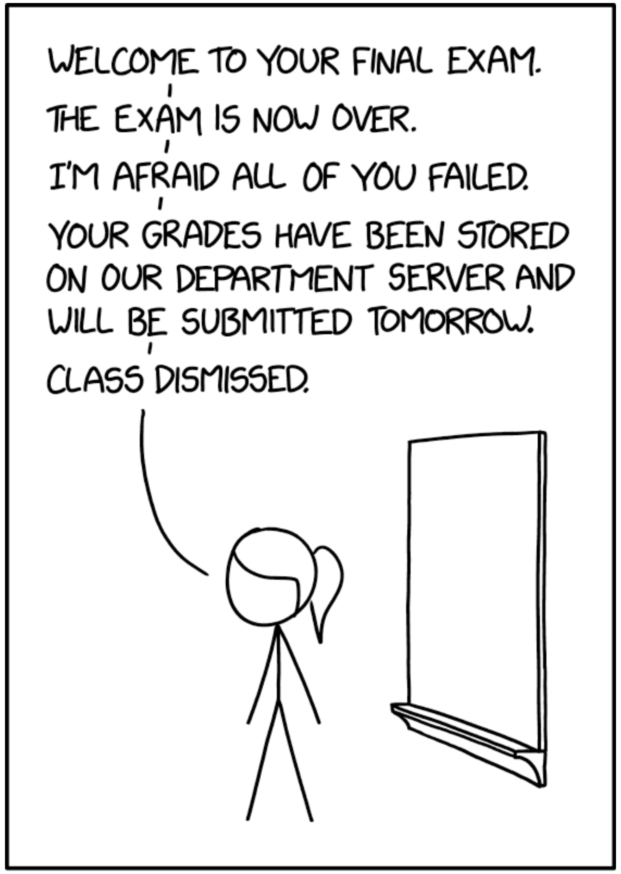
COS 217: Introduction to Programming Systems

Buffer Overrun Vulnerabilities and Assignment 6 (The ‘B’ Attack)


WELCOME TO YOUR FINAL EXAM.
THE EXAM IS NOW OVER.
I'M AFRAID ALL OF YOU FAILED.
YOUR GRADES HAVE BEEN STORED ON OUR DEPARTMENT SERVER AND WILL BE SUBMITTED TOMORROW.
CLASS DISMISSED.

CYBERSECURITY FINAL EXAMS

xkcd.com/2385

PRINCETON UNIVERSITY

Yet another character reading loop program …

```c
#include <stdio.h>
int main(void)
{
   char name[12], c;
   int i = 0, magic = 42;
   printf("What is your name?\n");
   while ((c = getchar()) != '\n')
      name[i++] = c;
   name[i] = '\0';
   printf("Thank you, %s.\n", name);
   printf("The answer to life, the universe, "
          "and everything is %d\n", magic);
   return 0;
}
```

```
$ ./a.out
  What is your name?
  John Smith
  Thank you, John Smith.
  The answer to life, the universe, and everything is 42
```

@grakozy

A Reason Why People With Long Names Can’t Have Nice Thin

```
#include <stdio.h>
int main(void)
{
   char name[12], c;
   int i = 0, magic = 42;
   printf("What is your name?\n");
   while ((c = getchar()) != '\n')
      name[i++] = c;
   name[i] = '\0';
   printf("Thank you, %s.\n", name);
   printf("The answer to life, the universe, "
          "and everything is %d\n", magic);
   return 0;
}
```

THE PROSPECT

Hello, my name is...

José Pablo Fernández García / The Daily Princetonian

José Pablo Fernández García

November 28, 2022 | 11:39pm EST

```
$ ./a.out
  What is your name?
  Christopher Moretti
  Thank you, Christopher Mor
  tti.
  The answer to life, the universe, and everything is 6911092
```

?

??? (!)

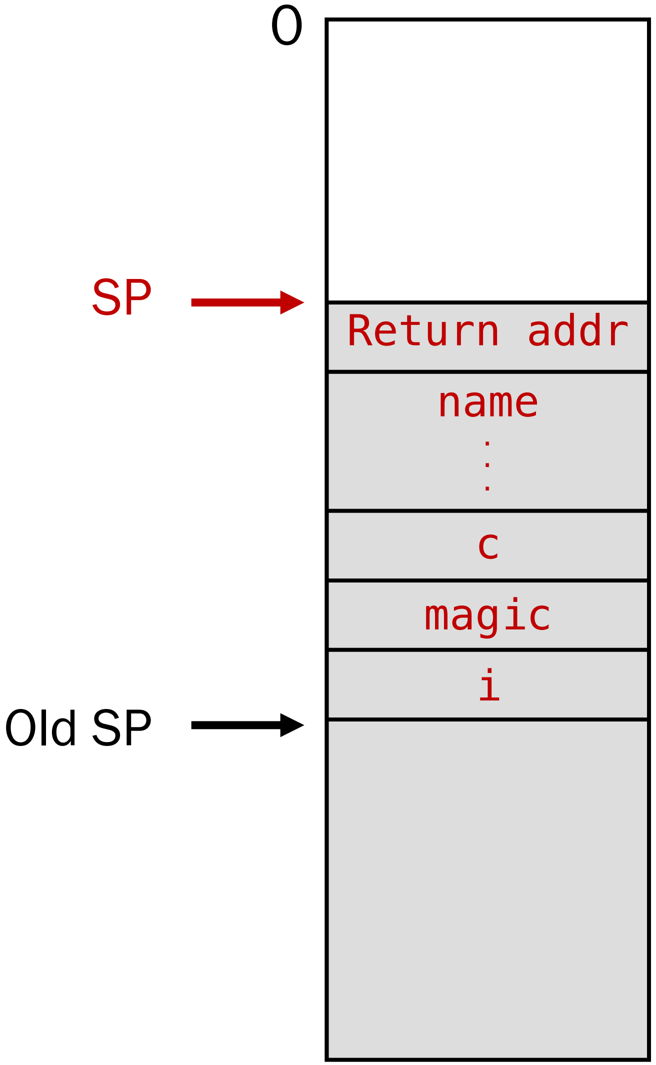
(Note: this is just the number that’s actually printed when you run the code. It’s not an attempt to Easter egg a phone number or anything like that. Please don’t try to call it. Doing so almost certainly won't give you the answer to life, the universe, and everything.)

Explanation: Stack Frame Layout

When there are too many characters, program carelessly writes beyond space “belonging” to name.

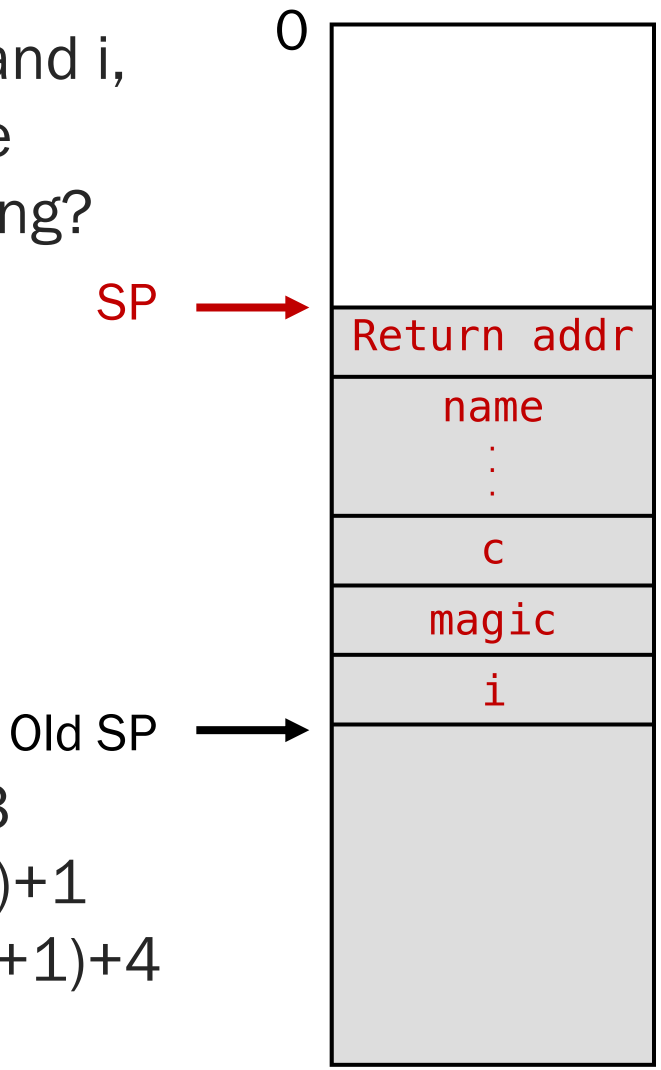
- Overwrites other variables
- This is a *buffer overrun*, or *stack smash*
- The program has a security bug!

```
#include <stdio.h>
int main(void)
{
   char name[12], c;
   int i = 0, magic = 42;
   printf("What is your name?\n");
   while ((c = getchar()) != '\n')
      name[i++] = c;
   name[i] = '\0';
   printf("Thank you, %s.\n", name);
   printf("The answer to life, the universe, "
          "and everything is %d\n", magic);
   return 0;
}
```



We’re offset and running

What are the offsets from sp of name[0], c, magic, and i, assuming they are stored in the order you see at the right, and that the .s each represent 1 byte of padding?



A. 0, 12, 13, 17

B. 8, 20, 21, 25

C. 8, 23, 24, 28

D. 8, 24, 28, 32

C.

X30: SP+0

name: SP+8

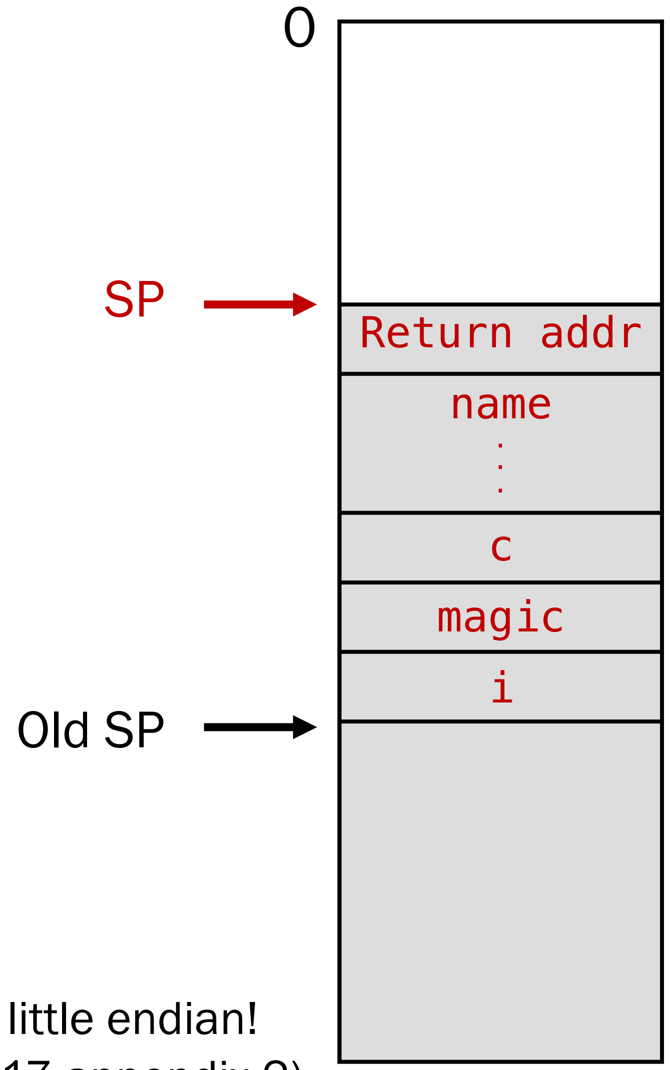
c: (SP+8)+12+3

magic: (SP+8+12+3)+1

i: (SP+8+12+3+1)+4

Example Trace

```
#include <stdio.h>
int main(void)
{
   char name[12], c;
   int i = 0, magic = 42;
   printf("What is your name?\n");
   while ((c = getchar()) != '\n')
      name[i++] = c;
   name[i] = '\0';
   printf("Thank you, %s.\n", name);
   printf("The answer to life, the universe, "
          "and everything is %d\n", magic);
   return 0;
}
```



`Christopher`$_s$ (not `\0` terminated) in `name[0]–name[11]`
`Mor` in 3 padding bytes before `c`, effectively: `name[12]–name[14]`

Each letter from `getchar` updates `c` , until `c` becomes `‘\n’`.
(It is also overwritten once by `name[i++] = c`,
when `i` is 15 and `c` is `‘e’` because `&c==&(name[15])`)

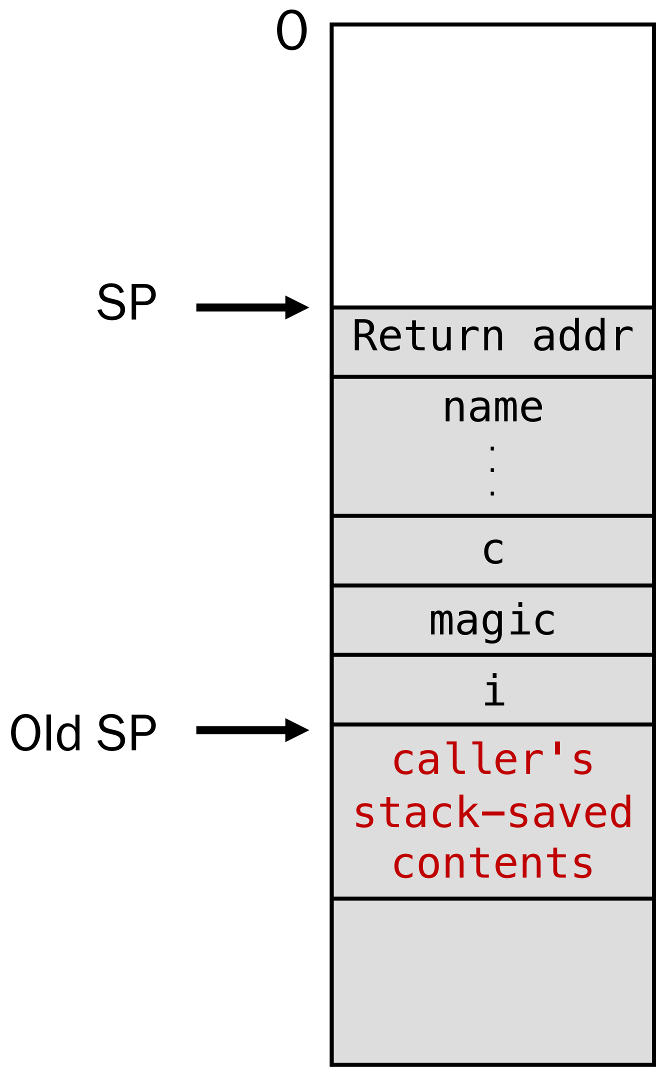
First `'t'` overwrites 42 with `0x74` (`‘t’`) (2 high-order bytes still `0`)
Second `'t'` makes `magic 29812` (2 high-order bytes still `0`)
Final `'i'` makes `magic 6911092` (1 high-order byte still `0`)

little endian!
(L17 appendix 2)

It Gets Worse...

Buffer overrun can overwrite onto its caller function's stack frame!

```
#include <stdio.h>
int callee(void)
{
   char name[12], c;
   int i = 0, magic = 42;
   printf("What is your name?\n");
   while ((c = getchar()) != '\n')
      name[i++] = c;
   name[i] = '\0';
   printf("Thank you, %s.\n", name);
   printf("The answer to life, the universe, "
          "and everything is %d\n", magic);
   return 0;
}
```



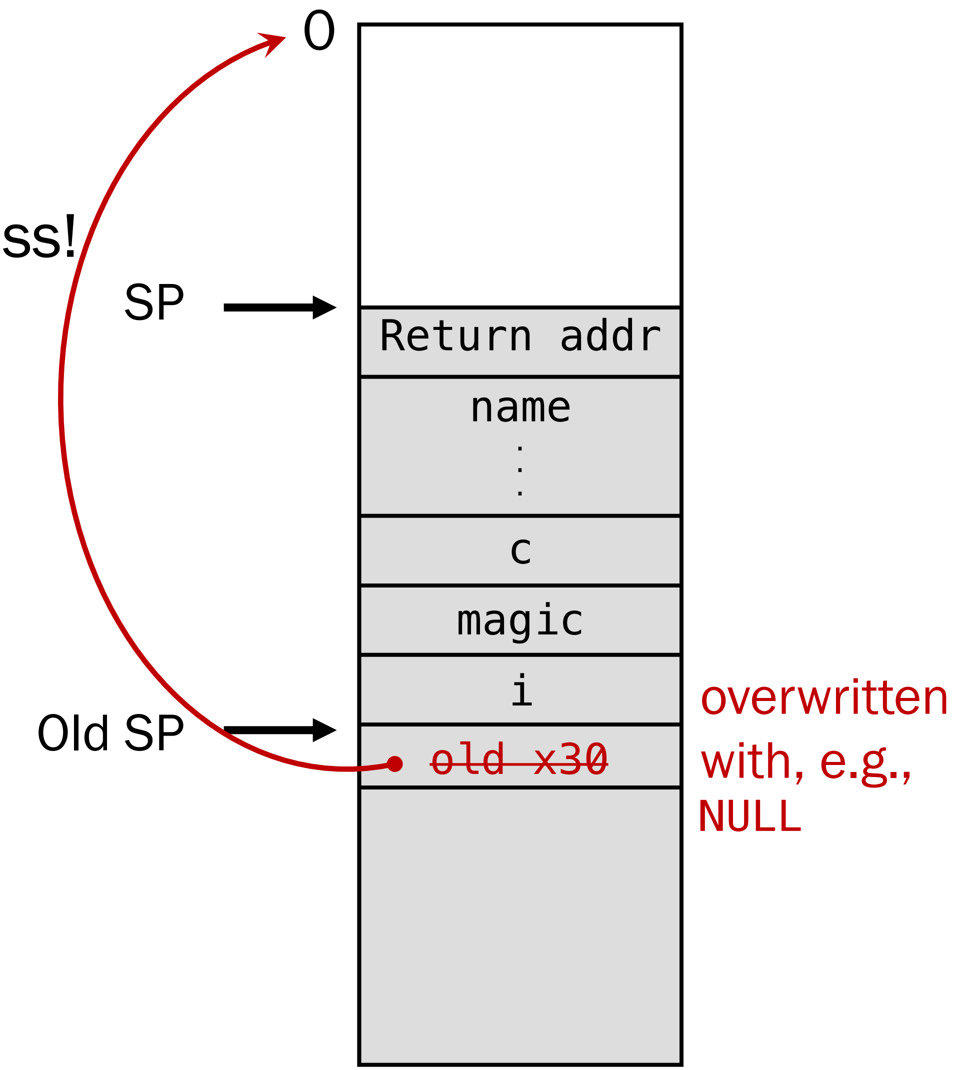
It Gets Even Worse...

And somewhere on caller's stack frame is the saved return address for that function ...

Buffer overrun can overwrite caller's return address!

- Replacement value can be an invalid address, leading to a segfault.

```
#include <stdio.h>
int callee(void)
{
   char name[12], c;
   int i = 0, magic = 42;
   printf("What is your name?\n");
   while ((c = getchar()) != '\n')
      name[i++] = c;
   name[i] = '\0';
   printf("Thank you, %s.\n", name);
   printf("The answer to life, the universe, "
          "and everything is %d\n", magic);
   return 0;
}
```



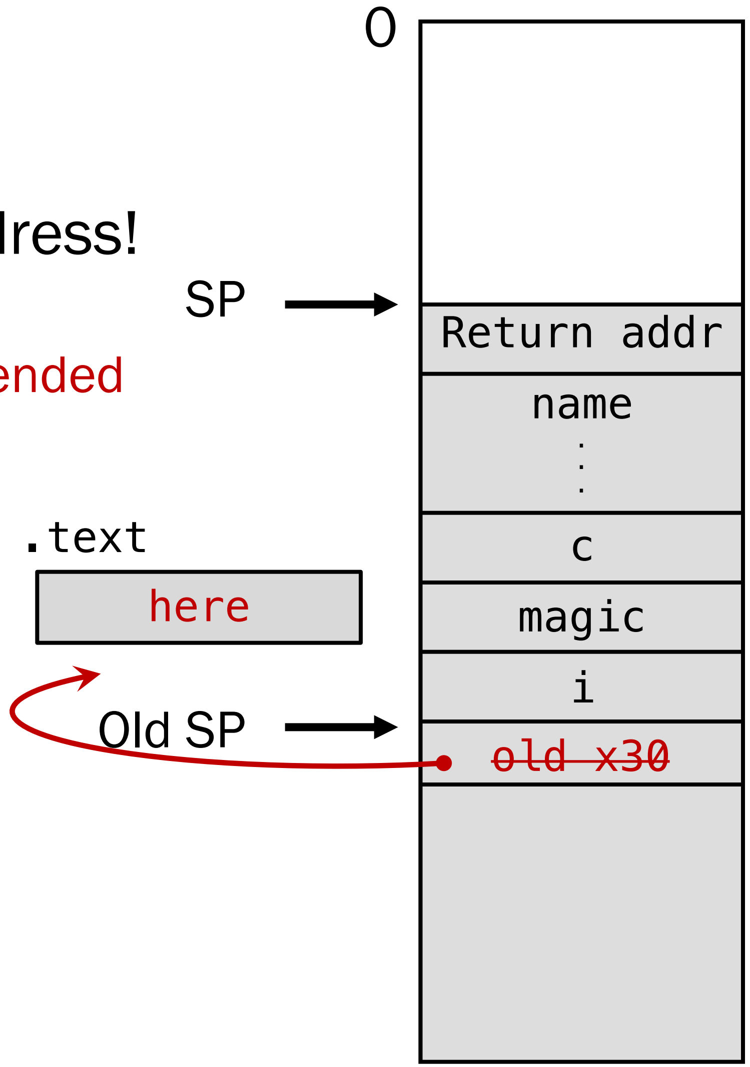
It Gets Much Worse…

And somewhere on caller's stack frame is the saved return address for that function …

Buffer overrun can overwrite caller's return address!

- Replacement value can be an invalid address, leading to a segfault, or it can cleverly cause unintended control flow!

```
#include <stdio.h>
int callee(void)
{
   char name[12], c;
   int i = 0, magic = 42;
   printf("What is your name?\n");
   while ((c = getchar()) != '\n')
      name[i++] = c;
   name[i] = '\0';
   printf("Thank you, %s.\n", name);
   printf("The answer to life, the universe, "
          "and everything is %d\n", magic);
   return 0;
}
```



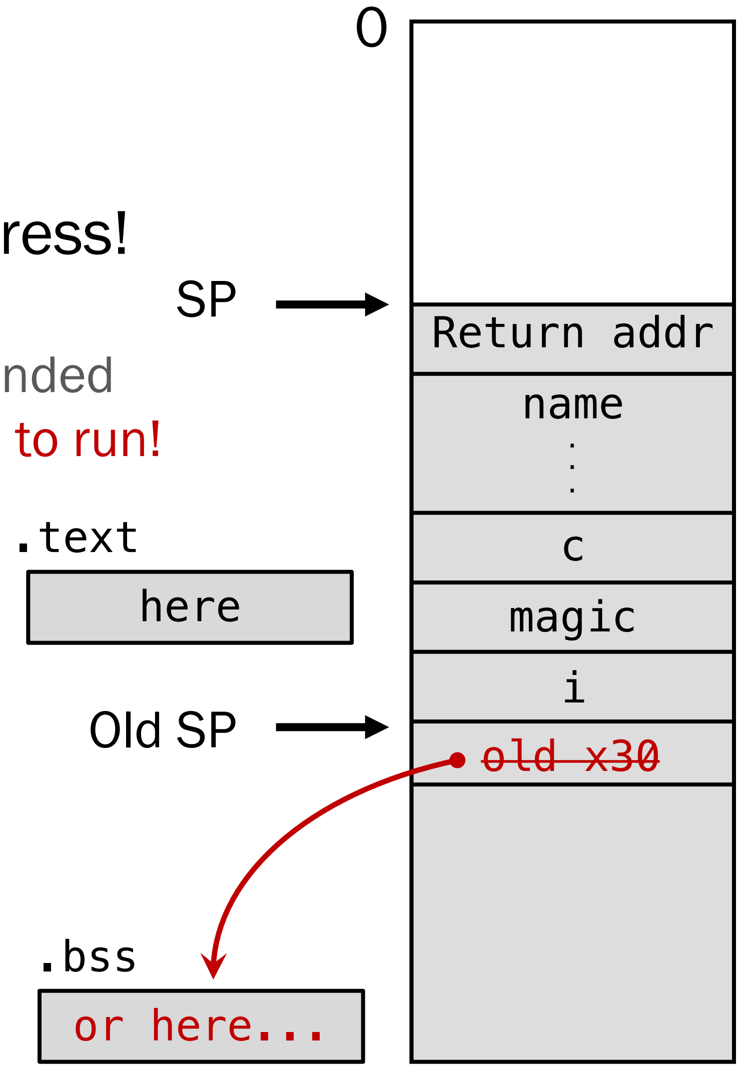
It Gets Much, Much Worse...

And somewhere on caller's stack frame is the saved return address for that function ...

Buffer overrun can overwrite caller's return address!

- Replacement value can be an invalid address, leading to a segfault, or it can cleverly cause unintended control flow, or even cause arbitrary malicious code to run!

```
#include <stdio.h>
int callee(void)
{
   char name[12], c;
   int i = 0, magic = 42;
   printf("What is your name?\n");
   while ((c = getchar()) != '\n')
      name[i++] = c;
   name[i] = '\0';
   printf("Thank you, %s.\n", name);
   printf("The answer to life, the universe, "
          "and everything is %d\n", magic);
   return 0;
}
```



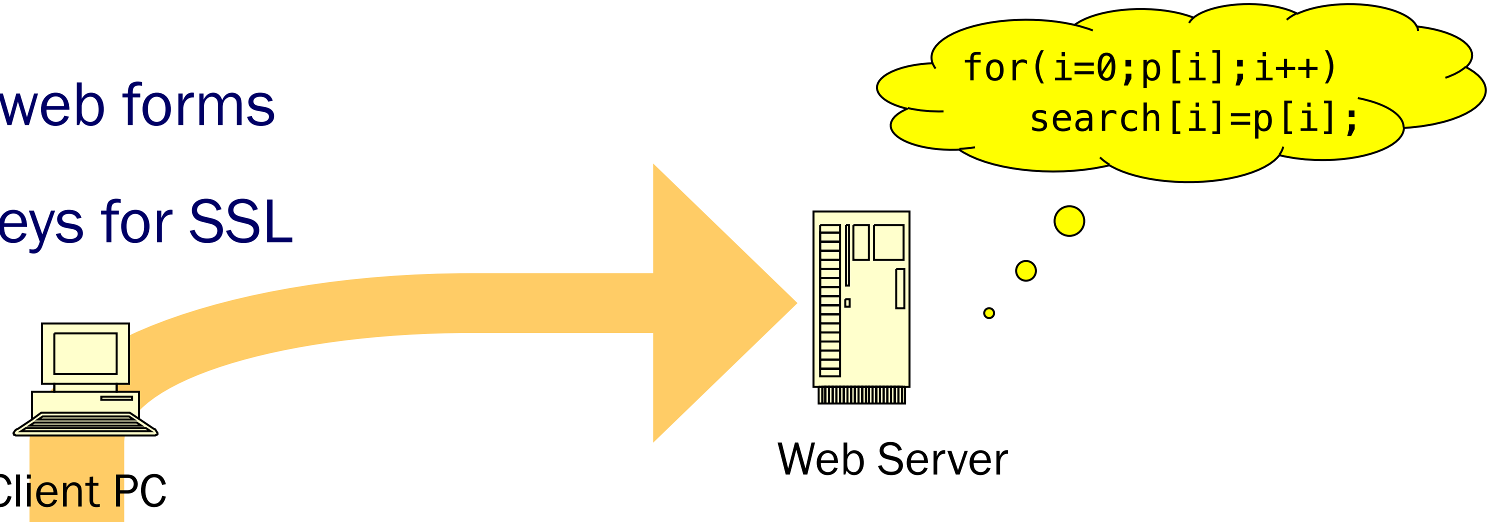
Attacking a Web Server

URLs

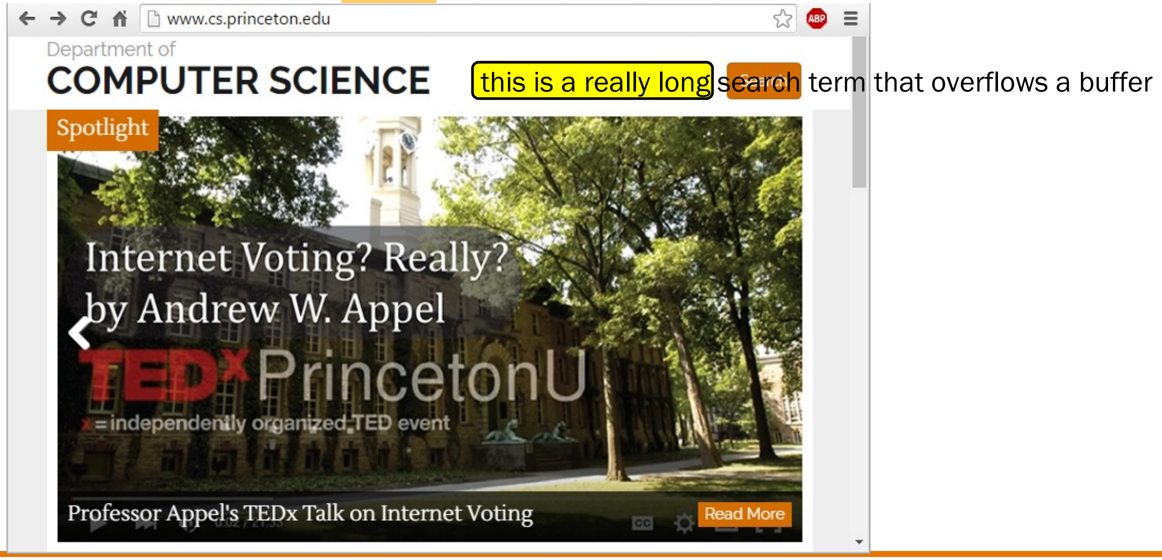
Input in web forms

Crypto keys for SSL

etc.



```
for(i=0;p[i];i++)
   search[i]=p[i];
```



www.cs.princeton.edu

Department of COMPUTER SCIENCE

this is a really long search term that overflows a buffer

Internet Voting? Really? by Andrew W. Appel

TEDx PrincetonU

x = independently organized TED event

Professor Appel's TEDx Talk on Internet Voting

Attacking Everything in Sight

Just in 2025 >100, including:
  Adobe, Excel, FFmpeg,
  GNU objdump, router software

Zoom (dozens, most recent 4/2025)

webp image library (9/2023)

C/C++ MP4 video library (4/2023)

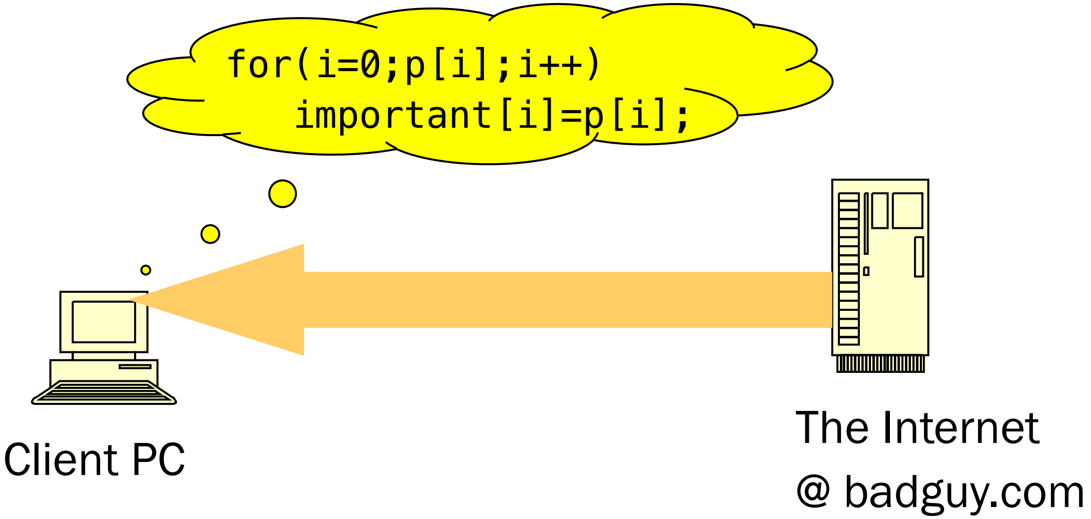
OpenSSL crypto library (11/2022)

Smart UPS devices (3/2022)

VLC media player (1/2019)

Nintendo Switch (4/2018)

…



```
for(i=0;p[i];i++)
  important[i]=p[i];
```

E-mail clients

PDF viewers

Operating-system kernels

TCP/IP Stack

Any **application that ever sees input directly from the outside!**

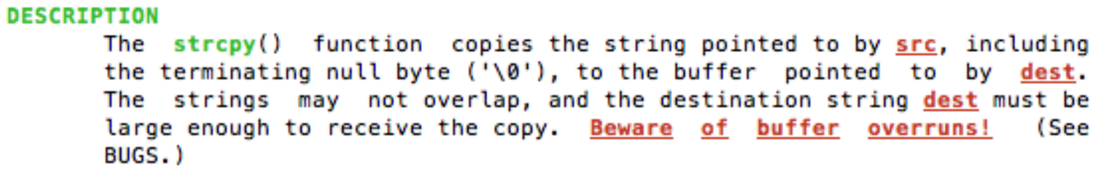
Defenses Against This Attack

Best: program in languages that make array-out-of-bounds impossible (Java, python, C#, ML, …)

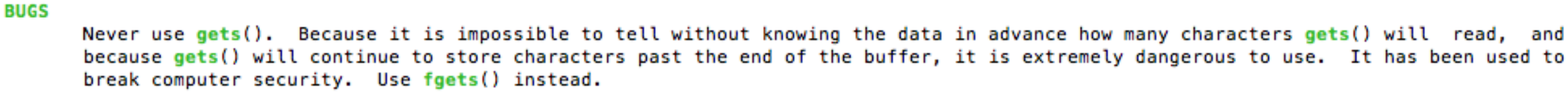
But if you need to use C…

Defenses Against This Attack

In C: use discipline and software analysis tools to check bounds of array subscripts



```
DESCRIPTION
       The  strcpy()  function  copies the string pointed to by src, including
       the terminating null byte ('\0'), to the buffer  pointed  to  by  dest.
       The  strings  may  not overlap, and the destination string dest must be
       large enough to receive the copy.  Beware  of  buffer  overruns!   (See
       BUGS.)
```



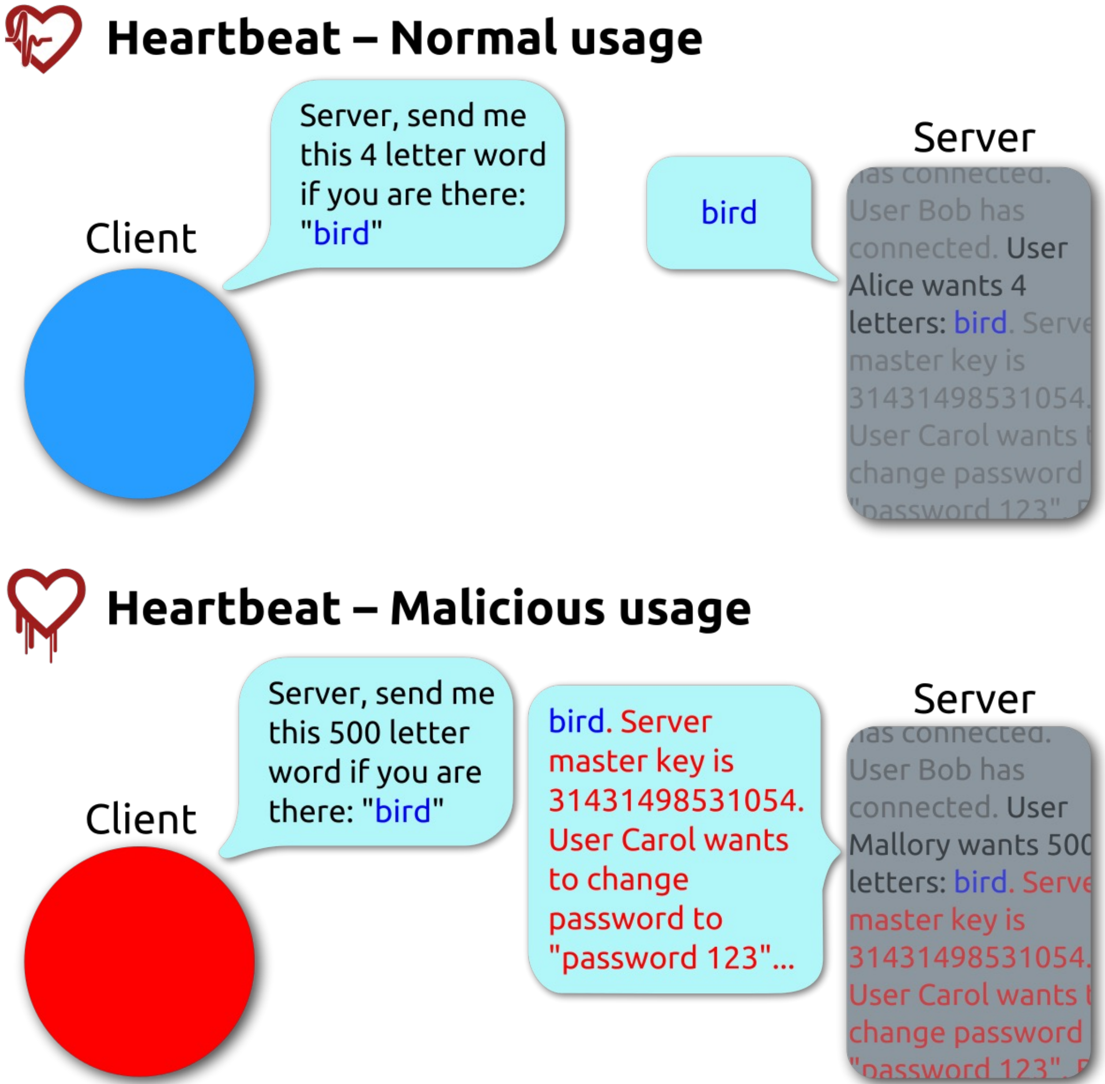
```
BUGS
       Never use gets().  Because it is impossible to tell without knowing the data in advance how many characters gets() will  read,  and
       because gets() will continue to store characters past the end of the buffer, it is extremely dangerous to use.  It has been used to
       break computer security.  Use fgets() instead.
```

Augmented by OS- or compiler-level mitigations:

- Randomize initial stack pointer
- “No-execute” memory permission for sections other than .text
- “Canaries” at end of stack frames

None of these would have prevented the “Heartbleed” attack

Half a billion dollars worth of heartburn …


Heartbeat – Normal usage
Client
Server, send me this 4 letter word if you are there: "bird"
bird
Server
as connected. User Bob has connected. User Alice wants 4 letters: bird. Serve master key is 31431498531054. User Carol wants t change password "password 123". P
Heartbeat – Malicious usage
Client
Server, send me this 500 letter word if you are there: "bird"
bird. Server master key is 31431498531054. User Carol wants to change password to "password 123"...
Server
as connected. User Bob has connected. User Mallory wants 500 letters: bird. Serve master key is 31431498531054. User Carol wants t change password "password 123". P

https://en.wikipedia.org/wiki/Heartbleed#/media/File:Simplified_Heartbleed_explanation.svg
Wikipedian FenixFeather - Creative Commons Attribution-Share Alike 3.0 Unported

Assignment 6: Attack the “Grader” Program

```
enum {BUFSIZE = 48};
char grade = 'D';
char name[BUFSIZE];
...
int main(void)
{
   mprotect(...);
   getname();
   if (strcmp(name, "Andrew Appel") == 0)
      grade = 'B';
   printf("%c is your grade.\n", grade);
   printf("Thank you, %s.\n", name);
   return 0;
}
```

```
$ ./grader
What is your name?
Joe Student
D is your grade.
Thank you, Joe Student.
$ ./grader
What is your name?
Andrew Appel
B is your grade.
Thank you, Andrew Appel.
```

Assignment 6: Attack the “Grader” Program

```
/* Prompt for name and read it */
void getName() {
  printf("What is your name?\n");
  readString();
}
```

```
/* Read a string into name */
void readString() {
  char buf[BUFSIZE];
  int i = 0;
  int c;

  /* Read string into buf[] */
  for (;;) {
    c = fgetc(stdin);
    if (c == EOF || c == '\n')
      break;
    buf[i] = c;
    i++;
  }
  buf[i] = '\0';

  /* Copy buf[] to name[] */
  for (i = 0; i < BUFSIZE; i++)
    name[i] = buf[i];
}
```

Unchecked write to buffer!

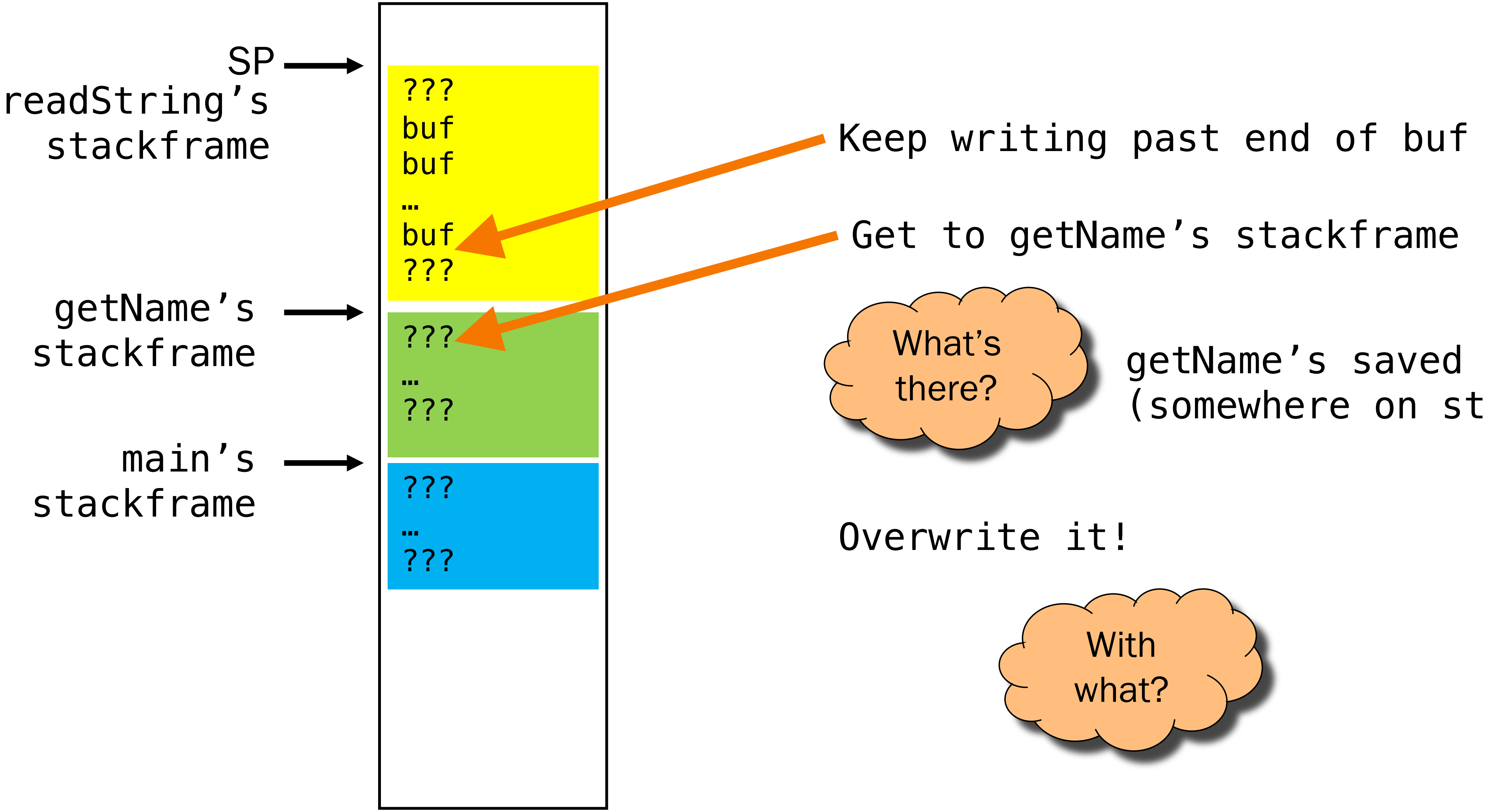
Assignment 6: Attack the “Grader” Program

```
enum {BUFSIZE = 48};
char grade = 'D';
char name[BUFSIZE];
...
int main(void)
{
   mprotect(...);
   getname();
   if (strcmp(name, "Andrew Appel") == 0)
      grade = 'B';
   printf("%c is your grade.\n", grade);
   printf("Thank you, %s.\n", name);
   return 0;
}
```

```
$ ./grader
What is your name?
Joe Student\0(#@&$%*#&(*^!@%*!(&$
B is your grade.
Thank you, Joe Student.
```

Smash the stack!

Memory Map of STACK Section



Keep writing past end of buf

Get to getName's stackframe

What's there?

getName's saved x30!
(somewhere on stack)

Overwrite it!

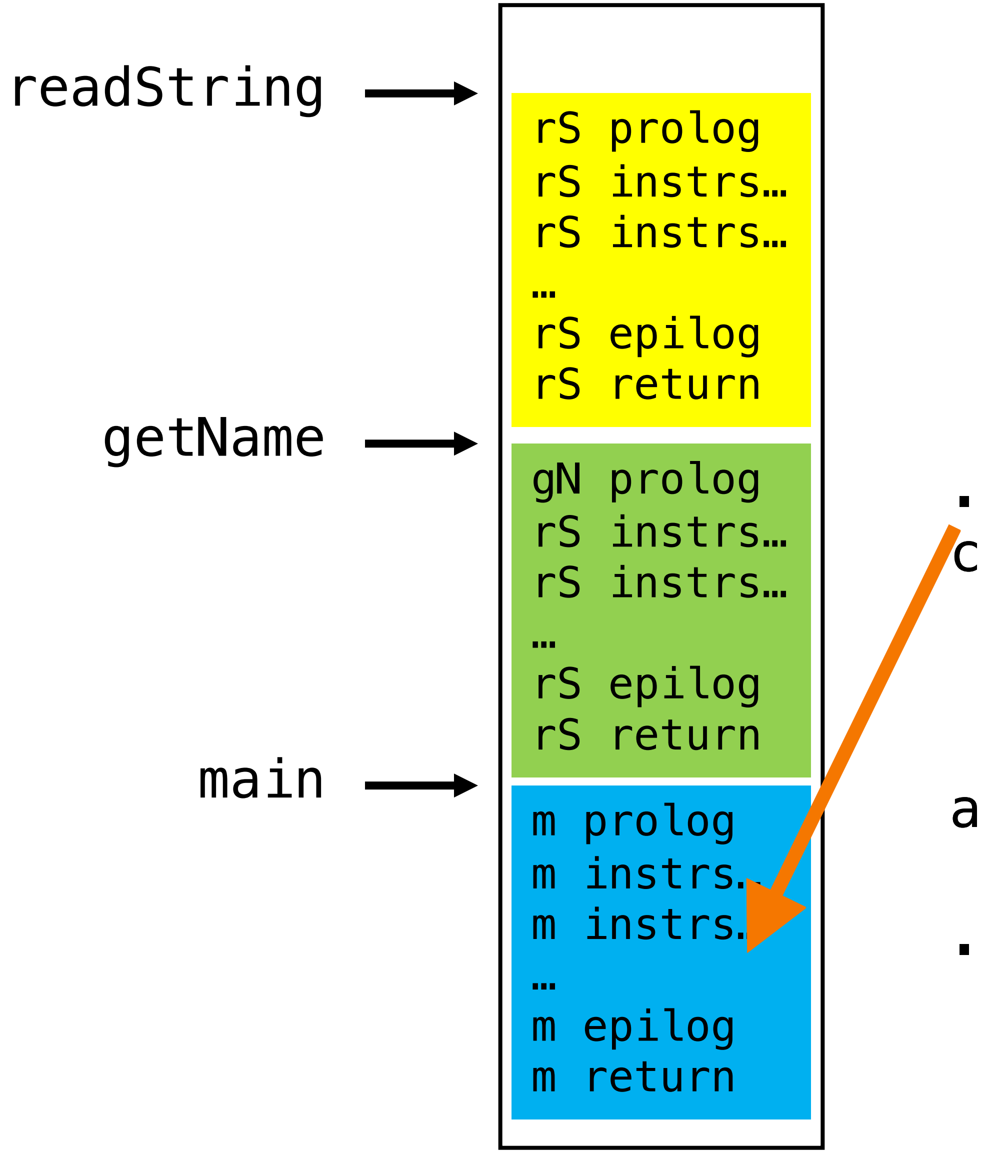
With what?

Assignment 6: Attack the “Grader” Program

```c
enum {BUFSIZE = 48};
char grade = 'D';
char name[BUFSIZE];
...
int main(void)
{
   mprotect(...);
   getname();
   if (strcmp(name, "Andrew Appel") == 0)
      grade = 'B';
   printf("%c is your grade.\n", grade);
   printf("Thank you, %s.\n", name);
   return 0;
}
```

```
$ ./grader
What is your name?
Joe Student\0(#@&$%*#&(*^!@%*!(&$
B is your grade.
Thank you, Joe Student.
```

Memory Map of TEXT Section



readString

rS prolog
rS instrs…
rS instrs…
…
rS epilog
rS return

getName

gN prolog
rS instrs…
rS instrs…
…
rS epilog
rS return

main

m prolog
m instrs…
m instrs…
…
m epilog
m return

(All of these instructions are actually machine code, not flattened C, of course!)

```
...
checkappel:
   if (strcmp(name, "Andrew Appel") != 0)
      goto afterb
   grade = 'B' ← HERE!
afterb:
   print ...
...
```

Construct Your Exploit String (`createdataB.c`)

1. Your name.
   - After all, the `grader` program's last line of output must be: "`Thank you, [your name].`"

`fopen` the file `"dataB"` and write your name into that file (e.g. with `fprintf`)

2. A null byte.
   - Otherwise, the `grader` program's last line of output will be corrupted.

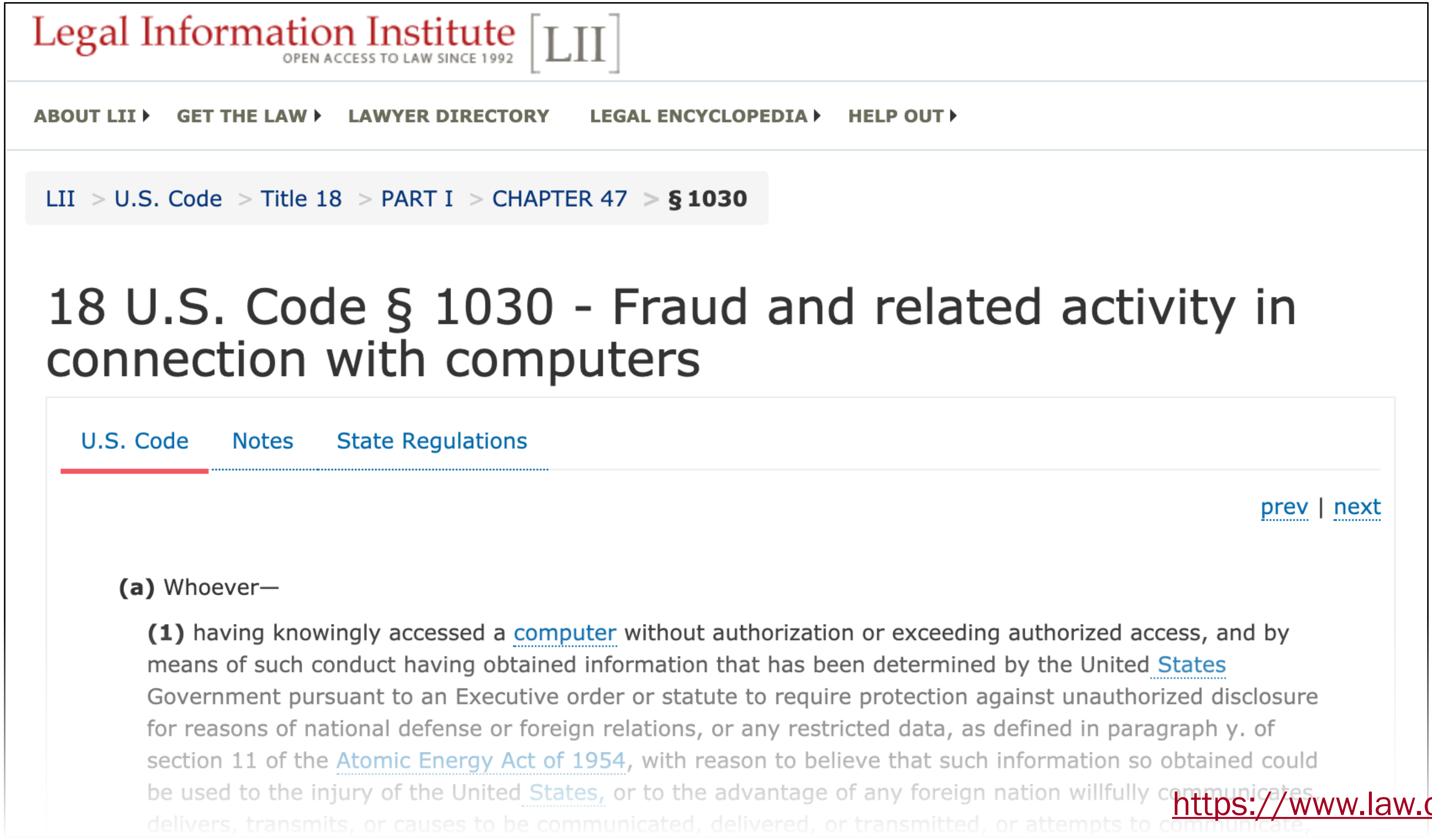
See "Writing Binary Data" precept handout. `'\0'` is just a single byte of binary data.

3. Filler to overrun until `x30`.
   - Presumably more null bytes are easiest, but easter eggs are fine.

4. The address of the target
   - The statement `grade = 'B'`.

Address is a 64-bit (little-endian) unsigned integer: C `unsigned long`

Let’s Not Get Thrown in Jail, Please



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HELP OUT
LII > U.S. Code > Title 18 > PART I > CHAPTER 47 > § 1030

18 U.S. Code § 1030 - Fraud and related activity in connection with computers

U.S. Code
Notes
State Regulations
prev | next

(a) Whoever—

(1) having knowingly accessed a computer without authorization or exceeding authorized access, and by means of such conduct having obtained information that has been determined by the United States Government pursuant to an Executive order or statute to require protection against unauthorized disclosure for reasons of national defense or foreign relations, or any restricted data, as defined in paragraph y. of section 11 of the Atomic Energy Act of 1954, with reason to believe that such information so obtained could be used to the injury of the United States, or to the advantage of any foreign nation willfully communicates, delivers, transmits, or causes to be communicated, delivered, or transmitted, or attempts to communicate,

https://www.law.cornell.edu/

Summary

- This lecture:
  - Buffer overrun attacks in general
  - Assignment 6 “B Attack” principles of operation
- Next precept:
  - Assignment 6 “B Attack” recap
  - Memory map using gdb
  - Writing binary data
- Final 2 lectures:
  - Assignment 6 “A Attack” overview
  - Machine language details needed for “A Attack”
  - *Finally* finishing the 4-stage build process: the Linker!
- Final precept:
  - MiniAssembler and ”A Attack” details

Final Exam Info

What: Final Exam!

When: 4 weeks from yesterday⌛😱
Tuesday, May 13
8:30am – 11:30 am

Where: McCosh 50

How: On paper. Closed book, but 1 two-sided study sheet allowed.

Why: Cumulative assessment. You've learned a lot, so show us!

Info: https://www.cs.princeton.edu/courses/archive/spr25/cos217/exam2.php