Modern C++ Programming

14. C++ Ecosystem I

Debugging

Federico Busato

2023-12-21

Table of Contents

Table of Contents

Table of Contents

Feature Complete

Debugging

Is this a bug?

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

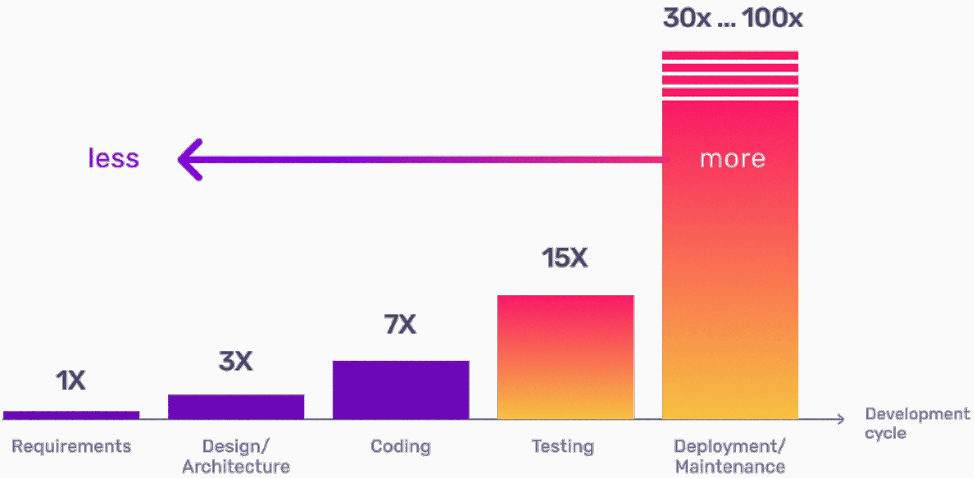
"Software developers spend 35-50 percent of their time validating and debugging software. The cost of debugging, testing, and verification is estimated to account for 50-75 percent of the total budget of software development projects"

from: John Regehr (on Twitter)

Errors, Defects, and Failures

- An **error** is a human mistake. *Errors* lead to *software defects*
- A **defects** is an unexpected behavior of the software (correctness, performance, etc.). *Defects* potentially lead to *software failures*
- A **failure** is an observable incorrect behavior

Cost of Software Defects



Types of Software Defects

Ordered by fix complexity, (time to fix):

(1) Typos, Syntax, Formatting (seconds)

(2) Compilation Warnings/Errors (seconds, minutes)

(3) Logic, Arithmetic, Runtime Errors (minutes, hours, days)

(4) Resource Errors (minutes, hours, days)

(5) Accuracy Errors (hours, days)

(6) Performance Errors (days)

(7) Design Errors (weeks, months)

Causes of Bugs

- *C++ is very error prone language*, see `60 terrible tips for a C++ developer`
- *Human behavior*, e.g. copying & pasting code is very common practice and can introduce subtle bugs → check the code carefully, deep understanding of its behavior

Dealing with Software Defects

Software defects can be identifies by:

Dynamic Analysis A *mitigation* strategy that acts on the runtime state of a program.

Techniques: Print, run-time debugging, sanitizers, fuzzing, unit test support, performance regression tests

Limitations: Infeasible to cover all program states

Static Analysis A *proactive* strategy that examines the source code for (potential) errors.

Techniques: Warnings, static analysis tool, compile-time checks

Limitations: Turing's undecidability theorem, exponential code paths

Program Errors

A **program error** is a set of conditions that produce an *incorrect result* or *unexpected behavior*, including performance regression, memory consumption, early termination, etc.

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.

Sometimes a *recoverable* error is considered *unrecoverable* if it is extremely rare and difficult to handle, e.g. bad allocation due to out-of-memory error

Assertions

Unrecoverable Errors and Assertions

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

Execution Debugging (gdb)

How to compile and run for debugging:

```
g++ -O0 -g [-g3] <program.cpp> -o program
gdb [--args] ./program <args...>
```

-O0 Disable any code optimization for helping the debugger. It is implicit for most compilers

-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 and the execution

-g3 Produces enhanced debugging information, e.g. macro definitions. Available for most compilers. Suggested instead of -g

gdb - Breakpoints

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*>	**`d`**	delete a specific breakpoint
`clear` [*function_name/line_number*]		delete a specific breakpoint
`enable/disable` <*breakpoint_number*>		enable/disable a specific breakpoint
`info breakpoints`	**info `b`**	list all active breakpoints

gdb - Watchpoints / Catchpoints

Command	Abbr.	Description
watch <*expression*>		stop execution when the value of `expression` changes (variable, comparison, etc.)
rwatch <*variable/location*>		stop execution when `variable/location` is read
delete <*watchpoint_number*>	**d**	delete a specific watchpoint
info watchpoints		list all active watchpoints
catch throw		stop execution when an *exception* is thrown

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 [full]`	`bt`	prints stack backtrace (call stack) [local vars]
`info args`		print current function arguments
`info locals`		print local variables
`info variables`		print 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/nb` <*variable*>	`p/nb`	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

"you can expect at least 65% of your security vulnerabilities to be caused by memory unsafety"

What science can tell us about C and C++'s security

`Microsoft: 70% of all security bugs are memory safety issues`
`Chrome: 70% of all security bugs are memory safety issues`
`What science can tell us about C and C++'s security`

"Memory Unsafety in Apple's OS represents 66.3%- 88.2% of all the vulnerabilities"

"Out of bounds (OOB) reads/writes comprise ∼70% of all the vulnerabilities in Android"

***Jeff Vander**, Google, Android Media Team*

"Memory corruption issues are the root-cause of 68% of listed CVEs"

***Ben Hawkes**, Google, Project Zero*

Memory Unsafety in Apple's Operating Systems

Google Security Blog: Queue the Hardening Enhancements

Google Project Zero

Memory Vulnerabilities 2/2

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***

Mitigation:

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

valgrind

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-3.21.tar.bz2
$ tar xf valgrind-3.21.tar.bz2
$ cd valgrind-3.21
$ ./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) (main.cpp:86)
==60127==    by 0x100000C22: main (main.cpp: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) (main.cpp:75)
==60127==    by 0x100000C22: main (main.cpp: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 (main.cpp:5)
==19182==    by 0x80483AB: main (main.cpp: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();                   // early abnormal termination
    // 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

```
#include <cstdlib>
int main() {
    int* array = new int[3];
    array++;                         // pointer arithmetic
    std::abort();                    // early abnormal termination
    // 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...>
```

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

---

Use compiler flags for stack protection in GCC and Clang

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` .

Recent compilers (e.g. GCC 12) allow detects buffer overflows with enhanced coverage, e.g. dynamic pointers, with `_FORTIFY_SOURCE=3` *

*GCC's new fortification level: The gains and costs

Stack Protection - Run-time

```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

`Address Sanitizer` 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

`LeakSanitizer` 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)

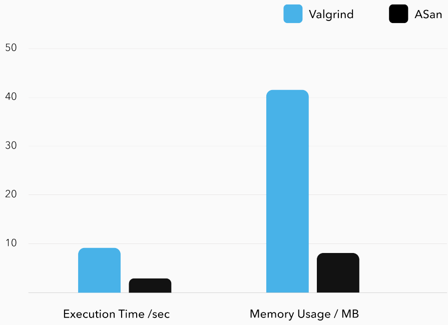
`-fsanitize=nullability` Checks passing `null` as a function parameter, assigning `null` to an lvalue, and returning `null` from a function

---

- `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 **



Debugging Summary

How to Debug Common Errors

Segmentation fault

- `gdb`, `valgrind`, `sanitizers`
- `Segmentation fault when just entered in a function` → `stack overflow`

Double free or corruption

- `gdb`, `valgrind`, `sanitizers`

Infinite execution

- `gdb` + (`CTRL + C`)

Incorrect results

- `valgrind` + `assertion` + `gdb` + `sanitizers`

Compiler Warnings

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`

Static Analysis

Overview

Source level analysis to find issues.

Detect known patterns in source code.

Analysis all possible paths.

Conservative approach to analysis.

Can analyze outside of the execution environment.

- Quickly scan for known patterns
- Improve code quality
- Enhance security
- Ensure compliance
- Increase developer efficiency

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 dereferencing, memory leak, coding conventions, unavailable APIs, etc.

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

Static Analyzers - DeepCode, SonarSource

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

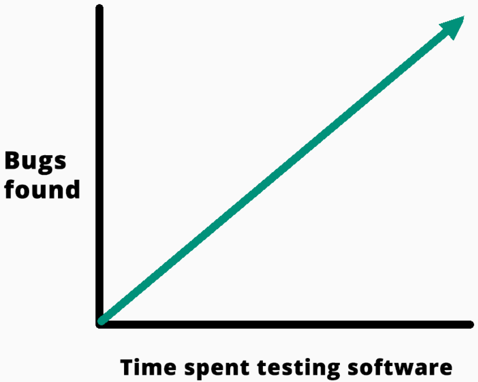
Available for Visual Studio Code, Sublime, IntelliJ IDEA, and Atom

`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



see `Case Study 4: The $440 Million Software Error at Knight Capital`

from: Kat Maddox (on Twitter)

Code Testing

Unit Test A *unit* is the smallest piece of code that can be logically isolated in a system. *Unit test* refers to the verification of a *unit*. It supposes the full knowledge of the code under testing (*white-box* testing)
Goals: meet specifications/requirements, fast development/debugging

Functional Test Output validation instead of the internal structure (*black-box* testing)
Goals: performance, regression (same functionalities of previous version), stability, security (e.g. sanitizers), composability (e.g. integration test)

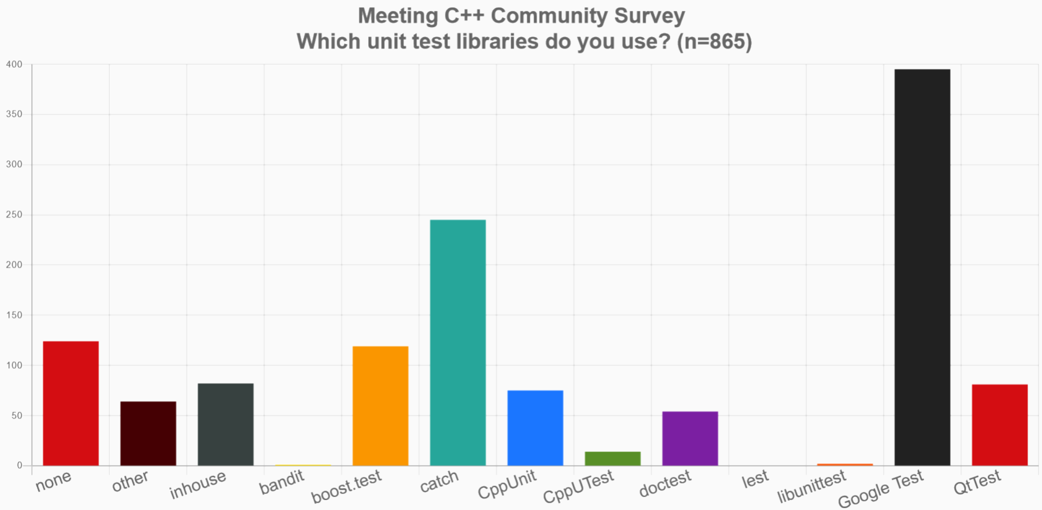
Unit testing involves breaking your program into pieces, and subjecting each piece to a series of tests

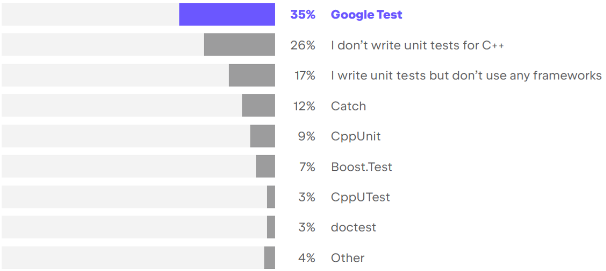
Unit testing should observe the following key features:

- **Isolation**: Each unit test should be *independent* and avoid external interference from other parts of the code
- **Automation**: Non-user interaction, easy to run, and manage
- **Small Scope**: Unit tests focus on small portions of code or specific functionalities, making it easier to identify bugs

Popular C++ Unit testing frameworks:

`catch`, `doctest`, `Google Test`, `CppUnit`, `Boost.Test`


Meeting C++ Community Survey
Which unit test libraries do you use? (n=865)
400
350
300
250
200
150
100
50
0
none
other
inhouse
bandit
boost.test
catch
CppUnit
CppUTest
doctest
lest
libunittest
Google Test
QtTest



The statistic that a quarter of developers aren't writing unit tests freaks me out. I don't feel strongly about how you express those or what framework you use, but we all do need to be writing tests.

Titus Winters
Principal Engineer at Google

Test-Driven Development (TDD)

Unit testing is often associated with the **Test-Driven Development (TDD)** methodology. The practice involves the definition of *automated functional tests* before implementing the functionality

The process consists of the following steps:

1. Write a test for a new functionality
2. Write the minimal code to pass the test
3. Improve/Refactor the code iterating with the test verification
4. Go to 1.

Test-Driven Development (TDD) - Main advantages

- **Software design**. Strong focus on interface definition, expected behavior, specifications, and requirements before working at lower level
- **Maintainability/Debugging Cost** Small, incremental changes allow you to catch bugs as they are introduced. Later refactoring or the introduction of new features still rely on well-defined tests
- **Understandable behavior**. New user can learn how the system works and its properties from the tests
- **Increase confidence**. Developers are more confident that their code will work as intended because it has been extensively tested
- **Faster development**. Incremental changes, high confidence, and automation make it easy to move through different functionalities or enhance existing ones

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

```
#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

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

`gcov` and `llvm-profdata/llvm-cov` are tools used in conjunction with compiler instrumentation (`gcc`, `clang`) to interpret and visualize the raw code coverage generated during the execution

`gcovr` and `lcov` are utilities for managing `gcov/llvm-cov` at higher level and generating code coverage results

Step for code coverage:

- Compile with `--coverage` flag (objects + linking)
- Run the program / test
- Visualize the results with `gcovr`, `llvm-cov`, `lcov`

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";
}
```

```bash
$ gcc -g --coverage program.cpp -o program
$ ./program 9
first
$ gcovr -r --html --html-details <path>  # generate html
# or
$ lcov --coverage --directory . --output-file coverage.info
$ genhtml coverage.info --output-directory <path> # generate html
```

Code Coverage

```
    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:}
```

Current view: top level - /home/ubuntu/workspace/prove
Test: coverage.info
Date: 2018-02-09

	Hit	Total	Coverage
Lines:	6	7	85.7 %
Functions:	3	3	100.0 %

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

Current view: top level - home/ubuntu/workspace/prove - program.cpp (source / functions)
Test: coverage.info
Date: 2018-02-09

	Hit	Total	Coverage
Lines:	6	7	85.7 %
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:

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

Code Quality

Linters - `clang-tidy` 1/2

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-*'
```