Week 6: Lecture B
Automated Bug Finding

Thursday, September 26, 2024

Announcements

- **Project 2: AppSec** released
  - **Deadline:** Thursday, October 17th by 11:59PM

Project 2: Application Security

Deadline: Thursday, October 17 by 11:59PM.

Before you start, review the course syllabus for the Lateness, Collaboration, and Ethical Use policies.

You may optionally work alone, or in teams of **at most two** and submit **one project per team**. If you have difficulties forming a team, post on **Piazza's Search for Teammates** forum. Note that the final exam will cover project material, so you and your partner should collaborate on each part.

The code and other answers your group submits must be entirely your own work, and you are bound by the University's Student Code. You may consult with other students about the conceptualization of the project and the meaning of the questions, but you may not look at any part of someone else's solution or collaborate with anyone outside your group. You may consult published references, provided that you appropriately cite them (e.g., in your code comments). **Don't risk your grade and degree by cheating!**

Complete your work in the **CS 4440 VM**—we will use this same environment for grading. You may not use any **external dependencies**. Use only default Python 3 libraries and/or modules we provide you.

Helpful Resources

- The CS 4440 Course Wiki
- VM Setup and Troubleshooting
- Terminal Cheat Sheet
- GDB Cheat Sheet
- x86 Cheat Sheet
- C Cheat Sheet

Table of Contents:

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  - What to Submit
- Part 2: Intermediate Exploits
  - Target 2: Shellcode Redirect
  - Target 3: Indirect Overwrite
  - Target 4: Beyond Strings
  - What to Submit
- Part 3: Advanced Exploits
  - Target 5: Bypassing DEP
  - Target 6: Bypassing ASLR
  - What to Submit
- Part 4: Super L33T Pwnage
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Project 2 Progress Update!

Finished Target 0!	0%
Finished Target 1!	0%
Finished Target 2!	0%
Finished Target 3!	0%
Finished Target 4!	0%
Haven't started :(	0%

Announcements

- **Project 1** grades are now available on **Canvas**

- Think we made an error? Request a regrade!
  - Valid regrade requests:
    - You have verified your solution is correct (i.e., we made an error in grading)

Project 1 Regrade Requests (see **Piazza** pinned link):
Submit by **11:59 PM** on **Monday 9/30** via **Google Form**

Announcements

ACM

AT THE

UNIVERSITY OF UTAH

See Discord for meeting info!

acm.cs.utah.edu

Announcements

utahsec

See Discord for meeting info!

utahsec.cs.utah.edu

Questions?

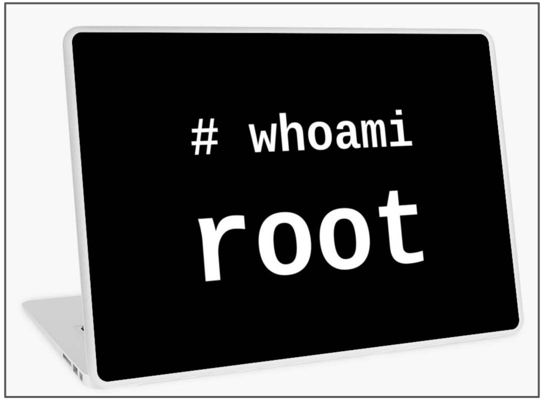
Last time on CS 4440…

Advanced Exploitation Techniques
ASLR, DEP, and Workarounds
Other Application-level Defenses

Recap: Spawning Shells

- **Attacker goal:** make program open a **root shell**
  - Root-level permissions = **total system ownage**
  - **You'll do this in Project 2!**

- **Shellcode** = code to open a root shell
  - Inject this somewhere and **direct execution to it**
  - Basic structure:
    1. Call `setuid(0)` to set user ID to "`root`"
    2. Open a shell with `execve("/bin/sh")`



`setuid(0)` + `execve("/bin/sh")`

Shell Spawning in C

```
#include <stdio.h>

void main() {
    char *argv[1];
    argv[0] = "/bin/sh";
    execve(argv[0], NULL, NULL);
}
```

Shell inherits same **privileges** as the original "parent" process

If the original process **run as root**, shell gives **????** access

Shell Spawning in C

```c
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If the original process **run as** **root**, shell gives **root** access

Shell Spawning in C

```
#include <s

void main()
    char *a
    argv[0]
    execve(
}
```

privileges
nt” process

ss run as
ot access

Invoking a Shell

```
main:
      pushl   %ebp
      movl    %esp, %ebp
      pushl   $0
      pushl   $0
      pushl   $.LC0
      call    execve
      leave
      ret
```

main()'s **locals**

??????????????????
??????????????????
??????????????????

Invoking a Shell

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   $0
        pushl   $0
        pushl   $.LC0
        call    execve
        leave
        ret

.LC0:
        .string "/bin/sh"
```

main()'s **locals**

arg3 = **NULL**
arg2 = **NULL**
addr to “**/bin/sh**”

Invoking a Shell

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   $0
        pushl   $0
        pushl   $.LC0
        call
        leav
        ret

.LC0:
        .string "/bin/sh"
```

execve("/bin/sh", NULL, NULL);

main()'s **locals**
arg3 = **NULL**
arg2 = **NULL**
addr to "**/bin/sh**"
execve()'s **ret addr**

Invoking a Shell

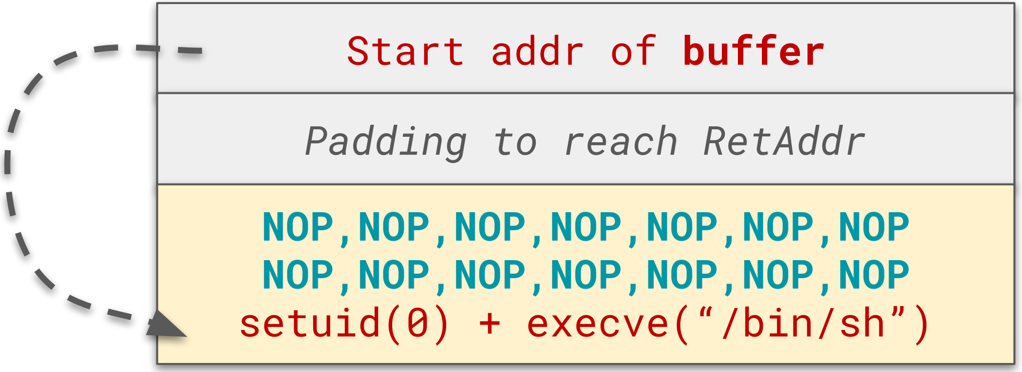
- **Project 2:** we give you shellcode to set up and call **`execve(/bin/sh)`**
  - This will initialize the correct call frame accordingly

- **Key idea: ???**

Vulnerable Function's RetAddr
Saved EBP, local vars, etc.
Vulnerable Buffer

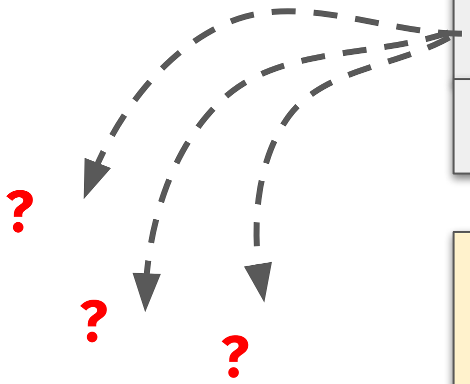
Invoking a Shell

- **Project 2:** we give you shellcode to set up and call **`execve(/bin/sh)`**
  - This will initialize the correct call frame accordingly
- **Key idea:** place the shellcode in an **executable buffer**
  - **“Executable”** means you are able to **execute code inside of it**
  - ... then direct execution to it, and **BOOM!**



Pesky Defenses

- Our provided shellcode requires an **executable buffer**
- **What if the buffer is relocated on every new run?**




```
Start addr of buffer = ?????
```

Padding to reach RetAddr

WHERE?

Defeating ASLR

- Suppose the buffer is **sufficiently large**
  - We can still place our shellcode there
  - Prepend it with a ton of **NOPs**

- We cannot know buffer's **exact start…**
  - But we can **guess an address inside of it**
    - It is a really large buffer, after all

- **Idea: ????**

?

```
NOP,NOP,NOP,NOP,NOP,NOP,NOP
NOP,NOP,NOP,NOP,NOP,NOP,NOP
NOP,NOP,NOP,NOP,NOP,NOP,NOP
NOP,NOP,NOP,NOP,NOP,NOP,NOP
NOP,NOP,NOP,NOP,NOP,NOP,NOP
setuid(0) + execve("/bin/sh")
```

Defeating ASLR

- Suppose the buffer is **sufficiently large**
  - We can still place our shellcode there
  - Prepend it with a ton of **NOPs**
- We cannot know buffer's **exact start…**
  - But we can **guess an address inside of it**
    - It is a really large buffer, after all
- **Idea:** spam **"guessed" buffer addr** up the stack

```
Guessed addr within buffer
Guessed addr within buffer
Guessed addr within buffer
Guessed addr within buffer
Guessed addr within buffer
```

```
setuid(0) + execve("/bin/sh")
NOP,NOP,NOP,NOP,NOP,NOP,NOP
NOP,NOP,NOP,NOP,NOP,NOP,NOP
NOP,NOP,NOP,NOP,NOP,NOP,NOP
NOP,NOP,NOP,NOP,NOP,NOP,NOP
NOP,NOP,NOP,NOP,NOP,NOP,NOP
```

Defeating ASLR

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- **Idea:** spam **"guessed" buffer addr** up the stack
  - Eventually we'll overwrite some **return address**

Guessed addr within **buffer**
Guessed addr within **buffer**
Overwritten **Return Addr**
Guessed addr within **buffer**
Guessed addr within **buffer**

```
setuid(0) + execve("/bin/sh")
NOP,NOP,NOP,NOP,NOP,NOP,NOP
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```

Defeating ASLR

- Suppose the buffer is **sufficiently large**
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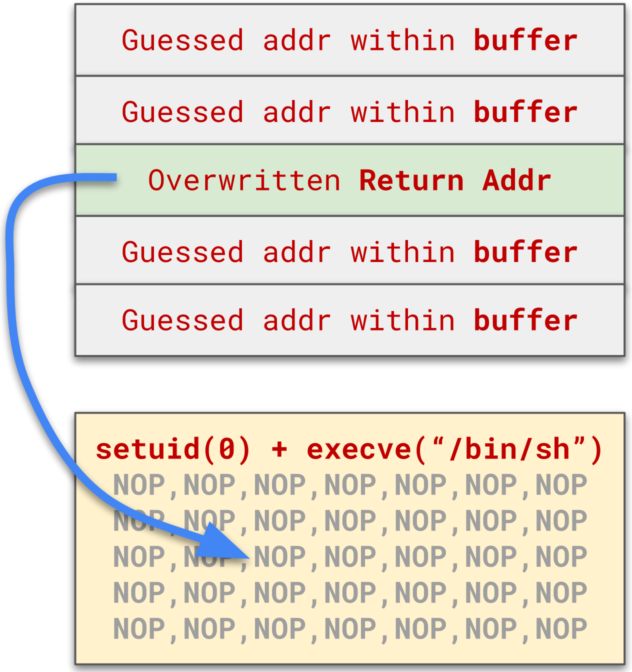
- **Idea:** spam **"guessed" buffer addr** up the stack
  - Eventually we'll overwrite some **return address**
  - When that function returns, jump inside buffer
  - **Hit the huge NOP sled → BOOM!**



Pesky Defenses

- Our provided shellcode requires an **executable buffer**
- **What if the buffer is prohibited from being executable?**

Start addr of **buffer**
Padding to reach RetAddr
NOP,NOP,NOP,NOP,NOP,NOP,NOP **NOP,NOP,NOP,NOP,NOP,NOP,NOP** setuid(0) + execve("/bin/sh")

Pesky Defenses

- Our provided shellcode requires an **executable buffer**
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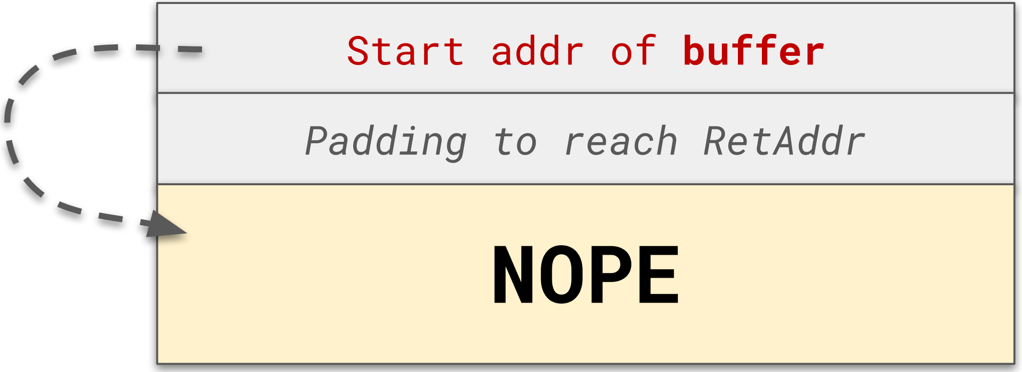


Defeating DEP

- Suppose we can still overwrite buffer
  - We **cannot** place our shellcode there
  - But, we can **overwrite other stack items**
- Suppose the program calls a function that can **execute arbitrary commands**
  - execve()
  - system()
- **Idea #1:** overwrite **????**

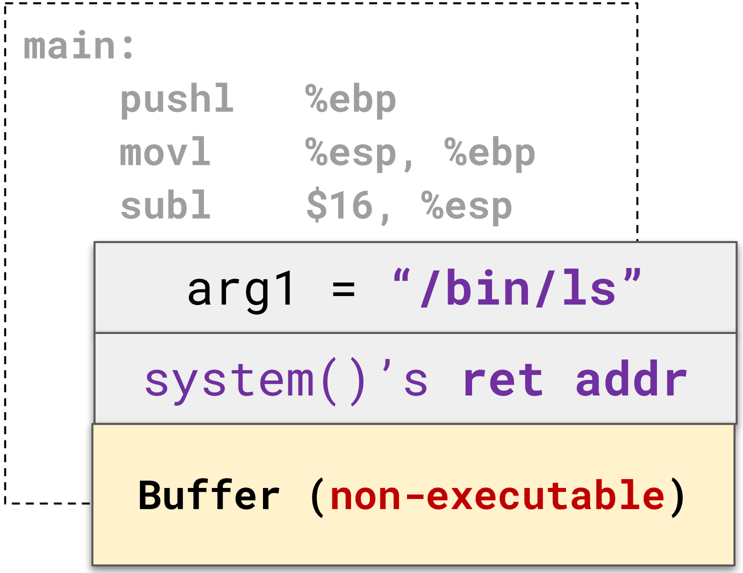
```
main:
    pushl   %ebp
    movl    %esp, %ebp
    subl    $16, %esp
    pushl   "/bin/ls"
    call    system
    leave
    ret
```

Defeating DEP

- Suppose we can still overwrite buffer
  - We **cannot** place our shellcode there
  - But, we can **overwrite other stack items**

- Suppose the program calls a function that can **execute arbitrary commands**
  - `execve()`
  - `system()`

- **Idea #1:** overwrite argument to `system()`
  - Replace it with our shell command (“`/bin/sh`”)



Defeating DEP

- Suppose we can still overwrite buffer
  - We **cannot** place our shellcode there
  - But, we can **overwrite other stack items**
- Suppose the program calls a function that can **execute arbitrary commands**
  - `execve()`
  - `system()`
- **Idea #1:** overwrite argument to `system()`
  - Replace it with our shell command (`"/bin/sh"`)
  - Will now execute **`system("/bin/sh")`**!

```
main:
     pushl   %ebp
     movl    %esp, %ebp
     subl    $16, %esp
```

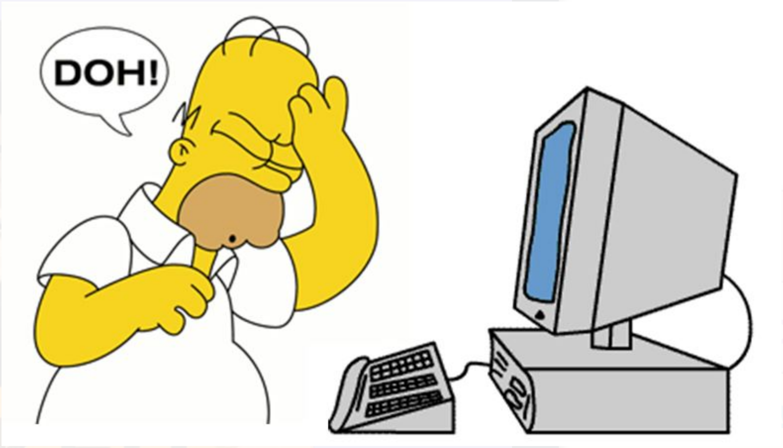
`arg1 = "/bin/sh"`
`system()'s ret addr`
AAAAAAAAAAAAAAAAAAAAAAA AAAAAAAAAAAAAAAAAAAAAAA

Defeating DEP

- Suppose
  - We car
  - But, we
- Suppose
  that can e
  - execv
  - syste
- **Idea #1:** o
  - Replac
  - Will no

%ebp
%esp
"/bin/sh"
s ret addr
AAAAAAAAAAAA
AAAAAAAAAAAA

Defeating DEP

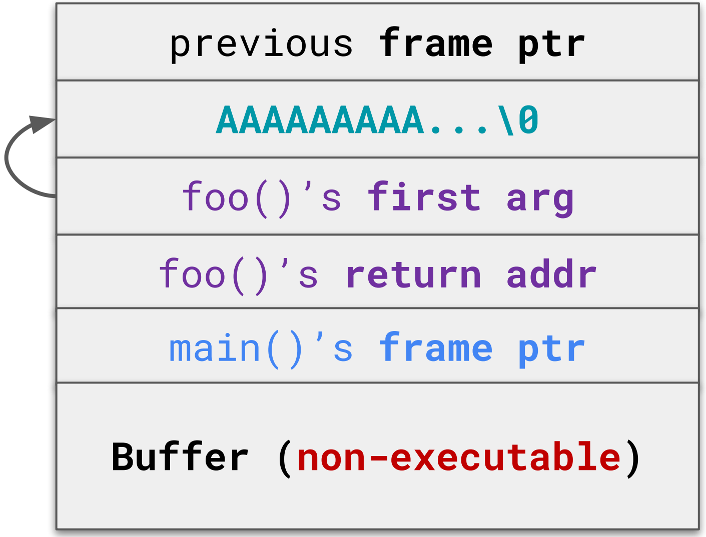



```
segmentation fault.
(Core dumped)
```

Defeating DEP

- Suppose system( ) isn't executed, but **a call to it exists somewhere**
  - You can examine the **objdump** to look for "interesting" functions in the program

```
void foo(char *str) {
    char buffer[16];
    strcpy(buffer, str)
}
void main() {
    char buf[256];
    memset(buf, 'A', 255);
    buf[255] = '\x00';
    foo(buf);
}
```



Defeating DEP

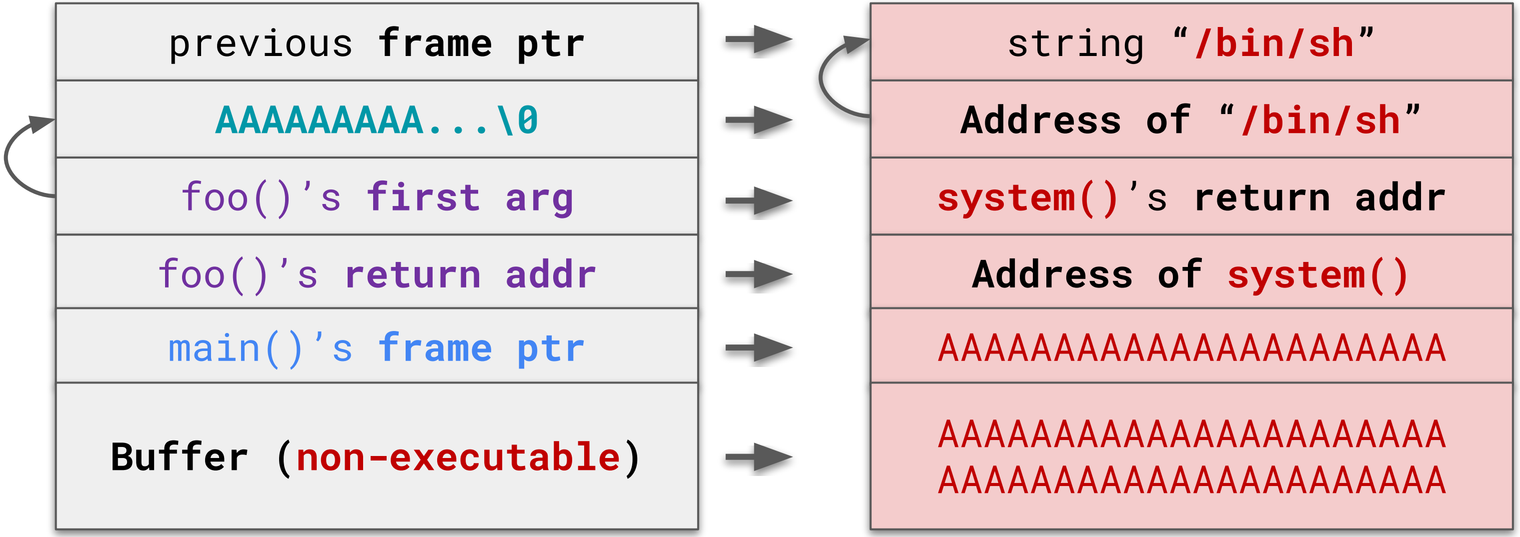
- **Idea #2:** create a **????**

previous **frame ptr**
AAAAAAAAA...\0
foo()'s **first arg**
foo()'s **return addr**
main()'s **frame ptr**
Buffer (non-executable)

previous **frame ptr**
AAAAAAAAA...\0
foo()'s **first arg**
foo()'s **return addr**
main()'s **frame ptr**
Buffer (non-executable)

Defeating DEP

- **Idea #2:** create a **"fake" call frame for `system()`** with our desired arg



Defeating DEP

- **Idea #2:** c ... red arg

pre
A
fo
foo
ma
Buffe

rg
ddr
()
AAA
AAA AAA

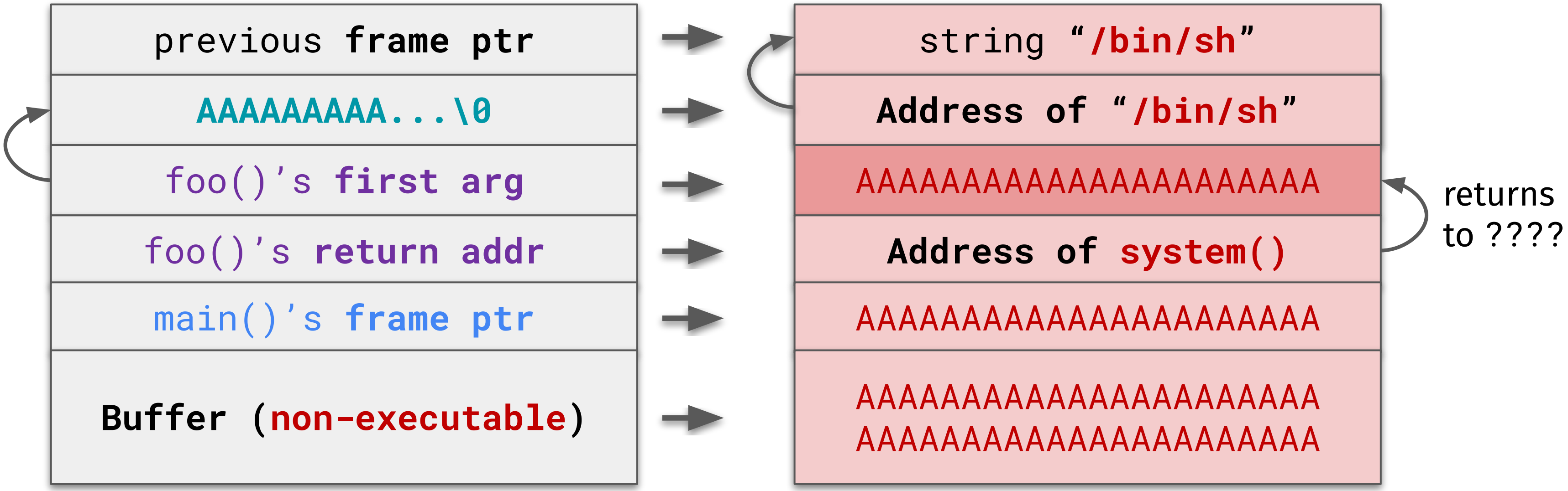
Defeating DEP

- What happens **when `system()` returns** (i.e., the spawned shell is closed)?

previous **frame ptr**	string "**/bin/sh**"
AAAAAAAAA...\0	**Address of "/bin/sh"**
foo()'s **first arg**	AAAAAAAAAAAAAAAAAAAAAA
foo()'s **return addr**	**Address of system()**
main()'s **frame ptr**	AAAAAAAAAAAAAAAAAAAAAA
Buffer (non-executable)	AAAAAAAAAAAAAAAAAAAAAA AAAAAAAAAAAAAAAAAAAAAA

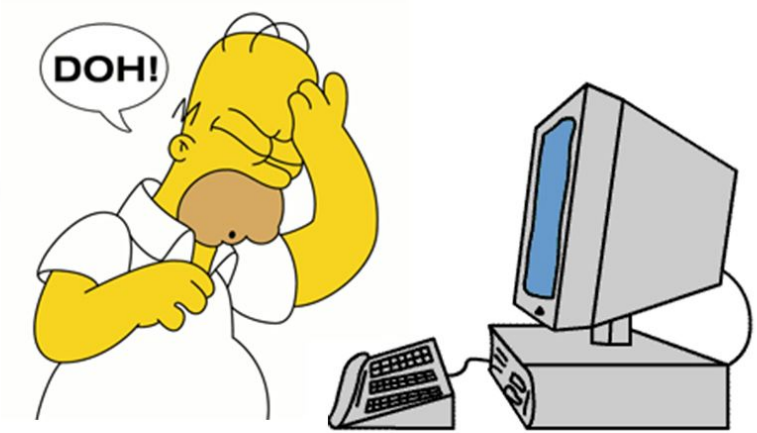
Defeating DEP

- What happens **when `system()` returns** (i.e., the spawned shell is closed)?



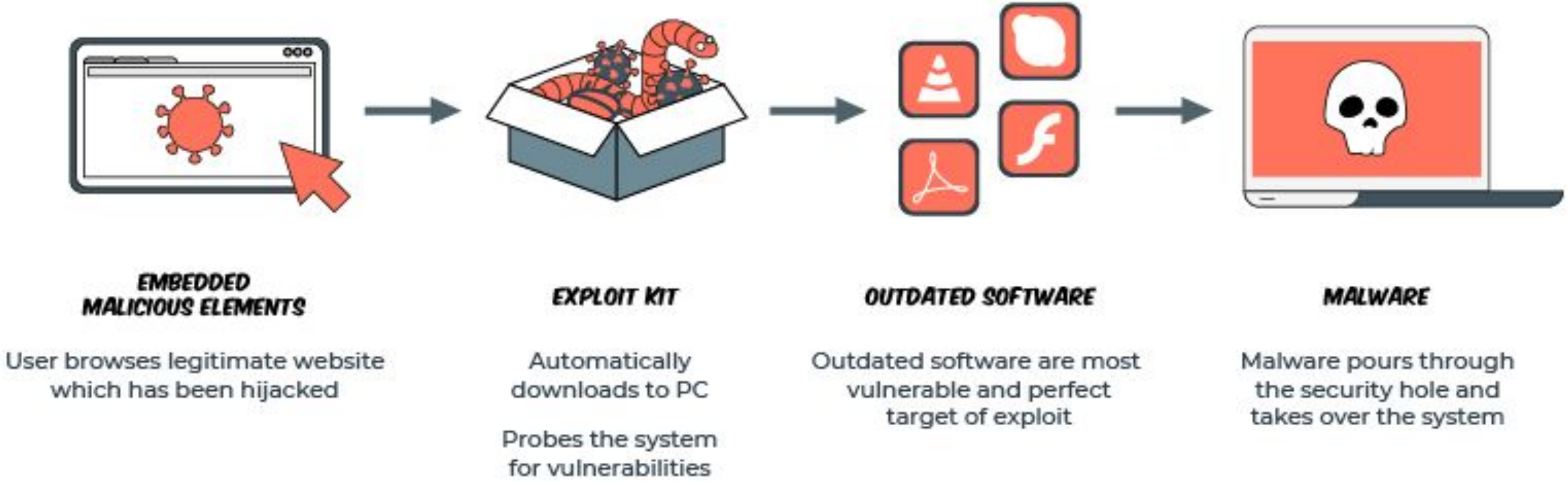
Defeating DEP

- What happens **when system() returns** (i.e., the spawned shell is closed)?

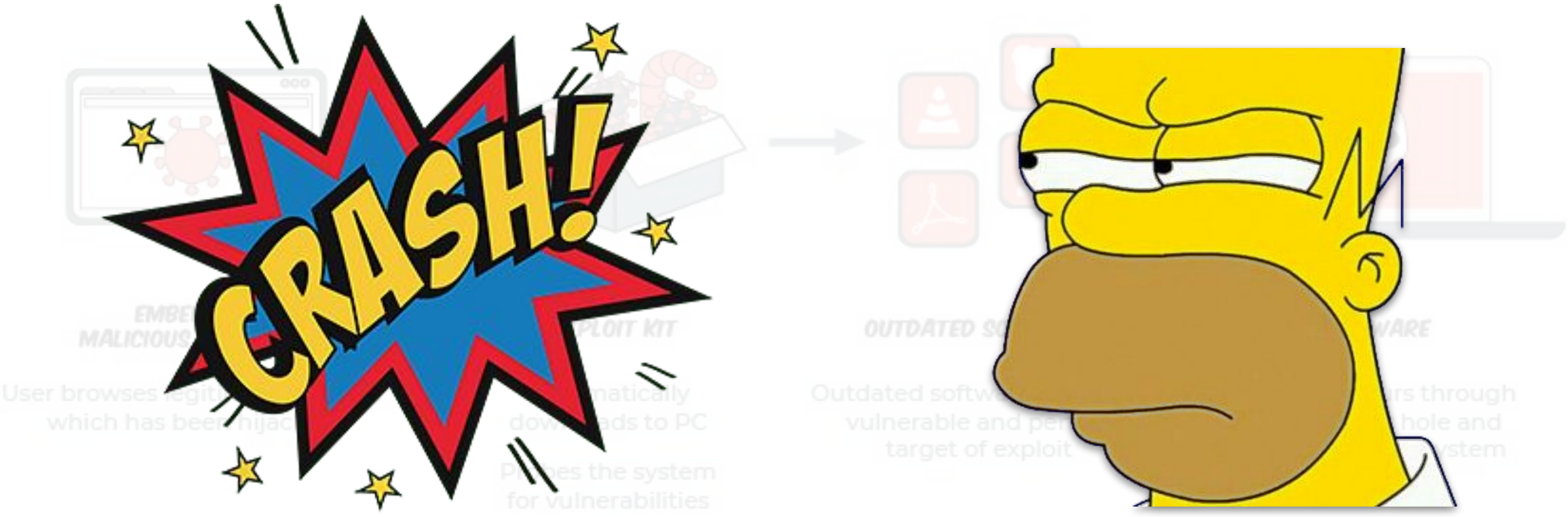



```
segmentation fault.
(Core dumped)
```

Case Study: Drive-by-Downloads



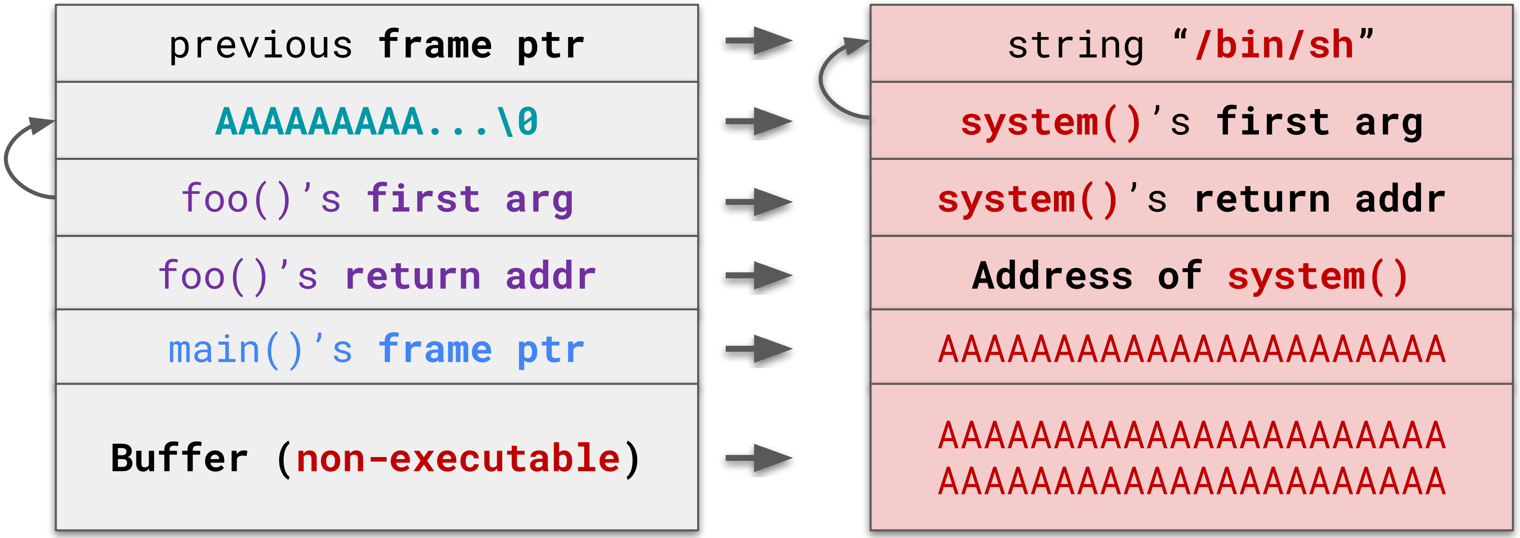
Case Study: Drive-by-Downloads



- **Web browser crashing** = a dead giveaway you're being **exploited**!

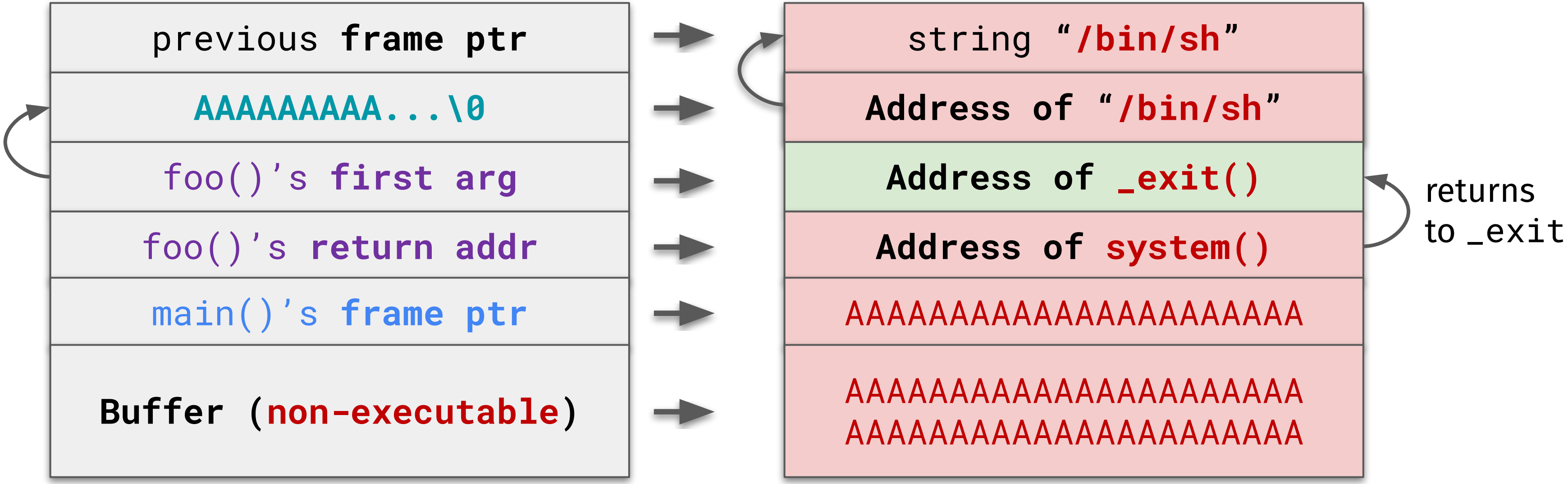
Defeating DEP

- How can we make this stealthy (i.e., **not segfault when system( ) returns**)?



Defeating DEP

- How can we make this stealthy (i.e., **not segfault when `system()` returns**)?
  - Replace the **return address** in our fake **`system()`** call frame with the **address of `_exit()`**



Defeating DEP

- How can w ... () **returns**)?
  - Replac ... **ess of** `_exit()`

pre
A
fo
foo
ma
Buffe

rg
)
()
AAA
AAA AAA

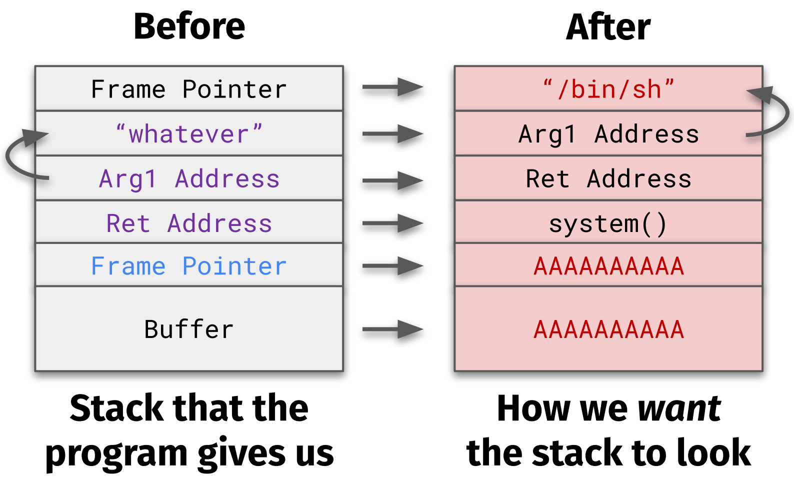
returns to _exit

Project 2 Tips

- **Targets 0, 1, 2**
  - Relatively simple attacks
  - Should not require too much effort
  - They build up your skills for the others!
- **Suggestion: get these finished ASAP**
- **Having trouble? Come to office hours**
  - See **CS 4440 Wiki** for cheat sheets!

Project 2 Tips: Attack Planning

1. Establish a plan of attack
   - Draw a **before/after stack diagram**
2. What object do you **control**?
   - Vulnerable buffer
3. What objects are **adjacent** to it?
   - `main()`'s frame pointer
   - `foo()`'s return address
4. What do you need to **overwrite**?
   - `foo()`'s return address, etc.



Project 2 Tips: Memory Inspection

1. Get familiar with **memory inspection** in GDB
2. Begin with simple, **easily-identifiable payload**
   - E.g., the string "AAAAAAAAA..."
3. Set **breakpoint** on payload-inserting function
   - E.g., the function that calls `strcpy()`
4. Single-step to **right before function returns**
5. Inspect memory and **look for payload bytes**
   - At what address does `0x41414141`... appear?

```
(gdb) x/32bx 0xfff6d8c0

0xfff6d8c0: 0x00 0x00 0x00 0x00
            0x00 0x00 0x00 0x00
0xfff6d8c8: 0x00 0x00 0x00 0x00
            0x41 0x41 0x41 0x41
0xfff6d8d0: 0x41 0x41 0x41 0x41
            0x41 0x41 0x41 0x41
```

Buffer probably begins at `0xfff6d8c8 + 4`

Project 2 Tips: Overflowing

- **Segfaults** = you're on the right track!
  - Means you've overwritten **something of value**
  - E.g., the current function's return address
- Get a dummy "**AAAA**" payload down **first**
  - Are you overwriting the objects you want?
  - **How many bytes** do you need to do so?
- **Then** move onto your full shellcode attack
  - **Suggestion:** replace "**A**"s with `0x90`s (NOPs)

RetAddr Partial Overwrite

```
Program received signal
SIGSEGV, Segmentation
fault.

0x08004141 in ?? ()
```

RetAddr Full Overwrite

```
Program received signal
SIGSEGV, Segmentation
fault.

0x41414141 in ?? ()
```

Questions?

This time on CS 4440...

Automated Bug-Finding
Fuzz Testing
Symbolic Execution

Today's Guest Lecturer

Gabriel Sherman

Reach out!
gabesherman6@gmail.com

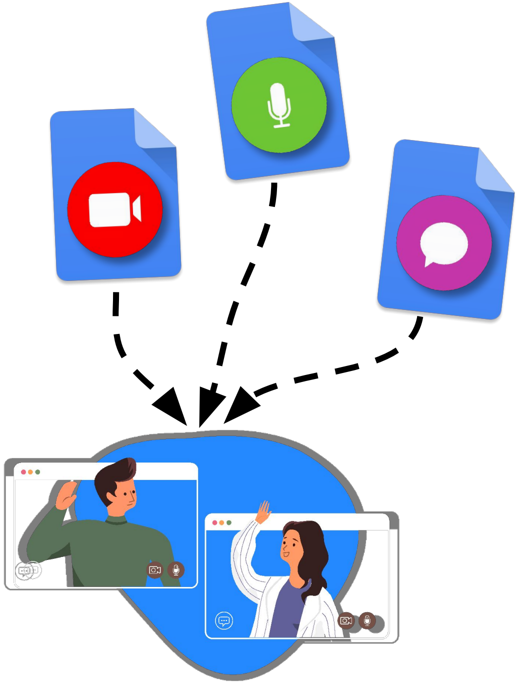
- **About Me:**
  - First year PhD Student
  - This class sparked my interest in Computer Security
  - I love to hike and snowboard
  - I have a weiner dog

- **My Research:**
  - Novel automatic harness generation techniques
  - Bridging the gap between untested code and fuzzing
  - Uncovering bugs in software
  - Discovered **40+ vulnerabilities** in popular software libraries

Programs run on inputs

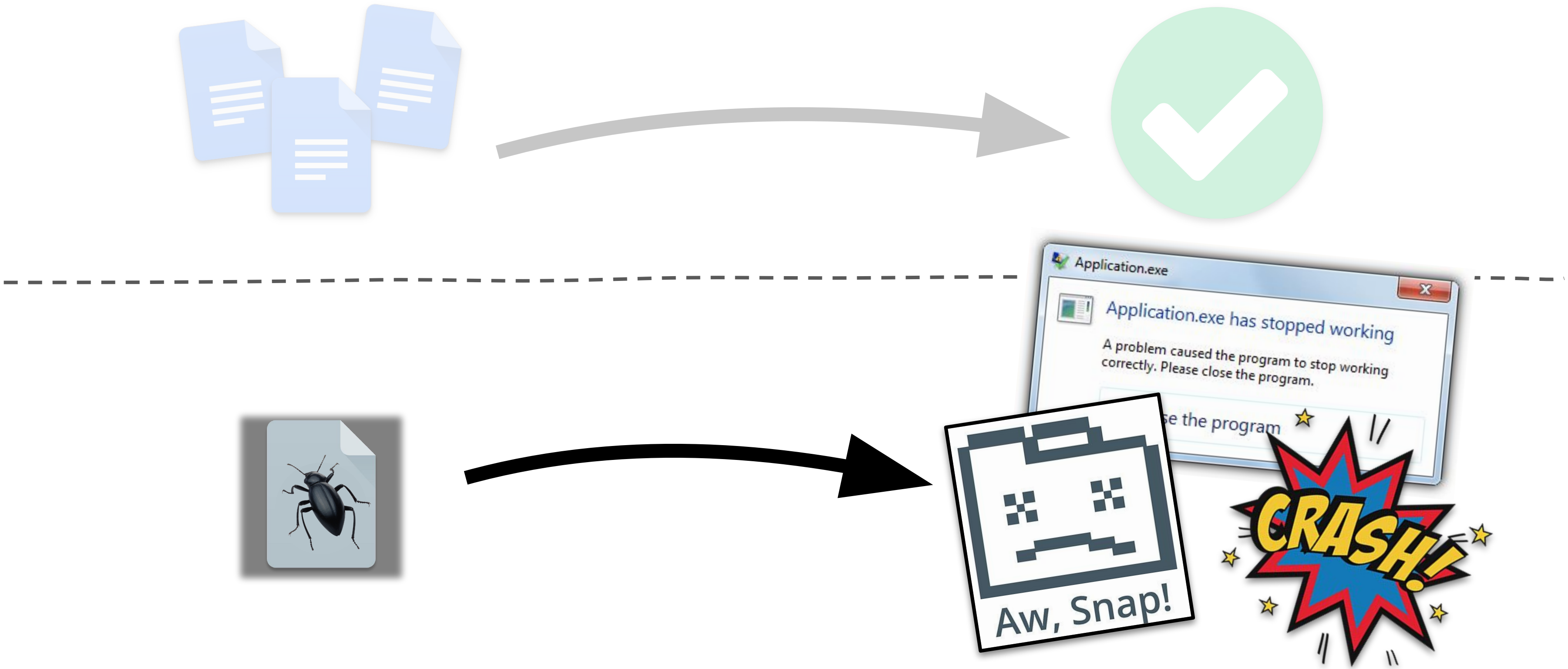
- Modern applications accept many sources of input:
  - **Files**
  - **Arguments**
  - **Environment variables**
  - **Network packets**
  - …

- Nowadays: multiple sources of inputs



Software Bugs

Software Bugs



When bugs go bad

- Improper input validation leads to **security vulnerabilities**
  - Bugs that violate the system's confidentiality, integrity, or availability

- **Exploitation**: leveraging a vulnerability to perform unauthorized actions

Exploitation

Common Vulnerabilities

- Missed initialization check
- Free'd pointers not NULL'd
- Unchecked memory writes

Consequences

- Use uninitialized memory
- Use non-owned memory
- Overflowing a data buffer

Attacker Exploitation

- Software denial of service
- Leak sensitive information
- Inject & run arbitrary code

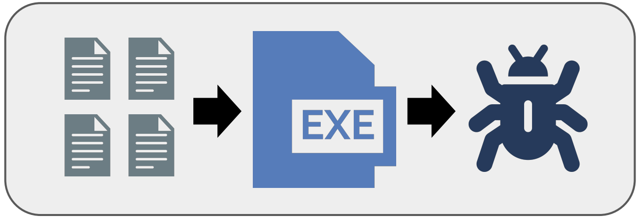
Race against time to **find & fix** vulnerabilities
before they are **exploited**

Proactive Vulnerability Discovery

Static Analysis:

- Analyze program **without running it**
- Accuracy a major concern
  - **False negatives** (vulnerabilities missed)
  - **False positives** (results are unusable)
- As code size grows, **speed drops**

Dynamic Testing:



- Analyze program **by executing it**
- Better accuracy: **no false positives**
  - Execution reveals only what exists
  - Program crashed? You found a bug!
- Capable of very **high throughput**

Proactive Vulnerability Discovery

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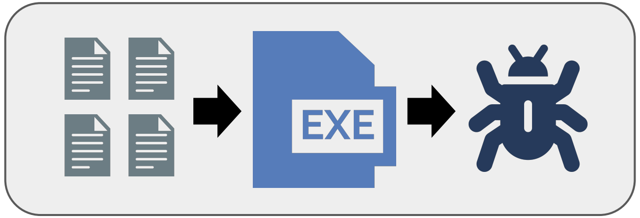

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- Better accuracy: **no false positives**
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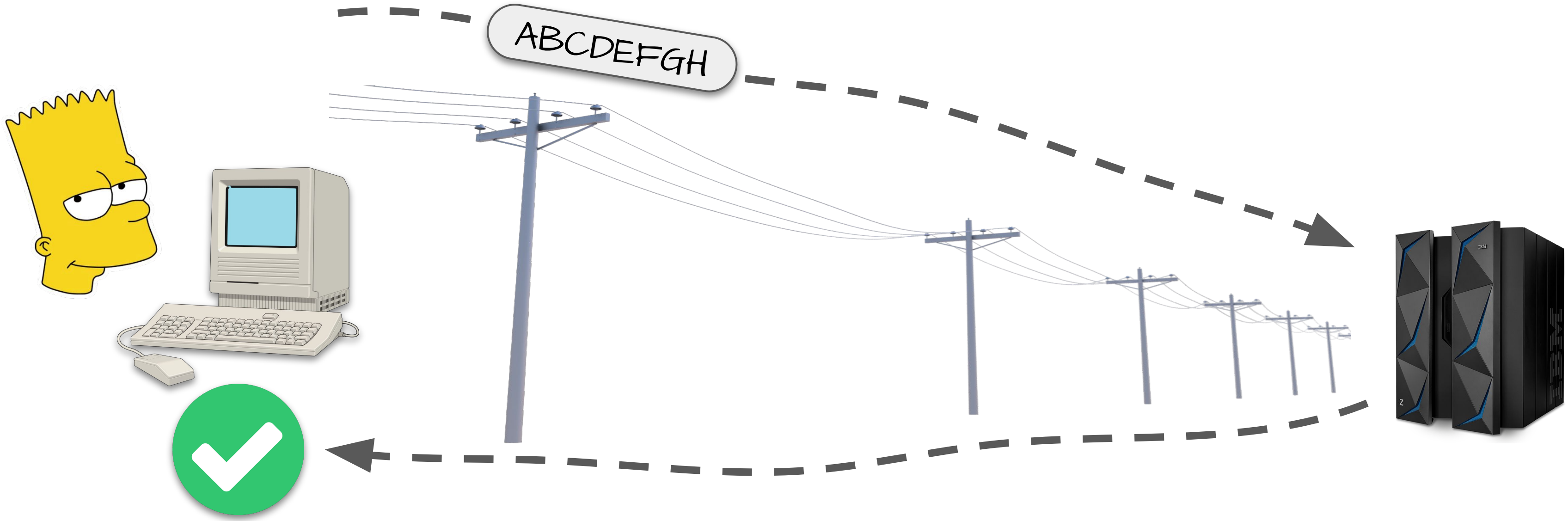
Questions?

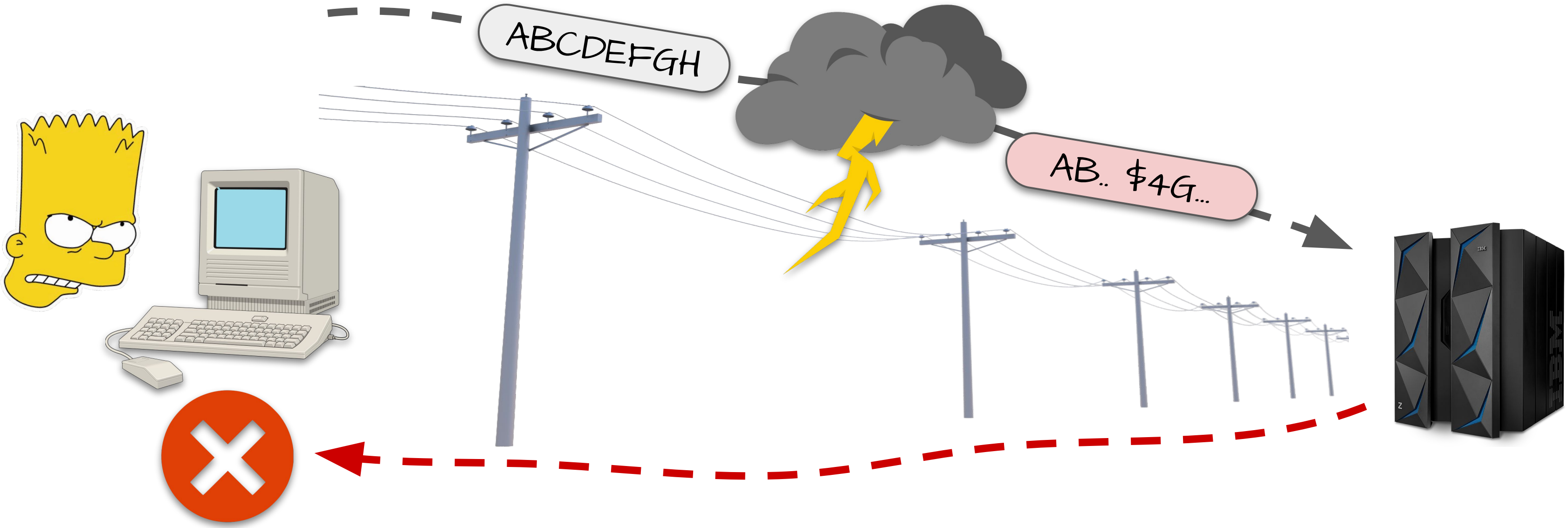
“Fuzz” Testing (aka Fuzzing)

One dark and stormy night...



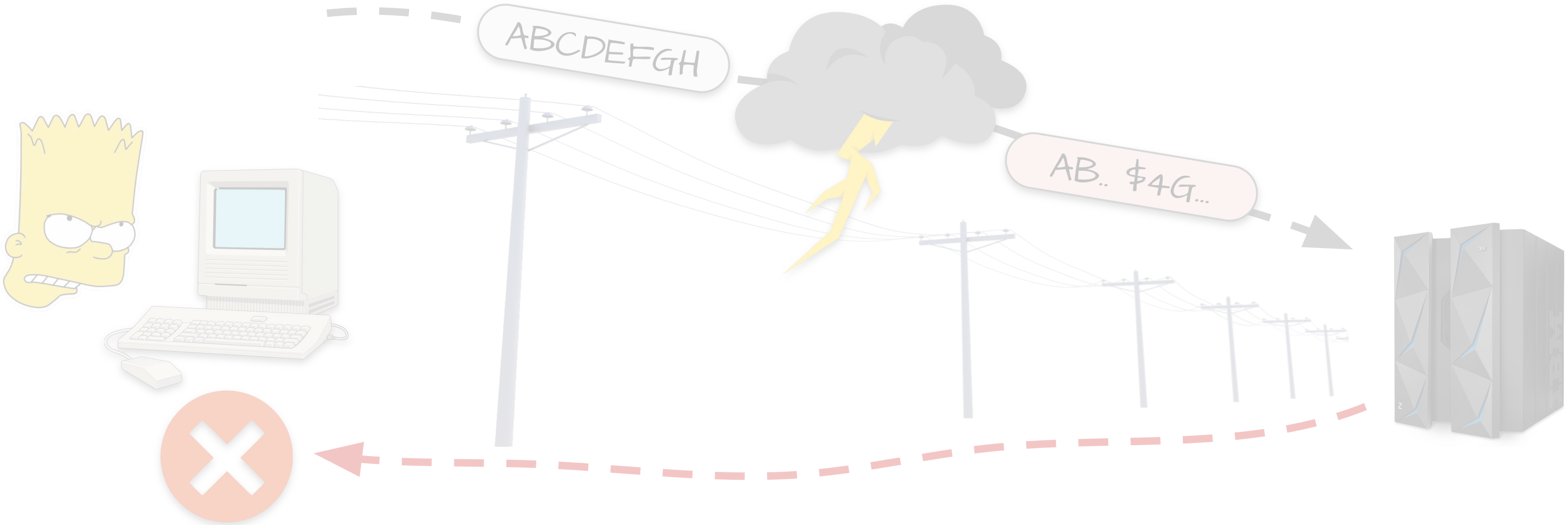
Source: https://www.linux-magazine.com/Issues/2022/255/Fuzz-Testing

One dark and stormy night...



Source: https://www.linux-magazine.com/Issues/2022/255/Fuzz-Testing

One dark and stormy night…



- Shouldn't programs do much better with **glitched or invalid input**?

Source: https://www.linux-magazine.com/Issues/2022/255/Fuzz-Testing

Bart's idea: test programs on *random* inputs

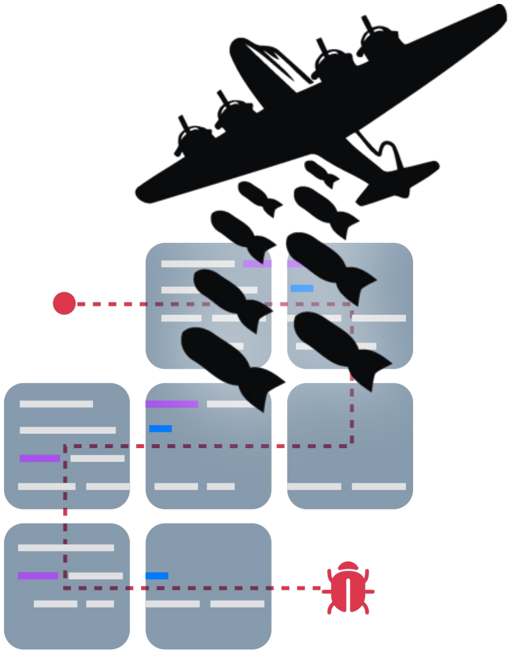
Listing 1 Simple Fuzzer in Python

```
import random
def fuzzer(max_length=100, char_start=32, char_range=32):
  """Generate a string of up to `max_length` characters
   in the range [`char_start`, `char_start` + `char_range` - 1]"""
  string_length = random.randrange(0, max_length + 1)
  out = ""
  for i in range(0, string_length):
    out += chr(random.randrange(char_start, char_start + char_range))
  return out
```

```
!7#%"*#0=)$;%6*;>638:*>80"=</>(/*
:-(2<4 !:5*6856&?""11<7+%<%7,4.8+
```

Bart’s idea: test programs on *random* inputs

- Quickly generate lots and lots of **random inputs**
- Execute each on the target program
- **See what happens**
  - Crash
  - Hang
  - Nothing at all



Random inputs work!

- Crash or hang **25–33%** of utility programs in **seven** UNIX variants
- Results reveal several common mistakes made by programmers
- They called this *fuzz* testing
  - Known today as **fuzzing**

An Empirical Study of the Reliability of UNIX Utilities

Barton P. Miller
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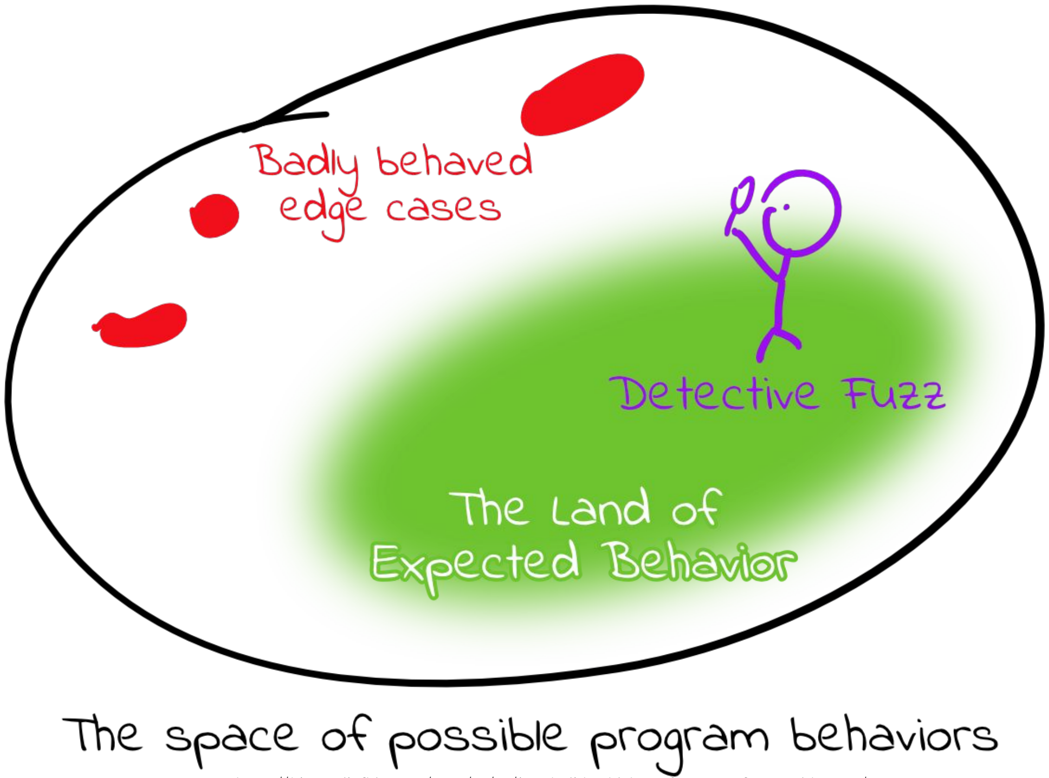
Lars Fredriksen
L.Fredriksen@att.com

Bryan So
so@cs.wisc.edu

Finding Bugs with Fuzzing



Source: https://blog.trailofbits.com/2020/10/22/lets-build-a-high-performance-fuzzer-with-gpus/

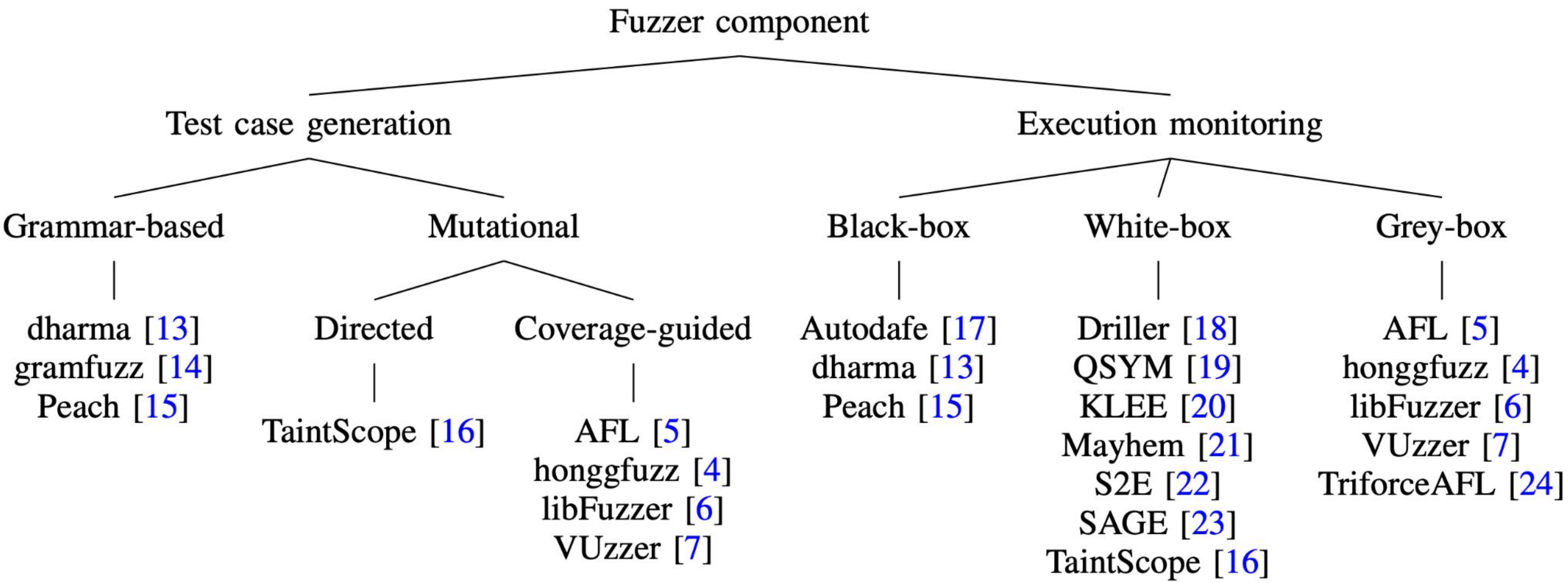
Fuzzing across the industry

- Fuzzing = today's most popular bug-finding technique
  - Most real-world fuzzing is **coverage-guided**

Google: We've open-sourced ClusterFuzz tool that found 16,000 bugs in Chrome

New fuzzing tool finds 26 USB bugs in Linux, Windows, macOS, and FreeBSD

Taxonomy of Fuzzers



Tools of the trade: AFL

- Most historically significant fuzzer ever developed

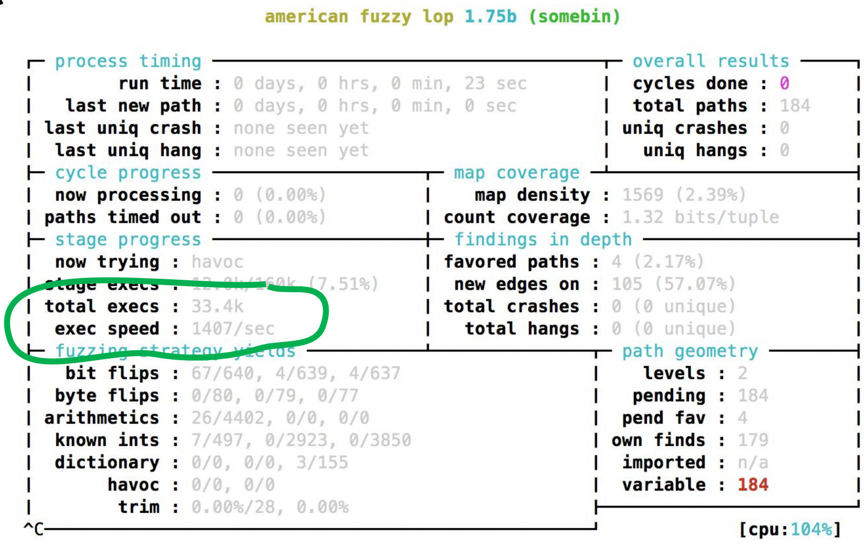
- Authors: Michal Zalewski (2013)
  - Google (2019–2022)
  - The AFL++ team (2020–onwards)

- Versatile, easy to spin up & modify
  - Spawned probably ~100 PhD & MS theses
  - (mine included)

- **Mix of carefully chosen trade-offs**

What AFL aims to be

- Primary goal: **high test case throughput**
- Sacrifice precision in most areas
  - Lightweight, simple mutators
  - Coarse, approximated code coverage
  - Little reasoning about seed selection
- Revolutionary & still insanely effective
  - Ideas ported over to honggFuzz, libFuzzer
  - and nearly all other fuzzers



Tools of the trade: AFL++

- **By far today's most popular fuzzer**

- Official successor to vanilla AFL
  - Started out as a community-led fork
  - Google has since archived vanilla AFL

- **A platform for trying-out new features**
  - Integrated lots of academic prototypes
  - Easily tailorable to your target's needs

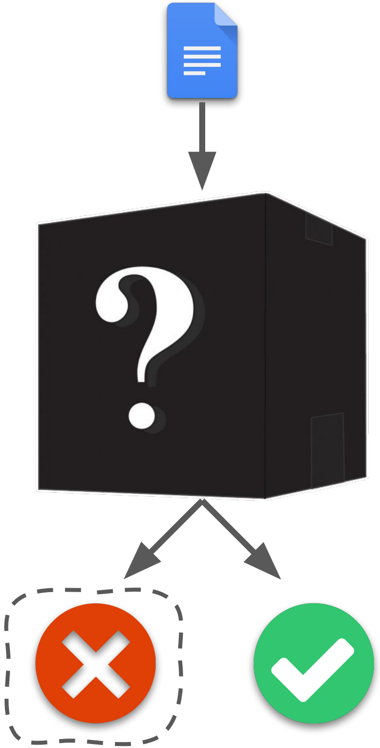
https://github.com/AFLplusplus/AFLplusplus

Demo

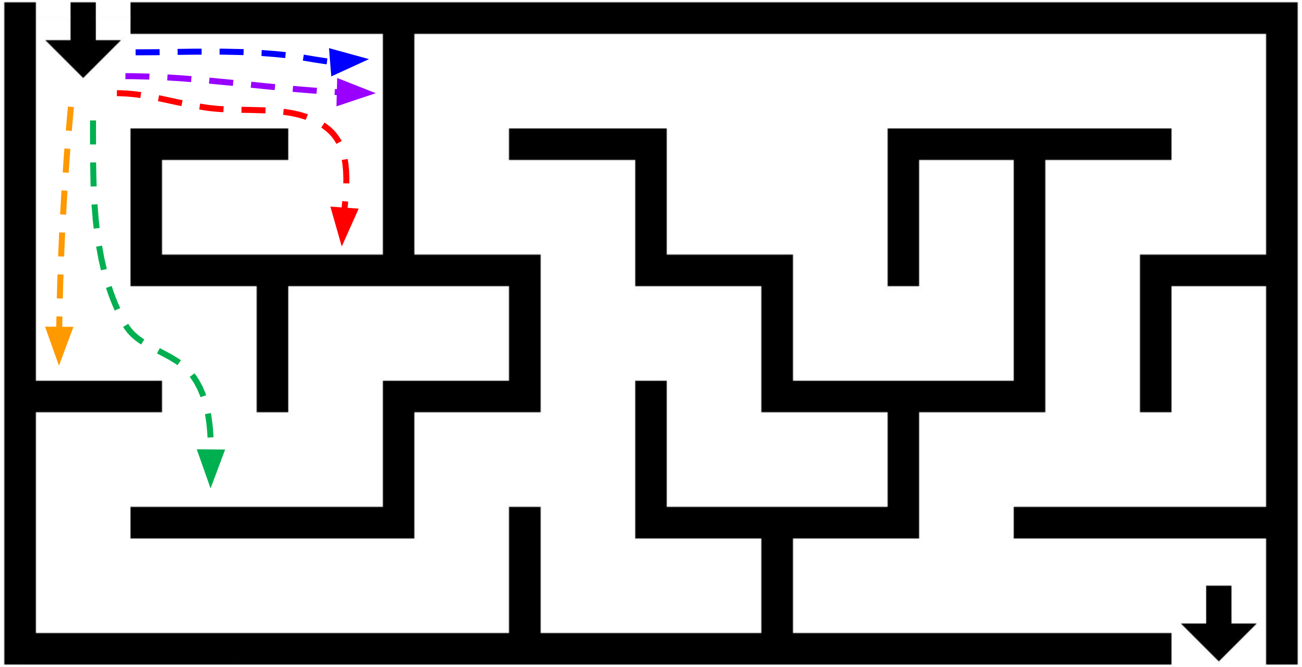
Feedback-driven Fuzzing

Fuzzing like it's 1989

- Random inputs
- **Black-box:** only check program's **end result**
  - Signals
  - Return values
  - Program-specific output
- Save inputs that trigger **weird behavior**
  - SIGSEGV, SIGFPE, SIGILL, etc.
  - Assertion failures
  - Other reported errors

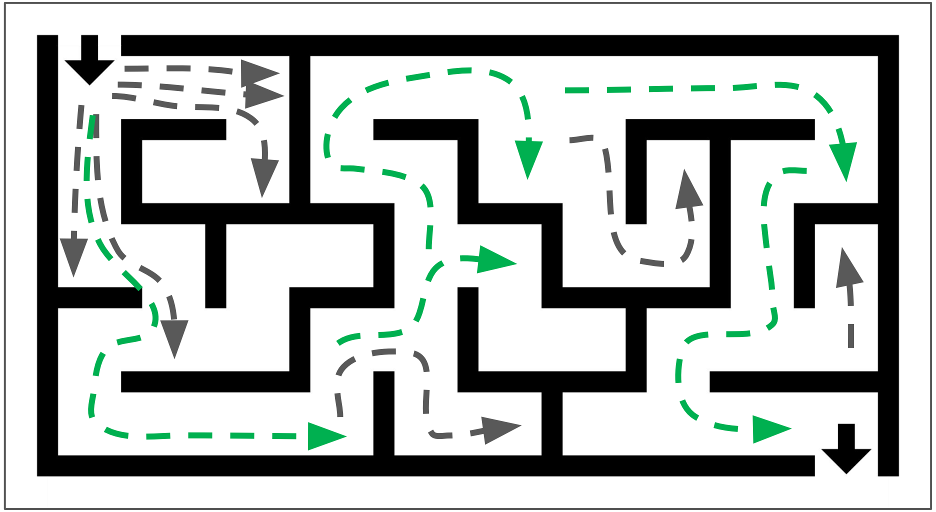


Black-box fuzzing only gets you so far

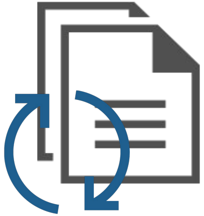


How can fuzzing exploration be guided?

- Idea: track some measure of exploration "progress"
  - Coverage of program code
  - Stack traces
  - Memory accesses
- Pinpoint inputs that further progress over the others
- **Mutate only those inputs**



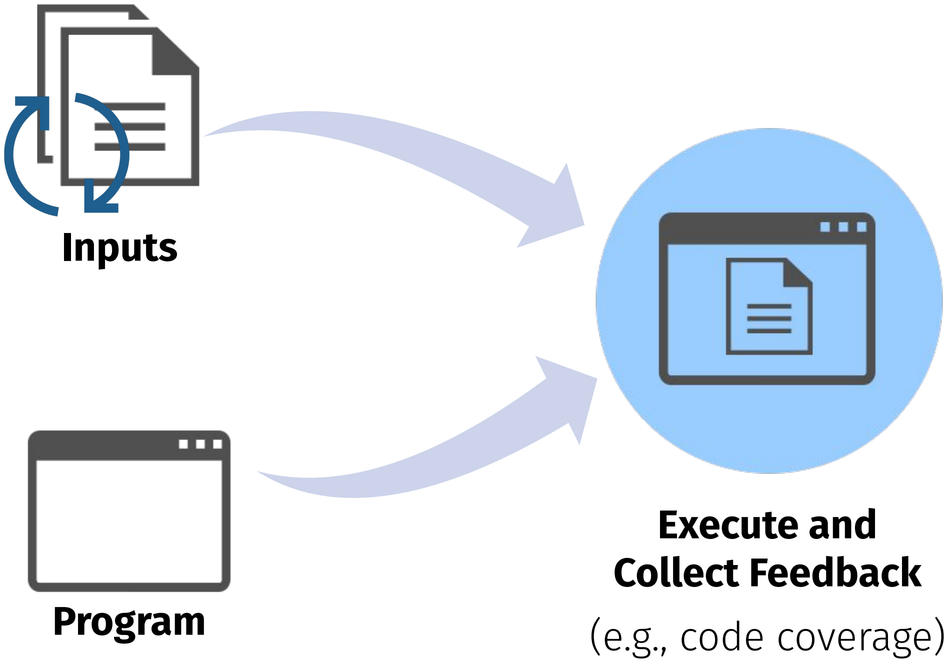
Feedback-driven Fuzzing



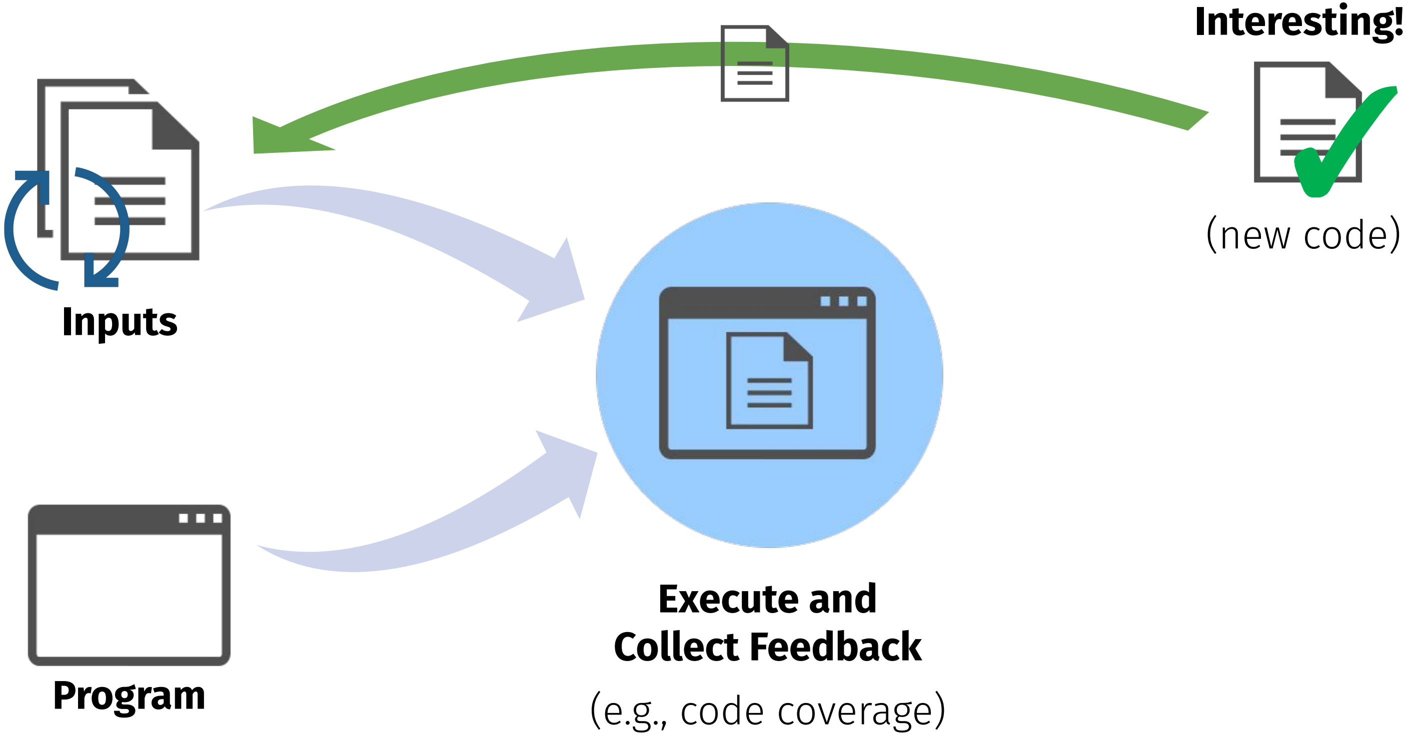
Inputs

Program

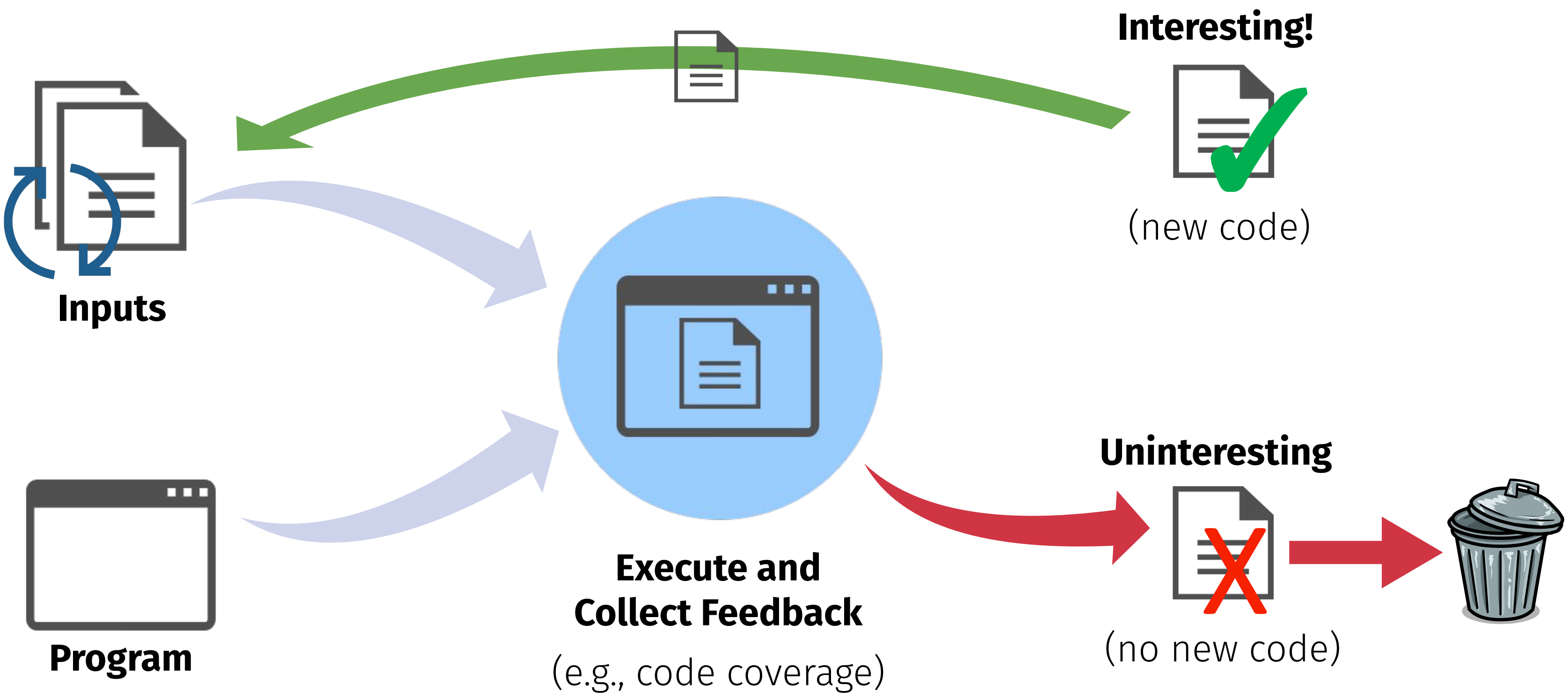
Feedback-driven Fuzzing



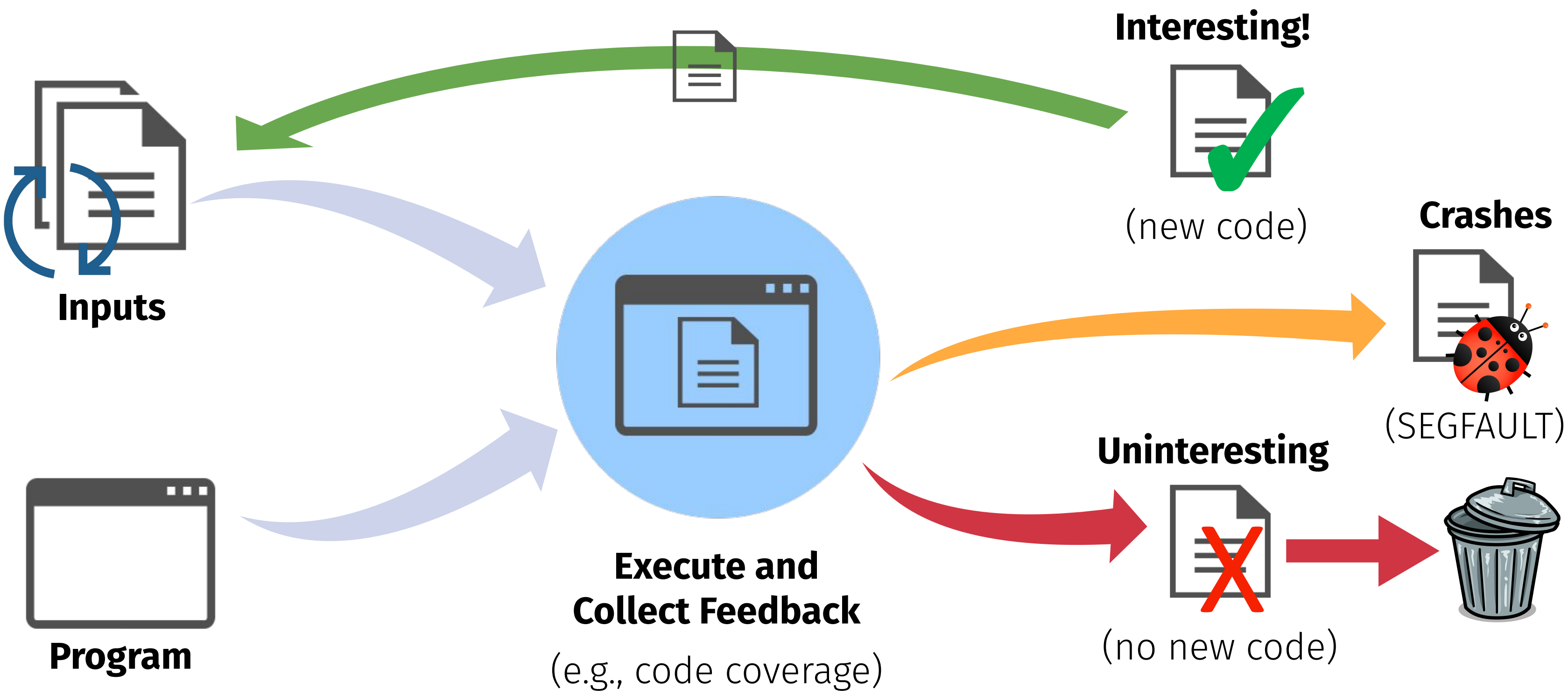
Feedback-driven Fuzzing



Feedback-driven Fuzzing

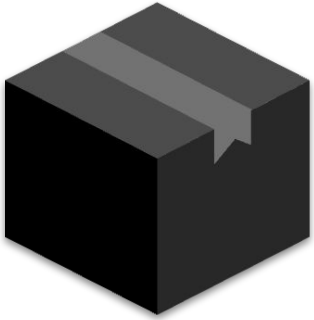


Feedback-driven Fuzzing



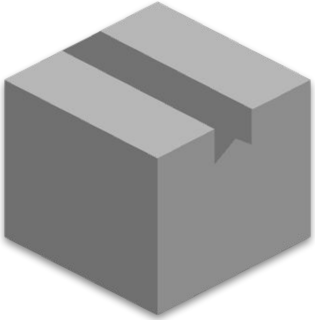
Types of Feedback-driven Fuzzers

Black-box



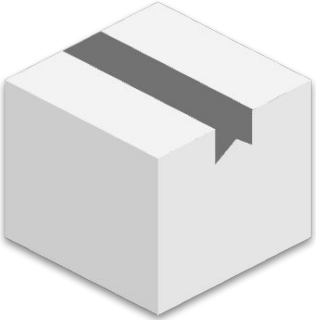
Zero Introspection

Grey-box



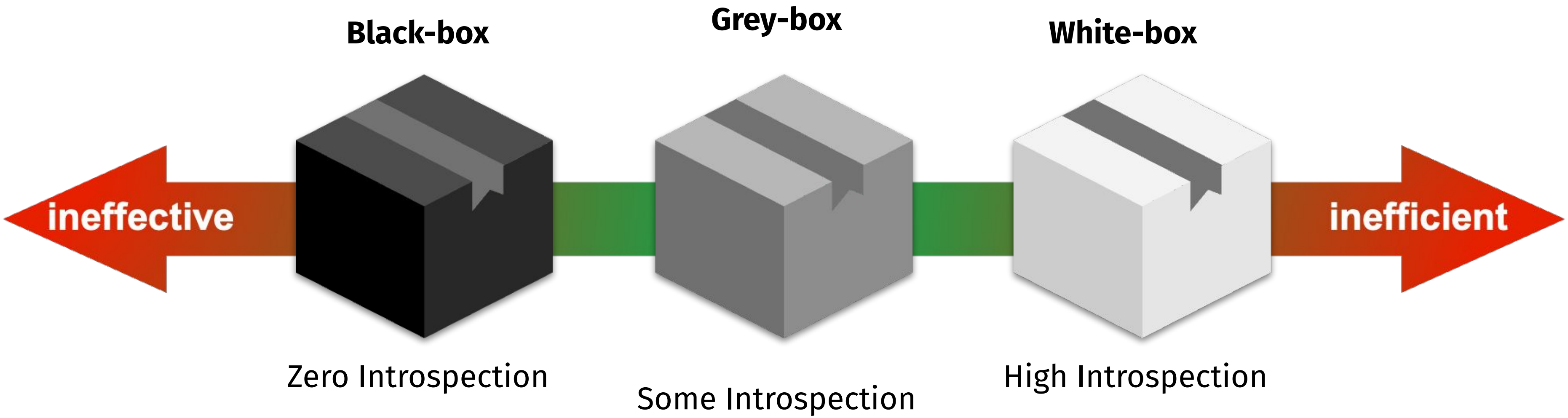
Some Introspection

White-box

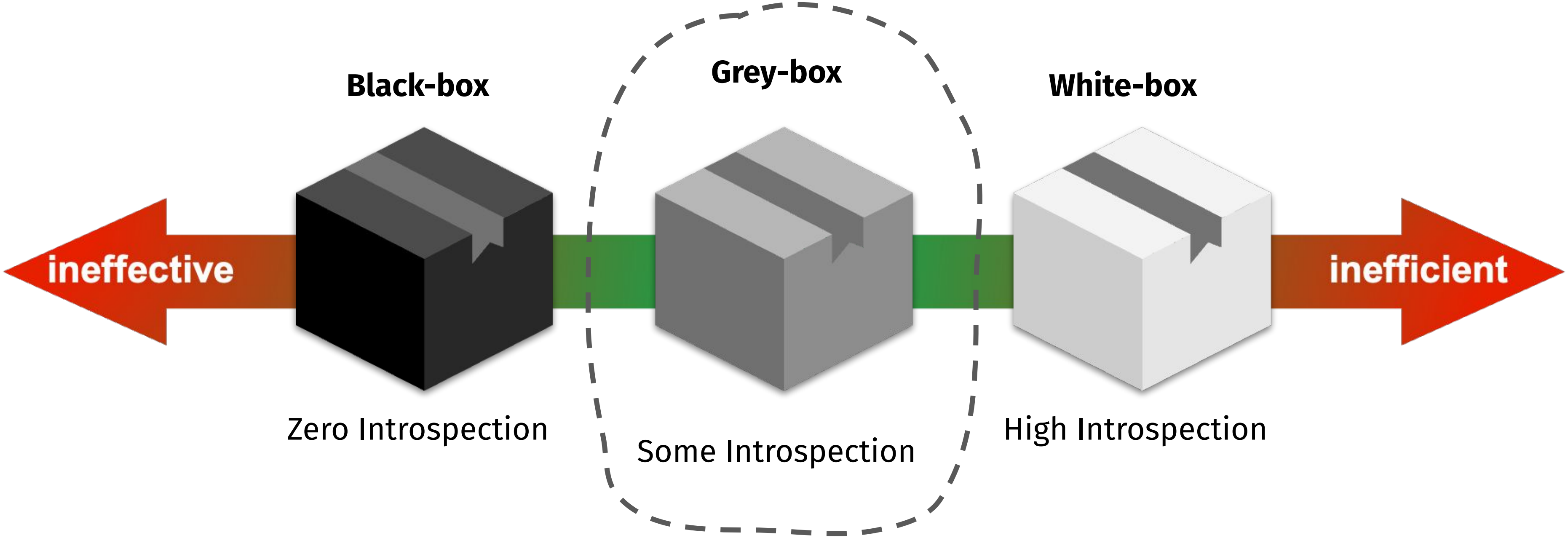


High Introspection

Types of Feedback-driven Fuzzers



Types of Feedback-driven Fuzzers



Coverage-guided Grey-box Fuzzing

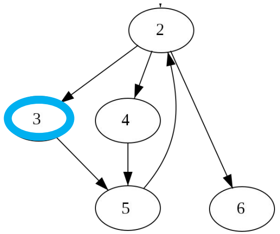
- **Code coverage:** program regions exercised by each test case
- **Horse racing analogy:** "breed" (**mutate**) only the "winning" (**coverage-increasing**) inputs
  - New coverage? **Keep and mutate the input**
  - Old coverage? **Discard it and try again**
- Most fuzzing today is **coverage-guided**
  - Good balance of performance and precision

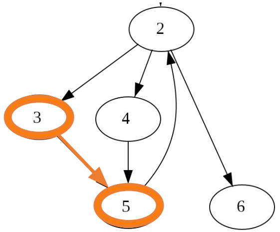
```
177x  function fib(n) {
177x    if (n === 0) {
 34x      return 0
177x    } else if (n === 1) {
 55x      return 1
143x    } else if (n > 1) {
 88x      return fib(n - 1) + fib(n - 2)
        } else {
          thrower()
        }
177x  }
  1x  console.log('fib(10):', fib(10))
```

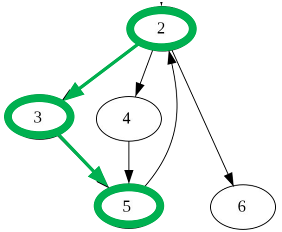
Code Coverage

- Program represented as **control-flow graphs (CFG)**
  - Directed graph encompassing all program paths
  - Basis of virtually all software analysis techniques

- Various coverage metrics in use today
  - **Instructions:** units that make up basic blocks
  - **Basic blocks:** nodes of the program's CFG
  - **Edges:** transitions between basic blocks
  - **Hit counts:** frequencies of basic blocks
  - **Paths:** sequences of edges

Blocks


Edges


Paths


Tracking Code Coverage

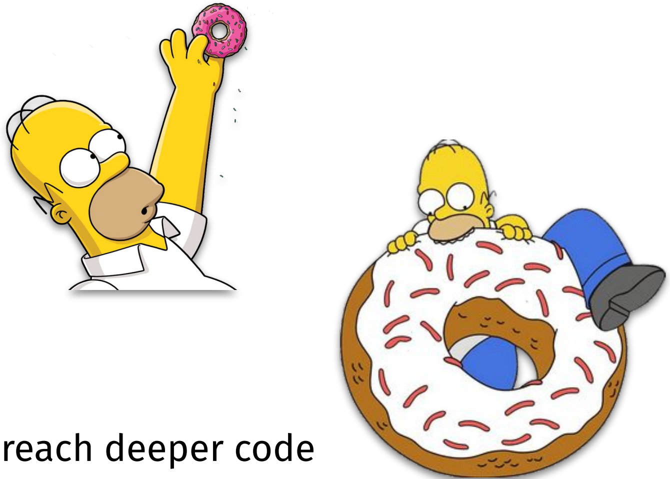
- **Challenge:** coverage-tracing **instrumentation**
  - Modifying program to track test case code coverage
- Target is **open-source**? **Easy and fast!**
  - Can **compile-in** coverage-tracing instrumentation
- Target is **closed-source**? **Difficult and slow!**
  - **Dynamic Translation:** modify executable **as it's running**
    - Easy, but really slows down runtime speed
  - **Static Rewriting:** modify executable **before running it**
    - Conceptually similar to compiler instrumentation
    - Fast, but difficult to do without breaking the program

Questions?

Fuzzing Input Generation

Before you start: choose your seeds

- **Seeds:** starting inputs from which to mutate from
- Small seeds
  - Smallest-possible PDF file
  - Empty file
- Large seeds
  - Crawl web for every PDF ever created
- **No right answer—it is target-dependent!**
  - **Smaller seeds** = cover earlier code, but struggle to reach deeper code
  - **Larger seeds** = cover deeper code to start, but are slower to execute



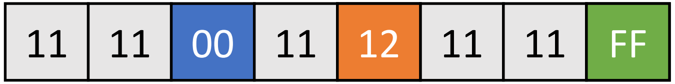
Types of Input Generation

- **Model-agnostic:** brute-force your way to valid inputs
  - Random insertions, deletions, and splicing
- **Model-guided:** follow a pre-defined input specification
  - Follow “rules” to create highly-structured inputs
- **White-box approaches:**
  - **Symbolic execution:** solve branches as **symbolic** expressions
  - **Concolic execution:** solve branches as **concrete** values
  - **Taint tracking:** infer critical input **“parts”** and mutate those

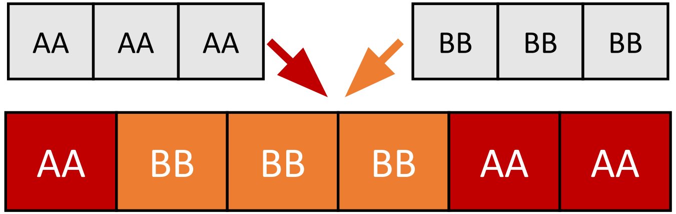
Source: The Art, Science, and Engineering of Fuzzing: A Survey

Model-agnostic Generation

- Brute-force your way to valid inputs
  - Bit and byte “flipping”
  - Addition and subtraction
  - Inserting random chunks
  - Inserting dictionary “tokens”
  - Splicing two inputs together

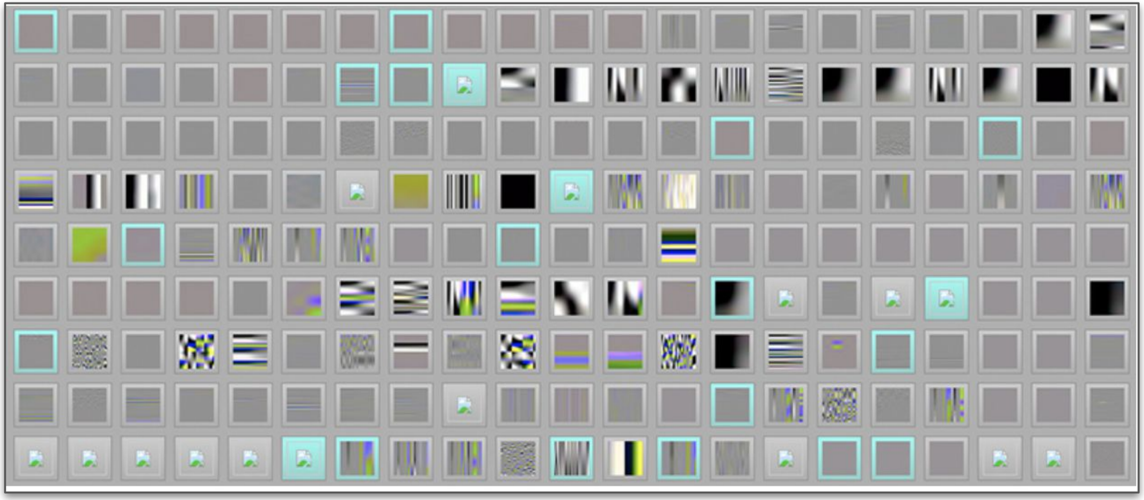


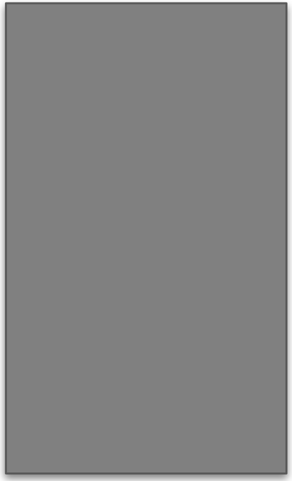
- **The good:** super fast
  - Incorporating feedback like coverage enables you to **synthesize valid inputs** (eventually)



Model-agnostic Generation Trade-offs

- **Surprisingly effective:** valid inputs appear out of thin air





Model-agnostic Generation Trade-offs

- **Need a lot of luck** to solve magic bytes checks and nested checksums

```
if(u64(input)==u64("MAGICHDR"))
  bug(1);
```

Listing 2: Fuzzing problem (1): finding valid input to bypass magic bytes.

```
if(u64(input)==sum(input+8, len-8))
  if(u64(input+8)==sum(input+16, len-16))
    if(input[16]=='R' && input[17]=='Q')
      bug(2);
```

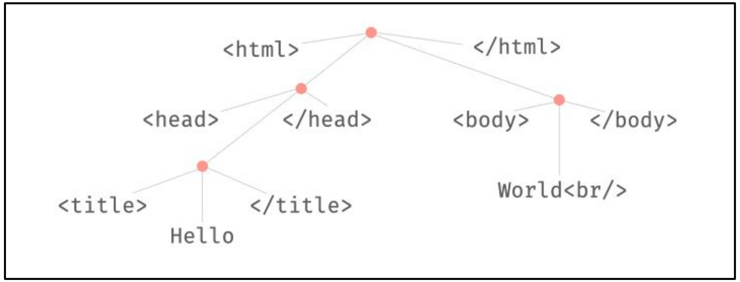
Listing 3: Fuzzing problem (2): finding valid input to bypass checksums.

Model-guided Generation

- Follow a pre-defined input **specification**
  - Pre-defined input grammars
  - Dynamically-learned grammars
  - Domain-specific generators

- **The good:** many more valid inputs
  - Model-agnostic inputs are often discarded because they fail basic input sanity checks
  - Valid inputs = **higher code coverage**

```
XML_GRAMMAR: Grammar = {
    "<start>": ["<xml-tree>"],
    "<xml-tree>": ["<text>",
                   "<xml-open-tag><xml-tree><xml-close-tag>",
                   "<xml-openclose-tag>",
                   "<xml-tree><xml-tree>"],
    "<xml-open-tag>":      ["<<id>>", "<<id> <xml-attribute>>"],
    "<xml-openclose-tag>": ["<<id>/>", "<<id> <xml-attribute>/>"],
    "<xml-close-tag>":     ["</<id>>"],
    "<xml-attribute>":     ["<id>=<id>", "<xml-attribute> <xml-attribute>"],
    "<id>":                ["<letter>", "<id><letter>"],
    "<text>":              ["<text><letter_space>", "<letter_space>"],
    "<letter>":            srange(string.ascii_letters + string.digits +
                                  "\"" + "'" + "."),
    "<letter_space>":      srange(string.ascii_letters + string.digits +
                                  "\"" + "'" + " " + "\t"),
}
```

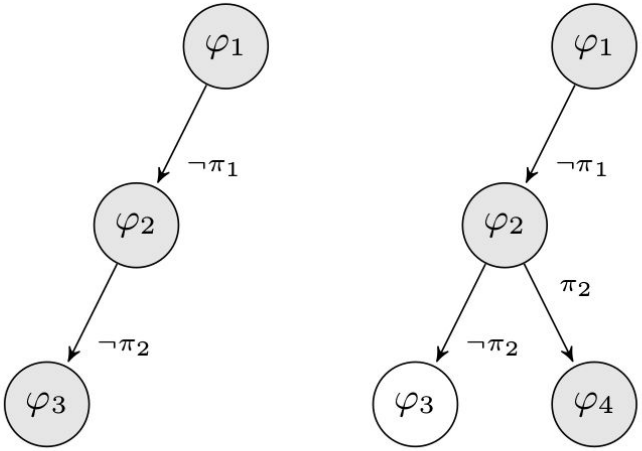


Model-guided Generation Trade-offs

- **Writing or learning specifications is hard**
  - E.g., CSmith written in 40,000+ LoC
  - Domain expertise is critical
- **Seemingly impossible for many inputs**
  - For example, no grammar for x86 binaries
- **Deeper coverage is not always better**
  - Likely to miss bugs hidden in shallow code (e.g., input validity checks)

Symbolic and Concolic Execution

- Model paths as **symbolic expressions**
  - Construct a system of boolean equations
  - Pass this off to an SMT solver
  - Attempt to find all satisfiable assignments
  - **Concolic execution:** test *one* concrete path
- Many solvers available today
  - E.g., Z3, Yices, CVC4
- **The good:** great for many branches
  - Cuts through magic bytes without much trouble



(a) Iteration 1 (b) Iteration 2

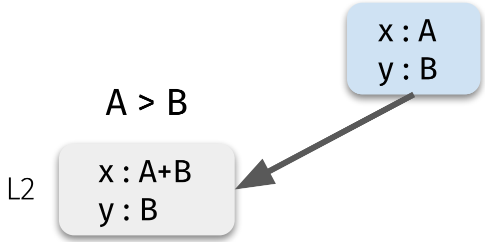
Symbolic Execution Example

```
def f (x, y):
   if (x > y):
      x = x + y
      y = x - y
      x = x - y
      if (x - y > 0):
         assert false
   return (x, y)
```

x : A
y : B

Symbolic Execution Example

```
0. def f (x, y):
1.    if (x > y):
2.       x = x + y
3.       y = x - y
4.       x = x - y
5.       if (x - y > 0):
6.          assert false
7.    return (x, y)
```



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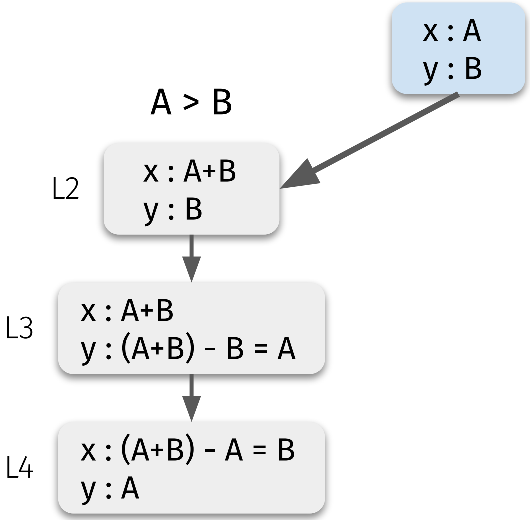

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```
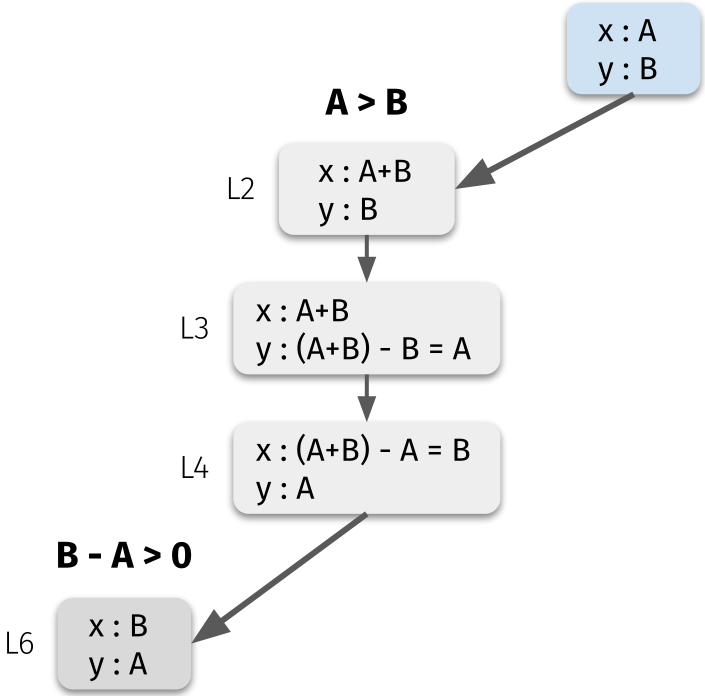

Possible path constraints:

- (A > B) and (B-A > 0) = **satisfiable?**



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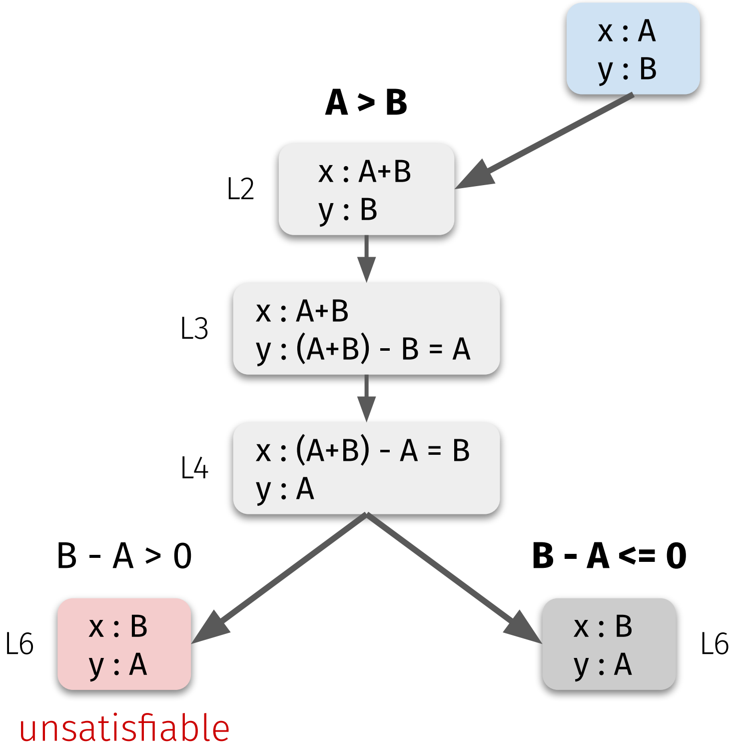
```

Possible path constraints:

- (A > B) and (B-A > 0) = unsatisfiable
- (A > B) and (B-A <= 0) = **satisfiable?**



Symbolic Execution Example

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3.       y = x - y
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```
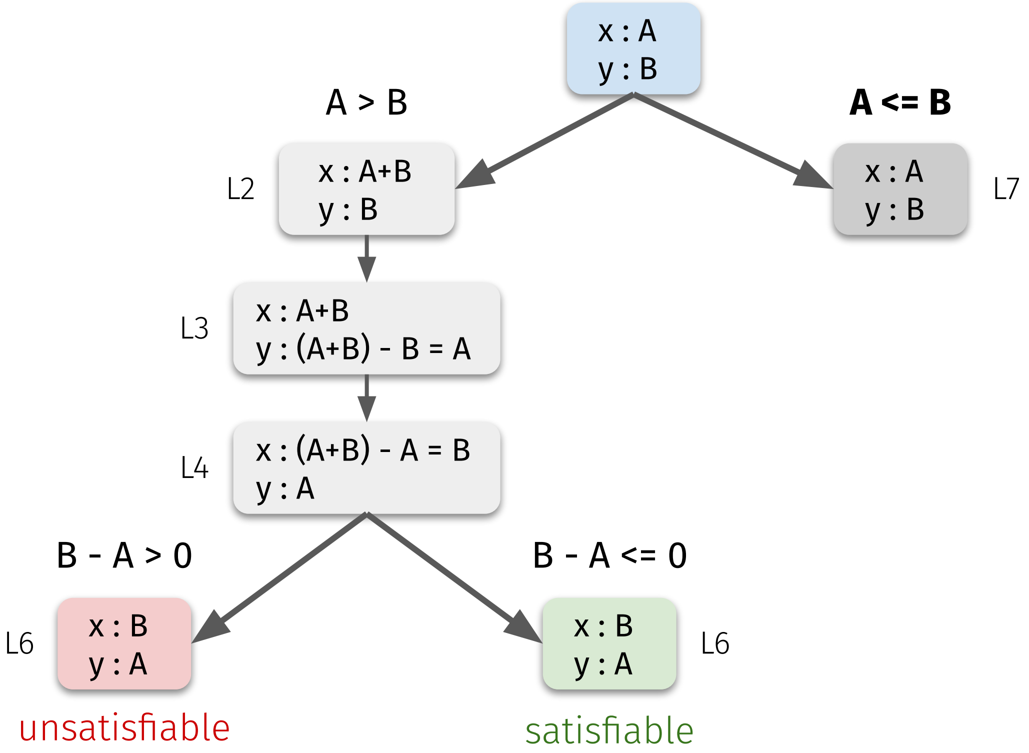

Possible path constraints:

- (A > B) and (B-A > 0) = unsatisfiable
- (A > B) and (B-A <= 0) = satisfiable
- (A <= B) = **satisfiable?**



Symbolic Execution Example

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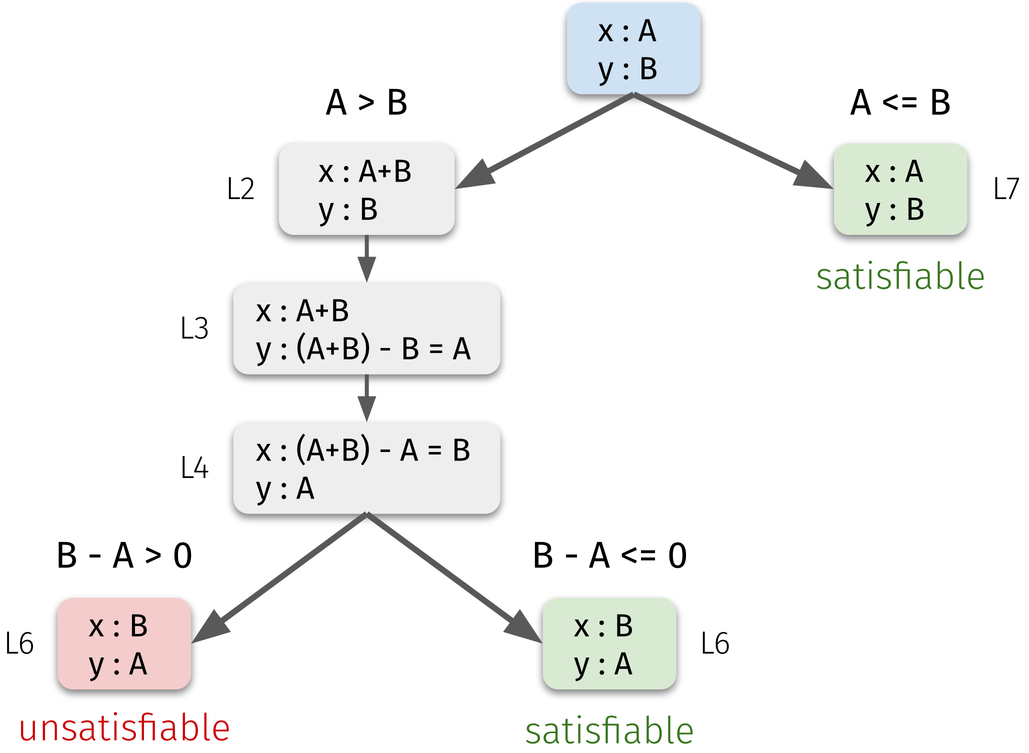

Taint Tracking

- Track input bytes' flow throughout program
  - Identify input "chunks" that affect program state
    - Chunks that affect branches
    - Chunks that flow to function calls
  - **Mutate these chunks**
    - Random mutation
    - Insert fun or useful tokens

```
0. def f (x, y):
1.    if (x > y):
2.       .........
```

11	11	11	11	11	11	11	11
11	11	11	11	11	11	11	11

- **The good:** finding vulnerable buffers, solving branches

Taint Tracking

- Track input bytes’ flow throughout program
  - Identify input “chunks” that affect program state
    - Chunks that affect branches
    - Chunks that flow to function calls

  - **Mutate these chunks**
    - Random mutation
    - Insert fun or useful tokens

- **The good:** finding vulnerable buffers,
  solving branches

```
0. def f (x, y):
1.    if (x > y):
2.       .........
```

11	11	11	Bytes that comprise X
11	Bytes that comprise Y	11	11

Taint Tracking

- Track input bytes' flow throughout program
  - Identify input "chunks" that affect program state
    - Chunks that affect branches
    - Chunks that flow to function calls

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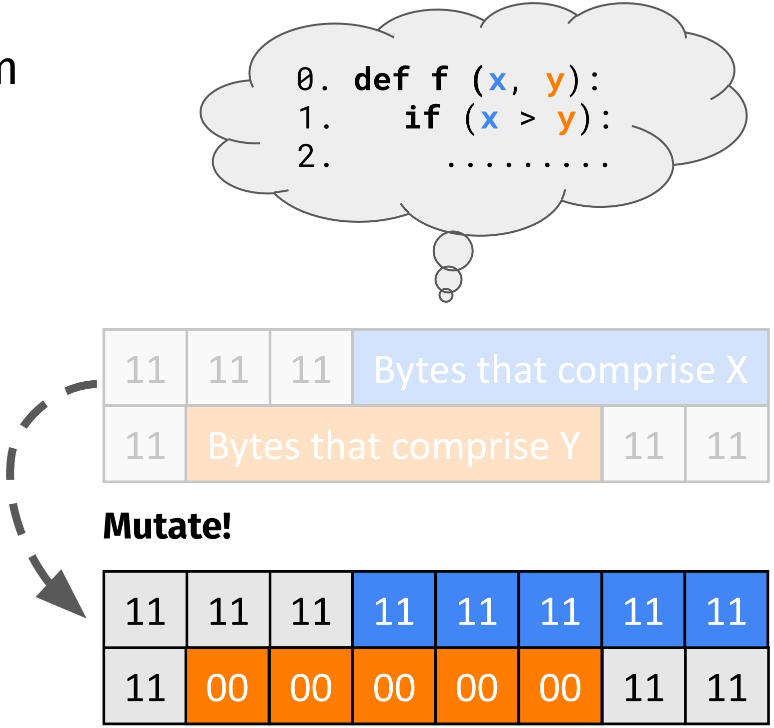
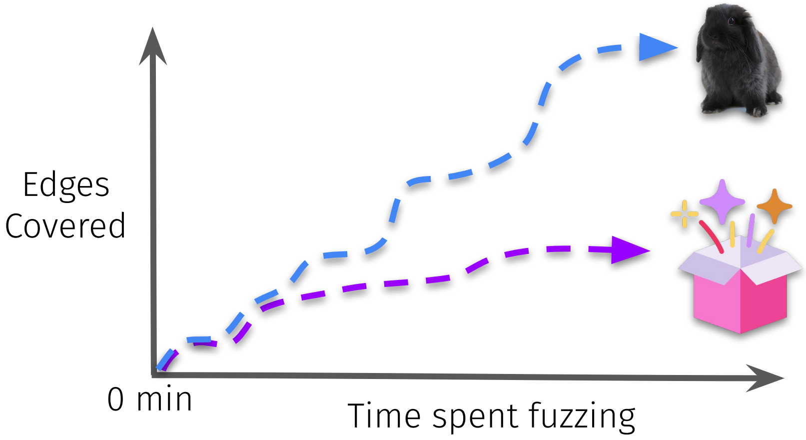


White-box Generation Trade-offs

- **All of these techniques are heavyweight**
  - Too slow to deploy for every input, branch, etc.
  - Must decide *which* problems to feed it
    - Scheduling problem
- **Generally limited to simple software**
  - Good luck doing taint tracking on MS Office…
- **Emerging techniques give us hope!**
  - Fast taint tracking: RedQueen
  - Fast concolic exec: SymCC



Types of Input Generation

- **Model-agnostic:** great on simple, easy-to-solve branches
  - Need a lot of luck to solve **multi-byte conditionals** and **checksums**
- **Model-guided:** more valid inputs leads to higher coverage
  - Out of luck if specification is **not defined** or **hard-to-define**
- **White-box approaches:**
  - **Symbolic / concolic exec:** precise solving of multi-byte conditionals
  - **Taint tracking:** easily identifies key data objects, branch constraints
  - Far too **heavyweight** to deploy on *every single* generated input

Source: The Art, Science, and Engineering of Fuzzing: A Survey

Questions?

Testing Takeaways

Demo

- **Results?**

Trade-offs are target-dependent

Building a good fuzzer is all about finding the right balance of **performance & precision**.

Any fuzzing is better than not fuzzing

If something has not been fuzzed before,
any fuzzing will probably find *lots* of bugs.

Interested in fuzzing?

- **Spring 2025: CS 5963/6963: Applied Software Security Testing**
  - **Everything you'd ever want to know about fuzzing for finding security bugs!**
  - Course project: team up to fuzz **a real program** (of your choice), and find and report its bugs!
  - https://cs.utah.edu/~snagy/courses/cs5963/

CS 5963/6963: Applied Software Security Testing

This special topics course will dive into today's state-of-the-art techniques for uncovering hidden security vulnerabilities in software. Projects will provide hands-on experience with real-world security tools like AFL++ and AddressSanitizer, culminating in a final project where **you'll team up to hunt down, analyze, and report security bugs in a real application or system of your choice**.

This class is open to graduate students and upper-level undergraduates. It is recommended you have a solid grasp over topics like software security, systems programming, and C/C++.

Professor

Stefan Nagy

Questions?

Food for Thought

- Today, we've talked about **thwarting bugs** by **proactively** discovering them
  - E.g., run fuzzing and try to catch all the bugs!
  - Hopefully the **attacker** will not beat us to it…

- **Question:** how can we redesign our **systems** to prevent software exploits?

Next time on CS 4440…

Virtualization, Isolation, Sandboxing