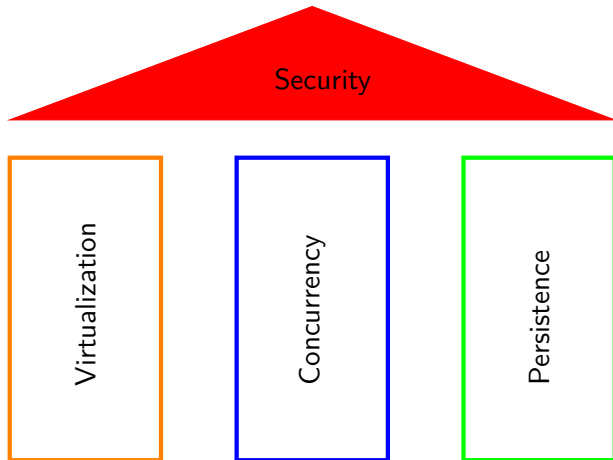


CS323 Operating Systems

Testing (Fuzzing/Sanitization)

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Topics covered in this lecture

- Software testing
- Fuzzing
- Sanitization

This slide deck covers [chapter 5.3](#) in SS3P.

Why testing?

*Testing is the process of **executing code** to **find errors**.*

An error is a deviation between observed behavior and specified behavior, i.e., a violation of the underlying specification:

- Functional requirements (features a, b, c)
- Operational requirements (performance, usability)
- Security requirements?

Testing can only show the presence of bugs, never their absence. (Edsger W. Dijkstra)

A successful test finds a deviation. Testing is a form of dynamic analysis. Code is executed, the testing environment observes the behavior of the code, detecting violations.

- Key advantage: reproducible, generally testing gives you the concrete input for failed test cases.
- Key disadvantage: complete testing of all control-flow/data-flow paths reduces to the halting problem, in practice, testing is hindered due to state explosion.

Forms of testing

- Manual testing
- Fuzz testing
- Symbolic and concolic testing

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We focus on *security* testing or testing to find *security* bugs, i.e., bugs that are reachable through attacker-controlled inputs.

Recommended reading: [A Few Billion Lines of Code Later: Using Static Analysis to Find Bugs in the Real World](#)

Intuition: A software flaw is only detected if the flawed statement is executed. Effectiveness of test suite therefore depends on how many statements are executed.

How to measure code coverage?

Several (many) tools exist:

- gcov: <https://gcc.gnu.org/onlinedocs/gcc/Gcov.html>
- SanitizerCoverage:
<https://clang.llvm.org/docs/SourceBasedCodeCoverage.html>

Fuzz testing (fuzzing) is an automated software testing technique. Key idea: execute the target program with an input and check if it crashes. The fuzzing engine automatically generates new inputs based on some criteria:

- Random mutation
- Leveraging input structure
- Leveraging program structure

The inputs are then run on the test program and, if it crashes, a crash report is generated.

- Fuzzing finds bugs effectively (CVEs)
- Proactive defense, part of testing
- Preparing offense, part of exploit development

Fuzzers generate new input based on generations or mutations.

- **Generation-based** input generation produces new input seeds in each round, independent from each other.
- **Mutation-based** input generation leverages existing inputs and modifies them based on feedback from previous rounds.

Programs accept some form of *input/output* Generally, the input/output is structured and follows some form of protocol.

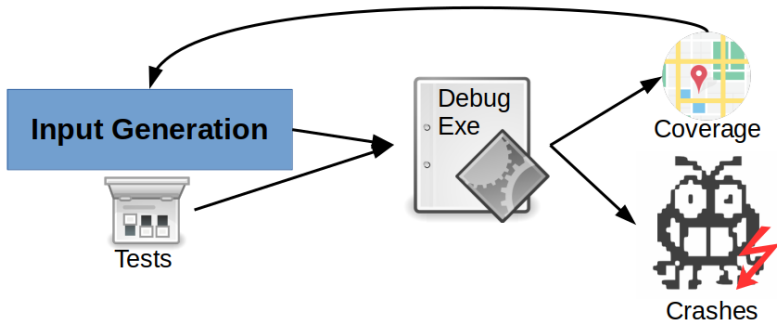
- ***Dumb fuzzing*** is unaware of the underlying structure.
- ***Smart fuzzing*** is aware of the protocol and modifies the input accordingly.

Example: a checksum at the end of the input. A dumb fuzzer will likely fail the checksum.

The input is processed by the program, based on the *program structure* (and from the past executions), input can be adapted to trigger new conditions.

- **White box** fuzzing leverages semantic program analysis to mutate input
- **Grey box** leverages program instrumentation based on previous inputs
- **Black box** fuzzing is unaware of the program structure

Coverage-guided grey box fuzzing

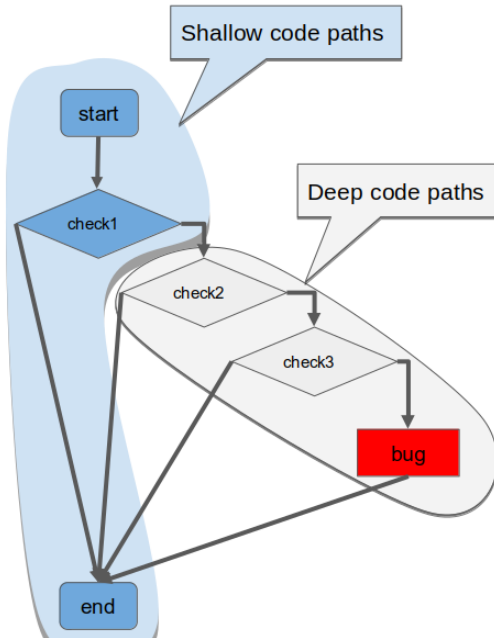


- AFL is the most well-known fuzzer currently
- AFL uses grey-box instrumentation to track branch coverage and mutate fuzzing seeds based on previous branch coverage
- The branch coverage tracks the last two executed basic blocks
- New coverage is detected on the history of the last two branches: `cur XOR prev>>1`
- AFL: <http://lcamtuf.coredump.cx/afl/>

Fuzzer challenges: coverage wall

- After certain iterations the fuzzer no longer makes progress
- Hard to satisfy checks
- Chains of checks
- Leaps in input changes

Fuzzer challenges: coverage wall



- How do we detect program faults?

- How do we detect program faults?
- Test cases detect bugs through
 - Assertions (`assert(var != 0x23 && "var has illegal value");`) detect violations
 - Segmentation faults
 - Division by zero traps
 - Uncaught exceptions
 - Mitigations triggering termination
- How can you increase the chances of detecting a bug?

Sanitizers enforce a given policy, detect bugs earlier and increase effectiveness of testing. Most sanitizers rely on a combination of static analysis, instrumentation, and dynamic analysis.

- The program is analyzed during compilation (e.g., to learn properties such as type graphs or to enable optimizations)
- The program is instrumented, often to record metadata at certain places and to enforce metadata checks at other places.
- At runtime, the instrumentation constantly verified that the policy is not violated.

What policies are interesting? What metadata do you need? Where would you check?

AddressSanitizer (1/2)

AddressSanitizer (ASan) detects memory errors. It places red zones around objects and checks those objects on trigger events. The tool can detect the following types of bugs:

- Out-of-bounds accesses to heap, stack and globals
- Use-after-free
- Use-after-return (configurable)
- Use-after-scope (configurable)
- Double-free, invalid free
- Memory leaks (experimental)

Typical slowdown introduced by AddressSanitizer is 2x.

- What kind of metadata would you record? Where?
- What kind of operations would you instrument?
- What kind of optimizations could you think of?

Idea: store the state of each word in shadow memory (i.e., is it accessible or not)

- An 8-byte aligned word of memory has only 9 states
- First N-bytes are accessible, 8-N are not
 - 0: all accessible
 - 7: first 7 accessible
 - 6: first 6 accessible
 - ...
 - 1: first byte accessible
 - -1: no byte accessible
- Trade-off between alignment and encoding (extreme: 128 byte alignment, per byte)

ASan instrumentation: memory access

```
long *addr = getAddr();
long val;
char *shadow = (addr>>3) + shadowbse;

// 8-byte access (read/write)
if (*shadow)
    ReportError(a);
val = *addr;

// N-byte access instead:
if (*shadow && *shadow <= ((addr&7)+N-1))
```

ASan instrumentation: asm

```
shr $0x3,%rax      # shift by 3
mov $0x100000000000,%rcx
or %rax,%rcx       # add offset
cmpb $0x0,(%rcx)   # load shadow
je .out
ud2                # generate SIGILL
.out:
movq $0x1234,(%rdi) # original store
```

ASan instrumentation: stack

Insert red zones around objects on stack, poison them when entering stack frames.

```
void foo() {  
    char rz1[32]; // 32-byte aligned  
    char a[8];  
    char rz2[24];  
    char rz3[32];  
    int *shadow = (&rz1 >> 3) + kOffset;  
    shadow[0] = 0xffffffff; // poison rz1  
    shadow[1] = 0xffffffff00; // poison rz2  
    shadow[2] = 0xffffffff; // poison rz3  
    <----- CODE ----->  
    shadow[0] = shadow[1] = shadow[2] = 0;  
}
```

ASan instrumentation: globals

Insert red zone after global object, poison in init.

```
int a;  
// translates to  
struct {  
    int original;  
    char redzone[60];  
} a; // again, 32-byte aligned
```

- Initializes shadow map at startup
- Replaces malloc/free to update metadata (and pad allocations with redzones)
- Intercepts special functions such as `memset`

ASan report (1/2)

```
int main(int argc, char **argv) {  
    int *array = new int[100];  
    delete [] array;  
    return array[argc]; // BOOM  
}
```

ASan report (2/2)

```
gannimo@wasp clang++ -fsanitize=address -g test.cpp
gannimo@wasp ./a.out test
=====
==7862==ERROR: AddressSanitizer: heap-use-after-free on address 0x61400000fe48 at pc 0x0000004ed812 bp 0x7ffdf6c39de0 sp 0x7ffdf6c39dd8
READ of size 4 at 0x61400000fe48 thread T0
#0 0x4ed811 (/home/gannimo/a.out+0x4ed811)
#1 0x7f3686d382e0 (/lib/x86_64-linux-gnu/libc.so.6+0x202e0)
#2 0x41b2f9 (/home/gannimo/a.out+0x41b2f9)

0x61400000fe48 is located 8 bytes inside of 400-byte region [0x61400000fe40,0x61400000ffd0)
freed by thread T0 here:
#0 0x4eb0d0 (/home/gannimo/a.out+0x4eb0d0)
#1 0x4ed7c6 (/home/gannimo/a.out+0x4ed7c6)
#2 0x7f3686d382e0 (/lib/x86_64-linux-gnu/libc.so.6+0x202e0)

previously allocated by thread T0 here:
#0 0x4eaad0 (/home/gannimo/a.out+0x4eaad0)
#1 0x4ed7a4 (/home/gannimo/a.out+0x4ed7a4)
#2 0x7f3686d382e0 (/lib/x86_64-linux-gnu/libc.so.6+0x202e0)

SUMMARY: AddressSanitizer: heap-use-after-free (/home/gannimo/a.out+0x4ed811)
Shadow bytes around the buggy address:
 0x0c287fff9f70: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
 0x0c287fff9f80: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
 0x0c287fff9f90: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
 0x0c287fff9fa0: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
 0x0c287fff9fb0: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
=>0x0c287fff9fc0: fa fa fa fa fa fa fa fa fd[fd]fd fd fd fd fd fd
 0x0c287fff9fd0: fd fd fd fd fd fd fd fd fd fd fd fd fd fd fd
 0x0c287fff9fe0: fd fd fd fd fd fd fd fd fd fd fd fd fd fd fd
 0x0c287fff9ff0: fd fd fd fd fd fd fd fd fd fd fa fa fa fa fa
 0x0c287fffa000: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
 0x0c287fffa010: fa fa fa fa fa fa fa fa fa fa fa fa fa fa fa
Shadow byte legend (one shadow byte represents 8 application bytes):
Addressable: 00
Partially addressable: 01 02 03 04 05 06 07
Heap left redzone: fa
Heap right redzone: fb
Freed heap region: fd
Stack left redzone: f1
Stack mid redzone: f2
Stack right redzone: f3
Stack partial redzone: f4
Stack after return: f5
Stack use after scope: f8
Global redzone: f9
Global init order: f6
Poisoned by user: f7
Container overflow: fc
Freeing buffer: ff
```

- Instrument every single access, check for poison value in shadow table
- Advantage: fast checks
- Disadvantage: large memory overhead (especially on 64 bit), still slow (2x)

LeakSanitizer detects run-time memory leaks. It can be combined with AddressSanitizer to get both memory error and leak detection, or used in a stand-alone mode.

LSan adds almost no performance overhead until process termination, when the extra leak detection phase runs.

MemorySanitizer detects uninitialized reads. Memory allocations are tagged and uninitialized reads are flagged.

Typical slowdown of MemorySanitizer is 3x.

Note: do not confuse MemorySanitizer and AddressSanitizer.

UndefinedBehaviorSanitizer (UBSan) detects undefined behavior. It instruments code to trap on typical undefined behavior in C/C++ programs. Detectable errors are:

- Unsigned/misaligned pointers
- Signed integer overflow
- Conversion between floating point types leading to overflow
- Illegal use of NULL pointers
- Illegal pointer arithmetic
- ...

Slowdown depends on the amount and frequency of checks. This is the only sanitizer that can be used in production. For production use, a special minimal runtime library is used with minimal attack surface.

ThreadSanitizer detects data races between threads. It instruments writes to global and heap variables and records which thread wrote the value last, allowing detecting of WAW, RAW, WAR data races.

Typical slowdown is 5-15x with 5-15x memory overhead.

HexType detects type safety violations. It records the true type of allocated objects and makes all type casts explicit.

Typical slowdown is 0.5x.

- AddressSanitizer:
<https://clang.llvm.org/docs/AddressSanitizer.html>
- LeakSanitizer: <https://clang.llvm.org/docs/LeakSanitizer.html>
- MemorySanitizer:
<https://clang.llvm.org/docs/MemorySanitizer.html>
- UndefinedBehaviorSanitizer:
<https://clang.llvm.org/docs/UndefinedBehaviorSanitizer.html>
- ThreadSanitizer:
<https://clang.llvm.org/docs/ThreadSanitizer.html>
- HexType: <https://github.com/HexHive/HexType>

Use sanitizers to test your code. More sanitizers are in development.

Summary and conclusion

- Software testing finds bugs before an attacker can exploit them
- Manual testing: write test cases to trigger exceptions
- Fuzz testing automates and randomizes testing
- Sanitizers allow early bug detection, not just on exceptions
- AddressSanitizer is the most commonly used sanitizer and enforces probabilistic memory safety by recording metadata for every allocated object and checking every memory read/write.

Don't forget to get your learning feedback through the Moodle quiz!