Beyond Traditional Compilation

Why the Linux community should stop the single compiler monopoly

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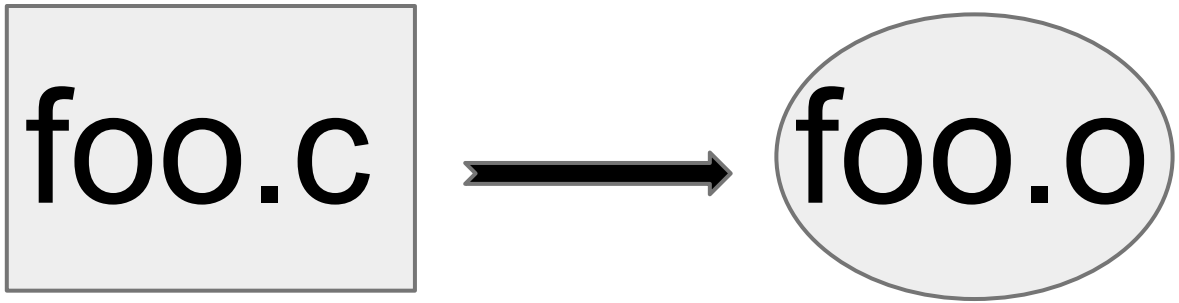
Linux Plumbers / LLVM, Aug 19 2015

“Dynamic Testing Tools” team at Google

- Goal: our users find their bugs w/o our help
  - 10000+ bugs fixed since 2008
- Chromium, Android, server-side devs; C++
- Since 2011: compiler instrumentation

Traditional C/C++ compilation



One

them all

https://en.wikipedia.org/wiki/Monopoly

A **monopoly** (from Greek *monos* μόνος (alone or single) + *polein* πωλεῖν (to sell)) exists when a specific person or enterprise is the only supplier of a particular commodity [...]

Monopolies are [...] characterized by a lack of economic competition to produce the good or service, a lack of viable substitute goods

Monopoly is bad

- Yet “the one compiler” monopolized the Linux ecosystem
  - Kernel sources
  - GLIBC
  - Distribution builds

Why break the monopoly?

ASan report example: stack-buffer-overflow

```
int main(int argc, char **argv) {
  int stack_array[100];
  stack_array[1] = 0;
  return stack_array[argc + 100];  } // BOOM
% anccc++ -O1 -fsanitize=address a.cc; ./a.out
==10589== ERROR: AddressSanitizer stack-buffer-overflow
READ of size 4 at 0x7f5620d981b4 thread T0
    #0 0x4024e8 in main a.cc:4
Address 0x7f5620d981b4 is located at offset 436 in frame
  <main> of T0's stack:
  This frame has 1 object(s):
    [32, 432) 'stack_array'
```

ASan report example: use-after-free

```
int main(int argc, char **argv) {
   int *array = new int[100];
   delete [] array;
   return array[argc]; } // BOOM
% anccc++ -O1 -fsanitize=address a.cc && ./a.out
==30226== ERROR: AddressSanitizer heap-use-after-free
READ of size 4 at 0x7faa07fce084 thread T0
   #0 0x40433c in main a.cc:4
0x7faa07fce084 is located 4 bytes inside of 400-byte region
freed by thread T0 here:
   #0 0x4058fd in operator delete[](void*) _asan_rtl_
   #1 0x404303 in main a.cc:3
previously allocated by thread T0 here:
   #0 0x405579 in operator new[](unsigned long) _asan_rtl_
   #1 0x4042f3 in main a.cc:2
```

ASan report example: stack-use-after-return

```
int *g;
void LeakLocal() {
  int local;
  g = &local;
}
```

```
int main() {
  LeakLocal();
  return *g;
}
```

```
% ancc -g -fsanitize=address a.cc
% ASAN_OPTIONS=detect_stack_use_after_return=1 ./a.out
==19177==ERROR: AddressSanitizer: stack-use-after-return
READ of size 4 at 0x7f473d0000a0 thread T0
    #0 0x461ccf in main   a.cc:8

Address is located in stack of thread T0 at offset 32 in frame
    #0 0x461a5f in LeakLocal()  a.cc:2
  This frame has 1 object(s):
    [32, 36) 'local' <== Memory access at offset 32
```

TSan report example: data race

```
int X;
std::thread t([&]{X = 42;});
X = 43;
t.join();
```

```
% ancc -fsanitize=thread -g race.cc && ./a.out
WARNING: ThreadSanitizer: data race (pid=25493)
  Write of size 4 at 0x7fff7f10e338 by thread T1:
    #0 main::$_0::operator()() const race.cc:4      ...
  Previous write of size 4 at 0x7...8 by main thread:
    #0 main race.cc:5
```

MSan report example

```
int main(int argc, char **argv) {
  int x[10];
  x[0] = 1;
  return x[argc];  }
% ancc -fsanitize=memory a.c -g; ./a.out
WARNING: Use of uninitialized value
    #0 0x7f1c31f16d10 in main a.cc:4
Uninitialized value was created by an
allocation of 'x' in the stack frame of
function 'main'
```

UBSan report example: int overflow

```
int main(int argc, char **argv) {
  int t = argc << 16;
  return t * t;
}
% ancc -fsanitize=undefined a.cc -g; ./a.out
a.cc:3:12: runtime error:
signed integer overflow: 65536 * 65536
cannot be represented in type 'int'
```

UBSan report example: invalid shift

```
int main(int argc, char **argv) {
  return (1 << (32 * argc)) == 0;
}
```

```
% ancc -fsanitize=undefined a.cc -g; ./a.out
```

```
a.cc:2:13: runtime error: shift exponent 32 is
too large for 32-bit type 'int'
```

Kernel/GLIBC/Distros

- Kernel
  - KASAN: in trunk, 65+ bugs found
    - 35 use-after-free, 18 heap-out-of-bounds, 8 stack-out-of-bounds, 2 global-out-of-bounds, 2 user-memory-access
  - KTSAN: POC, 1 bug found & fixed
  - KMSAN: nope
  - KUBSAN: ???
- GLIBC:
  - Can build with ASan (tons of hacks)
  - 10+ bugs found
- Ubuntu distro:
  - Can build 60+ key libs with ASan/MSan/TSan using external scripts
  - Hard to use and maintain

- Cool, but “the one compiler” already has some of these too!

- Yes, but not all
- Yes, as the result of competition
- Wait, there is more

Sanitizers are not enough

- ASan, TSan, MSan, UBSan are “best-effort tools”:
  - They do not prove correctness
  - They are only as good as the tests are

- Beyond Sanitizers:
  - Improve test quality (aka test coverage) by fuzzing
  - Protect from security-sensitive bugs in production (hardening)

Control-flow-guided (coverage-guided) fuzzing

- Acquire a test corpus (e.g. crawl the web)
- Minimize the corpus according to some metric, e.g. (code coverage)/(execution time)
- Mutate tests from the corpus and execute them
- Run the mutations with code coverage instrumentation
- Add the mutations to the corpus if new coverage is discovered

Sanitizer Coverage instrumentation

- `-fsanitize-coverage=`
  - `func/bb/edge`: records if a function, basic block or edge was executed
  - `indirect-calls`: records unique indirect caller-callee pairs
  - `8bit-counters`: similar to AFL, provides 8 state counter for edges
    - (1, 2, 3, 4-7, 8-15, 16-31, 32-127, 128+)

- Provides the status in-process and dumps data on disk at exit and
  - i.e. supports in-process and out-of-process clients
- Should be combined with ASan, MSan, LSan, or UBSan
- Typical slowdown within 10%
  - 8bit counters may be unfriendly to multi-threaded apps

libFuzzer

- Lightweight in-process control-flow guided fuzzer
  - Provide your own target function
    - `void TestOneInput (const uint8_t *Data, size_t Size);`
  - Build: `-fsanitize-coverage=edge[,indirect-calls][,8bit-counters]`
  - Build: `-fsanitize={address,memory,undefined,leak}`
  - Link with libFuzzer

- Targeted at libraries/APIs, not at large applications

Example: OpenSSL

```
SSL_CTX *sctx;
int Init() { ... }
extern "C" void TestOneInput(unsigned char *Data, size_t Size) {
  static int unused = Init();
  SSL *server = SSL_new(sctx);
  BIO *sinbio = BIO_new(BIO_s_mem());
  BIO *soutbio = BIO_new(BIO_s_mem());
  SSL_set_bio(server, sinbio, soutbio);
  SSL_set_accept_state(server);
  BIO_write(sinbio, Data, Size);
  SSL_do_handshake(server);
  SSL_free(server);
}
```

How quickly can you find Heartbleed with fuzzing?

I. 1 Second
II. 1 Minute
III. 1 Hour
IV. 1 Day
V. 1 Month
VI. 1 Year

Yet, we still need code hardening

- Heap-buffer-overflow or heap-use-after-free may overwrite VPTRs, function pointers, array sizes, etc
  - Hijacked VPTR in Chromium: Pwn2Own 2013 (CVE-2013-0912)

- Stack-buffer-overflow or stack-use-after-return may also overwrite return addresses

- Running ASan in production costs 2x CPU/RAM -- infeasible
  - ASan can be bypassed anyway

CFI (Control Flow Integrity)

- Compile with `-fsanitize=cfi-vcall -flto` (LTO!)
- Every disjoint class hierarchy is handled separately
  - Assumes the class hierarchy is a closed system; ok for Chrome
- Layout the vtables for the entire class hierarchy as a contiguous array
  - Align every vtable by the same power-of-2
- For every virtual function call site
  - Compile-time: compute the strict set of allowed functions
  - Run-time: perform a range check, alignment check, and a bitset lookup
- Optimizations:
  - A bitset of <= 64 bits requires no memory loads
  - No check if the bitset contains all ones
  - Optimize the layouts to minimize the bitset sizes
- Chrome: builds, runs, catches real bugs, costs < 1% CPU (Linux)

CFI: generated x86_64 assembler

All ones

```
mov     $0x4008f0,%ecx
mov     %rax,%rdx
sub     %rcx,%rdx
rol     $0x3b,%rdx
cmp     $0x2,%rdx
jae     CRASH
mov     %rbx,%rdi
callq   *(%rax)
…
CRASH:  ud2
```

<= 64 bits

```
mov     $0x400e20,%edx
mov     %rax,%rcx
sub     %rdx,%rcx
rol     $0x3b,%rcx
cmp     $0xe,%rcx
ja      CRASH
mov     $0x4007,%edx
bt      %ecx,%edx
jae     CRASH
mov     %rbx,%rdi
callq   *(%rax)
…
CRASH:  ud2
```

Full check

```
mov     $0x401810,%edx
mov     %rax,%rcx
sub     %rdx,%rcx
rol     $0x3b,%rcx
cmp     $0x40,%rcx
ja      400936 CRASH
testb   $0x1,0x402140(%rcx)
je      400936 CRASH
mov     %rbx,%rdi
callq   *(%rax)
…
CRASH:  ud2
```

More CFI

- Non-virtual member calls, indirect calls
  - -fsanitize=cfi-nvcall, -fsanitize=cfi-icall
- Casts (for polymorphic types)
  - -fsanitize=cfi-derived-cast, -fsanitize=cfi-unrelated-cast
- Do not require LTO??
- Allow class hierarchies to cross the DSO boundaries
  - Maybe not a great idea??
  - Control Flow Guard (`/d2guard4 + /Guard:cf`)
- More platforms
  - Coming soon: Android, OSX, Windows

SafeStack

- Place local variables on a separate stack (separately mmaped region)
  - -fsanitize=safe-stack
  - Linux, FreeBSD, OSX
- stack-buffer-overflow/use-after-return can’t touch the return addresses
- VTPRs and function pointers can still be affected
  - Combine with -fsanitize=cfi
- Chromium: costs < 1% CPU

SafeStack: code example

```
push   %r14
push   %rbx
push   %rax
mov    0x207d0d(%rip),%r14
mov    %fs:(%r14),%rbx  # Get unsafe_stack_ptr
lea    -0x10(%rbx),%rax # Update unsafe_stack_ptr
mov    %rax,%fs:(%r14)  # Store unsafe_stack_ptr
lea    -0x4(%rbx),%rdi
movl   $0x123456,-0x4(%rbx)
callq  40f2c0 <_Z3barPi>
mov    %rbx,%fs:(%r14)  # Restore unsafe_stack_ptr
xor    %eax,%eax
add    $0x8,%rsp
pop    %rbx
pop    %r14
retq
```

```
int main() {
  int local_var = 0x123456;
  bar(&local_var);
}
```

The community can break the monopoly!

- First, make everything build with “another” compiler
  - Kernel, GLIBC, Distros
- Setup contiguous builds, don’t let it regress, ever
- Do not switch to “another” compiler completely, continue to use both
- Wait for 3-rd and 4-th compilers to appear and let them compete
- Profit!

Conclusions

- ASAN, TSAN, MSAN, UBSAN
  - Like a toothbrush: use them or risk losing your teeth
- Guided fuzzing is an extremely powerful yet under-utilized technique
  - Use it with Sanitizers
  - libFuzzer makes it easy
- Bugs will still slip into production -- use hardening
  - CFI for virtual calls, other calls, and casts
  - SafeStack
- The arms race continues, we are not done yet