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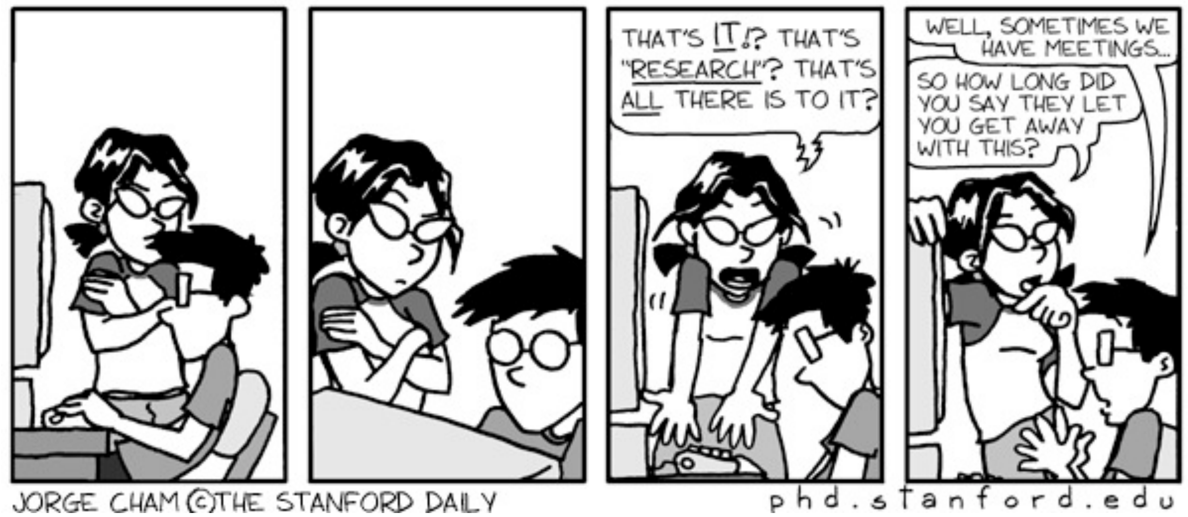
Machine Programming 5: Buffer Overruns and Stack Exploits

CS61, Lecture 6

Prof. Stephen Chong

September 22, 2011



Thinking about grad school in Computer Science?

Panel discussion
Tuesday September 27th, 6:00pm
Maxwell Dworkin 119

CS faculty and grad students will answer your questions about grad school in Computer Science: Why to apply, how to apply, how to get in, research, reference letters, personal statement, common pitfalls, what to do during your **sophomore** and **junior** years, and more…

Undergraduates at all levels are encouraged to attend.

Questions? Email chong@seas.harvard.edu

Pizza will be served!

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Announcements

- HW 2 (Binary bomb) due tonight
- HW 3 (Buffer bomb) will be released today
  - Due Thurs Oct 6 (2 weeks)

- Final will be in class on Thurs 1 Dec
  - Extension school final will also be on or around 1 Dec

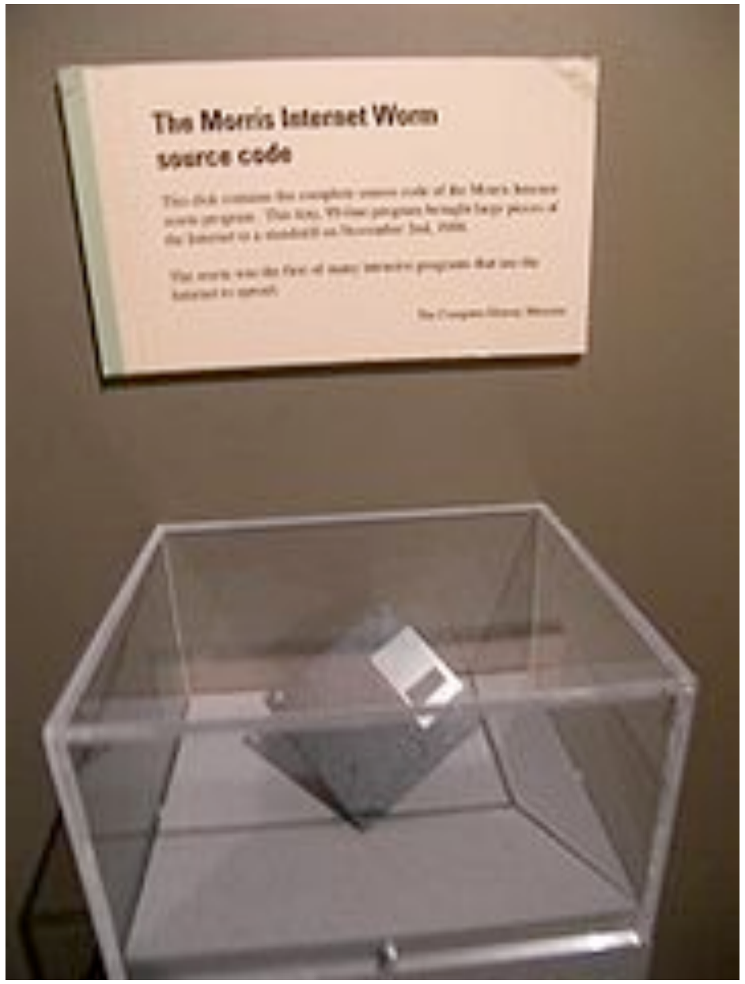
Memory vulnerabilities

- Many C programs contain subtle bugs that can lead to remote exploits
- Most common case: **Buffer overflow attacks**
  - Program reads data into a fixed-size buffer
  - Remote attacker feeds program data that overflows the buffer
  - How can this lead to a security hole?
- Buffer overflow overwrites other memory used by the program
  - For example, the return address on the stack
- Attacker sends machine instructions that end up being executed by the remote host!
  - Allows the attacker to cause the remote machine to run (almost) any code.

Real vulnerabilities

- Internet Worm: 1988
  - First widespread worm on the Internet
  - Estimated infected 10% of machines on the Internet
- Code Red, Code Red II, NIMDA, SQL Slammer
  - Various worms that attacked Windows machines
  - Led to denial of service attacks, backdoors, web pages being defaced, etc.
- AOL vs. Microsoft in the Internet Messaging Wars
  - AOL exploiting a buffer overrun in its own AIM client
- iPhone jail breaking, Xbox modding, Wii modding...
- Homework 3!!

The Internet Worm



http://en.wikipedia.org/wiki/File:Morris_Worm.jpg

- November 2, 1988: One of first large-scale worm attacks on the Internet launched
  - At the time, just 60,000 machines on Internet
  - Most were VAX or Sun machines running BSD UNIX
- Worm repeatedly infected machines, causing huge load, slow down, lots of weird activity
  - At first it was not clear what was going on
  - Lots of universities and companies notice the attack
- Very rapid response by the community
  - Nov 3, teams at MIT and Berkeley “capture” worm and disassemble it
  - Within few days they have a basic understanding of how it works, and patches to prevent its spread
- See “The Internet Worm Program: An Analysis” by Eugene H. Spafford (Purdue Technical Report CSD-TR-823)

Details of the Worm

- Three basic attack mechanisms:
- 1) Exploited debugging "feature" of sendmail
  - Allowed remote user to send an email with a program as the recipient
  - Caused remote machine to interpret email message as a shell script!
  - Shell script extracted a C program from the message, compiled it, and ran it
- 2) Exploited rsh ".rhosts" feature
  - rsh allows users to create file of machines trusted to log in with no password!
  - Worm cracks user's password locally, sh to that user, then rsh to remotely
- 3) **Buffer overflow** in fingerd
  - Finger daemon (fingerd) provides info on users on machine
  - fingerd reads its input insecurely, allows arbitrary code to run within fingerd
  - Since fingerd generally runs as root, gives remote user root access!

Example: gets() library routine

```
/* Get string from stdin */
char *gets(char *dest){
    int c = getc();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getc();
    }
    *p = '\0';
    return dest;
}
```

- `char *gets(char*)` reads a string from stdin and stores it in buffer provided by caller
- What's wrong with this code?

Example: gets() library routine

```
/* Get string from stdin */
char *gets(char *dest){
    int c = getc();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getc();
    }
    *p = '\0';
    return dest;
}
```

- Does not check the size of buffer `dest`!
  - No way to check it: not passed in as an argument
- Similar problems with other Unix functions
  - `strcpy`: copy string of arbitrary length
  - `scanf`, `fscanf`, `sscanf`, when given `%s` specification

Example of badly written code

```
/* Echo Line */
void echo() {
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

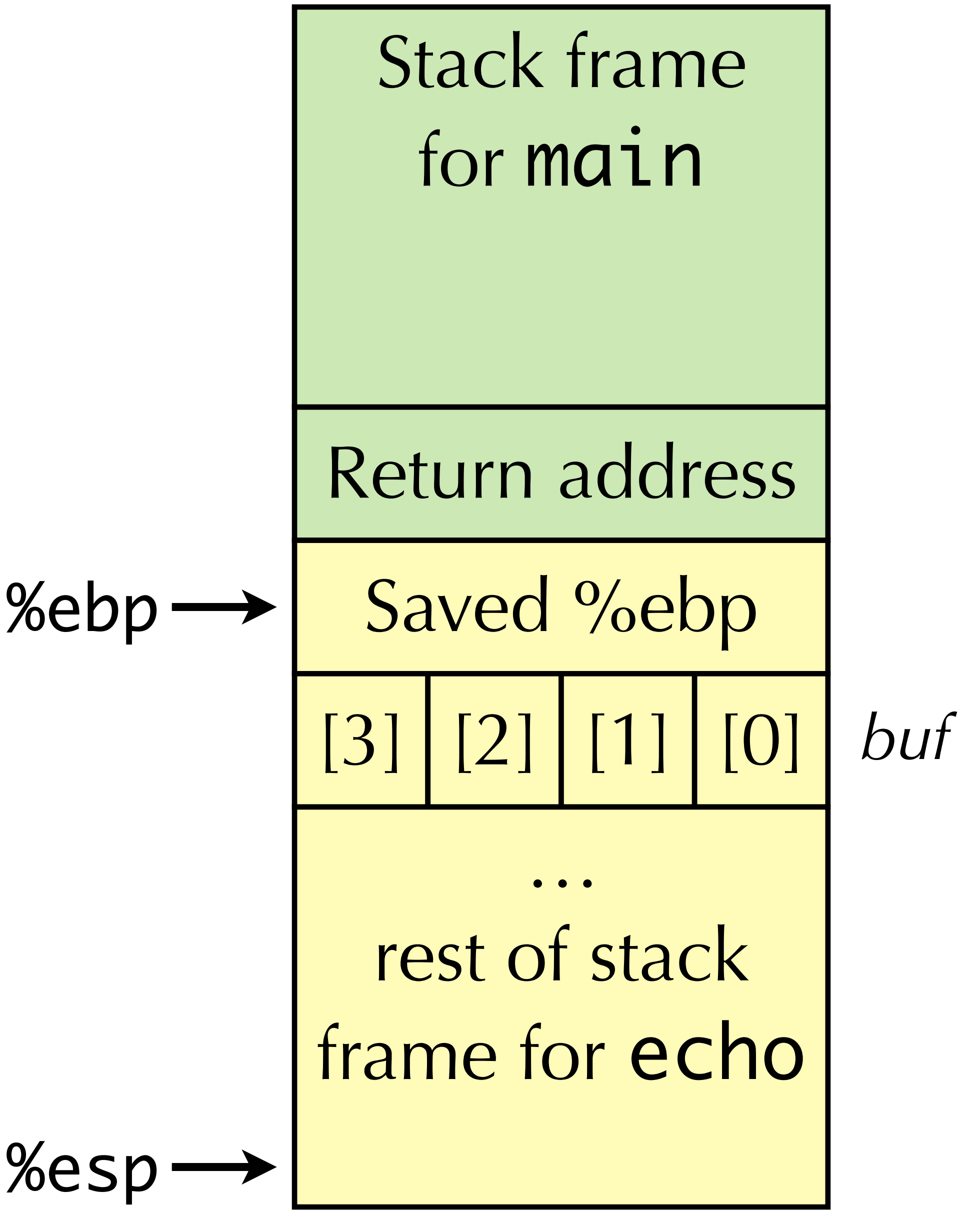
```
int main() {
    printf("Type a string:");
    echo();
    return 0;
}
```

What happens when we run?

```
/* Echo Line */
void echo() {
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
[chong@cs61 ~]$ ./bufdemo
Type a string:123
123
[chong@cs61 ~]$ ./bufdemo
Type a string:123456
123456
[chong@cs61 ~]$ ./bufdemo
Type a string:1234567890
1234567890
Segmentation fault
```

Code disassembly

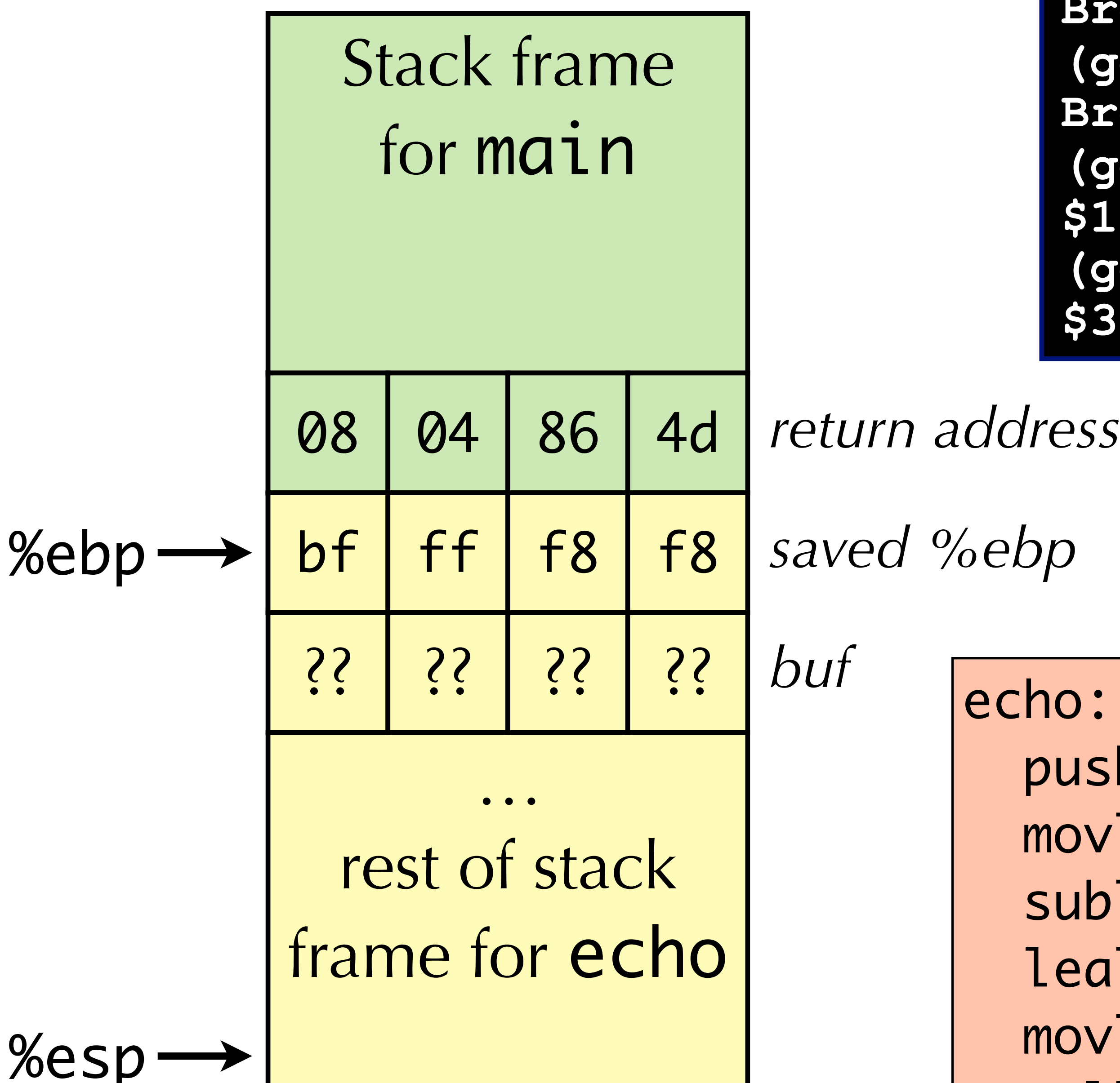



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
  pushl %ebp             # save %ebp on stack
  movl  %esp, %ebp
  subl  $12, %esp        # allocate space on stack
  leal  -4(%ebp), %eax # %eax = buf = %ebp-4
  movl  %eax, (%esp)     # push buf on stack
  call  gets             # call gets
  ...
```

Stack layout for echo()

```
unix> gdb bufdemo
(gdb) break echo
Breakpoint 1 at 0x8048583
(gdb) run
Breakpoint 1, 0x8048583 in echo ()
(gdb) print /x *(unsigned *)$ebp
$1 = 0xbffff8f8
(gdb) print /x *((unsigned *)$ebp + 1)
$3 = 0x804864d
```




```
echo:
  pushl  %ebp              # save %ebp on stack
  movl   %esp, %ebp
  subl   $12, %esp         # allocate space on stack
  leal   -4(%ebp), %eax    # %eax = buf = %ebp-4
  movl   %eax, (%esp)      # push buf on stack
  call   gets              # call gets
  ...
```

Entering a string that fits in buf[]

Before Call to `gets`

	Stack frame for `main`				
	`08`	`04`	`86`	`4d`	*return address*
`%ebp` →	`bf`	`ff`	`f8`	`f8`	*saved %ebp*
	`??`	`??`	`??`	`??`	*buf*
	… rest of stack frame for `echo`				
`%esp` →					

After Call to `gets` with input "123"

	Stack frame for `main`				
	`08`	`04`	`86`	`4d`	*return address*
`%ebp` →	`bf`	`ff`	`f8`	`f8`	*saved %ebp*
	`00`	`33`	`32`	`31`	*buf*
	… rest of stack frame for `echo`				
`%esp` →					

Entering a string TOO BIG for buf[]

- What if we enter the string "12345"?
  - Will overflow the buffer
  - Where do the extra bytes end up?
- Overwrite the saved `%ebp` on the stack!
  - What will this do to the program?

After Call to `gets` with input "12345"

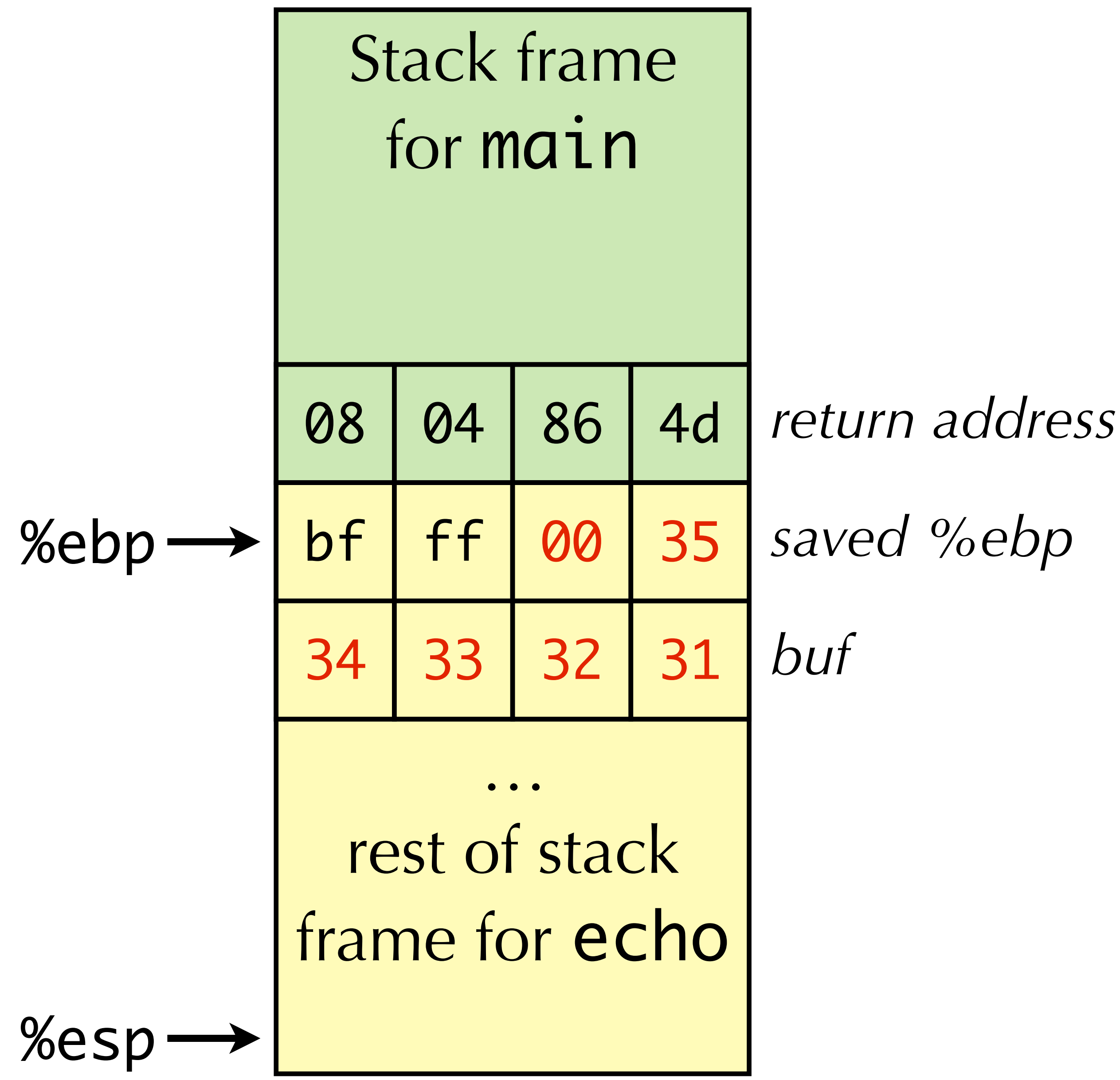
	Stack frame for `main`				
	`08`	`04`	`86`	`4d`	*return address*
`%ebp` →	`bf`	`ff`	`00`	`35`	*saved %ebp*
	`34`	`33`	`32`	`31`	*buf*
	… rest of stack frame for `echo`				
`%esp` →					

Entering a string TOO BIG for buf[]

```
echo:
  ...
  call   gets          # call gets
  ...
  movl   %ebp, %esp    # %esp = %ebp
  popl   %ebp          # restore old %ebp
  ret
```

- Restores incorrect value for `%ebp`!!!
  - Restores `0xbfff0035` instead of `0xbffff8f8`

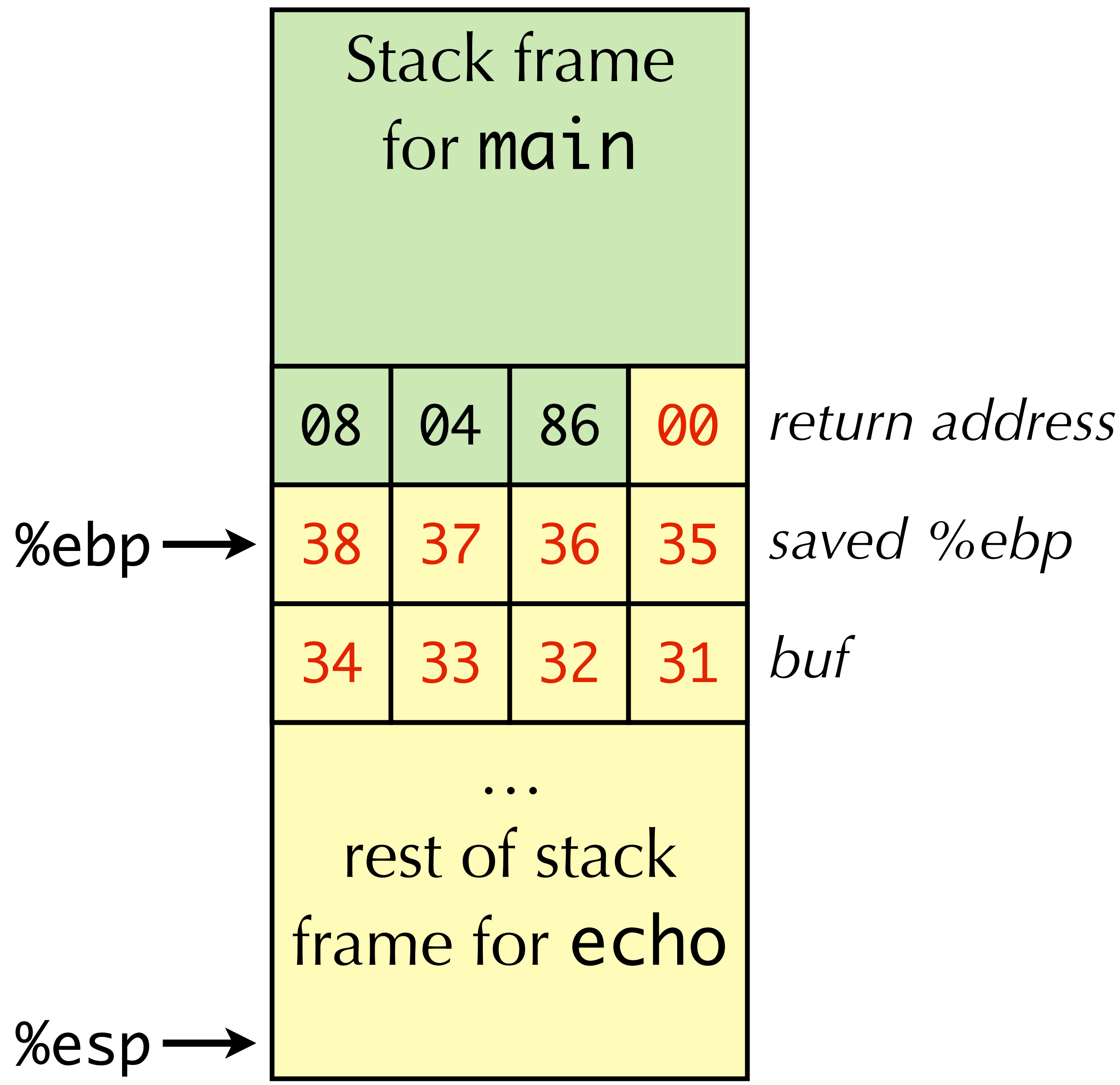
After Call to `gets` with input "12345"



Entering EVEN BIGGER string

```
echo:
  ...
  call   gets          # call gets
  ...
  movl   %ebp, %esp    # %esp = %ebp
  popl   %ebp          # restore old %ebp
  ret
```

After Call to `gets`
with input "12345678"



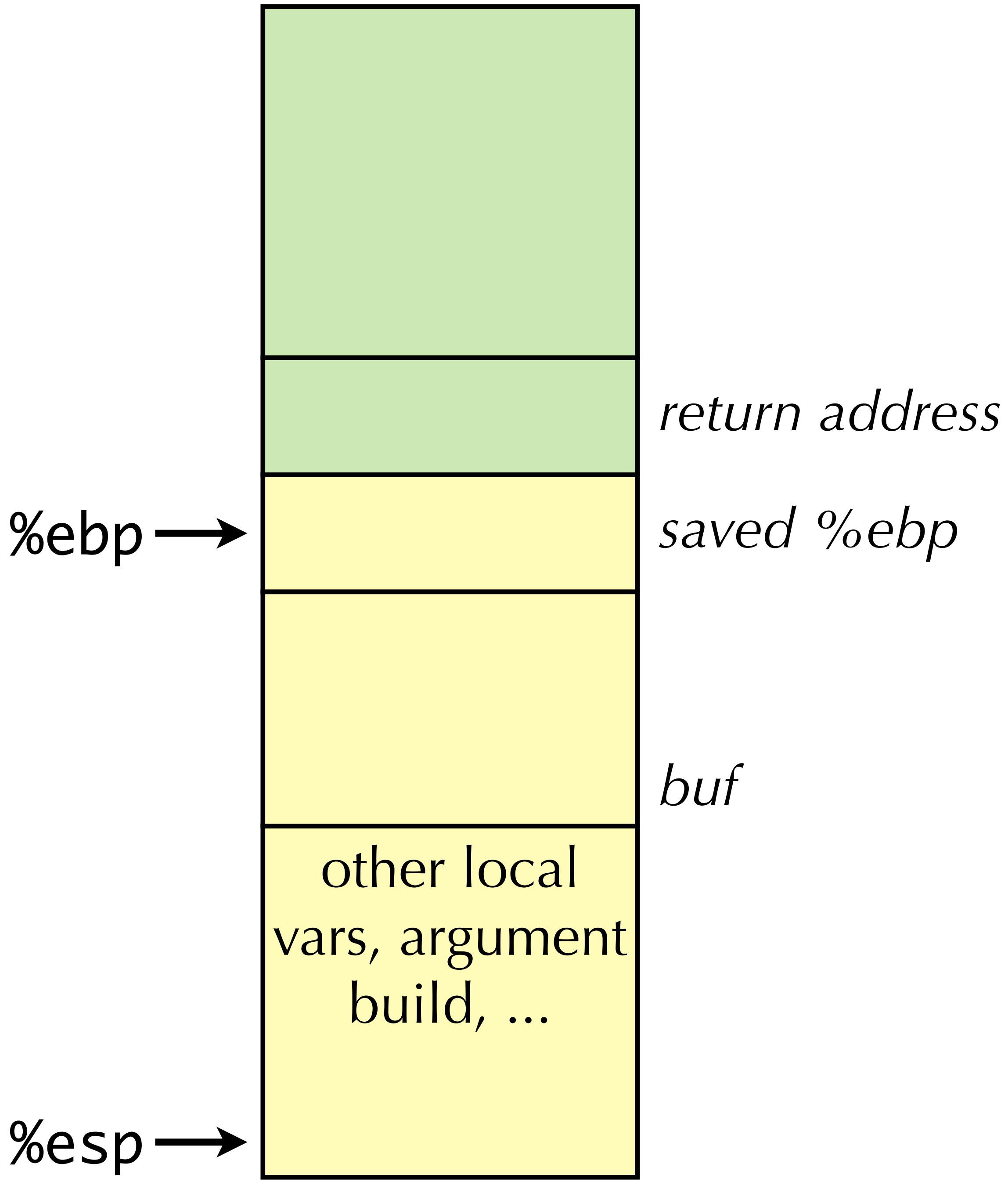
- Restores incorrect value for `%ebp`
- Jumps to wrong return address!!!

Malicious use of buffer overflow

- If we can overwrite portions of the stack, we can cause the program **to jump to an address of our choosing**!
- This can be used to do all kinds of nasty things.
- Say we knew the memory address of a routine that, say, deleted all of the files in the user's home directory.
  - Most programs would not contain such a routine, but it could happen ...
  - If we can coerce the program to jump to that routine, we can do major damage.
- This attack is fundamentally limited, however...
  - Can only cause the program to run code that's already part of the program.
- How can we **inject our own code** into the running program?

Injecting code

- Suppose routine puts data into buffer on stack (like previous example)
- Provide **x86 machine code** as input to the routine!
  - Fill buffer with instructions we want to run
  - Overwrite return address to point to buffer

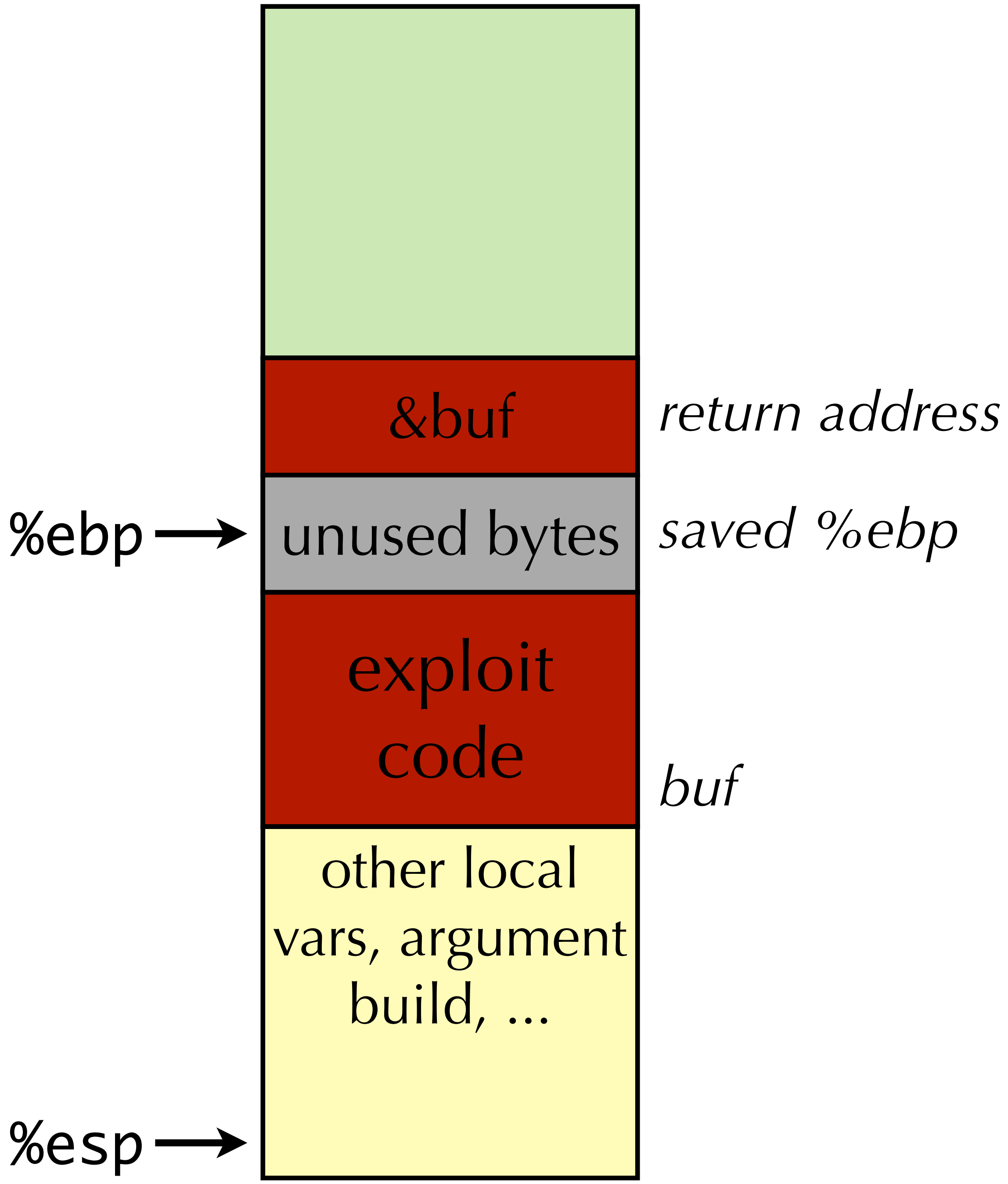



```
void some_routine() {
    char buf[64];
    gets(buf);
}
```

Injecting code

- Suppose routine puts data into buffer on stack (like previous example)
- Provide **x86 machine code** as input to the routine!
    - Fill buffer with instructions we want to run
    - Overwrite return address to point to buffer
- When routine tries to to return...
    - `ret` pops return address off the stack
    - **But return address now points to buffer!**
    - Processor starts running code in buffer!

```
void some_routine() {
    char buf[64];
    gets(buf);
}
```



Some limitations of this attack

- Executing this attack on arbitrary programs is tricky.
  - 1) Need to know where on the stack the buffer is (and how big it is)
  - 2) Need to know where return address is on the stack (relative to the buffer).
    - Remember, you can only control what goes into the buffer (and any addresses beyond the end of the buffer).
- If you have access to the binary, this is not too difficult...
  - Can just use gdb, set breakpoints, inspect the stack, and figure it out.
- If you're attacking a service on the Internet and don't have the binary, this becomes much harder.
  - But it can be done, usually with a lot of trial and error.

Mitigating buffer overflow attacks

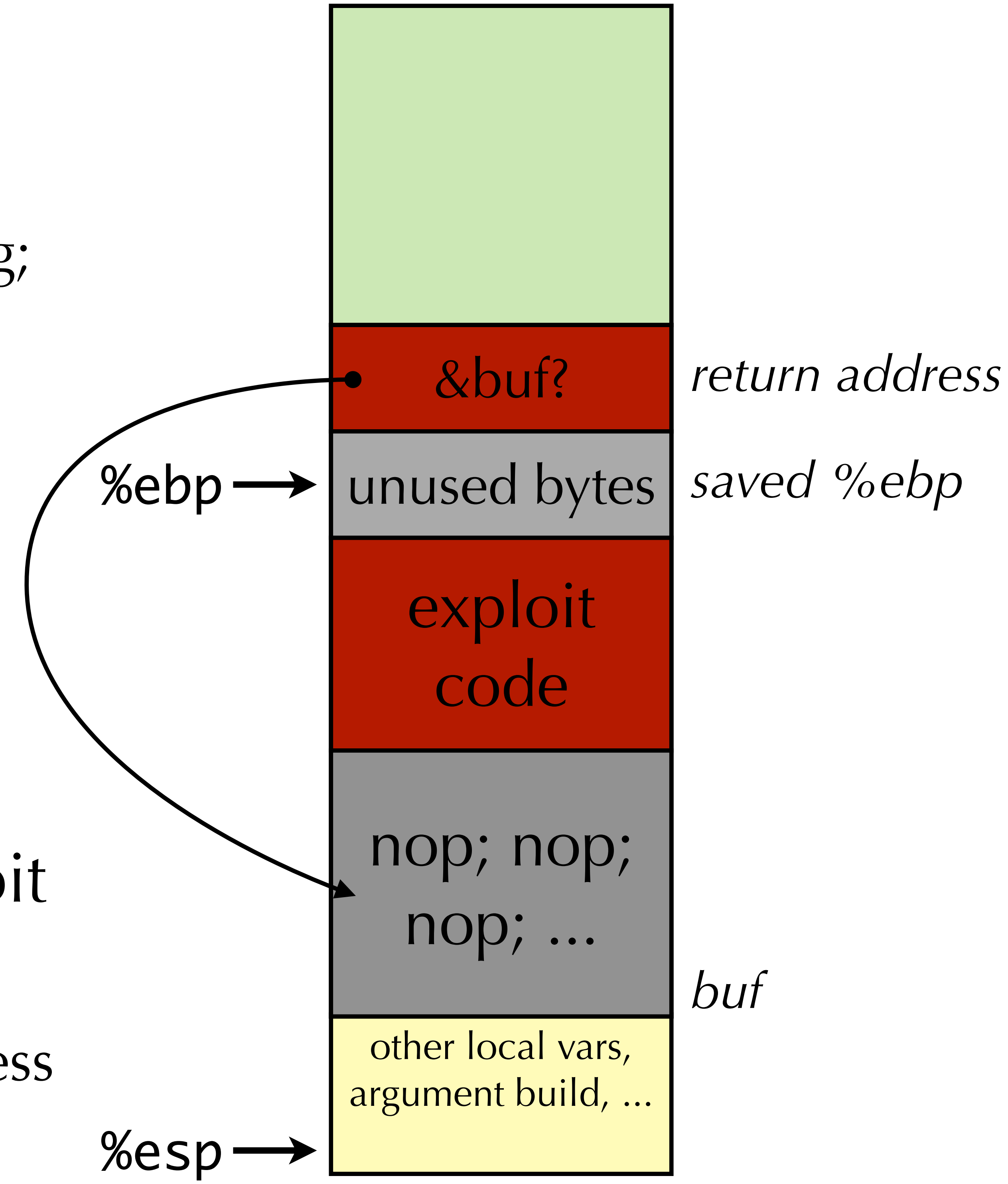
- Three common mechanisms
  - Stack randomization
  - Stack corruption detection
  - Non-executable memory

Stack randomization

- Exploiting stack-based buffer overflows requires knowing where buffer is in memory
  - Need to overwrite return address on stack with pointer to buffer
- One way to thwart this: **Address space randomization**
  - When kernel runs a program, it puts the stack at a (slightly) random location in memory each time.
  - Thus attacker unlikely to correctly guess buffer's address.
  - Implemented by recent Linux kernels by default.
  - (We have disabled this on your VMs to let you do Assignment 3)
- To thwart address space randomization...

The NOP Sled attack

- Idea: Start out buffer with long string of **nop** instructions
  - "No-op" instruction doesn't do anything; just moves to next instruction.
- Put best guess of exploit code location in return address.
  - OK if we "undershoot" a bit.
- When program resumes execution within the NOP sled region, code will execute until it hits your exploit code.
  - Note: won't work if we "overshoot" guess of exploit code location.



Detecting stack corruption

- Try to detect when array on stack has overflowed
- Store special **canary value** (aka **guard value**) on stack
  - Generated randomly every time program is run
    - Attacker can't predict value
- Before returning from function check canary value unchanged
  - If changed, stop execution
- Recent versions of gcc do this for functions that may be vulnerable

Non-executable memory

- Idea: limit which memory regions can hold executable code
  - Modern operating systems and hardware support different forms of memory protection
    - Readable memory, writeable memory, executable memory
  - We'll learn more about the mechanisms that enable this
- Make stack readable, writeable, but not executable
- Note: some languages/programs dynamically generated code
  - E.g., Just-in-time (JIT) compilation of Java bytecode
  - Non-executable memory may not be a feasible in these settings

Avoiding Overflow Vulnerability

- Mitigation techniques (stack randomization, detecting stack corruption, non-executable memory) make it harder to perform buffer overflow attacks
  - But not impossible!

- How do we prevent all overflow vulnerabilities?

Avoiding Overflow Vulnerability

- **Rule #1: Don't program in C!**
- Java (and many other languages) make this kind of attack more or less impossible. How?
- In Java, all array accesses are bounds-checked at runtime.
  - No way to stuff data into an array beyond its size limit.
- Also, Java doesn't let you directly manipulate pointers.
  - No way to cause the program to jump to an arbitrary memory address.
- Of course, this relies on the Java Virtual Machine being free of any bugs itself...
  - No guarantees that this is the case!

Avoiding Overflow Vulnerability

- **Rule #2: Always check buffer lengths!**
  - Especially when reading data from the outside world – a user or a network socket.
- Use standard library routines that check buffer bounds
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy` – checks length of string.
  - Don't use `scanf` with `%s` conversion specification
    - Use `fgets` to read the string

```
/* Echo Line */
void echo() {
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

Buffer exploits over the network

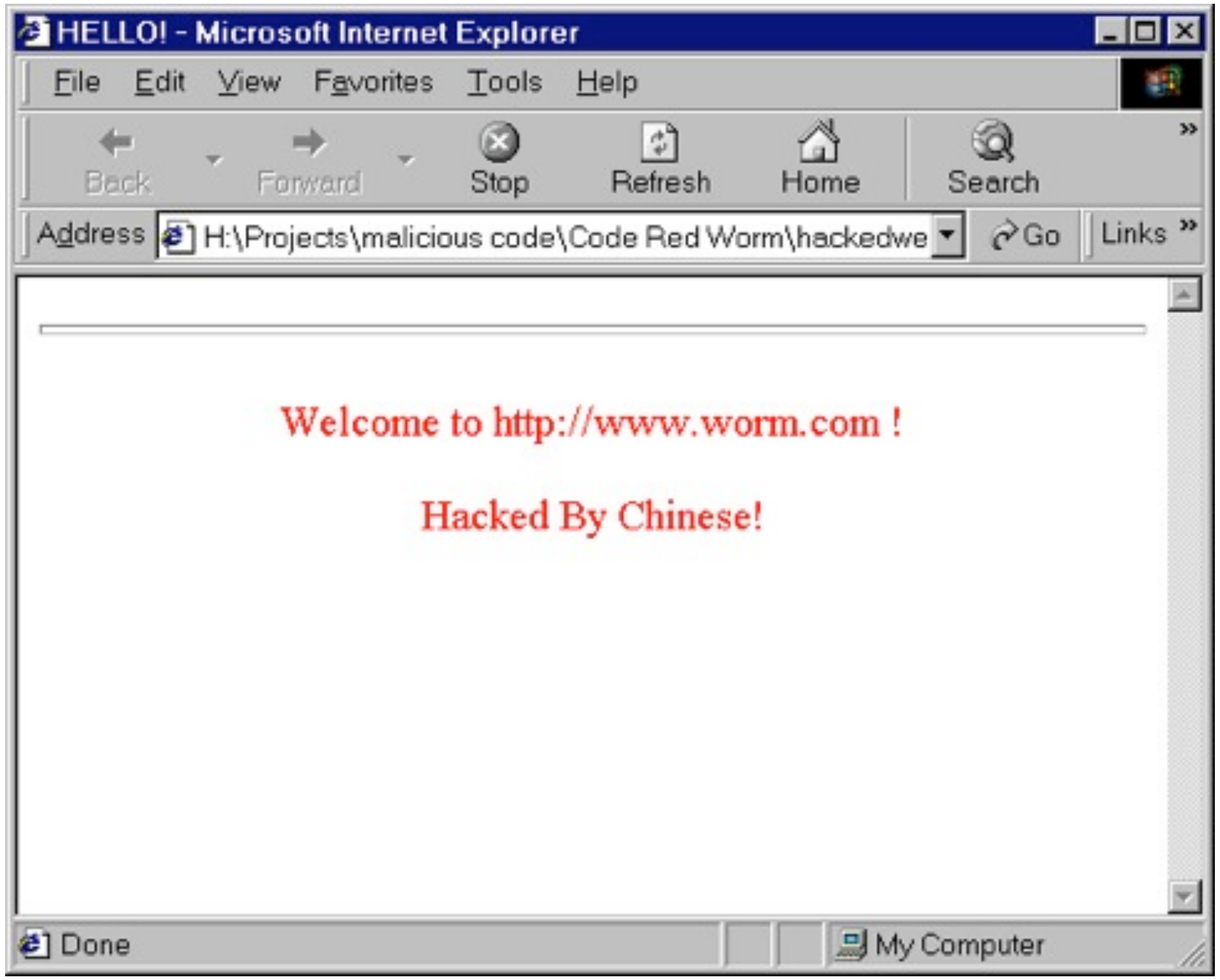
- Attacks so far use the `gets()` routine
  - Reads a string from standard input, typically user input, or from a file
- Problems also exists in programs that read data from the network.
  - Web browsers, IM clients, MP3 players, games, ...
  - Program reads data from network into buffer on the stack, and fails to check the data fits into the buffer ⇒ vulnerable to buffer overflow exploits
  - Happens a lot in the real world.
- More serious issue: Programs running as the "root" user
  - Many services on UNIX systems run as "root": Admin user that can do anything on the machine.
    - Example: Web servers, file servers, ssh daemon, etc.
  - If you can attack these services, exploit code will run as root, and can do arbitrary damage to machine.

Code Red Worm

- June 18, 2001 – Buffer overflow vulnerability in Microsoft IIS Web server announced
- June 26, 2001 – Microsoft releases patch for vulnerability
- July 13, 2001 – Code Red v1 worm released
  - Infects machines and causes them to perform denial-of-service attacks
  - Bug in random number generator slows infection rate. New version released a few days later
- August 4, 2001 – Code Red II worm released
  - Same basic attack vector, but somewhat different behavior

How does Code Red work?

- Overflows stack of the IIS web server
  - Causes it to overwrite return address on the stack
  - IIS then jumps into the machine code in HTTP request
- Defaces server's home page



How does Code Red work?

- Start 100 threads running
- Spread self
  - Open connections to random IP addresses and send attack string
    - May or may not be IIS
  - Between 1st and 19th of month
- Attack several static IP addresses, including www.whitehouse.gov
  - Send 98,304 packets; sleep for 4-1/2 hours; repeat
  - This is called a **denial-of-service** attack
  - Between 21st and 27th of month
  - White House had to change IP address

The Code Red II Attack

Padding (overflows buffer)

Machine code for exploit

```
0000    47 45 54 20 2f 64 65 66  61 75 6c 74 2e 69 64 61   GET /default.ida
0010    3f 58 58 58 58 58 58 58  58 58 58 58 58 58 58 58   ?XXXXXXXXXXXXXXX
0020    58 58 58 58 58 58 58 58  58 58 58 58 58 58 58 58   XXXXXXXXXXXXXXXX
0030    58 58 58 58 58 58 58 58  58 58 58 58 58 58 58 58   XXXXXXXXXXXXXXXX
0040    58 58 58 58 58 58 58 58  58 58 58 58 58 58 58 58   XXXXXXXXXXXXXXXX
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00b0    58 58 58 58 58 58 58 58  58 58 58 58 58 58 58 58   XXXXXXXXXXXXXXXX
00c0    58 58 58 58 58 58 58 58  58 58 58 58 58 58 58 58   XXXXXXXXXXXXXXXX
00d0    58 58 58 58 58 58 58 58  58 58 58 58 58 58 58 58   XXXXXXXXXXXXXXXX
00e0    58 58 58 58 58 58 58 58  58 58 58 58 58 58 58 58   XXXXXXXXXXXXXXXX
00f0    58 25 75 39 30 39 30 25  75 36 38 35 38 25 75 63   X%u9090%u6858%uc
0100    62 64 33 25 75 37 38 30  31 25 75 39 30 39 30 25   bd3%u7801%u9090%
0110    75 36 38 35 38 25 75 63  62 64 33 25 75 37 38 30   u6858%ucbd3%u780
0120    31 25 75 39 30 39 30 25  75 36 38 35 38 25 75 63   1%u9090%u6858%uc
0130    62 64 33 25 75 37 38 30  31 25 75 39 30 39 30 25   bd3%u7801%u9090%
0140    75 39 30 39 30 25 75 38  31 39 30 25 75 30 30 63   u9090%u8190%u00c
0150    33 25 75 30 30 30 33 25  75 38 62 30 30 25 75 35   3%u0003%u8b00%u5
0160    33 31 62 25 75 35 33 66  66 25 75 30 30 37 38 25   31b%u53ff%u0078%
0170    75 30 30 30 30 25 75 30  30 3d 61 20 20 48 54 54   u0000%u00=a  HTT
0180    50 2f 31 2e 30 0d 0a 43  6f 6e 74 65 6e 74 2d 74   P/1.0..Content-t
0190    79 70 65 3a 20 74 65 78  74 2f 78 6d 6c 0a 43 6f   ype: text/xml.Co
01a0    6e 74 65 6e 74 2d 6c 65  6e 67 74 68 3a 20 33 33   ntent-length: 33
01b0    37 39 20 0d 0a 0d 0a c8  c8 01 00 60 e8 03 00 00   79 ........`....
01c0    00 cc eb fe 64 67 ff 36  00 00 64 67 89 26 00 00   ....dg.6..dg.&..
01d0    e8 df 02 00 00 68 04 01  00 00 8d 85 5c fe ff ff   .....h......\...
01e0    50 ff 55 9c 8d 85 5c fe  ff ff 50 ff 55 98 8b 40   P.U...\...P.U..@
01f0    10 8b 08 89 8d 58 fe ff  ff ff 55 e4 3d 04 04 00   .....X....U.=...
```
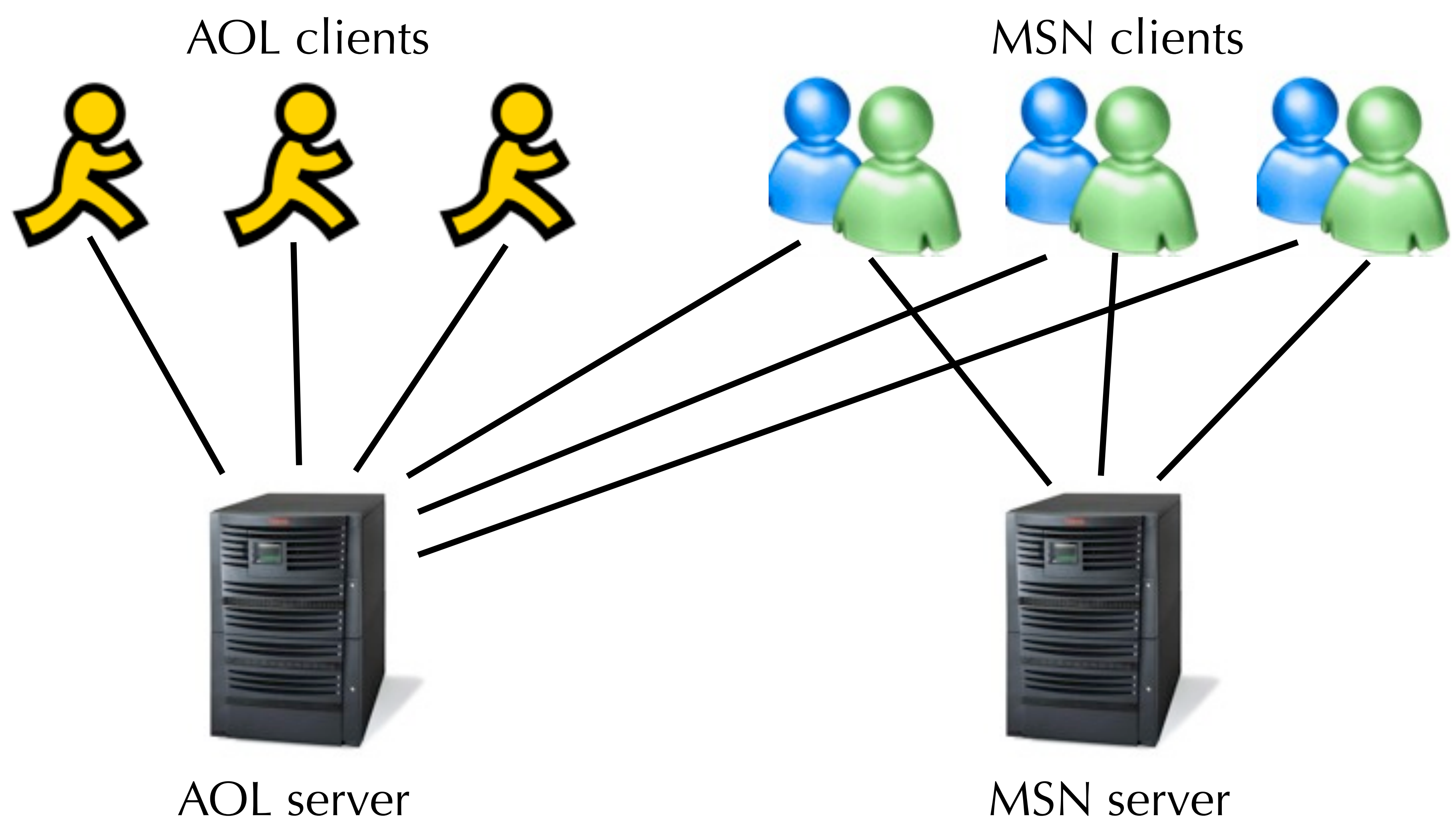

The Instant Messaging Wars of 1999

- Microsoft launches MSN Messenger (instant messaging system).
- MSN clients can also access popular AOL Instant Messaging Service (AIM) servers



The Instant Messaging Wars of 1999

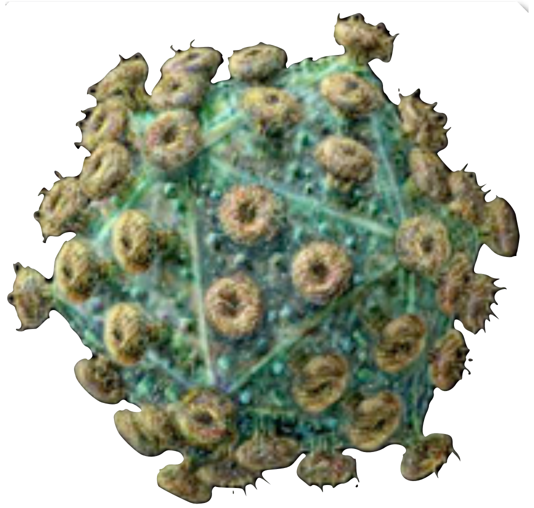
- AOL wanted to prevent MSN clients from accessing its servers.
  - But, the MSN clients mimicked the AIM protocol exactly.
  - And, AOL didn't want to change their protocol – that would require that all of their users download a new client.
- Instead, AOL exploited a buffer overrun bug in their own client!
  - One case of the protocol reads a string into a buffer of size 0x100
  - AIM code was not checking that the string would fit into this size buffer
- AOL crafted an attack on their own client that would:
  - Overflow buffer with about 40 bytes of x86 code
  - Exploit code causes client to read data from a portion of the AIM binary
  - Send that data back to the server, as a kind of "signature"
  - AOL server would only accept the client if it sent back the right signature
- This attack would not work on the MSN client, of course.
  - So MSN clients could not send back the correct signature, and would be rejected.

The Instant Messaging Wars of 1999

- Microsoft caught onto this pretty quick.
  - Changed the MSN client so it would send back the right signature.
- AOL just changed the attack code slightly so a different signature would be sent back to the server.
- Microsoft changed their clients again...
- This skirmish went back and forth 13 times!

Worm vs. Virus

- Worm
  - Spreads from one computer to another
  - Can propagate fully working version of itself to another machine
  - Can spread without human interaction
  - Derived from *tapeworm*: a parasite that lives inside a host and uses its resources to maintain itself.



- Virus
  - Spreads from one computer to another
  - Attaches itself to program or file
  - Cannot exist independently
  - Requires a human action to spread (e.g., executing or opening a file)

Next Lecture

- Processor architecture
  - How does a computer implement machine-level instructions?