Clang Documentation

Release 3.9

The Clang Team

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Contents

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CHAPTER 1

Introduction

This document contains the release notes for the Clang C/C++/Objective-C frontend, part of the LLVM Compiler Infrastructure, release 3.9. Here we describe the status of Clang in some detail, including major improvements from the previous release and new feature work. For the general LLVM release notes, see the LLVM documentation. All LLVM releases may be downloaded from the LLVM releases web site.

For more information about Clang or LLVM, including information about the latest release, please check out the main please see the Clang Web Site or the LLVM Web Site.

CHAPTER 2

What's New in Clang 3.9?

Some of the major new features and improvements to Clang are listed here. Generic improvements to Clang as a whole or to its underlying infrastructure are described first, followed by language-specific sections with improvements to Clang's support for those languages.

Major New Features

- Clang will no longer pass `--build-id` by default to the linker. In modern linkers that is a relatively expensive option. It can be passed explicitly with `-Wl,--build-id`. To have clang always pass it, build clang with `-DENABLE_LINKER_BUILD_ID`.
- On Itanium ABI targets, attribute abi_tag is now supported for compatibility with GCC. Clang's implementation of abi_tag is mostly compatible with GCC ABI version 10.

Improvements to Clang's diagnostics

Clang's diagnostics are constantly being improved to catch more issues, explain them more clearly, and provide more accurate source information about them. The improvements since the 3.8 release include:

- `-Wcomma` is a new warning to show most uses of the builtin comma operator.
- `-Wfloat-conversion` has two new sub-warnings to give finer grain control for floating point to integer conversion warnings.
  - `-Wfloat-overflow-conversion` detects when a constant floating point value is converted to an integer type and will overflow the target type.
  - `-Wfloat-zero-conversion` detects when a non-zero floating point value is converted to a zero integer value.

Attribute Changes in Clang

- The `nodebug` attribute may now be applied to static, global, and local variables (but not parameters or non-static data members). This will suppress all debugging information for the variable (and its type, if there are no other uses of the type).

Windows Support

TLS is enabled for Cygwin and defaults to -femulated-tls.

Proper support, including correct mangling and overloading, added for MS-specific "__unaligned" type qualifier.

clang-cl now has limited support for the precompiled header flags /Yc, /Yu, and /Fp. If the precompiled header is passed on the compile command with /FI, then the precompiled header flags are honored. But if the precompiled header is included by an `#include <stdafx.h>` in each source file instead of by a `/FIstdafx.h` flag, these flag continue to be ignored.

clang-cl has a new flag, `/imsvc <dir>`, for adding a directory to the system include search path (where warnings are disabled by default) without having to set `%INCLUDE%`.

C Language Changes in Clang

The -faltivec and -maltivec flags no longer silently include altivec.h on Power platforms.

RenderScript support has been added to the frontend and enabled by the '-x renderscript' option or the '.rs' file extension.

C++ Language Changes in Clang

- Clang now enforces the rule that a *using-declaration* cannot name an enumerator of a scoped enumeration.

```
namespace Foo { enum class E { e }; }
namespace Bar {
  using Foo::E::e; // error
  constexpr auto e = Foo::E::e; // ok
}
```

- Clang now enforces the rule that an enumerator of an unscoped enumeration declared at class scope can only be named by a *using-declaration* in a derived class.

```
class Foo { enum E { e }; }
using Foo::e; // error
static constexpr auto e = Foo::e; // ok
```

C++1z Feature Support

Clang's experimental support for the upcoming C++1z standard can be enabled with `-std=c++1z`. Changes to C++1z features since Clang 3.8:

- The `[[fallthrough]]`, `[[nodiscard]]`, and `[[maybe_unused]]` attributes are supported in C++11 onwards, and are largely synonymous with Clang's existing attributes `[[clang::fallthrough]]`, `[[gnu::warn_unused_result]]`, and `[[gnu::unused]]`. Use `-Wimplicit-fallthrough` to warn on unannotated fallthrough within `switch` statements.
- In C++1z mode, aggregate initialization can be performed for classes with base classes:

```
struct A { int n; };
struct B : A { int x, y; };
B b = { 1, 2, 3 }; // b.n == 1, b.x == 2, b.y == 3
```

- The range in a range-based `for` statement can have different types for its `begin` and `end` iterators. This is permitted as an extension in C++11 onwards.
- Lambda-expressions can explicitly capture `*this` (to capture the surrounding object by copy). This is permitted as an extension in C++11 onwards.
- Objects of enumeration type can be direct-list-initialized from a value of the underlying type. `E{n}` is equivalent to `E(n)`, except that it implies a check for a narrowing conversion.
- Unary *fold-expressions* over an empty pack are now rejected for all operators other than `&&`, `||`, and `,`.

OpenCL C Language Changes in Clang

Clang now has support for all OpenCL 2.0 features. In particular, the following features have been completed since the previous release:

- Pipe builtin functions (s6.13.16.2-4).
- Dynamic parallelism support via the `enqueue_kernel` Clang builtin function, as well as the kernel query functions from s6.13.17.6.
- Address space conversion functions `to_{global/local/private}`.
- `nosvm` attribute support.
- Improved diagnostic and generation of Clang Blocks used in OpenCL kernel code.
- `opencl_unroll_hint` pragma.

Several miscellaneous improvements have been made:

- Supported extensions are now part of the target representation to give correct diagnostics for unsupported target features during compilation. For example, when compiling for a target that does not support the double precision floating point extension, Clang will give an error when encountering the `cl_khr_fp64` pragma. Several missing extensions were added covering up to and including OpenCL 2.0.
- Clang now comes with the OpenCL standard headers declaring builtin types and functions up to and including OpenCL 2.0 in `lib/Headers/opencl-c.h`. By default, Clang will not include this header. It can be included either using the regular `-I<path to header location>` directive or (if the default one from installation is to be used) using the `-finclude-default-header` frontend flag.

  Example:

```
echo "bool is_wg_uniform(int i){return get_enqueued_local_size(i)==get_local_
↪size(i);}" > test.cl
clang -cc1 -finclude-default-header -cl-std=CL2.0 test.cl
```

  All builtin function declarations from OpenCL 2.0 will be automatically visible in test.cl.

- Image types have been improved with better diagnostics for access qualifiers. Images with one access qualifier type cannot be used in declarations for another type. Also qualifiers are now propagated from the frontend down to libraries and backends.
- Diagnostic improvements for OpenCL types, address spaces and vectors.
- Half type literal support has been added. For example, `1.0h` represents a floating point literal in half precision, i.e., the value `0xH3C00`.
- The Clang driver now accepts OpenCL compiler options `-cl-*` (following the OpenCL Spec v1.1-1.2 s5.8). For example, the `-cl-std=CL1.2` option from the spec enables compilation for OpenCL 1.2, or `-cl-mad-enable` will enable fusing multiply-and-add operations.
- Clang now uses function metadata instead of module metadata to propagate information related to OpenCL kernels e.g. kernel argument information.

OpenMP Support in Clang

Added support for all non-offloading features from OpenMP 4.5, including using data members in private clauses of non-static member functions. Additionally, data members can be used as loop control variables in loop-based directives.

Currently Clang supports OpenMP 3.1 and all non-offloading features of OpenMP 4.0/4.5. Offloading features are under development. Clang defines macro _OPENMP and sets it to OpenMP 3.1 (in accordance with OpenMP standard) by default. User may change this value using `-fopenmp-version=[31|40|45]` option.

The codegen for OpenMP constructs was significantly improved to produce much more stable and faster code.

AST Matchers

- has and hasAnyArgument: Matchers no longer ignore parentheses and implicit casts on the argument before applying the inner matcher. The fix was done to allow for greater control by the user. In all existing checkers that use this matcher all instances of code `hasAnyArgument(<inner matcher>)` or `has(<inner matcher>)` must be changed to `hasAnyArgument(ignoringParenImpCasts(<inner matcher>))` or `has(ignoringParenImpCasts(<inner matcher>))`.

Static Analyzer

The analyzer now checks for incorrect usage of MPI APIs in C and C++. This check can be enabled by passing the following command to scan-build: `-enable-checker optin.mpi.MPI-Checker`.

The analyzer now checks for improper instance cleanup up in Objective-C `-dealloc` methods under manual retain/release.

On Windows, checks for memory leaks, double frees, and use-after-free problems are now enabled by default.

The analyzer now includes scan-build-py, an experimental reimplementation of scan-build in Python that also creates compilation databases.

The scan-build tool now supports a `--force-analyze-debug-code` flag that forces projects to analyze in debug mode. This flag leaves in assertions and so typically results in fewer false positives.

CHAPTER 3

Additional Information

A wide variety of additional information is available on the Clang web page. The web page contains versions of the API documentation which are up-to-date with the Subversion version of the source code. You can access versions of these documents specific to this release by going into the "`clang/docs/`" directory in the Clang tree.

If you have any questions or comments about Clang, please feel free to contact us via the mailing list.

CHAPTER 4

Using Clang as a Compiler

Clang Compiler User's Manual

Introduction

The Clang Compiler is an open-source compiler for the C family of programming languages, aiming to be the best in class implementation of these languages. Clang builds on the LLVM optimizer and code generator, allowing it to provide high-quality optimization and code generation support for many targets. For more general information, please see the Clang Web Site or the LLVM Web Site.

This document describes important notes about using Clang as a compiler for an end-user, documenting the supported features, command line options, etc. If you are interested in using Clang to build a tool that processes code, please see *"Clang" CFE Internals Manual*. If you are interested in the Clang Static Analyzer, please see its web page.

Clang is designed to support the C family of programming languages, which includes *C*, *Objective-C*, *C++*, and *Objective-C++* as well as many dialects of those. For language-specific information, please see the corresponding language specific section:

- *C Language*: K&R C, ANSI C89, ISO C90, ISO C94 (C89+AMD1), ISO C99 (+TC1, TC2, TC3).
- *Objective-C Language*: ObjC 1, ObjC 2, ObjC 2.1, plus variants depending on base language.
- *C++ Language*
- *Objective C++ Language*

In addition to these base languages and their dialects, Clang supports a broad variety of language extensions, which are documented in the corresponding language section. These extensions are provided to be compatible with the GCC, Microsoft, and other popular compilers as well as to improve functionality through Clang-specific features. The Clang driver and language features are intentionally designed to be as compatible with the GNU GCC compiler as reasonably possible, easing migration from GCC to Clang. In most cases, code "just works". Clang also provides an alternative driver, *clang-cl*, that is designed to be compatible with the Visual C++ compiler, cl.exe.

In addition to language specific features, Clang has a variety of features that depend on what CPU architecture or operating system is being compiled for. Please see the *Target-Specific Features and Limitations* section for more details.

The rest of the introduction introduces some basic *compiler terminology* that is used throughout this manual and contains a basic *introduction to using Clang* as a command line compiler.

Terminology

Front end, parser, backend, preprocessor, undefined behavior, diagnostic, optimizer

Basic Usage

Intro to how to use a C compiler for newbies.

compile + link compile then link debug info enabling optimizations picking a language to use, defaults to C11 by default. Autosenses based on extension. using a makefile

Command Line Options

This section is generally an index into other sections. It does not go into depth on the ones that are covered by other sections. However, the first part introduces the language selection and other high level options like `-c`, `-g`, etc.

Options to Control Error and Warning Messages

-Werror
Turn warnings into errors.

`-Werror=foo`

Turn warning "foo" into an error.

-Wno-error=foo
Turn warning "foo" into an warning even if `-Werror` is specified.

-Wfoo
Enable warning "foo".

-Wno-foo
Disable warning "foo".

-w
Disable all diagnostics.

-Weverything
Enable all diagnostics.

-pedantic
Warn on language extensions.

-pedantic-errors
Error on language extensions.

-Wsystem-headers
Enable warnings from system headers.

-ferror-limit=123
Stop emitting diagnostics after 123 errors have been produced. The default is 20, and the error limit can be disabled with *-ferror-limit=0*.

-ftemplate-backtrace-limit=123
Only emit up to 123 template instantiation notes within the template instantiation backtrace for a single warning or error. The default is 10, and the limit can be disabled with *-ftemplate-backtrace-limit=0*.

Formatting of Diagnostics

Clang aims to produce beautiful diagnostics by default, particularly for new users that first come to Clang. However, different people have different preferences, and sometimes Clang is driven not by a human, but by a program that wants consistent and easily parsable output. For these cases, Clang provides a wide range of options to control the exact output format of the diagnostics that it generates.

-f[no-]show-column Print column number in diagnostic.

This option, which defaults to on, controls whether or not Clang prints the column number of a diagnostic. For example, when this is enabled, Clang will print something like:

```
test.c:28:8: warning: extra tokens at end of #endif directive [-Wextra-tokens]
#endif bad
       ^
       //
```

When this is disabled, Clang will print "test.c:28: warning..." with no column number.

The printed column numbers count bytes from the beginning of the line; take care if your source contains multibyte characters.

-f[no-]show-source-location Print source file/line/column information in diagnostic.

This option, which defaults to on, controls whether or not Clang prints the filename, line number and column number of a diagnostic. For example, when this is enabled, Clang will print something like:

```
test.c:28:8: warning: extra tokens at end of #endif directive [-Wextra-tokens]
#endif bad
       ^
       //
```

When this is disabled, Clang will not print the "test.c:28:8: " part.

-f[no-]caret-diagnostics Print source line and ranges from source code in diagnostic. This option, which defaults to on, controls whether or not Clang prints the source line, source ranges, and caret when emitting a diagnostic. For example, when this is enabled, Clang will print something like:

```
test.c:28:8: warning: extra tokens at end of #endif directive [-Wextra-tokens]
#endif bad
       ^
       //
```

-f[no-]color-diagnostics This option, which defaults to on when a color-capable terminal is detected, controls whether or not Clang prints diagnostics in color.

When this option is enabled, Clang will use colors to highlight specific parts of the diagnostic, e.g.,

When this is disabled, Clang will just print:

```
test.c:2:8: warning: extra tokens at end of #endif directive [-Wextra-tokens]
#endif bad
       ^
       //
```

-fansi-escape-codes Controls whether ANSI escape codes are used instead of the Windows Console API to output colored diagnostics. This option is only used on Windows and defaults to off.

-fdiagnostics-format=clang/msvc/vi
Changes diagnostic output format to better match IDEs and command line tools.

This option controls the output format of the filename, line number, and column printed in diagnostic messages. The options, and their affect on formatting a simple conversion diagnostic, follow:

clang (default)

```
t.c:3:11: warning: conversion specifies type 'char *' but the argument has␣
↪type 'int'
```

msvc

```
t.c(3,11) : warning: conversion specifies type 'char *' but the argument has␣
↪type 'int'
```

vi

```
t.c +3:11: warning: conversion specifies type 'char *' but the argument has␣
↪type 'int'
```

-f[no-]diagnostics-show-option Enable `[-Woption]` information in diagnostic line.

This option, which defaults to on, controls whether or not Clang prints the associated *warning group* option name when outputting a warning diagnostic. For example, in this output:

```
test.c:28:8: warning: extra tokens at end of #endif directive [-Wextra-tokens]
#endif bad
       ^
       //
```

Passing **-fno-diagnostics-show-option** will prevent Clang from printing the [*-Wextra-tokens*] information in the diagnostic. This information tells you the flag needed to enable or disable the diagnostic, either from the command line or through *#pragma GCC diagnostic*.

-fdiagnostics-show-category=none/id/name
Enable printing category information in diagnostic line.

This option, which defaults to "none", controls whether or not Clang prints the category associated with a diagnostic when emitting it. Each diagnostic may or many not have an associated category, if it has one, it is listed in the diagnostic categorization field of the diagnostic line (in the []'s).

For example, a format string warning will produce these three renditions based on the setting of this option:

```
t.c:3:11: warning: conversion specifies type 'char *' but the argument has type
↪'int' [-Wformat]
t.c:3:11: warning: conversion specifies type 'char *' but the argument has type
↪'int' [-Wformat,1]
t.c:3:11: warning: conversion specifies type 'char *' but the argument has type
↪'int' [-Wformat,Format String]
```

This category can be used by clients that want to group diagnostics by category, so it should be a high level category. We want dozens of these, not hundreds or thousands of them.

-f[no-]diagnostics-fixit-info Enable "FixIt" information in the diagnostics output.

This option, which defaults to on, controls whether or not Clang prints the information on how to fix a specific diagnostic underneath it when it knows. For example, in this output:

```
test.c:28:8: warning: extra tokens at end of #endif directive [-Wextra-tokens]
#endif bad
       ^
       //
```

Passing **-fno-diagnostics-fixit-info** will prevent Clang from printing the "//" line at the end of the message. This information is useful for users who may not understand what is wrong, but can be confusing for machine parsing.

-fdiagnostics-print-source-range-info Print machine parsable information about source ranges. This option makes Clang print information about source ranges in a machine parsable format after the file/line/column number information. The information is a simple sequence of brace enclosed ranges, where each range lists the start and end line/column locations. For example, in this output:

```
exprs.c:47:15:{47:8-47:14}{47:17-47:24}: error: invalid operands to binary␣
↪expression ('int *' and '_Complex float')
   P = (P-42) + Gamma*4;
       ~~~~~~ ^ ~~~~~~~
```

The {}'s are generated by -fdiagnostics-print-source-range-info.

The printed column numbers count bytes from the beginning of the line; take care if your source contains multibyte characters.

-fdiagnostics-parseable-fixits
Print Fix-Its in a machine parseable form.

This option makes Clang print available Fix-Its in a machine parseable format at the end of diagnostics. The following example illustrates the format:

```
fix-it:"t.cpp":{7:25-7:29}:"Gamma"
```

The range printed is a half-open range, so in this example the characters at column 25 up to but not including column 29 on line 7 in t.cpp should be replaced with the string "Gamma". Either the range or the replacement string may be empty (representing strict insertions and strict erasures, respectively). Both the file name and the insertion string escape backslash (as "\\"), tabs (as "\t"), newlines (as "\n"), double quotes(as "\"") and non-printable characters (as octal "\xxx").

The printed column numbers count bytes from the beginning of the line; take care if your source contains multibyte characters.

-fno-elide-type
Turns off elision in template type printing.

The default for template type printing is to elide as many template arguments as possible, removing those which are the same in both template types, leaving only the differences. Adding this flag will print all the template arguments. If supported by the terminal, highlighting will still appear on differing arguments.

Default:

```
t.cc:4:5: note: candidate function not viable: no known conversion from 'vector
↪<map<[...], map<float, [...]>>>' to 'vector<map<[...], map<double, [...]>>>'␣
↪for 1st argument;
```

-fno-elide-type:

```
t.cc:4:5: note: candidate function not viable: no known conversion from 'vector
↪<map<int, map<float, int>>>' to 'vector<map<int, map<double, int>>>' for 1st␣
↪argument;
```

-fdiagnostics-show-template-tree
Template type diffing prints a text tree.

For diffing large templated types, this option will cause Clang to display the templates as an indented text tree, one argument per line, with differences marked inline. This is compatible with -fno-elide-type.

Default:

```
t.cc:4:5: note: candidate function not viable: no known conversion from 'vector
↪<map<[...], map<float, [...]>>>' to 'vector<map<[...], map<double, [...]>>>'␣
↪for 1st argument;
```

With *-fdiagnostics-show-template-tree*:

```
t.cc:4:5: note: candidate function not viable: no known conversion for 1st␣
↪argument;
  vector<
    map<
      [...],
      map<
        [float != double],
        [...]>>>
```

Individual Warning Groups

TODO: Generate this from tblgen. Define one anchor per warning group.

-Wextra-tokens
Warn about excess tokens at the end of a preprocessor directive.

This option, which defaults to on, enables warnings about extra tokens at the end of preprocessor directives. For example:

```
test.c:28:8: warning: extra tokens at end of #endif directive [-Wextra-tokens]
#endif bad
       ^
```

These extra tokens are not strictly conforming, and are usually best handled by commenting them out.

-Wambiguous-member-template
Warn about unqualified uses of a member template whose name resolves to another template at the location of the use.

This option, which defaults to on, enables a warning in the following code:

```
template<typename T> struct set{};
template<typename T> struct trait { typedef const T& type; };
struct Value {
  template<typename T> void set(typename trait<T>::type value) {}
};
void foo() {
  Value v;
  v.set<double>(3.2);
}
```

C++ [basic.lookup.classref] requires this to be an error, but, because it's hard to work around, Clang downgrades it to a warning as an extension.

-Wbind-to-temporary-copy
Warn about an unusable copy constructor when binding a reference to a temporary.

This option enables warnings about binding a reference to a temporary when the temporary doesn't have a usable copy constructor. For example:

```
struct NonCopyable {
  NonCopyable();
private:
  NonCopyable(const NonCopyable&);
};
void foo(const NonCopyable&);
void bar() {
  foo(NonCopyable());  // Disallowed in C++98; allowed in C++11.
}
```

```
struct NonCopyable2 {
  NonCopyable2();
  NonCopyable2(NonCopyable2&);
};
void foo(const NonCopyable2&);
void bar() {
  foo(NonCopyable2());  // Disallowed in C++98; allowed in C++11.
}
```

Note that if `NonCopyable2::NonCopyable2()` has a default argument whose instantiation produces a compile error, that error will still be a hard error in C++98 mode even if this warning is turned off.

Options to Control Clang Crash Diagnostics

As unbelievable as it may sound, Clang does crash from time to time. Generally, this only occurs to those living on the bleeding edge. Clang goes to great lengths to assist you in filing a bug report. Specifically, Clang generates preprocessed source file(s) and associated run script(s) upon a crash. These files should be attached to a bug report to ease reproducibility of the failure. Below are the command line options to control the crash diagnostics.

-fno-crash-diagnostics
Disable auto-generation of preprocessed source files during a clang crash.

The -fno-crash-diagnostics flag can be helpful for speeding the process of generating a delta reduced test case.

Options to Emit Optimization Reports

Optimization reports trace, at a high-level, all the major decisions done by compiler transformations. For instance, when the inliner decides to inline function `foo()` into `bar()`, or the loop unroller decides to unroll a loop N times, or the vectorizer decides to vectorize a loop body.

Clang offers a family of flags which the optimizers can use to emit a diagnostic in three cases:

1. When the pass makes a transformation (*-Rpass*).
2. When the pass fails to make a transformation (*-Rpass-missed*).
3. When the pass determines whether or not to make a transformation (*-Rpass-analysis*).

NOTE: Although the discussion below focuses on *-Rpass*, the exact same options apply to *-Rpass-missed* and *-Rpass-analysis*.

Since there are dozens of passes inside the compiler, each of these flags take a regular expression that identifies the name of the pass which should emit the associated diagnostic. For example, to get a report from the inliner, compile the code with:

```
$ clang -O2 -Rpass=inline code.cc -o code
code.cc:4:25: remark: foo inlined into bar [-Rpass=inline]
```

```
int bar(int j) { return foo(j, j - 2); }
                        ^
```

Note that remarks from the inliner are identified with *[-Rpass=inline]*. To request a report from every optimization pass, you should use *-Rpass=.** (in fact, you can use any valid POSIX regular expression). However, do not expect a report from every transformation made by the compiler. Optimization remarks do not really make sense outside of the major transformations (e.g., inlining, vectorization, loop optimizations) and not every optimization pass supports this feature.

Current limitations

1. Optimization remarks that refer to function names will display the mangled name of the function. Since these remarks are emitted by the back end of the compiler, it does not know anything about the input language, nor its mangling rules.
2. Some source locations are not displayed correctly. The front end has a more detailed source location tracking than the locations included in the debug info (e.g., the front end can locate code inside macro expansions). However, the locations used by *-Rpass* are translated from debug annotations. That translation can be lossy, which results in some remarks having no location information.

Other Options

Clang options that that don't fit neatly into other categories.

-MV
: When emitting a dependency file, use formatting conventions appropriate for NMake or Jom. Ignored unless another option causes Clang to emit a dependency file.

When Clang emits a dependency file (e.g., you supplied the -M option) most filenames can be written to the file without any special formatting. Different Make tools will treat different sets of characters as "special" and use different conventions for telling the Make tool that the character is actually part of the filename. Normally Clang uses backslash to "escape" a special character, which is the convention used by GNU Make. The -MV option tells Clang to put double-quotes around the entire filename, which is the convention used by NMake and Jom.

Language and Target-Independent Features

Controlling Errors and Warnings

Clang provides a number of ways to control which code constructs cause it to emit errors and warning messages, and how they are displayed to the console.

Controlling How Clang Displays Diagnostics

When Clang emits a diagnostic, it includes rich information in the output, and gives you fine-grain control over which information is printed. Clang has the ability to print this information, and these are the options that control it:

1. A file/line/column indicator that shows exactly where the diagnostic occurs in your code [*-fshow-column*, *-fshow-source-location*].
2. A categorization of the diagnostic as a note, warning, error, or fatal error.
3. A text string that describes what the problem is.

4. An option that indicates how to control the diagnostic (for diagnostics that support it) [*-fdiagnostics-show-option*].
5. A *high-level category* for the diagnostic for clients that want to group diagnostics by class (for diagnostics that support it) [*-fdiagnostics-show-category*].
6. The line of source code that the issue occurs on, along with a caret and ranges that indicate the important locations [*-fcaret-diagnostics*].
7. "FixIt" information, which is a concise explanation of how to fix the problem (when Clang is certain it knows) [*-fdiagnostics-fixit-info*].
8. A machine-parsable representation of the ranges involved (off by default) [*-fdiagnostics-print-source-range-info*].

For more information please see *Formatting of Diagnostics*.

Diagnostic Mappings

All diagnostics are mapped into one of these 6 classes:

- Ignored
- Note
- Remark
- Warning
- Error
- Fatal

Diagnostic Categories

Though not shown by default, diagnostics may each be associated with a high-level category. This category is intended to make it possible to triage builds that produce a large number of errors or warnings in a grouped way.

Categories are not shown by default, but they can be turned on with the *-fdiagnostics-show-category* option. When set to "`name`", the category is printed textually in the diagnostic output. When it is set to "`id`", a category number is printed. The mapping of category names to category id's can be obtained by running '`clang --print-diagnostic-categories`'.

Controlling Diagnostics via Command Line Flags

TODO: -W flags, -pedantic, etc

Controlling Diagnostics via Pragmas

Clang can also control what diagnostics are enabled through the use of pragmas in the source code. This is useful for turning off specific warnings in a section of source code. Clang supports GCC's pragma for compatibility with existing source code, as well as several extensions.

The pragma may control any warning that can be used from the command line. Warnings may be set to ignored, warning, error, or fatal. The following example code will tell Clang or GCC to ignore the -Wall warnings:

```
#pragma GCC diagnostic ignored "-Wall"
```

In addition to all of the functionality provided by GCC's pragma, Clang also allows you to push and pop the current warning state. This is particularly useful when writing a header file that will be compiled by other people, because you don't know what warning flags they build with.

In the below example `-Wextra-tokens` is ignored for only a single line of code, after which the diagnostics return to whatever state had previously existed.

```
#if foo
#endif foo // warning: extra tokens at end of #endif directive

#pragma clang diagnostic ignored "-Wextra-tokens"

#if foo
#endif foo // no warning

#pragma clang diagnostic pop
```

The push and pop pragmas will save and restore the full diagnostic state of the compiler, regardless of how it was set. That means that it is possible to use push and pop around GCC compatible diagnostics and Clang will push and pop them appropriately, while GCC will ignore the pushes and pops as unknown pragmas. It should be noted that while Clang supports the GCC pragma, Clang and GCC do not support the exact same set of warnings, so even when using GCC compatible #pragmas there is no guarantee that they will have identical behaviour on both compilers.

In addition to controlling warnings and errors generated by the compiler, it is possible to generate custom warning and error messages through the following pragmas:

```
// The following will produce warning messages
#pragma message "some diagnostic message"
#pragma GCC warning "TODO: replace deprecated feature"

// The following will produce an error message
#pragma GCC error "Not supported"
```

These pragmas operate similarly to the `#warning` and `#error` preprocessor directives, except that they may also be embedded into preprocessor macros via the C99 `_Pragma` operator, for example:

```
#define STR(X) #X
#define DEFER(M,...) M(__VA_ARGS__)
#define CUSTOM_ERROR(X) _Pragma(STR(GCC error(X " at line " DEFER(STR,__LINE__))))

CUSTOM_ERROR("Feature not available");
```

Controlling Diagnostics in System Headers

Warnings are suppressed when they occur in system headers. By default, an included file is treated as a system header if it is found in an include path specified by `-isystem`, but this can be overridden in several ways.

The `system_header` pragma can be used to mark the current file as being a system header. No warnings will be produced from the location of the pragma onwards within the same file.

```
#if foo
#endif foo // warning: extra tokens at end of #endif directive

#pragma clang system_header
```

```
#if foo
#endif foo // no warning
```

The *–system-header-prefix=* and *–no-system-header-prefix=* command-line arguments can be used to override whether subsets of an include path are treated as system headers. When the name in a `#include` directive is found within a header search path and starts with a system prefix, the header is treated as a system header. The last prefix on the command-line which matches the specified header name takes precedence. For instance:

```
$ clang -Ifoo -isystem bar --system-header-prefix=x/ \
    --no-system-header-prefix=x/y/
```

Here, `#include "x/a.h"` is treated as including a system header, even if the header is found in `foo`, and `#include "x/y/b.h"` is treated as not including a system header, even if the header is found in `bar`.

A `#include` directive which finds a file relative to the current directory is treated as including a system header if the including file is treated as a system header.

Enabling All Diagnostics

In addition to the traditional `-W` flags, one can enable **all** diagnostics by passing *`-Weverything`*. This works as expected with *`-Werror`*, and also includes the warnings from *`-pedantic`*.

Note that when combined with *`-w`* (which disables all warnings), that flag wins.

Controlling Static Analyzer Diagnostics

While not strictly part of the compiler, the diagnostics from Clang's static analyzer can also be influenced by the user via changes to the source code. See the available annotations and the analyzer's FAQ page for more information.

Precompiled Headers

Precompiled headers are a general approach employed by many compilers to reduce compilation time. The underlying motivation of the approach is that it is common for the same (and often large) header files to be included by multiple source files. Consequently, compile times can often be greatly improved by caching some of the (redundant) work done by a compiler to process headers. Precompiled header files, which represent one of many ways to implement this optimization, are literally files that represent an on-disk cache that contains the vital information necessary to reduce some of the work needed to process a corresponding header file. While details of precompiled headers vary between compilers, precompiled headers have been shown to be highly effective at speeding up program compilation on systems with very large system headers (e.g., Mac OS X).

Generating a PCH File

To generate a PCH file using Clang, one invokes Clang with the *-x <language>-header* option. This mirrors the interface in GCC for generating PCH files:

```
$ gcc -x c-header test.h -o test.h.gch
$ clang -x c-header test.h -o test.h.pch
```

Using a PCH File

A PCH file can then be used as a prefix header when a *-include* option is passed to `clang`:

```
$ clang -include test.h test.c -o test
```

The `clang` driver will first check if a PCH file for `test.h` is available; if so, the contents of `test.h` (and the files it includes) will be processed from the PCH file. Otherwise, Clang falls back to directly processing the content of `test.h`. This mirrors the behavior of GCC.

Note: Clang does *not* automatically use PCH files for headers that are directly included within a source file. For example:

```
$ clang -x c-header test.h -o test.h.pch
$ cat test.c
#include "test.h"
$ clang test.c -o test
```

In this example, `clang` will not automatically use the PCH file for `test.h` since `test.h` was included directly in the source file and not specified on the command line using *-include*.

Relocatable PCH Files

It is sometimes necessary to build a precompiled header from headers that are not yet in their final, installed locations. For example, one might build a precompiled header within the build tree that is then meant to be installed alongside the headers. Clang permits the creation of "relocatable" precompiled headers, which are built with a given path (into the build directory) and can later be used from an installed location.

To build a relocatable precompiled header, place your headers into a subdirectory whose structure mimics the installed location. For example, if you want to build a precompiled header for the header `mylib.h` that will be installed into `/usr/include`, create a subdirectory `build/usr/include` and place the header `mylib.h` into that subdirectory. If `mylib.h` depends on other headers, then they can be stored within `build/usr/include` in a way that mimics the installed location.

Building a relocatable precompiled header requires two additional arguments. First, pass the `--relocatable-pch` flag to indicate that the resulting PCH file should be relocatable. Second, pass *-isysroot /path/to/build*, which makes all includes for your library relative to the build directory. For example:

```
# clang -x c-header --relocatable-pch -isysroot /path/to/build /path/to/build/mylib.h␣
↪mylib.h.pch
```

When loading the relocatable PCH file, the various headers used in the PCH file are found from the system header root. For example, `mylib.h` can be found in `/usr/include/mylib.h`. If the headers are installed in some other system root, the *-isysroot* option can be used provide a different system root from which the headers will be based. For example, *-isysroot /Developer/SDKs/MacOSX10.4u.sdk* will look for `mylib.h` in `/Developer/SDKs/MacOSX10.4u.sdk/usr/include/mylib.h`.

Relocatable precompiled headers are intended to be used in a limited number of cases where the compilation environment is tightly controlled and the precompiled header cannot be generated after headers have been installed.

Controlling Code Generation

Clang provides a number of ways to control code generation. The options are listed below.

-f[no-]sanitize=check1,check2,... Turn on runtime checks for various forms of undefined or suspicious behavior.

This option controls whether Clang adds runtime checks for various forms of undefined or suspicious behavior, and is disabled by default. If a check fails, a diagnostic message is produced at runtime explaining the problem. The main checks are:

- `-fsanitize=address`: *AddressSanitizer*, a memory error detector.
- `-fsanitize=thread`: *ThreadSanitizer*, a data race detector.
- `-fsanitize=memory`: *MemorySanitizer*, a detector of uninitialized reads. Requires instrumentation of all program code.
- `-fsanitize=undefined`: *UndefinedBehaviorSanitizer*, a fast and compatible undefined behavior checker.
- `-fsanitize=dataflow`: *DataFlowSanitizer*, a general data flow analysis.
- `-fsanitize=cfi`: *control flow integrity* checks. Requires `-flto`.
- `-fsanitize=safe-stack`: *safe stack* protection against stack-based memory corruption errors.

There are more fine-grained checks available: see the *list* of specific kinds of undefined behavior that can be detected and the *list* of control flow integrity schemes.

The `-fsanitize=` argument must also be provided when linking, in order to link to the appropriate runtime library.

It is not possible to combine more than one of the `-fsanitize=address`, `-fsanitize=thread`, and `-fsanitize=memory` checkers in the same program.

-f[no-]sanitize-recover=check1,check2,...

-f[no-]sanitize-recover=all

Controls which checks enabled by `-fsanitize=` flag are non-fatal. If the check is fatal, program will halt after the first error of this kind is detected and error report is printed.

By default, non-fatal checks are those enabled by *UndefinedBehaviorSanitizer*, except for `-fsanitize=return` and `-fsanitize=unreachable`. Some sanitizers may not support recovery (or not support it by default e.g. *AddressSanitizer*), and always crash the program after the issue is detected.

Note that the `-fsanitize-trap` flag has precedence over this flag. This means that if a check has been configured to trap elsewhere on the command line, or if the check traps by default, this flag will not have any effect unless that sanitizer's trapping behavior is disabled with `-fno-sanitize-trap`.

For example, if a command line contains the flags `-fsanitize=undefined -fsanitize-trap=undefined`, the flag `-fsanitize-recover=alignment` will have no effect on its own; it will need to be accompanied by `-fno-sanitize-trap=alignment`.

-f[no-]sanitize-trap=check1,check2,...

Controls which checks enabled by the `-fsanitize=` flag trap. This option is intended for use in cases where the sanitizer runtime cannot be used (for instance, when building libc or a kernel module), or where the binary size increase caused by the sanitizer runtime is a concern.

This flag is only compatible with *control flow integrity* schemes and *UndefinedBehaviorSanitizer* checks other than `vptr`. If this flag is supplied together with `-fsanitize=undefined`, the `vptr` sanitizer will be implicitly disabled.

This flag is enabled by default for sanitizers in the `cfi` group.

-fsanitize-blacklist=/path/to/blacklist/file
Disable or modify sanitizer checks for objects (source files, functions, variables, types) listed in the file. See *Sanitizer special case list* for file format description.

-fno-sanitize-blacklist
Don't use blacklist file, if it was specified earlier in the command line.

-f[no-]sanitize-coverage=[type,features,...]

Enable simple code coverage in addition to certain sanitizers. See *SanitizerCoverage* for more details.

-f[no-]sanitize-stats

Enable simple statistics gathering for the enabled sanitizers. See *SanitizerStats* for more details.

-fsanitize-undefined-trap-on-error
Deprecated alias for `-fsanitize-trap=undefined`.

-fsanitize-cfi-cross-dso
Enable cross-DSO control flow integrity checks. This flag modifies the behavior of sanitizers in the `cfi` group to allow checking of cross-DSO virtual and indirect calls.

-ffast-math
Enable fast-math mode. This defines the `__FAST_MATH__` preprocessor macro, and lets the compiler make aggressive, potentially-lossy assumptions about floating-point math. These include:

- Floating-point math obeys regular algebraic rules for real numbers (e.g. `+` and `*` are associative, `x/y == x * (1/y)`, and `(a + b) * c == a * c + b * c`),
- operands to floating-point operations are not equal to `NaN` and `Inf`, and
- `+0` and `-0` are interchangeable.

-fwhole-program-vtables
Enable whole-program vtable optimizations, such as single-implementation devirtualization and virtual constant propagation, for classes with *hidden LTO visibility*. Requires `-flto`.

-fno-assume-sane-operator-new
Don't assume that the C++'s new operator is sane.

This option tells the compiler to do not assume that C++'s global new operator will always return a pointer that does not alias any other pointer when the function returns.

-ftrap-function=[name]
Instruct code generator to emit a function call to the specified function name for `__builtin_trap()`.

LLVM code generator translates `__builtin_trap()` to a trap instruction if it is supported by the target ISA. Otherwise, the builtin is translated into a call to `abort`. If this option is set, then the code generator will always lower the builtin to a call to the specified function regardless of whether the target ISA has a trap instruction. This option is useful for environments (e.g. deeply embedded) where a trap cannot be properly handled, or when some custom behavior is desired.

-ftls-model=[model]
Select which TLS model to use.

Valid values are: `global-dynamic`, `local-dynamic`, `initial-exec` and `local-exec`. The default value is `global-dynamic`. The compiler may use a different model if the selected model is not supported by the target, or if a more efficient model can be used. The TLS model can be overridden per variable using the `tls_model` attribute.

-femulated-tls
Select emulated TLS model, which overrides all -ftls-model choices.

In emulated TLS mode, all access to TLS variables are converted to calls to __emutls_get_address in the runtime library.

-mhwdiv=[values]
Select the ARM modes (arm or thumb) that support hardware division instructions.

Valid values are: `arm`, `thumb` and `arm,thumb`. This option is used to indicate which mode (arm or thumb) supports hardware division instructions. This only applies to the ARM architecture.

-m[no-]crc
Enable or disable CRC instructions.

This option is used to indicate whether CRC instructions are to be generated. This only applies to the ARM architecture.

CRC instructions are enabled by default on ARMv8.

-mgeneral-regs-only
Generate code which only uses the general purpose registers.

This option restricts the generated code to use general registers only. This only applies to the AArch64 architecture.

-mcompact-branches=[values]
Control the usage of compact branches for MIPSR6.

Valid values are: `never`, `optimal` and `always`. The default value is `optimal` which generates compact branches when a delay slot cannot be filled. `never` disables the usage of compact branches and `always` generates compact branches whenever possible.

-f[no-]max-type-align=[number] Instruct the code generator to not enforce a higher alignment than the given number (of bytes) when accessing memory via an opaque pointer or reference. This cap is ignored when directly accessing a variable or when the pointee type has an explicit "aligned" attribute.

The value should usually be determined by the properties of the system allocator. Some builtin types, especially vector types, have very high natural alignments; when working with values of those types, Clang usually wants to use instructions that take advantage of that alignment. However, many system allocators do not promise to return memory that is more than 8-byte or 16-byte-aligned. Use this option to limit the alignment that the compiler can assume for an arbitrary pointer, which may point onto the heap.

This option does not affect the ABI alignment of types; the layout of structs and unions and the value returned by the alignof operator remain the same.

This option can be overridden on a case-by-case basis by putting an explicit "aligned" alignment on a struct, union, or typedef. For example:

```
#include <immintrin.h>
// Make an aligned typedef of the AVX-512 16-int vector type.
typedef __v16si __aligned_v16si __attribute__((aligned(64)));

void initialize_vector(__aligned_v16si *v) {
  // The compiler may assume that 'v' is 64-byte aligned, regardless of the
  // value of -fmax-type-align.
}
```

Profile Guided Optimization

Profile information enables better optimization. For example, knowing that a branch is taken very frequently helps the compiler make better decisions when ordering basic blocks. Knowing that a function `foo` is called more frequently than another function `bar` helps the inliner.

Clang supports profile guided optimization with two different kinds of profiling. A sampling profiler can generate a profile with very low runtime overhead, or you can build an instrumented version of the code that collects more detailed profile information. Both kinds of profiles can provide execution counts for instructions in the code and information on branches taken and function invocation.

Regardless of which kind of profiling you use, be careful to collect profiles by running your code with inputs that are representative of the typical behavior. Code that is not exercised in the profile will be optimized as if it is unimportant, and the compiler may make poor optimization choices for code that is disproportionately used while profiling.

Differences Between Sampling and Instrumentation

Although both techniques are used for similar purposes, there are important differences between the two:

1. Profile data generated with one cannot be used by the other, and there is no conversion tool that can convert one to the other. So, a profile generated via `-fprofile-instr-generate` must be used with `-fprofile-instr-use`. Similarly, sampling profiles generated by external profilers must be converted and used with `-fprofile-sample-use`.
2. Instrumentation profile data can be used for code coverage analysis and optimization.
3. Sampling profiles can only be used for optimization. They cannot be used for code coverage analysis. Although it would be technically possible to use sampling profiles for code coverage, sample-based profiles are too coarse-grained for code coverage purposes; it would yield poor results.
4. Sampling profiles must be generated by an external tool. The profile generated by that tool must then be converted into a format that can be read by LLVM. The section on sampling profilers describes one of the supported sampling profile formats.

Using Sampling Profilers

Sampling profilers are used to collect runtime information, such as hardware counters, while your application executes. They are typically very efficient and do not incur a large runtime overhead. The sample data collected by the profiler can be used during compilation to determine what the most executed areas of the code are.

Using the data from a sample profiler requires some changes in the way a program is built. Before the compiler can use profiling information, the code needs to execute under the profiler. The following is the usual build cycle when using sample profilers for optimization:

1. Build the code with source line table information. You can use all the usual build flags that you always build your application with. The only requirement is that you add `-gline-tables-only` or `-g` to the command line. This is important for the profiler to be able to map instructions back to source line locations.

   ```
   $ clang++ -O2 -gline-tables-only code.cc -o code
   ```

2. Run the executable under a sampling profiler. The specific profiler you use does not really matter, as long as its output can be converted into the format that the LLVM optimizer understands. Currently, there exists a conversion tool for the Linux Perf profiler (https://perf.wiki.kernel.org/), so these examples assume that you are using Linux Perf to profile your code.

   ```
   $ perf record -b ./code
   ```

   Note the use of the `-b` flag. This tells Perf to use the Last Branch Record (LBR) to record call chains. While this is not strictly required, it provides better call information, which improves the accuracy of the profile data.

3. Convert the collected profile data to LLVM's sample profile format. This is currently supported via the AutoFDO converter `create_llvm_prof`. It is available at http://github.com/google/autofdo. Once built and installed, you can convert the `perf.data` file to LLVM using the command:

```
$ create_llvm_prof --binary=./code --out=code.prof
```

This will read `perf.data` and the binary file `./code` and emit the profile data in `code.prof`. Note that if you ran `perf` without the `-b` flag, you need to use `--use_lbr=false` when calling `create_llvm_prof`.

4. Build the code again using the collected profile. This step feeds the profile back to the optimizers. This should result in a binary that executes faster than the original one. Note that you are not required to build the code with the exact same arguments that you used in the first step. The only requirement is that you build the code with `-gline-tables-only` and `-fprofile-sample-use`.

```
$ clang++ -O2 -gline-tables-only -fprofile-sample-use=code.prof code.cc -o code
```

Sample Profile Formats

Since external profilers generate profile data in a variety of custom formats, the data generated by the profiler must be converted into a format that can be read by the backend. LLVM supports three different sample profile formats:

1. ASCII text. This is the easiest one to generate. The file is divided into sections, which correspond to each of the functions with profile information. The format is described below. It can also be generated from the binary or gcov formats using the `llvm-profdata` tool.
2. Binary encoding. This uses a more efficient encoding that yields smaller profile files. This is the format generated by the `create_llvm_prof` tool in http://github.com/google/autofdo.
3. GCC encoding. This is based on the gcov format, which is accepted by GCC. It is only interesting in environments where GCC and Clang co-exist. This encoding is only generated by the `create_gcov` tool in http://github.com/google/autofdo. It can be read by LLVM and `llvm-profdata`, but it cannot be generated by either.

If you are using Linux Perf to generate sampling profiles, you can use the conversion tool `create_llvm_prof` described in the previous section. Otherwise, you will need to write a conversion tool that converts your profiler's native format into one of these three.

Sample Profile Text Format

This section describes the ASCII text format for sampling profiles. It is, arguably, the easiest one to generate. If you are interested in generating any of the other two, consult the `ProfileData` library in in LLVM's source tree (specifically, `include/llvm/ProfileData/SampleProfReader.h`).

```
function1:total_samples:total_head_samples
 offset1[.discriminator]: number_of_samples [fn1:num fn2:num ... ]
 offset2[.discriminator]: number_of_samples [fn3:num fn4:num ... ]
 ...
 offsetN[.discriminator]: number_of_samples [fn5:num fn6:num ... ]
 offsetA[.discriminator]: fnA:num_of_total_samples
  offsetA1[.discriminator]: number_of_samples [fn7:num fn8:num ... ]
  offsetA1[.discriminator]: number_of_samples [fn9:num fn10:num ... ]
  offsetB[.discriminator]: fnB:num_of_total_samples
   offsetB1[.discriminator]: number_of_samples [fn11:num fn12:num ... ]
```

This is a nested tree in which the identation represents the nesting level of the inline stack. There are no blank lines in the file. And the spacing within a single line is fixed. Additional spaces will result in an error while reading the file.

Any line starting with the '#' character is completely ignored.

Inlined calls are represented with indentation. The Inline stack is a stack of source locations in which the top of the stack represents the leaf function, and the bottom of the stack represents the actual symbol to which the instruction belongs.

Function names must be mangled in order for the profile loader to match them in the current translation unit. The two numbers in the function header specify how many total samples were accumulated in the function (first number), and the total number of samples accumulated in the prologue of the function (second number). This head sample count provides an indicator of how frequently the function is invoked.

There are two types of lines in the function body.

- Sampled line represents the profile information of a source location. `offsetN[.discriminator]: number_of_samples [fn5:num fn6:num ... ]`
- Callsite line represents the profile information of an inlined callsite. `offsetA[.discriminator]: fnA:num_of_total_samples`

Each sampled line may contain several items. Some are optional (marked below):

1. Source line offset. This number represents the line number in the function where the sample was collected. The line number is always relative to the line where symbol of the function is defined. So, if the function has its header at line 280, the offset 13 is at line 293 in the file.

   Note that this offset should never be a negative number. This could happen in cases like macros. The debug machinery will register the line number at the point of macro expansion. So, if the macro was expanded in a line before the start of the function, the profile converter should emit a 0 as the offset (this means that the optimizers will not be able to associate a meaningful weight to the instructions in the macro).

2. [OPTIONAL] Discriminator. This is used if the sampled program was compiled with DWARF discriminator support (http://wiki.dwarfstd.org/index.php?title=Path_Discriminators). DWARF discriminators are unsigned integer values that allow the compiler to distinguish between multiple execution paths on the same source line location.

   For example, consider the line of code `if (cond) foo(); else bar();`. If the predicate `cond` is true 80% of the time, then the edge into function `foo` should be considered to be taken most of the time. But both calls to `foo` and `bar` are at the same source line, so a sample count at that line is not sufficient. The compiler needs to know which part of that line is taken more frequently.

   This is what discriminators provide. In this case, the calls to `foo` and `bar` will be at the same line, but will have different discriminator values. This allows the compiler to correctly set edge weights into `foo` and `bar`.

3. Number of samples. This is an integer quantity representing the number of samples collected by the profiler at this source location.

4. [OPTIONAL] Potential call targets and samples. If present, this line contains a call instruction. This models both direct and number of samples. For example,

   ```
   130: 7  foo:3  bar:2  baz:7
   ```

   The above means that at relative line offset 130 there is a call instruction that calls one of `foo()`, `bar()` and `baz()`, with `baz()` being the relatively more frequently called target.

As an example, consider a program with the call chain `main -> foo -> bar`. When built with optimizations enabled, the compiler may inline the calls to `bar` and `foo` inside `main`. The generated profile could then be something like this:

```
main:35504:0
1: _Z3foov:35504
  2: _Z32bari:31977
  1.1: 31977
2: 0
```

This profile indicates that there were a total of 35,504 samples collected in main. All of those were at line 1 (the call to `foo`). Of those, 31,977 were spent inside the body of `bar`. The last line of the profile (`2: 0`) corresponds to line 2 inside `main`. No samples were collected there.

Profiling with Instrumentation

Clang also supports profiling via instrumentation. This requires building a special instrumented version of the code and has some runtime overhead during the profiling, but it provides more detailed results than a sampling profiler. It also provides reproducible results, at least to the extent that the code behaves consistently across runs.

Here are the steps for using profile guided optimization with instrumentation:

1. Build an instrumented version of the code by compiling and linking with the `-fprofile-instr-generate` option.

```
$ clang++ -O2 -fprofile-instr-generate code.cc -o code
```

2. Run the instrumented executable with inputs that reflect the typical usage. By default, the profile data will be written to a `default.profraw` file in the current directory. You can override that default by setting the `LLVM_PROFILE_FILE` environment variable to specify an alternate file. Any instance of `%p` in that file name will be replaced by the process ID, so that you can easily distinguish the profile output from multiple runs.

```
$ LLVM_PROFILE_FILE="code-%p.profraw" ./code
```

3. Combine profiles from multiple runs and convert the "raw" profile format to the input expected by clang. Use the `merge` command of the `llvm-profdata` tool to do this.

```
$ llvm-profdata merge -output=code.profdata code-*.profraw
```

   Note that this step is necessary even when there is only one "raw" profile, since the merge operation also changes the file format.

4. Build the code again using the `-fprofile-instr-use` option to specify the collected profile data.

```
$ clang++ -O2 -fprofile-instr-use=code.profdata code.cc -o code
```

   You can repeat step 4 as often as you like without regenerating the profile. As you make changes to your code, clang may no longer be able to use the profile data. It will warn you when this happens.

Profile generation using an alternative instrumentation method can be controlled by the GCC-compatible flags `-fprofile-generate` and `-fprofile-use`. Although these flags are semantically equivalent to their GCC counterparts, they *do not* handle GCC-compatible profiles. They are only meant to implement GCC's semantics with respect to profile creation and use.

`-fprofile-generate``[=<dirname>]`

The `-fprofile-generate` and `-fprofile-generate=` flags will use an alterantive instrumentation method for profile generation. When given a directory name, it generates the profile file `default.profraw` in the directory named `dirname`. If `dirname` does not exist, it will be created at runtime. The environment variable `LLVM_PROFILE_FILE` can be used to override the directory and filename for the profile file at runtime. For example,

```
$ clang++ -O2 -fprofile-generate=yyy/zzz code.cc -o code
```

When `code` is executed, the profile will be written to the file `yyy/zzz/default.profraw`. This can be altered at runtime via the `LLVM_PROFILE_FILE` environment variable:

```
$ LLVM_PROFILE_FILE=/tmp/myprofile/code.profraw ./code
```

The above invocation will produce the profile file `/tmp/myprofile/code.profraw` instead of `yyy/zzz/default.profraw`. Notice that `LLVM_PROFILE_FILE` overrides the directory *and* the file name for the profile file.

-fprofile-use[=<pathname>]
Without any other arguments, `-fprofile-use` behaves identically to `-fprofile-instr-use`. Otherwise, if `pathname` is the full path to a profile file, it reads from that file. If `pathname` is a directory name, it reads from `pathname/default.profdata`.

Disabling Instrumentation

In certain situations, it may be useful to disable profile generation or use for specific files in a build, without affecting the main compilation flags used for the other files in the project.

In these cases, you can use the flag `-fno-profile-instr-generate` (or `-fno-profile-generate`) to disable profile generation, and `-fno-profile-instr-use` (or `-fno-profile-use`) to disable profile use.

Note that these flags should appear after the corresponding profile flags to have an effect.

Controlling Debug Information

Controlling Size of Debug Information

Debug info kind generated by Clang can be set by one of the flags listed below. If multiple flags are present, the last one is used.

-g0
Don't generate any debug info (default).

-gline-tables-only
Generate line number tables only.

This kind of debug info allows to obtain stack traces with function names, file names and line numbers (by such tools as `gdb` or `addr2line`). It doesn't contain any other data (e.g. description of local variables or function parameters).

-fstandalone-debug
Clang supports a number of optimizations to reduce the size of debug information in the binary. They work based on the assumption that the debug type information can be spread out over multiple compilation units. For instance, Clang will not emit type definitions for types that are not needed by a module and could be replaced with a forward declaration. Further, Clang will only emit type info for a dynamic C++ class in the module that contains the vtable for the class.

The **-fstandalone-debug** option turns off these optimizations. This is useful when working with 3rd-party libraries that don't come with debug information. Note that Clang will never emit type information for types that are not referenced at all by the program.

-fno-standalone-debug
On Darwin **-fstandalone-debug** is enabled by default. The **-fno-standalone-debug** option can be used to get to turn on the vtable-based optimization described above.

-g
Generate complete debug info.

Controlling Debugger "Tuning"

While Clang generally emits standard DWARF debug info (http://dwarfstd.org), different debuggers may know how to take advantage of different specific DWARF features. You can "tune" the debug info for one of several different debuggers.

-ggdb, -glldb, -gsce
Tune the debug info for the `gdb`, `lldb`, or Sony Computer Entertainment debugger, respectively. Each of these options implies **-g**. (Therefore, if you want both **-gline-tables-only** and debugger tuning, the tuning option must come first.)

Comment Parsing Options

Clang parses Doxygen and non-Doxygen style documentation comments and attaches them to the appropriate declaration nodes. By default, it only parses Doxygen-style comments and ignores ordinary comments starting with `//` and `/*`.

-Wdocumentation
Emit warnings about use of documentation comments. This warning group is off by default.

This includes checking that `\param` commands name parameters that actually present in the function signature, checking that `\returns` is used only on functions that actually return a value etc.

-Wno-documentation-unknown-command
Don't warn when encountering an unknown Doxygen command.

-fparse-all-comments
Parse all comments as documentation comments (including ordinary comments starting with `//` and `/*`).

-fcomment-block-commands`=[commands]`
Define custom documentation commands as block commands. This allows Clang to construct the correct AST for these custom commands, and silences warnings about unknown commands. Several commands must be separated by a comma *without trailing space*; e.g. `-fcomment-block-commands=foo,bar` defines custom commands `\foo` and `\bar`.

It is also possible to use `-fcomment-block-commands` several times; e.g. `-fcomment-block-commands=foo -fcomment-block-commands=bar` does the same as above.

C Language Features

The support for standard C in clang is feature-complete except for the C99 floating-point pragmas.

Extensions supported by clang

See *Clang Language Extensions*.

Differences between various standard modes

clang supports the -std option, which changes what language mode clang uses. The supported modes for C are c89, gnu89, c94, c99, gnu99, c11, gnu11, and various aliases for those modes. If no -std option is specified, clang defaults to gnu11 mode. Many C99 and C11 features are supported in earlier modes as a conforming extension, with a warning. Use `-pedantic-errors` to request an error if a feature from a later standard revision is used in an earlier mode.

Differences between all `c*` and `gnu*` modes:

- `c*` modes define "__STRICT_ANSI__".
- Target-specific defines not prefixed by underscores, like "linux", are defined in `gnu*` modes.
- Trigraphs default to being off in `gnu*` modes; they can be enabled by the -trigraphs option.
- The parser recognizes "asm" and "typeof" as keywords in `gnu*` modes; the variants "__asm__" and "__typeof__" are recognized in all modes.
- The Apple "blocks" extension is recognized by default in `gnu*` modes on some platforms; it can be enabled in any mode with the "-fblocks" option.
- Arrays that are VLA's according to the standard, but which can be constant folded by the frontend are treated as fixed size arrays. This occurs for things like "int X[(1, 2)];", which is technically a VLA. `c*` modes are strictly compliant and treat these as VLAs.

Differences between `*89` and `*99` modes:

- The `*99` modes default to implementing "inline" as specified in C99, while the `*89` modes implement the GNU version. This can be overridden for individual functions with the __gnu_inline__ attribute.
- Digraphs are not recognized in c89 mode.
- The scope of names defined inside a "for", "if", "switch", "while", or "do" statement is different. (example: "`if ((struct x {int x;}*)0) {}`".)
- __STDC_VERSION__ is not defined in `*89` modes.
- "inline" is not recognized as a keyword in c89 mode.
- "restrict" is not recognized as a keyword in `*89` modes.
- Commas are allowed in integer constant expressions in `*99` modes.
- Arrays which are not lvalues are not implicitly promoted to pointers in `*89` modes.
- Some warnings are different.

Differences between `*99` and `*11` modes:

- Warnings for use of C11 features are disabled.
- __STDC_VERSION__ is defined to `201112L` rather than `199901L`.

c94 mode is identical to c89 mode except that digraphs are enabled in c94 mode (FIXME: And __STDC_VERSION__ should be defined!).

GCC extensions not implemented yet

clang tries to be compatible with gcc as much as possible, but some gcc extensions are not implemented yet:

- clang does not support decimal floating point types (`_Decimal32` and friends) or fixed-point types (`_Fract` and friends); nobody has expressed interest in these features yet, so it's hard to say when they will be implemented.
- clang does not support nested functions; this is a complex feature which is infrequently used, so it is unlikely to be implemented anytime soon. In C++11 it can be emulated by assigning lambda functions to local variables, e.g:

```
auto const local_function = [&](int parameter) {
  // Do something
};
...
local_function(1);
```

- clang does not support static initialization of flexible array members. This appears to be a rarely used extension, but could be implemented pending user demand.
- clang does not support `__builtin_va_arg_pack`/`__builtin_va_arg_pack_len`. This is used rarely, but in some potentially interesting places, like the glibc headers, so it may be implemented pending user demand. Note that because clang pretends to be like GCC 4.2, and this extension was introduced in 4.3, the glibc headers will not try to use this extension with clang at the moment.
- clang does not support the gcc extension for forward-declaring function parameters; this has not shown up in any real-world code yet, though, so it might never be implemented.

This is not a complete list; if you find an unsupported extension missing from this list, please send an e-mail to cfe-dev. This list currently excludes C++; see *C++ Language Features*. Also, this list does not include bugs in mostly-implemented features; please see the bug tracker for known existing bugs (FIXME: Is there a section for bug-reporting guidelines somewhere?).

Intentionally unsupported GCC extensions

- clang does not support the gcc extension that allows variable-length arrays in structures. This is for a few reasons: one, it is tricky to implement, two, the extension is completely undocumented, and three, the extension appears to be rarely used. Note that clang *does* support flexible array members (arrays with a zero or unspecified size at the end of a structure).
- clang does not have an equivalent to gcc's "fold"; this means that clang doesn't accept some constructs gcc might accept in contexts where a constant expression is required, like "x-x" where x is a variable.
- clang does not support `__builtin_apply` and friends; this extension is extremely obscure and difficult to implement reliably.

Microsoft extensions

clang has support for many extensions from Microsoft Visual C++. To enable these extensions, use the `-fms-extensions` command-line option. This is the default for Windows targets. Clang does not implement every pragma or declspec provided by MSVC, but the popular ones, such as `__declspec(dllexport)` and `#pragma comment(lib)` are well supported.

clang has a `-fms-compatibility` flag that makes clang accept enough invalid C++ to be able to parse most Microsoft headers. For example, it allows unqualified lookup of dependent base class members, which is a common compatibility issue with clang. This flag is enabled by default for Windows targets.

`-fdelayed-template-parsing` lets clang delay parsing of function template definitions until the end of a translation unit. This flag is enabled by default for Windows targets.

For compatibility with existing code that compiles with MSVC, clang defines the `_MSC_VER` and `_MSC_FULL_VER` macros. These default to the values of 1800 and 180000000 respectively, making clang look like an early release of Visual C++ 2013. The `-fms-compatibility-version=` flag overrides these values. It accepts a dotted version tuple, such as 19.00.23506. Changing the MSVC compatibility version makes clang behave more like that version of MSVC. For example, `-fms-compatibility-version=19` will enable C++14 features and define `char16_t` and `char32_t` as builtin types.

C++ Language Features

clang fully implements all of standard C++98 except for exported templates (which were removed in C++11), and all of standard C++11 and the current draft standard for C++1y.

Controlling implementation limits

-fbracket-depth=N
Sets the limit for nested parentheses, brackets, and braces to N. The default is 256.

-fconstexpr-depth=N
Sets the limit for recursive constexpr function invocations to N. The default is 512.

-ftemplate-depth=N
Sets the limit for recursively nested template instantiations to N. The default is 256.

-foperator-arrow-depth=N
Sets the limit for iterative calls to 'operator->' functions to N. The default is 256.

Objective-C Language Features

Objective-C++ Language Features

OpenMP Features

Clang supports all OpenMP 3.1 directives and clauses. In addition, some features of OpenMP 4.0 are supported. For example, `#pragma omp simd`, `#pragma omp for simd`, `#pragma omp parallel for simd` directives, extended set of atomic constructs, `proc_bind` clause for all parallel-based directives, `depend` clause for `#pragma omp task` directive (except for array sections), `#pragma omp cancel` and `#pragma omp cancellation point` directives, and `#pragma omp taskgroup` directive.

Use *-fopenmp* to enable OpenMP. Support for OpenMP can be disabled with *-fno-openmp*.

Controlling implementation limits

-fopenmp-use-tls
Controls code generation for OpenMP threadprivate variables. In presence of this option all threadprivate variables are generated the same way as thread local variables, using TLS support. If *-fno-openmp-use-tls* is provided or target does not support TLS, code generation for threadprivate variables relies on OpenMP runtime library.

Target-Specific Features and Limitations

CPU Architectures Features and Limitations

X86

The support for X86 (both 32-bit and 64-bit) is considered stable on Darwin (Mac OS X), Linux, FreeBSD, and Dragonfly BSD: it has been tested to correctly compile many large C, C++, Objective-C, and Objective-C++ codebases.

On `x86_64-mingw32`, passing i128(by value) is incompatible with the Microsoft x64 calling convention. You might need to tweak `WinX86_64ABIInfo::classify()` in lib/CodeGen/TargetInfo.cpp.

For the X86 target, clang supports the *-m16* command line argument which enables 16-bit code output. This is broadly similar to using `asm(".code16gcc")` with the GNU toolchain. The generated code and the ABI remains 32-bit but the assembler emits instructions appropriate for a CPU running in 16-bit mode, with address-size and operand-size prefixes to enable 32-bit addressing and operations.

ARM

The support for ARM (specifically ARMv6 and ARMv7) is considered stable on Darwin (iOS): it has been tested to correctly compile many large C, C++, Objective-C, and Objective-C++ codebases. Clang only supports a limited number of ARM architectures. It does not yet fully support ARMv5, for example.

PowerPC

The support for PowerPC (especially PowerPC64) is considered stable on Linux and FreeBSD: it has been tested to correctly compile many large C and C++ codebases. PowerPC (32bit) is still missing certain features (e.g. PIC code on ELF platforms).

Other platforms

clang currently contains some support for other architectures (e.g. Sparc); however, significant pieces of code generation are still missing, and they haven't undergone significant testing.

clang contains limited support for the MSP430 embedded processor, but both the clang support and the LLVM backend support are highly experimental.

Other platforms are completely unsupported at the moment. Adding the minimal support needed for parsing and semantic analysis on a new platform is quite easy; see `lib/Basic/Targets.cpp` in the clang source tree. This level of support is also sufficient for conversion to LLVM IR for simple programs. Proper support for conversion to LLVM IR requires adding code to `lib/CodeGen/CGCall.cpp` at the moment; this is likely to change soon, though. Generating assembly requires a suitable LLVM backend.

Operating System Features and Limitations

Darwin (Mac OS X)

Thread Sanitizer is not supported.

Windows

Clang has experimental support for targeting "Cygming" (Cygwin / MinGW) platforms.

See also *Microsoft Extensions*.

Cygwin

Clang works on Cygwin-1.7.

MinGW32

Clang works on some mingw32 distributions. Clang assumes directories as below;

- `C:/mingw/include`
- `C:/mingw/lib`
- `C:/mingw/lib/gcc/mingw32/4.[3-5].0/include/c++`

On MSYS, a few tests might fail.

MinGW-w64

For 32-bit (i686-w64-mingw32), and 64-bit (x86_64-w64-mingw32), Clang assumes as below;

- `GCC versions 4.5.0 to 4.5.3, 4.6.0 to 4.6.2, or 4.7.0 (for the C++ header search path)`
- `some_directory/bin/gcc.exe`
- `some_directory/bin/clang.exe`
- `some_directory/bin/clang++.exe`
- `some_directory/bin/../include/c++/GCC_version`
- `some_directory/bin/../include/c++/GCC_version/x86_64-w64-mingw32`
- `some_directory/bin/../include/c++/GCC_version/i686-w64-mingw32`
- `some_directory/bin/../include/c++/GCC_version/backward`
- `some_directory/bin/../x86_64-w64-mingw32/include`
- `some_directory/bin/../i686-w64-mingw32/include`
- `some_directory/bin/../include`

This directory layout is standard for any toolchain you will find on the official MinGW-w64 website.

Clang expects the GCC executable "gcc.exe" compiled for `i686-w64-mingw32` (or `x86_64-w64-mingw32`) to be present on PATH.

Some tests might fail on `x86_64-w64-mingw32`.

clang-cl

clang-cl is an alternative command-line interface to Clang driver, designed for compatibility with the Visual C++ compiler, cl.exe.

To enable clang-cl to find system headers, libraries, and the linker when run from the command-line, it should be executed inside a Visual Studio Native Tools Command Prompt or a regular Command Prompt where the environment has been set up using e.g. vcvars32.bat.

clang-cl can also be used from inside Visual Studio by using an LLVM Platform Toolset.

Command-Line Options

To be compatible with cl.exe, clang-cl supports most of the same command-line options. Those options can start with either `/` or `-`. It also supports some of Clang's core options, such as the `-W` options.

Options that are known to clang-cl, but not currently supported, are ignored with a warning. For example:

```
clang-cl.exe: warning: argument unused during compilation: '/AI'
```

To suppress warnings about unused arguments, use the `-Qunused-arguments` option.

Options that are not known to clang-cl will be ignored by default. Use the `-Werror=unknown-argument` option in order to treat them as errors. If these options are spelled with a leading `/`, they will be mistaken for a filename:

```
clang-cl.exe: error: no such file or directory: '/foobar'
```

Please file a bug for any valid cl.exe flags that clang-cl does not understand.

Execute `clang-cl /?` to see a list of supported options:

```
CL.EXE COMPATIBILITY OPTIONS:
  /?                      Display available options
  /arch:<value>           Set architecture for code generation
  /Brepro-                Emit an object file which cannot be reproduced over␣
↪time
  /Brepro                 Emit an object file which can be reproduced over␣
↪time
  /C                      Don't discard comments when preprocessing
  /c                      Compile only
  /D <macro[=value]>      Define macro
  /EH<value>              Exception handling model
  /EP                     Disable linemarker output and preprocess to stdout
  /E                      Preprocess to stdout
  /fallback               Fall back to cl.exe if clang-cl fails to compile
  /FA                     Output assembly code file during compilation
  /Fa<file or directory>  Output assembly code to this file during␣
↪compilation (with /FA)
  /Fe<file or directory>  Set output executable file or directory (ends in /␣
↪or \)
  /FI <value>             Include file before parsing
  /Fi<file>               Set preprocess output file name (with /P)
  /Fo<file or directory>  Set output object file, or directory (ends in / or␣
↪\) (with /c)
  /fp:except-
  /fp:except
  /fp:fast
  /fp:precise
  /fp:strict
  /Fp<filename>           Set pch filename (with /Yc and /Yu)
  /GA                     Assume thread-local variables are defined in the␣
↪executable
  /Gd                     Set __cdecl as a default calling convention
  /GF-                    Disable string pooling
  /GR-                    Disable emission of RTTI data
  /GR                     Enable emission of RTTI data
  /Gr                     Set __fastcall as a default calling convention
  /GS-                    Disable buffer security check
  /GS                     Enable buffer security check
  /Gs<value>              Set stack probe size
  /Gv                     Set __vectorcall as a default calling convention
  /Gw-                    Don't put each data item in its own section
  /Gw                     Put each data item in its own section
  /GX-                    Enable exception handling
  /GX                     Enable exception handling
  /Gy-                    Don't put each function in its own section
  /Gy                     Put each function in its own section
  /Gz                     Set __stdcall as a default calling convention
  /help                   Display available options
  /imsvc <dir>            Add directory to system include search path, as if␣
↪part of %INCLUDE%
  /I <dir>                Add directory to include search path
  /J                      Make char type unsigned
```

```
  /LDd                    Create debug DLL
  /LD                     Create DLL
  /link <options>         Forward options to the linker
  /MDd                    Use DLL debug run-time
  /MD                     Use DLL run-time
  /MTd                    Use static debug run-time
  /MT                     Use static run-time
  /Od                     Disable optimization
  /Oi-                    Disable use of builtin functions
  /Oi                     Enable use of builtin functions
  /Os                     Optimize for size
  /Ot                     Optimize for speed
  /O<value>               Optimization level
  /o <file or directory> Set output file or directory (ends in / or \)
  /P                      Preprocess to file
  /Qvec-                  Disable the loop vectorization passes
  /Qvec                   Enable the loop vectorization passes
  /showIncludes           Print info about included files to stderr
  /std:<value>            Language standard to compile for
  /TC                     Treat all source files as C
  /Tc <filename>          Specify a C source file
  /TP                     Treat all source files as C++
  /Tp <filename>          Specify a C++ source file
  /U <macro>              Undefine macro
  /vd<value>              Control vtordisp placement
  /vmb                    Use a best-case representation method for member␣
↪pointers
  /vmg                    Use a most-general representation for member␣
↪pointers
  /vmm                    Set the default most-general representation to␣
↪multiple inheritance
  /vms                    Set the default most-general representation to␣
↪single inheritance
  /vmv                    Set the default most-general representation to␣
↪virtual inheritance
  /volatile:iso           Volatile loads and stores have standard semantics
  /volatile:ms            Volatile loads and stores have acquire and release␣
↪semantics
  /W0                     Disable all warnings
  /W1                     Enable -Wall
  /W2                     Enable -Wall
  /W3                     Enable -Wall
  /W4                     Enable -Wall and -Wextra
  /Wall                   Enable -Wall and -Wextra
  /WX-                    Do not treat warnings as errors
  /WX                     Treat warnings as errors
  /w                      Disable all warnings
  /Y-                     Disable precompiled headers, overrides /Yc and /Yu
  /Yc<filename>           Generate a pch file for all code up to and␣
↪including <filename>
  /Yu<filename>           Load a pch file and use it instead of all code up␣
↪to and including <filename>
  /Z7                     Enable CodeView debug information in object files
  /Zc:sizedDealloc-       Disable C++14 sized global deallocation functions
  /Zc:sizedDealloc        Enable C++14 sized global deallocation functions
  /Zc:strictStrings       Treat string literals as const
  /Zc:threadSafeInit-     Disable thread-safe initialization of static␣
↪variables
```

```
  /Zc:threadSafeInit      Enable thread-safe initialization of static␣
↪variables
  /Zc:trigraphs-          Disable trigraphs (default)
  /Zc:trigraphs           Enable trigraphs
  /Zd                     Emit debug line number tables only
  /Zi                     Alias for /Z7. Does not produce PDBs.
  /Zl                     Don't mention any default libraries in the object␣
↪file
  /Zp                     Set the default maximum struct packing alignment to␣
↪1
  /Zp<value>              Specify the default maximum struct packing alignment
  /Zs                     Syntax-check only

OPTIONS:
  -###                     Print (but do not run) the commands to run for␣
↪this compilation
  --analyze                Run the static analyzer
  -fansi-escape-codes      Use ANSI escape codes for diagnostics
  -fcolor-diagnostics      Use colors in diagnostics
  -fdiagnostics-parseable-fixits
                           Print fix-its in machine parseable form
  -fms-compatibility-version=<value>
                           Dot-separated value representing the Microsoft␣
↪compiler version
                           number to report in _MSC_VER (0 = don't define it␣
↪(default))
  -fms-compatibility       Enable full Microsoft Visual C++ compatibility
  -fms-extensions          Accept some non-standard constructs supported by␣
↪the Microsoft compiler
  -fmsc-version=<value>    Microsoft compiler version number to report in _
↪MSC_VER
                           (0 = don't define it (default))
  -fno-sanitize-coverage=<value>
                           Disable specified features of coverage␣
↪instrumentation for Sanitizers
  -fno-sanitize-recover=<value>
                           Disable recovery for specified sanitizers
  -fno-sanitize-trap=<value>
                           Disable trapping for specified sanitizers
  -fsanitize-blacklist=<value>
                           Path to blacklist file for sanitizers
  -fsanitize-coverage=<value>
                           Specify the type of coverage instrumentation for␣
↪Sanitizers
  -fsanitize-recover=<value>
                           Enable recovery for specified sanitizers
  -fsanitize-trap=<value> Enable trapping for specified sanitizers
  -fsanitize=<check>       Turn on runtime checks for various forms of␣
↪undefined or suspicious
                           behavior. See user manual for available checks
  -gcodeview               Generate CodeView debug information
  -gline-tables-only       Emit debug line number tables only
  -miamcu                  Use Intel MCU ABI
  -mllvm <value>           Additional arguments to forward to LLVM's option␣
↪processing
  -Qunused-arguments       Don't emit warning for unused driver arguments
  -R<remark>               Enable the specified remark
  --target=<value>         Generate code for the given target
```

```
-v                      Show commands to run and use verbose output
-W<warning>             Enable the specified warning
-Xclang <arg>           Pass <arg> to the clang compiler
```

The /fallback Option

When clang-cl is run with the `/fallback` option, it will first try to compile files itself. For any file that it fails to compile, it will fall back and try to compile the file by invoking cl.exe.

This option is intended to be used as a temporary means to build projects where clang-cl cannot successfully compile all the files. clang-cl may fail to compile a file either because it cannot generate code for some C++ feature, or because it cannot parse some Microsoft language extension.

Clang Language Extensions

Objective-C Literals

Introduction

Three new features were introduced into clang at the same time: *NSNumber Literals* provide a syntax for creating `NSNumber` from scalar literal expressions; *Collection Literals* provide a short-hand for creating arrays and dictionaries; *Object Subscripting* provides a way to use subscripting with Objective-C objects. Users of Apple compiler releases can use these features starting with the Apple LLVM Compiler 4.0. Users of open-source LLVM.org compiler releases can use these features starting with clang v3.1.

These language additions simplify common Objective-C programming patterns, make programs more concise, and improve the safety of container creation.

This document describes how the features are implemented in clang, and how to use them in your own programs.

NSNumber Literals

The framework class `NSNumber` is used to wrap scalar values inside objects: signed and unsigned integers (`char`, `short`, `int`, `long`, `long long`), floating point numbers (`float`, `double`), and boolean values (`BOOL`, C++ `bool`). Scalar values wrapped in objects are also known as *boxed* values.

In Objective-C, any character, numeric or boolean literal prefixed with the `'@'` character will evaluate to a pointer to an `NSNumber` object initialized with that value. C's type suffixes may be used to control the size of numeric literals.

Examples

The following program illustrates the rules for `NSNumber` literals:

```
void main(int argc, const char *argv[]) {
  // character literals.
  NSNumber *theLetterZ = @'Z';          // equivalent to [NSNumber numberWithChar:'Z']

  // integral literals.
  NSNumber *fortyTwo = @42;             // equivalent to [NSNumber numberWithInt:42]
  NSNumber *fortyTwoUnsigned = @42U;    // equivalent to [NSNumber␣
↪numberWithUnsignedInt:42U]
  NSNumber *fortyTwoLong = @42L;        // equivalent to [NSNumber numberWithLong:42L]
  NSNumber *fortyTwoLongLong = @42LL;   // equivalent to [NSNumber␣
↪numberWithLongLong:42LL]

  // floating point literals.
  NSNumber *piFloat = @3.141592654F;    // equivalent to [NSNumber numberWithFloat:3.
↪141592654F]
  NSNumber *piDouble = @3.1415926535;   // equivalent to [NSNumber numberWithDouble:3.
↪1415926535]

  // BOOL literals.
  NSNumber *yesNumber = @YES;           // equivalent to [NSNumber numberWithBool:YES]
  NSNumber *noNumber = @NO;             // equivalent to [NSNumber numberWithBool:NO]

#ifdef __cplusplus
  NSNumber *trueNumber = @true;         // equivalent to [NSNumber␣
↪numberWithBool:(BOOL)true]
  NSNumber *falseNumber = @false;       // equivalent to [NSNumber␣
↪numberWithBool:(BOOL)false]
#endif
}
```

Discussion

NSNumber literals only support literal scalar values after the `'@'`. Consequently, `@INT_MAX` works, but `@INT_MIN` does not, because they are defined like this:

```
#define INT_MAX   2147483647  /* max value for an int */
#define INT_MIN   (-2147483647-1) /* min value for an int */
```

The definition of `INT_MIN` is not a simple literal, but a parenthesized expression. Parenthesized expressions are supported using the *boxed expression* syntax, which is described in the next section.

Because `NSNumber` does not currently support wrapping `long double` values, the use of a `long double NSNumber` literal (e.g. `@123.23L`) will be rejected by the compiler.

Previously, the `BOOL` type was simply a typedef for `signed char`, and `YES` and `NO` were macros that expand to `(BOOL)1` and `(BOOL)0` respectively. To support `@YES` and `@NO` expressions, these macros are now defined using new language keywords in `<objc/objc.h>`:

```
#if __has_feature(objc_bool)
#define YES             __objc_yes
#define NO              __objc_no
#else
#define YES             ((BOOL)1)
#define NO              ((BOOL)0)
#endif
```

The compiler implicitly converts `__objc_yes` and `__objc_no` to `(BOOL)1` and `(BOOL)0`. The keywords are used to disambiguate `BOOL` and integer literals.

Objective-C++ also supports `@true` and `@false` expressions, which are equivalent to `@YES` and `@NO`.

Boxed Expressions

Objective-C provides a new syntax for boxing C expressions:

```
@( <expression> )
```

Expressions of scalar (numeric, enumerated, BOOL), C string pointer and some C structures (via NSValue) are supported:

```
// numbers.
NSNumber *smallestInt = @(-INT_MAX - 1);  // [NSNumber numberWithInt:(-INT_MAX - 1)]
NSNumber *piOverTwo = @(M_PI / 2);        // [NSNumber numberWithDouble:(M_PI / 2)]

// enumerated types.
typedef enum { Red, Green, Blue } Color;
NSNumber *favoriteColor = @(Green);       // [NSNumber numberWithInt:((int)Green)]

// strings.
NSString *path = @(getenv("PATH"));       // [NSString stringWithUTF8String:(getenv(
↪"PATH"))]
NSArray *pathComponents = [path componentsSeparatedByString:@":"];

// structs.
NSValue *center = @(view.center);         // Point p = view.center;
                                          // [NSValue valueWithBytes:&p␣
↪objCType:@encode(Point)];
```

```
NSValue *frame = @(view.frame);           // Rect r = view.frame;
                                          // [NSValue valueWithBytes:&r␣
↪objCType:@encode(Rect)];
```

Boxed Enums

Cocoa frameworks frequently define constant values using *enums*. Although enum values are integral, they may not be used directly as boxed literals (this avoids conflicts with future `'@'`-prefixed Objective-C keywords). Instead, an enum value must be placed inside a boxed expression. The following example demonstrates configuring an `AVAudioRecorder` using a dictionary that contains a boxed enumeration value:

```
enum {
  AVAudioQualityMin = 0,
  AVAudioQualityLow = 0x20,
  AVAudioQualityMedium = 0x40,
  AVAudioQualityHigh = 0x60,
  AVAudioQualityMax = 0x7F
};

- (AVAudioRecorder *)recordToFile:(NSURL *)fileURL {
  NSDictionary *settings = @{ AVEncoderAudioQualityKey : @(AVAudioQualityMax) };
  return [[AVAudioRecorder alloc] initWithURL:fileURL settings:settings error:NULL];
}
```

The expression `@(AVAudioQualityMax)` converts `AVAudioQualityMax` to an integer type, and boxes the value accordingly. If the enum has a *fixed underlying type* as in:

```
typedef enum : unsigned char { Red, Green, Blue } Color;
NSNumber *red = @(Red), *green = @(Green), *blue = @(Blue); // => [NSNumber␣
↪numberWithUnsignedChar:]
```

then the fixed underlying type will be used to select the correct `NSNumber` creation method.

Boxing a value of enum type will result in a `NSNumber` pointer with a creation method according to the underlying type of the enum, which can be a *fixed underlying type* or a compiler-defined integer type capable of representing the values of all the members of the enumeration:

```
typedef enum : unsigned char { Red, Green, Blue } Color;
Color col = Red;
NSNumber *nsCol = @(col); // => [NSNumber numberWithUnsignedChar:]
```

Boxed C Strings

A C string literal prefixed by the `'@'` token denotes an `NSString` literal in the same way a numeric literal prefixed by the `'@'` token denotes an `NSNumber` literal. When the type of the parenthesized expression is `(char *)` or `(const char *)`, the result of the boxed expression is a pointer to an `NSString` object containing equivalent character data, which is assumed to be '\0'-terminated and UTF-8 encoded. The following example converts C-style command line arguments into `NSString` objects.

```
// Partition command line arguments into positional and option arguments.
NSMutableArray *args = [NSMutableArray new];
NSMutableDictionary *options = [NSMutableDictionary new];
while (--argc) {
    const char *arg = *++argv;
```

```
    if (strncmp(arg, "--", 2) == 0) {
        options[@(arg + 2)] = @(*++argv);    // --key value
    } else {
        [args addObject:@(arg)];             // positional argument
    }
}
```

As with all C pointers, character pointer expressions can involve arbitrary pointer arithmetic, therefore programmers must ensure that the character data is valid. Passing `NULL` as the character pointer will raise an exception at runtime. When possible, the compiler will reject `NULL` character pointers used in boxed expressions.

Boxed C Structures

Boxed expressions support construction of NSValue objects. It said that C structures can be used, the only requirement is: structure should be marked with `objc_boxable` attribute. To support older version of frameworks and/or third-party libraries you may need to add the attribute via `typedef`.

```
struct __attribute__((objc_boxable)) Point {
    // ...
};

typedef struct __attribute__((objc_boxable)) _Size {
    // ...
} Size;

typedef struct _Rect {
    // ...
} Rect;

struct Point p;
NSValue *point = @(p);          // ok
Size s;
NSValue *size = @(s);           // ok

Rect r;
NSValue *bad_rect = @(r);       // error

typedef struct __attribute__((objc_boxable)) _Rect Rect;

NSValue *good_rect = @(r);      // ok
```

Container Literals

Objective-C now supports a new expression syntax for creating immutable array and dictionary container objects.

Examples

Immutable array expression:

```
NSArray *array = @[ @"Hello", NSApp, [NSNumber numberWithInt:42] ];
```

This creates an `NSArray` with 3 elements. The comma-separated sub-expressions of an array literal can be any Objective-C object pointer typed expression.

Immutable dictionary expression:

```
NSDictionary *dictionary = @{
    @"name" : NSUserName(),
    @"date" : [NSDate date],
    @"processInfo" : [NSProcessInfo processInfo]
};
```

This creates an `NSDictionary` with 3 key/value pairs. Value sub-expressions of a dictionary literal must be Objective-C object pointer typed, as in array literals. Key sub-expressions must be of an Objective-C object pointer type that implements the `<NSCopying>` protocol.

Discussion

Neither keys nor values can have the value `nil` in containers. If the compiler can prove that a key or value is `nil` at compile time, then a warning will be emitted. Otherwise, a runtime error will occur.

Using array and dictionary literals is safer than the variadic creation forms commonly in use today. Array literal expressions expand to calls to `+[NSArray arrayWithObjects:count:]`, which validates that all objects are non-`nil`. The variadic form, `+[NSArray arrayWithObjects:]` uses `nil` as an argument list terminator, which can lead to malformed array objects. Dictionary literals are similarly created with `+[NSDictionary dictionaryWithObjects:forKeys:count:]` which validates all objects and keys, unlike `+[NSDictionary dictionaryWithObjectsAndKeys:]` which also uses a `nil` parameter as an argument list terminator.

Object Subscripting

Objective-C object pointer values can now be used with C's subscripting operator.

Examples

The following code demonstrates the use of object subscripting syntax with `NSMutableArray` and `NSMutableDictionary` objects:

```
NSMutableArray *array = ...;
NSUInteger idx = ...;
id newObject = ...;
id oldObject = array[idx];
array[idx] = newObject;         // replace oldObject with newObject

NSMutableDictionary *dictionary = ...;
NSString *key = ...;
oldObject = dictionary[key];
dictionary[key] = newObject;    // replace oldObject with newObject
```

The next section explains how subscripting expressions map to accessor methods.

Subscripting Methods

Objective-C supports two kinds of subscript expressions: *array-style* subscript expressions use integer typed subscripts; *dictionary-style* subscript expressions use Objective-C object pointer typed subscripts. Each type of subscript expression is mapped to a message send using a predefined selector. The advantage of this design is flexibility: class

designers are free to introduce subscripting by declaring methods or by adopting protocols. Moreover, because the method names are selected by the type of the subscript, an object can be subscripted using both array and dictionary styles.

Array-Style Subscripting

When the subscript operand has an integral type, the expression is rewritten to use one of two different selectors, depending on whether the element is being read or written. When an expression reads an element using an integral index, as in the following example:

```
NSUInteger idx = ...;
id value = object[idx];
```

it is translated into a call to `objectAtIndexedSubscript:`

```
id value = [object objectAtIndexedSubscript:idx];
```

When an expression writes an element using an integral index:

```
object[idx] = newValue;
```

it is translated to a call to `setObject:atIndexedSubscript:`

```
[object setObject:newValue atIndexedSubscript:idx];
```

These message sends are then type-checked and performed just like explicit message sends. The method used for objectAtIndexedSubscript: must be declared with an argument of integral type and a return value of some Objective-C object pointer type. The method used for setObject:atIndexedSubscript: must be declared with its first argument having some Objective-C pointer type and its second argument having integral type.

The meaning of indexes is left up to the declaring class. The compiler will coerce the index to the appropriate argument type of the method it uses for type-checking. For an instance of `NSArray`, reading an element using an index outside the range `[0, array.count)` will raise an exception. For an instance of `NSMutableArray`, assigning to an element using an index within this range will replace that element, but assigning to an element using an index outside this range will raise an exception; no syntax is provided for inserting, appending, or removing elements for mutable arrays.

A class need not declare both methods in order to take advantage of this language feature. For example, the class `NSArray` declares only `objectAtIndexedSubscript:`, so that assignments to elements will fail to type-check; moreover, its subclass `NSMutableArray` declares `setObject:atIndexedSubscript:`.

Dictionary-Style Subscripting

When the subscript operand has an Objective-C object pointer type, the expression is rewritten to use one of two different selectors, depending on whether the element is being read from or written to. When an expression reads an element using an Objective-C object pointer subscript operand, as in the following example:

```
id key = ...;
id value = object[key];
```

it is translated into a call to the `objectForKeyedSubscript:` method:

```
id value = [object objectForKeyedSubscript:key];
```

When an expression writes an element using an Objective-C object pointer subscript:

```
object[key] = newValue;
```

it is translated to a call to `setObject:forKeyedSubscript:`

```
[object setObject:newValue forKeyedSubscript:key];
```

The behavior of `setObject:forKeyedSubscript:` is class-specific; but in general it should replace an existing value if one is already associated with a key, otherwise it should add a new value for the key. No syntax is provided for removing elements from mutable dictionaries.

Discussion

An Objective-C subscript expression occurs when the base operand of the C subscript operator has an Objective-C object pointer type. Since this potentially collides with pointer arithmetic on the value, these expressions are only supported under the modern Objective-C runtime, which categorically forbids such arithmetic.

Currently, only subscripts of integral or Objective-C object pointer type are supported. In C++, a class type can be used if it has a single conversion function to an integral or Objective-C pointer type, in which case that conversion is applied and analysis continues as appropriate. Otherwise, the expression is ill-formed.

An Objective-C object subscript expression is always an l-value. If the expression appears on the left-hand side of a simple assignment operator (=), the element is written as described below. If the expression appears on the left-hand side of a compound assignment operator (e.g. +=), the program is ill-formed, because the result of reading an element is always an Objective-C object pointer and no binary operators are legal on such pointers. If the expression appears in any other position, the element is read as described below. It is an error to take the address of a subscript expression, or (in C++) to bind a reference to it.

Programs can use object subscripting with Objective-C object pointers of type `id`. Normal dynamic message send rules apply; the compiler must see *some* declaration of the subscripting methods, and will pick the declaration seen first.

Caveats

Objects created using the literal or boxed expression syntax are not guaranteed to be uniqued by the runtime, but nor are they guaranteed to be newly-allocated. As such, the result of performing direct comparisons against the location of an object literal (using ==, !=, <, <=, >, or >=) is not well-defined. This is usually a simple mistake in code that intended to call the `isEqual:` method (or the `compare:` method).

This caveat applies to compile-time string literals as well. Historically, string literals (using the `@"..."` syntax) have been uniqued across translation units during linking. This is an implementation detail of the compiler and should not be relied upon. If you are using such code, please use global string constants instead (`NSString * const MyConst = @"..."`) or use `isEqual:`.

Grammar Additions

To support the new syntax described above, the Objective-C `@`-expression grammar has the following new productions:

```
objc-at-expression : '@' (string-literal | encode-literal | selector-literal |␣
↪protocol-literal | object-literal)
                   ;

object-literal : ('+' | '-')? numeric-constant
               | character-constant
               | boolean-constant
```

```
                | array-literal
                | dictionary-literal
                ;

boolean-constant : '__objc_yes' | '__objc_no' | 'true' | 'false'  /* boolean keywords.
↪ */
                 ;

array-literal : '[' assignment-expression-list ']'
              ;

assignment-expression-list : assignment-expression (',' assignment-expression-list)?
                           | /* empty */
                           ;

dictionary-literal : '{' key-value-list '}'
                   ;

key-value-list : key-value-pair (',' key-value-list)?
               | /* empty */
               ;

key-value-pair : assignment-expression ':' assignment-expression
               ;
```

Note: `@true` and `@false` are only supported in Objective-C++.

Availability Checks

Programs test for the new features by using clang's __has_feature checks. Here are examples of their use:

```
#if __has_feature(objc_array_literals)
    // new way.
    NSArray *elements = @[ @"H", @"He", @"O", @"C" ];
#else
    // old way (equivalent).
    id objects[] = { @"H", @"He", @"O", @"C" };
    NSArray *elements = [NSArray arrayWithObjects:objects count:4];
#endif

#if __has_feature(objc_dictionary_literals)
    // new way.
    NSDictionary *masses = @{ @"H" : @1.0078,  @"He" : @4.0026, @"O" : @15.9990, @"C"␣
↪: @12.0096 };
#else
    // old way (equivalent).
    id keys[] = { @"H", @"He", @"O", @"C" };
    id values[] = { [NSNumber numberWithDouble:1.0078], [NSNumber numberWithDouble:4.
↪0026],
                    [NSNumber numberWithDouble:15.9990], [NSNumber␣
↪numberWithDouble:12.0096] };
    NSDictionary *masses = [NSDictionary dictionaryWithObjects:objects forKeys:keys␣
↪count:4];
#endif

#if __has_feature(objc_subscripting)
    NSUInteger i, count = elements.count;
```

```
    for (i = 0; i < count; ++i) {
        NSString *element = elements[i];
        NSNumber *mass = masses[element];
        NSLog(@"the mass of %@ is %@", element, mass);
    }
#else
    NSUInteger i, count = [elements count];
    for (i = 0; i < count; ++i) {
        NSString *element = [elements objectAtIndex:i];
        NSNumber *mass = [masses objectForKey:element];
        NSLog(@"the mass of %@ is %@", element, mass);
    }
#endif

#if __has_attribute(objc_boxable)
    typedef struct __attribute__((objc_boxable)) _Rect Rect;
#endif

#if __has_feature(objc_boxed_nsvalue_expressions)
    CABasicAnimation animation = [CABasicAnimation animationWithKeyPath:@"position"];
    animation.fromValue = @(layer.position);
    animation.toValue = @(newPosition);
    [layer addAnimation:animation forKey:@"move"];
#else
    CABasicAnimation animation = [CABasicAnimation animationWithKeyPath:@"position"];
    animation.fromValue = [NSValue valueWithCGPoint:layer.position];
    animation.toValue = [NSValue valueWithCGPoint:newPosition];
    [layer addAnimation:animation forKey:@"move"];
#endif
```

Code can use also `__has_feature(objc_bool)` to check for the availability of numeric literals support. This checks for the new `__objc_yes / __objc_no` keywords, which enable the use of `@YES / @NO` literals.

To check whether boxed expressions are supported, use `__has_feature(objc_boxed_expressions)` feature macro.

Language Specification for Blocks

Revisions

- 2008/2/25 — created
- 2008/7/28 — revised, __block syntax
- 2008/8/13 — revised, Block globals
- 2008/8/21 — revised, C++ elaboration
- 2008/11/1 — revised, __weak support
- 2009/1/12 — revised, explicit return types
- 2009/2/10 — revised, __block objects need retain

Overview

A new derived type is introduced to C and, by extension, Objective-C, C++, and Objective-C++

The Block Type

Like function types, the Block type is a pair consisting of a result value type and a list of parameter types very similar to a function type. Blocks are intended to be used much like functions with the key distinction being that in addition to executable code they also contain various variable bindings to automatic (stack) or managed (heap) memory.

The abstract declarator,

```
int (^)(char, float)
```

describes a reference to a Block that, when invoked, takes two parameters, the first of type char and the second of type float, and returns a value of type int. The Block referenced is of opaque data that may reside in automatic (stack) memory, global memory, or heap memory.

Block Variable Declarations

A variable with Block type is declared using function pointer style notation substituting ^ for *. The following are valid Block variable declarations:

```
void (^blockReturningVoidWithVoidArgument)(void);
int (^blockReturningIntWithIntAndCharArguments)(int, char);
void (^arrayOfTenBlocksReturningVoidWithIntArgument[10])(int);
```

Variadic . . . arguments are supported. [variadic.c] A Block that takes no arguments must specify void in the argument list [voidarg.c]. An empty parameter list does not represent, as K&R provide, an unspecified argument list. Note: both gcc and clang support K&R style as a convenience.

A Block reference may be cast to a pointer of arbitrary type and vice versa. [cast.c] A Block reference may not be dereferenced via the pointer dereference operator *, and thus a Block's size may not be computed at compile time. [sizeof.c]

Block Literal Expressions

A Block literal expression produces a reference to a Block. It is introduced by the use of the ^ token as a unary operator.

```
Block_literal_expression ::=   ^ block_decl compound_statement_body
block_decl ::=
block_decl ::= parameter_list
block_decl ::= type_expression
```

where type expression is extended to allow ^ as a Block reference (pointer) where * is allowed as a function reference (pointer).

The following Block literal:

```
^ void (void) { printf("hello world\n"); }
```

produces a reference to a Block with no arguments with no return value.

The return type is optional and is inferred from the return statements. If the return statements return a value, they all must return a value of the same type. If there is no value returned the inferred type of the Block is void; otherwise it is the type of the return statement value.

If the return type is omitted and the argument list is `( void )`, the `( void )` argument list may also be omitted.

So:

```
^ ( void ) { printf("hello world\n"); }
```

and:

```
^ { printf("hello world\n"); }
```

are exactly equivalent constructs for the same expression.

The type_expression extends C expression parsing to accommodate Block reference declarations as it accommodates function pointer declarations.

Given:

```
typedef int (*pointerToFunctionThatReturnsIntWithCharArg)(char);
pointerToFunctionThatReturnsIntWithCharArg functionPointer;
^ pointerToFunctionThatReturnsIntWithCharArg (float x) { return functionPointer; }
```

and:

```
^ int ((*)(float x))(char) { return functionPointer; }
```

are equivalent expressions, as is:

```
^(float x) { return functionPointer; }
```

[returnfunctionptr.c]

The compound statement body establishes a new lexical scope within that of its parent. Variables used within the scope of the compound statement are bound to the Block in the normal manner with the exception of those in automatic (stack) storage. Thus one may access functions and global variables as one would expect, as well as static local variables. [testme]

Local automatic (stack) variables referenced within the compound statement of a Block are imported and captured by the Block as const copies. The capture (binding) is performed at the time of the Block literal expression evaluation.

The compiler is not required to capture a variable if it can prove that no references to the variable will actually be evaluated. Programmers can force a variable to be captured by referencing it in a statement at the beginning of the Block, like so:

```
(void) foo;
```

This matters when capturing the variable has side-effects, as it can in Objective-C or C++.

The lifetime of variables declared in a Block is that of a function; each activation frame contains a new copy of variables declared within the local scope of the Block. Such variable declarations should be allowed anywhere [testme] rather than only when C99 parsing is requested, including for statements. [testme]

Block literal expressions may occur within Block literal expressions (nest) and all variables captured by any nested blocks are implicitly also captured in the scopes of their enclosing Blocks.

A Block literal expression may be used as the initialization value for Block variables at global or local static scope.

The Invoke Operator

Blocks are invoked using function call syntax with a list of expression parameters of types corresponding to the declaration and returning a result type also according to the declaration. Given:

```
int (^x)(char);
void (^z)(void);
int (^(*y))(char) = &x;
```

the following are all legal Block invocations:

```
x('a');
(*y)('a');
(true ? x : *y)('a')
```

The Copy and Release Operations

The compiler and runtime provide copy and release operations for Block references that create and, in matched use, release allocated storage for referenced Blocks.

The copy operation `Block_copy()` is styled as a function that takes an arbitrary Block reference and returns a Block reference of the same type. The release operation, `Block_release()`, is styled as a function that takes an arbitrary Block reference and, if dynamically matched to a Block copy operation, allows recovery of the referenced allocated memory.

The `__block` Storage Qualifier

In addition to the new Block type we also introduce a new storage qualifier, __block, for local variables. [testme: a __block declaration within a block literal] The `__block` storage qualifier is mutually exclusive to the existing local storage qualifiers auto, register, and static. [testme] Variables qualified by `__block` act as if they were in allocated storage and this storage is automatically recovered after last use of said variable. An implementation may choose an optimization where the storage is initially automatic and only "moved" to allocated (heap) storage upon a Block_copy of a referencing Block. Such variables may be mutated as normal variables are.

In the case where a `__block` variable is a Block one must assume that the `__block` variable resides in allocated storage and as such is assumed to reference a Block that is also in allocated storage (that it is the result of a `Block_copy` operation). Despite this there is no provision to do a `Block_copy` or a `Block_release` if an implementation provides initial automatic storage for Blocks. This is due to the inherent race condition of potentially several threads

trying to update the shared variable and the need for synchronization around disposing of older values and copying new ones. Such synchronization is beyond the scope of this language specification.

Control Flow

The compound statement of a Block is treated much like a function body with respect to control flow in that goto, break, and continue do not escape the Block. Exceptions are treated *normally* in that when thrown they pop stack frames until a catch clause is found.

Objective-C Extensions

Objective-C extends the definition of a Block reference type to be that also of id. A variable or expression of Block type may be messaged or used as a parameter wherever an id may be. The converse is also true. Block references may thus appear as properties and are subject to the assign, retain, and copy attribute logic that is reserved for objects.

All Blocks are constructed to be Objective-C objects regardless of whether the Objective-C runtime is operational in the program or not. Blocks using automatic (stack) memory are objects and may be messaged, although they may not be assigned into `__weak` locations if garbage collection is enabled.

Within a Block literal expression within a method definition references to instance variables are also imported into the lexical scope of the compound statement. These variables are implicitly qualified as references from self, and so self is imported as a const copy. The net effect is that instance variables can be mutated.

The Block_copy operator retains all objects held in variables of automatic storage referenced within the Block expression (or form strong references if running under garbage collection). Object variables of `__block` storage type are assumed to hold normal pointers with no provision for retain and release messages.

Foundation defines (and supplies) `-copy` and `-release` methods for Blocks.

In the Objective-C and Objective-C++ languages, we allow the `__weak` specifier for `__block` variables of object type. If garbage collection is not enabled, this qualifier causes these variables to be kept without retain messages being sent. This knowingly leads to dangling pointers if the Block (or a copy) outlives the lifetime of this object.

In garbage collected environments, the `__weak` variable is set to nil when the object it references is collected, as long as the `__block` variable resides in the heap (either by default or via `Block_copy()`). The initial Apple implementation does in fact start `__block` variables on the stack and migrate them to the heap only as a result of a `Block_copy()` operation.

It is a runtime error to attempt to assign a reference to a stack-based Block into any storage marked `__weak`, including `__weak __block` variables.

C++ Extensions

Block literal expressions within functions are extended to allow const use of C++ objects, pointers, or references held in automatic storage.

As usual, within the block, references to captured variables become const-qualified, as if they were references to members of a const object. Note that this does not change the type of a variable of reference type.

For example, given a class Foo:

```
Foo foo;
Foo &fooRef = foo;
Foo *fooPtr = &foo;
```

A Block that referenced these variables would import the variables as const variations:

```
const Foo block_foo = foo;
Foo &block_fooRef = fooRef;
Foo *const block_fooPtr = fooPtr;
```

Captured variables are copied into the Block at the instant of evaluating the Block literal expression. They are also copied when calling `Block_copy()` on a Block allocated on the stack. In both cases, they are copied as if the variable were const-qualified, and it's an error if there's no such constructor.

Captured variables in Blocks on the stack are destroyed when control leaves the compound statement that contains the Block literal expression. Captured variables in Blocks on the heap are destroyed when the reference count of the Block drops to zero.

Variables declared as residing in `__block` storage may be initially allocated in the heap or may first appear on the stack and be copied to the heap as a result of a `Block_copy()` operation. When copied from the stack, `__block` variables are copied using their normal qualification (i.e. without adding const). In C++11, `__block` variables are copied as x-values if that is possible, then as l-values if not; if both fail, it's an error. The destructor for any initial stack-based version is called at the variable's normal end of scope.

References to `this`, as well as references to non-static members of any enclosing class, are evaluated by capturing `this` just like a normal variable of C pointer type.

Member variables that are Blocks may not be overloaded by the types of their arguments.

Block Implementation Specification

History

- 2008/7/14 - created.
- 2008/8/21 - revised, C++.
- 2008/9/24 - add `NULL isa` field to `__block` storage.
- 2008/10/1 - revise block layout to use a `static` descriptor structure.
- 2008/10/6 - revise block layout to use an unsigned long int flags.
- 2008/10/28 - specify use of `_Block_object_assign` and `_Block_object_dispose` for all "Object" types in helper functions.
- 2008/10/30 - revise new layout to have invoke function in same place.
- 2008/10/30 - add `__weak` support.
- 2010/3/16 - rev for stret return, signature field.
- 2010/4/6 - improved wording.
- 2013/1/6 - improved wording and converted to rst.

This document describes the Apple ABI implementation specification of Blocks.

The first shipping version of this ABI is found in Mac OS X 10.6, and shall be referred to as 10.6.ABI. As of 2010/3/16, the following describes the ABI contract with the runtime and the compiler, and, as necessary, will be referred to as ABI.2010.3.16.

Since the Apple ABI references symbols from other elements of the system, any attempt to use this ABI on systems prior to SnowLeopard is undefined.

High Level

The ABI of `Blocks` consist of their layout and the runtime functions required by the compiler. A `Block` consists of a structure of the following form:

```
struct Block_literal_1 {
    void *isa; // initialized to &_NSConcreteStackBlock or &_NSConcreteGlobalBlock
    int flags;
    int reserved;
    void (*invoke)(void *, ...);
    struct Block_descriptor_1 {
    unsigned long int reserved;         // NULL
        unsigned long int size;         // sizeof(struct Block_literal_1)
        // optional helper functions
        void (*copy_helper)(void *dst, void *src);     // IFF (1<<25)
        void (*dispose_helper)(void *src);             // IFF (1<<25)
        // required ABI.2010.3.16
        const char *signature;                         // IFF (1<<30)
    } *descriptor;
    // imported variables
};
```

The following flags bits are in use thusly for a possible ABI.2010.3.16:

```
enum {
    BLOCK_HAS_COPY_DISPOSE =  (1 << 25),
    BLOCK_HAS_CTOR =          (1 << 26), // helpers have C++ code
    BLOCK_IS_GLOBAL =         (1 << 28),
    BLOCK_HAS_STRET =         (1 << 29), // IFF BLOCK_HAS_SIGNATURE
    BLOCK_HAS_SIGNATURE =     (1 << 30),
};
```

In 10.6.ABI the (1<<29) was usually set and was always ignored by the runtime - it had been a transitional marker that did not get deleted after the transition. This bit is now paired with (1<<30), and represented as the pair (3<<30), for the following combinations of valid bit settings, and their meanings:

```
switch (flags & (3<<29)) {
  case (0<<29):      10.6.ABI, no signature field available
  case (1<<29):      10.6.ABI, no signature field available
  case (2<<29): ABI.2010.3.16, regular calling convention, presence of signature field
  case (3<<29): ABI.2010.3.16, stret calling convention, presence of signature field,
}
```

The signature field is not always populated.

The following discussions are presented as 10.6.ABI otherwise.

`Block` literals may occur within functions where the structure is created in stack local memory. They may also appear as initialization expressions for `Block` variables of global or `static` local variables.

When a `Block` literal expression is evaluated the stack based structure is initialized as follows:

1. A `static` descriptor structure is declared and initialized as follows:

   a. The `invoke` function pointer is set to a function that takes the `Block` structure as its first argument and the rest of the arguments (if any) to the `Block` and executes the `Block` compound statement.

   b. The `size` field is set to the size of the following `Block` literal structure.

   c. The `copy_helper` and `dispose_helper` function pointers are set to respective helper functions if they are required by the `Block` literal.

2. A stack (or global) `Block` literal data structure is created and initialized as follows:

   a. The `isa` field is set to the address of the external `_NSConcreteStackBlock`, which is a block of uninitialized memory supplied in `libSystem`, or `_NSConcreteGlobalBlock` if this is a static or file level `Block` literal.

   b. The `flags` field is set to zero unless there are variables imported into the `Block` that need helper functions for program level `Block_copy()` and `Block_release()` operations, in which case the (1<<25) flags bit is set.

As an example, the `Block` literal expression:

```
^ { printf("hello world\n"); }
```

would cause the following to be created on a 32-bit system:

```
struct __block_literal_1 {
    void *isa;
    int flags;
    int reserved;
    void (*invoke)(struct __block_literal_1 *);
    struct __block_descriptor_1 *descriptor;
```

```
};

void __block_invoke_1(struct __block_literal_1 *_block) {
    printf("hello world\n");
}

static struct __block_descriptor_1 {
    unsigned long int reserved;
    unsigned long int Block_size;
} __block_descriptor_1 = { 0, sizeof(struct __block_literal_1), __block_invoke_1 };
```

and where the `Block` literal itself appears:

```
struct __block_literal_1 _block_literal = {
     &_NSConcreteStackBlock,
     (1<<29), <uninitialized>,
     __block_invoke_1,
     &__block_descriptor_1
};
```

A `Block` imports other `Block` references, `const` copies of other variables, and variables marked `__block`. In Objective-C, variables may additionally be objects.

When a `Block` literal expression is used as the initial value of a global or `static` local variable, it is initialized as follows:

```
struct __block_literal_1 __block_literal_1 = {
      &_NSConcreteGlobalBlock,
      (1<<28)|(1<<29), <uninitialized>,
      __block_invoke_1,
      &__block_descriptor_1
};
```

that is, a different address is provided as the first value and a particular (1<<28) bit is set in the `flags` field, and otherwise it is the same as for stack based `Block` literals. This is an optimization that can be used for any `Block` literal that imports no `const` or `__block` storage variables.

Imported Variables

Variables of `auto` storage class are imported as `const` copies. Variables of `__block` storage class are imported as a pointer to an enclosing data structure. Global variables are simply referenced and not considered as imported.

Imported `const` copy variables

Automatic storage variables not marked with `__block` are imported as `const` copies.

The simplest example is that of importing a variable of type `int`:

```
int x = 10;
void (^vv)(void) = ^{ printf("x is %d\n", x); }
x = 11;
vv();
```

which would be compiled to:

```
struct __block_literal_2 {
    void *isa;
    int flags;
    int reserved;
    void (*invoke)(struct __block_literal_2 *);
    struct __block_descriptor_2 *descriptor;
    const int x;
};

void __block_invoke_2(struct __block_literal_2 *_block) {
    printf("x is %d\n", _block->x);
}

static struct __block_descriptor_2 {
    unsigned long int reserved;
    unsigned long int Block_size;
} __block_descriptor_2 = { 0, sizeof(struct __block_literal_2) };
```

and:

```
struct __block_literal_2 __block_literal_2 = {
      &_NSConcreteStackBlock,
      (1<<29), <uninitialized>,
      __block_invoke_2,
      &__block_descriptor_2,
      x
 };
```

In summary, scalars, structures, unions, and function pointers are generally imported as `const` copies with no need for helper functions.

Imported `const` copy of `Block` reference

The first case where copy and dispose helper functions are required is for the case of when a `Block` itself is imported. In this case both a `copy_helper` function and a `dispose_helper` function are needed. The `copy_helper` function is passed both the existing stack based pointer and the pointer to the new heap version and should call back into the runtime to actually do the copy operation on the imported fields within the `Block`. The runtime functions are all described in *Runtime Helper Functions*.

A quick example:

```
void (^existingBlock)(void) = ...;
void (^vv)(void) = ^{ existingBlock(); }
vv();

struct __block_literal_3 {
   ...; // existing block
};

struct __block_literal_4 {
    void *isa;
    int flags;
    int reserved;
    void (*invoke)(struct __block_literal_4 *);
    struct __block_literal_3 *const existingBlock;
};
```

```
void __block_invoke_4(struct __block_literal_2 *_block) {
   __block->existingBlock->invoke(__block->existingBlock);
}

void __block_copy_4(struct __block_literal_4 *dst, struct __block_literal_4 *src) {
     //_Block_copy_assign(&dst->existingBlock, src->existingBlock, 0);
     _Block_object_assign(&dst->existingBlock, src->existingBlock, BLOCK_FIELD_IS_
↪BLOCK);
}

void __block_dispose_4(struct __block_literal_4 *src) {
     // was _Block_destroy
     _Block_object_dispose(src->existingBlock, BLOCK_FIELD_IS_BLOCK);
}

static struct __block_descriptor_4 {
    unsigned long int reserved;
    unsigned long int Block_size;
    void (*copy_helper)(struct __block_literal_4 *dst, struct __block_literal_4 *src);
    void (*dispose_helper)(struct __block_literal_4 *);
} __block_descriptor_4 = {
    0,
    sizeof(struct __block_literal_4),
    __block_copy_4,
    __block_dispose_4,
};
```

and where said `Block` is used:

```
struct __block_literal_4 _block_literal = {
      &_NSConcreteStackBlock,
      (1<<25)|(1<<29), <uninitialized>
      __block_invoke_4,
      & __block_descriptor_4
      existingBlock,
};
```

Importing `__attribute__((NSObject))` variables

GCC introduces `__attribute__((NSObject))` on structure pointers to mean "this is an object". This is useful because many low level data structures are declared as opaque structure pointers, e.g. `CFStringRef`, `CFArrayRef`, etc. When used from C, however, these are still really objects and are the second case where that requires copy and dispose helper functions to be generated. The copy helper functions generated by the compiler should use the `_Block_object_assign` runtime helper function and in the dispose helper the `_Block_object_dispose` runtime helper function should be called.

For example, `Block` foo in the following:

```
struct Opaque *__attribute__((NSObject)) objectPointer = ...;
...
void (^foo)(void) = ^{  CFPrint(objectPointer); };
```

would have the following helper functions generated:

```
void __block_copy_foo(struct __block_literal_5 *dst, struct __block_literal_5 *src) {
     _Block_object_assign(&dst->objectPointer, src-> objectPointer, BLOCK_FIELD_IS_
↪OBJECT);
}

void __block_dispose_foo(struct __block_literal_5 *src) {
     _Block_object_dispose(src->objectPointer, BLOCK_FIELD_IS_OBJECT);
}
```

Imported `__block` marked variables

Layout of `__block` marked variables

The compiler must embed variables that are marked `__block` in a specialized structure of the form:

```
struct _block_byref_foo {
    void *isa;
    struct Block_byref *forwarding;
    int flags;   //refcount;
    int size;
    typeof(marked_variable) marked_variable;
};
```

Variables of certain types require helper functions for when `Block_copy()` and `Block_release()` are performed upon a referencing `Block`. At the "C" level only variables that are of type `Block` or ones that have `__attribute__((NSObject))` marked require helper functions. In Objective-C objects require helper functions and in C++ stack based objects require helper functions. Variables that require helper functions use the form:

```
struct _block_byref_foo {
    void *isa;
    struct _block_byref_foo *forwarding;
    int flags;   //refcount;
    int size;
    // helper functions called via Block_copy() and Block_release()
    void (*byref_keep)(void  *dst, void *src);
    void (*byref_dispose)(void *);
    typeof(marked_variable) marked_variable;
};
```

The structure is initialized such that:

a. The `forwarding` pointer is set to the beginning of its enclosing structure.

b. The `size` field is initialized to the total size of the enclosing structure.

c. The `flags` field is set to either 0 if no helper functions are needed or (1<<25) if they are.

4. The helper functions are initialized (if present).

5. The variable itself is set to its initial value.

6. The `isa` field is set to `NULL`.

Access to `__block` variables from within its lexical scope

In order to "move" the variable to the heap upon a `copy_helper` operation the compiler must rewrite access to such a variable to be indirect through the structures `forwarding` pointer. For example:

```
int __block i = 10;
i = 11;
```

would be rewritten to be:

```
struct _block_byref_i {
  void *isa;
  struct _block_byref_i *forwarding;
  int flags;   //refcount;
  int size;
  int captured_i;
} i = { NULL, &i, 0, sizeof(struct _block_byref_i), 10 };

i.forwarding->captured_i = 11;
```

In the case of a `Block` reference variable being marked `__block` the helper code generated must use the `_Block_object_assign` and `_Block_object_dispose` routines supplied by the runtime to make the copies. For example:

```
__block void (voidBlock)(void) = blockA;
voidBlock = blockB;
```

would translate into:

```
struct _block_byref_voidBlock {
    void *isa;
    struct _block_byref_voidBlock *forwarding;
    int flags;   //refcount;
    int size;
    void (*byref_keep)(struct _block_byref_voidBlock *dst, struct _block_byref_
↪voidBlock *src);
    void (*byref_dispose)(struct _block_byref_voidBlock *);
    void (^captured_voidBlock)(void);
};

void _block_byref_keep_helper(struct _block_byref_voidBlock *dst, struct _block_byref_
↪voidBlock *src) {
    //_Block_copy_assign(&dst->captured_voidBlock, src->captured_voidBlock, 0);
    _Block_object_assign(&dst->captured_voidBlock, src->captured_voidBlock, BLOCK_
↪FIELD_IS_BLOCK | BLOCK_BYREF_CALLER);
}

void _block_byref_dispose_helper(struct _block_byref_voidBlock *param) {
    //_Block_destroy(param->captured_voidBlock, 0);
    _Block_object_dispose(param->captured_voidBlock, BLOCK_FIELD_IS_BLOCK | BLOCK_
↪BYREF_CALLER)}
```

and:

```
struct _block_byref_voidBlock voidBlock = {( .forwarding=&voidBlock, .flags=(1<<25), .
↪size=sizeof(struct _block_byref_voidBlock *),
    .byref_keep=_block_byref_keep_helper, .byref_dispose=_block_byref_dispose_helper,
    .captured_voidBlock=blockA )};
```

```
voidBlock.forwarding->captured_voidBlock = blockB;
```

Importing `__block` variables into `Blocks`

A `Block` that uses a `__block` variable in its compound statement body must import the variable and emit `copy_helper` and `dispose_helper` helper functions that, in turn, call back into the runtime to actually copy or release the `byref` data block using the functions `_Block_object_assign` and `_Block_object_dispose`.

For example:

```
int __block i = 2;
functioncall(^{ i = 10; });
```

would translate to:

```
struct _block_byref_i {
    void *isa;  // set to NULL
    struct _block_byref_voidBlock *forwarding;
    int flags;   //refcount;
    int size;
    void (*byref_keep)(struct _block_byref_i *dst, struct _block_byref_i *src);
    void (*byref_dispose)(struct _block_byref_i *);
    int captured_i;
};


struct __block_literal_5 {
    void *isa;
    int flags;
    int reserved;
    void (*invoke)(struct __block_literal_5 *);
    struct __block_descriptor_5 *descriptor;
    struct _block_byref_i *i_holder;
};

void __block_invoke_5(struct __block_literal_5 *_block) {
   _block->forwarding->captured_i = 10;
}

void __block_copy_5(struct __block_literal_5 *dst, struct __block_literal_5 *src) {
     //_Block_byref_assign_copy(&dst->captured_i, src->captured_i);
     _Block_object_assign(&dst->captured_i, src->captured_i, BLOCK_FIELD_IS_BYREF |␣
↪BLOCK_BYREF_CALLER);
}

void __block_dispose_5(struct __block_literal_5 *src) {
     //_Block_byref_release(src->captured_i);
     _Block_object_dispose(src->captured_i, BLOCK_FIELD_IS_BYREF | BLOCK_BYREF_
↪CALLER);
}

static struct __block_descriptor_5 {
    unsigned long int reserved;
    unsigned long int Block_size;
    void (*copy_helper)(struct __block_literal_5 *dst, struct __block_literal_5 *src);
```

```
    void (*dispose_helper)(struct __block_literal_5 *);
} __block_descriptor_5 = { 0, sizeof(struct __block_literal_5) __block_copy_5, __
↪block_dispose_5 };
```

and:

```
struct _block_byref_i i = {( .forwarding=&i, .flags=0, .size=sizeof(struct _block_
↪byref_i) )};
struct __block_literal_5 _block_literal = {
      &_NSConcreteStackBlock,
      (1<<25)|(1<<29), <uninitialized>,
      __block_invoke_5,
      &__block_descriptor_5,
      2,
};
```

Importing `__attribute__((NSObject))` `__block` variables

A `__block` variable that is also marked `__attribute__((NSObject))` should have `byref_keep` and `byref_dispose` helper functions that use `_Block_object_assign` and `_Block_object_dispose`.

`__block` escapes

Because `Blocks` referencing `__block` variables may have `Block_copy()` performed upon them the underlying storage for the variables may move to the heap. In Objective-C Garbage Collection Only compilation environments the heap used is the garbage collected one and no further action is required. Otherwise the compiler must issue a call to potentially release any heap storage for `__block` variables at all escapes or terminations of their scope. The call should be:

```
_Block_object_dispose(&_block_byref_foo, BLOCK_FIELD_IS_BYREF);
```

Nesting

`Blocks` may contain `Block` literal expressions. Any variables used within inner blocks are imported into all enclosing `Block` scopes even if the variables are not used. This includes `const` imports as well as `__block` variables.

Objective C Extensions to `Blocks`

Importing Objects

Objects should be treated as `__attribute__((NSObject))` variables; all `copy_helper`, `dispose_helper`, `byref_keep`, and `byref_dispose` helper functions should use `_Block_object_assign` and `_Block_object_dispose`. There should be no code generated that uses `*-retain` or `*-release` methods.

`Blocks` as Objects

The compiler will treat `Blocks` as objects when synthesizing property setters and getters, will characterize them as objects when generating garbage collection strong and weak layout information in the same manner as objects, and

will issue strong and weak write-barrier assignments in the same manner as objects.

__weak __block Support

Objective-C (and Objective-C++) support the __weak attribute on __block variables. Under normal circumstances the compiler uses the Objective-C runtime helper support functions objc_assign_weak and objc_read_weak. Both should continue to be used for all reads and writes of __weak __block variables:

```
objc_read_weak(&block->byref_i->forwarding->i)
```

The __weak variable is stored in a _block_byref_foo structure and the Block has copy and dispose helpers for this structure that call:

```
_Block_object_assign(&dest->_block_byref_i, src-> _block_byref_i, BLOCK_FIELD_IS_WEAK␣
↪| BLOCK_FIELD_IS_BYREF);
```

and:

```
_Block_object_dispose(src->_block_byref_i, BLOCK_FIELD_IS_WEAK | BLOCK_FIELD_IS_
↪BYREF);
```

In turn, the block_byref copy support helpers distinguish between whether the __block variable is a Block or not and should either call:

```
_Block_object_assign(&dest->_block_byref_i, src->_block_byref_i, BLOCK_FIELD_IS_WEAK␣
↪| BLOCK_FIELD_IS_OBJECT | BLOCK_BYREF_CALLER);
```

for something declared as an object or:

```
_Block_object_assign(&dest->_block_byref_i, src->_block_byref_i, BLOCK_FIELD_IS_WEAK␣
↪| BLOCK_FIELD_IS_BLOCK | BLOCK_BYREF_CALLER);
```

for something declared as a Block.

A full example follows:

```
__block __weak id obj = <initialization expression>;
functioncall(^{ [obj somemessage]; });
```

would translate to:

```
struct _block_byref_obj {
    void *isa;  // uninitialized
    struct _block_byref_obj *forwarding;
    int flags;   //refcount;
    int size;
    void (*byref_keep)(struct _block_byref_i *dst, struct _block_byref_i *src);
    void (*byref_dispose)(struct _block_byref_i *);
    id captured_obj;
};

void _block_byref_obj_keep(struct _block_byref_voidBlock *dst, struct _block_byref_
↪voidBlock *src) {
    //_Block_copy_assign(&dst->captured_obj, src->captured_obj, 0);
    _Block_object_assign(&dst->captured_obj, src->captured_obj, BLOCK_FIELD_IS_OBJECT␣
↪| BLOCK_FIELD_IS_WEAK | BLOCK_BYREF_CALLER);
}
```

```
void _block_byref_obj_dispose(struct _block_byref_voidBlock *param) {
    //_Block_destroy(param->captured_obj, 0);
    _Block_object_dispose(param->captured_obj, BLOCK_FIELD_IS_OBJECT | BLOCK_FIELD_IS_
↪WEAK | BLOCK_BYREF_CALLER);
};
```

for the block `byref` part and:

```
struct __block_literal_5 {
    void *isa;
    int flags;
    int reserved;
    void (*invoke)(struct __block_literal_5 *);
    struct __block_descriptor_5 *descriptor;
    struct _block_byref_obj *byref_obj;
};

void __block_invoke_5(struct __block_literal_5 *_block) {
   [objc_read_weak(&_block->byref_obj->forwarding->captured_obj) somemessage];
}

void __block_copy_5(struct __block_literal_5 *dst, struct __block_literal_5 *src) {
     //_Block_byref_assign_copy(&dst->byref_obj, src->byref_obj);
     _Block_object_assign(&dst->byref_obj, src->byref_obj, BLOCK_FIELD_IS_BYREF |␣
↪BLOCK_FIELD_IS_WEAK);
}

void __block_dispose_5(struct __block_literal_5 *src) {
     //_Block_byref_release(src->byref_obj);
     _Block_object_dispose(src->byref_obj, BLOCK_FIELD_IS_BYREF | BLOCK_FIELD_IS_
↪WEAK);
}

static struct __block_descriptor_5 {
    unsigned long int reserved;
    unsigned long int Block_size;
    void (*copy_helper)(struct __block_literal_5 *dst, struct __block_literal_5 *src);
    void (*dispose_helper)(struct __block_literal_5 *);
} __block_descriptor_5 = { 0, sizeof(struct __block_literal_5), __block_copy_5, __
↪block_dispose_5 };
```

and within the compound statement:

```
truct _block_byref_obj obj = {( .forwarding=&obj, .flags=(1<<25), .size=sizeof(struct␣
↪_block_byref_obj),
                  .byref_keep=_block_byref_obj_keep, .byref_dispose=_block_byref_obj_
↪dispose,
                  .captured_obj = <initialization expression> )};

truct __block_literal_5 _block_literal = {
     &_NSConcreteStackBlock,
     (1<<25)|(1<<29), <uninitialized>,
     __block_invoke_5,
     &__block_descriptor_5,
     &obj,        // a reference to the on-stack structure containing "captured_obj"
};
```

```
functioncall(_block_literal->invoke(&_block_literal));
```

C++ Support

Within a block stack based C++ objects are copied into `const` copies using the copy constructor. It is an error if a stack based C++ object is used within a block if it does not have a copy constructor. In addition both copy and destroy helper routines must be synthesized for the block to support the `Block_copy()` operation, and the flags work marked with the (1<<26) bit in addition to the (1<<25) bit. The copy helper should call the constructor using appropriate offsets of the variable within the supplied stack based block source and heap based destination for all `const` constructed copies, and similarly should call the destructor in the destroy routine.

As an example, suppose a C++ class `FOO` existed with a copy constructor. Within a code block a stack version of a `FOO` object is declared and used within a `Block` literal expression:

```
{
    FOO foo;
    void (^block)(void) = ^{ printf("%d\n", foo.value()); };
}
```

The compiler would synthesize:

```
struct __block_literal_10 {
    void *isa;
    int flags;
    int reserved;
    void (*invoke)(struct __block_literal_10 *);
    struct __block_descriptor_10 *descriptor;
    const FOO foo;
};

void __block_invoke_10(struct __block_literal_10 *_block) {
   printf("%d\n", _block->foo.value());
}

void __block_literal_10(struct __block_literal_10 *dst, struct __block_literal_10␣
↪*src) {
     FOO_ctor(&dst->foo, &src->foo);
}

void __block_dispose_10(struct __block_literal_10 *src) {
     FOO_dtor(&src->foo);
}

static struct __block_descriptor_10 {
    unsigned long int reserved;
    unsigned long int Block_size;
    void (*copy_helper)(struct __block_literal_10 *dst, struct __block_literal_10␣
↪*src);
    void (*dispose_helper)(struct __block_literal_10 *);
} __block_descriptor_10 = { 0, sizeof(struct __block_literal_10), __block_copy_10, __
↪block_dispose_10 };
```

and the code would be:

```
{
  FOO foo;
  comp_ctor(&foo); // default constructor
  struct __block_literal_10 _block_literal = {
    &_NSConcreteStackBlock,
    (1<<25)|(1<<26)|(1<<29), <uninitialized>,
    __block_invoke_10,
    &__block_descriptor_10,
   };
   comp_ctor(&_block_literal->foo, &foo);  // const copy into stack version
   struct __block_literal_10 &block = &_block_literal;  // assign literal to block␣
↪variable
   block->invoke(block);    // invoke block
   comp_dtor(&_block_literal->foo); // destroy stack version of const block copy
   comp_dtor(&foo); // destroy original version
}
```

C++ objects stored in `__block` storage start out on the stack in a `block_byref` data structure as do other variables. Such objects (if not `const` objects) must support a regular copy constructor. The `block_byref` data structure will have copy and destroy helper routines synthesized by the compiler. The copy helper will have code created to perform the copy constructor based on the initial stack `block_byref` data structure, and will also set the (1<<26) bit in addition to the (1<<25) bit. The destroy helper will have code to do the destructor on the object stored within the supplied `block_byref` heap data structure. For example,

```
__block FOO blockStorageFoo;
```

requires the normal constructor for the embedded `blockStorageFoo` object:

```
FOO_ctor(& _block_byref_blockStorageFoo->blockStorageFoo);
```

and at scope termination the destructor:

```
FOO_dtor(& _block_byref_blockStorageFoo->blockStorageFoo);
```

Note that the forwarding indirection is *NOT* used.

The compiler would need to generate (if used from a block literal) the following copy/dispose helpers:

```
void _block_byref_obj_keep(struct _block_byref_blockStorageFoo *dst, struct _block_
↪byref_blockStorageFoo *src) {
     FOO_ctor(&dst->blockStorageFoo, &src->blockStorageFoo);
}

void _block_byref_obj_dispose(struct _block_byref_blockStorageFoo *src) {
     FOO_dtor(&src->blockStorageFoo);
}
```

for the appropriately named constructor and destructor for the class/struct `FOO`.

To support member variable and function access the compiler will synthesize a `const` pointer to a block version of the `this` pointer.

Runtime Helper Functions

The runtime helper functions are described in `/usr/local/include/Block_private.h`. To summarize their use, a `Block` requires copy/dispose helpers if it imports any block variables, `__block` storage variables,

__attribute__((NSObject)) variables, or C++ const copied objects with constructor/destructors. The (1<<26) bit is set and functions are generated.

The block copy helper function should, for each of the variables of the type mentioned above, call:

```
_Block_object_assign(&dst->target, src->target, BLOCK_FIELD_<appropo>);
```

in the copy helper and:

```
_Block_object_dispose(->target, BLOCK_FIELD_<appropo>);
```

in the dispose helper where <appropo> is:

```
enum {
    BLOCK_FIELD_IS_OBJECT   =  3,  // id, NSObject, __attribute__((NSObject)), block, ...
    BLOCK_FIELD_IS_BLOCK    =  7,  // a block variable
    BLOCK_FIELD_IS_BYREF    =  8,  // the on stack structure holding the __block variable

    BLOCK_FIELD_IS_WEAK     = 16,  // declared __weak

    BLOCK_BYREF_CALLER      = 128, // called from byref copy/dispose helpers
};
```

and of course the constructors/destructors for const copied C++ objects.

The block_byref data structure similarly requires copy/dispose helpers for block variables, __attribute__((NSObject)) variables, or C++ const copied objects with constructor/destructors, and again the (1<<26) bit is set and functions are generated in the same manner.

Under ObjC we allow __weak as an attribute on __block variables, and this causes the addition of BLOCK_FIELD_IS_WEAK orred onto the BLOCK_FIELD_IS_BYREF flag when copying the block_byref structure in the Block copy helper, and onto the BLOCK_FIELD_<appropo> field within the block_byref copy/dispose helper calls.

The prototypes, and summary, of the helper functions are:

```
/* Certain field types require runtime assistance when being copied to the
   heap.  The following function is used to copy fields of types: blocks,
   pointers to byref structures, and objects (including
   __attribute__((NSObject)) pointers.  BLOCK_FIELD_IS_WEAK is orthogonal to
   the other choices which are mutually exclusive.  Only in a Block copy
   helper will one see BLOCK_FIELD_IS_BYREF.
*/
void _Block_object_assign(void *destAddr, const void *object, const int flags);

/* Similarly a compiler generated dispose helper needs to call back for each
   field of the byref data structure.  (Currently the implementation only
   packs one field into the byref structure but in principle there could be
   more).  The same flags used in the copy helper should be used for each
   call generated to this function:
*/
void _Block_object_dispose(const void *object, const int flags);
```

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Objective-C Automatic Reference Counting (ARC)

```
- void objc_destroyWeak(id *object);
- id objc_initWeak(id *object, id value);
- id objc_loadWeak(id *object);
- id objc_loadWeakRetained(id *object);
- void objc_moveWeak(id *dest, id *src);
- void objc_release(id value);
- id objc_retain(id value);
- id objc_retainAutorelease(id value);
- id objc_retainAutoreleaseReturnValue(id value);
- id objc_retainAutoreleasedReturnValue(id value);
- id objc_retainBlock(id value);
- id objc_storeStrong(id *object, id value);
- id objc_storeWeak(id *object, id value);
```

About this document

Purpose

The first and primary purpose of this document is to serve as a complete technical specification of Automatic Reference Counting. Given a core Objective-C compiler and runtime, it should be possible to write a compiler and runtime which implements these new semantics.

The secondary purpose is to act as a rationale for why ARC was designed in this way. This should remain tightly focused on the technical design and should not stray into marketing speculation.

Background

This document assumes a basic familiarity with C.

Blocks are a C language extension for creating anonymous functions. Users interact with and transfer block objects using block pointers, which are represented like a normal pointer. A block may capture values from local variables; when this occurs, memory must be dynamically allocated. The initial allocation is done on the stack, but the runtime provides a `Block_copy` function which, given a block pointer, either copies the underlying block object to the heap, setting its reference count to 1 and returning the new block pointer, or (if the block object is already on the heap) increases its reference count by 1. The paired function is `Block_release`, which decreases the reference count by 1 and destroys the object if the count reaches zero and is on the heap.

Objective-C is a set of language extensions, significant enough to be considered a different language. It is a strict superset of C. The extensions can also be imposed on C++, producing a language called Objective-C++. The primary feature is a single-inheritance object system; we briefly describe the modern dialect.

Objective-C defines a new type kind, collectively called the object pointer types. This kind has two notable builtin members, `id` and `Class`; `id` is the final supertype of all object pointers. The validity of conversions between object pointer types is not checked at runtime. Users may define classes; each class is a type, and the pointer to that type is an object pointer type. A class may have a superclass; its pointer type is a subtype of its superclass's pointer type. A class has a set of ivars, fields which appear on all instances of that class. For every class *T* there's an associated metaclass; it has no fields, its superclass is the metaclass of *T*'s superclass, and its metaclass is a global class. Every class has a

global object whose class is the class's metaclass; metaclasses have no associated type, so pointers to this object have type `Class`.

A class declaration (`@interface`) declares a set of methods. A method has a return type, a list of argument types, and a selector: a name like `foo:bar:baz:`, where the number of colons corresponds to the number of formal arguments. A method may be an instance method, in which case it can be invoked on objects of the class, or a class method, in which case it can be invoked on objects of the metaclass. A method may be invoked by providing an object (called the receiver) and a list of formal arguments interspersed with the selector, like so:

```
[receiver foo: fooArg bar: barArg baz: bazArg]
```

This looks in the dynamic class of the receiver for a method with this name, then in that class's superclass, etc., until it finds something it can execute. The receiver "expression" may also be the name of a class, in which case the actual receiver is the class object for that class, or (within method definitions) it may be `super`, in which case the lookup algorithm starts with the static superclass instead of the dynamic class. The actual methods dynamically found in a class are not those declared in the `@interface`, but those defined in a separate `@implementation` declaration; however, when compiling a call, typechecking is done based on the methods declared in the `@interface`.

Method declarations may also be grouped into protocols, which are not inherently associated with any class, but which classes may claim to follow. Object pointer types may be qualified with additional protocols that the object is known to support.

Class extensions are collections of ivars and methods, designed to allow a class's `@interface` to be split across multiple files; however, there is still a primary implementation file which must see the `@interface`s of all class extensions. Categories allow methods (but not ivars) to be declared *post hoc* on an arbitrary class; the methods in the category's `@implementation` will be dynamically added to that class's method tables which the category is loaded at runtime, replacing those methods in case of a collision.

In the standard environment, objects are allocated on the heap, and their lifetime is manually managed using a reference count. This is done using two instance methods which all classes are expected to implement: `retain` increases the object's reference count by 1, whereas `release` decreases it by 1 and calls the instance method `dealloc` if the count reaches 0. To simplify certain operations, there is also an autorelease pool, a thread-local list of objects to call `release` on later; an object can be added to this pool by calling `autorelease` on it.

Block pointers may be converted to type `id`; block objects are laid out in a way that makes them compatible with Objective-C objects. There is a builtin class that all block objects are considered to be objects of; this class implements `retain` by adjusting the reference count, not by calling `Block_copy`.

Evolution

ARC is under continual evolution, and this document must be updated as the language progresses.

If a change increases the expressiveness of the language, for example by lifting a restriction or by adding new syntax, the change will be annotated with a revision marker, like so:

> ARC applies to Objective-C pointer types, block pointer types, and [beginning Apple 8.0, LLVM 3.8] BPTRs declared within `extern "BCPL"` blocks.

For now, it is sensible to version this document by the releases of its sole implementation (and its host project), clang. "LLVM X.Y" refers to an open-source release of clang from the LLVM project. "Apple X.Y" refers to an Apple-provided release of the Apple LLVM Compiler. Other organizations that prepare their own, separately-versioned clang releases and wish to maintain similar information in this document should send requests to cfe-dev.

If a change decreases the expressiveness of the language, for example by imposing a new restriction, this should be taken as an oversight in the original specification and something to be avoided in all versions. Such changes are generally to be avoided.

General

Automatic Reference Counting implements automatic memory management for Objective-C objects and blocks, freeing the programmer from the need to explicitly insert retains and releases. It does not provide a cycle collector; users must explicitly manage the lifetime of their objects, breaking cycles manually or with weak or unsafe references.

ARC may be explicitly enabled with the compiler flag `-fobjc-arc`. It may also be explicitly disabled with the compiler flag `-fno-objc-arc`. The last of these two flags appearing on the compile line "wins".

If ARC is enabled, `__has_feature(objc_arc)` will expand to 1 in the preprocessor. For more information about `__has_feature`, see the *language extensions* document.

Retainable object pointers

This section describes retainable object pointers, their basic operations, and the restrictions imposed on their use under ARC. Note in particular that it covers the rules for pointer *values* (patterns of bits indicating the location of a pointed-to object), not pointer *objects* (locations in memory which store pointer values). The rules for objects are covered in the next section.

A retainable object pointer (or "retainable pointer") is a value of a retainable object pointer type ("retainable type"). There are three kinds of retainable object pointer types:

- block pointers (formed by applying the caret (`^`) declarator sigil to a function type)
- Objective-C object pointers (`id`, `Class`, `NSFoo*`, etc.)
- typedefs marked with `__attribute__((NSObject))`

Other pointer types, such as `int*` and `CFStringRef`, are not subject to ARC's semantics and restrictions.

Rationale

We are not at liberty to require all code to be recompiled with ARC; therefore, ARC must interoperate with Objective-C code which manages retains and releases manually. In general, there are three requirements in order for a compiler-supported reference-count system to provide reliable interoperation:

- The type system must reliably identify which objects are to be managed. An `int*` might be a pointer to a `malloc`'ed array, or it might be an interior pointer to such an array, or it might point to some field or local variable. In contrast, values of the retainable object pointer types are never interior.
- The type system must reliably indicate how to manage objects of a type. This usually means that the type must imply a procedure for incrementing and decrementing retain counts. Supporting single-ownership objects requires a lot more explicit mediation in the language.
- There must be reliable conventions for whether and when "ownership" is passed between caller and callee, for both arguments and return values. Objective-C methods follow such a convention very reliably, at least for system libraries on Mac OS X, and functions always pass objects at +0. The C-based APIs for Core Foundation objects, on the other hand, have much more varied transfer semantics.

The use of `__attribute__((NSObject))` typedefs is not recommended. If it's absolutely necessary to use this attribute, be very explicit about using the typedef, and do not assume that it will be preserved by language features like `__typeof` and C++ template argument substitution.

Rationale

Any compiler operation which incidentally strips type "sugar" from a type will yield a type without the attribute, which may result in unexpected behavior.

Retain count semantics

A retainable object pointer is either a null pointer or a pointer to a valid object. Furthermore, if it has block pointer type and is not `null` then it must actually be a pointer to a block object, and if it has `Class` type (possibly protocol-qualified) then it must actually be a pointer to a class object. Otherwise ARC does not enforce the Objective-C type system as long as the implementing methods follow the signature of the static type. It is undefined behavior if ARC is exposed to an invalid pointer.

For ARC's purposes, a valid object is one with "well-behaved" retaining operations. Specifically, the object must be laid out such that the Objective-C message send machinery can successfully send it the following messages:

- `retain`, taking no arguments and returning a pointer to the object.
- `release`, taking no arguments and returning `void`.
- `autorelease`, taking no arguments and returning a pointer to the object.

The behavior of these methods is constrained in the following ways. The term high-level semantics is an intentionally vague term; the intent is that programmers must implement these methods in a way such that the compiler, modifying code in ways it deems safe according to these constraints, will not violate their requirements. For example, if the user puts logging statements in `retain`, they should not be surprised if those statements are executed more or less often depending on optimization settings. These constraints are not exhaustive of the optimization opportunities: values held in local variables are subject to additional restrictions, described later in this document.

It is undefined behavior if a computation history featuring a send of `retain` followed by a send of `release` to the same object, with no intervening `release` on that object, is not equivalent under the high-level semantics to a computation history in which these sends are removed. Note that this implies that these methods may not raise exceptions.

It is undefined behavior if a computation history features any use whatsoever of an object following the completion of a send of `release` that is not preceded by a send of `retain` to the same object.

The behavior of `autorelease` must be equivalent to sending `release` when one of the autorelease pools currently in scope is popped. It may not throw an exception.

When the semantics call for performing one of these operations on a retainable object pointer, if that pointer is `null` then the effect is a no-op.

All of the semantics described in this document are subject to additional *optimization rules* which permit the removal or optimization of operations based on local knowledge of data flow. The semantics describe the high-level behaviors that the compiler implements, not an exact sequence of operations that a program will be compiled into.

Retainable object pointers as operands and arguments

In general, ARC does not perform retain or release operations when simply using a retainable object pointer as an operand within an expression. This includes:

- loading a retainable pointer from an object with non-weak *ownership*,
- passing a retainable pointer as an argument to a function or method, and
- receiving a retainable pointer as the result of a function or method call.

Rationale

While this might seem uncontroversial, it is actually unsafe when multiple expressions are evaluated in "parallel", as with binary operators and calls, because (for example) one expression might load from an object while another writes

to it. However, C and C++ already call this undefined behavior because the evaluations are unsequenced, and ARC simply exploits that here to avoid needing to retain arguments across a large number of calls.

The remainder of this section describes exceptions to these rules, how those exceptions are detected, and what those exceptions imply semantically.

Consumed parameters

A function or method parameter of retainable object pointer type may be marked as consumed, signifying that the callee expects to take ownership of a +1 retain count. This is done by adding the `ns_consumed` attribute to the parameter declaration, like so:

```
void foo(__attribute((ns_consumed)) id x);
- (void) foo: (id) __attribute((ns_consumed)) x;
```

This attribute is part of the type of the function or method, not the type of the parameter. It controls only how the argument is passed and received.

When passing such an argument, ARC retains the argument prior to making the call.

When receiving such an argument, ARC releases the argument at the end of the function, subject to the usual optimizations for local values.

Rationale

This formalizes direct transfers of ownership from a caller to a callee. The most common scenario here is passing the `self` parameter to `init`, but it is useful to generalize. Typically, local optimization will remove any extra retains and releases: on the caller side the retain will be merged with a +1 source, and on the callee side the release will be rolled into the initialization of the parameter.

The implicit `self` parameter of a method may be marked as consumed by adding `__attribute__((ns_consumes_self))` to the method declaration. Methods in the `init` *family* are treated as if they were implicitly marked with this attribute.

It is undefined behavior if an Objective-C message send to a method with `ns_consumed` parameters (other than self) is made with a null receiver. It is undefined behavior if the method to which an Objective-C message send statically resolves to has a different set of `ns_consumed` parameters than the method it dynamically resolves to. It is undefined behavior if a block or function call is made through a static type with a different set of `ns_consumed` parameters than the implementation of the called block or function.

Rationale

Consumed parameters with null receiver are a guaranteed leak. Mismatches with consumed parameters will cause over-retains or over-releases, depending on the direction. The rule about function calls is really just an application of the existing C/C++ rule about calling functions through an incompatible function type, but it's useful to state it explicitly.

Retained return values

A function or method which returns a retainable object pointer type may be marked as returning a retained value, signifying that the caller expects to take ownership of a +1 retain count. This is done by adding the `ns_returns_retained` attribute to the function or method declaration, like so:

```
id foo(void) __attribute((ns_returns_retained));
- (id) foo __attribute((ns_returns_retained));
```

This attribute is part of the type of the function or method.

When returning from such a function or method, ARC retains the value at the point of evaluation of the return statement, before leaving all local scopes.

When receiving a return result from such a function or method, ARC releases the value at the end of the full-expression it is contained within, subject to the usual optimizations for local values.

Rationale

This formalizes direct transfers of ownership from a callee to a caller. The most common scenario this models is the retained return from `init`, `alloc`, `new`, and `copy` methods, but there are other cases in the frameworks. After optimization there are typically no extra retains and releases required.

Methods in the `alloc`, `copy`, `init`, `mutableCopy`, and `new` *families* are implicitly marked `__attribute__((ns_returns_retained))`. This may be suppressed by explicitly marking the method `__attribute__((ns_returns_not_retained))`.

It is undefined behavior if the method to which an Objective-C message send statically resolves has different retain semantics on its result from the method it dynamically resolves to. It is undefined behavior if a block or function call is made through a static type with different retain semantics on its result from the implementation of the called block or function.

Rationale

Mismatches with returned results will cause over-retains or over-releases, depending on the direction. Again, the rule about function calls is really just an application of the existing C/C++ rule about calling functions through an incompatible function type.

Unretained return values

A method or function which returns a retainable object type but does not return a retained value must ensure that the object is still valid across the return boundary.

When returning from such a function or method, ARC retains the value at the point of evaluation of the return statement, then leaves all local scopes, and then balances out the retain while ensuring that the value lives across the call boundary. In the worst case, this may involve an `autorelease`, but callers must not assume that the value is actually in the autorelease pool.

ARC performs no extra mandatory work on the caller side, although it may elect to do something to shorten the lifetime of the returned value.

Rationale

It is common in non-ARC code to not return an autoreleased value; therefore the convention does not force either path. It is convenient to not be required to do unnecessary retains and autoreleases; this permits optimizations such as eliding retain/autoreleases when it can be shown that the original pointer will still be valid at the point of return.

A method or function may be marked with `__attribute__((ns_returns_autoreleased))` to indicate that it returns a pointer which is guaranteed to be valid at least as long as the innermost autorelease pool. There are no additional semantics enforced in the definition of such a method; it merely enables optimizations in callers.

Bridged casts

A bridged cast is a C-style cast annotated with one of three keywords:

- `(__bridge T) op` casts the operand to the destination type `T`. If `T` is a retainable object pointer type, then `op` must have a non-retainable pointer type. If `T` is a non-retainable pointer type, then `op` must have a retainable object pointer type. Otherwise the cast is ill-formed. There is no transfer of ownership, and ARC inserts no retain operations.
- `(__bridge_retained T) op` casts the operand, which must have retainable object pointer type, to the destination type, which must be a non-retainable pointer type. ARC retains the value, subject to the usual optimizations on local values, and the recipient is responsible for balancing that +1.
- `(__bridge_transfer T) op` casts the operand, which must have non-retainable pointer type, to the destination type, which must be a retainable object pointer type. ARC will release the value at the end of the enclosing full-expression, subject to the usual optimizations on local values.

These casts are required in order to transfer objects in and out of ARC control; see the rationale in the section on *conversion of retainable object pointers*.

Using a `__bridge_retained` or `__bridge_transfer` cast purely to convince ARC to emit an unbalanced retain or release, respectively, is poor form.

Restrictions

Conversion of retainable object pointers

In general, a program which attempts to implicitly or explicitly convert a value of retainable object pointer type to any non-retainable type, or vice-versa, is ill-formed. For example, an Objective-C object pointer shall not be converted to `void*`. As an exception, cast to `intptr_t` is allowed because such casts are not transferring ownership. The *bridged casts* may be used to perform these conversions where necessary.

Rationale

We cannot ensure the correct management of the lifetime of objects if they may be freely passed around as unmanaged types. The bridged casts are provided so that the programmer may explicitly describe whether the cast transfers control into or out of ARC.

However, the following exceptions apply.

Conversion to retainable object pointer type of expressions with known semantics

[beginning Apple 4.0, LLVM 3.1] These exceptions have been greatly expanded; they previously applied only to a much-reduced subset which is difficult to categorize but which included null pointers, message sends (under the given rules), and the various global constants.

An unbridged conversion to a retainable object pointer type from a type other than a retainable object pointer type is ill-formed, as discussed above, unless the operand of the cast has a syntactic form which is known retained, known unretained, or known retain-agnostic.

An expression is known retain-agnostic if it is:

- an Objective-C string literal,
- a load from a `const` system global variable of *C retainable pointer type*, or
- a null pointer constant.

An expression is known unretained if it is an rvalue of *C retainable pointer type* and it is:

- a direct call to a function, and either that function has the `cf_returns_not_retained` attribute or it is an *audited* function that does not have the `cf_returns_retained` attribute and does not follow the create/copy naming convention,
- a message send, and the declared method either has the `cf_returns_not_retained` attribute or it has neither the `cf_returns_retained` attribute nor a *selector family* that implies a retained result, or
- [beginning LLVM 3.6] a load from a `const` non-system global variable.

An expression is known retained if it is an rvalue of *C retainable pointer type* and it is:

- a message send, and the declared method either has the `cf_returns_retained` attribute, or it does not have the `cf_returns_not_retained` attribute but it does have a *selector family* that implies a retained result.

Furthermore:

- a comma expression is classified according to its right-hand side,
- a statement expression is classified according to its result expression, if it has one,
- an lvalue-to-rvalue conversion applied to an Objective-C property lvalue is classified according to the underlying message send, and
- a conditional operator is classified according to its second and third operands, if they agree in classification, or else the other if one is known retain-agnostic.

If the cast operand is known retained, the conversion is treated as a `__bridge_transfer` cast. If the cast operand is known unretained or known retain-agnostic, the conversion is treated as a `__bridge` cast.

Rationale

Bridging casts are annoying. Absent the ability to completely automate the management of CF objects, however, we are left with relatively poor attempts to reduce the need for a glut of explicit bridges. Hence these rules.

We've so far consciously refrained from implicitly turning retained CF results from function calls into `__bridge_transfer` casts. The worry is that some code patterns — for example, creating a CF value, assigning it to an ObjC-typed local, and then calling `CFRelease` when done — are a bit too likely to be accidentally accepted, leading to mysterious behavior.

For loads from `const` global variables of *C retainable pointer type*, it is reasonable to assume that global system constants were initializted with true constants (e.g. string literals), but user constants might have been initialized with something dynamically allocated, using a global initializer.

Conversion from retainable object pointer type in certain contexts

[beginning Apple 4.0, LLVM 3.1]

If an expression of retainable object pointer type is explicitly cast to a *C retainable pointer type*, the program is ill-formed as discussed above unless the result is immediately used:

- to initialize a parameter in an Objective-C message send where the parameter is not marked with the `cf_consumed` attribute, or
- to initialize a parameter in a direct call to an *audited* function where the parameter is not marked with the `cf_consumed` attribute.

Rationale

Consumed parameters are left out because ARC would naturally balance them with a retain, which was judged too treacherous. This is in part because several of the most common consuming functions are in the `Release` family, and it would be quite unfortunate for explicit releases to be silently balanced out in this way.

Ownership qualification

This section describes the behavior of *objects* of retainable object pointer type; that is, locations in memory which store retainable object pointers.

A type is a retainable object owner type if it is a retainable object pointer type or an array type whose element type is a retainable object owner type.

An ownership qualifier is a type qualifier which applies only to retainable object owner types. An array type is ownership-qualified according to its element type, and adding an ownership qualifier to an array type so qualifies its element type.

A program is ill-formed if it attempts to apply an ownership qualifier to a type which is already ownership-qualified, even if it is the same qualifier. There is a single exception to this rule: an ownership qualifier may be applied to a substituted template type parameter, which overrides the ownership qualifier provided by the template argument.

When forming a function type, the result type is adjusted so that any top-level ownership qualifier is deleted.

Except as described under the *inference rules*, a program is ill-formed if it attempts to form a pointer or reference type to a retainable object owner type which lacks an ownership qualifier.

Rationale

These rules, together with the inference rules, ensure that all objects and lvalues of retainable object pointer type have an ownership qualifier. The ability to override an ownership qualifier during template substitution is required to counteract the *inference of __strong for template type arguments*. Ownership qualifiers on return types are dropped because they serve no purpose there except to cause spurious problems with overloading and templates.

There are four ownership qualifiers:

- `__autoreleasing`
- `__strong`
- `__unsafe_unretained`
- `__weak`

A type is nontrivially ownership-qualified if it is qualified with `__autoreleasing`, `__strong`, or `__weak`.

Spelling

The names of the ownership qualifiers are reserved for the implementation. A program may not assume that they are or are not implemented with macros, or what those macros expand to.

An ownership qualifier may be written anywhere that any other type qualifier may be written.

If an ownership qualifier appears in the *declaration-specifiers*, the following rules apply:

- if the type specifier is a retainable object owner type, the qualifier initially applies to that type;
- otherwise, if the outermost non-array declarator is a pointer or block pointer declarator, the qualifier initially applies to that type;
- otherwise the program is ill-formed.
- If the qualifier is so applied at a position in the declaration where the next-innermost declarator is a function declarator, and there is an block declarator within that function declarator, then the qualifier applies instead to that block declarator and this rule is considered afresh beginning from the new position.

If an ownership qualifier appears on the declarator name, or on the declared object, it is applied to the innermost pointer or block-pointer type.

If an ownership qualifier appears anywhere else in a declarator, it applies to the type there.

Rationale

Ownership qualifiers are like `const` and `volatile` in the sense that they may sensibly apply at multiple distinct positions within a declarator. However, unlike those qualifiers, there are many situations where they are not meaningful, and so we make an effort to "move" the qualifier to a place where it will be meaningful. The general goal is to allow the programmer to write, say, `__strong` before the entire declaration and have it apply in the leftmost sensible place.

Property declarations

A property of retainable object pointer type may have ownership. If the property's type is ownership-qualified, then the property has that ownership. If the property has one of the following modifiers, then the property has the corresponding ownership. A property is ill-formed if it has conflicting sources of ownership, or if it has redundant ownership modifiers, or if it has `__autoreleasing` ownership.

- `assign` implies `__unsafe_unretained` ownership.
- `copy` implies `__strong` ownership, as well as the usual behavior of copy semantics on the setter.
- `retain` implies `__strong` ownership.
- `strong` implies `__strong` ownership.
- `unsafe_unretained` implies `__unsafe_unretained` ownership.
- `weak` implies `__weak` ownership.

With the exception of `weak`, these modifiers are available in non-ARC modes.

A property's specified ownership is preserved in its metadata, but otherwise the meaning is purely conventional unless the property is synthesized. If a property is synthesized, then the associated instance variable is the instance variable which is named, possibly implicitly, by the `@synthesize` declaration. If the associated instance variable already exists, then its ownership qualification must equal the ownership of the property; otherwise, the instance variable is created with that ownership qualification.

A property of retainable object pointer type which is synthesized without a source of ownership has the ownership of its associated instance variable, if it already exists; otherwise, [beginning Apple 3.1, LLVM 3.1] its ownership is implicitly `strong`. Prior to this revision, it was ill-formed to synthesize such a property.

Rationale

Using `strong` by default is safe and consistent with the generic ARC rule about *inferring ownership*. It is, unfortunately, inconsistent with the non-ARC rule which states that such properties are implicitly `assign`. However, that rule is clearly untenable in ARC, since it leads to default-unsafe code. The main merit to banning the properties is to avoid confusion with non-ARC practice, which did not ultimately strike us as sufficient to justify requiring extra syntax and (more importantly) forcing novices to understand ownership rules just to declare a property when the default is so reasonable. Changing the rule away from non-ARC practice was acceptable because we had conservatively banned the synthesis in order to give ourselves exactly this leeway.

Applying `__attribute__((NSObject))` to a property not of retainable object pointer type has the same behavior it does outside of ARC: it requires the property type to be some sort of pointer and permits the use of modifiers other than `assign`. These modifiers only affect the synthesized getter and setter; direct accesses to the ivar (even if synthesized) still have primitive semantics, and the value in the ivar will not be automatically released during deallocation.

Semantics

There are five managed operations which may be performed on an object of retainable object pointer type. Each qualifier specifies different semantics for each of these operations. It is still undefined behavior to access an object outside of its lifetime.

A load or store with "primitive semantics" has the same semantics as the respective operation would have on an `void*` lvalue with the same alignment and non-ownership qualification.

Reading occurs when performing a lvalue-to-rvalue conversion on an object lvalue.

- For `__weak` objects, the current pointee is retained and then released at the end of the current full-expression. This must execute atomically with respect to assignments and to the final release of the pointee.
- For all other objects, the lvalue is loaded with primitive semantics.

Assignment occurs when evaluating an assignment operator. The semantics vary based on the qualification:

- For `__strong` objects, the new pointee is first retained; second, the lvalue is loaded with primitive semantics; third, the new pointee is stored into the lvalue with primitive semantics; and finally, the old pointee is released. This is not performed atomically; external synchronization must be used to make this safe in the face of concurrent loads and stores.
- For `__weak` objects, the lvalue is updated to point to the new pointee, unless the new pointee is an object currently undergoing deallocation, in which case the lvalue is updated to a null pointer. This must execute atomically with respect to other assignments to the object, to reads from the object, and to the final release of the new pointee.
- For `__unsafe_unretained` objects, the new pointee is stored into the lvalue using primitive semantics.
- For `__autoreleasing` objects, the new pointee is retained, autoreleased, and stored into the lvalue using primitive semantics.

Initialization occurs when an object's lifetime begins, which depends on its storage duration. Initialization proceeds in two stages:

1. First, a null pointer is stored into the lvalue using primitive semantics. This step is skipped if the object is `__unsafe_unretained`.
2. Second, if the object has an initializer, that expression is evaluated and then assigned into the object using the usual assignment semantics.

Destruction occurs when an object's lifetime ends. In all cases it is semantically equivalent to assigning a null pointer to the object, with the proviso that of course the object cannot be legally read after the object's lifetime ends.

Moving occurs in specific situations where an lvalue is "moved from", meaning that its current pointee will be used but the object may be left in a different (but still valid) state. This arises with `__block` variables and rvalue references in C++. For `__strong` lvalues, moving is equivalent to loading the lvalue with primitive semantics, writing a null pointer to it with primitive semantics, and then releasing the result of the load at the end of the current full-expression. For all other lvalues, moving is equivalent to reading the object.

Restrictions

Weak-unavailable types

It is explicitly permitted for Objective-C classes to not support `__weak` references. It is undefined behavior to perform an operation with weak assignment semantics with a pointer to an Objective-C object whose class does not support `__weak` references.

Rationale

Historically, it has been possible for a class to provide its own reference-count implementation by overriding `retain`, `release`, etc. However, weak references to an object require coordination with its class's reference-count implementation because, among other things, weak loads and stores must be atomic with respect to the final release. Therefore, existing custom reference-count implementations will generally not support weak references without additional effort. This is unavoidable without breaking binary compatibility.

A class may indicate that it does not support weak references by providing the `objc_arc_weak_unavailable` attribute on the class's interface declaration. A retainable object pointer type is **weak-unavailable** if is a pointer to an (optionally protocol-qualified) Objective-C class `T` where `T` or one of its superclasses has the `objc_arc_weak_unavailable` attribute. A program is ill-formed if it applies the `__weak` ownership qualifier to a weak-unavailable type or if the value operand of a weak assignment operation has a weak-unavailable type.

Storage duration of `__autoreleasing` objects

A program is ill-formed if it declares an `__autoreleasing` object of non-automatic storage duration. A program is ill-formed if it captures an `__autoreleasing` object in a block or, unless by reference, in a C++11 lambda.

Rationale

Autorelease pools are tied to the current thread and scope by their nature. While it is possible to have temporary objects whose instance variables are filled with autoreleased objects, there is no way that ARC can provide any sort of safety guarantee there.

It is undefined behavior if a non-null pointer is assigned to an `__autoreleasing` object while an autorelease pool is in scope and then that object is read after the autorelease pool's scope is left.

Conversion of pointers to ownership-qualified types

A program is ill-formed if an expression of type `T*` is converted, explicitly or implicitly, to the type `U*`, where `T` and `U` have different ownership qualification, unless:

- `T` is qualified with `__strong`, `__autoreleasing`, or `__unsafe_unretained`, and `U` is qualified with both `const` and `__unsafe_unretained`; or
- either `T` or `U` is `cv void`, where `cv` is an optional sequence of non-ownership qualifiers; or
- the conversion is requested with a `reinterpret_cast` in Objective-C++; or
- the conversion is a well-formed *pass-by-writeback*.

The analogous rule applies to `T&` and `U&` in Objective-C++.

Rationale

These rules provide a reasonable level of type-safety for indirect pointers, as long as the underlying memory is not deallocated. The conversion to `const __unsafe_unretained` is permitted because the semantics of reads are equivalent across all these ownership semantics, and that's a very useful and common pattern. The interconversion with `void*` is useful for allocating memory or otherwise escaping the type system, but use it carefully. `reinterpret_cast` is considered to be an obvious enough sign of taking responsibility for any problems.

It is undefined behavior to access an ownership-qualified object through an lvalue of a differently-qualified type, except that any non-`__weak` object may be read through an `__unsafe_unretained` lvalue.

It is undefined behavior if a managed operation is performed on a `__strong` or `__weak` object without a guarantee that it contains a primitive zero bit-pattern, or if the storage for such an object is freed or reused without the object being first assigned a null pointer.

Rationale

ARC cannot differentiate between an assignment operator which is intended to "initialize" dynamic memory and one which is intended to potentially replace a value. Therefore the object's pointer must be valid before letting ARC at it. Similarly, C and Objective-C do not provide any language hooks for destroying objects held in dynamic memory, so it is the programmer's responsibility to avoid leaks (`__strong` objects) and consistency errors (`__weak` objects).

These requirements are followed automatically in Objective-C++ when creating objects of retainable object owner type with `new` or `new[]` and destroying them with `delete`, `delete[]`, or a pseudo-destructor expression. Note that arrays of nontrivially-ownership-qualified type are not ABI compatible with non-ARC code because the element type is non-POD: such arrays that are `new[]`'d in ARC translation units cannot be `delete[]`'d in non-ARC translation units and vice-versa.

Passing to an out parameter by writeback

If the argument passed to a parameter of type `T __autoreleasing *` has type `U oq *`, where `oq` is an ownership qualifier, then the argument is a candidate for pass-by-writeback' if:

- `oq` is `__strong` or `__weak`, and
- it would be legal to initialize a `T __strong *` with a `U __strong *`.

For purposes of overload resolution, an implicit conversion sequence requiring a pass-by-writeback is always worse than an implicit conversion sequence not requiring a pass-by-writeback.

The pass-by-writeback is ill-formed if the argument expression does not have a legal form:

- `&var`, where `var` is a scalar variable of automatic storage duration with retainable object pointer type
- a conditional expression where the second and third operands are both legal forms
- a cast whose operand is a legal form

- a null pointer constant

Rationale

The restriction in the form of the argument serves two purposes. First, it makes it impossible to pass the address of an array to the argument, which serves to protect against an otherwise serious risk of mis-inferring an "array" argument as an out-parameter. Second, it makes it much less likely that the user will see confusing aliasing problems due to the implementation, below, where their store to the writeback temporary is not immediately seen in the original argument variable.

A pass-by-writeback is evaluated as follows:

1. The argument is evaluated to yield a pointer `p` of type `U oq *`.
2. If `p` is a null pointer, then a null pointer is passed as the argument, and no further work is required for the pass-by-writeback.
3. Otherwise, a temporary of type `T __autoreleasing` is created and initialized to a null pointer.
4. If the parameter is not an Objective-C method parameter marked `out`, then `*p` is read, and the result is written into the temporary with primitive semantics.
5. The address of the temporary is passed as the argument to the actual call.
6. After the call completes, the temporary is loaded with primitive semantics, and that value is assigned into `*p`.

Rationale

This is all admittedly convoluted. In an ideal world, we would see that a local variable is being passed to an out-parameter and retroactively modify its type to be `__autoreleasing` rather than `__strong`. This would be remarkably difficult and not always well-founded under the C type system. However, it was judged unacceptably invasive to require programmers to write `__autoreleasing` on all the variables they intend to use for out-parameters. This was the least bad solution.

Ownership-qualified fields of structs and unions

A program is ill-formed if it declares a member of a C struct or union to have a nontrivially ownership-qualified type.

Rationale

The resulting type would be non-POD in the C++ sense, but C does not give us very good language tools for managing the lifetime of aggregates, so it is more convenient to simply forbid them. It is still possible to manage this with a `void*` or an `__unsafe_unretained` object.

This restriction does not apply in Objective-C++. However, nontrivially ownership-qualified types are considered non-POD: in C++11 terms, they are not trivially default constructible, copy constructible, move constructible, copy assignable, move assignable, or destructible. It is a violation of C++'s One Definition Rule to use a class outside of ARC that, under ARC, would have a nontrivially ownership-qualified member.

Rationale

Unlike in C, we can express all the necessary ARC semantics for ownership-qualified subobjects as suboperations of the (default) special member functions for the class. These functions then become non-trivial. This has the non-obvious

result that the class will have a non-trivial copy constructor and non-trivial destructor; if this would not normally be true outside of ARC, objects of the type will be passed and returned in an ABI-incompatible manner.

Ownership inference

Objects

If an object is declared with retainable object owner type, but without an explicit ownership qualifier, its type is implicitly adjusted to have `__strong` qualification.

As a special case, if the object's base type is `Class` (possibly protocol-qualified), the type is adjusted to have `__unsafe_unretained` qualification instead.

Indirect parameters

If a function or method parameter has type `T*`, where `T` is an ownership-unqualified retainable object pointer type, then:

- if `T` is `const`-qualified or `Class`, then it is implicitly qualified with `__unsafe_unretained`;
- otherwise, it is implicitly qualified with `__autoreleasing`.

Rationale

`__autoreleasing` exists mostly for this case, the Cocoa convention for out-parameters. Since a pointer to `const` is obviously not an out-parameter, we instead use a type more useful for passing arrays. If the user instead intends to pass in a *mutable* array, inferring `__autoreleasing` is the wrong thing to do; this directs some of the caution in the following rules about writeback.

Such a type written anywhere else would be ill-formed by the general rule requiring ownership qualifiers.

This rule does not apply in Objective-C++ if a parameter's type is dependent in a template pattern and is only *instantiated* to a type which would be a pointer to an unqualified retainable object pointer type. Such code is still ill-formed.

Rationale

The convention is very unlikely to be intentional in template code.

Template arguments

If a template argument for a template type parameter is an retainable object owner type that does not have an explicit ownership qualifier, it is adjusted to have `__strong` qualification. This adjustment occurs regardless of whether the template argument was deduced or explicitly specified.

Rationale

`__strong` is a useful default for containers (e.g., `std::vector<id>`), which would otherwise require explicit qualification. Moreover, unqualified retainable object pointer types are unlikely to be useful within templates, since they generally need to have a qualifier applied to the before being used.

Method families

An Objective-C method may fall into a method family, which is a conventional set of behaviors ascribed to it by the Cocoa conventions.

A method is in a certain method family if:

- it has a `objc_method_family` attribute placing it in that family; or if not that,
- it does not have an `objc_method_family` attribute placing it in a different or no family, and
- its selector falls into the corresponding selector family, and
- its signature obeys the added restrictions of the method family.

A selector is in a certain selector family if, ignoring any leading underscores, the first component of the selector either consists entirely of the name of the method family or it begins with that name followed by a character other than a lowercase letter. For example, `_perform:with:` and `performWith:` would fall into the `perform` family (if we recognized one), but `performing:with` would not.

The families and their added restrictions are:

- `alloc` methods must return a retainable object pointer type.
- `copy` methods must return a retainable object pointer type.
- `mutableCopy` methods must return a retainable object pointer type.
- `new` methods must return a retainable object pointer type.
- `init` methods must be instance methods and must return an Objective-C pointer type. Additionally, a program is ill-formed if it declares or contains a call to an `init` method whose return type is neither `id` nor a pointer to a super-class or sub-class of the declaring class (if the method was declared on a class) or the static receiver type of the call (if it was declared on a protocol).

Rationale

There are a fair number of existing methods with `init`-like selectors which nonetheless don't follow the `init` conventions. Typically these are either accidental naming collisions or helper methods called during initialization. Because of the peculiar retain/release behavior of `init` methods, it's very important not to treat these methods as `init` methods if they aren't meant to be. It was felt that implicitly defining these methods out of the family based on the exact relationship between the return type and the declaring class would be much too subtle and fragile. Therefore we identify a small number of legitimate-seeming return types and call everything else an error. This serves the secondary purpose of encouraging programmers not to accidentally give methods names in the `init` family.

Note that a method with an `init`-family selector which returns a non-Objective-C type (e.g. `void`) is perfectly well-formed; it simply isn't in the `init` family.

A program is ill-formed if a method's declarations, implementations, and overrides do not all have the same method family.

Explicit method family control

A method may be annotated with the `objc_method_family` attribute to precisely control which method family it belongs to. If a method in an `@implementation` does not have this attribute, but there is a method declared in the corresponding `@interface` that does, then the attribute is copied to the declaration in the `@implementation`. The attribute is available outside of ARC, and may be tested for with the preprocessor query `__has_attribute(objc_method_family)`.

The attribute is spelled `__attribute__((objc_method_family(`*family*`)))`. If *family* is `none`, the method has no family, even if it would otherwise be considered to have one based on its selector and type. Otherwise, *family* must be one of `alloc`, `copy`, `init`, `mutableCopy`, or `new`, in which case the method is considered to belong to the corresponding family regardless of its selector. It is an error if a method that is explicitly added to a family in this way does not meet the requirements of the family other than the selector naming convention.

Rationale

The rules codified in this document describe the standard conventions of Objective-C. However, as these conventions have not heretofore been enforced by an unforgiving mechanical system, they are only imperfectly kept, especially as they haven't always even been precisely defined. While it is possible to define low-level ownership semantics with attributes like `ns_returns_retained`, this attribute allows the user to communicate semantic intent, which is of use both to ARC (which, e.g., treats calls to `init` specially) and the static analyzer.

Semantics of method families

A method's membership in a method family may imply non-standard semantics for its parameters and return type.

Methods in the `alloc`, `copy`, `mutableCopy`, and `new` families — that is, methods in all the currently-defined families except `init` — implicitly *return a retained object* as if they were annotated with the `ns_returns_retained` attribute. This can be overridden by annotating the method with either of the `ns_returns_autoreleased` or `ns_returns_not_retained` attributes.

Properties also follow same naming rules as methods. This means that those in the `alloc`, `copy`, `mutableCopy`, and `new` families provide access to *retained objects*. This can be overridden by annotating the property with `ns_returns_not_retained` attribute.

Semantics of `init`

Methods in the `init` family implicitly *consume* their `self` parameter and *return a retained object*. Neither of these properties can be altered through attributes.

A call to an `init` method with a receiver that is either `self` (possibly parenthesized or casted) or `super` is called a delegate init call. It is an error for a delegate init call to be made except from an `init` method, and excluding blocks within such methods.

As an exception to the *usual rule*, the variable `self` is mutable in an `init` method and has the usual semantics for a `__strong` variable. However, it is undefined behavior and the program is ill-formed, no diagnostic required, if an `init` method attempts to use the previous value of `self` after the completion of a delegate init call. It is conventional, but not required, for an `init` method to return `self`.

It is undefined behavior for a program to cause two or more calls to `init` methods on the same object, except that each `init` method invocation may perform at most one delegate init call.

Related result types

Certain methods are candidates to have related result types:

- class methods in the `alloc` and `new` method families
- instance methods in the `init` family
- the instance method `self`

- outside of ARC, the instance methods `retain` and `autorelease`

If the formal result type of such a method is `id` or protocol-qualified `id`, or a type equal to the declaring class or a superclass, then it is said to have a related result type. In this case, when invoked in an explicit message send, it is assumed to return a type related to the type of the receiver:

- if it is a class method, and the receiver is a class name `T`, the message send expression has type `T*`; otherwise
- if it is an instance method, and the receiver has type `T`, the message send expression has type `T`; otherwise
- the message send expression has the normal result type of the method.

This is a new rule of the Objective-C language and applies outside of ARC.

Rationale

ARC's automatic code emission is more prone than most code to signature errors, i.e. errors where a call was emitted against one method signature, but the implementing method has an incompatible signature. Having more precise type information helps drastically lower this risk, as well as catching a number of latent bugs.

Optimization

Within this section, the word function will be used to refer to any structured unit of code, be it a C function, an Objective-C method, or a block.

This specification describes ARC as performing specific `retain` and `release` operations on retainable object pointers at specific points during the execution of a program. These operations make up a non-contiguous subsequence of the computation history of the program. The portion of this sequence for a particular retainable object pointer for which a specific function execution is directly responsible is the formal local retain history of the object pointer. The corresponding actual sequence executed is the *dynamic local retain history*.

However, under certain circumstances, ARC is permitted to re-order and eliminate operations in a manner which may alter the overall computation history beyond what is permitted by the general "as if" rule of C/C++ and the *restrictions* on the implementation of `retain` and `release`.

Rationale

Specifically, ARC is sometimes permitted to optimize `release` operations in ways which might cause an object to be deallocated before it would otherwise be. Without this, it would be almost impossible to eliminate any `retain`/`release` pairs. For example, consider the following code:

```
id x = _ivar;
[x foo];
```

If we were not permitted in any event to shorten the lifetime of the object in `x`, then we would not be able to eliminate this retain and release unless we could prove that the message send could not modify `_ivar` (or deallocate `self`). Since message sends are opaque to the optimizer, this is not possible, and so ARC's hands would be almost completely tied.

ARC makes no guarantees about the execution of a computation history which contains undefined behavior. In particular, ARC makes no guarantees in the presence of race conditions.

ARC may assume that any retainable object pointers it receives or generates are instantaneously valid from that point until a point which, by the concurrency model of the host language, happens-after the generation of the pointer and happens-before a release of that object (possibly via an aliasing pointer or indirectly due to destruction of a different object).

Rationale

There is very little point in trying to guarantee correctness in the presence of race conditions. ARC does not have a stack-scanning garbage collector, and guaranteeing the atomicity of every load and store operation would be prohibitive and preclude a vast amount of optimization.

ARC may assume that non-ARC code engages in sensible balancing behavior and does not rely on exact or minimum retain count values except as guaranteed by `__strong` object invariants or +1 transfer conventions. For example, if an object is provably double-retained and double-released, ARC may eliminate the inner retain and release; it does not need to guard against code which performs an unbalanced release followed by a "balancing" retain.

Object liveness

ARC may not allow a retainable object `X` to be deallocated at a time `T` in a computation history if:

- `X` is the value stored in a `__strong` object `S` with *precise lifetime semantics*, or
- `X` is the value stored in a `__strong` object `S` with imprecise lifetime semantics and, at some point after `T` but before the next store to `S`, the computation history features a load from `S` and in some way depends on the value loaded, or
- `X` is a value described as being released at the end of the current full-expression and, at some point after `T` but before the end of the full-expression, the computation history depends on that value.

Rationale

The intent of the second rule is to say that objects held in normal `__strong` local variables may be released as soon as the value in the variable is no longer being used: either the variable stops being used completely or a new value is stored in the variable.

The intent of the third rule is to say that return values may be released after they've been used.

A computation history depends on a pointer value `P` if it:

- performs a pointer comparison with `P`,
- loads from `P`,
- stores to `P`,
- depends on a pointer value `Q` derived via pointer arithmetic from `P` (including an instance-variable or field access), or
- depends on a pointer value `Q` loaded from `P`.

Dependency applies only to values derived directly or indirectly from a particular expression result and does not occur merely because a separate pointer value dynamically aliases `P`. Furthermore, this dependency is not carried by values that are stored to objects.

Rationale

The restrictions on dependency are intended to make this analysis feasible by an optimizer with only incomplete information about a program. Essentially, dependence is carried to "obvious" uses of a pointer. Merely passing a pointer argument to a function does not itself cause dependence, but since generally the optimizer will not be able to prove that the function doesn't depend on that parameter, it will be forced to conservatively assume it does.

Dependency propagates to values loaded from a pointer because those values might be invalidated by deallocating the object. For example, given the code `__strong id x = p->ivar;`, ARC must not move the release of `p` to between the load of `p->ivar` and the retain of that value for storing into `x`.

Dependency does not propagate through stores of dependent pointer values because doing so would allow dependency to outlive the full-expression which produced the original value. For example, the address of an instance variable could be written to some global location and then freely accessed during the lifetime of the local, or a function could return an inner pointer of an object and store it to a local. These cases would be potentially impossible to reason about and so would basically prevent any optimizations based on imprecise lifetime. There are also uncommon enough to make it reasonable to require the precise-lifetime annotation if someone really wants to rely on them.

Dependency does propagate through return values of pointer type. The compelling source of need for this rule is a property accessor which returns an un-autoreleased result; the calling function must have the chance to operate on the value, e.g. to retain it, before ARC releases the original pointer. Note again, however, that dependence does not survive a store, so ARC does not guarantee the continued validity of the return value past the end of the full-expression.

No object lifetime extension

If, in the formal computation history of the program, an object `X` has been deallocated by the time of an observable side-effect, then ARC must cause `X` to be deallocated by no later than the occurrence of that side-effect, except as influenced by the re-ordering of the destruction of objects.

Rationale

This rule is intended to prohibit ARC from observably extending the lifetime of a retainable object, other than as specified in this document. Together with the rule limiting the transformation of releases, this rule requires ARC to eliminate retains and release only in pairs.

ARC's power to reorder the destruction of objects is critical to its ability to do any optimization, for essentially the same reason that it must retain the power to decrease the lifetime of an object. Unfortunately, while it's generally poor style for the destruction of objects to have arbitrary side-effects, it's certainly possible. Hence the caveat.

Precise lifetime semantics

In general, ARC maintains an invariant that a retainable object pointer held in a `__strong` object will be retained for the full formal lifetime of the object. Objects subject to this invariant have precise lifetime semantics.

By default, local variables of automatic storage duration do not have precise lifetime semantics. Such objects are simply strong references which hold values of retainable object pointer type, and these values are still fully subject to the optimizations on values under local control.

Rationale

Applying these precise-lifetime semantics strictly would be prohibitive. Many useful optimizations that might theoretically decrease the lifetime of an object would be rendered impossible. Essentially, it promises too much.

A local variable of retainable object owner type and automatic storage duration may be annotated with the `objc_precise_lifetime` attribute to indicate that it should be considered to be an object with precise lifetime semantics.

Rationale

Nonetheless, it is sometimes useful to be able to force an object to be released at a precise time, even if that object does not appear to be used. This is likely to be uncommon enough that the syntactic weight of explicitly requesting these semantics will not be burdensome, and may even make the code clearer.

Miscellaneous

Special methods

Memory management methods

A program is ill-formed if it contains a method definition, message send, or `@selector` expression for any of the following selectors:

- `autorelease`
- `release`
- `retain`
- `retainCount`

Rationale

`retainCount` is banned because ARC robs it of consistent semantics. The others were banned after weighing three options for how to deal with message sends:

Honoring them would work out very poorly if a programmer naively or accidentally tried to incorporate code written for manual retain/release code into an ARC program. At best, such code would do twice as much work as necessary; quite frequently, however, ARC and the explicit code would both try to balance the same retain, leading to crashes. The cost is losing the ability to perform "unrooted" retains, i.e. retains not logically corresponding to a strong reference in the object graph.

Ignoring them would badly violate user expectations about their code. While it *would* make it easier to develop code simultaneously for ARC and non-ARC, there is very little reason to do so except for certain library developers. ARC and non-ARC translation units share an execution model and can seamlessly interoperate. Within a translation unit, a developer who faithfully maintains their code in non-ARC mode is suffering all the restrictions of ARC for zero benefit, while a developer who isn't testing the non-ARC mode is likely to be unpleasantly surprised if they try to go back to it.

Banning them has the disadvantage of making it very awkward to migrate existing code to ARC. The best answer to that, given a number of other changes and restrictions in ARC, is to provide a specialized tool to assist users in that migration.

Implementing these methods was banned because they are too integral to the semantics of ARC; many tricks which worked tolerably under manual reference counting will misbehave if ARC performs an ephemeral extra retain or two. If absolutely required, it is still possible to implement them in non-ARC code, for example in a category; the implementations must obey the *semantics* laid out elsewhere in this document.

`dealloc`

A program is ill-formed if it contains a message send or `@selector` expression for the selector `dealloc`.

Rationale

There are no legitimate reasons to call `dealloc` directly.

A class may provide a method definition for an instance method named `dealloc`. This method will be called after the final `release` of the object but before it is deallocated or any of its instance variables are destroyed. The superclass's implementation of `dealloc` will be called automatically when the method returns.

Rationale

Even though ARC destroys instance variables automatically, there are still legitimate reasons to write a `dealloc` method, such as freeing non-retainable resources. Failing to call `[super dealloc]` in such a method is nearly always a bug. Sometimes, the object is simply trying to prevent itself from being destroyed, but `dealloc` is really far too late for the object to be raising such objections. Somewhat more legitimately, an object may have been pool-allocated and should not be deallocated with `free`; for now, this can only be supported with a `dealloc` implementation outside of ARC. Such an implementation must be very careful to do all the other work that `NSObject`'s `dealloc` would, which is outside the scope of this document to describe.

The instance variables for an ARC-compiled class will be destroyed at some point after control enters the `dealloc` method for the root class of the class. The ordering of the destruction of instance variables is unspecified, both within a single class and between subclasses and superclasses.

Rationale

The traditional, non-ARC pattern for destroying instance variables is to destroy them immediately before calling `[super dealloc]`. Unfortunately, message sends from the superclass are quite capable of reaching methods in the subclass, and those methods may well read or write to those instance variables. Making such message sends from dealloc is generally discouraged, since the subclass may well rely on other invariants that were broken during `dealloc`, but it's not so inescapably dangerous that we felt comfortable calling it undefined behavior. Therefore we chose to delay destroying the instance variables to a point at which message sends are clearly disallowed: the point at which the root class's deallocation routines take over.

In most code, the difference is not observable. It can, however, be observed if an instance variable holds a strong reference to an object whose deallocation will trigger a side-effect which must be carefully ordered with respect to the destruction of the super class. Such code violates the design principle that semantically important behavior should be explicit. A simple fix is to clear the instance variable manually during `dealloc`; a more holistic solution is to move semantically important side-effects out of `dealloc` and into a separate teardown phase which can rely on working with well-formed objects.

`@autoreleasepool`

To simplify the use of autorelease pools, and to bring them under the control of the compiler, a new kind of statement is available in Objective-C. It is written `@autoreleasepool` followed by a *compound-statement*, i.e. by a new scope delimited by curly braces. Upon entry to this block, the current state of the autorelease pool is captured. When the block is exited normally, whether by fallthrough or directed control flow (such as `return` or `break`), the autorelease pool is restored to the saved state, releasing all the objects in it. When the block is exited with an exception, the pool is not drained.

`@autoreleasepool` may be used in non-ARC translation units, with equivalent semantics.

A program is ill-formed if it refers to the `NSAutoreleasePool` class.

Rationale

Autorelease pools are clearly important for the compiler to reason about, but it is far too much to expect the compiler to accurately reason about control dependencies between two calls. It is also very easy to accidentally forget to drain an autorelease pool when using the manual API, and this can significantly inflate the process's high-water-mark. The introduction of a new scope is unfortunate but basically required for sane interaction with the rest of the language. Not draining the pool during an unwind is apparently required by the Objective-C exceptions implementation.

`self`

The `self` parameter variable of an Objective-C method is never actually retained by the implementation. It is undefined behavior, or at least dangerous, to cause an object to be deallocated during a message send to that object.

To make this safe, for Objective-C instance methods `self` is implicitly `const` unless the method is in the *init family*. Further, `self` is **always** implicitly `const` within a class method.

Rationale

The cost of retaining `self` in all methods was found to be prohibitive, as it tends to be live across calls, preventing the optimizer from proving that the retain and release are unnecessary — for good reason, as it's quite possible in theory to cause an object to be deallocated during its execution without this retain and release. Since it's extremely uncommon to actually do so, even unintentionally, and since there's no natural way for the programmer to remove this retain/release pair otherwise (as there is for other parameters by, say, making the variable `__unsafe_unretained`), we chose to make this optimizing assumption and shift some amount of risk to the user.

Fast enumeration iteration variables

If a variable is declared in the condition of an Objective-C fast enumeration loop, and the variable has no explicit ownership qualifier, then it is qualified with `const __strong` and objects encountered during the enumeration are not actually retained.

Rationale

This is an optimization made possible because fast enumeration loops promise to keep the objects retained during enumeration, and the collection itself cannot be synchronously modified. It can be overridden by explicitly qualifying the variable with `__strong`, which will make the variable mutable again and cause the loop to retain the objects it encounters.

Blocks

The implicit `const` capture variables created when evaluating a block literal expression have the same ownership semantics as the local variables they capture. The capture is performed by reading from the captured variable and initializing the capture variable with that value; the capture variable is destroyed when the block literal is, i.e. at the end of the enclosing scope.

The *inference* rules apply equally to `__block` variables, which is a shift in semantics from non-ARC, where `__block` variables did not implicitly retain during capture.

`__block` variables of retainable object owner type are moved off the stack by initializing the heap copy with the result of moving from the stack copy.

With the exception of retains done as part of initializing a `__strong` parameter variable or reading a `__weak` variable, whenever these semantics call for retaining a value of block-pointer type, it has the effect of a `Block_copy`. The optimizer may remove such copies when it sees that the result is used only as an argument to a call.

Exceptions

By default in Objective C, ARC is not exception-safe for normal releases:

- It does not end the lifetime of `__strong` variables when their scopes are abnormally terminated by an exception.
- It does not perform releases which would occur at the end of a full-expression if that full-expression throws an exception.

A program may be compiled with the option `-fobjc-arc-exceptions` in order to enable these, or with the option `-fno-objc-arc-exceptions` to explicitly disable them, with the last such argument "winning".

Rationale

The standard Cocoa convention is that exceptions signal programmer error and are not intended to be recovered from. Making code exceptions-safe by default would impose severe runtime and code size penalties on code that typically does not actually care about exceptions safety. Therefore, ARC-generated code leaks by default on exceptions, which is just fine if the process is going to be immediately terminated anyway. Programs which do care about recovering from exceptions should enable the option.

In Objective-C++, `-fobjc-arc-exceptions` is enabled by default.

Rationale

C++ already introduces pervasive exceptions-cleanup code of the sort that ARC introduces. C++ programmers who have not already disabled exceptions are much more likely to actual require exception-safety.

ARC does end the lifetimes of `__weak` objects when an exception terminates their scope unless exceptions are disabled in the compiler.

Rationale

The consequence of a local `__weak` object not being destroyed is very likely to be corruption of the Objective-C runtime, so we want to be safer here. Of course, potentially massive leaks are about as likely to take down the process as this corruption is if the program does try to recover from exceptions.

Interior pointers

An Objective-C method returning a non-retainable pointer may be annotated with the `objc_returns_inner_pointer` attribute to indicate that it returns a handle to the internal data of an object, and that this reference will be invalidated if the object is destroyed. When such a message is sent to an object, the object's lifetime will be extended until at least the earliest of:

- the last use of the returned pointer, or any pointer derived from it, in the calling function or
- the autorelease pool is restored to a previous state.

Rationale

Rationale: not all memory and resources are managed with reference counts; it is common for objects to manage private resources in their own, private way. Typically these resources are completely encapsulated within the object, but some classes offer their users direct access for efficiency. If ARC is not aware of methods that return such "interior" pointers, its optimizations can cause the owning object to be reclaimed too soon. This attribute informs ARC that it must tread lightly.

The extension rules are somewhat intentionally vague. The autorelease pool limit is there to permit a simple implementation to simply retain and autorelease the receiver. The other limit permits some amount of optimization. The phrase "derived from" is intended to encompass the results both of pointer transformations, such as casts and arithmetic, and of loading from such derived pointers; furthermore, it applies whether or not such derivations are applied directly in the calling code or by other utility code (for example, the C library routine `strchr`). However, the implementation never need account for uses after a return from the code which calls the method returning an interior pointer.

As an exception, no extension is required if the receiver is loaded directly from a `__strong` object with *precise lifetime semantics*.

Rationale

Implicit autoreleases carry the risk of significantly inflating memory use, so it's important to provide users a way of avoiding these autoreleases. Tying this to precise lifetime semantics is ideal, as for local variables this requires a very explicit annotation, which allows ARC to trust the user with good cheer.

C retainable pointer types

A type is a C retainable pointer type if it is a pointer to (possibly qualified) `void` or a pointer to a (possibly qualifier) `struct` or `class` type.

Rationale

ARC does not manage pointers of CoreFoundation type (or any of the related families of retainable C pointers which interoperate with Objective-C for retain/release operation). In fact, ARC does not even know how to distinguish these types from arbitrary C pointer types. The intent of this concept is to filter out some obviously non-object types while leaving a hook for later tightening if a means of exhaustively marking CF types is made available.

Auditing of C retainable pointer interfaces

[beginning Apple 4.0, LLVM 3.1]

A C function may be marked with the `cf_audited_transfer` attribute to express that, except as otherwise marked with attributes, it obeys the parameter (consuming vs. non-consuming) and return (retained vs. non-retained) conventions for a C function of its name, namely:

- A parameter of C retainable pointer type is assumed to not be consumed unless it is marked with the `cf_consumed` attribute, and
- A result of C retainable pointer type is assumed to not be returned retained unless the function is either marked `cf_returns_retained` or it follows the create/copy naming convention and is not marked `cf_returns_not_retained`.

A function obeys the create/copy naming convention if its name contains as a substring:

- either "Create" or "Copy" not followed by a lowercase letter, or
- either "create" or "copy" not followed by a lowercase letter and not preceded by any letter, whether uppercase or lowercase.

A second attribute, `cf_unknown_transfer`, signifies that a function's transfer semantics cannot be accurately captured using any of these annotations. A program is ill-formed if it annotates the same function with both `cf_audited_transfer` and `cf_unknown_transfer`.

A pragma is provided to facilitate the mass annotation of interfaces:

```
#pragma clang arc_cf_code_audited begin
...
#pragma clang arc_cf_code_audited end
```

All C functions declared within the extent of this pragma are treated as if annotated with the `cf_audited_transfer` attribute unless they otherwise have the `cf_unknown_transfer` attribute. The pragma is accepted in all language modes. A program is ill-formed if it attempts to change files, whether by including a file or ending the current file, within the extent of this pragma.

It is possible to test for all the features in this section with `__has_feature(arc_cf_code_audited)`.

Rationale

A significant inconvenience in ARC programming is the necessity of interacting with APIs based around C retainable pointers. These features are designed to make it relatively easy for API authors to quickly review and annotate their interfaces, in turn improving the fidelity of tools such as the static analyzer and ARC. The single-file restriction on the pragma is designed to eliminate the risk of accidentally annotating some other header's interfaces.

Runtime support

This section describes the interaction between the ARC runtime and the code generated by the ARC compiler. This is not part of the ARC language specification; instead, it is effectively a language-specific ABI supplement, akin to the "Itanium" generic ABI for C++.

Ownership qualification does not alter the storage requirements for objects, except that it is undefined behavior if a `__weak` object is inadequately aligned for an object of type `id`. The other qualifiers may be used on explicitly under-aligned memory.

The runtime tracks `__weak` objects which holds non-null values. It is undefined behavior to direct modify a `__weak` object which is being tracked by the runtime except through an *objc_storeWeak*, *objc_destroyWeak*, or *objc_moveWeak* call.

The runtime must provide a number of new entrypoints which the compiler may emit, which are described in the remainder of this section.

Rationale

Several of these functions are semantically equivalent to a message send; we emit calls to C functions instead because:

- the machine code to do so is significantly smaller,
- it is much easier to recognize the C functions in the ARC optimizer, and
- a sufficient sophisticated runtime may be able to avoid the message send in common cases.

Several other of these functions are "fused" operations which can be described entirely in terms of other operations. We use the fused operations primarily as a code-size optimization, although in some cases there is also a real potential for avoiding redundant operations in the runtime.

`id objc_autorelease(id value);`

Precondition: `value` is null or a pointer to a valid object.

If `value` is null, this call has no effect. Otherwise, it adds the object to the innermost autorelease pool exactly as if the object had been sent the `autorelease` message.

Always returns `value`.

`void objc_autoreleasePoolPop(void *pool);`

Precondition: `pool` is the result of a previous call to *objc_autoreleasePoolPush* on the current thread, where neither `pool` nor any enclosing pool have previously been popped.

Releases all the objects added to the given autorelease pool and any autorelease pools it encloses, then sets the current autorelease pool to the pool directly enclosing `pool`.

`void *objc_autoreleasePoolPush(void);`

Creates a new autorelease pool that is enclosed by the current pool, makes that the current pool, and returns an opaque "handle" to it.

Rationale

While the interface is described as an explicit hierarchy of pools, the rules allow the implementation to just keep a stack of objects, using the stack depth as the opaque pool handle.

`id objc_autoreleaseReturnValue(id value);`

Precondition: `value` is null or a pointer to a valid object.

If `value` is null, this call has no effect. Otherwise, it makes a best effort to hand off ownership of a retain count on the object to a call to *objc_retainAutoreleasedReturnValue* for the same object in an enclosing call frame. If this is not possible, the object is autoreleased as above.

Always returns `value`.

`void objc_copyWeak(id *dest, id *src);`

Precondition: `src` is a valid pointer which either contains a null pointer or has been registered as a `__weak` object. `dest` is a valid pointer which has not been registered as a `__weak` object.

`dest` is initialized to be equivalent to `src`, potentially registering it with the runtime. Equivalent to the following code:

```
void objc_copyWeak(id *dest, id *src) {
  objc_release(objc_initWeak(dest, objc_loadWeakRetained(src)));
}
```

Must be atomic with respect to calls to `objc_storeWeak` on `src`.

void objc_destroyWeak(id *object);

Precondition: `object` is a valid pointer which either contains a null pointer or has been registered as a `__weak` object.

`object` is unregistered as a weak object, if it ever was. The current value of `object` is left unspecified; otherwise, equivalent to the following code:

```
void objc_destroyWeak(id *object) {
  objc_storeWeak(object, nil);
}
```

Does not need to be atomic with respect to calls to `objc_storeWeak` on `object`.

id objc_initWeak(id *object, id value);

Precondition: `object` is a valid pointer which has not been registered as a `__weak` object. `value` is null or a pointer to a valid object.

If `value` is a null pointer or the object to which it points has begun deallocation, `object` is zero-initialized. Otherwise, `object` is registered as a `__weak` object pointing to `value`. Equivalent to the following code:

```
id objc_initWeak(id *object, id value) {
  *object = nil;
  return objc_storeWeak(object, value);
}
```

Returns the value of `object` after the call.

Does not need to be atomic with respect to calls to `objc_storeWeak` on `object`.

id objc_loadWeak(id *object);

Precondition: `object` is a valid pointer which either contains a null pointer or has been registered as a `__weak` object.

If `object` is registered as a `__weak` object, and the last value stored into `object` has not yet been deallocated or begun deallocation, retains and autoreleases that value and returns it. Otherwise returns null. Equivalent to the following code:

```
id objc_loadWeak(id *object) {
  return objc_autorelease(objc_loadWeakRetained(object));
}
```

Must be atomic with respect to calls to `objc_storeWeak` on `object`.

Rationale

Loading weak references would be inherently prone to race conditions without the retain.

id objc_loadWeakRetained(id *object);

Precondition: `object` is a valid pointer which either contains a null pointer or has been registered as a `__weak` object.

If `object` is registered as a `__weak` object, and the last value stored into `object` has not yet been deallocated or begun deallocation, retains that value and returns it. Otherwise returns null.

Must be atomic with respect to calls to `objc_storeWeak` on `object`.

void objc_moveWeak(id *dest, id *src);

Precondition: `src` is a valid pointer which either contains a null pointer or has been registered as a `__weak` object. `dest` is a valid pointer which has not been registered as a `__weak` object.

`dest` is initialized to be equivalent to `src`, potentially registering it with the runtime. `src` may then be left in its original state, in which case this call is equivalent to *objc_copyWeak*, or it may be left as null.

Must be atomic with respect to calls to `objc_storeWeak` on `src`.

void objc_release(id value);

Precondition: `value` is null or a pointer to a valid object.

If `value` is null, this call has no effect. Otherwise, it performs a release operation exactly as if the object had been sent the `release` message.

id objc_retain(id value);

Precondition: `value` is null or a pointer to a valid object.

If `value` is null, this call has no effect. Otherwise, it performs a retain operation exactly as if the object had been sent the `retain` message.

Always returns `value`.

id objc_retainAutorelease(id value);

Precondition: `value` is null or a pointer to a valid object.

If `value` is null, this call has no effect. Otherwise, it performs a retain operation followed by an autorelease operation. Equivalent to the following code:

```
id objc_retainAutorelease(id value) {
  return objc_autorelease(objc_retain(value));
}
```

Always returns `value`.

id objc_retainAutoreleaseReturnValue(id value);

Precondition: `value` is null or a pointer to a valid object.

If `value` is null, this call has no effect. Otherwise, it performs a retain operation followed by the operation described in *objc_autoreleaseReturnValue*. Equivalent to the following code:

```
id objc_retainAutoreleaseReturnValue(id value) {
  return objc_autoreleaseReturnValue(objc_retain(value));
}
```

Always returns `value`.

id objc_retainAutoreleasedReturnValue(id value);

Precondition: `value` is null or a pointer to a valid object.

If `value` is null, this call has no effect. Otherwise, it attempts to accept a hand off of a retain count from a call to *objc_autoreleaseReturnValue* on `value` in a recently-called function or something it calls. If that fails, it performs a retain operation exactly like *objc_retain*.

Always returns `value`.

id objc_retainBlock(id value);

Precondition: `value` is null or a pointer to a valid block object.

If `value` is null, this call has no effect. Otherwise, if the block pointed to by `value` is still on the stack, it is copied to the heap and the address of the copy is returned. Otherwise a retain operation is performed on the block exactly as if it had been sent the `retain` message.

id objc_storeStrong(id *object, id value);

Precondition: `object` is a valid pointer to a `__strong` object which is adequately aligned for a pointer. `value` is null or a pointer to a valid object.

Performs the complete sequence for assigning to a `__strong` object of non-block type*[0]. Equivalent to the following code:

```
id objc_storeStrong(id *object, id value) {
  value = [value retain];
  id oldValue = *object;
  *object = value;
  [oldValue release];
  return value;
}
```

Always returns `value`.

[0] This does not imply that a `__strong` object of block type is an invalid argument to this function. Rather it implies that an `objc_retain` and not an `objc_retainBlock` operation will be emitted if the argument is a block.

```
id objc_storeWeak(id *object, id value);
```

Precondition: `object` is a valid pointer which either contains a null pointer or has been registered as a `__weak` object. `value` is null or a pointer to a valid object.

If `value` is a null pointer or the object to which it points has begun deallocation, `object` is assigned null and unregistered as a `__weak` object. Otherwise, `object` is registered as a `__weak` object or has its registration updated to point to `value`.

Returns the value of `object` after the call.

Introduction

This document describes the language extensions provided by Clang. In addition to the language extensions listed here, Clang aims to support a broad range of GCC extensions. Please see the GCC manual for more information on these extensions.

Feature Checking Macros

Language extensions can be very useful, but only if you know you can depend on them. In order to allow fine-grain features checks, we support three builtin function-like macros. This allows you to directly test for a feature in your code without having to resort to something like autoconf or fragile "compiler version checks".

`__has_builtin`

This function-like macro takes a single identifier argument that is the name of a builtin function. It evaluates to 1 if the builtin is supported or 0 if not. It can be used like this:

```
#ifndef __has_builtin         // Optional of course.
  #define __has_builtin(x) 0  // Compatibility with non-clang compilers.
#endif

...
#if __has_builtin(__builtin_trap)
  __builtin_trap();
#else
  abort();
#endif
...
```

`__has_feature` and `__has_extension`

These function-like macros take a single identifier argument that is the name of a feature. `__has_feature` evaluates to 1 if the feature is both supported by Clang and standardized in the current language standard or 0 if not (but see *below*), while `__has_extension` evaluates to 1 if the feature is supported by Clang in the current language (either as a language extension or a standard language feature) or 0 if not. They can be used like this:

```
#ifndef __has_feature         // Optional of course.
  #define __has_feature(x) 0  // Compatibility with non-clang compilers.
#endif
#ifndef __has_extension
  #define __has_extension __has_feature // Compatibility with pre-3.0 compilers.
#endif
```

```
...
#if __has_feature(cxx_rvalue_references)
// This code will only be compiled with the -std=c++11 and -std=gnu++11
// options, because rvalue references are only standardized in C++11.
#endif

#if __has_extension(cxx_rvalue_references)
// This code will be compiled with the -std=c++11, -std=gnu++11, -std=c++98
// and -std=gnu++98 options, because rvalue references are supported as a
// language extension in C++98.
#endif
```

For backward compatibility, `__has_feature` can also be used to test for support for non-standardized features, i.e. features not prefixed `c_`, `cxx_` or `objc_`.

Another use of `__has_feature` is to check for compiler features not related to the language standard, such as e.g. *AddressSanitizer*.

If the `-pedantic-errors` option is given, `__has_extension` is equivalent to `__has_feature`.

The feature tag is described along with the language feature below.

The feature name or extension name can also be specified with a preceding and following `__` (double underscore) to avoid interference from a macro with the same name. For instance, `__cxx_rvalue_references__` can be used instead of `cxx_rvalue_references`.

`__has_cpp_attribute`

This function-like macro takes a single argument that is the name of a C++11-style attribute. The argument can either be a single identifier, or a scoped identifier. If the attribute is supported, a nonzero value is returned. If the attribute is a standards-based attribute, this macro returns a nonzero value based on the year and month in which the attribute was voted into the working draft. If the attribute is not supported by the current compliation target, this macro evaluates to 0. It can be used like this:

```
#ifndef __has_cpp_attribute         // Optional of course.
  #define __has_cpp_attribute(x) 0  // Compatibility with non-clang compilers.
#endif

...
#if __has_cpp_attribute(clang::fallthrough)
#define FALLTHROUGH [[clang::fallthrough]]
#else
#define FALLTHROUGH
#endif
...
```

The attribute identifier (but not scope) can also be specified with a preceding and following `__` (double underscore) to avoid interference from a macro with the same name. For instance, `gnu::__const__` can be used instead of `gnu::const`.

`__has_attribute`

This function-like macro takes a single identifier argument that is the name of a GNU-style attribute. It evaluates to 1 if the attribute is supported by the current compilation target, or 0 if not. It can be used like this:

```
#ifndef __has_attribute         // Optional of course.
  #define __has_attribute(x) 0  // Compatibility with non-clang compilers.
#endif

...
#if __has_attribute(always_inline)
#define ALWAYS_INLINE __attribute__((always_inline))
#else
#define ALWAYS_INLINE
#endif
...
```

The attribute name can also be specified with a preceding and following __ (double underscore) to avoid interference from a macro with the same name. For instance, `__always_inline__` can be used instead of `always_inline`.

__has_declspec_attribute

This function-like macro takes a single identifier argument that is the name of an attribute implemented as a Microsoft-style `__declspec` attribute. It evaluates to 1 if the attribute is supported by the current compilation target, or 0 if not. It can be used like this:

```
#ifndef __has_declspec_attribute         // Optional of course.
  #define __has_declspec_attribute(x) 0  // Compatibility with non-clang compilers.
#endif

...
#if __has_declspec_attribute(dllexport)
#define DLLEXPORT __declspec(dllexport)
#else
#define DLLEXPORT
#endif
...
```

The attribute name can also be specified with a preceding and following __ (double underscore) to avoid interference from a macro with the same name. For instance, `__dllexport__` can be used instead of `dllexport`.

__is_identifier

This function-like macro takes a single identifier argument that might be either a reserved word or a regular identifier. It evaluates to 1 if the argument is just a regular identifier and not a reserved word, in the sense that it can then be used as the name of a user-defined function or variable. Otherwise it evaluates to 0. It can be used like this:

```
...
#ifdef __is_identifier          // Compatibility with non-clang compilers.
  #if __is_identifier(__wchar_t)
    typedef wchar_t __wchar_t;
  #endif
#endif

__wchar_t WideCharacter;
...
```

Include File Checking Macros

Not all developments systems have the same include files. The *__has_include* and *__has_include_next* macros allow you to check for the existence of an include file before doing a possibly failing `#include` directive. Include file checking macros must be used as expressions in `#if` or `#elif` preprocessing directives.

__has_include

This function-like macro takes a single file name string argument that is the name of an include file. It evaluates to 1 if the file can be found using the include paths, or 0 otherwise:

```
// Note the two possible file name string formats.
#if __has_include("myinclude.h") && __has_include(<stdint.h>)
# include "myinclude.h"
#endif
```

To test for this feature, use `#if defined(__has_include)`:

```
// To avoid problem with non-clang compilers not having this macro.
#if defined(__has_include)
#if __has_include("myinclude.h")
# include "myinclude.h"
#endif
#endif
```

__has_include_next

This function-like macro takes a single file name string argument that is the name of an include file. It is like `__has_include` except that it looks for the second instance of the given file found in the include paths. It evaluates to 1 if the second instance of the file can be found using the include paths, or 0 otherwise:

```
// Note the two possible file name string formats.
#if __has_include_next("myinclude.h") && __has_include_next(<stdint.h>)
# include_next "myinclude.h"
#endif

// To avoid problem with non-clang compilers not having this macro.
#if defined(__has_include_next)
#if __has_include_next("myinclude.h")
# include_next "myinclude.h"
#endif
#endif
```

Note that `__has_include_next`, like the GNU extension `#include_next` directive, is intended for use in headers only, and will issue a warning if used in the top-level compilation file. A warning will also be issued if an absolute path is used in the file argument.

__has_warning

This function-like macro takes a string literal that represents a command line option for a warning and returns true if that is a valid warning option.

```
#if __has_warning("-Wformat")
...
#endif
```

Builtin Macros

__BASE_FILE__ Defined to a string that contains the name of the main input file passed to Clang.

__COUNTER__ Defined to an integer value that starts at zero and is incremented each time the __COUNTER__ macro is expanded.

__INCLUDE_LEVEL__ Defined to an integral value that is the include depth of the file currently being translated. For the main file, this value is zero.

__TIMESTAMP__ Defined to the date and time of the last modification of the current source file.

__clang__ Defined when compiling with Clang

__clang_major__ Defined to the major marketing version number of Clang (e.g., the 2 in 2.0.1). Note that marketing version numbers should not be used to check for language features, as different vendors use different numbering schemes. Instead, use the *Feature Checking Macros*.

__clang_minor__ Defined to the minor version number of Clang (e.g., the 0 in 2.0.1). Note that marketing version numbers should not be used to check for language features, as different vendors use different numbering schemes. Instead, use the *Feature Checking Macros*.

__clang_patchlevel__ Defined to the marketing patch level of Clang (e.g., the 1 in 2.0.1).

__clang_version__ Defined to a string that captures the Clang marketing version, including the Subversion tag or revision number, e.g., "`1.5 (trunk 102332)`".

Vectors and Extended Vectors

Supports the GCC, OpenCL, AltiVec and NEON vector extensions.

OpenCL vector types are created using `ext_vector_type` attribute. It support for `V.xyzw` syntax and other tidbits as seen in OpenCL. An example is:

```
typedef float float4 __attribute__((ext_vector_type(4)));
typedef float float2 __attribute__((ext_vector_type(2)));

float4 foo(float2 a, float2 b) {
  float4 c;
  c.xz = a;
  c.yw = b;
  return c;
}
```

Query for this feature with `__has_extension(attribute_ext_vector_type)`.

Giving `-faltivec` option to clang enables support for AltiVec vector syntax and functions. For example:

```
vector float foo(vector int a) {
  vector int b;
  b = vec_add(a, a) + a;
  return (vector float)b;
}
```

NEON vector types are created using `neon_vector_type` and `neon_polyvector_type` attributes. For example:

```
typedef __attribute__((neon_vector_type(8))) int8_t int8x8_t;
typedef __attribute__((neon_polyvector_type(16))) poly8_t poly8x16_t;

int8x8_t foo(int8x8_t a) {
  int8x8_t v;
  v = a;
  return v;
}
```

Vector Literals

Vector literals can be used to create vectors from a set of scalars, or vectors. Either parentheses or braces form can be used. In the parentheses form the number of literal values specified must be one, i.e. referring to a scalar value, or must match the size of the vector type being created. If a single scalar literal value is specified, the scalar literal value will be replicated to all the components of the vector type. In the brackets form any number of literals can be specified. For example:

```
typedef int v4si __attribute__((__vector_size__(16)));
typedef float float4 __attribute__((ext_vector_type(4)));
typedef float float2 __attribute__((ext_vector_type(2)));

v4si vsi = (v4si){1, 2, 3, 4};
float4 vf = (float4)(1.0f, 2.0f, 3.0f, 4.0f);
vector int vi1 = (vector int)(1);    // vi1 will be (1, 1, 1, 1).
vector int vi2 = (vector int){1};    // vi2 will be (1, 0, 0, 0).
vector int vi3 = (vector int)(1, 2); // error
vector int vi4 = (vector int){1, 2}; // vi4 will be (1, 2, 0, 0).
vector int vi5 = (vector int)(1, 2, 3, 4);
float4 vf = (float4)((float2)(1.0f, 2.0f), (float2)(3.0f, 4.0f));
```

Vector Operations

The table below shows the support for each operation by vector extension. A dash indicates that an operation is not accepted according to a corresponding specification.

Operator	OpenCL	AltiVec	GCC	NEON
[]	yes	yes	yes	–
unary operators +, –	yes	yes	yes	–
++, – –	yes	yes	yes	–
+,–,*,/,%	yes	yes	yes	–
bitwise operators &,|,^,~	yes	yes	yes	–
>>,<<	yes	yes	yes	–
!, &&, ||	yes	–	–	–
==, !=, >, <, >=, <=	yes	yes	–	–
=	yes	yes	yes	yes
:?	yes	–	–	–
sizeof	yes	yes	yes	yes
C-style cast	yes	yes	yes	no
reinterpret_cast	yes	no	yes	no
static_cast	yes	no	yes	no
const_cast	no	no	no	no

See also *__builtin_shufflevector*, *__builtin_convertvector*.

Messages on `deprecated` and `unavailable` Attributes

An optional string message can be added to the `deprecated` and `unavailable` attributes. For example:

```
void explode(void) __attribute__((deprecated("extremely unsafe, use 'combust' instead!
↪!!")));
```

If the deprecated or unavailable declaration is used, the message will be incorporated into the appropriate diagnostic:

```
harmless.c:4:3: warning: 'explode' is deprecated: extremely unsafe, use 'combust'␣
↪instead!!!
      [-Wdeprecated-declarations]
  explode();
  ^
```

Query for this feature with `__has_extension(attribute_deprecated_with_message)` and `__has_extension(attribute_unavailable_with_message)`.

Attributes on Enumerators

Clang allows attributes to be written on individual enumerators. This allows enumerators to be deprecated, made unavailable, etc. The attribute must appear after the enumerator name and before any initializer, like so:

```
enum OperationMode {
  OM_Invalid,
  OM_Normal,
  OM_Terrified __attribute__((deprecated)),
  OM_AbortOnError __attribute__((deprecated)) = 4
};
```

Attributes on the `enum` declaration do not apply to individual enumerators.

Query for this feature with `__has_extension(enumerator_attributes)`.

'User-Specified' System Frameworks

Clang provides a mechanism by which frameworks can be built in such a way that they will always be treated as being "system frameworks", even if they are not present in a system framework directory. This can be useful to system framework developers who want to be able to test building other applications with development builds of their framework, including the manner in which the compiler changes warning behavior for system headers.

Framework developers can opt-in to this mechanism by creating a "`.system_framework`" file at the top-level of their framework. That is, the framework should have contents like:

```
.../TestFramework.framework
.../TestFramework.framework/.system_framework
.../TestFramework.framework/Headers
.../TestFramework.framework/Headers/TestFramework.h
...
```

Clang will treat the presence of this file as an indicator that the framework should be treated as a system framework, regardless of how it was found in the framework search path. For consistency, we recommend that such files never be included in installed versions of the framework.

Checks for Standard Language Features

The `__has_feature` macro can be used to query if certain standard language features are enabled. The `__has_extension` macro can be used to query if language features are available as an extension when compiling for a standard which does not provide them. The features which can be tested are listed here.

Since Clang 3.4, the C++ SD-6 feature test macros are also supported. These are macros with names of the form `__cpp_<feature_name>`, and are intended to be a portable way to query the supported features of the compiler. See the C++ status page for information on the version of SD-6 supported by each Clang release, and the macros provided by that revision of the recommendations.

C++98

The features listed below are part of the C++98 standard. These features are enabled by default when compiling C++ code.

C++ exceptions

Use `__has_feature(cxx_exceptions)` to determine if C++ exceptions have been enabled. For example, compiling code with `-fno-exceptions` disables C++ exceptions.

C++ RTTI

Use `__has_feature(cxx_rtti)` to determine if C++ RTTI has been enabled. For example, compiling code with `-fno-rtti` disables the use of RTTI.

C++11

The features listed below are part of the C++11 standard. As a result, all these features are enabled with the `-std=c++11` or `-std=gnu++11` option when compiling C++ code.

C++11 SFINAE includes access control

Use `__has_feature(cxx_access_control_sfinae)` or `__has_extension(cxx_access_control_sfinae)` to determine whether access-control errors (e.g., calling a private constructor) are considered to be template argument deduction errors (aka SFINAE errors), per C++ DR1170.

C++11 alias templates

Use `__has_feature(cxx_alias_templates)` or `__has_extension(cxx_alias_templates)` to determine if support for C++11's alias declarations and alias templates is enabled.

C++11 alignment specifiers

Use `__has_feature(cxx_alignas)` or `__has_extension(cxx_alignas)` to determine if support for alignment specifiers using `alignas` is enabled.

Use `__has_feature(cxx_alignof)` or `__has_extension(cxx_alignof)` to determine if support for the `alignof` keyword is enabled.

C++11 attributes

Use `__has_feature(cxx_attributes)` or `__has_extension(cxx_attributes)` to determine if support for attribute parsing with C++11's square bracket notation is enabled.

C++11 generalized constant expressions

Use `__has_feature(cxx_constexpr)` to determine if support for generalized constant expressions (e.g., `constexpr`) is enabled.

C++11 `decltype()`

Use `__has_feature(cxx_decltype)` or `__has_extension(cxx_decltype)` to determine if support for the `decltype()` specifier is enabled. C++11's `decltype` does not require type-completeness of a function call expression. Use `__has_feature(cxx_decltype_incomplete_return_types)` or `__has_extension(cxx_decltype_incomplete_return_types)` to determine if support for this feature is enabled.

C++11 default template arguments in function templates

Use `__has_feature(cxx_default_function_template_args)` or `__has_extension(cxx_default_function_` to determine if support for default template arguments in function templates is enabled.

C++11 `defaulted` functions

Use `__has_feature(cxx_defaulted_functions)` or `__has_extension(cxx_defaulted_functions)` to determine if support for defaulted function definitions (with `= default`) is enabled.

C++11 delegating constructors

Use `__has_feature(cxx_delegating_constructors)` to determine if support for delegating constructors is enabled.

C++11 `deleted` functions

Use `__has_feature(cxx_deleted_functions)` or `__has_extension(cxx_deleted_functions)` to determine if support for deleted function definitions (with `= delete`) is enabled.

C++11 explicit conversion functions

Use `__has_feature(cxx_explicit_conversions)` to determine if support for `explicit` conversion functions is enabled.

C++11 generalized initializers

Use `__has_feature(cxx_generalized_initializers)` to determine if support for generalized initializers (using braced lists and `std::initializer_list`) is enabled.

C++11 implicit move constructors/assignment operators

Use `__has_feature(cxx_implicit_moves)` to determine if Clang will implicitly generate move constructors and move assignment operators where needed.

C++11 inheriting constructors

Use `__has_feature(cxx_inheriting_constructors)` to determine if support for inheriting constructors is enabled.

C++11 inline namespaces

Use `__has_feature(cxx_inline_namespaces)` or `__has_extension(cxx_inline_namespaces)` to determine if support for inline namespaces is enabled.

C++11 lambdas

Use `__has_feature(cxx_lambdas)` or `__has_extension(cxx_lambdas)` to determine if support for lambdas is enabled.

C++11 local and unnamed types as template arguments

Use `__has_feature(cxx_local_type_template_args)` or `__has_extension(cxx_local_type_template_arg` to determine if support for local and unnamed types as template arguments is enabled.

C++11 noexcept

Use `__has_feature(cxx_noexcept)` or `__has_extension(cxx_noexcept)` to determine if support for noexcept exception specifications is enabled.

C++11 in-class non-static data member initialization

Use `__has_feature(cxx_nonstatic_member_init)` to determine whether in-class initialization of non-static data members is enabled.

C++11 `nullptr`

Use `__has_feature(cxx_nullptr)` or `__has_extension(cxx_nullptr)` to determine if support for `nullptr` is enabled.

C++11 `override control`

Use `__has_feature(cxx_override_control)` or `__has_extension(cxx_override_control)` to determine if support for the override control keywords is enabled.

C++11 reference-qualified functions

Use `__has_feature(cxx_reference_qualified_functions)` or `__has_extension(cxx_reference_qualifie` to determine if support for reference-qualified functions (e.g., member functions with `&` or `&&` applied to `*this`) is enabled.

C++11 range-based `for` loop

Use `__has_feature(cxx_range_for)` or `__has_extension(cxx_range_for)` to determine if support for the range-based for loop is enabled.

C++11 raw string literals

Use `__has_feature(cxx_raw_string_literals)` to determine if support for raw string literals (e.g., `R"x(foo\bar)x"`) is enabled.

C++11 rvalue references

Use `__has_feature(cxx_rvalue_references)` or `__has_extension(cxx_rvalue_references)` to determine if support for rvalue references is enabled.

C++11 `static_assert()`

Use `__has_feature(cxx_static_assert)` or `__has_extension(cxx_static_assert)` to determine if support for compile-time assertions using `static_assert` is enabled.

C++11 `thread_local`

Use `__has_feature(cxx_thread_local)` to determine if support for `thread_local` variables is enabled.

C++11 type inference

Use `__has_feature(cxx_auto_type)` or `__has_extension(cxx_auto_type)` to determine C++11 type inference is supported using the `auto` specifier. If this is disabled, `auto` will instead be a storage class specifier, as in C or C++98.

C++11 strongly typed enumerations

Use `__has_feature(cxx_strong_enums)` or `__has_extension(cxx_strong_enums)` to determine if support for strongly typed, scoped enumerations is enabled.

C++11 trailing return type

Use `__has_feature(cxx_trailing_return)` or `__has_extension(cxx_trailing_return)` to determine if support for the alternate function declaration syntax with trailing return type is enabled.

C++11 Unicode string literals

Use `__has_feature(cxx_unicode_literals)` to determine if support for Unicode string literals is enabled.

C++11 unrestricted unions

Use `__has_feature(cxx_unrestricted_unions)` to determine if support for unrestricted unions is enabled.

C++11 user-defined literals

Use `__has_feature(cxx_user_literals)` to determine if support for user-defined literals is enabled.

C++11 variadic templates

Use `__has_feature(cxx_variadic_templates)` or `__has_extension(cxx_variadic_templates)` to determine if support for variadic templates is enabled.

C++1y

The features listed below are part of the committee draft for the C++1y standard. As a result, all these features are enabled with the `-std=c++1y` or `-std=gnu++1y` option when compiling C++ code.

C++1y binary literals

Use `__has_feature(cxx_binary_literals)` or `__has_extension(cxx_binary_literals)` to determine whether binary literals (for instance, `0b10010`) are recognized. Clang supports this feature as an extension in all language modes.

C++1y contextual conversions

Use `__has_feature(cxx_contextual_conversions)` or `__has_extension(cxx_contextual_conversions)` to determine if the C++1y rules are used when performing an implicit conversion for an array bound in a *new-expression*, the operand of a *delete-expression*, an integral constant expression, or a condition in a `switch` statement.

C++1y decltype(auto)

Use `__has_feature(cxx_decltype_auto)` or `__has_extension(cxx_decltype_auto)` to determine if support for the `decltype(auto)` placeholder type is enabled.

C++1y default initializers for aggregates

Use `__has_feature(cxx_aggregate_nsdmi)` or `__has_extension(cxx_aggregate_nsdmi)` to determine if support for default initializers in aggregate members is enabled.

C++1y digit separators

Use `__cpp_digit_separators` to determine if support for digit separators using single quotes (for instance, `10'000`) is enabled. At this time, there is no corresponding `__has_feature` name

C++1y generalized lambda capture

Use `__has_feature(cxx_init_captures)` or `__has_extension(cxx_init_captures)` to determine if support for lambda captures with explicit initializers is enabled (for instance, `[n(0)] { return ++n; }`).

C++1y generic lambdas

Use `__has_feature(cxx_generic_lambdas)` or `__has_extension(cxx_generic_lambdas)` to determine if support for generic (polymorphic) lambdas is enabled (for instance, `[] (auto x) { return x + 1; }`).

C++1y relaxed constexpr

Use `__has_feature(cxx_relaxed_constexpr)` or `__has_extension(cxx_relaxed_constexpr)` to determine if variable declarations, local variable modification, and control flow constructs are permitted in `constexpr` functions.

C++1y return type deduction

Use `__has_feature(cxx_return_type_deduction)` or `__has_extension(cxx_return_type_deduction)` to determine if support for return type deduction for functions (using `auto` as a return type) is enabled.

C++1y runtime-sized arrays

Use `__has_feature(cxx_runtime_array)` or `__has_extension(cxx_runtime_array)` to determine if support for arrays of runtime bound (a restricted form of variable-length arrays) is enabled. Clang's implementation of this feature is incomplete.

C++1y variable templates

Use `__has_feature(cxx_variable_templates)` or `__has_extension(cxx_variable_templates)` to determine if support for templated variable declarations is enabled.

C11

The features listed below are part of the C11 standard. As a result, all these features are enabled with the `-std=c11` or `-std=gnu11` option when compiling C code. Additionally, because these features are all backward-compatible, they are available as extensions in all language modes.

C11 alignment specifiers

Use `__has_feature(c_alignas)` or `__has_extension(c_alignas)` to determine if support for alignment specifiers using `_Alignas` is enabled.

Use `__has_feature(c_alignof)` or `__has_extension(c_alignof)` to determine if support for the `_Alignof` keyword is enabled.

C11 atomic operations

Use `__has_feature(c_atomic)` or `__has_extension(c_atomic)` to determine if support for atomic types using `_Atomic` is enabled. Clang also provides *a set of builtins* which can be used to implement the `<stdatomic.h>` operations on `_Atomic` types. Use `__has_include(<stdatomic.h>)` to determine if C11's `<stdatomic.h>` header is available.

Clang will use the system's `<stdatomic.h>` header when one is available, and will otherwise use its own. When using its own, implementations of the atomic operations are provided as macros. In the cases where C11 also requires a real function, this header provides only the declaration of that function (along with a shadowing macro implementation), and you must link to a library which provides a definition of the function if you use it instead of the macro.

C11 generic selections

Use `__has_feature(c_generic_selections)` or `__has_extension(c_generic_selections)` to determine if support for generic selections is enabled.

As an extension, the C11 generic selection expression is available in all languages supported by Clang. The syntax is the same as that given in the C11 standard.

In C, type compatibility is decided according to the rules given in the appropriate standard, but in C++, which lacks the type compatibility rules used in C, types are considered compatible only if they are equivalent.

C11 `_Static_assert()`

Use `__has_feature(c_static_assert)` or `__has_extension(c_static_assert)` to determine if support for compile-time assertions using `_Static_assert` is enabled.

C11 `_Thread_local`

Use `__has_feature(c_thread_local)` or `__has_extension(c_thread_local)` to determine if support for `_Thread_local` variables is enabled.

Modules

Use `__has_feature(modules)` to determine if Modules have been enabled. For example, compiling code with `-fmodules` enables the use of Modules.

More information could be found here.

Checks for Type Trait Primitives

Type trait primitives are special builtin constant expressions that can be used by the standard C++ library to facilitate or simplify the implementation of user-facing type traits in the <type_traits> header.

They are not intended to be used directly by user code because they are implementation-defined and subject to change – as such they're tied closely to the supported set of system headers, currently:

- LLVM's own libc++
- GNU libstdc++
- The Microsoft standard C++ library

Clang supports the GNU C++ type traits and a subset of the Microsoft Visual C++ Type traits.

Feature detection is supported only for some of the primitives at present. User code should not use these checks because they bear no direct relation to the actual set of type traits supported by the C++ standard library.

For type trait `__X`, `__has_extension(X)` indicates the presence of the type trait primitive in the compiler. A simplistic usage example as might be seen in standard C++ headers follows:

```
#if __has_extension(is_convertible_to)
template<typename From, typename To>
struct is_convertible_to {
  static const bool value = __is_convertible_to(From, To);
};
#else
// Emulate type trait for compatibility with other compilers.
#endif
```

The following type trait primitives are supported by Clang:

- `__has_nothrow_assign` (GNU, Microsoft)
- `__has_nothrow_copy` (GNU, Microsoft)
- `__has_nothrow_constructor` (GNU, Microsoft)
- `__has_trivial_assign` (GNU, Microsoft)
- `__has_trivial_copy` (GNU, Microsoft)
- `__has_trivial_constructor` (GNU, Microsoft)
- `__has_trivial_destructor` (GNU, Microsoft)
- `__has_virtual_destructor` (GNU, Microsoft)
- `__is_abstract` (GNU, Microsoft)
- `__is_base_of` (GNU, Microsoft)
- `__is_class` (GNU, Microsoft)
- `__is_convertible_to` (Microsoft)

- `__is_empty` (GNU, Microsoft)
- `__is_enum` (GNU, Microsoft)
- `__is_interface_class` (Microsoft)
- `__is_pod` (GNU, Microsoft)
- `__is_polymorphic` (GNU, Microsoft)
- `__is_union` (GNU, Microsoft)
- `__is_literal(type)`: Determines whether the given type is a literal type
- `__is_final`: Determines whether the given type is declared with a `final` class-virt-specifier.
- `__underlying_type(type)`: Retrieves the underlying type for a given `enum` type. This trait is required to implement the C++11 standard library.
- `__is_trivially_assignable(totype, fromtype)`: Determines whether a value of type `totype` can be assigned to from a value of type `fromtype` such that no non-trivial functions are called as part of that assignment. This trait is required to implement the C++11 standard library.
- `__is_trivially_constructible(type, argtypes...)`: Determines whether a value of type `type` can be direct-initialized with arguments of types `argtypes...` such that no non-trivial functions are called as part of that initialization. This trait is required to implement the C++11 standard library.
- `__is_destructible` (MSVC 2013)
- `__is_nothrow_destructible` (MSVC 2013)
- `__is_nothrow_assignable` (MSVC 2013, clang)
- `__is_constructible` (MSVC 2013, clang)
- `__is_nothrow_constructible` (MSVC 2013, clang)
- `__is_assignable` (MSVC 2015, clang)

Blocks

The syntax and high level language feature description is in *BlockLanguageSpec*. Implementation and ABI details for the clang implementation are in *Block-ABI-Apple*.

Query for this feature with `__has_extension(blocks)`.

Objective-C Features

Related result types

According to Cocoa conventions, Objective-C methods with certain names ("`init`", "`alloc`", etc.) always return objects that are an instance of the receiving class's type. Such methods are said to have a "related result type", meaning that a message send to one of these methods will have the same static type as an instance of the receiver class. For example, given the following classes:

```
@interface NSObject
+ (id)alloc;
- (id)init;
@end
```

```
@interface NSArray : NSObject
@end
```

and this common initialization pattern

```
NSArray *array = [[NSArray alloc] init];
```

the type of the expression `[NSArray alloc]` is `NSArray*` because `alloc` implicitly has a related result type. Similarly, the type of the expression `[[NSArray alloc] init]` is `NSArray*`, since `init` has a related result type and its receiver is known to have the type `NSArray *`. If neither `alloc` nor `init` had a related result type, the expressions would have had type `id`, as declared in the method signature.

A method with a related result type can be declared by using the type `instancetype` as its result type. `instancetype` is a contextual keyword that is only permitted in the result type of an Objective-C method, e.g.

```
@interface A
+ (instancetype)constructAnA;
@end
```

The related result type can also be inferred for some methods. To determine whether a method has an inferred related result type, the first word in the camel-case selector (e.g., "`init`" in "`initWithObjects`") is considered, and the method will have a related result type if its return type is compatible with the type of its class and if:

- the first word is "`alloc`" or "`new`", and the method is a class method, or
- the first word is "`autorelease`", "`init`", "`retain`", or "`self`", and the method is an instance method.

If a method with a related result type is overridden by a subclass method, the subclass method must also return a type that is compatible with the subclass type. For example:

```
@interface NSString : NSObject
- (NSUnrelated *)init; // incorrect usage: NSUnrelated is not NSString or a␣
↪superclass of NSString
@end
```

Related result types only affect the type of a message send or property access via the given method. In all other respects, a method with a related result type is treated the same way as method that returns `id`.

Use `__has_feature(objc_instancetype)` to determine whether the `instancetype` contextual keyword is available.

Automatic reference counting

Clang provides support for *automated reference counting* in Objective-C, which eliminates the need for manual `retain`/`release`/`autorelease` message sends. There are two feature macros associated with automatic reference counting: `__has_feature(objc_arc)` indicates the availability of automated reference counting in general, while `__has_feature(objc_arc_weak)` indicates that automated reference counting also includes support for `__weak` pointers to Objective-C objects.

Enumerations with a fixed underlying type

Clang provides support for C++11 enumerations with a fixed underlying type within Objective-C. For example, one can write an enumeration type as:

```
typedef enum : unsigned char { Red, Green, Blue } Color;
```

This specifies that the underlying type, which is used to store the enumeration value, is `unsigned char`.

Use `__has_feature(objc_fixed_enum)` to determine whether support for fixed underlying types is available in Objective-C.

Interoperability with C++11 lambdas

Clang provides interoperability between C++11 lambdas and blocks-based APIs, by permitting a lambda to be implicitly converted to a block pointer with the corresponding signature. For example, consider an API such as `NSArray`'s array-sorting method:

```
- (NSArray *)sortedArrayUsingComparator:(NSComparator)cmptr;
```

`NSComparator` is simply a typedef for the block pointer `NSComparisonResult (^)(id, id)`, and parameters of this type are generally provided with block literals as arguments. However, one can also use a C++11 lambda so long as it provides the same signature (in this case, accepting two parameters of type `id` and returning an `NSComparisonResult`):

```
NSArray *array = @[@"string 1", @"string 21", @"string 12", @"String 11",
                   @"String 02"];
const NSStringCompareOptions comparisonOptions
  = NSCaseInsensitiveSearch | NSNumericSearch |
    NSWidthInsensitiveSearch | NSForcedOrderingSearch;
NSLocale *currentLocale = [NSLocale currentLocale];
NSArray *sorted
  = [array sortedArrayUsingComparator:[=](id s1, id s2) -> NSComparisonResult {
              NSRange string1Range = NSMakeRange(0, [s1 length]);
              return [s1 compare:s2 options:comparisonOptions
              range:string1Range locale:currentLocale];
     }];
NSLog(@"sorted: %@", sorted);
```

This code relies on an implicit conversion from the type of the lambda expression (an unnamed, local class type called the *closure type*) to the corresponding block pointer type. The conversion itself is expressed by a conversion operator in that closure type that produces a block pointer with the same signature as the lambda itself, e.g.,

```
operator NSComparisonResult (^)(id, id)() const;
```

This conversion function returns a new block that simply forwards the two parameters to the lambda object (which it captures by copy), then returns the result. The returned block is first copied (with `Block_copy`) and then autoreleased. As an optimization, if a lambda expression is immediately converted to a block pointer (as in the first example, above), then the block is not copied and autoreleased: rather, it is given the same lifetime as a block literal written at that point in the program, which avoids the overhead of copying a block to the heap in the common case.

The conversion from a lambda to a block pointer is only available in Objective-C++, and not in C++ with blocks, due to its use of Objective-C memory management (autorelease).

Object Literals and Subscripting

Clang provides support for *Object Literals and Subscripting* in Objective-C, which simplifies common Objective-C programming patterns, makes programs more concise, and improves the safety of container creation. There are several feature macros associated with object literals and subscripting: `__has_feature(objc_array_literals)` tests the availability of array literals; `__has_feature(objc_dictionary_literals)` tests the availability of dictionary literals; `__has_feature(objc_subscripting)` tests the availability of object subscripting.

Objective-C Autosynthesis of Properties

Clang provides support for autosynthesis of declared properties. Using this feature, clang provides default synthesis of those properties not declared @dynamic and not having user provided backing getter and setter methods. `__has_feature(objc_default_synthesize_properties)` checks for availability of this feature in version of clang being used.

Objective-C retaining behavior attributes

In Objective-C, functions and methods are generally assumed to follow the Cocoa Memory Management conventions for ownership of object arguments and return values. However, there are exceptions, and so Clang provides attributes to allow these exceptions to be documented. This are used by ARC and the static analyzer Some exceptions may be better described using the `objc_method_family` attribute instead.

Usage: The `ns_returns_retained`, `ns_returns_not_retained`, `ns_returns_autoreleased`, `cf_returns_retained`, and `cf_returns_not_retained` attributes can be placed on methods and functions that return Objective-C or CoreFoundation objects. They are commonly placed at the end of a function prototype or method declaration:

```
id foo() __attribute__((ns_returns_retained));

- (NSString *)bar:(int)x __attribute__((ns_returns_retained));
```

The `*_returns_retained` attributes specify that the returned object has a +1 retain count. The `*_returns_not_retained` attributes specify that the return object has a +0 retain count, even if the normal convention for its selector would be +1. `ns_returns_autoreleased` specifies that the returned object is +0, but is guaranteed to live at least as long as the next flush of an autorelease pool.

Usage: The `ns_consumed` and `cf_consumed` attributes can be placed on an parameter declaration; they specify that the argument is expected to have a +1 retain count, which will be balanced in some way by the function or method. The `ns_consumes_self` attribute can only be placed on an Objective-C method; it specifies that the method expects its `self` parameter to have a +1 retain count, which it will balance in some way.

```
void foo(__attribute__((ns_consumed)) NSString *string);

- (void) bar __attribute__((ns_consumes_self));
- (void) baz:(id) __attribute__((ns_consumed)) x;
```

Further examples of these attributes are available in the static analyzer's list of annotations for analysis.

Query for these features with `__has_attribute(ns_consumed)`, `__has_attribute(ns_returns_retained)`, etc.

Objective-C++ ABI: protocol-qualifier mangling of parameters

Starting with LLVM 3.4, Clang produces a new mangling for parameters whose type is a qualified-`id` (e.g., `id<Foo>`). This mangling allows such parameters to be differentiated from those with the regular unqualified `id` type.

This was a non-backward compatible mangling change to the ABI. This change allows proper overloading, and also prevents mangling conflicts with template parameters of protocol-qualified type.

Query the presence of this new mangling with `__has_feature(objc_protocol_qualifier_mangling)`.

Initializer lists for complex numbers in C

clang supports an extension which allows the following in C:

```
#include <math.h>
#include <complex.h>
complex float x = { 1.0f, INFINITY }; // Init to (1, Inf)
```

This construct is useful because there is no way to separately initialize the real and imaginary parts of a complex variable in standard C, given that clang does not support `_Imaginary`. (Clang also supports the `__real__` and `__imag__` extensions from gcc, which help in some cases, but are not usable in static initializers.)

Note that this extension does not allow eliding the braces; the meaning of the following two lines is different:

```
complex float x[] = { { 1.0f, 1.0f } }; // [0] = (1, 1)
complex float x[] = { 1.0f, 1.0f }; // [0] = (1, 0), [1] = (1, 0)
```

This extension also works in C++ mode, as far as that goes, but does not apply to the C++ `std::complex`. (In C++11, list initialization allows the same syntax to be used with `std::complex` with the same meaning.)

Builtin Functions

Clang supports a number of builtin library functions with the same syntax as GCC, including things like `__builtin_nan`, `__builtin_constant_p`, `__builtin_choose_expr`, `__builtin_types_compatible_p`, `__builtin_assume_aligned`, `__sync_fetch_and_add`, etc. In addition to the GCC builtins, Clang supports a number of builtins that GCC does not, which are listed here.

Please note that Clang does not and will not support all of the GCC builtins for vector operations. Instead of using builtins, you should use the functions defined in target-specific header files like `<xmmintrin.h>`, which define portable wrappers for these. Many of the Clang versions of these functions are implemented directly in terms of *extended vector support* instead of builtins, in order to reduce the number of builtins that we need to implement.

`__builtin_assume`

`__builtin_assume` is used to provide the optimizer with a boolean invariant that is defined to be true.

Syntax:

```
__builtin_assume(bool)
```

Example of Use:

```
int foo(int x) {
  __builtin_assume(x != 0);

  // The optimizer may short-circuit this check using the invariant.
  if (x == 0)
    return do_something();

  return do_something_else();
}
```

Description:

The boolean argument to this function is defined to be true. The optimizer may analyze the form of the expression provided as the argument and deduce from that information used to optimize the program. If the condition is violated

during execution, the behavior is undefined. The argument itself is never evaluated, so any side effects of the expression will be discarded.

Query for this feature with `__has_builtin(__builtin_assume)`.

`__builtin_readcyclecounter`

`__builtin_readcyclecounter` is used to access the cycle counter register (or a similar low-latency, high-accuracy clock) on those targets that support it.

Syntax:

```
__builtin_readcyclecounter()
```

Example of Use:

```
unsigned long long t0 = __builtin_readcyclecounter();
do_something();
unsigned long long t1 = __builtin_readcyclecounter();
unsigned long long cycles_to_do_something = t1 - t0; // assuming no overflow
```

Description:

The `__builtin_readcyclecounter()` builtin returns the cycle counter value, which may be either global or process/thread-specific depending on the target. As the backing counters often overflow quickly (on the order of seconds) this should only be used for timing small intervals. When not supported by the target, the return value is always zero. This builtin takes no arguments and produces an unsigned long long result.

Query for this feature with `__has_builtin(__builtin_readcyclecounter)`. Note that even if present, its use may depend on run-time privilege or other OS controlled state.

`__builtin_shufflevector`

`__builtin_shufflevector` is used to express generic vector permutation/shuffle/swizzle operations. This builtin is also very important for the implementation of various target-specific header files like `<xmmintrin.h>`.

Syntax:

```
__builtin_shufflevector(vec1, vec2, index1, index2, ...)
```

Examples:

```
// identity operation - return 4-element vector v1.
__builtin_shufflevector(v1, v1, 0, 1, 2, 3)

// "Splat" element 0 of V1 into a 4-element result.
__builtin_shufflevector(V1, V1, 0, 0, 0, 0)

// Reverse 4-element vector V1.
__builtin_shufflevector(V1, V1, 3, 2, 1, 0)

// Concatenate every other element of 4-element vectors V1 and V2.
__builtin_shufflevector(V1, V2, 0, 2, 4, 6)

// Concatenate every other element of 8-element vectors V1 and V2.
__builtin_shufflevector(V1, V2, 0, 2, 4, 6, 8, 10, 12, 14)
```

```
// Shuffle v1 with some elements being undefined
__builtin_shufflevector(v1, v1, 3, -1, 1, -1)
```

Description:

The first two arguments to `__builtin_shufflevector` are vectors that have the same element type. The remaining arguments are a list of integers that specify the elements indices of the first two vectors that should be extracted and returned in a new vector. These element indices are numbered sequentially starting with the first vector, continuing into the second vector. Thus, if `vec1` is a 4-element vector, index 5 would refer to the second element of `vec2`. An index of -1 can be used to indicate that the corresponding element in the returned vector is a don't care and can be optimized by the backend.

The result of `__builtin_shufflevector` is a vector with the same element type as `vec1`/`vec2` but that has an element count equal to the number of indices specified.

Query for this feature with `__has_builtin(__builtin_shufflevector)`.

`__builtin_convertvector`

`__builtin_convertvector` is used to express generic vector type-conversion operations. The input vector and the output vector type must have the same number of elements.

Syntax:

```
__builtin_convertvector(src_vec, dst_vec_type)
```

Examples:

```
typedef double vector4double __attribute__((__vector_size__(32)));
typedef float  vector4float  __attribute__((__vector_size__(16)));
typedef short  vector4short  __attribute__((__vector_size__(8)));
vector4float vf; vector4short vs;

// convert from a vector of 4 floats to a vector of 4 doubles.
__builtin_convertvector(vf, vector4double)
// equivalent to:
(vector4double) { (double) vf[0], (double) vf[1], (double) vf[2], (double) vf[3] }

// convert from a vector of 4 shorts to a vector of 4 floats.
__builtin_convertvector(vs, vector4float)
// equivalent to:
(vector4float) { (float) vs[0], (float) vs[1], (float) vs[2], (float) vs[3] }
```

Description:

The first argument to `__builtin_convertvector` is a vector, and the second argument is a vector type with the same number of elements as the first argument.

The result of `__builtin_convertvector` is a vector with the same element type as the second argument, with a value defined in terms of the action of a C-style cast applied to each element of the first argument.

Query for this feature with `__has_builtin(__builtin_convertvector)`.

`__builtin_bitreverse`

- `__builtin_bitreverse8`
- `__builtin_bitreverse16`

- `__builtin_bitreverse32`
- `__builtin_bitreverse64`

Syntax:

```
__builtin_bitreverse32(x)
```

Examples:

```
uint8_t rev_x = __builtin_bitreverse8(x);
uint16_t rev_x = __builtin_bitreverse16(x);
uint32_t rev_y = __builtin_bitreverse32(y);
uint64_t rev_z = __builtin_bitreverse64(z);
```

Description:

The '`__builtin_bitreverse`' family of builtins is used to reverse the bitpattern of an integer value; for example `0b10110110` becomes `0b01101101`.

`__builtin_unreachable`

`__builtin_unreachable` is used to indicate that a specific point in the program cannot be reached, even if the compiler might otherwise think it can. This is useful to improve optimization and eliminates certain warnings. For example, without the `__builtin_unreachable` in the example below, the compiler assumes that the inline asm can fall through and prints a "function declared '`noreturn`' should not return" warning.

Syntax:

```
__builtin_unreachable()
```

Example of use:

```
void myabort(void) __attribute__((noreturn));
void myabort(void) {
  asm("int3");
  __builtin_unreachable();
}
```

Description:

The `__builtin_unreachable()` builtin has completely undefined behavior. Since it has undefined behavior, it is a statement that it is never reached and the optimizer can take advantage of this to produce better code. This builtin takes no arguments and produces a void result.

Query for this feature with `__has_builtin(__builtin_unreachable)`.

`__builtin_unpredictable`

`__builtin_unpredictable` is used to indicate that a branch condition is unpredictable by hardware mechanisms such as branch prediction logic.

Syntax:

```
__builtin_unpredictable(long long)
```

Example of use:

```
if (__builtin_unpredictable(x > 0)) {
   foo();
}
```

Description:

The `__builtin_unpredictable()` builtin is expected to be used with control flow conditions such as in `if` and `switch` statements.

Query for this feature with `__has_builtin(__builtin_unpredictable)`.

`__sync_swap`

`__sync_swap` is used to atomically swap integers or pointers in memory.

Syntax:

```
type __sync_swap(type *ptr, type value, ...)
```

Example of Use:

```
int old_value = __sync_swap(&value, new_value);
```

Description:

The `__sync_swap()` builtin extends the existing `__sync_*()` family of atomic intrinsics to allow code to atomically swap the current value with the new value. More importantly, it helps developers write more efficient and correct code by avoiding expensive loops around `__sync_bool_compare_and_swap()` or relying on the platform specific implementation details of `__sync_lock_test_and_set()`. The `__sync_swap()` builtin is a full barrier.

`__builtin_addressof`

`__builtin_addressof` performs the functionality of the built-in `&` operator, ignoring any `operator&` overload. This is useful in constant expressions in C++11, where there is no other way to take the address of an object that overloads `operator&`.

Example of use:

```
template<typename T> constexpr T *addressof(T &value) {
  return __builtin_addressof(value);
}
```

`__builtin_operator_new` and `__builtin_operator_delete`

`__builtin_operator_new` allocates memory just like a non-placement non-class *new-expression*. This is exactly like directly calling the normal non-placement `::operator new`, except that it allows certain optimizations that the C++ standard does not permit for a direct function call to `::operator new` (in particular, removing `new` / `delete` pairs and merging allocations).

Likewise, `__builtin_operator_delete` deallocates memory just like a non-class *delete-expression*, and is exactly like directly calling the normal `::operator delete`, except that it permits optimizations. Only the unsized form of `__builtin_operator_delete` is currently available.

These builtins are intended for use in the implementation of `std::allocator` and other similar allocation libraries, and are only available in C++.

Multiprecision Arithmetic Builtins

Clang provides a set of builtins which expose multiprecision arithmetic in a manner amenable to C. They all have the following form:

```
unsigned x = ..., y = ..., carryin = ..., carryout;
unsigned sum = __builtin_addc(x, y, carryin, &carryout);
```

Thus one can form a multiprecision addition chain in the following manner:

```
unsigned *x, *y, *z, carryin=0, carryout;
z[0] = __builtin_addc(x[0], y[0], carryin, &carryout);
carryin = carryout;
z[1] = __builtin_addc(x[1], y[1], carryin, &carryout);
carryin = carryout;
z[2] = __builtin_addc(x[2], y[2], carryin, &carryout);
carryin = carryout;
z[3] = __builtin_addc(x[3], y[3], carryin, &carryout);
```

The complete list of builtins are:

```
unsigned char      __builtin_addcb (unsigned char x, unsigned char y, unsigned char␣
↪carryin, unsigned char *carryout);
unsigned short     __builtin_addcs (unsigned short x, unsigned short y, unsigned␣
↪short carryin, unsigned short *carryout);
unsigned           __builtin_addc  (unsigned x, unsigned y, unsigned carryin,␣
↪unsigned *carryout);
unsigned long      __builtin_addcl (unsigned long x, unsigned long y, unsigned long␣
↪carryin, unsigned long *carryout);
unsigned long long __builtin_addcll(unsigned long long x, unsigned long long y,␣
↪unsigned long long carryin, unsigned long long *carryout);
unsigned char      __builtin_subcb (unsigned char x, unsigned char y, unsigned char␣
↪carryin, unsigned char *carryout);
unsigned short     __builtin_subcs (unsigned short x, unsigned short y, unsigned␣
↪short carryin, unsigned short *carryout);
unsigned           __builtin_subc  (unsigned x, unsigned y, unsigned carryin,␣
↪unsigned *carryout);
unsigned long      __builtin_subcl (unsigned long x, unsigned long y, unsigned long␣
↪carryin, unsigned long *carryout);
unsigned long long __builtin_subcll(unsigned long long x, unsigned long long y,␣
↪unsigned long long carryin, unsigned long long *carryout);
```

Checked Arithmetic Builtins

Clang provides a set of builtins that implement checked arithmetic for security critical applications in a manner that is fast and easily expressable in C. As an example of their usage:

```
errorcode_t security_critical_application(...) {
  unsigned x, y, result;
  ...
  if (__builtin_mul_overflow(x, y, &result))
    return kErrorCodeHackers;
  ...
  use_multiply(result);
  ...
}
```

Clang provides the following checked arithmetic builtins:

```
bool __builtin_add_overflow   (type1 x, type2 y, type3 *sum);
bool __builtin_sub_overflow   (type1 x, type2 y, type3 *diff);
bool __builtin_mul_overflow   (type1 x, type2 y, type3 *prod);
bool __builtin_uadd_overflow  (unsigned x, unsigned y, unsigned *sum);
bool __builtin_uaddl_overflow (unsigned long x, unsigned long y, unsigned long *sum);
bool __builtin_uaddll_overflow(unsigned long long x, unsigned long long y, unsigned␣
↪long long *sum);
bool __builtin_usub_overflow  (unsigned x, unsigned y, unsigned *diff);
bool __builtin_usubl_overflow (unsigned long x, unsigned long y, unsigned long *diff);
bool __builtin_usubll_overflow(unsigned long long x, unsigned long long y, unsigned␣
↪long long *diff);
bool __builtin_umul_overflow  (unsigned x, unsigned y, unsigned *prod);
bool __builtin_umull_overflow (unsigned long x, unsigned long y, unsigned long *prod);
bool __builtin_umulll_overflow(unsigned long long x, unsigned long long y, unsigned␣
↪long long *prod);
bool __builtin_sadd_overflow  (int x, int y, int *sum);
bool __builtin_saddl_overflow (long x, long y, long *sum);
bool __builtin_saddll_overflow(long long x, long long y, long long *sum);
bool __builtin_ssub_overflow  (int x, int y, int *diff);
bool __builtin_ssubl_overflow (long x, long y, long *diff);
bool __builtin_ssubll_overflow(long long x, long long y, long long *diff);
bool __builtin_smul_overflow  (int x, int y, int *prod);
bool __builtin_smull_overflow (long x, long y, long *prod);
bool __builtin_smulll_overflow(long long x, long long y, long long *prod);
```

Each builtin performs the specified mathematical operation on the first two arguments and stores the result in the third argument. If possible, the result will be equal to mathematically-correct result and the builtin will return 0. Otherwise, the builtin will return 1 and the result will be equal to the unique value that is equivalent to the mathematically-correct result modulo two raised to the *k* power, where *k* is the number of bits in the result type. The behavior of these builtins is well-defined for all argument values.

The first three builtins work generically for operands of any integer type, including boolean types. The operands need not have the same type as each other, or as the result. The other builtins may implicitly promote or convert their operands before performing the operation.

Query for this feature with `__has_builtin(__builtin_add_overflow)`, etc.

Floating point builtins

__builtin_canonicalize

```
double __builtin_canonicalize(double);
float __builtin_canonicalizef(float);
long double__builtin_canonicalizel(long double);
```

Returns the platform specific canonical encoding of a floating point number. This canonicalization is useful for implementing certain numeric primitives such as frexp. See LLVM canonicalize intrinsic for more information on the semantics.

__c11_atomic builtins

Clang provides a set of builtins which are intended to be used to implement C11's `<stdatomic.h>` header. These builtins provide the semantics of the `_explicit` form of the corresponding C11 operation, and are named with a `__c11_` prefix. The supported operations, and the differences from the corresponding C11 operations, are:

- __c11_atomic_init
- __c11_atomic_thread_fence
- __c11_atomic_signal_fence
- __c11_atomic_is_lock_free (The argument is the size of the _Atomic(...) object, instead of its address)
- __c11_atomic_store
- __c11_atomic_load
- __c11_atomic_exchange
- __c11_atomic_compare_exchange_strong
- __c11_atomic_compare_exchange_weak
- __c11_atomic_fetch_add
- __c11_atomic_fetch_sub
- __c11_atomic_fetch_and
- __c11_atomic_fetch_or
- __c11_atomic_fetch_xor

The macros __ATOMIC_RELAXED, __ATOMIC_CONSUME, __ATOMIC_ACQUIRE, __ATOMIC_RELEASE, __ATOMIC_ACQ_REL, and __ATOMIC_SEQ_CST are provided, with values corresponding to the enumerators of C11's memory_order enumeration.

(Note that Clang additionally provides GCC-compatible __atomic_* builtins)

Low-level ARM exclusive memory builtins

Clang provides overloaded builtins giving direct access to the three key ARM instructions for implementing atomic operations.

```
T __builtin_arm_ldrex(const volatile T *addr);
T __builtin_arm_ldaex(const volatile T *addr);
int __builtin_arm_strex(T val, volatile T *addr);
int __builtin_arm_stlex(T val, volatile T *addr);
void __builtin_arm_clrex(void);
```

The types T currently supported are:

- Integer types with width at most 64 bits (or 128 bits on AArch64).
- Floating-point types
- Pointer types.

Note that the compiler does not guarantee it will not insert stores which clear the exclusive monitor in between an ldrex type operation and its paired strex. In practice this is only usually a risk when the extra store is on the same cache line as the variable being modified and Clang will only insert stack stores on its own, so it is best not to use these operations on variables with automatic storage duration.

Also, loads and stores may be implicit in code written between the ldrex and strex. Clang will not necessarily mitigate the effects of these either, so care should be exercised.

For these reasons the higher level atomic primitives should be preferred where possible.

Non-temporal load/store builtins

Clang provides overloaded builtins allowing generation of non-temporal memory accesses.

```
T __builtin_nontemporal_load(T *addr);
void __builtin_nontemporal_store(T value, T *addr);
```

The types `T` currently supported are:

- Integer types.
- Floating-point types.
- Vector types.

Note that the compiler does not guarantee that non-temporal loads or stores will be used.

Non-standard C++11 Attributes

Clang's non-standard C++11 attributes live in the `clang` attribute namespace.

Clang supports GCC's `gnu` attribute namespace. All GCC attributes which are accepted with the `__attribute__((foo))` syntax are also accepted as `[[gnu::foo]]`. This only extends to attributes which are specified by GCC (see the list of GCC function attributes, GCC variable attributes, and GCC type attributes). As with the GCC implementation, these attributes must appertain to the *declarator-id* in a declaration, which means they must go either at the start of the declaration or immediately after the name being declared.

For example, this applies the GNU `unused` attribute to `a` and `f`, and also applies the GNU `noreturn` attribute to `f`.

```
[[gnu::unused]] int a, f [[gnu::noreturn]] ();
```

Target-Specific Extensions

Clang supports some language features conditionally on some targets.

ARM/AArch64 Language Extensions

Memory Barrier Intrinsics

Clang implements the `__dmb`, `__dsb` and `__isb` intrinsics as defined in the ARM C Language Extensions Release 2.0. Note that these intrinsics are implemented as motion barriers that block reordering of memory accesses and side effect instructions. Other instructions like simple arithmetic may be reordered around the intrinsic. If you expect to have no reordering at all, use inline assembly instead.

X86/X86-64 Language Extensions

The X86 backend has these language extensions:

Memory references to specified segments

Annotating a pointer with address space #256 causes it to be code generated relative to the X86 GS segment register, address space #257 causes it to be relative to the X86 FS segment, and address space #258 causes it to be relative to

the X86 SS segment. Note that this is a very very low-level feature that should only be used if you know what you're doing (for example in an OS kernel).

Here is an example:

```
#define GS_RELATIVE __attribute__((address_space(256)))
int foo(int GS_RELATIVE *P) {
  return *P;
}
```

Which compiles to (on X86-32):

```
_foo:
        movl    4(%esp), %eax
        movl    %gs:(%eax), %eax
        ret
```

Extensions for Static Analysis

Clang supports additional attributes that are useful for documenting program invariants and rules for static analysis tools, such as the Clang Static Analyzer. These attributes are documented in the analyzer's list of source-level annotations.

Extensions for Dynamic Analysis

Use `__has_feature(address_sanitizer)` to check if the code is being built with *AddressSanitizer*.

Use `__has_feature(thread_sanitizer)` to check if the code is being built with *ThreadSanitizer*.

Use `__has_feature(memory_sanitizer)` to check if the code is being built with *MemorySanitizer*.

Use `__has_feature(safe_stack)` to check if the code is being built with *SafeStack*.

Extensions for selectively disabling optimization

Clang provides a mechanism for selectively disabling optimizations in functions and methods.

To disable optimizations in a single function definition, the GNU-style or C++11 non-standard attribute `optnone` can be used.

```
// The following functions will not be optimized.
// GNU-style attribute
__attribute__((optnone)) int foo() {
  // ... code
}
// C++11 attribute
[[clang::optnone]] int bar() {
  // ... code
}
```

To facilitate disabling optimization for a range of function definitions, a range-based pragma is provided. Its syntax is `#pragma clang optimize` followed by `off` or `on`.

All function definitions in the region between an `off` and the following `on` will be decorated with the `optnone` attribute unless doing so would conflict with explicit attributes already present on the function (e.g. the ones that control inlining).

```
#pragma clang optimize off
// This function will be decorated with optnone.
int foo() {
  // ... code
}

// optnone conflicts with always_inline, so bar() will not be decorated.
__attribute__((always_inline)) int bar() {
  // ... code
}
#pragma clang optimize on
```

If no `on` is found to close an `off` region, the end of the region is the end of the compilation unit.

Note that a stray `#pragma clang optimize on` does not selectively enable additional optimizations when compiling at low optimization levels. This feature can only be used to selectively disable optimizations.

The pragma has an effect on functions only at the point of their definition; for function templates, this means that the state of the pragma at the point of an instantiation is not necessarily relevant. Consider the following example:

```
template<typename T> T twice(T t) {
  return 2 * t;
}

#pragma clang optimize off
template<typename T> T thrice(T t) {
  return 3 * t;
}

int container(int a, int b) {
  return twice(a) + thrice(b);
}
#pragma clang optimize on
```

In this example, the definition of the template function `twice` is outside the pragma region, whereas the definition of `thrice` is inside the region. The `container` function is also in the region and will not be optimized, but it causes the instantiation of `twice` and `thrice` with an `int` type; of these two instantiations, `twice` will be optimized (because its definition was outside the region) and `thrice` will not be optimized.

Extensions for loop hint optimizations

The `#pragma clang loop` directive is used to specify hints for optimizing the subsequent for, while, do-while, or c++11 range-based for loop. The directive provides options for vectorization, interleaving, unrolling and distribution. Loop hints can be specified before any loop and will be ignored if the optimization is not safe to apply.

Vectorization and Interleaving

A vectorized loop performs multiple iterations of the original loop in parallel using vector instructions. The instruction set of the target processor determines which vector instructions are available and their vector widths. This restricts the types of loops that can be vectorized. The vectorizer automatically determines if the loop is safe and profitable to vectorize. A vector instruction cost model is used to select the vector width.

Interleaving multiple loop iterations allows modern processors to further improve instruction-level parallelism (ILP) using advanced hardware features, such as multiple execution units and out-of-order execution. The vectorizer uses a cost model that depends on the register pressure and generated code size to select the interleaving count.

Vectorization is enabled by `vectorize(enable)` and interleaving is enabled by `interleave(enable)`. This is useful when compiling with `-Os` to manually enable vectorization or interleaving.

```
#pragma clang loop vectorize(enable)
#pragma clang loop interleave(enable)
for(...) {
  ...
}
```

The vector width is specified by `vectorize_width(_value_)` and the interleave count is specified by `interleave_count(_value_)`, where _value_ is a positive integer. This is useful for specifying the optimal width/count of the set of target architectures supported by your application.

```
#pragma clang loop vectorize_width(2)
#pragma clang loop interleave_count(2)
for(...) {
  ...
}
```

Specifying a width/count of 1 disables the optimization, and is equivalent to `vectorize(disable)` or `interleave(disable)`.

Loop Unrolling

Unrolling a loop reduces the loop control overhead and exposes more opportunities for ILP. Loops can be fully or partially unrolled. Full unrolling eliminates the loop and replaces it with an enumerated sequence of loop iterations. Full unrolling is only possible if the loop trip count is known at compile time. Partial unrolling replicates the loop body within the loop and reduces the trip count.

If `unroll(enable)` is specified the unroller will attempt to fully unroll the loop if the trip count is known at compile time. If the fully unrolled code size is greater than an internal limit the loop will be partially unrolled up to this limit. If the trip count is not known at compile time the loop will be partially unrolled with a heuristically chosen unroll factor.

```
#pragma clang loop unroll(enable)
for(...) {
  ...
}
```

If `unroll(full)` is specified the unroller will attempt to fully unroll the loop if the trip count is known at compile time identically to `unroll(enable)`. However, with `unroll(full)` the loop will not be unrolled if the loop count is not known at compile time.

```
#pragma clang loop unroll(full)
for(...) {
  ...
}
```

The unroll count can be specified explicitly with `unroll_count(_value_)` where _value_ is a positive integer. If this value is greater than the trip count the loop will be fully unrolled. Otherwise the loop is partially unrolled subject to the same code size limit as with `unroll(enable)`.

```
#pragma clang loop unroll_count(8)
for(...) {
  ...
}
```

Unrolling of a loop can be prevented by specifying `unroll(disable)`.

Loop Distribution

Loop Distribution allows splitting a loop into multiple loops. This is beneficial for example when the entire loop cannot be vectorized but some of the resulting loops can.

If `distribute(enable))` is specified and the loop has memory dependencies that inhibit vectorization, the compiler will attempt to isolate the offending operations into a new loop. This optimization is not enabled by default, only loops marked with the pragma are considered.

```
#pragma clang loop distribute(enable)
for (i = 0; i < N; ++i) {
  S1: A[i + 1] = A[i] + B[i];
  S2: C[i] = D[i] * E[i];
}
```

This loop will be split into two loops between statements S1 and S2. The second loop containing S2 will be vectorized.

Loop Distribution is currently not enabled by default in the optimizer because it can hurt performance in some cases. For example, instruction-level parallelism could be reduced by sequentializing the execution of the statements S1 and S2 above.

If Loop Distribution is turned on globally with `-mllvm -enable-loop-distribution`, specifying `distribute(disable)` can be used the disable it on a per-loop basis.

Additional Information

For convenience multiple loop hints can be specified on a single line.

```
#pragma clang loop vectorize_width(4) interleave_count(8)
for(...) {
  ...
}
```

If an optimization cannot be applied any hints that apply to it will be ignored. For example, the hint `vectorize_width(4)` is ignored if the loop is not proven safe to vectorize. To identify and diagnose optimization issues use *-Rpass*, *-Rpass-missed*, and *-Rpass-analysis* command line options. See the user guide for details.

Attributes in Clang

- *assert_capability (assert_shared_capability, clang::assert_capability, clang::assert_shared_capability)*
- *assume_aligned (gnu::assume_aligned)*
- *availability*
- *_Noreturn*
- *noreturn*
- *carries_dependency*
- *deprecated (gnu::deprecated)*
- *disable_tail_calls (clang::disable_tail_calls)*
- *enable_if*
- *flatten (gnu::flatten)*
- *format (gnu::format)*
- *ifunc (gnu::ifunc)*
- *internal_linkage (clang::internal_linkage)*
- *interrupt*
- *noalias*
- *noduplicate (clang::noduplicate)*
- *no_sanitize (clang::no_sanitize)*
- *no_sanitize_address (no_address_safety_analysis, gnu::no_address_safety_analysis, gnu::no_sanitize_address)*
- *no_sanitize_thread*
- *no_sanitize_memory*
- *no_split_stack (gnu::no_split_stack)*
- *not_tail_called (clang::not_tail_called)*
- *#pragma omp declare simd*
- *#pragma omp declare target*
- *objc_boxable*
- *objc_method_family*
- *objc_requires_super*
- *objc_runtime_name*
- *objc_runtime_visible*
- *optnone (clang::optnone)*
- *overloadable*
- *release_capability (release_shared_capability, clang::release_capability, clang::release_shared_capability)*
- *kernel*

Introduction

This page lists the attributes currently supported by Clang.

Function Attributes

interrupt

Table 4.1: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Clang supports the GNU style `__attribute__((interrupt("TYPE")))` attribute on ARM targets. This attribute may be attached to a function definition and instructs the backend to generate appropriate function entry/exit code so that it can be used directly as an interrupt service routine.

The parameter passed to the interrupt attribute is optional, but if provided it must be a string literal with one of the following values: "IRQ", "FIQ", "SWI", "ABORT", "UNDEF".

The semantics are as follows:

- If the function is AAPCS, Clang instructs the backend to realign the stack to 8 bytes on entry. This is a general requirement of the AAPCS at public interfaces, but may not hold when an exception is taken. Doing this allows other AAPCS functions to be called.
- If the CPU is M-class this is all that needs to be done since the architecture itself is designed in such a way that functions obeying the normal AAPCS ABI constraints are valid exception handlers.
- If the CPU is not M-class, the prologue and epilogue are modified to save all non-banked registers that are used, so that upon return the user-mode state will not be corrupted. Note that to avoid unnecessary overhead, only general-purpose (integer) registers are saved in this way. If VFP operations are needed, that state must be saved manually.

  Specifically, interrupt kinds other than "FIQ" will save all core registers except "lr" and "sp". "FIQ" interrupts will save r0-r7.
- If the CPU is not M-class, the return instruction is changed to one of the canonical sequences permitted by the architecture for exception return. Where possible the function itself will make the necessary "lr" adjustments so that the "preferred return address" is selected.

  Unfortunately the compiler is unable to make this guarantee for an "UNDEF" handler, where the offset from "lr" to the preferred return address depends on the execution state of the code which generated the exception. In this case a sequence equivalent to "movs pc, lr" will be used.

abi_tag (gnu::abi_tag)

Table 4.2: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `abi_tag` attribute can be applied to a function, variable, class or inline namespace declaration to modify the mangled name of the entity. It gives the ability to distinguish between different versions of the same entity but with different ABI versions supported. For example, a newer version of a class could have a different set of data members and thus have a different size. Using the `abi_tag` attribute, it is possible to have different mangled names for a

global variable of the class type. Therefor, the old code could keep using the old manged name and the new code will use the new mangled name with tags.

acquire_capability (acquire_shared_capability, clang::acquire_capability, clang::acquire_shared_capability)

Table 4.3: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Marks a function as acquiring a capability.

interrupt

Table 4.4: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Clang supports the GNU style `__attribute__((interrupt))` attribute on x86/x86-64 targets.The compiler generates function entry and exit sequences suitable for use in an interrupt handler when this attribute is present. The 'IRET' instruction, instead of the 'RET' instruction, is used to return from interrupt or exception handlers. All registers, except for the EFLAGS register which is restored by the 'IRET' instruction, are preserved by the compiler.

Any interruptible-without-stack-switch code must be compiled with -mno-red-zone since interrupt handlers can and will, because of the hardware design, touch the red zone.

1. interrupt handler must be declared with a mandatory pointer argument:

```
struct interrupt_frame
{
  uword_t ip;
  uword_t cs;
  uword_t flags;
  uword_t sp;
  uword_t ss;
};

__attribute__ ((interrupt))
void f (struct interrupt_frame *frame) {
  ...
}
```

2. exception handler:

   The exception handler is very similar to the interrupt handler with a different mandatory function signature:

```
__attribute__ ((interrupt))
void f (struct interrupt_frame *frame, uword_t error_code) {
  ...
}
```

   and compiler pops 'ERROR_CODE' off stack before the 'IRET' instruction.

The exception handler should only be used for exceptions which push an error code and all other exceptions must use the interrupt handler. The system will crash if the wrong handler is used.

assert_capability (assert_shared_capability, clang::assert_capability, clang::assert_shared_capability)

Table 4.5: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Marks a function that dynamically tests whether a capability is held, and halts the program if it is not held.

assume_aligned (gnu::assume_aligned)

Table 4.6: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Use `__attribute__((assume_aligned(<alignment>[,<offset>]))` on a function declaration to specify that the return value of the function (which must be a pointer type) has the specified offset, in bytes, from an address with the specified alignment. The offset is taken to be zero if omitted.

```
// The returned pointer value has 32-byte alignment.
void *a() __attribute__((assume_aligned (32)));

// The returned pointer value is 4 bytes greater than an address having
// 32-byte alignment.
void *b() __attribute__((assume_aligned (32, 4)));
```

Note that this attribute provides information to the compiler regarding a condition that the code already ensures is true. It does not cause the compiler to enforce the provided alignment assumption.

availability

Table 4.7: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

The `availability` attribute can be placed on declarations to describe the lifecycle of that declaration relative to operating system versions. Consider the function declaration for a hypothetical function `f`:

```
void f(void) __attribute__((availability(macos,introduced=10.4,deprecated=10.6,
↪obsoleted=10.7)));
```

The availability attribute states that `f` was introduced in Mac OS X 10.4, deprecated in Mac OS X 10.6, and obsoleted in Mac OS X 10.7. This information is used by Clang to determine when it is safe to use `f`: for example, if Clang is instructed to compile code for Mac OS X 10.5, a call to `f()` succeeds. If Clang is instructed to compile code for Mac OS X 10.6, the call succeeds but Clang emits a warning specifying that the function is deprecated. Finally, if Clang is instructed to compile code for Mac OS X 10.7, the call fails because `f()` is no longer available.

The availability attribute is a comma-separated list starting with the platform name and then including clauses specifying important milestones in the declaration's lifetime (in any order) along with additional information. Those clauses can be:

introduced=*version* The first version in which this declaration was introduced.

deprecated=*version* The first version in which this declaration was deprecated, meaning that users should migrate away from this API.

obsoleted=*version* The first version in which this declaration was obsoleted, meaning that it was removed completely and can no longer be used.

unavailable This declaration is never available on this platform.

message=*string-literal* Additional message text that Clang will provide when emitting a warning or error about use of a deprecated or obsoleted declaration. Useful to direct users to replacement APIs.

replacement=*string-literal* Additional message text that Clang will use to provide Fix-It when emitting a warning about use of a deprecated declaration. The Fix-It will replace the deprecated declaration with the new declaration specified.

Multiple availability attributes can be placed on a declaration, which may correspond to different platforms. Only the availability attribute with the platform corresponding to the target platform will be used; any others will be ignored. If no availability attribute specifies availability for the current target platform, the availability attributes are ignored. Supported platforms are:

`ios` Apple's iOS operating system. The minimum deployment target is specified by the `-mios-version-min=*version*` or `-miphoneos-version-min=*version*` command-line arguments.

`macos` Apple's Mac OS X operating system. The minimum deployment target is specified by the `-mmacosx-version-min=*version*` command-line argument. `macosx` is supported for backward-compatibility reasons, but it is deprecated.

`tvos` Apple's tvOS operating system. The minimum deployment target is specified by the `-mtvos-version-min=*version*` command-line argument.

`watchos` Apple's watchOS operating system. The minimum deployment target is specified by the `-mwatchos-version-min=*version*` command-line argument.

A declaration can typically be used even when deploying back to a platform version prior to when the declaration was introduced. When this happens, the declaration is weakly linked, as if the `weak_import` attribute were added to the declaration. A weakly-linked declaration may or may not be present a run-time, and a program can determine whether the declaration is present by checking whether the address of that declaration is non-NULL.

The flag `strict` disallows using API when deploying back to a platform version prior to when the declaration was introduced. An attempt to use such API before its introduction causes a hard error. Weakly-linking is almost always a better API choice, since it allows users to query availability at runtime.

If there are multiple declarations of the same entity, the availability attributes must either match on a per-platform basis or later declarations must not have availability attributes for that platform. For example:

```
void g(void) __attribute__((availability(macos,introduced=10.4)));
void g(void) __attribute__((availability(macos,introduced=10.4))); // okay, matches
void g(void) __attribute__((availability(ios,introduced=4.0))); // okay, adds a new␣
↪platform
void g(void); // okay, inherits both macos and ios availability from above.
void g(void) __attribute__((availability(macos,introduced=10.5))); // error: mismatch
```

When one method overrides another, the overriding method can be more widely available than the overridden method, e.g.,:

```
@interface A
- (id)method __attribute__((availability(macos,introduced=10.4)));
- (id)method2 __attribute__((availability(macos,introduced=10.4)));
@end

@interface B : A
- (id)method __attribute__((availability(macos,introduced=10.3))); // okay: method␣
↪moved into base class later
- (id)method __attribute__((availability(macos,introduced=10.5))); // error: this␣
↪method was available via the base class in 10.4
@end
```

_Noreturn

Table 4.8: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

A function declared as `_Noreturn` shall not return to its caller. The compiler will generate a diagnostic for a function declared as `_Noreturn` that appears to be capable of returning to its caller.

noreturn

Table 4.9: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
	X			

A function declared as `[[noreturn]]` shall not return to its caller. The compiler will generate a diagnostic for a function declared as `[[noreturn]]` that appears to be capable of returning to its caller.

carries_dependency

Table 4.10: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `carries_dependency` attribute specifies dependency propagation into and out of functions.

When specified on a function or Objective-C method, the `carries_dependency` attribute means that the return value carries a dependency out of the function, so that the implementation need not constrain ordering upon return from that function. Implementations of the function and its caller may choose to preserve dependencies instead of emitting memory ordering instructions such as fences.

Note, this attribute does not change the meaning of the program, but may result in generation of more efficient code.

deprecated (gnu::deprecated)

Table 4.11: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X	X		

The `deprecated` attribute can be applied to a function, a variable, or a type. This is useful when identifying functions, variables, or types that are expected to be removed in a future version of a program.

Consider the function declaration for a hypothetical function `f`:

```
void f(void) __attribute__((deprecated("message", "replacement")));
```

When spelled as *__attribute__((deprecated))*, the deprecated attribute can have two optional string arguments. The first one is the message to display when emitting the warning; the second one enables the compiler to provide a Fix-It to replace the deprecated name with a new name. Otherwise, when spelled as *[[gnu::deprecated]] or [[deprecated]]*, the attribute can have one optional string argument which is the message to display when emitting the warning.

disable_tail_calls (clang::disable_tail_calls)

Table 4.12: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `disable_tail_calls` attribute instructs the backend to not perform tail call optimization inside the marked function.

For example:

```
int callee(int);

int foo(int a) __attribute__((disable_tail_calls)) {
  return callee(a); // This call is not tail-call optimized.
}
```

Marking virtual functions as `disable_tail_calls` is legal.

```
int callee(int);

class Base {
public:
  [[clang::disable_tail_calls]] virtual int foo1() {
    return callee(); // This call is not tail-call optimized.
  }
};

class Derived1 : public Base {
public:
  int foo1() override {
    return callee(); // This call is tail-call optimized.
  }
};
```

enable_if

Table 4.13: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Note: Some features of this attribute are experimental. The meaning of multiple enable_if attributes on a single declaration is subject to change in a future version of clang. Also, the ABI is not standardized and the name mangling may change in future versions. To avoid that, use asm labels.

The `enable_if` attribute can be placed on function declarations to control which overload is selected based on the values of the function's arguments. When combined with the `overloadable` attribute, this feature is also available in C.

```
int isdigit(int c);
int isdigit(int c) __attribute__((enable_if(c <= -1 || c > 255, "chosen when 'c' is␣
↪out of range"))) __attribute__((unavailable("'c' must have the value of an unsigned␣
↪char or EOF")));

void foo(char c) {
  isdigit(c);
  isdigit(10);
  isdigit(-10);  // results in a compile-time error.
}
```

The enable_if attribute takes two arguments, the first is an expression written in terms of the function parameters, the second is a string explaining why this overload candidate could not be selected to be displayed in diagnostics. The expression is part of the function signature for the purposes of determining whether it is a redeclaration (following the rules used when determining whether a C++ template specialization is ODR-equivalent), but is not part of the type.

The enable_if expression is evaluated as if it were the body of a bool-returning constexpr function declared with the arguments of the function it is being applied to, then called with the parameters at the call site. If the result is false or could not be determined through constant expression evaluation, then this overload will not be chosen and the provided string may be used in a diagnostic if the compile fails as a result.

Because the enable_if expression is an unevaluated context, there are no global state changes, nor the ability to pass information from the enable_if expression to the function body. For example, suppose we want calls to strnlen(strbuf, maxlen) to resolve to strnlen_chk(strbuf, maxlen, size of strbuf) only if the size of strbuf can be determined:

```
__attribute__((always_inline))
static inline size_t strnlen(const char *s, size_t maxlen)
  __attribute__((overloadable))
  __attribute__((enable_if(__builtin_object_size(s, 0) != -1))),
                           "chosen when the buffer size is known but 'maxlen' is not
↪")))
{
  return strnlen_chk(s, maxlen, __builtin_object_size(s, 0));
}
```

Multiple enable_if attributes may be applied to a single declaration. In this case, the enable_if expressions are evaluated from left to right in the following manner. First, the candidates whose enable_if expressions evaluate to false or cannot be evaluated are discarded. If the remaining candidates do not share ODR-equivalent enable_if expressions, the overload resolution is ambiguous. Otherwise, enable_if overload resolution continues with the next enable_if attribute on the candidates that have not been discarded and have remaining enable_if attributes. In this way, we pick the most specific overload out of a number of viable overloads using enable_if.

```
void f() __attribute__((enable_if(true, ""))); // #1
void f() __attribute__((enable_if(true, ""))) __attribute__((enable_if(true, ""))); /
↪/ #2

void g(int i, int j) __attribute__((enable_if(i, ""))); // #1
void g(int i, int j) __attribute__((enable_if(j, ""))) __attribute__((enable_
↪if(true))); // #2
```

In this example, a call to f() is always resolved to #2, as the first enable_if expression is ODR-equivalent for both declarations, but #1 does not have another enable_if expression to continue evaluating, so the next round of evaluation has only a single candidate. In a call to g(1, 1), the call is ambiguous even though #2 has more enable_if attributes, because the first enable_if expressions are not ODR-equivalent.

Query for this feature with `__has_attribute(enable_if)`.

Note that functions with one or more `enable_if` attributes may not have their address taken, unless all of the conditions specified by said `enable_if` are constants that evaluate to `true`. For example:

```
const int TrueConstant = 1;
const int FalseConstant = 0;
int f(int a) __attribute__((enable_if(a > 0, "")));
int g(int a) __attribute__((enable_if(a == 0 || a != 0, "")));
int h(int a) __attribute__((enable_if(1, "")));
int i(int a) __attribute__((enable_if(TrueConstant, "")));
int j(int a) __attribute__((enable_if(FalseConstant, "")));

void fn() {
  int (*ptr)(int);
  ptr = &f; // error: 'a > 0' is not always true
  ptr = &g; // error: 'a == 0 || a != 0' is not a truthy constant
  ptr = &h; // OK: 1 is a truthy constant
  ptr = &i; // OK: 'TrueConstant' is a truthy constant
  ptr = &j; // error: 'FalseConstant' is a constant, but not truthy
}
```

Because `enable_if` evaluation happens during overload resolution, `enable_if` may give unintuitive results when used with templates, depending on when overloads are resolved. In the example below, clang will emit a diagnostic about no viable overloads for `foo` in `bar`, but not in `baz`:

```
double foo(int i) __attribute__((enable_if(i > 0, "")));
void *foo(int i) __attribute__((enable_if(i <= 0, "")));
template <int I>
auto bar() { return foo(I); }

template <typename T>
auto baz() { return foo(T::number); }

struct WithNumber { constexpr static int number = 1; };
void callThem() {
  bar<sizeof(WithNumber)>();
  baz<WithNumber>();
}
```

This is because, in `bar`, `foo` is resolved prior to template instantiation, so the value for `I` isn't known (thus, both `enable_if` conditions for `foo` fail). However, in `baz`, `foo` is resolved during template instantiation, so the value for `T::number` is known.

flatten (gnu::flatten)

Table 4.14: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `flatten` attribute causes calls within the attributed function to be inlined unless it is impossible to do so, for example if the body of the callee is unavailable or if the callee has the `noinline` attribute.

format (gnu::format)

Table 4.15: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Clang supports the `format` attribute, which indicates that the function accepts a `printf` or `scanf`-like format string and corresponding arguments or a `va_list` that contains these arguments.

Please see GCC documentation about format attribute to find details about attribute syntax.

Clang implements two kinds of checks with this attribute.

1. Clang checks that the function with the `format` attribute is called with a format string that uses format specifiers that are allowed, and that arguments match the format string. This is the `-Wformat` warning, it is on by default.

2. Clang checks that the format string argument is a literal string. This is the `-Wformat-nonliteral` warning, it is off by default.

   Clang implements this mostly the same way as GCC, but there is a difference for functions that accept a `va_list` argument (for example, `vprintf`). GCC does not emit `-Wformat-nonliteral` warning for calls to such functions. Clang does not warn if the format string comes from a function parameter, where the function is annotated with a compatible attribute, otherwise it warns. For example:

```
__attribute__((__format__ (__scanf__, 1, 3)))
void foo(const char* s, char *buf, ...) {
  va_list ap;
  va_start(ap, buf);

  vprintf(s, ap); // warning: format string is not a string literal
}
```

   In this case we warn because `s` contains a format string for a `scanf`-like function, but it is passed to a `printf`-like function.

   If the attribute is removed, clang still warns, because the format string is not a string literal.

   Another example:

```
__attribute__((__format__ (__printf__, 1, 3)))
void foo(const char* s, char *buf, ...) {
  va_list ap;
  va_start(ap, buf);

  vprintf(s, ap); // warning
}
```

In this case Clang does not warn because the format string `s` and the corresponding arguments are annotated. If the arguments are incorrect, the caller of `foo` will receive a warning.

ifunc (gnu::ifunc)

Table 4.16: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

`__attribute__((ifunc("resolver")))` is used to mark that the address of a declaration should be resolved at runtime by calling a resolver function.

The symbol name of the resolver function is given in quotes. A function with this name (after mangling) must be defined in the current translation unit; it may be `static`. The resolver function should take no arguments and return a pointer.

The `ifunc` attribute may only be used on a function declaration. A function declaration with an `ifunc` attribute is considered to be a definition of the declared entity. The entity must not have weak linkage; for example, in C++, it cannot be applied to a declaration if a definition at that location would be considered inline.

Not all targets support this attribute. ELF targets support this attribute when using binutils v2.20.1 or higher and glibc v2.11.1 or higher. Non-ELF targets currently do not support this attribute.

internal_linkage (clang::internal_linkage)

Table 4.17: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `internal_linkage` attribute changes the linkage type of the declaration to internal. This is similar to C-style `static`, but can be used on classes and class methods. When applied to a class definition, this attribute affects all methods and static data members of that class. This can be used to contain the ABI of a C++ library by excluding unwanted class methods from the export tables.

interrupt

Table 4.18: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Clang supports the GNU style `__attribute__((interrupt("ARGUMENT")))` attribute on MIPS targets. This attribute may be attached to a function definition and instructs the backend to generate appropriate function entry/exit code so that it can be used directly as an interrupt service routine.

By default, the compiler will produce a function prologue and epilogue suitable for an interrupt service routine that handles an External Interrupt Controller (eic) generated interrupt. This behaviour can be explicitly requested with the "eic" argument.

Otherwise, for use with vectored interrupt mode, the argument passed should be of the form "vector=LEVEL" where LEVEL is one of the following values: "sw0", "sw1", "hw0", "hw1", "hw2", "hw3", "hw4", "hw5". The compiler

will then set the interrupt mask to the corresponding level which will mask all interrupts up to and including the argument.

The semantics are as follows:

- The prologue is modified so that the Exception Program Counter (EPC) and Status coprocessor registers are saved to the stack. The interrupt mask is set so that the function can only be interrupted by a higher priority interrupt. The epilogue will restore the previous values of EPC and Status.
- The prologue and epilogue are modified to save and restore all non-kernel registers as necessary.
- The FPU is disabled in the prologue, as the floating pointer registers are not spilled to the stack.
- The function return sequence is changed to use an exception return instruction.
- The parameter sets the interrupt mask for the function corresponding to the interrupt level specified. If no mask is specified the interrupt mask defaults to "eic".

noalias

Table 4.19: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
		X		

The `noalias` attribute indicates that the only memory accesses inside function are loads and stores from objects pointed to by its pointer-typed arguments, with arbitrary offsets.

noduplicate (clang::noduplicate)

Table 4.20: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `noduplicate` attribute can be placed on function declarations to control whether function calls to this function can be duplicated or not as a result of optimizations. This is required for the implementation of functions with certain special requirements, like the OpenCL "barrier" function, that might need to be run concurrently by all the threads that are executing in lockstep on the hardware. For example this attribute applied on the function "nodupfunc" in the code below avoids that:

```
void nodupfunc() __attribute__((noduplicate));
// Setting it as a C++11 attribute is also valid
// void nodupfunc() [[clang::noduplicate]];
void foo();
void bar();

nodupfunc();
if (a > n) {
  foo();
} else {
  bar();
}
```

gets possibly modified by some optimizations into code similar to this:

```
if (a > n) {
  nodupfunc();
  foo();
} else {
  nodupfunc();
  bar();
}
```

where the call to "nodupfunc" is duplicated and sunk into the two branches of the condition.

no_sanitize (clang::no_sanitize)

Table 4.21: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Use the `no_sanitize` attribute on a function declaration to specify that a particular instrumentation or set of instrumentations should not be applied to that function. The attribute takes a list of string literals, which have the same meaning as values accepted by the `-fno-sanitize=` flag. For example, `__attribute__((no_sanitize("address", "thread")))` specifies that AddressSanitizer and ThreadSanitizer should not be applied to the function.

See *Controlling Code Generation* for a full list of supported sanitizer flags.

no_sanitize_address (no_address_safety_analysis, gnu::no_address_safety_analysis, gnu::no_sanitize_address)

Table 4.22: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Use `__attribute__((no_sanitize_address))` on a function declaration to specify that address safety instrumentation (e.g. AddressSanitizer) should not be applied to that function.

no_sanitize_thread

Table 4.23: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Use `__attribute__((no_sanitize_thread))` on a function declaration to specify that checks for data races on plain (non-atomic) memory accesses should not be inserted by ThreadSanitizer. The function is still instrumented by the tool to avoid false positives and provide meaningful stack traces.

no_sanitize_memory

Table 4.24: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Use `__attribute__((no_sanitize_memory))` on a function declaration to specify that checks for uninitialized memory should not be inserted (e.g. by MemorySanitizer). The function may still be instrumented by the tool to avoid false positives in other places.

no_split_stack (gnu::no_split_stack)

Table 4.25: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `no_split_stack` attribute disables the emission of the split stack preamble for a particular function. It has no effect if `-fsplit-stack` is not specified.

not_tail_called (clang::not_tail_called)

Table 4.26: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `not_tail_called` attribute prevents tail-call optimization on statically bound calls. It has no effect on indirect calls. Virtual functions, objective-c methods, and functions marked as `always_inline` cannot be marked as `not_tail_called`.

For example, it prevents tail-call optimization in the following case:

```
int __attribute__((not_tail_called)) foo1(int);

int foo2(int a) {
  return foo1(a); // No tail-call optimization on direct calls.
}
```

However, it doesn't prevent tail-call optimization in this case:

```
int __attribute__((not_tail_called)) foo1(int);

int foo2(int a) {
  int (*fn)(int) = &foo1;

  // not_tail_called has no effect on an indirect call even if the call can␣
↪be
  // resolved at compile time.
  return (*fn)(a);
}
```

Marking virtual functions as `not_tail_called` is an error:

```
class Base {
public:
  // not_tail_called on a virtual function is an error.
  [[clang::not_tail_called]] virtual int foo1();

  virtual int foo2();

  // Non-virtual functions can be marked ``not_tail_called``.
  [[clang::not_tail_called]] int foo3();
};

class Derived1 : public Base {
public:
  int foo1() override;

  // not_tail_called on a virtual function is an error.
  [[clang::not_tail_called]] int foo2() override;
};
```

#pragma omp declare simd

Table 4.27: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
				X

The *declare simd* construct can be applied to a function to enable the creation of one or more versions that can process multiple arguments using SIMD instructions from a single invocation in a SIMD loop. The *declare simd* directive is a declarative directive. There may be multiple *declare simd* directives for a function. The use of a *declare simd* construct on a function enables the creation of SIMD versions of the associated function that can be used to process multiple arguments from a single invocation from a SIMD loop concurrently. The syntax of the *declare simd* construct is as follows:

```
```

#pragma omp declare simd [clause[[,] clause] ...] new-line [#pragma omp declare simd [clause[[,] clause] ...] new-line] [...] function definition or declaration

where clause is one of the following:

```
```

simdlen(length) linear(argument-list[:constant-linear-step]) aligned(argument-list[:alignment]) uniform(argument-list) inbranch notinbranch

#pragma omp declare target

Table 4.28: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
				X

The *declare target* directive specifies that variables and functions are mapped to a device for OpenMP offload mechanism.

The syntax of the declare target directive is as follows:

#pragma omp declare target new-line declarations-definition-seq #pragma omp end declare target new-line

objc_boxable

Table 4.29: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Structs and unions marked with the `objc_boxable` attribute can be used with the Objective-C boxed expression syntax, `@(...)`.

Usage: `__attribute__((objc_boxable))`. This attribute can only be placed on a declaration of a trivially-copyable struct or union:

```
struct __attribute__((objc_boxable)) some_struct {
  int i;
};
union __attribute__((objc_boxable)) some_union {
  int i;
  float f;
};
typedef struct __attribute__((objc_boxable)) _some_struct some_struct;

// ...

some_struct ss;
NSValue *boxed = @(ss);
```

objc_method_family

Table 4.30: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Many methods in Objective-C have conventional meanings determined by their selectors. It is sometimes useful to be able to mark a method as having a particular conventional meaning despite not having the right selector, or as not having the conventional meaning that its selector would suggest. For these use cases, we provide an attribute to specifically describe the "method family" that a method belongs to.

Usage: `__attribute__((objc_method_family(X)))`, where `X` is one of `none`, `alloc`, `copy`, `init`, `mutableCopy`, or `new`. This attribute can only be placed at the end of a method declaration:

```
- (NSString *)initMyStringValue __attribute__((objc_method_family(none)));
```

Users who do not wish to change the conventional meaning of a method, and who merely want to document its non-standard retain and release semantics, should use the retaining behavior attributes (`ns_returns_retained`, `ns_returns_not_retained`, etc).

Query for this feature with `__has_attribute(objc_method_family)`.

objc_requires_super

Table 4.31: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Some Objective-C classes allow a subclass to override a particular method in a parent class but expect that the overriding method also calls the overridden method in the parent class. For these cases, we provide an attribute to designate that a method requires a "call to `super`" in the overriding method in the subclass.

Usage: `__attribute__((objc_requires_super))`. This attribute can only be placed at the end of a method declaration:

```
- (void)foo __attribute__((objc_requires_super));
```

This attribute can only be applied the method declarations within a class, and not a protocol. Currently this attribute does not enforce any placement of where the call occurs in the overriding method (such as in the case of `-dealloc` where the call must appear at the end). It checks only that it exists.

Note that on both OS X and iOS that the Foundation framework provides a convenience macro `NS_REQUIRES_SUPER` that provides syntactic sugar for this attribute:

```
- (void)foo NS_REQUIRES_SUPER;
```

This macro is conditionally defined depending on the compiler's support for this attribute. If the compiler does not support the attribute the macro expands to nothing.

Operationally, when a method has this annotation the compiler will warn if the implementation of an override in a subclass does not call super. For example:

```
warning: method possibly missing a [super AnnotMeth] call
- (void) AnnotMeth{};
                  ^
```

objc_runtime_name

Table 4.32: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

By default, the Objective-C interface or protocol identifier is used in the metadata name for that object. The *objc_runtime_name* attribute allows annotated interfaces or protocols to use the specified string argument in the object's metadata name instead of the default name.

Usage: `__attribute__((objc_runtime_name("MyLocalName")))`. This attribute can only be placed before an @protocol or @interface declaration:

```
__attribute__((objc_runtime_name("MyLocalName")))
@interface Message
@end
```

objc_runtime_visible

Table 4.33: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

This attribute specifies that the Objective-C class to which it applies is visible to the Objective-C runtime but not to the linker. Classes annotated with this attribute cannot be subclassed and cannot have categories defined for them.

optnone (clang::optnone)

Table 4.34: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `optnone` attribute suppresses essentially all optimizations on a function or method, regardless of the optimization level applied to the compilation unit as a whole. This is particularly useful when you need to debug a particular function, but it is infeasible to build the entire application without optimization. Avoiding optimization on the specified function can improve the quality of the debugging information for that function.

This attribute is incompatible with the `always_inline` and `minsize` attributes.

overloadable

Table 4.35: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Clang provides support for C++ function overloading in C. Function overloading in C is introduced using the `overloadable` attribute. For example, one might provide several overloaded versions of a `tgsin` function that invokes the appropriate standard function computing the sine of a value with `float`, `double`, or `long double` precision:

```
#include <math.h>
float __attribute__((overloadable)) tgsin(float x) { return sinf(x); }
double __attribute__((overloadable)) tgsin(double x) { return sin(x); }
long double __attribute__((overloadable)) tgsin(long double x) { return sinl(x); }
```

Given these declarations, one can call `tgsin` with a `float` value to receive a `float` result, with a `double` to receive a `double` result, etc. Function overloading in C follows the rules of C++ function overloading to pick the best overload given the call arguments, with a few C-specific semantics:

- Conversion from `float` or `double` to `long double` is ranked as a floating-point promotion (per C99) rather than as a floating-point conversion (as in C++).
- A conversion from a pointer of type `T*` to a pointer of type `U*` is considered a pointer conversion (with conversion rank) if `T` and `U` are compatible types.
- A conversion from type `T` to a value of type `U` is permitted if `T` and `U` are compatible types. This conversion is given "conversion" rank.

The declaration of `overloadable` functions is restricted to function declarations and definitions. Most importantly, if any function with a given name is given the `overloadable` attribute, then all function declarations and definitions with that name (and in that scope) must have the `overloadable` attribute. This rule even applies to redeclarations of functions whose original declaration had the `overloadable` attribute, e.g.,

```
int f(int) __attribute__((overloadable));
float f(float); // error: declaration of "f" must have the "overloadable" attribute

int g(int) __attribute__((overloadable));
int g(int) { } // error: redeclaration of "g" must also have the "overloadable"␣
↪attribute
```

Functions marked `overloadable` must have prototypes. Therefore, the following code is ill-formed:

```
int h() __attribute__((overloadable)); // error: h does not have a prototype
```

However, `overloadable` functions are allowed to use a ellipsis even if there are no named parameters (as is permitted in C++). This feature is particularly useful when combined with the `unavailable` attribute:

```
void honeypot(...) __attribute__((overloadable, unavailable)); // calling me is an␣
↪error
```

Functions declared with the `overloadable` attribute have their names mangled according to the same rules as C++ function names. For example, the three `tgsin` functions in our motivating example get the mangled names `_Z5tgsinf`, `_Z5tgsind`, and `_Z5tgsine`, respectively. There are two caveats to this use of name mangling:

- Future versions of Clang may change the name mangling of functions overloaded in C, so you should not depend on an specific mangling. To be completely safe, we strongly urge the use of `static inline` with `overloadable` functions.
- The `overloadable` attribute has almost no meaning when used in C++, because names will already be mangled and functions are already overloadable. However, when an `overloadable` function occurs within an `extern "C"` linkage specification, it's name *will* be mangled in the same way as it would in C.

Query for this feature with `__has_extension(attribute_overloadable)`.

release_capability (release_shared_capability, clang::release_capability, clang::release_shared_capability)

Table 4.36: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Marks a function as releasing a capability.

kernel

Table 4.37: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

`__attribute__((kernel))` is used to mark a `kernel` function in RenderScript.

In RenderScript, `kernel` functions are used to express data-parallel computations. The RenderScript runtime efficiently parallelizes `kernel` functions to run on computational resources such as multi-core CPUs and GPUs. See the RenderScript documentation for more information.

target (gnu::target)

Table 4.38: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Clang supports the GNU style `__attribute__((target("OPTIONS")))` attribute. This attribute may be attached to a function definition and instructs the backend to use different code generation options than were passed on the command line.

The current set of options correspond to the existing "subtarget features" for the target with or without a "-mno-" in front corresponding to the absence of the feature, as well as `arch="CPU"` which will change the default "CPU" for the function.

Example "subtarget features" from the x86 backend include: "mmx", "sse", "sse4.2", "avx", "xop" and largely correspond to the machine specific options handled by the front end.

try_acquire_capability (try_acquire_shared_capability, clang::try_acquire_capability, clang::try_acquire_shared_capability)

Table 4.39: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Marks a function that attempts to acquire a capability. This function may fail to actually acquire the capability; they accept a Boolean value determining whether acquiring the capability means success (true), or failing to acquire the capability means success (false).

nodiscard, warn_unused_result, clang::warn_unused_result, gnu::warn_unused_result

Table 4.40: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

Clang supports the ability to diagnose when the results of a function call expression are discarded under suspicious circumstances. A diagnostic is generated when a function or its return type is marked with `[[nodiscard]]` (or `__attribute__((warn_unused_result))`) and the function call appears as a potentially-evaluated discarded-value expression that is not explicitly cast to *void*.

xray_always_instrument (clang::xray_always_instrument), xray_never_instrument (clang::xray_never_instrument)

Table 4.41: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

`__attribute__((xray_always_instrument))` or `[[clang::xray_always_instrument]]` is used to mark member functions (in C++), methods (in Objective C), and free functions (in C, C++, and Objective C) to be instrumented with XRay. This will cause the function to always have space at the beginning and exit points to allow for runtime patching.

Conversely, `__attribute__((xray_never_instrument))` or `[[clang::xray_never_instrument]]` will inhibit the insertion of these instrumentation points.

If a function has neither of these attributes, they become subject to the XRay heuristics used to determine whether a function should be instrumented or otherwise.

Variable Attributes

dllexport (gnu::dllexport)

Table 4.42: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X	X		

The `__declspec(dllexport)` attribute declares a variable, function, or Objective-C interface to be exported from the module. It is available under the `-fdeclspec` flag for compatibility with various compilers. The primary use is for COFF object files which explicitly specify what interfaces are available for external use. See the dllexport documentation on MSDN for more information.

dllimport (gnu::dllimport)

Table 4.43: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X	X		

The `__declspec(dllimport)` attribute declares a variable, function, or Objective-C interface to be imported from an external module. It is available under the `-fdeclspec` flag for compatibility with various compilers. The primary use is for COFF object files which explicitly specify what interfaces are imported from external modules. See the dllimport documentation on MSDN for more information.

init_seg

Table 4.44: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
				X

The attribute applied by `pragma init_seg()` controls the section into which global initialization function pointers are emitted. It is only available with `-fms-extensions`. Typically, this function pointer is emitted into `.CRT$XCU` on Windows. The user can change the order of initialization by using a different section name with the same `.CRT$XC` prefix and a suffix that sorts lexicographically before or after the standard `.CRT$XCU` sections. See the init_seg documentation on MSDN for more information.

nodebug (gnu::nodebug)

Table 4.45: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `nodebug` attribute allows you to suppress debugging information for a function or method, or for a variable that is not a parameter or a non-static data member.

nosvm

Table 4.46: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

OpenCL 2.0 supports the optional `__attribute__((nosvm))` qualifier for pointer variable. It informs the compiler that the pointer does not refer to a shared virtual memory region. See OpenCL v2.0 s6.7.2 for details.

Since it is not widely used and has been removed from OpenCL 2.1, it is ignored by Clang.

pass_object_size

Table 4.47: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Note: The mangling of functions with parameters that are annotated with `pass_object_size` is subject to change. You can get around this by using `__asm__("foo")` to explicitly name your functions, thus preserving your ABI; also, non-overloadable C functions with `pass_object_size` are not mangled.

The `pass_object_size(Type)` attribute can be placed on function parameters to instruct clang to call `__builtin_object_size(param, Type)` at each callsite of said function, and implicitly pass the result of this call in as an invisible argument of type `size_t` directly after the parameter annotated with `pass_object_size`. Clang will also replace any calls to `__builtin_object_size(param, Type)` in the function by said implicit parameter.

Example usage:

```
int bzero1(char *const p __attribute__((pass_object_size(0))))
    __attribute__((noinline)) {
  int i = 0;
  for (/**/; i < (int)__builtin_object_size(p, 0); ++i) {
    p[i] = 0;
```

```
  }
  return i;
}

int main() {
  char chars[100];
  int n = bzero1(&chars[0]);
  assert(n == sizeof(chars));
  return 0;
}
```

If successfully evaluating `__builtin_object_size(param, Type)` at the callsite is not possible, then the "failed" value is passed in. So, using the definition of `bzero1` from above, the following code would exit cleanly:

```
int main2(int argc, char *argv[]) {
  int n = bzero1(argv);
  assert(n == -1);
  return 0;
}
```

`pass_object_size` plays a part in overload resolution. If two overload candidates are otherwise equally good, then the overload with one or more parameters with `pass_object_size` is preferred. This implies that the choice between two identical overloads both with `pass_object_size` on one or more parameters will always be ambiguous; for this reason, having two such overloads is illegal. For example:

```
#define PS(N) __attribute__((pass_object_size(N)))
// OK
void Foo(char *a, char *b); // Overload A
// OK -- overload A has no parameters with pass_object_size.
void Foo(char *a PS(0), char *b PS(0)); // Overload B
// Error -- Same signature (sans pass_object_size) as overload B, and both
// overloads have one or more parameters with the pass_object_size attribute.
void Foo(void *a PS(0), void *b);

// OK
void Bar(void *a PS(0)); // Overload C
// OK
void Bar(char *c PS(1)); // Overload D

void main() {
  char known[10], *unknown;
  Foo(unknown, unknown); // Calls overload B
  Foo(known, unknown); // Calls overload B
  Foo(unknown, known); // Calls overload B
  Foo(known, known); // Calls overload B

  Bar(known); // Calls overload D
  Bar(unknown); // Calls overload D
}
```

Currently, `pass_object_size` is a bit restricted in terms of its usage:

- Only one use of `pass_object_size` is allowed per parameter.
- It is an error to take the address of a function with `pass_object_size` on any of its parameters. If you wish to do this, you can create an overload without `pass_object_size` on any parameters.
- It is an error to apply the `pass_object_size` attribute to parameters that are not pointers. Additionally, any parameter that `pass_object_size` is applied to must be marked `const` at its function's definition.

section (gnu::section, __declspec(allocate))

Table 4.48: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X	X		

The `section` attribute allows you to specify a specific section a global variable or function should be in after translation.

swiftcall (gnu::swiftcall)

Table 4.49: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `swiftcall` attribute indicates that a function should be called using the Swift calling convention for a function or function pointer.

The lowering for the Swift calling convention, as described by the Swift ABI documentation, occurs in multiple phases. The first, "high-level" phase breaks down the formal parameters and results into innately direct and indirect components, adds implicit paraameters for the generic signature, and assigns the context and error ABI treatments to parameters where applicable. The second phase breaks down the direct parameters and results from the first phase and assigns them to registers or the stack. The `swiftcall` convention only handles this second phase of lowering; the C function type must accurately reflect the results of the first phase, as follows:

- Results classified as indirect by high-level lowering should be represented as parameters with the `swift_indirect_result` attribute.
- Results classified as direct by high-level lowering should be represented as follows:
  - First, remove any empty direct results.
  - If there are no direct results, the C result type should be `void`.
  - If there is one direct result, the C result type should be a type with the exact layout of that result type.
  - If there are a multiple direct results, the C result type should be a struct type with the exact layout of a tuple of those results.
- Parameters classified as indirect by high-level lowering should be represented as parameters of pointer type.
- Parameters classified as direct by high-level lowering should be omitted if they are empty types; otherwise, they should be represented as a parameter type with a layout exactly matching the layout of the Swift parameter type.
- The context parameter, if present, should be represented as a trailing parameter with the `swift_context` attribute.
- The error result parameter, if present, should be represented as a trailing parameter (always following a context parameter) with the `swift_error_result` attribute.

`swiftcall` does not support variadic arguments or unprototyped functions.

The parameter ABI treatment attributes are aspects of the function type. A function type which which applies an ABI treatment attribute to a parameter is a different type from an otherwise-identical function type that does not. A single parameter may not have multiple ABI treatment attributes.

Support for this feature is target-dependent, although it should be supported on every target that Swift supports. Query for this support with `__has_attribute(swiftcall)`. This implies support for the `swift_context`, `swift_error_result`, and `swift_indirect_result` attributes.

swift_context (gnu::swift_context)

Table 4.50: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `swift_context` attribute marks a parameter of a `swiftcall` function as having the special context-parameter ABI treatment.

This treatment generally passes the context value in a special register which is normally callee-preserved.

A `swift_context` parameter must either be the last parameter or must be followed by a `swift_error_result` parameter (which itself must always be the last parameter).

A context parameter must have pointer or reference type.

swift_error_result (gnu::swift_error_result)

Table 4.51: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `swift_error_result` attribute marks a parameter of a `swiftcall` function as having the special error-result ABI treatment.

This treatment generally passes the underlying error value in and out of the function through a special register which is normally callee-preserved. This is modeled in C by pretending that the register is addressable memory:

- The caller appears to pass the address of a variable of pointer type. The current value of this variable is copied into the register before the call; if the call returns normally, the value is copied back into the variable.
- The callee appears to receive the address of a variable. This address is actually a hidden location in its own stack, initialized with the value of the register upon entry. When the function returns normally, the value in that hidden location is written back to the register.

A `swift_error_result` parameter must be the last parameter, and it must be preceded by a `swift_context` parameter.

A `swift_error_result` parameter must have type `T**` or `T*&` for some type T. Note that no qualifiers are permitted on the intermediate level.

It is undefined behavior if the caller does not pass a pointer or reference to a valid object.

The standard convention is that the error value itself (that is, the value stored in the apparent argument) will be null upon function entry, but this is not enforced by the ABI.

swift_indirect_result (gnu::swift_indirect_result)

Table 4.52: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `swift_indirect_result` attribute marks a parameter of a `swiftcall` function as having the special indirect-result ABI treatmenet.

This treatment gives the parameter the target's normal indirect-result ABI treatment, which may involve passing it differently from an ordinary parameter. However, only the first indirect result will receive this treatment. Furthermore, low-level lowering may decide that a direct result must be returned indirectly; if so, this will take priority over the `swift_indirect_result` parameters.

A `swift_indirect_result` parameter must either be the first parameter or follow another `swift_indirect_result` parameter.

A `swift_indirect_result` parameter must have type `T*` or `T&` for some object type `T`. If `T` is a complete type at the point of definition of a function, it is undefined behavior if the argument value does not point to storage of adequate size and alignment for a value of type `T`.

Making indirect results explicit in the signature allows C functions to directly construct objects into them without relying on language optimizations like C++'s named return value optimization (NRVO).

tls_model (gnu::tls_model)

Table 4.53: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `tls_model` attribute allows you to specify which thread-local storage model to use. It accepts the following strings:

- global-dynamic
- local-dynamic
- initial-exec
- local-exec

TLS models are mutually exclusive.

thread

Table 4.54: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
		X		

The `__declspec(thread)` attribute declares a variable with thread local storage. It is available under the `-fms-extensions` flag for MSVC compatibility. See the documentation for __declspec(thread) on MSDN.

In Clang, `__declspec(thread)` is generally equivalent in functionality to the GNU `__thread` keyword. The variable must not have a destructor and must have a constant initializer, if any. The attribute only applies to variables declared with static storage duration, such as globals, class static data members, and static locals.

maybe_unused, unused, gnu::unused

Table 4.55: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

When passing the `-Wunused` flag to Clang, entities that are unused by the program may be diagnosed. The `[[maybe_unused]]` (or `__attribute__((unused))`) attribute can be used to silence such diagnostics when the entity cannot be removed. For instance, a local variable may exist solely for use in an `assert()` statement, which makes the local variable unused when `NDEBUG` is defined.

The attribute may be applied to the declaration of a class, a typedef, a variable, a function or method, a function parameter, an enumeration, an enumerator, a non-static data member, or a label.

Type Attributes

align_value

Table 4.56: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

The align_value attribute can be added to the typedef of a pointer type or the declaration of a variable of pointer or reference type. It specifies that the pointer will point to, or the reference will bind to, only objects with at least the provided alignment. This alignment value must be some positive power of 2.

```
typedef double * aligned_double_ptr __attribute__((align_value(64)));
void foo(double & x  __attribute__((align_value(128)),
         aligned_double_ptr y) { ... }
```

If the pointer value does not have the specified alignment at runtime, the behavior of the program is undefined.

empty_bases

Table 4.57: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
		X		

The empty_bases attribute permits the compiler to utilize the empty-base-optimization more frequently. This attribute only applies to struct, class, and union types. It is only supported when using the Microsoft C++ ABI.

flag_enum

Table 4.58: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

This attribute can be added to an enumerator to signal to the compiler that it is intended to be used as a flag type. This will cause the compiler to assume that the range of the type includes all of the values that you can get by manipulating bits of the enumerator when issuing warnings.

lto_visibility_public (clang::lto_visibility_public)

Table 4.59: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
	X			

See *LTO Visibility*.

layout_version

Table 4.60: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
		X		

The layout_version attribute requests that the compiler utilize the class layout rules of a particular compiler version. This attribute only applies to struct, class, and union types. It is only supported when using the Microsoft C++ ABI.

__single_inhertiance, __multiple_inheritance, __virtual_inheritance

Table 4.61: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

This collection of keywords is enabled under `-fms-extensions` and controls the pointer-to-member representation used on `*-*-win32` targets.

The `*-*-win32` targets utilize a pointer-to-member representation which varies in size and alignment depending on the definition of the underlying class.

However, this is problematic when a forward declaration is only available and no definition has been made yet. In such cases, Clang is forced to utilize the most general representation that is available to it.

These keywords make it possible to use a pointer-to-member representation other than the most general one regardless of whether or not the definition will ever be present in the current translation unit.

This family of keywords belong between the `class-key` and `class-name`:

```
struct __single_inheritance S;
int S::*i;
struct S {};
```

This keyword can be applied to class templates but only has an effect when used on full specializations:

```
template <typename T, typename U> struct __single_inheritance A; // warning:␣
↪inheritance model ignored on primary template
template <typename T> struct __multiple_inheritance A<T, T>; // warning: inheritance␣
↪model ignored on partial specialization
template <> struct __single_inheritance A<int, float>;
```

Note that choosing an inheritance model less general than strictly necessary is an error:

```
struct __multiple_inheritance S; // error: inheritance model does not match definition
int S::*i;
struct S {};
```

novtable

Table 4.62: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
		X		

This attribute can be added to a class declaration or definition to signal to the compiler that constructors and destructors will not reference the virtual function table. It is only supported when using the Microsoft C++ ABI.

Statement Attributes

fallthrough, clang::fallthrough

Table 4.63: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
	X			

The `fallthrough` (or `clang::fallthrough`) attribute is used to annotate intentional fall-through between switch labels. It can only be applied to a null statement placed at a point of execution between any statement and the next switch label. It is common to mark these places with a specific comment, but this attribute is meant to replace comments with a more strict annotation, which can be checked by the compiler. This attribute doesn't change semantics of the code and can be used wherever an intended fall-through occurs. It is designed to mimic control-flow statements like `break;`, so it can be placed in most places where `break;` can, but only if there are no statements on the execution path between it and the next switch label.

By default, Clang does not warn on unannotated fallthrough from one `switch` case to another. Diagnostics on fallthrough without a corresponding annotation can be enabled with the `-Wimplicit-fallthrough` argument.

Here is an example:

```
// compile with -Wimplicit-fallthrough
switch (n) {
case 22:
case 33:  // no warning: no statements between case labels
  f();
case 44:  // warning: unannotated fall-through
  g();
  [[clang::fallthrough]];
```

```
case 55:  // no warning
  if (x) {
    h();
    break;
  }
  else {
    i();
    [[clang::fallthrough]];
  }
case 66:  // no warning
  p();
  [[clang::fallthrough]]; // warning: fallthrough annotation does not
                          //          directly precede case label
  q();
case 77:  // warning: unannotated fall-through
  r();
}
```

#pragma clang loop

Table 4.64: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
				X

The `#pragma clang loop` directive allows loop optimization hints to be specified for the subsequent loop. The directive allows vectorization, interleaving, and unrolling to be enabled or disabled. Vector width as well as interleave and unrolling count can be manually specified. See language extensions for details.

#pragma unroll, #pragma nounroll

Table 4.65: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
				X

Loop unrolling optimization hints can be specified with `#pragma unroll` and `#pragma nounroll`. The pragma is placed immediately before a for, while, do-while, or c++11 range-based for loop.

Specifying `#pragma unroll` without a parameter directs the loop unroller to attempt to fully unroll the loop if the trip count is known at compile time and attempt to partially unroll the loop if the trip count is not known at compile time:

```
#pragma unroll
for (...) {
  ...
}
```

Specifying the optional parameter, `#pragma unroll _value_`, directs the unroller to unroll the loop `_value_` times. The parameter may optionally be enclosed in parentheses:

```
#pragma unroll 16
for (...) {
  ...
```

```
}

#pragma unroll(16)
for (...) {
  ...
}
```

Specifying `#pragma nounroll` indicates that the loop should not be unrolled:

```
#pragma nounroll
for (...) {
  ...
}
```

`#pragma unroll` and `#pragma unroll _value_` have identical semantics to `#pragma clang loop unroll(full)` and `#pragma clang loop unroll_count(_value_)` respectively. `#pragma nounroll` is equivalent to `#pragma clang loop unroll(disable)`. See language extensions for further details including limitations of the unroll hints.

__read_only, __write_only, __read_write (read_only, write_only, read_write)

Table 4.66: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

The access qualifiers must be used with image object arguments or pipe arguments to declare if they are being read or written by a kernel or function.

The read_only/__read_only, write_only/__write_only and read_write/__read_write names are reserved for use as access qualifiers and shall not be used otherwise.

```
kernel void
foo (read_only image2d_t imageA,
     write_only image2d_t imageB) {
  ...
}
```

In the above example imageA is a read-only 2D image object, and imageB is a write-only 2D image object.

The read_write (or __read_write) qualifier can not be used with pipe.

More details can be found in the OpenCL C language Spec v2.0, Section 6.6.

__attribute__((opencl_unroll_hint))

Table 4.67: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

The opencl_unroll_hint attribute qualifier can be used to specify that a loop (for, while and do loops) can be unrolled. This attribute qualifier can be used to specify full unrolling or partial unrolling by a specified amount. This is a compiler hint and the compiler may ignore this directive. See OpenCL v2.0 s6.11.5 for details.

AMD GPU Register Attributes

Clang supports attributes for controlling register usage on AMD GPU targets. These attributes may be attached to a kernel function definition and is an optimization hint to the backend for the maximum number of registers to use. This is useful in cases where register limited occupancy is known to be an important factor for the performance for the kernel.

The semantics are as follows:

- The backend will attempt to limit the number of used registers to the specified value, but the exact number used is not guaranteed. The number used may be rounded up to satisfy the allocation requirements or ABI constraints of the subtarget. For example, on Southern Islands VGPRs may only be allocated in increments of 4, so requesting a limit of 39 VGPRs will really attempt to use up to 40. Requesting more registers than the subtarget supports will truncate to the maximum allowed. The backend may also use fewer registers than requested whenever possible.
- 0 implies the default no limit on register usage.
- Ignored on older VLIW subtargets which did not have separate scalar and vector registers, R600 through Northern Islands.

amdgpu_num_sgpr

Table 4.68: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Clang supports the `__attribute__((amdgpu_num_sgpr(<num_registers>)))` attribute on AMD Southern Islands GPUs and later for controlling the number of scalar registers. A typical value would be between 8 and 104 in increments of 8.

Due to common instruction constraints, an additional 2-4 SGPRs are typically required for internal use depending on features used. This value is a hint for the total number of SGPRs to use, and not the number of user SGPRs, so no special consideration needs to be given for these.

amdgpu_num_vgpr

Table 4.69: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Clang supports the `__attribute__((amdgpu_num_vgpr(<num_registers>)))` attribute on AMD Southern Islands GPUs and later for controlling the number of vector registers. A typical value would be between 4 and 256 in increments of 4.

Calling Conventions

Clang supports several different calling conventions, depending on the target platform and architecture. The calling convention used for a function determines how parameters are passed, how results are returned to the caller, and other low-level details of calling a function.

fastcall (gnu::fastcall, __fastcall, _fastcall)

Table 4.70: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X		X	

On 32-bit x86 targets, this attribute changes the calling convention of a function to use ECX and EDX as register parameters and clear parameters off of the stack on return. This convention does not support variadic calls or unprototyped functions in C, and has no effect on x86_64 targets. This calling convention is supported primarily for compatibility with existing code. Users seeking register parameters should use the `regparm` attribute, which does not require callee-cleanup. See the documentation for __fastcall on MSDN.

ms_abi (gnu::ms_abi)

Table 4.71: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

On non-Windows x86_64 targets, this attribute changes the calling convention of a function to match the default convention used on Windows x86_64. This attribute has no effect on Windows targets or non-x86_64 targets.

pcs (gnu::pcs)

Table 4.72: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

On ARM targets, this attribute can be used to select calling conventions similar to `stdcall` on x86. Valid parameter values are "aapcs" and "aapcs-vfp".

preserve_all

Table 4.73: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

On X86-64 and AArch64 targets, this attribute changes the calling convention of a function. The `preserve_all` calling convention attempts to make the code in the caller even less intrusive than the `preserve_most` calling convention. This calling convention also behaves identical to the `C` calling convention on how arguments and return values are passed, but it uses a different set of caller/callee-saved registers. This removes the burden of saving and recovering a large register set before and after the call in the caller. If the arguments are passed in callee-saved registers, then they will be preserved by the callee across the call. This doesn't apply for values returned in callee-saved registers.

- On X86-64 the callee preserves all general purpose registers, except for R11. R11 can be used as a scratch register. Furthermore it also preserves all floating-point registers (XMMs/YMMs).

The idea behind this convention is to support calls to runtime functions that don't need to call out to any other functions.

This calling convention, like the `preserve_most` calling convention, will be used by a future version of the Objective-C runtime and should be considered experimental at this time.

preserve_most

Table 4.74: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

On X86-64 and AArch64 targets, this attribute changes the calling convention of a function. The `preserve_most` calling convention attempts to make the code in the caller as unintrusive as possible. This convention behaves identically to the `C` calling convention on how arguments and return values are passed, but it uses a different set of caller/callee-saved registers. This alleviates the burden of saving and recovering a large register set before and after the call in the caller. If the arguments are passed in callee-saved registers, then they will be preserved by the callee across the call. This doesn't apply for values returned in callee-saved registers.

- On X86-64 the callee preserves all general purpose registers, except for R11. R11 can be used as a scratch register. Floating-point registers (XMMs/YMMs) are not preserved and need to be saved by the caller.

The idea behind this convention is to support calls to runtime functions that have a hot path and a cold path. The hot path is usually a small piece of code that doesn't use many registers. The cold path might need to call out to another function and therefore only needs to preserve the caller-saved registers, which haven't already been saved by the caller. The *preserve_most* calling convention is very similar to the `cold` calling convention in terms of caller/callee-saved registers, but they are used for different types of function calls. `coldcc` is for function calls that are rarely executed, whereas *preserve_most* function calls are intended to be on the hot path and definitely executed a lot. Furthermore `preserve_most` doesn't prevent the inliner from inlining the function call.

This calling convention will be used by a future version of the Objective-C runtime and should therefore still be considered experimental at this time. Although this convention was created to optimize certain runtime calls to the Objective-C runtime, it is not limited to this runtime and might be used by other runtimes in the future too. The current implementation only supports X86-64 and AArch64, but the intention is to support more architectures in the future.

regparm (gnu::regparm)

Table 4.75: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

On 32-bit x86 targets, the regparm attribute causes the compiler to pass the first three integer parameters in EAX, EDX, and ECX instead of on the stack. This attribute has no effect on variadic functions, and all parameters are passed via the stack as normal.

stdcall (gnu::stdcall, __stdcall, _stdcall)

Table 4.76: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X		X	

On 32-bit x86 targets, this attribute changes the calling convention of a function to clear parameters off of the stack on return. This convention does not support variadic calls or unprototyped functions in C, and has no effect on x86_64

targets. This calling convention is used widely by the Windows API and COM applications. See the documentation for __stdcall on MSDN.

thiscall (gnu::thiscall, __thiscall, _thiscall)

Table 4.77: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X		X	

On 32-bit x86 targets, this attribute changes the calling convention of a function to use ECX for the first parameter (typically the implicit `this` parameter of C++ methods) and clear parameters off of the stack on return. This convention does not support variadic calls or unprototyped functions in C, and has no effect on x86_64 targets. See the documentation for __thiscall on MSDN.

vectorcall (__vectorcall, _vectorcall)

Table 4.78: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X			X	

On 32-bit x86 *and* x86_64 targets, this attribute changes the calling convention of a function to pass vector parameters in SSE registers.

On 32-bit x86 targets, this calling convention is similar to `__fastcall`. The first two integer parameters are passed in ECX and EDX. Subsequent integer parameters are passed in memory, and callee clears the stack. On x86_64 targets, the callee does *not* clear the stack, and integer parameters are passed in RCX, RDX, R8, and R9 as is done for the default Windows x64 calling convention.

On both 32-bit x86 and x86_64 targets, vector and floating point arguments are passed in XMM0-XMM5. Homogenous vector aggregates of up to four elements are passed in sequential SSE registers if enough are available. If AVX is enabled, 256 bit vectors are passed in YMM0-YMM5. Any vector or aggregate type that cannot be passed in registers for any reason is passed by reference, which allows the caller to align the parameter memory.

See the documentation for __vectorcall on MSDN for more details.

Consumed Annotation Checking

Clang supports additional attributes for checking basic resource management properties, specifically for unique objects that have a single owning reference. The following attributes are currently supported, although **the implementation for these annotations is currently in development and are subject to change.**

callable_when

Table 4.79: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Use `__attribute__((callable_when(...)))` to indicate what states a method may be called in. Valid states are unconsumed, consumed, or unknown. Each argument to this attribute must be a quoted string. E.g.:

```
__attribute__((callable_when("unconsumed", "unknown")))
```

consumable

Table 4.80: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Each `class` that uses any of the typestate annotations must first be marked using the `consumable` attribute. Failure to do so will result in a warning.

This attribute accepts a single parameter that must be one of the following: `unknown`, `consumed`, or `unconsumed`.

param_typestate

Table 4.81: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

This attribute specifies expectations about function parameters. Calls to an function with annotated parameters will issue a warning if the corresponding argument isn't in the expected state. The attribute is also used to set the initial state of the parameter when analyzing the function's body.

return_typestate

Table 4.82: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

The `return_typestate` attribute can be applied to functions or parameters. When applied to a function the attribute specifies the state of the returned value. The function's body is checked to ensure that it always returns a value in the specified state. On the caller side, values returned by the annotated function are initialized to the given state.

When applied to a function parameter it modifies the state of an argument after a call to the function returns. The function's body is checked to ensure that the parameter is in the expected state before returning.

set_typestate

Table 4.83: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Annotate methods that transition an object into a new state with `__attribute__((set_typestate(new_state)))`. The new state must be unconsumed, consumed, or unknown.

test_typestate

Table 4.84: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Use `__attribute__((test_typestate(tested_state)))` to indicate that a method returns true if the object is in the specified state..

Type Safety Checking

Clang supports additional attributes to enable checking type safety properties that can't be enforced by the C type system. Use cases include:

- MPI library implementations, where these attributes enable checking that the buffer type matches the passed `MPI_Datatype`;
- for HDF5 library there is a similar use case to MPI;
- checking types of variadic functions' arguments for functions like `fcntl()` and `ioctl()`.

You can detect support for these attributes with `__has_attribute()`. For example:

```
#if defined(__has_attribute)
#  if __has_attribute(argument_with_type_tag) && \
      __has_attribute(pointer_with_type_tag) && \
      __has_attribute(type_tag_for_datatype)
#    define ATTR_MPI_PWT(buffer_idx, type_idx) __attribute__((pointer_with_type_
↪tag(mpi,buffer_idx,type_idx)))
/* ... other macros ...  */
#  endif
#endif

#if !defined(ATTR_MPI_PWT)
# define ATTR_MPI_PWT(buffer_idx, type_idx)
#endif

int MPI_Send(void *buf, int count, MPI_Datatype datatype /*, other args omitted */)
    ATTR_MPI_PWT(1,3);
```

argument_with_type_tag

Table 4.85: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Use `__attribute__((argument_with_type_tag(arg_kind, arg_idx, type_tag_idx)))` on a function declaration to specify that the function accepts a type tag that determines the type of some other argument. `arg_kind` is an identifier that should be used when annotating all applicable type tags.

This attribute is primarily useful for checking arguments of variadic functions (`pointer_with_type_tag` can be used in most non-variadic cases).

For example:

```
int fcntl(int fd, int cmd, ...)
    __attribute__(( argument_with_type_tag(fcntl,3,2) ));
```

pointer_with_type_tag

Table 4.86: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Use `__attribute__((pointer_with_type_tag(ptr_kind, ptr_idx, type_tag_idx)))` on a function declaration to specify that the function accepts a type tag that determines the pointee type of some other pointer argument.

For example:

```
int MPI_Send(void *buf, int count, MPI_Datatype datatype /*, other args omitted */)
    __attribute__(( pointer_with_type_tag(mpi,1,3) ));
```

type_tag_for_datatype

Table 4.87: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X				

Clang supports annotating type tags of two forms.

- **Type tag that is an expression containing a reference to some declared identifier.** Use `__attribute__((type_tag_for_datatype(kind, type)))` on a declaration with that identifier:

  ```
  extern struct mpi_datatype mpi_datatype_int
      __attribute__(( type_tag_for_datatype(mpi,int) ));
  #define MPI_INT ((MPI_Datatype) &mpi_datatype_int)
  ```

- **Type tag that is an integral literal.** Introduce a `static const` variable with a corresponding initializer value and attach `__attribute__((type_tag_for_datatype(kind, type)))` on that declaration, for example:

  ```
  #define MPI_INT ((MPI_Datatype) 42)
  static const MPI_Datatype mpi_datatype_int
      __attribute__(( type_tag_for_datatype(mpi,int) )) = 42
  ```

The attribute also accepts an optional third argument that determines how the expression is compared to the type tag. There are two supported flags:

- `layout_compatible` will cause types to be compared according to layout-compatibility rules (C++11 [class.mem] p 17, 18). This is implemented to support annotating types like `MPI_DOUBLE_INT`.

  For example:

  ```
  /* In mpi.h */
  struct internal_mpi_double_int { double d; int i; };
  extern struct mpi_datatype mpi_datatype_double_int
      __attribute__(( type_tag_for_datatype(mpi, struct internal_mpi_double_int,␣
  ↪layout_compatible) ));
  ```

```
#define MPI_DOUBLE_INT ((MPI_Datatype) &mpi_datatype_double_int)

/* In user code */
struct my_pair { double a; int b; };
struct my_pair *buffer;
MPI_Send(buffer, 1, MPI_DOUBLE_INT /*, ...  */); // no warning

struct my_int_pair { int a; int b; }
struct my_int_pair *buffer2;
MPI_Send(buffer2, 1, MPI_DOUBLE_INT /*, ...  */); // warning: actual buffer␣
↪element
                                                  // type 'struct my_int_pair'
                                                  // doesn't match specified MPI_
↪Datatype
```

- `must_be_null` specifies that the expression should be a null pointer constant, for example:

```
/* In mpi.h */
extern struct mpi_datatype mpi_datatype_null
    __attribute__(( type_tag_for_datatype(mpi, void, must_be_null) ));

#define MPI_DATATYPE_NULL ((MPI_Datatype) &mpi_datatype_null)

/* In user code */
MPI_Send(buffer, 1, MPI_DATATYPE_NULL /*, ...  */); // warning: MPI_DATATYPE_NULL
                                                    // was specified but buffer
                                                    // is not a null pointer
```

OpenCL Address Spaces

The address space qualifier may be used to specify the region of memory that is used to allocate the object. OpenCL supports the following address spaces: __generic(generic), __global(global), __local(local), __private(private), __constant(constant).

```
__constant int c = ...;

__generic int* foo(global int* g) {
  __local int* l;
  private int p;
  ...
  return l;
}
```

More details can be found in the OpenCL C language Spec v2.0, Section 6.5.

constant (__constant)

Table 4.88: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

The constant address space attribute signals that an object is located in a constant (non-modifiable) memory region. It

is available to all work items. Any type can be annotated with the constant address space attribute. Objects with the constant address space qualifier can be declared in any scope and must have an initializer.

generic (__generic)

Table 4.89: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

The generic address space attribute is only available with OpenCL v2.0 and later. It can be used with pointer types. Variables in global and local scope and function parameters in non-kernel functions can have the generic address space type attribute. It is intended to be a placeholder for any other address space except for '__constant' in OpenCL code which can be used with multiple address spaces.

global (__global)

Table 4.90: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

The global address space attribute specifies that an object is allocated in global memory, which is accessible by all work items. The content stored in this memory area persists between kernel executions. Pointer types to the global address space are allowed as function parameters or local variables. Starting with OpenCL v2.0, the global address space can be used with global (program scope) variables and static local variable as well.

local (__local)

Table 4.91: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

The local address space specifies that an object is allocated in the local (work group) memory area, which is accessible to all work items in the same work group. The content stored in this memory region is not accessible after the kernel execution ends. In a kernel function scope, any variable can be in the local address space. In other scopes, only pointer types to the local address space are allowed. Local address space variables cannot have an initializer.

private (__private)

Table 4.92: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

The private address space specifies that an object is allocated in the private (work item) memory. Other work items cannot access the same memory area and its content is destroyed after work item execution ends. Local variables can be declared in the private address space. Function arguments are always in the private address space. Kernel function arguments of a pointer or an array type cannot point to the private address space.

Nullability Attributes

Whether a particular pointer may be "null" is an important concern when working with pointers in the C family of languages. The various nullability attributes indicate whether a particular pointer can be null or not, which makes APIs more expressive and can help static analysis tools identify bugs involving null pointers. Clang supports several kinds of nullability attributes: the `nonnull` and `returns_nonnull` attributes indicate which function or method parameters and result types can never be null, while nullability type qualifiers indicate which pointer types can be null (`_Nullable`) or cannot be null (`_Nonnull`).

The nullability (type) qualifiers express whether a value of a given pointer type can be null (the `_Nullable` qualifier), doesn't have a defined meaning for null (the `_Nonnull` qualifier), or for which the purpose of null is unclear (the `_Null_unspecified` qualifier). Because nullability qualifiers are expressed within the type system, they are more general than the `nonnull` and `returns_nonnull` attributes, allowing one to express (for example) a nullable pointer to an array of nonnull pointers. Nullability qualifiers are written to the right of the pointer to which they apply. For example:

```
// No meaningful result when 'ptr' is null (here, it happens to be undefined␣
↪behavior).
int fetch(int * _Nonnull ptr) { return *ptr; }

// 'ptr' may be null.
int fetch_or_zero(int * _Nullable ptr) {
  return ptr ? *ptr : 0;
}

// A nullable pointer to non-null pointers to const characters.
const char *join_strings(const char * _Nonnull * _Nullable strings, unsigned␣
↪n);
```

In Objective-C, there is an alternate spelling for the nullability qualifiers that can be used in Objective-C methods and properties using context-sensitive, non-underscored keywords. For example:

```
@interface NSView : NSResponder
  - (nullable NSView *)ancestorSharedWithView:(nonnull NSView *)aView;
  @property (assign, nullable) NSView *superview;
  @property (readonly, nonnull) NSArray *subviews;
@end
```

nonnull (gnu::nonnull)

Table 4.93: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `nonnull` attribute indicates that some function parameters must not be null, and can be used in several different ways. It's original usage (from GCC) is as a function (or Objective-C method) attribute that specifies which parameters of the function are nonnull in a comma-separated list. For example:

```
extern void * my_memcpy (void *dest, const void *src, size_t len)
                  __attribute__((nonnull (1, 2)));
```

Here, the `nonnull` attribute indicates that parameters 1 and 2 cannot have a null value. Omitting the parenthesized list of parameter indices means that all parameters of pointer type cannot be null:

```
extern void * my_memcpy (void *dest, const void *src, size_t len)
                __attribute__((nonnull));
```

Clang also allows the `nonnull` attribute to be placed directly on a function (or Objective-C method) parameter, eliminating the need to specify the parameter index ahead of type. For example:

```
extern void * my_memcpy (void *dest __attribute__((nonnull)),
                         const void *src __attribute__((nonnull)), size_t␣
↪len);
```

Note that the `nonnull` attribute indicates that passing null to a non-null parameter is undefined behavior, which the optimizer may take advantage of to, e.g., remove null checks. The `_Nonnull` type qualifier indicates that a pointer cannot be null in a more general manner (because it is part of the type system) and does not imply undefined behavior, making it more widely applicable.

returns_nonnull (gnu::returns_nonnull)

Table 4.94: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
X	X			

The `returns_nonnull` attribute indicates that a particular function (or Objective-C method) always returns a non-null pointer. For example, a particular system `malloc` might be defined to terminate a process when memory is not available rather than returning a null pointer:

```
extern void * malloc (size_t size) __attribute__((returns_nonnull));
```

The `returns_nonnull` attribute implies that returning a null pointer is undefined behavior, which the optimizer may take advantage of. The `_Nonnull` type qualifier indicates that a pointer cannot be null in a more general manner (because it is part of the type system) and does not imply undefined behavior, making it more widely applicable

_Nonnull

Table 4.95: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

The `_Nonnull` nullability qualifier indicates that null is not a meaningful value for a value of the `_Nonnull` pointer type. For example, given a declaration such as:

```
int fetch(int * _Nonnull ptr);
```

a caller of `fetch` should not provide a null value, and the compiler will produce a warning if it sees a literal null value passed to `fetch`. Note that, unlike the declaration attribute `nonnull`, the presence of `_Nonnull` does not imply that passing null is undefined behavior: `fetch` is free to consider null undefined behavior or (perhaps for backward-compatibility reasons) defensively handle null.

_Null_unspecified

Table 4.96: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

The `_Null_unspecified` nullability qualifier indicates that neither the `_Nonnull` nor `_Nullable` qualifiers make sense for a particular pointer type. It is used primarily to indicate that the role of null with specific pointers in a nullability-annotated header is unclear, e.g., due to overly-complex implementations or historical factors with a long-lived API.

_Nullable

Table 4.97: Supported Syntaxes

GNU	C++11	__declspec	Keyword	Pragma
			X	

The `_Nullable` nullability qualifier indicates that a value of the `_Nullable` pointer type can be null. For example, given:

```
int fetch_or_zero(int * _Nullable ptr);
```

a caller of `fetch_or_zero` can provide null.

Cross-compilation using Clang

Introduction

This document will guide you in choosing the right Clang options for cross-compiling your code to a different architecture. It assumes you already know how to compile the code in question for the host architecture, and that you know how to choose additional include and library paths.

However, this document is *not* a "how to" and won't help you setting your build system or Makefiles, nor choosing the right CMake options, etc. Also, it does not cover all the possible options, nor does it contain specific examples for specific architectures. For a concrete example, the instructions for cross-compiling LLVM itself may be of interest.

After reading this document, you should be familiar with the main issues related to cross-compilation, and what main compiler options Clang provides for performing cross-compilation.

Cross compilation issues

In GCC world, every host/target combination has its own set of binaries, headers, libraries, etc. So, it's usually simple to download a package with all files in, unzip to a directory and point the build system to that compiler, that will know about its location and find all it needs to when compiling your code.

On the other hand, Clang/LLVM is natively a cross-compiler, meaning that one set of programs can compile to all targets by setting the `-target` option. That makes it a lot easier for programmers wishing to compile to different platforms and architectures, and for compiler developers that only have to maintain one build system, and for OS distributions, that need only one set of main packages.

But, as is true to any cross-compiler, and given the complexity of different architectures, OS's and options, it's not always easy finding the headers, libraries or binutils to generate target specific code. So you'll need special options to help Clang understand what target you're compiling to, where your tools are, etc.

Another problem is that compilers come with standard libraries only (like `compiler-rt`, `libcxx`, `libgcc`, `libm`, etc), so you'll have to find and make available to the build system, every other library required to build your software, that is specific to your target. It's not enough to have your host's libraries installed.

Finally, not all toolchains are the same, and consequently, not every Clang option will work magically. Some options, like `--sysroot` (which effectively changes the logical root for headers and libraries), assume all your binaries and libraries are in the same directory, which may not true when your cross-compiler was installed by the distribution's package management. So, for each specific case, you may use more than one option, and in most cases, you'll end up setting include paths (`-I`) and library paths (`-L`) manually.

To sum up, different toolchains can:

- be host/target specific or more flexible
- be in a single directory, or spread out across your system
- have different sets of libraries and headers by default
- need special options, which your build system won't be able to figure out by itself

General Cross-Compilation Options in Clang

Target Triple

The basic option is to define the target architecture. For that, use `-target <triple>`. If you don't specify the target, CPU names won't match (since Clang assumes the host triple), and the compilation will go ahead, creating code for the host platform, which will break later on when assembling or linking.

The triple has the general format `<arch><sub>-<vendor>-<sys>-<abi>`, where:

- `arch` = `x86`, `arm`, `thumb`, `mips`, etc.
- `sub` = for ex. on ARM: `v5`, `v6m`, `v7a`, `v7m`, etc.
- `vendor` = `pc`, `apple`, `nvidia`, `ibm`, etc.
- `sys` = `none`, `linux`, `win32`, `darwin`, `cuda`, etc.
- `abi` = `eabi`, `gnu`, `android`, `macho`, `elf`, etc.

The sub-architecture options are available for their own architectures, of course, so "x86v7a" doesn't make sense. The vendor needs to be specified only if there's a relevant change, for instance between PC and Apple. Most of the time it can be omitted (and Unknown) will be assumed, which sets the defaults for the specified architecture. The system name is generally the OS (linux, darwin), but could be special like the bare-metal "none".

When a parameter is not important, it can be omitted, or you can choose `unknown` and the defaults will be used. If you choose a parameter that Clang doesn't know, like `blerg`, it'll ignore and assume `unknown`, which is not always desired, so be careful.

Finally, the ABI option is something that will pick default CPU/FPU, define the specific behaviour of your code (PCS, extensions), and also choose the correct library calls, etc.

CPU, FPU, ABI

Once your target is specified, it's time to pick the hardware you'll be compiling to. For every architecture, a default set of CPU/FPU/ABI will be chosen, so you'll almost always have to change it via flags.

Typical flags include:

- `-mcpu=<cpu-name>`, like x86-64, swift, cortex-a15
- `-mfpu=<fpu-name>`, like SSE3, NEON, controlling the FP unit available
- `-mfloat-abi=<fabi>`, like soft, hard, controlling which registers to use for floating-point

The default is normally the common denominator, so that Clang doesn't generate code that breaks. But that also means you won't get the best code for your specific hardware, which may mean orders of magnitude slower than you expect.

For example, if your target is `arm-none-eabi`, the default CPU will be `arm7tdmi` using soft float, which is extremely slow on modern cores, whereas if your triple is `armv7a-none-eabi`, it'll be Cortex-A8 with NEON, but still using soft-float, which is much better, but still not great.

Toolchain Options

There are three main options to control access to your cross-compiler: `--sysroot`, `-I`, and `-L`. The two last ones are well known, but they're particularly important for additional libraries and headers that are specific to your target.

There are two main ways to have a cross-compiler:

1. When you have extracted your cross-compiler from a zip file into a directory, you have to use `--sysroot=<path>`. The path is the root directory where you have unpacked your file, and Clang will look for the directories `bin`, `lib`, `include` in there.

   In this case, your setup should be pretty much done (if no additional headers or libraries are needed), as Clang will find all binaries it needs (assembler, linker, etc) in there.

2. When you have installed via a package manager (modern Linux distributions have cross-compiler packages available), make sure the target triple you set is *also* the prefix of your cross-compiler toolchain.

   In this case, Clang will find the other binaries (assembler, linker), but not always where the target headers and libraries are. People add system-specific clues to Clang often, but as things change, it's more likely that it won't find than the other way around.

   So, here, you'll be a lot safer if you specify the include/library directories manually (via `-I` and `-L`).

Target-Specific Libraries

All libraries that you compile as part of your build will be cross-compiled to your target, and your build system will probably find them in the right place. But all dependencies that are normally checked against (like `libxml` or `libz` etc) will match against the host platform, not the target.

So, if the build system is not aware that you want to cross-compile your code, it will get every dependency wrong, and your compilation will fail during build time, not configure time.

Also, finding the libraries for your target are not as easy as for your host machine. There aren't many cross-libraries available as packages to most OS's, so you'll have to either cross-compile them from source, or download the package for your target platform, extract the libraries and headers, put them in specific directories and add `-I` and `-L` pointing to them.

Also, some libraries have different dependencies on different targets, so configuration tools to find dependencies in the host can get the list wrong for the target platform. This means that the configuration of your build can get things wrong when setting their own library paths, and you'll have to augment it via additional flags (configure, Make, CMake, etc).

Multilibs

When you want to cross-compile to more than one configuration, for example hard-float-ARM and soft-float-ARM, you'll have to have multiple copies of your libraries and (possibly) headers.

Some Linux distributions have support for Multilib, which handle that for you in an easier way, but if you're not careful and, for instance, forget to specify `-ccc-gcc-name armv7l-linux-gnueabihf-gcc` (which uses hard-float), Clang will pick the `armv7l-linux-gnueabi-ld` (which uses soft-float) and linker errors will happen.

The same is true if you're compiling for different ABIs, like `gnueabi` and `androideabi`, and might even link and run, but produce run-time errors, which are much harder to track down and fix.

Thread Safety Analysis

Introduction

Clang Thread Safety Analysis is a C++ language extension which warns about potential race conditions in code. The analysis is completely static (i.e. compile-time); there is no run-time overhead. The analysis is still under active development, but it is mature enough to be deployed in an industrial setting. It is being developed by Google, in collaboration with CERT/SEI, and is used extensively in Google's internal code base.

Thread safety analysis works very much like a type system for multi-threaded programs. In addition to declaring the *type* of data (e.g. `int`, `float`, etc.), the programmer can (optionally) declare how access to that data is controlled in a multi-threaded environment. For example, if `foo` is *guarded by* the mutex `mu`, then the analysis will issue a warning whenever a piece of code reads or writes to `foo` without first locking `mu`. Similarly, if there are particular routines that should only be called by the GUI thread, then the analysis will warn if other threads call those routines.

Getting Started

```
#include "mutex.h"

class BankAccount {
private:
  Mutex mu;
  int   balance GUARDED_BY(mu);

  void depositImpl(int amount) {
    balance += amount;       // WARNING! Cannot write balance without locking mu.
  }

  void withdrawImpl(int amount) REQUIRES(mu) {
    balance -= amount;       // OK. Caller must have locked mu.
  }

public:
  void withdraw(int amount) {
    mu.Lock();
    withdrawImpl(amount);    // OK.  We've locked mu.
  }                          // WARNING!  Failed to unlock mu.

  void transferFrom(BankAccount& b, int amount) {
    mu.Lock();
    b.withdrawImpl(amount);  // WARNING!  Calling withdrawImpl() requires locking b.
↪mu.
```

```
    depositImpl(amount);      // OK.  depositImpl() has no requirements.
    mu.Unlock();
  }
};
```

This example demonstrates the basic concepts behind the analysis. The `GUARDED_BY` attribute declares that a thread must lock `mu` before it can read or write to `balance`, thus ensuring that the increment and decrement operations are atomic. Similarly, `REQUIRES` declares that the calling thread must lock `mu` before calling `withdrawImpl`. Because the caller is assumed to have locked `mu`, it is safe to modify `balance` within the body of the method.

The `depositImpl()` method does not have `REQUIRES`, so the analysis issues a warning. Thread safety analysis is not inter-procedural, so caller requirements must be explicitly declared. There is also a warning in `transferFrom()`, because although the method locks `this->mu`, it does not lock `b.mu`. The analysis understands that these are two separate mutexes, in two different objects.

Finally, there is a warning in the `withdraw()` method, because it fails to unlock `mu`. Every lock must have a corresponding unlock, and the analysis will detect both double locks, and double unlocks. A function is allowed to acquire a lock without releasing it, (or vice versa), but it must be annotated as such (using `ACQUIRE`/`RELEASE`).

Running The Analysis

To run the analysis, simply compile with the `-Wthread-safety` flag, e.g.

```
clang -c -Wthread-safety example.cpp
```

Note that this example assumes the presence of a suitably annotated *mutex.h* that declares which methods perform locking, unlocking, and so on.

Basic Concepts: Capabilities

Thread safety analysis provides a way of protecting *resources* with *capabilities*. A resource is either a data member, or a function/method that provides access to some underlying resource. The analysis ensures that the calling thread cannot access the *resource* (i.e. call the function, or read/write the data) unless it has the *capability* to do so.

Capabilities are associated with named C++ objects which declare specific methods to acquire and release the capability. The name of the object serves to identify the capability. The most common example is a mutex. For example, if `mu` is a mutex, then calling `mu.Lock()` causes the calling thread to acquire the capability to access data that is protected by `mu`. Similarly, calling `mu.Unlock()` releases that capability.

A thread may hold a capability either *exclusively* or *shared*. An exclusive capability can be held by only one thread at a time, while a shared capability can be held by many threads at the same time. This mechanism enforces a multiple-reader, single-writer pattern. Write operations to protected data require exclusive access, while read operations require only shared access.

At any given moment during program execution, a thread holds a specific set of capabilities (e.g. the set of mutexes that it has locked.) These act like keys or tokens that allow the thread to access a given resource. Just like physical security keys, a thread cannot make copy of a capability, nor can it destroy one. A thread can only release a capability to another thread, or acquire one from another thread. The annotations are deliberately agnostic about the exact mechanism used to acquire and release capabilities; it assumes that the underlying implementation (e.g. the Mutex implementation) does the handoff in an appropriate manner.

The set of capabilities that are actually held by a given thread at a given point in program execution is a run-time concept. The static analysis works by calculating an approximation of that set, called the *capability environment*. The capability environment is calculated for every program point, and describes the set of capabilities that are statically known to be held, or not held, at that particular point. This environment is a conservative approximation of the full set of capabilities that will actually held by a thread at run-time.

Reference Guide

The thread safety analysis uses attributes to declare threading constraints. Attributes must be attached to named declarations, such as classes, methods, and data members. Users are *strongly advised* to define macros for the various attributes; example definitions can be found in *mutex.h*, below. The following documentation assumes the use of macros.

For historical reasons, prior versions of thread safety used macro names that were very lock-centric. These macros have since been renamed to fit a more general capability model. The prior names are still in use, and will be mentioned under the tag *previously* where appropriate.

GUARDED_BY(c) and PT_GUARDED_BY(c)

GUARDED_BY is an attribute on data members, which declares that the data member is protected by the given capability. Read operations on the data require shared access, while write operations require exclusive access.

PT_GUARDED_BY is similar, but is intended for use on pointers and smart pointers. There is no constraint on the data member itself, but the *data that it points to* is protected by the given capability.

```
Mutex mu;
int *p1             GUARDED_BY(mu);
int *p2             PT_GUARDED_BY(mu);
unique_ptr<int> p3  PT_GUARDED_BY(mu);

void test() {
  p1 = 0;             // Warning!

  *p2 = 42;           // Warning!
  p2 = new int;       // OK.

  *p3 = 42;           // Warning!
  p3.reset(new int);  // OK.
}
```

REQUIRES(...), REQUIRES_SHARED(...)

Previously: EXCLUSIVE_LOCKS_REQUIRED, SHARED_LOCKS_REQUIRED

REQUIRES is an attribute on functions or methods, which declares that the calling thread must have exclusive access to the given capabilities. More than one capability may be specified. The capabilities must be held on entry to the function, *and must still be held on exit*.

REQUIRES_SHARED is similar, but requires only shared access.

```
Mutex mu1, mu2;
int a GUARDED_BY(mu1);
int b GUARDED_BY(mu2);

void foo() REQUIRES(mu1, mu2) {
  a = 0;
  b = 0;
}

void test() {
  mu1.Lock();
  foo();          // Warning!  Requires mu2.
```

```
  mu1.Unlock();
}
```

ACQUIRE(...), ACQUIRE_SHARED(...), RELEASE(...), RELEASE_SHARED(...)

Previously: EXCLUSIVE_LOCK_FUNCTION, SHARED_LOCK_FUNCTION, UNLOCK_FUNCTION

ACQUIRE is an attribute on functions or methods, which declares that the function acquires a capability, but does not release it. The caller must not hold the given capability on entry, and it will hold the capability on exit. ACQUIRE_SHARED is similar.

RELEASE and RELEASE_SHARED declare that the function releases the given capability. The caller must hold the capability on entry, and will no longer hold it on exit. It does not matter whether the given capability is shared or exclusive.

```
Mutex mu;
MyClass myObject GUARDED_BY(mu);

void lockAndInit() ACQUIRE(mu) {
  mu.Lock();
  myObject.init();
}

void cleanupAndUnlock() RELEASE(mu) {
  myObject.cleanup();
}                          // Warning!  Need to unlock mu.

void test() {
  lockAndInit();
  myObject.doSomething();
  cleanupAndUnlock();
  myObject.doSomething();  // Warning, mu is not locked.
}
```

If no argument is passed to ACQUIRE or RELEASE, then the argument is assumed to be this, and the analysis will not check the body of the function. This pattern is intended for use by classes which hide locking details behind an abstract interface. For example:

```
template <class T>
class CAPABILITY("mutex") Container {
private:
  Mutex mu;
  T* data;

public:
  // Hide mu from public interface.
  void Lock()   ACQUIRE() { mu.Lock(); }
  void Unlock() RELEASE() { mu.Unlock(); }

  T& getElem(int i) { return data[i]; }
};

void test() {
  Container<int> c;
  c.Lock();
  int i = c.getElem(0);
```

```
  c.Unlock();
}
```

EXCLUDES(...)

Previously: LOCKS_EXCLUDED

EXCLUDES is an attribute on functions or methods, which declares that the caller must *not* hold the given capabilities. This annotation is used to prevent deadlock. Many mutex implementations are not re-entrant, so deadlock can occur if the function acquires the mutex a second time.

```
Mutex mu;
int a GUARDED_BY(mu);

void clear() EXCLUDES(mu) {
  mu.Lock();
  a = 0;
  mu.Unlock();
}

void reset() {
  mu.Lock();
  clear();     // Warning!  Caller cannot hold 'mu'.
  mu.Unlock();
}
```

Unlike REQUIRES, EXCLUDES is optional. The analysis will not issue a warning if the attribute is missing, which can lead to false negatives in some cases. This issue is discussed further in *Negative Capabilities*.

NO_THREAD_SAFETY_ANALYSIS

NO_THREAD_SAFETY_ANALYSIS is an attribute on functions or methods, which turns off thread safety checking for that method. It provides an escape hatch for functions which are either (1) deliberately thread-unsafe, or (2) are thread-safe, but too complicated for the analysis to understand. Reasons for (2) will be described in the *Known Limitations*, below.

```
class Counter {
  Mutex mu;
  int a GUARDED_BY(mu);

  void unsafeIncrement() NO_THREAD_SAFETY_ANALYSIS { a++; }
};
```

Unlike the other attributes, NO_THREAD_SAFETY_ANALYSIS is not part of the interface of a function, and should thus be placed on the function definition (in the .cc or .cpp file) rather than on the function declaration (in the header).

RETURN_CAPABILITY(c)

Previously: LOCK_RETURNED

RETURN_CAPABILITY is an attribute on functions or methods, which declares that the function returns a reference to the given capability. It is used to annotate getter methods that return mutexes.

```
class MyClass {
private:
  Mutex mu;
  int a GUARDED_BY(mu);

public:
  Mutex* getMu() RETURN_CAPABILITY(mu) { return &mu; }

  // analysis knows that getMu() == mu
  void clear() REQUIRES(getMu()) { a = 0; }
};
```

ACQUIRED_BEFORE(...), ACQUIRED_AFTER(...)

ACQUIRED_BEFORE and ACQUIRED_AFTER are attributes on member declarations, specifically declarations of mutexes or other capabilities. These declarations enforce a particular order in which the mutexes must be acquired, in order to prevent deadlock.

```
Mutex m1;
Mutex m2 ACQUIRED_AFTER(m1);

// Alternative declaration
// Mutex m2;
// Mutex m1 ACQUIRED_BEFORE(m2);

void foo() {
  m2.Lock();
  m1.Lock();  // Warning!  m2 must be acquired after m1.
  m1.Unlock();
  m2.Unlock();
}
```

CAPABILITY(<string>)

Previously: LOCKABLE

CAPABILITY is an attribute on classes, which specifies that objects of the class can be used as a capability. The string argument specifies the kind of capability in error messages, e.g. "mutex". See the Container example given above, or the Mutex class in *mutex.h*.

SCOPED_CAPABILITY

Previously: SCOPED_LOCKABLE

SCOPED_CAPABILITY is an attribute on classes that implement RAII-style locking, in which a capability is acquired in the constructor, and released in the destructor. Such classes require special handling because the constructor and destructor refer to the capability via different names; see the MutexLocker class in *mutex.h*, below.

TRY_ACQUIRE(<bool>, ...), TRY_ACQUIRE_SHARED(<bool>, ...)

Previously: EXCLUSIVE_TRYLOCK_FUNCTION, SHARED_TRYLOCK_FUNCTION

These are attributes on a function or method that tries to acquire the given capability, and returns a boolean value indicating success or failure. The first argument must be `true` or `false`, to specify which return value indicates success, and the remaining arguments are interpreted in the same way as `ACQUIRE`. See *mutex.h*, below, for example uses.

ASSERT_CAPABILITY(...) and ASSERT_SHARED_CAPABILITY(...)

Previously: `ASSERT_EXCLUSIVE_LOCK`, `ASSERT_SHARED_LOCK`

These are attributes on a function or method that does a run-time test to see whether the calling thread holds the given capability. The function is assumed to fail (no return) if the capability is not held. See *mutex.h*, below, for example uses.

GUARDED_VAR and PT_GUARDED_VAR

Use of these attributes has been deprecated.

Warning flags

- `-Wthread-safety`: Umbrella flag which turns on the following three:
  - `-Wthread-safety-attributes`: Sanity checks on attribute syntax.
  - `-Wthread-safety-analysis`: The core analysis.
  - **`-Wthread-safety-precise`: Requires that mutex expressions match precisely.** This warning can be disabled for code which has a lot of aliases.
  - `-Wthread-safety-reference`: Checks when guarded members are passed by reference.

Negative Capabilities are an experimental feature, which are enabled with:

- `-Wthread-safety-negative`: Negative capabilities. Off by default.

When new features and checks are added to the analysis, they can often introduce additional warnings. Those warnings are initially released as *beta* warnings for a period of time, after which they are migrated into the standard analysis.

- `-Wthread-safety-beta`: New features. Off by default.

Negative Capabilities

Thread Safety Analysis is designed to prevent both race conditions and deadlock. The GUARDED_BY and REQUIRES attributes prevent race conditions, by ensuring that a capability is held before reading or writing to guarded data, and the EXCLUDES attribute prevents deadlock, by making sure that a mutex is *not* held.

However, EXCLUDES is an optional attribute, and does not provide the same safety guarantee as REQUIRES. In particular:

- A function which acquires a capability does not have to exclude it.
- A function which calls a function that excludes a capability does not have transitively exclude that capability.

As a result, EXCLUDES can easily produce false negatives:

```
class Foo {
  Mutex mu;

  void foo() {
```

```
    mu.Lock();
    bar();            // No warning.
    baz();            // No warning.
    mu.Unlock();
  }

  void bar() {        // No warning.  (Should have EXCLUDES(mu)).
    mu.Lock();
    // ...
    mu.Unlock();
  }

  void baz() {
    bif();            // No warning.  (Should have EXCLUDES(mu)).
  }

  void bif() EXCLUDES(mu);
};
```

Negative requirements are an alternative EXCLUDES that provide a stronger safety guarantee. A negative requirement uses the REQUIRES attribute, in conjunction with the `!` operator, to indicate that a capability should *not* be held.

For example, using `REQUIRES(!mu)` instead of `EXCLUDES(mu)` will produce the appropriate warnings:

```
class FooNeg {
  Mutex mu;

  void foo() REQUIRES(!mu) {   // foo() now requires !mu.
    mu.Lock();
    bar();
    baz();
    mu.Unlock();
  }

  void bar() {
    mu.Lock();        // WARNING!  Missing REQUIRES(!mu).
    // ...
    mu.Unlock();
  }

  void baz() {
    bif();            // WARNING!  Missing REQUIRES(!mu).
  }

  void bif() REQUIRES(!mu);
};
```

Negative requirements are an experimental feature which is off by default, because it will produce many warnings in existing code. It can be enabled by passing `-Wthread-safety-negative`.

Frequently Asked Questions

17. Should I put attributes in the header file, or in the .cc/.cpp/.cxx file?

(A) Attributes are part of the formal interface of a function, and should always go in the header, where they are visible to anything that includes the header. Attributes in the .cpp file are not visible outside of the immediate translation unit, which leads to false negatives and false positives.

17. "*Mutex is not locked on every path through here?*" What does that mean?

    1. See *No conditionally held locks.*, below.

Known Limitations

Lexical scope

Thread safety attributes contain ordinary C++ expressions, and thus follow ordinary C++ scoping rules. In particular, this means that mutexes and other capabilities must be declared before they can be used in an attribute. Use-before-declaration is okay within a single class, because attributes are parsed at the same time as method bodies. (C++ delays parsing of method bodies until the end of the class.) However, use-before-declaration is not allowed between classes, as illustrated below.

```
class Foo;

class Bar {
  void bar(Foo* f) REQUIRES(f->mu);  // Error: mu undeclared.
};

class Foo {
  Mutex mu;
};
```

Private Mutexes

Good software engineering practice dictates that mutexes should be private members, because the locking mechanism used by a thread-safe class is part of its internal implementation. However, private mutexes can sometimes leak into the public interface of a class. Thread safety attributes follow normal C++ access restrictions, so if `mu` is a private member of `c`, then it is an error to write `c.mu` in an attribute.

One workaround is to (ab)use the `RETURN_CAPABILITY` attribute to provide a public *name* for a private mutex, without actually exposing the underlying mutex. For example:

```
class MyClass {
private:
  Mutex mu;

public:
  // For thread safety analysis only.  Does not actually return mu.
  Mutex* getMu() RETURN_CAPABILITY(mu) { return 0; }

  void doSomething() REQUIRES(mu);
};

void doSomethingTwice(MyClass& c) REQUIRES(c.getMu()) {
  // The analysis thinks that c.getMu() == c.mu
  c.doSomething();
  c.doSomething();
}
```

In the above example, `doSomethingTwice()` is an external routine that requires `c.mu` to be locked, which cannot be declared directly because `mu` is private. This pattern is discouraged because it violates encapsulation, but it is sometimes necessary, especially when adding annotations to an existing code base. The workaround is to define `getMu()` as a fake getter method, which is provided only for the benefit of thread safety analysis.

No conditionally held locks.

The analysis must be able to determine whether a lock is held, or not held, at every program point. Thus, sections of code where a lock *might be held* will generate spurious warnings (false positives). For example:

```
void foo() {
  bool b = needsToLock();
  if (b) mu.Lock();
  ...  // Warning!  Mutex 'mu' is not held on every path through here.
  if (b) mu.Unlock();
}
```

No checking inside constructors and destructors.

The analysis currently does not do any checking inside constructors or destructors. In other words, every constructor and destructor is treated as if it was annotated with `NO_THREAD_SAFETY_ANALYSIS`. The reason for this is that during initialization, only one thread typically has access to the object which is being initialized, and it is thus safe (and common practice) to initialize guarded members without acquiring any locks. The same is true of destructors.

Ideally, the analysis would allow initialization of guarded members inside the object being initialized or destroyed, while still enforcing the usual access restrictions on everything else. However, this is difficult to enforce in practice, because in complex pointer-based data structures, it is hard to determine what data is owned by the enclosing object.

No inlining.

Thread safety analysis is strictly intra-procedural, just like ordinary type checking. It relies only on the declared attributes of a function, and will not attempt to inline any method calls. As a result, code such as the following will not work:

```
template<class T>
class AutoCleanup {
  T* object;
  void (T::*mp)();

public:
  AutoCleanup(T* obj, void (T::*imp)()) : object(obj), mp(imp) { }
  ~AutoCleanup() { (object->*mp)(); }
};

Mutex mu;
void foo() {
  mu.Lock();
  AutoCleanup<Mutex>(&mu, &Mutex::Unlock);
  // ...
}  // Warning, mu is not unlocked.
```

In this case, the destructor of `Autocleanup` calls `mu.Unlock()`, so the warning is bogus. However, thread safety analysis cannot see the unlock, because it does not attempt to inline the destructor. Moreover, there is no way to annotate the destructor, because the destructor is calling a function that is not statically known. This pattern is simply not supported.

No alias analysis.

The analysis currently does not track pointer aliases. Thus, there can be false positives if two pointers both point to the same mutex.

```
class MutexUnlocker {
  Mutex* mu;

public:
  MutexUnlocker(Mutex* m) RELEASE(m) : mu(m)  { mu->Unlock(); }
  ~MutexUnlocker() ACQUIRE(mu) { mu->Lock(); }
};

Mutex mutex;
void test() REQUIRES(mutex) {
  {
    MutexUnlocker munl(&mutex);  // unlocks mutex
    doSomeIO();
  }                              // Warning: locks munl.mu
}
```

The MutexUnlocker class is intended to be the dual of the MutexLocker class, defined in *mutex.h*. However, it doesn't work because the analysis doesn't know that munl.mu == mutex. The SCOPED_CAPABILITY attribute handles aliasing for MutexLocker, but does so only for that particular pattern.

ACQUIRED_BEFORE(...) and ACQUIRED_AFTER(...) are currently unimplemented.

To be fixed in a future update.

mutex.h

Thread safety analysis can be used with any threading library, but it does require that the threading API be wrapped in classes and methods which have the appropriate annotations. The following code provides `mutex.h` as an example; these methods should be filled in to call the appropriate underlying implementation.

```
#ifndef THREAD_SAFETY_ANALYSIS_MUTEX_H
#define THREAD_SAFETY_ANALYSIS_MUTEX_H

// Enable thread safety attributes only with clang.
// The attributes can be safely erased when compiling with other compilers.
#if defined(__clang__) && (!defined(SWIG))
#define THREAD_ANNOTATION_ATTRIBUTE__(x)   __attribute__((x))
#else
#define THREAD_ANNOTATION_ATTRIBUTE__(x)   // no-op
#endif

#define THREAD_ANNOTATION_ATTRIBUTE__(x)   __attribute__((x))

#define CAPABILITY(x) \
  THREAD_ANNOTATION_ATTRIBUTE__(capability(x))

#define SCOPED_CAPABILITY \
  THREAD_ANNOTATION_ATTRIBUTE__(scoped_lockable)

#define GUARDED_BY(x) \
```

```
  THREAD_ANNOTATION_ATTRIBUTE__(guarded_by(x))

#define PT_GUARDED_BY(x) \
  THREAD_ANNOTATION_ATTRIBUTE__(pt_guarded_by(x))

#define ACQUIRED_BEFORE(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(acquired_before(__VA_ARGS__))

#define ACQUIRED_AFTER(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(acquired_after(__VA_ARGS__))

#define REQUIRES(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(requires_capability(__VA_ARGS__))

#define REQUIRES_SHARED(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(requires_shared_capability(__VA_ARGS__))

#define ACQUIRE(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(acquire_capability(__VA_ARGS__))

#define ACQUIRE_SHARED(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(acquire_shared_capability(__VA_ARGS__))

#define RELEASE(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(release_capability(__VA_ARGS__))

#define RELEASE_SHARED(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(release_shared_capability(__VA_ARGS__))

#define TRY_ACQUIRE(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(try_acquire_capability(__VA_ARGS__))

#define TRY_ACQUIRE_SHARED(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(try_acquire_shared_capability(__VA_ARGS__))

#define EXCLUDES(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(locks_excluded(__VA_ARGS__))

#define ASSERT_CAPABILITY(x) \
  THREAD_ANNOTATION_ATTRIBUTE__(assert_capability(x))

#define ASSERT_SHARED_CAPABILITY(x) \
  THREAD_ANNOTATION_ATTRIBUTE__(assert_shared_capability(x))

#define RETURN_CAPABILITY(x) \
  THREAD_ANNOTATION_ATTRIBUTE__(lock_returned(x))

#define NO_THREAD_SAFETY_ANALYSIS \
  THREAD_ANNOTATION_ATTRIBUTE__(no_thread_safety_analysis)


// Defines an annotated interface for mutexes.
// These methods can be implemented to use any internal mutex implementation.
class CAPABILITY("mutex") Mutex {
public:
  // Acquire/lock this mutex exclusively.  Only one thread can have exclusive
  // access at any one time.  Write operations to guarded data require an
  // exclusive lock.
```

```
  void Lock() ACQUIRE();

  // Acquire/lock this mutex for read operations, which require only a shared
  // lock.  This assumes a multiple-reader, single writer semantics.  Multiple
  // threads may acquire the mutex simultaneously as readers, but a writer
  // must wait for all of them to release the mutex before it can acquire it
  // exclusively.
  void ReaderLock() ACQUIRE_SHARED();

  // Release/unlock an exclusive mutex.
  void Unlock() RELEASE();

  // Release/unlock a shared mutex.
  void ReaderUnlock() RELEASE_SHARED();

  // Try to acquire the mutex.  Returns true on success, and false on failure.
  bool TryLock() TRY_ACQUIRE(true);

  // Try to acquire the mutex for read operations.
  bool ReaderTryLock() TRY_ACQUIRE_SHARED(true);

  // Assert that this mutex is currently held by the calling thread.
  void AssertHeld() ASSERT_CAPABILITY(this);

  // Assert that is mutex is currently held for read operations.
  void AssertReaderHeld() ASSERT_SHARED_CAPABILITY(this);

  // For negative capabilities.
  const Mutex& operator!() const { return *this; }
};


// MutexLocker is an RAII class that acquires a mutex in its constructor, and
// releases it in its destructor.
class SCOPED_CAPABILITY MutexLocker {
private:
  Mutex* mut;

public:
  MutexLocker(Mutex *mu) ACQUIRE(mu) : mut(mu) {
    mu->Lock();
  }
  ~MutexLocker() RELEASE() {
    mut->Unlock();
  }
};


#ifdef USE_LOCK_STYLE_THREAD_SAFETY_ATTRIBUTES
// The original version of thread safety analysis the following attribute
// definitions.  These use a lock-based terminology.  They are still in use
// by existing thread safety code, and will continue to be supported.

// Deprecated.
#define PT_GUARDED_VAR \
  THREAD_ANNOTATION_ATTRIBUTE__(pt_guarded)

// Deprecated.
```

```
#define GUARDED_VAR \
  THREAD_ANNOTATION_ATTRIBUTE__(guarded)

// Replaced by REQUIRES
#define EXCLUSIVE_LOCKS_REQUIRED(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(exclusive_locks_required(__VA_ARGS__))

// Replaced by REQUIRES_SHARED
#define SHARED_LOCKS_REQUIRED(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(shared_locks_required(__VA_ARGS__))

// Replaced by CAPABILITY
#define LOCKABLE \
  THREAD_ANNOTATION_ATTRIBUTE__(lockable)

// Replaced by SCOPED_CAPABILITY
#define SCOPED_LOCKABLE \
  THREAD_ANNOTATION_ATTRIBUTE__(scoped_lockable)

// Replaced by ACQUIRE
#define EXCLUSIVE_LOCK_FUNCTION(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(exclusive_lock_function(__VA_ARGS__))

// Replaced by ACQUIRE_SHARED
#define SHARED_LOCK_FUNCTION(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(shared_lock_function(__VA_ARGS__))

// Replaced by RELEASE and RELEASE_SHARED
#define UNLOCK_FUNCTION(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(unlock_function(__VA_ARGS__))

// Replaced by TRY_ACQUIRE
#define EXCLUSIVE_TRYLOCK_FUNCTION(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(exclusive_trylock_function(__VA_ARGS__))

// Replaced by TRY_ACQUIRE_SHARED
#define SHARED_TRYLOCK_FUNCTION(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(shared_trylock_function(__VA_ARGS__))

// Replaced by ASSERT_CAPABILITY
#define ASSERT_EXCLUSIVE_LOCK(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(assert_exclusive_lock(__VA_ARGS__))

// Replaced by ASSERT_SHARED_CAPABILITY
#define ASSERT_SHARED_LOCK(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(assert_shared_lock(__VA_ARGS__))

// Replaced by EXCLUDE_CAPABILITY.
#define LOCKS_EXCLUDED(...) \
  THREAD_ANNOTATION_ATTRIBUTE__(locks_excluded(__VA_ARGS__))

// Replaced by RETURN_CAPABILITY
#define LOCK_RETURNED(x) \
  THREAD_ANNOTATION_ATTRIBUTE__(lock_returned(x))

#endif  // USE_LOCK_STYLE_THREAD_SAFETY_ATTRIBUTES

#endif  // THREAD_SAFETY_ANALYSIS_MUTEX_H
```

AddressSanitizer

Introduction

AddressSanitizer is a fast memory error detector. It consists of a compiler instrumentation module and a run-time library. The tool can detect the following types of bugs:

- Out-of-bounds accesses to heap, stack and globals
- Use-after-free
- Use-after-return (to some extent)
- Double-free, invalid free
- Memory leaks (experimental)

Typical slowdown introduced by AddressSanitizer is **2x**.

How to build

Build LLVM/Clang with CMake.

Usage

Simply compile and link your program with `-fsanitize=address` flag. The AddressSanitizer run-time library should be linked to the final executable, so make sure to use `clang` (not `ld`) for the final link step. When linking shared libraries, the AddressSanitizer run-time is not linked, so `-Wl,-z,defs` may cause link errors (don't use it with AddressSanitizer). To get a reasonable performance add `-O1` or higher. To get nicer stack traces in error messages add `-fno-omit-frame-pointer`. To get perfect stack traces you may need to disable inlining (just use `-O1`) and tail call elimination (`-fno-optimize-sibling-calls`).

```
% cat example_UseAfterFree.cc
int main(int argc, char **argv) {
  int *array = new int[100];
  delete [] array;
  return array[argc];  // BOOM
}

# Compile and link
% clang -O1 -g -fsanitize=address -fno-omit-frame-pointer example_UseAfterFree.cc
```

or:

```
# Compile
% clang -O1 -g -fsanitize=address -fno-omit-frame-pointer -c example_UseAfterFree.cc
# Link
% clang -g -fsanitize=address example_UseAfterFree.o
```

If a bug is detected, the program will print an error message to stderr and exit with a non-zero exit code. AddressSanitizer exits on the first detected error. This is by design:

- This approach allows AddressSanitizer to produce faster and smaller generated code (both by ~5%).
- Fixing bugs becomes unavoidable. AddressSanitizer does not produce false alarms. Once a memory corruption occurs, the program is in an inconsistent state, which could lead to confusing results and potentially misleading subsequent reports.

If your process is sandboxed and you are running on OS X 10.10 or earlier, you will need to set `DYLD_INSERT_LIBRARIES` environment variable and point it to the ASan library that is packaged with the compiler used to build the executable. (You can find the library by searching for dynamic libraries with `asan` in their name.) If the environment variable is not set, the process will try to re-exec. Also keep in mind that when moving the executable to another machine, the ASan library will also need to be copied over.

Symbolizing the Reports

To make AddressSanitizer symbolize its output you need to set the `ASAN_SYMBOLIZER_PATH` environment variable to point to the `llvm-symbolizer` binary (or make sure `llvm-symbolizer` is in your `$PATH`):

```
% ASAN_SYMBOLIZER_PATH=/usr/local/bin/llvm-symbolizer ./a.out
==9442== ERROR: AddressSanitizer heap-use-after-free on address 0x7f7ddab8c084 at pc␣
↪0x403c8c bp 0x7fff87fb82d0 sp 0x7fff87fb82c8
READ of size 4 at 0x7f7ddab8c084 thread T0
    #0 0x403c8c in main example_UseAfterFree.cc:4
    #1 0x7f7ddabcac4d in __libc_start_main ??:0
0x7f7ddab8c084 is located 4 bytes inside of 400-byte region [0x7f7ddab8c080,
↪0x7f7ddab8c210)
freed by thread T0 here:
    #0 0x404704 in operator delete[](void*) ??:0
    #1 0x403c53 in main example_UseAfterFree.cc:4
```

```
    #2 0x7f7ddabcac4d in __libc_start_main ??:0
previously allocated by thread T0 here:
    #0 0x404544 in operator new[](unsigned long) ??:0
    #1 0x403c43 in main example_UseAfterFree.cc:2
    #2 0x7f7ddabcac4d in __libc_start_main ??:0
==9442== ABORTING
```

If that does not work for you (e.g. your process is sandboxed), you can use a separate script to symbolize the result offline (online symbolization can be force disabled by setting `ASAN_OPTIONS=symbolize=0`):

```
% ASAN_OPTIONS=symbolize=0 ./a.out 2> log
% projects/compiler-rt/lib/asan/scripts/asan_symbolize.py / < log | c++filt
==9442== ERROR: AddressSanitizer heap-use-after-free on address 0x7f7ddab8c084 at pc␣
↪0x403c8c bp 0x7fff87fb82d0 sp 0x7fff87fb82c8
READ of size 4 at 0x7f7ddab8c084 thread T0
    #0 0x403c8c in main example_UseAfterFree.cc:4
    #1 0x7f7ddabcac4d in __libc_start_main ??:0
...
```

Note that on OS X you may need to run `dsymutil` on your binary to have the file:line info in the AddressSanitizer reports.

Additional Checks

Initialization order checking

AddressSanitizer can optionally detect dynamic initialization order problems, when initialization of globals defined in one translation unit uses globals defined in another translation unit. To enable this check at runtime, you should set environment variable `ASAN_OPTIONS=check_initialization_order=1`.

Note that this option is not supported on OS X.

Memory leak detection

For more information on leak detector in AddressSanitizer, see *LeakSanitizer*. The leak detection is turned on by default on Linux; however, it is not yet supported on other platforms.

Issue Suppression

AddressSanitizer is not expected to produce false positives. If you see one, look again; most likely it is a true positive!

Suppressing Reports in External Libraries

Runtime interposition allows AddressSanitizer to find bugs in code that is not being recompiled. If you run into an issue in external libraries, we recommend immediately reporting it to the library maintainer so that it gets addressed. However, you can use the following suppression mechanism to unblock yourself and continue on with the testing. This suppression mechanism should only be used for suppressing issues in external code; it does not work on code recompiled with AddressSanitizer. To suppress errors in external libraries, set the `ASAN_OPTIONS` environment variable to point to a suppression file. You can either specify the full path to the file or the path of the file relative to the location of your executable.

```
ASAN_OPTIONS=suppressions=MyASan.supp
```

Use the following format to specify the names of the functions or libraries you want to suppress. You can see these in the error report. Remember that the narrower the scope of the suppression, the more bugs you will be able to catch.

```
interceptor_via_fun:NameOfCFunctionToSuppress
interceptor_via_fun:-[ClassName objCMethodToSuppress:]
interceptor_via_lib:NameOfTheLibraryToSuppress
```

Conditional Compilation with `__has_feature(address_sanitizer)`

In some cases one may need to execute different code depending on whether AddressSanitizer is enabled. *__has_feature* can be used for this purpose.

```
#if defined(__has_feature)
#  if __has_feature(address_sanitizer)
// code that builds only under AddressSanitizer
#  endif
#endif
```

Disabling Instrumentation with `__attribute__((no_sanitize("address")))`

Some code should not be instrumented by AddressSanitizer. One may use the function attribute `__attribute__((no_sanitize("address")))` (which has deprecated synonyms *no_sanitize_address* and *no_address_safety_analysis*) to disable instrumentation of a particular function. This attribute may not be supported by other compilers, so we suggest to use it together with `__has_feature(address_sanitizer)`.

Suppressing Errors in Recompiled Code (Blacklist)

AddressSanitizer supports `src` and `fun` entity types in *Sanitizer special case list*, that can be used to suppress error reports in the specified source files or functions. Additionally, AddressSanitizer introduces `global` and `type` entity types that can be used to suppress error reports for out-of-bound access to globals with certain names and types (you may only specify class or struct types).

You may use an `init` category to suppress reports about initialization-order problems happening in certain source files or with certain global variables.

```
# Suppress error reports for code in a file or in a function:
src:bad_file.cpp
# Ignore all functions with names containing MyFooBar:
fun:*MyFooBar*
# Disable out-of-bound checks for global:
global:bad_array
# Disable out-of-bound checks for global instances of a given class ...
type:Namespace::BadClassName
# ... or a given struct. Use wildcard to deal with anonymous namespace.
type:Namespace2::*::BadStructName
# Disable initialization-order checks for globals:
global:bad_init_global=init
type:*BadInitClassSubstring*=init
src:bad/init/files/*=init
```

Suppressing memory leaks

Memory leak reports produced by *LeakSanitizer* (if it is run as a part of AddressSanitizer) can be suppressed by a separate file passed as

```
LSAN_OPTIONS=suppressions=MyLSan.supp
```

which contains lines of the form *leak:<pattern>*. Memory leak will be suppressed if pattern matches any function name, source file name, or library name in the symbolized stack trace of the leak report. See full documentation for more details.

Limitations

- AddressSanitizer uses more real memory than a native run. Exact overhead depends on the allocations sizes. The smaller the allocations you make the bigger the overhead is.
- AddressSanitizer uses more stack memory. We have seen up to 3x increase.
- On 64-bit platforms AddressSanitizer maps (but not reserves) 16+ Terabytes of virtual address space. This means that tools like `ulimit` may not work as usually expected.
- Static linking is not supported.

Supported Platforms

AddressSanitizer is supported on:

- Linux i386/x86_64 (tested on Ubuntu 12.04)
- OS X 10.7 - 10.11 (i386/x86_64)
- iOS Simulator
- Android ARM
- FreeBSD i386/x86_64 (tested on FreeBSD 11-current)

Ports to various other platforms are in progress.

Current Status

AddressSanitizer is fully functional on supported platforms starting from LLVM 3.1. The test suite is integrated into CMake build and can be run with `make check-asan` command.

More Information

https://github.com/google/sanitizers/wiki/AddressSanitizer

ThreadSanitizer

Introduction

ThreadSanitizer is a tool that detects data races. It consists of a compiler instrumentation module and a run-time library. Typical slowdown introduced by ThreadSanitizer is about **5x-15x**. Typical memory overhead introduced by ThreadSanitizer is about **5x-10x**.

How to build

Build LLVM/Clang with CMake.

Supported Platforms

ThreadSanitizer is supported on Linux x86_64 (tested on Ubuntu 12.04). Support for other 64-bit architectures is possible, contributions are welcome. Support for 32-bit platforms is problematic and is not planned.

Usage

Simply compile and link your program with `-fsanitize=thread`. To get a reasonable performance add `-O1` or higher. Use `-g` to get file names and line numbers in the warning messages.

Example:

```
% cat projects/compiler-rt/lib/tsan/lit_tests/tiny_race.c
#include <pthread.h>
int Global;
void *Thread1(void *x) {
  Global = 42;
  return x;
}
int main() {
  pthread_t t;
  pthread_create(&t, NULL, Thread1, NULL);
  Global = 43;
  pthread_join(t, NULL);
  return Global;
}

$ clang -fsanitize=thread -g -O1 tiny_race.c
```

If a bug is detected, the program will print an error message to stderr. Currently, ThreadSanitizer symbolizes its output using an external `addr2line` process (this will be fixed in future).

```
% ./a.out
WARNING: ThreadSanitizer: data race (pid=19219)
  Write of size 4 at 0x7fcf47b21bc0 by thread T1:
    #0 Thread1 tiny_race.c:4 (exe+0x00000000a360)

  Previous write of size 4 at 0x7fcf47b21bc0 by main thread:
    #0 main tiny_race.c:10 (exe+0x00000000a3b4)

  Thread T1 (running) created at:
```

```
    #0 pthread_create tsan_interceptors.cc:705 (exe+0x00000000c790)
    #1 main tiny_race.c:9 (exe+0x00000000a3a4)
```

__has_feature(thread_sanitizer)

In some cases one may need to execute different code depending on whether ThreadSanitizer is enabled. *__has_feature* can be used for this purpose.

```
#if defined(__has_feature)
#  if __has_feature(thread_sanitizer)
// code that builds only under ThreadSanitizer
#  endif
#endif
```

__attribute__((no_sanitize_thread))

Some code should not be instrumented by ThreadSanitizer. One may use the function attribute *no_sanitize_thread* to disable instrumentation of plain (non-atomic) loads/stores in a particular function. ThreadSanitizer still instruments such functions to avoid false positives and provide meaningful stack traces. This attribute may not be supported by other compilers, so we suggest to use it together with `__has_feature(thread_sanitizer)`.

Blacklist

ThreadSanitizer supports `src` and `fun` entity types in *Sanitizer special case list*, that can be used to suppress data race reports in the specified source files or functions. Unlike functions marked with *no_sanitize_thread* attribute, blacklisted functions are not instrumented at all. This can lead to false positives due to missed synchronization via atomic operations and missed stack frames in reports.

Limitations

- ThreadSanitizer uses more real memory than a native run. At the default settings the memory overhead is 5x plus 1Mb per each thread. Settings with 3x (less accurate analysis) and 9x (more accurate analysis) overhead are also available.
- ThreadSanitizer maps (but does not reserve) a lot of virtual address space. This means that tools like `ulimit` may not work as usually expected.
- Libc/libstdc++ static linking is not supported.
- Non-position-independent executables are not supported. Therefore, the `fsanitize=thread` flag will cause Clang to act as though the `-fPIE` flag had been supplied if compiling without `-fPIC`, and as though the `-pie` flag had been supplied if linking an executable.

Current Status

ThreadSanitizer is in beta stage. It is known to work on large C++ programs using pthreads, but we do not promise anything (yet). C++11 threading is supported with llvm libc++. The test suite is integrated into CMake build and can be run with `make check-tsan` command.

We are actively working on enhancing the tool — stay tuned. Any help, especially in the form of minimized standalone tests is more than welcome.

More Information

https://github.com/google/sanitizers/wiki/ThreadSanitizerCppManual

MemorySanitizer

Introduction

MemorySanitizer is a detector of uninitialized reads. It consists of a compiler instrumentation module and a run-time library.

Typical slowdown introduced by MemorySanitizer is **3x**.

How to build

Build LLVM/Clang with CMake.

Usage

Simply compile and link your program with `-fsanitize=memory` flag. The MemorySanitizer run-time library should be linked to the final executable, so make sure to use `clang` (not `ld`) for the final link step. When linking shared libraries, the MemorySanitizer run-time is not linked, so `-Wl,-z,defs` may cause link errors (don't use it with MemorySanitizer). To get a reasonable performance add `-O1` or higher. To get meaninful stack traces in error messages add `-fno-omit-frame-pointer`. To get perfect stack traces you may need to disable inlining (just use `-O1`) and tail call elimination (`-fno-optimize-sibling-calls`).

```
% cat umr.cc
#include <stdio.h>

int main(int argc, char** argv) {
  int* a = new int[10];
  a[5] = 0;
  if (a[argc])
    printf("xx\n");
  return 0;
}

% clang -fsanitize=memory -fno-omit-frame-pointer -g -O2 umr.cc
```

If a bug is detected, the program will print an error message to stderr and exit with a non-zero exit code.

```
% ./a.out
WARNING: MemorySanitizer: use-of-uninitialized-value
    #0 0x7f45944b418a in main umr.cc:6
    #1 0x7f45938b676c in __libc_start_main libc-start.c:226
```

By default, MemorySanitizer exits on the first detected error. If you find the error report hard to understand, try enabling *origin tracking*.

__has_feature(memory_sanitizer)

In some cases one may need to execute different code depending on whether MemorySanitizer is enabled. *__has_feature* can be used for this purpose.

```
#if defined(__has_feature)
#  if __has_feature(memory_sanitizer)
// code that builds only under MemorySanitizer
#  endif
#endif
```

__attribute__((no_sanitize_memory))

Some code should not be checked by MemorySanitizer. One may use the function attribute *no_sanitize_memory* to disable uninitialized checks in a particular function. MemorySanitizer may still instrument such functions to avoid false positives. This attribute may not be supported by other compilers, so we suggest to use it together with `__has_feature(memory_sanitizer)`.

Blacklist

MemorySanitizer supports `src` and `fun` entity types in *Sanitizer special case list*, that can be used to relax MemorySanitizer checks for certain source files and functions. All "Use of uninitialized value" warnings will be suppressed and all values loaded from memory will be considered fully initialized.

Report symbolization

MemorySanitizer uses an external symbolizer to print files and line numbers in reports. Make sure that `llvm-symbolizer` binary is in `PATH`, or set environment variable `MSAN_SYMBOLIZER_PATH` to point to it.

Origin Tracking

MemorySanitizer can track origins of uninitialized values, similar to Valgrind's –track-origins option. This feature is enabled by `-fsanitize-memory-track-origins=2` (or simply `-fsanitize-memory-track-origins`) Clang option. With the code from the example above,

```
% cat umr2.cc
#include <stdio.h>

int main(int argc, char** argv) {
  int* a = new int[10];
  a[5] = 0;
  volatile int b = a[argc];
  if (b)
    printf("xx\n");
  return 0;
}

% clang -fsanitize=memory -fsanitize-memory-track-origins=2 -fno-omit-frame-pointer -
↪g -O2 umr2.cc
% ./a.out
WARNING: MemorySanitizer: use-of-uninitialized-value
    #0 0x7f7893912f0b in main umr2.cc:7
    #1 0x7f789249b76c in __libc_start_main libc-start.c:226

  Uninitialized value was stored to memory at
    #0 0x7f78938b5c25 in __msan_chain_origin msan.cc:484
    #1 0x7f7893912ecd in main umr2.cc:6

  Uninitialized value was created by a heap allocation
    #0 0x7f7893901cbd in operator new[](unsigned long) msan_new_delete.cc:44
    #1 0x7f7893912e06 in main umr2.cc:4
```

By default, MemorySanitizer collects both allocation points and all intermediate stores the uninitialized value went through. Origin tracking has proved to be very useful for debugging MemorySanitizer reports. It slows down program execution by a factor of 1.5x-2x on top of the usual MemorySanitizer slowdown and increases memory overhead.

Clang option `-fsanitize-memory-track-origins=1` enables a slightly faster mode when MemorySanitizer collects only allocation points but not intermediate stores.

Use-after-destruction detection

You can enable experimental use-after-destruction detection in MemorySanitizer. After invocation of the destructor, the object will be considered no longer readable, and using underlying memory will lead to error reports in runtime.

This feature is still experimental, in order to enable it at runtime you need to:

1. Pass addition Clang option `-fsanitize-memory-use-after-dtor` during compilation.
2. Set environment variable *MSAN_OPTIONS=poison_in_dtor=1* before running the program.

Handling external code

MemorySanitizer requires that all program code is instrumented. This also includes any libraries that the program depends on, even libc. Failing to achieve this may result in false reports. For the same reason you may need to replace all inline assembly code that writes to memory with a pure C/C++ code.

Full MemorySanitizer instrumentation is very difficult to achieve. To make it easier, MemorySanitizer runtime library includes 70+ interceptors for the most common libc functions. They make it possible to run MemorySanitizer-instrumented programs linked with uninstrumented libc. For example, the authors were able to bootstrap MemorySanitizer-instrumented Clang compiler by linking it with self-built instrumented libc++ (as a replacement for libstdc++).

Supported Platforms

MemorySanitizer is supported on Linux x86_64/MIPS64/AArch64.

Limitations

- MemorySanitizer uses 2x more real memory than a native run, 3x with origin tracking.
- MemorySanitizer maps (but not reserves) 64 Terabytes of virtual address space. This means that tools like `ulimit` may not work as usually expected.
- Static linking is not supported.
- Older versions of MSan (LLVM 3.7 and older) didn't work with non-position-independent executables, and could fail on some Linux kernel versions with disabled ASLR. Refer to documentation for older versions for more details.

Current Status

MemorySanitizer is known to work on large real-world programs (like Clang/LLVM itself) that can be recompiled from source, including all dependent libraries.

More Information

https://github.com/google/sanitizers/wiki/MemorySanitizer

UndefinedBehaviorSanitizer

Introduction

UndefinedBehaviorSanitizer (UBSan) is a fast undefined behavior detector. UBSan modifies the program at compile-time to catch various kinds of undefined behavior during program execution, for example:

- Using misaligned or null pointer
- Signed integer overflow
- Conversion to, from, or between floating-point types which would overflow the destination

See the full list of available *checks* below.

UBSan has an optional run-time library which provides better error reporting. The checks have small runtime cost and no impact on address space layout or ABI.

How to build

Build LLVM/Clang with CMake.

Usage

Use `clang++` to compile and link your program with `-fsanitize=undefined` flag. Make sure to use `clang++` (not `ld`) as a linker, so that your executable is linked with proper UBSan runtime libraries. You can use `clang` instead of `clang++` if you're compiling/linking C code.

```
% cat test.cc
int main(int argc, char **argv) {
  int k = 0x7fffffff;
  k += argc;
  return 0;
}
% clang++ -fsanitize=undefined test.cc
% ./a.out
test.cc:3:5: runtime error: signed integer overflow: 2147483647 + 1 cannot be␣
↪represented in type 'int'
```

You can enable only a subset of *checks* offered by UBSan, and define the desired behavior for each kind of check:

- print a verbose error report and continue execution (default);
- print a verbose error report and exit the program;
- execute a trap instruction (doesn't require UBSan run-time support).

For example if you compile/link your program as:

```
% clang++ -fsanitize=signed-integer-overflow,null,alignment -fno-sanitize-
↪recover=null -fsanitize-trap=alignment
```

the program will continue execution after signed integer overflows, exit after the first invalid use of a null pointer, and trap after the first use of misaligned pointer.

Availablle checks

Available checks are:

- `-fsanitize=alignment`: Use of a misaligned pointer or creation of a misaligned reference.
- `-fsanitize=bool`: Load of a `bool` value which is neither `true` nor `false`.
- `-fsanitize=bounds`: Out of bounds array indexing, in cases where the array bound can be statically determined.
- `-fsanitize=enum`: Load of a value of an enumerated type which is not in the range of representable values for that enumerated type.
- `-fsanitize=float-cast-overflow`: Conversion to, from, or between floating-point types which would overflow the destination.
- `-fsanitize=float-divide-by-zero`: Floating point division by zero.
- `-fsanitize=function`: Indirect call of a function through a function pointer of the wrong type (Linux, C++ and x86/x86_64 only).
- `-fsanitize=integer-divide-by-zero`: Integer division by zero.
- `-fsanitize=nonnull-attribute`: Passing null pointer as a function parameter which is declared to never be null.
- `-fsanitize=null`: Use of a null pointer or creation of a null reference.
- `-fsanitize=object-size`: An attempt to potentially use bytes which the optimizer can determine are not part of the object being accessed. This will also detect some types of undefined behavior that may not directly access memory, but are provably incorrect given the size of the objects involved, such as invalid downcasts and calling methods on invalid pointers. These checks are made in terms of `__builtin_object_size`, and consequently may be able to detect more problems at higher optimization levels.
- `-fsanitize=return`: In C++, reaching the end of a value-returning function without returning a value.
- `-fsanitize=returns-nonnull-attribute`: Returning null pointer from a function which is declared to never return null.
- `-fsanitize=shift`: Shift operators where the amount shifted is greater or equal to the promoted bit-width of the left hand side or less than zero, or where the left hand side is negative. For a signed left shift, also checks for signed overflow in C, and for unsigned overflow in C++. You can use `-fsanitize=shift-base` or `-fsanitize=shift-exponent` to check only left-hand side or right-hand side of shift operation, respectively.
- `-fsanitize=signed-integer-overflow`: Signed integer overflow, including all the checks added by `-ftrapv`, and checking for overflow in signed division (`INT_MIN / -1`).
- `-fsanitize=unreachable`: If control flow reaches `__builtin_unreachable`.
- `-fsanitize=unsigned-integer-overflow`: Unsigned integer overflows.
- `-fsanitize=vla-bound`: A variable-length array whose bound does not evaluate to a positive value.
- `-fsanitize=vptr`: Use of an object whose vptr indicates that it is of the wrong dynamic type, or that its lifetime has not begun or has ended. Incompatible with `-fno-rtti`. Link must be performed by `clang++`, not `clang`, to make sure C++-specific parts of the runtime library and C++ standard libraries are present.

You can also use the following check groups:

- `-fsanitize=undefined`: All of the checks listed above other than `unsigned-integer-overflow`.
- `-fsanitize=undefined-trap`: Deprecated alias of `-fsanitize=undefined`.
- `-fsanitize=integer`: Checks for undefined or suspicious integer behavior (e.g. unsigned integer overflow).

Stack traces and report symbolization

If you want UBSan to print symbolized stack trace for each error report, you will need to:

1. Compile with `-g` and `-fno-omit-frame-pointer` to get proper debug information in your binary.
2. Run your program with environment variable `UBSAN_OPTIONS=print_stacktrace=1`.
3. Make sure `llvm-symbolizer` binary is in `PATH`.

Issue Suppression

UndefinedBehaviorSanitizer is not expected to produce false positives. If you see one, look again; most likely it is a true positive!

Disabling Instrumentation with `__attribute__((no_sanitize("undefined")))`

You disable UBSan checks for particular functions with `__attribute__((no_sanitize("undefined")))`. You can use all values of `-fsanitize=` flag in this attribute, e.g. if your function deliberately contains possible signed integer overflow, you can use `__attribute__((no_sanitize("signed-integer-overflow")))`.

This attribute may not be supported by other compilers, so consider using it together with `#if defined(__clang__)`.

Suppressing Errors in Recompiled Code (Blacklist)

UndefinedBehaviorSanitizer supports `src` and `fun` entity types in *Sanitizer special case list*, that can be used to suppress error reports in the specified source files or functions.

Runtime suppressions

Sometimes you can suppress UBSan error reports for specific files, functions, or libraries without recompiling the code. You need to pass a path to suppression file in a `UBSAN_OPTIONS` environment variable.

```
UBSAN_OPTIONS=suppressions=MyUBSan.supp
```

You need to specify a *check* you are suppressing and the bug location. For example:

```
signed-integer-overflow:file-with-known-overflow.cpp
alignment:function_doing_unaligned_access
vptr:shared_object_with_vptr_failures.so
```

There are several limitations:

- Sometimes your binary must have enough debug info and/or symbol table, so that the runtime could figure out source file or function name to match against the suppression.
- It is only possible to suppress recoverable checks. For the example above, you can additionally pass `-fsanitize-recover=signed-integer-overflow,alignment,vptr`, although most of UBSan checks are recoverable by default.
- Check groups (like `undefined`) can't be used in suppressions file, only fine-grained checks are supported.

Supported Platforms

UndefinedBehaviorSanitizer is supported on the following OS:

- Android
- Linux
- FreeBSD
- OS X 10.6 onwards

and for the following architectures:

- i386/x86_64
- ARM
- AArch64
- PowerPC64
- MIPS/MIPS64

Current Status

UndefinedBehaviorSanitizer is available on selected platforms starting from LLVM 3.3. The test suite is integrated into the CMake build and can be run with `check-ubsan` command.

Additional Configuration

UndefinedBehaviorSanitizer adds static check data for each check unless it is in trap mode. This check data includes the full file name. The option `-fsanitize-undefined-strip-path-components=N` can be used to trim this information. If `N` is positive, file information emitted by UndefinedBehaviorSanitizer will drop the first `N` components from the file path. If `N` is negative, the last `N` components will be kept.

Example

For a file called `/code/library/file.cpp`, here is what would be emitted: * Default (No flag, or `-fsanitize-undefined-strip-path-components=0`): `/code/library/file.cpp` * `-fsanitize-undefined-strip-path-components=1`: `code/library/file.cpp` * `-fsanitize-undefined-strip-path-components=2`: `library/file.cpp` * `-fsanitize-undefined-strip-path-components=-1`: `file.cpp` * `-fsanitize-undefined-strip-path-components=-2`: `library/file.cpp`

More Information

- From LLVM project blog: What Every C Programmer Should Know About Undefined Behavior
- From John Regehr's *Embedded in Academia* blog: A Guide to Undefined Behavior in C and C++

DataFlowSanitizer

DataFlowSanitizer Design Document

This document sets out the design for DataFlowSanitizer, a general dynamic data flow analysis. Unlike other Sanitizer tools, this tool is not designed to detect a specific class of bugs on its own. Instead, it provides a generic dynamic data flow analysis framework to be used by clients to help detect application-specific issues within their own code.

DataFlowSanitizer is a program instrumentation which can associate a number of taint labels with any data stored in any memory region accessible by the program. The analysis is dynamic, which means that it operates on a running program, and tracks how the labels propagate through that program. The tool shall support a large (>100) number of labels, such that programs which operate on large numbers of data items may be analysed with each data item being tracked separately.

Use Cases

This instrumentation can be used as a tool to help monitor how data flows from a program's inputs (sources) to its outputs (sinks). This has applications from a privacy/security perspective in that one can audit how a sensitive data item is used within a program and ensure it isn't exiting the program anywhere it shouldn't be.

Interface

A number of functions are provided which will create taint labels, attach labels to memory regions and extract the set of labels associated with a specific memory region. These functions are declared in the header file `sanitizer/dfsan_interface.h`.

```
/// Creates and returns a base label with the given description and user data.
dfsan_label dfsan_create_label(const char *desc, void *userdata);

/// Sets the label for each address in [addr,addr+size) to \c label.
void dfsan_set_label(dfsan_label label, void *addr, size_t size);

/// Sets the label for each address in [addr,addr+size) to the union of the
/// current label for that address and \c label.
void dfsan_add_label(dfsan_label label, void *addr, size_t size);

/// Retrieves the label associated with the given data.
///
/// The type of 'data' is arbitrary.  The function accepts a value of any type,
/// which can be truncated or extended (implicitly or explicitly) as necessary.
/// The truncation/extension operations will preserve the label of the original
/// value.
dfsan_label dfsan_get_label(long data);

/// Retrieves a pointer to the dfsan_label_info struct for the given label.
const struct dfsan_label_info *dfsan_get_label_info(dfsan_label label);
```

```
/// Returns whether the given label label contains the label elem.
int dfsan_has_label(dfsan_label label, dfsan_label elem);

/// If the given label label contains a label with the description desc, returns
/// that label, else returns 0.
dfsan_label dfsan_has_label_with_desc(dfsan_label label, const char *desc);
```

Taint label representation

As stated above, the tool must track a large number of taint labels. This poses an implementation challenge, as most multiple-label tainting systems assign one label per bit to shadow storage, and union taint labels using a bitwise or operation. This will not scale to clients which use hundreds or thousands of taint labels, as the label union operation becomes O(n) in the number of supported labels, and data associated with it will quickly dominate the live variable set, causing register spills and hampering performance.

Instead, a low overhead approach is proposed which is best-case $O(\log_2 n)$ during execution. The underlying assumption is that the required space of label unions is sparse, which is a reasonable assumption to make given that we are optimizing for the case where applications mostly copy data from one place to another, without often invoking the need for an actual union operation. The representation of a taint label is a 16-bit integer, and new labels are allocated sequentially from a pool. The label identifier 0 is special, and means that the data item is unlabelled.

When a label union operation is requested at a join point (any arithmetic or logical operation with two or more operands, such as addition), the code checks whether a union is required, whether the same union has been requested before, and whether one union label subsumes the other. If so, it returns the previously allocated union label. If not, it allocates a new union label from the same pool used for new labels.

Specifically, the instrumentation pass will insert code like this to decide the union label `lu` for a pair of labels `l1` and `l2`:

```
if (l1 == l2)
  lu = l1;
else
  lu = __dfsan_union(l1, l2);
```

The equality comparison is outlined, to provide an early exit in the common cases where the program is processing unlabelled data, or where the two data items have the same label. `__dfsan_union` is a runtime library function which performs all other union computation.

Further optimizations are possible, for example if `l1` is known at compile time to be zero (e.g. it is derived from a constant), `l2` can be used for `lu`, and vice versa.

Memory layout and label management

The following is the current memory layout for Linux/x86_64:

Start	End	Use
0x700000008000	0x800000000000	application memory
0x200200000000	0x700000008000	unused
0x200000000000	0x200200000000	union table
0x000000010000	0x200000000000	shadow memory
0x000000000000	0x000000010000	reserved by kernel

Each byte of application memory corresponds to two bytes of shadow memory, which are used to store its taint label. As for LLVM SSA registers, we have not found it necessary to associate a label with each byte or bit of data, as some other tools do. Instead, labels are associated directly with registers. Loads will result in a union of all shadow labels

corresponding to bytes loaded (which most of the time will be short circuited by the initial comparison) and stores will result in a copy of the label to the shadow of all bytes stored to.

Propagating labels through arguments

In order to propagate labels through function arguments and return values, DataFlowSanitizer changes the ABI of each function in the translation unit. There are currently two supported ABIs:

- Args – Argument and return value labels are passed through additional arguments and by modifying the return type.
- TLS – Argument and return value labels are passed through TLS variables `__dfsan_arg_tls` and `__dfsan_retval_tls`.

The main advantage of the TLS ABI is that it is more tolerant of ABI mismatches (TLS storage is not shared with any other form of storage, whereas extra arguments may be stored in registers which under the native ABI are not used for parameter passing and thus could contain arbitrary values). On the other hand the args ABI is more efficient and allows ABI mismatches to be more easily identified by checking for nonzero labels in nominally unlabelled programs.

Implementing the ABI list

The ABI list provides a list of functions which conform to the native ABI, each of which is callable from an instrumented program. This is implemented by replacing each reference to a native ABI function with a reference to a function which uses the instrumented ABI. Such functions are automatically-generated wrappers for the native functions. For example, given the ABI list example provided in the user manual, the following wrappers will be generated under the args ABI:

```
define linkonce_odr { i8*, i16 } @"dfsw$malloc"(i64 %0, i16 %1) {
entry:
  %2 = call i8* @malloc(i64 %0)
  %3 = insertvalue { i8*, i16 } undef, i8* %2, 0
  %4 = insertvalue { i8*, i16 } %3, i16 0, 1
  ret { i8*, i16 } %4
}

define linkonce_odr { i32, i16 } @"dfsw$tolower"(i32 %0, i16 %1) {
entry:
  %2 = call i32 @tolower(i32 %0)
  %3 = insertvalue { i32, i16 } undef, i32 %2, 0
  %4 = insertvalue { i32, i16 } %3, i16 %1, 1
  ret { i32, i16 } %4
}

define linkonce_odr { i8*, i16 } @"dfsw$memcpy"(i8* %0, i8* %1, i64 %2, i16 %3, i16
↪%4, i16 %5) {
entry:
  %labelreturn = alloca i16
  %6 = call i8* @__dfsw_memcpy(i8* %0, i8* %1, i64 %2, i16 %3, i16 %4, i16 %5, i16*
↪%labelreturn)
  %7 = load i16* %labelreturn
  %8 = insertvalue { i8*, i16 } undef, i8* %6, 0
  %9 = insertvalue { i8*, i16 } %8, i16 %7, 1
  ret { i8*, i16 } %9
}
```

As an optimization, direct calls to native ABI functions will call the native ABI function directly and the pass will compute the appropriate label internally. This has the advantage of reducing the number of union operations required

when the return value label is known to be zero (i.e. `discard` functions, or `functional` functions with known unlabelled arguments).

Checking ABI Consistency

DFSan changes the ABI of each function in the module. This makes it possible for a function with the native ABI to be called with the instrumented ABI, or vice versa, thus possibly invoking undefined behavior. A simple way of statically detecting instances of this problem is to prepend the prefix "dfs$" to the name of each instrumented-ABI function.

This will not catch every such problem; in particular function pointers passed across the instrumented-native barrier cannot be used on the other side. These problems could potentially be caught dynamically.

Introduction

DataFlowSanitizer is a generalised dynamic data flow analysis.

Unlike other Sanitizer tools, this tool is not designed to detect a specific class of bugs on its own. Instead, it provides a generic dynamic data flow analysis framework to be used by clients to help detect application-specific issues within their own code.

Usage

With no program changes, applying DataFlowSanitizer to a program will not alter its behavior. To use DataFlowSanitizer, the program uses API functions to apply tags to data to cause it to be tracked, and to check the tag of a specific data item. DataFlowSanitizer manages the propagation of tags through the program according to its data flow.

The APIs are defined in the header file `sanitizer/dfsan_interface.h`. For further information about each function, please refer to the header file.

ABI List

DataFlowSanitizer uses a list of functions known as an ABI list to decide whether a call to a specific function should use the operating system's native ABI or whether it should use a variant of this ABI that also propagates labels through function parameters and return values. The ABI list file also controls how labels are propagated in the former case. DataFlowSanitizer comes with a default ABI list which is intended to eventually cover the glibc library on Linux but it may become necessary for users to extend the ABI list in cases where a particular library or function cannot be instrumented (e.g. because it is implemented in assembly or another language which DataFlowSanitizer does not support) or a function is called from a library or function which cannot be instrumented.

DataFlowSanitizer's ABI list file is a *Sanitizer special case list*. The pass treats every function in the `uninstrumented` category in the ABI list file as conforming to the native ABI. Unless the ABI list contains additional categories for those functions, a call to one of those functions will produce a warning message, as the labelling behavior of the function is unknown. The other supported categories are `discard`, `functional` and `custom`.

- `discard` – To the extent that this function writes to (user-accessible) memory, it also updates labels in shadow memory (this condition is trivially satisfied for functions which do not write to user-accessible memory). Its return value is unlabelled.
- `functional` – Like `discard`, except that the label of its return value is the union of the label of its arguments.
- `custom` – Instead of calling the function, a custom wrapper `__dfsw_F` is called, where `F` is the name of the function. This function may wrap the original function or provide its own implementation. This category is generally used for uninstrumentable functions which write to user-accessible memory or which have more complex label propagation behavior. The signature of `__dfsw_F` is based on that of `F` with each argument having a label of type `dfsan_label` appended to the argument list. If `F` is of non-void return type a final argument of type `dfsan_label *` is appended to which the custom function can store the label for the return value. For example:

```
void f(int x);
void __dfsw_f(int x, dfsan_label x_label);

void *memcpy(void *dest, const void *src, size_t n);
void *__dfsw_memcpy(void *dest, const void *src, size_t n,
                    dfsan_label dest_label, dfsan_label src_label,
                    dfsan_label n_label, dfsan_label *ret_label);
```

If a function defined in the translation unit being compiled belongs to the `uninstrumented` category, it will be compiled so as to conform to the native ABI. Its arguments will be assumed to be unlabelled, but it will propagate labels in shadow memory.

For example:

```
# main is called by the C runtime using the native ABI.
fun:main=uninstrumented
fun:main=discard

# malloc only writes to its internal data structures, not user-accessible memory.
fun:malloc=uninstrumented
fun:malloc=discard

# tolower is a pure function.
fun:tolower=uninstrumented
fun:tolower=functional

# memcpy needs to copy the shadow from the source to the destination region.
# This is done in a custom function.
fun:memcpy=uninstrumented
fun:memcpy=custom
```

Example

The following program demonstrates label propagation by checking that the correct labels are propagated.

```
#include <sanitizer/dfsan_interface.h>
#include <assert.h>
```

```
int main(void) {
  int i = 1;
  dfsan_label i_label = dfsan_create_label("i", 0);
  dfsan_set_label(i_label, &i, sizeof(i));

  int j = 2;
  dfsan_label j_label = dfsan_create_label("j", 0);
  dfsan_set_label(j_label, &j, sizeof(j));

  int k = 3;
  dfsan_label k_label = dfsan_create_label("k", 0);
  dfsan_set_label(k_label, &k, sizeof(k));

  dfsan_label ij_label = dfsan_get_label(i + j);
  assert(dfsan_has_label(ij_label, i_label));
  assert(dfsan_has_label(ij_label, j_label));
  assert(!dfsan_has_label(ij_label, k_label));

  dfsan_label ijk_label = dfsan_get_label(i + j + k);
  assert(dfsan_has_label(ijk_label, i_label));
  assert(dfsan_has_label(ijk_label, j_label));
  assert(dfsan_has_label(ijk_label, k_label));

  return 0;
}
```

Current status

DataFlowSanitizer is a work in progress, currently under development for x86_64 Linux.

Design

Please refer to the *design document*.

LeakSanitizer

Introduction

LeakSanitizer is a run-time memory leak detector. It can be combined with *AddressSanitizer* to get both memory error and leak detection, or used in a stand-alone mode. LSan adds almost no performance overhead until the very end of the process, at which point there is an extra leak detection phase.

Usage

LeakSanitizer is only supported on x86_64 Linux. In order to use it, simply build your program with *AddressSanitizer*:

```
$ cat memory-leak.c
#include <stdlib.h>
void *p;
int main() {
  p = malloc(7);
  p = 0; // The memory is leaked here.
  return 0;
}
% clang -fsanitize=address -g memory-leak.c ; ./a.out
==23646==ERROR: LeakSanitizer: detected memory leaks
Direct leak of 7 byte(s) in 1 object(s) allocated from:
    #0 0x4af01b in __interceptor_malloc /projects/compiler-rt/lib/asan/asan_malloc_
↪linux.cc:52:3
    #1 0x4da26a in main memory-leak.c:4:7
    #2 0x7f076fd9cec4 in __libc_start_main libc-start.c:287
SUMMARY: AddressSanitizer: 7 byte(s) leaked in 1 allocation(s).
```

To use LeakSanitizer in stand-alone mode, link your program with `-fsanitize=leak` flag. Make sure to use `clang` (not `ld`) for the link step, so that it would link in proper LeakSanitizer run-time library into the final executable.

More Information

https://github.com/google/sanitizers/wiki/AddressSanitizerLeakSanitizer

SanitizerCoverage

Introduction

Sanitizer tools have a very simple code coverage tool built in. It allows to get function-level, basic-block-level, and edge-level coverage at a very low cost.

How to build and run

SanitizerCoverage can be used with *AddressSanitizer*, *LeakSanitizer*, *MemorySanitizer*, UndefinedBehaviorSanitizer, or without any sanitizer. Pass one of the following compile-time flags:

- `-fsanitize-coverage=func` for function-level coverage (very fast).
- `-fsanitize-coverage=bb` for basic-block-level coverage (may add up to 30% **extra** slowdown).
- `-fsanitize-coverage=edge` for edge-level coverage (up to 40% slowdown).

You may also specify `-fsanitize-coverage=indirect-calls` for additional *caller-callee coverage*.

At run time, pass `coverage=1` in `ASAN_OPTIONS`, `LSAN_OPTIONS`, `MSAN_OPTIONS` or `UBSAN_OPTIONS`, as appropriate. For the standalone coverage mode, use `UBSAN_OPTIONS`.

To get *Coverage counters*, add `-fsanitize-coverage=8bit-counters` to one of the above compile-time flags. At runtime, use `*SAN_OPTIONS=coverage=1:coverage_counters=1`.

Example:

```
% cat -n cov.cc
     1  #include <stdio.h>
     2  __attribute__((noinline))
     3  void foo() { printf("foo\n"); }
     4
     5  int main(int argc, char **argv) {
     6    if (argc == 2)
     7      foo();
     8    printf("main\n");
     9  }
% clang++ -g cov.cc -fsanitize=address -fsanitize-coverage=func
% ASAN_OPTIONS=coverage=1 ./a.out; ls -l *sancov
main
-rw-r----- 1 kcc eng 4 Nov 27 12:21 a.out.22673.sancov
% ASAN_OPTIONS=coverage=1 ./a.out foo ; ls -l *sancov
foo
main
-rw-r----- 1 kcc eng 4 Nov 27 12:21 a.out.22673.sancov
-rw-r----- 1 kcc eng 8 Nov 27 12:21 a.out.22679.sancov
```

Every time you run an executable instrumented with SanitizerCoverage one `*.sancov` file is created during the process shutdown. If the executable is dynamically linked against instrumented DSOs, one `*.sancov` file will be also created for every DSO.

Postprocessing

The format of `*.sancov` files is very simple: the first 8 bytes is the magic, one of `0xC0BFFFFFFFFFFF64` and `0xC0BFFFFFFFFFFF32`. The last byte of the magic defines the size of the following offsets. The rest of the data is the offsets in the corresponding binary/DSO that were executed during the run.

A simple script `$LLVM/projects/compiler-rt/lib/sanitizer_common/scripts/sancov.py` is provided to dump these offsets.

```
% sancov.py print a.out.22679.sancov a.out.22673.sancov
sancov.py: read 2 PCs from a.out.22679.sancov
sancov.py: read 1 PCs from a.out.22673.sancov
sancov.py: 2 files merged; 2 PCs total
0x465250
0x4652a0
```

You can then filter the output of `sancov.py` through `addr2line --exe ObjectFile` or `llvm-symbolizer --obj ObjectFile` to get file names and line numbers:

```
% sancov.py print a.out.22679.sancov a.out.22673.sancov 2> /dev/null | llvm-
↪symbolizer --obj a.out
cov.cc:3
cov.cc:5
```

Sancov Tool

A new experimental `sancov` tool is developed to process coverage files. The tool is part of LLVM project and is currently supported only on Linux. It can handle symbolization tasks autonomously without any extra support from the environment. You need to pass .sancov files (named `<module_name>.<pid>.sancov` and paths to all corresponding binary elf files. Sancov matches these files using module names and binaries file names.

```
USAGE: sancov [options] <action> (<binary file>|<.sancov file>)...

Action (required)
  -print                    - Print coverage addresses
  -covered-functions        - Print all covered functions.
  -not-covered-functions    - Print all not covered functions.
  -html-report              - Print HTML coverage report.

Options
  -blacklist=<string>         - Blacklist file (sanitizer blacklist format).
  -demangle                   - Print demangled function name.
  -strip_path_prefix=<string> - Strip this prefix from file paths in reports
```

Automatic HTML Report Generation

If `*SAN_OPTIONS` contains `html_cov_report=1` option set, then html coverage report would be automatically generated alongside the coverage files. The `sancov` binary should be present in `PATH` or `sancov_path=<path_to_sancov` option can be used to specify tool location.

How good is the coverage?

It is possible to find out which PCs are not covered, by subtracting the covered set from the set of all instrumented PCs. The latter can be obtained by listing all callsites of `__sanitizer_cov()` in the binary. On Linux, `sancov.py`

can do this for you. Just supply the path to binary and a list of covered PCs:

```
% sancov.py print a.out.12345.sancov > covered.txt
sancov.py: read 2 64-bit PCs from a.out.12345.sancov
sancov.py: 1 file merged; 2 PCs total
% sancov.py missing a.out < covered.txt
sancov.py: found 3 instrumented PCs in a.out
sancov.py: read 2 PCs from stdin
sancov.py: 1 PCs missing from coverage
0x4cc61c
```

Edge coverage

Consider this code:

```
void foo(int *a) {
  if (a)
    *a = 0;
}
```

It contains 3 basic blocks, let's name them A, B, C:

```
A
|\
| \
|  B
| /
|/
C
```

If blocks A, B, and C are all covered we know for certain that the edges A=>B and B=>C were executed, but we still don't know if the edge A=>C was executed. Such edges of control flow graph are called critical. The edge-level coverage (`-fsanitize-coverage=edge`) simply splits all critical edges by introducing new dummy blocks and then instruments those blocks:

```
A
|\
| \
D  B
| /
|/
C
```

Bitset

When `coverage_bitset=1` run-time flag is given, the coverage will also be dumped as a bitset (text file with 1 for blocks that have been executed and 0 for blocks that were not).

```
% clang++ -fsanitize=address -fsanitize-coverage=edge cov.cc
% ASAN_OPTIONS="coverage=1:coverage_bitset=1" ./a.out
main
% ASAN_OPTIONS="coverage=1:coverage_bitset=1" ./a.out 1
foo
main
% head *bitset*
```

```
==> a.out.38214.bitset-sancov <==
01101
==> a.out.6128.bitset-sancov <==
11011%
```

For a given executable the length of the bitset is always the same (well, unless dlopen/dlclose come into play), so the bitset coverage can be easily used for bitset-based corpus distillation.

Caller-callee coverage

(Experimental!) Every indirect function call is instrumented with a run-time function call that captures caller and callee. At the shutdown time the process dumps a separate file called `caller-callee.PID.sancov` which contains caller/callee pairs as pairs of lines (odd lines are callers, even lines are callees)

```
a.out 0x4a2e0c
a.out 0x4a6510
a.out 0x4a2e0c
a.out 0x4a87f0
```

Current limitations:

- Only the first 14 callees for every caller are recorded, the rest are silently ignored.
- The output format is not very compact since caller and callee may reside in different modules and we need to spell out the module names.
- The routine that dumps the output is not optimized for speed
- Only Linux x86_64 is tested so far.
- Sandboxes are not supported.

Coverage counters

This experimental feature is inspired by AFL's coverage instrumentation. With additional compile-time and run-time flags you can get more sensitive coverage information. In addition to boolean values assigned to every basic block (edge) the instrumentation will collect imprecise counters. On exit, every counter will be mapped to a 8-bit bitset representing counter ranges: `1, 2, 3, 4-7, 8-15, 16-31, 32-127, 128+` and those 8-bit bitsets will be dumped to disk.

```
% clang++ -g cov.cc -fsanitize=address -fsanitize-coverage=edge,8bit-counters
% ASAN_OPTIONS="coverage=1:coverage_counters=1" ./a.out
% ls -l *counters-sancov
... a.out.17110.counters-sancov
% xxd *counters-sancov
0000000: 0001 0100 01
```

These counters may also be used for in-process coverage-guided fuzzers. See `include/sanitizer/coverage_interface.h`:

```
// The coverage instrumentation may optionally provide imprecise counters.
// Rather than exposing the counter values to the user we instead map
// the counters to a bitset.
// Every counter is associated with 8 bits in the bitset.
// We define 8 value ranges: 1, 2, 3, 4-7, 8-15, 16-31, 32-127, 128+
// The i-th bit is set to 1 if the counter value is in the i-th range.
```

```
// This counter-based coverage implementation is *not* thread-safe.

// Returns the number of registered coverage counters.
uintptr_t __sanitizer_get_number_of_counters();
// Updates the counter 'bitset', clears the counters and returns the number of
// new bits in 'bitset'.
// If 'bitset' is nullptr, only clears the counters.
// Otherwise 'bitset' should be at least
// __sanitizer_get_number_of_counters bytes long and 8-aligned.
uintptr_t
__sanitizer_update_counter_bitset_and_clear_counters(uint8_t *bitset);
```

Tracing basic blocks

Experimental support for basic block (or edge) tracing. With `-fsanitize-coverage=trace-bb` the compiler will insert `__sanitizer_cov_trace_basic_block(s32 *id)` before every function, basic block, or edge (depending on the value of `-fsanitize-coverage=[func,bb,edge]`). Example:

```
% clang -g -fsanitize=address -fsanitize-coverage=edge,trace-bb foo.cc
% ASAN_OPTIONS=coverage=1 ./a.out
```

This will produce two files after the process exit: *trace-points.PID.sancov* and *trace-events.PID.sancov*. The first file will contain a textual description of all the instrumented points in the program in the form that you can feed into llvm-symbolizer (e.g. *a.out 0x4dca89*), one per line. The second file will contain the actual execution trace as a sequence of 4-byte integers – these integers are the indices into the array of instrumented points (the first file).

Basic block tracing is currently supported only for single-threaded applications.

Tracing PCs

Experimental feature similar to tracing basic blocks, but with a different API. With `-fsanitize-coverage=trace-pc` the compiler will insert `__sanitizer_cov_trace_pc()` on every edge. With an additional `...=trace-pc,indirect-calls` flag `__sanitizer_cov_trace_pc_indirect(void *callee)` will be inserted on every indirect call. These callbacks are not implemented in the Sanitizer run-time and should be defined by the user. So, these flags do not require the other sanitizer to be used. This mechanism is used for fuzzing the Linux kernel (https://github.com/google/syzkaller) and can be used with AFL.

Tracing data flow

An *experimental* feature to support data-flow-guided fuzzing. With `-fsanitize-coverage=trace-cmp` the compiler will insert extra instrumentation around comparison instructions and switch statements. The fuzzer will need to define the following functions, they will be called by the instrumented code.

```
// Called before a comparison instruction.
// SizeAndType is a packed value containing
//   - [63:32] the Size of the operands of comparison in bits
//   - [31:0] the Type of comparison (one of ICMP_EQ, ... ICMP_SLE)
// Arg1 and Arg2 are arguments of the comparison.
void __sanitizer_cov_trace_cmp(uint64_t SizeAndType, uint64_t Arg1, uint64_t Arg2);

// Called before a switch statement.
// Val is the switch operand.
```

```
// Cases[0] is the number of case constants.
// Cases[1] is the size of Val in bits.
// Cases[2:] are the case constants.
void __sanitizer_cov_trace_switch(uint64_t Val, uint64_t *Cases);
```

This interface is a subject to change. The current implementation is not thread-safe and thus can be safely used only for single-threaded targets.

Output directory

By default, .sancov files are created in the current working directory. This can be changed with `ASAN_OPTIONS=coverage_dir=/path`:

```
% ASAN_OPTIONS="coverage=1:coverage_dir=/tmp/cov" ./a.out foo
% ls -l /tmp/cov/*sancov
-rw-r----- 1 kcc eng 4 Nov 27 12:21 a.out.22673.sancov
-rw-r----- 1 kcc eng 8 Nov 27 12:21 a.out.22679.sancov
```

Sudden death

Normally, coverage data is collected in memory and saved to disk when the program exits (with an `atexit()` handler), when a SIGSEGV is caught, or when `__sanitizer_cov_dump()` is called.

If the program ends with a signal that ASan does not handle (or can not handle at all, like SIGKILL), coverage data will be lost. This is a big problem on Android, where SIGKILL is a normal way of evicting applications from memory.

With `ASAN_OPTIONS=coverage=1:coverage_direct=1` coverage data is written to a memory-mapped file as soon as it collected.

```
% ASAN_OPTIONS="coverage=1:coverage_direct=1" ./a.out
main
% ls
7036.sancov.map  7036.sancov.raw  a.out
% sancov.py rawunpack 7036.sancov.raw
sancov.py: reading map 7036.sancov.map
sancov.py: unpacking 7036.sancov.raw
writing 1 PCs to a.out.7036.sancov
% sancov.py print a.out.7036.sancov
sancov.py: read 1 PCs from a.out.7036.sancov
sancov.py: 1 files merged; 1 PCs total
0x4b2bae
```

Note that on 64-bit platforms, this method writes 2x more data than the default, because it stores full PC values instead of 32-bit offsets.

In-process fuzzing

Coverage data could be useful for fuzzers and sometimes it is preferable to run a fuzzer in the same process as the code being fuzzed (in-process fuzzer).

You can use `__sanitizer_get_total_unique_coverage()` from `<sanitizer/coverage_interface.h>` which returns the number of currently covered entities in the program. This will tell the fuzzer if the coverage has increased after testing every new input.

If a fuzzer finds a bug in the ASan run, you will need to save the reproducer before exiting the process. Use `__asan_set_death_callback` from `<sanitizer/asan_interface.h>` to do that.

An example of such fuzzer can be found in the LLVM tree.

Performance

This coverage implementation is **fast**. With function-level coverage (`-fsanitize-coverage=func`) the overhead is not measurable. With basic-block-level coverage (`-fsanitize-coverage=bb`) the overhead varies between 0 and 25%.

benchmark	cov0	cov1	diff 0-1	cov2	diff 0-2	diff 1-2
400.perlbench	1296.00	1307.00	1.01	1465.00	1.13	1.12
401.bzip2	858.00	854.00	1.00	1010.00	1.18	1.18
403.gcc	613.00	617.00	1.01	683.00	1.11	1.11
429.mcf	605.00	582.00	0.96	610.00	1.01	1.05
445.gobmk	896.00	880.00	0.98	1050.00	1.17	1.19
456.hmmer	892.00	892.00	1.00	918.00	1.03	1.03
458.sjeng	995.00	1009.00	1.01	1217.00	1.22	1.21
462.libquantum	497.00	492.00	0.99	534.00	1.07	1.09
464.h264ref	1461.00	1467.00	1.00	1543.00	1.06	1.05
471.omnetpp	575.00	590.00	1.03	660.00	1.15	1.12
473.astar	658.00	652.00	0.99	715.00	1.09	1.10
483.xalancbmk	471.00	491.00	1.04	582.00	1.24	1.19
433.milc	616.00	627.00	1.02	627.00	1.02	1.00
444.namd	602.00	601.00	1.00	654.00	1.09	1.09
447.dealII	630.00	634.00	1.01	653.00	1.04	1.03
450.soplex	365.00	368.00	1.01	395.00	1.08	1.07
453.povray	427.00	434.00	1.02	495.00	1.16	1.14
470.lbm	357.00	375.00	1.05	370.00	1.04	0.99
482.sphinx3	927.00	928.00	1.00	1000.00	1.08	1.08

Why another coverage?

Why did we implement yet another code coverage?

- We needed something that is lightning fast, plays well with AddressSanitizer, and does not significantly increase the binary size.
- Traditional coverage implementations based in global counters suffer from contention on counters.

SanitizerStats

Introduction

The sanitizers support a simple mechanism for gathering profiling statistics to help understand the overhead associated with sanitizers.

How to build and run

SanitizerStats can currently only be used with *Control Flow Integrity*. In addition to `-fsanitize=cfi*`, pass the `-fsanitize-stats` flag. This will cause the program to count the number of times that each control flow integrity check in the program fires.

At run time, set the `SANITIZER_STATS_PATH` environment variable to direct statistics output to a file. The file will be written on process exit. The following substitutions will be applied to the environment variable:

- `%b` – The executable basename.
- `%p` – The process ID.

You can also send the `SIGUSR2` signal to a process to make it write sanitizer statistics immediately.

The `sanstats` program can be used to dump statistics. It takes as a command line argument the path to a statistics file produced by a program compiled with `-fsanitize-stats`.

The output of `sanstats` is in four columns, separated by spaces. The first column is the file and line number of the call site. The second column is the function name. The third column is the type of statistic gathered (in this case, the type of control flow integrity check). The fourth column is the call count.

Example:

```
$ cat -n vcall.cc
     1 struct A {
     2   virtual void f() {}
     3 };
     4
     5 __attribute__((noinline)) void g(A *a) {
     6   a->f();
     7 }
     8
     9 int main() {
    10   A a;
    11   g(&a);
    12 }
$ clang++ -fsanitize=cfi -flto -fuse-ld=gold vcall.cc -fsanitize-stats -g
$ SANITIZER_STATS_PATH=a.stats ./a.out
$ sanstats a.stats
vcall.cc:6 _Z1gP1A cfi-vcall 1
```

Sanitizer special case list

Introduction

This document describes the way to disable or alter the behavior of sanitizer tools for certain source-level entities by providing a special file at compile-time.

Goal and usage

User of sanitizer tools, such as *AddressSanitizer*, *ThreadSanitizer* or *MemorySanitizer* may want to disable or alter some checks for certain source-level entities to:

- speedup hot function, which is known to be correct;
- ignore a function that does some low-level magic (e.g. walks through the thread stack, bypassing the frame boundaries);
- ignore a known problem.

To achieve this, user may create a file listing the entities they want to ignore, and pass it to clang at compile-time using `-fsanitize-blacklist` flag. See *Clang Compiler User's Manual* for details.

Example

```
$ cat foo.c
#include <stdlib.h>
void bad_foo() {
  int *a = (int*)malloc(40);
  a[10] = 1;
}
int main() { bad_foo(); }
$ cat blacklist.txt
# Ignore reports from bad_foo function.
fun:bad_foo
$ clang -fsanitize=address foo.c ; ./a.out
# AddressSanitizer prints an error report.
$ clang -fsanitize=address -fsanitize-blacklist=blacklist.txt foo.c ; ./a.out
# No error report here.
```

Format

Each line contains an entity type, followed by a colon and a regular expression, specifying the names of the entities, optionally followed by an equals sign and a tool-specific category. Empty lines and lines starting with "#" are ignored. The meanining of `*` in regular expression for entity names is different - it is treated as in shell wildcarding. Two generic entity types are `src` and `fun`, which allow user to add, respectively, source files and functions to special case list. Some sanitizer tools may introduce custom entity types - refer to tool-specific docs.

```
# Lines starting with # are ignored.
# Turn off checks for the source file (use absolute path or path relative
# to the current working directory):
src:/path/to/source/file.c
# Turn off checks for a particular functions (use mangled names):
```

```
fun:MyFooBar
fun:_Z8MyFooBarv
# Extended regular expressions are supported:
fun:bad_(foo|bar)
src:bad_source[1-9].c
# Shell like usage of * is supported (* is treated as .*):
src:bad/sources/*
fun:*BadFunction*
# Specific sanitizer tools may introduce categories.
src:/special/path/*=special_sources
```

Control Flow Integrity

Control Flow Integrity Design Documentation

This page documents the design of the *Control Flow Integrity* schemes supported by Clang.

Forward-Edge CFI for Virtual Calls

This scheme works by allocating, for each static type used to make a virtual call, a region of read-only storage in the object file holding a bit vector that maps onto to the region of storage used for those virtual tables. Each set bit in the bit vector corresponds to the address point for a virtual table compatible with the static type for which the bit vector is being built.

For example, consider the following three C++ classes:

```
struct A {
  virtual void f1();
  virtual void f2();
  virtual void f3();
};

struct B : A {
  virtual void f1();
  virtual void f2();
  virtual void f3();
};

struct C : A {
  virtual void f1();
  virtual void f2();
  virtual void f3();
};
```

The scheme will cause the virtual tables for A, B and C to be laid out consecutively:

Table 4.98: Virtual Table Layout for A, B, C

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A::offset-to-top	&A::rtti	&A::f1	&A::f2	&A::f3	B::offset-to-top	&B::rtti	&B::f1	&B::f2	&B::f3	C::offset-to-top	&C::rtti	&C::f1	&C::f2	&C::f3

The bit vector for static types A, B and C will look like this:

Table 4.99: Bit Vectors for A, B, C

Class	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
B	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

Bit vectors are represented in the object file as byte arrays. By loading from indexed offsets into the byte array and applying a mask, a program can test bits from the bit set with a relatively short instruction sequence. Bit vectors may overlap so long as they use different bits. For the full details, see the ByteArrayBuilder class.

In this case, assuming A is laid out at offset 0 in bit 0, B at offset 0 in bit 1 and C at offset 0 in bit 2, the byte array would look like this:

```
char bits[] = { 0, 0, 1, 0, 0, 0, 3, 0, 0, 0, 0, 5, 0, 0 };
```

To emit a virtual call, the compiler will assemble code that checks that the object's virtual table pointer is in-bounds and aligned and that the relevant bit is set in the bit vector.

For example on x86 a typical virtual call may look like this:

```
ca7fbb:       48 8b 0f                mov    (%rdi),%rcx
ca7fbe:       48 8d 15 c3 42 fb 07    lea    0x7fb42c3(%rip),%rdx
ca7fc5:       48 89 c8                mov    %rcx,%rax
ca7fc8:       48 29 d0                sub    %rdx,%rax
ca7fcb:       48 c1 c0 3d             rol    $0x3d,%rax
ca7fcf:       48 3d 7f 01 00 00       cmp    $0x17f,%rax
ca7fd5:       0f 87 36 05 00 00       ja     ca8511
ca7fdb:       48 8d 15 c0 0b f7 06    lea    0x6f70bc0(%rip),%rdx
ca7fe2:       f6 04 10 10             testb  $0x10,(%rax,%rdx,1)
ca7fe6:       0f 84 25 05 00 00       je     ca8511
ca7fec:       ff 91 98 00 00 00       callq  *0x98(%rcx)
  [...]
ca8511:       0f 0b                   ud2
```

The compiler relies on co-operation from the linker in order to assemble the bit vectors for the whole program. It currently does this using LLVM's type metadata mechanism together with link-time optimization.

Optimizations

The scheme as described above is the fully general variant of the scheme. Most of the time we are able to apply one or more of the following optimizations to improve binary size or performance.

In fact, if you try the above example with the current version of the compiler, you will probably find that it will not use the described virtual table layout or machine instructions. Some of the optimizations we are about to introduce cause the compiler to use a different layout or a different sequence of machine instructions.

Stripping Leading/Trailing Zeros in Bit Vectors

If a bit vector contains leading or trailing zeros, we can strip them from the vector. The compiler will emit code to check if the pointer is in range of the region covered by ones, and perform the bit vector check using a truncated version of the bit vector. For example, the bit vectors for our example class hierarchy will be emitted like this:

Table 4.100: Bit Vectors for A, B, C

Class	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A			1	0	0	0	0	1	0	0	0	0	1		
B								1							
C													1		

Short Inline Bit Vectors

If the vector is sufficiently short, we can represent it as an inline constant on x86. This saves us a few instructions when reading the correct element of the bit vector.

If the bit vector fits in 32 bits, the code looks like this:

```
 dc2:       48 8b 03                mov    (%rbx),%rax
 dc5:       48 8d 15 14 1e 00 00    lea    0x1e14(%rip),%rdx
 dcc:       48 89 c1                mov    %rax,%rcx
 dcf:       48 29 d1                sub    %rdx,%rcx
 dd2:       48 c1 c1 3d             rol    $0x3d,%rcx
 dd6:       48 83 f9 03             cmp    $0x3,%rcx
 dda:       77 2f                   ja     e0b <main+0x9b>
 ddc:       ba 09 00 00 00          mov    $0x9,%edx
 de1:       0f a3 ca                bt     %ecx,%edx
 de4:       73 25                   jae    e0b <main+0x9b>
 de6:       48 89 df                mov    %rbx,%rdi
 de9:       ff 10                   callq  *(%rax)
[...]
 e0b:       0f 0b                   ud2
```

Or if the bit vector fits in 64 bits:

```
11a6:       48 8b 03                mov    (%rbx),%rax
11a9:       48 8d 15 d0 28 00 00    lea    0x28d0(%rip),%rdx
11b0:       48 89 c1                mov    %rax,%rcx
11b3:       48 29 d1                sub    %rdx,%rcx
11b6:       48 c1 c1 3d             rol    $0x3d,%rcx
11ba:       48 83 f9 2a             cmp    $0x2a,%rcx
11be:       77 35                   ja     11f5 <main+0xb5>
11c0:       48 ba 09 00 00 00 00    movabs $0x40000000009,%rdx
11c7:       04 00 00
11ca:       48 0f a3 ca             bt     %rcx,%rdx
11ce:       73 25                   jae    11f5 <main+0xb5>
11d0:       48 89 df                mov    %rbx,%rdi
11d3:       ff 10                   callq  *(%rax)
[...]
11f5:       0f 0b                   ud2
```

If the bit vector consists of a single bit, there is only one possible virtual table, and the check can consist of a single equality comparison:

```
9a2:   48 8b 03                mov    (%rbx),%rax
9a5:   48 8d 0d a4 13 00 00    lea    0x13a4(%rip),%rcx
9ac:   48 39 c8                cmp    %rcx,%rax
9af:   75 25                   jne    9d6 <main+0x86>
9b1:   48 89 df                mov    %rbx,%rdi
9b4:   ff 10                   callq  *(%rax)
```

```
[...]
9d6:   0f 0b                    ud2
```

Virtual Table Layout

The compiler lays out classes of disjoint hierarchies in separate regions of the object file. At worst, bit vectors in disjoint hierarchies only need to cover their disjoint hierarchy. But the closer that classes in sub-hierarchies are laid out to each other, the smaller the bit vectors for those sub-hierarchies need to be (see "Stripping Leading/Trailing Zeros in Bit Vectors" above). The GlobalLayoutBuilder class is responsible for laying out the globals efficiently to minimize the sizes of the underlying bitsets.

Alignment

If all gaps between address points in a particular bit vector are multiples of powers of 2, the compiler can compress the bit vector by strengthening the alignment requirements of the virtual table pointer. For example, given this class hierarchy:

```
struct A {
  virtual void f1();
  virtual void f2();
};

struct B : A {
  virtual void f1();
  virtual void f2();
  virtual void f3();
  virtual void f4();
  virtual void f5();
  virtual void f6();
};

struct C : A {
  virtual void f1();
  virtual void f2();
};
```

The virtual tables will be laid out like this:

Table 4.101: Virtual Table Layout for A, B, C

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A::offset-to-top	&A::rtti	&A::f1	&A::f2	B::offset-to-top	&B::rtti	&B::f1	&B::f2	&B::f3	&B::f4	&B::f5	&B::f6	C::offset-to-top	&C::rtti	&C::f1	&C::f2

Notice that each address point for A is separated by 4 words. This lets us emit a compressed bit vector for A that looks like this:

2	6	10	14
1	1	0	1

At call sites, the compiler will strengthen the alignment requirements by using a different rotate count. For example, on a 64-bit machine where the address points are 4-word aligned (as in A from our example), the `rol` instruction may look like this:

```
dd2:       48 c1 c1 3b             rol    $0x3b,%rcx
```

Padding to Powers of 2

Of course, this alignment scheme works best if the address points are in fact aligned correctly. To make this more likely to happen, we insert padding between virtual tables that in many cases aligns address points to a power of 2. Specifically, our padding aligns virtual tables to the next highest power of 2 bytes; because address points for specific base classes normally appear at fixed offsets within the virtual table, this normally has the effect of aligning the address points as well.

This scheme introduces tradeoffs between decreased space overhead for instructions and bit vectors and increased overhead in the form of padding. We therefore limit the amount of padding so that we align to no more than 128 bytes. This number was found experimentally to provide a good tradeoff.

Eliminating Bit Vector Checks for All-Ones Bit Vectors

If the bit vector is all ones, the bit vector check is redundant; we simply need to check that the address is in range and well aligned. This is more likely to occur if the virtual tables are padded.

Forward-Edge CFI for Indirect Function Calls

Under forward-edge CFI for indirect function calls, each unique function type has its own bit vector, and at each call site we need to check that the function pointer is a member of the function type's bit vector. This scheme works in a similar way to forward-edge CFI for virtual calls, the distinction being that we need to build bit vectors of function entry points rather than of virtual tables.

Unlike when re-arranging global variables, we cannot re-arrange functions in a particular order and base our calculations on the layout of the functions' entry points, as we have no idea how large a particular function will end up being (the function sizes could even depend on how we arrange the functions). Instead, we build a jump table, which is a block of code consisting of one branch instruction for each of the functions in the bit set that branches to the target function, and redirect any taken function addresses to the corresponding jump table entry. In this way, the distance between function entry points is predictable and controllable. In the object file's symbol table, the symbols for the target functions also refer to the jump table entries, so that addresses taken outside the module will pass any verification done inside the module.

In more concrete terms, suppose we have three functions `f`, `g`, `h` which are all of the same type, and a function foo that returns their addresses:

```
f:
mov 0, %eax
ret

g:
mov 1, %eax
ret

h:
mov 2, %eax
ret

foo:
mov f, %eax
mov g, %edx
```

```
mov h, %ecx
ret
```

Our jump table will (conceptually) look like this:

```
f:
jmp .Ltmp0 ; 5 bytes
int3       ; 1 byte
int3       ; 1 byte
int3       ; 1 byte

g:
jmp .Ltmp1 ; 5 bytes
int3       ; 1 byte
int3       ; 1 byte
int3       ; 1 byte

h:
jmp .Ltmp2 ; 5 bytes
int3       ; 1 byte
int3       ; 1 byte
int3       ; 1 byte

.Ltmp0:
mov 0, %eax
ret

.Ltmp1:
mov 1, %eax
ret

.Ltmp2:
mov 2, %eax
ret

foo:
mov f, %eax
mov g, %edx
mov h, %ecx
ret
```

Because the addresses of `f`, `g`, `h` are evenly spaced at a power of 2, and function types do not overlap (unlike class types with base classes), we can normally apply the *Alignment* and *Eliminating Bit Vector Checks for All-Ones Bit Vectors* optimizations thus simplifying the check at each call site to a range and alignment check.

Shared library support

EXPERIMENTAL

The basic CFI mode described above assumes that the application is a monolithic binary; at least that all possible virtual/indirect call targets and the entire class hierarchy are known at link time. The cross-DSO mode, enabled with **-f[no-]sanitize-cfi-cross-dso** relaxes this requirement by allowing virtual and indirect calls to cross the DSO boundary.

Assuming the following setup: the binary consists of several instrumented and several uninstrumented DSOs. Some of them may be dlopen-ed/dlclose-d periodically, even frequently.

- Calls made from uninstrumented DSOs are not checked and just work.

- Calls inside any instrumented DSO are fully protected.
- **Calls between different instrumented DSOs are also protected, with** a performance penalty (in addition to the monolithic CFI overhead).
- **Calls from an instrumented DSO to an uninstrumented one are** unchecked and just work, with performance penalty.
- **Calls from an instrumented DSO outside of any known DSO are** detected as CFI violations.

In the monolithic scheme a call site is instrumented as

```
if (!InlinedFastCheck(f))
  abort();
call *f
```

In the cross-DSO scheme it becomes

```
if (!InlinedFastCheck(f))
  __cfi_slowpath(CallSiteTypeId, f);
call *f
```

CallSiteTypeId

`CallSiteTypeId` is a stable process-wide identifier of the call-site type. For a virtual call site, the type in question is the class type; for an indirect function call it is the function signature. The mapping from a type to an identifier is an ABI detail. In the current, experimental, implementation the identifier of type T is calculated as follows:

- Obtain the mangled name for "typeinfo name for T".
- Calculate MD5 hash of the name as a string.
- Reinterpret the first 8 bytes of the hash as a little-endian 64-bit integer.

It is possible, but unlikely, that collisions in the `CallSiteTypeId` hashing will result in weaker CFI checks that would still be conservatively correct.

CFI_Check

In the general case, only the target DSO knows whether the call to function `f` with type `CallSiteTypeId` is valid or not. To export this information, every DSO implements

```
void __cfi_check(uint64 CallSiteTypeId, void *TargetAddr)
```

This function provides external modules with access to CFI checks for the targets inside this DSO. For each known `CallSiteTypeId`, this function performs an `llvm.type.test` with the corresponding type identifier. It aborts if the type is unknown, or if the check fails.

The basic implementation is a large switch statement over all values of CallSiteTypeId supported by this DSO, and each case is similar to the InlinedFastCheck() in the basic CFI mode.

CFI Shadow

To route CFI checks to the target DSO's __cfi_check function, a mapping from possible virtual / indirect call targets to the corresponding __cfi_check functions is maintained. This mapping is implemented as a sparse array of 2 bytes for every possible page (4096 bytes) of memory. The table is kept readonly (FIXME: not yet) most of the time.

There are 3 types of shadow values:

- Address in a CFI-instrumented DSO.
- Unchecked address (a "trusted" non-instrumented DSO). Encoded as value 0xFFFF.
- Invalid address (everything else). Encoded as value 0.

For a CFI-instrumented DSO, a shadow value encodes the address of the __cfi_check function for all call targets in the corresponding memory page. If Addr is the target address, and V is the shadow value, then the address of __cfi_check is calculated as

```
__cfi_check = AlignUpTo(Addr, 4096) - (V + 1) * 4096
```

This works as long as __cfi_check is aligned by 4096 bytes and located below any call targets in its DSO, but not more than 256MB apart from them.

CFI_SlowPath

The slow path check is implemented in compiler-rt library as

```
void __cfi_slowpath(uint64 CallSiteTypeId, void *TargetAddr)
```

This functions loads a shadow value for `TargetAddr`, finds the address of __cfi_check as described above and calls that.

Position-independent executable requirement

Cross-DSO CFI mode requires that the main executable is built as PIE. In non-PIE executables the address of an external function (taken from the main executable) is the address of that function's PLT record in the main executable. This would break the CFI checks.

Introduction

Clang includes an implementation of a number of control flow integrity (CFI) schemes, which are designed to abort the program upon detecting certain forms of undefined behavior that can potentially allow attackers to subvert the program's control flow. These schemes have been optimized for performance, allowing developers to enable them in release builds.

To enable Clang's available CFI schemes, use the flag `-fsanitize=cfi`. You can also enable a subset of available *schemes*. As currently implemented, all schemes rely on link-time optimization (LTO); so it is required to specify `-flto`, and the linker used must support LTO, for example via the gold plugin.

To allow the checks to be implemented efficiently, the program must be structured such that certain object files are compiled with CFI enabled, and are statically linked into the program. This may preclude the use of shared libraries in some cases.

The compiler will only produce CFI checks for a class if it can infer hidden LTO visibility for that class. LTO visibility is a property of a class that is inferred from flags and attributes. For more details, see the documentation for *LTO visibility*.

The `-fsanitize=cfi-{vcall,nvcall,derived-cast,unrelated-cast}` flags require that a `-fvisibility=` flag also be specified. This is because the default visibility setting is `-fvisibility=default`, which would disable CFI checks for classes without visibility attributes. Most users will want to specify `-fvisibility=hidden`, which enables CFI checks for such classes.

Experimental support for *cross-DSO control flow integrity* exists that does not require classes to have hidden LTO visibility. This cross-DSO support has unstable ABI at this time.

Available schemes

Available schemes are:

- `-fsanitize=cfi-cast-strict`: Enables *strict cast checks*.
- `-fsanitize=cfi-derived-cast`: Base-to-derived cast to the wrong dynamic type.
- `-fsanitize=cfi-unrelated-cast`: Cast from `void*` or another unrelated type to the wrong dynamic type.
- `-fsanitize=cfi-nvcall`: Non-virtual call via an object whose vptr is of the wrong dynamic type.
- `-fsanitize=cfi-vcall`: Virtual call via an object whose vptr is of the wrong dynamic type.
- `-fsanitize=cfi-icall`: Indirect call of a function with wrong dynamic type.

You can use `-fsanitize=cfi` to enable all the schemes and use `-fno-sanitize` flag to narrow down the set of schemes as desired. For example, you can build your program with `-fsanitize=cfi -fno-sanitize=cfi-nvcall,cfi-icall` to use all schemes except for non-virtual member function call and indirect call checking.

Remember that you have to provide `-flto` if at least one CFI scheme is enabled.

Trapping and Diagnostics

By default, CFI will abort the program immediately upon detecting a control flow integrity violation. You can use the *-fno-sanitize-trap=* flag to cause CFI to print a diagnostic similar to the one below before the program aborts.

```
bad-cast.cpp:109:7: runtime error: control flow integrity check for type 'B' failed␣
↪during base-to-derived cast (vtable address 0x000000425a50)
0x000000425a50: note: vtable is of type 'A'
```

```
 00 00 00 00  f0 f1 41 00 00 00 00 00  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00␣
↪00  20 5a 42 00
             ^
```

If diagnostics are enabled, you can also configure CFI to continue program execution instead of aborting by using the *-fsanitize-recover=* flag.

Forward-Edge CFI for Virtual Calls

This scheme checks that virtual calls take place using a vptr of the correct dynamic type; that is, the dynamic type of the called object must be a derived class of the static type of the object used to make the call. This CFI scheme can be enabled on its own using `-fsanitize=cfi-vcall`.

For this scheme to work, all translation units containing the definition of a virtual member function (whether inline or not), other than members of *blacklisted* types, must be compiled with `-fsanitize=cfi-vcall` enabled and be statically linked into the program.

Performance

A performance overhead of less than 1% has been measured by running the Dromaeo benchmark suite against an instrumented version of the Chromium web browser. Another good performance benchmark for this mechanism is the virtual-call-heavy SPEC 2006 xalancbmk.

Note that this scheme has not yet been optimized for binary size; an increase of up to 15% has been observed for Chromium.

Bad Cast Checking

This scheme checks that pointer casts are made to an object of the correct dynamic type; that is, the dynamic type of the object must be a derived class of the pointee type of the cast. The checks are currently only introduced where the class being casted to is a polymorphic class.

Bad casts are not in themselves control flow integrity violations, but they can also create security vulnerabilities, and the implementation uses many of the same mechanisms.

There are two types of bad cast that may be forbidden: bad casts from a base class to a derived class (which can be checked with `-fsanitize=cfi-derived-cast`), and bad casts from a pointer of type `void*` or another unrelated type (which can be checked with `-fsanitize=cfi-unrelated-cast`).

The difference between these two types of casts is that the first is defined by the C++ standard to produce an undefined value, while the second is not in itself undefined behavior (it is well defined to cast the pointer back to its original type) unless the object is uninitialized and the cast is a `static_cast` (see C++14 [basic.life]p5).

If a program as a matter of policy forbids the second type of cast, that restriction can normally be enforced. However it may in some cases be necessary for a function to perform a forbidden cast to conform with an external API (e.g. the `allocate` member function of a standard library allocator). Such functions may be *blacklisted*.

For this scheme to work, all translation units containing the definition of a virtual member function (whether inline or not), other than members of *blacklisted* types, must be compiled with `-fsanitize=cfi-derived-cast` or `-fsanitize=cfi-unrelated-cast` enabled and be statically linked into the program.

Non-Virtual Member Function Call Checking

This scheme checks that non-virtual calls take place using an object of the correct dynamic type; that is, the dynamic type of the called object must be a derived class of the static type of the object used to make the call. The checks are currently only introduced where the object is of a polymorphic class type. This CFI scheme can be enabled on its own using `-fsanitize=cfi-nvcall`.

For this scheme to work, all translation units containing the definition of a virtual member function (whether inline or not), other than members of *blacklisted* types, must be compiled with `-fsanitize=cfi-nvcall` enabled and be statically linked into the program.

Strictness

If a class has a single non-virtual base and does not introduce or override virtual member functions or fields other than an implicitly defined virtual destructor, it will have the same layout and virtual function semantics as its base. By default, casts to such classes are checked as if they were made to the least derived such class.

Casting an instance of a base class to such a derived class is technically undefined behavior, but it is a relatively common hack for introducing member functions on class instances with specific properties that works under most compilers and should not have security implications, so we allow it by default. It can be disabled with `-fsanitize=cfi-cast-strict`.

Indirect Function Call Checking

This scheme checks that function calls take place using a function of the correct dynamic type; that is, the dynamic type of the function must match the static type used at the call. This CFI scheme can be enabled on its own using `-fsanitize=cfi-icall`.

For this scheme to work, each indirect function call in the program, other than calls in *blacklisted* functions, must call a function which was either compiled with `-fsanitize=cfi-icall` enabled, or whose address was taken by a function in a translation unit compiled with `-fsanitize=cfi-icall`.

If a function in a translation unit compiled with `-fsanitize=cfi-icall` takes the address of a function not compiled with `-fsanitize=cfi-icall`, that address may differ from the address taken by a function in a translation unit not compiled with `-fsanitize=cfi-icall`. This is technically a violation of the C and C++ standards, but it should not affect most programs.

Each translation unit compiled with `-fsanitize=cfi-icall` must be statically linked into the program or shared library, and calls across shared library boundaries are handled as if the callee was not compiled with `-fsanitize=cfi-icall`.

This scheme is currently only supported on the x86 and x86_64 architectures.

`-fsanitize=cfi-icall` and `-fsanitize=function`

This tool is similar to `-fsanitize=function` in that both tools check the types of function calls. However, the two tools occupy different points on the design space; `-fsanitize=function` is a developer tool designed to find bugs in local development builds, whereas `-fsanitize=cfi-icall` is a security hardening mechanism designed to be deployed in release builds.

`-fsanitize=function` has a higher space and time overhead due to a more complex type check at indirect call sites, as well as a need for run-time type information (RTTI), which may make it unsuitable for deployment. Because of the need for RTTI, `-fsanitize=function` can only be used with C++ programs, whereas `-fsanitize=cfi-icall` can protect both C and C++ programs.

On the other hand, `-fsanitize=function` conforms more closely with the C++ standard and user expectations around interaction with shared libraries; the identity of function pointers is maintained, and calls across shared library boundaries are no different from calls within a single program or shared library.

Blacklist

A *Sanitizer special case list* can be used to relax CFI checks for certain source files, functions and types using the `src`, `fun` and `type` entity types.

```
# Suppress checking for code in a file.
src:bad_file.cpp
src:bad_header.h
# Ignore all functions with names containing MyFooBar.
fun:*MyFooBar*
# Ignore all types in the standard library.
type:std::*
```

Shared library support

Use **-f[no-]sanitize-cfi-cross-dso** to enable the cross-DSO control flow integrity mode, which allows all CFI schemes listed above to apply across DSO boundaries. As in the regular CFI, each DSO must be built with `-flto`.

Normally, CFI checks will only be performed for classes that have hidden LTO visibility. With this flag enabled, the compiler will emit cross-DSO CFI checks for all classes, except for those which appear in the CFI blacklist or which use a `no_sanitize` attribute.

Design

Please refer to the *design document*.

Publications

Control-Flow Integrity: Principles, Implementations, and Applications. Martin Abadi, Mihai Budiu, Úlfar Erlingsson, Jay Ligatti.

Enforcing Forward-Edge Control-Flow Integrity in GCC & LLVM. Caroline Tice, Tom Roeder, Peter Collingbourne, Stephen Checkoway, Úlfar Erlingsson, Luis Lozano, Geoff Pike.

LTO Visibility

LTO visibility is a property of an entity that specifies whether it can be referenced from outside the current LTO unit. A *linkage unit* is a set of translation units linked together into an executable or DSO, and a linkage unit's *LTO unit* is the subset of the linkage unit that is linked together using link-time optimization; in the case where LTO is not being used, the linkage unit's LTO unit is empty. Each linkage unit has only a single LTO unit.

The LTO visibility of a class is used by the compiler to determine which classes the virtual function call optimization and control flow integrity features apply to. These features use whole-program information, so they require the entire class hierarchy to be visible in order to work correctly.

If any translation unit in the program uses either of the virtual function call optimization or control flow integrity features, it is effectively an ODR violation to define a class with hidden LTO visibility in multiple linkage units. A

class with public LTO visibility may be defined in multiple linkage units, but the tradeoff is that the virtual function call optimization and control flow integrity features can only be applied to classes with hidden LTO visibility. A class's LTO visibility is treated as an ODR-relevant property of its definition, so it must be consistent between translation units.

In translation units built with LTO, LTO visibility is based on the class's symbol visibility as expressed at the source level (i.e. the `__attribute__((visibility("...")))` attribute, or the `-fvisibility=` flag) or, on the Windows platform, the dllimport and dllexport attributes. When targeting non-Windows platforms, classes with a visibility other than hidden visibility receive public LTO visibility. When targeting Windows, classes with dllimport or dllexport attributes receive public LTO visibility. All other classes receive hidden LTO visibility. Classes with internal linkage (e.g. classes declared in unnamed namespaces) also receive hidden LTO visibility.

A class defined in a translation unit built without LTO receives public LTO visibility regardless of its object file visibility, linkage or other attributes.

This mechanism will produce the correct result in most cases, but there are two cases where it may wrongly infer hidden LTO visibility.

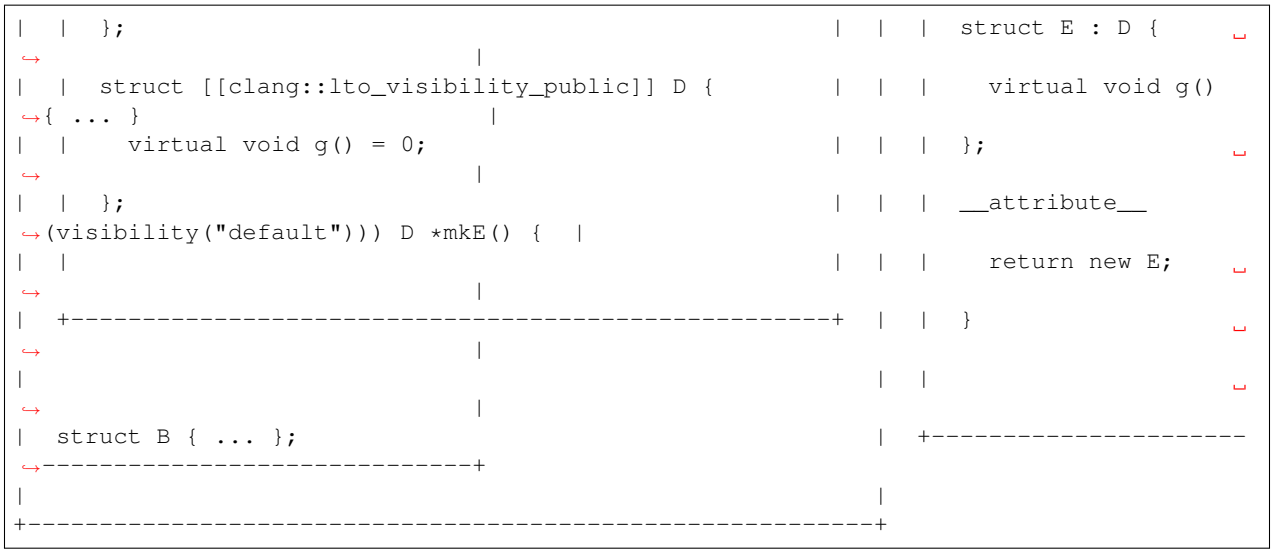
1. As a corollary of the above rules, if a linkage unit is produced from a combination of LTO object files and non-LTO object files, any hidden visibility class defined in both a translation unit built with LTO and a translation unit built without LTO must be defined with public LTO visibility in order to avoid an ODR violation.
2. Some ABIs provide the ability to define an abstract base class without visibility attributes in multiple linkage units and have virtual calls to derived classes in other linkage units work correctly. One example of this is COM on Windows platforms. If the ABI allows this, any base class used in this way must be defined with public LTO visibility.

Classes that fall into either of these categories can be marked up with the `[[clang::lto_visibility_public]]` attribute. To specifically handle the COM case, classes with the `__declspec(uuid())` attribute receive public LTO visibility. On Windows platforms, clang-cl's `/MT` and `/MTd` flags statically link the program against a prebuilt standard library; these flags imply public LTO visibility for every class declared in the `std` and `stdext` namespaces.

Example

The following example shows how LTO visibility works in practice in several cases involving two linkage units, `main` and `dso.so`.

```
+-------------------------------------------------------------+  +----------------------
↪------------------------------+
| main (clang++ -fvisibility=hidden):                         |  | dso.so (clang++ -
↪fvisibility=hidden):              |
|                                                             |  |                      ␣
↪                                |
|  +--------------------------------------------------+       |  |  struct __attribute__
↪((visibility("default"))) C { |
|  | LTO unit (clang++ -fvisibility=hidden -flto):    |       |  |    virtual void f();␣
↪                                |
|  |                                                  |       |  |  }                   ␣
↪                                |
|  |  struct A { ... };                               |       |  |  void C::f() {}      ␣
↪                                |
|  |  struct [[clang::lto_visibility_public]] B { ... }; |    |  |  struct D {          ␣
↪                                |
|  |  struct __attribute__((visibility("default"))) C {  |    |  |    virtual void g()␣
↪= 0;                            |
|  |    virtual void f();                             |       |  |  };                  ␣
↪                                |
```



We will now describe the LTO visibility of each of the classes defined in these linkage units.

Class `A` is not defined outside of `main`'s LTO unit, so it can have hidden LTO visibility. This is inferred from the object file visibility specified on the command line.

Class `B` is defined in `main`, both inside and outside its LTO unit. The definition outside the LTO unit has public LTO visibility, so the definition inside the LTO unit must also have public LTO visibility in order to avoid an ODR violation.

Class `C` is defined in both `main` and `dso.so` and therefore must have public LTO visibility. This is correctly inferred from the `visibility` attribute.

Class `D` is an abstract base class with a derived class `E` defined in `dso.so`. This is an example of the COM scenario; the definition of `D` in `main`'s LTO unit must have public LTO visibility in order to be compatible with the definition of `D` in `dso.so`, which is observable by calling the function `mkE`.

SafeStack

Introduction

SafeStack is an instrumentation pass that protects programs against attacks based on stack buffer overflows, without introducing any measurable performance overhead. It works by separating the program stack into two distinct regions: the safe stack and the unsafe stack. The safe stack stores return addresses, register spills, and local variables that are always accessed in a safe way, while the unsafe stack stores everything else. This separation ensures that buffer overflows on the unsafe stack cannot be used to overwrite anything on the safe stack.

SafeStack is a part of the Code-Pointer Integrity (CPI) Project.

Performance

The performance overhead of the SafeStack instrumentation is less than 0.1% on average across a variety of benchmarks (see the Code-Pointer Integrity paper for details). This is mainly because most small functions do not have any variables that require the unsafe stack and, hence, do not need unsafe stack frames to be created. The cost of creating unsafe stack frames for large functions is amortized by the cost of executing the function.

In some cases, SafeStack actually improves the performance. Objects that end up being moved to the unsafe stack are usually large arrays or variables that are used through multiple stack frames. Moving such objects away from the safe stack increases the locality of frequently accessed values on the stack, such as register spills, return addresses, and small local variables.

Compatibility

Most programs, static libraries, or individual files can be compiled with SafeStack as is. SafeStack requires basic runtime support, which, on most platforms, is implemented as a compiler-rt library that is automatically linked in when the program is compiled with SafeStack.

Linking a DSO with SafeStack is not currently supported.

Known compatibility limitations

Certain code that relies on low-level stack manipulations requires adaption to work with SafeStack. One example is mark-and-sweep garbage collection implementations for C/C++ (e.g., Oilpan in chromium/blink), which must be changed to look for the live pointers on both safe and unsafe stacks.

SafeStack supports linking statically modules that are compiled with and without SafeStack. An executable compiled with SafeStack can load dynamic libraries that are not compiled with SafeStack. At the moment, compiling dynamic libraries with SafeStack is not supported.

Signal handlers that use `sigaltstack()` must not use the unsafe stack (see `__attribute__((no_sanitize("safe-stack")))` below).

Programs that use APIs from `ucontext.h` are not supported yet.

Security

SafeStack protects return addresses, spilled registers and local variables that are always accessed in a safe way by separating them in a dedicated safe stack region. The safe stack is automatically protected against stack-based buffer overflows, since it is disjoint from the unsafe stack in memory, and it itself is always accessed in a safe way. In the current implementation, the safe stack is protected against arbitrary memory write vulnerabilities though randomization and information hiding: the safe stack is allocated at a random address and the instrumentation ensures that no pointers to the safe stack are ever stored outside of the safe stack itself (see limitations below).

Known security limitations

A complete protection against control-flow hijack attacks requires combining SafeStack with another mechanism that enforces the integrity of code pointers that are stored on the heap or the unsafe stack, such as CPI, or a forward-edge control flow integrity mechanism that enforces correct calling conventions at indirect call sites, such as IFCC with arity checks. Clang has control-flow integrity protection scheme for *C++ virtual calls*, but not non-virtual indirect calls. With SafeStack alone, an attacker can overwrite a function pointer on the heap or the unsafe stack and cause a program to call arbitrary location, which in turn might enable stack pivoting and return-oriented programming.

In its current implementation, SafeStack provides precise protection against stack-based buffer overflows, but protection against arbitrary memory write vulnerabilities is probabilistic and relies on randomization and information hiding. The randomization is currently based on system-enforced ASLR and shares its known security limitations. The safe stack pointer hiding is not perfect yet either: system library functions such as `swapcontext`, exception handling mechanisms, intrinsics such as `__builtin_frame_address`, or low-level bugs in runtime support could leak the safe stack pointer. In the future, such leaks could be detected by static or dynamic analysis tools and prevented by adjusting such functions to either encrypt the stack pointer when storing it in the heap (as already done e.g., by `setjmp`/`longjmp` implementation in glibc), or store it in a safe region instead.

The CPI paper describes two alternative, stronger safe stack protection mechanisms, that rely on software fault isolation, or hardware segmentation (as available on x86-32 and some x86-64 CPUs).

At the moment, SafeStack assumes that the compiler's implementation is correct. This has not been verified except through manual code inspection, and could always regress in the future. It's therefore desirable to have a separate static or dynamic binary verification tool that would check the correctness of the SafeStack instrumentation in final binaries.

Usage

To enable SafeStack, just pass `-fsanitize=safe-stack` flag to both compile and link command lines.

Supported Platforms

SafeStack was tested on Linux, FreeBSD and MacOSX.

Low-level API

`__has_feature(safe_stack)`

In some rare cases one may need to execute different code depending on whether SafeStack is enabled. The macro `__has_feature(safe_stack)` can be used for this purpose.

```
#if __has_feature(safe_stack)
// code that builds only under SafeStack
#endif
```

__attribute__((no_sanitize("safe-stack")))

Use `__attribute__((no_sanitize("safe-stack")))` on a function declaration to specify that the safe stack instrumentation should not be applied to that function, even if enabled globally (see `-fsanitize=safe-stack` flag). This attribute may be required for functions that make assumptions about the exact layout of their stack frames.

All local variables in functions with this attribute will be stored on the safe stack. The safe stack remains unprotected against memory errors when accessing these variables, so extra care must be taken to manually ensure that all such accesses are safe. Furthermore, the addresses of such local variables should never be stored on the heap, as it would leak the location of the SafeStack.

__builtin___get_unsafe_stack_ptr()

This builtin function returns current unsafe stack pointer of the current thread.

__builtin___get_unsafe_stack_start()

This builtin function returns a pointer to the start of the unsafe stack of the current thread.

Design

Please refer to the Code-Pointer Integrity project page for more information about the design of the SafeStack and its related technologies.

setjmp and exception handling

The OSDI'14 paper mentions that on Linux the instrumentation pass finds calls to setjmp or functions that may throw an exception, and inserts required instrumentation at their call sites. Specifically, the instrumentation pass saves the shadow stack pointer on the safe stack before the call site, and restores it either after the call to setjmp or after an exception has been caught. This is implemented in the function `SafeStack::createStackRestorePoints`.

Publications

Code-Pointer Integrity. Volodymyr Kuznetsov, Laszlo Szekeres, Mathias Payer, George Candea, R. Sekar, Dawn Song. USENIX Symposium on Operating Systems Design and Implementation (OSDI), Broomfield, CO, October 2014

Source-based Code Coverage

Introduction

This document explains how to use clang's source-based code coverage feature. It's called "source-based" because it operates on AST and preprocessor information directly. This allows it to generate very precise coverage data.

Clang ships two other code coverage implementations:

- *SanitizerCoverage* - A low-overhead tool meant for use alongside the various sanitizers. It can provide up to edge-level coverage.
- gcov - A GCC-compatible coverage implementation which operates on DebugInfo.

From this point onwards "code coverage" will refer to the source-based kind.

The code coverage workflow

The code coverage workflow consists of three main steps:

- Compiling with coverage enabled.
- Running the instrumented program.
- Creating coverage reports.

The next few sections work through a complete, copy-'n-paste friendly example based on this program:

```
% cat <<EOF > foo.cc
#define BAR(x) ((x) || (x))
template <typename T> void foo(T x) {
  for (unsigned I = 0; I < 10; ++I) { BAR(I); }
}
int main() {
  foo<int>(0);
  foo<float>(0);
  return 0;
}
EOF
```

Compiling with coverage enabled

To compile code with coverage enabled, pass `-fprofile-instr-generate -fcoverage-mapping` to the compiler:

```
# Step 1: Compile with coverage enabled.
% clang++ -fprofile-instr-generate -fcoverage-mapping foo.cc -o foo
```

Note that linking together code with and without coverage instrumentation is supported: any uninstrumented code simply won't be accounted for.

Running the instrumented program

The next step is to run the instrumented program. When the program exits it will write a **raw profile** to the path specified by the `LLVM_PROFILE_FILE` environment variable. If that variable does not exist, the profile is written to `default.profraw` in the current directory of the program. If `LLVM_PROFILE_FILE` contains a path to a non-existent directory, the missing directory structure will be created. Additionally, the following special **pattern strings** are rewritten:

- "%p" expands out to the process ID.
- "%h" expands out to the hostname of the machine running the program.
- "%Nm" expands out to the instrumented binary's signature. When this pattern is specified, the runtime creates a pool of N raw profiles which are used for on-line profile merging. The runtime takes care of selecting a raw profile from the pool, locking it, and updating it before the program exits. If N is not specified (i.e the pattern is "%m"), it's assumed that `N = 1`. N must be between 1 and 9. The merge pool specifier can only occur once per filename pattern.

```
# Step 2: Run the program.
% LLVM_PROFILE_FILE="foo.profraw" ./foo
```

Creating coverage reports

Raw profiles have to be **indexed** before they can be used to generate coverage reports. This is done using the "merge" tool in `llvm-profdata`, so named because it can combine and index profiles at the same time:

```
# Step 3(a): Index the raw profile.
% llvm-profdata merge -sparse foo.profraw -o foo.profdata
```

There are multiple different ways to render coverage reports. One option is to generate a line-oriented report:

```
# Step 3(b): Create a line-oriented coverage report.
% llvm-cov show ./foo -instr-profile=foo.profdata
```

To demangle any C++ identifiers in the output, use:

```
% llvm-cov show ./foo -instr-profile=foo.profdata | c++filt -n
```

This report includes a summary view as well as dedicated sub-views for templated functions and their instantiations. For our example program, we get distinct views for `foo<int>(...)` and `foo<float>(...)`. If `-show-line-counts-or-regions` is enabled, `llvm-cov` displays sub-line region counts (even in macro expansions):

```
  20|    1|#define BAR(x) ((x) || (x))
                          ^20     ^2
   2|    2|template <typename T> void foo(T x) {
  22|    3|  for (unsigned I = 0; I < 10; ++I) { BAR(I); }
                                  ^22     ^20  ^20^20
   2|    4|}
```

```
------------------
| void foo<int>(int):
|      1|    2|template <typename T> void foo(T x) {
|     11|    3|  for (unsigned I = 0; I < 10; ++I) { BAR(I); }
|                                    ^11     ^10  ^10^10
|      1|    4|}
------------------
| void foo<float>(int):
|      1|    2|template <typename T> void foo(T x) {
|     11|    3|  for (unsigned I = 0; I < 10; ++I) { BAR(I); }
|                                    ^11     ^10  ^10^10
|      1|    4|}
------------------
```

It's possible to generate a file-level summary of coverage statistics (instead of a line-oriented report) with:

```
# Step 3(c): Create a coverage summary.
% llvm-cov report ./foo -instr-profile=foo.profdata
Filename                      Regions    Miss   Cover Functions  Executed
-----------------------------------------------------------------------
/tmp/foo.cc                        13       0 100.00%         3   100.00%
-----------------------------------------------------------------------
TOTAL                              13       0 100.00%         3   100.00%
```

A few final notes:

- The `-sparse` flag is optional but can result in dramatically smaller indexed profiles. This option should not be used if the indexed profile will be reused for PGO.
- Raw profiles can be discarded after they are indexed. Advanced use of the profile runtime library allows an instrumented program to merge profiling information directly into an existing raw profile on disk. The details are out of scope.
- The `llvm-profdata` tool can be used to merge together multiple raw or indexed profiles. To combine profiling data from multiple runs of a program, try e.g:

```
% llvm-profdata merge -sparse foo1.profraw foo2.profdata -o foo3.profdata
```

Format compatibility guarantees

- There are no backwards or forwards compatibility guarantees for the raw profile format. Raw profiles may be dependent on the specific compiler revision used to generate them. It's inadvisable to store raw profiles for long periods of time.
- Tools must retain **backwards** compatibility with indexed profile formats. These formats are not forwards-compatible: i.e, a tool which uses format version X will not be able to understand format version (X+k).
- There is a third format in play: the format of the coverage mappings emitted into instrumented binaries. Tools must retain **backwards** compatibility with these formats. These formats are not forwards-compatible.

Using the profiling runtime without static initializers

By default the compiler runtime uses a static initializer to determine the profile output path and to register a writer function. To collect profiles without using static initializers, do this manually:

- Export a `int __llvm_profile_runtime` symbol from each instrumented shared library and executable. When the linker finds a definition of this symbol, it knows to skip loading the object which contains the profiling runtime's static initializer.
- Forward-declare `void __llvm_profile_initialize_file(void)` and call it once from each instrumented executable. This function parses `LLVM_PROFILE_FILE`, sets the output path, and truncates any existing files at that path. To get the same behavior without truncating existing files, pass a filename pattern string to `void __llvm_profile_set_filename(char *)`. These calls can be placed anywhere so long as they precede all calls to `__llvm_profile_write_file`.
- Forward-declare `int __llvm_profile_write_file(void)` and call it to write out a profile. This function returns 0 when it succeeds, and a non-zero value otherwise. Calling this function multiple times appends profile data to an existing on-disk raw profile.

Drawbacks and limitations

- Code coverage does not handle unpredictable changes in control flow or stack unwinding in the presence of exceptions precisely. Consider the following function:

```
int f() {
  may_throw();
  return 0;
}
```

  If the call to `may_throw()` propagates an exception into `f`, the code coverage tool may mark the `return` statement as executed even though it is not. A call to `longjmp()` can have similar effects.

Modules

Introduction

Most software is built using a number of software libraries, including libraries supplied by the platform, internal libraries built as part of the software itself to provide structure, and third-party libraries. For each library, one needs to access both its interface (API) and its implementation. In the C family of languages, the interface to a library is accessed by including the appropriate header files(s):

```
#include <SomeLib.h>
```

The implementation is handled separately by linking against the appropriate library. For example, by passing `-lSomeLib` to the linker.

Modules provide an alternative, simpler way to use software libraries that provides better compile-time scalability and eliminates many of the problems inherent to using the C preprocessor to access the API of a library.

Problems with the current model

The `#include` mechanism provided by the C preprocessor is a very poor way to access the API of a library, for a number of reasons:

- **Compile-time scalability**: Each time a header is included, the compiler must preprocess and parse the text in that header and every header it includes, transitively. This process must be repeated for every translation unit in the application, which involves a huge amount of redundant work. In a project with *N* translation units and *M* headers included in each translation unit, the compiler is performing *M x N* work even though most of the *M* headers are shared among multiple translation units. C++ is particularly bad, because the compilation model for templates forces a huge amount of code into headers.
- **Fragility**: `#include` directives are treated as textual inclusion by the preprocessor, and are therefore subject to any active macro definitions at the time of inclusion. If any of the active macro definitions happens to collide with a name in the library, it can break the library API or cause compilation failures in the library header itself. For

an extreme example, `#define std "The C++ Standard"` and then include a standard library header: the result is a horrific cascade of failures in the C++ Standard Library's implementation. More subtle real-world problems occur when the headers for two different libraries interact due to macro collisions, and users are forced to reorder `#include` directives or introduce `#undef` directives to break the (unintended) dependency.

- **Conventional workarounds**: C programmers have adopted a number of conventions to work around the fragility of the C preprocessor model. Include guards, for example, are required for the vast majority of headers to ensure that multiple inclusion doesn't break the compile. Macro names are written with `LONG_PREFIXED_UPPERCASE_IDENTIFIERS` to avoid collisions, and some library/framework developers even use `__underscored` names in headers to avoid collisions with "normal" names that (by convention) shouldn't even be macros. These conventions are a barrier to entry for developers coming from non-C languages, are boilerplate for more experienced developers, and make our headers far uglier than they should be.
- **Tool confusion**: In a C-based language, it is hard to build tools that work well with software libraries, because the boundaries of the libraries are not clear. Which headers belong to a particular library, and in what order should those headers be included to guarantee that they compile correctly? Are the headers C, C++, Objective-C++, or one of the variants of these languages? What declarations in those headers are actually meant to be part of the API, and what declarations are present only because they had to be written as part of the header file?

Semantic import

Modules improve access to the API of software libraries by replacing the textual preprocessor inclusion model with a more robust, more efficient semantic model. From the user's perspective, the code looks only slightly different, because one uses an `import` declaration rather than a `#include` preprocessor directive:

```
import std.io; // pseudo-code; see below for syntax discussion
```

However, this module import behaves quite differently from the corresponding `#include <stdio.h>`: when the compiler sees the module import above, it loads a binary representation of the `std.io` module and makes its API available to the application directly. Preprocessor definitions that precede the import declaration have no impact on the API provided by `std.io`, because the module itself was compiled as a separate, standalone module. Additionally, any linker flags required to use the `std.io` module will automatically be provided when the module is imported[1] This semantic import model addresses many of the problems of the preprocessor inclusion model:

- **Compile-time scalability**: The `std.io` module is only compiled once, and importing the module into a translation unit is a constant-time operation (independent of module system). Thus, the API of each software library is only parsed once, reducing the *M x N* compilation problem to an *M + N* problem.
- **Fragility**: Each module is parsed as a standalone entity, so it has a consistent preprocessor environment. This completely eliminates the need for `__underscored` names and similarly defensive tricks. Moreover, the current preprocessor definitions when an import declaration is encountered are ignored, so one software library can not affect how another software library is compiled, eliminating include-order dependencies.
- **Tool confusion**: Modules describe the API of software libraries, and tools can reason about and present a module as a representation of that API. Because modules can only be built standalone, tools can rely on the module definition to ensure that they get the complete API for the library. Moreover, modules can specify which languages they work with, so, e.g., one can not accidentally attempt to load a C++ module into a C program.

Problems modules do not solve

Many programming languages have a module or package system, and because of the variety of features provided by these languages it is important to define what modules do *not* do. In particular, all of the following are considered out-of-scope for modules:

[1] Automatic linking against the libraries of modules requires specific linker support, which is not widely available.

- **Rewrite the world's code**: It is not realistic to require applications or software libraries to make drastic or non-backward-compatible changes, nor is it feasible to completely eliminate headers. Modules must interoperate with existing software libraries and allow a gradual transition.
- **Versioning**: Modules have no notion of version information. Programmers must still rely on the existing versioning mechanisms of the underlying language (if any exist) to version software libraries.
- **Namespaces**: Unlike in some languages, modules do not imply any notion of namespaces. Thus, a struct declared in one module will still conflict with a struct of the same name declared in a different module, just as they would if declared in two different headers. This aspect is important for backward compatibility, because (for example) the mangled names of entities in software libraries must not change when introducing modules.
- **Binary distribution of modules**: Headers (particularly C++ headers) expose the full complexity of the language. Maintaining a stable binary module format across architectures, compiler versions, and compiler vendors is technically infeasible.

Using Modules

To enable modules, pass the command-line flag `-fmodules`. This will make any modules-enabled software libraries available as modules as well as introducing any modules-specific syntax. Additional *command-line parameters* are described in a separate section later.

Objective-C Import declaration

Objective-C provides syntax for importing a module via an *@import declaration*, which imports the named module:

```
@import std;
```

The `@import` declaration above imports the entire contents of the `std` module (which would contain, e.g., the entire C or C++ standard library) and make its API available within the current translation unit. To import only part of a module, one may use dot syntax to specific a particular submodule, e.g.,

```
@import std.io;
```

Redundant import declarations are ignored, and one is free to import modules at any point within the translation unit, so long as the import declaration is at global scope.

At present, there is no C or C++ syntax for import declarations. Clang will track the modules proposal in the C++ committee. See the section *Includes as imports* to see how modules get imported today.

Includes as imports

The primary user-level feature of modules is the import operation, which provides access to the API of software libraries. However, today's programs make extensive use of `#include`, and it is unrealistic to assume that all of this code will change overnight. Instead, modules automatically translate `#include` directives into the corresponding module import. For example, the include directive

```
#include <stdio.h>
```

will be automatically mapped to an import of the module `std.io`. Even with specific `import` syntax in the language, this particular feature is important for both adoption and backward compatibility: automatic translation of `#include` to `import` allows an application to get the benefits of modules (for all modules-enabled libraries) without any changes to the application itself. Thus, users can easily use modules with one compiler while falling back to the preprocessor-inclusion mechanism with other compilers.

Note: The automatic mapping of `#include` to `import` also solves an implementation problem: importing a module with a definition of some entity (say, a `struct Point`) and then parsing a header containing another definition of `struct Point` would cause a redefinition error, even if it is the same `struct Point`. By mapping `#include` to `import`, the compiler can guarantee that it always sees just the already-parsed definition from the module.

While building a module, `#include_next` is also supported, with one caveat. The usual behavior of `#include_next` is to search for the specified filename in the list of include paths, starting from the path *after* the one in which the current file was found. Because files listed in module maps are not found through include paths, a different strategy is used for `#include_next` directives in such files: the list of include paths is searched for the specified header name, to find the first include path that would refer to the current file. `#include_next` is interpreted as if the current file had been found in that path. If this search finds a file named by a module map, the `#include_next` directive is translated into an import, just like for a `#include` directive.‘‘

Module maps

The crucial link between modules and headers is described by a *module map*, which describes how a collection of existing headers maps on to the (logical) structure of a module. For example, one could imagine a module `std` covering the C standard library. Each of the C standard library headers (`<stdio.h>`, `<stdlib.h>`, `<math.h>`, etc.) would contribute to the `std` module, by placing their respective APIs into the corresponding submodule (`std.io`, `std.lib`, `std.math`, etc.). Having a list of the headers that are part of the `std` module allows the compiler to build the `std` module as a standalone entity, and having the mapping from header names to (sub)modules allows the automatic translation of `#include` directives to module imports.

Module maps are specified as separate files (each named `module.modulemap`) alongside the headers they describe, which allows them to be added to existing software libraries without having to change the library headers themselves (in most cases[2]). The actual *Module map language* is described in a later section.

Note: To actually see any benefits from modules, one first has to introduce module maps for the underlying C standard library and the libraries and headers on which it depends. The section *Modularizing a Platform* describes the steps one must take to write these module maps.

One can use module maps without modules to check the integrity of the use of header files. To do this, use the `-fimplicit-module-maps` option instead of the `-fmodules` option, or use `-fmodule-map-file=` option to explicitly specify the module map files to load.

Compilation model

The binary representation of modules is automatically generated by the compiler on an as-needed basis. When a module is imported (e.g., by an `#include` of one of the module's headers), the compiler will spawn a second instance of itself[3], with a fresh preprocessing context[4], to parse just the headers in that module. The resulting Abstract Syntax Tree (AST) is then persisted into the binary representation of the module that is then loaded into translation unit where the module import was encountered.

[2] There are certain anti-patterns that occur in headers, particularly system headers, that cause problems for modules. The section *Modularizing a Platform* describes some of them.

[3] The second instance is actually a new thread within the current process, not a separate process. However, the original compiler instance is blocked on the execution of this thread.

[4] The preprocessing context in which the modules are parsed is actually dependent on the command-line options provided to the compiler, including the language dialect and any `-D` options. However, the compiled modules for different command-line options are kept distinct, and any preprocessor directives that occur within the translation unit are ignored. See the section on the *Configuration macros declaration* for more information.

The binary representation of modules is persisted in the *module cache*. Imports of a module will first query the module cache and, if a binary representation of the required module is already available, will load that representation directly. Thus, a module's headers will only be parsed once per language configuration, rather than once per translation unit that uses the module.

Modules maintain references to each of the headers that were part of the module build. If any of those headers changes, or if any of the modules on which a module depends change, then the module will be (automatically) recompiled. The process should never require any user intervention.

Command-line parameters

-fmodules Enable the modules feature.

-fimplicit-module-maps Enable implicit search for module map files named `module.modulemap` and similar. This option is implied by `-fmodules`. If this is disabled with `-fno-implicit-module-maps`, module map files will only be loaded if they are explicitly specified via `-fmodule-map-file` or transitively used by another module map file.

-fmodules-cache-path=<directory> Specify the path to the modules cache. If not provided, Clang will select a system-appropriate default.

-fno-autolink Disable automatic linking against the libraries associated with imported modules.

-fmodules-ignore-macro=macroname Instruct modules to ignore the named macro when selecting an appropriate module variant. Use this for macros defined on the command line that don't affect how modules are built, to improve sharing of compiled module files.

-fmodules-prune-interval=seconds Specify the minimum delay (in seconds) between attempts to prune the module cache. Module cache pruning attempts to clear out old, unused module files so that the module cache itself does not grow without bound. The default delay is large (604,800 seconds, or 7 days) because this is an expensive operation. Set this value to 0 to turn off pruning.

-fmodules-prune-after=seconds Specify the minimum time (in seconds) for which a file in the module cache must be unused (according to access time) before module pruning will remove it. The default delay is large (2,678,400 seconds, or 31 days) to avoid excessive module rebuilding.

-module-file-info <module file name> Debugging aid that prints information about a given module file (with a `.pcm` extension), including the language and preprocessor options that particular module variant was built with.

-fmodules-decluse Enable checking of module `use` declarations.

-fmodule-name=module-id Consider a source file as a part of the given module.

-fmodule-map-file=<file> Load the given module map file if a header from its directory or one of its subdirectories is loaded.

-fmodules-search-all If a symbol is not found, search modules referenced in the current module maps but not imported for symbols, so the error message can reference the module by name. Note that if the global module index has not been built before, this might take some time as it needs to build all the modules. Note that this option doesn't apply in module builds, to avoid the recursion.

-fno-implicit-modules All modules used by the build must be specified with `-fmodule-file`.

-fmodule-file=<file> Load the given precompiled module file.

Module Semantics

Modules are modeled as if each submodule were a separate translation unit, and a module import makes names from the other translation unit visible. Each submodule starts with a new preprocessor state and an empty translation unit.

Note: This behavior is currently only approximated when building a module with submodules. Entities within a submodule that has already been built are visible when building later submodules in that module. This can lead to fragile modules that depend on the build order used for the submodules of the module, and should not be relied upon. This behavior is subject to change.

As an example, in C, this implies that if two structs are defined in different submodules with the same name, those two types are distinct types (but may be *compatible* types if their definitions match). In C++, two structs defined with the same name in different submodules are the *same* type, and must be equivalent under C++'s One Definition Rule.

Note: Clang currently only performs minimal checking for violations of the One Definition Rule.

If any submodule of a module is imported into any part of a program, the entire top-level module is considered to be part of the program. As a consequence of this, Clang may diagnose conflicts between an entity declared in an unimported submodule and an entity declared in the current translation unit, and Clang may inline or devirtualize based on knowledge from unimported submodules.

Macros

The C and C++ preprocessor assumes that the input text is a single linear buffer, but with modules this is not the case. It is possible to import two modules that have conflicting definitions for a macro (or where one `#defines` a macro and the other `#undef`ines it). The rules for handling macro definitions in the presence of modules are as follows:

- Each definition and undefinition of a macro is considered to be a distinct entity.
- Such entities are *visible* if they are from the current submodule or translation unit, or if they were exported from a submodule that has been imported.
- A `#define X` or `#undef X` directive *overrides* all definitions of `X` that are visible at the point of the directive.
- A `#define` or `#undef` directive is *active* if it is visible and no visible directive overrides it.
- A set of macro directives is *consistent* if it consists of only `#undef` directives, or if all `#define` directives in the set define the macro name to the same sequence of tokens (following the usual rules for macro redefinitions).
- If a macro name is used and the set of active directives is not consistent, the program is ill-formed. Otherwise, the (unique) meaning of the macro name is used.

For example, suppose:

- `<stdio.h>` defines a macro `getc` (and exports its `#define`)
- `<cstdio>` imports the `<stdio.h>` module and undefines the macro (and exports its `#undef`)

The `#undef` overrides the `#define`, and a source file that imports both modules *in any order* will not see `getc` defined as a macro.

Module Map Language

Warning: The module map language is not currently guaranteed to be stable between major revisions of Clang.

The module map language describes the mapping from header files to the logical structure of modules. To enable support for using a library as a module, one must write a `module.modulemap` file for that library. The `module.modulemap` file is placed alongside the header files themselves, and is written in the module map language described below.

Note: For compatibility with previous releases, if a module map file named `module.modulemap` is not found, Clang will also search for a file named `module.map`. This behavior is deprecated and we plan to eventually remove it.

As an example, the module map file for the C standard library might look a bit like this:

```
module std [system] [extern_c] {
  module assert {
    textual header "assert.h"
    header "bits/assert-decls.h"
    export *
  }

  module complex {
    header "complex.h"
    export *
  }

  module ctype {
    header "ctype.h"
    export *
  }

  module errno {
    header "errno.h"
    header "sys/errno.h"
    export *
  }

  module fenv {
    header "fenv.h"
    export *
  }

  // ...more headers follow...
}
```

Here, the top-level module `std` encompasses the whole C standard library. It has a number of submodules containing different parts of the standard library: `complex` for complex numbers, `ctype` for character types, etc. Each submodule lists one of more headers that provide the contents for that submodule. Finally, the `export *` command specifies that anything included by that submodule will be automatically re-exported.

Lexical structure

Module map files use a simplified form of the C99 lexer, with the same rules for identifiers, tokens, string literals, `/* */` and `//` comments. The module map language has the following reserved words; all other C identifiers are valid identifiers.

```
config_macros export     private
conflict      framework  requires
exclude       header     textual
explicit      link       umbrella
extern        module     use
```

Module map file

A module map file consists of a series of module declarations:

```
module-map-file:
  module-declaration*
```

Within a module map file, modules are referred to by a *module-id*, which uses periods to separate each part of a module's name:

```
module-id:
  identifier ('.' identifier)*
```

Module declaration

A module declaration describes a module, including the headers that contribute to that module, its submodules, and other aspects of the module.

```
module-declaration:
  explicit$_opt$ framework$_opt$ module module-id attributes$_opt$ '{' module-
↪member* '}'
  extern module module-id string-literal
```

The *module-id* should consist of only a single *identifier*, which provides the name of the module being defined. Each module shall have a single definition.

The `explicit` qualifier can only be applied to a submodule, i.e., a module that is nested within another module. The contents of explicit submodules are only made available when the submodule itself was explicitly named in an import declaration or was re-exported from an imported module.

The `framework` qualifier specifies that this module corresponds to a Darwin-style framework. A Darwin-style framework (used primarily on Mac OS X and iOS) is contained entirely in directory `Name.framework`, where `Name` is the name of the framework (and, therefore, the name of the module). That directory has the following layout:

```
Name.framework/
  Modules/module.modulemap  Module map for the framework
  Headers/                  Subdirectory containing framework headers
  Frameworks/               Subdirectory containing embedded frameworks
  Resources/                Subdirectory containing additional resources
  Name                      Symbolic link to the shared library for the framework
```

The `system` attribute specifies that the module is a system module. When a system module is rebuilt, all of the module's headers will be considered system headers, which suppresses warnings. This is equivalent to placing `#pragma GCC system_header` in each of the module's headers. The form of attributes is described in the section *Attributes*, below.

The `extern_c` attribute specifies that the module contains C code that can be used from within C++. When such a module is built for use in C++ code, all of the module's headers will be treated as if they were contained within an implicit `extern "C"` block. An import for a module with this attribute can appear within an `extern "C"` block. No other restrictions are lifted, however: the module currently cannot be imported within an `extern "C"` block in a namespace.

Modules can have a number of different kinds of members, each of which is described below:

```
module-member:
  requires-declaration
  header-declaration
  umbrella-dir-declaration
  submodule-declaration
  export-declaration
  use-declaration
  link-declaration
  config-macros-declaration
  conflict-declaration
```

An extern module references a module defined by the *module-id* in a file given by the *string-literal*. The file can be referenced either by an absolute path or by a path relative to the current map file.

Requires declaration

A *requires-declaration* specifies the requirements that an importing translation unit must satisfy to use the module.

```
requires-declaration:
  requires feature-list

feature-list:
  feature (',' feature)*

feature:
  !$_opt$ identifier
```

The requirements clause allows specific modules or submodules to specify that they are only accessible with certain language dialects or on certain platforms. The feature list is a set of identifiers, defined below. If any of the features is not available in a given translation unit, that translation unit shall not import the module. The optional `!` indicates that a feature is incompatible with the module.

The following features are defined:

altivec The target supports AltiVec.

blocks The "blocks" language feature is available.

cplusplus C++ support is available.

cplusplus11 C++11 support is available.

objc Objective-C support is available.

objc_arc Objective-C Automatic Reference Counting (ARC) is available

opencl OpenCL is available

tls Thread local storage is available.

target feature A specific target feature (e.g., `sse4`, `avx`, `neon`) is available.

Example: The `std` module can be extended to also include C++ and C++11 headers using a *requires-declaration*:

```
module std {
   // C standard library...

   module vector {
     requires cplusplus
     header "vector"
   }

   module type_traits {
     requires cplusplus11
     header "type_traits"
   }
 }
```

Header declaration

A header declaration specifies that a particular header is associated with the enclosing module.

header-declaration:
  private$_opt$ textual$_opt$ header *string-literal*
  umbrella header *string-literal*
  exclude header *string-literal*

A header declaration that does not contain `exclude` nor `textual` specifies a header that contributes to the enclosing module. Specifically, when the module is built, the named header will be parsed and its declarations will be (logically) placed into the enclosing submodule.

A header with the `umbrella` specifier is called an umbrella header. An umbrella header includes all of the headers within its directory (and any subdirectories), and is typically used (in the `#include` world) to easily access the full API provided by a particular library. With modules, an umbrella header is a convenient shortcut that eliminates the need to write out `header` declarations for every library header. A given directory can only contain a single umbrella header.

Note: Any headers not included by the umbrella header should have explicit `header` declarations. Use the `-Wincomplete-umbrella` warning option to ask Clang to complain about headers not covered by the umbrella header or the module map.

A header with the `private` specifier may not be included from outside the module itself.

A header with the `textual` specifier will not be compiled when the module is built, and will be textually included if it is named by a `#include` directive. However, it is considered to be part of the module for the purpose of checking *use-declaration*s, and must still be a lexically-valid header file. In the future, we intend to pre-tokenize such headers and include the token sequence within the prebuilt module representation.

A header with the `exclude` specifier is excluded from the module. It will not be included when the module is built, nor will it be considered to be part of the module, even if an `umbrella` header or directory would otherwise make it part of the module.

Example: The C header `assert.h` is an excellent candidate for a textual header, because it is meant to be included multiple times (possibly with different `NDEBUG` settings). However, declarations within it should typically be split into a separate modular header.

```
module std [system] {
  textual header "assert.h"
}
```

A given header shall not be referenced by more than one *header-declaration*.

Umbrella directory declaration

An umbrella directory declaration specifies that all of the headers in the specified directory should be included within the module.

```
umbrella-dir-declaration:
  umbrella string-literal
```

The *string-literal* refers to a directory. When the module is built, all of the header files in that directory (and its subdirectories) are included in the module.

An *umbrella-dir-declaration* shall not refer to the same directory as the location of an umbrella *header-declaration*. In other words, only a single kind of umbrella can be specified for a given directory.

Note: Umbrella directories are useful for libraries that have a large number of headers but do not have an umbrella header.

Submodule declaration

Submodule declarations describe modules that are nested within their enclosing module.

```
submodule-declaration:
  module-declaration
  inferred-submodule-declaration
```

A *submodule-declaration* that is a *module-declaration* is a nested module. If the *module-declaration* has a `framework` specifier, the enclosing module shall have a `framework` specifier; the submodule's contents shall be contained within the subdirectory `Frameworks/SubName.framework`, where `SubName` is the name of the submodule.

A *submodule-declaration* that is an *inferred-submodule-declaration* describes a set of submodules that correspond to any headers that are part of the module but are not explicitly described by a *header-declaration*.

```
inferred-submodule-declaration:
  explicit$_opt$ framework$_opt$ module '*' attributes$_opt$ '{' inferred-
↪submodule-member* '}'

inferred-submodule-member:
  export '*'
```

A module containing an *inferred-submodule-declaration* shall have either an umbrella header or an umbrella directory. The headers to which the *inferred-submodule-declaration* applies are exactly those headers included by the umbrella header (transitively) or included in the module because they reside within the umbrella directory (or its subdirectories).

For each header included by the umbrella header or in the umbrella directory that is not named by a *header-declaration*, a module declaration is implicitly generated from the *inferred-submodule-declaration*. The module will:

- Have the same name as the header (without the file extension)
- Have the `explicit` specifier, if the *inferred-submodule-declaration* has the `explicit` specifier
- Have the `framework` specifier, if the *inferred-submodule-declaration* has the `framework` specifier
- Have the attributes specified by the *inferred-submodule-declaration*

- Contain a single *header-declaration* naming that header
- Contain a single *export-declaration* `export *`, if the *inferred-submodule-declaration* contains the *inferred-submodule-member* `export *`

Example: If the subdirectory "MyLib" contains the headers `A.h` and `B.h`, then the following module map:

```
module MyLib {
  umbrella "MyLib"
  explicit module * {
    export *
  }
}
```

is equivalent to the (more verbose) module map:

```
module MyLib {
  explicit module A {
    header "A.h"
    export *
  }

  explicit module B {
    header "B.h"
    export *
  }
}
```

Export declaration

An *export-declaration* specifies which imported modules will automatically be re-exported as part of a given module's API.

export-declaration:
  export *wildcard-module-id*

wildcard-module-id:
  identifier
  '*'
  identifier '.' *wildcard-module-id*

The *export-declaration* names a module or a set of modules that will be re-exported to any translation unit that imports the enclosing module. Each imported module that matches the *wildcard-module-id* up to, but not including, the first `*` will be re-exported.

Example: In the following example, importing `MyLib.Derived` also provides the API for `MyLib.Base`:

```
module MyLib {
  module Base {
    header "Base.h"
  }

  module Derived {
    header "Derived.h"
    export Base
  }
}
```

Note that, if `Derived.h` includes `Base.h`, one can simply use a wildcard export to re-export everything `Derived.h` includes:

```
module MyLib {
  module Base {
    header "Base.h"
  }

  module Derived {
    header "Derived.h"
    export *
  }
}
```

Note: The wildcard export syntax `export *` re-exports all of the modules that were imported in the actual header file. Because `#include` directives are automatically mapped to module imports, `export *` provides the same transitive-inclusion behavior provided by the C preprocessor, e.g., importing a given module implicitly imports all of the modules on which it depends. Therefore, liberal use of `export *` provides excellent backward compatibility for programs that rely on transitive inclusion (i.e., all of them).

Use declaration

A *use-declaration* specifies another module that the current top-level module intends to use. When the option *-fmodules-decluse* is specified, a module can only use other modules that are explicitly specified in this way.

use-declaration:
  use *module-id*

Example: In the following example, use of A from C is not declared, so will trigger a warning.

```
module A {
  header "a.h"
}

module B {
  header "b.h"
}

module C {
  header "c.h"
  use B
}
```

When compiling a source file that implements a module, use the option `-fmodule-name=module-id` to indicate that the source file is logically part of that module.

The compiler at present only applies restrictions to the module directly being built.

Link declaration

A *link-declaration* specifies a library or framework against which a program should be linked if the enclosing module is imported in any translation unit in that program.

link-declaration:

```
link framework$_opt$ string-literal
```

The *string-literal* specifies the name of the library or framework against which the program should be linked. For example, specifying "clangBasic" would instruct the linker to link with `-lclangBasic` for a Unix-style linker.

A *link-declaration* with the `framework` specifies that the linker should link against the named framework, e.g., with `-framework MyFramework`.

Note: Automatic linking with the `link` directive is not yet widely implemented, because it requires support from both the object file format and the linker. The notion is similar to Microsoft Visual Studio's `#pragma comment(lib...)`.

Configuration macros declaration

The *config-macros-declaration* specifies the set of configuration macros that have an effect on the API of the enclosing module.

```
config-macros-declaration:
  config_macros attributes$_opt$ config-macro-list$_opt$

config-macro-list:
  identifier (',' identifier)*
```

Each *identifier* in the *config-macro-list* specifies the name of a macro. The compiler is required to maintain different variants of the given module for differing definitions of any of the named macros.

A *config-macros-declaration* shall only be present on a top-level module, i.e., a module that is not nested within an enclosing module.

The `exhaustive` attribute specifies that the list of macros in the *config-macros-declaration* is exhaustive, meaning that no other macro definition is intended to have an effect on the API of that module.

Note: The `exhaustive` attribute implies that any macro definitions for macros not listed as configuration macros should be ignored completely when building the module. As an optimization, the compiler could reduce the number of unique module variants by not considering these non-configuration macros. This optimization is not yet implemented in Clang.

A translation unit shall not import the same module under different definitions of the configuration macros.

Note: Clang implements a weak form of this requirement: the definitions used for configuration macros are fixed based on the definitions provided by the command line. If an import occurs and the definition of any configuration macro has changed, the compiler will produce a warning (under the control of `-Wconfig-macros`).

Example: A logging library might provide different API (e.g., in the form of different definitions for a logging macro) based on the `NDEBUG` macro setting:

```
module MyLogger {
  umbrella header "MyLogger.h"
  config_macros [exhaustive] NDEBUG
}
```

Conflict declarations

A *conflict-declaration* describes a case where the presence of two different modules in the same translation unit is likely to cause a problem. For example, two modules may provide similar-but-incompatible functionality.

conflict-declaration:
  conflict *module-id* ',' *string-literal*

The *module-id* of the *conflict-declaration* specifies the module with which the enclosing module conflicts. The specified module shall not have been imported in the translation unit when the enclosing module is imported.

The *string-literal* provides a message to be provided as part of the compiler diagnostic when two modules conflict.

Note: Clang emits a warning (under the control of `-Wmodule-conflict`) when a module conflict is discovered.

Example:

```
module Conflicts {
  explicit module A {
    header "conflict_a.h"
    conflict B, "we just don't like B"
  }

  module B {
    header "conflict_b.h"
  }
}
```

Attributes

Attributes are used in a number of places in the grammar to describe specific behavior of other declarations. The format of attributes is fairly simple.

attributes:
  attribute attributes$_opt$

attribute:
  '[' *identifier* ']'

Any *identifier* can be used as an attribute, and each declaration specifies what attributes can be applied to it.

Private Module Map Files

Module map files are typically named `module.modulemap` and live either alongside the headers they describe or in a parent directory of the headers they describe. These module maps typically describe all of the API for the library.

However, in some cases, the presence or absence of particular headers is used to distinguish between the "public" and "private" APIs of a particular library. For example, a library may contain the headers `Foo.h` and `Foo_Private.h`, providing public and private APIs, respectively. Additionally, `Foo_Private.h` may only be available on some versions of library, and absent in others. One cannot easily express this with a single module map file in the library:

```
module Foo {
  header "Foo.h"

  explicit module Private {
```

```
    header "Foo_Private.h"
  }
}
```

because the header `Foo_Private.h` won't always be available. The module map file could be customized based on whether `Foo_Private.h` is available or not, but doing so requires custom build machinery.

Private module map files, which are named `module.private.modulemap` (or, for backward compatibility, `module_private.map`), allow one to augment the primary module map file with an additional submodule. For example, we would split the module map file above into two module map files:

```
/* module.modulemap */
module Foo {
  header "Foo.h"
}

/* module.private.modulemap */
explicit module Foo.Private {
  header "Foo_Private.h"
}
```

When a `module.private.modulemap` file is found alongside a `module.modulemap` file, it is loaded after the `module.modulemap` file. In our example library, the `module.private.modulemap` file would be available when `Foo_Private.h` is available, making it easier to split a library's public and private APIs along header boundaries.

Modularizing a Platform

To get any benefit out of modules, one needs to introduce module maps for software libraries starting at the bottom of the stack. This typically means introducing a module map covering the operating system's headers and the C standard library headers (in `/usr/include`, for a Unix system).

The module maps will be written using the *module map language*, which provides the tools necessary to describe the mapping between headers and modules. Because the set of headers differs from one system to the next, the module map will likely have to be somewhat customized for, e.g., a particular distribution and version of the operating system. Moreover, the system headers themselves may require some modification, if they exhibit any anti-patterns that break modules. Such common patterns are described below.

Macro-guarded copy-and-pasted definitions System headers vend core types such as `size_t` for users. These types are often needed in a number of system headers, and are almost trivial to write. Hence, it is fairly common to see a definition such as the following copy-and-pasted throughout the headers:

```
#ifndef _SIZE_T
#define _SIZE_T
typedef __SIZE_TYPE__ size_t;
#endif
```

Unfortunately, when modules compiles all of the C library headers together into a single module, only the first actual type definition of `size_t` will be visible, and then only in the submodule corresponding to the lucky first header. Any other headers that have copy-and-pasted versions of this pattern will *not* have a definition of `size_t`. Importing the submodule corresponding to one of those headers will therefore not yield `size_t` as part of the API, because it wasn't there when the header was parsed. The fix for this problem is either to pull the copied declarations into a common header that gets included everywhere `size_t` is part of the API, or to eliminate the `#ifndef` and redefine the `size_t` type. The latter works for C++ headers and C11, but will cause an error for non-modules C90/C99, where redefinition of `typedefs` is not permitted.

Conflicting definitions Different system headers may provide conflicting definitions for various macros, functions, or types. These conflicting definitions don't tend to cause problems in a pre-modules world unless someone happens to include both headers in one translation unit. Since the fix is often simply "don't do that", such problems persist. Modules requires that the conflicting definitions be eliminated or that they be placed in separate modules (the former is generally the better answer).

Missing includes Headers are often missing `#include` directives for headers that they actually depend on. As with the problem of conflicting definitions, this only affects unlucky users who don't happen to include headers in the right order. With modules, the headers of a particular module will be parsed in isolation, so the module may fail to build if there are missing includes.

Headers that vend multiple APIs at different times Some systems have headers that contain a number of different kinds of API definitions, only some of which are made available with a given include. For example, the header may vend `size_t` only when the macro `__need_size_t` is defined before that header is included, and also vend `wchar_t` only when the macro `__need_wchar_t` is defined. Such headers are often included many times in a single translation unit, and will have no include guards. There is no sane way to map this header to a submodule. One can either eliminate the header (e.g., by splitting it into separate headers, one per actual API) or simply `exclude` it in the module map.

To detect and help address some of these problems, the `clang-tools-extra` repository contains a `modularize` tool that parses a set of given headers and attempts to detect these problems and produce a report. See the tool's in-source documentation for information on how to check your system or library headers.

Future Directions

Modules support is under active development, and there are many opportunities remaining to improve it. Here are a few ideas:

Detect unused module imports Unlike with `#include` directives, it should be fairly simple to track whether a directly-imported module has ever been used. By doing so, Clang can emit `unused import` or `unused #include` diagnostics, including Fix-Its to remove the useless imports/includes.

Fix-Its for missing imports It's fairly common for one to make use of some API while writing code, only to get a compiler error about "unknown type" or "no function named" because the corresponding header has not been included. Clang can detect such cases and auto-import the required module, but should provide a Fix-It to add the import.

Improve modularize The modularize tool is both extremely important (for deployment) and extremely crude. It needs better UI, better detection of problems (especially for C++), and perhaps an assistant mode to help write module maps for you.

Where To Learn More About Modules

The Clang source code provides additional information about modules:

`clang/lib/Headers/module.modulemap` Module map for Clang's compiler-specific header files.

`clang/test/Modules/` Tests specifically related to modules functionality.

`clang/include/clang/Basic/Module.h` The `Module` class in this header describes a module, and is used throughout the compiler to implement modules.

`clang/include/clang/Lex/ModuleMap.h` The `ModuleMap` class in this header describes the full module map, consisting of all of the module map files that have been parsed, and providing facilities for looking up module maps and mapping between modules and headers (in both directions).

PCHInternals Information about the serialized AST format used for precompiled headers and modules. The actual implementation is in the `clangSerialization` library.

MSVC compatibility

When Clang compiles C++ code for Windows, it attempts to be compatible with MSVC. There are multiple dimensions to compatibility.

First, Clang attempts to be ABI-compatible, meaning that Clang-compiled code should be able to link against MSVC-compiled code successfully. However, C++ ABIs are particularly large and complicated, and Clang's support for MSVC's C++ ABI is a work in progress. If you don't require MSVC ABI compatibility or don't want to use Microsoft's C and C++ runtimes, the mingw32 toolchain might be a better fit for your project.

Second, Clang implements many MSVC language extensions, such as `__declspec(dllexport)` and a handful of pragmas. These are typically controlled by `-fms-extensions`.

Third, MSVC accepts some C++ code that Clang will typically diagnose as invalid. When these constructs are present in widely included system headers, Clang attempts to recover and continue compiling the user's program. Most parsing and semantic compatibility tweaks are controlled by `-fms-compatibility` and `-fdelayed-template-parsing`, and they are a work in progress.

Finally, there is *clang-cl*, a driver program for clang that attempts to be compatible with MSVC's cl.exe.

ABI features

The status of major ABI-impacting C++ features:

- Record layout: Complete. We've tested this with a fuzzer and have fixed all known bugs.
- Class inheritance: Mostly complete. This covers all of the standard OO features you would expect: virtual method inheritance, multiple inheritance, and virtual inheritance. Every so often we uncover a bug where our tables are incompatible, but this is pretty well in hand. This feature has also been fuzz tested.
- Name mangling: Ongoing. Every new C++ feature generally needs its own mangling. For example, member pointer template arguments have an interesting and distinct mangling. Fortunately, incorrect manglings usually do not result in runtime errors. Non-inline functions with incorrect manglings usually result in link errors, which are relatively easy to diagnose. Incorrect manglings for inline functions and templates result in multiple copies in the final image. The C++ standard requires that those addresses be equal, but few programs rely on this.
- Member pointers: Mostly complete. Standard C++ member pointers are fully implemented and should be ABI compatible. Both #pragma pointers_to_members and the /vm flags are supported. However, MSVC supports an extension to allow creating a pointer to a member of a virtual base class. Clang does not yet support this.
- Debug info: Minimal. Clang emits both CodeView line tables (similar to what MSVC emits when given the `/Z7` flag) and DWARF debug information into the object file. Microsoft's link.exe will transform the CodeView line tables into a PDB, enabling stack traces in all modern Windows debuggers. Clang does not emit any CodeView-compatible type info or description of variable layout. Binaries linked with either binutils' ld or LLVM's lld should be usable with GDB however sophisticated C++ expressions are likely to fail.
- RTTI: Complete. Generation of RTTI data structures has been finished, along with support for the `/GR` flag.
- C++ Exceptions: Mostly complete. Support for C++ exceptions (`try` / `catch` / `throw`) have been implemented for x86 and x64. Our implementation has been well tested but we still get the odd bug report now and again. C++ exception specifications are ignored, but this is consistent with Visual C++.
- Asynchronous Exceptions (SEH): Partial. Structured exceptions (`__try` / `__except` / `__finally`) mostly work on x86 and x64. LLVM does not model asynchronous exceptions, so it is currently impossible to catch an asynchronous exception generated in the same frame as the catching `__try`.
- Thread-safe initialization of local statics: Complete. MSVC 2015 added support for thread-safe initialization of such variables by taking an ABI break. We are ABI compatible with both the MSVC 2013 and 2015 ABI for static local variables.

- Lambdas: Mostly complete. Clang is compatible with Microsoft's implementation of lambdas except for providing overloads for conversion to function pointer for different calling conventions. However, Microsoft's extension is non-conforming.

Template instantiation and name lookup

MSVC allows many invalid constructs in class templates that Clang has historically rejected. In order to parse widely distributed headers for libraries such as the Active Template Library (ATL) and Windows Runtime Library (WRL), some template rules have been relaxed or extended in Clang on Windows.

The first major semantic difference is that MSVC appears to defer all parsing an analysis of inline method bodies in class templates until instantiation time. By default on Windows, Clang attempts to follow suit. This behavior is controlled by the `-fdelayed-template-parsing` flag. While Clang delays parsing of method bodies, it still parses the bodies *before* template argument substitution, which is not what MSVC does. The following compatibility tweaks are necessary to parse the template in those cases.

MSVC allows some name lookup into dependent base classes. Even on other platforms, this has been a frequently asked question for Clang users. A dependent base class is a base class that depends on the value of a template parameter. Clang cannot see any of the names inside dependent bases while it is parsing your template, so the user is sometimes required to use the `typename` keyword to assist the parser. On Windows, Clang attempts to follow the normal lookup rules, but if lookup fails, it will assume that the user intended to find the name in a dependent base. While parsing the following program, Clang will recover as if the user had written the commented-out code:

```
template <typename T>
struct Foo : T {
  void f() {
    /*typename*/ T::UnknownType x =  /*this->*/unknownMember;
  }
};
```

After recovery, Clang warns the user that this code is non-standard and issues a hint suggesting how to fix the problem.

As of this writing, Clang is able to compile a simple ATL hello world application. There are still issues parsing WRL headers for modern Windows 8 apps, but they should be addressed soon.

Clang "man" pages

The following documents are command descriptions for all of the Clang tools. These pages describe how to use the Clang commands and what their options are. Note that these pages do not describe all of the options available for all tools. To get a complete listing, pass the `--help` (general options) or `--help-hidden` (general and debugging options) arguments to the tool you are interested in.

Basic Commands

clang - the Clang C, C++, and Objective-C compiler

SYNOPSIS

clang [*options*] *filename ...*

DESCRIPTION

clang is a C, C++, and Objective-C compiler which encompasses preprocessing, parsing, optimization, code generation, assembly, and linking. Depending on which high-level mode setting is passed, Clang will stop before doing a full link. While Clang is highly integrated, it is important to understand the stages of compilation, to understand how to invoke it. These stages are:

Driver The clang executable is actually a small driver which controls the overall execution of other tools such as the compiler, assembler and linker. Typically you do not need to interact with the driver, but you transparently use it to run the other tools.

Preprocessing This stage handles tokenization of the input source file, macro expansion, #include expansion and handling of other preprocessor directives. The output of this stage is typically called a ".i" (for C), ".ii" (for C++), ".mi" (for Objective-C), or ".mii" (for Objective-C++) file.

Parsing and Semantic Analysis This stage parses the input file, translating preprocessor tokens into a parse tree. Once in the form of a parse tree, it applies semantic analysis to compute types for expressions as well and determine whether the code is well formed. This stage is responsible for generating most of the compiler warnings as well as parse errors. The output of this stage is an "Abstract Syntax Tree" (AST).

Code Generation and Optimization This stage translates an AST into low-level intermediate code (known as "LLVM IR") and ultimately to machine code. This phase is responsible for optimizing the generated code and handling target-specific code generation. The output of this stage is typically called a ".s" file or "assembly" file.

Clang also supports the use of an integrated assembler, in which the code generator produces object files directly. This avoids the overhead of generating the ".s" file and of calling the target assembler.

Assembler This stage runs the target assembler to translate the output of the compiler into a target object file. The output of this stage is typically called a ".o" file or "object" file.

Linker This stage runs the target linker to merge multiple object files into an executable or dynamic library. The output of this stage is typically called an "a.out", ".dylib" or ".so" file.

Clang Static Analyzer

The Clang Static Analyzer is a tool that scans source code to try to find bugs through code analysis. This tool uses many parts of Clang and is built into the same driver. Please see <http://clang-analyzer.llvm.org> for more details on how to use the static analyzer.

OPTIONS

Stage Selection Options

-E
Run the preprocessor stage.

-fsyntax-only
Run the preprocessor, parser and type checking stages.

-S
Run the previous stages as well as LLVM generation and optimization stages and target-specific code generation, producing an assembly file.

-c
Run all of the above, plus the assembler, generating a target ".o" object file.

no `stage selection option`
If no stage selection option is specified, all stages above are run, and the linker is run to combine the results into an executable or shared library.

Language Selection and Mode Options

-x `<language>`
Treat subsequent input files as having type language.

-std=`<language>`
Specify the language standard to compile for.

-stdlib=`<library>`
Specify the C++ standard library to use; supported options are libstdc++ and libc++.

-ansi
Same as -std=c89.

-ObjC, -ObjC++
Treat source input files as Objective-C and Object-C++ inputs respectively.

-trigraphs
Enable trigraphs.

-ffreestanding
Indicate that the file should be compiled for a freestanding, not a hosted, environment.

-fno-builtin
Disable special handling and optimizations of builtin functions like `strlen()` and `malloc()`.

-fmath-errno
Indicate that math functions should be treated as updating `errno`.

-fpascal-strings
Enable support for Pascal-style strings with "\pfoo".

-fms-extensions
Enable support for Microsoft extensions.

-fmsc-version=
Set _MSC_VER. Defaults to 1300 on Windows. Not set otherwise.

-fborland-extensions
Enable support for Borland extensions.

-fwritable-strings
Make all string literals default to writable. This disables uniquing of strings and other optimizations.

-flax-vector-conversions
Allow loose type checking rules for implicit vector conversions.

-fblocks
Enable the "Blocks" language feature.

-fobjc-gc-only
Indicate that Objective-C code should be compiled in GC-only mode, which only works when Objective-C Garbage Collection is enabled.

-fobjc-gc
Indicate that Objective-C code should be compiled in hybrid-GC mode, which works with both GC and non-GC mode.

-fobjc-abi-version=version
Select the Objective-C ABI version to use. Available versions are 1 (legacy "fragile" ABI), 2 (non-fragile ABI 1), and 3 (non-fragile ABI 2).

-fobjc-nonfragile-abi-version=<version>
Select the Objective-C non-fragile ABI version to use by default. This will only be used as the Objective-C ABI when the non-fragile ABI is enabled (either via *-fobjc-nonfragile-abi*, or because it is the platform default).

-fobjc-nonfragile-abi, -fno-objc-nonfragile-abi
Enable use of the Objective-C non-fragile ABI. On platforms for which this is the default ABI, it can be disabled with *-fno-objc-nonfragile-abi*.

Target Selection Options

Clang fully supports cross compilation as an inherent part of its design. Depending on how your version of Clang is configured, it may have support for a number of cross compilers, or may only support a native target.

-arch <architecture>
Specify the architecture to build for.

-mmacosx-version-min=<version>
When building for Mac OS X, specify the minimum version supported by your application.

-miphoneos-version-min
When building for iPhone OS, specify the minimum version supported by your application.

-march=<cpu>
Specify that Clang should generate code for a specific processor family member and later. For example, if you specify -march=i486, the compiler is allowed to generate instructions that are valid on i486 and later processors, but which may not exist on earlier ones.

Code Generation Options

-O0, -O1, -O2, -O3, -Ofast, -Os, -Oz, -O, -O4
Specify which optimization level to use:

-O0 Means "no optimization": this level compiles the fastest and generates the most debuggable code.

-O1 Somewhere between *-O0* and *-O2*.

-O2 Moderate level of optimization which enables most optimizations.

-O3 Like *-O2*, except that it enables optimizations that take longer to perform or that may generate larger code (in an attempt to make the program run faster).

-Ofast Enables all the optimizations from *-O3* along with other aggressive optimizations that may violate strict compliance with language standards.

-Os Like *-O2* with extra optimizations to reduce code size.

-Oz Like *-Os* (and thus *-O2*), but reduces code size further.

-O Equivalent to *-O2*.

-O4 and higher

Currently equivalent to *-O3*

-g, -gline-tables-only, -gmodules
Control debug information output. Note that Clang debug information works best at *-O0*. When more than one option starting with *-g* is specified, the last one wins:

-g Generate debug information.

-gline-tables-only Generate only line table debug information. This allows for symbolicated backtraces with inlining information, but does not include any information about variables, their locations or types.

-gmodules Generate debug information that contains external references to types defined in Clang modules or precompiled headers instead of emitting redundant debug type information into every object file. This option transparently switches the Clang module format to object file containers that hold the Clang module together with the debug information. When compiling a program that uses Clang modules or precompiled headers, this option produces complete debug information with faster compile times and much smaller object files.

This option should not be used when building static libraries for distribution to other machines because the debug info will contain references to the module cache on the machine the object files in the library were built on.

-fstandalone-debug -fno-standalone-debug
Clang supports a number of optimizations to reduce the size of debug information in the binary. They work based on the assumption that the debug type information can be spread out over multiple compilation units. For instance, Clang will not emit type definitions for types that are not needed by a module and could be replaced with a forward declaration. Further, Clang will only emit type info for a dynamic C++ class in the module that contains the vtable for the class.

The *-fstandalone-debug* option turns off these optimizations. This is useful when working with 3rd-party libraries that don't come with debug information. This is the default on Darwin. Note that Clang will never emit type information for types that are not referenced at all by the program.

-fexceptions
Enable generation of unwind information. This allows exceptions to be thrown through Clang compiled stack frames. This is on by default in x86-64.

-ftrapv
Generate code to catch integer overflow errors. Signed integer overflow is undefined in C. With this flag, extra code is generated to detect this and abort when it happens.

-fvisibility
This flag sets the default visibility level.

-fcommon, -fno-common
This flag specifies that variables without initializers get common linkage. It can be disabled with *-fno-common*.

-ftls-model=<model>
Set the default thread-local storage (TLS) model to use for thread-local variables. Valid values are: "global-dynamic", "local-dynamic", "initial-exec" and "local-exec". The default is "global-dynamic". The default model can be overridden with the tls_model attribute. The compiler will try to choose a more efficient model if possible.

-flto, -emit-llvm
Generate output files in LLVM formats, suitable for link time optimization. When used with *-S* this generates LLVM intermediate language assembly files, otherwise this generates LLVM bitcode format object files (which may be passed to the linker depending on the stage selection options).

Driver Options

-###
Print (but do not run) the commands to run for this compilation.

--help
Display available options.

-Qunused-arguments
Do not emit any warnings for unused driver arguments.

-Wa,<args>
Pass the comma separated arguments in args to the assembler.

-Wl,<args>
Pass the comma separated arguments in args to the linker.

-Wp,<args>
Pass the comma separated arguments in args to the preprocessor.

-Xanalyzer <arg>
Pass arg to the static analyzer.

-Xassembler <arg>
Pass arg to the assembler.

-Xlinker <arg>
Pass arg to the linker.

-Xpreprocessor <arg>
Pass arg to the preprocessor.

-o <file>
Write output to file.

-print-file-name=<file>
Print the full library path of file.

-print-libgcc-file-name
Print the library path for "libgcc.a".

-print-prog-name=<name>
Print the full program path of name.

-print-search-dirs
Print the paths used for finding libraries and programs.

-save-temps
Save intermediate compilation results.

-integrated-as, -no-integrated-as
Used to enable and disable, respectively, the use of the integrated assembler. Whether the integrated assembler is on by default is target dependent.

-time
Time individual commands.

-ftime-report
Print timing summary of each stage of compilation.

-v
Show commands to run and use verbose output.

Diagnostics Options

-fshow-column, -fshow-source-location, -fcaret-diagnostics, -fdiagnostics-fixit-info, -fdia
These options control how Clang prints out information about diagnostics (errors and warnings). Please see the Clang User's Manual for more information.

Preprocessor Options

-D<macroname>=<value>
Adds an implicit #define into the predefines buffer which is read before the source file is preprocessed.

-U<macroname>
Adds an implicit #undef into the predefines buffer which is read before the source file is preprocessed.

-include <filename>
Adds an implicit #include into the predefines buffer which is read before the source file is preprocessed.

-I<directory>
Add the specified directory to the search path for include files.

-F<directory>
Add the specified directory to the search path for framework include files.

-nostdinc
Do not search the standard system directories or compiler builtin directories for include files.

-nostdlibinc
Do not search the standard system directories for include files, but do search compiler builtin include directories.

-nobuiltininc
Do not search clang's builtin directory for include files.

ENVIRONMENT

TMPDIR, TEMP, TMP
These environment variables are checked, in order, for the location to write temporary files used during the compilation process.

CPATH
If this environment variable is present, it is treated as a delimited list of paths to be added to the default system include path list. The delimiter is the platform dependent delimiter, as used in the PATH environment variable.

Empty components in the environment variable are ignored.

C_INCLUDE_PATH, OBJC_INCLUDE_PATH, CPLUS_INCLUDE_PATH, OBJCPLUS_INCLUDE_PATH
These environment variables specify additional paths, as for *CPATH*, which are only used when processing the appropriate language.

MACOSX_DEPLOYMENT_TARGET
If *-mmacosx-version-min* is unspecified, the default deployment target is read from this environment variable. This option only affects Darwin targets.

BUGS

To report bugs, please visit <http://llvm.org/bugs/>. Most bug reports should include preprocessed source files (use the *-E* option) and the full output of the compiler, along with information to reproduce.

SEE ALSO

as(1), ld(1)

Frequently Asked Questions (FAQ)

Driver

I run `clang -cc1 ...` and get weird errors about missing headers

Given this source file:

```
#include <stdio.h>

int main() {
  printf("Hello world\n");
}
```

If you run:

```
$ clang -cc1 hello.c
hello.c:1:10: fatal error: 'stdio.h' file not found
#include <stdio.h>
         ^
1 error generated.
```

`clang -cc1` is the frontend, `clang` is the *driver*. The driver invokes the frontend with options appropriate for your system. To see these options, run:

```
$ clang -### -c hello.c
```

Some clang command line options are driver-only options, some are frontend-only options. Frontend-only options are intended to be used only by clang developers. Users should not run `clang -cc1` directly, because `-cc1` options are not guaranteed to be stable.

If you want to use a frontend-only option ("a `-cc1` option"), for example `-ast-dump`, then you need to take the `clang -cc1` line generated by the driver and add the option you need. Alternatively, you can run `clang -Xclang <option> ...` to force the driver pass `<option>` to `clang -cc1`.

I get errors about some headers being missing (`stddef.h`, `stdarg.h`)

Some header files (`stddef.h`, `stdarg.h`, and others) are shipped with Clang — these are called builtin includes. Clang searches for them in a directory relative to the location of the `clang` binary. If you moved the `clang` binary, you need to move the builtin headers, too.

More information can be found in the *Builtin includes* section.

CHAPTER 5

Using Clang as a Library

Choosing the Right Interface for Your Application

Clang provides infrastructure to write tools that need syntactic and semantic information about a program. This document will give a short introduction of the different ways to write clang tools, and their pros and cons.

LibClang

LibClang is a stable high level C interface to clang. When in doubt LibClang is probably the interface you want to use. Consider the other interfaces only when you have a good reason not to use LibClang.

Canonical examples of when to use LibClang:

- Xcode
- Clang Python Bindings

Use LibClang when you...:

- want to interface with clang from other languages than C++
- need a stable interface that takes care to be backwards compatible
- want powerful high-level abstractions, like iterating through an AST with a cursor, and don't want to learn all the nitty gritty details of Clang's AST.

Do not use LibClang when you...:

- want full control over the Clang AST

Clang Plugins

Clang Plugins allow you to run additional actions on the AST as part of a compilation. Plugins are dynamic libraries that are loaded at runtime by the compiler, and they're easy to integrate into your build environment.

Canonical examples of when to use Clang Plugins:

- special lint-style warnings or errors for your project
- creating additional build artifacts from a single compile step

Use Clang Plugins when you...:

- need your tool to rerun if any of the dependencies change
- want your tool to make or break a build
- need full control over the Clang AST

Do not use Clang Plugins when you...:

- want to run tools outside of your build environment
- want full control on how Clang is set up, including mapping of in-memory virtual files
- need to run over a specific subset of files in your project which is not necessarily related to any changes which would trigger rebuilds

LibTooling

LibTooling is a C++ interface aimed at writing standalone tools, as well as integrating into services that run clang tools. Canonical examples of when to use LibTooling:

- a simple syntax checker
- refactoring tools

Use LibTooling when you...:

- want to run tools over a single file, or a specific subset of files, independently of the build system
- want full control over the Clang AST
- want to share code with Clang Plugins

Do not use LibTooling when you...:

- want to run as part of the build triggered by dependency changes
- want a stable interface so you don't need to change your code when the AST API changes
- want high level abstractions like cursors and code completion out of the box
- do not want to write your tools in C++

Clang tools are a collection of specific developer tools built on top of the LibTooling infrastructure as part of the Clang project. They are targeted at automating and improving core development activities of C/C++ developers.

Examples of tools we are building or planning as part of the Clang project:

- Syntax checking (**`clang-check`**)
- Automatic fixing of compile errors (**`clang-fixit`**)
- Automatic code formatting (**`clang-format`**)
- Migration tools for new features in new language standards
- Core refactoring tools

External Clang Examples

Introduction

This page provides some examples of the kinds of things that people have done with Clang that might serve as useful guides (or starting points) from which to develop your own tools. They may be helpful even for something as banal (but necessary) as how to set up your build to integrate Clang.

Clang's library-based design is deliberately aimed at facilitating use by external projects, and we are always interested in improving Clang to better serve our external users. Some typical categories of applications where Clang is used are:

- Static analysis.
- Documentation/cross-reference generation.

If you know of (or wrote!) a tool or project using Clang, please send an email to Clang's development discussion mailing list to have it added. (or if you are already a Clang contributor, feel free to directly commit additions). Since the primary purpose of this page is to provide examples that can help developers, generally they must have code available.

List of projects and tools

https://github.com/Andersbakken/rtags/ "RTags is a client/server application that indexes c/c++ code and keeps a persistent in-memory database of references, symbolnames, completions etc."

http://rprichard.github.com/sourceweb/ "A C/C++ source code indexer and navigator"

https://github.com/etaoins/qconnectlint "qconnectlint is a Clang tool for statically verifying the consistency of signal and slot connections made with Qt's `QObject::connect`."

https://github.com/woboq/woboq_codebrowser "The Woboq Code Browser is a web-based code browser for C/C++ projects. Check out http://code.woboq.org/ for an example!"

https://github.com/mozilla/dxr "DXR is a source code cross-reference tool that uses static analysis data collected by instrumented compilers."

https://github.com/eschulte/clang-mutate "This tool performs a number of operations on C-language source files."

https://github.com/gmarpons/Crisp "A coding rule validation add-on for LLVM/clang. Crisp rules are written in Prolog. A high-level declarative DSL to easily write new rules is under development. It will be called CRISP, an acronym for *Coding Rules in Sugared Prolog*."

https://github.com/drothlis/clang-ctags "Generate tag file for C++ source code."

https://github.com/exclipy/clang_indexer "This is an indexer for C and C++ based on the libclang library."

https://github.com/holtgrewe/linty "Linty - C/C++ Style Checking with Python & libclang."

https://github.com/axw/cmonster "cmonster is a Python wrapper for the Clang C++ parser."

https://github.com/rizsotto/Constantine "Constantine is a toy project to learn how to write clang plugin. Implements pseudo const analysis. Generates warnings about variables, which were declared without const qualifier."

https://github.com/jessevdk/cldoc "cldoc is a Clang based documentation generator for C and C++. cldoc tries to solve the issue of writing C/C++ software documentation with a modern, non-intrusive and robust approach."

https://github.com/AlexDenisov/ToyClangPlugin "The simplest Clang plugin implementing a semantic check for Objective-C. This example shows how to use the `DiagnosticsEngine` (emit warnings, errors, fixit hints). See also http://l.rw.rw/clang_plugin for step-by-step instructions."

Introduction to the Clang AST

This document gives a gentle introduction to the mysteries of the Clang AST. It is targeted at developers who either want to contribute to Clang, or use tools that work based on Clang's AST, like the AST matchers.

Slides

Introduction

Clang's AST is different from ASTs produced by some other compilers in that it closely resembles both the written C++ code and the C++ standard. For example, parenthesis expressions and compile time constants are available in an unreduced form in the AST. This makes Clang's AST a good fit for refactoring tools.

Documentation for all Clang AST nodes is available via the generated Doxygen. The doxygen online documentation is also indexed by your favorite search engine, which will make a search for clang and the AST node's class name usually turn up the doxygen of the class you're looking for (for example, search for: clang ParenExpr).

Examining the AST

A good way to familarize yourself with the Clang AST is to actually look at it on some simple example code. Clang has a builtin AST-dump mode, which can be enabled with the flag `-ast-dump`.

Let's look at a simple example AST:

```
$ cat test.cc
int f(int x) {
  int result = (x / 42);
  return result;
}

# Clang by default is a frontend for many tools; -Xclang is used to pass
# options directly to the C++ frontend.
$ clang -Xclang -ast-dump -fsyntax-only test.cc
TranslationUnitDecl 0x5aea0d0 <<invalid sloc>>
... cutting out internal declarations of clang ...
`-FunctionDecl 0x5aeab50 <test.cc:1:1, line:4:1> f 'int (int)'
  |-ParmVarDecl 0x5aeaa90 <line:1:7, col:11> x 'int'
  `-CompoundStmt 0x5aead88 <col:14, line:4:1>
    |-DeclStmt 0x5aead10 <line:2:3, col:24>
    | `-VarDecl 0x5aeac10 <col:3, col:23> result 'int'
    |   `-ParenExpr 0x5aeacf0 <col:16, col:23> 'int'
    |     `-BinaryOperator 0x5aeacc8 <col:17, col:21> 'int' '/'
    |       |-ImplicitCastExpr 0x5aeacb0 <col:17> 'int' <LValueToRValue>
    |       | `-DeclRefExpr 0x5aeac68 <col:17> 'int' lvalue ParmVar 0x5aeaa90 'x' 'int
↪'
    |       `-IntegerLiteral 0x5aeac90 <col:21> 'int' 42
    `-ReturnStmt 0x5aead68 <line:3:3, col:10>
      `-ImplicitCastExpr 0x5aead50 <col:10> 'int' <LValueToRValue>
        `-DeclRefExpr 0x5aead28 <col:10> 'int' lvalue Var 0x5aeac10 'result' 'int'
```

The toplevel declaration in a translation unit is always the translation unit declaration. In this example, our first user written declaration is the function declaration of "`f`". The body of "`f`" is a compound statement, whose child nodes are a declaration statement that declares our result variable, and the return statement.

AST Context

All information about the AST for a translation unit is bundled up in the class ASTContext. It allows traversal of the whole translation unit starting from getTranslationUnitDecl, or to access Clang's table of identifiers for the parsed translation unit.

AST Nodes

Clang's AST nodes are modeled on a class hierarchy that does not have a common ancestor. Instead, there are multiple larger hierarchies for basic node types like Decl and Stmt. Many important AST nodes derive from Type, Decl, DeclContext or Stmt, with some classes deriving from both Decl and DeclContext.

There are also a multitude of nodes in the AST that are not part of a larger hierarchy, and are only reachable from specific other nodes, like CXXBaseSpecifier.

Thus, to traverse the full AST, one starts from the TranslationUnitDecl and then recursively traverses everything that can be reached from that node - this information has to be encoded for each specific node type. This algorithm is encoded in the RecursiveASTVisitor. See the RecursiveASTVisitor tutorial.

The two most basic nodes in the Clang AST are statements (Stmt) and declarations (Decl). Note that expressions (Expr) are also statements in Clang's AST.

LibTooling

LibTooling is a library to support writing standalone tools based on Clang. This document will provide a basic walkthrough of how to write a tool using LibTooling.

For the information on how to setup Clang Tooling for LLVM see *How To Setup Clang Tooling For LLVM*

Introduction

Tools built with LibTooling, like Clang Plugins, run `FrontendActions` over code.

In this tutorial, we'll demonstrate the different ways of running Clang's `SyntaxOnlyAction`, which runs a quick syntax check, over a bunch of code.

Parsing a code snippet in memory

If you ever wanted to run a `FrontendAction` over some sample code, for example to unit test parts of the Clang AST, `runToolOnCode` is what you looked for. Let me give you an example:

```
#include "clang/Tooling/Tooling.h"

TEST(runToolOnCode, CanSyntaxCheckCode) {
  // runToolOnCode returns whether the action was correctly run over the
  // given code.
  EXPECT_TRUE(runToolOnCode(new clang::SyntaxOnlyAction, "class X {};"));
}
```

Writing a standalone tool

Once you unit tested your `FrontendAction` to the point where it cannot possibly break, it's time to create a standalone tool. For a standalone tool to run clang, it first needs to figure out what command line arguments to use for a specified file. To that end we create a `CompilationDatabase`. There are different ways to create a compilation database, and we need to support all of them depending on command-line options. There's the `CommonOptionsParser` class that takes the responsibility to parse command-line parameters related to compilation databases and inputs, so that all tools share the implementation.

Parsing common tools options

`CompilationDatabase` can be read from a build directory or the command line. Using `CommonOptionsParser` allows for explicit specification of a compile command line, specification of build path using the `-p` command-line option, and automatic location of the compilation database using source files paths.

```
#include "clang/Tooling/CommonOptionsParser.h"
#include "llvm/Support/CommandLine.h"

using namespace clang::tooling;

// Apply a custom category to all command-line options so that they are the
// only ones displayed.
static llvm::cl::OptionCategory MyToolCategory("my-tool options");

int main(int argc, const char **argv) {
  // CommonOptionsParser constructor will parse arguments and create a
  // CompilationDatabase.  In case of error it will terminate the program.
  CommonOptionsParser OptionsParser(argc, argv, MyToolCategory);

  // Use OptionsParser.getCompilations() and OptionsParser.getSourcePathList()
  // to retrieve CompilationDatabase and the list of input file paths.
}
```

Creating and running a ClangTool

Once we have a `CompilationDatabase`, we can create a `ClangTool` and run our `FrontendAction` over some code. For example, to run the `SyntaxOnlyAction` over the files "a.cc" and "b.cc" one would write:

```
// A clang tool can run over a number of sources in the same process...
std::vector<std::string> Sources;
Sources.push_back("a.cc");
Sources.push_back("b.cc");

// We hand the CompilationDatabase we created and the sources to run over into
// the tool constructor.
ClangTool Tool(OptionsParser.getCompilations(), Sources);

// The ClangTool needs a new FrontendAction for each translation unit we run
// on.  Thus, it takes a FrontendActionFactory as parameter.  To create a
// FrontendActionFactory from a given FrontendAction type, we call
// newFrontendActionFactory<clang::SyntaxOnlyAction>().
int result = Tool.run(newFrontendActionFactory<clang::SyntaxOnlyAction>().get());
```

Putting it together — the first tool

Now we combine the two previous steps into our first real tool. A more advanced version of this example tool is also checked into the clang tree at `tools/clang-check/ClangCheck.cpp`.

```
// Declares clang::SyntaxOnlyAction.
#include "clang/Frontend/FrontendActions.h"
#include "clang/Tooling/CommonOptionsParser.h"
#include "clang/Tooling/Tooling.h"
// Declares llvm::cl::extrahelp.
#include "llvm/Support/CommandLine.h"

using namespace clang::tooling;
using namespace llvm;

// Apply a custom category to all command-line options so that they are the
// only ones displayed.
static cl::OptionCategory MyToolCategory("my-tool options");

// CommonOptionsParser declares HelpMessage with a description of the common
// command-line options related to the compilation database and input files.
// It's nice to have this help message in all tools.
static cl::extrahelp CommonHelp(CommonOptionsParser::HelpMessage);

// A help message for this specific tool can be added afterwards.
static cl::extrahelp MoreHelp("\nMore help text...");

int main(int argc, const char **argv) {
  CommonOptionsParser OptionsParser(argc, argv, MyToolCategory);
  ClangTool Tool(OptionsParser.getCompilations(),
                 OptionsParser.getSourcePathList());
  return Tool.run(newFrontendActionFactory<clang::SyntaxOnlyAction>().get());
}
```

Running the tool on some code

When you check out and build clang, clang-check is already built and available to you in bin/clang-check inside your build directory.

You can run clang-check on a file in the llvm repository by specifying all the needed parameters after a "--" separator:

```
$ cd /path/to/source/llvm
$ export BD=/path/to/build/llvm
$ $BD/bin/clang-check tools/clang/tools/clang-check/ClangCheck.cpp -- \
      clang++ -D__STDC_CONSTANT_MACROS -D__STDC_LIMIT_MACROS \
      -Itools/clang/include -I$BD/include -Iinclude \
      -Itools/clang/lib/Headers -c
```

As an alternative, you can also configure cmake to output a compile command database into its build directory:

```
# Alternatively to calling cmake, use ccmake, toggle to advanced mode and
# set the parameter CMAKE_EXPORT_COMPILE_COMMANDS from the UI.
$ cmake -DCMAKE_EXPORT_COMPILE_COMMANDS=ON .
```

This creates a file called `compile_commands.json` in the build directory. Now you can run **`clang-check`** over files in the project by specifying the build path as first argument and some source files as further positional arguments:

```
$ cd /path/to/source/llvm
$ export BD=/path/to/build/llvm
$ $BD/bin/clang-check -p $BD tools/clang/tools/clang-check/ClangCheck.cpp
```

Builtin includes

Clang tools need their builtin headers and search for them the same way Clang does. Thus, the default location to look for builtin headers is in a path `$(dirname /path/to/tool)/../lib/clang/3.3/include` relative to the tool binary. This works out-of-the-box for tools running from llvm's toplevel binary directory after building clang-headers, or if the tool is running from the binary directory of a clang install next to the clang binary.

Tips: if your tool fails to find `stddef.h` or similar headers, call the tool with `-v` and look at the search paths it looks through.

Linking

For a list of libraries to link, look at one of the tools' Makefiles (for example clang-check/Makefile).

LibFormat

LibFormat is a library that implements automatic source code formatting based on Clang. This documents describes the LibFormat interface and design as well as some basic style discussions.

If you just want to use *clang-format* as a tool or integrated into an editor, checkout *ClangFormat*.

Design

FIXME: Write up design.

Interface

The core routine of LibFormat is `reformat()`:

```
tooling::Replacements reformat(const FormatStyle &Style, Lexer &Lex,
                               SourceManager &SourceMgr,
                               std::vector<CharSourceRange> Ranges);
```

This reads a token stream out of the lexer `Lex` and reformats all the code ranges in `Ranges`. The `FormatStyle` controls basic decisions made during formatting. A list of options can be found under *Style Options*.

Style Options

The style options describe specific formatting options that can be used in order to make *ClangFormat* comply with different style guides. Currently, two style guides are hard-coded:

```
/// \brief Returns a format style complying with the LLVM coding standards:
/// http://llvm.org/docs/CodingStandards.html.
FormatStyle getLLVMStyle();
```

```
/// \brief Returns a format style complying with Google's C++ style guide:
/// http://google-styleguide.googlecode.com/svn/trunk/cppguide.xml.
FormatStyle getGoogleStyle();
```

These options are also exposed in the *standalone tools* through the *-style* option.

In the future, we plan on making this configurable.

Clang Plugins

Clang Plugins make it possible to run extra user defined actions during a compilation. This document will provide a basic walkthrough of how to write and run a Clang Plugin.

Introduction

Clang Plugins run FrontendActions over code. See the *FrontendAction tutorial* on how to write a `FrontendAction` using the `RecursiveASTVisitor`. In this tutorial, we'll demonstrate how to write a simple clang plugin.

Writing a `PluginASTAction`

The main difference from writing normal `FrontendActions` is that you can handle plugin command line options. The `PluginASTAction` base class declares a `ParseArgs` method which you have to implement in your plugin.

```
bool ParseArgs(const CompilerInstance &CI,
               const std::vector<std::string>& args) {
  for (unsigned i = 0, e = args.size(); i != e; ++i) {
    if (args[i] == "-some-arg") {
      // Handle the command line argument.
    }
  }
  return true;
}
```

Registering a plugin

A plugin is loaded from a dynamic library at runtime by the compiler. To register a plugin in a library, use `FrontendPluginRegistry::Add<>`:

```
static FrontendPluginRegistry::Add<MyPlugin> X("my-plugin-name", "my plugin␣
↪description");
```

Defining pragmas

Plugins can also define pragmas by declaring a `PragmaHandler` and registering it using `PragmaHandlerRegistry::Add<>`:

```
// Define a pragma handler for #pragma example_pragma
class ExamplePragmaHandler : public PragmaHandler {
public:
  ExamplePragmaHandler() : PragmaHandler("example_pragma") { }
```

```
  void HandlePragma(Preprocessor &PP, PragmaIntroducerKind Introducer,
                    Token &PragmaTok) {
    // Handle the pragma
  }
};

static PragmaHandlerRegistry::Add<ExamplePragmaHandler> Y("example_pragma","example␣
↪pragma description");
```

Putting it all together

Let's look at an example plugin that prints top-level function names. This example is checked into the clang repository; please take a look at the latest version of PrintFunctionNames.cpp.

Running the plugin

Using the cc1 command line

To run a plugin, the dynamic library containing the plugin registry must be loaded via the *-load* command line option. This will load all plugins that are registered, and you can select the plugins to run by specifying the *-plugin* option. Additional parameters for the plugins can be passed with *-plugin-arg-<plugin-name>*.

Note that those options must reach clang's cc1 process. There are two ways to do so:

- Directly call the parsing process by using the *-cc1* option; this has the downside of not configuring the default header search paths, so you'll need to specify the full system path configuration on the command line.
- Use clang as usual, but prefix all arguments to the cc1 process with *-Xclang*.

For example, to run the `print-function-names` plugin over a source file in clang, first build the plugin, and then call clang with the plugin from the source tree:

```
$ export BD=/path/to/build/directory
$ (cd $BD && make PrintFunctionNames )
$ clang++ -D_GNU_SOURCE -D_DEBUG -D__STDC_CONSTANT_MACROS \
          -D__STDC_FORMAT_MACROS -D__STDC_LIMIT_MACROS -D_GNU_SOURCE \
          -I$BD/tools/clang/include -Itools/clang/include -I$BD/include -Iinclude \
          tools/clang/tools/clang-check/ClangCheck.cpp -fsyntax-only \
          -Xclang -load -Xclang $BD/lib/PrintFunctionNames.so -Xclang \
          -plugin -Xclang print-fns
```

Also see the print-function-name plugin example's README

Using the clang command line

Using *-fplugin=plugin* on the clang command line passes the plugin through as an argument to *-load* on the cc1 command line. If the plugin class implements the `getActionType` method then the plugin is run automatically. For example, to run the plugin automatically after the main AST action (i.e. the same as using *-add-plugin*):

```
// Automatically run the plugin after the main AST action
PluginASTAction::ActionType getActionType() override {
  return AddAfterMainAction;
}
```

How to write RecursiveASTVisitor based ASTFrontendActions.

Introduction

In this tutorial you will learn how to create a FrontendAction that uses a RecursiveASTVisitor to find CXXRecordDecl AST nodes with a specified name.

Creating a FrontendAction

When writing a clang based tool like a Clang Plugin or a standalone tool based on LibTooling, the common entry point is the FrontendAction. FrontendAction is an interface that allows execution of user specific actions as part of the compilation. To run tools over the AST clang provides the convenience interface ASTFrontendAction, which takes care of executing the action. The only part left is to implement the CreateASTConsumer method that returns an ASTConsumer per translation unit.

```
class FindNamedClassAction : public clang::ASTFrontendAction {
public:
  virtual std::unique_ptr<clang::ASTConsumer> CreateASTConsumer(
    clang::CompilerInstance &Compiler, llvm::StringRef InFile) {
    return std::unique_ptr<clang::ASTConsumer>(
        new FindNamedClassConsumer);
  }
};
```

Creating an ASTConsumer

ASTConsumer is an interface used to write generic actions on an AST, regardless of how the AST was produced. ASTConsumer provides many different entry points, but for our use case the only one needed is HandleTranslationUnit, which is called with the ASTContext for the translation unit.

```
class FindNamedClassConsumer : public clang::ASTConsumer {
public:
  virtual void HandleTranslationUnit(clang::ASTContext &Context) {
    // Traversing the translation unit decl via a RecursiveASTVisitor
    // will visit all nodes in the AST.
    Visitor.TraverseDecl(Context.getTranslationUnitDecl());
  }
private:
  // A RecursiveASTVisitor implementation.
  FindNamedClassVisitor Visitor;
};
```

Using the RecursiveASTVisitor

Now that everything is hooked up, the next step is to implement a RecursiveASTVisitor to extract the relevant information from the AST.

The RecursiveASTVisitor provides hooks of the form bool VisitNodeType(NodeType *) for most AST nodes; the exception are TypeLoc nodes, which are passed by-value. We only need to implement the methods for the relevant node types.

Let's start by writing a RecursiveASTVisitor that visits all CXXRecordDecl's.

```
class FindNamedClassVisitor
  : public RecursiveASTVisitor<FindNamedClassVisitor> {
public:
  bool VisitCXXRecordDecl(CXXRecordDecl *Declaration) {
    // For debugging, dumping the AST nodes will show which nodes are already
    // being visited.
    Declaration->dump();

    // The return value indicates whether we want the visitation to proceed.
    // Return false to stop the traversal of the AST.
    return true;
  }
};
```

In the methods of our RecursiveASTVisitor we can now use the full power of the Clang AST to drill through to the parts that are interesting for us. For example, to find all class declaration with a certain name, we can check for a specific qualified name:

```
bool VisitCXXRecordDecl(CXXRecordDecl *Declaration) {
  if (Declaration->getQualifiedNameAsString() == "n::m::C")
    Declaration->dump();
  return true;
}
```

Accessing the SourceManager and ASTContext

Some of the information about the AST, like source locations and global identifier information, are not stored in the AST nodes themselves, but in the ASTContext and its associated source manager. To retrieve them we need to hand the ASTContext into our RecursiveASTVisitor implementation.

The ASTContext is available from the CompilerInstance during the call to CreateASTConsumer. We can thus extract it there and hand it into our freshly created FindNamedClassConsumer:

```
virtual std::unique_ptr<clang::ASTConsumer> CreateASTConsumer(
  clang::CompilerInstance &Compiler, llvm::StringRef InFile) {
  return std::unique_ptr<clang::ASTConsumer>(
      new FindNamedClassConsumer(&Compiler.getASTContext()));
}
```

Now that the ASTContext is available in the RecursiveASTVisitor, we can do more interesting things with AST nodes, like looking up their source locations:

```
bool VisitCXXRecordDecl(CXXRecordDecl *Declaration) {
  if (Declaration->getQualifiedNameAsString() == "n::m::C") {
    // getFullLoc uses the ASTContext's SourceManager to resolve the source
    // location and break it up into its line and column parts.
    FullSourceLoc FullLocation = Context->getFullLoc(Declaration->getLocStart());
    if (FullLocation.isValid())
      llvm::outs() << "Found declaration at "
                   << FullLocation.getSpellingLineNumber() << ":"
                   << FullLocation.getSpellingColumnNumber() << "\n";
  }
  return true;
}
```

Putting it all together

Now we can combine all of the above into a small example program:

```
#include "clang/AST/ASTConsumer.h"
#include "clang/AST/RecursiveASTVisitor.h"
#include "clang/Frontend/CompilerInstance.h"
#include "clang/Frontend/FrontendAction.h"
#include "clang/Tooling/Tooling.h"

using namespace clang;

class FindNamedClassVisitor
  : public RecursiveASTVisitor<FindNamedClassVisitor> {
public:
  explicit FindNamedClassVisitor(ASTContext *Context)
    : Context(Context) {}

  bool VisitCXXRecordDecl(CXXRecordDecl *Declaration) {
    if (Declaration->getQualifiedNameAsString() == "n::m::C") {
      FullSourceLoc FullLocation = Context->getFullLoc(Declaration->getLocStart());
      if (FullLocation.isValid())
        llvm::outs() << "Found declaration at "
                     << FullLocation.getSpellingLineNumber() << ":"
                     << FullLocation.getSpellingColumnNumber() << "\n";
    }
    return true;
  }

private:
  ASTContext *Context;
};

class FindNamedClassConsumer : public clang::ASTConsumer {
public:
  explicit FindNamedClassConsumer(ASTContext *Context)
    : Visitor(Context) {}

  virtual void HandleTranslationUnit(clang::ASTContext &Context) {
    Visitor.TraverseDecl(Context.getTranslationUnitDecl());
  }
private:
  FindNamedClassVisitor Visitor;
};

class FindNamedClassAction : public clang::ASTFrontendAction {
public:
  virtual std::unique_ptr<clang::ASTConsumer> CreateASTConsumer(
    clang::CompilerInstance &Compiler, llvm::StringRef InFile) {
    return std::unique_ptr<clang::ASTConsumer>(
        new FindNamedClassConsumer(&Compiler.getASTContext()));
  }
};

int main(int argc, char **argv) {
  if (argc > 1) {
    clang::tooling::runToolOnCode(new FindNamedClassAction, argv[1]);
  }
```

```
}
```

We store this into a file called FindClassDecls.cpp and create the following CMakeLists.txt to link it:

```
add_clang_executable(find-class-decls FindClassDecls.cpp)

target_link_libraries(find-class-decls clangTooling)
```

When running this tool over a small code snippet it will output all declarations of a class n::m::C it found:

```
$ ./bin/find-class-decls "namespace n { namespace m { class C {}; } }"
Found declaration at 1:29
```

Tutorial for building tools using LibTooling and LibASTMatchers

This document is intended to show how to build a useful source-to-source translation tool based on Clang's LibTooling. It is explicitly aimed at people who are new to Clang, so all you should need is a working knowledge of C++ and the command line.

In order to work on the compiler, you need some basic knowledge of the abstract syntax tree (AST). To this end, the reader is incouraged to skim the *Introduction to the Clang AST*

Step 0: Obtaining Clang

As Clang is part of the LLVM project, you'll need to download LLVM's source code first. Both Clang and LLVM are maintained as Subversion repositories, but we'll be accessing them through the git mirror. For further information, see the getting started guide.

```
mkdir ~/clang-llvm && cd ~/clang-llvm
git clone http://llvm.org/git/llvm.git
cd llvm/tools
git clone http://llvm.org/git/clang.git
cd clang/tools
git clone http://llvm.org/git/clang-tools-extra.git extra
```

Next you need to obtain the CMake build system and Ninja build tool. You may already have CMake installed, but current binary versions of CMake aren't built with Ninja support.

```
cd ~/clang-llvm
git clone https://github.com/martine/ninja.git
cd ninja
git checkout release
./bootstrap.py
sudo cp ninja /usr/bin/

cd ~/clang-llvm
git clone git://cmake.org/stage/cmake.git
cd cmake
git checkout next
./bootstrap
make
sudo make install
```

Okay. Now we'll build Clang!

```
cd ~/clang-llvm
mkdir build && cd build
cmake -G Ninja ../llvm -DLLVM_BUILD_TESTS=ON  # Enable tests; default is off.
ninja
ninja check       # Test LLVM only.
ninja clang-test  # Test Clang only.
ninja install
```

And we're live.

All of the tests should pass, though there is a (very) small chance that you can catch LLVM and Clang out of sync. Running `'git svn rebase'` in both the llvm and clang directories should fix any problems.

Finally, we want to set Clang as its own compiler.

```
cd ~/clang-llvm/build
ccmake ../llvm
```

The second command will bring up a GUI for configuring Clang. You need to set the entry for `CMAKE_CXX_COMPILER`. Press `'t'` to turn on advanced mode. Scroll down to `CMAKE_CXX_COMPILER`, and set it to `/usr/bin/clang++`, or wherever you installed it. Press `'c'` to configure, then `'g'` to generate CMake's files.

Finally, run ninja one last time, and you're done.

Step 1: Create a ClangTool

Now that we have enough background knowledge, it's time to create the simplest productive ClangTool in existence: a syntax checker. While this already exists as `clang-check`, it's important to understand what's going on.

First, we'll need to create a new directory for our tool and tell CMake that it exists. As this is not going to be a core clang tool, it will live in the `tools/extra` repository.

```
cd ~/clang-llvm/llvm/tools/clang
mkdir tools/extra/loop-convert
echo 'add_subdirectory(loop-convert)' >> tools/extra/CMakeLists.txt
vim tools/extra/loop-convert/CMakeLists.txt
```

CMakeLists.txt should have the following contents:

```
set(LLVM_LINK_COMPONENTS support)

add_clang_executable(loop-convert
  LoopConvert.cpp
  )
target_link_libraries(loop-convert
  clangTooling
  clangBasic
  clangASTMatchers
  )
```

With that done, Ninja will be able to compile our tool. Let's give it something to compile! Put the following into `tools/extra/loop-convert/LoopConvert.cpp`. A detailed explanation of why the different parts are needed can be found in the LibTooling documentation.

```
// Declares clang::SyntaxOnlyAction.
#include "clang/Frontend/FrontendActions.h"
```

```
#include "clang/Tooling/CommonOptionsParser.h"
#include "clang/Tooling/Tooling.h"
// Declares llvm::cl::extrahelp.
#include "llvm/Support/CommandLine.h"

using namespace clang::tooling;
using namespace llvm;

// Apply a custom category to all command-line options so that they are the
// only ones displayed.
static llvm::cl::OptionCategory MyToolCategory("my-tool options");

// CommonOptionsParser declares HelpMessage with a description of the common
// command-line options related to the compilation database and input files.
// It's nice to have this help message in all tools.
static cl::extrahelp CommonHelp(CommonOptionsParser::HelpMessage);

// A help message for this specific tool can be added afterwards.
static cl::extrahelp MoreHelp("\nMore help text...");

int main(int argc, const char **argv) {
  CommonOptionsParser OptionsParser(argc, argv, MyToolCategory);
  ClangTool Tool(OptionsParser.getCompilations(),
                 OptionsParser.getSourcePathList());
  return Tool.run(newFrontendActionFactory<clang::SyntaxOnlyAction>().get());
}
```

And that's it! You can compile our new tool by running ninja from the `build` directory.

```
cd ~/clang-llvm/build
ninja
```

You should now be able to run the syntax checker, which is located in `~/clang-llvm/build/bin`, on any source file. Try it!

```
echo "int main() { return 0; }" > test.cpp
bin/loop-convert test.cpp --
```

Note the two dashes after we specify the source file. The additional options for the compiler are passed after the dashes rather than loading them from a compilation database - there just aren't any options needed right now.

Intermezzo: Learn AST matcher basics

Clang recently introduced the *ASTMatcher library* to provide a simple, powerful, and concise way to describe specific patterns in the AST. Implemented as a DSL powered by macros and templates (see ASTMatchers.h if you're curious), matchers offer the feel of algebraic data types common to functional programming languages.

For example, suppose you wanted to examine only binary operators. There is a matcher to do exactly that, conveniently named `binaryOperator`. I'll give you one guess what this matcher does:

```
binaryOperator(hasOperatorName("+"), hasLHS(integerLiteral(equals(0))))
```

Shockingly, it will match against addition expressions whose left hand side is exactly the literal 0. It will not match against other forms of 0, such as `'\0'` or `NULL`, but it will match against macros that expand to 0. The matcher will also not match against calls to the overloaded operator `'+'`, as there is a separate `operatorCallExpr` matcher to handle overloaded operators.

There are AST matchers to match all the different nodes of the AST, narrowing matchers to only match AST nodes fulfilling specific criteria, and traversal matchers to get from one kind of AST node to another. For a complete list of AST matchers, take a look at the AST Matcher References

All matcher that are nouns describe entities in the AST and can be bound, so that they can be referred to whenever a match is found. To do so, simply call the method `bind` on these matchers, e.g.:

```
variable(hasType(isInteger())).bind("intvar")
```

Step 2: Using AST matchers

Okay, on to using matchers for real. Let's start by defining a matcher which will capture all `for` statements that define a new variable initialized to zero. Let's start with matching all `for` loops:

```
forStmt()
```

Next, we want to specify that a single variable is declared in the first portion of the loop, so we can extend the matcher to

```
forStmt(hasLoopInit(declStmt(hasSingleDecl(varDecl()))))
```

Finally, we can add the condition that the variable is initialized to zero.

```
forStmt(hasLoopInit(declStmt(hasSingleDecl(varDecl(
  hasInitializer(integerLiteral(equals(0))))))))
```

It is fairly easy to read and understand the matcher definition ("match loops whose init portion declares a single variable which is initialized to the integer literal 0"), but deciding that every piece is necessary is more difficult. Note that this matcher will not match loops whose variables are initialized to `'\0'`, `0.0`, `NULL`, or any form of zero besides the integer 0.

The last step is giving the matcher a name and binding the `ForStmt` as we will want to do something with it:

```
StatementMatcher LoopMatcher =
  forStmt(hasLoopInit(declStmt(hasSingleDecl(varDecl(
    hasInitializer(integerLiteral(equals(0)))))))).bind("forLoop");
```

Once you have defined your matchers, you will need to add a little more scaffolding in order to run them. Matchers are paired with a `MatchCallback` and registered with a `MatchFinder` object, then run from a `ClangTool`. More code!

Add the following to `LoopConvert.cpp`:

```
#include "clang/ASTMatchers/ASTMatchers.h"
#include "clang/ASTMatchers/ASTMatchFinder.h"

using namespace clang;
using namespace clang::ast_matchers;

StatementMatcher LoopMatcher =
  forStmt(hasLoopInit(declStmt(hasSingleDecl(varDecl(
    hasInitializer(integerLiteral(equals(0)))))))).bind("forLoop");

class LoopPrinter : public MatchFinder::MatchCallback {
public :
  virtual void run(const MatchFinder::MatchResult &Result) {
    if (const ForStmt *FS = Result.Nodes.getNodeAs<clang::ForStmt>("forLoop"))
```

```
      FS->dump();
  }
};
```

And change `main()` to:

```
int main(int argc, const char **argv) {
  CommonOptionsParser OptionsParser(argc, argv, MyToolCategory);
  ClangTool Tool(OptionsParser.getCompilations(),
                 OptionsParser.getSourcePathList());

  LoopPrinter Printer;
  MatchFinder Finder;
  Finder.addMatcher(LoopMatcher, &Printer);

  return Tool.run(newFrontendActionFactory(&Finder).get());
}
```

Now, you should be able to recompile and run the code to discover for loops. Create a new file with a few examples, and test out our new handiwork:

```
cd ~/clang-llvm/llvm/llvm_build/
ninja loop-convert
vim ~/test-files/simple-loops.cc
bin/loop-convert ~/test-files/simple-loops.cc
```

Step 3.5: More Complicated Matchers

Our simple matcher is capable of discovering for loops, but we would still need to filter out many more ourselves. We can do a good portion of the remaining work with some cleverly chosen matchers, but first we need to decide exactly which properties we want to allow.

How can we characterize for loops over arrays which would be eligible for translation to range-based syntax? Range based loops over arrays of size `N` that:

- start at index `0`
- iterate consecutively
- end at index `N-1`

We already check for (1), so all we need to add is a check to the loop's condition to ensure that the loop's index variable is compared against `N` and another check to ensure that the increment step just increments this same variable. The matcher for (2) is straightforward: require a pre- or post-increment of the same variable declared in the init portion.

Unfortunately, such a matcher is impossible to write. Matchers contain no logic for comparing two arbitrary AST nodes and determining whether or not they are equal, so the best we can do is matching more than we would like to allow, and punting extra comparisons to the callback.

In any case, we can start building this sub-matcher. We can require that the increment step be a unary increment like this:

```
hasIncrement(unaryOperator(hasOperatorName("++")))
```

Specifying what is incremented introduces another quirk of Clang's AST: Usages of variables are represented as `DeclRefExpr`'s ("declaration reference expressions") because they are expressions which refer to variable declarations. To find a `unaryOperator` that refers to a specific declaration, we can simply add a second condition to it:

```
hasIncrement(unaryOperator(
  hasOperatorName("++"),
  hasUnaryOperand(declRefExpr())))
```

Furthermore, we can restrict our matcher to only match if the incremented variable is an integer:

```
hasIncrement(unaryOperator(
  hasOperatorName("++"),
  hasUnaryOperand(declRefExpr(to(varDecl(hasType(isInteger()))))))
```

And the last step will be to attach an identifier to this variable, so that we can retrieve it in the callback:

```
hasIncrement(unaryOperator(
  hasOperatorName("++"),
  hasUnaryOperand(declRefExpr(to(
    varDecl(hasType(isInteger())).bind("incrementVariable"))))))
```

We can add this code to the definition of `LoopMatcher` and make sure that our program, outfitted with the new matcher, only prints out loops that declare a single variable initialized to zero and have an increment step consisting of a unary increment of some variable.

Now, we just need to add a matcher to check if the condition part of the `for` loop compares a variable against the size of the array. There is only one problem - we don't know which array we're iterating over without looking at the body of the loop! We are again restricted to approximating the result we want with matchers, filling in the details in the callback. So we start with:

```
hasCondition(binaryOperator(hasOperatorName("<"))
```

It makes sense to ensure that the left-hand side is a reference to a variable, and that the right-hand side has integer type.

```
hasCondition(binaryOperator(
  hasOperatorName("<"),
  hasLHS(declRefExpr(to(varDecl(hasType(isInteger()))))),
  hasRHS(expr(hasType(isInteger())))))
```

Why? Because it doesn't work. Of the three loops provided in `test-files/simple.cpp`, zero of them have a matching condition. A quick look at the AST dump of the first for loop, produced by the previous iteration of loop-convert, shows us the answer:

```
(ForStmt 0x173b240
  (DeclStmt 0x173afc8
    0x173af50 "int i =
      (IntegerLiteral 0x173afa8 'int' 0)")
  <<<>>>
  (BinaryOperator 0x173b060 '_Bool' '<'
    (ImplicitCastExpr 0x173b030 'int'
      (DeclRefExpr 0x173afe0 'int' lvalue Var 0x173af50 'i' 'int'))
    (ImplicitCastExpr 0x173b048 'int'
      (DeclRefExpr 0x173b008 'const int' lvalue Var 0x170fa80 'N' 'const int')))
  (UnaryOperator 0x173b0b0 'int' lvalue prefix '++'
    (DeclRefExpr 0x173b088 'int' lvalue Var 0x173af50 'i' 'int'))
  (CompoundStatement ...
```

We already know that the declaration and increments both match, or this loop wouldn't have been dumped. The culprit lies in the implicit cast applied to the first operand (i.e. the LHS) of the less-than operator, an L-value to R-value conversion applied to the expression referencing `i`. Thankfully, the matcher library offers a solution to this problem

in the form of `ignoringParenImpCasts`, which instructs the matcher to ignore implicit casts and parentheses before continuing to match. Adjusting the condition operator will restore the desired match.

```
hasCondition(binaryOperator(
  hasOperatorName("<"),
  hasLHS(ignoringParenImpCasts(declRefExpr(
    to(varDecl(hasType(isInteger()))))),
  hasRHS(expr(hasType(isInteger())))))
```

After adding binds to the expressions we wished to capture and extracting the identifier strings into variables, we have array-step-2 completed.

Step 4: Retrieving Matched Nodes

So far, the matcher callback isn't very interesting: it just dumps the loop's AST. At some point, we will need to make changes to the input source code. Next, we'll work on using the nodes we bound in the previous step.

The `MatchFinder::run()` callback takes a `MatchFinder::MatchResult&` as its parameter. We're most interested in its `Context` and `Nodes` members. Clang uses the `ASTContext` class to represent contextual information about the AST, as the name implies, though the most functionally important detail is that several operations require an `ASTContext*` parameter. More immediately useful is the set of matched nodes, and how we retrieve them.

Since we bind three variables (identified by ConditionVarName, InitVarName, and IncrementVarName), we can obtain the matched nodes by using the `getNodeAs()` member function.

In `LoopConvert.cpp` add

```
#include "clang/AST/ASTContext.h"
```

Change `LoopMatcher` to

```
StatementMatcher LoopMatcher =
    forStmt(hasLoopInit(declStmt(
                hasSingleDecl(varDecl(hasInitializer(integerLiteral(equals(0))))
                              .bind("initVarName")))),
            hasIncrement(unaryOperator(
                hasOperatorName("++"),
                hasUnaryOperand(declRefExpr(
                    to(varDecl(hasType(isInteger())).bind("incVarName")))))),
            hasCondition(binaryOperator(
                hasOperatorName("<"),
                hasLHS(ignoringParenImpCasts(declRefExpr(
                    to(varDecl(hasType(isInteger())).bind("condVarName"))))),
                hasRHS(expr(hasType(isInteger()))).bind("forLoop");
```

And change `LoopPrinter::run` to

```
void LoopPrinter::run(const MatchFinder::MatchResult &Result) {
  ASTContext *Context = Result.Context;
  const ForStmt *FS = Result.Nodes.getStmtAs<ForStmt>("forLoop");
  // We do not want to convert header files!
  if (!FS || !Context->getSourceManager().isFromMainFile(FS->getForLoc()))
    return;
  const VarDecl *IncVar = Result.Nodes.getNodeAs<VarDecl>("incVarName");
  const VarDecl *CondVar = Result.Nodes.getNodeAs<VarDecl>("condVarName");
  const VarDecl *InitVar = Result.Nodes.getNodeAs<VarDecl>("initVarName");
```

```
  if (!areSameVariable(IncVar, CondVar) || !areSameVariable(IncVar, InitVar))
    return;
  llvm::outs() << "Potential array-based loop discovered.\n";
}
```

Clang associates a `VarDecl` with each variable to represent the variable's declaration. Since the "canonical" form of each declaration is unique by address, all we need to do is make sure neither `ValueDecl` (base class of `VarDecl`) is `NULL` and compare the canonical Decls.

```
static bool areSameVariable(const ValueDecl *First, const ValueDecl *Second) {
  return First && Second &&
         First->getCanonicalDecl() == Second->getCanonicalDecl();
}
```

If execution reaches the end of `LoopPrinter::run()`, we know that the loop shell that looks like

```
for (int i= 0; i < expr(); ++i) { ... }
```

For now, we will just print a message explaining that we found a loop. The next section will deal with recursively traversing the AST to discover all changes needed.

As a side note, it's not as trivial to test if two expressions are the same, though Clang has already done the hard work for us by providing a way to canonicalize expressions:

```
static bool areSameExpr(ASTContext *Context, const Expr *First,
                        const Expr *Second) {
  if (!First || !Second)
    return false;
  llvm::FoldingSetNodeID FirstID, SecondID;
  First->Profile(FirstID, *Context, true);
  Second->Profile(SecondID, *Context, true);
  return FirstID == SecondID;
}
```

This code relies on the comparison between two `llvm::FoldingSetNodeIDs`. As the documentation for `Stmt::Profile()` indicates, the `Profile()` member function builds a description of a node in the AST, based on its properties, along with those of its children. `FoldingSetNodeID` then serves as a hash we can use to compare expressions. We will need `areSameExpr` later. Before you run the new code on the additional loops added to test-files/simple.cpp, try to figure out which ones will be considered potentially convertible.

Matching the Clang AST

This document explains how to use Clang's LibASTMatchers to match interesting nodes of the AST and execute code that uses the matched nodes. Combined with *LibTooling*, LibASTMatchers helps to write code-to-code transformation tools or query tools.

We assume basic knowledge about the Clang AST. See the *Introduction to the Clang AST* if you want to learn more about how the AST is structured.

Introduction

LibASTMatchers provides a domain specific language to create predicates on Clang's AST. This DSL is written in and can be used from C++, allowing users to write a single program to both match AST nodes and access the node's C++ interface to extract attributes, source locations, or any other information provided on the AST level.

AST matchers are predicates on nodes in the AST. Matchers are created by calling creator functions that allow building up a tree of matchers, where inner matchers are used to make the match more specific.

For example, to create a matcher that matches all class or union declarations in the AST of a translation unit, you can call recordDecl(). To narrow the match down, for example to find all class or union declarations with the name "`Foo`", insert a hasName matcher: the call `recordDecl(hasName("Foo"))` returns a matcher that matches classes or unions that are named "`Foo`", in any namespace. By default, matchers that accept multiple inner matchers use an implicit allOf(). This allows further narrowing down the match, for example to match all classes that are derived from "`Bar`": `recordDecl(hasName("Foo"), isDerivedFrom("Bar"))`.

How to create a matcher

With more than a thousand classes in the Clang AST, one can quickly get lost when trying to figure out how to create a matcher for a specific pattern. This section will teach you how to use a rigorous step-by-step pattern to build the matcher you are interested in. Note that there will always be matchers missing for some part of the AST. See the section about *how to write your own AST matchers* later in this document.

The precondition to using the matchers is to understand how the AST for what you want to match looks like. The *Introduction to the Clang AST* teaches you how to dump a translation unit's AST into a human readable format.

In general, the strategy to create the right matchers is:

1. Find the outermost class in Clang's AST you want to match.
2. Look at the AST Matcher Reference for matchers that either match the node you're interested in or narrow down attributes on the node.
3. Create your outer match expression. Verify that it works as expected.
4. Examine the matchers for what the next inner node you want to match is.
5. Repeat until the matcher is finished.

Binding nodes in match expressions

Matcher expressions allow you to specify which parts of the AST are interesting for a certain task. Often you will want to then do something with the nodes that were matched, like building source code transformations.

To that end, matchers that match specific AST nodes (so called node matchers) are bindable; for example, `recordDecl(hasName("MyClass")).bind("id")` will bind the matched `recordDecl` node to the string "`id`", to be later retrieved in the match callback.

Writing your own matchers

There are multiple different ways to define a matcher, depending on its type and flexibility.

`VariadicDynCastAllOfMatcher<Base, Derived>`

Those match all nodes of type *Base* if they can be dynamically casted to *Derived*. The names of those matchers are nouns, which closely resemble *Derived*. `VariadicDynCastAllOfMatchers` are the backbone of the matcher hierarchy. Most often, your match expression will start with one of them, and you can *bind* the node they represent to ids for later processing.

`VariadicDynCastAllOfMatchers` are callable classes that model variadic template functions in C++03. They take an aribtrary number of `Matcher<Derived>` and return a `Matcher<Base>`.

AST_MATCHER_P(Type, Name, ParamType, Param)

Most matcher definitions use the matcher creation macros. Those define both the matcher of type `Matcher<Type>` itself, and a matcher-creation function named *Name* that takes a parameter of type *ParamType* and returns the corresponding matcher.

There are multiple matcher definition macros that deal with polymorphic return values and different parameter counts. See ASTMatchersMacros.h.

Matcher creation functions

Matchers are generated by nesting calls to matcher creation functions. Most of the time those functions are either created by using `VariadicDynCastAllOfMatcher` or the matcher creation macros (see below). The free-standing functions are an indication that this matcher is just a combination of other matchers, as is for example the case with callee.

How To Setup Clang Tooling For LLVM

Clang Tooling provides infrastructure to write tools that need syntactic and semantic information about a program. This term also relates to a set of specific tools using this infrastructure (e.g. `clang-check`). This document provides information on how to set up and use Clang Tooling for the LLVM source code.

Introduction

Clang Tooling needs a compilation database to figure out specific build options for each file. Currently it can create a compilation database from the `compilation_commands.json` file, generated by CMake. When invoking clang tools, you can either specify a path to a build directory using a command line parameter `-p` or let Clang Tooling find this file in your source tree. In either case you need to configure your build using CMake to use clang tools.

Setup Clang Tooling Using CMake and Make

If you intend to use make to build LLVM, you should have CMake 2.8.6 or later installed (can be found here).

First, you need to generate Makefiles for LLVM with CMake. You need to make a build directory and run CMake from it:

```
$ mkdir your/build/directory
$ cd your/build/directory
$ cmake -DCMAKE_EXPORT_COMPILE_COMMANDS=ON path/to/llvm/sources
```

If you want to use clang instead of GCC, you can add `-DCMAKE_C_COMPILER=/path/to/clang -DCMAKE_CXX_COMPILER=/path/to/clang++`. You can also use `ccmake`, which provides a curses interface to configure CMake variables for lazy people.

As a result, the new `compile_commands.json` file should appear in the current directory. You should link it to the LLVM source tree so that Clang Tooling is able to use it:

```
$ ln -s $PWD/compile_commands.json path/to/llvm/source/
```

Now you are ready to build and test LLVM using make:

```
$ make check-all
```

Using Clang Tools

After you completed the previous steps, you are ready to run clang tools. If you have a recent clang installed, you should have `clang-check` in `$PATH`. Try to run it on any `.cpp` file inside the LLVM source tree:

```
$ clang-check tools/clang/lib/Tooling/CompilationDatabase.cpp
```

If you're using vim, it's convenient to have clang-check integrated. Put this into your `.vimrc`:

```
function! ClangCheckImpl(cmd)
  if &autowrite | wall | endif
  echo "Running " . a:cmd . " ..."
  let l:output = system(a:cmd)
  cexpr l:output
  cwindow
  let w:quickfix_title = a:cmd
  if v:shell_error != 0
    cc
  endif
  let g:clang_check_last_cmd = a:cmd
endfunction

function! ClangCheck()
  let l:filename = expand('%')
  if l:filename =~ '\.\(cpp\|cxx\|cc\|c\)$'
    call ClangCheckImpl("clang-check " . l:filename)
  elseif exists("g:clang_check_last_cmd")
    call ClangCheckImpl(g:clang_check_last_cmd)
  else
    echo "Can't detect file's compilation arguments and no previous clang-check␣
↪invocation!"
  endif
endfunction

nmap <silent> <F5> :call ClangCheck()<CR><CR>
```

When editing a .cpp/.cxx/.cc/.c file, hit F5 to reparse the file. In case the current file has a different extension (for example, .h), F5 will re-run the last clang-check invocation made from this vim instance (if any). The output will go into the error window, which is opened automatically when clang-check finds errors, and can be re-opened with `:cope`.

Other `clang-check` options that can be useful when working with clang AST:

- `-ast-print` — Build ASTs and then pretty-print them.
- `-ast-dump` — Build ASTs and then debug dump them.
- `-ast-dump-filter=<string>` — Use with `-ast-dump` or `-ast-print` to dump/print only AST declaration nodes having a certain substring in a qualified name. Use `-ast-list` to list all filterable declaration node names.
- `-ast-list` — Build ASTs and print the list of declaration node qualified names.

Examples:

```
$ clang-check tools/clang/tools/clang-check/ClangCheck.cpp -ast-dump -ast-dump-filter␣
↪ActionFactory::newASTConsumer
Processing: tools/clang/tools/clang-check/ClangCheck.cpp.
Dumping ::ActionFactory::newASTConsumer:
clang::ASTConsumer *newASTConsumer() (CompoundStmt 0x44da290 </home/alexfh/local/llvm/
↪tools/clang/tools/clang-check/ClangCheck.cpp:64:40, line:72:3>
  (IfStmt 0x44d97c8 <line:65:5, line:66:45>
    <<<NULL>>>
      (ImplicitCastExpr 0x44d96d0 <line:65:9> '_Bool':'_Bool' <UserDefinedConversion>
...
$ clang-check tools/clang/tools/clang-check/ClangCheck.cpp -ast-print -ast-dump-
↪filter ActionFactory::newASTConsumer
Processing: tools/clang/tools/clang-check/ClangCheck.cpp.
Printing <anonymous namespace>::ActionFactory::newASTConsumer:
clang::ASTConsumer *newASTConsumer() {
    if (this->ASTList.operator _Bool())
        return clang::CreateASTDeclNodeLister();
    if (this->ASTDump.operator _Bool())
        return clang::CreateASTDumper(this->ASTDumpFilter);
    if (this->ASTPrint.operator _Bool())
        return clang::CreateASTPrinter(&llvm::outs(), this->ASTDumpFilter);
    return new clang::ASTConsumer();
}
```

(Experimental) Using Ninja Build System

Optionally you can use the Ninja build system instead of make. It is aimed at making your builds faster. Currently this step will require building Ninja from sources.

To take advantage of using Clang Tools along with Ninja build you need at least CMake 2.8.9.

Clone the Ninja git repository and build Ninja from sources:

```
$ git clone git://github.com/martine/ninja.git
$ cd ninja/
$ ./bootstrap.py
```

This will result in a single binary `ninja` in the current directory. It doesn't require installation and can just be copied to any location inside `$PATH`, say `/usr/local/bin/`:

```
$ sudo cp ninja /usr/local/bin/
$ sudo chmod a+rx /usr/local/bin/ninja
```

After doing all of this, you'll need to generate Ninja build files for LLVM with CMake. You need to make a build directory and run CMake from it:

```
$ mkdir your/build/directory
$ cd your/build/directory
$ cmake -G Ninja -DCMAKE_EXPORT_COMPILE_COMMANDS=ON path/to/llvm/sources
```

If you want to use clang instead of GCC, you can add `-DCMAKE_C_COMPILER=/path/to/clang -DCMAKE_CXX_COMPILER=/path/to/clang++`. You can also use `ccmake`, which provides a curses interface to configure CMake variables in an interactive manner.

As a result, the new `compile_commands.json` file should appear in the current directory. You should link it to the LLVM source tree so that Clang Tooling is able to use it:

```
$ ln -s $PWD/compile_commands.json path/to/llvm/source/
```

Now you are ready to build and test LLVM using Ninja:

```
$ ninja check-all
```

Other target names can be used in the same way as with make.

JSON Compilation Database Format Specification

This document describes a format for specifying how to replay single compilations independently of the build system.

Background

Tools based on the C++ Abstract Syntax Tree need full information how to parse a translation unit. Usually this information is implicitly available in the build system, but running tools as part of the build system is not necessarily the best solution:

- Build systems are inherently change driven, so running multiple tools over the same code base without changing the code does not fit into the architecture of many build systems.
- Figuring out whether things have changed is often an IO bound process; this makes it hard to build low latency end user tools based on the build system.
- Build systems are inherently sequential in the build graph, for example due to generated source code. While tools that run independently of the build still need the generated source code to exist, running tools multiple times over unchanging source does not require serialization of the runs according to the build dependency graph.

Supported Systems

Currently CMake (since 2.8.5) supports generation of compilation databases for Unix Makefile builds (Ninja builds in the works) with the option `CMAKE_EXPORT_COMPILE_COMMANDS`.

For projects on Linux, there is an alternative to intercept compiler calls with a tool called Bear.

Clang's tooling interface supports reading compilation databases; see the *LibTooling documentation*. libclang and its python bindings also support this (since clang 3.2); see CXCompilationDatabase.h.

Format

A compilation database is a JSON file, which consist of an array of "command objects", where each command object specifies one way a translation unit is compiled in the project.

Each command object contains the translation unit's main file, the working directory of the compile run and the actual compile command.

Example:

```
[
  { "directory": "/home/user/llvm/build",
    "command": "/usr/bin/clang++ -Irelative -DSOMEDEF=\"With spaces, quotes and \\-es.
↪\" -c -o file.o file.cc",
    "file": "file.cc" },
```

```
  ...
]
```

The contracts for each field in the command object are:

- **directory:** The working directory of the compilation. All paths specified in the **command** or **file** fields must be either absolute or relative to this directory.
- **file:** The main translation unit source processed by this compilation step. This is used by tools as the key into the compilation database. There can be multiple command objects for the same file, for example if the same source file is compiled with different configurations.
- **command:** The compile command executed. After JSON unescaping, this must be a valid command to rerun the exact compilation step for the translation unit in the environment the build system uses. Parameters use shell quoting and shell escaping of quotes, with ‘"‘ and ‘\‘ being the only special characters. Shell expansion is not supported.

Build System Integration

The convention is to name the file compile_commands.json and put it at the top of the build directory. Clang tools are pointed to the top of the build directory to detect the file and use the compilation database to parse C++ code in the source tree.

CHAPTER 6

Using Clang Tools

Overview

Clang Tools are standalone command line (and potentially GUI) tools designed for use by C++ developers who are already using and enjoying Clang as their compiler. These tools provide developer-oriented functionality such as fast syntax checking, automatic formatting, refactoring, etc.

Only a couple of the most basic and fundamental tools are kept in the primary Clang Subversion project. The rest of the tools are kept in a side-project so that developers who don't want or need to build them don't. If you want to get access to the extra Clang Tools repository, simply check it out into the tools tree of your Clang checkout and follow the usual process for building and working with a combined LLVM/Clang checkout:

- With Subversion:
  - `cd llvm/tools/clang/tools`
  - `svn co http://llvm.org/svn/llvm-project/clang-tools-extra/trunk extra`
- Or with Git:
  - `cd llvm/tools/clang/tools`
  - `git clone http://llvm.org/git/clang-tools-extra.git extra`

This document describes a high-level overview of the organization of Clang Tools within the project as well as giving an introduction to some of the more important tools. However, it should be noted that this document is currently focused on Clang and Clang Tool developers, not on end users of these tools.

Clang Tools Organization

Clang Tools are CLI or GUI programs that are intended to be directly used by C++ developers. That is they are *not* primarily for use by Clang developers, although they are hopefully useful to C++ developers who happen to work on Clang, and we try to actively dogfood their functionality. They are developed in three components: the underlying infrastructure for building a standalone tool based on Clang, core shared logic used by many different tools in the form of refactoring and rewriting libraries, and the tools themselves.

The underlying infrastructure for Clang Tools is the *LibTooling* platform. See its documentation for much more detailed information about how this infrastructure works. The common refactoring and rewriting toolkit-style library is also part of LibTooling organizationally.

A few Clang Tools are developed along side the core Clang libraries as examples and test cases of fundamental functionality. However, most of the tools are developed in a side repository to provide easy separation from the core libraries. We intentionally do not support public libraries in the side repository, as we want to carefully review and find good APIs for libraries as they are lifted out of a few tools and into the core Clang library set.

Regardless of which repository Clang Tools' code resides in, the development process and practices for all Clang Tools are exactly those of Clang itself. They are entirely within the Clang *project*, regardless of the version control scheme.

Core Clang Tools

The core set of Clang tools that are within the main repository are tools that very specifically complement, and allow use and testing of *Clang* specific functionality.

clang-check

ClangCheck combines the LibTooling framework for running a Clang tool with the basic Clang diagnostics by syntax checking specific files in a fast, command line interface. It can also accept flags to re-display the diagnostics in different formats with different flags, suitable for use driving an IDE or editor. Furthermore, it can be used in fixit-mode to directly apply fixit-hints offered by clang. See *How To Setup Clang Tooling For LLVM* for instructions on how to setup and used *clang-check*.

clang-format

Clang-format is both a *library* and a *stand-alone tool* with the goal of automatically reformatting C++ sources files according to configurable style guides. To do so, clang-format uses Clang's `Lexer` to transform an input file into a token stream and then changes all the whitespace around those tokens. The goal is for clang-format to serve both as a user tool (ideally with powerful IDE integrations) and as part of other refactoring tools, e.g. to do a reformatting of all the lines changed during a renaming.

Extra Clang Tools

As various categories of Clang Tools are added to the extra repository, they'll be tracked here. The focus of this documentation is on the scope and features of the tools for other tool developers; each tool should provide its own user-focused documentation.

clang-tidy

clang-tidy is a clang-based C++ linter tool. It provides an extensible framework for building compiler-based static analyses detecting and fixing bug-prone patterns, performance, portability and maintainability issues.

Ideas for new Tools

- C++ cast conversion tool. Will convert C-style casts (`(type) value`) to appropriate C++ cast (`static_cast`, `const_cast` or `reinterpret_cast`).
- Non-member `begin()` and `end()` conversion tool. Will convert `foo.begin()` into `begin(foo)` and similarly for `end()`, where `foo` is a standard container. We could also detect similar patterns for arrays.

- `tr1` removal tool. Will migrate source code from using TR1 library features to C++11 library. For example:

```
#include <tr1/unordered_map>
int main()
{
    std::tr1::unordered_map <int, int> ma;
    std::cout << ma.size () << std::endl;
    return 0;
}
```

  should be rewritten to:

```
#include <unordered_map>
int main()
{
    std::unordered_map <int, int> ma;
    std::cout << ma.size () << std::endl;
    return 0;
}
```

- A tool to remove `auto`. Will convert `auto` to an explicit type or add comments with deduced types. The motivation is that there are developers that don't want to use `auto` because they are afraid that they might lose control over their code.
- C++14: less verbose operator function objects (N3421). For example:

```
sort(v.begin(), v.end(), greater<ValueType>());
```

  should be rewritten to:

```
sort(v.begin(), v.end(), greater<>());
```

ClangCheck

ClangCheck is a small wrapper around *LibTooling* which can be used to do basic error checking and AST dumping.

```
$ cat <<EOF > snippet.cc
> void f() {
>   int a = 0
> }
> EOF
$ ~/clang/build/bin/clang-check snippet.cc -ast-dump --
Processing: /Users/danieljasper/clang/llvm/tools/clang/docs/snippet.cc.
/Users/danieljasper/clang/llvm/tools/clang/docs/snippet.cc:2:12: error: expected ';'␣
↪at end of
      declaration
  int a = 0
           ^
           ;
(TranslationUnitDecl 0x7ff3a3029ed0 <<invalid sloc>>
  (TypedefDecl 0x7ff3a302a410 <<invalid sloc>> __int128_t '__int128')
  (TypedefDecl 0x7ff3a302a470 <<invalid sloc>> __uint128_t 'unsigned __int128')
  (TypedefDecl 0x7ff3a302a830 <<invalid sloc>> __builtin_va_list '__va_list_tag [1]')
  (FunctionDecl 0x7ff3a302a8d0 </Users/danieljasper/clang/llvm/tools/clang/docs/
↪snippet.cc:1:1, line:3:1> f 'void (void)'
    (CompoundStmt 0x7ff3a302aa10 <line:1:10, line:3:1>
```

```
      (DeclStmt 0x7ff3a302a9f8 <line:2:3, line:3:1>
        (VarDecl 0x7ff3a302a980 <line:2:3, col:11> a 'int'
          (IntegerLiteral 0x7ff3a302a9d8 <col:11> 'int' 0))))))
1 error generated.
Error while processing snippet.cc.
```

The '–' at the end is important as it prevents *clang-check* from search for a compilation database. For more information on how to setup and use *clang-check* in a project, see *How To Setup Clang Tooling For LLVM*.

ClangFormat

ClangFormat describes a set of tools that are built on top of *LibFormat*. It can support your workflow in a variety of ways including a standalone tool and editor integrations.

Standalone Tool

clang-format is located in *clang/tools/clang-format* and can be used to format C/C++/Obj-C code.

```
$ clang-format -help
OVERVIEW: A tool to format C/C++/Java/JavaScript/Objective-C/Protobuf code.

If no arguments are specified, it formats the code from standard input
and writes the result to the standard output.
If <file>s are given, it reformats the files. If -i is specified
together with <file>s, the files are edited in-place. Otherwise, the
result is written to the standard output.

USAGE: clang-format [options] [<file> ...]

OPTIONS:

Clang-format options:

  -assume-filename=<string> - When reading from stdin, clang-format assumes this
                              filename to look for a style config file (with
                              -style=file) and to determine the language.
  -cursor=<uint>            - The position of the cursor when invoking
                              clang-format from an editor integration
  -dump-config              - Dump configuration options to stdout and exit.
                              Can be used with -style option.
  -fallback-style=<string>  - The name of the predefined style used as a
                              fallback in case clang-format is invoked with
                              -style=file, but can not find the .clang-format
                              file to use.
                              Use -fallback-style=none to skip formatting.
  -i                        - Inplace edit <file>s, if specified.
  -length=<uint>            - Format a range of this length (in bytes).
                              Multiple ranges can be formatted by specifying
                              several -offset and -length pairs.
                              When only a single -offset is specified without
                              -length, clang-format will format up to the end
                              of the file.
                              Can only be used with one input file.
  -lines=<string>           - <start line>:<end line> - format a range of
```

```
                              lines (both 1-based).
                              Multiple ranges can be formatted by specifying
                              several -lines arguments.
                              Can't be used with -offset and -length.
                              Can only be used with one input file.
  -offset=<uint>              - Format a range starting at this byte offset.
                              Multiple ranges can be formatted by specifying
                              several -offset and -length pairs.
                              Can only be used with one input file.
  -output-replacements-xml    - Output replacements as XML.
  -sort-includes              - Sort touched include lines
  -style=<string>             - Coding style, currently supports:
                                LLVM, Google, Chromium, Mozilla, WebKit.
                              Use -style=file to load style configuration from
                              .clang-format file located in one of the parent
                              directories of the source file (or current
                              directory for stdin).
                              Use -style="{key: value, ...}" to set specific
                              parameters, e.g.:
                                -style="{BasedOnStyle: llvm, IndentWidth: 8}"

Generic Options:

  -help                       - Display available options (-help-hidden for more)
  -help-list                  - Display list of available options (-help-list-hidden
↪for more)
  -version                    - Display the version of this program
```

When the desired code formatting style is different from the available options, the style can be customized using the `-style="{key: value, ...}"` option or by putting your style configuration in the `.clang-format` or `_clang-format` file in your project's directory and using `clang-format -style=file`.

An easy way to create the `.clang-format` file is:

```
clang-format -style=llvm -dump-config > .clang-format
```

Available style options are described in *Clang-Format Style Options*.

Vim Integration

There is an integration for **vim** which lets you run the **clang-format** standalone tool on your current buffer, optionally selecting regions to reformat. The integration has the form of a *python*-file which can be found under *clang/tools/clang-format/clang-format.py*.

This can be integrated by adding the following to your *.vimrc*:

```
map <C-K> :pyf <path-to-this-file>/clang-format.py<cr>
imap <C-K> <c-o>:pyf <path-to-this-file>/clang-format.py<cr>
```

The first line enables **clang-format** for NORMAL and VISUAL mode, the second line adds support for INSERT mode. Change "C-K" to another binding if you need **clang-format** on a different key (C-K stands for Ctrl+k).

With this integration you can press the bound key and clang-format will format the current line in NORMAL and INSERT mode or the selected region in VISUAL mode. The line or region is extended to the next bigger syntactic entity.

It operates on the current, potentially unsaved buffer and does not create or save any files. To revert a formatting, just undo.

Emacs Integration

Similar to the integration for **vim**, there is an integration for **emacs**. It can be found at *clang/tools/clang-format/clang-format.el* and used by adding this to your *.emacs*:

```
(load "<path-to-clang>/tools/clang-format/clang-format.el")
(global-set-key [C-M-tab] 'clang-format-region)
```

This binds the function *clang-format-region* to C-M-tab, which then formats the current line or selected region.

BBEdit Integration

clang-format cannot be used as a text filter with BBEdit, but works well via a script. The AppleScript to do this integration can be found at *clang/tools/clang-format/clang-format-bbedit.applescript*; place a copy in *~/Library/Application Support/BBEdit/Scripts*, and edit the path within it to point to your local copy of **clang-format**.

With this integration you can select the script from the Script menu and **clang-format** will format the selection. Note that you can rename the menu item by renaming the script, and can assign the menu item a keyboard shortcut in the BBEdit preferences, under Menus & Shortcuts.

Visual Studio Integration

Download the latest Visual Studio extension from the alpha build site. The default key-binding is Ctrl-R,Ctrl-F.

Script for patch reformatting

The python script *clang/tools/clang-format-diff.py* parses the output of a unified diff and reformats all contained lines with **clang-format**.

```
usage: clang-format-diff.py [-h] [-i] [-p NUM] [-regex PATTERN] [-style STYLE]

Reformat changed lines in diff. Without -i option just output the diff that
would be introduced.

optional arguments:
  -h, --help      show this help message and exit
  -i              apply edits to files instead of displaying a diff
  -p NUM          strip the smallest prefix containing P slashes
  -regex PATTERN  custom pattern selecting file paths to reformat
  -style STYLE    formatting style to apply (LLVM, Google, Chromium, Mozilla,
                  WebKit)
```

So to reformat all the lines in the latest **git** commit, just do:

```
git diff -U0 HEAD^ | clang-format-diff.py -i -p1
```

In an SVN client, you can do:

```
svn diff --diff-cmd=diff -x -U0 | clang-format-diff.py -i
```

The option *-U0* will create a diff without context lines (the script would format those as well).

Clang-Format Style Options

Clang-Format Style Options describes configurable formatting style options supported by *LibFormat* and *ClangFormat*.

When using **clang-format** command line utility or `clang::format::reformat(...)` functions from code, one can either use one of the predefined styles (LLVM, Google, Chromium, Mozilla, WebKit) or create a custom style by configuring specific style options.

Configuring Style with clang-format

clang-format supports two ways to provide custom style options: directly specify style configuration in the `-style=` command line option or use `-style=file` and put style configuration in the `.clang-format` or `_clang-format` file in the project directory.

When using `-style=file`, **clang-format** for each input file will try to find the `.clang-format` file located in the closest parent directory of the input file. When the standard input is used, the search is started from the current directory.

The `.clang-format` file uses YAML format:

```
key1: value1
key2: value2
# A comment.
...
```

The configuration file can consist of several sections each having different `Language:` parameter denoting the programming language this section of the configuration is targeted at. See the description of the **Language** option below for the list of supported languages. The first section may have no language set, it will set the default style options for all lanugages. Configuration sections for specific language will override options set in the default section.

When **clang-format** formats a file, it auto-detects the language using the file name. When formatting standard input or a file that doesn't have the extension corresponding to its language, `-assume-filename=` option can be used to override the file name **clang-format** uses to detect the language.

An example of a configuration file for multiple languages:

```
---
# We'll use defaults from the LLVM style, but with 4 columns indentation.
BasedOnStyle: LLVM
IndentWidth: 4
---
Language: Cpp
# Force pointers to the type for C++.
DerivePointerAlignment: false
PointerAlignment: Left
---
Language: JavaScript
# Use 100 columns for JS.
ColumnLimit: 100
---
Language: Proto
# Don't format .proto files.
DisableFormat: true
...
```

An easy way to get a valid `.clang-format` file containing all configuration options of a certain predefined style is:

```
clang-format -style=llvm -dump-config > .clang-format
```

When specifying configuration in the `-style=` option, the same configuration is applied for all input files. The format of the configuration is:

```
-style='{key1: value1, key2: value2, ...}'
```

Disabling Formatting on a Piece of Code

Clang-format understands also special comments that switch formatting in a delimited range. The code between a comment `// clang-format off` or `/* clang-format off */` up to a comment `// clang-format on` or `/* clang-format on */` will not be formatted. The comments themselves will be formatted (aligned) normally.

```
int formatted_code;
// clang-format off
    void    unformatted_code  ;
// clang-format on
void formatted_code_again;
```

Configuring Style in Code

When using `clang::format::reformat(...)` functions, the format is specified by supplying the clang::format::FormatStyle structure.

Configurable Format Style Options

This section lists the supported style options. Value type is specified for each option. For enumeration types possible values are specified both as a C++ enumeration member (with a prefix, e.g. `LS_Auto`), and as a value usable in the configuration (without a prefix: `Auto`).

BasedOnStyle (`string`) The style used for all options not specifically set in the configuration.

This option is supported only in the **`clang-format`** configuration (both within `-style='{...}'` and the `.clang-format` file).

Possible values:

- `LLVM` A style complying with the LLVM coding standards
- `Google` A style complying with Google's C++ style guide
- `Chromium` A style complying with Chromium's style guide
- `Mozilla` A style complying with Mozilla's style guide
- `WebKit` A style complying with WebKit's style guide

AccessModifierOffset (`int`) The extra indent or outdent of access modifiers, e.g. `public:`.

AlignAfterOpenBracket (`BracketAlignmentStyle`) If `true`, horizontally aligns arguments after an open bracket.

This applies to round brackets (parentheses), angle brackets and square brackets.

Possible values:

- `BAS_Align` (in configuration: `Align`) Align parameters on the open bracket, e.g.:

```
someLongFunction(argument1,
                 argument2);
```

- `BAS_DontAlign` (in configuration: `DontAlign`) Don't align, instead use `ContinuationIndentWidth`, e.g.:

```
someLongFunction(argument1,
    argument2);
```

- `BAS_AlwaysBreak` (in configuration: `AlwaysBreak`) Always break after an open bracket, if the parameters don't fit on a single line, e.g.:

```
someLongFunction(
    argument1, argument2);
```

AlignConsecutiveAssignments (`bool`) If `true`, aligns consecutive assignments.

This will align the assignment operators of consecutive lines. This will result in formattings like

```
int aaaa = 12;
int b    = 23;
int ccc  = 23;
```

AlignConsecutiveDeclarations (`bool`) If `true`, aligns consecutive declarations.

This will align the declaration names of consecutive lines. This will result in formattings like

```
int          aaaa = 12;
float        b = 23;
std::string ccc = 23;
```

AlignEscapedNewlinesLeft (`bool`) If `true`, aligns escaped newlines as far left as possible. Otherwise puts them into the right-most column.

AlignOperands (`bool`) If `true`, horizontally align operands of binary and ternary expressions.

Specifically, this aligns operands of a single expression that needs to be split over multiple lines, e.g.:

```
int aaa = bbbbbbbbbbbbbbb +
          ccccccccccccccc;
```

AlignTrailingComments (`bool`) If `true`, aligns trailing comments.

AllowAllParametersOfDeclarationOnNextLine (`bool`) Allow putting all parameters of a function declaration onto the next line even if `BinPackParameters` is `false`.

AllowShortBlocksOnASingleLine (`bool`) Allows contracting simple braced statements to a single line.

E.g., this allows `if (a) { return; }` to be put on a single line.

AllowShortCaseLabelsOnASingleLine (`bool`) If `true`, short case labels will be contracted to a single line.

AllowShortFunctionsOnASingleLine (`ShortFunctionStyle`) Dependent on the value, `int f() { return 0; }` can be put on a single line.

Possible values:

- `SFS_None` (in configuration: `None`) Never merge functions into a single line.
- `SFS_Empty` (in configuration: `Empty`) Only merge empty functions.

- SFS_Inline (in configuration: Inline) Only merge functions defined inside a class. Implies "empty".
- SFS_All (in configuration: All) Merge all functions fitting on a single line.

AllowShortIfStatementsOnASingleLine (bool) If true, if (a) return; can be put on a single line.

AllowShortLoopsOnASingleLine (bool) If true, while (true) continue; can be put on a single line.

AlwaysBreakAfterDefinitionReturnType (DefinitionReturnTypeBreakingStyle) The function definition return type breaking style to use. This option is deprecated and is retained for backwards compatibility.

Possible values:

- DRTBS_None (in configuration: None) Break after return type automatically. PenaltyReturnTypeOnItsOwnLine is taken into account.
- DRTBS_All (in configuration: All) Always break after the return type.
- DRTBS_TopLevel (in configuration: TopLevel) Always break after the return types of top-level functions.

AlwaysBreakAfterReturnType (ReturnTypeBreakingStyle) The function declaration return type breaking style to use.

Possible values:

- RTBS_None (in configuration: None) Break after return type automatically. PenaltyReturnTypeOnItsOwnLine is taken into account.
- RTBS_All (in configuration: All) Always break after the return type.
- RTBS_TopLevel (in configuration: TopLevel) Always break after the return types of top-level functions.
- RTBS_AllDefinitions (in configuration: AllDefinitions) Always break after the return type of function definitions.
- RTBS_TopLevelDefinitions (in configuration: TopLevelDefinitions) Always break after the return type of top-level definitions.

AlwaysBreakBeforeMultilineStrings (bool) If true, always break before multiline string literals.

This flag is mean to make cases where there are multiple multiline strings in a file look more consistent. Thus, it will only take effect if wrapping the string at that point leads to it being indented ContinuationIndentWidth spaces from the start of the line.

AlwaysBreakTemplateDeclarations (bool) If true, always break after the template<...> of a template declaration.

BinPackArguments (bool) If false, a function call's arguments will either be all on the same line or will have one line each.

BinPackParameters (bool) If false, a function declaration's or function definition's parameters will either all be on the same line or will have one line each.

BraceWrapping (BraceWrappingFlags) Control of individual brace wrapping cases.

If BreakBeforeBraces is set to BS_Custom, use this to specify how each individual brace case should be handled. Otherwise, this is ignored.

Nested configuration flags:

- bool AfterClass Wrap class definitions.
- bool AfterControlStatement Wrap control statements (if/for/while/switch/..).
- bool AfterEnum Wrap enum definitions.

- `bool AfterFunction` Wrap function definitions.
- `bool AfterNamespace` Wrap namespace definitions.
- `bool AfterObjCDeclaration` Wrap ObjC definitions (`@autoreleasepool`, interfaces, ..).
- `bool AfterStruct` Wrap struct definitions.
- `bool AfterUnion` Wrap union definitions.
- `bool BeforeCatch` Wrap before `catch`.
- `bool BeforeElse` Wrap before `else`.
- `bool IndentBraces` Indent the wrapped braces themselves.

BreakAfterJavaFieldAnnotations (`bool`) Break after each annotation on a field in Java files.

BreakBeforeBinaryOperators (`BinaryOperatorStyle`) The way to wrap binary operators.

Possible values:

- `BOS_None` (in configuration: `None`) Break after operators.
- `BOS_NonAssignment` (in configuration: `NonAssignment`) Break before operators that aren't assignments.
- `BOS_All` (in configuration: `All`) Break before operators.

BreakBeforeBraces (`BraceBreakingStyle`) The brace breaking style to use.

Possible values:

- `BS_Attach` (in configuration: `Attach`) Always attach braces to surrounding context.
- `BS_Linux` (in configuration: `Linux`) Like `Attach`, but break before braces on function, namespace and class definitions.
- `BS_Mozilla` (in configuration: `Mozilla`) Like `Attach`, but break before braces on enum, function, and record definitions.
- `BS_Stroustrup` (in configuration: `Stroustrup`) Like `Attach`, but break before function definitions, `catch`, and `else`.
- `BS_Allman` (in configuration: `Allman`) Always break before braces.
- `BS_GNU` (in configuration: `GNU`) Always break before braces and add an extra level of indentation to braces of control statements, not to those of class, function or other definitions.
- `BS_WebKit` (in configuration: `WebKit`) Like `Attach`, but break before functions.
- `BS_Custom` (in configuration: `Custom`) Configure each individual brace in *BraceWrapping*.

BreakBeforeTernaryOperators (`bool`) If `true`, ternary operators will be placed after line breaks.

BreakConstructorInitializersBeforeComma (`bool`) Always break constructor initializers before commas and align the commas with the colon.

BreakStringLiterals (`bool`) Allow breaking string literals when formatting.

ColumnLimit (`unsigned`) The column limit.

A column limit of `0` means that there is no column limit. In this case, clang-format will respect the input's line breaking decisions within statements unless they contradict other rules.

CommentPragmas (`std::string`) A regular expression that describes comments with special meaning, which should not be split into lines or otherwise changed.

ConstructorInitializerAllOnOneLineOrOnePerLine (`bool`) If the constructor initializers don't fit on a line, put each initializer on its own line.

ConstructorInitializerIndentWidth (`unsigned`) The number of characters to use for indentation of constructor initializer lists.

ContinuationIndentWidth (`unsigned`) Indent width for line continuations.

Cpp11BracedListStyle (`bool`) If `true`, format braced lists as best suited for C++11 braced lists.

Important differences: - No spaces inside the braced list. - No line break before the closing brace. - Indentation with the continuation indent, not with the block indent.

Fundamentally, C++11 braced lists are formatted exactly like function calls would be formatted in their place. If the braced list follows a name (e.g. a type or variable name), clang-format formats as if the `{}` were the parentheses of a function call with that name. If there is no name, a zero-length name is assumed.

DerivePointerAlignment (`bool`) If `true`, analyze the formatted file for the most common alignment of `&` and `\*`. `PointerAlignment` is then used only as fallback.

DisableFormat (`bool`) Disables formatting completely.

ExperimentalAutoDetectBinPacking (`bool`) If `true`, clang-format detects whether function calls and definitions are formatted with one parameter per line.

Each call can be bin-packed, one-per-line or inconclusive. If it is inconclusive, e.g. completely on one line, but a decision needs to be made, clang-format analyzes whether there are other bin-packed cases in the input file and act accordingly.

NOTE: This is an experimental flag, that might go away or be renamed. Do not use this in config files, etc. Use at your own risk.

ForEachMacros (`std::vector<std::string>`) A vector of macros that should be interpreted as foreach loops instead of as function calls.

These are expected to be macros of the form:

```
FOREACH(<variable-declaration>, ...)
  <loop-body>
```

In the .clang-format configuration file, this can be configured like:

```
ForEachMacros: ['RANGES_FOR', 'FOREACH']
```

For example: BOOST_FOREACH.

IncludeCategories (`std::vector<IncludeCategory>`) Regular expressions denoting the different `#include` categories used for ordering `#includes`.

These regular expressions are matched against the filename of an include (including the <> or "") in order. The value belonging to the first matching regular expression is assigned and `#includes` are sorted first according to increasing category number and then alphabetically within each category.

If none of the regular expressions match, INT_MAX is assigned as category. The main header for a source file automatically gets category 0. so that it is generally kept at the beginning of the `#includes` (http://llvm.org/docs/CodingStandards.html#include-style). However, you can also assign negative priorities if you have certain headers that always need to be first.

To configure this in the .clang-format file, use:

```
IncludeCategories:
  - Regex:           '^"(llvm|llvm-c|clang|clang-c)/'
    Priority:        2
```

```
  - Regex:           '^(<|"(gtest|isl|json)/)'
    Priority:        3
  - Regex:           '.\*'
    Priority:        1
```

IncludeIsMainRegex (`std::string`) Specify a regular expression of suffixes that are allowed in the file-to-main-include mapping.

When guessing whether a #include is the "main" include (to assign category 0, see above), use this regex of allowed suffixes to the header stem. A partial match is done, so that: - "" means "arbitrary suffix" - "$" means "no suffix"

For example, if configured to "(_test)?$", then a header a.h would be seen as the "main" include in both a.cc and a_test.cc.

IndentCaseLabels (`bool`) Indent case labels one level from the switch statement.

When `false`, use the same indentation level as for the switch statement. Switch statement body is always indented one level more than case labels.

IndentWidth (`unsigned`) The number of columns to use for indentation.

IndentWrappedFunctionNames (`bool`) Indent if a function definition or declaration is wrapped after the type.

JavaScriptQuotes (`JavaScriptQuoteStyle`) The JavaScriptQuoteStyle to use for JavaScript strings.

Possible values:

- `JSQS_Leave` (in configuration: `Leave`) Leave string quotes as they are.
- `JSQS_Single` (in configuration: `Single`) Always use single quotes.
- `JSQS_Double` (in configuration: `Double`) Always use double quotes.

KeepEmptyLinesAtTheStartOfBlocks (`bool`) If true, empty lines at the start of blocks are kept.

Language (`LanguageKind`) Language, this format style is targeted at.

Possible values:

- `LK_None` (in configuration: `None`) Do not use.
- `LK_Cpp` (in configuration: `Cpp`) Should be used for C, C++, ObjectiveC, ObjectiveC++.
- `LK_Java` (in configuration: `Java`) Should be used for Java.
- `LK_JavaScript` (in configuration: `JavaScript`) Should be used for JavaScript.
- `LK_Proto` (in configuration: `Proto`) Should be used for Protocol Buffers (https://developers.google.com/protocol-buffers/).
- `LK_TableGen` (in configuration: `TableGen`) Should be used for TableGen code.

MacroBlockBegin (`std::string`) A regular expression matching macros that start a block.

MacroBlockEnd (`std::string`) A regular expression matching macros that end a block.

MaxEmptyLinesToKeep (`unsigned`) The maximum number of consecutive empty lines to keep.

NamespaceIndentation (`NamespaceIndentationKind`) The indentation used for namespaces.

Possible values:

- `NI_None` (in configuration: `None`) Don't indent in namespaces.
- `NI_Inner` (in configuration: `Inner`) Indent only in inner namespaces (nested in other namespaces).
- `NI_All` (in configuration: `All`) Indent in all namespaces.

ObjCBlockIndentWidth (unsigned) The number of characters to use for indentation of ObjC blocks.

ObjCSpaceAfterProperty (bool) Add a space after `@property` in Objective-C, i.e. use `@property (readonly)` instead of `@property(readonly)`.

ObjCSpaceBeforeProtocolList (bool) Add a space in front of an Objective-C protocol list, i.e. use `Foo <Protocol>` instead of `Foo<Protocol>`.

PenaltyBreakBeforeFirstCallParameter (unsigned) The penalty for breaking a function call after `call(`.

PenaltyBreakComment (unsigned) The penalty for each line break introduced inside a comment.

PenaltyBreakFirstLessLess (unsigned) The penalty for breaking before the first <<.

PenaltyBreakString (unsigned) The penalty for each line break introduced inside a string literal.

PenaltyExcessCharacter (unsigned) The penalty for each character outside of the column limit.

PenaltyReturnTypeOnItsOwnLine (unsigned) Penalty for putting the return type of a function onto its own line.

PointerAlignment (PointerAlignmentStyle) Pointer and reference alignment style.

Possible values:

- `PAS_Left` (in configuration: `Left`) Align pointer to the left.
- `PAS_Right` (in configuration: `Right`) Align pointer to the right.
- `PAS_Middle` (in configuration: `Middle`) Align pointer in the middle.

ReflowComments (bool) If `true`, clang-format will attempt to re-flow comments.

SortIncludes (bool) If `true`, clang-format will sort `#includes`.

SpaceAfterCStyleCast (bool) If `true`, a space may be inserted after C style casts.

SpaceBeforeAssignmentOperators (bool) If `false`, spaces will be removed before assignment operators.

SpaceBeforeParens (SpaceBeforeParensOptions) Defines in which cases to put a space before opening parentheses.

Possible values:

- `SBPO_Never` (in configuration: `Never`) Never put a space before opening parentheses.
- `SBPO_ControlStatements` (in configuration: `ControlStatements`) Put a space before opening parentheses only after control statement keywords (`for/if/while...`).
- `SBPO_Always` (in configuration: `Always`) Always put a space before opening parentheses, except when it's prohibited by the syntax rules (in function-like macro definitions) or when determined by other style rules (after unary operators, opening parentheses, etc.)

SpaceInEmptyParentheses (bool) If `true`, spaces may be inserted into `()`.

SpacesBeforeTrailingComments (unsigned) The number of spaces before trailing line comments (`//` - comments).

This does not affect trailing block comments (`/*` - comments) as those commonly have different usage patterns and a number of special cases.

SpacesInAngles (bool) If `true`, spaces will be inserted after < and before > in template argument lists.

SpacesInCStyleCastParentheses (bool) If `true`, spaces may be inserted into C style casts.

SpacesInContainerLiterals (bool) If `true`, spaces are inserted inside container literals (e.g. ObjC and Javascript array and dict literals).

SpacesInParentheses (bool) If `true`, spaces will be inserted after `(` and before `)`.

SpacesInSquareBrackets (`bool`) If `true`, spaces will be inserted after `[` and before `]`.

Standard (`LanguageStandard`) Format compatible with this standard, e.g. use `A<A<int> >` instead of `A<A<int>>` for `LS_Cpp03`.

Possible values:

- `LS_Cpp03` (in configuration: `Cpp03`) Use C++03-compatible syntax.
- `LS_Cpp11` (in configuration: `Cpp11`) Use features of C++11 (e.g. `A<A<int>>` instead of `A<A<int> >`).
- `LS_Auto` (in configuration: `Auto`) Automatic detection based on the input.

TabWidth (`unsigned`) The number of columns used for tab stops.

UseTab (`UseTabStyle`) The way to use tab characters in the resulting file.

Possible values:

- `UT_Never` (in configuration: `Never`) Never use tab.
- `UT_ForIndentation` (in configuration: `ForIndentation`) Use tabs only for indentation.
- `UT_Always` (in configuration: `Always`) Use tabs whenever we need to fill whitespace that spans at least from one tab stop to the next one.

Adding additional style options

Each additional style option adds costs to the clang-format project. Some of these costs affect the clang-format development itself, as we need to make sure that any given combination of options work and that new features don't break any of the existing options in any way. There are also costs for end users as options become less discoverable and people have to think about and make a decision on options they don't really care about.

The goal of the clang-format project is more on the side of supporting a limited set of styles really well as opposed to supporting every single style used by a codebase somewhere in the wild. Of course, we do want to support all major projects and thus have established the following bar for adding style options. Each new style option must ..

- be used in a project of significant size (have dozens of contributors)
- have a publicly accessible style guide
- have a person willing to contribute and maintain patches

Examples

A style similar to the Linux Kernel style:

```
BasedOnStyle: LLVM
IndentWidth: 8
UseTab: Always
BreakBeforeBraces: Linux
AllowShortIfStatementsOnASingleLine: false
IndentCaseLabels: false
```

The result is (imagine that tabs are used for indentation here):

```
void test()
{
        switch (x) {
        case 0:
```

```
        case 1:
                do_something();
                break;
        case 2:
                do_something_else();
                break;
        default:
                break;
        }
        if (condition)
                do_something_completely_different();

        if (x == y) {
                q();
        } else if (x > y) {
                w();
        } else {
                r();
        }
}
```

A style similar to the default Visual Studio formatting style:

```
UseTab: Never
IndentWidth: 4
BreakBeforeBraces: Allman
AllowShortIfStatementsOnASingleLine: false
IndentCaseLabels: false
ColumnLimit: 0
```

The result is:

```
void test()
{
    switch (suffix)
    {
    case 0:
    case 1:
        do_something();
        break;
    case 2:
        do_something_else();
        break;
    default:
        break;
    }
    if (condition)
        do_somthing_completely_different();

    if (x == y)
    {
        q();
    }
    else if (x > y)
    {
        w();
    }
    else
```

```
    {
        r();
    }
}
```

CHAPTER 7

Design Documents

"Clang" CFE Internals Manual

Introduction

This document describes some of the more important APIs and internal design decisions made in the Clang C front-end. The purpose of this document is to both capture some of this high level information and also describe some of the design decisions behind it. This is meant for people interested in hacking on Clang, not for end-users. The description below is categorized by libraries, and does not describe any of the clients of the libraries.

LLVM Support Library

The LLVM `libSupport` library provides many underlying libraries and data-structures, including command line option processing, various containers and a system abstraction layer, which is used for file system access.

The Clang "Basic" Library

This library certainly needs a better name. The "basic" library contains a number of low-level utilities for tracking and manipulating source buffers, locations within the source buffers, diagnostics, tokens, target abstraction, and information about the subset of the language being compiled for.

Part of this infrastructure is specific to C (such as the `TargetInfo` class), other parts could be reused for other non-C-based languages (`SourceLocation`, `SourceManager`, `Diagnostics`, `FileManager`). When and if there is future demand we can figure out if it makes sense to introduce a new library, move the general classes somewhere else, or introduce some other solution.

We describe the roles of these classes in order of their dependencies.

The Diagnostics Subsystem

The Clang Diagnostics subsystem is an important part of how the compiler communicates with the human. Diagnostics are the warnings and errors produced when the code is incorrect or dubious. In Clang, each diagnostic produced has (at the minimum) a unique ID, an English translation associated with it, a *SourceLocation* to "put the caret", and a severity (e.g., `WARNING` or `ERROR`). They can also optionally include a number of arguments to the dianostic (which fill in "%0"'s in the string) as well as a number of source ranges that related to the diagnostic.

In this section, we'll be giving examples produced by the Clang command line driver, but diagnostics can be *rendered in many different ways* depending on how the `DiagnosticClient` interface is implemented. A representative example of a diagnostic is:

```
t.c:38:15: error: invalid operands to binary expression ('int *' and '_Complex float')
P = (P-42) + Gamma*4;
    ~~~~~~ ^ ~~~~~~~
```

In this example, you can see the English translation, the severity (error), you can see the source location (the caret ("^") and file/line/column info), the source ranges "~~~~", arguments to the diagnostic ("`int*`" and "`_Complex float`"). You'll have to believe me that there is a unique ID backing the diagnostic :).

Getting all of this to happen has several steps and involves many moving pieces, this section describes them and talks about best practices when adding a new diagnostic.

The `Diagnostic*Kinds.td` files

Diagnostics are created by adding an entry to one of the `clang/Basic/Diagnostic*Kinds.td` files, depending on what library will be using it. From this file, **`tblgen`** generates the unique ID of the diagnostic, the severity of the diagnostic and the English translation + format string.

There is little sanity with the naming of the unique ID's right now. Some start with `err_`, `warn_`, `ext_` to encode the severity into the name. Since the enum is referenced in the C++ code that produces the diagnostic, it is somewhat useful for it to be reasonably short.

The severity of the diagnostic comes from the set {`NOTE`, `REMARK`, `WARNING`, `EXTENSION`, `EXTWARN`, `ERROR`}. The `ERROR` severity is used for diagnostics indicating the program is never acceptable under any circumstances. When an error is emitted, the AST for the input code may not be fully built. The `EXTENSION` and `EXTWARN` severities are used for extensions to the language that Clang accepts. This means that Clang fully understands and can represent them in the AST, but we produce diagnostics to tell the user their code is non-portable. The difference is that the former are ignored by default, and the later warn by default. The `WARNING` severity is used for constructs that are valid in the currently selected source language but that are dubious in some way. The `REMARK` severity provides generic information about the compilation that is not necessarily related to any dubious code. The `NOTE` level is used to staple more information onto previous diagnostics.

These *severities* are mapped into a smaller set (the `Diagnostic::Level` enum, {`Ignored`, `Note`, `Remark`, `Warning`, `Error`, `Fatal`}) of output *levels* by the diagnostics subsystem based on various configuration options. Clang internally supports a fully fine grained mapping mechanism that allows you to map almost any diagnostic to the output level that you want. The only diagnostics that cannot be mapped are `NOTE`s, which always follow the severity of the previously emitted diagnostic and `ERROR`s, which can only be mapped to `Fatal` (it is not possible to turn an error into a warning, for example).

Diagnostic mappings are used in many ways. For example, if the user specifies `-pedantic`, `EXTENSION` maps to `Warning`, if they specify `-pedantic-errors`, it turns into `Error`. This is used to implement options like `-Wunused_macros`, `-Wundef` etc.

Mapping to `Fatal` should only be used for diagnostics that are considered so severe that error recovery won't be able to recover sensibly from them (thus spewing a ton of bogus errors). One example of this class of error are failure to `#include` a file.

The Format String

The format string for the diagnostic is very simple, but it has some power. It takes the form of a string in English with markers that indicate where and how arguments to the diagnostic are inserted and formatted. For example, here are some simple format strings:

```
"binary integer literals are an extension"
"format string contains '\\0' within the string body"
"more '%%' conversions than data arguments"
"invalid operands to binary expression (%0 and %1)"
"overloaded '%0' must be a %select{unary|binary|unary or binary}2 operator"
     " (has %1 parameter%s1)"
```

These examples show some important points of format strings. You can use any plain ASCII character in the diagnostic string except "`%`" without a problem, but these are C strings, so you have to use and be aware of all the C escape sequences (as in the second example). If you want to produce a "`%`" in the output, use the "`%%`" escape sequence, like the third diagnostic. Finally, Clang uses the "`%...[digit]`" sequences to specify where and how arguments to the diagnostic are formatted.

Arguments to the diagnostic are numbered according to how they are specified by the C++ code that *produces them*, and are referenced by `%0` .. `%9`. If you have more than 10 arguments to your diagnostic, you are doing something

wrong :). Unlike `printf`, there is no requirement that arguments to the diagnostic end up in the output in the same order as they are specified, you could have a format string with "`%1 %0`" that swaps them, for example. The text in between the percent and digit are formatting instructions. If there are no instructions, the argument is just turned into a string and substituted in.

Here are some "best practices" for writing the English format string:

- Keep the string short. It should ideally fit in the 80 column limit of the `DiagnosticKinds.td` file. This avoids the diagnostic wrapping when printed, and forces you to think about the important point you are conveying with the diagnostic.
- Take advantage of location information. The user will be able to see the line and location of the caret, so you don't need to tell them that the problem is with the 4th argument to the function: just point to it.
- Do not capitalize the diagnostic string, and do not end it with a period.
- If you need to quote something in the diagnostic string, use single quotes.

Diagnostics should never take random English strings as arguments: you shouldn't use "`you have a problem with %0`" and pass in things like "`your argument`" or "`your return value`" as arguments. Doing this prevents *translating* the Clang diagnostics to other languages (because they'll get random English words in their otherwise localized diagnostic). The exceptions to this are C/C++ language keywords (e.g., `auto`, `const`, `mutable`, etc) and C/C++ operators (`/=`). Note that things like "pointer" and "reference" are not keywords. On the other hand, you *can* include anything that comes from the user's source code, including variable names, types, labels, etc. The "`select`" format can be used to achieve this sort of thing in a localizable way, see below.

Formatting a Diagnostic Argument

Arguments to diagnostics are fully typed internally, and come from a couple different classes: integers, types, names, and random strings. Depending on the class of the argument, it can be optionally formatted in different ways. This gives the `DiagnosticClient` information about what the argument means without requiring it to use a specific presentation (consider this MVC for Clang :).

Here are the different diagnostic argument formats currently supported by Clang:

"s" format

Example: `"requires %1 parameter%s1"`

Class: Integers

Description: This is a simple formatter for integers that is useful when producing English diagnostics. When the integer is 1, it prints as nothing. When the integer is not 1, it prints as "`s`". This allows some simple grammatical forms to be to be handled correctly, and eliminates the need to use gross things like `"requires %1 parameter(s)"`.

"select" format

Example: `"must be a %select{unary|binary|unary or binary}2 operator"`

Class: Integers

Description: This format specifier is used to merge multiple related diagnostics together into one common one, without requiring the difference to be specified as an English string argument. Instead of specifying the string, the diagnostic gets an integer argument and the format string selects the numbered option. In this case, the "`%2`" value must be an integer in the range [0..2]. If it is 0, it prints "unary", if it is 1 it prints "binary" if it is 2, it prints "unary or binary". This allows other language translations to substitute reasonable words (or entire phrases) based on the semantics of the diagnostic instead of having to do things textually. The selected string does undergo formatting.

"plural" format

Example: `"you have %1 %plural{1:mouse|:mice}1 connected to your computer"`

Class: Integers

Description: This is a formatter for complex plural forms. It is designed to handle even the requirements of languages with very complex plural forms, as many Baltic languages have. The argument consists of a series of expression/form pairs, separated by ":", where the first form whose expression evaluates to true is the result of the modifier.

An expression can be empty, in which case it is always true. See the example at the top. Otherwise, it is a series of one or more numeric conditions, separated by ",". If any condition matches, the expression matches. Each numeric condition can take one of three forms.

- number: A simple decimal number matches if the argument is the same as the number. Example: `"%plural{1:mouse|:mice}4"`
- range: A range in square brackets matches if the argument is within the range. Then range is inclusive on both ends. Example: `"%plural{0:none|1:one|[2,5]:some|:many}2"`
- modulo: A modulo operator is followed by a number, and equals sign and either a number or a range. The tests are the same as for plain numbers and ranges, but the argument is taken modulo the number first. Example: `"%plural{%100=0:even hundred|%100=[1,50]:lower half|:everything else}1"`

The parser is very unforgiving. A syntax error, even whitespace, will abort, as will a failure to match the argument against any expression.

"ordinal" format

Example: `"ambiguity in %ordinal0 argument"`

Class: Integers

Description: This is a formatter which represents the argument number as an ordinal: the value `1` becomes `1st`, `3` becomes `3rd`, and so on. Values less than `1` are not supported. This formatter is currently hard-coded to use English ordinals.

"objcclass" format

Example: `"method %objcclass0 not found"`

Class: `DeclarationName`

Description: This is a simple formatter that indicates the `DeclarationName` corresponds to an Objective-C class method selector. As such, it prints the selector with a leading "+".

"objcinstance" format

Example: `"method %objcinstance0 not found"`

Class: `DeclarationName`

Description: This is a simple formatter that indicates the `DeclarationName` corresponds to an Objective-C instance method selector. As such, it prints the selector with a leading "−".

"q" format

Example: `"candidate found by name lookup is %q0"`

Class: `NamedDecl *`

Description: This formatter indicates that the fully-qualified name of the declaration should be printed, e.g., "`std::vector`" rather than "`vector`".

"diff" format

Example: "no known conversion %diff{from $ to $|from argument type to parameter type}1,2"

Class: QualType

Description: This formatter takes two QualTypes and attempts to print a template difference between the two. If tree printing is off, the text inside the braces before the pipe is printed, with the formatted text replacing the $. If tree printing is on, the text after the pipe is printed and a type tree is printed after the diagnostic message.

It is really easy to add format specifiers to the Clang diagnostics system, but they should be discussed before they are added. If you are creating a lot of repetitive diagnostics and/or have an idea for a useful formatter, please bring it up on the cfe-dev mailing list.

Producing the Diagnostic

Now that you've created the diagnostic in the Diagnostic*Kinds.td file, you need to write the code that detects the condition in question and emits the new diagnostic. Various components of Clang (e.g., the preprocessor, Sema, etc.) provide a helper function named "Diag". It creates a diagnostic and accepts the arguments, ranges, and other information that goes along with it.

For example, the binary expression error comes from code like this:

```
if (various things that are bad)
  Diag(Loc, diag::err_typecheck_invalid_operands)
    << lex->getType() << rex->getType()
    << lex->getSourceRange() << rex->getSourceRange();
```

This shows that use of the Diag method: it takes a location (a *SourceLocation* object) and a diagnostic enum value (which matches the name from Diagnostic*Kinds.td). If the diagnostic takes arguments, they are specified with the << operator: the first argument becomes %0, the second becomes %1, etc. The diagnostic interface allows you to specify arguments of many different types, including int and unsigned for integer arguments, const char* and std::string for string arguments, DeclarationName and const IdentifierInfo * for names, QualType for types, etc. SourceRanges are also specified with the << operator, but do not have a specific ordering requirement.

As you can see, adding and producing a diagnostic is pretty straightforward. The hard part is deciding exactly what you need to say to help the user, picking a suitable wording, and providing the information needed to format it correctly. The good news is that the call site that issues a diagnostic should be completely independent of how the diagnostic is formatted and in what language it is rendered.

Fix-It Hints

In some cases, the front end emits diagnostics when it is clear that some small change to the source code would fix the problem. For example, a missing semicolon at the end of a statement or a use of deprecated syntax that is easily rewritten into a more modern form. Clang tries very hard to emit the diagnostic and recover gracefully in these and other cases.

However, for these cases where the fix is obvious, the diagnostic can be annotated with a hint (referred to as a "fix-it hint") that describes how to change the code referenced by the diagnostic to fix the problem. For example, it might add the missing semicolon at the end of the statement or rewrite the use of a deprecated construct into something more palatable. Here is one such example from the C++ front end, where we warn about the right-shift operator changing meaning from C++98 to C++11:

```
test.cpp:3:7: warning: use of right-shift operator ('>>') in template argument
                       will require parentheses in C++11
A<100 >> 2> *a;
```

```
      ^
  (       )
```

Here, the fix-it hint is suggesting that parentheses be added, and showing exactly where those parentheses would be inserted into the source code. The fix-it hints themselves describe what changes to make to the source code in an abstract manner, which the text diagnostic printer renders as a line of "insertions" below the caret line. *Other diagnostic clients* might choose to render the code differently (e.g., as markup inline) or even give the user the ability to automatically fix the problem.

Fix-it hints on errors and warnings need to obey these rules:

- Since they are automatically applied if `-Xclang -fixit` is passed to the driver, they should only be used when it's very likely they match the user's intent.
- Clang must recover from errors as if the fix-it had been applied.

If a fix-it can't obey these rules, put the fix-it on a note. Fix-its on notes are not applied automatically.

All fix-it hints are described by the `FixItHint` class, instances of which should be attached to the diagnostic using the << operator in the same way that highlighted source ranges and arguments are passed to the diagnostic. Fix-it hints can be created with one of three constructors:

- `FixItHint::CreateInsertion(Loc, Code)`

  Specifies that the given `Code` (a string) should be inserted before the source location `Loc`.

- `FixItHint::CreateRemoval(Range)`

  Specifies that the code in the given source `Range` should be removed.

- `FixItHint::CreateReplacement(Range, Code)`

  Specifies that the code in the given source `Range` should be removed, and replaced with the given `Code` string.

The `DiagnosticClient` Interface

Once code generates a diagnostic with all of the arguments and the rest of the relevant information, Clang needs to know what to do with it. As previously mentioned, the diagnostic machinery goes through some filtering to map a severity onto a diagnostic level, then (assuming the diagnostic is not mapped to "`Ignore`") it invokes an object that implements the `DiagnosticClient` interface with the information.

It is possible to implement this interface in many different ways. For example, the normal Clang `DiagnosticClient` (named `TextDiagnosticPrinter`) turns the arguments into strings (according to the various formatting rules), prints out the file/line/column information and the string, then prints out the line of code, the source ranges, and the caret. However, this behavior isn't required.

Another implementation of the `DiagnosticClient` interface is the `TextDiagnosticBuffer` class, which is used when Clang is in `-verify` mode. Instead of formatting and printing out the diagnostics, this implementation just captures and remembers the diagnostics as they fly by. Then `-verify` compares the list of produced diagnostics to the list of expected ones. If they disagree, it prints out its own output. Full documentation for the `-verify` mode can be found in the Clang API documentation for VerifyDiagnosticConsumer.

There are many other possible implementations of this interface, and this is why we prefer diagnostics to pass down rich structured information in arguments. For example, an HTML output might want declaration names be linkified to where they come from in the source. Another example is that a GUI might let you click on typedefs to expand them. This application would want to pass significantly more information about types through to the GUI than a simple flat string. The interface allows this to happen.

Adding Translations to Clang

Not possible yet! Diagnostic strings should be written in UTF-8, the client can translate to the relevant code page if needed. Each translation completely replaces the format string for the diagnostic.

The `SourceLocation` and `SourceManager` classes

Strangely enough, the `SourceLocation` class represents a location within the source code of the program. Important design points include:

1. `sizeof(SourceLocation)` must be extremely small, as these are embedded into many AST nodes and are passed around often. Currently it is 32 bits.
2. `SourceLocation` must be a simple value object that can be efficiently copied.
3. We should be able to represent a source location for any byte of any input file. This includes in the middle of tokens, in whitespace, in trigraphs, etc.
4. A `SourceLocation` must encode the current `#include` stack that was active when the location was processed. For example, if the location corresponds to a token, it should contain the set of `#includes` active when the token was lexed. This allows us to print the `#include` stack for a diagnostic.
5. `SourceLocation` must be able to describe macro expansions, capturing both the ultimate instantiation point and the source of the original character data.

In practice, the `SourceLocation` works together with the `SourceManager` class to encode two pieces of information about a location: its spelling location and its instantiation location. For most tokens, these will be the same. However, for a macro expansion (or tokens that came from a `_Pragma` directive) these will describe the location of the characters corresponding to the token and the location where the token was used (i.e., the macro instantiation point or the location of the `_Pragma` itself).

The Clang front-end inherently depends on the location of a token being tracked correctly. If it is ever incorrect, the front-end may get confused and die. The reason for this is that the notion of the "spelling" of a `Token` in Clang depends on being able to find the original input characters for the token. This concept maps directly to the "spelling location" for the token.

`SourceRange` and `CharSourceRange`

Clang represents most source ranges by [first, last], where "first" and "last" each point to the beginning of their respective tokens. For example consider the `SourceRange` of the following statement:

```
x = foo + bar;
^first    ^last
```

To map from this representation to a character-based representation, the "last" location needs to be adjusted to point to (or past) the end of that token with either `Lexer::MeasureTokenLength()` or `Lexer::getLocForEndOfToken()`. For the rare cases where character-level source ranges information is needed we use the `CharSourceRange` class.

The Driver Library

The clang Driver and library are documented *here*.

Precompiled Headers

Clang supports two implementations of precompiled headers. The default implementation, precompiled headers (*PCH*) uses a serialized representation of Clang's internal data structures, encoded with the LLVM bitstream format. Pretokenized headers (*PTH*), on the other hand, contain a serialized representation of the tokens encountered when preprocessing a header (and anything that header includes).

The Frontend Library

The Frontend library contains functionality useful for building tools on top of the Clang libraries, for example several methods for outputting diagnostics.

The Lexer and Preprocessor Library

The Lexer library contains several tightly-connected classes that are involved with the nasty process of lexing and preprocessing C source code. The main interface to this library for outside clients is the large `Preprocessor` class. It contains the various pieces of state that are required to coherently read tokens out of a translation unit.

The core interface to the `Preprocessor` object (once it is set up) is the `Preprocessor::Lex` method, which returns the next *Token* from the preprocessor stream. There are two types of token providers that the preprocessor is capable of reading from: a buffer lexer (provided by the *Lexer* class) and a buffered token stream (provided by the *TokenLexer* class).

The Token class

The `Token` class is used to represent a single lexed token. Tokens are intended to be used by the lexer/preprocess and parser libraries, but are not intended to live beyond them (for example, they should not live in the ASTs).

Tokens most often live on the stack (or some other location that is efficient to access) as the parser is running, but occasionally do get buffered up. For example, macro definitions are stored as a series of tokens, and the C++ front-end periodically needs to buffer tokens up for tentative parsing and various pieces of look-ahead. As such, the size of a `Token` matters. On a 32-bit system, `sizeof(Token)` is currently 16 bytes.

Tokens occur in two forms: *annotation tokens* and normal tokens. Normal tokens are those returned by the lexer, annotation tokens represent semantic information and are produced by the parser, replacing normal tokens in the token stream. Normal tokens contain the following information:

- **A SourceLocation** — This indicates the location of the start of the token.
- **A length** — This stores the length of the token as stored in the `SourceBuffer`. For tokens that include them, this length includes trigraphs and escaped newlines which are ignored by later phases of the compiler. By pointing into the original source buffer, it is always possible to get the original spelling of a token completely accurately.
- **IdentifierInfo** — If a token takes the form of an identifier, and if identifier lookup was enabled when the token was lexed (e.g., the lexer was not reading in "raw" mode) this contains a pointer to the unique hash value for the identifier. Because the lookup happens before keyword identification, this field is set even for language keywords like "`for`".
- **TokenKind** — This indicates the kind of token as classified by the lexer. This includes things like `tok::starequal` (for the "`*=`" operator), `tok::ampamp` for the "`&&`" token, and keyword values (e.g., `tok::kw_for`) for identifiers that correspond to keywords. Note that some tokens can be spelled multiple ways. For example, C++ supports "operator keywords", where things like "`and`" are treated exactly like the "`&&`" operator. In these cases, the kind value is set to `tok::ampamp`, which is good for the parser, which

doesn't have to consider both forms. For something that cares about which form is used (e.g., the preprocessor "stringize" operator) the spelling indicates the original form.

- **Flags** — There are currently four flags tracked by the lexer/preprocessor system on a per-token basis:
  1. **StartOfLine** — This was the first token that occurred on its input source line.
  2. **LeadingSpace** — There was a space character either immediately before the token or transitively before the token as it was expanded through a macro. The definition of this flag is very closely defined by the stringizing requirements of the preprocessor.
  3. **DisableExpand** — This flag is used internally to the preprocessor to represent identifier tokens which have macro expansion disabled. This prevents them from being considered as candidates for macro expansion ever in the future.
  4. **NeedsCleaning** — This flag is set if the original spelling for the token includes a trigraph or escaped newline. Since this is uncommon, many pieces of code can fast-path on tokens that did not need cleaning.

One interesting (and somewhat unusual) aspect of normal tokens is that they don't contain any semantic information about the lexed value. For example, if the token was a pp-number token, we do not represent the value of the number that was lexed (this is left for later pieces of code to decide). Additionally, the lexer library has no notion of typedef names vs variable names: both are returned as identifiers, and the parser is left to decide whether a specific identifier is a typedef or a variable (tracking this requires scope information among other things). The parser can do this translation by replacing tokens returned by the preprocessor with "Annotation Tokens".

Annotation Tokens

Annotation tokens are tokens that are synthesized by the parser and injected into the preprocessor's token stream (replacing existing tokens) to record semantic information found by the parser. For example, if "`foo`" is found to be a typedef, the "`foo`" `tok::identifier` token is replaced with an `tok::annot_typename`. This is useful for a couple of reasons: 1) this makes it easy to handle qualified type names (e.g., "`foo::bar::baz<42>::t`") in C++ as a single "token" in the parser. 2) if the parser backtracks, the reparse does not need to redo semantic analysis to determine whether a token sequence is a variable, type, template, etc.

Annotation tokens are created by the parser and reinjected into the parser's token stream (when backtracking is enabled). Because they can only exist in tokens that the preprocessor-proper is done with, it doesn't need to keep around flags like "start of line" that the preprocessor uses to do its job. Additionally, an annotation token may "cover" a sequence of preprocessor tokens (e.g., "`a::b::c`" is five preprocessor tokens). As such, the valid fields of an annotation token are different than the fields for a normal token (but they are multiplexed into the normal `Token` fields):

- **SourceLocation "Location"** — The `SourceLocation` for the annotation token indicates the first token replaced by the annotation token. In the example above, it would be the location of the "`a`" identifier.
- **SourceLocation "AnnotationEndLoc"** — This holds the location of the last token replaced with the annotation token. In the example above, it would be the location of the "`c`" identifier.
- **void* "AnnotationValue"** — This contains an opaque object that the parser gets from `Sema`. The parser merely preserves the information for `Sema` to later interpret based on the annotation token kind.
- **TokenKind "Kind"** — This indicates the kind of Annotation token this is. See below for the different valid kinds.

Annotation tokens currently come in three kinds:

1. **tok::annot_typename**: This annotation token represents a resolved typename token that is potentially qualified. The `AnnotationValue` field contains the `QualType` returned by `Sema::getTypeName()`, possibly with source location information attached.
2. **tok::annot_cxxscope**: This annotation token represents a C++ scope specifier, such as "`A::B::`". This corresponds to the grammar productions "*::*" and "*:: [opt] nested-name-specifier*". The `AnnotationValue`

pointer is a `NestedNameSpecifier *` returned by the `Sema::ActOnCXXGlobalScopeSpecifier` and `Sema::ActOnCXXNestedNameSpecifier` callbacks.

3. **tok::annot_template_id**: This annotation token represents a C++ template-id such as "`foo<int, 4>`", where "`foo`" is the name of a template. The `AnnotationValue` pointer is a pointer to a `malloc`'d `TemplateIdAnnotation` object. Depending on the context, a parsed template-id that names a type might become a typename annotation token (if all we care about is the named type, e.g., because it occurs in a type specifier) or might remain a template-id token (if we want to retain more source location information or produce a new type, e.g., in a declaration of a class template specialization). template-id annotation tokens that refer to a type can be "upgraded" to typename annotation tokens by the parser.

As mentioned above, annotation tokens are not returned by the preprocessor, they are formed on demand by the parser. This means that the parser has to be aware of cases where an annotation could occur and form it where appropriate. This is somewhat similar to how the parser handles Translation Phase 6 of C99: String Concatenation (see C99 5.1.1.2). In the case of string concatenation, the preprocessor just returns distinct `tok::string_literal` and `tok::wide_string_literal` tokens and the parser eats a sequence of them wherever the grammar indicates that a string literal can occur.

In order to do this, whenever the parser expects a `tok::identifier` or `tok::coloncolon`, it should call the `TryAnnotateTypeOrScopeToken` or `TryAnnotateCXXScopeToken` methods to form the annotation token. These methods will maximally form the specified annotation tokens and replace the current token with them, if applicable. If the current tokens is not valid for an annotation token, it will remain an identifier or "`::`" token.

The `Lexer` class

The `Lexer` class provides the mechanics of lexing tokens out of a source buffer and deciding what they mean. The `Lexer` is complicated by the fact that it operates on raw buffers that have not had spelling eliminated (this is a necessity to get decent performance), but this is countered with careful coding as well as standard performance techniques (for example, the comment handling code is vectorized on X86 and PowerPC hosts).

The lexer has a couple of interesting modal features:

- The lexer can operate in "raw" mode. This mode has several features that make it possible to quickly lex the file (e.g., it stops identifier lookup, doesn't specially handle preprocessor tokens, handles EOF differently, etc). This mode is used for lexing within an "`#if 0`" block, for example.
- The lexer can capture and return comments as tokens. This is required to support the `-C` preprocessor mode, which passes comments through, and is used by the diagnostic checker to identifier expect-error annotations.
- The lexer can be in `ParsingFilename` mode, which happens when preprocessing after reading a `#include` directive. This mode changes the parsing of "<" to return an "angled string" instead of a bunch of tokens for each thing within the filename.
- When parsing a preprocessor directive (after "`#`") the `ParsingPreprocessorDirective` mode is entered. This changes the parser to return EOD at a newline.
- The `Lexer` uses a `LangOptions` object to know whether trigraphs are enabled, whether C++ or ObjC keywords are recognized, etc.

In addition to these modes, the lexer keeps track of a couple of other features that are local to a lexed buffer, which change as the buffer is lexed:

- The `Lexer` uses `BufferPtr` to keep track of the current character being lexed.
- The `Lexer` uses `IsAtStartOfLine` to keep track of whether the next lexed token will start with its "start of line" bit set.
- The `Lexer` keeps track of the current "`#if`" directives that are active (which can be nested).

- The `Lexer` keeps track of an *MultipleIncludeOpt* object, which is used to detect whether the buffer uses the standard "`#ifndef XX` / `#define XX`" idiom to prevent multiple inclusion. If a buffer does, subsequent includes can be ignored if the "`XX`" macro is defined.

The `TokenLexer` class

The `TokenLexer` class is a token provider that returns tokens from a list of tokens that came from somewhere else. It typically used for two things: 1) returning tokens from a macro definition as it is being expanded 2) returning tokens from an arbitrary buffer of tokens. The later use is used by `_Pragma` and will most likely be used to handle unbounded look-ahead for the C++ parser.

The `MultipleIncludeOpt` class

The `MultipleIncludeOpt` class implements a really simple little state machine that is used to detect the standard "`#ifndef XX` / `#define XX`" idiom that people typically use to prevent multiple inclusion of headers. If a buffer uses this idiom and is subsequently `#include`'d, the preprocessor can simply check to see whether the guarding condition is defined or not. If so, the preprocessor can completely ignore the include of the header.

The Parser Library

This library contains a recursive-descent parser that polls tokens from the preprocessor and notifies a client of the parsing progress.

Historically, the parser used to talk to an abstract `Action` interface that had virtual methods for parse events, for example `ActOnBinOp()`. When Clang grew C++ support, the parser stopped supporting general `Action` clients – it now always talks to the *Sema libray*. However, the Parser still accesses AST objects only through opaque types like `ExprResult` and `StmtResult`. Only *Sema* looks at the AST node contents of these wrappers.

The AST Library

The `Type` class and its subclasses

The `Type` class (and its subclasses) are an important part of the AST. Types are accessed through the `ASTContext` class, which implicitly creates and uniques them as they are needed. Types have a couple of non-obvious features: 1) they do not capture type qualifiers like `const` or `volatile` (see *QualType*), and 2) they implicitly capture typedef information. Once created, types are immutable (unlike decls).

Typedefs in C make semantic analysis a bit more complex than it would be without them. The issue is that we want to capture typedef information and represent it in the AST perfectly, but the semantics of operations need to "see through" typedefs. For example, consider this code:

```
void func() {
  typedef int foo;
  foo X, *Y;
  typedef foo *bar;
  bar Z;
  *X; // error
  **Y; // error
  **Z; // error
}
```

The code above is illegal, and thus we expect there to be diagnostics emitted on the annotated lines. In this example, we expect to get:

```
test.c:6:1: error: indirection requires pointer operand ('foo' invalid)
  *X; // error
  ^~
test.c:7:1: error: indirection requires pointer operand ('foo' invalid)
  **Y; // error
  ^~~
test.c:8:1: error: indirection requires pointer operand ('foo' invalid)
  **Z; // error
  ^~~
```

While this example is somewhat silly, it illustrates the point: we want to retain typedef information where possible, so that we can emit errors about "`std::string`" instead of "`std::basic_string<char, std:...`". Doing this requires properly keeping typedef information (for example, the type of `X` is "`foo`", not "`int`"), and requires properly propagating it through the various operators (for example, the type of `*Y` is "`foo`", not "`int`"). In order to retain this information, the type of these expressions is an instance of the `TypedefType` class, which indicates that the type of these expressions is a typedef for "`foo`".

Representing types like this is great for diagnostics, because the user-specified type is always immediately available. There are two problems with this: first, various semantic checks need to make judgements about the *actual structure* of a type, ignoring typedefs. Second, we need an efficient way to query whether two types are structurally identical to each other, ignoring typedefs. The solution to both of these problems is the idea of canonical types.

Canonical Types

Every instance of the `Type` class contains a canonical type pointer. For simple types with no typedefs involved (e.g., "`int`", "`int*`", "`int**`"), the type just points to itself. For types that have a typedef somewhere in their structure (e.g., "`foo`", "`foo*`", "`foo**`", "`bar`"), the canonical type pointer points to their structurally equivalent type without any typedefs (e.g., "`int`", "`int*`", "`int**`", and "`int*`" respectively).

This design provides a constant time operation (dereferencing the canonical type pointer) that gives us access to the structure of types. For example, we can trivially tell that "`bar`" and "`foo*`" are the same type by dereferencing their canonical type pointers and doing a pointer comparison (they both point to the single "`int*`" type).

Canonical types and typedef types bring up some complexities that must be carefully managed. Specifically, the `isa/cast/dyn_cast` operators generally shouldn't be used in code that is inspecting the AST. For example, when type checking the indirection operator (unary "`*`" on a pointer), the type checker must verify that the operand has a pointer type. It would not be correct to check that with "`isa<PointerType>(SubExpr->getType())`", because this predicate would fail if the subexpression had a typedef type.

The solution to this problem are a set of helper methods on `Type`, used to check their properties. In this case, it would be correct to use "`SubExpr->getType()->isPointerType()`" to do the check. This predicate will return true if the *canonical type is a pointer*, which is true any time the type is structurally a pointer type. The only hard part here is remembering not to use the `isa/cast/dyn_cast` operations.

The second problem we face is how to get access to the pointer type once we know it exists. To continue the example, the result type of the indirection operator is the pointee type of the subexpression. In order to determine the type, we need to get the instance of `PointerType` that best captures the typedef information in the program. If the type of the expression is literally a `PointerType`, we can return that, otherwise we have to dig through the typedefs to find the pointer type. For example, if the subexpression had type "`foo*`", we could return that type as the result. If the subexpression had type "`bar`", we want to return "`foo*`" (note that we do *not* want "`int*`"). In order to provide all of this, `Type` has a `getAsPointerType()` method that checks whether the type is structurally a `PointerType` and, if so, returns the best one. If not, it returns a null pointer.

This structure is somewhat mystical, but after meditating on it, it will make sense to you :).

The QualType class

The QualType class is designed as a trivial value class that is small, passed by-value and is efficient to query. The idea of QualType is that it stores the type qualifiers (const, volatile, restrict, plus some extended qualifiers required by language extensions) separately from the types themselves. QualType is conceptually a pair of "Type*" and the bits for these type qualifiers.

By storing the type qualifiers as bits in the conceptual pair, it is extremely efficient to get the set of qualifiers on a QualType (just return the field of the pair), add a type qualifier (which is a trivial constant-time operation that sets a bit), and remove one or more type qualifiers (just return a QualType with the bitfield set to empty).

Further, because the bits are stored outside of the type itself, we do not need to create duplicates of types with different sets of qualifiers (i.e. there is only a single heap allocated "int" type: "const int" and "volatile const int" both point to the same heap allocated "int" type). This reduces the heap size used to represent bits and also means we do not have to consider qualifiers when uniquing types (*Type* does not even contain qualifiers).

In practice, the two most common type qualifiers (const and restrict) are stored in the low bits of the pointer to the Type object, together with a flag indicating whether extended qualifiers are present (which must be heap-allocated). This means that QualType is exactly the same size as a pointer.

Declaration names

The DeclarationName class represents the name of a declaration in Clang. Declarations in the C family of languages can take several different forms. Most declarations are named by simple identifiers, e.g., "f" and "x" in the function declaration f(int x). In C++, declaration names can also name class constructors ("Class" in struct Class { Class(); }), class destructors ("~Class"), overloaded operator names ("operator+"), and conversion functions ("operator void const *"). In Objective-C, declaration names can refer to the names of Objective-C methods, which involve the method name and the parameters, collectively called a *selector*, e.g., "setWidth:height:". Since all of these kinds of entities — variables, functions, Objective-C methods, C++ constructors, destructors, and operators — are represented as subclasses of Clang's common NamedDecl class, DeclarationName is designed to efficiently represent any kind of name.

Given a DeclarationName N, N.getNameKind() will produce a value that describes what kind of name N stores. There are 10 options (all of the names are inside the DeclarationName class).

Identifier

> The name is a simple identifier. Use N.getAsIdentifierInfo() to retrieve the corresponding IdentifierInfo* pointing to the actual identifier.

ObjCZeroArgSelector, ObjCOneArgSelector, ObjCMultiArgSelector

> The name is an Objective-C selector, which can be retrieved as a Selector instance via N.getObjCSelector(). The three possible name kinds for Objective-C reflect an optimization within the DeclarationName class: both zero- and one-argument selectors are stored as a masked IdentifierInfo pointer, and therefore require very little space, since zero- and one-argument selectors are far more common than multi-argument selectors (which use a different structure).

CXXConstructorName

> The name is a C++ constructor name. Use N.getCXXNameType() to retrieve the *type* that this constructor is meant to construct. The type is always the canonical type, since all constructors for a given type have the same name.

CXXDestructorName

> The name is a C++ destructor name. Use N.getCXXNameType() to retrieve the *type* whose destructor is being named. This type is always a canonical type.

CXXConversionFunctionName

The name is a C++ conversion function. Conversion functions are named according to the type they convert to, e.g., "`operator void const *`". Use `N.getCXXNameType()` to retrieve the type that this conversion function converts to. This type is always a canonical type.

`CXXOperatorName`

The name is a C++ overloaded operator name. Overloaded operators are named according to their spelling, e.g., "`operator+`" or "`operator new []`". Use `N.getCXXOverloadedOperator()` to retrieve the overloaded operator (a value of type `OverloadedOperatorKind`).

`CXXLiteralOperatorName`

The name is a C++11 user defined literal operator. User defined Literal operators are named according to the suffix they define, e.g., "`_foo`" for "`operator "" _foo`". Use `N.getCXXLiteralIdentifier()` to retrieve the corresponding `IdentifierInfo*` pointing to the identifier.

`CXXUsingDirective`

The name is a C++ using directive. Using directives are not really NamedDecls, in that they all have the same name, but they are implemented as such in order to store them in DeclContext effectively.

`DeclarationName`s are cheap to create, copy, and compare. They require only a single pointer's worth of storage in the common cases (identifiers, zero- and one-argument Objective-C selectors) and use dense, uniqued storage for the other kinds of names. Two `DeclarationName`s can be compared for equality (==, !=) using a simple bitwise comparison, can be ordered with <, >, <=, and >= (which provide a lexicographical ordering for normal identifiers but an unspecified ordering for other kinds of names), and can be placed into LLVM `DenseMap`s and `DenseSet`s.

`DeclarationName` instances can be created in different ways depending on what kind of name the instance will store. Normal identifiers (`IdentifierInfo` pointers) and Objective-C selectors (`Selector`) can be implicitly converted to `DeclarationName`s. Names for C++ constructors, destructors, conversion functions, and overloaded operators can be retrieved from the `DeclarationNameTable`, an instance of which is available as `ASTContext::DeclarationNames`. The member functions `getCXXConstructorName`, `getCXXDestructorName`, `getCXXConversionFunctionName`, and `getCXXOperatorName`, respectively, return `DeclarationName` instances for the four kinds of C++ special function names.

Declaration contexts

Every declaration in a program exists within some *declaration context*, such as a translation unit, namespace, class, or function. Declaration contexts in Clang are represented by the `DeclContext` class, from which the various declaration-context AST nodes (`TranslationUnitDecl`, `NamespaceDecl`, `RecordDecl`, `FunctionDecl`, etc.) will derive. The `DeclContext` class provides several facilities common to each declaration context:

Source-centric vs. Semantics-centric View of Declarations

`DeclContext` provides two views of the declarations stored within a declaration context. The source-centric view accurately represents the program source code as written, including multiple declarations of entities where present (see the section *Redeclarations and Overloads*), while the semantics-centric view represents the program semantics. The two views are kept synchronized by semantic analysis while the ASTs are being constructed.

Storage of declarations within that context

Every declaration context can contain some number of declarations. For example, a C++ class (represented by `RecordDecl`) contains various member functions, fields, nested types, and so on. All of these declarations will be stored within the `DeclContext`, and one can iterate over the declarations via [`DeclContext::decls_begin()`, `DeclContext::decls_end()`). This mechanism provides the source-centric view of declarations in the context.

Lookup of declarations within that context

The `DeclContext` structure provides efficient name lookup for names within that declaration context. For example, if `N` is a namespace we can look for the name `N::f` using `DeclContext::lookup`. The lookup itself is based on a lazily-constructed array (for declaration contexts with a small number of declarations) or hash table (for declaration contexts with more declarations). The lookup operation provides the semantics-centric view of the declarations in the context.

Ownership of declarations

The `DeclContext` owns all of the declarations that were declared within its declaration context, and is responsible for the management of their memory as well as their (de-)serialization.

All declarations are stored within a declaration context, and one can query information about the context in which each declaration lives. One can retrieve the `DeclContext` that contains a particular `Decl` using `Decl::getDeclContext`. However, see the section *Lexical and Semantic Contexts* for more information about how to interpret this context information.

Redeclarations and Overloads

Within a translation unit, it is common for an entity to be declared several times. For example, we might declare a function "`f`" and then later re-declare it as part of an inlined definition:

```
void f(int x, int y, int z = 1);

inline void f(int x, int y, int z) { /* ... */ }
```

The representation of "`f`" differs in the source-centric and semantics-centric views of a declaration context. In the source-centric view, all redeclarations will be present, in the order they occurred in the source code, making this view suitable for clients that wish to see the structure of the source code. In the semantics-centric view, only the most recent "`f`" will be found by the lookup, since it effectively replaces the first declaration of "`f`".

In the semantics-centric view, overloading of functions is represented explicitly. For example, given two declarations of a function "`g`" that are overloaded, e.g.,

```
void g();
void g(int);
```

the `DeclContext::lookup` operation will return a `DeclContext::lookup_result` that contains a range of iterators over declarations of "`g`". Clients that perform semantic analysis on a program that is not concerned with the actual source code will primarily use this semantics-centric view.

Lexical and Semantic Contexts

Each declaration has two potentially different declaration contexts: a *lexical* context, which corresponds to the source-centric view of the declaration context, and a *semantic* context, which corresponds to the semantics-centric view. The lexical context is accessible via `Decl::getLexicalDeclContext` while the semantic context is accessible via `Decl::getDeclContext`, both of which return `DeclContext` pointers. For most declarations, the two contexts are identical. For example:

```
class X {
public:
  void f(int x);
};
```

Here, the semantic and lexical contexts of `X::f` are the `DeclContext` associated with the class `X` (itself stored as a `RecordDecl` AST node). However, we can now define `X::f` out-of-line:

```
void X::f(int x = 17) { /* ... */ }
```

This definition of "f" has different lexical and semantic contexts. The lexical context corresponds to the declaration context in which the actual declaration occurred in the source code, e.g., the translation unit containing X. Thus, this declaration of X::f can be found by traversing the declarations provided by [decls_begin(), decls_end()) in the translation unit.

The semantic context of X::f corresponds to the class X, since this member function is (semantically) a member of X. Lookup of the name f into the DeclContext associated with X will then return the definition of X::f (including information about the default argument).

Transparent Declaration Contexts

In C and C++, there are several contexts in which names that are logically declared inside another declaration will actually "leak" out into the enclosing scope from the perspective of name lookup. The most obvious instance of this behavior is in enumeration types, e.g.,

```
enum Color {
  Red,
  Green,
  Blue
};
```

Here, Color is an enumeration, which is a declaration context that contains the enumerators Red, Green, and Blue. Thus, traversing the list of declarations contained in the enumeration Color will yield Red, Green, and Blue. However, outside of the scope of Color one can name the enumerator Red without qualifying the name, e.g.,

```
Color c = Red;
```

There are other entities in C++ that provide similar behavior. For example, linkage specifications that use curly braces:

```
extern "C" {
  void f(int);
  void g(int);
}
// f and g are visible here
```

For source-level accuracy, we treat the linkage specification and enumeration type as a declaration context in which its enclosed declarations ("Red", "Green", and "Blue"; "f" and "g") are declared. However, these declarations are visible outside of the scope of the declaration context.

These language features (and several others, described below) have roughly the same set of requirements: declarations are declared within a particular lexical context, but the declarations are also found via name lookup in scopes enclosing the declaration itself. This feature is implemented via *transparent* declaration contexts (see DeclContext::isTransparentContext()), whose declarations are visible in the nearest enclosing non-transparent declaration context. This means that the lexical context of the declaration (e.g., an enumerator) will be the transparent DeclContext itself, as will the semantic context, but the declaration will be visible in every outer context up to and including the first non-transparent declaration context (since transparent declaration contexts can be nested).

The transparent DeclContexts are:

- Enumerations (but not C++11 "scoped enumerations"):

  ```
  enum Color {
    Red,
  ```

```
  Green,
  Blue
};
// Red, Green, and Blue are in scope
```

- C++ linkage specifications:

```
extern "C" {
  void f(int);
  void g(int);
}
// f and g are in scope
```

- Anonymous unions and structs:

```
struct LookupTable {
  bool IsVector;
  union {
    std::vector<Item> *Vector;
    std::set<Item> *Set;
  };
};

LookupTable LT;
LT.Vector = 0; // Okay: finds Vector inside the unnamed union
```

- C++11 inline namespaces:

```
namespace mylib {
  inline namespace debug {
    class X;
  }
}
mylib::X *xp; // okay: mylib::X refers to mylib::debug::X
```

Multiply-Defined Declaration Contexts

C++ namespaces have the interesting — and, so far, unique — property that the namespace can be defined multiple times, and the declarations provided by each namespace definition are effectively merged (from the semantic point of view). For example, the following two code snippets are semantically indistinguishable:

```
// Snippet #1:
namespace N {
  void f();
}
namespace N {
  void f(int);
}

// Snippet #2:
namespace N {
  void f();
  void f(int);
}
```

In Clang's representation, the source-centric view of declaration contexts will actually have two separate `NamespaceDecl` nodes in Snippet #1, each of which is a declaration context that contains a single declaration of "`f`". However, the semantics-centric view provided by name lookup into the namespace `N` for "`f`" will return a `DeclContext::lookup_result` that contains a range of iterators over declarations of "`f`".

`DeclContext` manages multiply-defined declaration contexts internally. The function `DeclContext::getPrimaryContext` retrieves the "primary" context for a given `DeclContext` instance, which is the `DeclContext` responsible for maintaining the lookup table used for the semantics-centric view. Given a DeclContext, one can obtain the set of declaration contexts that are semanticaly connected to this declaration context, in source order, including this context (which will be the only result, for non-namespace contexts) via `DeclContext::collectAllContexts`. Note that these functions are used internally within the lookup and insertion methods of the `DeclContext`, so the vast majority of clients can ignore them.

The `CFG` class

The `CFG` class is designed to represent a source-level control-flow graph for a single statement (`Stmt*`). Typically instances of `CFG` are constructed for function bodies (usually an instance of `CompoundStmt`), but can also be instantiated to represent the control-flow of any class that subclasses `Stmt`, which includes simple expressions. Control-flow graphs are especially useful for performing flow- or path-sensitive program analyses on a given function.

Basic Blocks

Concretely, an instance of `CFG` is a collection of basic blocks. Each basic block is an instance of `CFGBlock`, which simply contains an ordered sequence of `Stmt*` (each referring to statements in the AST). The ordering of statements within a block indicates unconditional flow of control from one statement to the next. *Conditional control-flow* is represented using edges between basic blocks. The statements within a given `CFGBlock` can be traversed using the `CFGBlock::*iterator` interface.

A `CFG` object owns the instances of `CFGBlock` within the control-flow graph it represents. Each `CFGBlock` within a CFG is also uniquely numbered (accessible via `CFGBlock::getBlockID()`). Currently the number is based on the ordering the blocks were created, but no assumptions should be made on how `CFGBlocks` are numbered other than their numbers are unique and that they are numbered from 0..N-1 (where N is the number of basic blocks in the CFG).

Entry and Exit Blocks

Each instance of `CFG` contains two special blocks: an *entry* block (accessible via `CFG::getEntry()`), which has no incoming edges, and an *exit* block (accessible via `CFG::getExit()`), which has no outgoing edges. Neither block contains any statements, and they serve the role of providing a clear entrance and exit for a body of code such as a function body. The presence of these empty blocks greatly simplifies the implementation of many analyses built on top of CFGs.

Conditional Control-Flow

Conditional control-flow (such as those induced by if-statements and loops) is represented as edges between `CFGBlocks`. Because different C language constructs can induce control-flow, each `CFGBlock` also records an extra `Stmt*` that represents the *terminator* of the block. A terminator is simply the statement that caused the control-flow, and is used to identify the nature of the conditional control-flow between blocks. For example, in the case of an if-statement, the terminator refers to the `IfStmt` object in the AST that represented the given branch.

To illustrate, consider the following code example:

```
int foo(int x) {
  x = x + 1;
  if (x > 2)
    x++;
  else {
    x += 2;
    x *= 2;
  }

  return x;
}
```

After invoking the parser+semantic analyzer on this code fragment, the AST of the body of `foo` is referenced by a single `Stmt*`. We can then construct an instance of `CFG` representing the control-flow graph of this function body by single call to a static class method:

```
Stmt *FooBody = ...
std::unique_ptr<CFG> FooCFG = CFG::buildCFG(FooBody);
```

Along with providing an interface to iterate over its `CFGBlocks`, the `CFG` class also provides methods that are useful for debugging and visualizing CFGs. For example, the method `CFG::dump()` dumps a pretty-printed version of the CFG to standard error. This is especially useful when one is using a debugger such as gdb. For example, here is the output of `FooCFG->dump()`:

```
[ B5 (ENTRY) ]
   Predecessors (0):
   Successors (1): B4

[ B4 ]
   1: x = x + 1
   2: (x > 2)
   T: if [B4.2]
   Predecessors (1): B5
   Successors (2): B3 B2

[ B3 ]
   1: x++
   Predecessors (1): B4
   Successors (1): B1

[ B2 ]
   1: x += 2
   2: x *= 2
   Predecessors (1): B4
   Successors (1): B1

[ B1 ]
   1: return x;
   Predecessors (2): B2 B3
   Successors (1): B0

[ B0 (EXIT) ]
   Predecessors (1): B1
   Successors (0):
```

For each block, the pretty-printed output displays for each block the number of *predecessor* blocks (blocks that have outgoing control-flow to the given block) and *successor* blocks (blocks that have control-flow that have incoming

control-flow from the given block). We can also clearly see the special entry and exit blocks at the beginning and end of the pretty-printed output. For the entry block (block B5), the number of predecessor blocks is 0, while for the exit block (block B0) the number of successor blocks is 0.

The most interesting block here is B4, whose outgoing control-flow represents the branching caused by the sole if-statement in `foo`. Of particular interest is the second statement in the block, `(x > 2)`, and the terminator, printed as `if [B4.2]`. The second statement represents the evaluation of the condition of the if-statement, which occurs before the actual branching of control-flow. Within the `CFGBlock` for B4, the `Stmt*` for the second statement refers to the actual expression in the AST for `(x > 2)`. Thus pointers to subclasses of `Expr` can appear in the list of statements in a block, and not just subclasses of `Stmt` that refer to proper C statements.

The terminator of block B4 is a pointer to the `IfStmt` object in the AST. The pretty-printer outputs `if [B4.2]` because the condition expression of the if-statement has an actual place in the basic block, and thus the terminator is essentially *referring* to the expression that is the second statement of block B4 (i.e., B4.2). In this manner, conditions for control-flow (which also includes conditions for loops and switch statements) are hoisted into the actual basic block.

Constant Folding in the Clang AST

There are several places where constants and constant folding matter a lot to the Clang front-end. First, in general, we prefer the AST to retain the source code as close to how the user wrote it as possible. This means that if they wrote "`5+4`", we want to keep the addition and two constants in the AST, we don't want to fold to "`9`". This means that constant folding in various ways turns into a tree walk that needs to handle the various cases.

However, there are places in both C and C++ that require constants to be folded. For example, the C standard defines what an "integer constant expression" (i-c-e) is with very precise and specific requirements. The language then requires i-c-e's in a lot of places (for example, the size of a bitfield, the value for a case statement, etc). For these, we have to be able to constant fold the constants, to do semantic checks (e.g., verify bitfield size is non-negative and that case statements aren't duplicated). We aim for Clang to be very pedantic about this, diagnosing cases when the code does not use an i-c-e where one is required, but accepting the code unless running with `-pedantic-errors`.

Things get a little bit more tricky when it comes to compatibility with real-world source code. Specifically, GCC has historically accepted a huge superset of expressions as i-c-e's, and a lot of real world code depends on this unfortuate accident of history (including, e.g., the glibc system headers). GCC accepts anything its "fold" optimizer is capable of reducing to an integer constant, which means that the definition of what it accepts changes as its optimizer does. One example is that GCC accepts things like "`case X-X:`" even when `X` is a variable, because it can fold this to 0.

Another issue are how constants interact with the extensions we support, such as `__builtin_constant_p`, `__builtin_inf`, `__extension__` and many others. C99 obviously does not specify the semantics of any of these extensions, and the definition of i-c-e does not include them. However, these extensions are often used in real code, and we have to have a way to reason about them.

Finally, this is not just a problem for semantic analysis. The code generator and other clients have to be able to fold constants (e.g., to initialize global variables) and has to handle a superset of what C99 allows. Further, these clients can benefit from extended information. For example, we know that "`foo() || 1`" always evaluates to `true`, but we can't replace the expression with `true` because it has side effects.

Implementation Approach

After trying several different approaches, we've finally converged on a design (Note, at the time of this writing, not all of this has been implemented, consider this a design goal!). Our basic approach is to define a single recursive method evaluation method (`Expr::Evaluate`), which is implemented in `AST/ExprConstant.cpp`. Given an expression with "scalar" type (integer, fp, complex, or pointer) this method returns the following information:

- Whether the expression is an integer constant expression, a general constant that was folded but has no side effects, a general constant that was folded but that does have side effects, or an uncomputable/unfoldable value.

- If the expression was computable in any way, this method returns the `APValue` for the result of the expression.
- If the expression is not evaluatable at all, this method returns information on one of the problems with the expression. This includes a `SourceLocation` for where the problem is, and a diagnostic ID that explains the problem. The diagnostic should have `ERROR` type.
- If the expression is not an integer constant expression, this method returns information on one of the problems with the expression. This includes a `SourceLocation` for where the problem is, and a diagnostic ID that explains the problem. The diagnostic should have `EXTENSION` type.

This information gives various clients the flexibility that they want, and we will eventually have some helper methods for various extensions. For example, `Sema` should have a `Sema::VerifyIntegerConstantExpression` method, which calls `Evaluate` on the expression. If the expression is not foldable, the error is emitted, and it would return `true`. If the expression is not an i-c-e, the `EXTENSION` diagnostic is emitted. Finally it would return `false` to indicate that the AST is OK.

Other clients can use the information in other ways, for example, codegen can just use expressions that are foldable in any way.

Extensions

This section describes how some of the various extensions Clang supports interacts with constant evaluation:

- `__extension__`: The expression form of this extension causes any evaluatable subexpression to be accepted as an integer constant expression.
- `__builtin_constant_p`: This returns true (as an integer constant expression) if the operand evaluates to either a numeric value (that is, not a pointer cast to integral type) of integral, enumeration, floating or complex type, or if it evaluates to the address of the first character of a string literal (possibly cast to some other type). As a special case, if `__builtin_constant_p` is the (potentially parenthesized) condition of a conditional operator expression ("`?:`"), only the true side of the conditional operator is considered, and it is evaluated with full constant folding.
- `__builtin_choose_expr`: The condition is required to be an integer constant expression, but we accept any constant as an "extension of an extension". This only evaluates one operand depending on which way the condition evaluates.
- `__builtin_classify_type`: This always returns an integer constant expression.
- `__builtin_inf, nan, ...`: These are treated just like a floating-point literal.
- `__builtin_abs, copysign, ...`: These are constant folded as general constant expressions.
- `__builtin_strlen` and `strlen`: These are constant folded as integer constant expressions if the argument is a string literal.

The Sema Library

This library is called by the *Parser library* during parsing to do semantic analysis of the input. For valid programs, Sema builds an AST for parsed constructs.

The CodeGen Library

CodeGen takes an *AST* as input and produces LLVM IR code from it.

How to change Clang

How to add an attribute

Attributes are a form of metadata that can be attached to a program construct, allowing the programmer to pass semantic information along to the compiler for various uses. For example, attributes may be used to alter the code generation for a program construct, or to provide extra semantic information for static analysis. This document explains how to add a custom attribute to Clang. Documentation on existing attributes can be found here.

Attribute Basics

Attributes in Clang are handled in three stages: parsing into a parsed attribute representation, conversion from a parsed attribute into a semantic attribute, and then the semantic handling of the attribute.

Parsing of the attribute is determined by the various syntactic forms attributes can take, such as GNU, C++11, and Microsoft style attributes, as well as other information provided by the table definition of the attribute. Ultimately, the parsed representation of an attribute object is an `AttributeList` object. These parsed attributes chain together as a list of parsed attributes attached to a declarator or declaration specifier. The parsing of attributes is handled automatically by Clang, except for attributes spelled as keywords. When implementing a keyword attribute, the parsing of the keyword and creation of the `AttributeList` object must be done manually.

Eventually, `Sema::ProcessDeclAttributeList()` is called with a `Decl` and an `AttributeList`, at which point the parsed attribute can be transformed into a semantic attribute. The process by which a parsed attribute is converted into a semantic attribute depends on the attribute definition and semantic requirements of the attribute. The end result, however, is that the semantic attribute object is attached to the `Decl` object, and can be obtained by a call to `Decl::getAttr<T>()`.

The structure of the semantic attribute is also governed by the attribute definition given in Attr.td. This definition is used to automatically generate functionality used for the implementation of the attribute, such as a class derived from `clang::Attr`, information for the parser to use, automated semantic checking for some attributes, etc.

include/clang/Basic/Attr.td

The first step to adding a new attribute to Clang is to add its definition to include/clang/Basic/Attr.td. This tablegen definition must derive from the `Attr` (tablegen, not semantic) type, or one of its derivatives. Most attributes will derive from the `InheritableAttr` type, which specifies that the attribute can be inherited by later redeclarations of the `Decl` it is associated with. `InheritableParamAttr` is similar to `InheritableAttr`, except that the attribute is written on a parameter instead of a declaration. If the attribute is intended to apply to a type instead of a declaration, such an attribute should derive from `TypeAttr`, and will generally not be given an AST representation. (Note that this document does not cover the creation of type attributes.) An attribute that inherits from `IgnoredAttr` is parsed, but will generate an ignored attribute diagnostic when used, which may be useful when an attribute is supported by another vendor but not supported by clang.

The definition will specify several key pieces of information, such as the semantic name of the attribute, the spellings the attribute supports, the arguments the attribute expects, and more. Most members of the `Attr` tablegen type do not require definitions in the derived definition as the default suffice. However, every attribute must specify at least a spelling list, a subject list, and a documentation list.

Spellings

All attributes are required to specify a spelling list that denotes the ways in which the attribute can be spelled. For instance, a single semantic attribute may have a keyword spelling, as well as a C++11 spelling and a GNU spelling.

An empty spelling list is also permissible and may be useful for attributes which are created implicitly. The following spellings are accepted:

Spelling	Description
GNU	Spelled with a GNU-style __attribute__((attr)) syntax and placement.
CXX11	Spelled with a C++-style [[attr]] syntax. If the attribute is meant to be used by Clang, it should set the namespace to "clang".
Declspec	Spelled with a Microsoft-style __declspec(attr) syntax.
Keyword	The attribute is spelled as a keyword, and required custom parsing.
GCC	Specifies two spellings: the first is a GNU-style spelling, and the second is a C++-style spelling with the gnu namespace. Attributes should only specify this spelling for attributes supported by GCC.
Pragma	The attribute is spelled as a #pragma, and requires custom processing within the preprocessor. If the attribute is meant to be used by Clang, it should set the namespace to "clang". Note that this spelling is not used for declaration attributes.

Subjects

Attributes appertain to one or more Decl subjects. If the attribute attempts to attach to a subject that is not in the subject list, a diagnostic is issued automatically. Whether the diagnostic is a warning or an error depends on how the attribute's SubjectList is defined, but the default behavior is to warn. The diagnostics displayed to the user are automatically determined based on the subjects in the list, but a custom diagnostic parameter can also be specified in the SubjectList. The diagnostics generated for subject list violations are either diag::warn_attribute_wrong_decl_type or diag::err_attribute_wrong_decl_type, and the parameter enumeration is found in include/clang/Sema/AttributeList.h If a previously unused Decl node is added to the SubjectList, the logic used to automatically determine the diagnostic parameter in utils/TableGen/ClangAttrEmitter.cpp may need to be updated.

By default, all subjects in the SubjectList must either be a Decl node defined in DeclNodes.td, or a statement node defined in StmtNodes.td. However, more complex subjects can be created by creating a SubsetSubject object. Each such object has a base subject which it appertains to (which must be a Decl or Stmt node, and not a SubsetSubject node), and some custom code which is called when determining whether an attribute appertains to the subject. For instance, a NonBitField SubsetSubject appertains to a FieldDecl, and tests whether the given FieldDecl is a bit field. When a SubsetSubject is specified in a SubjectList, a custom diagnostic parameter must also be provided.

Diagnostic checking for attribute subject lists is automated except when HasCustomParsing is set to 1.

Documentation

All attributes must have some form of documentation associated with them. Documentation is table generated on the public web server by a server-side process that runs daily. Generally, the documentation for an attribute is a stand-alone definition in include/clang/Basic/AttrDocs.td that is named after the attribute being documented.

If the attribute is not for public consumption, or is an implicitly-created attribute that has no visible spelling, the documentation list can specify the Undocumented object. Otherwise, the attribute should have its documentation added to AttrDocs.td.

Documentation derives from the Documentation tablegen type. All derived types must specify a documentation category and the actual documentation itself. Additionally, it can specify a custom heading for the attribute, though a default heading will be chosen when possible.

There are four predefined documentation categories: DocCatFunction for attributes that appertain to function-like subjects, DocCatVariable for attributes that appertain to variable-like subjects, DocCatType for type attributes, and DocCatStmt for statement attributes. A custom documentation category should be used for groups of attributes

with similar functionality. Custom categories are good for providing overview information for the attributes grouped under it. For instance, the consumed annotation attributes define a custom category, `DocCatConsumed`, that explains what consumed annotations are at a high level.

Documentation content (whether it is for an attribute or a category) is written using reStructuredText (RST) syntax.

After writing the documentation for the attribute, it should be locally tested to ensure that there are no issues generating the documentation on the server. Local testing requires a fresh build of clang-tblgen. To generate the attribute documentation, execute the following command:

```
clang-tblgen -gen-attr-docs -I /path/to/clang/include /path/to/clang/include/clang/
↪Basic/Attr.td -o /path/to/clang/docs/AttributeReference.rst
```

When testing locally, *do not* commit changes to `AttributeReference.rst`. This file is generated by the server automatically, and any changes made to this file will be overwritten.

Arguments

Attributes may optionally specify a list of arguments that can be passed to the attribute. Attribute arguments specify both the parsed form and the semantic form of the attribute. For example, if `Args` is `[StringArgument<"Arg1">, IntArgument<"Arg2">]` then `__attribute__((myattribute("Hello", 3)))` will be a valid use; it requires two arguments while parsing, and the Attr subclass' constructor for the semantic attribute will require a string and integer argument.

All arguments have a name and a flag that specifies whether the argument is optional. The associated C++ type of the argument is determined by the argument definition type. If the existing argument types are insufficient, new types can be created, but it requires modifying utils/TableGen/ClangAttrEmitter.cpp to properly support the type.

Other Properties

The `Attr` definition has other members which control the behavior of the attribute. Many of them are special-purpose and beyond the scope of this document, however a few deserve mention.

If the parsed form of the attribute is more complex, or differs from the semantic form, the `HasCustomParsing` bit can be set to `1` for the class, and the parsing code in Parser::ParseGNUAttributeArgs() can be updated for the special case. Note that this only applies to arguments with a GNU spelling – attributes with a __declspec spelling currently ignore this flag and are handled by `Parser::ParseMicrosoftDeclSpec`.

Note that setting this member to 1 will opt out of common attribute semantic handling, requiring extra implementation efforts to ensure the attribute appertains to the appropriate subject, etc.

If the attribute should not be propagated from from a template declaration to an instantiation of the template, set the `Clone` member to 0. By default, all attributes will be cloned to template instantiations.

Attributes that do not require an AST node should set the `ASTNode` field to `0` to avoid polluting the AST. Note that anything inheriting from `TypeAttr` or `IgnoredAttr` automatically do not generate an AST node. All other attributes generate an AST node by default. The AST node is the semantic representation of the attribute.

The `LangOpts` field specifies a list of language options required by the attribute. For instance, all of the CUDA-specific attributes specify `[CUDA]` for the `LangOpts` field, and when the CUDA language option is not enabled, an "attribute ignored" warning diagnostic is emitted. Since language options are not table generated nodes, new language options must be created manually and should specify the spelling used by `LangOptions` class.

Custom accessors can be generated for an attribute based on the spelling list for that attribute. For instance, if an attribute has two different spellings: 'Foo' and 'Bar', accessors can be created: `[Accessor<"isFoo", [GNU<"Foo">]>, Accessor<"isBar", [GNU<"Bar">]>]` These accessors will be generated on the semantic form of the attribute, accepting no arguments and returning a `bool`.

Attributes that do not require custom semantic handling should set the `SemaHandler` field to `0`. Note that anything inheriting from `IgnoredAttr` automatically do not get a semantic handler. All other attributes are assumed to use a semantic handler by default. Attributes without a semantic handler are not given a parsed attribute `Kind` enumerator.

Target-specific attributes may share a spelling with other attributes in different targets. For instance, the ARM and MSP430 targets both have an attribute spelled `GNU<"interrupt">`, but with different parsing and semantic requirements. To support this feature, an attribute inheriting from `TargetSpecificAttribute` may specify a `ParseKind` field. This field should be the same value between all arguments sharing a spelling, and corresponds to the parsed attribute's `Kind` enumerator. This allows attributes to share a parsed attribute kind, but have distinct semantic attribute classes. For instance, `AttributeList::AT_Interrupt` is the shared parsed attribute kind, but ARMInterruptAttr and MSP430InterruptAttr are the semantic attributes generated.

By default, when declarations are merging attributes, an attribute will not be duplicated. However, if an attribute can be duplicated during this merging stage, set `DuplicatesAllowedWhileMerging` to `1`, and the attribute will be merged.

By default, attribute arguments are parsed in an evaluated context. If the arguments for an attribute should be parsed in an unevaluated context (akin to the way the argument to a `sizeof` expression is parsed), set `ParseArgumentsAsUnevaluated` to `1`.

If additional functionality is desired for the semantic form of the attribute, the `AdditionalMembers` field specifies code to be copied verbatim into the semantic attribute class object, with `public` access.

Boilerplate

All semantic processing of declaration attributes happens in lib/Sema/SemaDeclAttr.cpp, and generally starts in the `ProcessDeclAttribute()` function. If the attribute is a "simple" attribute – meaning that it requires no custom semantic processing aside from what is automatically provided, add a call to `handleSimpleAttribute<YourAttr>(S, D, Attr);` to the switch statement. Otherwise, write a new `handleYourAttr()` function, and add that to the switch statement. Please do not implement handling logic directly in the `case` for the attribute.

Unless otherwise specified by the attribute definition, common semantic checking of the parsed attribute is handled automatically. This includes diagnosing parsed attributes that do not appertain to the given `Decl`, ensuring the correct minimum number of arguments are passed, etc.

If the attribute adds additional warnings, define a `DiagGroup` in include/clang/Basic/DiagnosticGroups.td named after the attribute's `Spelling` with "_"s replaced by "-"s. If there is only a single diagnostic, it is permissible to use `InGroup<DiagGroup<"your-attribute">>` directly in DiagnosticSemaKinds.td

All semantic diagnostics generated for your attribute, including automatically- generated ones (such as subjects and argument counts), should have a corresponding test case.

Semantic handling

Most attributes are implemented to have some effect on the compiler. For instance, to modify the way code is generated, or to add extra semantic checks for an analysis pass, etc. Having added the attribute definition and conversion to the semantic representation for the attribute, what remains is to implement the custom logic requiring use of the attribute.

The `clang::Decl` object can be queried for the presence or absence of an attribute using `hasAttr<T>()`. To obtain a pointer to the semantic representation of the attribute, `getAttr<T>` may be used.

How to add an expression or statement

Expressions and statements are one of the most fundamental constructs within a compiler, because they interact with many different parts of the AST, semantic analysis, and IR generation. Therefore, adding a new expression or statement kind into Clang requires some care. The following list details the various places in Clang where an expression or statement needs to be introduced, along with patterns to follow to ensure that the new expression or statement works well across all of the C languages. We focus on expressions, but statements are similar.

1. Introduce parsing actions into the parser. Recursive-descent parsing is mostly self-explanatory, but there are a few things that are worth keeping in mind:

   - Keep as much source location information as possible! You'll want it later to produce great diagnostics and support Clang's various features that map between source code and the AST.
   - Write tests for all of the "bad" parsing cases, to make sure your recovery is good. If you have matched delimiters (e.g., parentheses, square brackets, etc.), use `Parser::BalancedDelimiterTracker` to give nice diagnostics when things go wrong.

2. Introduce semantic analysis actions into `Sema`. Semantic analysis should always involve two functions: an `ActOnXXX` function that will be called directly from the parser, and a `BuildXXX` function that performs the actual semantic analysis and will (eventually!) build the AST node. It's fairly common for the `ActOnCXX` function to do very little (often just some minor translation from the parser's representation to `Sema`'s representation of the same thing), but the separation is still important: C++ template instantiation, for example, should always call the `BuildXXX` variant. Several notes on semantic analysis before we get into construction of the AST:

   - Your expression probably involves some types and some subexpressions. Make sure to fully check that those types, and the types of those subexpressions, meet your expectations. Add implicit conversions where necessary to make sure that all of the types line up exactly the way you want them. Write extensive tests to check that you're getting good diagnostics for mistakes and that you can use various forms of subexpressions with your expression.
   - When type-checking a type or subexpression, make sure to first check whether the type is "dependent" (`Type::isDependentType()`) or whether a subexpression is type-dependent (`Expr::isTypeDependent()`). If any of these return `true`, then you're inside a template and you can't do much type-checking now. That's normal, and your AST node (when you get there) will have to deal with this case. At this point, you can write tests that use your expression within templates, but don't try to instantiate the templates.
   - For each subexpression, be sure to call `Sema::CheckPlaceholderExpr()` to deal with "weird" expressions that don't behave well as subexpressions. Then, determine whether you need to perform lvalue-to-rvalue conversions (`Sema::DefaultLvalueConversions`) or the usual unary conversions (`Sema::UsualUnaryConversions`), for places where the subexpression is producing a value you intend to use.
   - Your `BuildXXX` function will probably just return `ExprError()` at this point, since you don't have an AST. That's perfectly fine, and shouldn't impact your testing.

3. Introduce an AST node for your new expression. This starts with declaring the node in `include/Basic/StmtNodes.td` and creating a new class for your expression in the appropriate `include/AST/Expr*.h` header. It's best to look at the class for a similar expression to get ideas, and there are some specific things to watch for:

   - If you need to allocate memory, use the `ASTContext` allocator to allocate memory. Never use raw `malloc` or `new`, and never hold any resources in an AST node, because the destructor of an AST node is never called.
   - Make sure that `getSourceRange()` covers the exact source range of your expression. This is needed for diagnostics and for IDE support.

- Make sure that `children()` visits all of the subexpressions. This is important for a number of features (e.g., IDE support, C++ variadic templates). If you have sub-types, you'll also need to visit those sub-types in `RecursiveASTVisitor`.
- Add printing support (`StmtPrinter.cpp`) for your expression.
- Add profiling support (`StmtProfile.cpp`) for your AST node, noting the distinguishing (non-source location) characteristics of an instance of your expression. Omitting this step will lead to hard-to-diagnose failures regarding matching of template declarations.
- Add serialization support (`ASTReaderStmt.cpp`, `ASTWriterStmt.cpp`) for your AST node.

4. Teach semantic analysis to build your AST node. At this point, you can wire up your `Sema::BuildXXX` function to actually create your AST. A few things to check at this point:
   - If your expression can construct a new C++ class or return a new Objective-C object, be sure to update and then call `Sema::MaybeBindToTemporary` for your just-created AST node to be sure that the object gets properly destructed. An easy way to test this is to return a C++ class with a private destructor: semantic analysis should flag an error here with the attempt to call the destructor.
   - Inspect the generated AST by printing it using `clang -cc1 -ast-print`, to make sure you're capturing all of the important information about how the AST was written.
   - Inspect the generated AST under `clang -cc1 -ast-dump` to verify that all of the types in the generated AST line up the way you want them. Remember that clients of the AST should never have to "think" to understand what's going on. For example, all implicit conversions should show up explicitly in the AST.
   - Write tests that use your expression as a subexpression of other, well-known expressions. Can you call a function using your expression as an argument? Can you use the ternary operator?
5. Teach code generation to create IR to your AST node. This step is the first (and only) that requires knowledge of LLVM IR. There are several things to keep in mind:
   - Code generation is separated into scalar/aggregate/complex and lvalue/rvalue paths, depending on what kind of result your expression produces. On occasion, this requires some careful factoring of code to avoid duplication.
   - `CodeGenFunction` contains functions `ConvertType` and `ConvertTypeForMem` that convert Clang's types (`clang::Type*` or `clang::QualType`) to LLVM types. Use the former for values, and the later for memory locations: test with the C++ "`bool`" type to check this. If you find that you are having to use LLVM bitcasts to make the subexpressions of your expression have the type that your expression expects, STOP! Go fix semantic analysis and the AST so that you don't need these bitcasts.
   - The `CodeGenFunction` class has a number of helper functions to make certain operations easy, such as generating code to produce an lvalue or an rvalue, or to initialize a memory location with a given value. Prefer to use these functions rather than directly writing loads and stores, because these functions take care of some of the tricky details for you (e.g., for exceptions).
   - If your expression requires some special behavior in the event of an exception, look at the `push*Cleanup` functions in `CodeGenFunction` to introduce a cleanup. You shouldn't have to deal with exception-handling directly.
   - Testing is extremely important in IR generation. Use `clang -cc1 -emit-llvm` and FileCheck to verify that you're generating the right IR.
6. Teach template instantiation how to cope with your AST node, which requires some fairly simple code:
   - Make sure that your expression's constructor properly computes the flags for type dependence (i.e., the type your expression produces can change from one instantiation to the next), value dependence (i.e., the constant value your expression produces can change from one instantiation to the next), instantiation dependence (i.e., a template parameter occurs anywhere in your expression), and whether your expression

contains a parameter pack (for variadic templates). Often, computing these flags just means combining the results from the various types and subexpressions.

- Add `TransformXXX` and `RebuildXXX` functions to the `TreeTransform` class template in `Sema`. `TransformXXX` should (recursively) transform all of the subexpressions and types within your expression, using `getDerived().TransformYYY`. If all of the subexpressions and types transform without error, it will then call the `RebuildXXX` function, which will in turn call `getSema().BuildXXX` to perform semantic analysis and build your expression.
- To test template instantiation, take those tests you wrote to make sure that you were type checking with type-dependent expressions and dependent types (from step #2) and instantiate those templates with various types, some of which type-check and some that don't, and test the error messages in each case.

7. There are some "extras" that make other features work better. It's worth handling these extras to give your expression complete integration into Clang:
   - Add code completion support for your expression in `SemaCodeComplete.cpp`.
   - If your expression has types in it, or has any "interesting" features other than subexpressions, extend libclang's `CursorVisitor` to provide proper visitation for your expression, enabling various IDE features such as syntax highlighting, cross-referencing, and so on. The `c-index-test` helper program can be used to test these features.

Driver Design & Internals

Introduction

This document describes the Clang driver. The purpose of this document is to describe both the motivation and design goals for the driver, as well as details of the internal implementation.

Features and Goals

The Clang driver is intended to be a production quality compiler driver providing access to the Clang compiler and tools, with a command line interface which is compatible with the gcc driver.

Although the driver is part of and driven by the Clang project, it is logically a separate tool which shares many of the same goals as Clang:

Features

GCC Compatibility

The number one goal of the driver is to ease the adoption of Clang by allowing users to drop Clang into a build system which was designed to call GCC. Although this makes the driver much more complicated than might otherwise be necessary, we decided that being very compatible with the gcc command line interface was worth it in order to allow users to quickly test clang on their projects.

Flexible

The driver was designed to be flexible and easily accommodate new uses as we grow the clang and LLVM infrastructure. As one example, the driver can easily support the introduction of tools which have an integrated assembler; something we hope to add to LLVM in the future.

Similarly, most of the driver functionality is kept in a library which can be used to build other tools which want to implement or accept a gcc like interface.

Low Overhead

The driver should have as little overhead as possible. In practice, we found that the gcc driver by itself incurred a small but meaningful overhead when compiling many small files. The driver doesn't do much work compared to a compilation, but we have tried to keep it as efficient as possible by following a few simple principles:

- Avoid memory allocation and string copying when possible.
- Don't parse arguments more than once.
- Provide a few simple interfaces for efficiently searching arguments.

Simple

Finally, the driver was designed to be "as simple as possible", given the other goals. Notably, trying to be completely compatible with the gcc driver adds a significant amount of complexity. However, the design of the driver attempts to mitigate this complexity by dividing the process into a number of independent stages instead of a single monolithic task.

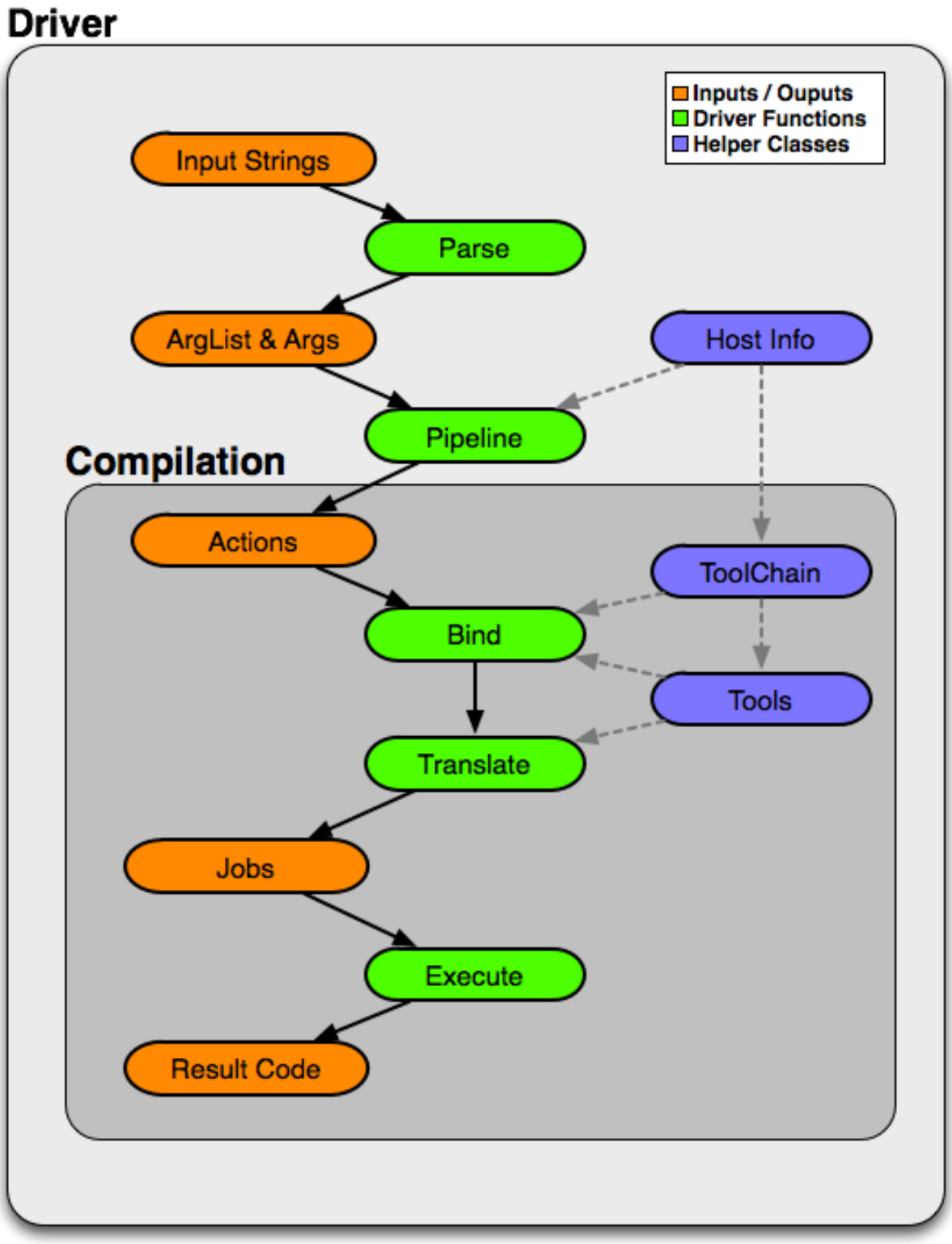
Internal Design and Implementation

Internals Introduction

In order to satisfy the stated goals, the driver was designed to completely subsume the functionality of the gcc executable; that is, the driver should not need to delegate to gcc to perform subtasks. On Darwin, this implies that the Clang driver also subsumes the gcc driver-driver, which is used to implement support for building universal images (binaries and object files). This also implies that the driver should be able to call the language specific compilers (e.g. cc1) directly, which means that it must have enough information to forward command line arguments to child processes correctly.

Design Overview

The diagram below shows the significant components of the driver architecture and how they relate to one another. The orange components represent concrete data structures built by the driver, the green components indicate conceptually distinct stages which manipulate these data structures, and the blue components are important helper classes.


Driver
Inputs / Ouputs
Driver Functions
Helper Classes
Input Strings
Parse
ArgList & Args
Host Info
Pipeline
Compilation
Actions
ToolChain
Bind
Tools
Translate
Jobs
Execute
Result Code

Driver Stages

The driver functionality is conceptually divided into five stages:

1. **Parse: Option Parsing**

   The command line argument strings are decomposed into arguments (`Arg` instances). The driver expects to understand all available options, although there is some facility for just passing certain classes of options through (like `-Wl,`).

   Each argument corresponds to exactly one abstract `Option` definition, which describes how the option is parsed along with some additional metadata. The Arg instances themselves are lightweight and merely contain enough information for clients to determine which option they correspond to and their values (if they have additional parameters).

   For example, a command line like "-Ifoo -I foo" would parse to two Arg instances (a JoinedArg and a SeparateArg instance), but each would refer to the same Option.

   Options are lazily created in order to avoid populating all Option classes when the driver is loaded. Most of the driver code only needs to deal with options by their unique ID (e.g., `options::OPT_I`),

   Arg instances themselves do not generally store the values of parameters. In many cases, this would simply result in creating unnecessary string copies. Instead, Arg instances are always embedded inside an ArgList structure, which contains the original vector of argument strings. Each Arg itself only needs to contain an index into this vector instead of storing its values directly.

   The clang driver can dump the results of this stage using the `-###` flag (which must precede any actual command line arguments). For example:

```
$ clang -### -Xarch_i386 -fomit-frame-pointer -Wa,-fast -Ifoo -I foo t.c
Option 0 - Name: "-Xarch_", Values: {"i386", "-fomit-frame-pointer"}
Option 1 - Name: "-Wa,", Values: {"-fast"}
Option 2 - Name: "-I", Values: {"foo"}
Option 3 - Name: "-I", Values: {"foo"}
Option 4 - Name: "<input>", Values: {"t.c"}
```

   After this stage is complete the command line should be broken down into well defined option objects with their appropriate parameters. Subsequent stages should rarely, if ever, need to do any string processing.

2. **Pipeline: Compilation Action Construction**

   Once the arguments are parsed, the tree of subprocess jobs needed for the desired compilation sequence are constructed. This involves determining the input files and their types, what work is to be done on them (preprocess, compile, assemble, link, etc.), and constructing a list of Action instances for each task. The result is a list of one or more top-level actions, each of which generally corresponds to a single output (for example, an object or linked executable).

   The majority of Actions correspond to actual tasks, however there are two special Actions. The first is InputAction, which simply serves to adapt an input argument for use as an input to other Actions. The second is BindArchAction, which conceptually alters the architecture to be used for all of its input Actions.

   The clang driver can dump the results of this stage using the `-ccc-print-phases` flag. For example:

```
$ clang -ccc-print-phases -x c t.c -x assembler t.s
0: input, "t.c", c
1: preprocessor, {0}, cpp-output
2: compiler, {1}, assembler
3: assembler, {2}, object
4: input, "t.s", assembler
5: assembler, {4}, object
6: linker, {3, 5}, image
```

Here the driver is constructing seven distinct actions, four to compile the "t.c" input into an object file, two to assemble the "t.s" input, and one to link them together.

A rather different compilation pipeline is shown here; in this example there are two top level actions to compile the input files into two separate object files, where each object file is built using `lipo` to merge results built for two separate architectures.

```
$ clang -ccc-print-phases -c -arch i386 -arch x86_64 t0.c t1.c
0: input, "t0.c", c
1: preprocessor, {0}, cpp-output
2: compiler, {1}, assembler
3: assembler, {2}, object
4: bind-arch, "i386", {3}, object
5: bind-arch, "x86_64", {3}, object
6: lipo, {4, 5}, object
7: input, "t1.c", c
8: preprocessor, {7}, cpp-output
9: compiler, {8}, assembler
10: assembler, {9}, object
11: bind-arch, "i386", {10}, object
12: bind-arch, "x86_64", {10}, object
13: lipo, {11, 12}, object
```

After this stage is complete the compilation process is divided into a simple set of actions which need to be performed to produce intermediate or final outputs (in some cases, like `-fsyntax-only`, there is no "real" final output). Phases are well known compilation steps, such as "preprocess", "compile", "assemble", "link", etc.

3. **Bind: Tool & Filename Selection**

   This stage (in conjunction with the Translate stage) turns the tree of Actions into a list of actual subprocess to run. Conceptually, the driver performs a top down matching to assign Action(s) to Tools. The ToolChain is responsible for selecting the tool to perform a particular action; once selected the driver interacts with the tool to see if it can match additional actions (for example, by having an integrated preprocessor).

   Once Tools have been selected for all actions, the driver determines how the tools should be connected (for example, using an inprocess module, pipes, temporary files, or user provided filenames). If an output file is required, the driver also computes the appropriate file name (the suffix and file location depend on the input types and options such as `-save-temps`).

   The driver interacts with a ToolChain to perform the Tool bindings. Each ToolChain contains information about all the tools needed for compilation for a particular architecture, platform, and operating system. A single driver invocation may query multiple ToolChains during one compilation in order to interact with tools for separate architectures.

   The results of this stage are not computed directly, but the driver can print the results via the `-ccc-print-bindings` option. For example:

```
$ clang -ccc-print-bindings -arch i386 -arch ppc t0.c
# "i386-apple-darwin9" - "clang", inputs: ["t0.c"], output: "/tmp/cc-Sn4RKF.s"
# "i386-apple-darwin9" - "darwin::Assemble", inputs: ["/tmp/cc-Sn4RKF.s"],␣
↪output: "/tmp/cc-gvSnbS.o"
# "i386-apple-darwin9" - "darwin::Link", inputs: ["/tmp/cc-gvSnbS.o"], output: "/
↪tmp/cc-jgHQxi.out"
# "ppc-apple-darwin9" - "gcc::Compile", inputs: ["t0.c"], output: "/tmp/cc-Q0bTox.
↪s"
# "ppc-apple-darwin9" - "gcc::Assemble", inputs: ["/tmp/cc-Q0bTox.s"], output: "/
↪tmp/cc-WCdicw.o"
```

```
# "ppc-apple-darwin9" - "gcc::Link", inputs: ["/tmp/cc-WCdicw.o"], output: "/tmp/
↪cc-HHBEBh.out"
# "i386-apple-darwin9" - "darwin::Lipo", inputs: ["/tmp/cc-jgHQxi.out", "/tmp/cc-
↪HHBEBh.out"], output: "a.out"
```

This shows the tool chain, tool, inputs and outputs which have been bound for this compilation sequence. Here clang is being used to compile t0.c on the i386 architecture and darwin specific versions of the tools are being used to assemble and link the result, but generic gcc versions of the tools are being used on PowerPC.

4. **Translate: Tool Specific Argument Translation**

   Once a Tool has been selected to perform a particular Action, the Tool must construct concrete Commands which will be executed during compilation. The main work is in translating from the gcc style command line options to whatever options the subprocess expects.

   Some tools, such as the assembler, only interact with a handful of arguments and just determine the path of the executable to call and pass on their input and output arguments. Others, like the compiler or the linker, may translate a large number of arguments in addition.

   The ArgList class provides a number of simple helper methods to assist with translating arguments; for example, to pass on only the last of arguments corresponding to some option, or all arguments for an option.

   The result of this stage is a list of Commands (executable paths and argument strings) to execute.

5. **Execute**

   Finally, the compilation pipeline is executed. This is mostly straightforward, although there is some interaction with options like `-pipe`, `-pass-exit-codes` and `-time`.

Additional Notes

The Compilation Object

The driver constructs a Compilation object for each set of command line arguments. The Driver itself is intended to be invariant during construction of a Compilation; an IDE should be able to construct a single long lived driver instance to use for an entire build, for example.

The Compilation object holds information that is particular to each compilation sequence. For example, the list of used temporary files (which must be removed once compilation is finished) and result files (which should be removed if compilation fails).

Unified Parsing & Pipelining

Parsing and pipelining both occur without reference to a Compilation instance. This is by design; the driver expects that both of these phases are platform neutral, with a few very well defined exceptions such as whether the platform uses a driver driver.

ToolChain Argument Translation

In order to match gcc very closely, the clang driver currently allows tool chains to perform their own translation of the argument list (into a new ArgList data structure). Although this allows the clang driver to match gcc easily, it also makes the driver operation much harder to understand (since the Tools stop seeing some arguments the user provided, and see new ones instead).

For example, on Darwin `-gfull` gets translated into two separate arguments, `-g` and `-fno-eliminate-unused-debug-symbols`. Trying to write Tool logic to do something with `-gfull` will not work, because Tool argument translation is done after the arguments have been translated.

A long term goal is to remove this tool chain specific translation, and instead force each tool to change its own logic to do the right thing on the untranslated original arguments.

Unused Argument Warnings

The driver operates by parsing all arguments but giving Tools the opportunity to choose which arguments to pass on. One downside of this infrastructure is that if the user misspells some option, or is confused about which options to use, some command line arguments the user really cared about may go unused. This problem is particularly important when using clang as a compiler, since the clang compiler does not support anywhere near all the options that gcc does, and we want to make sure users know which ones are being used.

To support this, the driver maintains a bit associated with each argument of whether it has been used (at all) during the compilation. This bit usually doesn't need to be set by hand, as the key ArgList accessors will set it automatically.

When a compilation is successful (there are no errors), the driver checks the bit and emits an "unused argument" warning for any arguments which were never accessed. This is conservative (the argument may not have been used to do what the user wanted) but still catches the most obvious cases.

Relation to GCC Driver Concepts

For those familiar with the gcc driver, this section provides a brief overview of how things from the gcc driver map to the clang driver.

- **Driver Driver**

  The driver driver is fully integrated into the clang driver. The driver simply constructs additional Actions to bind the architecture during the *Pipeline* phase. The tool chain specific argument translation is responsible for handling `-Xarch_`.

  The one caveat is that this approach requires `-Xarch_` not be used to alter the compilation itself (for example, one cannot provide `-S` as an `-Xarch_` argument). The driver attempts to reject such invocations, and overall there isn't a good reason to abuse `-Xarch_` to that end in practice.

  The upside is that the clang driver is more efficient and does little extra work to support universal builds. It also provides better error reporting and UI consistency.

- **Specs**

  The clang driver has no direct correspondent for "specs". The majority of the functionality that is embedded in specs is in the Tool specific argument translation routines. The parts of specs which control the compilation pipeline are generally part of the *Pipeline* stage.

- **Toolchains**

  The gcc driver has no direct understanding of tool chains. Each gcc binary roughly corresponds to the information which is embedded inside a single ToolChain.

  The clang driver is intended to be portable and support complex compilation environments. All platform and tool chain specific code should be protected behind either abstract or well defined interfaces (such as whether the platform supports use as a driver driver).

Pretokenized Headers (PTH)

This document first describes the low-level interface for using PTH and then briefly elaborates on its design and implementation. If you are interested in the end-user view, please see the *User's Manual*.

Using Pretokenized Headers with `clang` (Low-level Interface)

The Clang compiler frontend, `clang -cc1`, supports three command line options for generating and using PTH files.

To generate PTH files using `clang -cc1`, use the option `-emit-pth`:

```
$ clang -cc1 test.h -emit-pth -o test.h.pth
```

This option is transparently used by `clang` when generating PTH files. Similarly, PTH files can be used as prefix headers using the `-include-pth` option:

```
$ clang -cc1 -include-pth test.h.pth test.c -o test.s
```

Alternatively, Clang's PTH files can be used as a raw "token-cache" (or "content" cache) of the source included by the original header file. This means that the contents of the PTH file are searched as substitutes for *any* source files that are used by `clang -cc1` to process a source file. This is done by specifying the `-token-cache` option:

```
$ cat test.h
#include <stdio.h>
$ clang -cc1 -emit-pth test.h -o test.h.pth
$ cat test.c
#include "test.h"
$ clang -cc1 test.c -o test -token-cache test.h.pth
```

In this example the contents of `stdio.h` (and the files it includes) will be retrieved from `test.h.pth`, as the PTH file is being used in this case as a raw cache of the contents of `test.h`. This is a low-level interface used to both implement the high-level PTH interface as well as to provide alternative means to use PTH-style caching.

PTH Design and Implementation

Unlike GCC's precompiled headers, which cache the full ASTs and preprocessor state of a header file, Clang's pretokenized header files mainly cache the raw lexer *tokens* that are needed to segment the stream of characters in a source file into keywords, identifiers, and operators. Consequently, PTH serves to mainly directly speed up the lexing and preprocessing of a source file, while parsing and type-checking must be completely redone every time a PTH file is used.

Basic Design Tradeoffs

In the long term there are plans to provide an alternate PCH implementation for Clang that also caches the work for parsing and type checking the contents of header files. The current implementation of PCH in Clang as pretokenized header files was motivated by the following factors:

Language independence PTH files work with any language that Clang's lexer can handle, including C, Objective-C, and (in the early stages) C++. This means development on language features at the parsing level or above (which is basically almost all interesting pieces) does not require PTH to be modified.

Simple design Relatively speaking, PTH has a simple design and implementation, making it easy to test. Further, because the machinery for PTH resides at the lower-levels of the Clang library stack it is fairly straightforward to profile and optimize.

Further, compared to GCC's PCH implementation (which is the dominate precompiled header file implementation that Clang can be directly compared against) the PTH design in Clang yields several attractive features:

Architecture independence In contrast to GCC's PCH files (and those of several other compilers), Clang's PTH files are architecture independent, requiring only a single PTH file when building a program for multiple architectures.

For example, on Mac OS X one may wish to compile a "universal binary" that runs on PowerPC, 32-bit Intel (i386), and 64-bit Intel architectures. In contrast, GCC requires a PCH file for each architecture, as the definitions of types in the AST are architecture-specific. Since a Clang PTH file essentially represents a lexical cache of header files, a single PTH file can be safely used when compiling for multiple architectures. This can also reduce compile times because only a single PTH file needs to be generated during a build instead of several.

Reduced memory pressure Similar to GCC, Clang reads PTH files via the use of memory mapping (i.e., `mmap`). Clang, however, memory maps PTH files as read-only, meaning that multiple invocations of `clang -cc1` can share the same pages in memory from a memory-mapped PTH file. In comparison, GCC also memory maps its PCH files but also modifies those pages in memory, incurring the copy-on-write costs. The read-only nature of PTH can greatly reduce memory pressure for builds involving multiple cores, thus improving overall scalability.

Fast generation PTH files can be generated in a small fraction of the time needed to generate GCC's PCH files. Since PTH/PCH generation is a serial operation that typically blocks progress during a build, faster generation time leads to improved processor utilization with parallel builds on multicore machines.

Despite these strengths, PTH's simple design suffers some algorithmic handicaps compared to other PCH strategies such as those used by GCC. While PTH can greatly speed up the processing time of a header file, the amount of work required to process a header file is still roughly linear in the size of the header file. In contrast, the amount of work done by GCC to process a precompiled header is (theoretically) constant (the ASTs for the header are literally memory mapped into the compiler). This means that only the pieces of the header file that are referenced by the source file including the header are the only ones the compiler needs to process during actual compilation. While GCC's particular implementation of PCH mitigates some of these algorithmic strengths via the use of copy-on-write pages, the approach itself can fundamentally dominate at an algorithmic level, especially when one considers header files of arbitrary size.

There is also a PCH implementation for Clang based on the lazy deserialization of ASTs. This approach theoretically has the same constant-time algorithmic advantages just mentioned but also retains some of the strengths of PTH such as reduced memory pressure (ideal for multi-core builds).

Internal PTH Optimizations

While the main optimization employed by PTH is to reduce lexing time of header files by caching pre-lexed tokens, PTH also employs several other optimizations to speed up the processing of header files:

- `stat` caching: PTH files cache information obtained via calls to `stat` that `clang -cc1` uses to resolve which files are included by `#include` directives. This greatly reduces the overhead involved in context-switching to the kernel to resolve included files.
- Fast skipping of `#ifdef ... #endif` chains: PTH files record the basic structure of nested preprocessor blocks. When the condition of the preprocessor block is false, all of its tokens are immediately skipped instead of requiring them to be handled by Clang's preprocessor.

Precompiled Header and Modules Internals

This document describes the design and implementation of Clang's precompiled headers (PCH) and modules. If you are interested in the end-user view, please see the *User's Manual*.

Using Precompiled Headers with `clang`

The Clang compiler frontend, `clang -cc1`, supports two command line options for generating and using PCH files.

To generate PCH files using `clang -cc1`, use the option *-emit-pch*:

```
$ clang -cc1 test.h -emit-pch -o test.h.pch
```

This option is transparently used by `clang` when generating PCH files. The resulting PCH file contains the serialized form of the compiler's internal representation after it has completed parsing and semantic analysis. The PCH file can then be used as a prefix header with the *-include-pch* option:

```
$ clang -cc1 -include-pch test.h.pch test.c -o test.s
```

Design Philosophy

Precompiled headers are meant to improve overall compile times for projects, so the design of precompiled headers is entirely driven by performance concerns. The use case for precompiled headers is relatively simple: when there is a common set of headers that is included in nearly every source file in the project, we *precompile* that bundle of headers into a single precompiled header (PCH file). Then, when compiling the source files in the project, we load the PCH file first (as a prefix header), which acts as a stand-in for that bundle of headers.

A precompiled header implementation improves performance when:

- Loading the PCH file is significantly faster than re-parsing the bundle of headers stored within the PCH file. Thus, a precompiled header design attempts to minimize the cost of reading the PCH file. Ideally, this cost should not vary with the size of the precompiled header file.
- The cost of generating the PCH file initially is not so large that it counters the per-source-file performance improvement due to eliminating the need to parse the bundled headers in the first place. This is particularly important on multi-core systems, because PCH file generation serializes the build when all compilations require the PCH file to be up-to-date.

Modules, as implemented in Clang, use the same mechanisms as precompiled headers to save a serialized AST file (one per module) and use those AST modules. From an implementation standpoint, modules are a generalization of precompiled headers, lifting a number of restrictions placed on precompiled headers. In particular, there can only be one precompiled header and it must be included at the beginning of the translation unit. The extensions to the AST file format required for modules are discussed in the section on *modules*.

Clang's AST files are designed with a compact on-disk representation, which minimizes both creation time and the time required to initially load the AST file. The AST file itself contains a serialized representation of Clang's abstract syntax trees and supporting data structures, stored using the same compressed bitstream as LLVM's bitcode file format.

Clang's AST files are loaded "lazily" from disk. When an AST file is initially loaded, Clang reads only a small amount of data from the AST file to establish where certain important data structures are stored. The amount of data read in this initial load is independent of the size of the AST file, such that a larger AST file does not lead to longer AST load times. The actual header data in the AST file — macros, functions, variables, types, etc. — is loaded only when it is referenced from the user's code, at which point only that entity (and those entities it depends on) are deserialized from the AST file. With this approach, the cost of using an AST file for a translation unit is proportional to the amount of code actually used from the AST file, rather than being proportional to the size of the AST file itself.

When given the *-print-stats* option, Clang produces statistics describing how much of the AST file was actually loaded from disk. For a simple "Hello, World!" program that includes the Apple `Cocoa.h` header (which is built as a precompiled header), this option illustrates how little of the actual precompiled header is required:

```
*** AST File Statistics:
  895/39981 source location entries read (2.238563%)
  19/15315 types read (0.124061%)
  20/82685 declarations read (0.024188%)
  154/58070 identifiers read (0.265197%)
  0/7260 selectors read (0.000000%)
  0/30842 statements read (0.000000%)
  4/8400 macros read (0.047619%)
  1/4995 lexical declcontexts read (0.020020%)
  0/4413 visible declcontexts read (0.000000%)
  0/7230 method pool entries read (0.000000%)
  0 method pool misses
```

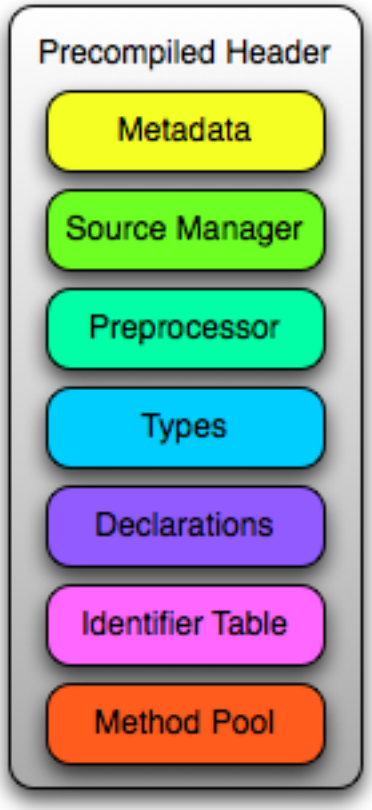
For this small program, only a tiny fraction of the source locations, types, declarations, identifiers, and macros were actually deserialized from the precompiled header. These statistics can be useful to determine whether the AST file implementation can be improved by making more of the implementation lazy.

Precompiled headers can be chained. When you create a PCH while including an existing PCH, Clang can create the new PCH by referencing the original file and only writing the new data to the new file. For example, you could create a PCH out of all the headers that are very commonly used throughout your project, and then create a PCH for every single source file in the project that includes the code that is specific to that file, so that recompiling the file itself is very fast, without duplicating the data from the common headers for every file. The mechanisms behind chained precompiled headers are discussed in a *later section*.

AST File Contents

An AST file produced by clang is an object file container with a `clangast` (COFF) or `__clangast` (ELF and Mach-O) section containing the serialized AST. Other target-specific sections in the object file container are used to hold debug information for the data types defined in the AST. Tools built on top of libclang that do not need debug information may also produce raw AST files that only contain the serialized AST.

The `clangast` section is organized into several different blocks, each of which contains the serialized representation of a part of Clang's internal representation. Each of the blocks corresponds to either a block or a record within LLVM's bitstream format. The contents of each of these logical blocks are described below.



The `llvm-objdump` utility provides a `-raw-clang-ast` option to extract the binary contents of the AST section from an object file container.

The llvm-bcanalyzer utility can be used to examine the actual structure of the bitstream for the AST section. This information can be used both to help understand the structure of the AST section and to isolate areas where the AST representation can still be optimized, e.g., through the introduction of abbreviations.

Metadata Block

The metadata block contains several records that provide information about how the AST file was built. This metadata is primarily used to validate the use of an AST file. For example, a precompiled header built for a 32-bit x86 target cannot be used when compiling for a 64-bit x86 target. The metadata block contains information about:

Language options Describes the particular language dialect used to compile the AST file, including major options (e.g., Objective-C support) and more minor options (e.g., support for "`//`" comments). The contents of this record correspond to the `LangOptions` class.

Target architecture The target triple that describes the architecture, platform, and ABI for which the AST file was generated, e.g., `i386-apple-darwin9`.

AST version The major and minor version numbers of the AST file format. Changes in the minor version number should not affect backward compatibility, while changes in the major version number imply that a newer compiler cannot read an older precompiled header (and vice-versa).

Original file name The full path of the header that was used to generate the AST file.

Predefines buffer Although not explicitly stored as part of the metadata, the predefines buffer is used in the validation of the AST file. The predefines buffer itself contains code generated by the compiler to initialize the preprocessor state according to the current target, platform, and command-line options. For example, the predefines buffer will contain "`#define __STDC__ 1`" when we are compiling C without Microsoft extensions. The predefines buffer itself is stored within the *Source Manager Block*, but its contents are verified along with the rest of the metadata.

A chained PCH file (that is, one that references another PCH) and a module (which may import other modules) have additional metadata containing the list of all AST files that this AST file depends on. Each of those files will be loaded along with this AST file.

For chained precompiled headers, the language options, target architecture and predefines buffer data is taken from the end of the chain, since they have to match anyway.

Source Manager Block

The source manager block contains the serialized representation of Clang's *SourceManager* class, which handles the mapping from source locations (as represented in Clang's abstract syntax tree) into actual column/line positions within a source file or macro instantiation. The AST file's representation of the source manager also includes information about all of the headers that were (transitively) included when building the AST file.

The bulk of the source manager block is dedicated to information about the various files, buffers, and macro instantiations into which a source location can refer. Each of these is referenced by a numeric "file ID", which is a unique number (allocated starting at 1) stored in the source location. Clang serializes the information for each kind of file ID, along with an index that maps file IDs to the position within the AST file where the information about that file ID is stored. The data associated with a file ID is loaded only when required by the front end, e.g., to emit a diagnostic that includes a macro instantiation history inside the header itself.

The source manager block also contains information about all of the headers that were included when building the AST file. This includes information about the controlling macro for the header (e.g., when the preprocessor identified that the contents of the header dependent on a macro like `LLVM_CLANG_SOURCEMANAGER_H`).

Preprocessor Block

The preprocessor block contains the serialized representation of the preprocessor. Specifically, it contains all of the macros that have been defined by the end of the header used to build the AST file, along with the token sequences that comprise each macro. The macro definitions are only read from the AST file when the name of the macro first occurs in the program. This lazy loading of macro definitions is triggered by lookups into the *identifier table*.

Types Block

The types block contains the serialized representation of all of the types referenced in the translation unit. Each Clang type node (`PointerType`, `FunctionProtoType`, etc.) has a corresponding record type in the AST file. When types are deserialized from the AST file, the data within the record is used to reconstruct the appropriate type node using the AST context.

Each type has a unique type ID, which is an integer that uniquely identifies that type. Type ID 0 represents the NULL type, type IDs less than `NUM_PREDEF_TYPE_IDS` represent predefined types (`void`, `float`, etc.), while other "user-defined" type IDs are assigned consecutively from `NUM_PREDEF_TYPE_IDS` upward as the types are encountered. The AST file has an associated mapping from the user-defined types block to the location within the types block where the serialized representation of that type resides, enabling lazy deserialization of types. When a type is referenced from within the AST file, that reference is encoded using the type ID shifted left by 3 bits. The lower three bits are used to represent the `const`, `volatile`, and `restrict` qualifiers, as in Clang's *QualType* class.

Declarations Block

The declarations block contains the serialized representation of all of the declarations referenced in the translation unit. Each Clang declaration node (`VarDecl`, `FunctionDecl`, etc.) has a corresponding record type in the AST file. When declarations are deserialized from the AST file, the data within the record is used to build and populate a new instance of the corresponding `Decl` node. As with types, each declaration node has a numeric ID that is used to refer to that declaration within the AST file. In addition, a lookup table provides a mapping from that numeric ID to the offset within the precompiled header where that declaration is described.

Declarations in Clang's abstract syntax trees are stored hierarchically. At the top of the hierarchy is the translation unit (`TranslationUnitDecl`), which contains all of the declarations in the translation unit but is not actually written as a specific declaration node. Its child declarations (such as functions or struct types) may also contain other declarations inside them, and so on. Within Clang, each declaration is stored within a *declaration context*, as represented by the `DeclContext` class. Declaration contexts provide the mechanism to perform name lookup within a given declaration (e.g., find the member named `x` in a structure) and iterate over the declarations stored within a context (e.g., iterate over all of the fields of a structure for structure layout).

In Clang's AST file format, deserializing a declaration that is a `DeclContext` is a separate operation from deserializing all of the declarations stored within that declaration context. Therefore, Clang will deserialize the translation unit declaration without deserializing the declarations within that translation unit. When required, the declarations stored within a declaration context will be deserialized. There are two representations of the declarations within a declaration context, which correspond to the name-lookup and iteration behavior described above:

- When the front end performs name lookup to find a name `x` within a given declaration context (for example, during semantic analysis of the expression `p->x`, where `p`'s type is defined in the precompiled header), Clang refers to an on-disk hash table that maps from the names within that declaration context to the declaration IDs that represent each visible declaration with that name. The actual declarations will then be deserialized to provide the results of name lookup.
- When the front end performs iteration over all of the declarations within a declaration context, all of those declarations are immediately de-serialized. For large declaration contexts (e.g., the translation unit), this operation is expensive; however, large declaration contexts are not traversed in normal compilation, since such a traversal is unnecessary. However, it is common for the code generator and semantic analysis to traverse declaration contexts for structs, classes, unions, and enumerations, although those contexts contain relatively few declarations in the common case.

Statements and Expressions

Statements and expressions are stored in the AST file in both the *types* and the *declarations* blocks, because every statement or expression will be associated with either a type or declaration. The actual statement and expression records are stored immediately following the declaration or type that owns the statement or expression. For example, the statement representing the body of a function will be stored directly following the declaration of the function.

As with types and declarations, each statement and expression kind in Clang's abstract syntax tree (`ForStmt`, `CallExpr`, etc.) has a corresponding record type in the AST file, which contains the serialized representation of that statement or expression. Each substatement or subexpression within an expression is stored as a separate record

(which keeps most records to a fixed size). Within the AST file, the subexpressions of an expression are stored, in reverse order, prior to the expression that owns those expression, using a form of Reverse Polish Notation. For example, an expression `3 - 4 + 5` would be represented as follows:

`IntegerLiteral(5)`
`IntegerLiteral(4)`
`IntegerLiteral(3)`
`IntegerLiteral(-)`
`IntegerLiteral(+)`
`STOP`

When reading this representation, Clang evaluates each expression record it encounters, builds the appropriate abstract syntax tree node, and then pushes that expression on to a stack. When a record contains *N* subexpressions — `BinaryOperator` has two of them — those expressions are popped from the top of the stack. The special STOP code indicates that we have reached the end of a serialized expression or statement; other expression or statement records may follow, but they are part of a different expression.

Identifier Table Block

The identifier table block contains an on-disk hash table that maps each identifier mentioned within the AST file to the serialized representation of the identifier's information (e.g, the `IdentifierInfo` structure). The serialized representation contains:

- The actual identifier string.
- Flags that describe whether this identifier is the name of a built-in, a poisoned identifier, an extension token, or a macro.
- If the identifier names a macro, the offset of the macro definition within the *Preprocessor Block*.
- If the identifier names one or more declarations visible from translation unit scope, the *declaration IDs* of these declarations.

When an AST file is loaded, the AST file reader mechanism introduces itself into the identifier table as an external lookup source. Thus, when the user program refers to an identifier that has not yet been seen, Clang will perform a lookup into the identifier table. If an identifier is found, its contents (macro definitions, flags, top-level declarations, etc.) will be deserialized, at which point the corresponding `IdentifierInfo` structure will have the same contents it would have after parsing the headers in the AST file.

Within the AST file, the identifiers used to name declarations are represented with an integral value. A separate table provides a mapping from this integral value (the identifier ID) to the location within the on-disk hash table where that identifier is stored. This mapping is used when deserializing the name of a declaration, the identifier of a token, or any other construct in the AST file that refers to a name.

Method Pool Block

The method pool block is represented as an on-disk hash table that serves two purposes: it provides a mapping from the names of Objective-C selectors to the set of Objective-C instance and class methods that have that particular selector (which is required for semantic analysis in Objective-C) and also stores all of the selectors used by entities within the AST file. The design of the method pool is similar to that of the *identifier table*: the first time a particular selector is formed during the compilation of the program, Clang will search in the on-disk hash table of selectors; if found, Clang will read the Objective-C methods associated with that selector into the appropriate front-end data structure (`Sema::InstanceMethodPool` and `Sema::FactoryMethodPool` for instance and class methods, respectively).

As with identifiers, selectors are represented by numeric values within the AST file. A separate index maps these numeric selector values to the offset of the selector within the on-disk hash table, and will be used when de-serializing an Objective-C method declaration (or other Objective-C construct) that refers to the selector.

AST Reader Integration Points

The "lazy" deserialization behavior of AST files requires their integration into several completely different submodules of Clang. For example, lazily deserializing the declarations during name lookup requires that the name-lookup routines be able to query the AST file to find entities stored there.

For each Clang data structure that requires direct interaction with the AST reader logic, there is an abstract class that provides the interface between the two modules. The `ASTReader` class, which handles the loading of an AST file, inherits from all of these abstract classes to provide lazy deserialization of Clang's data structures. `ASTReader` implements the following abstract classes:

`ExternalSLocEntrySource` This abstract interface is associated with the `SourceManager` class, and is used whenever the *source manager* needs to load the details of a file, buffer, or macro instantiation.

`IdentifierInfoLookup` This abstract interface is associated with the `IdentifierTable` class, and is used whenever the program source refers to an identifier that has not yet been seen. In this case, the AST reader searches for this identifier within its *identifier table* to load any top-level declarations or macros associated with that identifier.

`ExternalASTSource` This abstract interface is associated with the `ASTContext` class, and is used whenever the abstract syntax tree nodes need to loaded from the AST file. It provides the ability to de-serialize declarations and types identified by their numeric values, read the bodies of functions when required, and read the declarations stored within a declaration context (either for iteration or for name lookup).

`ExternalSemaSource` This abstract interface is associated with the `Sema` class, and is used whenever semantic analysis needs to read information from the *global method pool*.

Chained precompiled headers

Chained precompiled headers were initially intended to improve the performance of IDE-centric operations such as syntax highlighting and code completion while a particular source file is being edited by the user. To minimize the amount of reparsing required after a change to the file, a form of precompiled header — called a precompiled *preamble* — is automatically generated by parsing all of the headers in the source file, up to and including the last `#include`. When only the source file changes (and none of the headers it depends on), reparsing of that source file can use the precompiled preamble and start parsing after the `#includes`, so parsing time is proportional to the size of the source file (rather than all of its includes). However, the compilation of that translation unit may already use a precompiled header: in this case, Clang will create the precompiled preamble as a chained precompiled header that refers to the original precompiled header. This drastically reduces the time needed to serialize the precompiled preamble for use in reparsing.

Chained precompiled headers get their name because each precompiled header can depend on one other precompiled header, forming a chain of dependencies. A translation unit will then include the precompiled header that starts the chain (i.e., nothing depends on it). This linearity of dependencies is important for the semantic model of chained precompiled headers, because the most-recent precompiled header can provide information that overrides the information provided by the precompiled headers it depends on, just like a header file `B.h` that includes another header `A.h` can modify the state produced by parsing `A.h`, e.g., by `#undef`'ing a macro defined in `A.h`.

There are several ways in which chained precompiled headers generalize the AST file model:

Numbering of IDs Many different kinds of entities — identifiers, declarations, types, etc. — have ID numbers that start at 1 or some other predefined constant and grow upward. Each precompiled header records the maximum ID number it has assigned in each category. Then, when a new precompiled header is generated that depends

on (chains to) another precompiled header, it will start counting at the next available ID number. This way, one can determine, given an ID number, which AST file actually contains the entity.

Name lookup When writing a chained precompiled header, Clang attempts to write only information that has changed from the precompiled header on which it is based. This changes the lookup algorithm for the various tables, such as the *identifier table*: the search starts at the most-recent precompiled header. If no entry is found, lookup then proceeds to the identifier table in the precompiled header it depends on, and so one. Once a lookup succeeds, that result is considered definitive, overriding any results from earlier precompiled headers.

Update records There are various ways in which a later precompiled header can modify the entities described in an earlier precompiled header. For example, later precompiled headers can add entries into the various name-lookup tables for the translation unit or namespaces, or add new categories to an Objective-C class. Each of these updates is captured in an "update record" that is stored in the chained precompiled header file and will be loaded along with the original entity.

Modules

Modules generalize the chained precompiled header model yet further, from a linear chain of precompiled headers to an arbitrary directed acyclic graph (DAG) of AST files. All of the same techniques used to make chained precompiled headers work — ID number, name lookup, update records — are shared with modules. However, the DAG nature of modules introduce a number of additional complications to the model:

Numbering of IDs The simple, linear numbering scheme used in chained precompiled headers falls apart with the module DAG, because different modules may end up with different numbering schemes for entities they imported from common shared modules. To account for this, each module file provides information about which modules it depends on and which ID numbers it assigned to the entities in those modules, as well as which ID numbers it took for its own new entities. The AST reader then maps these "local" ID numbers into a "global" ID number space for the current translation unit, providing a 1-1 mapping between entities (in whatever AST file they inhabit) and global ID numbers. If that translation unit is then serialized into an AST file, this mapping will be stored for use when the AST file is imported.

Declaration merging It is possible for a given entity (from the language's perspective) to be declared multiple times in different places. For example, two different headers can have the declaration of `printf` or could forward-declare `struct stat`. If each of those headers is included in a module, and some third party imports both of those modules, there is a potentially serious problem: name lookup for `printf` or `struct stat` will find both declarations, but the AST nodes are unrelated. This would result in a compilation error, due to an ambiguity in name lookup. Therefore, the AST reader performs declaration merging according to the appropriate language semantics, ensuring that the two disjoint declarations are merged into a single redeclaration chain (with a common canonical declaration), so that it is as if one of the headers had been included before the other.

Name Visibility Modules allow certain names that occur during module creation to be "hidden", so that they are not part of the public interface of the module and are not visible to its clients. The AST reader maintains a "visible" bit on various AST nodes (declarations, macros, etc.) to indicate whether that particular AST node is currently visible; the various name lookup mechanisms in Clang inspect the visible bit to determine whether that entity, which is still in the AST (because other, visible AST nodes may depend on it), can actually be found by name lookup. When a new (sub)module is imported, it may make existing, non-visible, already-deserialized AST nodes visible; it is the responsibility of the AST reader to find and update these AST nodes when it is notified of the import.

ABI tags

Introduction

This text tries to describe gcc semantic for mangling "abi_tag" attributes described in https://gcc.gnu.org/onlinedocs/gcc/C_002b_002b-Attributes.html

There is no guarantee the following rules are correct, complete or make sense in any way as they were determined empirically by experiments with gcc5.

Declaration

ABI tags are declared in an abi_tag attribute and can be applied to a function, variable, class or inline namespace declaration. The attribute takes one or more strings (called tags); the order does not matter.

See https://gcc.gnu.org/onlinedocs/gcc/C_002b_002b-Attributes.html for details.

Tags on an inline namespace are called "implicit tags", all other tags are "explicit tags".

Mangling

All tags that are "active" on an <unqualified-name> are emitted after the <unqualified-name>, before <template-args> or <discriminator>, and are part of the same <substitution> the <unqualified-name> is.

They are mangled as:

```
<abi-tags> ::= <abi-tag>*   # sort by name
<abi-tag> ::= B <tag source-name>
```

Example:

```
__attribute__((abi_tag("test")))
void Func();
// gets mangled as: _Z4FuncB4testv (prettified as `Func[abi:test]()`)
```

Active tags

A namespace does not have any active tags. For types (class / struct / union / enum), the explicit tags are the active tags.

For variables and functions, the active tags are the explicit tags plus any "required tags" which are not in the "available tags" set:

```
derived-tags := (required-tags - available-tags)
active-tags := explicit-tags + derived-tags
```

Required tags for a function

If a function is used as a local scope for another name, and is part of another function as local scope, it doesn't have any required tags.

If a function is used as a local scope for a guard variable name, it doesn't have any required tags.

Otherwise the function requires any implicit or explicit tag used in the name for the return type.

Example:

```
namespace A {
  inline namespace B __attribute__((abi_tag)) {
    struct C { int x; };
  }
}

A::C foo(); // gets mangled as: _Z3fooB1Bv (prettified as `foo[abi:B]()`)
```

Required tags for a variable

A variable requires any implicit or explicit tag used in its type.

Available tags

All tags used in the prefix and in the template arguments for a name are available. Also, for functions, all tags from the <bare-function-type> (which might include the return type for template functions) are available.

For <local-name>s all active tags used in the local part (<function- encoding>) are available, but not implicit tags which were not active.

Implicit and explicit tags used in the <unqualified-name> for a function (as in the type of a cast operator) are NOT available.

Example: a cast operator to std::string (which is std::__cxx11::basic_string<...>) will use 'cxx11' as an active tag, as it is required from the return type *std::string* but not available.

CHAPTER 8

Indices and tables

- genindex
- modindex
- search

Index

Symbols

C

E

N