Automated Test-Case Generation: Address Sanitizer

Testing, Quality Assurance, and Maintenance
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based on
https://github.com/google/sanitizers/wiki/AddressSanitizerAlgorithm
Automated Test Case Generation

Test cases can be generated automatically, but…

How to generate interesting test inputs

- **Black box** – truly random, common / interesting test patterns
- **Grey box** – guided by coverage, new inputs should cover new code paths
- **White box** – symbolic reasoning about program code, new inputs are guaranteed to cover new code paths

How to generate automatic / generic test oracles

- do not crash! (easy to check, but often not informative / soon enough)
- do not misuse memory (buffer overflow, use-after-free, …)
- no data races
- user written assertions!
- domain specific specifications and oracles
How to detect bad memory accesses

```c
void foo() {
    int *x = malloc(10*sizeof(int));
    int *y = malloc(5*sizeof(int));

    *y = *(x + 12);
}
```

Will this program crash?

- depends on the implementation of the memory allocator (`malloc()`)
- If memory for `x` and `y` is allocated next to one another, then `*(x+12)` is the same as `*(y+2)` which is well defined
- otherwise, it might crash

Unpredictable behavior makes it difficult to test and diagnose the problem. Big issue for automatic testing!
Valgrind

An instrumentation framework for dynamic analysis tools

Interprets a program on “synthetic” CPU

Analysis tools inspect CPU instructions and insert additional checks at very low level

Execution of every instruction is interpreted in a sandbox and error report is produced when suspicious behavior is detected

Pros: very detailed analysis
Cons: 10x or more slowdown in performance
Address Sanitizer

Compile-time instrumentation

Supported by Clang and GCC

Run-time library (~ 5 KLOC)

Supports {x86, x86_64} x {Linux, Mac, Windows}

Found hundreds of bugs since 2011

- often used in production code
- major part of any automated test-case generation validation
Key Idea: Instrument all Memory Accesses

The compiler instruments each store and load instruction with a check whether the memory being accessed is accessible (not poisoned)

• instrumentation must be very very efficient!
• meta-information about memory (poison/non-poison/etc) must be stored somewhere

Original

*addr = e

e = *addr

Instrumented

if (IsPoisoned(addr))
    ReportError(addr, sz, true);
    *addr = e;

if (IsPoisoned(addr))
    ReportError(addr, sz, false);
    e = *addr;
Memory Mapping

Virtual memory is divided into two disjoint classes: Mem and Shadow

- **Mem** is the normal application memory
- **Shadow** is memory that keeps track of meta-data (information) about main memory. For each byte $addr$ of Mem, Shadow contains a descriptor $Shadow[addr]$.

Poisoning a byte $addr$ of Mem means writing a special value to corresponding place in Shadow.

**Mem** and **Shadow** must be organized in such a way that mapping Mem address to Shadow is super fast.

```plaintext
shadow_addr = MemToShadow(addr);
if (ShadowIsPoisoned(shadow_addr)) {
    ReportError(addr, sz, kIsWrite);
}
```
Memory Alignment

Process memory is divided into 8 byte words, called QWORDS.

Heap and stack allocation (malloc(), alloca(), local variables) are allocated at a qword boundary:
- i.e., address of an allocated memory is always divisible by 8
- this is called alignment (of 8 bytes)
- actual alignment depends on the architecture (4, 8, 16, 128 are possible)
- For simplicity, we fix all alignments at 8 bytes

Depending on the architecture (ARM, Intel, ...) unaligned memory accesses are expensive / impossible:
- Compilers and runtime allocators optimize the code so that most accesses are aligned
State of an allocated QWORD

AddressSanitizer maps each QWORD of Mem into one byte of Shadow

Each QWORD can be in one of 9 states
- All 8 bytes are accessible (not poisoned). Shadow value is 0
- All 8 bytes are inaccessible (poisoned). Shadow value is negative (< 0)
- First \( k \) bytes are accessible, the rest \( 8-k \) bytes are not, \( 0 < k < 8 \). Shadow is \( k \)

No other cases are possible because allocation is aligned at QWORD boundary
- e.g., \texttt{malloc(12)} allocated 2 QWORDS
  - all 8 bytes of the first qword are accessible
  - only 4 bytes of the second qword are accessible
New Instrumentation

byte *shadow_addr = MemToShadow(addr);
byte shadow_value = *shadow_addr;

if (shadow_value < 0) ReportError(addr, sz, kIsWrite);
else if (shadow_value) {
    if (SlowPathCheck(shadow_value, addr, sz)) {
        ReportError(addr, sz, kIsWrite);
    }
}

bool SlowPathCheck(shadow_value, addr, sz) {
    last_accessed_byte = (addr + sz - 1) % 8;
    return (last_accessed_byte >= shadow_value);
}
New Instrumentation (with some bit magic)

```c
byte *shadow_addr = MemToShadow(addr);
byte shadow_value = *shadow_addr;

if (shadow_value < 0) ReportError(addr, sz, kIsWrite);
else if (shadow_value) {
    if (SlowPathCheck(shadow_value, addr, sz)) {
        ReportError(addr, sz, kIsWrite);
    }
}

bool SlowPathCheck(shadow_value, addr, sz) {
    last_accessed_byte = (addr & 7) + sz - 1;
    return (last_accessed_byte >= shadow_value);
}
```
MemToShadow: The big trick

MemToShadow(addr) must map each QWORD of application memory Mem to a byte of the shadow memory Shadow

Must be very very very efficient
• as few CPU instructions as possible

Exploits the physical layout of process memory
Process Address Space Layout

Kernel space
User code CANNOT read from or write to these addresses, doing so results in a Segmentation Fault

Stack (grows down)

Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so

Heap

BSS segment
Uninitialized static variables, filled with zeros. Example: static char *userName;

Data segment
Static variables initialized by the programmer. Example: static char *gonzo = “God’s own prototype”;

Text segment (ELF)
Stores the binary image of the process (e.g., /bin/gonzo)

0x00000000 == TASK_SIZE
Random stack offset
RLIMIT_STACK (e.g., 8MB)
Random mmap offset

program break
brk
start_brk
Random brk offset

eend_data
start_data
end_code

0x08048000
0
Mapping: Shadow = (Mem >> 3) + 0x20000000

HighMem

HShadow

Unused

LShadow

LowMem
Final Instrumentation (with all the magic)

```c
byte *shadow_addr = addr >> 3 + 0x20000000;
byte shadow_value = *shadow_addr;

if (shadow_value < 0) ReportError(addr, sz, kIsWrite);
else if (shadow_value) {
    if (SlowPathCheck(shadow_value, addr, sz)) {
        ReportError(addr, sz, kIsWrite);
    }
}

bool SlowPathCheck(shadow_value, addr, sz) {
    last_accessed_byte = (addr & 7) + sz - 1;
    return (last_accessed_byte >= shadow_value);
}
```
But does this work for our original example?

```c
void foo() {
    int *x = malloc(10*sizeof(int));
    int *y = malloc(5*sizeof(int));

    *y = *(x + 12);
}
```

Will this program crash?

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Marking Allocation boundaries with redzones

Change heap allocator to mark boundaries of allocated segments
- The markers are called redzones
- All calls to malloc() are replaced with calls to __asan_malloc()

```c
void *__asan_malloc(size_t sz) {
    void *rz = malloc(RED_SZ);
    Poison(rz, RED_SZ);

    void *addr = malloc(sz);
    UnPoison(addr, sz);

    rz = malloc(RED_SZ);
    Poison(rz, RED_SZ);
    return addr;
}
```
What about the Stack

```c
void foo() {
    char a[8];

    ...

    return;
}
```

No explicit allocation
Need to ensure proper alignment
Need to insert redzones
void foo() {
    char redzone1[32];    // 32-byte aligned
    char a[8];            // 32-byte aligned
    char redzone2[24];
    char redzone3[32];    // 32-byte aligned
    int *shadow_base = MemToShadow(redzone1);
    shadow_base[0] = 0xffffffff;  // poison redzone1
    shadow_base[1] = 0xffffffff00;  // poison redzone2, unpoison 'a'
    shadow_base[2] = 0xffffffff;  // poison redzone3

    ...

    return;
}
Instrumentation in X86 ASM

```c
# long load8(long *a) { return *a; }

0000000000000030 <load8>:
30: 48 89 f8        mov     %rdi,%rax
 33:  48 c1 e8 03    shr     $0x3,%rax
 37:  80 b8 00 80 ff 7f 00 cmppb $0x0,0x7fff8000(%rax)
 3e:  75 04          jne    44 <load8+0x14>
 40:  48 8b 07      mov     (%rdi),%rax <<< original load
 43:  c3            retq
 44:  52            push    %rdx
 45:  e8 00 00 00 00 00 callq __asan_report_load8
```
Instrumentation in X86 ASM

```c
#include <asm/fatal.h>

int load4(int *a) { return *a; }
```

```assembly
0000000000000000 <load4>:
    0:  48 89 f8       mov   %rdi,%rax
    3:  48 89 fa       mov   %rdi,%rdx
    6:  48 c1 e8 03    shr   $0x3,%rax
   a:  83 e2 07       and   $0x7,%edx
   d:  0f b6 80 00 80 ff 7f  movzbl 0x7fff8000(%rax),%eax
   14: 83 c2 03       add   $0x3,%edx
   17: 38 c2          cmp   %al,%dl
   19: 7d 03          jge   1e <load4+0x1e>
   1b: 8b 07          mov   (%rdi),%eax <<<<<< original Load
   1d: c3             retq
   1e: 84 c0          test  %al,%al
   20: 74 f9          je    1b <load4+0x1b>
   22: 50             push  %rax
   23: e8 00 00 00 00 00 callq __asan_report_load4
```
Other Available Sanitizers (in Clang)

ThreadSafetySanitizers
• race conditions. Is a variable being modified/accessed by two threads without being protected by a lock

MemorySanitizer
• uninitialized reads. 3x slow-down
• requires **ALL** code to be instrumented

Undefined Behavior Sanitizer (ubsan)
• many checks for undefined behaviors such as integer overflow, nullptr, etc.

DataFlowSanitizer
• a framework to write data-flow dynamic sanitizers
  • CREATE YOUR OWN!

Leak Sanitizer
• detects memory leaks
• no performance overhead