Software Vulnerabilities and Exploits

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Imperfect Software

- To be useful, software must process input
  - From files, network connections, keyboard…
- Programmer typically intends his code to manipulate input in particular way
  - e.g., parse HTTP request, retrieve matching content, return it to requestor
- Programs are complex, and often include subtle bugs unforeseen by the programmer
- Fundamentally hard to prevent all programmer error
  - Design itself may use flawed logic
  - Even formal reasoning may not capture all ways in which program may deviate from desired behavior
  - Remember: security is a negative goal…

Imperfect Software (2)

- Even if logic correct, implementation may vary from programmer intent
- C and C++ particularly dangerous
  - Allow arbitrary manipulation of pointers
  - Require programmer-directed allocation and freeing of memory
  - Don't provide memory safety; very difficult to reason about which portions of memory a line of C changes
  - Offer high performance, so extremely prevalent, especially in network servers and OSes
- Java offers memory safety, but not a panacea
  - JRE written in (many thousands of lines of) C!

Software Vulnerabilities and Exploits

- Vulnerability: broadly speaking, input-dependent bug that can cause program to complete operations that deviate from programmer's intent
- Exploit: input that, when presented to program, triggers a particular vulnerability
- Attacker can use exploit to execute operations without authorization on vulnerable host
- Vulnerable program executes with some privilege level
  - Many network servers execute as superuser
  - Users run applications with their own user ID
  - Result: great opportunity for exploits to do harm

Software Vulnerabilities and Exploits

- Vulnerability: broadly speaking, input-dependent bug that can cause program to complete operations that deviate from programmer's intent

Today: vulnerabilities in C programs that **allow an attacker to execute his own arbitrary code within the vulnerable program**

- Vulnerable program executes with some privilege level
  - Many network servers execute as superuser
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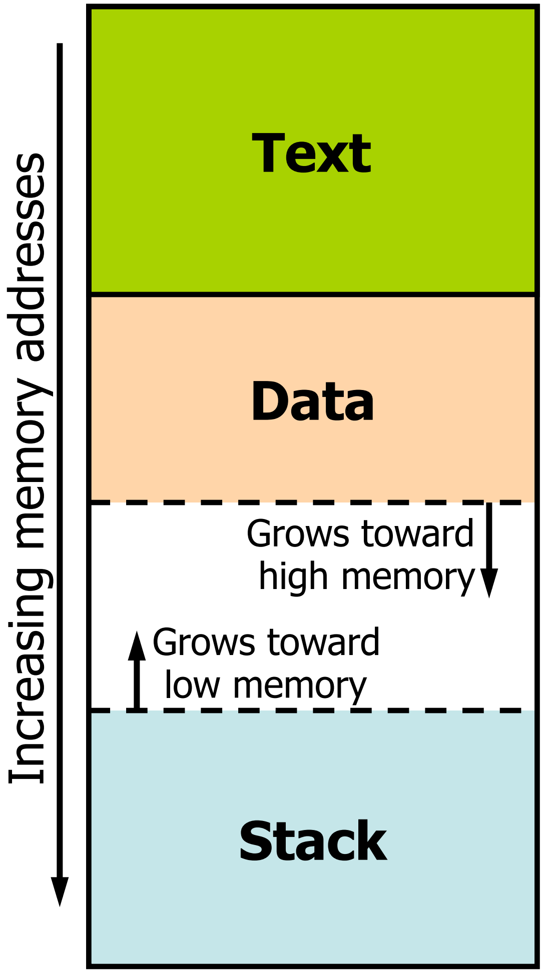
  - Result: great opportunity for exploits to do harm

Buffer Overflows in C: General Idea

- Buffers (arrays) in C manipulated using pointers
- C allows arbitrary arithmetic on pointers
  - Compiler has no notion of size of object pointed to
  - So programmers must explicitly check in code that pointer remains within intended object
  - But programmers often do not do so; **vulnerability!**
- Buffer overflows used in many exploits:
  - Input long data that runs past end of programmer's buffer, over memory that guides program control flow
  - Enclose code you want executed within data
  - Overwrite control flow info with address of your code!

Memory Map of a UNIX Process



Increasing memory addresses

Text

Data

Grows toward high memory

Grows toward low memory

Stack

- Text: executable instructions, read-only data; size fixed at compile time
- Data: initialized and uninitialized; grows towards higher addresses
- Stack: LIFO, holds function arguments and local variables; grows toward lower addresses

Intel X86 Stack: Stack Frames

- Region of stack used within C function: stack frame
- Within function, local variables allocated on stack
- SP register: stack pointer, points to top of stack
- BP register: frame pointer (aka base pointer), points to bottom of stack frame of currently executing function

Intel X86 Stack:
Calling and Returning from Functions

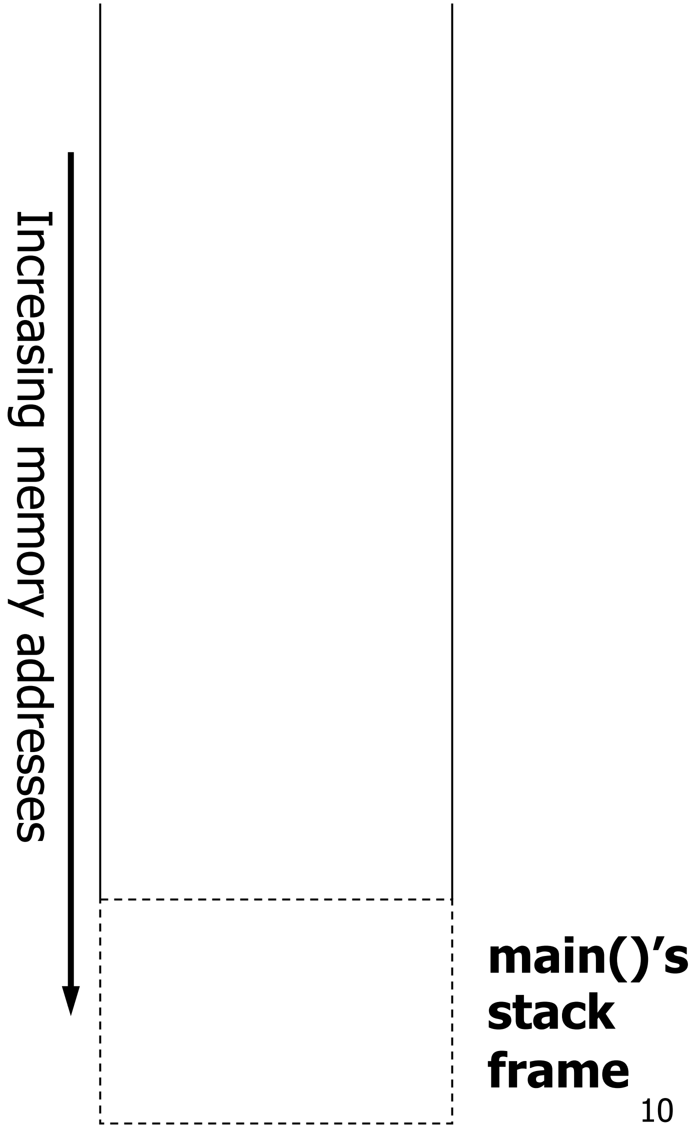
- To call function `f()`, allocate new stack frame:
  - Push arguments, e.g., `f(a, b, c)`
  - Push return address: next instruction (IP) in caller
  - Set IP = address of `f()`; jump to callee
  - Push saved frame pointer: BP for caller's stack frame
  - Set BP = SP; sets frame pointer to start of new frame
  - Set SP -= sizeof(locals); allocates local variables
- Upon return from `f()`, deallocate stack frame:
  - Set SP += sizeof(locals); deallocates local variables
  - Set BP = saved frame pointer from stack; change to caller's stack frame
  - Set IP = saved return address from stack; return to next instruction in caller

Example: Simple C Function Call

```
void dorequest(int a, int b)
{
   char request[256];

   scanf(“%s”, request);
   /* process the request... */
   ...
   return;
}

int main(int argc, char **argv)
{
   while (1) {
        dorequest(17, 38);
        fprintf (log, “completed\n”);
   }
}
```



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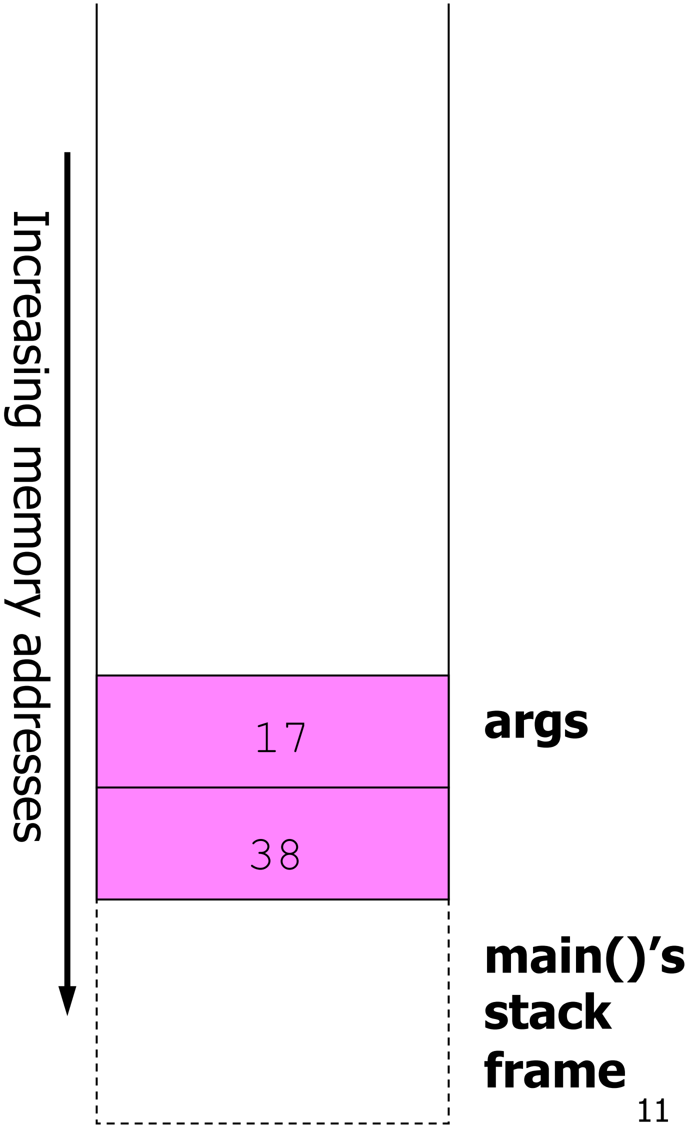

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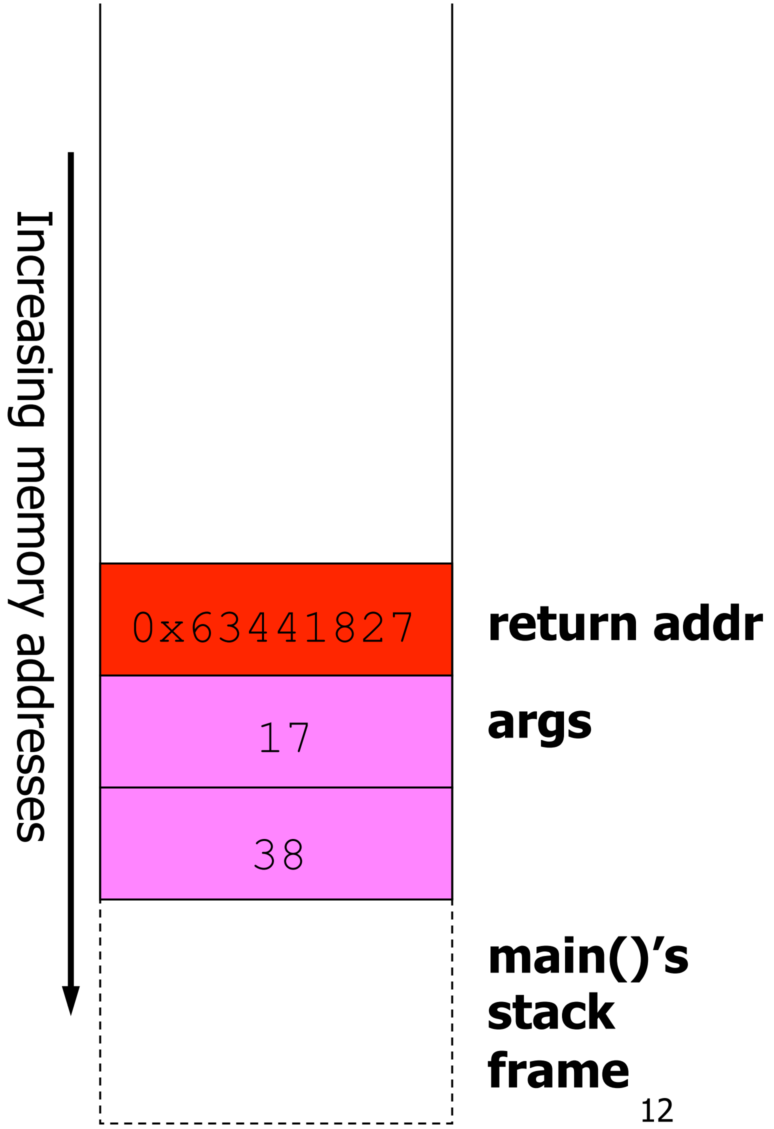

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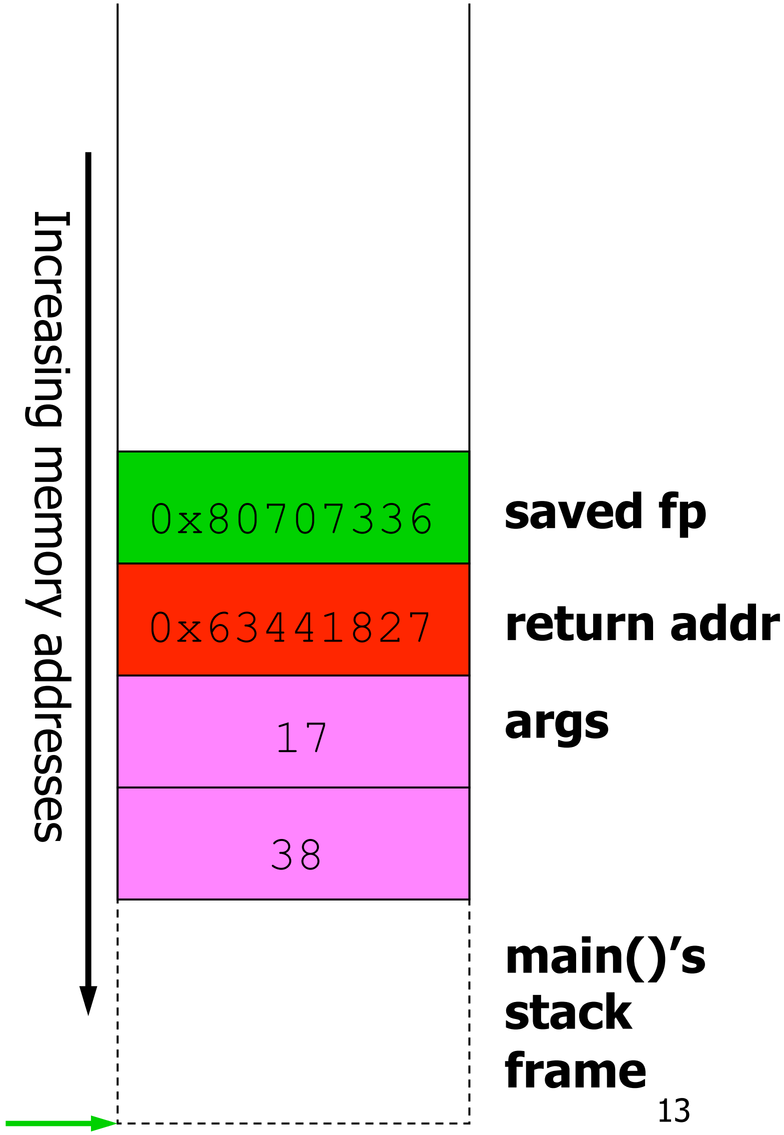

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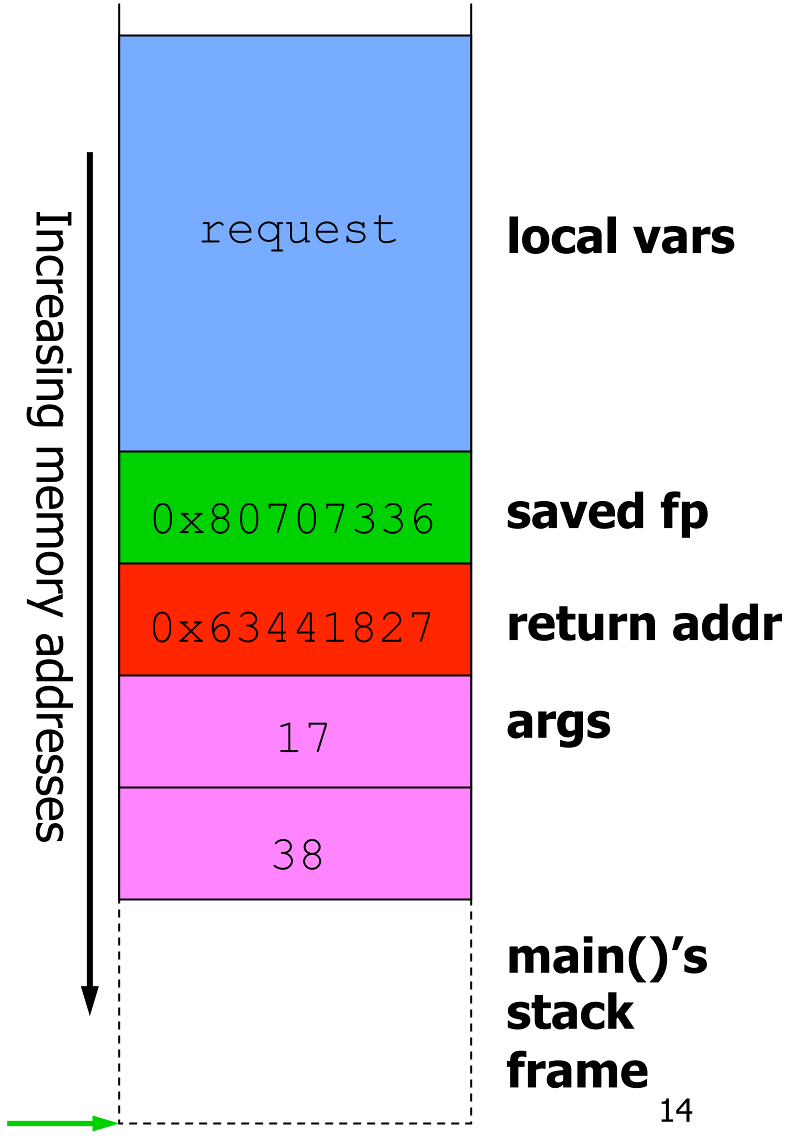

Stack Smashing Exploits: Basic Idea

- Return address stored on stack directly influences program control flow
- Stack frame layout: local variables allocated just before return address
- If programmer allocates buffer as local on stack, reads input, and writes it into buffer without checking input fits in buffer:
  - Send input containing shellcode you wish to run
  - Write past end of buffer, and overwrite return address with address of your code within stack buffer
  - When function returns, your code executes!

Example: Stack Smashing

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void dorequest(int a, int b)
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   char request[256];

   scanf("%s", request);
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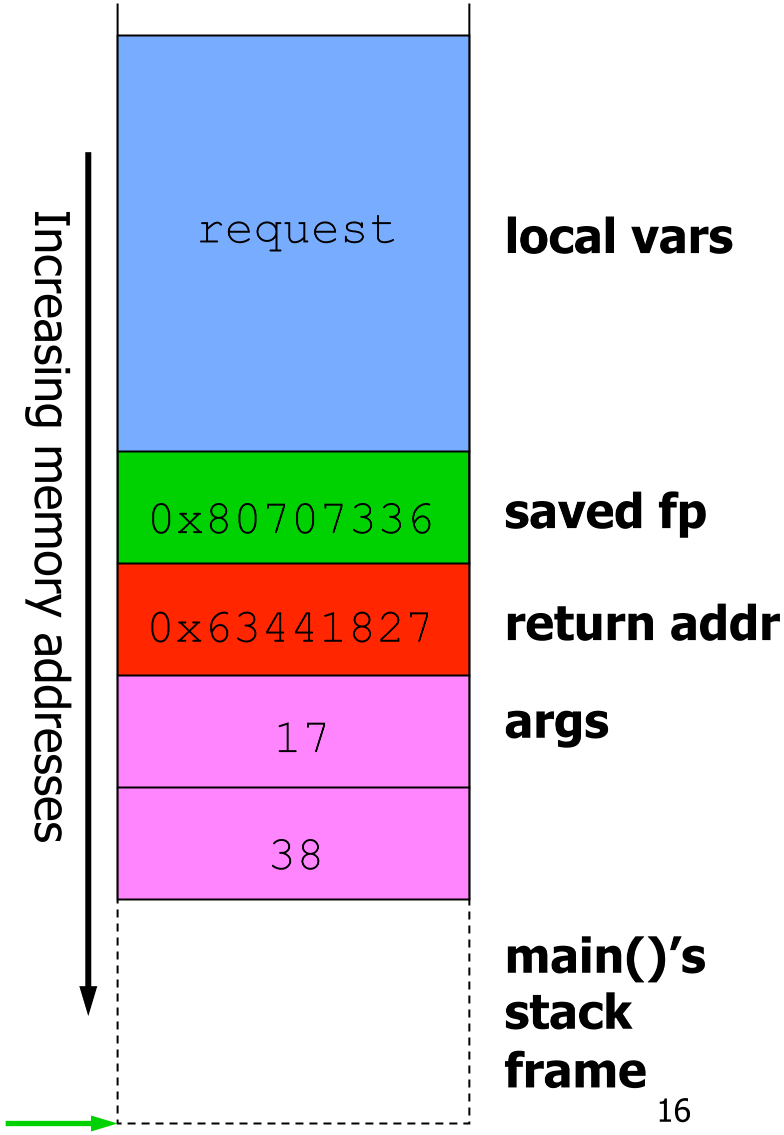

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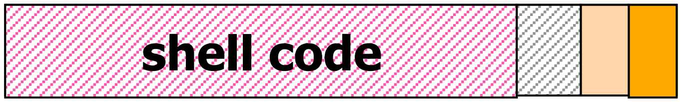
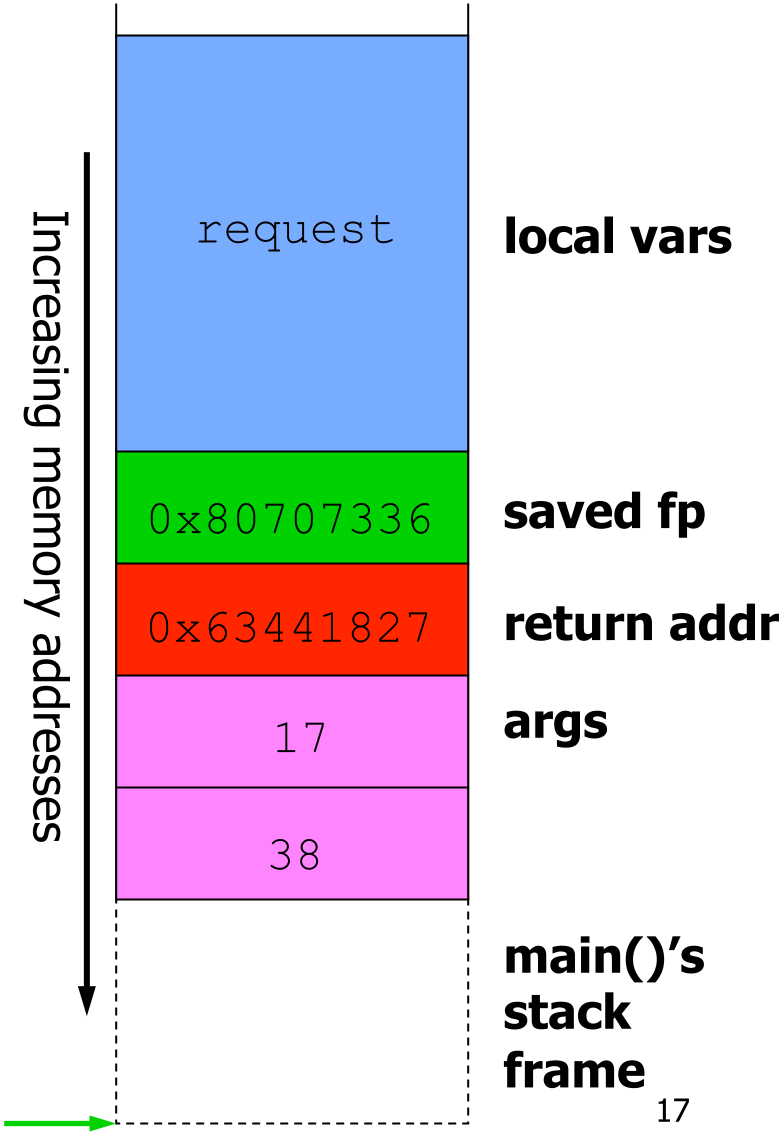
malicious input





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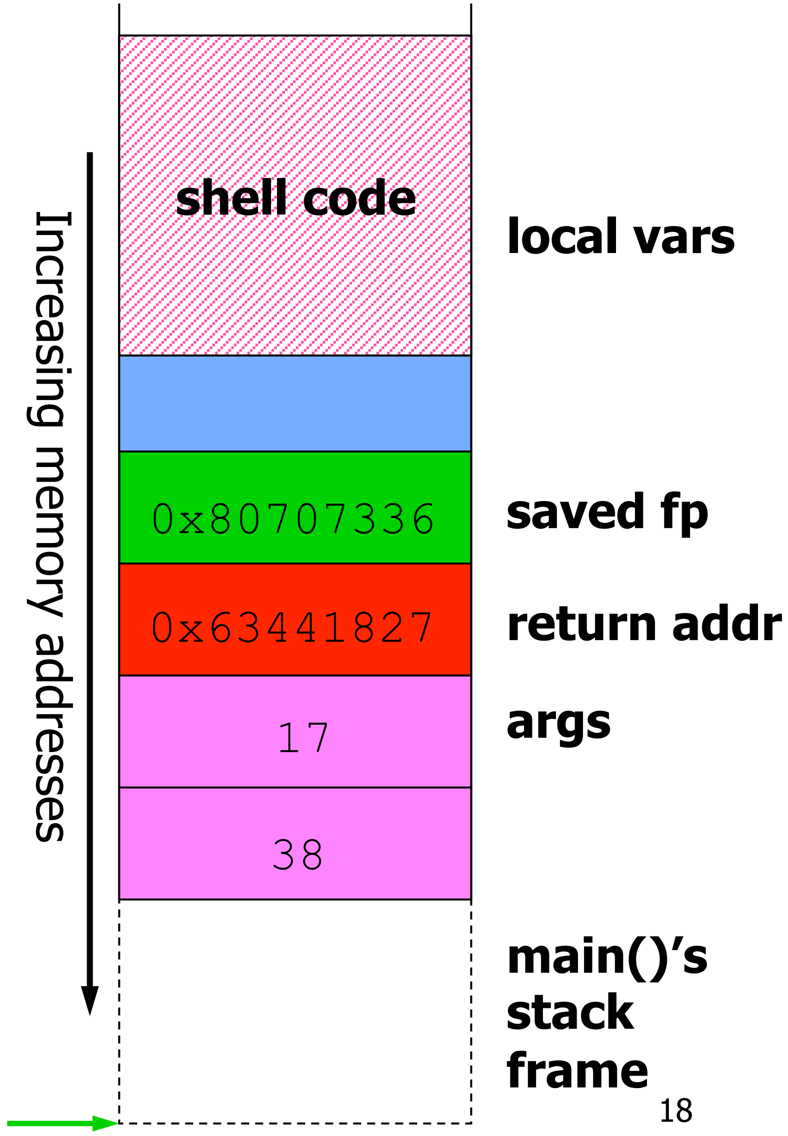

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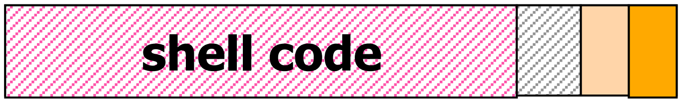

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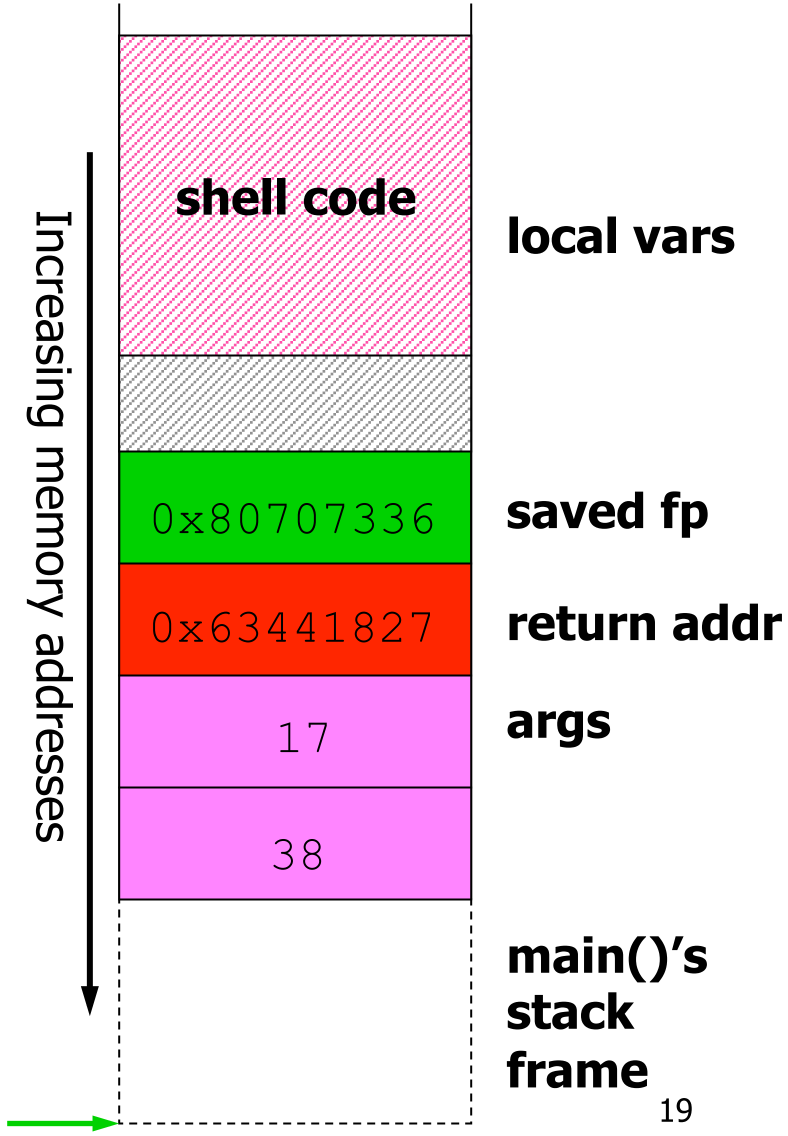

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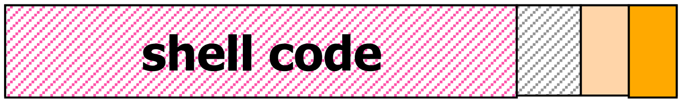

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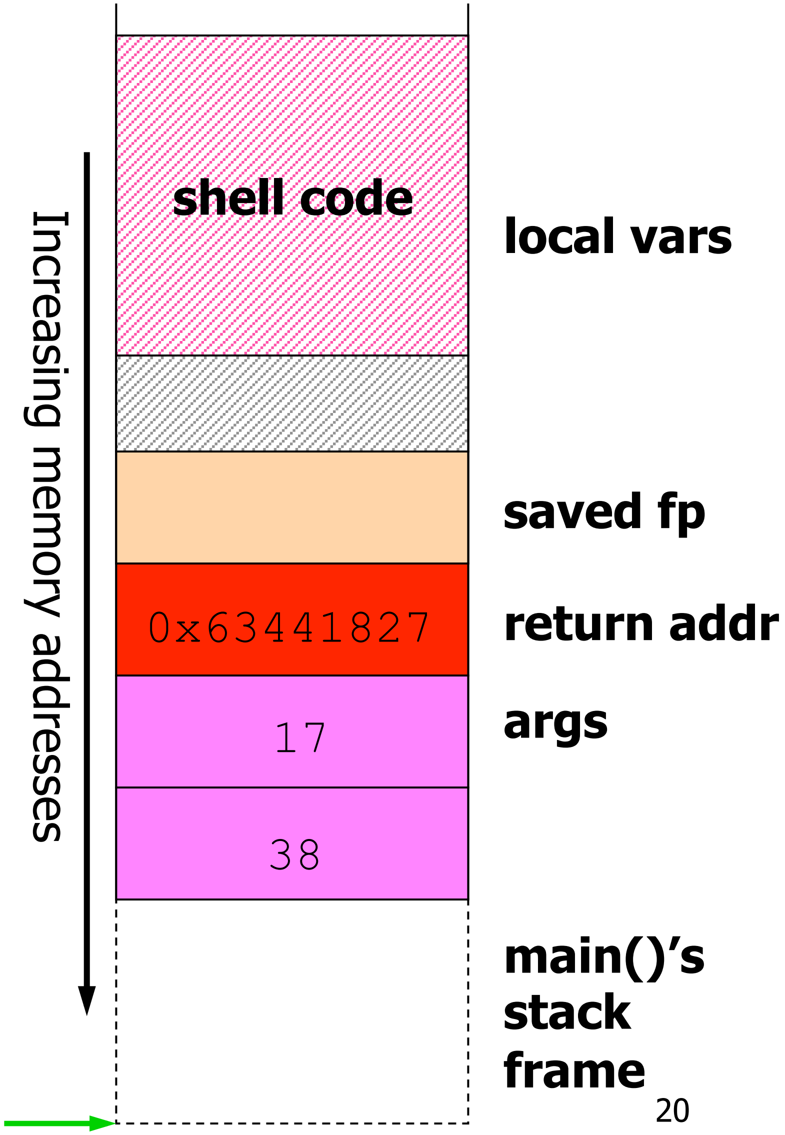

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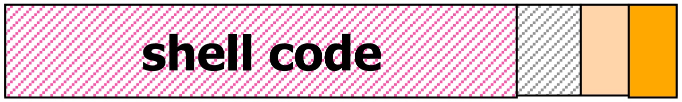

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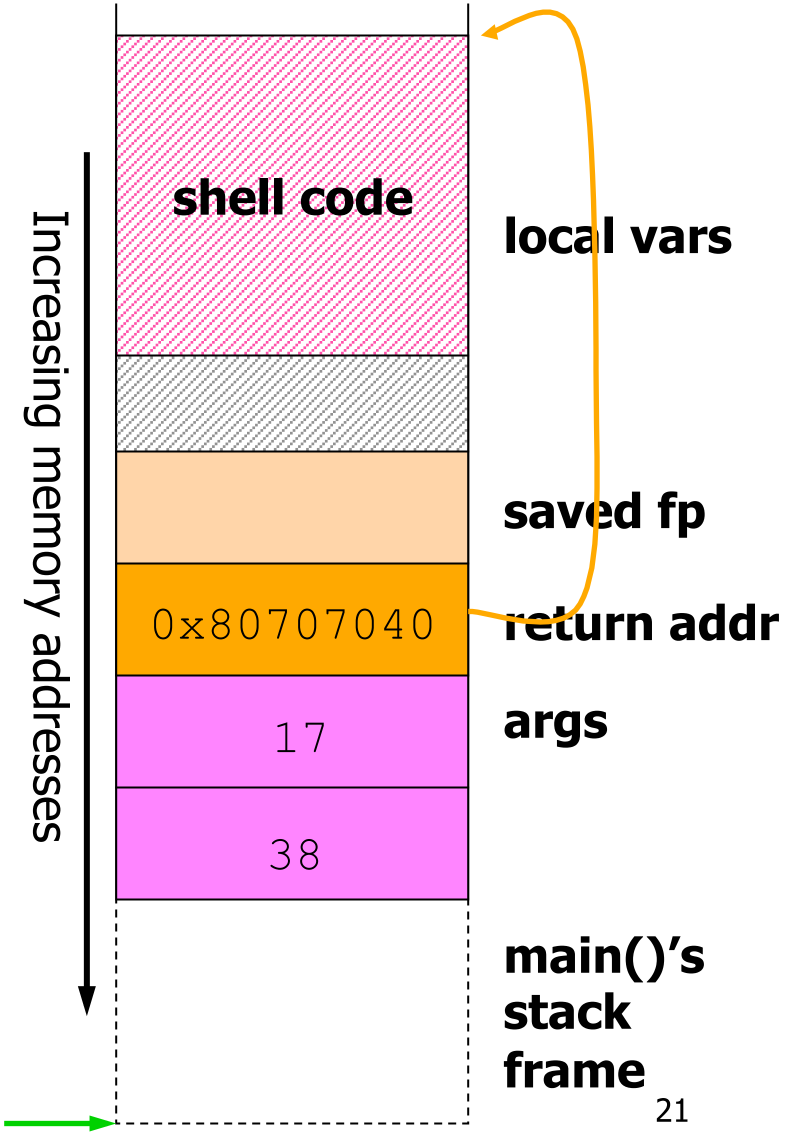

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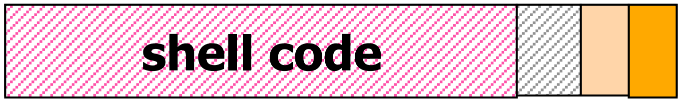

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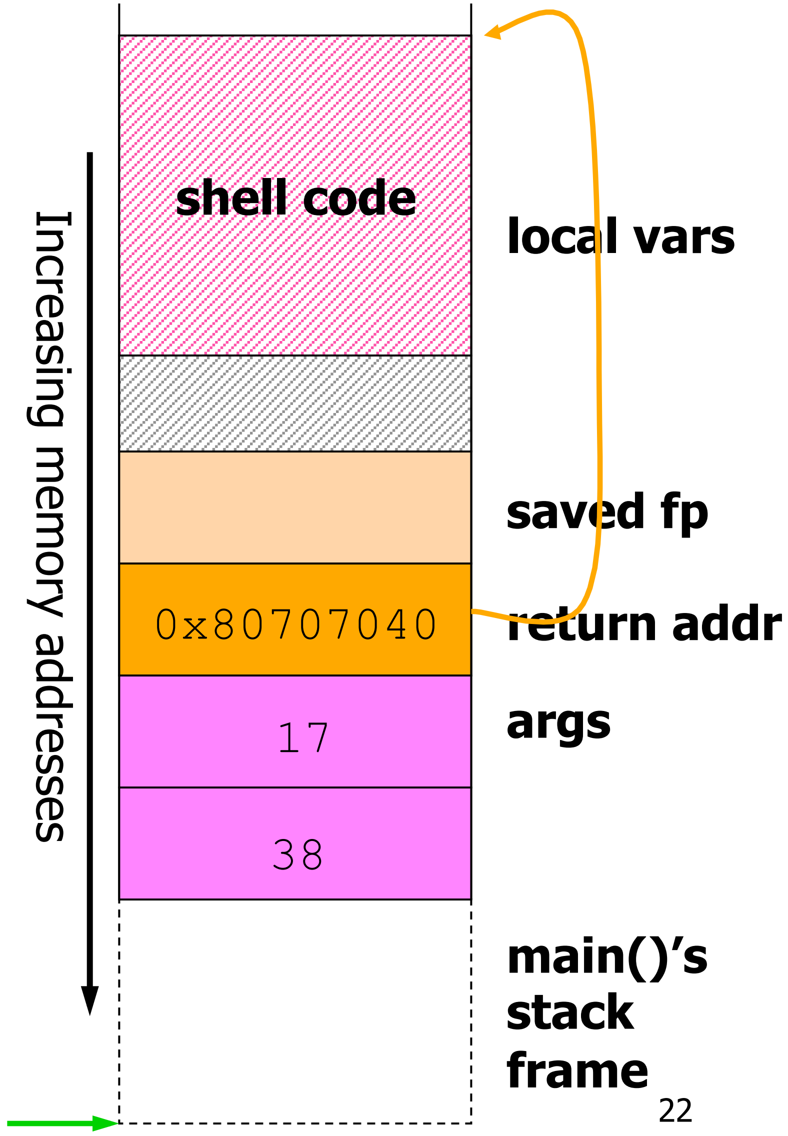
Owned!



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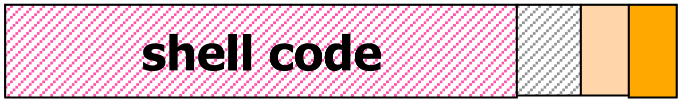

Designing a Stack Smashing Exploit

- In our example, attacker had to know:
  - existence of stack-allocated buffer without bounds check in program
  - exact address for start of stack-allocated buffer
  - exact offset of return address beyond buffer start
- Hard to predict these exact values:
  - stack size before call to function containing vulnerability may vary, changing exact buffer address
  - attacker may not know exact buffer size
- Don’t need to know either exact value, though!

Designing a Stack Smashing Exploit (2)

- No need to know exact return address:
  - Precede shellcode with NOP slide: long sequence of NOPs (or equivalent instructions)
  - So long as jump into NOP slide, shellcode executes
  - Effect: range of return addresses works
- No need to know exact offset of return address beyond buffer start:
  - Repeat shellcode's address many times in input
  - So long as first instance occurs before return address's location on stack, and enough repeats, will overwrite it

Example: Stack Smashing “2.0”

```
void dorequest(int a, int b)
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   char request[256];

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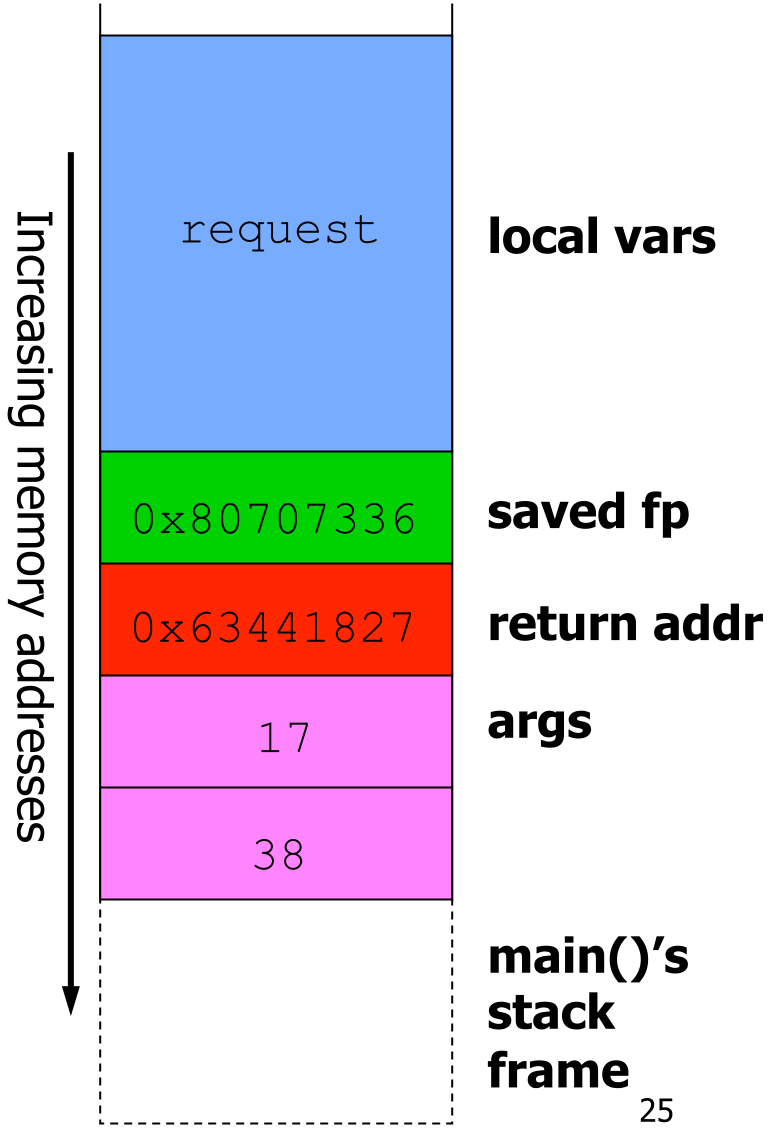

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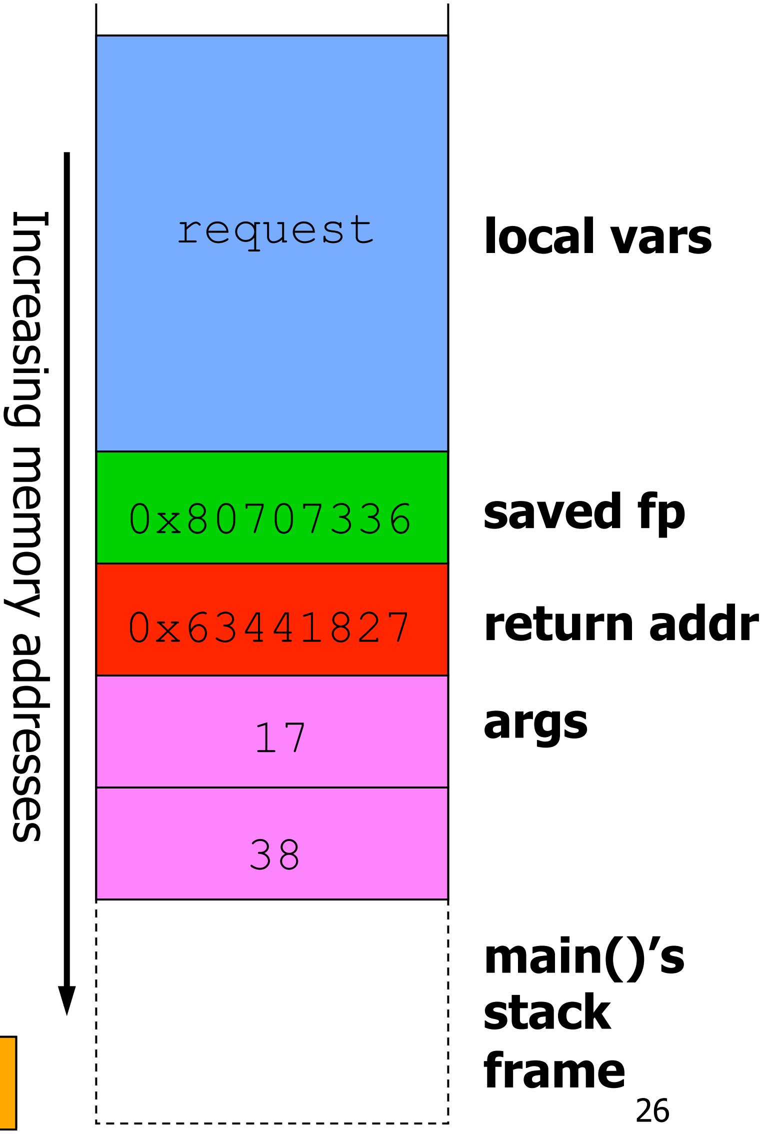

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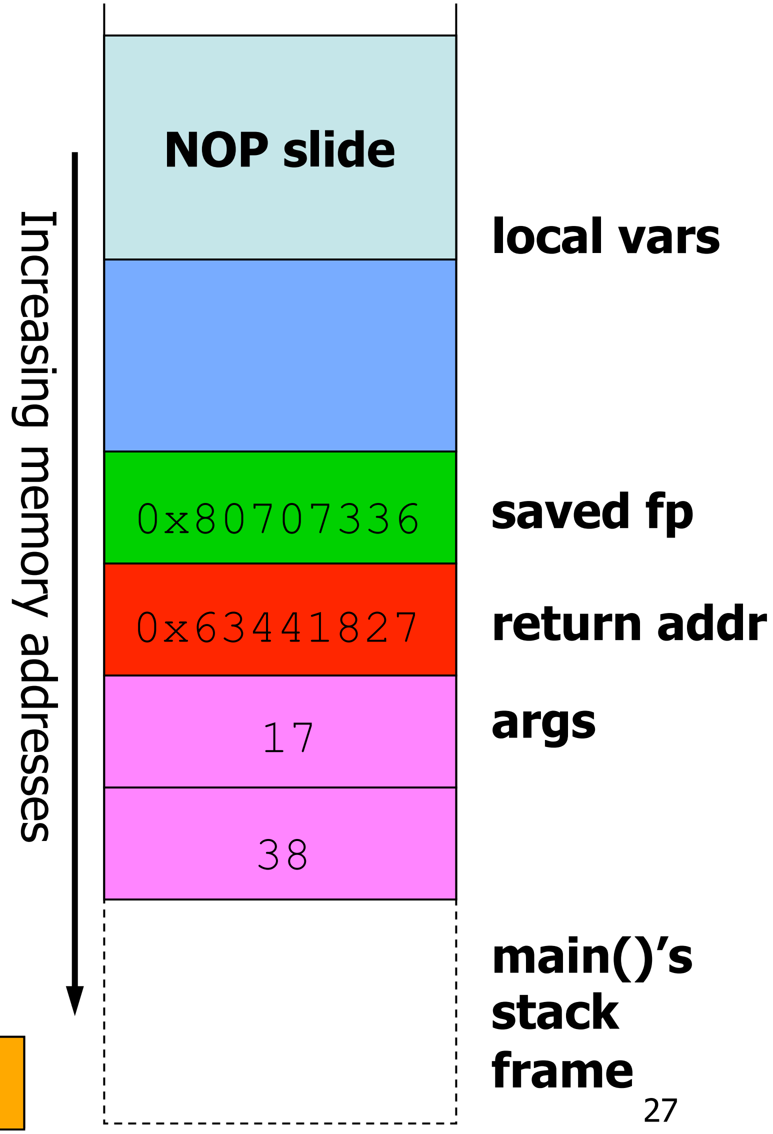

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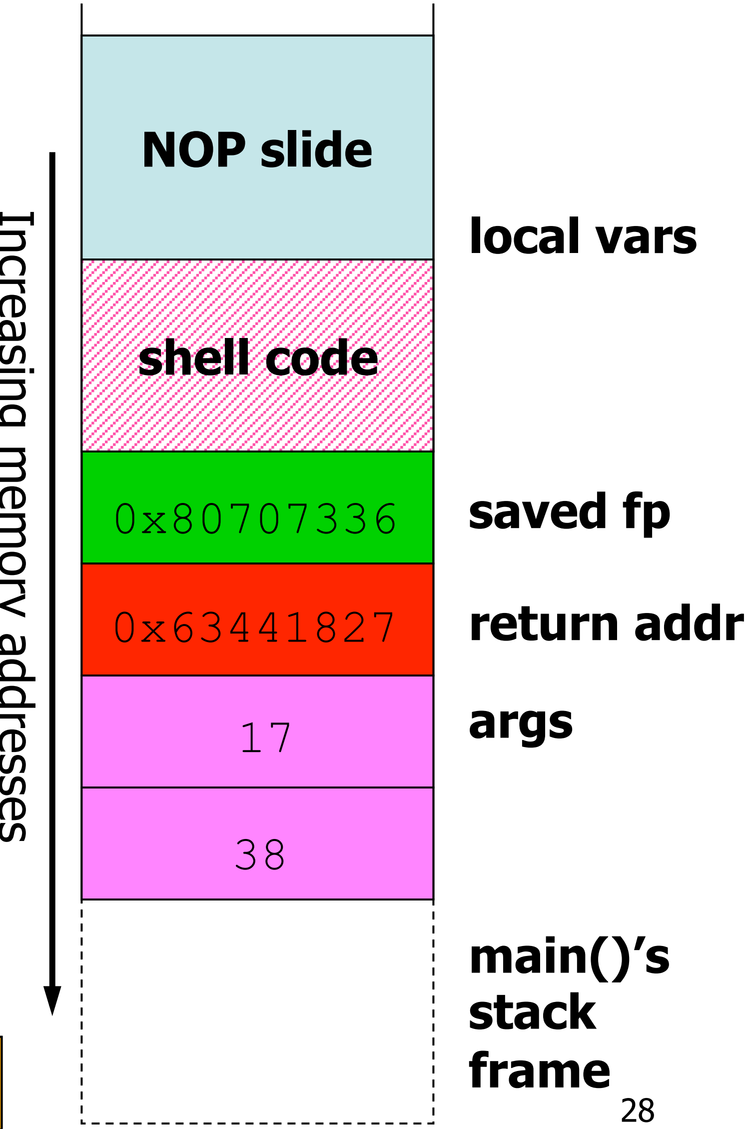

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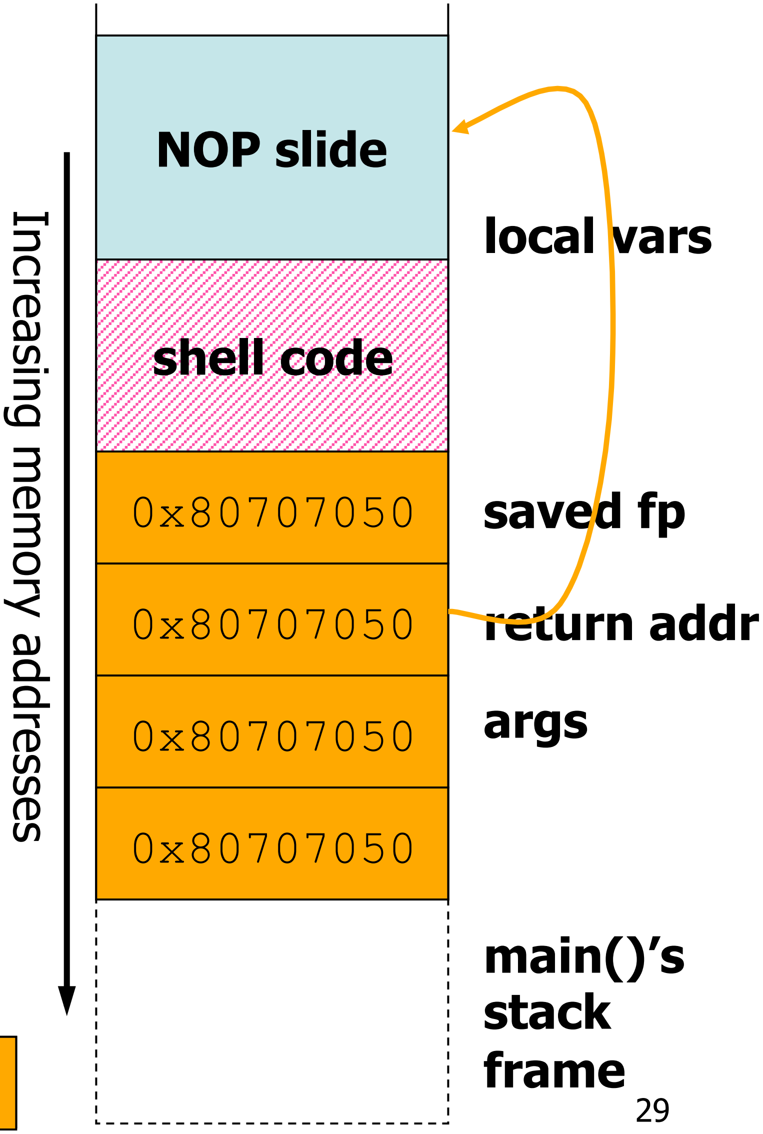


malicious input

Designing Practical Shellcode

- Shellcode normally executes /bin/sh; gives attacker a shell on exploited machine
- shellcode.c:

```
void main()
{
  char *name[2];
  name[0] = "/bin/sh";
  name[1] = NULL;
  execve(name[0], name, NULL);
  exit(0); /* if execve fails, don’t */
}          /* dump core */
```

Designing Practical Shellcode (2)

- Compile shellcode.c, disassemble in gdb to get hex representation of instructions
- Problem: to call execve(), must know exact address of string "/bin/sh" in memory (i.e., within stack buffer)
  - Difficult to predict, as before

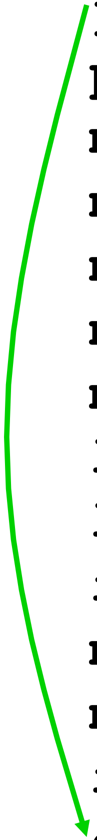
Designing Practical Shellcode (3)

- Both jmp and call instructions allow IP-relative addressing
  - Specify target by offset from current IP, not by absolute address
- Finding absolute address of "/bin/sh" at runtime:
  - add `call` instruction at end of shellcode, with target of first shellcode instruction, using relative addressing
  - place "/bin/sh" immediately after `call` instruction
  - `call` will push next "instruction's" address onto stack
  - precede first shellcode instruction with `jmp` to `call`, using relative addressing
  - after `call`, stack will contain address of "/bin/sh"

Practical Shellcode Example

```
jmp 0x2a # 3 bytes
popl %esi # 1 byte
movl %esi,0x8(%esi) # 3 bytes
movb $0x0,0x7(%esi) # 4 bytes
movl $0x0,0xc(%esi) # 7 bytes
movl $0xb,%eax # 5 bytes
movl %esi,%ebx # 2 bytes
leal 0x8(%esi),%ecx # 3 bytes
leal 0xc(%esi),%edx # 3 bytes
int $0x80 # 2 bytes
movl $0x1, %eax # 5 bytes
movl $0x0, %ebx # 5 bytes
int $0x80 # 2 bytes
call -0x2f # 5 bytes
.string \"/bin/sh\" # 8 bytes
```

Practical Shellcode Example



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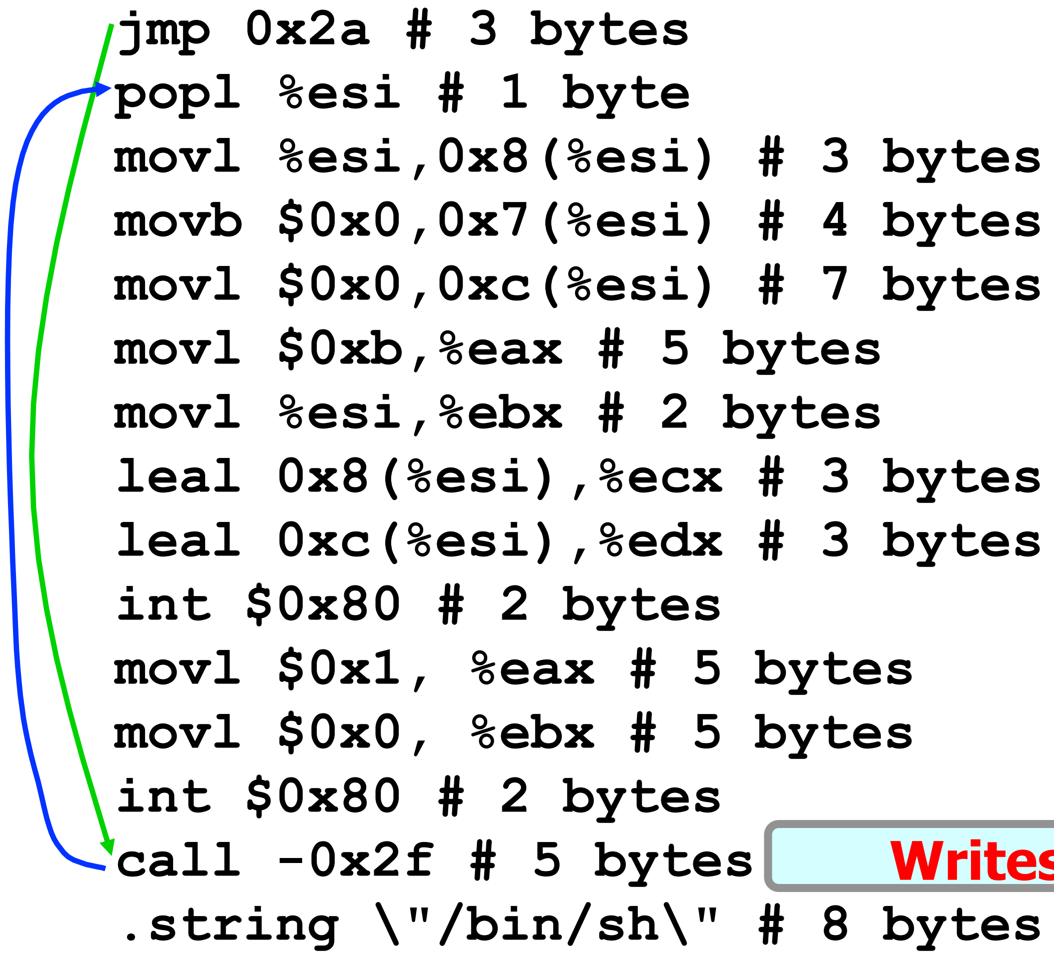
Writes string address on stack!

Practical Shellcode Example



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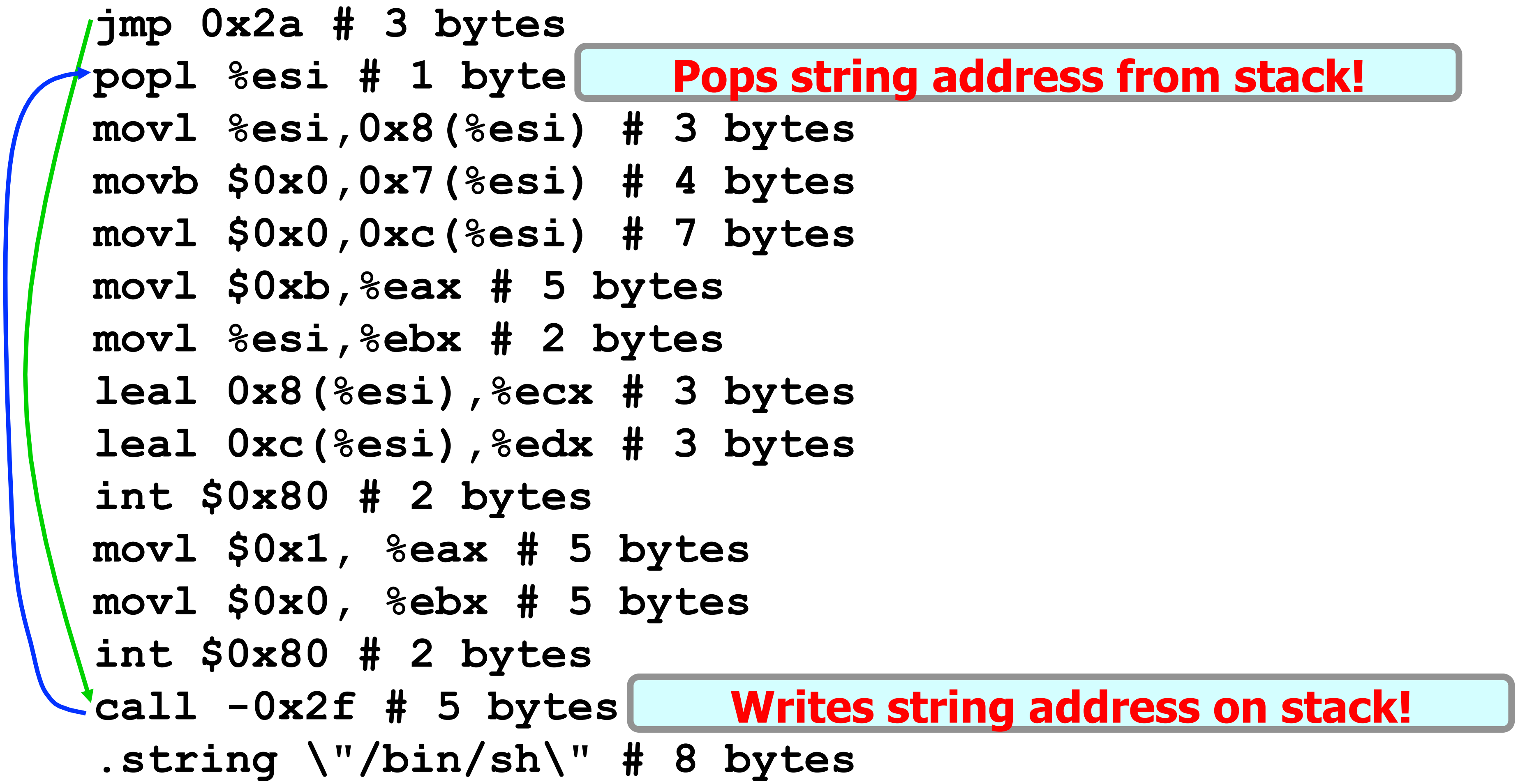

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Pops string address from stack!

Writes string address on stack!

Eliminating Null Bytes in Shellcode

- Often vulnerability copies string into buffer
- C marks end of string with zero byte
  - So functions like `strcpy()` will stop copying if they encounter zero byte in shellcode instructions!
- Solution: replace shellcode instructions containing zero bytes with equivalent instructions that don’t contain zeroes in their encodings

Defensive Coding to Avoid Buffer Overflows

- **Always explicitly check input length against target buffer size**
- Avoid C library calls that don't do length checking:
  - e.g., `sprintf(buf, …), scanf("%s", buf), strcpy(buf, input)`
- Better:
  - `snprintf(buf, buflen, …), scanf("%256s", buf), strncpy(buf, input, 256)`

Overview: Format String Vulnerabilities and Exploits

- Recall C's `printf`-like functions:
  - `printf(char *fmtstr, arg1, arg2, …)`
  - e.g., `printf("%d %d", 17, 42);`
  - Format string in 1st argument specifies number and type of further arguments
- Vulnerability:
  - If programmer allows input to be used as format string, attacker can force `printf`-like function to overwrite memory
  - So attacker can devise exploit input that includes shellcode, overwrites return address…

Background: %n Format String Specifier

- "%n" format string specifier directs printf to write number of bytes written thus far into the integer pointed to by the matching int * argument
- Example:

```
int i;
printf("foobar%n\n", (int *) &i));
printf("i = %d\n", i);
```

- Output:

```
foobar
i = 6
```

Abusing %n to Overwrite Memory

- printf’s caller often allocates format string buffer on stack
- C pushes parameters onto stack in right-to-left order
  - format string pointer on top of stack, last arg on bottom
- printf() increments pointer to point to successive arguments

```
[suppose input = “%d%d%d\n”]
char fmt[26];
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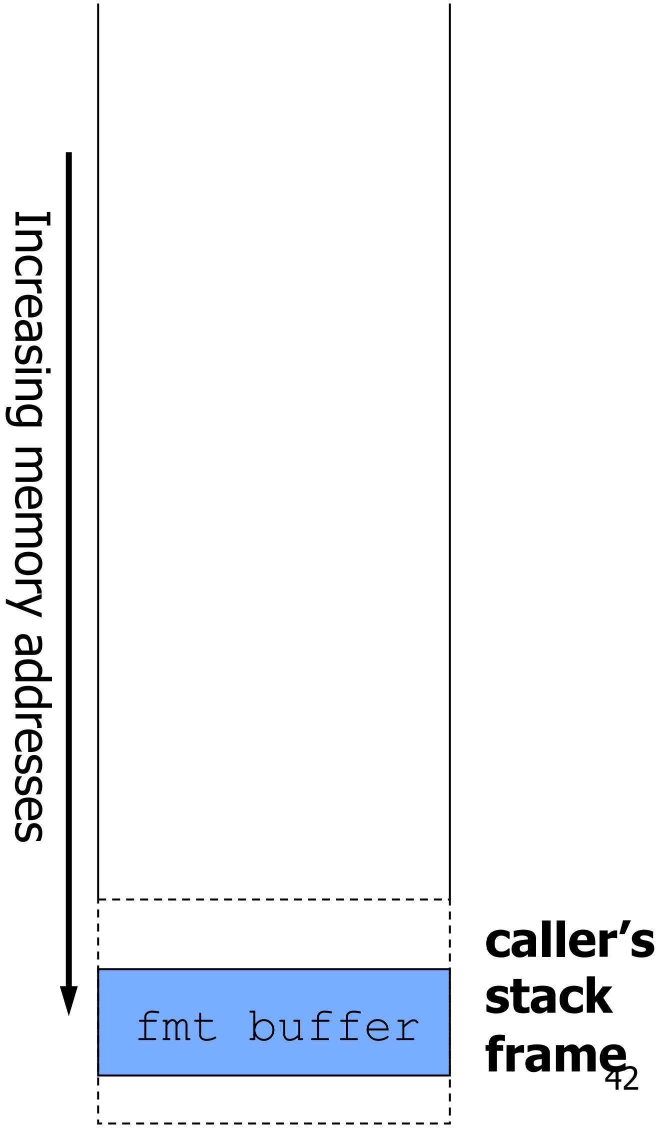

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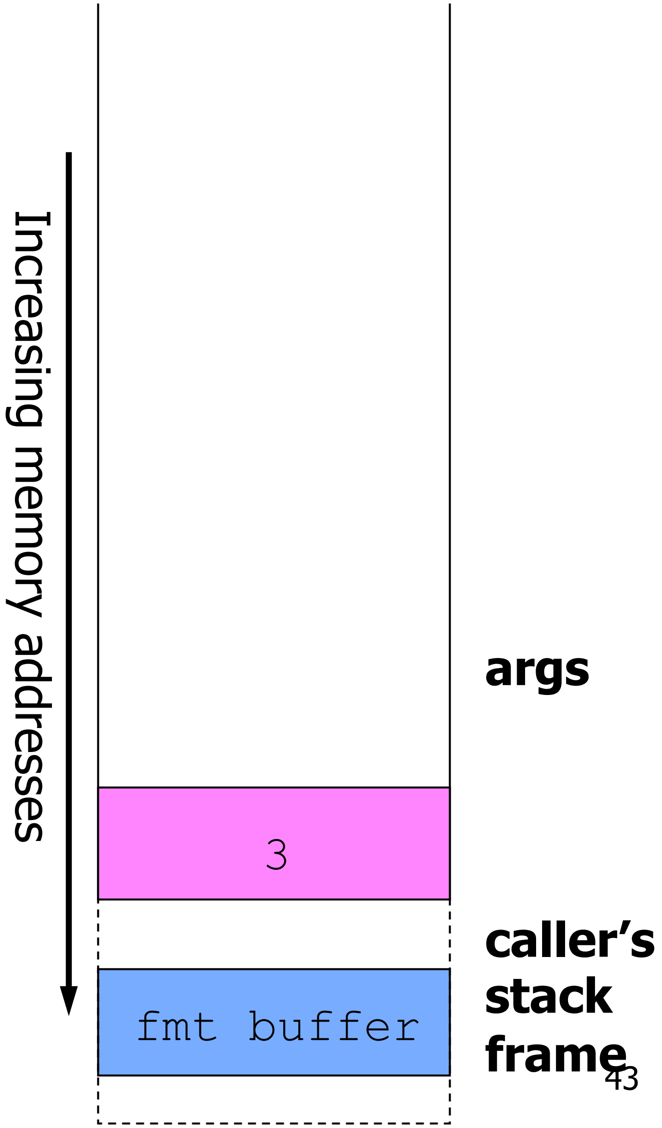

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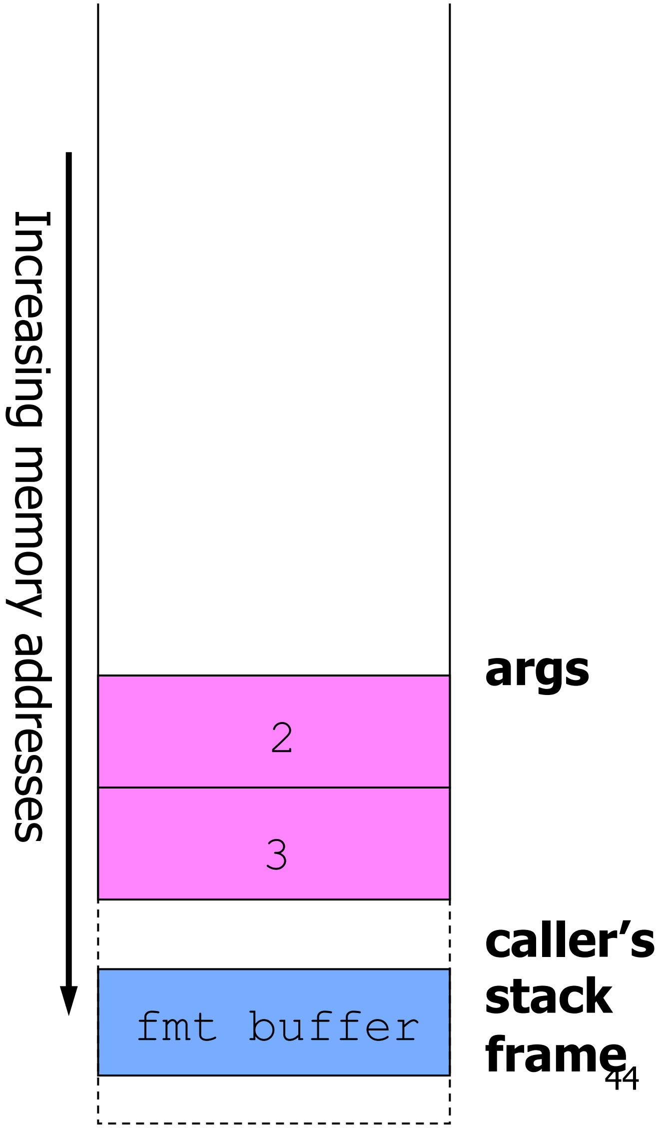

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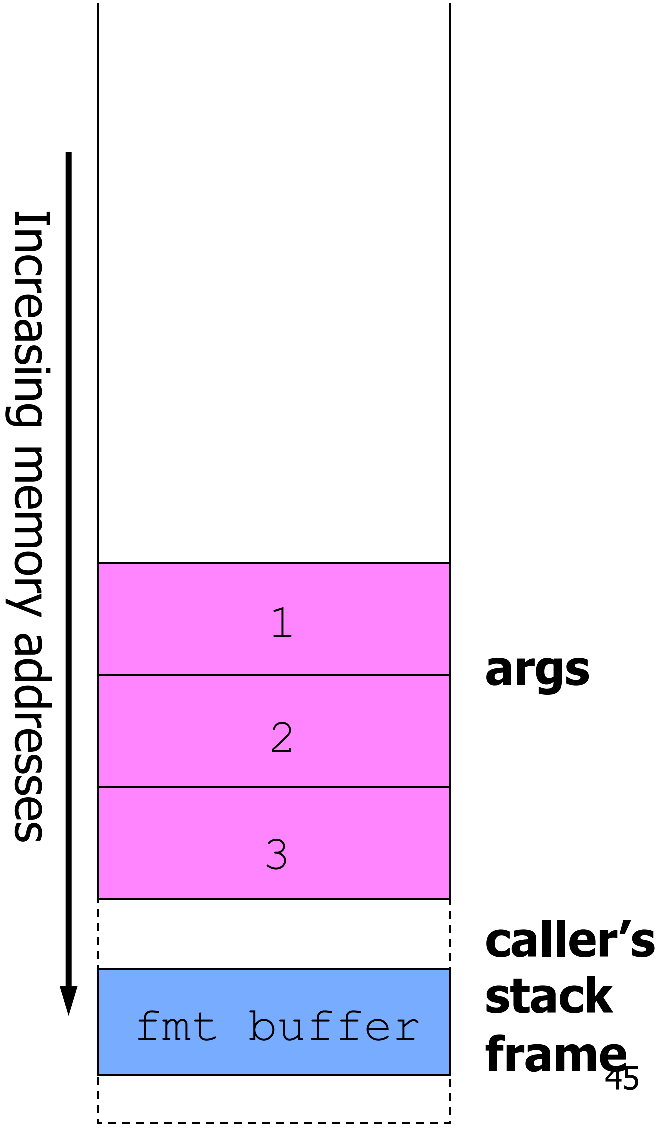

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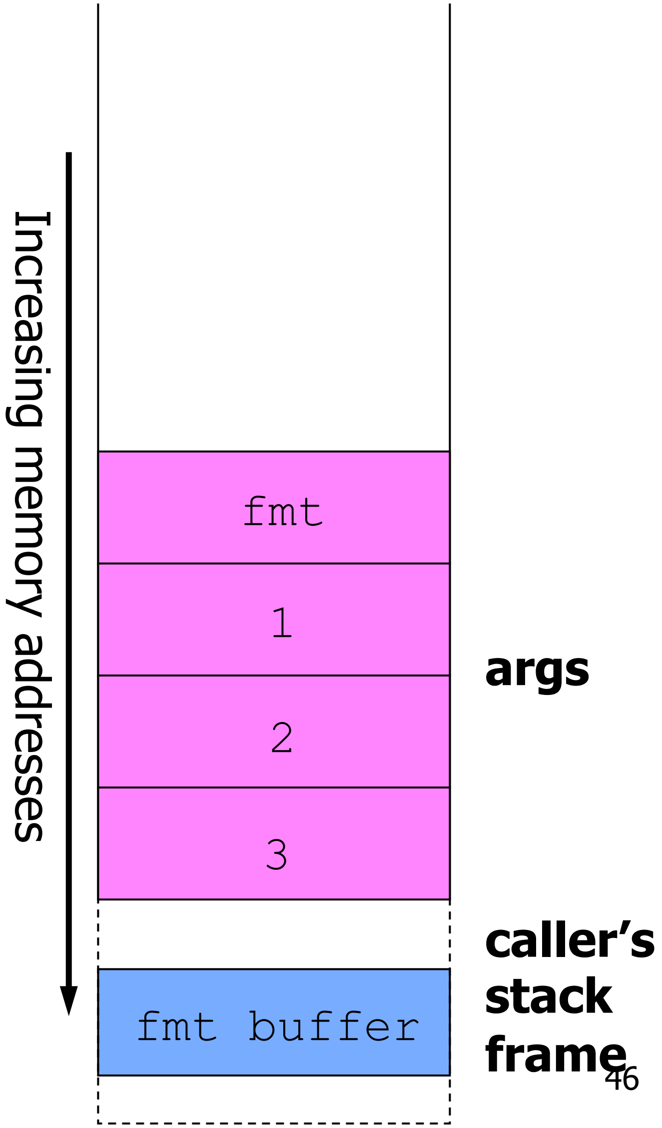

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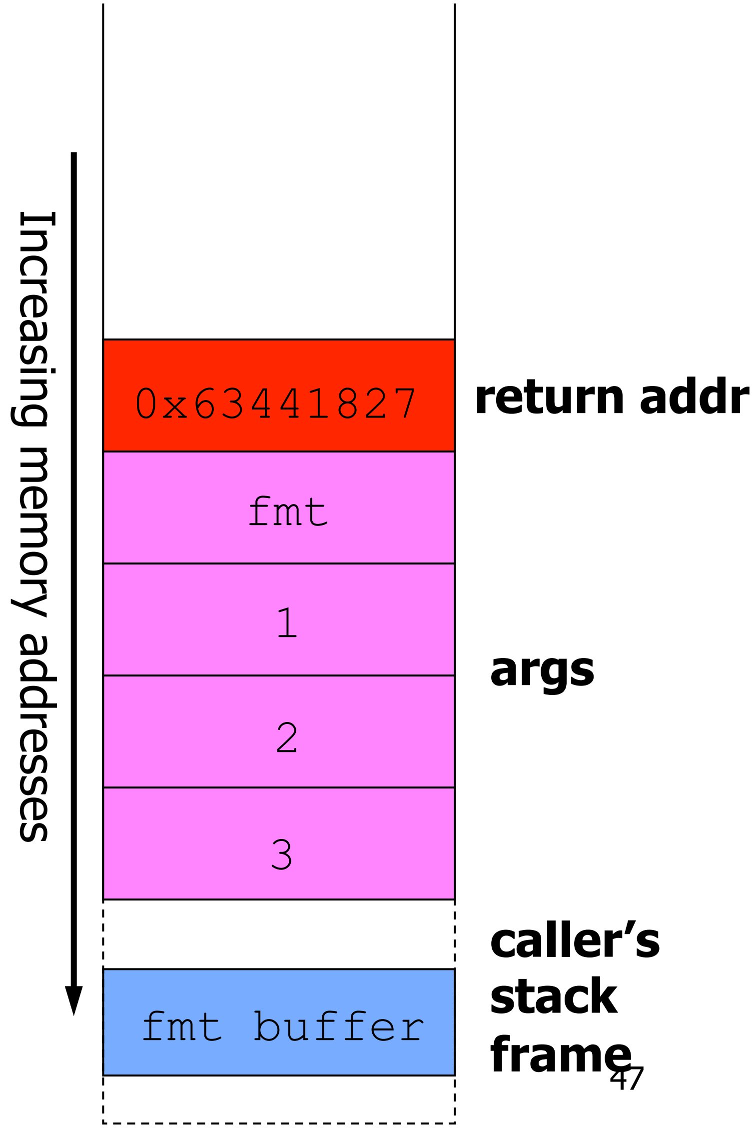

Increasing memory addresses

0x63441827 **return addr**

fmt

1

2 **args**

3

fmt buffer **caller’s stack frame**

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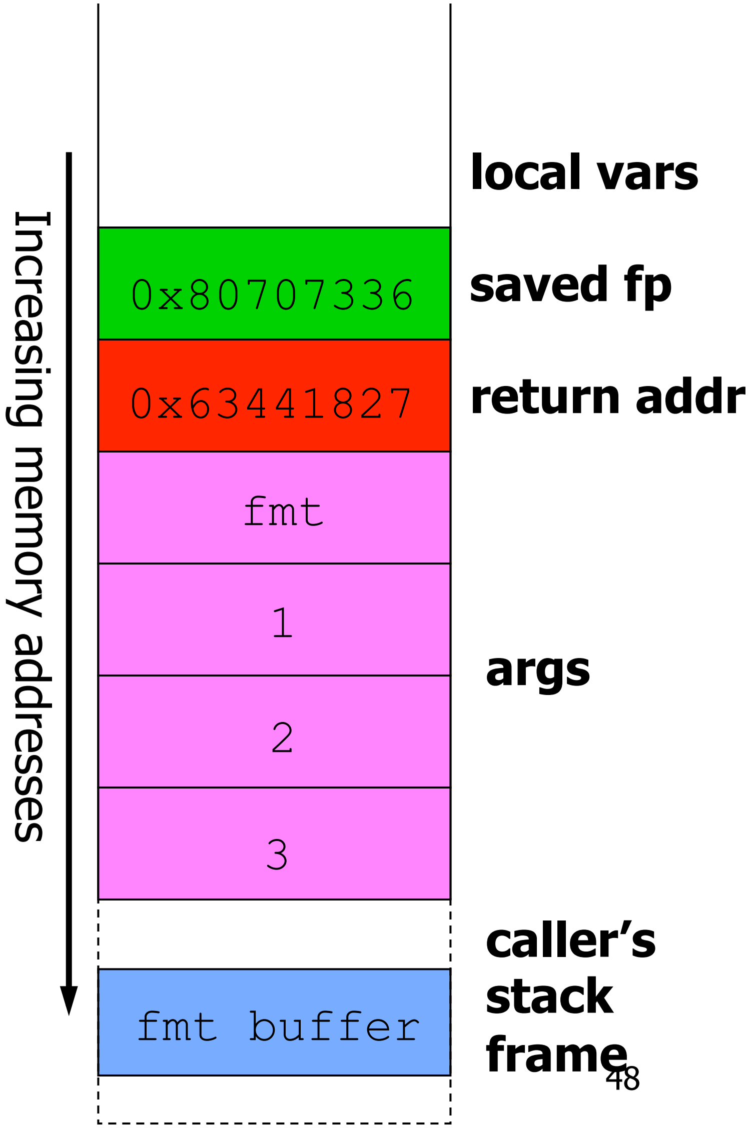

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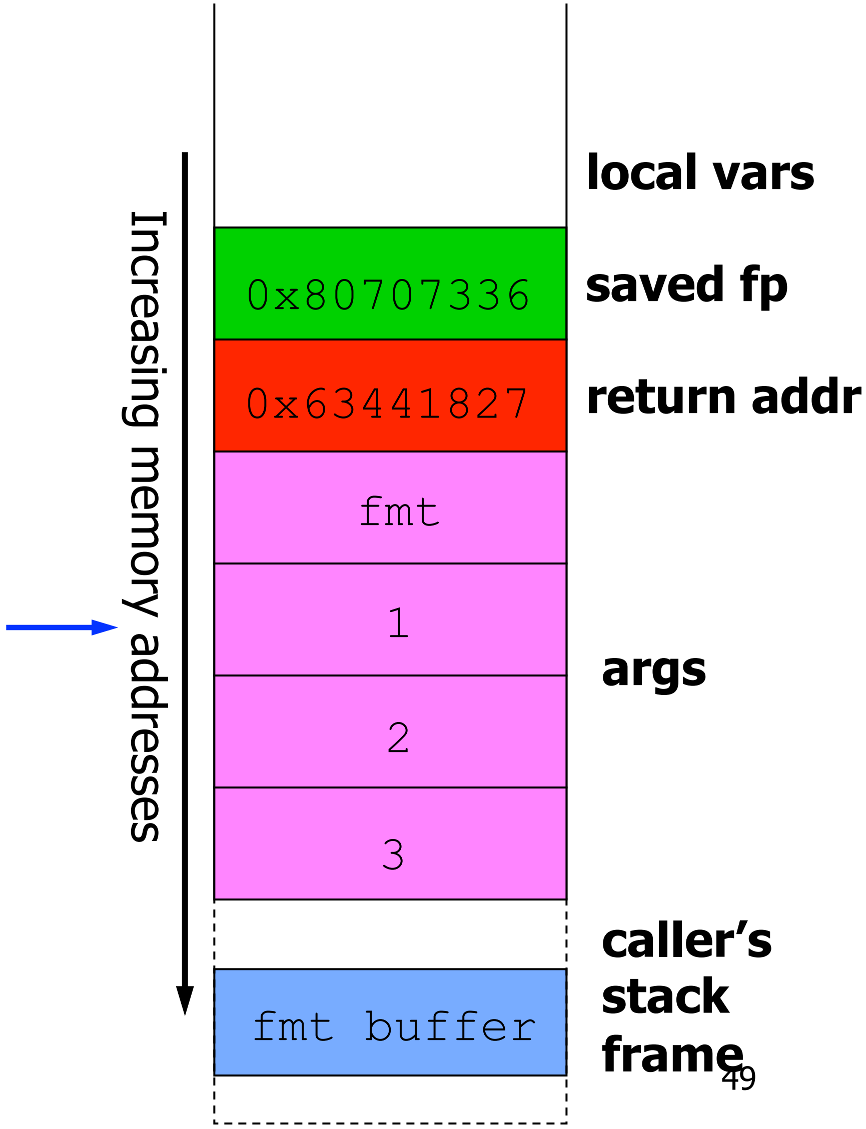

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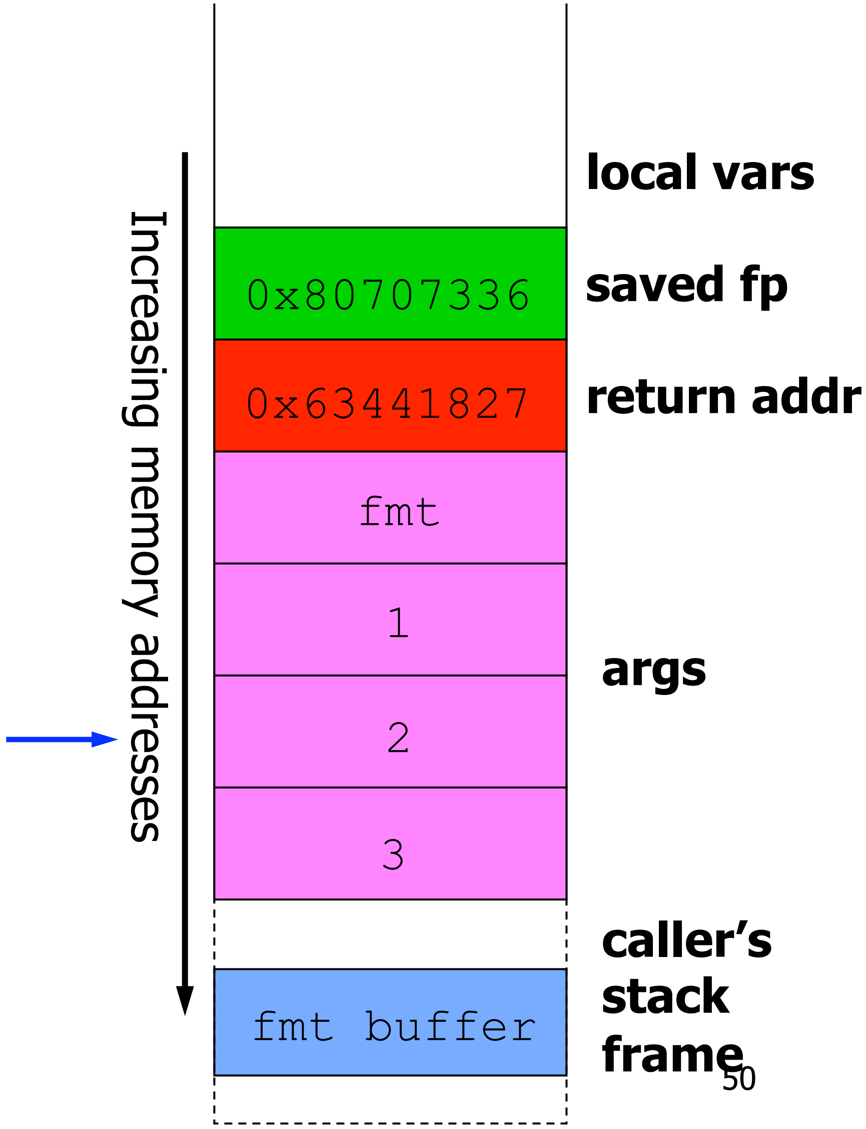

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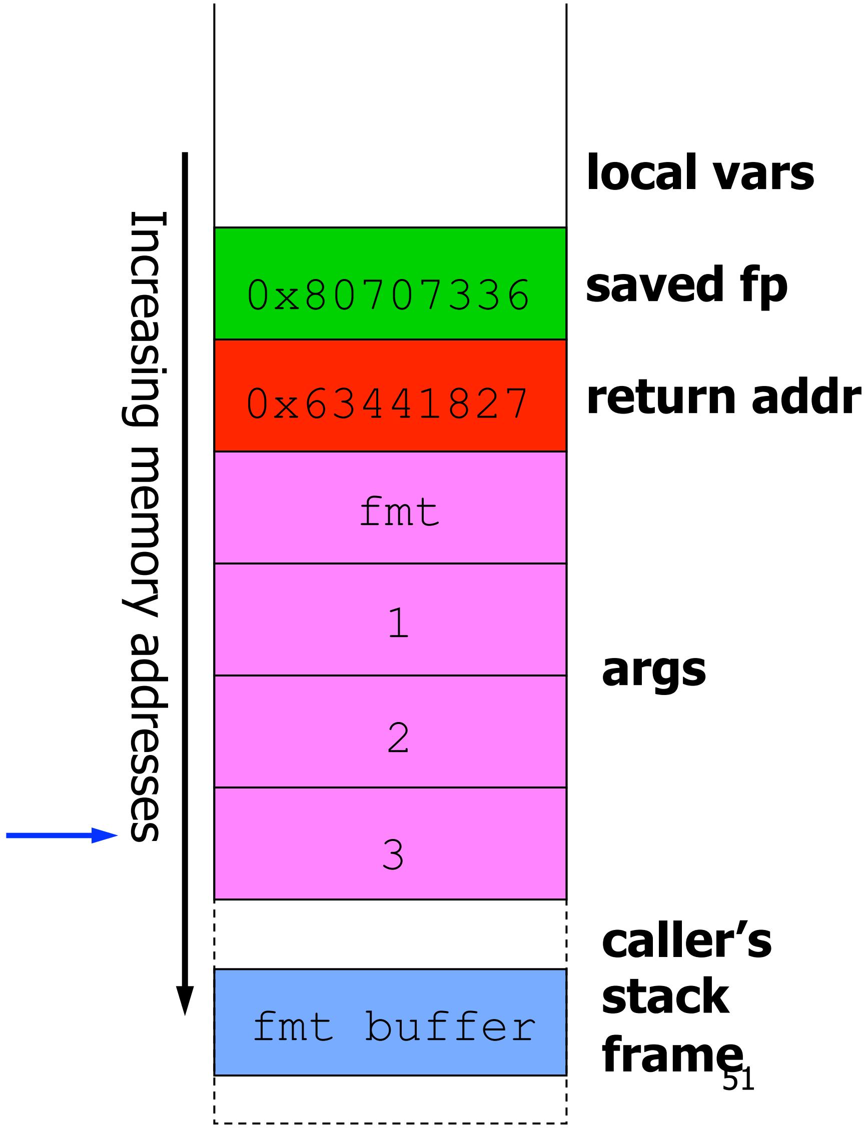

Abusing %n to Overwrite Memory (2)

- Idea:
  - Use specifiers in format string to increment printf()'s arg pointer so it points to format string itself
  - Supply target address to write at start of format string
  - Supply "%n" at end of format string

```
[input =
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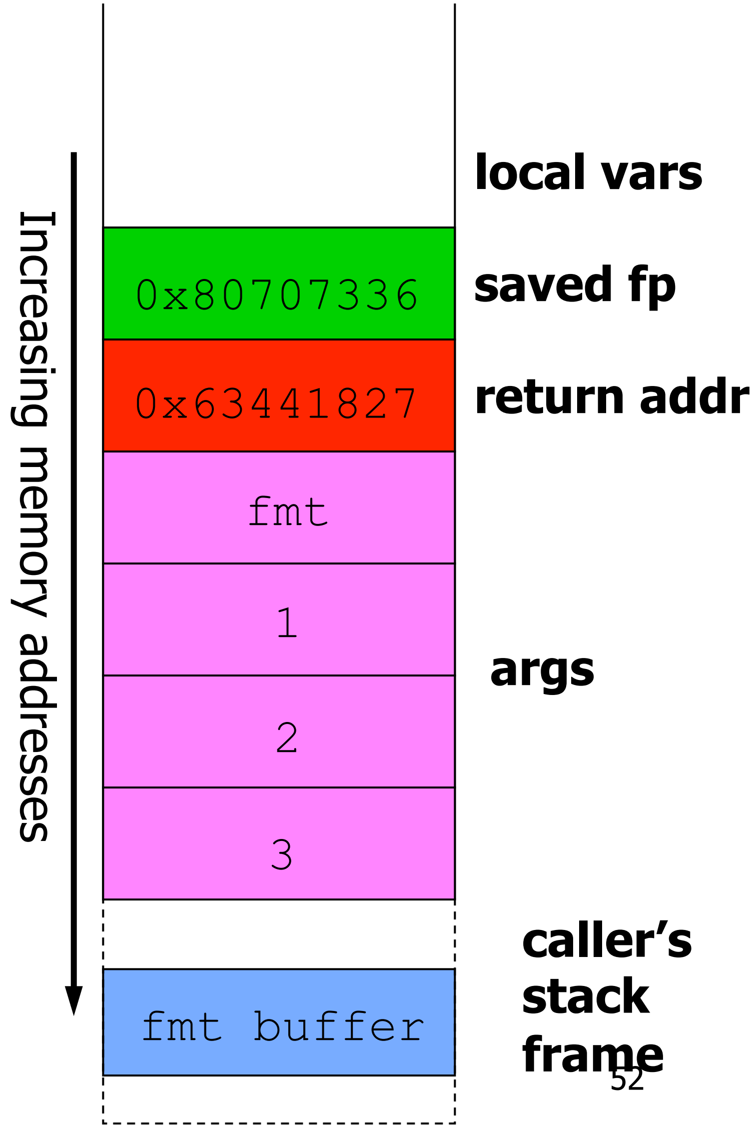
Increasing memory addresses

local vars

0x80707336 saved fp

0x63441827 return addr

fmt

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args

fmt buffer

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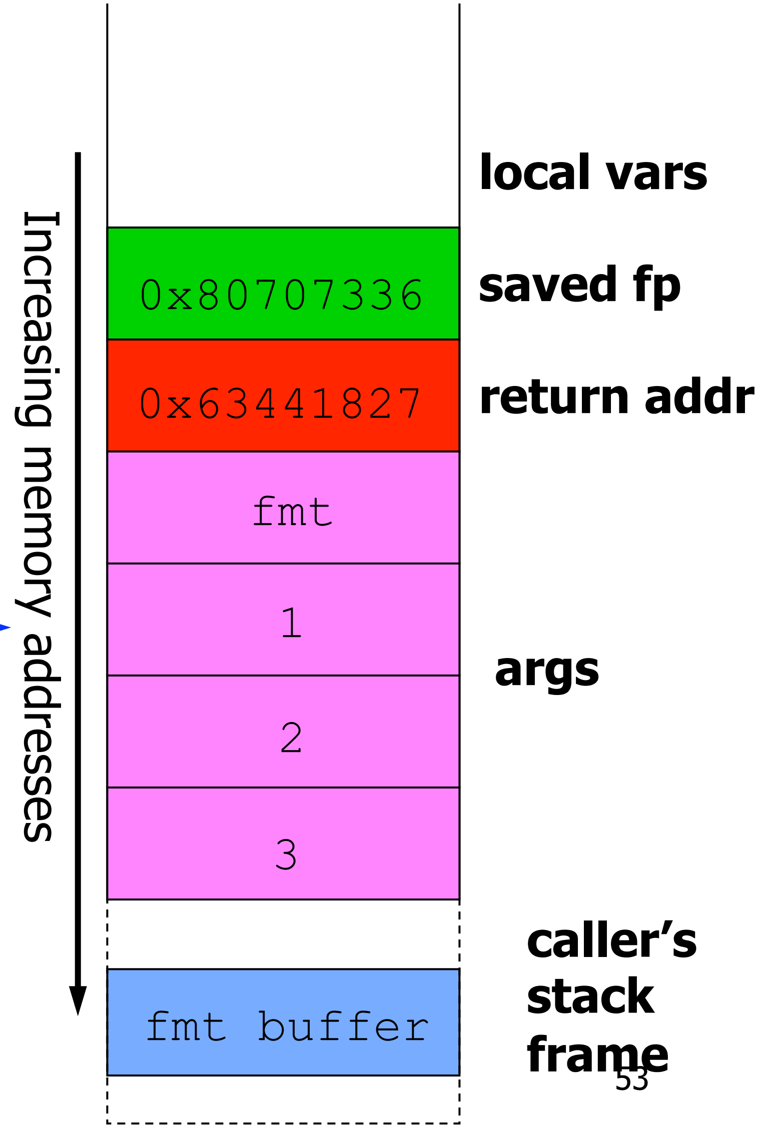

Increasing memory addresses

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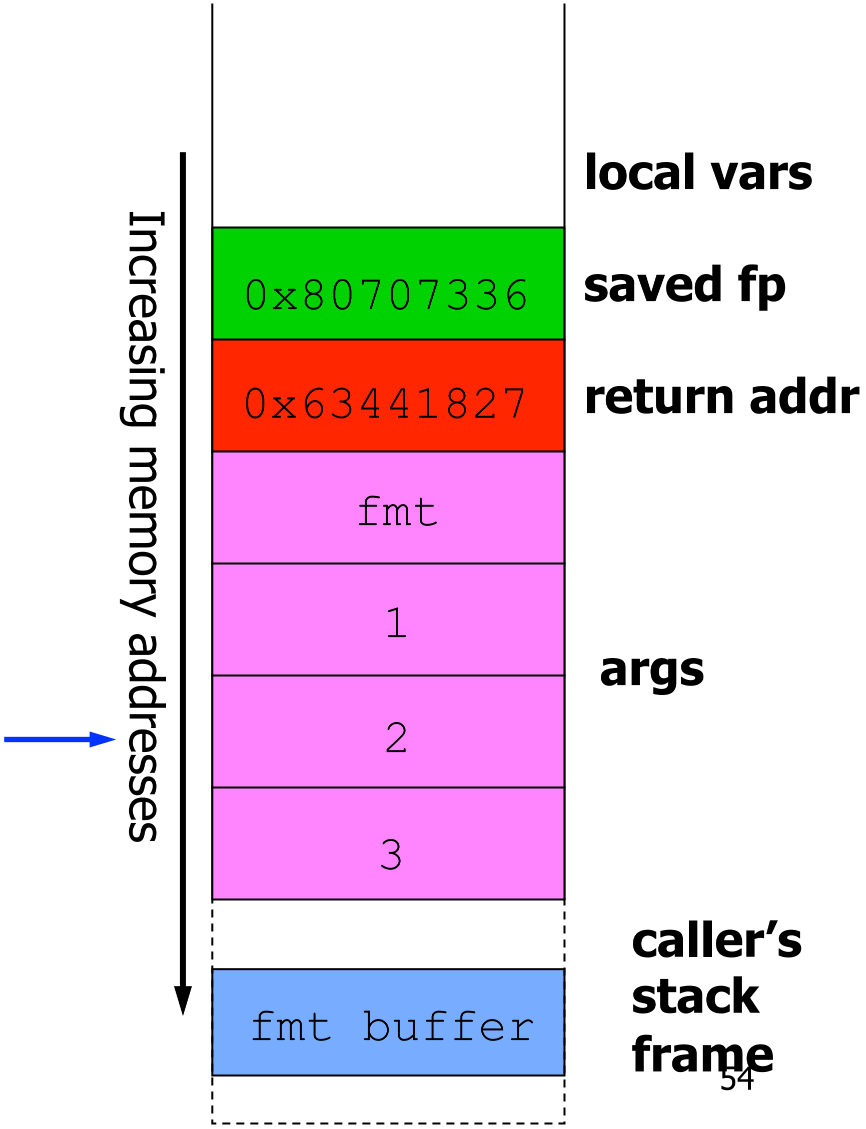

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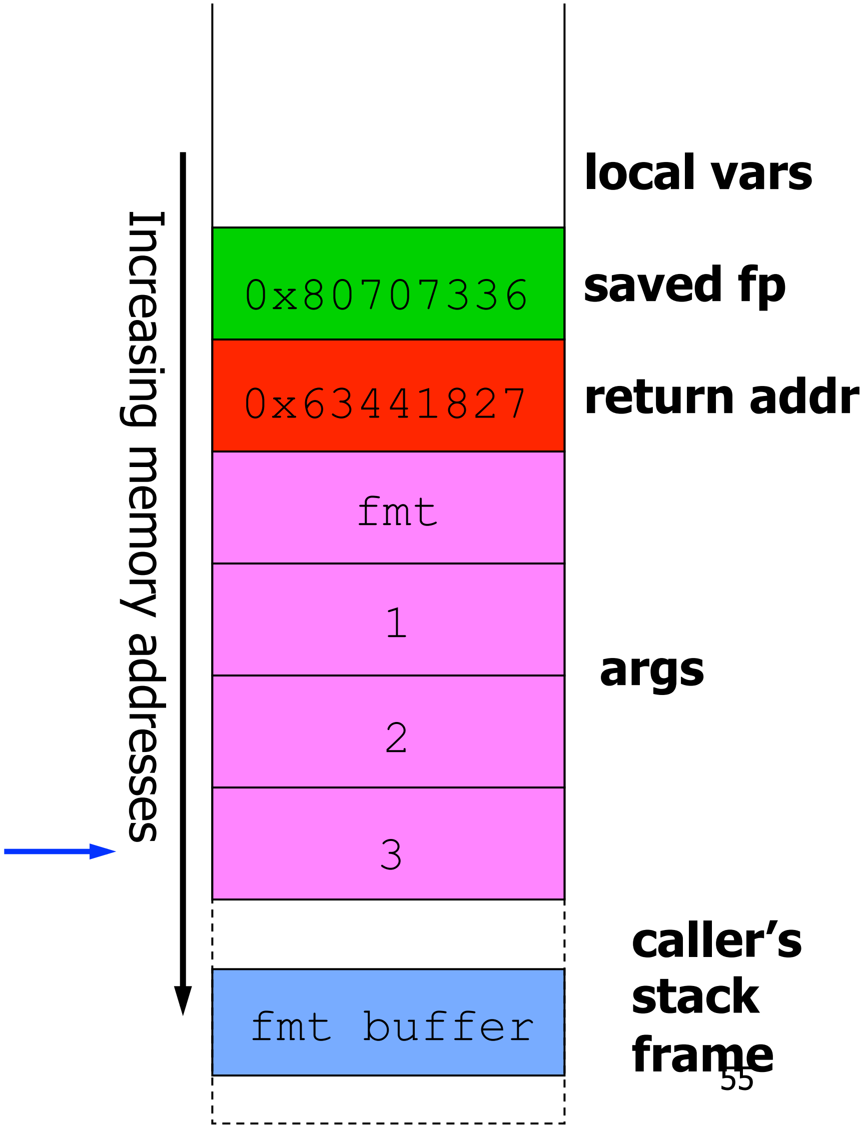

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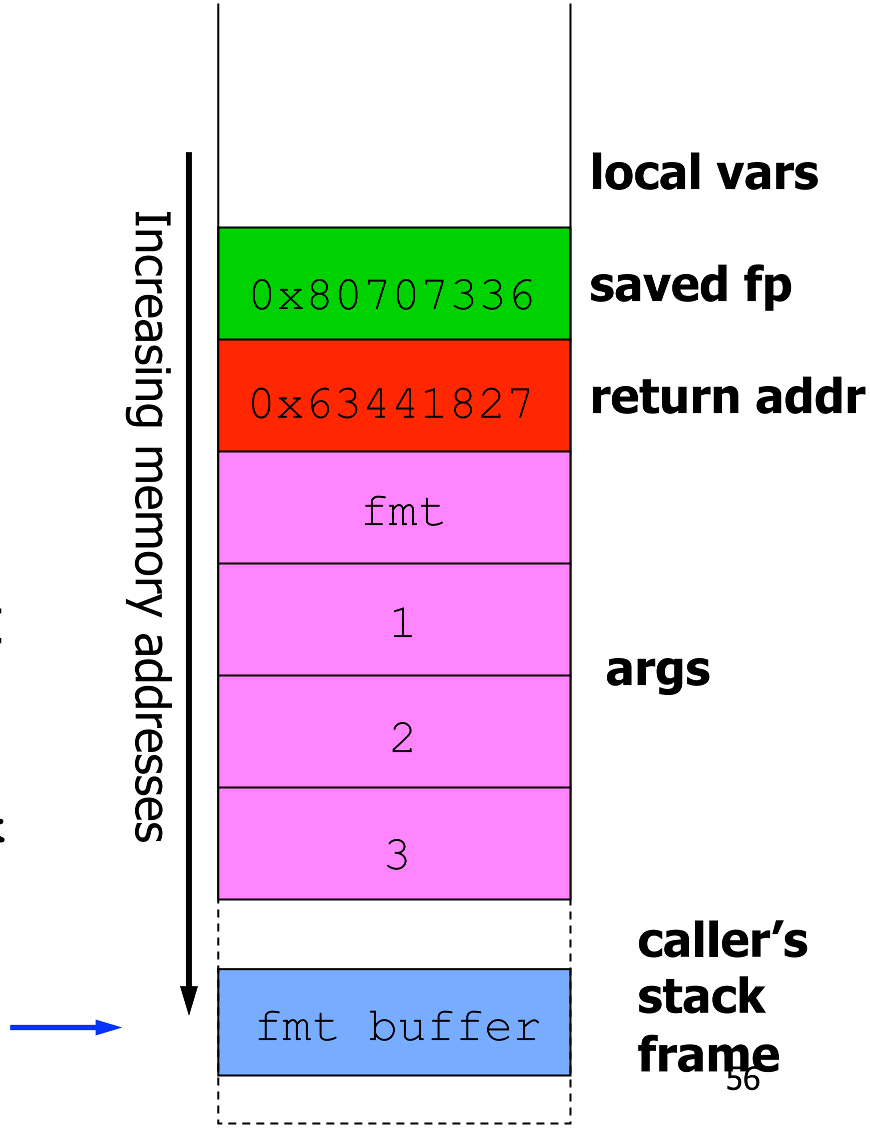

Abusing %n to Overwrite Memory (2)

- Idea:
  - Use specifiers in format string

Result: **can overwrite chosen location with small integer**

Still need to choose value we overwrite with…

  - Supply target address to write at start of format string
  - Supply “%n” at end of format string

```
[input =
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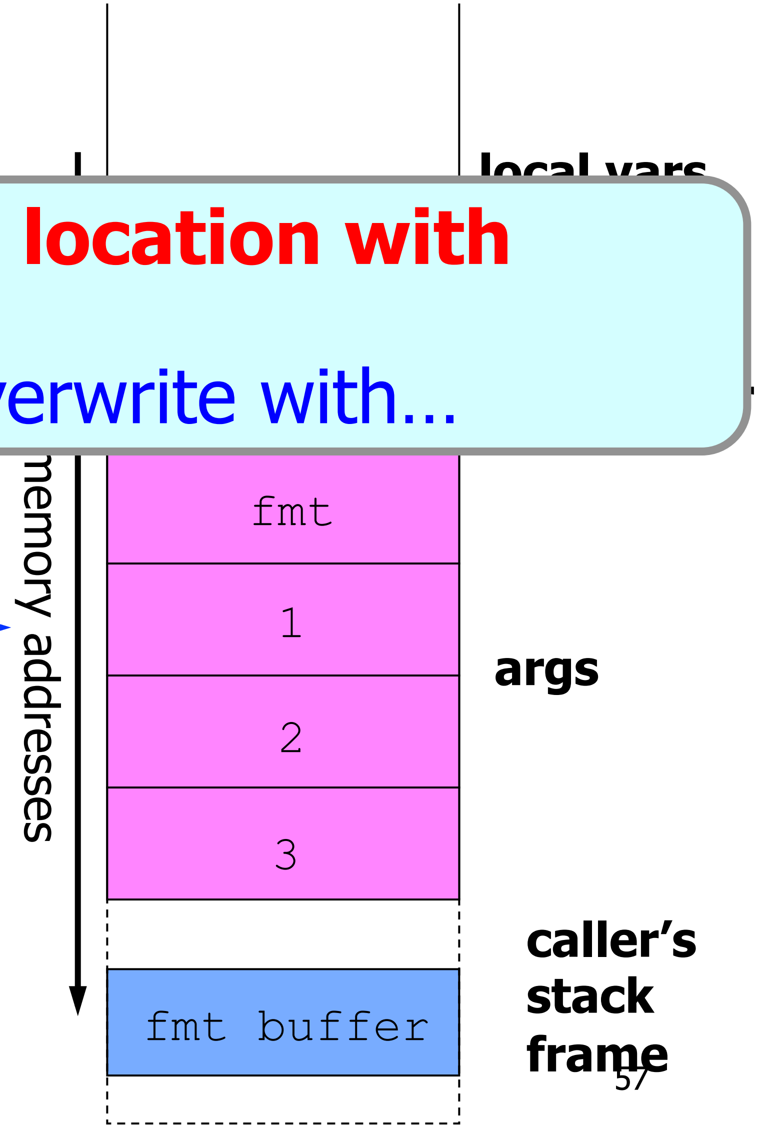


Controlling Value Written by %n

- %n writes number of bytes printed
- But number of bytes printed controlled by format string!
  - Format specifiers allow indication of exactly how many characters to output
  - e.g., “%20u” means “use 20 digits when printing this unsigned integer”
- So we can use “%[N]u%n” format specifier to set least significant byte of target address to value [N]!

Example: Using %[N]u%n

- Example format string:

  `“[spop]\x01\x01\x01\x01\xc0\xc8\xff\xbf%50u%n”`
- `[spop]` is sequence of “%08x” values, to advance printf()’s arg pointer to first byte after `[spop]`
- `\x01\x01\x01\x01` is dummy integer, to be consumed by %50u
- `\xc0\xc8\xff\xbf` is address of integer whose least significant byte will be changed by %n
- %50u sets number of output bytes to 50 (0x32)
- %n writes number of output bytes to target address
- Result: least significant byte of 4-byte value at 0xbfffc8c0 overwritten with number of bytes printed total: 0x32 + 0x08 + [bytes printed by spop]

Overwriting Full 4-Byte Values

- Template for format string:

  [4 non-zero bytes (dummy int)]
  [4 bytes target address]
  [dummy int][4 bytes (target address + 1)]
  [dummy int][4 bytes (target address + 2)]
  [dummy int][4 bytes (target address + 3)]

  [spop]

  %[1st byte value to write]u%n
  %[2nd byte value to write]u%n
  %[3rd byte value to write]u%n
  %[4th byte value to write]u%n

- N.B. LSB always in lowest memory address (Intel is little-endian)

Overwriting 4-Byte Values (2)

- Counter for %n is cumulative
- But only least significant byte written matters
- Say %n count is x so far, want next overwritten byte to have value y
- Next %u should be %[N]u, where:

```
N = (0x100 + y – (x mod 0x100)) mod 0x100
if (N < 10)
  N += 0x100
```

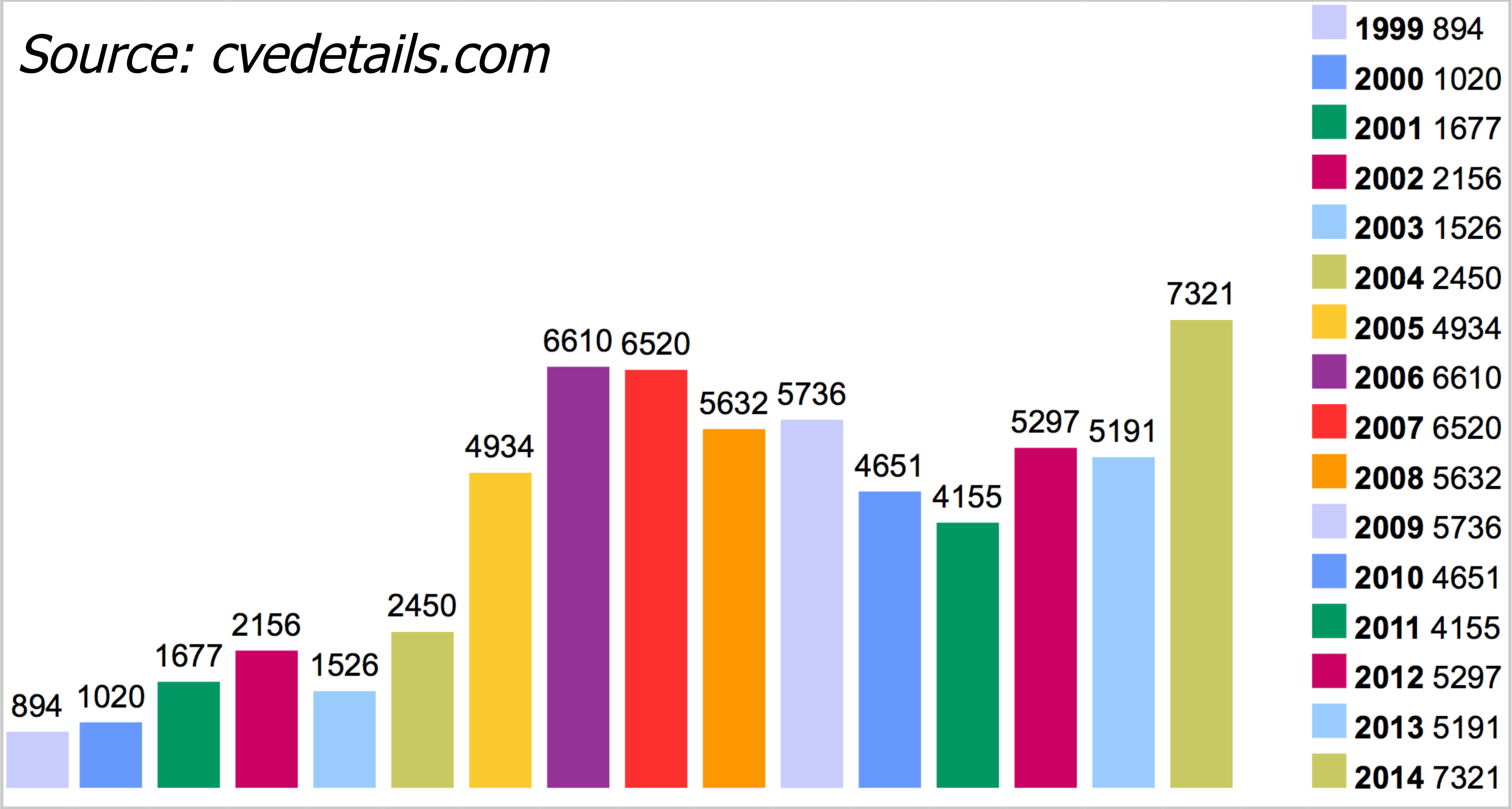
Format String Vulnerabilities Are Real and Versatile

- Example: wu-ftpd <= 2.6.0:

```
{
   char buffer[512];
   snprintf (buffer, sizeof (buffer), user);
   buffer[sizeof (buffer) - 1] = ’\0’;
}
```

- Ability to overwrite arbitrary memory makes format string vulnerabilities versatile:
  - Sure, can overwrite return address to return to shellcode, but other ways to attack, too
  - If server contains “superuser” flag (0 or 1), just overwrite that flag to be 1…

Vulnerability Prevalence



Vulnerabilities By Year

Source: cvedetails.com

- More scrutiny of software than ever
- Little overall progress in producing vulnerability-free software

Disclosure and Patching of Vulnerabilities

- Software vendors and open-source developers audit code, release vulnerability reports
  - Usually describe vulnerability, but don't give exploit
  - Often include announcement of patch
- Race after disclosure: users patch, attackers devise exploit
  - Users often lazy or unwilling to patch; "patches" can break software, or include new vulnerabilities
- Attackers prize exploits for undisclosed vulnerabilities: zero-day exploits
- Disclosure best for users: can patch or disable, vs. risk of widest harm by zero-day exploit

Summary

- Many categories of vulnerabilities in C/C++ binaries; 2 we've seen hardly exhaustive
- Incentives for attackers to find vulnerabilities and design exploits are high
  - Arbitrary code injection allows:
    - Defacing of widely viewed web site
    - Stealing valuable confidential data from server
    - Destruction of data on server
    - Recruitment of zombies to botnets (spam, DoS)
  - Market in vulnerabilities and exploits!
- Preventing all exploits extremely challenging
  - Stopping one category leads attackers to use others
  - New categories continually arising