

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

```
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) 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

```
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., `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)

```
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

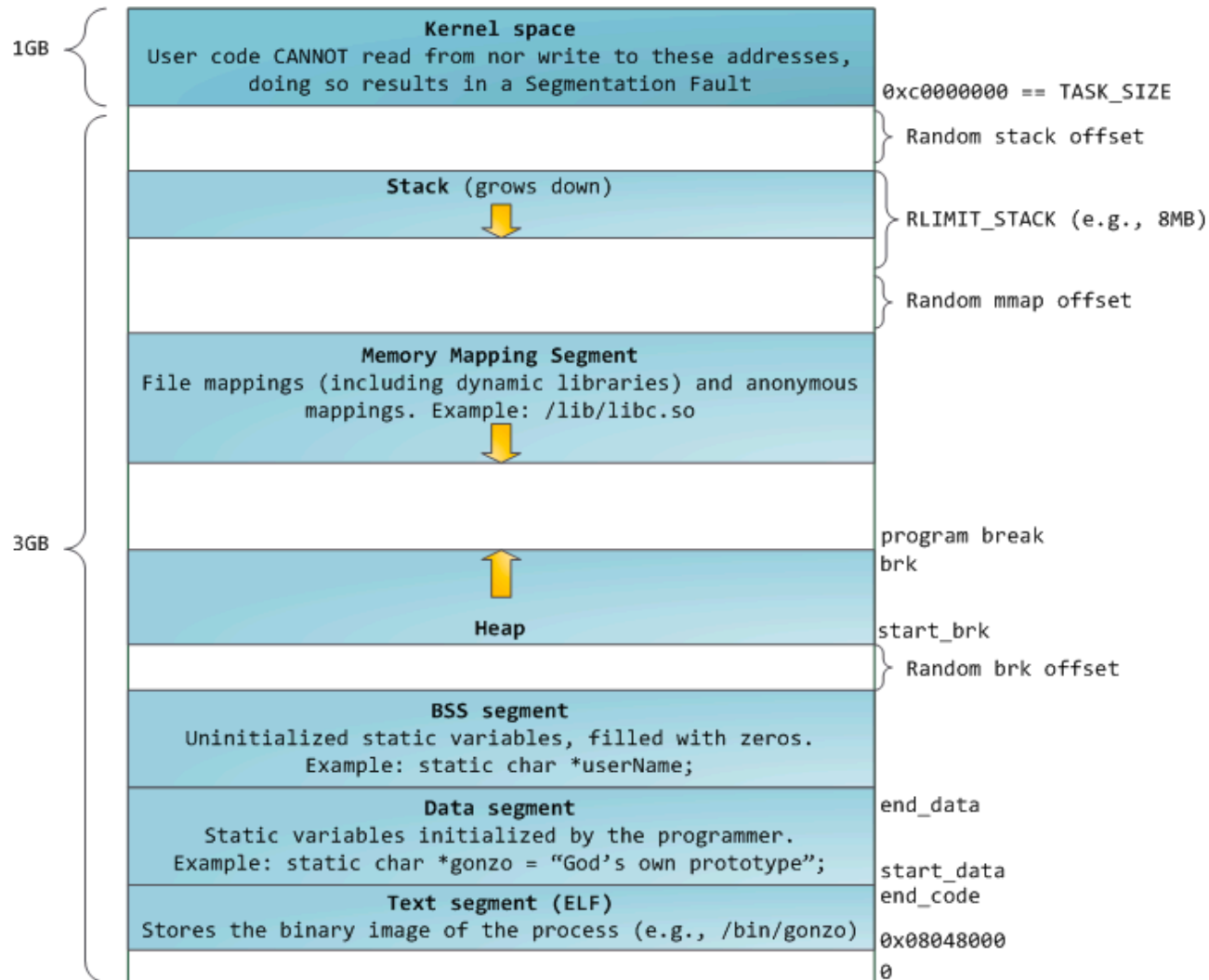
MemToShadow(addr) must map each QWORD of application memory Mem to a byte of the shadow memory Shadow

Must be very very very efficient

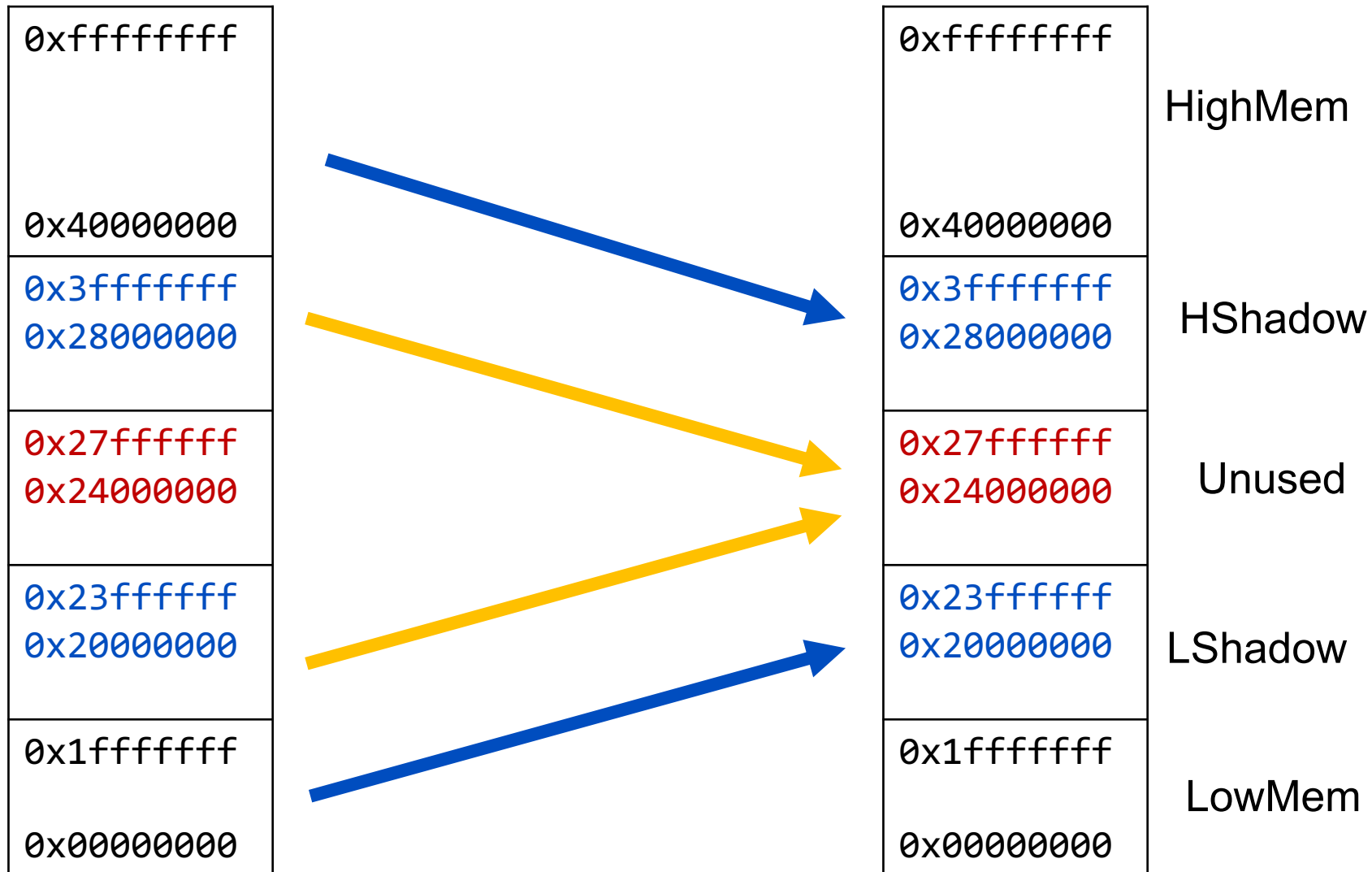
- as few CPU instructions as possible

Exploits the physical layout of process memory

Process Address Space Layout



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



Final Instrumentation (with all the magic)

```
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?

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

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()`

```
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

```
void foo() {  
    char a[8];  
  
    ...  
  
    return;  
}
```

No explicit allocation

Need to ensure proper alignment

Need to insert redzones

Instrumented Stack Example

```
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

    ...

    shadow_base[0] = shadow_base[1] = shadow_base[2] = 0; // unpoison all
    return;
}
```

Instrumentation in X86 ASM

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

```
000000000000000030 <load8>:
```

```
30: 48 89 f8          mov    %rdi,%rax
33: 48 c1 e8 03       shr    $0x3,%rax
37: 80 b8 00 80 ff 7f 00  cmpb  $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   callq __asan_report_load8
```

Instrumentation in X86 ASM

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

```
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   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