Dynamic Security Testing

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Today

- The world of software security

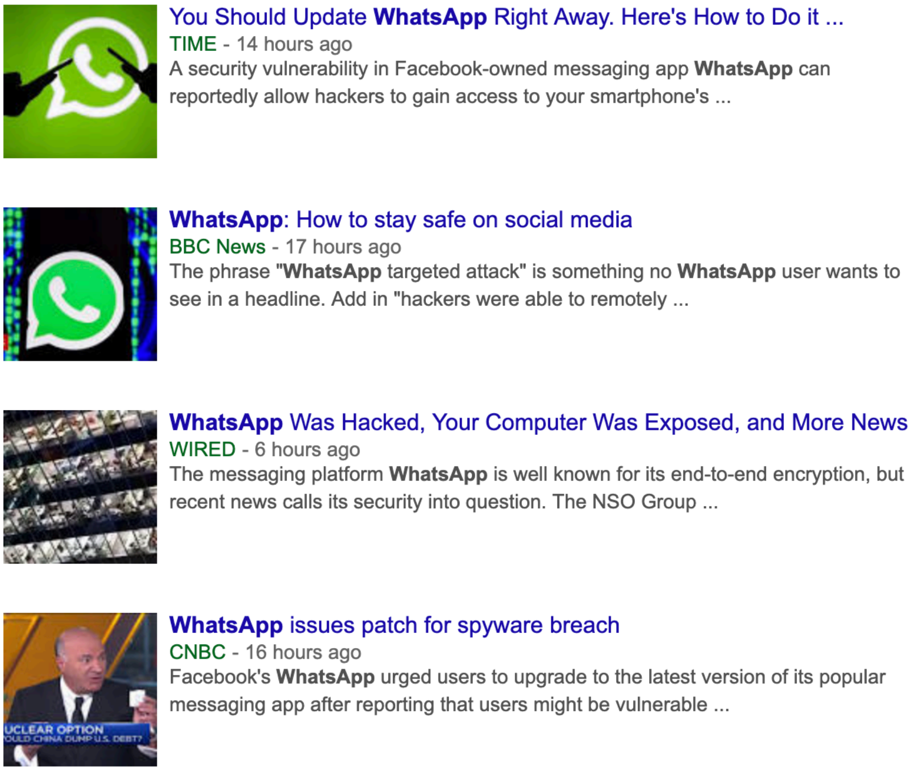
- How is it possible?
  - Integer overflows
  - Buffer overflows
  - Heartbleed
  - Stagefright

- How can it be prevented?
  - Fuzzing
  - Symbolic execution
  - Automated reversing

Many slides courtesy of Erik Poll (RU Nijmegen) and Dawn Song (Berkeley)

The world of software security

Who uses WhatsApp?



You Should Update **WhatsApp** Right Away. Here's How to Do it ...
TIME - 14 hours ago
A security vulnerability in Facebook-owned messaging app **WhatsApp** can reportedly allow hackers to gain access to your smartphone's ...

WhatsApp: How to stay safe on social media
BBC News - 17 hours ago
The phrase "**WhatsApp** targeted attack" is something no **WhatsApp** user wants to see in a headline. Add in "hackers were able to remotely ...

WhatsApp Was Hacked, Your Computer Was Exposed, and More News
WIRED - 6 hours ago
The messaging platform **WhatsApp** is well known for its end-to-end encryption, but recent news calls its security into question. The NSO Group ...

WhatsApp issues patch for spyware breach
CNBC - 16 hours ago
Facebook's **WhatsApp** urged users to upgrade to the latest version of its popular messaging app after reporting that users might be vulnerable ...

Before hacking

- In 1950s, Joe Engressia showed the telephone network could be hacked by phone phreaking:
  - ie. by whistling at right frequencies

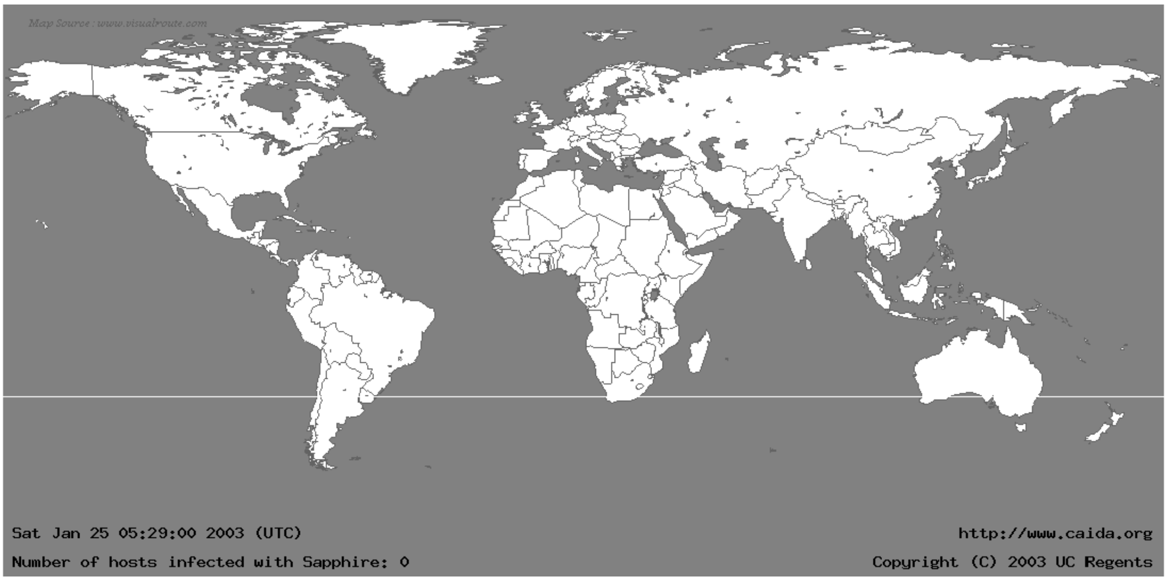
https://www.youtube.com/watch?v=vVZm7I1CTBs

- In 1970s, before founding Apple together with Steve Jobs, Steve Wozniak sold Blue Boxes for phone phreaking at university

Brief history of malware

- 1982:
  - Highschool student Rick Scrent wrote the Elk Cloner, the first computer virus that spread via floppy disks for Apple II
- 1988:
  - University student Robert Morris wrote the first internet worm, the Morris worm
    - Unintentionally, it crashed 10% of the internet.
    - First conviction under the 1986 US Computer Fraud and Abuse Act.
- late 1990/early 2000s, many more viruses and worms:
  - Email viruses: I Love You, Kournikova, …
  - Worms: Slammer, CodeRed, MyDoom, Nimda, …

Slammer worm (2003)


Map Source : www.visualroute.com
Sat Jan 25 05:29:00 2003 (UTC)
Number of hosts infected with Sapphire: 0
http://www.caida.org
Copyright (C) 2003 UC Regents

Pictures from *The Spread of the Sapphire/Slammer Worm,* by David Moore, Vem Paxson, Stefan Savage, Colleen Shannon, Stuart Staniford, Nicholas Weaver

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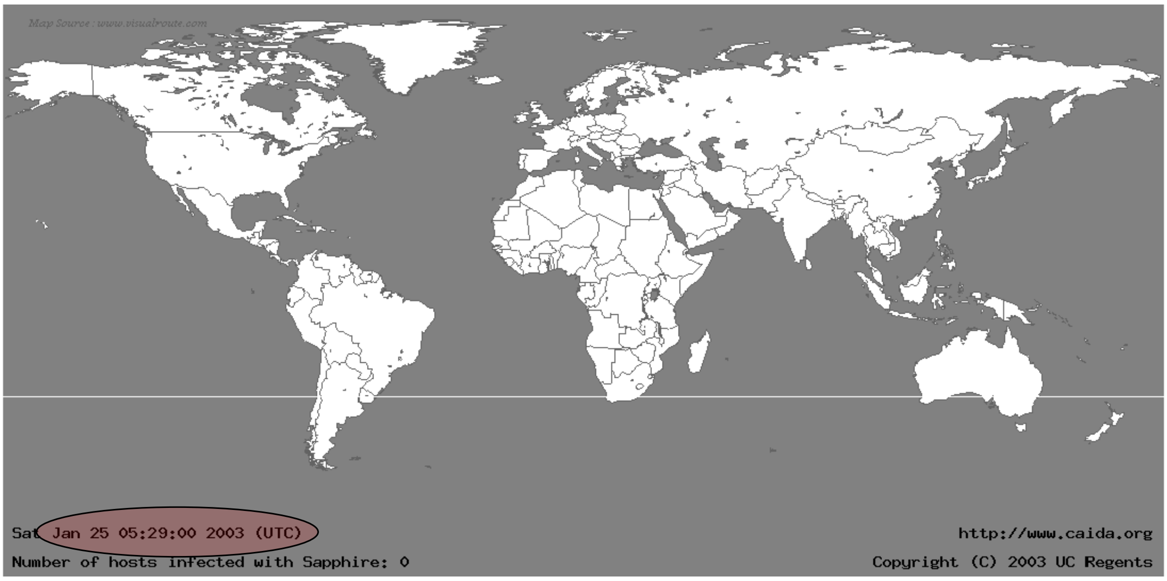
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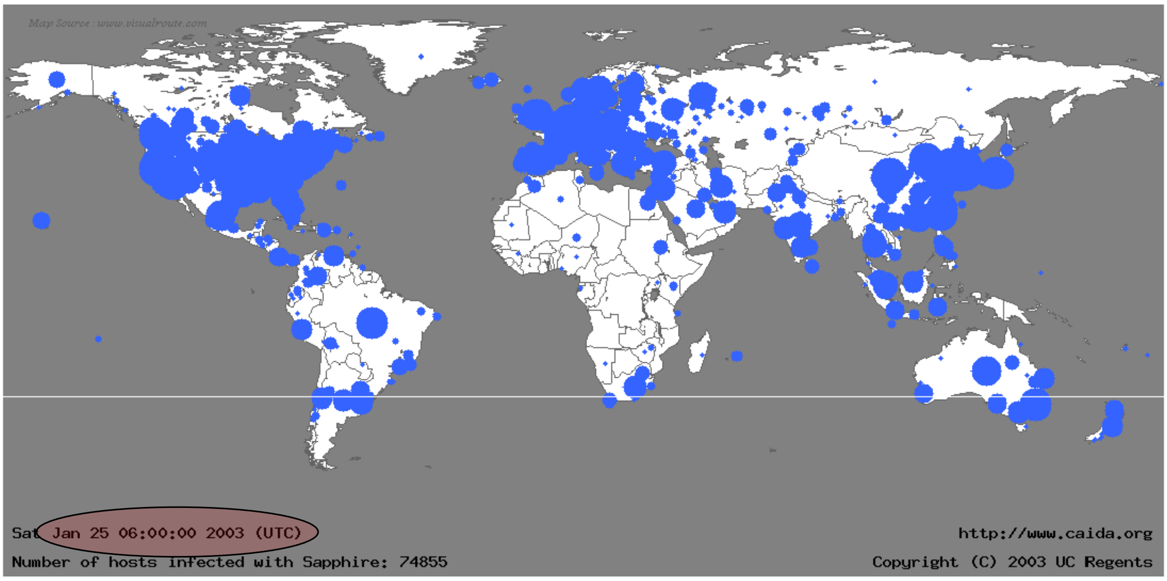
Map Source : www.visualroute.com
Sat Jan 25 06:00:00 2003 (UTC)
Number of hosts infected with Sapphire: 74855
http://www.caida.org
Copyright (C) 2003 UC Regents

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Slammer worm

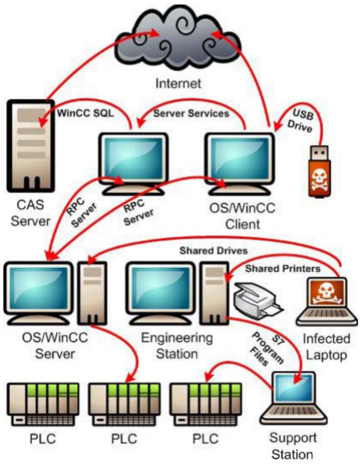
- Exploited a buffer overflow in SQL Server (Microsoft)
- This bug was already patched six months earlier!
- A small piece of code that continuously generates random IP addresses and sends itself to those addresses
  - Only 376 bytes large
- Drastically slowed-down internet traffic
  - crashing numerous routers
  - causing a flood of routing table updates

Hacking turns professional

- Hacking not just fun, but profitable:
  - stealing user data (usernames & passwords, credit card no’s, ...)
  - sending spam, eg for phishing
  - interfering with internet transactions (eg internet banking)
  - new business models for making money:
    - adware, scareware, or ransomware
  - creating botnets, large collections of infected computers (bots), which can then be used for all of the above
- *and for warfare, terrorism, espionage,…*

Stuxnet

- Advanced malware spread via USB sticks to stealthily target embedded software (SCADA systems in a Iranian nucleair facility using multiple (expensive) zero day vulnerabilities



Ralph Langer on stuxnet: http://www.youtube.com/watch?v=CS01Hmjv1pQ

Hacking today

- Several variants of Stuxnet found: Flame, Duqu, Gauss
  - All military grade malware, very hard to analyze due to advanced encryption
- Conficker worm found on French navy network
- Advanced attacks on infrastructure: Telvent attack
  - Closer to home: attacks on ports of Rotterdam and Antwerp
- Many instances of cyber espionage:
  - Nitro attack, Icefog, Putter Panda, PLATINUM, …

A marketplace for vulnerabilities

- Option 1: Bug bounty programs
  - Google vulnerability reward program: 3k $
  - Mozilla Bug Bounty program: 500 $
  - Pwn2Own competition: 15k $
- Option 2: Responsible dislosure
  - ZDI, iDefense: 2k – 25k $
- Option 3: Black market
  - “some exploits”: 200K-250k $
  - A “real good exploit”: over 100k $

Source: Charlie Miller
(securityevaluators.com/files/papers/0daymarket.pdf)

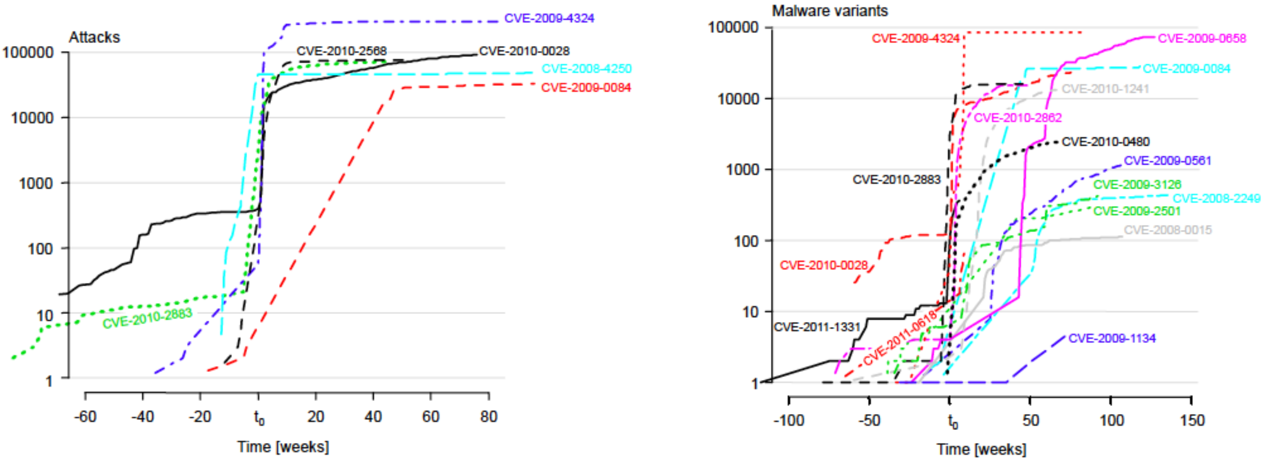
Reporting vulnerabilities

http://www.us-cert.gov/ncas/alerts/
http://www.securitytracker.com/
http://www.securityfocus.com/vulnerabilities

- Such sites use different policies:
  - publishing all vulnerabilities
    - possibly only after some waiting period for responsible disclosure
  - only publishing those that are known to be exploited
  - only publishing those for which there is a patch

Keep your system up-to-date!

- Vulnerability announcements cause patches, but also hacks:



(a) Attacks exploiting zero-day vulnerabilities before and after the disclosure (time = t_0).

(b) Malware variants exploiting zero-day vulnerabilities before and after disclosure (time = t_0).

Figures from *Before we knew it: An empirical study of zero-day attacks in the real world*, by Leyla Bilge and Tudor Dimitras

How bad is it for you?

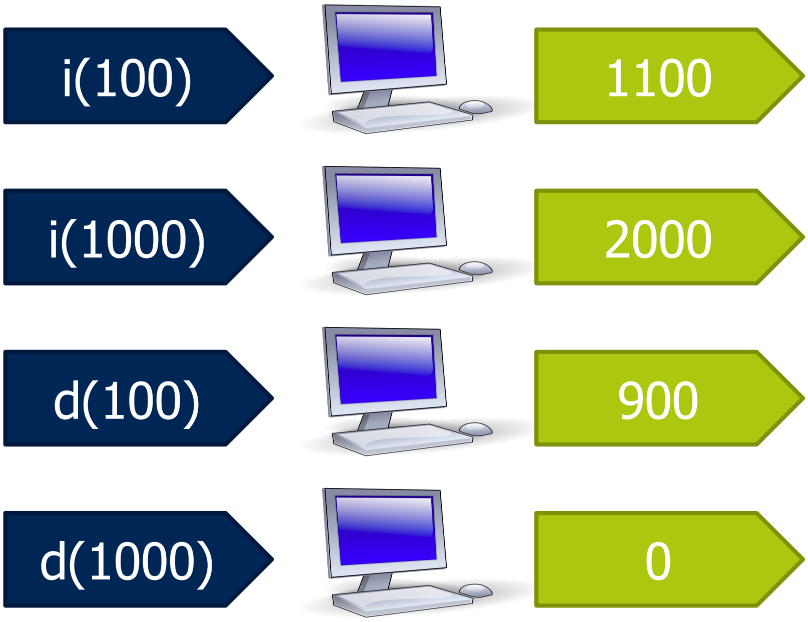
- Someone can take full control of your PC
  - take screen shots
  - monitor keystrokes for login credentials
  - lock your system
  - use it for DDoS attacks
  - …

- Nowadays, not only hackers can do so, *little programming experience in required*
  - Many sophisticated hacking tools exist with GUIs, all you need to know is how to use a mouse…

What causes the problem

What would you test?

- Testing increase i and decrease d, balance resets to 1000:



i(100) → 1100

i(1000) → 2000

d(100) → 900

d(1000) → 0

What would you test?

```
int balance = 1000;

void decrease(int amount)
{
    if (balance <= amount)
    {
        balance = balance – amount;
    }
    else
    {
        printf(“Insufficient funds\n”);
    }
}

void increase(int amount)
{
    balance = balance + amount;
}
```

Exercise: spot the bugs

```
int balance = 1000;

void decrease(int amount)
{
    if (balance <= amount)
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should be >=

what if amount is negative?

Exercise: spot the bugs

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should be >=

what if amount is negative?

what if sum is too large for int?

Exercise: spot the bugs

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void increase(int amount)
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}
```

should be >=

what if amount is negative?

what if sum is too large for int?

How to do this for thousands of lines of code….

Different implementation flaws

should be >=

1. Logic error

what if amount is negative?

2. Possible lack of input validation, problem when input is untrusted

what if sum is too large for int?

3. Possible overflow, depends on underlying hardware

Common theme in flaws: untrusted input

- A very common source of security problems is assuming that input values will be `sensible’

If an attacker can control the inputs, this assumption is false.

- Many security flaws are caused untrusted inputs that are not checked aka validated, eg:
  - a numerical input can be negative
  - a numerical input might even not be numerical
  - an image file (eg a JPEG) may be malformed
  - a user might choose a 1 Mbyte long username or email address

- The only safe default is treating all input as untrusted!

Spot the bugs 2

```
#define MAX_BUF 256

void BadCode (char* input)
{
        short len;
        char buf[MAX_BUF];

        len = strlen(input);
        if (len < MAX_BUF)
                strcpy(buf,input);
}
```

Spot the bugs 2

```
#define MAX_BUF 256

void BadCode (char* input)
{
        short len;
        char buf[MAX_BUF];

        len = strlen(input);
        if (len < MAX_BUF)
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}
```

max short = 32K

Spot the bugs 2

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#define MAX_BUF 256

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```

max short = 32K

what if input is larger then 32K?

Spot the bugs 2

```
#define MAX_BUF 256

void BadCode (char* input)
{
        short len;
        char buf[MAX_BUF];

        len = strlen(input);
        if (len < MAX_BUF)
                strcpy(buf,input);
}
```

max short = 32K

what if input is larger then 32K?

len will be negative

causing a buffer overflow…

What is a buffer overflow?

- Suppose in a C program we have an array of length 4

  ```
  char buffer[4];
  ```
- What happens if we execute the statement below ?

  ```
  buffer[4] = ‘a’;
  ```

- This is UNDEFINED! ANYTHING can happen!

- If the data written (ie. ‘a’) is user input that can be controlled by an attacker, this vulnerability can be exploited:

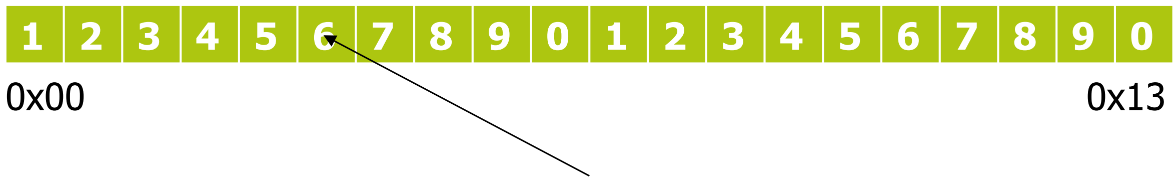
  anything that the attacker wants can happen!

The solution

- Check array bounds at runtime
  - Algol 60 proposed this back in 1960!
- Unfortunately, C and C++ have not adopted this solution for efficiency reasons
  - (Perl, Python, Java, C#, and even Visual Basic have)
- As a result, *buffer overflows have been the no 1 security problem in software ever since*
  - The first Internet worm, and all subsequent ones (CodeRed, Blaster, …), exploited buffer overflows
  - And they are still being exploited…

Pointers and memory

- Computer memory is a sequence of bytes, in hex notation



1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0

0x00 0x13

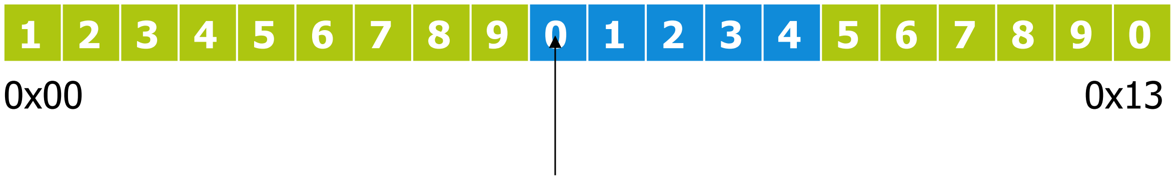
- A pointer is a memory reference: p* = 0x05

- In C you
  - copy pointer values to point to the same memory a = p
  - dereference a pointer to access memory content b = *p

  - a contains 0x05 , b contains 6

Pointers and memory

- Computer memory is a sequence of bytes, in hex notation



1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0

0x00 0x13

- An array is a fixed pointer: char a[5]
- Pointing to a fixed length memory block
  - use arrays as pointers *p = a
  - offset the pointer value b = p+1
  - dereference array values using brackets c = a[1]
  - but also works for pointers d = b[1]

  - p contains 0x09, b contains 0x10, c contains 1, d contains 2

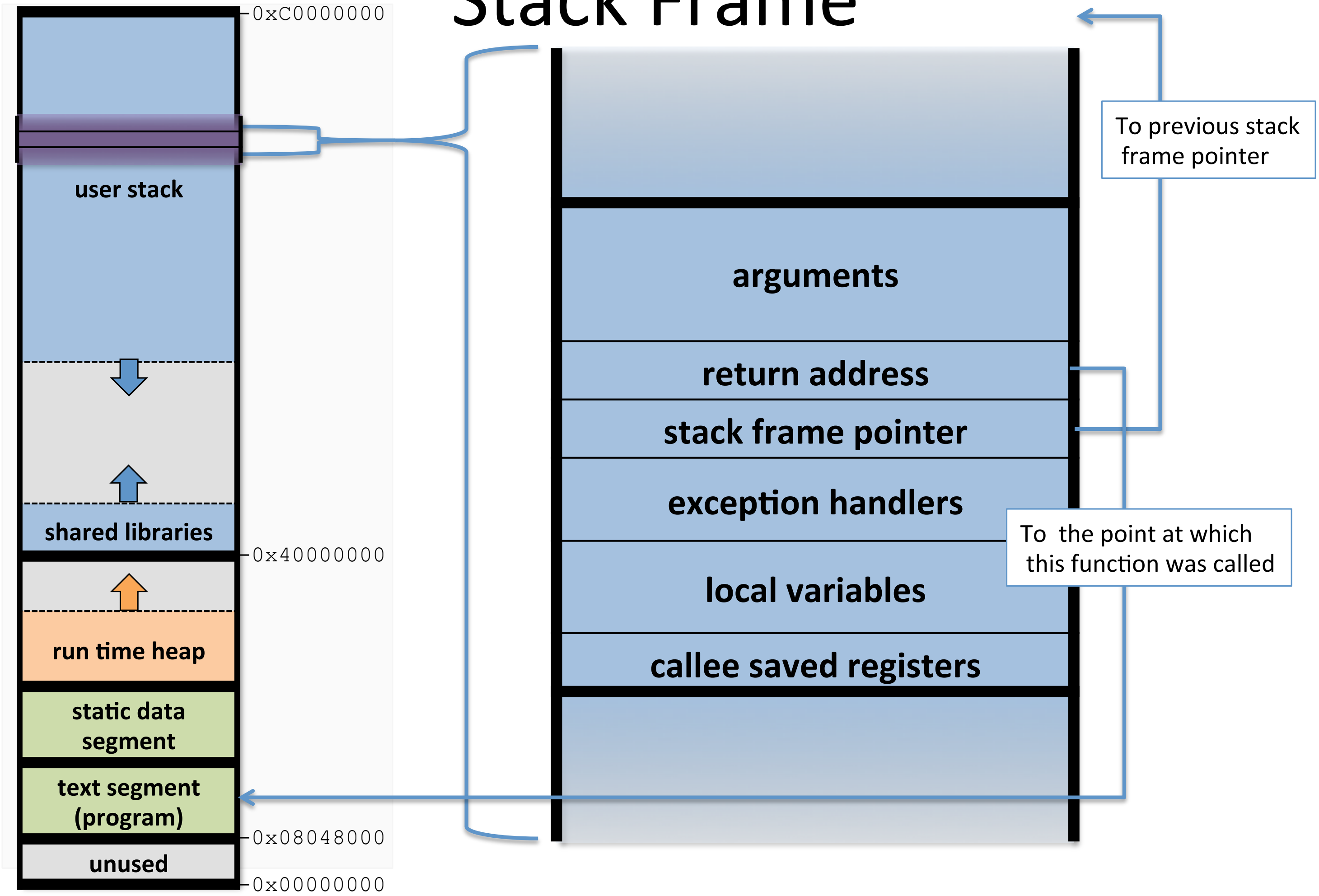
The Stack

- When calling functions, memory is allocated to hold local variables, this memory is called the stack

- The stack grows when calling functions
- The stack decreases when returning

- Ever function call gets assigned its own stack frame, simply a block of memory similar to an array

Stack Frame


0xC0000000
user stack
shared libraries
0x40000000
run time heap
static data segment
text segment (program)
0x08048000
unused
0x00000000
arguments
return address
stack frame pointer
exception handlers
local variables
callee saved registers
To previous stack frame pointer
To the point at which this function was called

Stack Frame

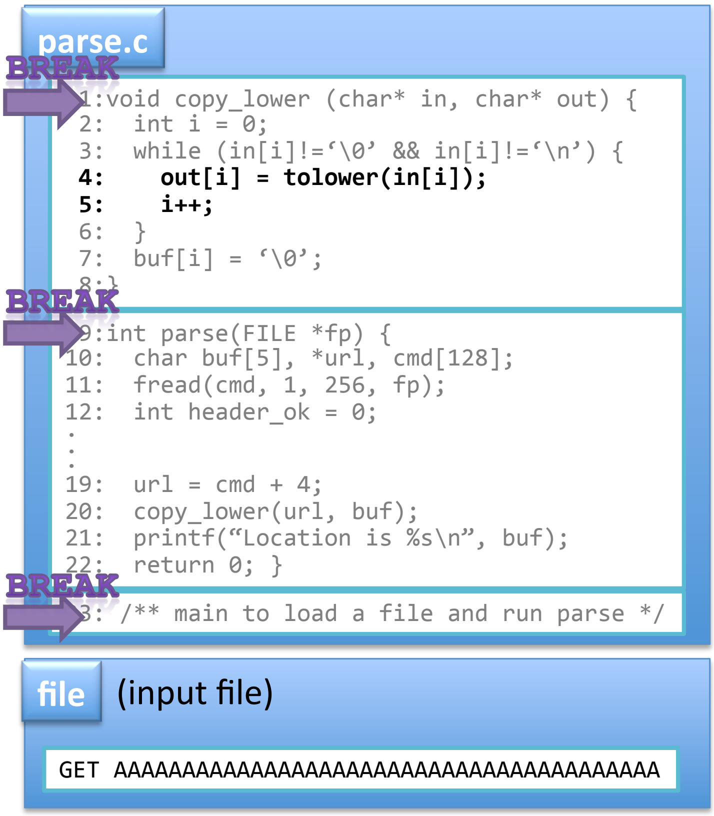
```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!=‘\0’ && in[i]!=‘\n’) {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = ‘\0’;
}
```

```
int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
  fread(cmd, 1, 128, fp);
  int header_ok = 0;
  if (cmd[0] == ‘G’)
    if (cmd[1] == ‘E’)
      if (cmd[2] == ‘T’)
        if (cmd[3] == ‘ ’)
          header_ok = 1;
  if (!header_ok) return -1;
  url = cmd + 4;
  copy_lower(url, buf);
  printf(“Location is %s\n”, buf);
  return 0; }
```

A quick example to illustrate multiple stack frames

Example and slides from Dawn Song

What are buffer overflows?

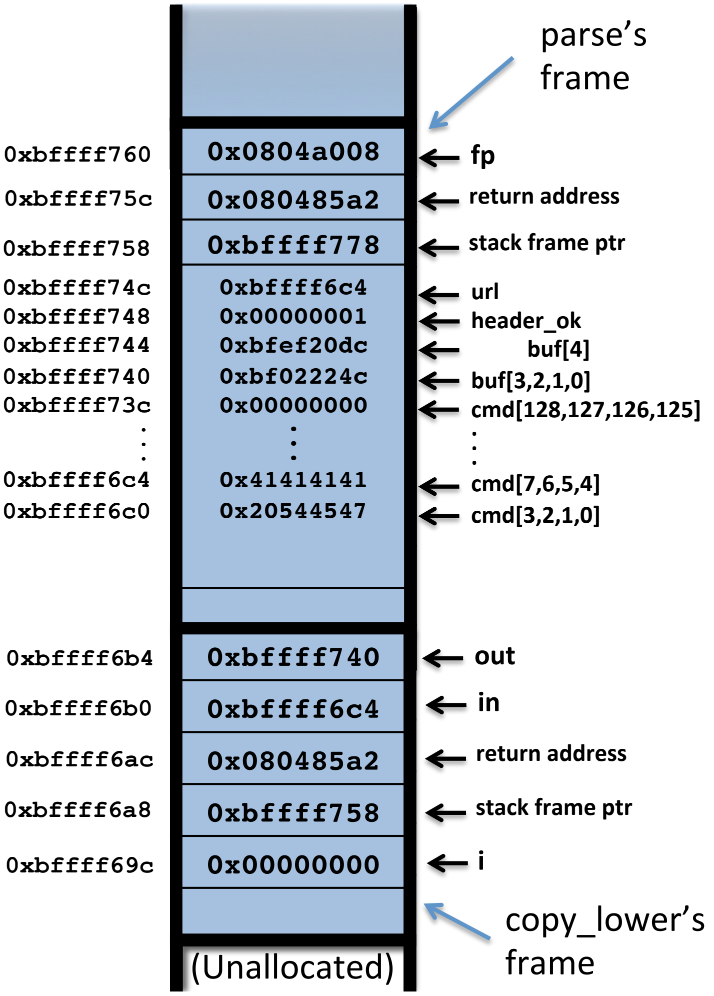


parse.c

```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!=‘\0’ && in[i]!=‘\n’) {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = ‘\0’;
}
int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
  fread(cmd, 1, 256, fp);
  int header_ok = 0;
.
:
  url = cmd + 4;
  copy_lower(url, buf);
  printf(“Location is %s\n”, buf);
  return 0; }
/** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```



0xbffff760	0x0804a008	fp
0xbffff75c	0x080485a2	return address
0xbffff758	0xbffff778	stack frame ptr
0xbffff74c	0xbffff6c4	url
0xbffff748	0x00000001	header_ok
0xbffff744	0xbfef20dc	buf[4]
0xbffff740	0xbf02224c	buf[3,2,1,0]
0xbffff73c	0x00000000	cmd[128,127,126,125]
:	:	:
0xbffff6c4	0x41414141	cmd[7,6,5,4]
0xbffff6c0	0x20544547	cmd[3,2,1,0]
0xbffff6b4	0xbffff740	out
0xbffff6b0	0xbffff6c4	in
0xbffff6ac	0x080485a2	return address
0xbffff6a8	0xbffff758	stack frame ptr
0xbffff69c	0x00000000	i
	(Unallocated)	

What are buffer overflows?

parse.c

BREAK

```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!='\0' && in[i]!='\n') {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = '\0';
}
```

BREAK

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int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
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  int header_ok = 0;
.
.
  url = cmd + 4;
  copy_lower(url, buf);
  printf("Location is %s\n", buf);
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```
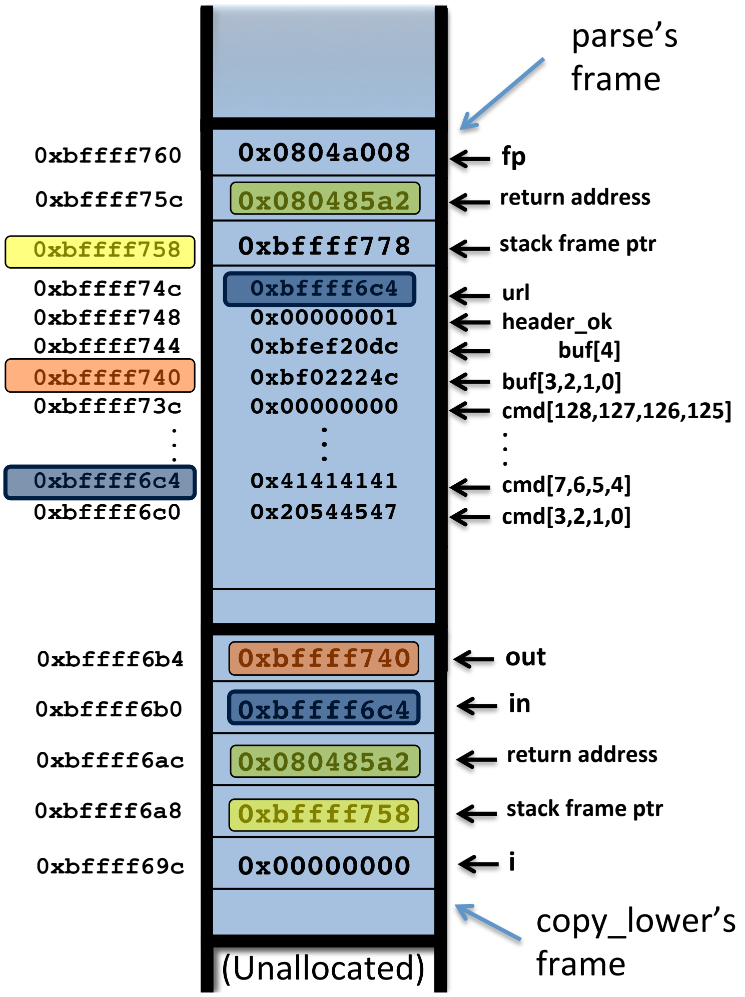

BREAK

```
/** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```



parse's frame

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copy_lower's frame

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 9:int parse(FILE *fp) {
10:  char buf[5], *url, cmd[128];
11:  fread(cmd, 1, 256, fp);
12:  int header_ok = 0;
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 :
19:  url = cmd + 4;
20:  copy_lower(url, buf);
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23: /** main to load a file and run parse */
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file (input file)

```
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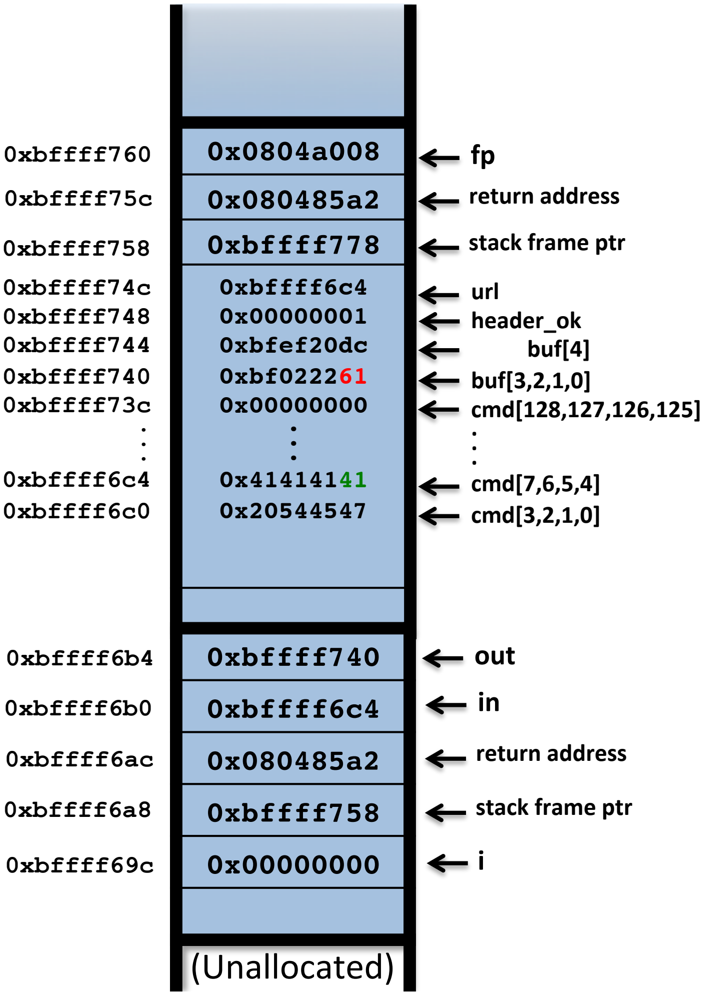

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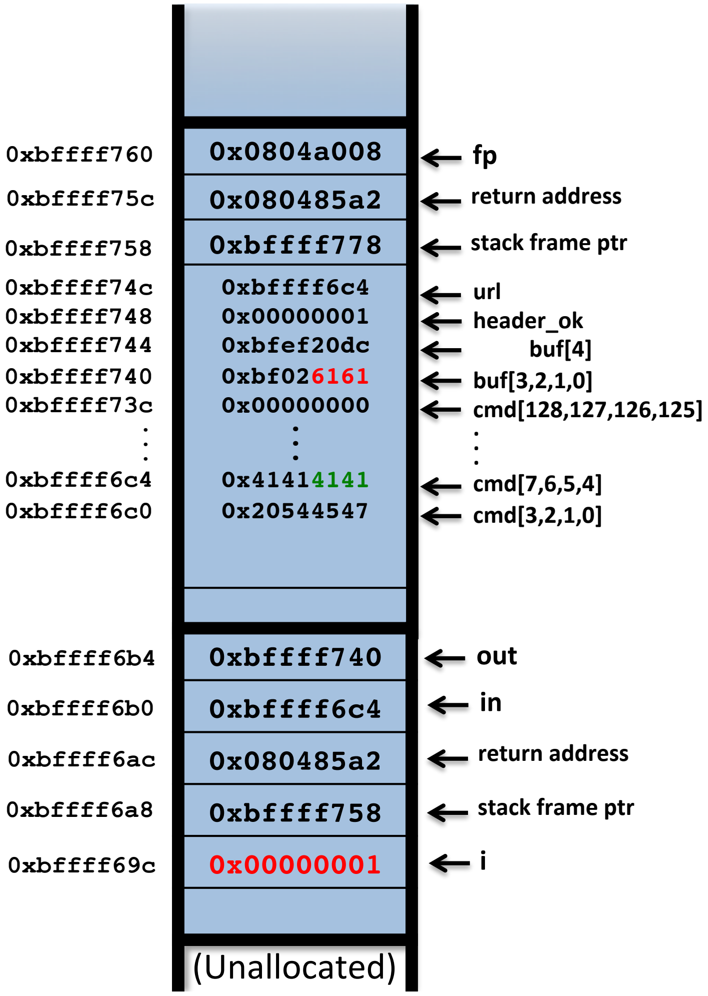

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0xbffff73c	0x00000000	← cmd[128,127,126,125]
⋮	⋮	⋮
0xbffff6c4	0x41414141	← cmd[7,6,5,4]
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 8:}
```
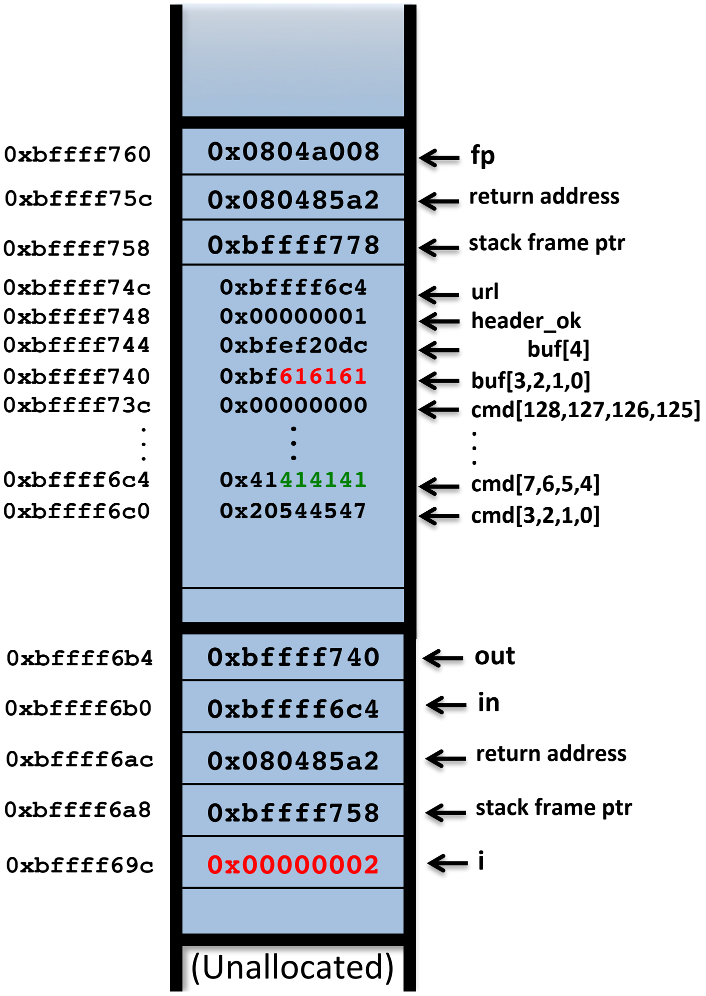

```
 9:int parse(FILE *fp) {
10:   char buf[5], *url, cmd[128];
11:   fread(cmd, 1, 256, fp);
12:   int header_ok = 0;
 .
 .
 .
19:   url = cmd + 4;
20:   copy_lower(url, buf);
21:   printf(“Location is %s\n”, buf);
22:   return 0; }
```

```
23: /** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```



0xbffff760	0x0804a008	← fp
0xbffff75c	0x080485a2	← return address
0xbffff758	0xbffff778	← stack frame ptr
0xbffff74c	0xbffff6c4	← url
0xbffff748	0x00000001	← header_ok
0xbffff744	0xbfef20dc	← buf[4]
0xbffff740	0xbf616161	← buf[3,2,1,0]
0xbffff73c	0x00000000	← cmd[128,127,126,125]
⋮	⋮	⋮
0xbffff6c4	0x41414141	← cmd[7,6,5,4]
0xbffff6c0	0x20544547	← cmd[3,2,1,0]

0xbffff6b4	0xbffff740	← out
0xbffff6b0	0xbffff6c4	← in
0xbffff6ac	0x080485a2	← return address
0xbffff6a8	0xbffff758	← stack frame ptr
0xbffff69c	0x00000002	← i

(Unallocated)

What are buffer overflows?

parse.c

BREAK

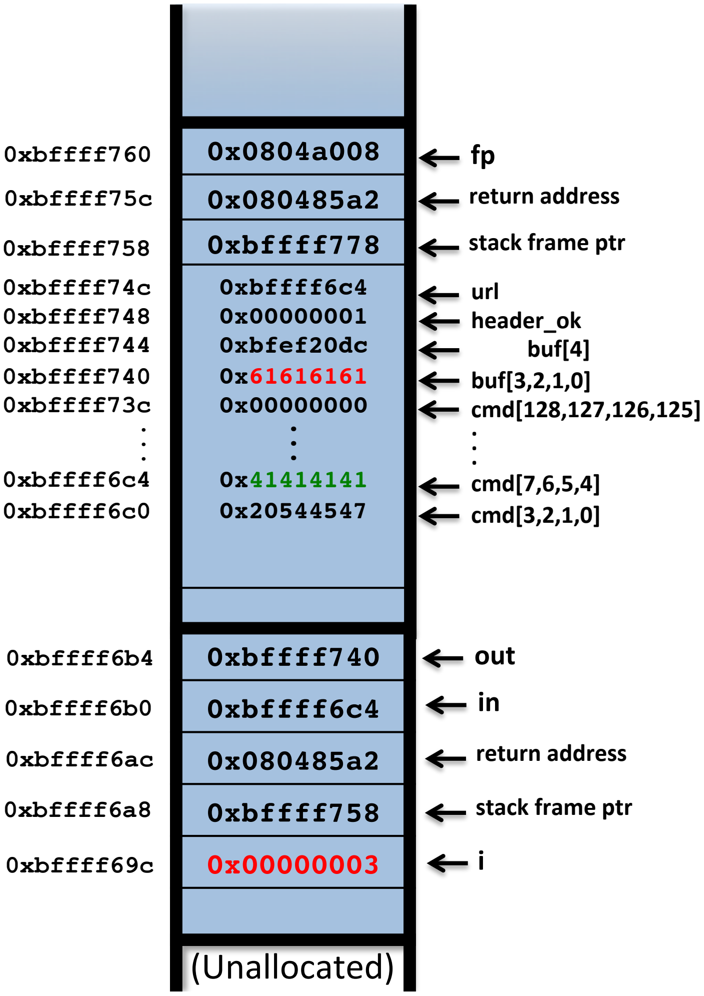
```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!=‘\0’ && in[i]!=‘\n’) {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = ‘\0’;
}
```

```
int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
  fread(cmd, 1, 256, fp);
  int header_ok = 0;
.
.
  url = cmd + 4;
  copy_lower(url, buf);
  printf(“Location is %s\n”, buf);
  return 0; }
```

```
/** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```



0xbffff760	0x0804a008	fp
0xbffff75c	0x080485a2	return address
0xbffff758	0xbffff778	stack frame ptr
0xbffff74c	0xbffff6c4	url
0xbffff748	0x00000001	header_ok
0xbffff744	0xbfef20dc	buf[4]
0xbffff740	0x61616161	buf[3,2,1,0]
0xbffff73c	0x00000000	cmd[128,127,126,125]
.	.	.
0xbffff6c4	0x41414141	cmd[7,6,5,4]
0xbffff6c0	0x20544547	cmd[3,2,1,0]
0xbffff6b4	0xbffff740	out
0xbffff6b0	0xbffff6c4	in
0xbffff6ac	0x080485a2	return address
0xbffff6a8	0xbffff758	stack frame ptr
0xbffff69c	0x00000003	i

(Unallocated)

What are buffer overflows?

parse.c

BREAK

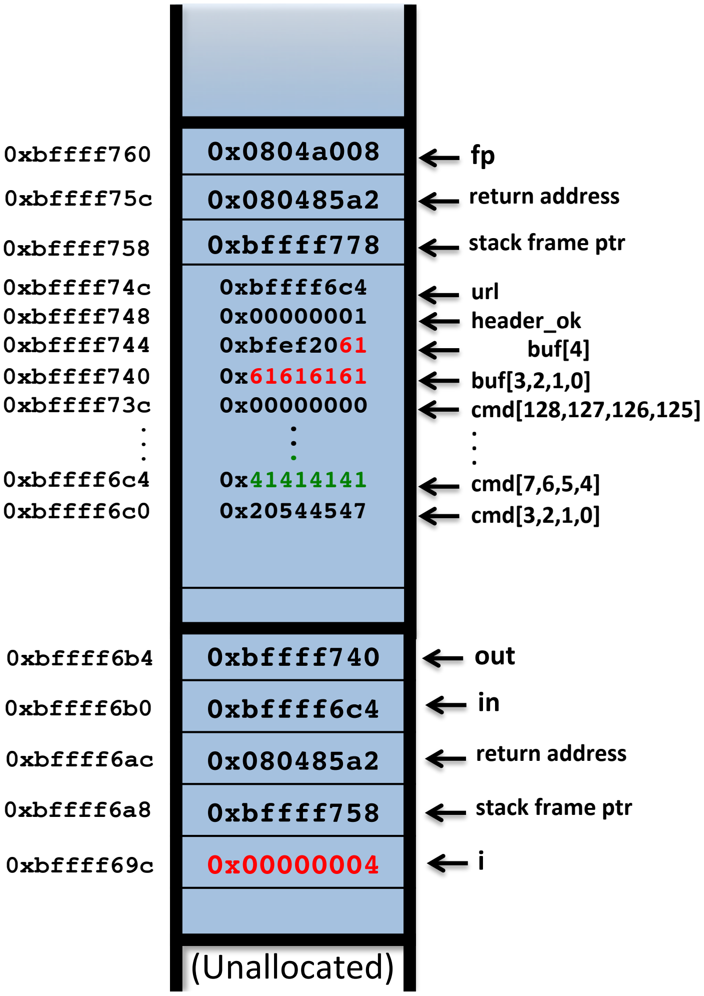
```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!=‘\0’ && in[i]!='\n') {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = ‘\0’;
}
```

```
int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
  fread(cmd, 1, 256, fp);
  int header_ok = 0;
.
.
  url = cmd + 4;
  copy_lower(url, buf);
  printf(“Location is %s\n”, buf);
  return 0; }
```

```
/** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```



0xbffff760	0x0804a008	fp
0xbffff75c	0x080485a2	return address
0xbffff758	0xbffff778	stack frame ptr
0xbffff74c	0xbffff6c4	url
0xbffff748	0x00000001	header_ok
0xbffff744	0xbfef2061	buf[4]
0xbffff740	0x61616161	buf[3,2,1,0]
0xbffff73c	0x00000000	cmd[128,127,126,125]
:	:	:
0xbffff6c4	0x41414141	cmd[7,6,5,4]
0xbffff6c0	0x20544547	cmd[3,2,1,0]
0xbffff6b4	0xbffff740	out
0xbffff6b0	0xbffff6c4	in
0xbffff6ac	0x080485a2	return address
0xbffff6a8	0xbffff758	stack frame ptr
0xbffff69c	0x00000004	i

(Unallocated)

What are buffer overflows?

parse.c

BREAK

```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!='\0' && in[i]!='\n') {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = '\0';
}
```

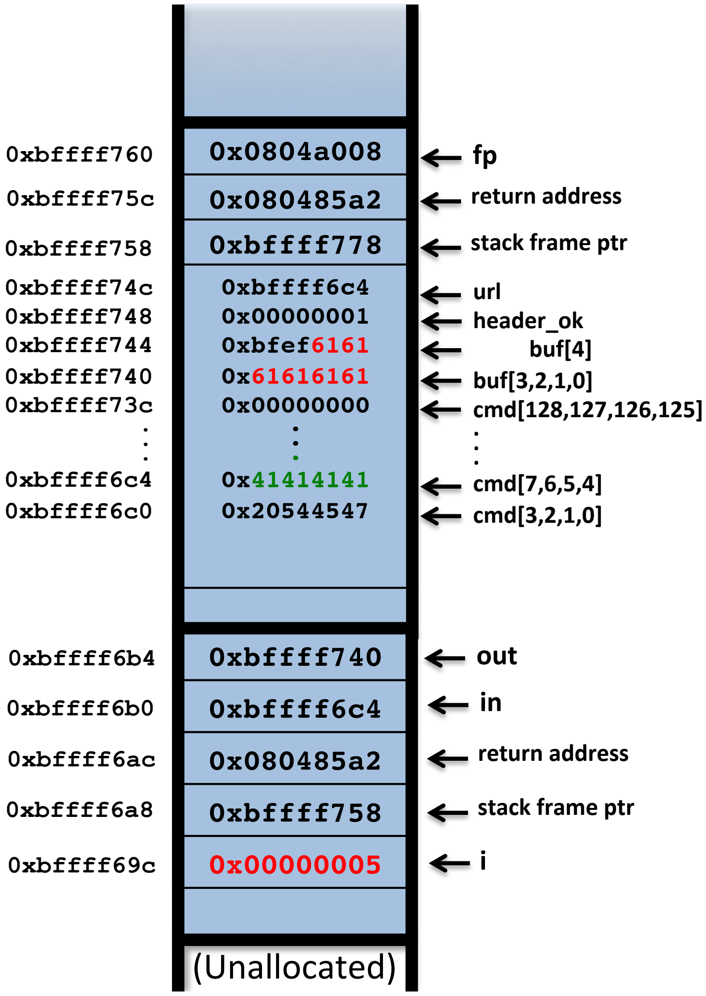
```
int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
  fread(cmd, 1, 256, fp);
  int header_ok = 0;
.
.
  url = cmd + 4;
  copy_lower(url, buf);
  printf("Location is %s\n", buf);
  return 0; }
```

```
/** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```

Uh oh….



0xbffff760	0x0804a008	fp
0xbffff75c	0x080485a2	return address
0xbffff758	0xbffff778	stack frame ptr
0xbffff74c	0xbffff6c4	url
0xbffff748	0x00000001	header_ok
0xbffff744	0xbfef6161	buf[4]
0xbffff740	0x61616161	buf[3,2,1,0]
0xbffff73c	0x00000000	cmd[128,127,126,125]
:	:	:
0xbffff6c4	0x41414141	cmd[7,6,5,4]
0xbffff6c0	0x20544547	cmd[3,2,1,0]
0xbffff6b4	0xbffff740	out
0xbffff6b0	0xbffff6c4	in
0xbffff6ac	0x080485a2	return address
0xbffff6a8	0xbffff758	stack frame ptr
0xbffff69c	0x00000005	i
	(Unallocated)	

What are buffer overflows?

parse.c

BREAK

```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!=‘\0’ && in[i]!='\n') {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = ‘\0’;
}
```

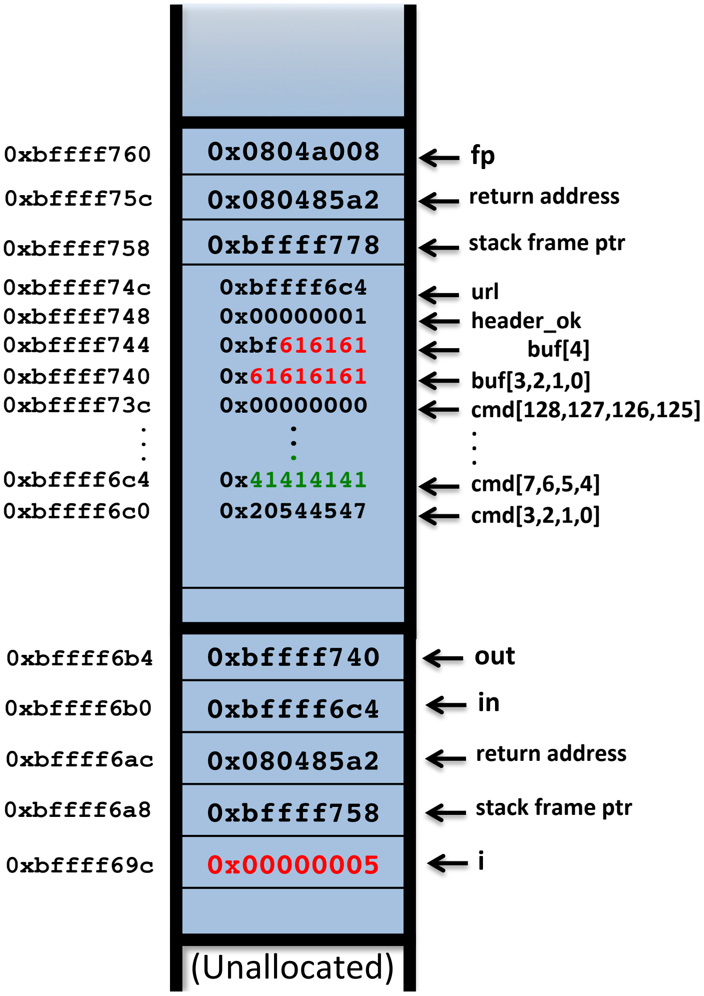
```
int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
  fread(cmd, 1, 256, fp);
  int header_ok = 0;
:
:
  url = cmd + 4;
  copy_lower(url, buf);
  printf(“Location is %s\n”, buf);
  return 0; }
```

```
/** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```

Uh oh….



0xbffff760	0x0804a008	fp
0xbffff75c	0x080485a2	return address
0xbffff758	0xbffff778	stack frame ptr
0xbffff74c	0xbffff6c4	url
0xbffff748	0x00000001	header_ok
0xbffff744	0xbf616161	buf[4]
0xbffff740	0x61616161	buf[3,2,1,0]
0xbffff73c	0x00000000	cmd[128,127,126,125]
:	:	:
0xbffff6c4	0x41414141	cmd[7,6,5,4]
0xbffff6c0	0x20544547	cmd[3,2,1,0]
0xbffff6b4	0xbffff740	out
0xbffff6b0	0xbffff6c4	in
0xbffff6ac	0x080485a2	return address
0xbffff6a8	0xbffff758	stack frame ptr
0xbffff69c	0x00000005	i

(Unallocated)

What are buffer overflows?

parse.c

BREAK

```
 1:void copy_lower (char* in, char* out) {
 2:  int i = 0;
     while (in[i]!=‘\0’ && in[i]!='\n') {
 4:    out[i] = tolower(in[i]);
 5:    i++;
 6:  }
 7:  buf[i] = ‘\0’;
 8:}
```

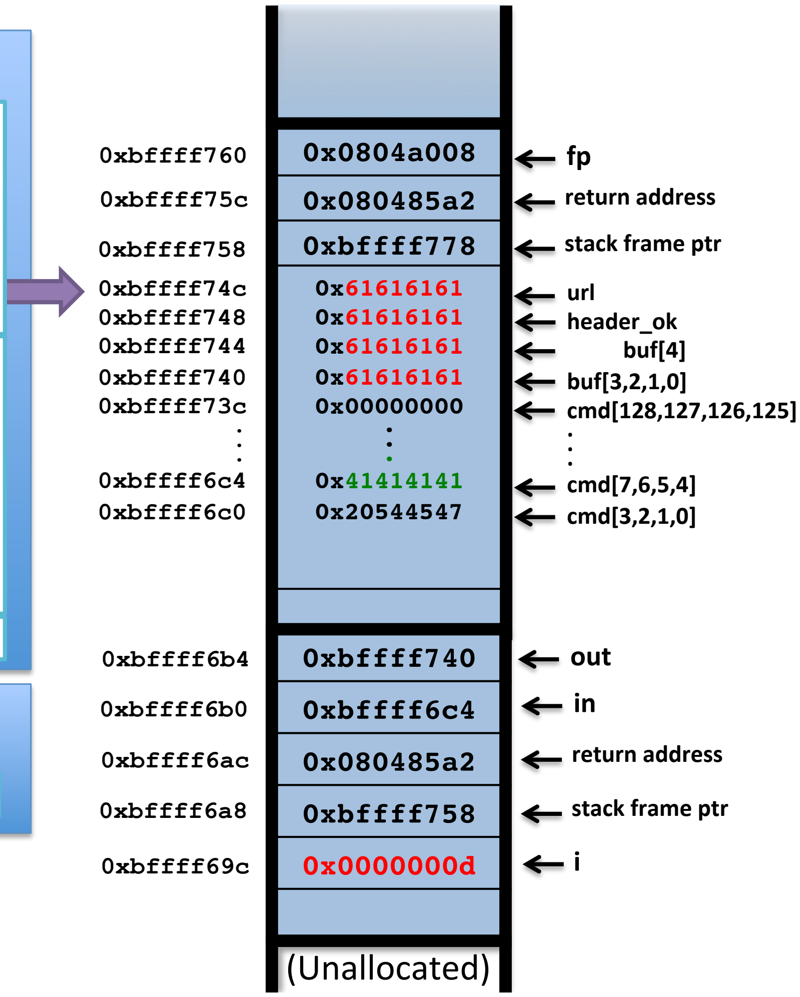
```
 9:int parse(FILE *fp) {
10:  char buf[5], *url, cmd[128];
11:  fread(cmd, 1, 256, fp);
12:  int header_ok = 0;
 :
 :
19:  url = cmd + 4;
20:  copy_lower(url, buf);
21:  printf(“Location is %s\n”, buf);
22:  return 0; }
```

```
23: /** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```

Uh oh….



0xbffff760	0x0804a008	← fp
0xbffff75c	0x080485a2	← return address
0xbffff758	0xbffff778	← stack frame ptr
0xbffff74c	0x61616161	← url
0xbffff748	0x61616161	← header_ok
0xbffff744	0x61616161	← buf[4]
0xbffff740	0x61616161	← buf[3,2,1,0]
0xbffff73c	0x00000000	← cmd[128,127,126,125]
⋮	⋮	⋮
0xbffff6c4	0x41414141	← cmd[7,6,5,4]
0xbffff6c0	0x20544547	← cmd[3,2,1,0]
0xbffff6b4	0xbffff740	← out
0xbffff6b0	0xbffff6c4	← in
0xbffff6ac	0x080485a2	← return address
0xbffff6a8	0xbffff758	← stack frame ptr
0xbffff69c	0x0000000d	← i

(Unallocated)

What are buffer overflows?

parse.c

BREAK

```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!=‘\0’ && in[i]!='\n') {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = ‘\0’;
}
```

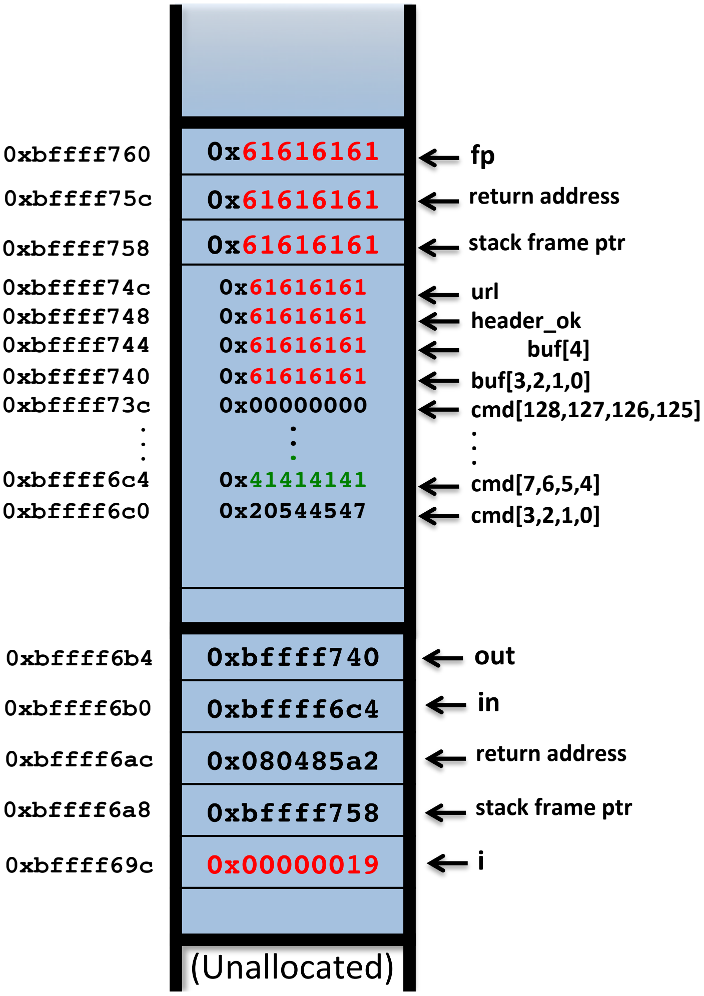
```
int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
  fread(cmd, 1, 256, fp);
  int header_ok = 0;
  .
  .
  url = cmd + 4;
  copy_lower(url, buf);
  printf(“Location is %s\n”, buf);
  return 0; }
```

```
/** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```

Uh oh….



0xbffff760	0x61616161	fp
0xbffff75c	0x61616161	return address
0xbffff758	0x61616161	stack frame ptr
0xbffff74c	0x61616161	url
0xbffff748	0x61616161	header_ok
0xbffff744	0x61616161	buf[4]
0xbffff740	0x61616161	buf[3,2,1,0]
0xbffff73c	0x00000000	cmd[128,127,126,125]
⋮	⋮	⋮
0xbffff6c4	0x41414141	cmd[7,6,5,4]
0xbffff6c0	0x20544547	cmd[3,2,1,0]
0xbffff6b4	0xbffff740	out
0xbffff6b0	0xbffff6c4	in
0xbffff6ac	0x080485a2	return address
0xbffff6a8	0xbffff758	stack frame ptr
0xbffff69c	0x00000019	i

(Unallocated)

What are buffer overflows?

parse.c

BREAK

```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!='\0' && in[i]!='\n') {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = '\0';
}
```

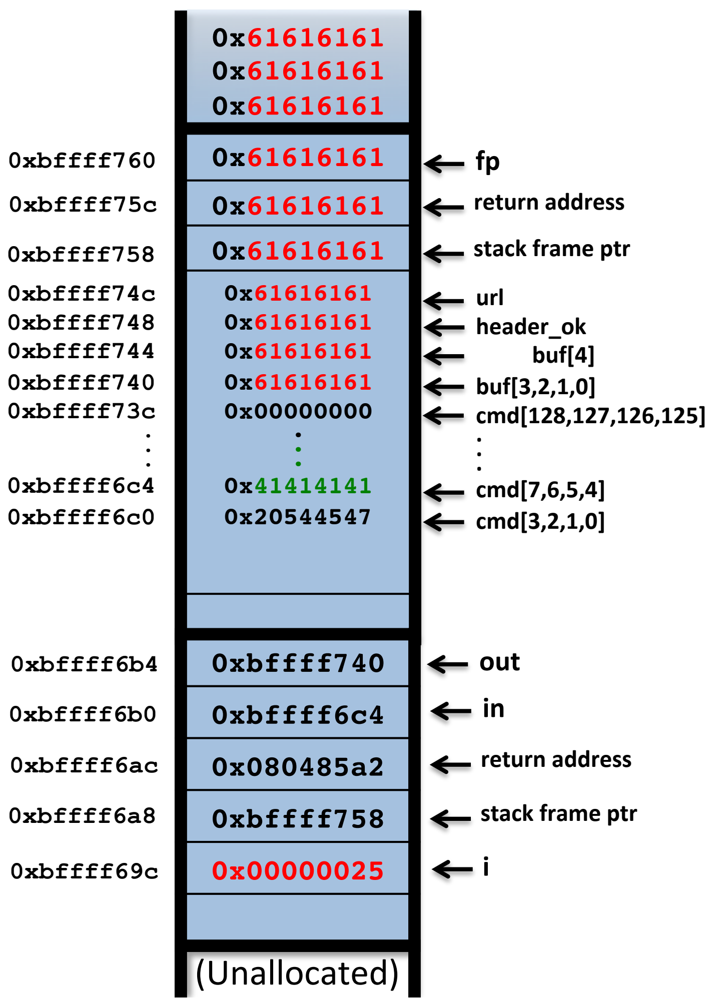
```
int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
  fread(cmd, 1, 256, fp);
  int header_ok = 0;
:
:
  url = cmd + 4;
  copy_lower(url, buf);
  printf("Location is %s\n", buf);
  return 0; }
```

```
/** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```

Uh oh….



	0x61616161 0x61616161 0x61616161	
0xbffff760	0x61616161	← fp
0xbffff75c	0x61616161	← return address
0xbffff758	0x61616161	← stack frame ptr
0xbffff74c	0x61616161	← url
0xbffff748	0x61616161	← header_ok
0xbffff744	0x61616161	← buf[4]
0xbffff740	0x61616161	← buf[3,2,1,0]
0xbffff73c	0x00000000	← cmd[128,127,126,125]
:	:	:
0xbffff6c4	0x41414141	← cmd[7,6,5,4]
0xbffff6c0	0x20544547	← cmd[3,2,1,0]
0xbffff6b4	0xbffff740	← out
0xbffff6b0	0xbffff6c4	← in
0xbffff6ac	0x080485a2	← return address
0xbffff6a8	0xbffff758	← stack frame ptr
0xbffff69c	0x00000025	← i
	(Unallocated)	

What are buffer overflows?

parse.c

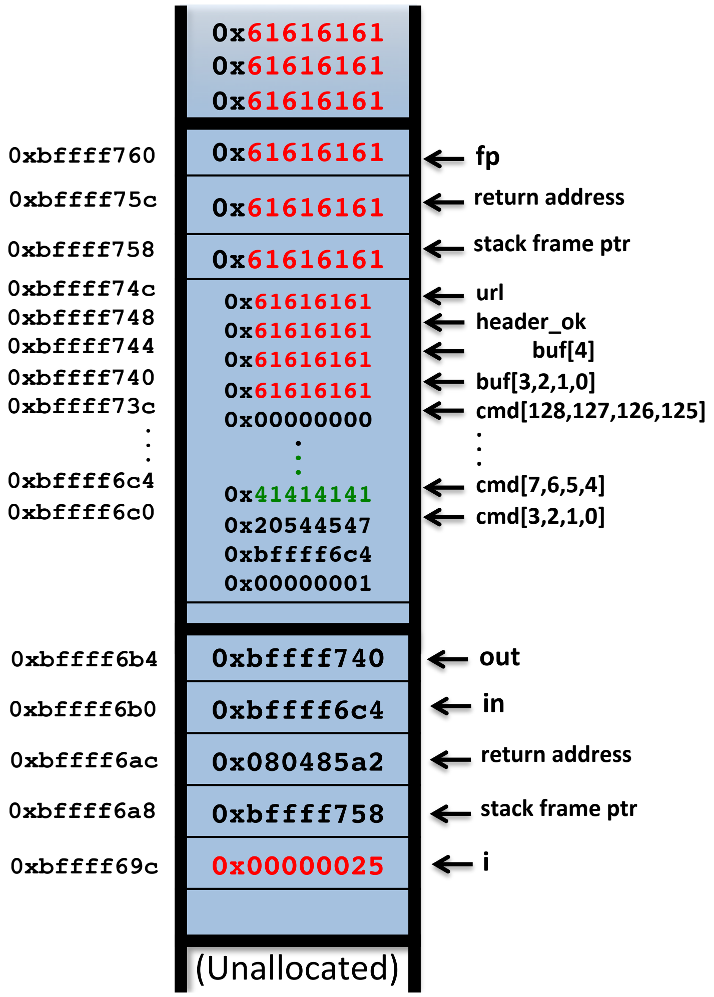
```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!=‘\0’ && in[i]!='\n') {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = ‘\0’;
}

int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
  fread(cmd, 1, 256, fp);
  int header_ok = 0;
:
:
  url = cmd + 4;
  copy_lower(url, buf);
  printf(“Location is %s\n”, buf);
  return 0; }

/** main to load a file and run parse */
```

BREAK

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```

And when you try to return from parse…
… SEGFAULT, since 0x61616161 is not a valid location to return to.



	0x61616161	
	0x61616161	
	0x61616161	
0xbffff760	0x61616161	← fp
0xbffff75c	0x61616161	← return address
0xbffff758	0x61616161	← stack frame ptr
0xbffff74c	0x61616161	← url
0xbffff748	0x61616161	← header_ok
0xbffff744	0x61616161	← buf[4]
0xbffff740	0x61616161	← buf[3,2,1,0]
0xbffff73c	0x00000000	← cmd[128,127,126,125]
⋮	⋮	⋮
0xbffff6c4	0x41414141	← cmd[7,6,5,4]
0xbffff6c0	0x20544547	← cmd[3,2,1,0]
	0xbffff6c4	
	0x00000001	
0xbffff6b4	0xbffff740	← out
0xbffff6b0	0xbffff6c4	← in
0xbffff6ac	0x080485a2	← return address
0xbffff6a8	0xbffff758	← stack frame ptr
0xbffff69c	0x00000025	← i
	(Unallocated)	

Overwriting memory

- Overwriting the return address and thereby causing SEGFAULTS causes programs to crash
- But this is not the main problem, by overwriting the memory now contains the input file name (AAAAA…A)
- In other words, *the user input is in control of what gets written in the programs memory!*
- Suppose we replace this with actual commands, called shellcode…

Basic Stack Exploit

parse.c

BREAK

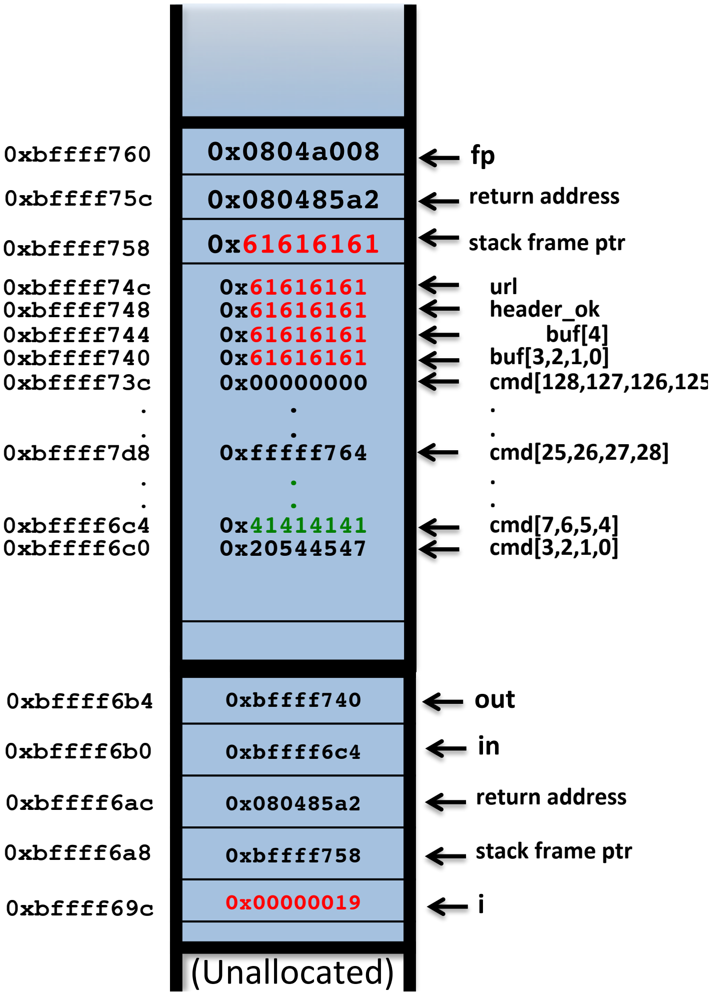
```
void copy_lower (char* in, char* out) {
  int i = 0;
  while (in[i]!=‘\0’ && in[i]!='\n') {
    out[i] = tolower(in[i]);
    i++;
  }
  buf[i] = ‘\0’;
}
```

```
int parse(FILE *fp) {
  char buf[5], *url, cmd[128];
  fread(cmd, 1, 256, fp);
  int header_ok = 0;
.
.
  url = cmd + 4;
  copy_lower(url, buf);
  printf(“Location is %s\n”, buf);
  return 0; }
```

```
/** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAA\x64\xf7\xff
\xffAAAA\xeb\x1f\x5e
\x89\x76\x08\x31\xc0\x88\x46\x46\x0c\xb0\x0b
\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb
\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\xff/bin/sh
```



0xbffff760	0x0804a008	fp
0xbffff75c	0x080485a2	return address
0xbffff758	0x61616161	stack frame ptr
0xbffff74c	0x61616161	url
0xbffff748	0x61616161	header_ok
0xbffff744	0x61616161	buf[4]
0xbffff740	0x61616161	buf[3,2,1,0]
0xbffff73c	0x00000000	cmd[128,127,126,125
.	.	.
0xbffff7d8	0xffff764	cmd[25,26,27,28]
.	.	.
0xbffff6c4	0x41414141	cmd[7,6,5,4]
0xbffff6c0	0x20544547	cmd[3,2,1,0]
0xbffff6b4	0xbffff740	out
0xbffff6b0	0xbffff6c4	in
0xbffff6ac	0x080485a2	return address
0xbffff6a8	0xbffff758	stack frame ptr
0xbffff69c	0x00000019	i

(Unallocated)

Basic Stack Exploit

parse.c

BREAK

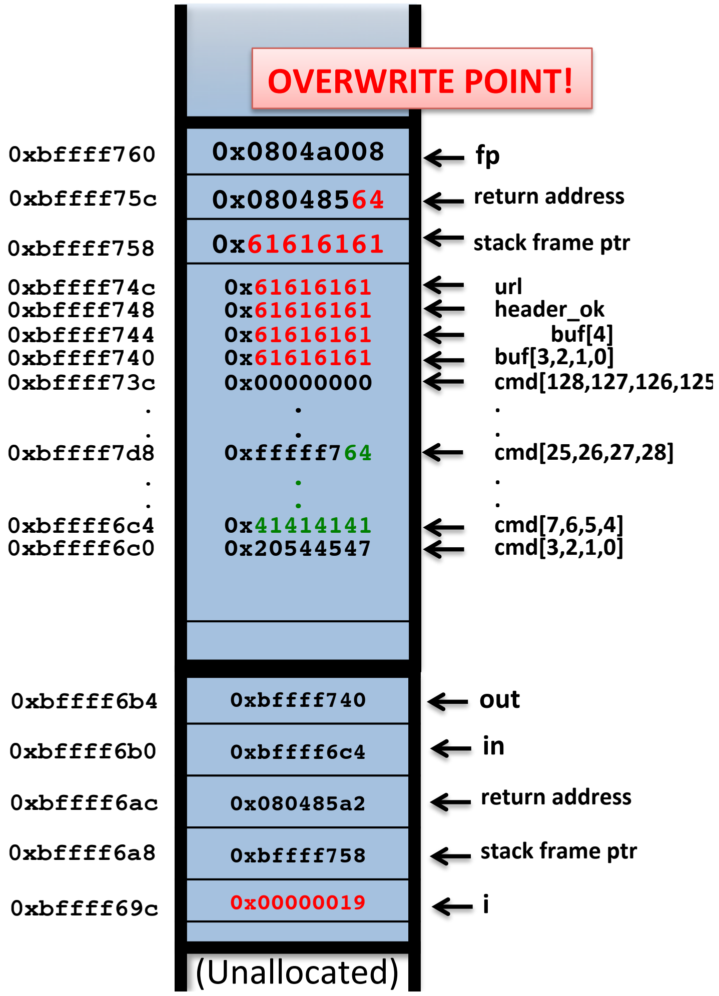
```
 1:void copy_lower (char* in, char* out) {
 2:   int i = 0;
 3:   while (in[i]!='\0' && in[i]!='\n') {
 4:     out[i] = tolower(in[i]);
 5:     i++;
 6:   }
 7:   buf[i] = '\0';
 8:}
```

```
 9:int parse(FILE *fp) {
10:   char buf[5], *url, cmd[128];
11:   fread(cmd, 1, 256, fp);
12:   int header_ok = 0;
 .
 .
19:   url = cmd + 4;
20:   copy_lower(url, buf);
21:   printf("Location is %s\n", buf);
22:   return 0; }
```

```
23: /** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAA\x64\xf7\xff
\xffAAAA\xeb\x1f\x5e
\x89\x76\x08\x31\xc0\x88\x46\x46\x0c\xb0\x0b
\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb
\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\xff/bin/sh
```



OVERWRITE POINT!

0xbffff760	0x0804a008	fp
0xbffff75c	0x08048564	return address
0xbffff758	0x61616161	stack frame ptr
0xbffff74c	0x61616161	url
0xbffff748	0x61616161	header_ok
0xbffff744	0x61616161	buf[4]
0xbffff740	0x61616161	buf[3,2,1,0]
0xbffff73c	0x00000000	cmd[128,127,126,125
.	.	.
.	.	.
0xbffff7d8	0xffff764	cmd[25,26,27,28]
.	.	.
.	.	.
0xbffff6c4	0x41414141	cmd[7,6,5,4]
0xbffff6c0	0x20544547	cmd[3,2,1,0]
0xbffff6b4	0xbffff740	out
0xbffff6b0	0xbffff6c4	in
0xbffff6ac	0x080485a2	return address
0xbffff6a8	0xbffff758	stack frame ptr
0xbffff69c	0x00000019	i

(Unallocated)

Basic Stack Exploit

parse.c

BREAK

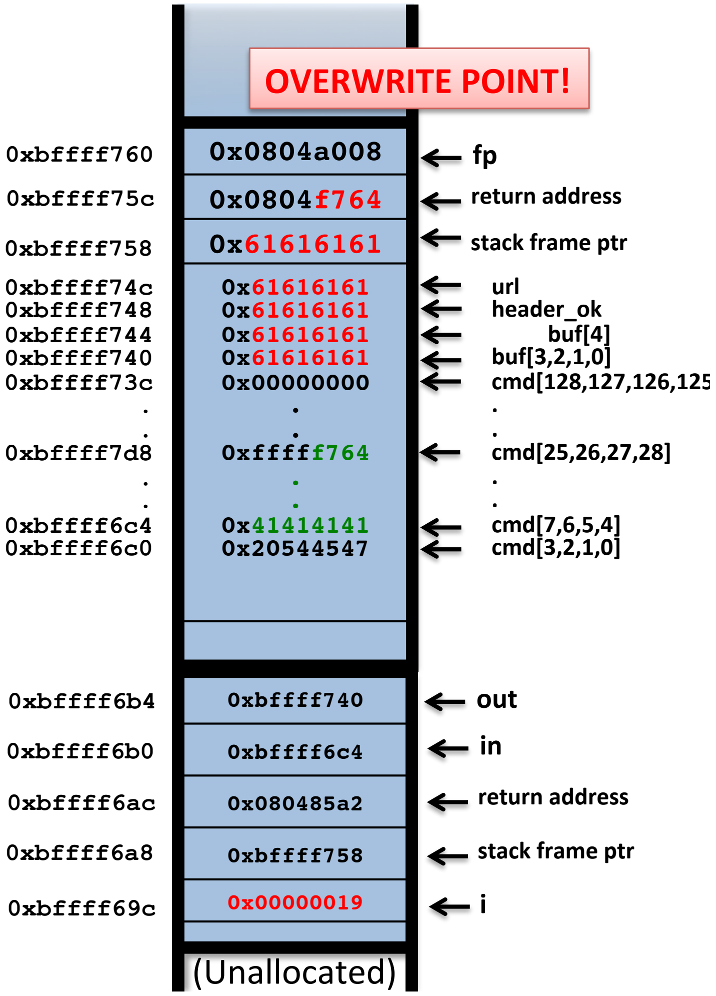
```
 1:void copy_lower (char* in, char* out) {
 2:   int i = 0;
 3:   while (in[i]!=‘\0’ && in[i]!='\n') {
 4:     out[i] = tolower(in[i]);
 5:     i++;
 6:   }
 7:   buf[i] = ‘\0’;
 8:}
```

```
 9:int parse(FILE *fp) {
10:   char buf[5], *url, cmd[128];
11:   fread(cmd, 1, 256, fp);
12:   int header_ok = 0;
 .
 .
19:   url = cmd + 4;
20:   copy_lower(url, buf);
21:   printf(“Location is %s\n”, buf);
22:   return 0; }
```

```
23: /** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAA\x64\xf7\xff
\xffAAAA\xeb\x1f\x5e
\x89\x76\x08\x31\xc0\x88\x46\x46\x0c\xb0\x0b
\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb
\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\xff/bin/sh
```



OVERWRITE POINT!

0xbffff760	0x0804a008	← fp
0xbffff75c	0x0804f764	← return address
0xbffff758	0x61616161	← stack frame ptr
0xbffff74c	0x61616161	← url
0xbffff748	0x61616161	← header_ok
0xbffff744	0x61616161	← buf[4]
0xbffff740	0x61616161	← buf[3,2,1,0]
0xbffff73c	0x00000000	← cmd[128,127,126,125
.	.	.
.	.	.
0xbffff7d8	0xfffff764	← cmd[25,26,27,28]
.	.	.
.	.	.
0xbffff6c4	0x41414141	← cmd[7,6,5,4]
0xbffff6c0	0x20544547	← cmd[3,2,1,0]
0xbffff6b4	0xbffff740	← out
0xbffff6b0	0xbffff6c4	← in
0xbffff6ac	0x080485a2	← return address
0xbffff6a8	0xbffff758	← stack frame ptr
0xbffff69c	0x00000019	← i

(Unallocated)

Basic Stack Exploit

parse.c

BREAK

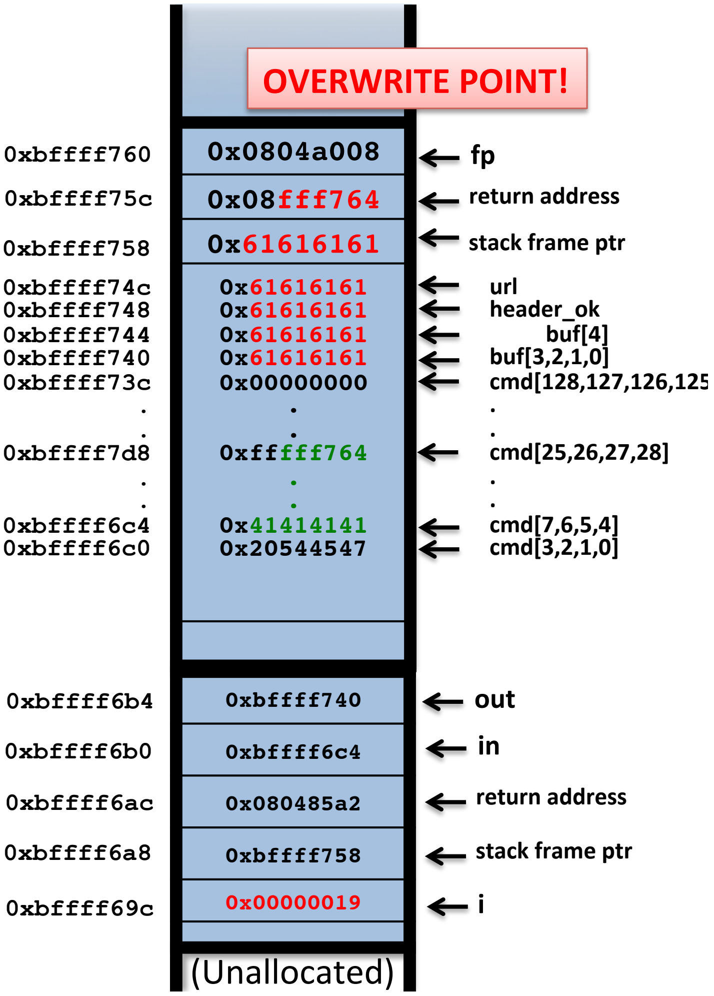
```
1:void copy_lower (char* in, char* out) {
2:   int i = 0;
3:   while (in[i]!=‘\0’ && in[i]!='\n') {
4:     out[i] = tolower(in[i]);
5:     i++;
6:   }
7:   buf[i] = ‘\0’;
8:}
```

```
 9:int parse(FILE *fp) {
10:   char buf[5], *url, cmd[128];
11:   fread(cmd, 1, 256, fp);
12:   int header_ok = 0;
.
.
.
19:   url = cmd + 4;
20:   copy_lower(url, buf);
21:   printf(“Location is %s\n”, buf);
22:   return 0; }
```

```
23: /** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAA\x64\xf7\xff
\xffAAAA\xeb\x1f\x5e
\x89\x76\x08\x31\xc0\x88\x46\x46\x0c\xb0\x0b
\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb
\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\xff/bin/sh
```



OVERWRITE POINT!

0xbffff760	0x0804a008	← fp
0xbffff75c	0x08fff764	← return address
0xbffff758	0x61616161	← stack frame ptr
0xbffff74c	0x61616161	← url
0xbffff748	0x61616161	← header_ok
0xbffff744	0x61616161	← buf[4]
0xbffff740	0x61616161	← buf[3,2,1,0]
0xbffff73c	0x00000000	← cmd[128,127,126,125
.	.	.
0xbffff7d8	0xfffff764	← cmd[25,26,27,28]
.	.	.
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0xbffff6c0	0x20544547	← cmd[3,2,1,0]
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0xbffff6b0	0xbffff6c4	← in
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Basic Stack Exploit

parse.c

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 6:   }
 7:   buf[i] = ‘\0’;
 8:}
```

```
 9:int parse(FILE *fp) {
10:   char buf[5], *url, cmd[128];
11:   fread(cmd, 1, 256, fp);
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\xffAAAA\xeb\x1f\x5e
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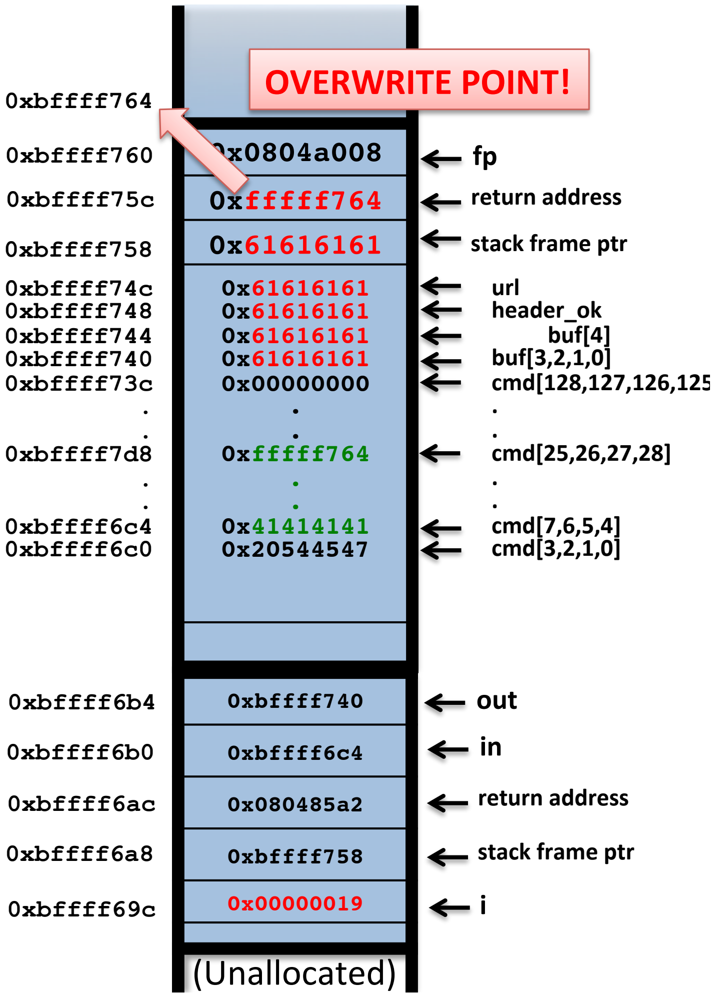
\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb
\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\xff/bin/sh
```



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0xbffff764		
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0xbffff748	0x61616161	← header_ok
0xbffff744	0x61616161	← buf[4]
0xbffff740	0x61616161	← buf[3,2,1,0]
0xbffff73c	0x00000000	← cmd[128,127,126,125
.	.	.
.	.	.
0xbffff7d8	0xffff764	← cmd[25,26,27,28]
.	.	.
.	.	.
0xbffff6c4	0x41414141	← cmd[7,6,5,4]
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Basic Stack Exploit

parse.c

BREAK

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 1:void copy_lower (char* in, char* out) {
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 6:   }
 7:   buf[i] = ‘\0’;
 8:}
```

BREAK

```
 9:int parse(FILE *fp) {
10:   char buf[5], *url, cmd[128];
11:   fread(cmd, 1, 256, fp);
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 .
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\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb
\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\xff/bin/sh
```
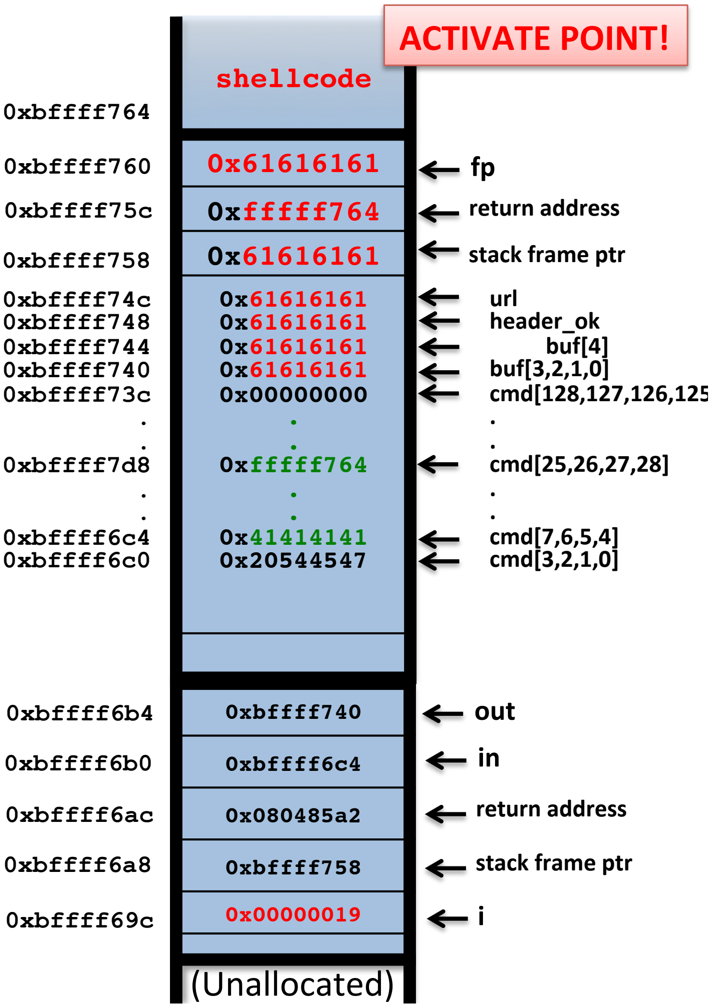



ACTIVATE POINT!

	shellcode	
0xbffff764		
0xbffff760	0x61616161	fp
0xbffff75c	0xffff764	return address
0xbffff758	0x61616161	stack frame ptr
0xbffff74c	0x61616161	url
0xbffff748	0x61616161	header_ok
0xbffff744	0x61616161	buf[4]
0xbffff740	0x61616161	buf[3,2,1,0]
0xbffff73c	0x00000000	cmd[128,127,126,125
.	.	.
.	.	
0xbffff7d8	0xffff764	cmd[25,26,27,28]
.	.	.
.	.	.
0xbffff6c4	0x41414141	cmd[7,6,5,4]
0xbffff6c0	0x20544547	cmd[3,2,1,0]
0xbffff6b4	0xbffff740	out
0xbffff6b0	0xbffff6c4	in
0xbffff6ac	0x080485a2	return address
0xbffff6a8	0xbffff758	stack frame ptr
0xbffff69c	0x00000019	i
	(Unallocated)	

Basic Stack Exploit

parse.c

BREAK

```
1:void copy_lower (char* in, char* out) {
2:  int i = 0;
    while (in[i]!='\0' && in[i]!='\n') {
4:    out[i] = tolower(in[i]);
5:    i++;
6:  }
7:  buf[i] = '\0';
8:}
```

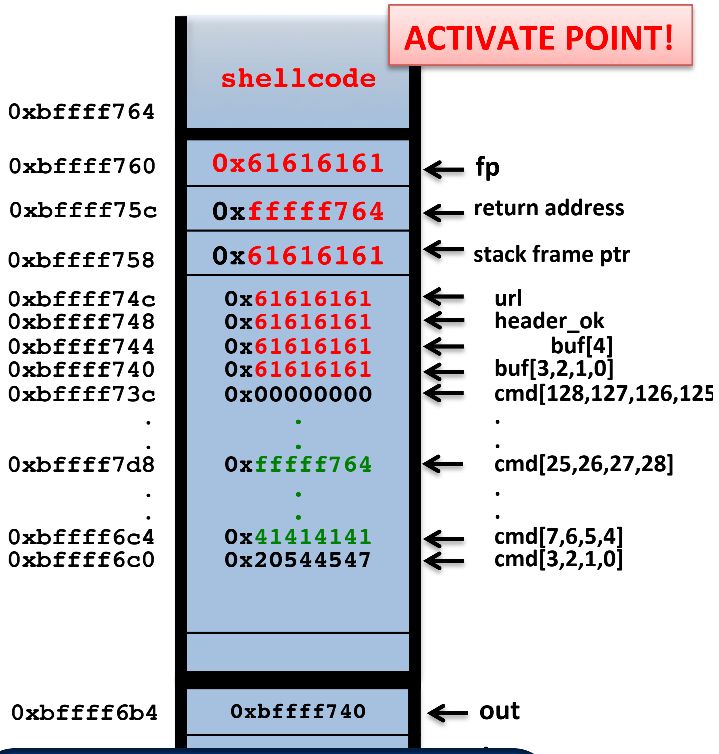
```
 9:int parse(FILE *fp) {
10:  char buf[5], *url, cmd[128];
11:  fread(cmd, 1, 256, fp);
12:  int header_ok = 0;
 .
 .
19:  url = cmd + 4;
20:  copy_lower(url, buf);
     printf("Location is %s\n", buf);
 2:  return 0; }
```

BREAK

```
23: /** main to load a file and run parse */
```

file (input file)

```
GET AAAAAAAAAAAAAAAAAAAAAAAA\x64\xf7\xff
\xffAAAA\xeb\x1f\x5e
\x89\x76\x08\x31\xc0\x88\x46\x46\x0c\xb0\x0b
\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb
\x89\xd8\x40\xcd\x80\xe8\xdc\xff\xff\xff/bin/sh
```



ACTIVATE POINT!

	shellcode	
0xbffff764		
0xbffff760	0x61616161	fp
0xbffff75c	0xffff764	return address
0xbffff758	0x61616161	stack frame ptr
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0xbffff748	0x61616161	header_ok
0xbffff744	0x61616161	buf[4]
0xbffff740	0x61616161	buf[3,2,1,0]
0xbffff73c	0x00000000	cmd[128,127,126,125
.	.	.
.	.	.
0xbffff7d8	0xffff764	cmd[25,26,27,28]
.	.	.
.	.	.
0xbffff6c4	0x41414141	cmd[7,6,5,4]
0xbffff6c0	0x20544547	cmd[3,2,1,0]
0xbffff6b4	0xbffff740	out

address

ame ptr

(unallocated)

user gets shell!

How to attack this code?

```
char buf[80];
void vulnerable() {
  int len = read_int_from_network();
  char *p = read_string_from_network();
  if (len > sizeof buf) {
    error(“length too large, nice try!”);
    return;
  }
  memcpy(buf, p, len);
}
```

How to attack this code?

```
char buf[80];
void vulnerable() {
  int len = read_int_from_network();
  char *p = read_string_from_network();
  if (len > sizeof buf) {
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    return;
  }
  memcpy(buf, p, len);
}
```

third argument expects an unsigned int

How to attack this code?

```
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void vulnerable() {
  int len = read_int_from_network();
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  if (len > sizeof buf) {
    error(“length too large, nice try!”);
    return;
  }
  memcpy(buf, p, len);
}
```

len is implicitly cast from int to unsigned int!

How to attack this code?

```
char buf[80];
void vulnerable() {
  int len = read_int_from_network();
  char *p = read_string_from_network();
  if (len > sizeof buf) {
    error(“length too large, nice try!”);
    return;
  }
  memcpy(buf, p, len);
}
```

provide a negative value for len

if statement is happy

but the cast makes a negative len a very large int! causing a buffer overflow…

Spot the bugs 3

```
#ifdef UNICODE
#define _sntprintf _snwprintf
#define TCHAR wchar_t
#else
#define _sntprintf _snprintf
#define TCHAR char
#endif

TCHAR buff[MAX_SIZE];
_sntprintf(buff, sizeof(buff), ”%s\n”, input);
```

Spot the bugs 3

```
#ifdef UNICODE
#define _sntprintf _snwprintf
#define TCHAR wchar_t
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#define _sntprintf _snprintf
#define TCHAR char
#endif

TCHAR buff[MAX_SIZE];
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```

_sntprintf’s 2nd argument is # of chars in buffer, not # of bytes

Spot the bugs 3

```
#ifdef UNICODE
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#define _sntprintf _snprintf
#define TCHAR char
#endif

TCHAR buff[MAX_SIZE];
_sntprintf(buff, sizeof(buff), ”%s\n”, input);
```

_sntprintf’s 2nd argument is # of chars in buffer, not # of bytes

The CodeRed worm exploited such an mismatch, where code written under the assumption that 1 char was 1 byte allowed buffer overflows after the move from ASCI to Unicode

From presentation by John Pincus

Stack/heap exploits

- Overwrite memory to contain your own code, or some library/shellcode of interest

- Not easy:
  - Have to determine return address (include NOP commands)
  - Overflow should not crash program before function exits
  - Shellcode may not contain '\0' causing string to end

- But very powerful:
  - Any code can be executed, eg. granting system access

- Bugs that make them possible are hard to spot!
  - *Avoid making input assumptions, be paranoid!*

Not unique to C/C++

- Memory safe languages such as Java can trigger buffer overflows, eg. due to graphic libraries relying on fast native code:

CVE reference: CVE-2007-0243, Release Date: 2007-01-17

Sun Java JRE GIF Image Processing Buffer Overflow Vulnerability

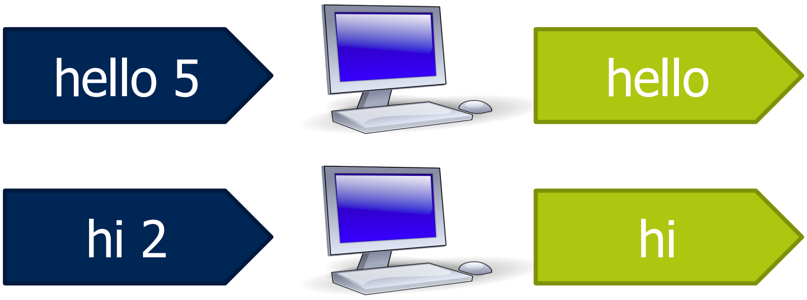
Critical: Highly critical, Impact: System access, Where: From remote

Description:

> *A vulnerability has been reported in Sun Java Runtime Environment (JRE), which can be exploited by malicious people to compromise a vulnerable system. The vulnerability is caused due to an error when processing GIF images and can be exploited to cause a heap-based buffer overflow via a specially crafted GIF image with an image width of 0.*
> *Successful exploitation allows execution of arbitrary* code.

What would you test?

- Testing a response system:



…

Spot the bug…

```
/* Read type and payload length first */
hbtype = *p++;
n2s(p, payload);
pl = p;
…
unsigned char *buffer, *bp; int r;
buffer = OPENSSL_malloc(1 + 2 + payload + padding);
bp = buffer;
…
*bp++ = TLS1_HB_RESPONSE;
s2n(payload, bp);
memcpy(bp, pl, payload);
r = ssl3_write_bytes(s, TLS1_RT_HEARTBEAT, buffer, 3 + payload + padding);
```

Missing bound check

```
/* Read type and payload length first */
hbtype = *p++;
n2s(p, payload);
pl = p;
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unsigned char *buffer, *bp; int r;
buffer = OPENSSL_malloc(1 + 2 + payload + padding);
bp = buffer;
…
*bp++ = TLS1_HB_RESPONSE;
s2n(payload, bp);
memcpy(bp, pl, payload);
r = ssl3_write_bytes(s, TLS1_RT_HEARTBEAT, buffer, 3 + payload + padding);
```

put payload length in payload,
pl is pointer to actual payload

Missing bound check

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/* Read type and payload length first */
hbtype = *p++;
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pl = p;
…
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allocate up to 65535+1+2+16 of memory

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```

put payload length in payload, pl is pointer to actual payload

allocate up to 65535+1+2+16 of memory

copy memory from pl pointer to bp pointer of length payload

Missing bound check

pl and payload are input and should not be trusted!

```
/* Read typ         ayload length first */
hbtype = *p++;
n2s(p, payload);
pl = p;
```

put payload length in payload, pl is pointer to actual payload

```
…
unsigned char *buffer, *bp; int r;
buffer = OPENSSL_malloc(1 + 2 + payload + padding);
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allocate up to 65535+1+2+16 of memory

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…
*bp++ = TLS1_HB_RESPONSE;
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memcpy(bp, pl, payload);
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```

copy memory from pl pointer to bp pointer of length payload

April 7, 2014: discovered that 2/3d of all web servers in world leak passwords. Programming oversight due to insufficient testing. #heartbleed #openssl

Who is to blame?

C/C++? – speed can be important

The OpenSSL developers? – a small group of volunteers with little funds

Vague specification? – should specifications cover all security bugs?

Functionality over security? – who uses heartbeat?

OpenSSL users? – billion dollar companies using free software without security audits…

April 7, 2014: discovered that 2/3d of all web servers in world leak passwords.
Programming oversight due to insufficient testing. #heartbleed #openssl

Another example, july 2015

slides from Joshua Drake

Spot the bug…

```
@@ -330,6 +330,10 @@ status_t SampleTable::setTimeToSampleParams
…
        mTimeToSampleCount = U32_AT(&header[4]);
        uint64_t allocSize = mTimeToSampleCount * 2 * sizeof(uint32_t);
        if (allocSize > SIZE_MAX) {
                return ERROR_OUT_OF_RANGE;
        }
        mTimeToSample = new uint32_t[mTimeToSampleCount * 2];
        size_t size = sizeof(uint32_t) * mTimeToSampleCount * 2;
…
```

Spot the bug…

in C, multiplying two 32-bit ints, gives a 32-bit int

```
@@ -330,6 +330,10 @@ status_t SampleTable::setTimeToS           ms
…
        mTimeToSampleCount = U32_AT(&header[4]);
        uint64_t allocSize = mTimeToSampleCount * 2 * sizeof(uint32_t);
        if (allocSize > SIZE_MAX) {
                return ERROR_OUT_OF_RANGE;
        }
        mTimeToSample = new uint32_t[mTimeToSampleCount * 2];
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```

Spot the bug…

in C, multiplying two 32-bit ints, gives a 32-bit int

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        uint64_t allocSize = mTimeToSampleCount * 2 * sizeof(uint32_t);
        if (allocSize > SIZE_MAX) {
                return ERROR_OUT_OF_RANGE;
        }
        mTi       ample = new uint32_t[mTimeToSampleCount * 2];
                   ze = sizeof(uint32_t) * mTimeToSampleCount * 2;
…
```

check for security problem does not work since upper 32-bits are not checked!

How bad is it? Worst exploit: MMS

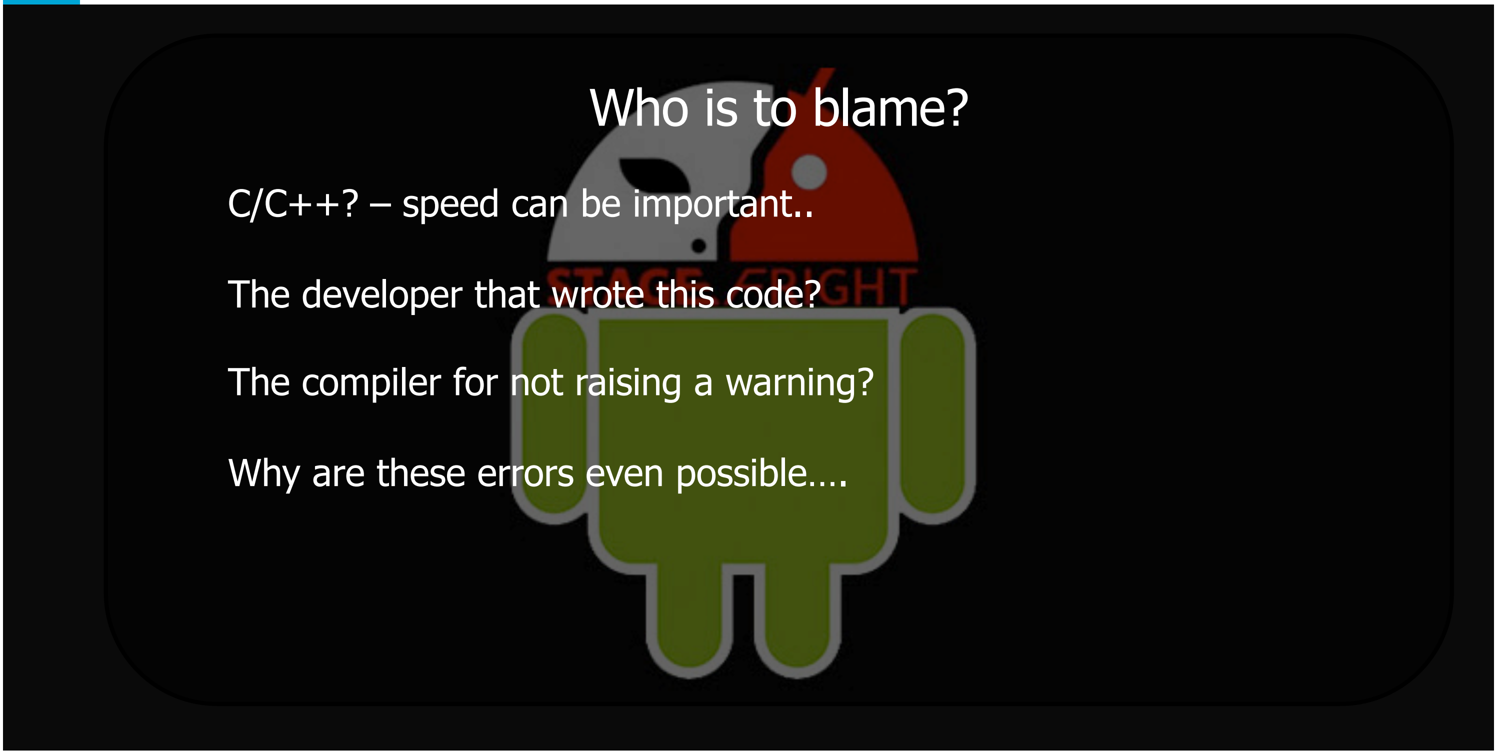
- Media is AUTOMATICALLY processed ON MMS RECEIPT.
- BEFORE creating a notification!
  - Actually, while creating the notification

- Exploiting a vulnerability in Stagefright via MMS could allow **SILENT, REMOTE, PRIVILEGED code execution.**

- The attacker's payload simply needs to prevent the notification.

- Who has your phone number?
  - ***When was the last time you updated your phone?***

Another example, july 2015



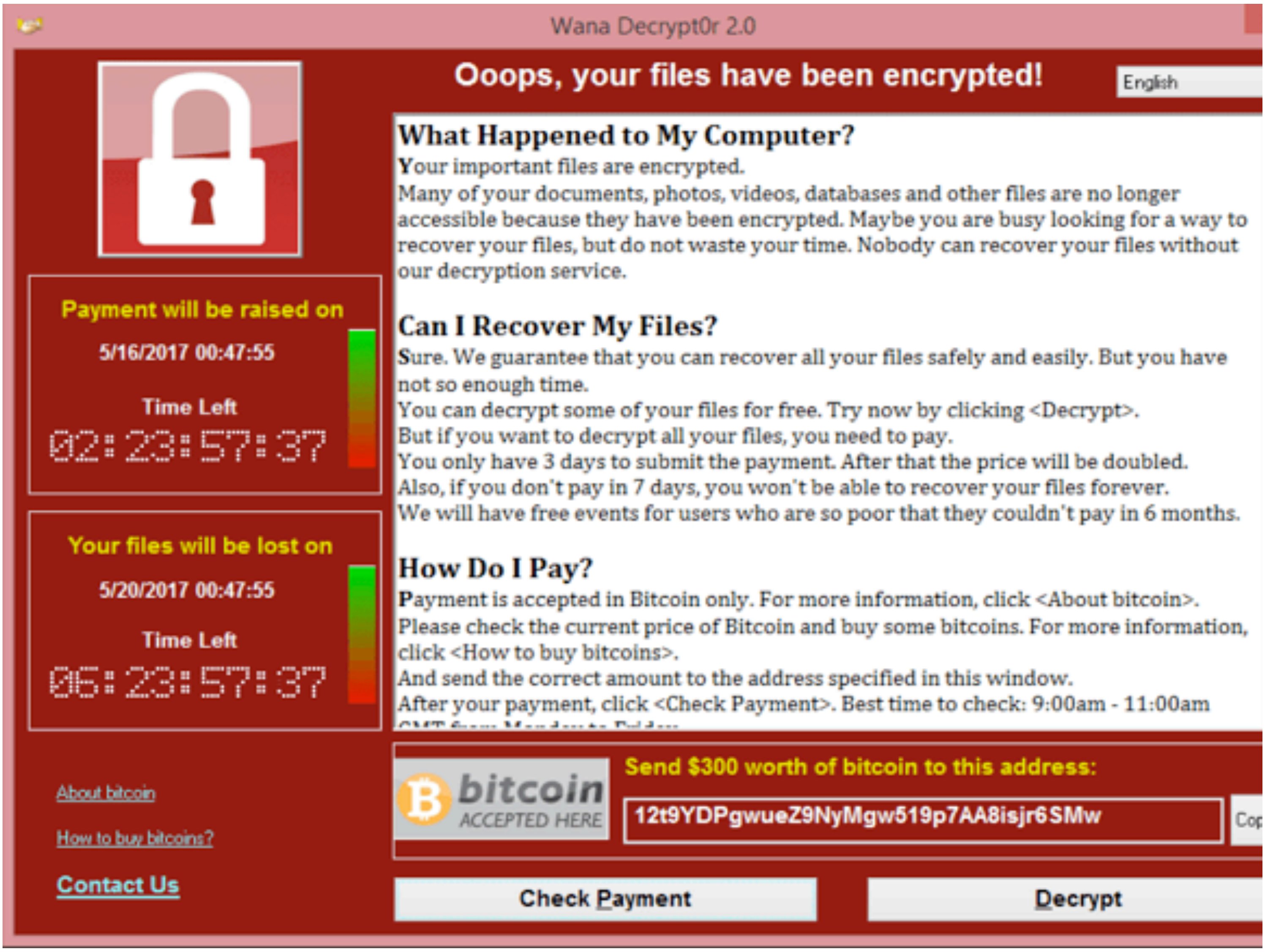
Who is to blame?

C/C++? – speed can be important..

The developer that wrote this code?

The compiler for not raising a warning?

Why are these errors even possible….



Ooops, your files have been encrypted!

Payment will be raised on
5/16/2017 00:47:55

Your files will be lost on
5/20/2017 00:47:55

What Happened to My Computer?

Your important files are encrypted.
Many of your documents, photos, videos, databases and other files are no longer accessible because they have been encrypted. Maybe you are busy looking for a way to recover your files, but do not waste your time. Nobody can recover your files without our decryption service.

Can I Recover My Files?

Sure. We guarantee that you can recover all your files safely and easily. But you have not so enough time.
You can decrypt some of your files for free. Try now by clicking <Decrypt>.
But if you want to decrypt all your files, you need to pay.
You only have 3 days to submit the payment. After that the price will be doubled.
Also, if you don't pay in 7 days, you won't be able to recover your files forever.
We will have free events for users who are so poor that they couldn't pay in 6 months.

How Do I Pay?

Payment is accepted in Bitcoin only. For more information, click <About bitcoin>.
Please check the current price of Bitcoin and buy some bitcoins. For more information, click <How to buy bitcoins>.
And send the correct amount to the address specified in this window.
After your payment, click <Check Payment>. Best time to check: 9:00am - 11:00am GMT from Monday to Friday.

Send $300 worth of bitcoin to this address:

12t9YDPgwueZ9NyMgw519p7AA8isjr6SMw

Spot the bug

```
int __stdcall SrvOs2FeaListSizeToNt(_DWORD *a1) {
    _WORD *v1; unsigned int v2; unsigned int v3; int v4; int v6;
    v1 = a1; v6 = 0;
    v2 = (unsigned int)a1 + *a1;
    v3 = (unsigned int)(a1 + 1);
    if ( (unsigned int)(a1 + 1) < v2 ) {
        while ( v3 + 4 < v2 ) {
            v4 = *(_WORD *)(v3 + 2) + *(_BYTE *)(v3 + 1);
            if ( v4 + v3 + 4 + 1 > v2 ) break;
            if ( RtlSizeTAdd(v6, (v4 + 12) & 0xFFFFFFFC, &v6) < 0 ) return 0;
            v3 += v4 + 5;
            if ( v3 >= v2 ) return v6;
            v1 = a1;
        }
    *v1 = (_WORD)(v3 - v1);
} return v6; }
```

Spot the bug

```
int __stdcall SrvOs2FeaListSizeToNt(_DWORD *a1) {
    _WORD *v1; unsigned int v2; unsigned int v3; int v4; int v6;
    v1 = a1; v6 = 0;
    v2 = (unsigned int)a1 + *a1;
    v3 = (unsigned int)(a1 + 1);
    if ( (unsigned int)(a1 + 1) < v2 ) {
        while ( v3 + 4 < v2 ) {
            v4 = *(_WORD *)(v3 + 2) + *(_BYTE *)(v3 + 1);
            if ( v4 + v3 + 4 + 1 > v2 ) break;
            if ( RtlSizeTAdd(v6, (v4 + 12) & 0xFFFFFFFC, &v6) < 0 ) return 0;
            v3 += v4 + 5;
```

puts a WORD (16 bits) into what is at address v1

```
    *v1 = (_WORD)(v3 - v1);
} return v6; }
```

Spot the bug

```
int __stdcall SrvO
    _WORD *v1; u
    v1 = a1; v6 
    v2 = (unsign
    v3 = (unsign
    if ( (unsign
        while ( v
            v4 = *(_WORD *)(v3 + 2) + *(_BYTE *)(v3 + 1);
            if ( v4 + v3 + 4 + 1 > v2 ) break;
            if ( RtlSizeTAdd(v6, (v4 + 12) & 0xFFFFFFFC, &v6) < 0 ) return 0;
            v3 += v4 + 5;
```

But *v1 is
SMB_FEA_LIST->SizeOfListInBytes
which is a DWORD (32 bits)

puts a WORD (16 bits) into what is at address v1

```
    *v1 = (_WORD)(v3 - v1);
} return v6; }
```

Spot the bug

```
int __stdcall SrvO
    _WORD *v1; u
    v1 = a1; v6
    v2 = (unsign
    v3 = (unsign
```

But *v1 is
SMB_FEA_LIST->SizeOfListInBytes

So if *v1 contains a large value 0x10000
and the assignment puts 0x0FFFF (MAX WORD) into it
the result is 0x1FFFF, instead of the intended 0x0FFFF

```
                                                                         urn 0;
            v3 += v4 + 5;
```

puts a WORD (16 bits) into what is at address v1

```
    *v1 = (_WORD)(v3 - v1);
} return v6; }
```

Spot the bug

```
int __stdcall SrvO
    _WORD *v1; u
    v1 = a1; v6
    v2 = (unsign
```

But *v1 is
SMB_FEA_LIST->SizeOfListInBytes

So if *v1 contains a large value 0x10000

and the
the res

When SMB_FEA_LIST->SizeOfListInBytes
with incorrect value is used in later code,
it can be used to create a **buffer overflow**,
and allows arbitrary code execution…

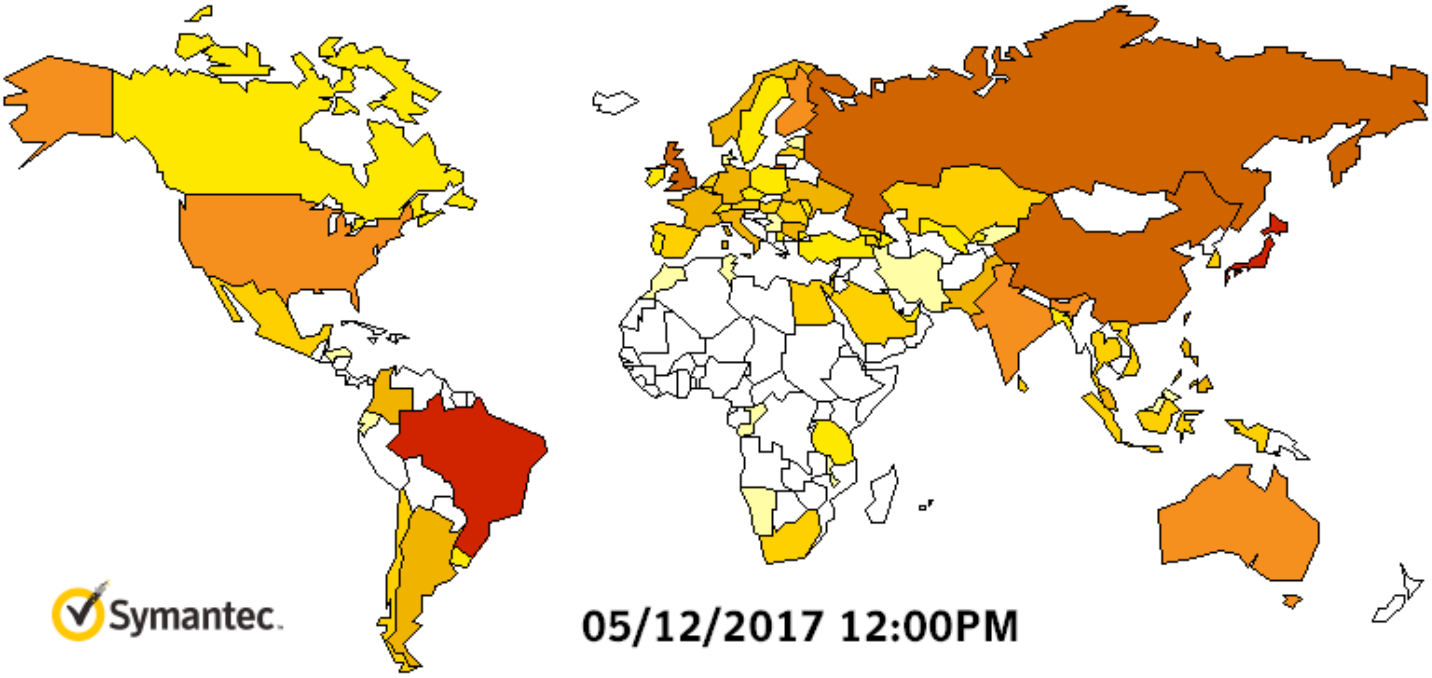
puts a WO

```
                                                                    0;

    *v1

} return v6; }
```

Spread all over the world in a day



Who is to blame?

- Simple arithmetic mistake
- In a function that is never used (legacy code)
- Who will test this thoroughly?
- But, from wikipedia:

“**EternalBlue**, sometimes stylized as **ETERNALBLUE**,[1] is an exploit generally believed to have been developed by the U.S. National Security Agency (NSA). It was leaked by the Shadow Brokers hacker group on April 14, 2017, and was used as part of the worldwide WannaCry ransomware attack on May 12, 2017.”

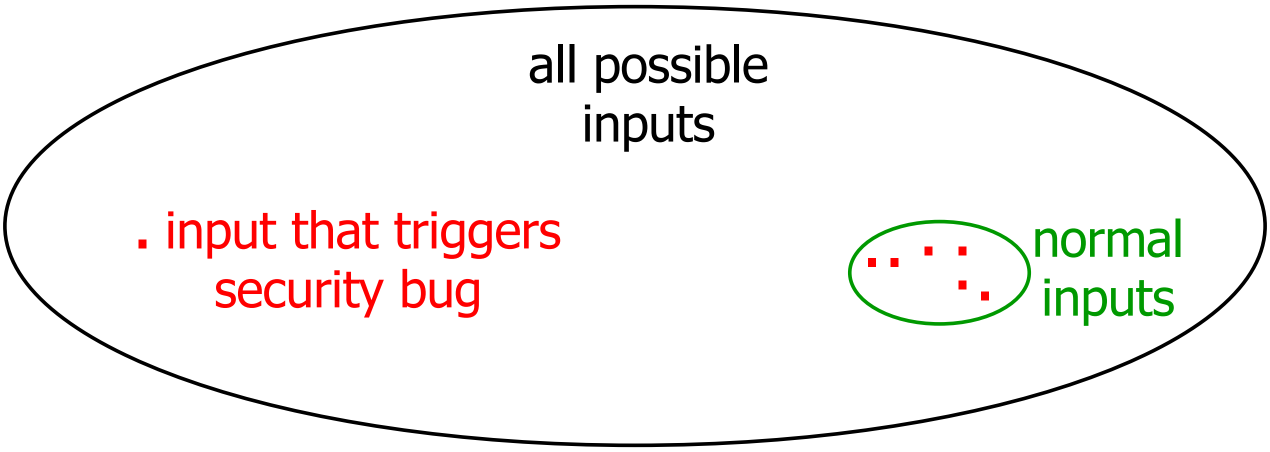
Security Testing

Security/penetration testing

- Normal testing investigates correct behavior for sensible inputs, and inputs on borderline conditions
- Security testing involves looking for the incorrect behavior for really silly inputs
- Try to crash the system!
  - and discover why it crashed!
- In general, this is very hard

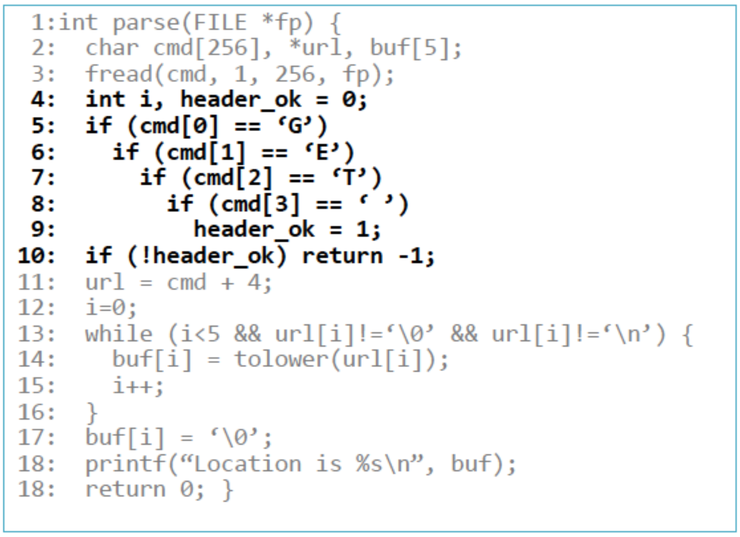
Why is it hard?

- Systems are (typically) not designed to crash, they work fine on most inputs
- Like finding a needle in a haystack:



Basic technique: random fuzzing

- Test different inputs at random, until the system crashes
- What is the probability of reaching line 11 with random input?



```
 1:int parse(FILE *fp) {
 2:  char cmd[256], *url, buf[5];
 3:  fread(cmd, 1, 256, fp);
 4:  int i, header_ok = 0;
 5:  if (cmd[0] == ‘G’)
 6:    if (cmd[1] == ‘E’)
 7:      if (cmd[2] == ‘T’)
 8:        if (cmd[3] == ‘ ’)
 9:          header_ok = 1;
10:  if (!header_ok) return -1;
11:  url = cmd + 4;
12:  i=0;
13:  while (i<5 && url[i]!=‘\0’ && url[i]!=‘\n’) {
14:    buf[i] = tolower(url[i]);
15:    i++;
16:  }
17:  buf[i] = ‘\0’;
18:  printf(“Location is %s\n”, buf);
18:  return 0; }
```

Structured input

- When input has to start with eg. ‘http’, testing all possible strings that start differently is a waste of time

- Fortunately, we often know:
  - Example input files or strings
  - Protocol specifications, or test implementations

- Solutions:
  - Generate random permutations from example files
    - Mutation-based fuzzing
  - Fuzz only values but keep in line with the specification
    - Protocol (generative) fuzzing

Mutation-based fuzzing example

1. Google for .pdf
2. Crawl pages to build a test set
3. Use mutation-based fuzzing tool (eg. ZZuf) or script:
   a) Load pdf file
   b) Mutate file (eg. randomly flipping bits, adding random chars)
   c) Feed to program
   d) Record if it crashed and what crashed it

A piece of cake, and it can find many real-world bugs!

Mutation-based fuzzing example 2

- Fuzzing with 5 lines of Python code:

```
numwrites = random.randrange(math.ceil((float(len(buf)) / FuzzFactor)))+1
for j in range(numwrites):
    rbyte = random.randrange(256)
    rn = random.randrange(len(buf))
    buf[rn] = "%c"%(rbyte)
```

- Given sufficient time/power this will crash your system!

Code by Charlie Miller

Example : GSM protocol fuzzing

- We can use an universal software radio peripheral (USRP) with open source cell tower software (OpenBTS)

to fuzz phones

[Mulliner et al, SMS of Death: from analyzing to attacking mobile phones on a large scale]

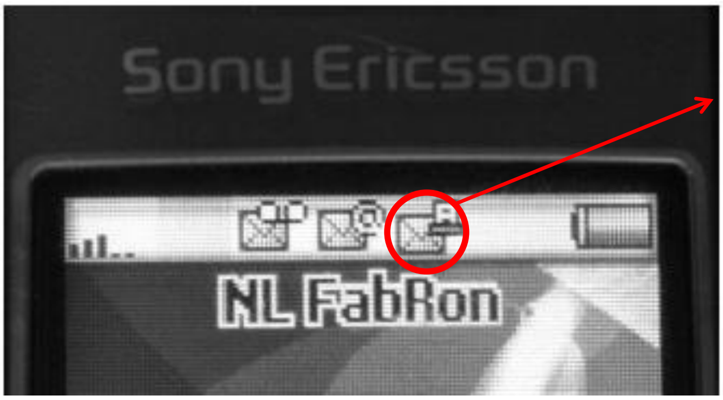
[Brinio Hond, Fuzzing the GSM protocol, MSc thesis, Radboud University]

Example : GSM protocol fuzzing

- Fuzzing SMS layer of GSM reveals weird functionality in GSM standard and on phones

Example : GSM protocol fuzzing

- Fuzzing SMS layer of GSM reveals weird functionality in GSM standard and on phones



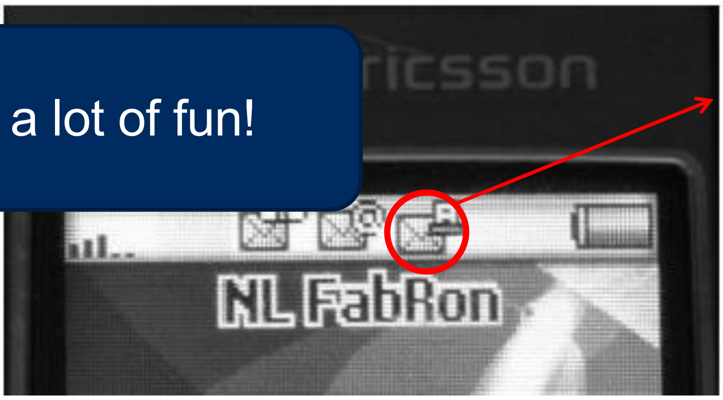
you have a fax!

eg possibility to send faxes (!?)

Only way to get rid if this icon: reboot the phone

Example : GSM protocol fuzzing

- Fuzzing SMS layer of GSM reveals weird functionality in GSM standard and on phones



Fuzzing is a lot of fun!

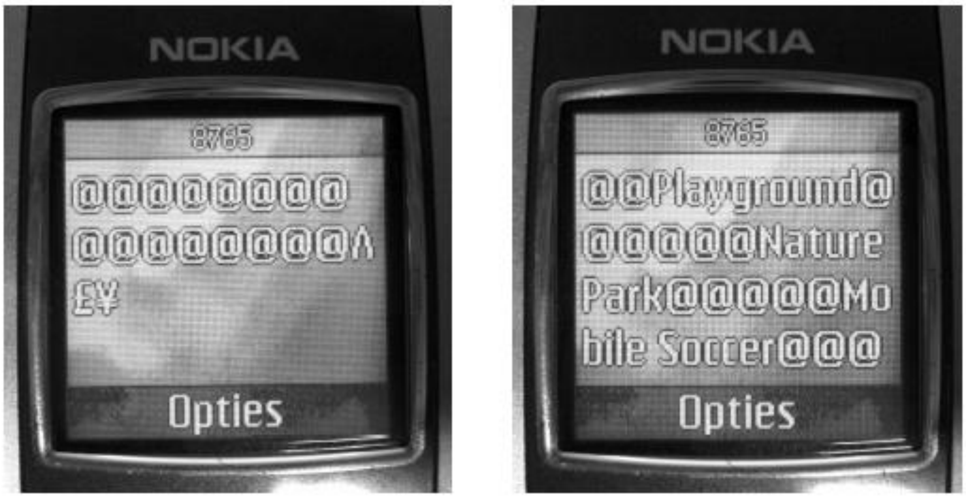
you have a fax!

eg possibility to send faxes (!?)

Only way to get rid if this icon: reboot the phone

Example : GSM protocol fuzzing

- More serious: malformed SMS text messages display raw memory content, rather than a text message



(a) Showing garbage

(b) Showing the name of a wallpaper and two games

AFL and ImageMagick

- AFL is a fast mutation-based fuzzer
  - http://lcamtuf.coredump.cx/afl/

- Azqa’s fuzzing video:
  - https://www.youtube.com/watch?v=ibjkz7GTT3I

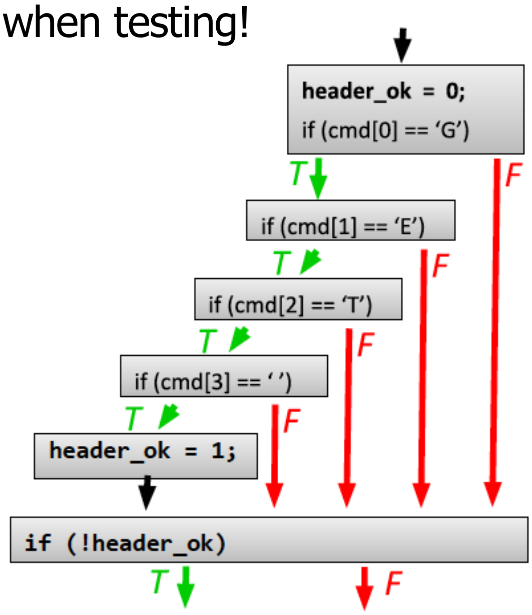
- More on:

https://imagetragick.com/

What other information is there?

- We have access the actual system code when testing!

```
int parse(FILE *fp) {
  char cmd[256], *url, buf[5];
  fread(cmd, 1, 256, fp);
  int i, header_ok = 0;
  if (cmd[0] == ‘G’)
    if (cmd[1] == ‘E’)
      if (cmd[2] == ‘T’)
        if (cmd[3] == ‘ ’)
          header_ok = 1;
  if (!header_ok) return -1;
  url = cmd + 4;
  i=0;
  while (i<5 && url[i]!=‘\0’ && url[i]!=‘\n’) {
    buf[i] = tolower(url[i]);
    i++;
  }
  buf[i] = ‘\0’;
  printf(“Location is %s\n”, buf);
  return 0; }
```



- Can we automatically generate interesting input values?

Code coverage

- Many fuzzing tests will result in the same behavior, to save time, use heuristics!
  - line coverage, statement coverage, branch coverage

- Statement coverage does not imply branch coverage:

```
void f(int x, y) { if (x>0) {y++}; y--; }
```

statement coverage needs 1 test case
branch coverage needs 2

Fuzzing heuristics

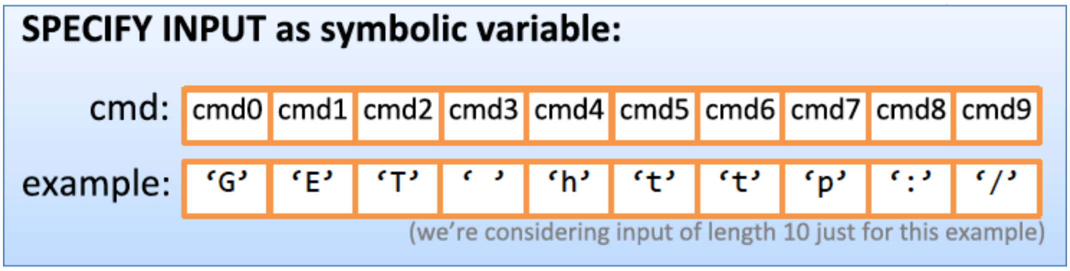
- To fuzz, you need to select an example input, and apply mutations

- Use code coverage to:
  - Not select an example with coverage identical to selected examples
  - Select examples that add new coverage
  - Apply mutations that led to more coverage
  - …

- Many fuzzing tools aim to generate new inputs that cover more code, but use different heuristics
  - *It pays off to try multiple tools!*

Path exploration

- Try to assignments to all values in cmd that make the program reach line 11:
  - Represent all values as symbolic variables
  - Write down a formula describing all paths through the program that reach line 11



SPECIFY INPUT as symbolic variable:

cmd:	cmd0	cmd1	cmd2	cmd3	cmd4	cmd5	cmd6	cmd7	cmd8	cmd9
example:	‘G’	‘E’	‘T’	‘ ’	‘h’	‘t’	‘t’	‘p’	‘:’	‘/’

(we’re considering input of length 10 just for this example)

Path exploration

SPECIFY INPUT:

cmd:	cmd0	cmd1	cmd2	cmd3	cmd4	cmd5	cmd6	cmd7	cmd8	cmd9

(we're considering input of length 10 just for this example)

SPECIFY PATH CONSTRAINTS:

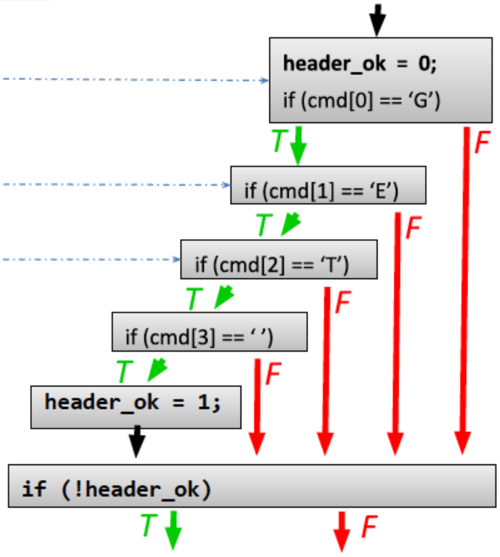
(cmd0 == 'G')

(cmd1 == 'E')

(cmd2 == 'T')

FINAL FORMULA:

(cmd0 == 'G') & (cmd1 == 'E') & (cmd2 == 'T') & (cmd3 == ' ')



Symbolic execution

- Represent all inputs as symbolic values and perform operations symbolically
  - cmd0, cmd1, …
- Path predicate: is there a value for command such that

  (cmd0 == ‘G’) & (cmd1 == ‘E’) & (cmd2 == ‘T’) & (cmd3 == ‘ ’) ?
- Provide all constraints to a combinatorial solver, eg. Z3
  - Answer: YES, with cmd0 = ‘G’, cmd1 = ‘E’, …, cmd9 = x
- *Only fuzz inputs that satisfy the provided answer!*

Symbolic execution, example

```
m(int x,y){
   x = x + y;
   y = y - x;
   if (2*y > 8) { ....
                }
   else if (3*x < 10){ ...
                     }
   }
```

Write down the path predicate needed to reach this line

Symbolic execution, example

```
m(int x,y){                // let x == N and y == M
   x = x + y;                  // x becomes N+M
   y = y - x;              // y becomes M-(N+M) == -N
   if (2*y > 8) {…      // taken if 2*-N > 8, ie N < -4
                }
   else if (3*x < 10){… // taken if N>=-4 and 3(M+N)<10
                     }
   }
```

So, (N>=-4) & 3(M+N)<10

Not always possible

```
m(function arg){
    a = 0
    call(arg)
    a = 1
}
```

To determine whether a will ever be 1, one needs to solve the Halting problem…

Not always possible

```
m(function arg){
    a = 0
    call(arg)
    a = 1
}
```

But used by Microsoft to find and prevent thousands of bugs in Windows!

check:
http://www.pexforfun.com

To determine whether a will ever be 1, one needs to solve the Halting problem…

Would security testing have found Heartbleed?

- The root cause is memory management, but it is not a standard buffer overflow since it reads memory instead of writes
- Why was it not discovered immediately?
  - Only manifests itself on malicious input, works fine normally
  - Does not cause a crash, reads memory from the same process
  - (strange) heartbeat requests are not logged
- Fuzzing will definitely trigger the bug, but since it does not crash, or leave a trace, *it is necessary to also test assertions/logic*

Would security testing have found Stagefright?

- **It did!**

- Using American Fuzzy Lop:
  - By Michal Zalewski “lcamtuf” (Google)
    - http://lcamtuf.coredump.cx/afl/

- Mutation based with genetic algorithm
  - Aims to maximize branch-coverage

- run for about 3 weeks, ~3200 tests per second
- *Total CPU hours was over 6 months!*

Would security testing have found WannaCry?

- **Probably not…**

- Requires the SMB server to be in a very specific state before the mistake occurs, and then it only leads to an error after additional steps…

- Fuzzers are not (yet) capable of testing this

- ***But the tools you learn in this course might be used for this purpose!***

Learning/Reversing

My research

- Traditional
  - code analysis and finding malware fingerprints
- Code/binary analysis is mostly manual and increasingly harder
  - Code obfuscation
  - Encryption
  - Self-modifying
- Behavior-based analysis is much harder to thwart
  - Bots need to communicate!

Learning (reverse-engineering)

- One last piece of information are all the examples that are tested while fuzzing, or collected from logs

- This form a big data set from which can be used to gain information about a system or protocol

This can help to

- analyze your own code and hunt for bugs, or
- reverse-engineer someone else’s unknown protocol, eg. a botnet, to fingerprint or to analyze (and attack) it

A simple state machine

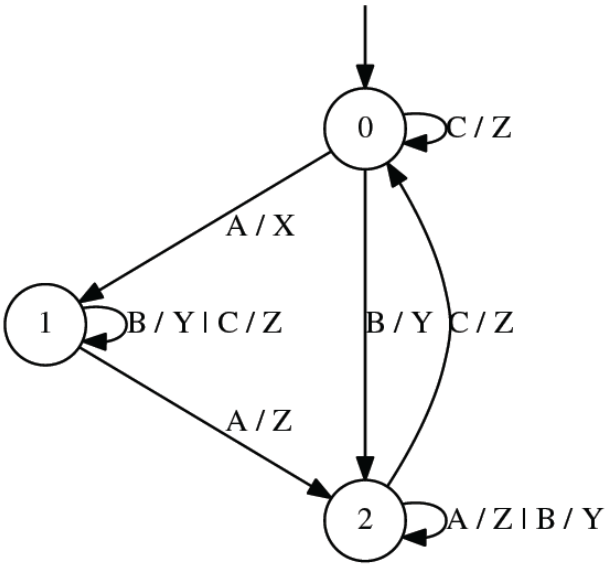
```
int current_state = 0;
char step(char input) {
  switch (current_state) {
    case 0:
      switch (input) {
        case 'A':
          current_state = 1;
          return 'X';
        case 'B':
          current_state = 2;
          return 'Y';
        case 'C':
          return 'Z';
        default:
          invalid_input();
      }
    case 1:
      switch (input) {
        case 'A':
          current_state = 3;
          return 'Z';
        case 'B':
          return 'Y';
        case 'C':
          return 'Z';
        default:
          invalid_input();
      }
    case 2:
      switch (input) {
        case 'A':
          return 'Z';
        case 'B':
          return 'Y';
        case 'C':
          current_state = 0;
          return 'Z';
        default:
          invalid_input();
      }
  }
  return 0;
}
```

The same code – *obfuscated*

```
l___2314 = o___11 != o___20 ? 7 : 10;
while (1) {
  switch (l___2314) {
    case 12:
      o___28(2, o___16);
      l___2314 = 11 - ((o___11 != o___20) + (o___11 !=
o___20));
      break;
    case 15:
      l___2305 = scanf((char const */* __restrict  */)
(o___19), &l___2303);
      l___2314 = 14 + !(o___11 == o___20);
      break;
    case 2:;
      l___2314 = (unsigned long) (o___20 != (struct t___8 *)
0UL)
          - (unsigned long) (o___11 == (struct t___8 *) 0UL);
      break;
    case 13:
      l___2306 = l___2307;
      l___2314 = 12 - ((o___20 == (struct t___8 *) 0UL)
          + (o___20 == (struct t___8 *) 0UL));
      break;
    case 1:
      o___13 = ((l___2304 & ~o___13) << 1) - (l___2304 ^
o___13);
      l___2314 = o___20 == (struct t___8 *) 0UL ? 8 : 8;
      break;
    case 3:
```

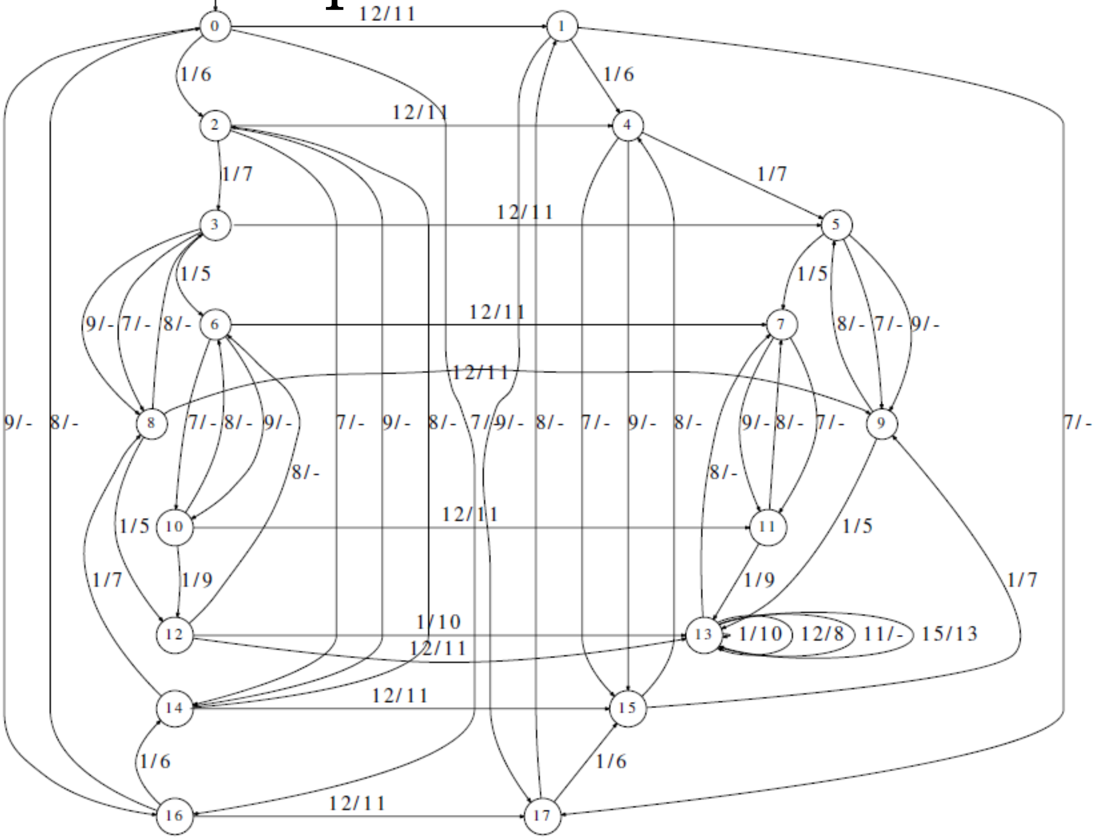
```
      l___2307 = o___12(l___2303);
      l___2314 = o___11 == (struct t___8 *) 0UL ? 13 &
l___2304 : 13;
      break;
    case 7:;
      if ((unsigned int) ((((l___2304
          - (-1 & (o___20 != (struct t___8 *) 0UL))
              * (-1 | (o___20 != (struct t___8 *) 0UL)))
          + (-0x7FFFFFFF - 1)) + (((l___2304
          - (-1 & (o___20 != (struct t___8 *) 0UL))
              * (-1 | (o___20 != (struct t___8 *) 0UL)))
          + (-0x7FFFFFFF - 1)) >> 31)) ^ (((l___2304
          - (-1 & (o___20 != (struct t___8 *) 0UL))
              * (-1 | (o___20 != (struct t___8 *) 0UL)))
          + (-0x7FFFFFFF - 1)) >> 31)) >> 31U) {
        l___2314 = o___20 == (struct t___8 *) 0UL ? 7 : 6;
      } else {
        l___2314 = o___20 != (struct t___8 *) 0UL ? 5 : 7;
      }
      break;
    // ...
  }
}
```

After learning



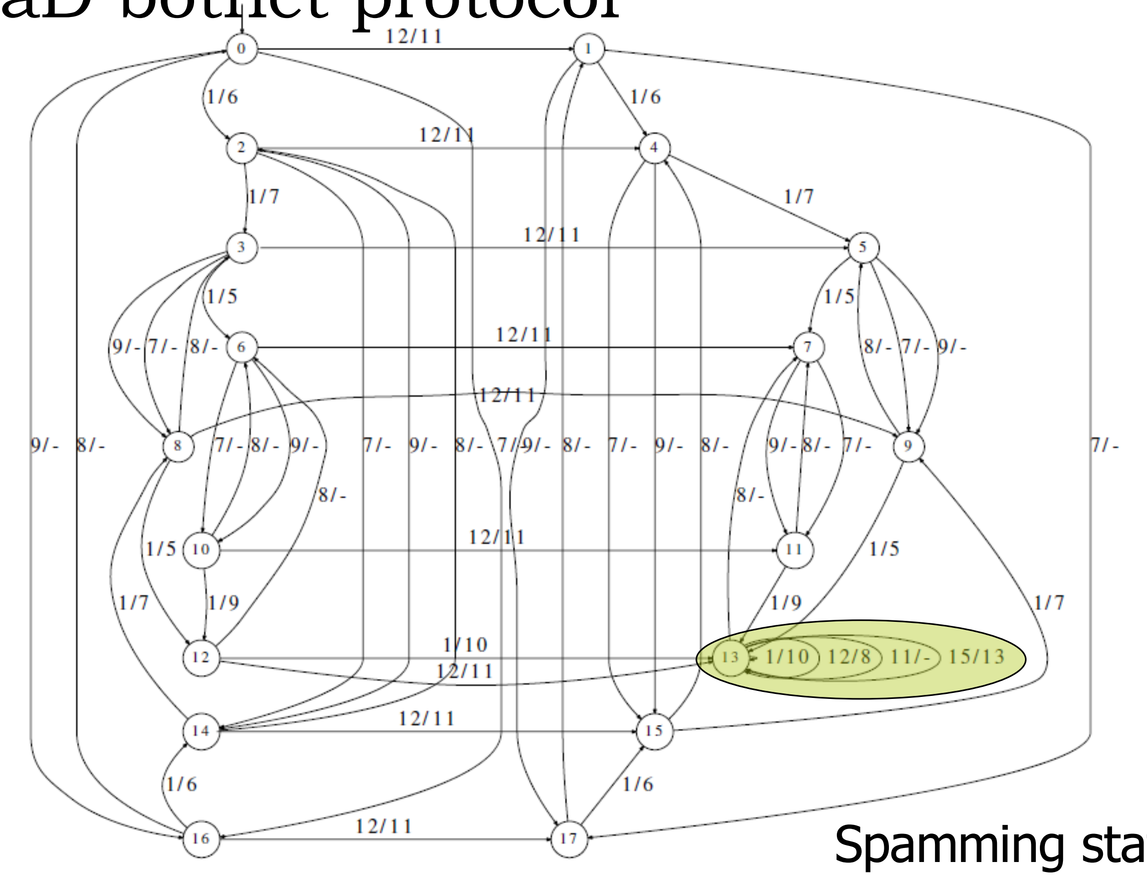
```
int current_state = 0;
char step(char input) {
  switch (current_state) {
    case 0:
      switch (input) {
        case 'A':
          current_state = 1;
          return 'X';
        case 'B':
          current_state = 2;
          return 'Y';
        case 'C':
          return 'Z';
        default:
          invalid_input();
      }
    case 1:
      switch (input) {
        case 'A':
          current_state = 3;
          return 'Z';
        case 'B':
          return 'Y';
        case 'C':
          return 'Z';
        default:
          invalid_input();
      }
    case 2:
      switch (input) {
        case 'A':
          return 'Z';
        case 'B':
          return 'Y';
        case 'C':
          current_state = 0;
          return 'Z';
        default:
          invalid_input();
      }
  }
  return 0;
}
```

MegaD botnet protocol



Cho et al. 2010

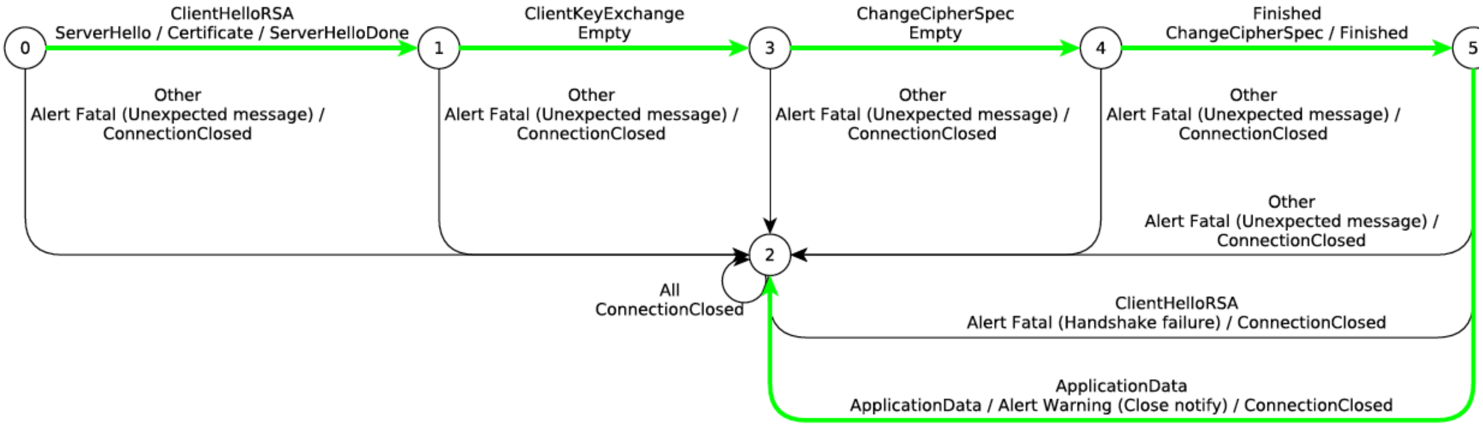
MegaD botnet protocol



Cho et al. 2010

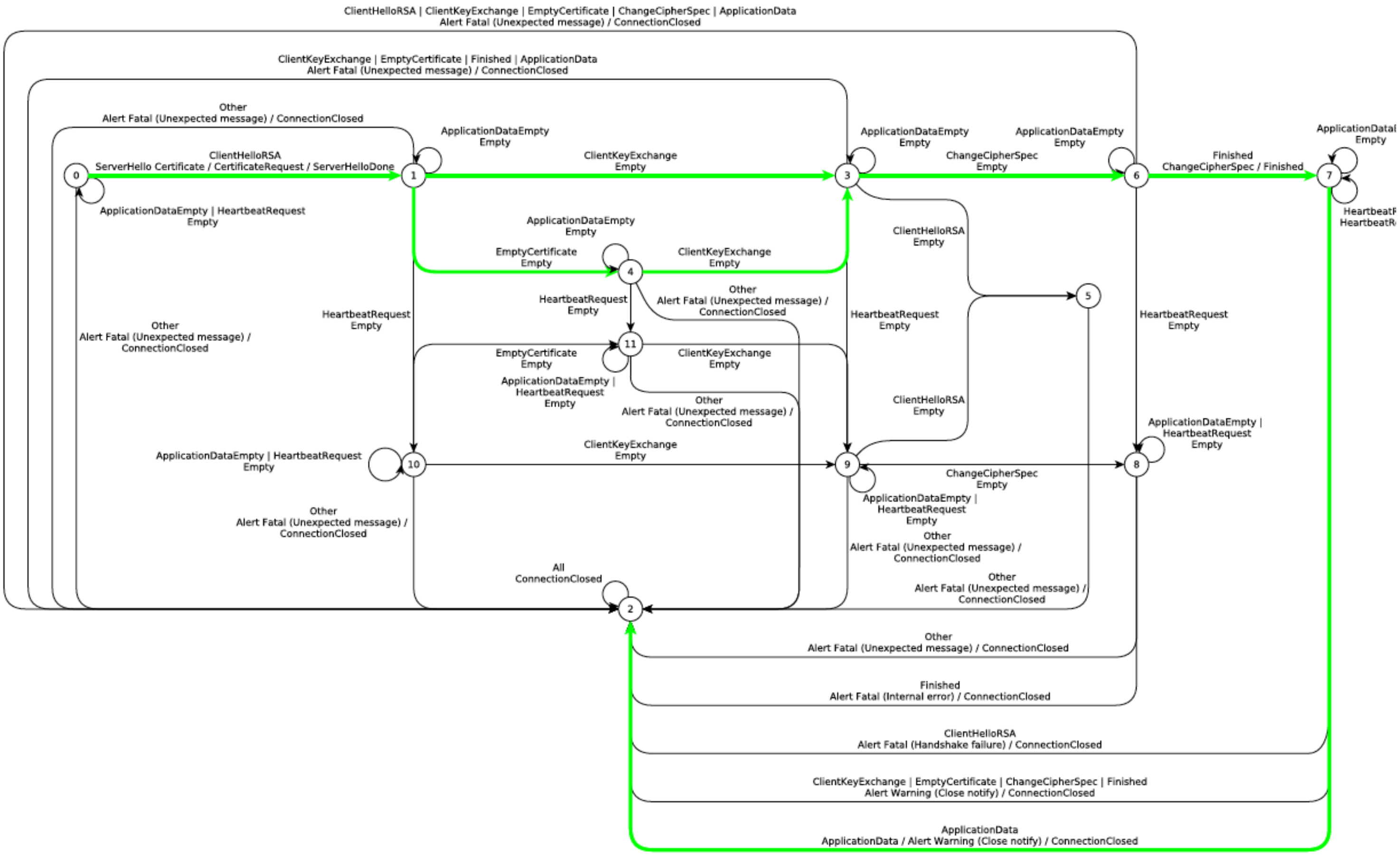
Spamming state

TLS RSA BSAFE


ClientHelloRSA
ServerHello / Certificate / ServerHelloDone
ClientKeyExchange
Empty
ChangeCipherSpec
Empty
Finished
ChangeCipherSpec / Finished
0
1
3
4
5
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
2
All
ConnectionClosed
ClientHelloRSA
Alert Fatal (Handshake failure) / ConnectionClosed
ApplicationData
ApplicationData / Alert Warning (Close notify) / ConnectionClosed

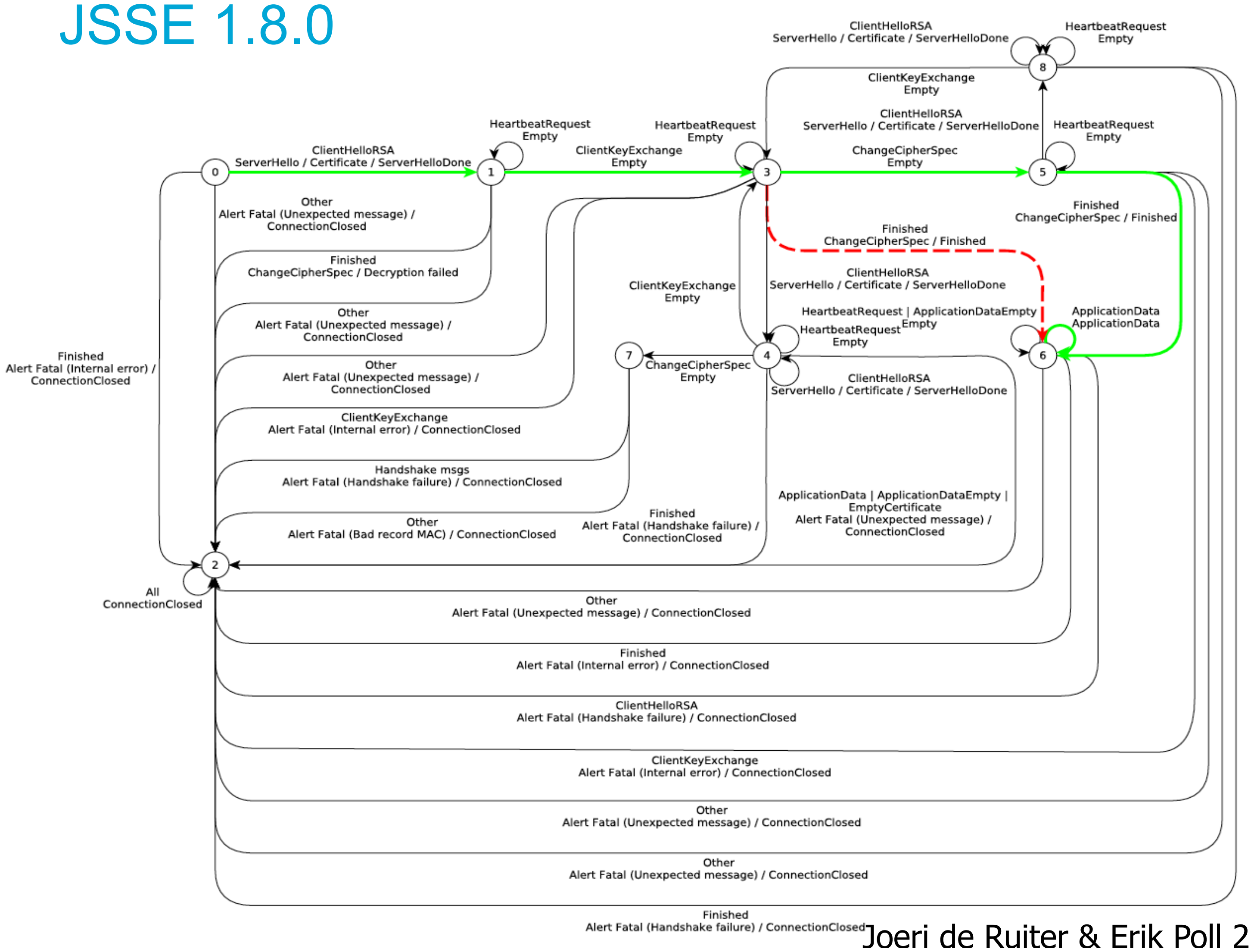
Joeri de Ruiter & Erik Poll 201

GNU TLS 3.3.8


ClientHelloRSA | ClientKeyExchange | EmptyCertificate | ChangeCipherSpec | ApplicationData
Alert Fatal (Unexpected message) / ConnectionClosed
ClientKeyExchange | EmptyCertificate | Finished | ApplicationData
Alert Fatal (Unexpected message) / ConnectionClosed
Other
Alert Fatal (Unexpected message) / ConnectionClosed
ApplicationDataEmpty
Empty
ClientHelloRSA
ServerHello Certificate / CertificateRequest / ServerHelloDone
0
1
ClientKeyExchange
Empty
3
ApplicationDataEmpty
Empty
ApplicationDataEmpty
Empty
ChangeCipherSpec
Empty
6
Finished
ChangeCipherSpec / Finished
7
ApplicationDataI
Empty
HeartbeatF
HeartbeatR
ApplicationDataEmpty | HeartbeatRequest
Empty
ApplicationDataEmpty
Empty
EmptyCertificate
Empty
4
ClientKeyExchange
Empty
ClientHelloRSA
Empty
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
5
HeartbeatRequest
Empty
HeartbeatRequest
Empty
HeartbeatRequest
Empty
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
HeartbeatRequest
Empty
11
EmptyCertificate
Empty
ClientKeyExchange
Empty
ApplicationDataEmpty |
HeartbeatRequest
Empty
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
ClientHelloRSA
Empty
ApplicationDataEmpty |
HeartbeatRequest
Empty
ApplicationDataEmpty | HeartbeatRequest
Empty
10
ClientKeyExchange
Empty
9
8
ChangeCipherSpec
Empty
ApplicationDataEmpty |
HeartbeatRequest
Empty
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
All
ConnectionClosed
2
Other
Alert Fatal (Unexpected message) / ConnectionClosed
Finished
Alert Fatal (Internal error) / ConnectionClosed
ClientHelloRSA
Alert Fatal (Handshake failure) / ConnectionClosed
ClientKeyExchange | EmptyCertificate | ChangeCipherSpec | Finished
Alert Warning (Close notify) / ConnectionClosed
ApplicationData
ApplicationData / Alert Warning (Close notify) / ConnectionClosed

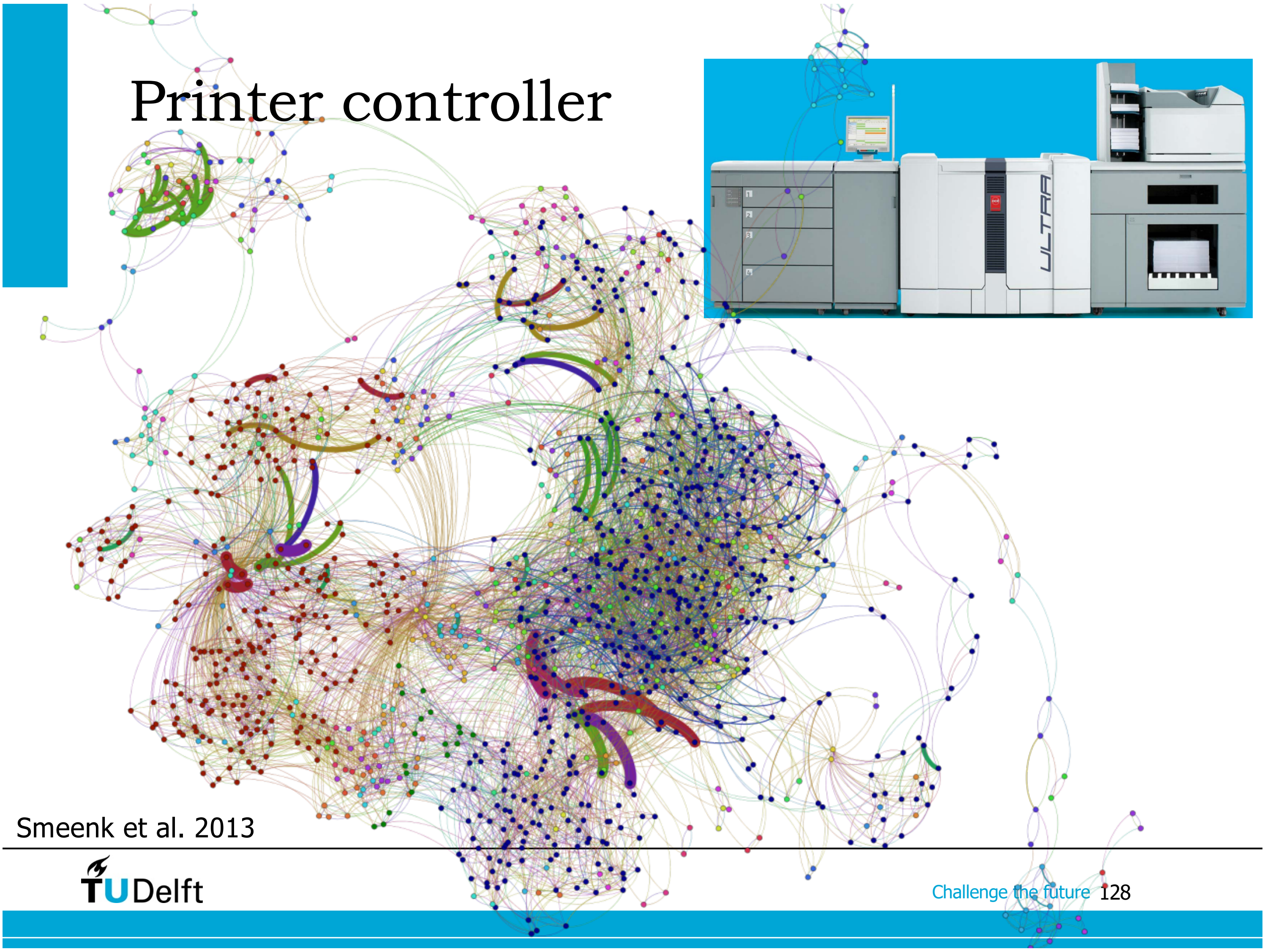
Joeri de Ruiter & Erik Poll 201

JSSE 1.8.0


0
1
2
3
4
5
6
7
8
ClientHelloRSA
ServerHello / Certificate / ServerHelloDone
HeartbeatRequest
Empty
ClientKeyExchange
Empty
HeartbeatRequest
Empty
ChangeCipherSpec
Empty
ClientHelloRSA
ServerHello / Certificate / ServerHelloDone
HeartbeatRequest
Empty
ClientKeyExchange
Empty
ClientHelloRSA
ServerHello / Certificate / ServerHelloDone
HeartbeatRequest
Empty
Finished
ChangeCipherSpec / Finished
Finished
ChangeCipherSpec / Finished
ClientKeyExchange
Empty
ClientHelloRSA
ServerHello / Certificate / ServerHelloDone
HeartbeatRequest | ApplicationDataEmpty
Empty
HeartbeatRequest
Empty
ApplicationData
ApplicationData
ChangeCipherSpec
Empty
ClientHelloRSA
ServerHello / Certificate / ServerHelloDone
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
Finished
ChangeCipherSpec / Decryption failed
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
Other
Alert Fatal (Unexpected message) /
ConnectionClosed
ClientKeyExchange
Alert Fatal (Internal error) / ConnectionClosed
Handshake msgs
Alert Fatal (Handshake failure) / ConnectionClosed
Other
Alert Fatal (Bad record MAC) / ConnectionClosed
Finished
Alert Fatal (Handshake failure) /
ConnectionClosed
ApplicationData | ApplicationDataEmpty |
EmptyCertificate
Alert Fatal (Unexpected message) /
ConnectionClosed
Finished
Alert Fatal (Internal error) /
ConnectionClosed
All
ConnectionClosed
Other
Alert Fatal (Unexpected message) / ConnectionClosed
Finished
Alert Fatal (Internal error) / ConnectionClosed
ClientHelloRSA
Alert Fatal (Handshake failure) / ConnectionClosed
ClientKeyExchange
Alert Fatal (Internal error) / ConnectionClosed
Other
Alert Fatal (Unexpected message) / ConnectionClosed
Other
Alert Fatal (Unexpected message) / ConnectionClosed
Finished
Alert Fatal (Handshake failure) / ConnectionClosed

Joeri de Ruiter & Erik Poll 201

Printer controller



Smeenk et al. 2013

Main messages

1. Be careful when programming in C(++)!
2. Never make input assumptions!
3. Test your software for unusual input!
4. Use tools to automate testing!
5. Keep your system up-to-date!

and understand WHY…