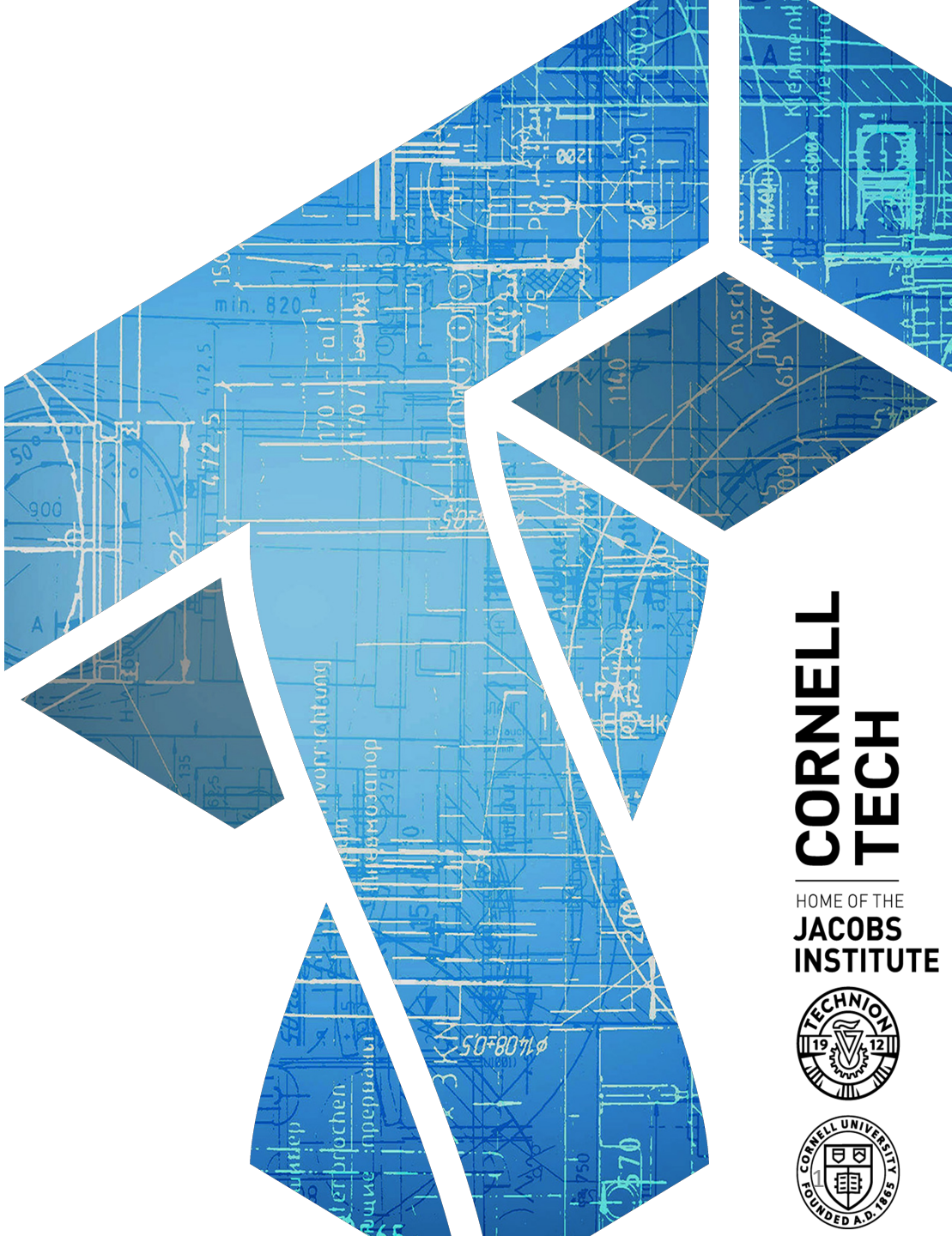
CS 5435: Finding & avoiding vulnerabilities

Instructor: Tom Ristenpart

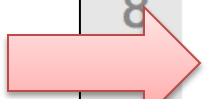
https://github.com/tomrist/cs5435-fall2024



CORNELL TECH

HOME OF THE JACOBS INSTITUTE

Running demo example
(modified from Gray hat hacking book linked in resources)



```c
#include <stdio.h>
#include <string.h>


void greeting( char* temp1 )
{
  char name[400];
  memset(name, 0, 400);
  strcpy(name, temp1);
  printf( "Hi %s\n", name );
}


int main(int argc, char* argv[] )
{
  greeting( argv[1] );
  printf( "Bye %s\n", argv[1] );
}
```

Language-based approaches

- Low-level languages such as C / C++ fast, but make it easy to make memory safety errors
- (More) type-safe languages prevent some vulnerabilities by design
  - Type-safety: "A language is type-safe if the only operations that can be performed on data in the language are those sanctioned by the type of the data."
  - Traditionally less performance
- New generation of safer high-performance languages:
  - Rust (Mozilla), Swift (Apple), Go (Google)
- Efforts to improve security of unsafe languages
  - Safe pointer libraries in C / C++
  - Coding standards, defensive programming, unit testing approaches

Software engineering approaches

- Organize software lifecycle around security
- Require use of organizational and software tools to improve security outcomes
- Microsoft security development lifecycle (SDL):

Training	Manage risk of third-party components
Design security requirements	Use approved tools
Metrics & compliance reporting	Static analysis security testing
Threat modeling	Dynamic analysis security testing
Establish design requirements	Penetration testing
Define & use crypto standards	Incident response

https://www.microsoft.com/en-us/securityengineering/sdl/practices

Most software very, very complex

In a Nutshell, Apache HTTP Server...

... has had 39,732 commits made by 125 contributors
representing 1,494,342 lines of code

... is mostly written in C
with an average number of source code comments

Linux kernel v.4.1:
~19.5 million lines of code
14,000 developers contributing

OpenSSL:
~608,000 lines of code
572 developers contributing

Heartbleed

OpenSSL implements TLS. Used in Apache and Nginx

March 2014: researchers discover vulnerability in heartbleed protocol implementation in OpenSSL

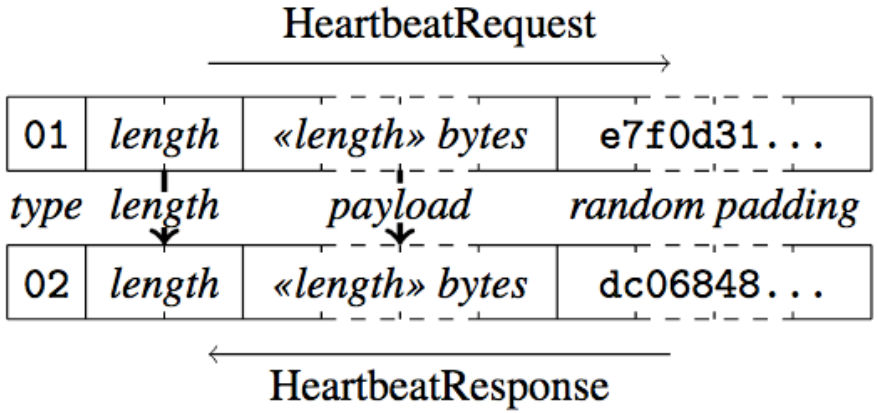


Figure 1: **Heartbeat Protocol.** Heartbeat requests include user data and random padding. The receiving peer responds by echoing back the data in the initial request along with its own padding.

[Durumeric et al. 2014]

Heartbleed

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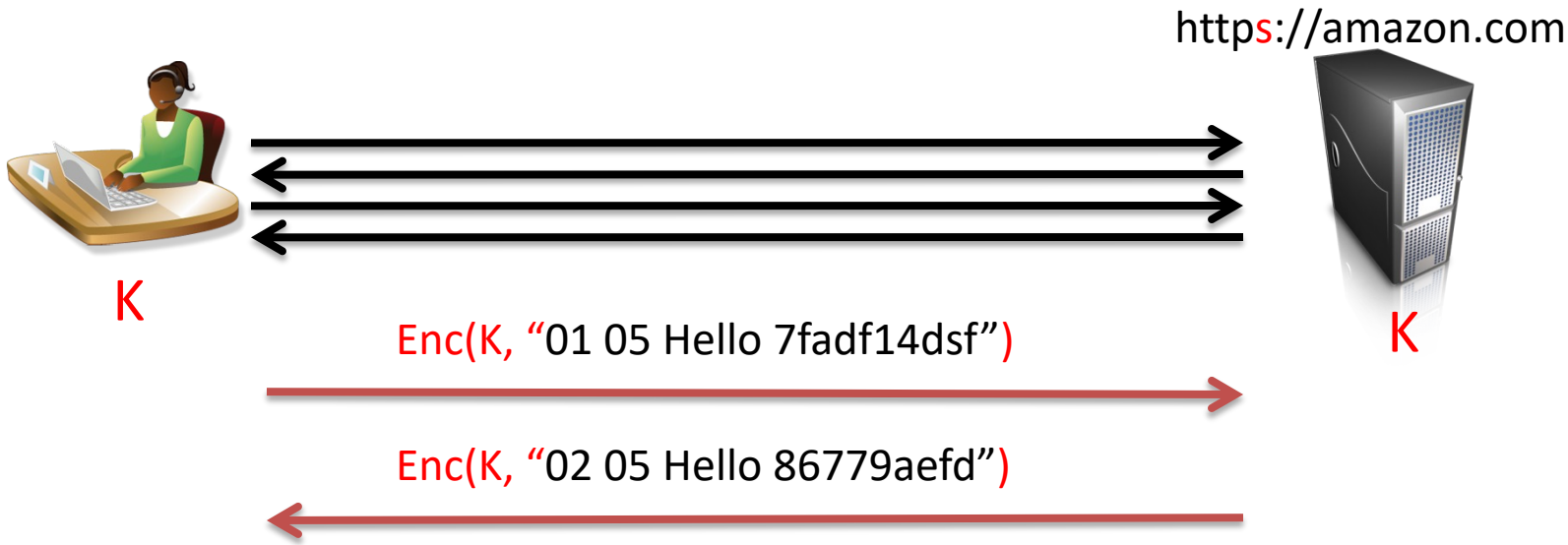
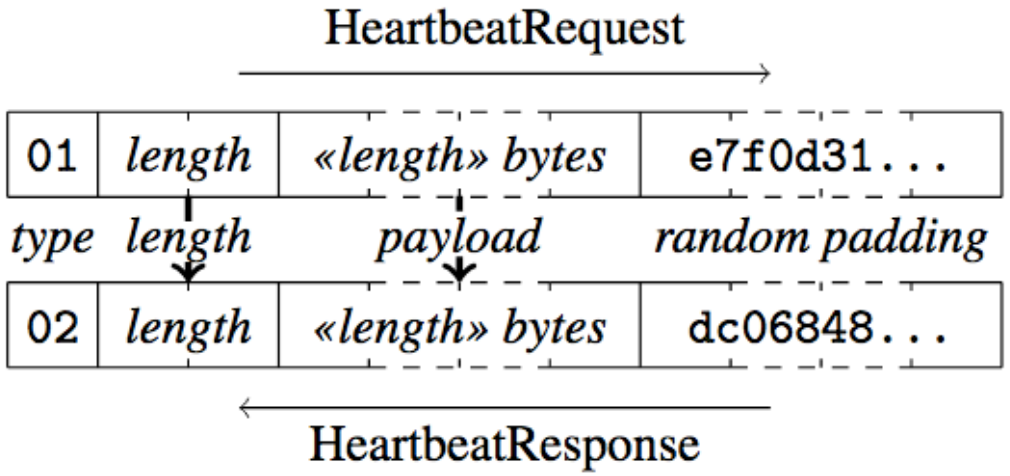


Heartbleed



Buffer overread vulnerability
Copy up to almost 2^{16} bytes of data from memory

```
1448 dtls1_process_heartbeat(SSL *s)
1449   {
1450   unsigned char *p = &s->s3->rrec.data[0], *pl;
1451   unsigned short hbtype;
1452   unsigned int payload;
1453   unsigned int padding = 16; /* Use minimum padding */
1454
1455   /* Read type and payload length first */
1456   hbtype = *p++;
1457   n2s(p, payload);
1458   pl = p;
1459
1460   if (s->msg_callback)
1461     s->msg_callback(0, s->version, TLS1_RT_HEARTBEAT,
1462       &s->s3->rrec.data[0], s->s3->rrec.length,
1463       s, s->msg_callback_arg);
1464
1465   if (hbtype == TLS1_HB_REQUEST)
1466     {
1467     unsigned char *buffer, *bp;
1468     int r;
1469
1470     /* Allocate memory for the response, size is 1 byte
1471      * message type, plus 2 bytes payload length, plus
1472      * payload, plus padding
1473      */
1474     buffer = OPENSSL_malloc(1 + 2 + payload + padding);
1475     bp = buffer;
1476
1477     /* Enter response type, length and copy payload */
1478     *bp++ = TLS1_HB_RESPONSE;
1479     s2n(payload, bp);
1480     memcpy(bp, pl, payload);
1481     bp += payload;
```

Heartbleed

OpenSSL implements TLS. Used in Apache and Nginx

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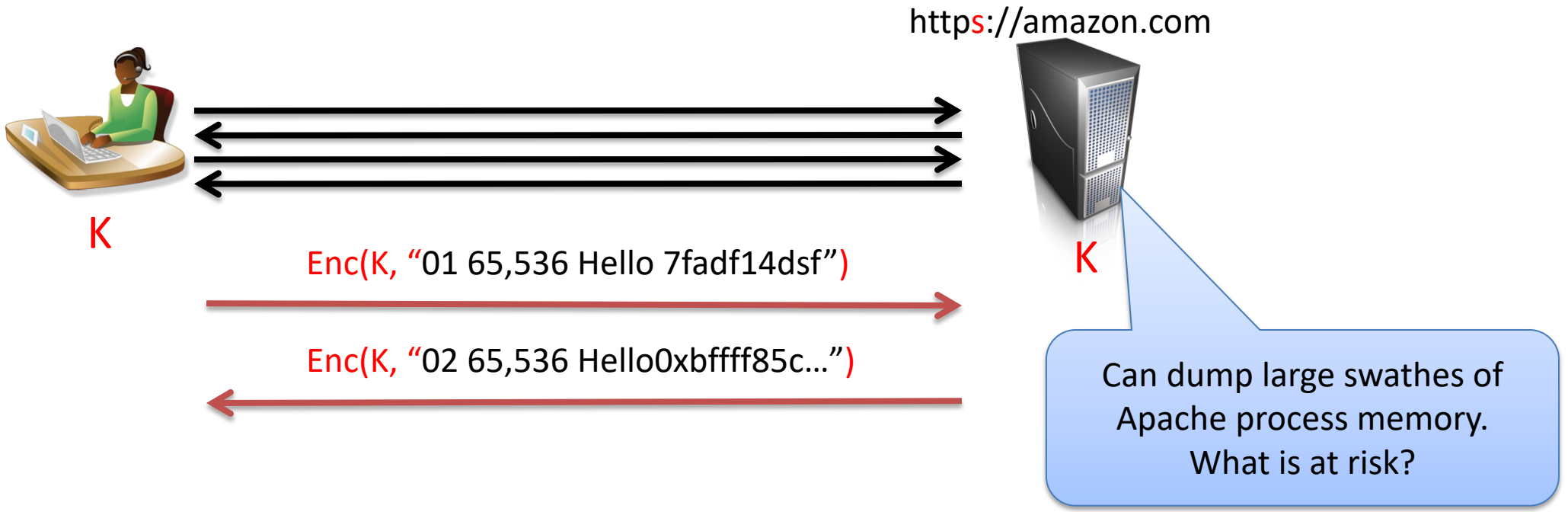


Heartbleed

"I was doing laborious auditing of OpenSSL, going through the [Secure Sockets Layer] stack line by line"

Date	Event
03/21	Neel Mehta of Google discovers Heartbleed
03/21	Google patches OpenSSL on their servers
03/31	CloudFlare is privately notified and patches
04/01	Google notifies the OpenSSL core team
04/02	Codenomicon independently discovers Heartbleed
04/03	Codenomicon informs NCSC-FI
04/04	Akamai is privately notified and patches
04/05	Codenomicon purchases the `heartbleed.com` domain
04/06	OpenSSL notifies several Linux distributions
04/07	NCSC-FI notifies OpenSSL core team
04/07	OpenSSL releases version 1.0.1g and a security advisory
04/07	CloudFlare and Codenomicon disclose on Twitter
04/08	Al-Bassam scans the Alexa Top 10,000
04/09	University of Michigan begins scanning

[Durumeric et al. 2014]

Heartbleed

Internet scanning to determine vulnerability:
Send heartbeat request with zero length (indicates vulnerable system)

Web Server	Alexa Sites	Heartbeat Ext.	Vulnerable
Apache	451,270 (47.3%)	95,217 (58.4%)	28,548 (64.4%)
Nginx	182,379 (19.1%)	46,450 (28.5%)	11,185 (25.2%)
Microsoft IIS	96,259 (10.1%)	637 (0.4%)	195 (0.4%)
Litespeed	17,597 (1.8%)	6,838 (4.2%)	1,601 (3.6%)
Other	76,817 (8.1%)	5,383 (3.3%)	962 (2.2%)
Unknown	129,006 (13.5%)	8,545 (5.2%)	1,833 (4.1%)

[Durumeric et al. 2014]

Heartbleed

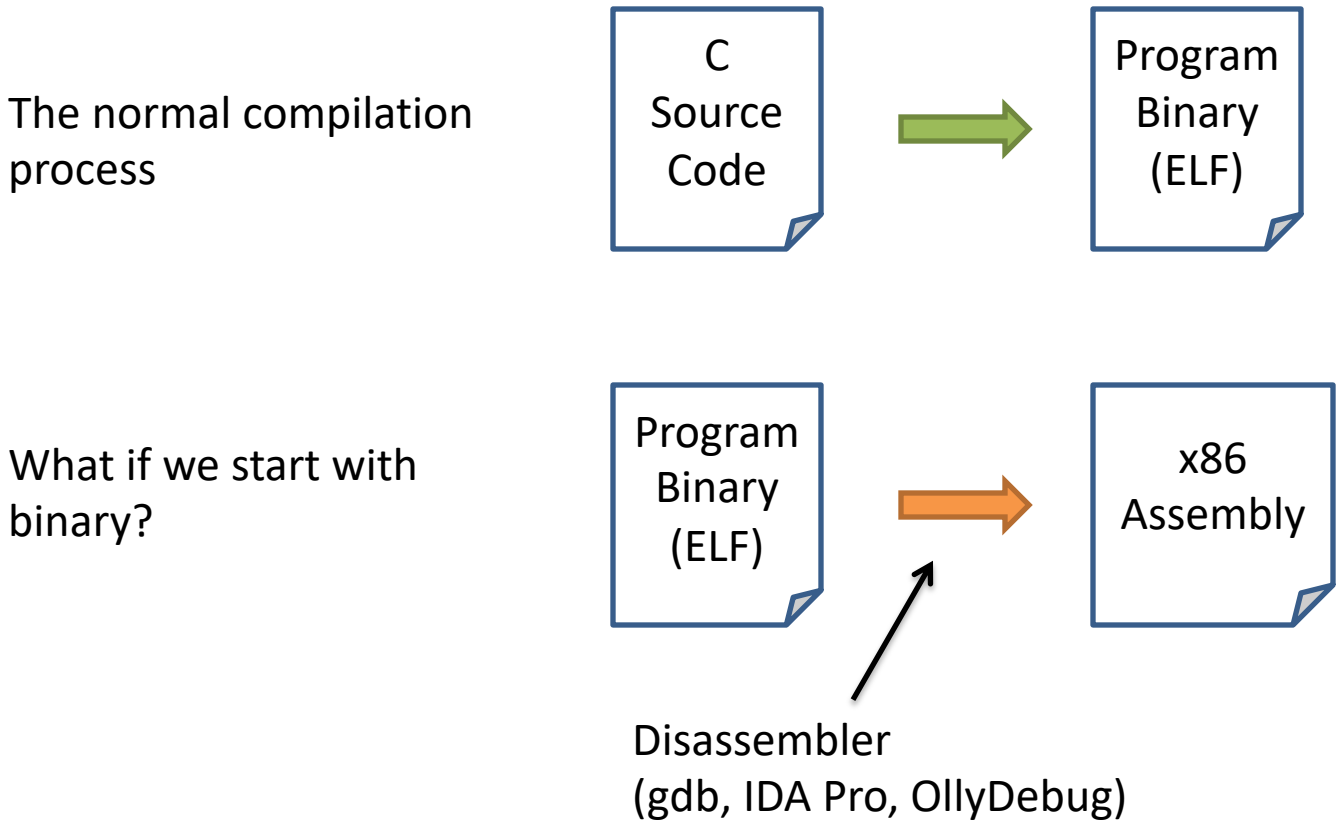
Internet scanning to determine vulnerability:
Send heartbeat request with zero length (indicates vulnerable system)

Site	Vuln.	Site	Vuln.	Site	Vuln.
Google	Yes	Bing	No	Wordpress	Yes
Facebook	No	Pinterest	Yes	Huff. Post	?
Youtube	Yes	Blogspot	Yes	ESPN	?
Yahoo	Yes	Go.com	?	Reddit	Yes
Amazon	No	Live	No	Netflix	Yes
Wikipedia	Yes	CNN	?	MSN.com	No
LinkedIn	No	Instagram	Yes	Weather.com	?
eBay	No	Paypal	No	IMDB	No
Twitter	No	Tumblr	Yes	Apple	No
Craigslist	?	Imgur	Yes	Yelp	?

[Durumeric et al. 2014]

Disassembly and decompiling

- Heartbleed discovered by direct C code inspection
- What if you only have binary?



```
d <main+9>:     movl   $0xf8,(%esp)
4 <main+16>:    call   0x8048364 <malloc@plt>
9 <main+21>:    mov    %eax,0x14(%esp)
d <main+25>:    movl   $0xf8,(%esp)
4 <main+32>:    call   0x8048364 <malloc@plt>
9 <main+37>:    mov    %eax,0x18(%esp)
d <main+41>:    mov    0x14(%esp),%eax
1 <main+45>:    mov    %eax,(%esp)
4 <main+48>:    call   0x8048354 <free@plt>
9 <main+53>:    mov    0x18(%esp),%eax
d <main+57>:    mov    %eax,(%esp)
0 <main+60>:    call   0x8048354 <free@plt>
5 <main+65>:    movl   $0x200,(%esp)
c <main+72>:    call   0x8048364 <malloc@plt>
1 <main+77>:    mov    %eax,0x1c(%esp)
5 <main+81>
8 <main+84>
b <main+87>:
d <main+89>:
5 <main+97>:
9 <main+101>:
d <main+105>:
0 <main+108>:
5 <main+113>:   mov    0x18(%esp),%eax
9 <main+117>:   mov    %eax,(%esp)
c <main+120>:   call   0x8048354 <free@plt>
1 <main+125>:   mov    0x1c(%esp),%eax
5 <main+129>:   mov    %eax,(%esp)
8 <main+132>:   call   0x8048354 <free@plt>
d <main+137>:   leave
e <main+138>:   ret
sembler dump.
```

Double-free vulnerability

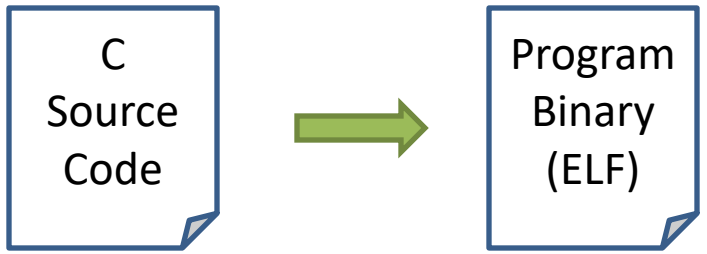
Exploit can trick heap management software into writing adversary-controlled value to adversary-controlled address

What type of vulnerability might this be?

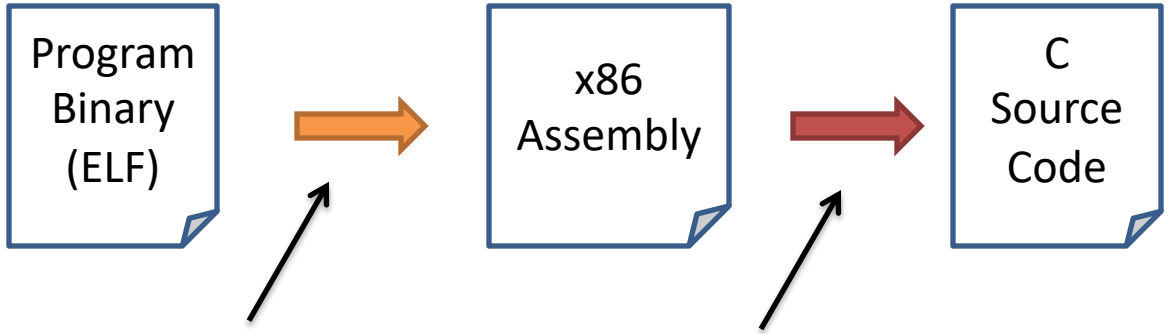
```
main(  int argc, char* argv[] ) {
  char* b1;
  char* b2;
  char* b3;

  if( argc != 3 ) then return 0;
  if( atoi(argv[2]) != 31337 )
      complicatedFunction();
  else {
      b1 = (char*)malloc(248);
      b2 = (char*)malloc(248);
      free(b1);
      free(b2);
      b3 = (char*)malloc(512);
      strncpy( b3, argv[1], 511 );
      free(b2);
      free(b3);
   }
}
```

Disassembly and decompiling

The normal compilation process



What if we start with binary?



Very complex, usually poor results

Reverse engineering and vulnerability discovery

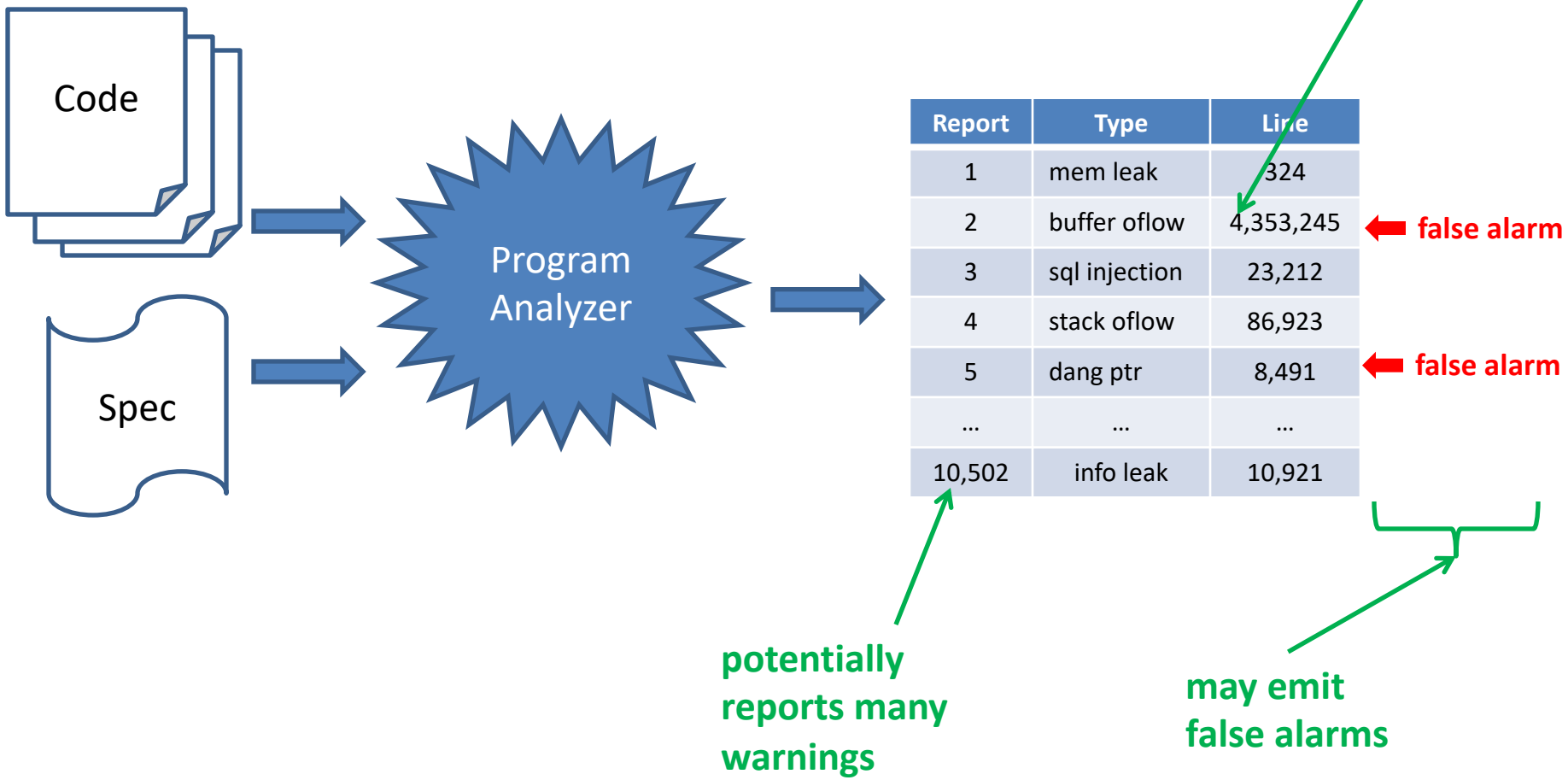
- Experienced analysts according to Aitel:
  - 1 hour of binary analysis:
    - Simple backdoors, coding style, bad API calls (strcpy)
  - 1 week of binary analysis:
    - Likely to find 1 good vulnerability
  - 1 month of binary analysis:
    - Likely to find 1 vulnerability *no one else will ever find*

http://www.immunityinc.com/downloads/DaveAitel_TheHackerStrategy.pdf

How do we find vulnerabilities?

- Manual analysis
  - Source code review
  - Reverse engineering
- Program analysis tools:
  - Static analysis
  - Fuzzing
  - Symbolic analysis

Program analyzers



Slide credit: Prof Mitchell Stanford's CS 155

Program analysis: false positives and false negatives

Term	Definition
False positive	A spurious warning that does not indicate an actual vulnerability
False negative	Does not emit a warning for an actual vulnerability

Complete analysis: no false negatives

Sound analysis: no false positives

	Complete	Incomplete
Sound	Reports all errors Reports no false alarms No false positives No false negatives **Undecidable**	Reports all errors May report false alarms No false negatives False positives **Decidable**
Unsound	May not report all errors Reports no false alarms False positives No false negatives **Decidable**	May not report all errors May report false alarms False negatives False positives **Decidable**

Slide credit: Prof Mitchell Stanford's CS 155

Example tools / approaches

Approach	Type	Comment
Lexical analyzers	Static analysis	Perform syntactic checks Ex: LINT, RATS, ITS4
Fuzz testing	Dynamic analysis	Run on specially crafted inputs to test
Symbolic execution	Emulated execution	Run program on many inputs at once, by Ex: KLEE, S2E, FiE
Model checking	Static analysis	Abstract program to a model, check that model satisfies security properties Ex: MOPS, SLAM, etc.

Source code scanners

Program that looks at source code, flags suspicious constructs

```
…
strcpy( ptr1, ptr2 );
…
```

Warning: Don’t use strcpy

Simplest example: grep
Lint is early example
RATS (Rough auditing tool for security)
ITS4 (It’s the Software Stupid Security Scanner)

Circa 1990’s technology: ***shouldn’t*** work for reasonable modern codebases

(… but probably will)

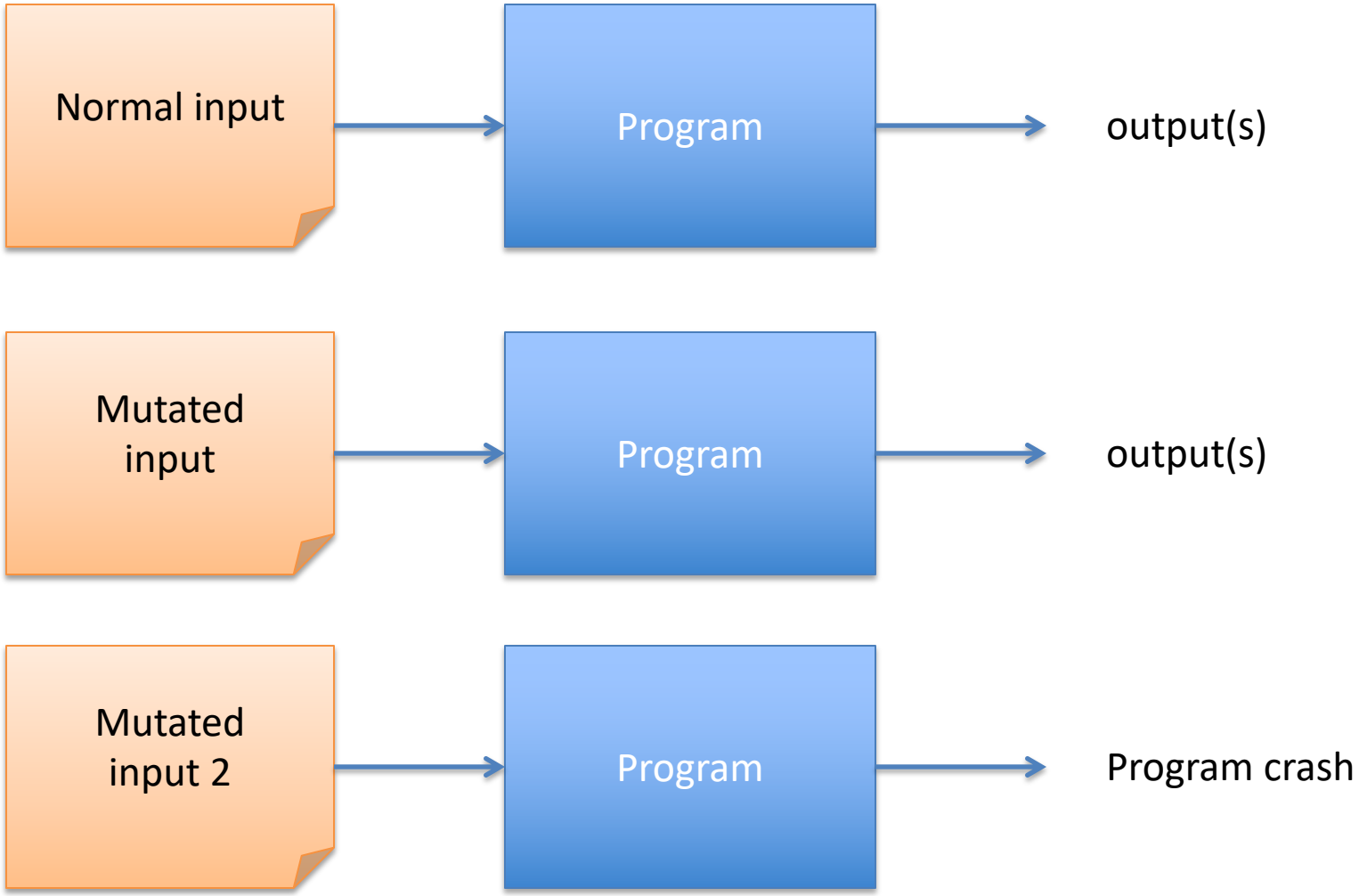
Dynamic analysis: fuzzing

Choose a bunch of inputs
See if they cause program to crash

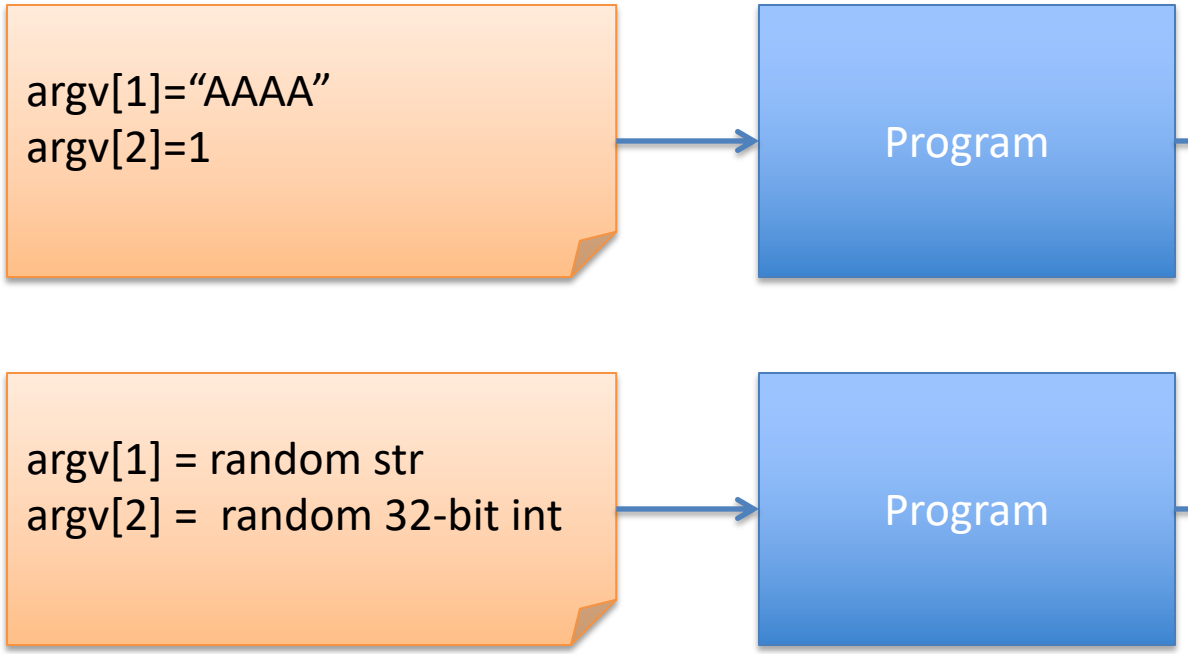
Key challenge: finding good inputs

“The term first originates from a class project at the University of Wisconsin 1988 although similar techniques have been used in the field of quality assurance, where they are referred to as robustness testing, syntax testing or negative testing.”
Wikipedia
http://en.wikipedia.org/wiki/Fuzz_testing

Dynamic analysis: fuzzing



Dynamic analysis: fuzzing




```
main(  int argc, char* argv[] ) {
  char* b1;
  char* b2;
  char* b3;

  if( argc != 3 ) then return 0;
  if( atoi(argv[2]) != 31337 )
      complicatedFunction();
  else {
      b1 = (char*)malloc(248);
      b2 = (char*)malloc(248);
      free(b1);
      free(b2);
      b3 = (char*)malloc(512);
      strncpy( b3, argv[1], 511 );
      free(b2);
      free(b3);
   }
}
```

If integers are 32 bits, then probability of crashing is **at most what**? $1/2^{32}$

Achieving code coverage can be very difficult

Code coverage and fuzzing

- Code coverage defined in many ways
  - # of basic blocks reached
  - # of paths followed
  - # of conditionals followed
  - gcov is useful standard tool
- Mutation based
  - Start with known-good examples
  - Mutate them to new test cases
    - heuristics: increase string lengths (AAAAAAAAA…)
    - randomly change items
- Generative
  - Start with specification of protocol, file format
  - Build test case files from it
    - Rarely used parts of spec

American Fuzzy Lop (AFL) fuzzer

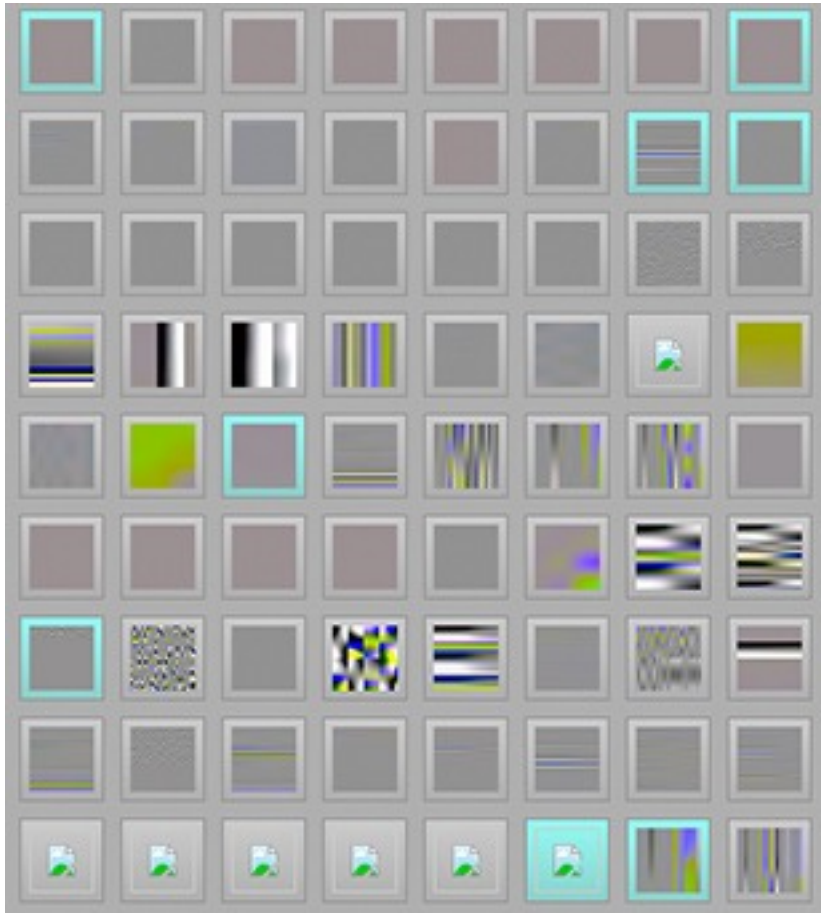
Widely used, highly effective fuzzing tool

- Specify example inputs
- Compile program with special afl compiler
- Run it

Performs mutation-based fuzzing:

- Deterministic transforms to input (flip each bit, “walking byte flips”,)
- Randomized stacked transforms
- Measure (approximation of) path coverage, keep and mutate set of files that increase coverage

Really fast & simple. Used to find bugs in:
Firefox, OpenSSH, BIND, ImageMagick, iOS, …

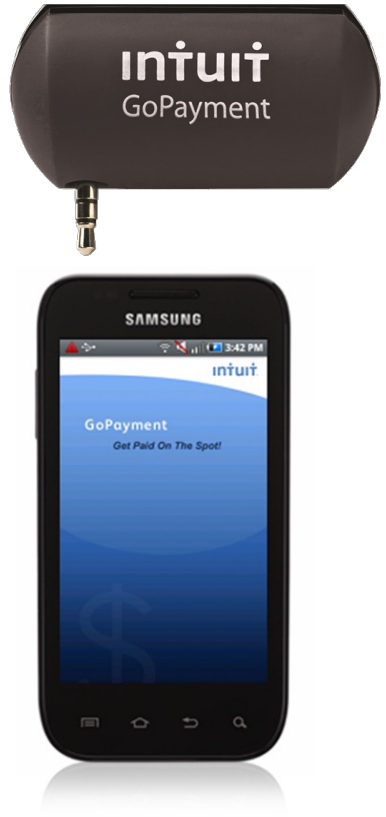


https://lcamtuf.blogspot.com/2014/11/pulling-jpegs-out-of-thin-air.html

Custom fuzzer example: IDTech Firmware

Point-of-sale credit card reader for smart phones

- No access to firmware binary, let alone source code



<u>What we did:</u>

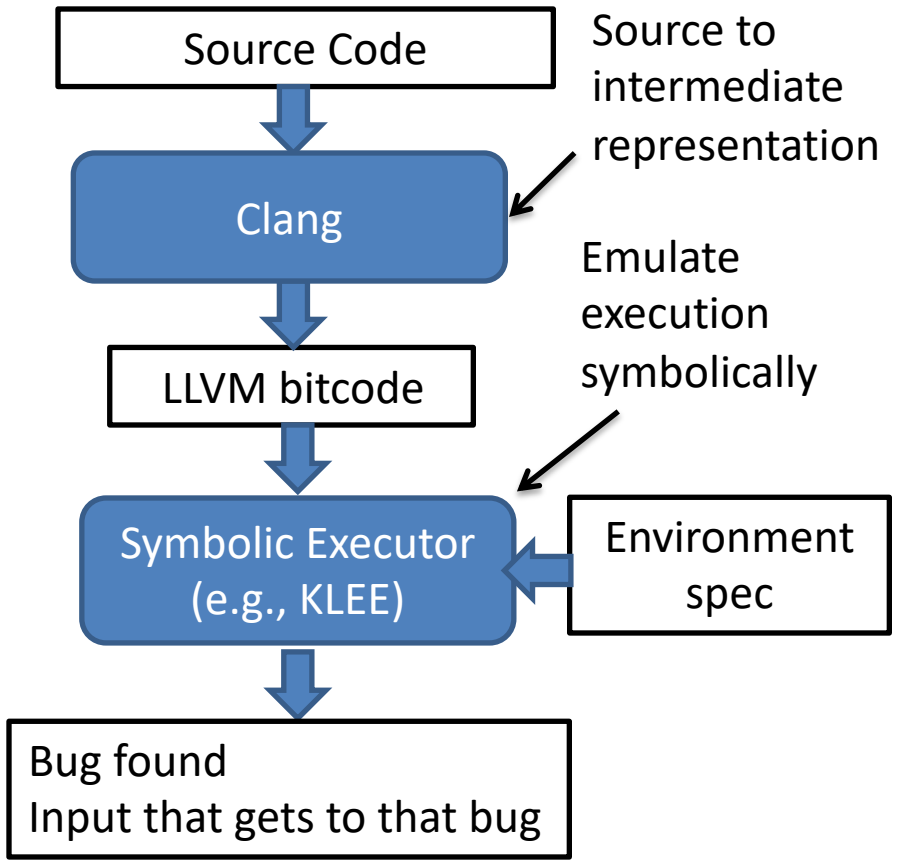
- Scour web for documentation
- Download SDK for app developers (bingo!)
  - Use to build fuzzing functionality for each API call we could find
  - Use to discover undocumented API calls

<u>Results:</u>

- Found unauthenticated API calls, buffer bound check problems, ultimately brick device, reveals crypto keys, cleartext credit card data

https://rist.tech.cornell.edu/papers/pos.pdf

Symbolic execution



- Technique for analyzing code paths and finding inputs
- Associate to input variables *symbols*
  - called symbolic variable
- Simulate execution symbolically
  - Update symbolic variable's value appropriately
  - Conditionals add constraints on possible values
- Cast constraints as satisfiability, and use SAT solver to find inputs
- Perform security checks at each execution state

Symbolic execution

```
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  char* b2;
  char* b3;

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      strncpy( b3, argv[1], 511 );
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      free(b3);
   }
}
```
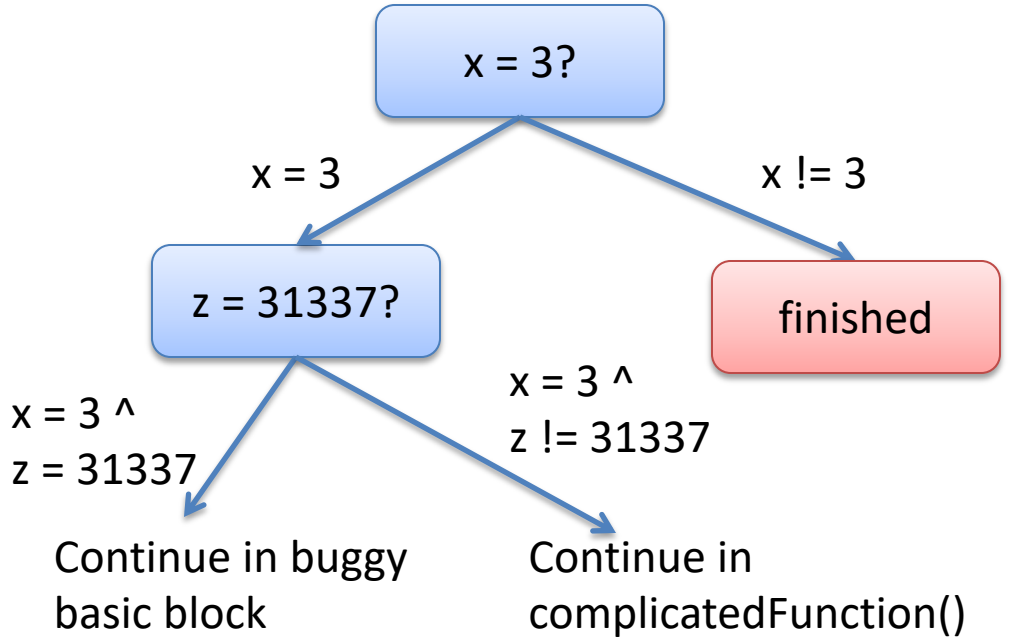

Initially:

argc = x (unconstrained int)
argv[2] = z (memory array)



- Eventually emulation hits a double free
- Can trace back up path to determine what x, z must have been to hit this basic block

Symbolic execution challenges

- Can we complete analyses?
  - Yes, but only for very simple programs
  - Exponential # of paths to explore
  - Each branch increases state size of symbolic emulator
- Path selection
  - Which state to explore next?
  - Might get stuck in complicatedFunction()
- Encoding checks on symbolic states
  - Must include logic for double free check
  - Symbolic execution on binary more challenging (lose most memory semantics)

Example tools / approaches

Approach	Type	Comment
Lexical analyzers	Static analysis	Perform syntactic checks Ex: LINT, RATS, ITS4
Fuzz testing	Dynamic analysis	Run on specially crafted inputs to test
Symbolic execution	Emulated execution	Run program on many inputs at once, by Ex: KLEE, S2E, FiE
Model checking	Static analysis	Abstract program to a model, check that model satisfies security properties Ex: MOPS, SLAM, etc.

Summary of Program Analysis

	Pros	Cons
Static	Enables quickly finding bugs at development time Can detect some problems that dynamic misses	Either over or under reports. Misses complex bugs. Generally requires code.
Dynamic	May uncover complex behavior missed by static. Can run on blackbox.	Depends on user input—only checks executed code

Bug finding is a big business

- Grammatech (Cornell startup, 1988)
- Coverity (Stanford startup)
- Fortify
- many, many others…

Great article on static analysis in the real world:
http://web.stanford.edu/~engler/BLOC-coverity.pdf

- Reverse engineers, exploit developers, & zero-day markets
  - Hacking team
- Bug bounty programs