Modern C++ Programming

12. C++ Ecosystem

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Table of Context

Table of Context

Table of Context

Table of Context

11 Other Tools

- Code Formatting - `clang-format`
- `Compiler Explorer`
- Code Transformation - `CppInsights`
- Code Autocompletion - `TabNine`, `Kite`
- Local Code Search - `ripgrep`
- Code Search Engine - `searchcode`, `grep.app`
- Code Exploration - `SourceTrail`
- Code Benchmarking - `Quick-Bench`
- Font for Coding

Debugging

Is this a bug?

```
for (int i = 0; i <= (2^32) - 1; i++) {


}
```

from: John Regehr (on Twitter)

A **program error** is a set of conditions that produce an *incorrect result* or *unexpected behavior*

We can distinguish between two kind of errors:

Recoverable *Conditions that are not under the control of the program*. They indicates *"exceptional"* run-time conditions. e.g. file not found, bad allocation, wrong user input, etc.

Unrecoverable *It is a synonym of a bug*. The program must terminate. e.g. out-of-bound, division by zero, etc.

Unrecoverable errors cannot be handled. They should be prevented by using *assertion* for ensuring *pre-conditions* and *post-conditions*

An **assertion** is a statement to detect a violated assumption. An assertion represents an *invariant* in the code

It can happen both at *run-time* (`assert`) and *compile-time* (`static_assert`). Run-time assertion failures should never be exposed in the normal program execution (e.g. release/public)

Assertion

```cpp
#include <cassert>    // <-- needed for "assert"
#include <cmath>      // std::is_finite
#include <type_traits> // std::is_arithmetic_v

template<typename T>
T sqrt(T value) {
    static_assert(std::is_arithmetic_v<T>,        // precondition
                  "T must be an arithmetic type");
    assert(std::is_finite(value) && value >= 0); // precondition
    int ret = ...                                 // sqrt computation
    assert(std::is_finite(value) && ret >= 0 &&  // postcondition
           (ret == 0 || ret == 1 || ret < value));
    return ret;
}
```

Assertions may slow down the execution. They can be disable by define the `NDEBUG` macro

```cpp
#define NDEBUG // or with the flag "-DNDEBUG"
```

Execution Debugging (gdb)

How to compile and run for debugging:

```
g++ -g [-ggdb3] <program.cpp> -o program
gdb [--args] ./program <args...>
```

-g Enable debugging
  - stores the *symbol table information* in the executable (mapping between assembly and source code lines)
  - for some compilers, it may disable certain optimizations
  - slow down the compilation phase

-ggdb3 Produces debugging information specifically intended for gdb
  - the last number produces extra debugging information, for example: including macro definitions
  - in general, it is not portable across different compiler (supported by gcc, clang)

gdb - **Breakpoints/Watchpoints**

Command	Abbr.	Description
`breakpoint` *<file>*:*<line>*	b	insert a breakpoint in a specific line
`breakpoint` *<function_name>*	b	insert a breakpoint in a specific function
`breakpoint` *<ref>* `if` *<condition>*	b	insert a breakpoint with a conditional statement
`delete`	d	delete all breakpoints or watchpoints
`delete` *<breakpoint_number>*		delete a specific breakpoint
`clear` [*function_name/line_number*]		delete a specific breakpoint
`enable/disable` *<breakpoint_number>*		enable/disable a specific breakpoint
`watch` *<expression>*		stop execution when the value of `expression` changes (variable, comparison, etc.)

gdb - **Control Flow**

Command	Abbr.		Description
run [args]	r		run the program
continue	c		continue the execution
finish	f		continue until the end of the current function
step	s		execute next line of code (follow function calls)
next	n		execute next line of code
until *<program_point>*			continue until reach line number, function name, address, etc.
CTRL+C			stop the execution (not quit)
quit	q		exit
help [*<command>*]	h		show help about command

gdb - **Stack and Info**

Command	Abbr.	Description
`list`	`l`	print code
`list` *<function or #start,#end>*	`l`	print function/range code
`up`	`u`	move up in the call stack
`down`	`d`	move down in the call stack
`backtrace`	`bt`	prints stack backtrace (call stack)
`backtrace` *<full>*	`bt`	print values of local variables
`info` *<args/locals/variables>*		print current function arguments/local variables/all variables
`info` *<breakpoints/watchpoints/registers>*		show information about program breakpoints/watchpoints/registers

gdb - **Print**

Command	Abbr.	Description
print <variable>	p	print variable
print/h <variable>	p/h	print variable in hex
print/**n**b <variable>	p/**n**b	print variable in binary (**n** bytes)
print/w <address>	p/w	print address in binary
p /s <char array/address>		print char array
p *array_var@**n**		print **n** array elements
p (int[4])<address>		print four elements of type int
p *(char**)&<std::string>		print std::string

gdb - **Disassemble**

Command	Description
`disasseble` <*function_name*>	disassemble a specified function
`disasseble` <0xStart,0xEnd addr>	disassemble function range
`nexti` <*variable*>	execute next line of code (follow function calls)
`stepi` <*variable*>	execute next line of code
`x`/`nfu` <*address*>	examine address n number of elements, f format (**d**: int, **f**: float, etc.), u data size (**b**: byte, **w**: word, etc.)

gdb - **Notes**

The debugger automatically stops when:

- breakpoint (by using the debugger)
- assertion fail
- segmentation fault
- trigger software breakpoint (e.g. SIGTRAP on Linux)
  github.com/scottt/debugbreak

Full story: www.yolinux.com/TUTORIALS/GDB-Commands.html (it also contains a script to *de-referencing* STL Containers)

gdb reference card V5 link

Memory Debugging

"70% of all the vulnerabilities in Microsoft products are memory safety issues"

Matt Miller, Microsoft Security Engineer

"Chrome: 70% of all security bugs are memory safety issues"

Chromium Security Report

Microsoft: 70% of all security bugs are memory safety issues
Chrome: 70% of all security bugs are memory safety issues

Terms like *buffer overflow*, *race condition*, *page fault*, *null pointer*, *stack exhaustion*, *heap exhaustion/corruption*, *use-after-free*, or *double free* – all describe **memory safety vulnerabilities**

Solutions:

- Run-time check
- Static analysis
- Avoid unsafe language constructs

valgrind is a tool suite to automatically detect many memory management and threading bugs

How to install the last version:

```
$ wget ftp://sourceware.org/pub/valgrind/valgrind-3.18.1.tar.bz2
$ tar xf valgrind-3.18.1.tar.bz2
$ cd valgrind-3.18.1
$ ./configure --enable-lto
$ make -j 12
$ sudo make install
$ sudo apt install libc6-dbg #if needed
```

some linux distributions provide the package through `apt install valgrid`, but it could be an old version

Basic usage:

- compile with `-g`

  - ```
    $ valgrind ./program <args...>
    ```

Output example 1:

```
==60127== Invalid read of size 4                    !!out-of-bound access
==60127==    at 0x100000D9E: f(int) (test01.C:86)
==60127==    by 0x100000C22: main (test01.C:40)
==60127==  Address 0x10042c148 is 0 bytes after a block of size 40 alloc'd
==60127==    at 0x1000161EF: malloc (vg_replace_malloc.c:236)
==60127==    by 0x100000C88: f(int) (test01.C:75)
==60127==    by 0x100000C22: main (test01.C:40)
```

Output example 2:

```
!!memory leak
==19182== 40 bytes in 1 blocks are definitely lost in loss record 1 of 1
==19182==    at 0x1B8FF5CD: malloc (vg_replace_malloc.c:130)
==19182==    by 0x8048385: f (a.c:5)
==19182==    by 0x80483AB: main (a.c:11)


==60127== HEAP SUMMARY:
==60127==     in use at exit: 4,184 bytes in 2 blocks
==60127==   total heap usage: 3 allocs, 1 frees, 4,224 bytes allocated
==60127==
==60127== LEAK SUMMARY:
==60127==    definitely lost: 128 bytes in 1 blocks       !!memory leak
==60127==    indirectly lost: 0 bytes in 0 blocks
==60127==      possibly lost: 0 bytes in 0 blocks
==60127==    still reachable: 4,184 bytes in 2 blocks  !!not deallocated
==60127==         suppressed: 0 bytes in 0 blocks
```

Memory leaks are divided into four categories:

- *Definitely lost*
- *Indirectly lost*
- *Still reachable*
- *Possibly lost*

When a program terminates, it releases all heap memory allocations. Despite this, leaving memory leaks is considered a *bad practice* and *makes the program unsafe* with respect to multiple internal iterations of a functionality. If a program has memory leaks for a single iteration, is it safe for multiple iterations?

A **robust program** prevents any memory leak even when abnormal conditions occur

Definitely lost indicates blocks that are *not deleted at the end of the program* (return from the `main()` function). The common case is local variables pointing to newly allocated heap memory

```
void f() {
    int* y = new int[3];  // 12 bytes definitely lost
}

int main() {
    int* x = new int[10]; // 40 bytes definitely lost
    f();
}
```

Indirectly lost indicates blocks pointed by other heap variables that are not deleted.
The common case is global variables pointing to newly allocated heap memory

```
struct A {
    int* array;
};

int main() {
    A* x    = new A;      //  8 bytes definitely lost
    x->array = new int[4]; // 16 bytes indirectly lost
}
```

Still reachable indicates blocks that are *not deleted but they are still reachable at the end of the program*

```
int* array;
int main() {
    array = new int[3];
}
// 12 bytes still reachable (global static class could delete it)
```

```
#include <cstdlib>
int main() {
    int* array = new int[3];
    std::abort();
    // 12 bytes still reachable
    ... // maybe it is delete here
}
```

Possibly lost indicates blocks that are still reachable but pointer arithmetic makes the deletion more complex, or even not possible

```cpp
#include <cstdlib>
int main() {
    int* array = new int[3];
    array++;
    std::abort();
    // 12 bytes still reachable
    ... // maybe it is delete here but you should be able
        // to revert pointer arithmetic
}
```

Advanced flags:

- `--leak-check=full` print details for each "definitely lost" or "possibly lost" block, including where it was allocated

- `--show-leak-kinds=all` to combine with --leak-check=full. Print all leak kinds

- `--track-fds=yes` list open file descriptors on exit (not closed)

- `--track-origins=yes` tracks the origin of uninitialized values (very slow execution)

```
valgrind --leak-check=full --show-leak-kinds=all
         --track-fds=yes --track-origins=yes ./program <args...>
```

Track stack usage:

```
valgrind --tool=drd --show-stack-usage=yes ./program <args...>
```

Compile-time stack size check:

- `-Wstack-usage=<byte-size>` Warn if the stack usage of a function might exceed byte-size. The computation done to determine the stack usage is conservative (no VLA)

- `-fstack-usage` Makes the compiler output stack usage information for the program, on a per-function basis

- `-Wvla` Warn if a variable-length array is used in the code

- `-Wvla-larger-than=<byte-size>` Warn for declarations of variable-length arrays whose size is either unbounded, or bounded by an argument that allows the array size to exceed byte-size bytes

Run-time detection of stack buffer overflows

Adding `_FORTIFY_SOURCE` define, the compiler provides buffer overflow checks for the following functions:

`memcpy` , `mempcpy` , `memmove` , `memset` , `strcpy` , `stpcpy` , `strncpy` , `strcat` , `strncat` , `sprintf` , `vsprintf` , `snprintf` , `vsnprintf` , `gets` .

```cpp
#include <cstring> // std::memset
#include <string>  // std::stoi
int main(int argc, char** argv) {
    int  size = std::stoi(argv[1]);
    char buffer[24];
    std::memset(buffer, 0xFF, size);
}
```

```
$ gcc -O1 -D_FORTIFY_SOURCE program.cpp -o program
$ ./program 12 # OK
$ ./program 32 # Wrong
$ *** buffer overflow detected ***: ./program terminated
```

Sanitizers

Address Sanitizer

Sanitizers are compiler-based instrumentation components to perform *dynamic* analysis

Sanitizer are used during development and testing to discover and diagnose memory misuse bugs and potentially dangerous undefined behavior

Sanitizer are implemented in `Clang` (from 3.1), `gcc` (from 4.8) and `Xcode`

Project using Sanitizers:
- Chromium
- Firefox
- Linux kernel
- Android

Address Sanitizer

<u>Address Sanitizer</u> is a memory error detector

- heap/*stack*/*global* out-of-bounds
- memory leaks
- use-after-free, use-after-return, use-after-scope
- double-free, invalid free
- initialization order bugs
- * Similar to `valgrind` but faster (50X slowdown)

```
clang++ -O1 -g -fsanitize=address -fno-omit-frame-pointer <program>
```

`-O1`   disable inlining

`-g`   generate symbol table

- clang.llvm.org/docs/AddressSanitizer.html
- github.com/google/sanitizers/wiki/AddressSanitizer
- gcc.gnu.org/onlinedocs/gcc/Instrumentation-Options.html

Leak Sanitizer

<u>LeakSanitizer</u> is a run-time *memory leak* detector

- integrated into AddressSanitizer, can be used as standalone tool
- * almost no performance overhead until the very end of the process

```
g++     -O1 -g -fsanitize=address -fno-omit-frame-pointer <program>
clang++ -O1 -g -fsanitize=leak -fno-omit-frame-pointer <program>
```

- clang.llvm.org/docs/LeakSanitizer.html
- github.com/google/sanitizers/wiki/AddressSanitizerLeakSanitizer
- gcc.gnu.org/onlinedocs/gcc/Instrumentation-Options.html

Memory Sanitizers

`Memory Sanitizer` is detector of *uninitialized* reads

- stack/heap-allocated memory read before it is written
- * Similar to `valgrind` but faster (3X slowdown)

```
clang++ -O1 -g -fsanitize=memory -fno-omit-frame-pointer <program>
```

`-fsanitize-memory-track-origins=2`
  track origins of uninitialized values

Note: not compatible with Address Sanitizer

- `clang.llvm.org/docs/MemorySanitizer.html`
- `github.com/google/sanitizers/wiki/MemorySanitizer`
- `gcc.gnu.org/onlinedocs/gcc/Instrumentation-Options.html`

Undefined Behavior Sanitizer

UndefinedBehaviorSanitizer is a *undefined behavior* detector

- signed integer overflow, floating-point types overflow, enumerated not in range
- out-of-bounds array indexing, misaligned address
- divide by zero
- etc.
* Not included in valgrind

```
clang++ -O1 -g -fsanitize=undefined -fno-omit-frame-pointer <program>
```
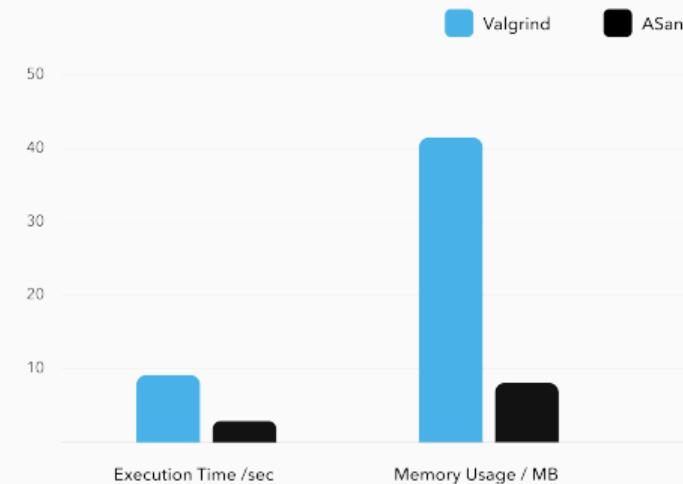
-fsanitize=integer	Checks for undefined or suspicious integer behavior (e.g. unsigned integer overflow)
-fsanitize=nullability	Checks passing null as a function parameter, assigning null to an lvalue, and returning null from a function

---

- clang.llvm.org/docs/UndefinedBehaviorSanitizer.html
- gcc.gnu.org/onlinedocs/gcc/Instrumentation-Options.html

Sanitizers vs. Valgrind

Bug	Valgrind detection	ASan detection
Uninitialized memory read	Yes	No *
Write overflow on heap	Yes	Yes
Write overflow on stack	No	Yes
Read overflow on heap	Yes	Yes
Read underflow on heap	Yes	Yes
Read overflow on stack	No	Yes
Use-after-free	Yes	Yes
Use-after-return	No	Yes
Double-free	Yes	Yes
Memory leak	Yes	Yes
Undefined behavior	No	No **

Valgrind — A neglected tool from the shadows or a serious debugging tool?

Debugging Summary

How to Debug Common Errors

Segmentation fault

- gdb
- valgrind
- Segmentation fault when just entered in a function $\rightarrow$ stack overflow

Double free or corruption

- gdb
- valgrind

Infinite execution

- gdb + (CTRL + C)

Incorrect results

- valgrind + assertion + gdb + UndefinedBehaviorSanitizer

Demangling

Name mangling is a technique used to solve various problems caused by the need to resolve unique names

Transforming C++ ABI (Application binary interface) identifiers into the original source identifiers is called **demangling**

Example (linking error):

```
_ZNSt13basic_filebufIcSt11char_traitsIcEED1Ev
```

After demangling:

```
std::basic_filebuf<char, std::char_traits<char> >::~basic_filebuf()
```

How to demangle:

- ```
  make |& c++filt | grep -P '`.*(?=))'
  ```

- Online Demangler: https://demangler.com

Code Checking and Analysis

Compiler Warnings

Enable specific warnings:

```
g++ -W<warning> <args...>
```

Disable specific warnings:

```
g++ -Wno-<warning> <args...>
```

Common warning flags to minimize accidental mismatches:

- `-Wall` Enables many standard warnings (∼50 warnings)

- `-Wextra` Enables some extra warning flags that are not enabled by `-Wall` (∼15 warnings)

- `-Wpedantic` Issue all the warnings demanded by strict ISO C/C++

Enable ALL warnings (only clang) `-Weverything`

GCC Warnings

Additional GCC warning flags ($\geq$ 5.0):

```
-Wcast-align
-Wcast-qual
-Wconversion
#  -Wfloat-conversion
#  -Wsign-conversion
-Wdate-time
-Wdouble-promotion
-Weffc++
#  -Wdelete-non-virtual-dtor
#  -Wnon-virtual-dtor
-Wformat-signedness
-Winvalid-pch
-Wlogical-op
-Wmissing-declarations
-Wmissing-include-dirs
-Wodr
```

```
-Wold-style-cast
-Wpragmas
-Wredundant-decls
-Wshadow
-Wsign-promo*
-Wstrict-aliasing
-Wstrict-overflow=1   #  5
-Wswitch-bool
#  -Wswitch-default
#  -Wswitch-enum
-Wtrampolines
-Wunused-macros
-Wuseless-cast
-Wvla
-Wformat=2
-Wno-long-long
```

- gcc.gnu.org/onlinedocs/gcc/Warning-Options.html

Static Analyzers - `clang static analyzer`

The `Clang Static Analyzer` is a source code analysis tool that finds bugs in C/C++ programs at compile-time

It find bugs by reasoning about the semantics of code (may produce false positives)

Example:

```
void test() {
    int i, a[10];
    int x = a[i]; // warning: array subscript is undefined
}
```

How to use:

```
scan-build make
```

scan-build is included in the LLVM suite

Static Analyzers - `cppcheck`

The `GCC Static Analyzer` can diagnose various kinds of problems in C/C++ code at compile-time (e.g. double-free, use-after-free, stdio related, etc) `-fanalyzer`

`cppcheck` provides code analysis to detect bugs, undefined behavior and dangerous coding construct. The goal is to detect only real errors in the code (i.e. have very few false positives)

```
cppcheck --enable=warning,performance,style,portability,information,error
         <src_file/directory>
```
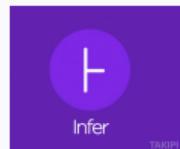
```
cmake -DCMAKE_EXPORT_COMPILE_COMMANDS=ON .
cppcheck --enable=<enable_flags> --project=compile_commands.json
```

Static Analyzers - `PVS-Studio, FBInfer`

`PVS-Studio` is a high-quality *proprietary* (free for open source projects) static code analyzer supporting C, C++

Customers: IBM, Intel, Adobe, Microsoft, Nvidia, Bosh, IdGames, EpicGames, etc.

`FBInfer` is a static analysis tool (also available online) to checks for null pointer deferencing, memory leak, coding conventions, unavailable APIs, etc.

Customers: Amazon AWS, Facebook/Ocolus, Instagram, Whatapp, Mozilla, Spotify, Uber, Sky, etc.

DEEP CODE `deepCode` is an AI-powered code review system, with machine learning systems trained on billions of lines of code from open-source projects

Available for Visual Studio Code, Sublime, IntelliJ IDEA, and Atom
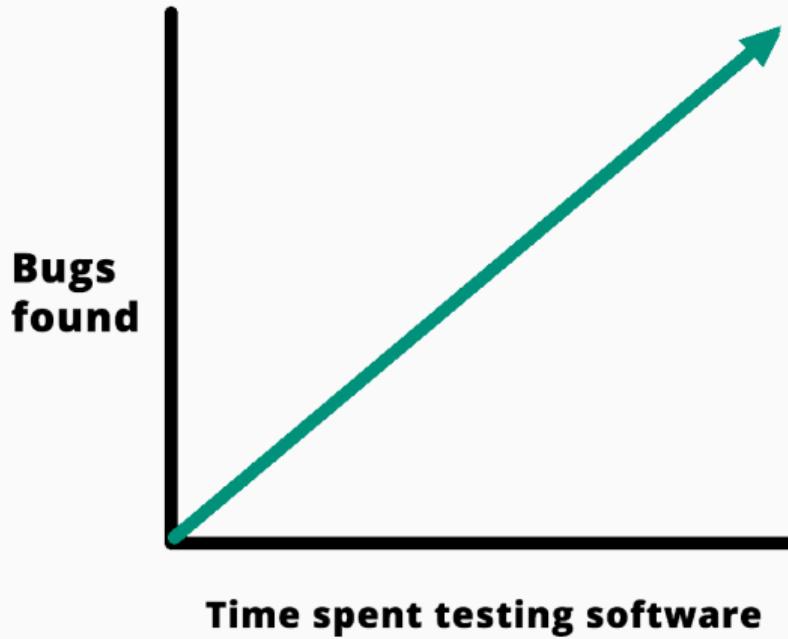
`SonarSource` is a static analyzer which inspects source code for bugs, code smells, and security vulnerabilities for multiple languages (C++, Java, etc.)

SonarLint plugin is available for Visual Code, Visual Studio Code, Eclipse, and IntelliJ IDEA

---

see also `A curated list of static analysis tool`

Code Testing

Bugs found

Time spent testing software

**Unit testing** involves breaking your program into pieces, and subjecting each piece to a series of tests
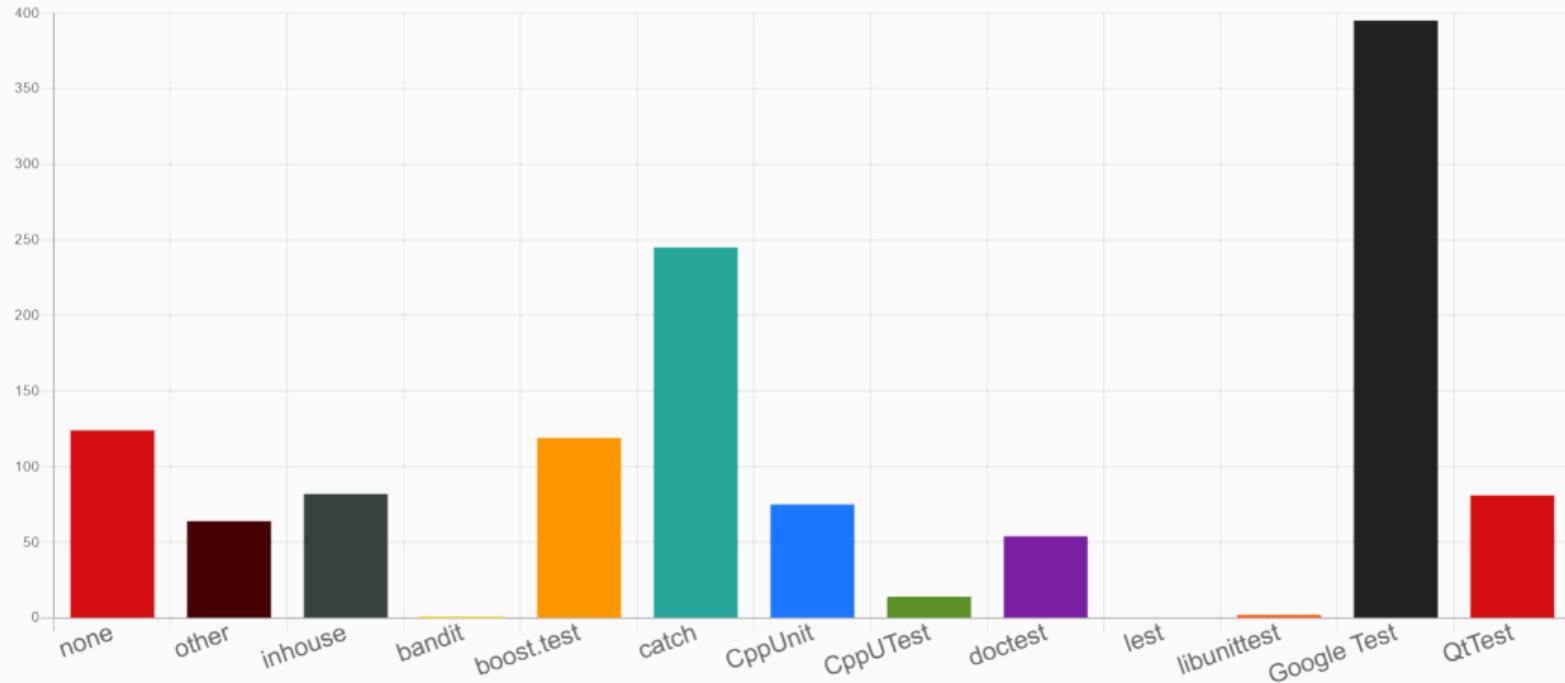
Unit Testing Benefits:

- Increases confidence in changing/ maintaining code
- The cost of fixing a defect detected during unit testing is lesser in comparison to that of defects detected at higher levels
- Debugging is easy. When a test fails, only the latest changes need to be debugged

C++ Unit testing frameworks:

- catch
- doctest
- Google Test
- CppUnit
- Boost.Test

Meeting C++ Community Survey
Which unit test libraries do you use? (n=865)

Catch2 is a multi-paradigm test framework for C++

Catch2 features

- Header only and no external dependencies
- Assertion macro
- Floating point tolerance comparisons

Basic usage:

- Create the test program
- Run the test

```
$./test_program [<TestName>]
```

- github.com/catchorg/Catch2
- The Little Things: Testing with Catch2

```cpp
#define CATCH_CONFIG_MAIN  // This tells Catch to provide a main()
#include "catch.hpp"       // only do this in one cpp file

unsigned Factorial(unsigned number) {
    return number <= 1 ? number : Factorial(number - 1) * number;
}

"Test description and tag name"
TEST_CASE( "Factorials are computed", "[Factorial]" ) {
    REQUIRE( Factorial(1) == 1 );
    REQUIRE( Factorial(2) == 2 );
    REQUIRE( Factorial(3) == 6 );
    REQUIRE( Factorial(10) == 3628800 );
}

float floatComputation() { ... }

TEST_CASE( "floatCmp computed", "[floatComputation]" ) {
    REQUIRE( floatComputation() == Approx( 2.1 ) );
}
```

Code coverage is a measure used to describe the degree to which the source code of a program is executed when a particular test suite runs

<u>gcov</u> is a tool you can use in conjunction with GCC to test code coverage in programs

<u>gcovr</u> is a utility for managing **gcov** and generating code coverage results

Step for code coverage:

- compile with `--coverage` flag (objects + linking)
- run the test
- visualize the results with **gcovr**

program.cpp:

```cpp
#include <iostream>
#include <string>

int main(int argc, char* argv[]) {
    int value = std::stoi(argv[1]);
    if (value % 3 == 0)
        std::cout << "first\n";
    if (value % 2 == 0)
        std::cout << "second\n";
}
```

```
$ gcc -g --coverage program.cpp -o program
$ ./program 9
first
$ gcovr -r --html --html-details <path_to_cover>
# generate coverage.html
```

```
   1:    4:int main(int argc, char* argv[]) {
   1:    5:    int value = std::stoi(argv[1]);
   1:    6:    if (value % 3 == 0)
   1:    7:        std::cout << "first\n";
   1:    8:    if (value % 2 == 0)
#####:  9:        std::cout << "second\n";
   4:   10:}
```

			Hit	Total	Coverage
Current view:	top level - /home/ubuntu/workspace/prove				
Test:	coverage.info	**Lines:**	6	7	85.7 %
Date:	2018-02-09	**Functions:**	3	3	100.0 %

Filename	Line Coverage ⬍		Functions ⬍	
program.cpp		85.7 %	6 / 7	100.0 %	3 / 3

			Hit	Total	Coverage
Current view:	top level - home/ubuntu/workspace/prove - program.cpp (source / functions)				
Test:	coverage.info	**Lines:**	6	7	85.7 %
Date:	2018-02-09	**Functions:**	3	3	100.0 %

```
    Line data    Source code
1        : #include <iostream>
2        : #include <string>
3        :
4      1 : int main(int argc, char* argv[]) {
5      1 :     int value = std::stoi(argv[1]); // convert to int
6      1 :     if (value % 3 == 0)
7      1 :         std::cout << "first";
8      1 :     if (value % 2 == 0)
9      0 :         std::cout << "second";
10     4 : }
```

Coverage-Guided Fuzz Testing

A **fuzzer** is a specialized tool that tracks which areas of the code are reached, and generates *mutations* on the corpus of input data in order to *maximize* the code coverage

`LibFuzzer` is the library provided by LLVM and feeds fuzzed inputs to the library via a specific fuzzing entrypoint

The *fuzz target function* accepts an array of bytes and does something interesting with these bytes using the API under test:

```cpp
extern "C" int LLVMFuzzerTestOneInput(const uint8_t* Data,
                                      size_t         Size) {
  DoSomethingInterestingWithMyAPI(Data, Size);
  return 0;
}
```

Code Quality

lint: The term was derived from the name of the undesirable bits of fiber

`clang-tidy` provides an extensible framework for diagnosing and fixing typical *programming errors*, like *style violations*, *interface misuse*, or *bugs* that can be deduced via static analysis

```
$cmake -DCMAKE_EXPORT_COMPILE_COMMANDS=ON .
$clang-tidy -p .
```

clang-tidy searches the configuration file `.clang-tidy` file located in the closest parent directory of the input file

clang-tidy is included in the LLVM suite

Coding Guidelines:

- CERT Secure Coding Guidelines
- C++ Core Guidelines
- High Integrity C++ Coding Standard

Supported Code Conventions:

- Fuchsia
- Google
- LLVM

Bug Related:

- Android related
- Boost library related
- Misc
- Modernize
- Performance
- Readability
- clang-analyzer checks
- bugprone code constructors

`.clang-tidy`

```
Checks: 'android-*,boost-*,bugprone-*,cert-*,cppcoreguidelines-*,
clang-analyzer-*,fuchsia-*,google-*,hicpp-*,llvm-*,misc-*,modernize-*,
performance-*,readability-*'
```

CMake

CMake Overview

CMake is an *open-source*, *cross-platform* family of tools designed to build, test and package software

CMake is used to control the software compilation process using simple platform and compiler independent configuration files, and *generate* native Makefile/Ninja and workspaces that can be used in the compiler environment of your choice

CMake features:

- Turing complete language (if/else, loops, functions, etc.)
- Multi-platform (Windows, Linux, etc.)
- Open-Source
- Generate: makefile, ninja, etc.
- Supported by many IDEs: Visual Studio, Clion, Eclipse, etc.

CMake - References

- 19 reasons why CMake is actually awesome

- An Introduction to Modern CMake

- Effective Modern CMake

- Awesome CMake

- Useful Variables

Install CMake

Using PPA repository

```
$ wget -O - https://apt.kitware.com/keys/kitware-archive-latest.asc 2>/dev/null |
  gpg --dearmor - | sudo tee /etc/apt/trusted.gpg.d/kitware.gpg >/dev/null
$ sudo apt-add-repository 'deb https://apt.kitware.com/ubuntu/ focal main' # bionic, xenial
$ sudo apt update
$ sudo apt install cmake cmake-curses-gui
```

Using the installer or the pre-compiled binaries: cmake.org/download/

```
# download the last cmake package, e.g. cmake-x.y.z-linux-x86_64.sh
$ sudo sh cmake-x.y.z-linux-x86_64.sh
```

A Minimal Example

CMakeLists.txt:

```
project(my_project)              # project name

add_executable(program program.cpp) # compile command
```

```
# we are in the project dir
$ mkdir build  # 'build' dir is needed for isolating temporary files
$ cd build
$ cmake ..     # search for CMakeLists.txt directory
$ make         # makefile automatically generated

Scanning dependencies of target program
[100%] Building CXX object CMakeFiles/out_program.dir/program.cpp.o
Linking CXX executable program
[100%] Built target program
```

Parameters and Message

CMakeLists.txt:

```
project(my_project)
add_executable(program program.cpp)

if (VAR)
    message("VAR is set, NUM is ${NUM}")
else()
    message(FATAL_ERROR "VAR is not set")
endif()
```

```
$ cmake ..
VAR is not set
$ cmake -DVAR=ON -DNUM=4 ..
VAR is set, NUM is 4
...
[100%] Built target program
```

Language Properties

```
project(my_project
        DESCRIPTION  "Hello World"
        HOMEPAGE_URL "github.com/"
        LANGUAGES    CXX)

cmake_minimum_required(VERSION 3.15)

set(CMAKE_CXX_STANDARD          14) # force C++14
set(CMAKE_CXX_STANDARD_REQUIRED  ON)
set(CMAKE_CXX_EXTENSIONS        OFF) # no compiler extensions

add_executable(program ${PROJECT_SOURCE_DIR}/program.cpp) #$
# PROJECT_SOURCE_DIR is the root directory of the project
```

Target Commands

```cmake
add_executable(program) # also add_library(program)

target_include_directories(program
                           PUBLIC  include/
                           PRIVATE src/)
# target_include_directories(program SYSTEM ...) for system headers

target_sources(program                   # best way for specifying
               PRIVATE src/program1.cpp   # program sources and headers
               PRIVATE src/program2.cpp
               PUBLIC  include/header.hpp)

target_compile_definitions(program PRIVATE MY_MACRO=ABCEF)

target_compile_options(program PRIVATE -g)

target_link_libraries(program PRIVATE boost_lib)

target_link_options(program PRIVATE -s)
```

Build Types

```cmake
project(my_project)                     # project name
cmake_minimum_required(VERSION 3.15)    # minimum version

add_executable(program program.cpp)

if (CMAKE_BUILD_TYPE STREQUAL "Debug")       # "Debug" mode
                                             # cmake already adds "-g -OO"
    message("DEBUG mode")
    if (CMAKE_COMPILER_IS_GNUCXX)            # if compiler is gcc
        target_compile_options(program "-ggdb3")
    endif()
elseif (CMAKE_BUILD_TYPE STREQUAL "Release") # "Release" mode
    message("RELEASE mode")                  # cmake already adds "-O3 -DNDEBUG"
endif()
```

```
$ cmake -DCMAKE_BUILD_TYPE=Debug ..
```

Custom Targets and File Managing

```
project(my_project)
add_executable(program)

add_custom_target(echo_target          # makefile target name
                  COMMAND echo "Hello"  # real command
                  COMMENT "Echo target")

# find all .cpp file in src/ directory
file(GLOB_RECURSE SRCS ${PROJECT_SOURCE_DIR}/src/*.cpp)
# compile all *.cpp file
target_sources(program PRIVATE ${SRCS}) # prefer the explicit file list instead
```

```
$ cmake ..
$ make echo_target
```

Local and Cached Variables

Cached variables can be reused across multiple runs, while *local variables* are only visible in a single run. Cached FORCE variables can be modified only after the initialization

```cmake
project(my_project)

set(VAR1 "var1")                              # local variable
set(VAR2 "var2" CACHE STRING "Description1")  # cached variable
set(VAR3 "var3" CACHE STRING "Description2" FORCE) # cached variable
option(OPT "This is an option" ON)            # boolean cached variable
                                              # same of var2
message(STATUS "${VAR1}, ${VAR2}, ${VAR3}, ${OPT}")
```

```
$ cmake .. # var1, var2, var3, ON
$ cmake -DVAR1=a -DVAR2=b -DVAR3=c -DOPT=d .. # var1, b, var3, d
```

Manage Cached Variables

```
$ ccmake .  # or 'cmake-gui'
```

```
                                                          Page 1 of 1
    CMAKE_BUILD_TYPE                      Release
    CMAKE_INSTALL_PREFIX                  /usr/local
    OPT                                  ON
    VAR2                                 var2
    VAR3                                 var3




    CMAKE_BUILD_TYPE: Choose the type of build, options are: None(CMAK
    Press [enter] to edit option Press [d] to delete an entry
    Press [c] to configure
    Press [h] for help            Press [q] to quit without generating
    Press [t] to toggle advanced mode (Currently Off)
```

Find Packages

```
project(my_project)                 # project name
cmake_minimum_required(VERSION 3.15) # minimum version

add_executable(program program.cpp)
find_package(Boost 1.36.0 REQUIRED) # compile only if Boost library
                                    # is found
if (Boost_FOUND)
    target_include_directories("${PROJECT_SOURCE_DIR}/include" PUBLIC ${Boost_INCLUDE_DIRS})
else()
    message(FATAL_ERROR "Boost Lib not found")
endif()
```

Compile Commands

Generate JSON compilation database (compile_commands.json)

It contains the exact compiler calls for each file that are used by other tools

```
project(my_project)
cmake_minimum_required(VERSION 3.15)

set(CMAKE_EXPORT_COMPILE_COMMANDS ON)  # <--

add_executable(program program.cpp)
```

Change the C/C++ compiler:

```
CC=clang CXX=clang++ cmake ..
```

CTest is a testing tool (integrated in CMake) that can be used to automate updating, configuring, building, testing, performing memory checking, performing coverage

```
project(my_project)
cmake_minimum_required(VERSION 3.5)
add_executable(program program.cpp)

enable_testing()

add_test(NAME Test1          # check if "program" returns 0
         WORKING_DIRECTORY ${PROJECT_SOURCE_DIR}/build
         COMMAND ./program <args>) # command can be anything

add_test(NAME Test2          # check if "program" print "Correct"
         WORKING_DIRECTORY ${PROJECT_SOURCE_DIR}/build
         COMMAND ./program <args>)

set_tests_properties(Test2
                     PROPERTIES PASS_REGULAR_EXPRESSION "Correct")
```

Basic usage (call ctest):

```
$ make test        # run all tests
```

ctest usage:

```
$ ctest -R Python    # run all tests that contains 'Python' string
$ ctest -E Iron      # run all tests that not contain 'Iron' string
$ ctest -I 3,5       # run tests from 3 to 5
```

Each ctest command can be combined with other tools (e.g. valgrind)

ctest with Different Compile Options

It is possible to combine a custom target with ctest to compile the same code with different compile options

```
add_custom_target(program-compile
                  COMMAND mkdir -p test-release test-ubsan test-asan  # create dirs
                  COMMAND cmake .. -B test-release                    # -B change working dir
                  COMMAND cmake .. -B test-ubsan   -DUBSAN=ON
                  COMMAND cmake .. -B test-asan    -DASAN=ON
                  COMMAND make -C test-release -j20 program           # -C run make in a
                  COMMAND make -C test-ubsan   -j20 program           # different dir
                  COMMAND make -C test-asan    -j20 program)

enable_testing()

add_test(NAME Program-Compile
         COMMAND make program-compile)
```

CMake Alternatives - `xmake`

xmake is a cross-platform build utility based on Lua.

Compared with makefile/CMakeLists.txt, the configuration syntax is more concise and intuitive. It is very friendly to novices and can quickly get started in a short time. Let users focus more on actual project development

Comparison: xmake vs cmake

Code Documentation

Doxygen is the de facto standard tool for generating documentation from annotated C++ sources
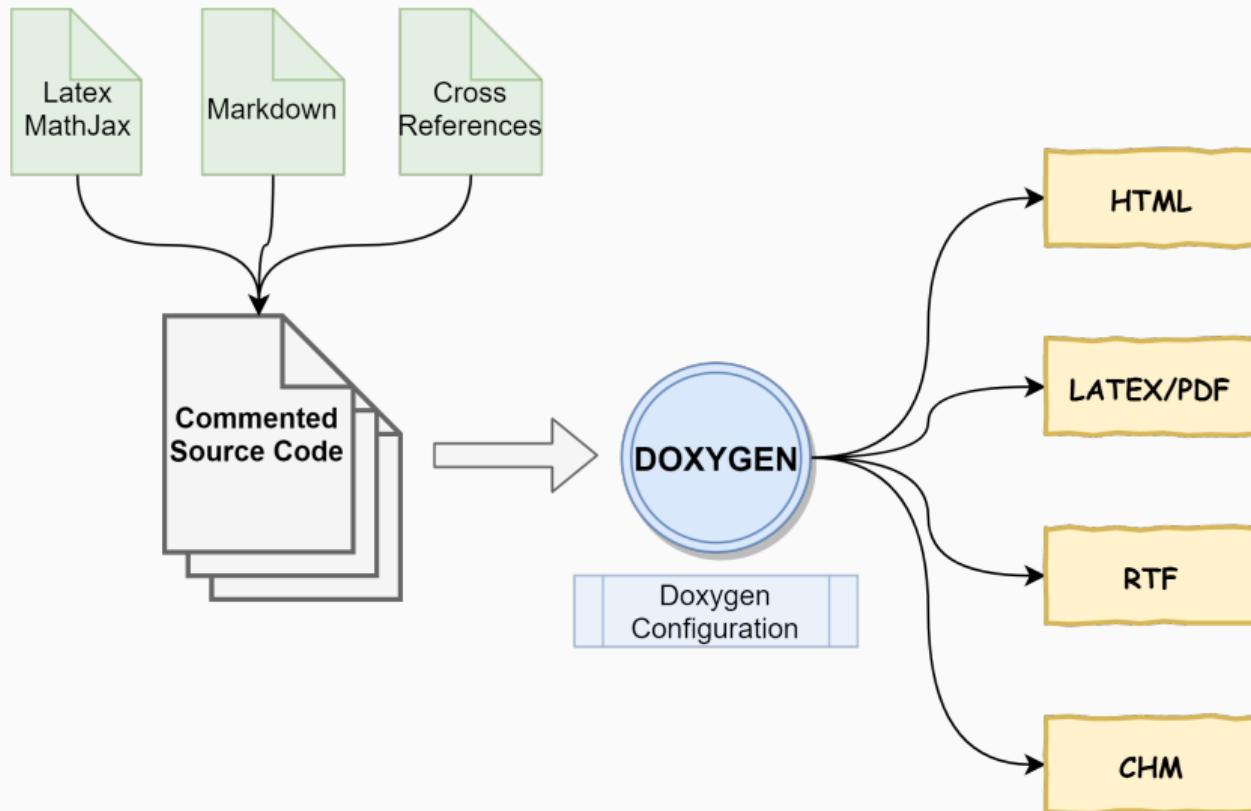
Doxygen usage

- comment the code with `///` or `/** comment */`
- generate doxygen base configuration file

```
$doxygen -g
```

- modify the configuration file doxygen.cfg
- generate the documentation

```
$doxygen <config_file>
```
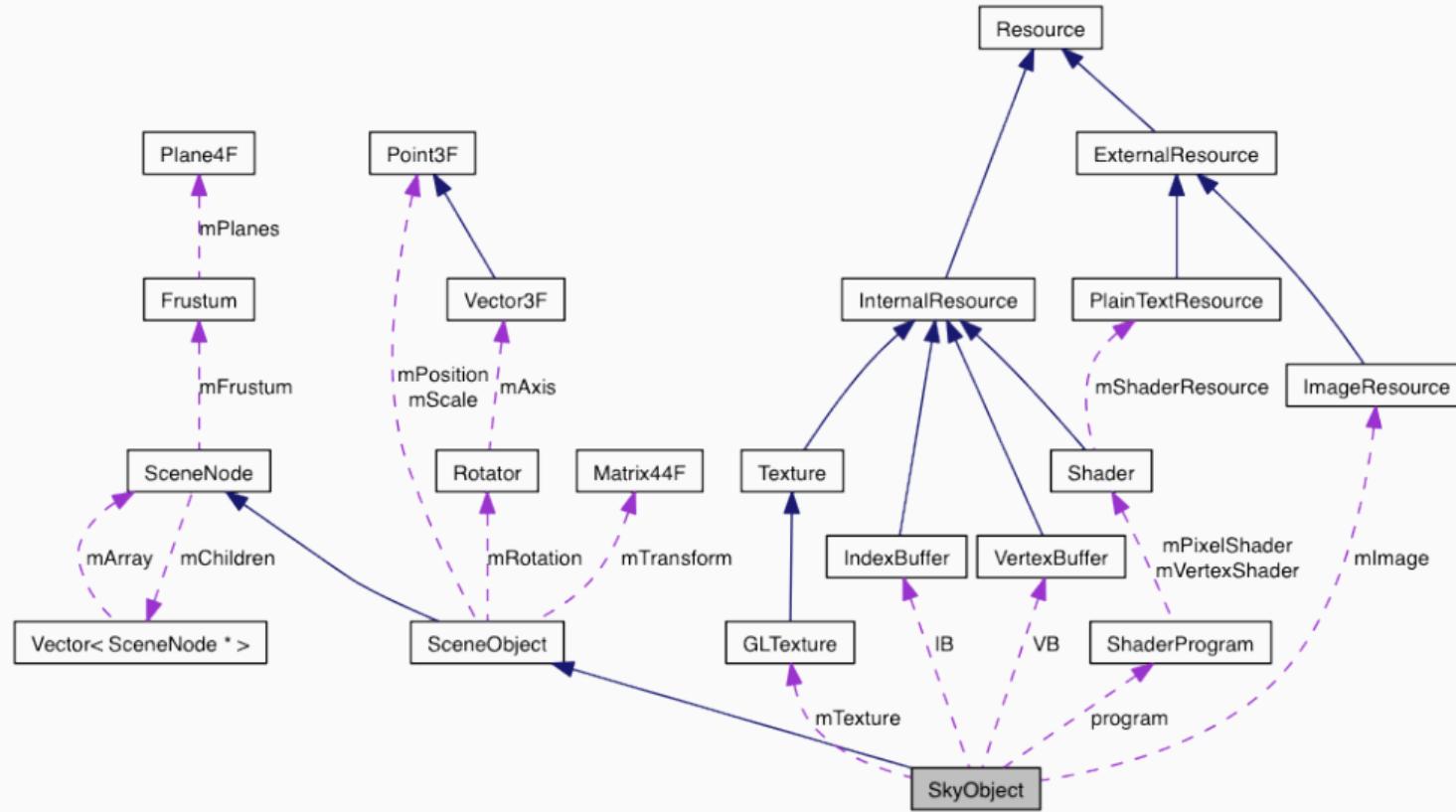
Doxygen requires the following tags for generating the documentation:

- `@file` Document a file

- `@brief` Brief description for an entity

- `@class`, `@struct`, `@union`, `@enum`, `@fn`, `@def`, `@var`, `@namespace`, `@typedef` Describe a specific entity

- *Automatic cross references* between functions, variables, etc.

- *Specific highlight*. Code `` `<code>` ``, input/output parameters `@param[in] <param>`

- *Latex/MathJax* `$<code>$`

- *Markdown* (Markdown Cheatsheet link), Italic text `*<code>*`, bold text `**<code>**`, table, list, etc.

- Call/Hierarchy graph can be useful in large projects (requires `graphviz`)
  `HAVE_DOT = YES`
  `GRAPHICAL_HIERARCHY = YES`
  `CALL_GRAPH = YES`
  `CALLER_GRAPH = YES`

```cpp
/**
 * @copyright MyProject
 * license BSD3, Apache, MIT, etc.
 * @author MySelf
 * @version v3.14159265359
 * @date March, 2018
 * @file
 */

/// @brief Namespace brief
///        description
namespace my_namespace {

/// @brief "Class brief description"
/// @tparam R "Class template for"
template<typename R>
class A {
```

```cpp
/**
 * @brief "What the function does?"
 * @details "Some additional details",
 *          Latex/MathJax: $\sqrt a$
 * @tparam T Type of input and output
 * @param[in] input Input array
 * @param[out] output Output array
 * @return `true` if correct,
 *         `false` otherwise
 * @remark it is *useful* if ...
 * @warning the behavior is **undefined** if
 *          @p input is `nullptr`
 * @see related_function
 */
template<typename T>
bool my_function(const T* input, T* output);

/// @brief
void related_function;
```

Doxygen Alternatives

M.CSS Doxygen C++ theme

Doxypress Doxygen fork

clang-doc LLVM tool

Sphinx Clear, Functional C++ Documentation with Sphinx + Breathe + Doxygen + CMake

standardese The nextgen Doxygen for C++ (experimental)

HDoc The modern documentation tool for C++ (alpha)

Adobe Hyde Utility to facilitate documenting C++

Code Statistics

Count Lines of Code - `cloc`

`cloc` counts blank lines, comment lines, and physical lines of source code in many programming languages

```
$cloc my_project/

4076 text files.
3883 unique files.
1521 files ignored.

http://cloc.sourceforge.net v 1.50  T=12.0 s (209.2 files/s, 70472.1 lines/s)
-------------------------------------------------------------------------------
Language                     files          blank        comment           code
-------------------------------------------------------------------------------
C                              135          18718          22862         140483
C/C++ Header                   147           7650          12093          44042
Bourne Shell                   116           3402           5789          36882
```

Features: filter by-file/language, SQL database, archive support, line count diff, etc.
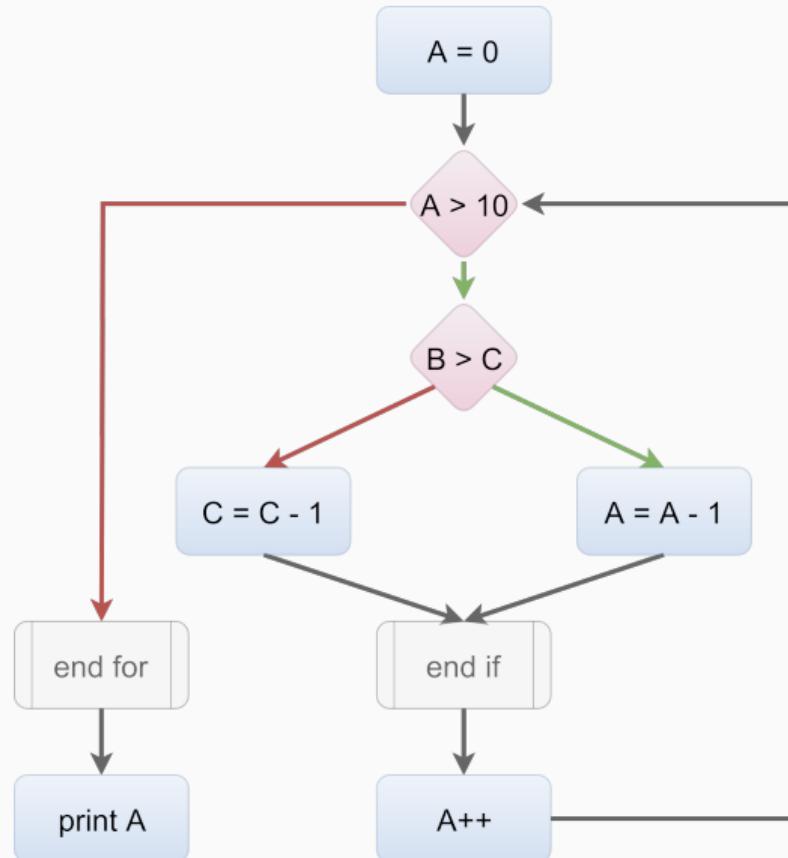
Lizard is an extensible Cyclomatic Complexity Analyzer for many programming languages including C/C++

Cyclomatic Complexity: is a software metric used to indicate the complexity of a program. It is a quantitative measure of the number of linearly independent paths through a program source code

```
$lizard my_project/
============================================================
NLOC    CCN  token  param    function@line@file
------------------------------------------------------------
10      2     29     2     start_new_player@26@./html_game.c
6       1      3     0     set_shutdown_flag@449@./httpd.c
24      3     61     1     server_main@454@./httpd.c
------------------------------------------------------------
```

- CCN: cyclomatic complexity (should not exceed a threshold)
- NLOC: lines of code without comments
- token: Number of conditional statements

80/93

CC	Risk Evaluation
1-10	a simple program, *without much risk*
11-20	more complex, *moderate risk*
21-50	complex, *high risk*
$> \mathbf{50}$	untestable program, *very high risk*

CC	Guidelines
1-5	The routine is probably fine
6-10	Start to think about ways to simplify the routine
$> \mathbf{10}$	Break part of the routine

Risk: `Lizard`: 15, `OCLint`: 10

- `www.microsoftpressstore.com/store/code-complete-9780735619678`
- `blog.feabhas.com/2018/07/code-quality-cyclomatic-complexity`

Other Tools

Code Formatting - `clang-format`

`clang-format` is a tool to automatically format C/C++ code (and other languages)

```
$ clang-format <file/directory>
```

clang-format searches the configuration file `.clang-format` file located in the closest parent directory of the input file

clang-format example:

```
IndentWidth: 4
UseTab: Never
BreakBeforeBraces: Linux
ColumnLimit: 80
SortIncludes: true
```

Compiler Explorer (assembly and execution)

Compiler Explorer is an interactive tool that lets you type source code and see assembly output, control flow graph, optimization hint, etc.
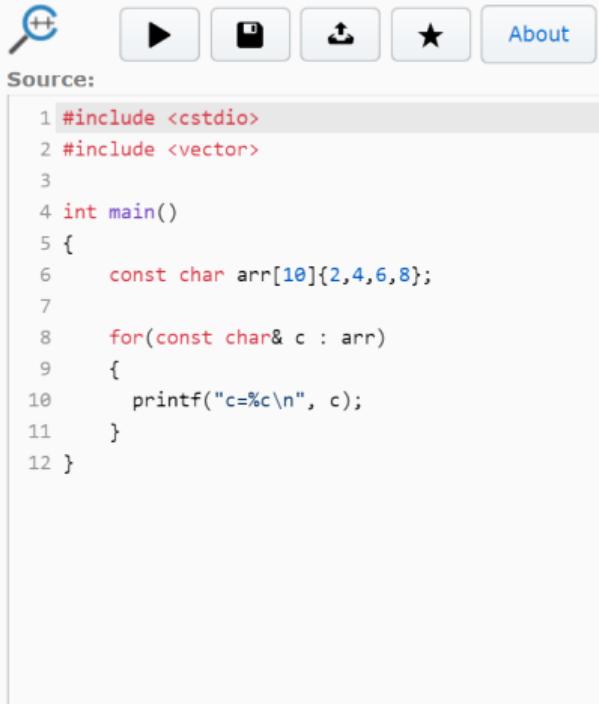
Code Transformation - CppInsights

CppInsights See what your compiler does behind the scenes

Source:

```cpp
1 #include <cstdio>
2 #include <vector>
3
4 int main()
5 {
6     const char arr[10]{2,4,6,8};
7
8     for(const char& c : arr)
9     {
10        printf("c=%c\n", c);
11    }
12 }
```

Insight:

```cpp
1 #include <cstdio>
2 #include <vector>
3
4 int main()
5 {
6     const char arr[10]{2,4,6,8};
7
8     {
9         auto&& __range1 = arr;
10        const char * __begin1 = __range1;
11        const char * __end1 = __range1 + 101;
12
13        for( ; __begin1 != __end1; ++__begin1 )
14        {
15            const char & c = *__begin1;
16            printf("c=%c\n", static_cast<int>(c));
17        }
18    }
19 }
```

`TabNine` uses deep learning to provide code completion

Features:

- Support all languages
- C++ semantic completion is available through `clangd`
- Project indexing
- Recognize common language patterns
- Use even the documentation to infer this function name, return type, and arguments

Available for Visual Studio Code, IntelliJ, Sublime, Atom, and Vim

Code Autocompletion - `Kite`

`Kite` adds AI powered code completions to your code editor

Support 13 languages

Available for Visual Studio Code, IntelliJ, Sublime, Atom, Vim, + others

`Ripgrep` is a code-searching-oriented tool for regex pattern

Features:

- Default recursively searches
- Skip `.gitignore` patterns, binary and hidden files/directories
- Windows, Linux, Mac OS support
- Up to 100x faster than `GNU grep`

```
[andrew@Cheetah rust] rg -i rustacean
src/doc/book/nightly-rust.md
92:[Mibbit][mibbit]. Click that link, and you'll be chatting with other Rustaceans

src/doc/book/glossary.md
3:Not every Rustacean has a background in systems programming, nor in computer

src/doc/book/getting-started.md
176:Rustaceans (a silly nickname we call ourselves) who can help us out. Other great
376:Cargo is Rust's build system and package manager, and Rustaceans use Cargo to

src/doc/book/guessing-game.md
444:it really easy to re-use libraries, and so Rustaceans tend to write smaller

CONTRIBUTING.md
322:* [rustaceans.org][ro] is helpful, but mostly dedicated to IRC
333:[ro]: http://www.rustaceans.org/
[andrew@Cheetah rust] []
```
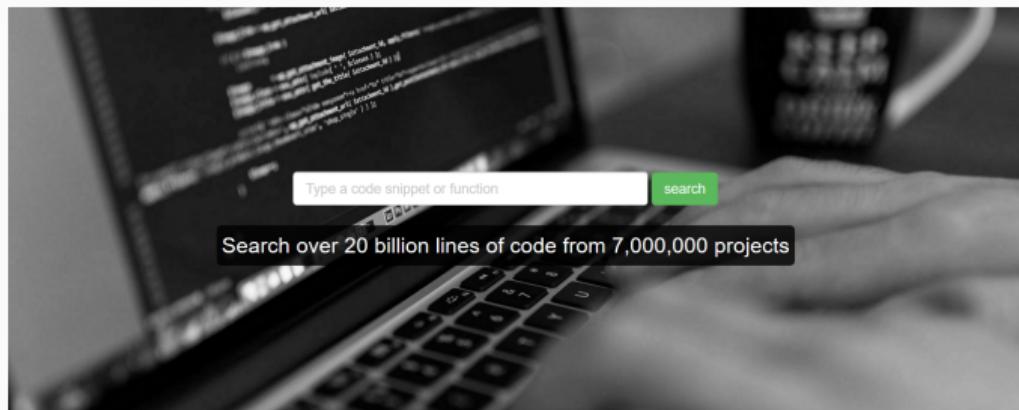
Code Search Engine - `searchcode`

`Searchcode` is a free source code search engine

Features:

- Search over 20 billion lines of code from 7,000,000 projects
- Search sources: `github`, `bitbucket`, `gitlab`, `google code`, `sourceforge`, etc.

`grep.app` searches across a half million GitHub repos
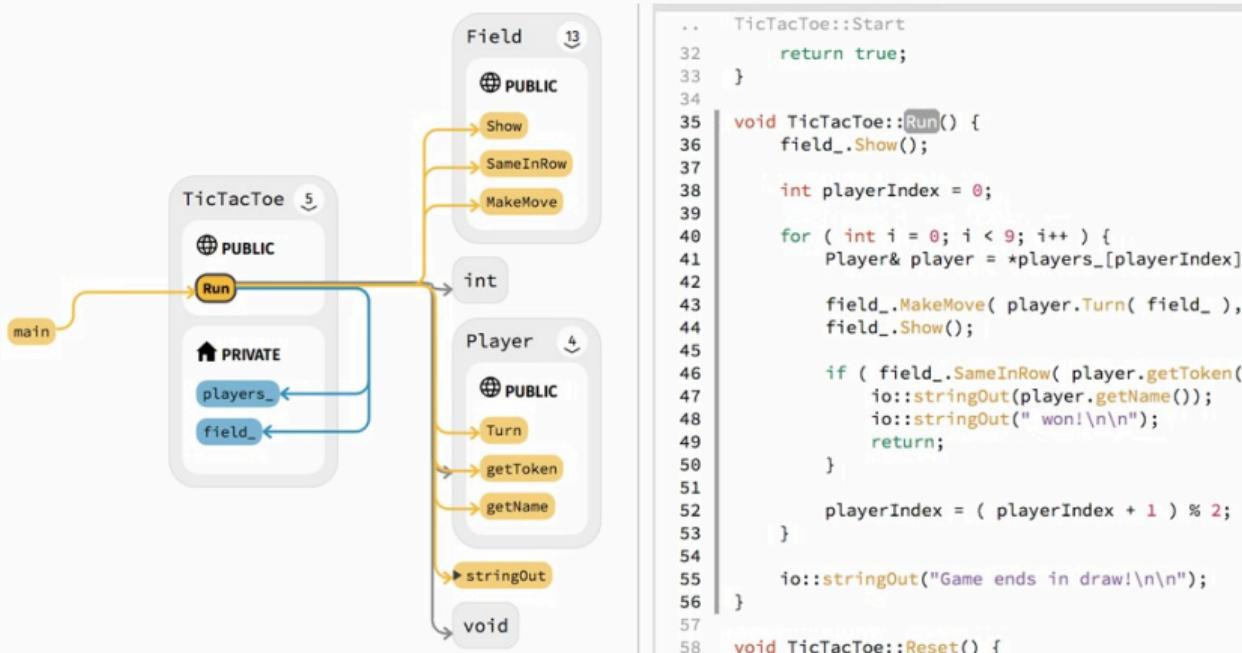
Code Exploration - `SourceTrail`

Sourcetrail is an interactive code explorer that simplifies navigation in complex source code
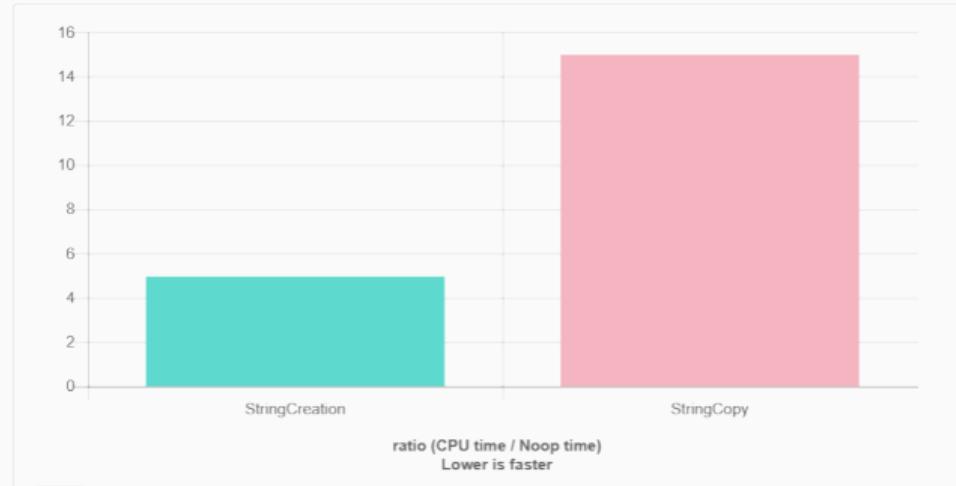
Code Benchmarking - `Quick-Bench`

<u>Quick-benchmark</u> is a micro benchmarking tool intended to quickly and simply compare the performances of two or more code snippets. The benchmark runs on a pool of AWS machines

Font for Coding

Many editors allow adding optimized fonts for programming which improve legibility and provide extra symbols (ligatures)

Scope	→ ⇒ :: __	-> => :: __
Equality	= ≡ ≠ ≠ == === ≠ =≠=	== === != =/= == === != !==
Comparisons	≤ ≥ ≤ ≥ ⟺	<= >= <= >= <=>

Some examples:

- `JetBrain Mono`
- `Fira Code`
- `Microsoft Cascadia`
- `Consolas Ligaturized`