COMP5111 – Fundamentals of Software Testing and Analysis

Software Vulnerabilities

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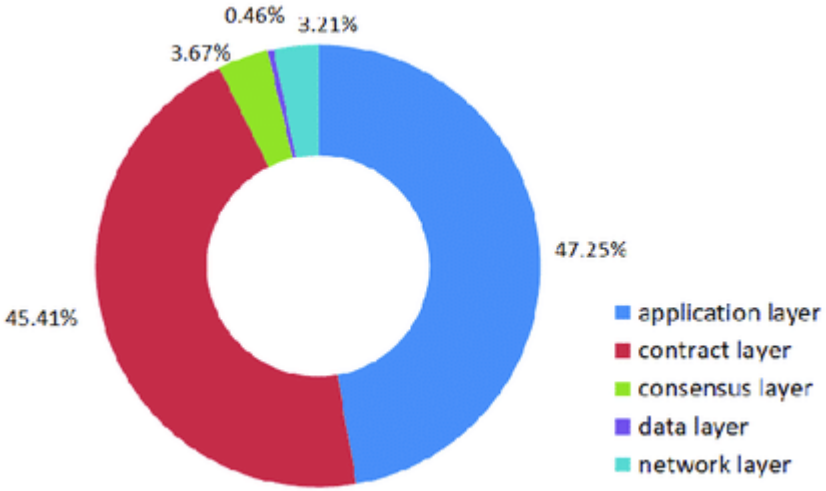
Some slides are adapted from CS155 course notes by John Mitchell, Stanford in his 2018 offering

Software vulnerabilities are a major cause of attacks

Proportion of attacks at different layers of decentralized apps



Huang, Yongfeng & Bian, Yiyang & Li, Renpu & Zhao, J. & Shi, Peizhong. (2019). Smart Contract Security: A Software Lifecycle Perspective. IEEE Access. 7. 1-1. 10.1109/ACCESS.2019.2946988.

Software Vulnerabilities

OMG! So many use-after-free?

- Vulnerabilities are software flaws or oversights that are subject to malicious actions
- Examples of malicious actions include
  - expose or alter sensitive information – data breaches
  - disrupt or destroy an intended service or functionality
  - take control of a program or computer system
- Software vulnerabilities are a major cause of security attacks
  - A major topic in computer security venues

Vulnerability Example

- Missed lower-bound check:

```
/* 2.4.5/drivers/char/drm/i810_dma.c */

if(copy_from_user(&d, arg, sizeof(arg)))
   return -EFAULT;
if(d.idx > dma->buf_count)   // upper-bound check
   return -EINVAL;
buf = dma->buflist[d.idx];
Copy_from_user(buf_priv->virtual, d.address, d.used);
```

Memory Related Vulnerabilities

- Crash Causing Defects
- Null pointer dereference
- Use after free
- Double free
- Array indexing errors
- Mismatched array new/delete
- Potential stack overrun
- Potential heap overrun
- Return pointers to local variables
- Logically inconsistent code
- Uninitialized variables
- Invalid use of negative values
- Passing large parameters by value
- Underallocation of dynamic data
- Memory leaks
- File handle leaks
- Network resource leaks
- Unused values
- Unhandled return codes
- Use of invalid iterators

Slide credit: Andy Chou

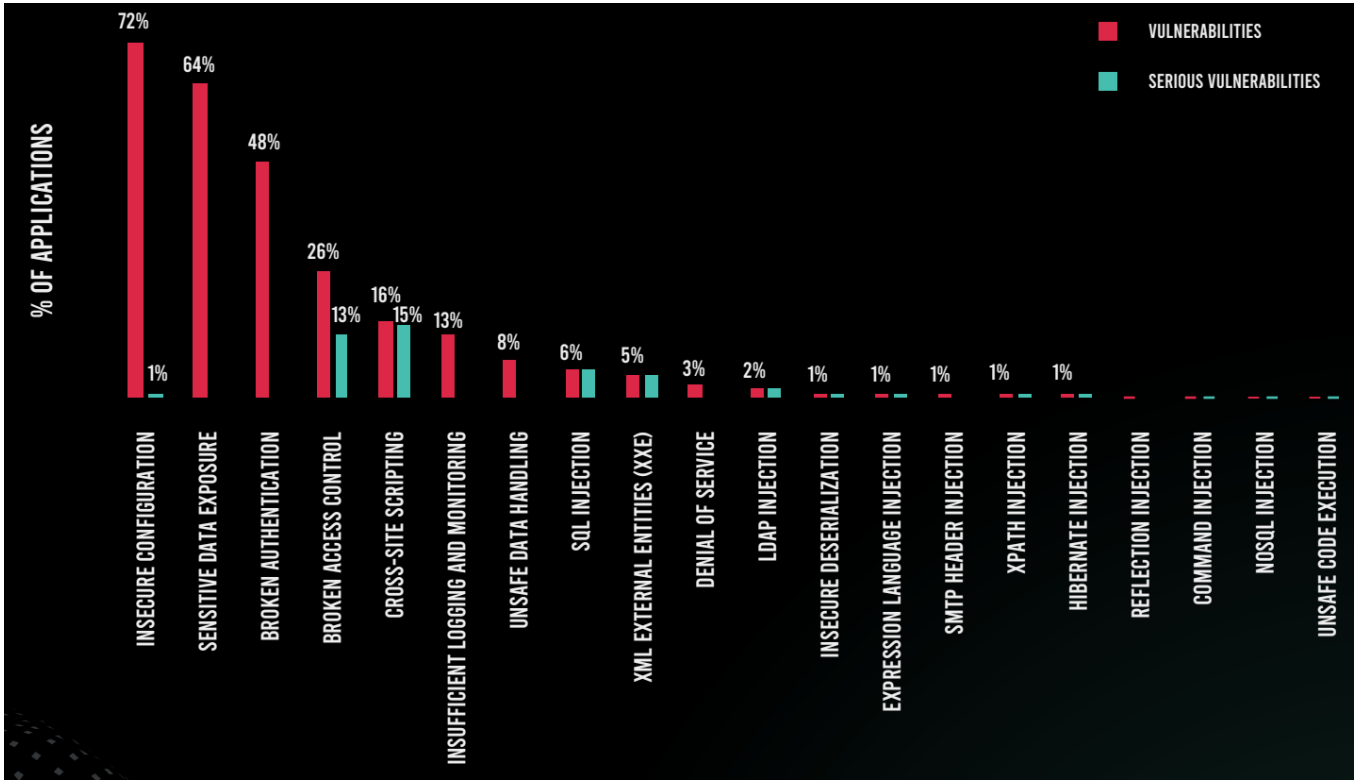
How Severe? 2020 Vulnerability Facts

- 96% of applications have at least one vulnerability; 26% (11%) of them contains at least one (six) serious vulnerabilities
- An application on average has 30+ vulnerabilities
  - Could be induced by vulnerable public libraries
- A software project on average introduces 1-2 new vulnerabilities every month
- Nearly one-half of data breaches in 2019 were the results of vulnerabilities
- 55% of open source libraries are never invoked – bloating
- Only 14% of libraries used by applications are the latest version

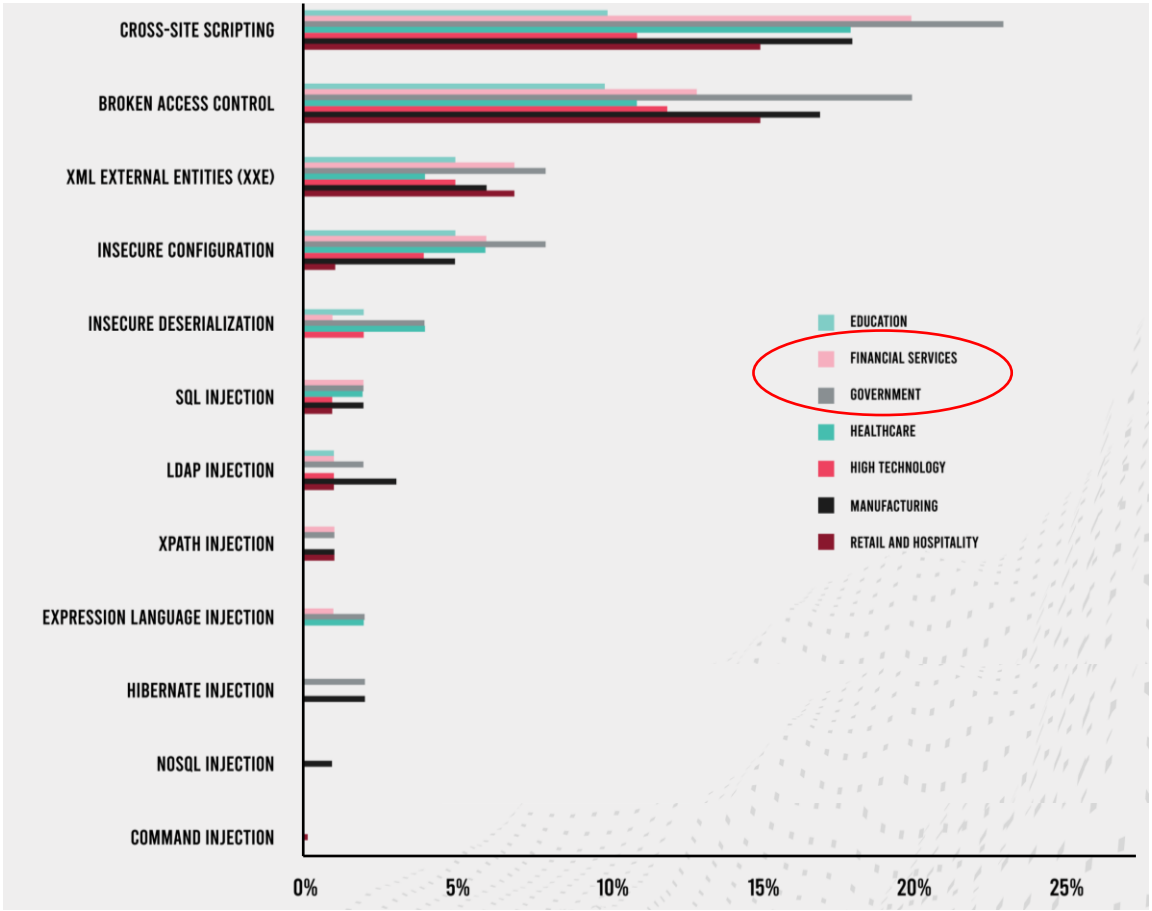
Contrast 2020 AppSec Observability Report

https://www.contrastsecurity.com/hubfs/2020-Contrast-Labs-Application-Security-Observability_Annual_Report_07152020.pdf

Percentage of applications with reported vulnerabilities by specific vulnerability categories

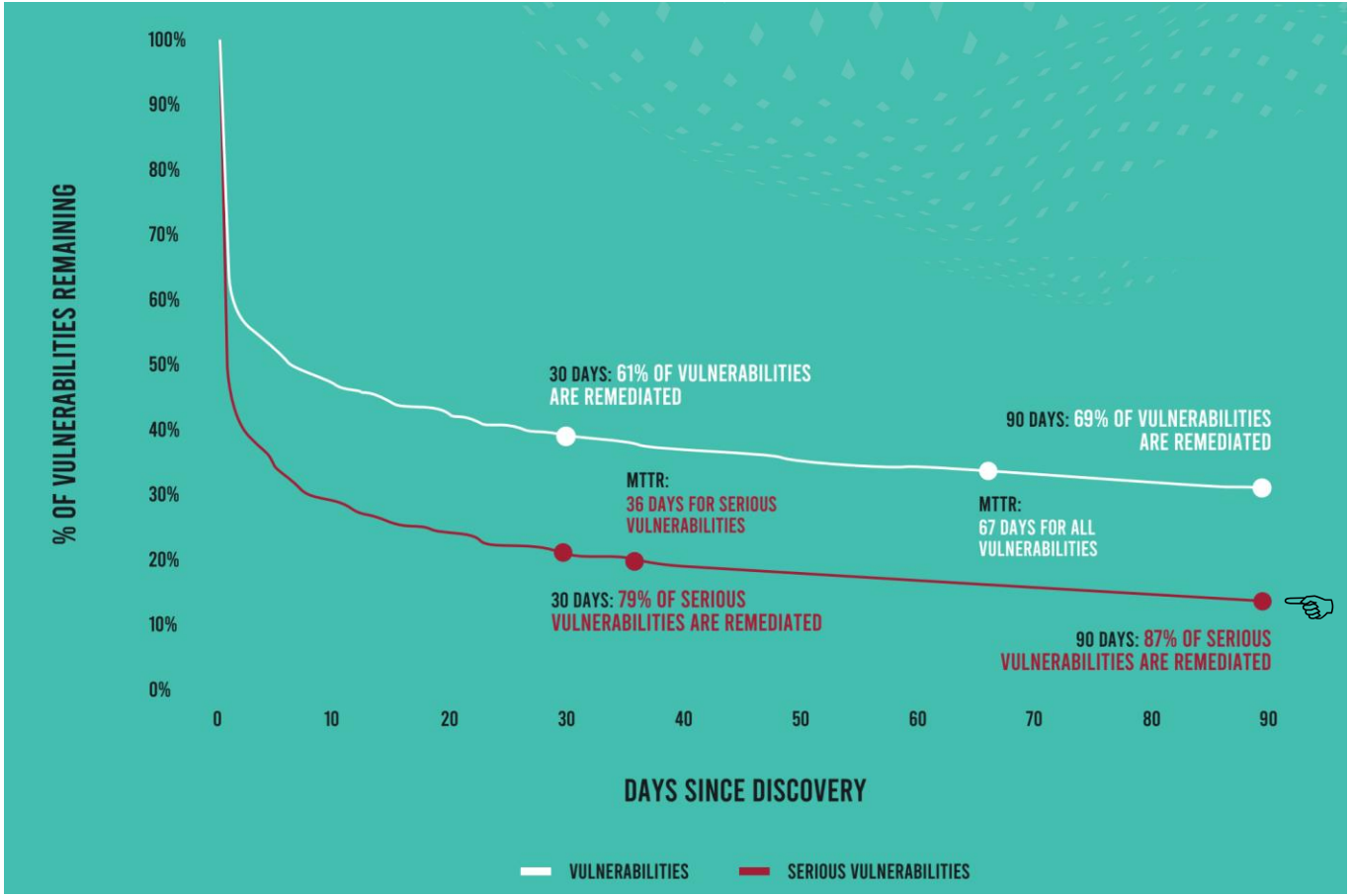


Source: Security Observability Report 2020



% of applications with at least one reported serious vulnerabilities by industry and vulnerability category

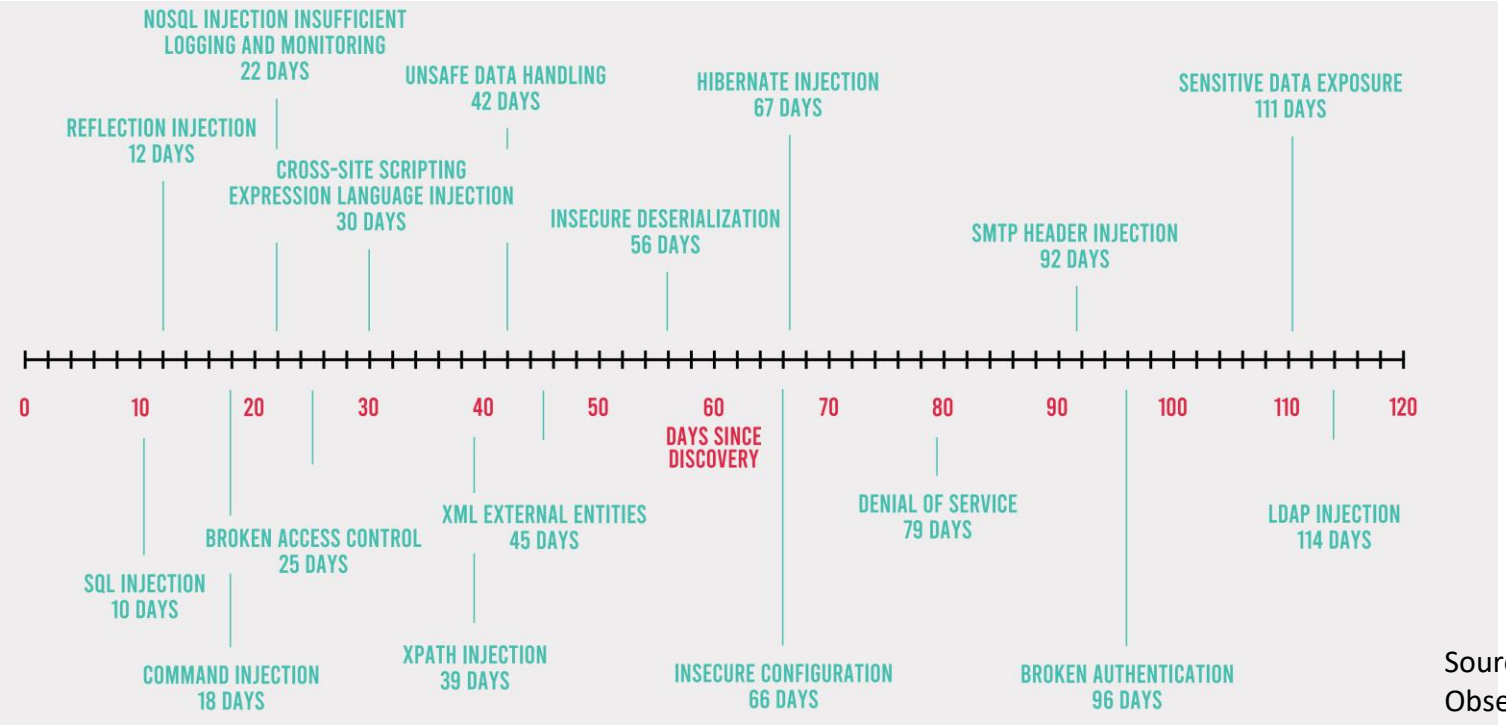
Source: Security Observability Report 2020



% of vulnerabilities remaining by days since they are first discovered

Source: Security Observability Report 2020

Mean time to remediate (MTTR) vulnerabilities by category



Source: Security Observability Report 2020

Top 50 Products By Total Number Of "Distinct" Vulnerabilities

Go to year: 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 201
2019 2020 2021 All Time Leaders

	Product Name	Vendor Name	Product Type	Number of Vulnerabilities
1	Debian Linux	Debian	OS	5356
2	Android	Google	OS	3865
3	Ubuntu Linux	Canonical	OS	3009
4	Mac Os X	Apple	OS	2911
5	Linux Kernel	Linux	OS	2721
6	Iphone Os	Apple	OS	2517
7	Windows 10	Microsoft	OS	2459
8	Fedora	Fedoraproject	OS	2306
9	Chrome	Google	Application	2259
10	Windows Server 2016	Microsoft	OS	2233
11	Windows Server 2008	Microsoft	OS	2091
12	Firefox	Mozilla	Application	1968

source: https://www.cvedetails.com/top-50-products.php?year=2021

Vulnerability Detection is Challenging

- Google Chrome: 7M LOC
- Mozilla Firefox: 10M LOC
- Windows NT4: 11M
- Android: 12M LOC
- MySQL: 13M LOC
- Adobe Acrobat: 13M LOC
- Linux 3.1: 15M LOC
- Apache Open Office: 23M LOC
- Windows 7: 40M LOC
- MS Office 2013: 44M LOC
- MS Visual Studio: 50M LOC
- Facebook: 61M LOC
- Debian 5.0 codebase: 67M LOC
- Mac OS X: 85M LOC
- Car software: 100M LOC
- Google services: 2000M LOC

source: https://www.visualcapitalist.com/millions-lines-of-code/

Effort can be rewarding: Mozilla

Novel vulnerability and exploit, new form of exploitation or an exceptional vulnerability	High quality bug report with clearly exploitable critical vulnerability[1]	High quality bug report of a critical or high vulnerability[2]	Minimum for a high or critical vulnerability[3]	Medium vulnerability
$10,000+	$7,500	$5,000	$3,000	$500 - $2500

- A vulnerability is exploitable if it can leveraged for malicious attacks using resources affordable by attackers

Bug Bounty Programs

- Google Vulnerability Reward Program: up to $31,337
- Microsoft Bounty Program: up to $100K
- Apple Bug Bounty program: up to $200K (secure boot firmware)

Black market offers competitive rewards

At a price that many will suffer from these attacks

ADOBE READER	$5,000–$30,000
MAC OSX	$20,000–$50,000
ANDROID	$30,000–$60,000
FLASH OR JAVA BROWSER PLUG-INS	$40,000–$100,000
MICROSOFT WORD	$50,000–$100,000
WINDOWS	$60,000–$120,000
FIREFOX OR SAFARI	$60,000–$150,000
CHROME OR INTERNET EXPLORER	$80,000–$200,000
IOS	$100,000–$250,000

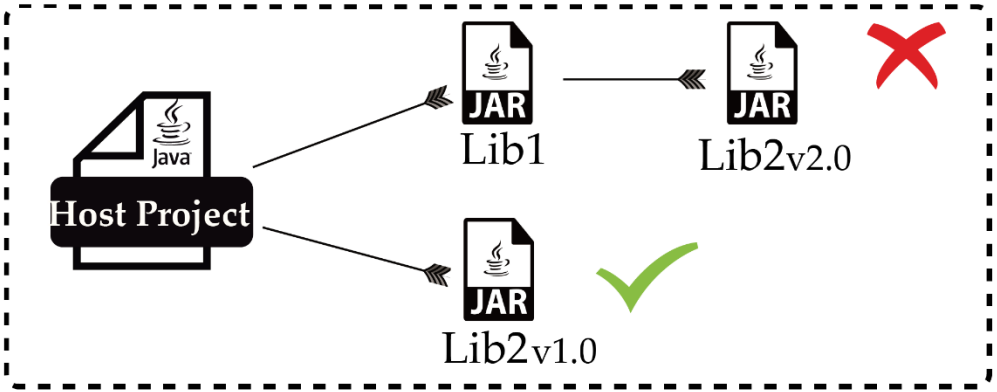
… and even up to $1.5M

Source: Andy Greenberg (Forbes, 3/23/2012)

Major Causes of Vulnerabilities

- Recent software heavily rely on library APIs, many of which are vulnerable
  - An application on average uses 32 different libraries though 56% of those libraries are not actually used
- Less than 14% (9%) of the open-source (Java) libraries uses are the latest version
- Developers commonly learn API usages from examples at online blogs such as Stack Overflow
  - These examples focus on API's functions rather than checks to guard against vulnerabilities
- The need to support an application over heterogeneous systems and devices
- API library dependency conflicts
  - Depends on different versions of the same API library

API Library Dependency Conflicts

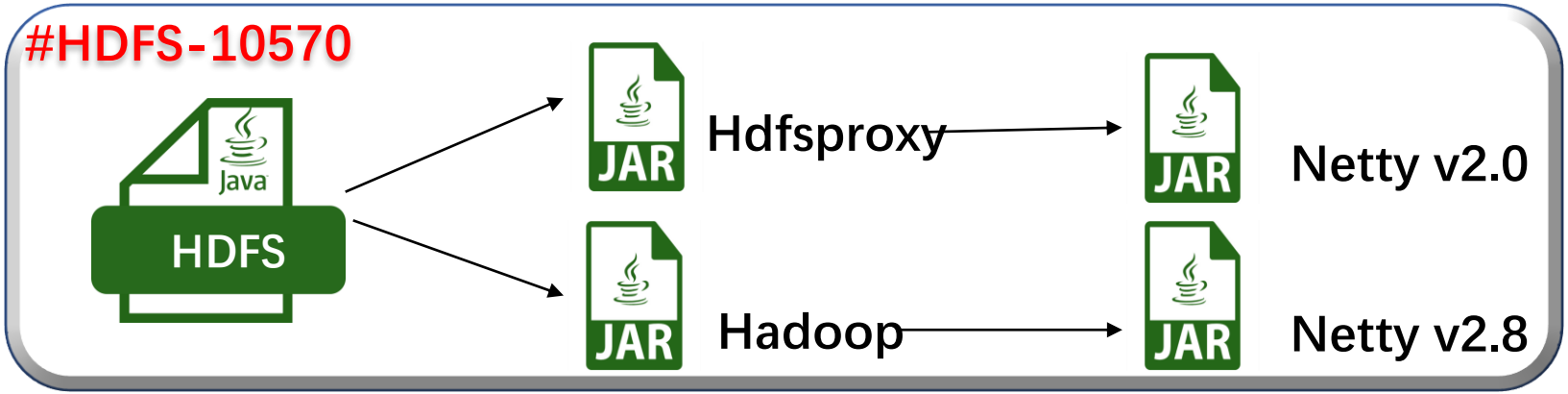



```
1. [INFO] [dependency:tree]
2. [INFO] groupId:Lib2:jar:v1.0
3. [INFO] groupId:Lib1:jar:v2.8
4. [INFO] +- (groupId:Lib2:jar:v2.0:compile - omitted
for duplicate)
```

- The project depends on two different version of Lib2
- Maven/Gradle build the project using only one version (based on dependency depth)
- Certain assumptions that Lib1 makes on Lib2 do not hold

API Library Dependency Conflicts

- Example
  - Fixed eventually after three patches
  - https://issues.apache.org/jira/browse/HDFS-10570



VULNERABILITY ANALYSIS APPROACHES

Three Major Approaches

Proposed by Barton Miller in 1990s
Inputs may be malformed or unmeaningful

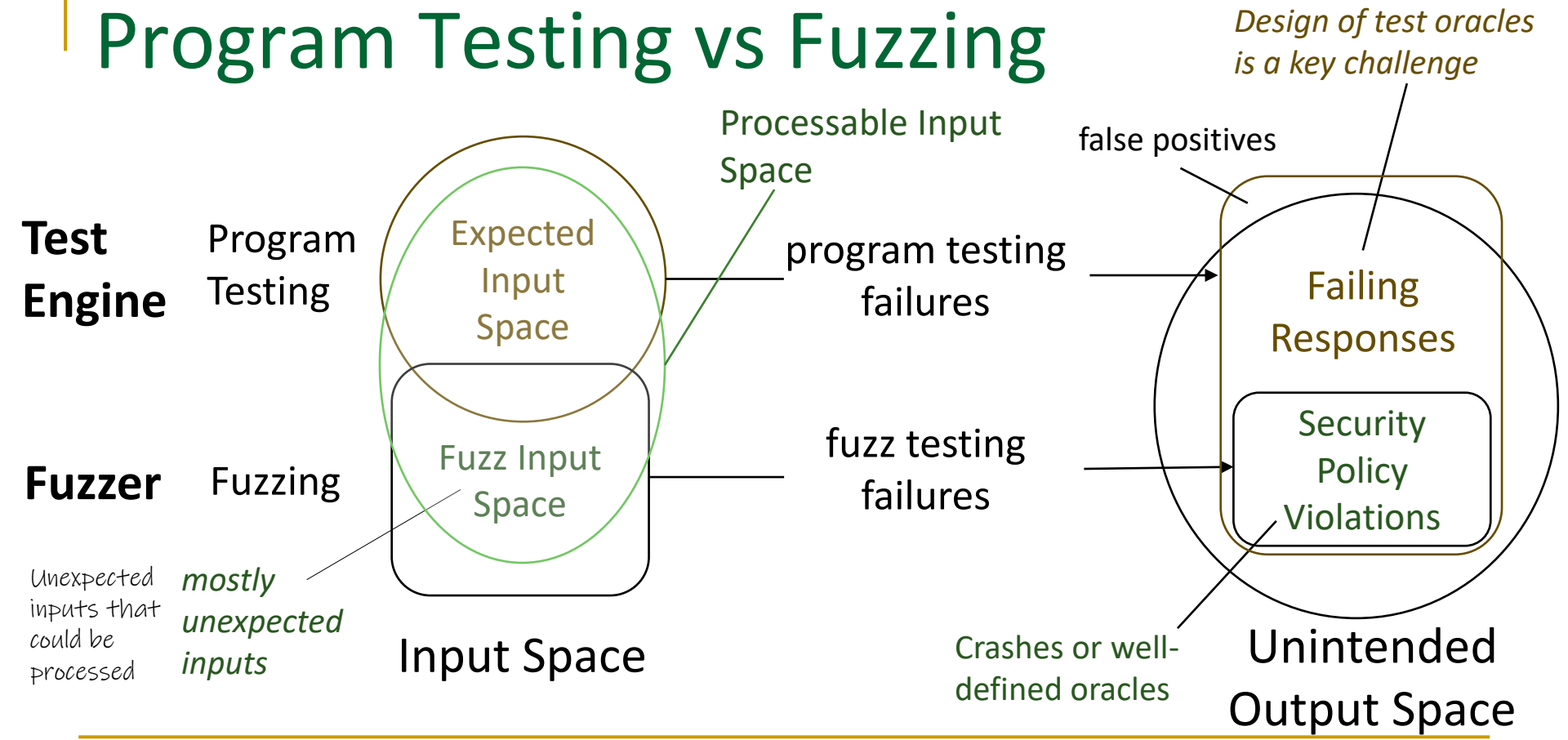
- Dynamic analysis
  - Fuzzing (testing by randomly generated inputs)
  - Slicing and tainting
- Static analysis
  - Slicing and tainting
  - Pointer analysis
- Statistical analysis / Machine learning
- Can be hybrid …

Origin of Fuzzing

- The term “fuzz” originates from a class project in a graduate level course on Advanced Operating Systems taught by Prof Barton Miller in Fall 1988
- The project was to test the reliability of UNIX command line programs by feeding them with a large number of random inputs until they crash
- The class was able to crash 33% of the utilities tested

Miller et al., An Empirical Study of the Reliability of UNIX Utilities. CACM, Dec 1990.

Program Testing vs Fuzzing



Fuzzing Input Space

- Mostly (semi-)malformed inputs/data
  - GEEEE…EET /index.html HTTP/1.1
  - GET ///////index.html HTTP/1.1
  - GET %n%n%n%n%n%n.html HTTP/1.1
  - GET /AAAAAAAAAAAAA.html HTTP/1.1

  Examples of malformed http GET request
- Generated randomly
  - Mutate a population of seeds (e.g., GET index.html HTTP/1.1)
  - Quality of the seeds greatly affects fuzzing performance
    - Smart selection of seeds is an outstanding research problem

Fuzzing vs Random Testing (more details)

Fuzzing	Random Testing
Detect faults exploitable by hackers	Detect faults unintentionally triggered by users
Target well-defined fault types (fault-based)	Target all unexpected program behaviors
Generic well-defined test (vulnerability) oracles; No need for regression test oracles	Test oracles vary across test cases; Regression test oracles are meaningful
Fuzz anything that can be manipulated (including binaries and memories)	Generate sensible test inputs or test scripts
Fuzzed inputs can be meaningless (e.g., a successful attack triggered by hitting buttons hundred times in a second is likely considered legitimate)	Test inputs should be sensible; otherwise faults detected can be false positives (e.g., a failure caused by hitting buttons hundred times in a second is likely considered false negative)

Crashes vs Security Policy Violations

Bug ID	Program		Bug	
	Project	Size	Type	Crash
giflib-bug-74	GIFLIB	59 Kb	DF	✗
CVE-2018-11496	lrzip	581 Kb	UAF	✗
yasm-issue-91	yasm	1.4 Mb	UAF	✗
CVE-2016-4487	Binutils	3.8 Mb	UAF	✓
CVE-2018-11416	jpegoptim	62 Kb	DF	✗
mjs-issue-78	mjs	255 Kb	UAF	✗
mjs-issue-73	mjs	254 Kb	UAF	✗
CVE-2018-10685	lrzip	576 Kb	UAF	✗
CVE-2019-6455	Recutils	604 Kb	DF	✗
CVE-2017-10686	NASM	1.8 Mb	UAF	✓
gifsicle-issue-122	Gifsicle	374 Kb	DF	✗
CVE-2016-3189	bzip2	26 Kb	UAF	✓

DF: Double Free
UAF: Use-After-Free

A recent benchmark in Nguyen et al., Binary-level Directed Fuzzing for Use-After-Free Vulunerabilities. USENIX RAID 20.

Can Fuzzing detect deep vulnerabilities?

YES! For example, AFL, a commonly used fuzzer, can uncover the Heartbleed vulnerability in the OpenSSL implementation in 3 minutes.

The vulnerability, reported on 7 April 2014, allows hackers to steal sensitive information including encryption keys and passwords over Websites using OpenSSL connections

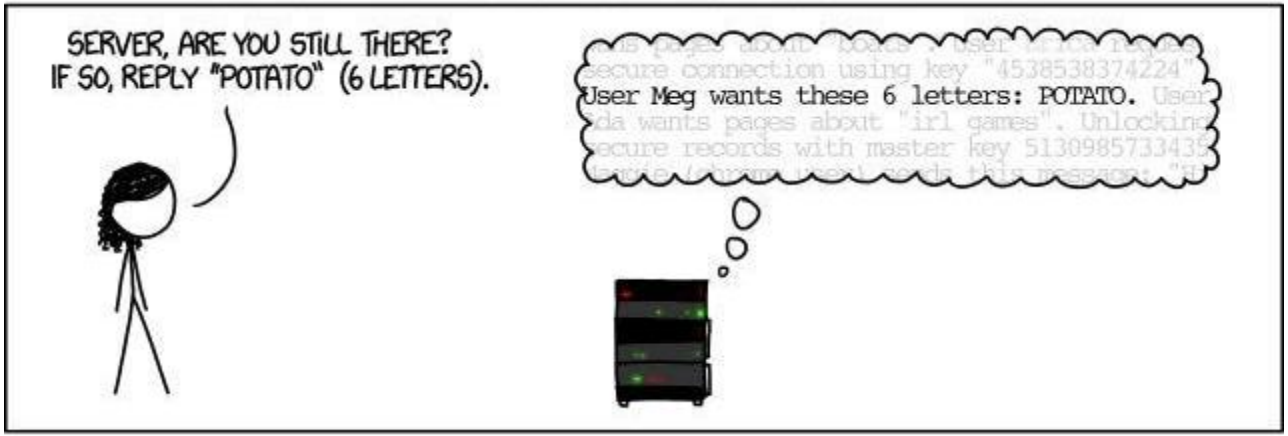
Affected applications included those run by Google, Yahoo, Dropbox, Netflix, Facebook, Amazon Web Services, Apple, Microsoft, PayPal, LinkedIn, eBay, Twitter, AOL, Bank of America, Chase,Fidelity, Schwab, US Bank, and Wells Fargo.

The mistake was traced to a single line of code in the OpenSSL implementation:
memcpy(bp, pl, payload);

https://www.vox.com/2014/6/19/18076318/heartbleed

How Heartbleed works - 1

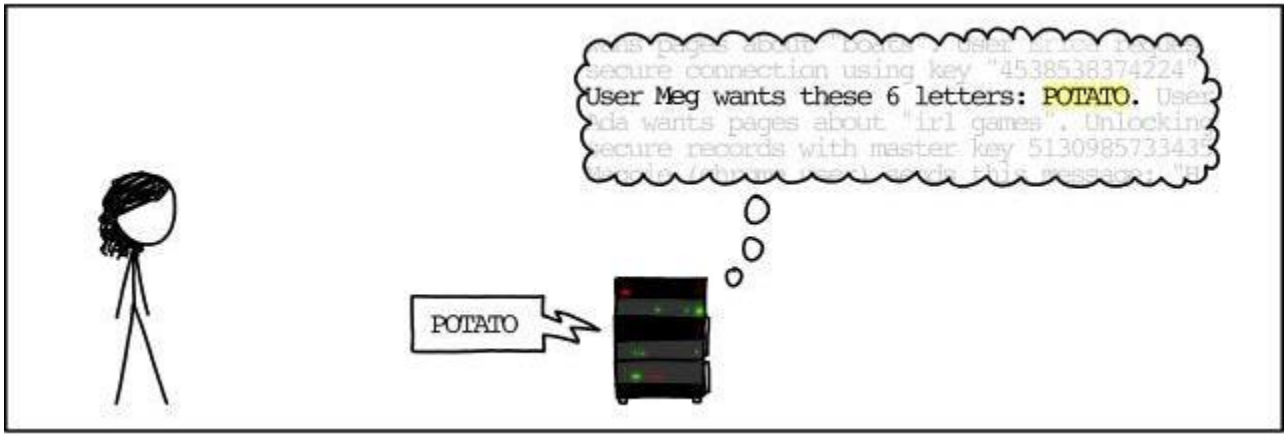
https://www.howtogeek.com/186735/htg-explains-what-the-heartbleed-bug-is-and-why-you-need-to-change-your-passwords-now/



OpenSSL keeps a side channel allowing users to send heartbeats to a server, checking if it is still awake. As heartbeats do not contain sensitive information, they are not encrypted for the sake of performance.

How Heartbleed works - 2

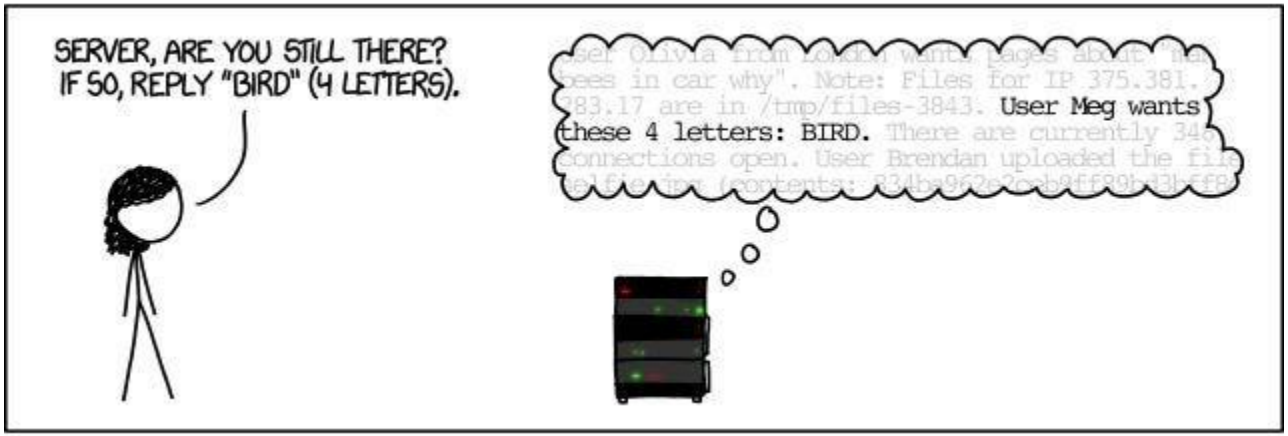
https://www.howtogeek.com/186735/htg-explains-what-the-heartbleed-bug-is-and-why-you-need-to-change-your-passwords-now/



An heartbeat request contains an insensitive payload (e.g., POTATO) and an integer indicating the payload size (e.g., 6). After receiving the request, server replies users with a heartbeat message containing the payload content.

How Heartbleed works - 3

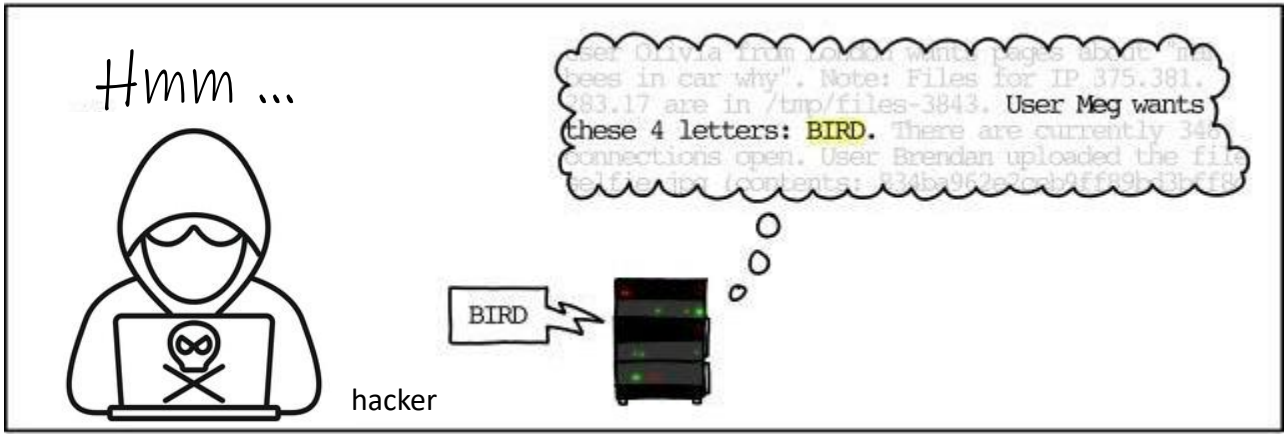
https://www.howtogeek.com/186735/htg-explains-what-the-heartbleed-bug-is-and-why-you-need-to-change-your-passwords-now/



After a while, users can send another heartbeat request with different payload (e.g., BIRD) and an integer indicating the payload size (e.g., 4).

How Heartbleed works - 4

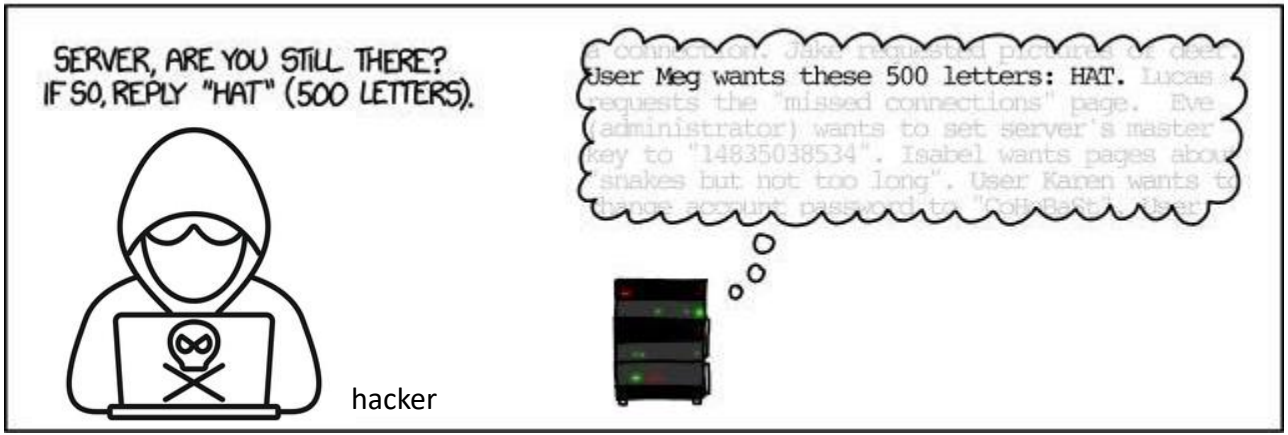
https://www.howtogeek.com/186735/htg-explains-what-the-heartbleed-bug-is-and-why-you-need-to-change-your-passwords-now/



Server replies with an heartbeat message containing the payload (e.g., BIRD).

How Heartbleed works - 5

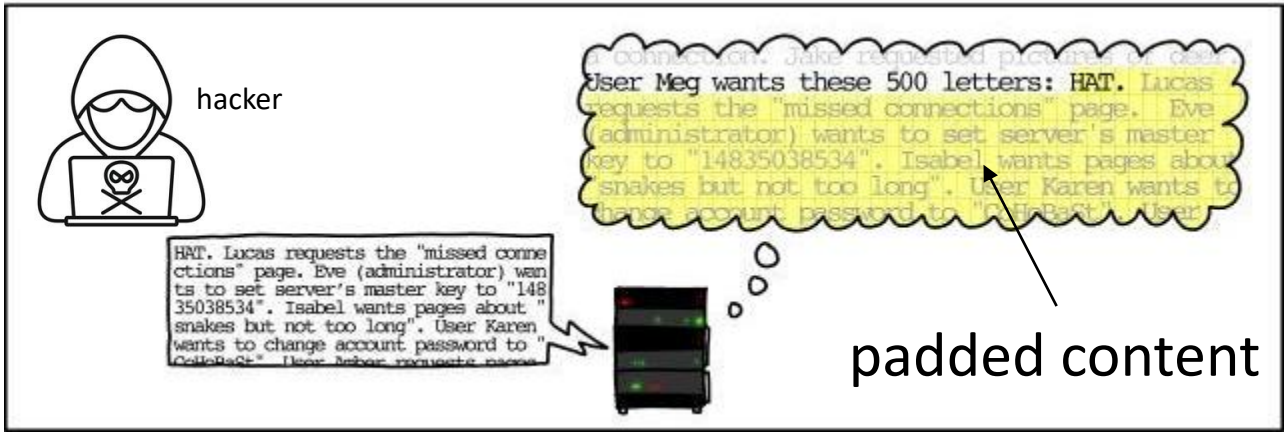
https://www.howtogeek.com/186735/htg-explains-what-the-heartbleed-bug-is-and-why-you-need-to-change-your-passwords-now/



However, a hacker can send a heartbeat request with little payload content (e.g., HAT) and tell that it has a large payload size (e.g., 500).

How Heartbleed works - 6

https://www.howtogeek.com/186735/htg-explains-what-the-heartbleed-bug-is-and-why-you-need-to-change-your-passwords-now/



The server does not check the consistency but constructs a reply padded with the content after HAT in the memory. The padded content likely contains sensitive information, and it is not encrypted!

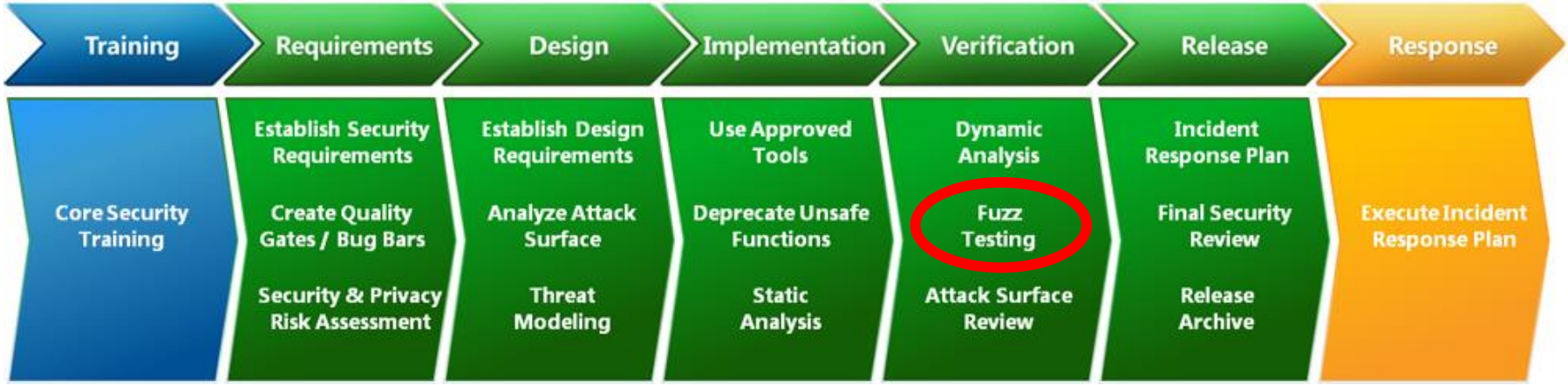
Detection of Heartbleed

```
shadowsword@shadowswordpl ~/HEARTBLEED/openssl-1.0.1f $ ./runError.sh afl_out/master/crashes/id\:000000\,sig\:06\,src\:000032\,op\:arith8\,pos\:0\,val\:+3
==================================================================
==16345== ERROR: AddressSanitizer: unknown-crash on address 0x60820001220b at pc 0x7f4a98de23f7 bp 0x7fffa0b72380 sp 0x7fffa0b71b40
READ of size 25600 at 0x60820001220b thread T0
    #0 0x7f4a98de23f6 (/usr/lib/x86_64-linux-gnu/libasan.so.0+0xe3f6)
    #1 0x410dad in memcpy /usr/include/x86_64-linux-gnu/bits/string3.h:51
    #2 0x410dad in tls1_process_heartbeat /home/shadowsword/HEARTBLEED/openssl-1.0.1f/ssl/t1_lib.c:2586
    #3 0x49d16c in ssl3_read_bytes /home/shadowsword/HEARTBLEED/openssl-1.0.1f/ssl/s3_pkt.c:1092
    #4 0x4a0ca3 in ssl3_get_message /home/shadowsword/HEARTBLEED/openssl-1.0.1f/ssl/s3_both.c:457
    #5 0x465a2d in ssl3_get_client_hello /home/shadowsword/HEARTBLEED/openssl-1.0.1f/ssl/s3_srvr.c:941
    #6 0x4764b3 in ssl3_accept /home/shadowsword/HEARTBLEED/openssl-1.0.1f/ssl/s3_srvr.c:357
    #7 0x402487 in main /home/shadowsword/HEARTBLEED/openssl-1.0.1f/selftls.c:95
    #8 0x7f4a9882cec4 (/lib/x86_64-linux-gnu/libc.so.6+0x21ec4)
    #9 0x40299c in _start (/home/shadowsword/HEARTBLEED/openssl-1.0.1f/selftls+0x40299c)
0x608200016748 is located 0 bytes to the right of 17736-byte region [0x608200012200,0x608200016748)
allocated by thread T0 here:
    #0 0x7f4a98de941a (/usr/lib/x86_64-linux-gnu/libasan.so.0+0x1541a)
    #1 0x4d7946 in CRYPTO_malloc /home/shadowsword/HEARTBLEED/openssl-1.0.1f/crypto/mem.c:308
```

After 3 minutes, a seed generated by the AFL fuzzer contains 0x18037F00020164 and causes a crash at the AddressSanitizer.

http://9livesdata.com/fuzzing-how-to-find-bugs-automagically-using-afl/

Do Companies use Fuzzing?

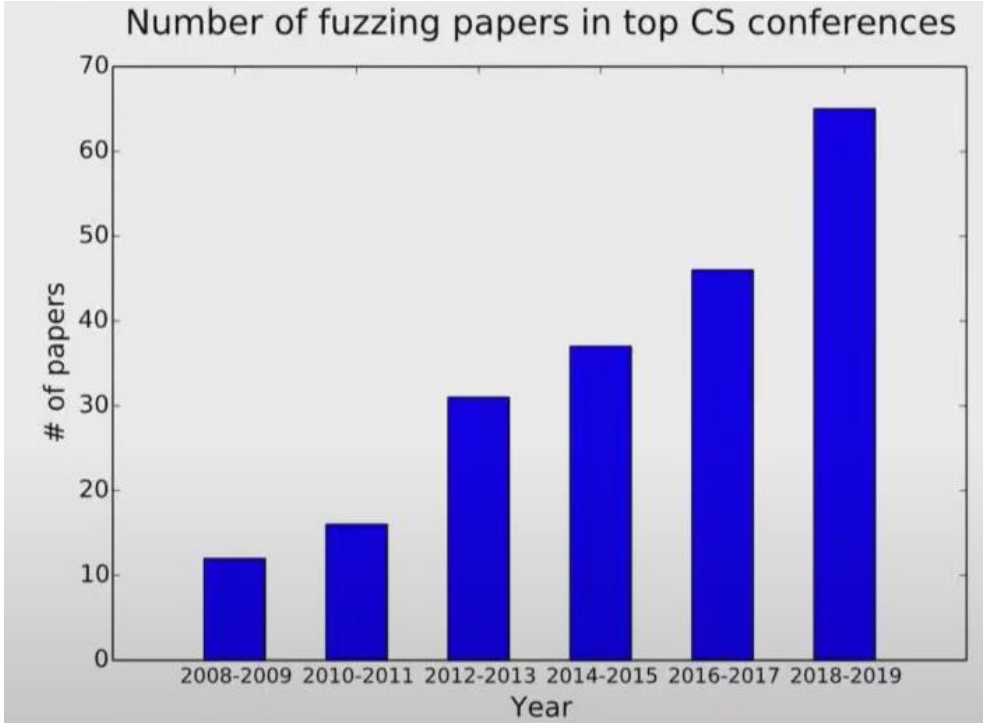


Microsoft Security Development Lifecycle

Industry Adoption

- Google has discovered 16,000+ bugs in Chrome and 11,000+ bugs in 160+ open-source projects using a greybox fuzzer
  - https://google.github.io/clusterfuzz/#trophies
- Microsoft saved millions of dollars in Win 7 using SAGE, a whitebox fuzzer [Godefroid et al. NDSS 2008]
- Trail of Bits provides the DeepState framework facilitating C/C++ developers to fuzz testing their systems
  - https://github.com/trailofbits/deepstate
- …

Fuzzing is hot!



- Increasing attention from academics
- Key problem: Huge input space of fuzzing
- She et al. S&P 2019 https://www.youtube.com/watch?v=j4ynjsA5CEQ

Three Fuzzing Approaches

Whitebox

- Input seeds and grammar
- Advanced code analysis (e.g., symbolic execution)
- Able to uncover hard corner cases
- Expensive and not scalable

Active ongoing research

Greybox

predominant

- Input seeds and grammar
- Able to uncover many corner cases
- Scalable
- Most popular
- Knowledge of code structure
- Coverage-based prioritization
  (Generates more mutants to cover prioritized branches/call sequences)
- Often guided by a fitness function

Blackbox

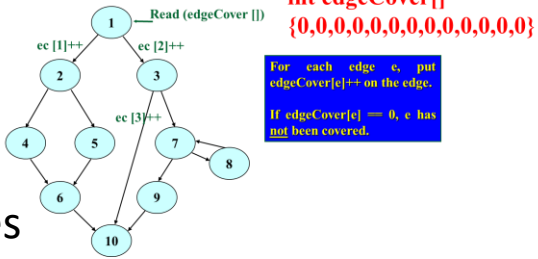
- Input seeds and grammar
- Able to uncover some corner cases
- Inexpensive and scalable
- Easy to deploy
- The original approach

Adopted more widely by practitioners

Frameworks of Fuzzing

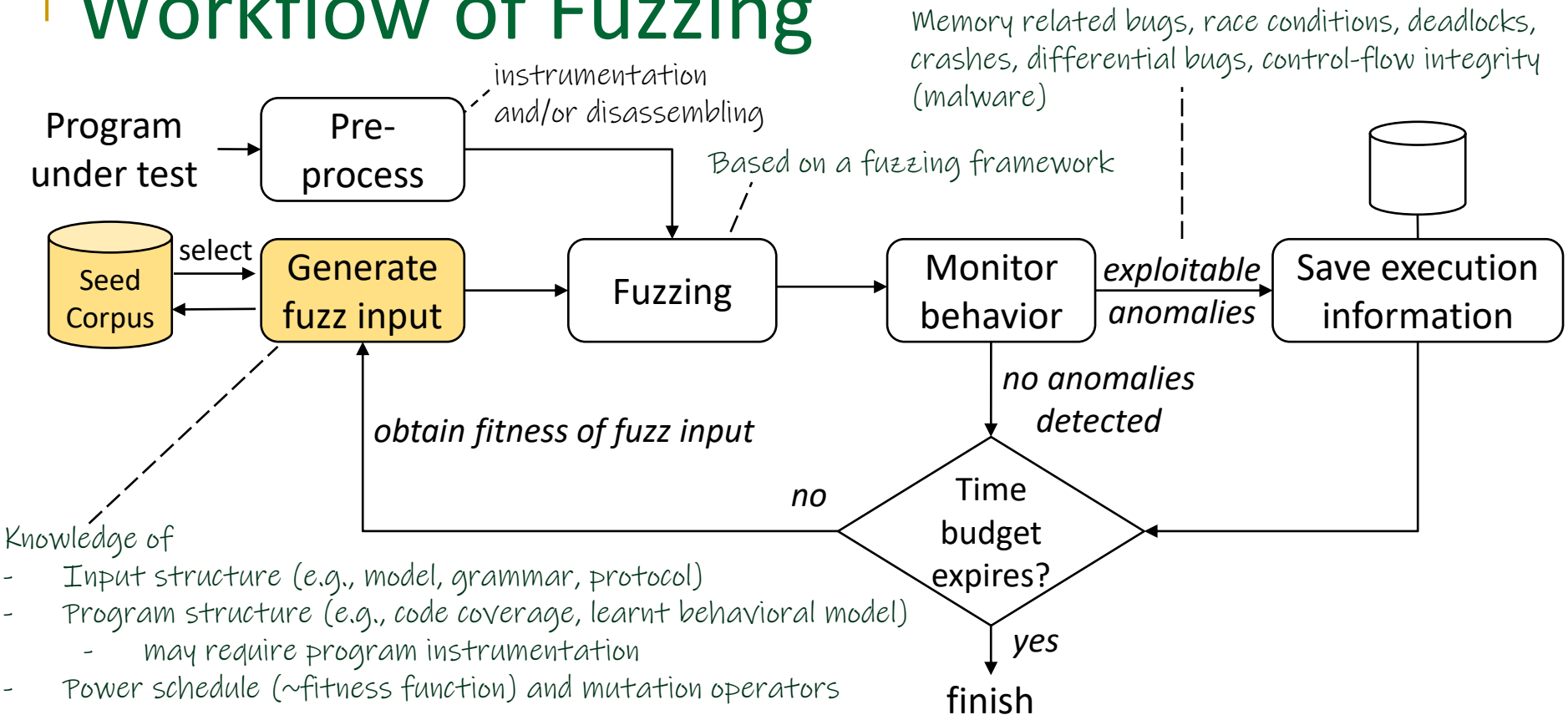
- Driven by a Fuzzer over a fuzzing framework (cf. JUnit)
  - Generate massive fuzzed data randomly (with an optional fitness function)
    - Based on either branch coverage or branch hit count (e.g., AFL)
    - Use of distance-based fitness function is possible:
      V. Manes, S. Kim, S. Cha. Ankou: Guiding Grey-box Fuzzing towards Combinatorial Differences. ICSE 2020.
  - Monitor crashes and security policy violations by means of resource (e.g., registry, memory, cpu) anomalies
    - Unlike conventional testing, test oracles are usually application-generic predefined by a fuzzer

Edge Coverage Instrumentation

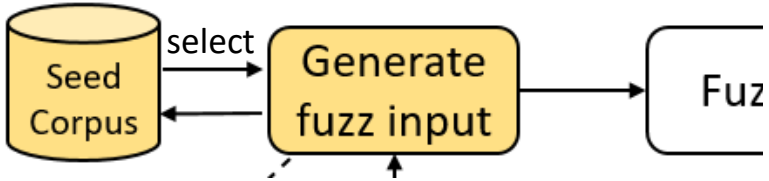


- Many frameworks are publicly available
  - Peach Fuzz, **AFL**, LibFuzzer, Honggfuzz, Radamsa, Zzuf, BFF, TAOF, KLEE, SAGE, …
  - AFL is a popular coverage-based greybox fuzzing framework used by academics

Workflow of Fuzzing



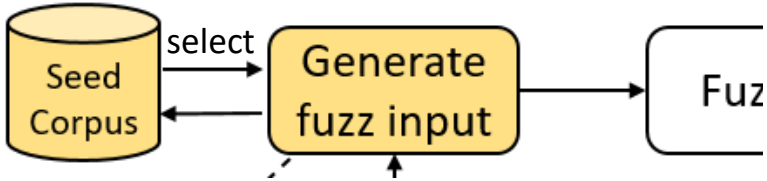
Generate Fuzz Input



- Seed selection
  - Search strategy: Decides the order in which seeds are chosen from the corpus based on a **fitness function**
  - Energy assignment (Power Schedule): Determine the number of mutants generated from a seed
    - AFL spends more energy fuzzing seeds that are small and execute quickly
    - Some fuzzers simply generate a small random number of mutants from a selected seed

… based on AFL

Generate Fuzz Input



- Seed mutation (assuming the seed is a string)
  - Insert a character randomly
  - Delete a character randomly
  - Select a character randomly and flip a random bit of it
  - Add the generated seed to the Seed Corpus

… based on AFL

Common Types of Faults Found by Fuzzing

- Memory corruption in native code
  - Stack and heap buffer overflows
  - Un-validated pointer arithmetic (offset can be controlled by attackers)
  - Integer overflows
  - Resource exhaustion (memory, disk, CPU)

Common Types of Faults Found by Fuzzing

- Unhandled exceptions
  - Illegal format exceptions (due to illegal inputs/data)
  - Memory exceptions
  - Null reference exceptions
- Exposure to injection
  - SQL injection
  - LDAP injection
  - HTML injection

What Types of Inputs/Data can be Fuzzed?

- No restriction
- Primitive data: bit, byte, word, dword, qword, …

```
for each {byte|word|dword|qword} aligned location in file
    for each bad_value in bad_valueset
    {
            file[location] := bad_value
            apply_test()
    }
```

What Types of Inputs/Data can be Fuzzed?

- Language specific data: strings, structs, arrays, …
- High level data: text, xml, header, trailer, …

```
…
o_jpeg = fz3AddObjectToList( NULL, TYPE_BYTE, PTR(0xff), 1 ); // new header
fz3AddObjectToList( o_jpeg, TYPE_BYTE, PTR(0xd8), 1 ); // unknown type (start of file?)
fz3AddObjectToList( o_jpeg, TYPE_BYTE, PTR(0xff), 1 );  // new header
fz3AddObjectToList( o_jpeg, TYPE_BYTE, PTR(0xe0), 1 );  // extension marker segment
o_jfif_len = fz3AddObjectToList( o_jpeg, TYPE_WORD, BE_W(0x10), 2 ); // length
…
```

- Abstract level data: state machine transitions, …

FUZZING APPROACHES

Fuzzing – Three Common Approaches

Mutation-based fuzzing

- Mutate existing good input seeds (e.g., test suite)

Generation-based fuzzing

- Generate inputs from specification of format, protocol, …

Evolutionary (responsive) fuzzing

- Leverage program instrumentation, code analysis
- Use program responses to build input sets

Recap: Unexpected inputs that can be processed by the target software

Source: https://crypto.stanford.edu/cs155/papers/fuzzing.pdf

Mutation-based fuzzing

Basic idea

- Mutate existing valid inputs randomly or according to some heuristics

Standard HTTP GET request

- GET /index.html HTTP/1.1 ← a given valid input seed

Malformed requests

- GEEEE…EET /index.html HTTP/1.1
- GET ///////index.html HTTP/1.1
- GET %n%n%n%n%n%n.html HTTP/1.1
- GET /AAAAAAAAAAAAA.html HTTP/1.1
- GET /index.html HTTTTTTTTTTTTP/1.1
- GET /index.html HTTP/1.1.1.1.1.1.1.1

Mutation-based fuzzing

Advantages

- Little or no knowledge of the structure of the inputs is assumed
- Requires little or no set up time

Disadvantages

- Dependent on the inputs being modified
- May fail for protocols with checksums, challenge-response, …

Examples fuzzing tools:

- Taof, GPF, ProxyFuzz, etc.

(Mutation-based) Fuzzing - Example

- Find bugs in pdf viewer
  - Difficult to randomly generate valid pdf files from scratch

Modify valid pdf files

PDF Viewer

Crash viewer and isolate causes

Generation-based Fuzzing

Request for Comments

Basic idea

- Tests generated from description of format: RFC, spec, etc.
- Anomalies are added to each possible spot in the test inputs

Advantages

- Knowledge of protocol may give better results than random fuzzing

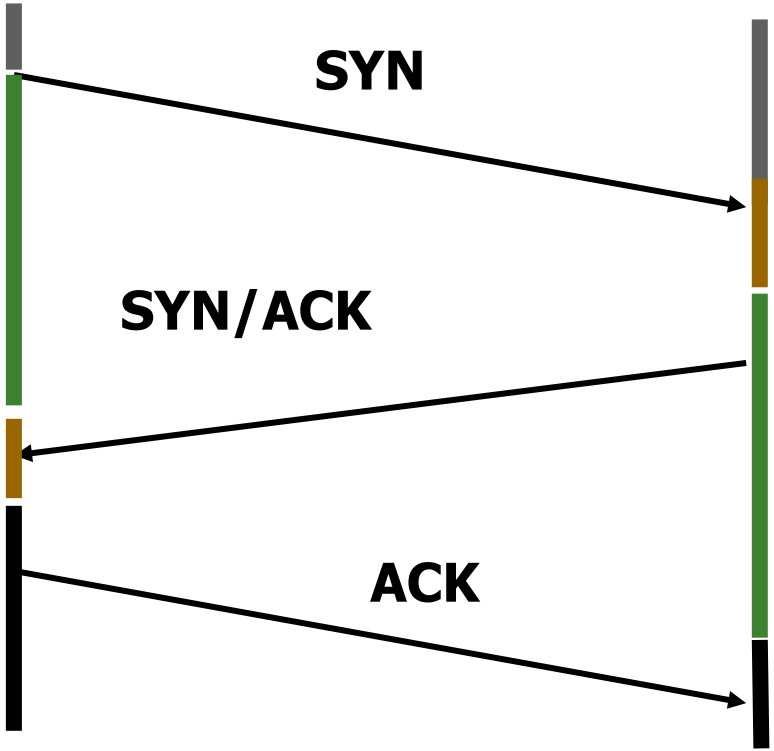
Disadvantages

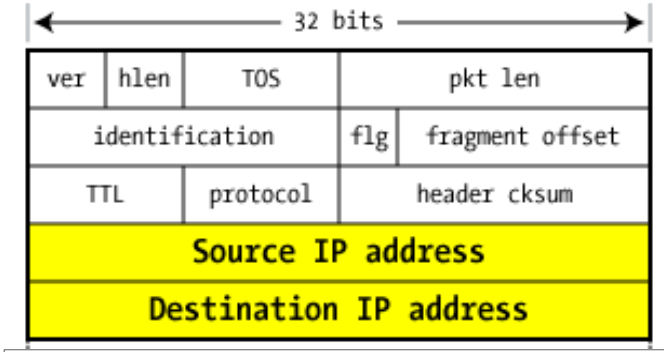
- Can take significant time to set up

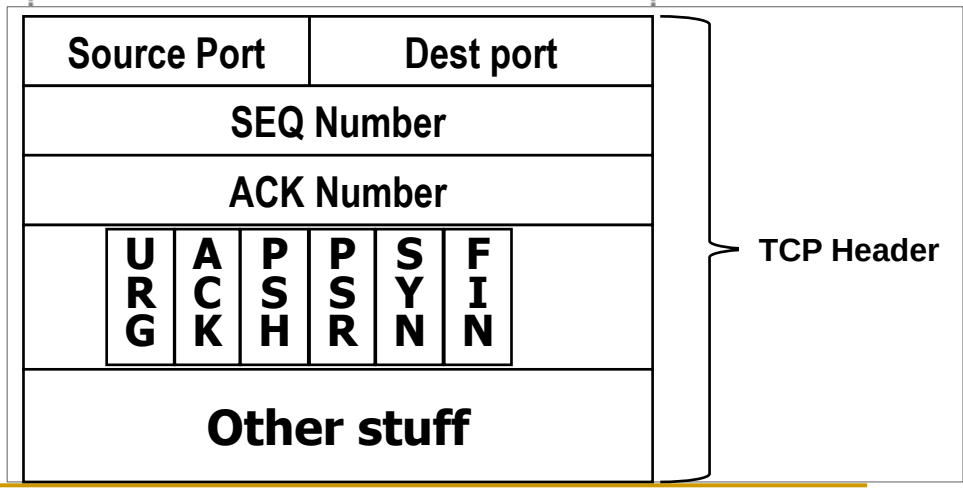
Example tools:

- SPIKE, Sulley, Mu-4000, Codenomicon

Generation-based Fuzzing for Protocol Bugs - Example







Generation-based Fuzzing for Zip file - Example

```
1  <!--  A.  Local file header -->
2    <Block name="LocalFileHeader">
3      <String name="lfh_Signature" valueType="hex" value="504b0304" token="true" mut
4      <Number name="lfh_Ver" size="16" endian="little" signed="false"/>
5      ...
6      [truncated for space]
7      ...
8      <Number name="lfh_CompSize" size="32" endian="little" signed="false">
9        <Relation type="size" of="lfh_CompData"/>
10     </Number>
11     <Number name="lfh_DecompSize" size="32" endian="little" signed="false"/>
12     <Number name="lfh_FileNameLen" size="16" endian="little" signed="false">
13       <Relation type="size" of="lfh_FileName"/>
14     </Number>
15     <Number name="lfh_ExtraFldLen" size="16" endian="little" signed="false">
16       <Relation type="size" of="lfh_FldName"/>
17     </Number>
18     <String name="lfh_FileName"/>
19     <String name="lfh_FldName"/>
20     <!--  B.  File data -->
21     <Blob name="lfh_CompData"/>
22   </Block>
```

Evolutionary (Responsive) Fuzzing

Basic idea

- Generate inputs based on the structure, response of the program

Advantages

- Exploits detailed knowledge of program
- Prioritizes inputs that may lead to vulnerability

Disadvantages

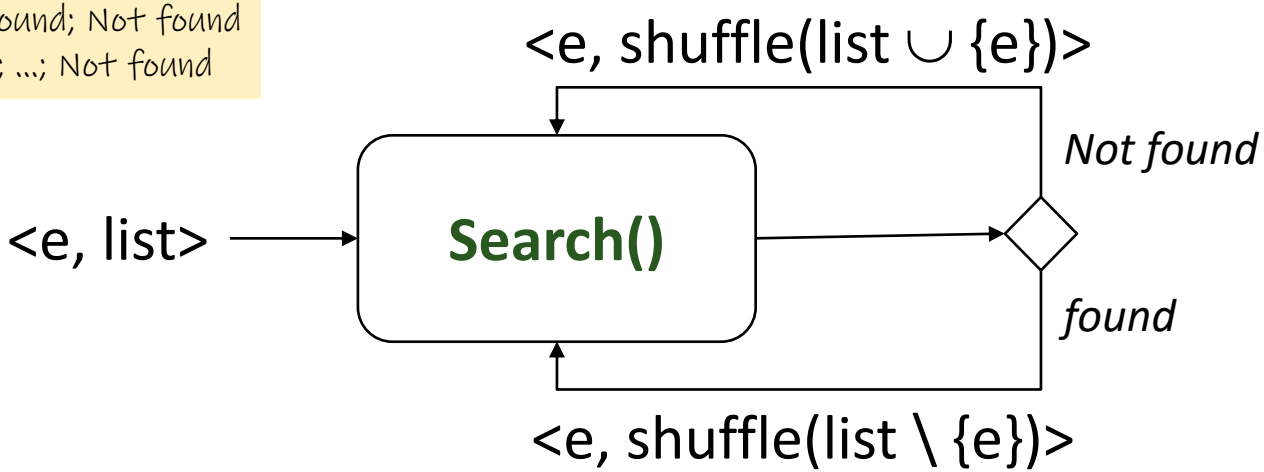
- Requires more effort and domain knowledge

Examples:

- Autodafe
  - Prioritizes test cases based on which inputs have reached dangerous API functions
- Metamorphic testing
  - Generates test cases based on metamorphic relations
- AFL
  - Fitness function based on branch hit count

Evolutionary (Responsive) Fuzzing - MT Example

Two example scenarios:
- Not found; found; Not found
- found; found; ...; Not found



Have knowledge of the search program structure that shuffling a list does not alter the search result.

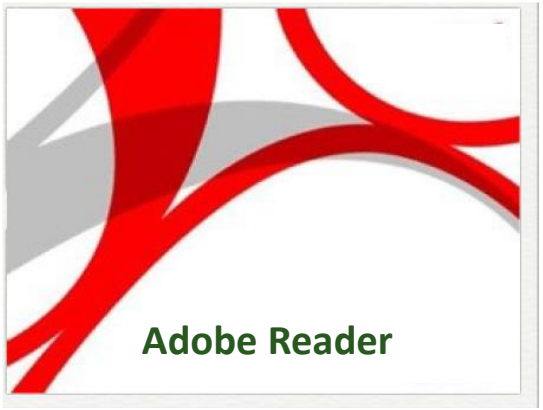
Fuzzing in Practice

Four fuzzing examples

- Mutation-based blackbox: PDF readers – Charlie Miller (2007)
- Generation-based blackbox: iPhone attack (http://www.it-docs.net/ddata/781.pdf) – Charlie Miller (2007)
- Hybrid whitebox: JS Engines by LangFuzz – Holler et al., Fuzzing with Code Fragments, USENIX Security 2012
- Evolutionary-based greybox: UAFuzz - Ngygen et al., Binary-level Directed Fuzzing for Use-After-Free Vulunerabilities, USENIX RAID 2020

BLACKBOX FUZZING (MUTATION BASED)

Fuzzing Acrobat and Mac Preview



100 crashes
30-40 unique
3-10 exploitable

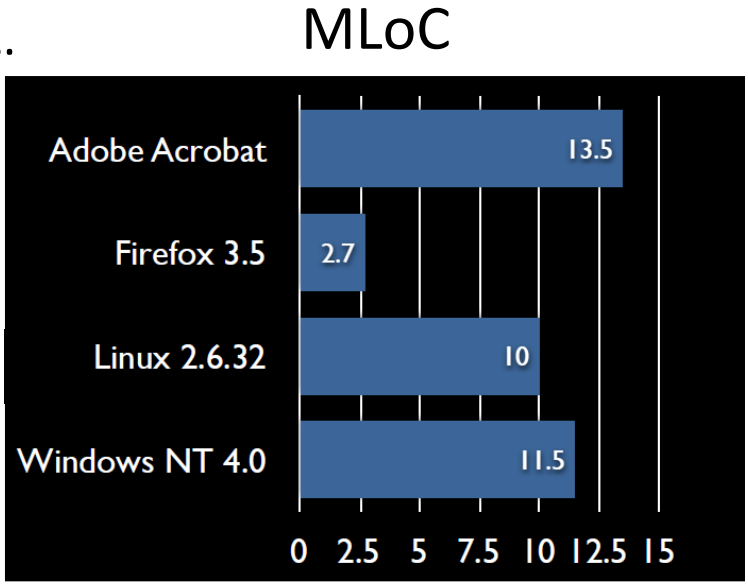
1373 crashes
230-280 unique
30-60 exploitable

Caveat: Several years ago; older versions of code

PDF Readers - Miller (2007)

PDF format is extremely complicated

- PDF files can require complex rendering
  - Flash, Quicktime video, 3-d animation, …
- PDF files can include executable JS
  - Extremely complicated code base



Mutation-based fuzzing with pdf

Similar process used for Acrobat and Mac Preview

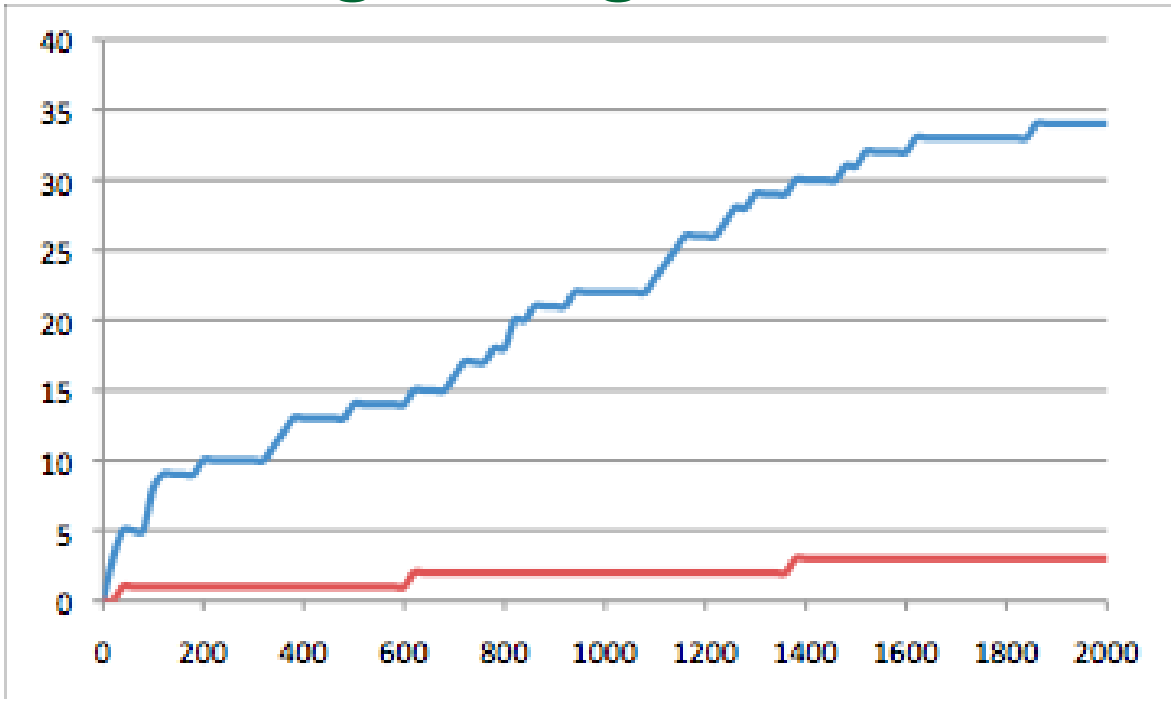
- Collect a large number of pdf files
  - Aim to exercise all features of pdf readers
  - Found 80,000 PDF's on Internet
- Reduce to smaller set with apparently equivalent code coverage
  - Used Adobe Reader + Valgrind in Linux to measure code coverage
  - Reduced to 1,515 files of 'equivalent' code coverage // test minimization
  - Same effect as fuzzing all 80k in 2% of the time
- Mutate these files and test Acrobat (Mac Preview) for vulnerabilities

Mutation

Modify each file in a number of ways

- Randomly mutate selected bytes to random values
- Produce ~3 million mutants from 1,515 files
  - Approximately same numbers for Acrobat and Preview,
  - Even though code and methods for testing code coverage are different
- Use standard platform-specific tools to determine if crash represents an exploit
  - Acrobat: 100 unique crashes, 4 actual exploits
  - Preview: maybe 250 unique crashes, 60 exploits (tools may over-estimate)

Was the fuzzing enough?



Shape of curve suggests further fuzzing: keep fuzzing until diminishing returns

BLACKBOX FUZZING (GENERATION BASED)

iPhone - Miller (2007)

Background

- Source code for key component (browser) is available
- Developer unit testing data also available

Approach used to find attack against iPhone:

- Survey known information about platform
- Select areas where testing might have been incomplete (based on test coverage)
- Use fuzzing to cause crash
- Use crash information to see if attacker can control phone

Information leveraged for strategy planning

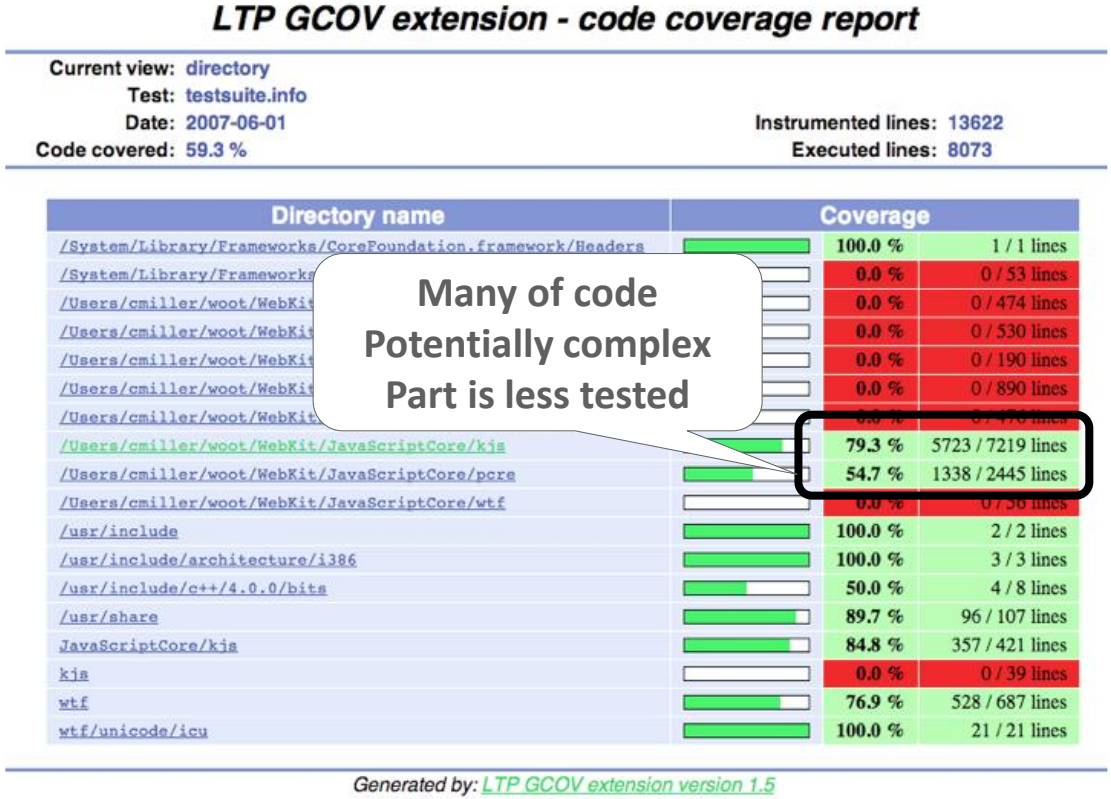
- **WebKit**
  - Most Apple Internet applications share a similar piece of code
  - WebKit is an open source library (source code on svn)
- **Test information available for JavaScript rendering**

  The JavaScriptCore Tests

  If you are making changes to JavaScriptCore, there is an additional test suite you must run before landing changes. This is the Mozilla JavaScript test suite.
- **Use the test suite and code coverage (source code!) to check which portions of code might not be well tested**

Initial steps: select potential “weak link”

- **Build browser and instrument it using standard tool gcov**
- **Run test suit to determine code coverage**
- **Select target**
  - Main JavaScript engine has 79.3% of its lines covered
  - Perl Compatible Regular Expression (PCRE) library is 17% of the overall code, 54.7% of its lines covered
  - Attack focused on PCRE



LTP GCOV extension - code coverage report

Current view: directory
Test: testsuite.info
Date: 2007-06-01
Code covered: 59.3 %
Instrumented lines: 13622
Executed lines: 8073

Directory name	Coverage	
/System/Library/Frameworks/CoreFoundation.framework/Headers	100.0 %	1 / 1 lines
/System/Library/Frameworks	0.0 %	0 / 53 lines
/Users/cmiller/woot/WebKit	0.0 %	0 / 474 lines
/Users/cmiller/woot/WebKit	0.0 %	0 / 530 lines
/Users/cmiller/woot/WebKit	0.0 %	0 / 190 lines
/Users/cmiller/woot/WebKit	0.0 %	0 / 890 lines
/Users/cmiller/woot/WebKit	0.0 %	0 / 476 lines
/Users/cmiller/woot/WebKit/JavaScriptCore/kjs	79.3 %	5723 / 7219 lines
/Users/cmiller/woot/WebKit/JavaScriptCore/pcre	54.7 %	1338 / 2445 lines
/Users/cmiller/woot/WebKit/JavaScriptCore/wtf	0.0 %	0 / 36 lines
/usr/include	100.0 %	2 / 2 lines
/usr/include/architecture/i386	100.0 %	3 / 3 lines
/usr/include/c++/4.0.0/bits	50.0 %	4 / 8 lines
/usr/share	89.7 %	96 / 107 lines
JavaScriptCore/kjs	84.8 %	357 / 421 lines
kjs	0.0 %	0 / 39 lines
wtf	76.9 %	528 / 687 lines
wtf/unicode/icu	100.0 %	21 / 21 lines

Generated by: LTP GCOV extension version 1.5

Find attack:

- **Fuzz standalone PCRE code**
  - Write regular expression fuzzer
    - Generated hundreds of regular expressions containing different number of “evil” strings: “[[**]]”
    - Some produced errors

      PCRE compilation failed at offset 6: internal error: code overflow.
    - Examined crash reports to find jump to registers that could be controlled
- **Build attack using this information – Lots of Hard Work!**
  - Select png file format and embed attack
  - Keep trying until attack works on actual phone

BLACKBOX HYBRID FUZZER (MUTATION AND GENERATION BASED)

LangFuzz – Holler et al. [Usenix 2012]

- Fuzz Mozilla's and Chrome's JS engines
- Extract JS code fragments from existing corpus
  - Corpus of existing JavaScript programs and test suites that have exposed bugs
- Generation-based
  - Create new random inputs based on JavaScript grammar
- Mutation-based
  - Derive new inputs based on JavaScript mutation operations

LangFuzz – Novel Mutation Operators

```
var x = new String (y);
for (let i = 0; i < 0x100; i++) {
  …
  arr[i] = i;
}
```

```
var arr = new String (i);
for (let i = 0; i < 0x100; i++) {
  …
  arr[i] = i;
}
```

- Introduce new mutation operators for JavaScript

LangFuzz – Novel Mutation Operators

```
var x = new String (y);
for (let i = 0; i < 0x100; i++) {
  …
  arr[i] = i;
}
```

```
var arr = new String (i);
for (let i = 0; i < 0x100; i++) {
  …
  arr[i] = i;
}
```

- Is LangFuzz a blackbox fuzzer or a whitebox fuzzer?
- Found many crashes mostly due to memory issues
- Rewarded with US$50,000 bug bounties

DIRECTED GREYBOX FUZZING (EVOLUTIONARY BASED)

Directed Greybox Fuzzing

- Direct the fuzzing to expose vulnerabilities at known dangerous locations or critical system calls
- Augment energy assignment of seeds with information about the targets
- Typical application scenarios include:
  - Patch testing: set changed statements as targets [Böhme ESEC/FSE13; Marinescu ESEC/FSE13]
  - Crash reproduction: set method calls in stack trace as targets [Jin ICSE12; Pham ICSE15]
  - Information flow detection: set sensitive sources and sinks as targets [Matthis ASE17]
  - Static analysis report verification: set statements, method call sequences or traces reported in a warning as targets [Christakis ICSE16; Nyugen RAID20]

Fuzzing Algorithm (based on AFL)

```
Input: Seed Corpus C
repeat
    s = ChooseNext(C)              // Selection strategy
    p = AssignEnergy(s)            // Power schedule
    for i from 1 to p do
        s' = MutateInput(s)        // Which mutators are used?
        if s' crashes then
            add s' to F
        else if IsInteresting(s') then  // s' introduces new coverage?
            add s' to C
        end if
    end for
until timeout reached or abort signal
Output: Crashing Inputs F
```

Scheduler

Generator

Updater

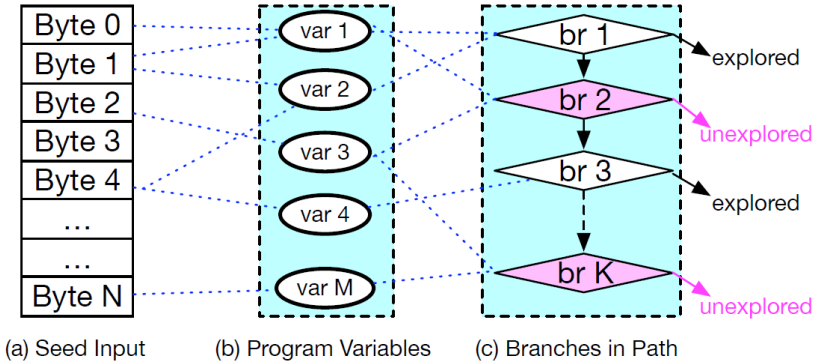
Enhancing the Scheduler

GreyOne [USENIX Security 2020]

Enhancing the seed scheduling for data flow sensitive fuzzing

Problem Uncertain if a seed after mutation will likely expose vulnerability bugs

Solution Apply taint analysis to record the impact of a seed on branch coverage



Pre-fuzzing: Mutate each byte of the initial seed input in turn and record which variables and branches are affected

During fuzzing: Prioritize the mutation of a byte that can affect more unexplored branches, and prioritize the exploration of an unexplored branch that is affected by more prioritized bytes

GreyOne [USENIX Security 2020]

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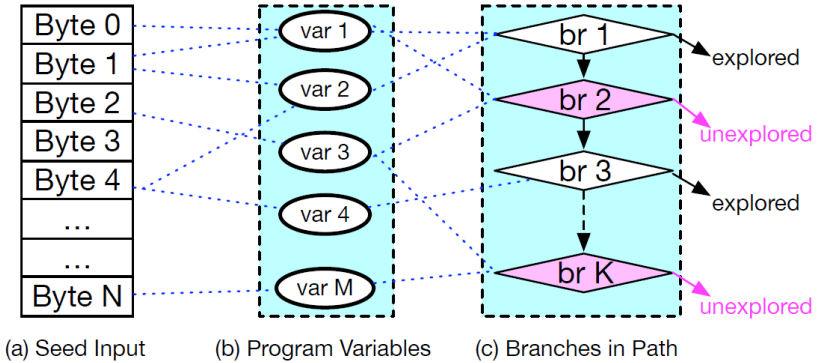

Intuition:

- A variable depends on an input byte if the variable's value changes after the byte is mutated.
- Mutating this input byte could change the constraints of branches that use this variable, leading to new branch exploration

GreyOne [USENIX Security 2020]

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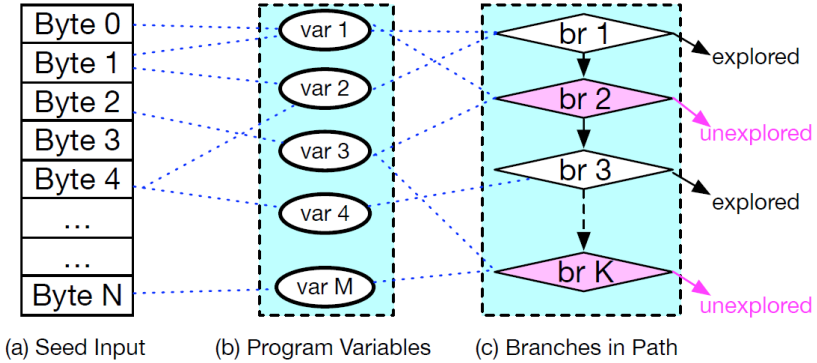
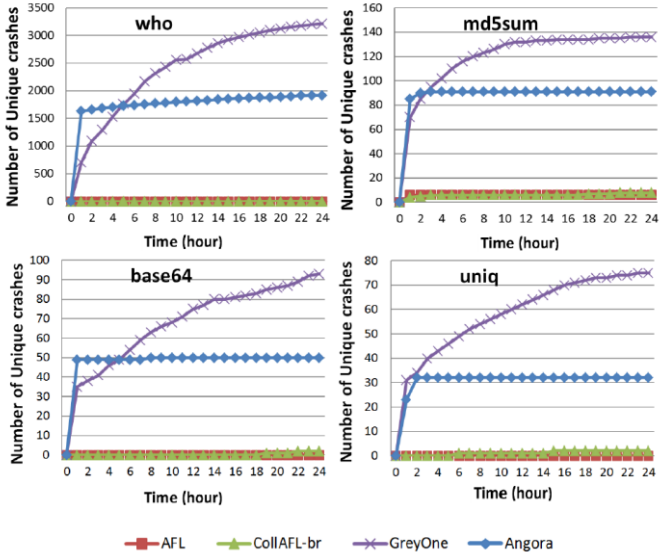




Double the number of crashes detected

UAFuzz [USENIX RAID 2020]

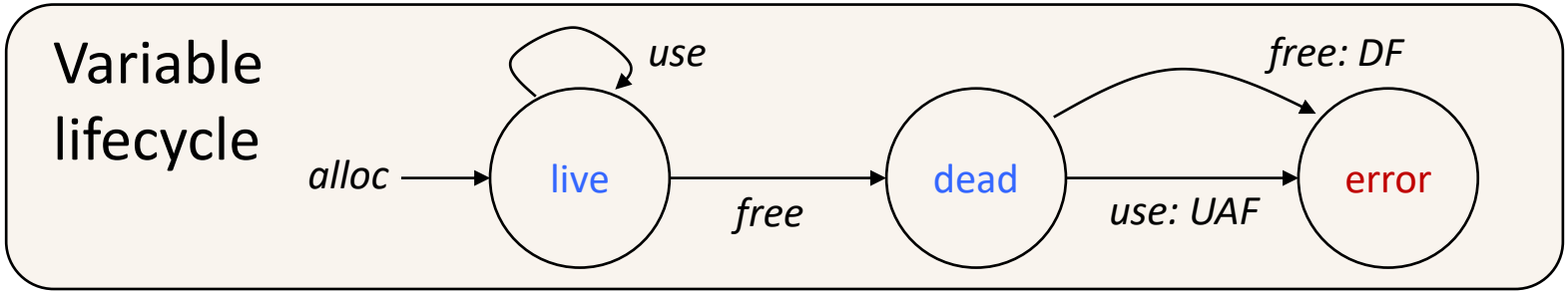
Source code is given here for the purpose of explanation.
Greybox fuzzer works on binary code or its disassembled version

```
1  int *p, *p_alias;
2  char buf[10];
3  void bad_func(int *p) {free(p);} /* exit() is missing */
4  void func() {
5    if (buf[1] == 'F')
6      bad_func(p);
7    else /* lots more code ... */
8  }
9  int main (int argc, char *argv[]) {
10   int f = open(argv[1], O_RDONLY);
11   read(f, buf, 10);
12   p = malloc(sizeof(int));
13   if (buf[0] == 'A'){
14     p_alias = malloc(sizeof(int));
15     p = p_alias;
16   }
17   func();
18   if (buf[2] == 'U')
19     *p_alias = 1;
20   return 0;
21 }
```

- Input seed: ‘AFU’
- Bug target: 14 (alloc) → 17 → 6 → 3 (free) → 19 (use)
- Execution: No crash but times out after 6 hours
- Many use-after-free bugs do not result in crash

Nguyen et al., Binary-level Directed Fuzzing for Use-After-Free Vulunerabilities. USENIX RAID 20

Fuzzing Use-After-Free (UAF) is Hard

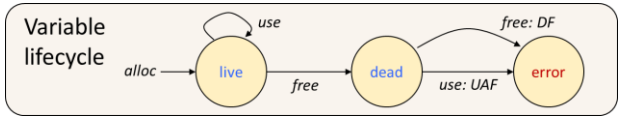


Problem **UAF bugs are rarely detected by blackbox fuzzers:**

- **Complexity**. Involves 3 events in sequence spanning multiple functions
- **Temporal & spatial constraints**. Hard to reach 3 different code locations sequentially with no events occurring in between invalidating the sequence
- **Often silence**. No segmentation fault but the consequence can be severe because the program continues to run, contaminating other data

Directed Greybox Fuzzing

```
1  int *p, *p_alias;
2  char buf[10];
3  void bad_func(int *p) {free(p);} /* exit() is missing */
4  void func() {
5    if (buf[1] == 'F')
6      bad_func(p);
7    else /* lots more code ... */
8  }
9  int main (int argc, char *argv[]) {
10   int f = open(argv[1], O_RDONLY);
11   read(f, buf, 10);
12   p = malloc(sizeof(int));
13   if (buf[0] == 'A'){
14     p_alias = malloc(sizeof(int));
15     p = p_alias;
16   }
17   func();
18   if (buf[2] == 'U')
19     *p_alias = 1;
20   return 0;
21 }
```



Derivation of a target trace:

- Target trace: UAF events + call sites
- UAF events: 14 (alloc) → 3 (free) → 19 (use)
- Simple dependency analysis: 17 → 6 → 3
- A target trace: 14 (alloc) → 17 → 6 → 3 (free) → 19 (use)

Solution Schedule seeds that fuzz target traces more

Nguyen et al., Binary-level Directed Fuzzing for Use-After-Free Vulunerabilities. USENIX RAID 20

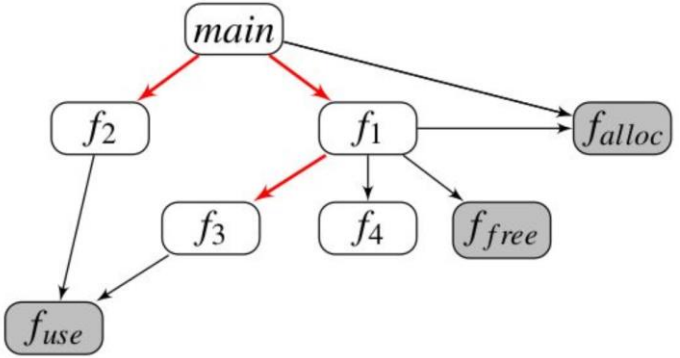
UAFuzz: Power Schedule

- UAFuzz: A state-of-the-art fuzzer for use-after-free (UAF) bugs
- Presented at the **blackhat** conference in August 2020.
- Energy (E) = E_f * E_e * E_b
- Function level (E_f): Prioritize function call relations that cover UAF events
- Edge level (E_e): Prioritize edges in a control flow graph that can reach targets more often
- Block level (E_b): Prioritize traces that are similar to the target trace

Nguyen et al., Binary-level Directed Fuzzing for Use-After-Free Vulunerabilities. USENIX RAID 20

UAFuzz: Function-level Energy (E_f)

- UAF events: f_{alloc}, f_{free} and f_{use}
- Select function call relations that cover more than one UAF event
  - main→f_2 covers f_{alloc} and f_{use}
  - main→f_1 covers f_{alloc} and f_{free}
  - f_1→f_3 covers f_{alloc}, f_{free} and f_{use}
- Assign higher energy to a seed whose execution triggers the selected call relations

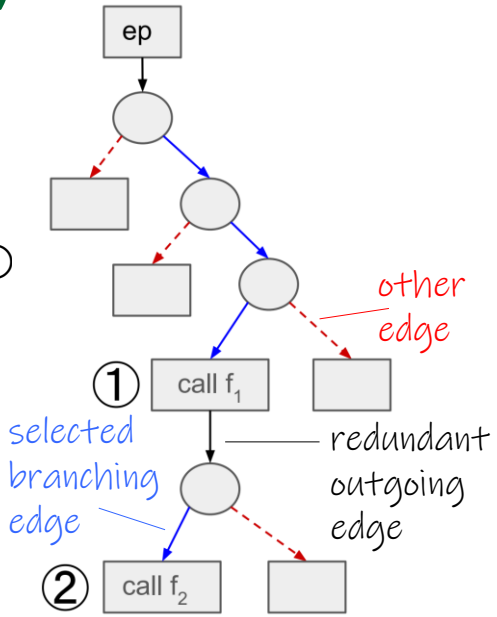


Call Graph Example, selected call relations (caller, callee) in red

Covers(x → y) = union of child events of x and child events of y

UAFuzz: Edge-level Energy (E_e)

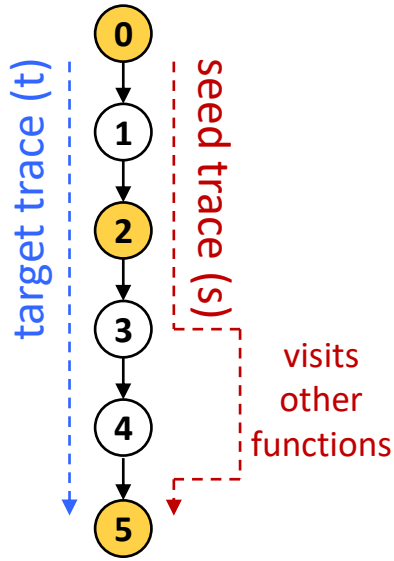
- Targets: Next node in a target trace
  - Target trace: ①→②
  - From entry point (ep), select branching edges that can reach ①
  - After reaching ①, select edges that can reach ②
- Assign higher energy to a seed whose execution (a) visits the selected edges (blue colored ones) more often and (b) visits the other edges (red colored ones) less often
- Ignore the redundant outgoing edges (black colored) from ep and targets



Control flow graph, selected branching edges are in blue
black edges are redundant

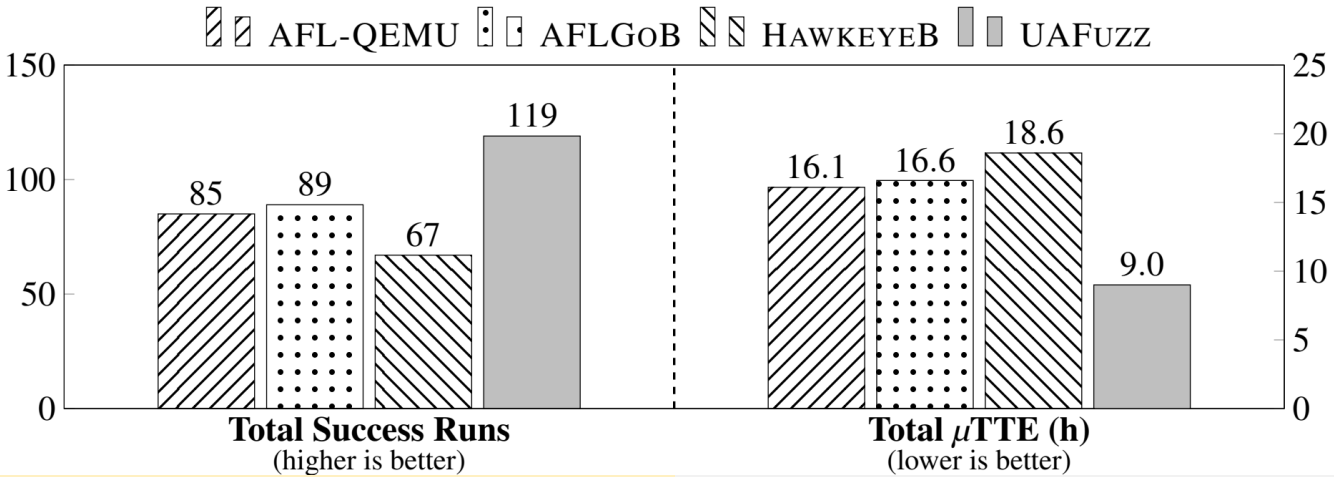
UAFuzz: Block-level Energy (E_b)

- Similarity between target and seed traces
  - Common prefix: common trace before divergence
    - E.g., ⓪→①→②→③
  - Target prefix (s1): #nodes in the common prefix, e.g., 4
  - UAF prefix (s2): #UAF events in the common prefix, e.g., 2
  - Target bag (s3): #nodes common, e.g., 5
  - UAF bag (s4): #UAF events common, e.g., 3
- Assign higher energy to a seed whose trace has higher similarity with weights s1 > s2 > s3 > s4



Trace similarity (UAF events are colored in yellow, where ⓪ alloc, ② free and ⑤ use)

Comparison on 13 UAF Vulnerabilities



Assign a time budget to each of the 13 vulnerable projects. Add up the #success runs that trigger the vulnerability in each project.

Average the time to trigger the vulnerability in each project within the assigned time budget.

AFL-QEMU: AFL emulation mode
AFL-GoB: Binary version of Aflgo. https://github.com/aflgo/aflgo, 2020.
HawkeyeB: Binary version of Hawkeye. Chen et al., Hawkeye: towards a desired directed grey-box fuzzer. CCS18.
UAFuzz: Nguyen et al., Binary-level Directed Fuzzing for Use-After-Free Vulunerabilities. USENIX RAID 20

30 New Zero-day Vulnerabilities Found

11 new UAF and DF bugs
7 new CVEs assigned
27 confirmations
20 fixes

Program	Code Size	Version (Commit)	Bug ID	Vulnerability Type	Crash	Vulnerable Function	Status	CVE
GPAC	545K	0.7.1 (987169b)	#1269	**User after free**	✗	gf_m2ts_process_pmt	Fixed	CVE-2019-20628
		0.8.0 (56eaea8)	#1440-1	**User after free**	✗	gf_isom_box_del	Fixed	CVE-2020-11558
		0.8.0 (56eaea8)	#1440-2	**User after free**	✗	gf_isom_box_del	Fixed	Pending
		0.8.0 (56eaea8)	#1440-3	**User after free**	✗	gf_isom_box_del	Fixed	Pending
		0.8.0 (5b37b21)	#1427	**User after free**	✓	gf_m2ts_process_pmt		
		0.7.1 (987169b)	#1263	NULL pointer dereference	✓	ilst_item_Read	Fixed	
		0.7.1 (987169b)	#1264	Heap buffer overflow	✓	gf_m2ts_process_pmt	Fixed	CVE-2019-20629
		0.7.1 (987169b)	#1265	Invalid read	✓	gf_m2ts_process_pmt	Fixed	
		0.7.1 (987169b)	#1266	Invalid read	✓	gf_m2ts_process_pmt	Fixed	
		0.7.1 (987169b)	#1267	NULL pointer dereference	✓	gf_m2ts_process_pmt	Fixed	
		0.7.1 (987169b)	#1268	Heap buffer overflow	✓	BS_ReadByte	Fixed	CVE-2019-20630
		0.7.1 (987169b)	#1270	Invalid read	✓	gf_list_count	Fixed	CVE-2019-20631
		0.7.1 (987169b)	#1271	Invalid read	✓	gf_odf_delete_descriptor	Fixed	CVE-2019-20632
		0.8.0 (5b37b21)	#1445	Heap buffer overflow	✓	gf_bs_read_data	Fixed	
		0.8.0 (5b37b21)	#1446	Stack buffer overflow	✓	gf_m2ts_get_adaptation_field	Fixed	
GNU patch	7K	2.7.6 (76e7758)	#56683	**Double free**	✓	another_hunk	Confirmed	CVE-2019-20633
		2.7.6 (76e7758)	#56681	Assertion failure	✓	pch_swap	Confirmed	
		2.7.6 (76e7758)	#56684	Memory leak	✗	xmalloc	Confirmed	
Perl 5	184K	5.31.3 (a3c7756)	#134324	**Use after free**	✓	S_reg	Confirmed	
		5.31.3 (a3c7756)	#134326	**Use after free**	✓	Perl_regnext	Fixed	
		5.31.3 (a3c7756)	#134329	**User after free**	✓	Perl_regnext	Fixed	
		5.31.3 (a3c7756)	#134322	NULL pointer dereference	✓	do_clean_named_objs	Confirmed	
		5.31.3 (a3c7756)	#134325	Heap buffer overflow	✓	S_reg	Fixed	
		5.31.3 (a3c7756)	#134327	Invalid read	✓	S_regmatch	Fixed	
		5.31.3 (a3c7756)	#134328	Invalid read	✓	S_regmatch	Fixed	
		5.31.3 (45f8e7b)	#134342	Invalid read	✓	Perl_mro_isa_changed_in	Confirmed	
MuPDF	539K	1.16.1 (6566de7)	#702253	**Use after free**	✗	fz_drop_band_writer	Fixed	
Boolector	79K	3.2.1 (3249ae0)	#90	NULL pointer dereference	✓	set_last_occurrence_of_symbols	Confirmed	
fontforge	578K	20200314 (1604c74)	#4266	**Use after free**	✓	SFDGetBitmapChar		
		20200314 (1604c74)	#4267	NULL pointer dereference	✓	SFDGetBitmapChar		

Summary of Directed Greybox Fuzzing

UAFuzz demonstrates the major design components of directed greybox fuzzing:

- Information that can be extracted from the target bug type
- Power schedule that smartly assigns energy based on:
  - Distance between a seed's execution from the targets
  - Frequency that the targets are executed by a seed

Enhancing the Generator

MOPT [USENIX Security 2019]

Optimized Mutation Scheduling for Fuzzers

Problem Generate input mutants to discover more paths and more vulnerability bugs

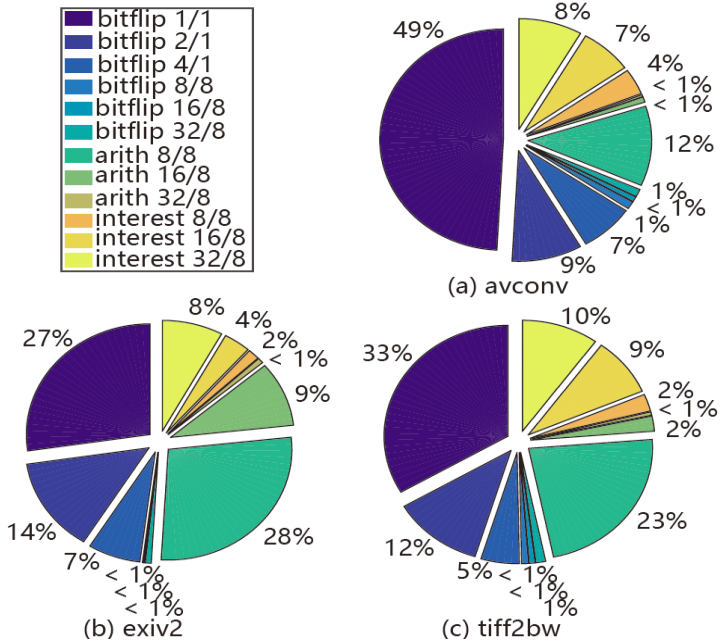
Solution Dynamically find an optimal probability distribution of mutation operators

Type	Meaning	Operators
bitflip	Invert one or several consecutive bits in a test case, where the stepover is 1 bit.	`bitflip 1/1`, `bitflip 2/1`, `bitflip 4/1`
byteflip	Invert one or several consecutive bytes in a test case, where the stepover is 8 bits.	`bitflip 8/8`, `bitflip 16/8`, `bitflip 32/8`
arithmetic inc/dec	Perform addition and subtraction operations on one byte or several consecutive bytes.	`arith 8/8`, `arith 16/8`, `arith 32/8`

Mutation operators defined by AFL

MOPT [USENIX Security 2019]

Optimized Mutation Scheduling for Fuzzers



- Mutation operators are not equally effective in generating interesting input mutants
- bitflip 1/1 and bitflip 2/1 are more effective than others
- Apply an optimization algorithm to dynamically determine the best next mutation operators based on the generated input mutants' usefulness
- Dynamically optimizing the mutation operators can find 382% more crashes and 118% more unique paths as compared with AFL

Enhancing the Updater

AnKou [ICSE 2020]

Guiding Grey-box Fuzzing towards Combinational Difference

Problem Bugs may not be triggered even their concerned branches are covered

Solution Needs to consider also the number of times a branch has been covered

Buffer Overflow Bugs

```
if (...) b1;
if (...) b2;
while (...) b3;
```

t1 = (1, 1, 1)
t2 = (1, 0, 2)
t3 = (1, 1, 0)
t4 = (0, 1, 8).

- AFL: Test input of t1 alone can cover all three branches. Other test inputs are not updated to the seed corpus because they are redundant.
- AnKou: Treat the number of branch visits as a vector. Determine redundancy based on the Euclidean distances of such vectors.

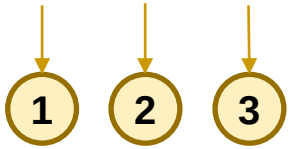
AnKou [ICSE 202

Guiding Grey-box Fuzzing t

Problem Bugs may not be tr

Solution Needs to consider

Buffer Overflow Bugs



t1 = (1, 0, 2)
t2 = (1, 1, 1)
t3 = (1, 1, 0)
t4 = (0, 1, 8).

Package Name	# of Bugs Found: Ankou	# of Bugs Found: AFL	# of Bugs Found: Ankou†	# of Bugs Found: Angora
binutils	11	36	11	4
bison	58	71	36	2
catdoc	0	15	0	0
cflow	21	18	13	1
clamav	0	0	0	0
dwarf	2	2	2	2
GraphicsMagick	22	27	21	11
jasper	42	37	0	0
libav	1	7	0	0
libexiv2	82	59	16	4
libgxps	5	5	0	0
liblouis	18	11	0	0
libming	84	60	0	0
libncurses	48	53	0	0
libraw	2	4	0	0
libsass	155	12	0	0
libtasn1	0	0	0	0
libtiff	3	2	0	0
libtorrent	0	0	0	0
mpg123	0	0	0	0
nasm	28	12	0	0
pspp	168	99	0	0
tcpdump	0	0	0	0
vim	2	2	0	0
Total	752	532	99	24

† As mentioned in §6.6.1, we were not able to compile Angora on all the packages. For fair comparison, we report bugs found by Ankou only on the subjects that Angora was able to run on.

Dynamic Symbolic Execution (a.k.a. Concolic Testing)

WHITEBOX FUZZING

Dynamic Symbolic Execution

- Whitebox fuzzing originates from Patrice Godefroid (Microsoft Research) when deploying dynamic symbolic execution (i.e., concolic testing) to detect software vulnerabilities
- Microsoft Research is maintaining a team that develop a whitebox fuzzer called SAGE
- SAGE has solved 1 Billion+ constraints
- SAGE exposed many Win7 security bugs
- SAGE is now used daily by the Windows and Office teams

Godefroid et al., Grammar-based Whitebox Fuzzing. PLDI 2008

Summary

- **We discussed multiple fuzzing techniques**
  - PDF readers: Acrobat and Preview
  - iPhone vulnerability based on browser rendering png files
  - LangFuzz: JavaScript fuzzer
  - GreyOne: Data flow sensitive fuzzing
  - UAFuzz: Directed greybox fuzzer for Use-after-Free vulnerabilities
  - MOPT: Optimized mutation scheduling for fuzzers
  - AnKou: Guiding grey-box fuzzing towards combinatorial difference
- **Some general themes**
  - Choosing good inputs is very important
    - Very unlikely to find significant crashes by chance
    - Use many samples and simplify them using information about system
  - Standard tools can diagnose crashes, find vulnerabilities
  - Lots of hard work and only small chances of success in many cases
    - But developer teams should use some of these methods too (easier for them!)