CS 88: Security and Privacy

04: Buffer Overflow and Format String Attacks

09-08-2022

SWARTHMORE COLLEGE

Announcements

- Clickers available through the bookstore and TAP
    - No more paper hand-ins next week ☺

Today

- CS 31 Recap:
    - functions and the stack
    - assembly instructions
- Stack Buffer Overflow

What is a software vulnerability?

- A bug in a program that allows an unprivileged user capabilities that should be denied to them.
- There are a lot of types of vulnerabilities
  - bugs that violate “control flow integrity”
  - why? lets attacker run code on your computer!
- Typically these involve violating assumptions of the programming language or its run-time

Exploiting vulnerabilities (the start)

- Dive into low level details of how exploits work
  - How can a remote attacker get a victim program to execute their code?

- Threat model: victim code is handling input that comes from across a security boundary
  - what are examples of this?

- Security policy: want to protect integrity of execution and confidentiality of data from being compromised by malicious and highly skilled users of our system.

Stack buffer overflows

- Understand how buffer overflow vulnerabilities can be exploited
- Identify buffer overflows and asses their impact
- Avoid introducing buffer overflow vulnerabilities
- Correctly fix buffer overflow vulnerabilities

Buffer Overflows

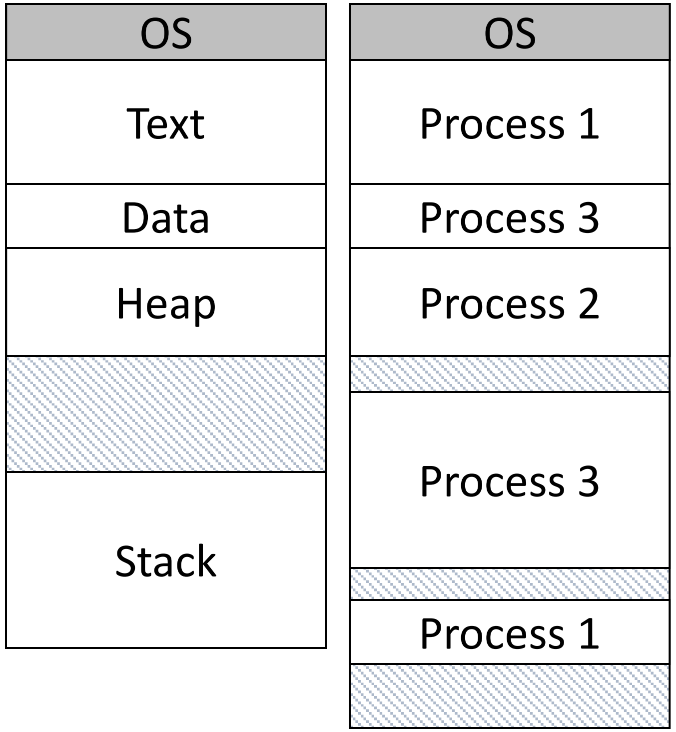
- An anomaly that occurs when a program writes/reads data beyond the boundary of a buffer
- Canonical software vulnerability
  - ubiquitous in system software
  - OSes, web servers, web browsers
- If your program crashes with memory faults, you probably have a buffer overflow vulnerability

CS 31 Recap

Memory

- Abstraction goal: make every process think it has the same memory layout.
  - MUCH simpler for compiler if the stack always starts at 0xFFFFFFFF, etc.

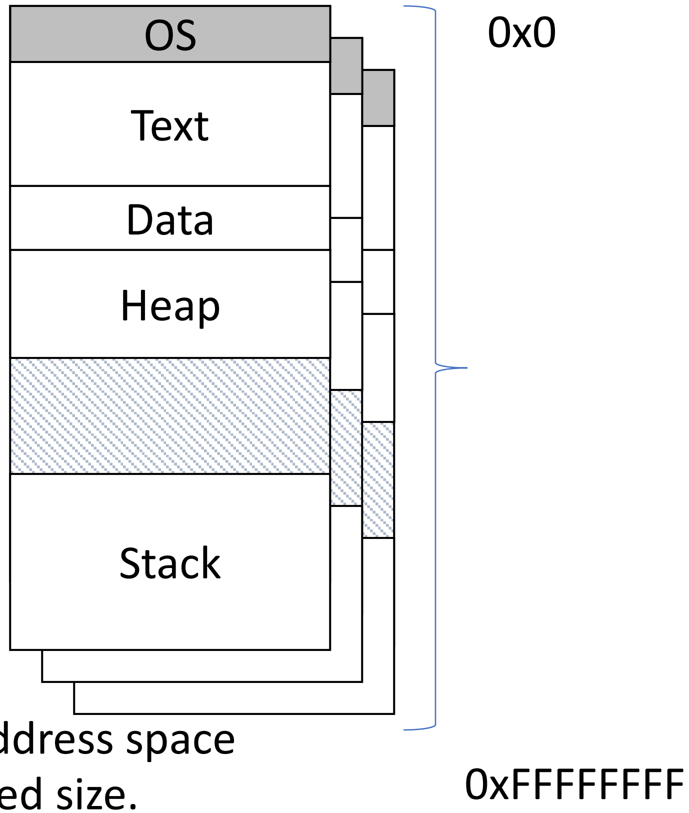
- Reality: there's only so much memory to go around, and no two processes should use the same (physical) memory addresses.



OS (with help from hardware) will keep track of who's using each memory region.

Memory Terminology

Virtual (logical) Memory: The abstract view of memory given to processes. Each process gets an independent view of the memory.

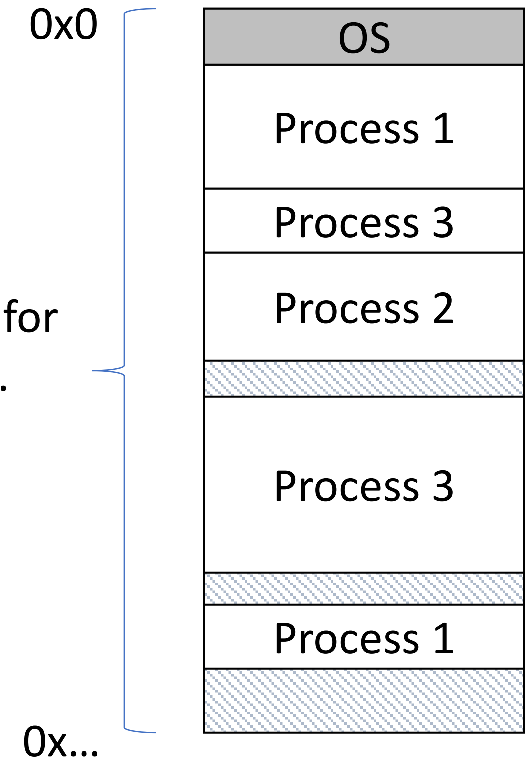


Virtual address space (VAS): fixed size.

Address Space: Range of addresses for a region of memory.

The set of available storage locations.

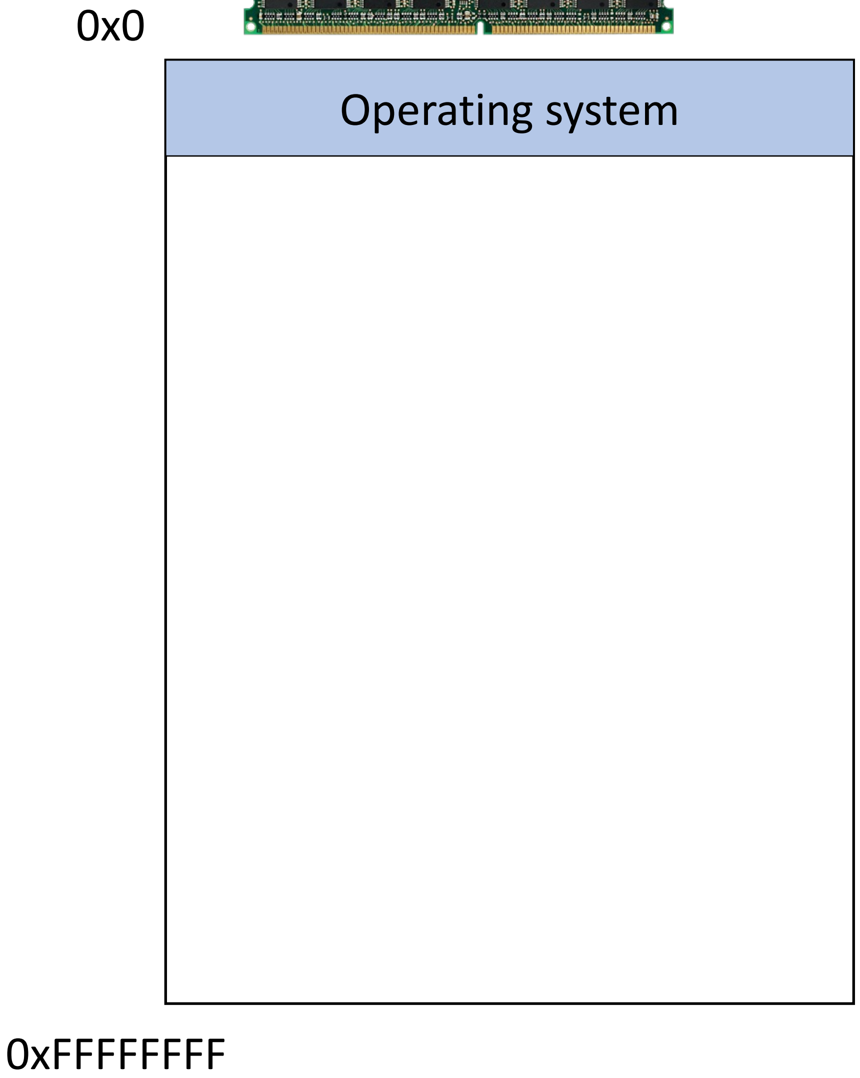
Physical Memory: The contents of the hardware (RAM) memory. Managed by OS. Only ONE of these for the entire machine!



(Determined by amount of installed RAM.)

Memory

- Behaves like a big array of bytes, each with an address (bucket #).
- By convention, we divide it into regions.
- The region at the lowest addresses is usually reserved for the OS.



0x0

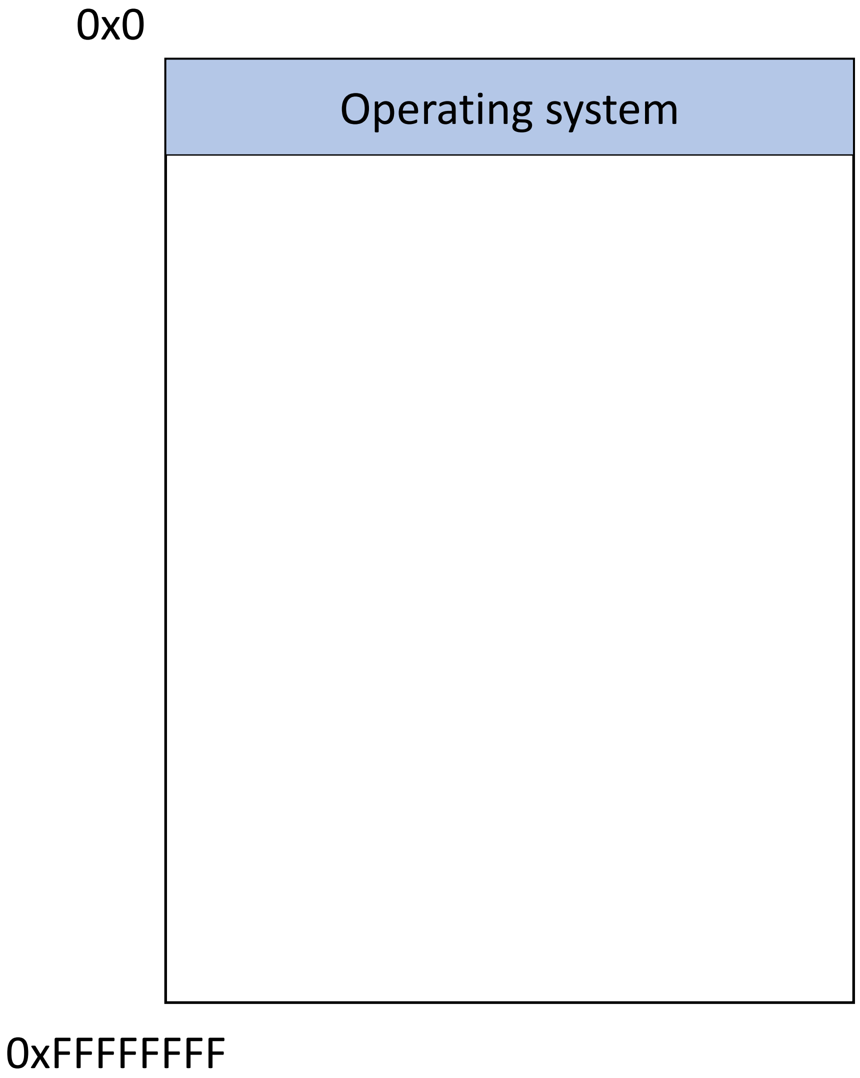
Operating system

0xFFFFFFFF

NULL: A special pointer value.

NULL is equivalent to pointing at memory address 0x0. This address is NEVER in a valid segment of your program's memory.

- This guarantees a segfault if you try to dereference it.
- Generally a good ideal to initialize pointers to NULL.



0x0

Operating system

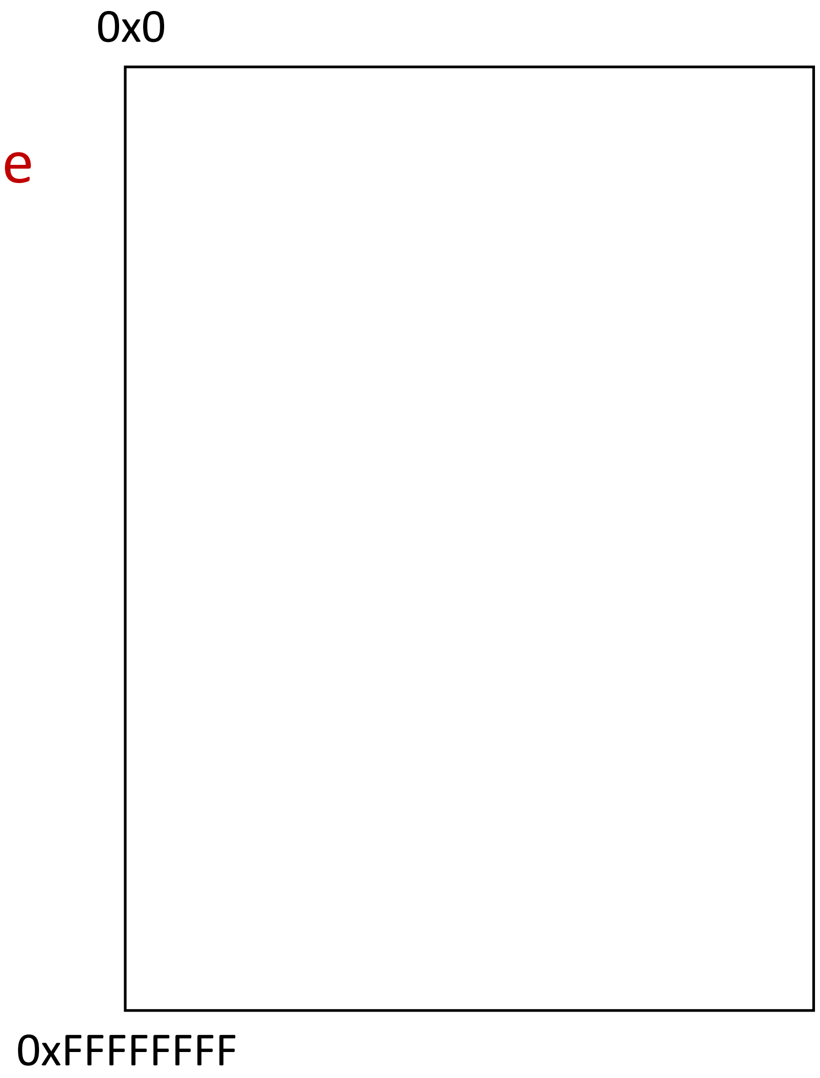
0xFFFFFFFF

What happens if we launch an attack where we load an instruction to execute at 0x0

A. Nothing will happen, this region is mapped to the NULL pointer, which does not have any effect

B. There will be some effect, but not necessarily devastating

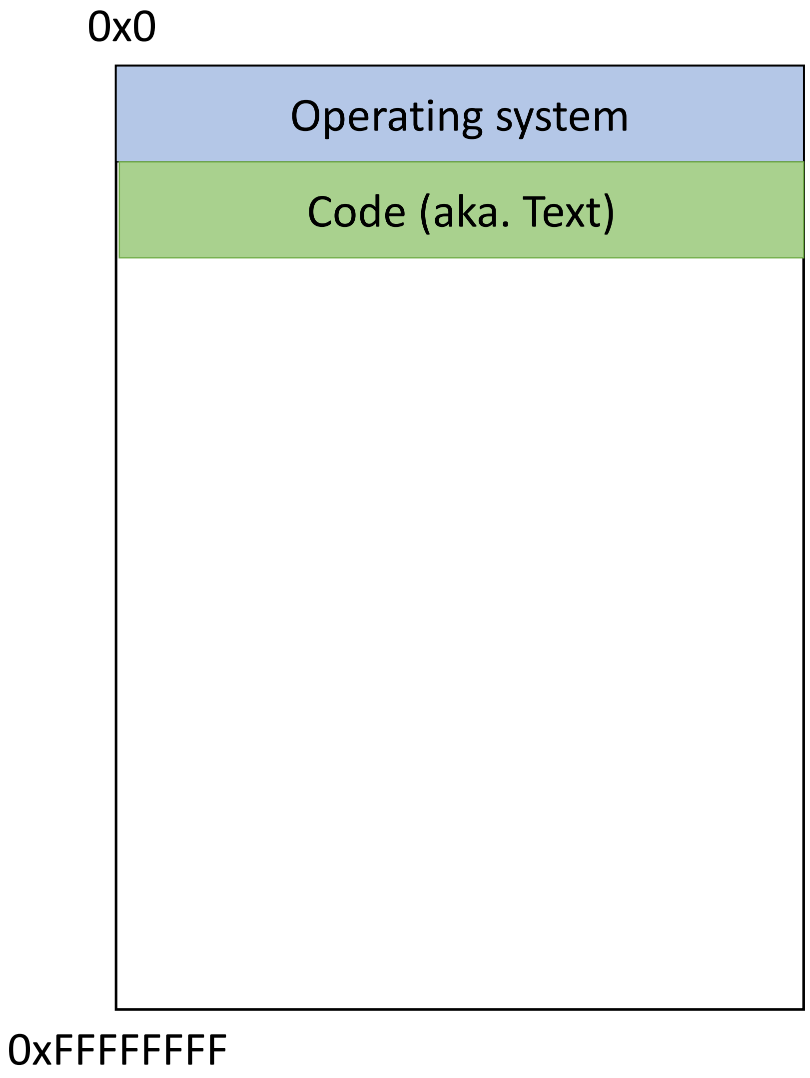
C. This will have a devastating effect.



Memory - Text

- After the OS, we store the program’s code.

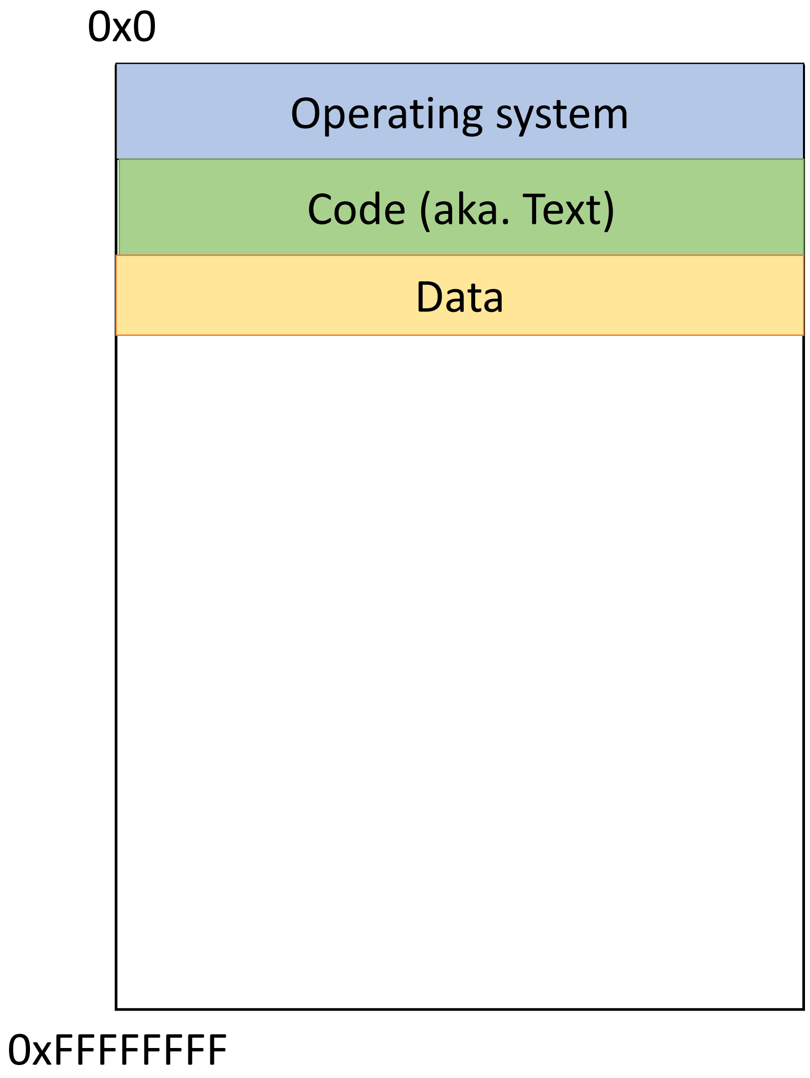
- Instructions generated by the compiler.



Memory – (Static) Data

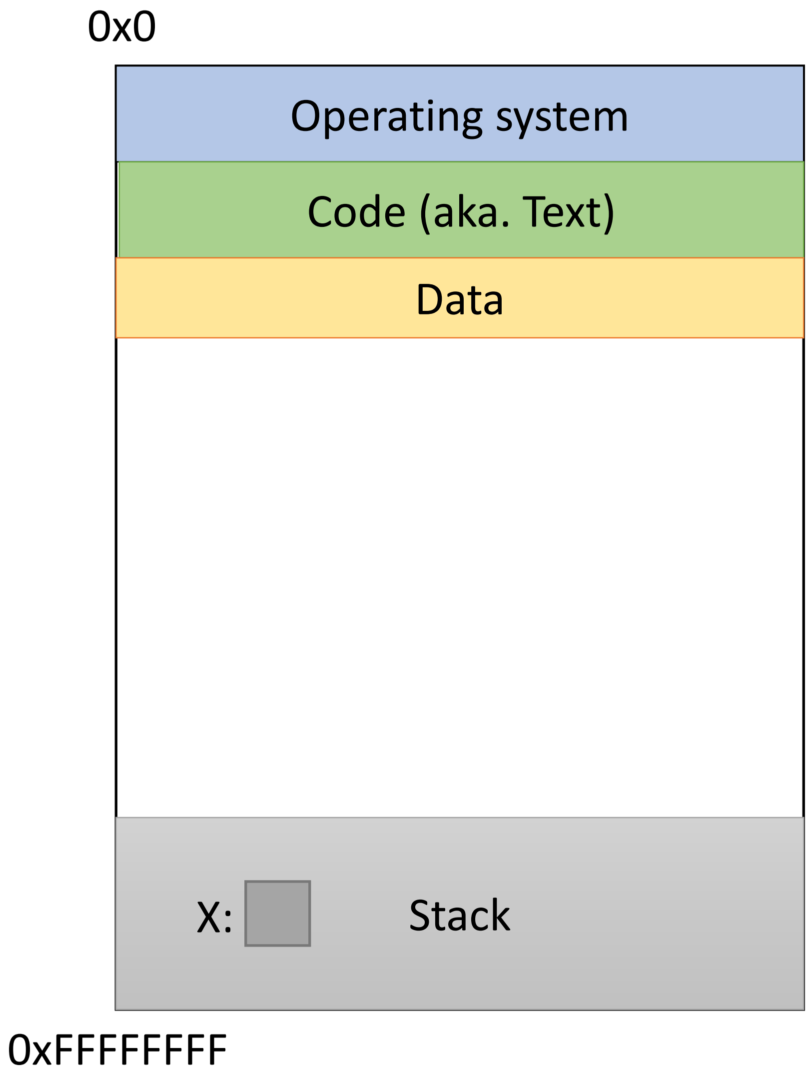
- Next, there's a fixed-size region for static data.

- This stores static variables that are known at compile time.
    - Global variables



Memory - Stack

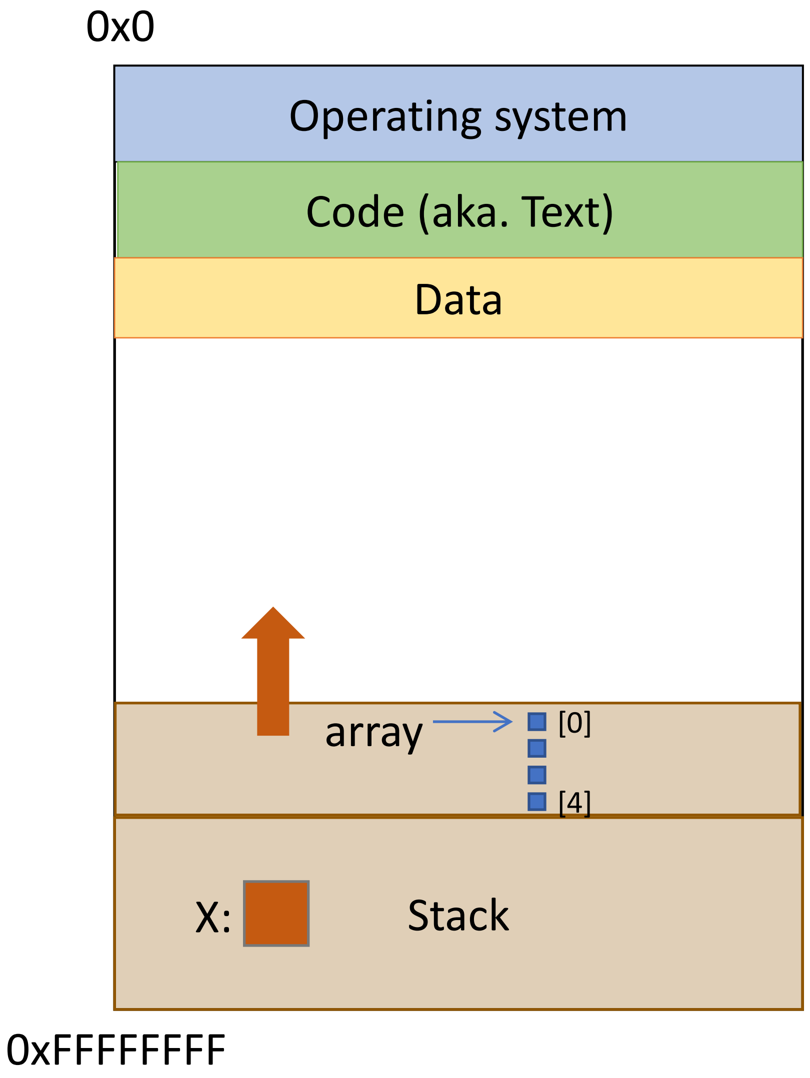
- At high addresses, we keep the stack.
- This stores local (automatic) variables.
  - The kind we’ve been using in C so far.
  - e.g., int x;



Memory - Stack

- The stack grows upwards towards lower addresses
  (negative direction).

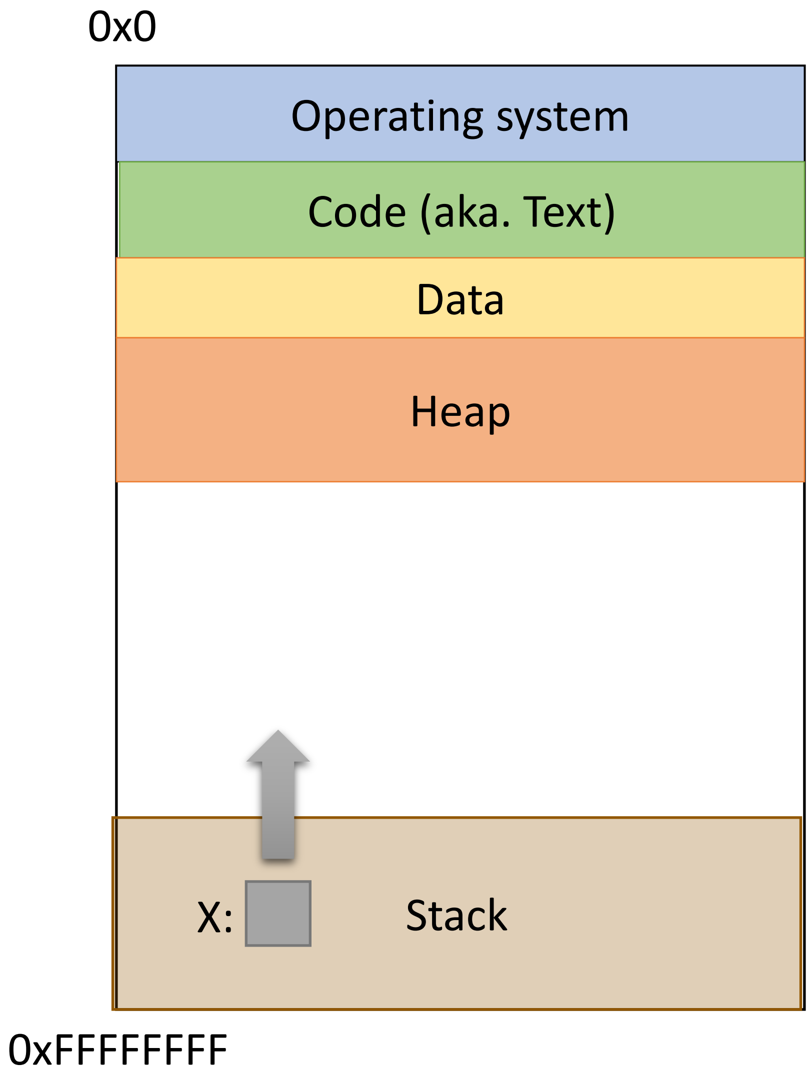
- Example: Allocating array
  - int array[4];



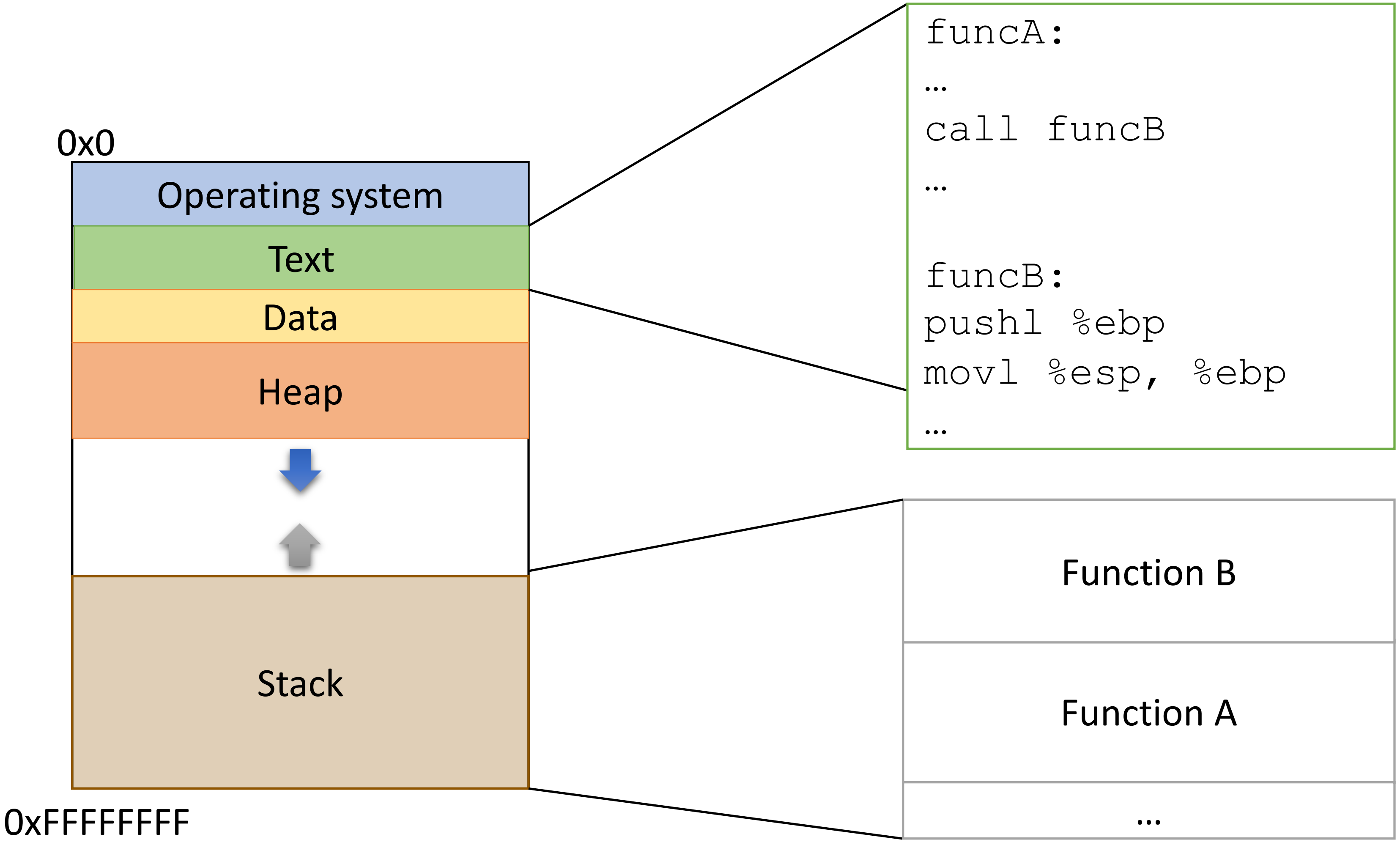
Memory - Heap

- The heap stores dynamically allocated variables.

- When programs explicitly ask the OS for memory, it comes from the heap.
  - malloc() function



Instructions in Memory



0x0

Operating system

Text

Data

Heap

Stack

0xFFFFFFFF

```
funcA:
…
call funcB
…

funcB:
pushl %ebp
movl %esp, %ebp
…
```

Function B

Function A

…

Process memory layout

.text

- Machine code of executable

.data

- Global initialized variables

.bss

- Below Stack Section

  global uninitialized vars

heap

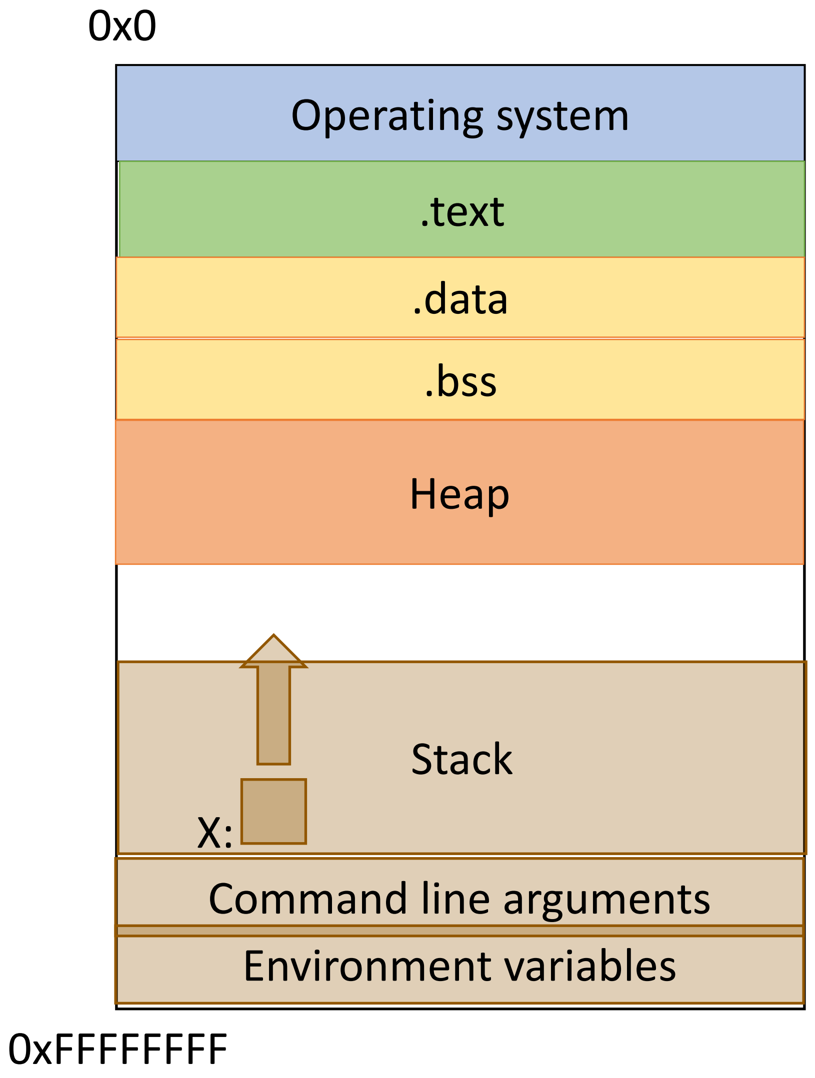
- Dynamic variables

stack

- Local variables
- Function call data

Env

- Environment variables
- Program arguments



Process memory layout

.text

- Machine code of executable

.data

- Global initialized variables

.bss

- Below Stack Section

  global uninitialized vars

heap

- Dynamic variables

stack

- Local variables
- Function call data

Env

- Environment variables
- Program arguments

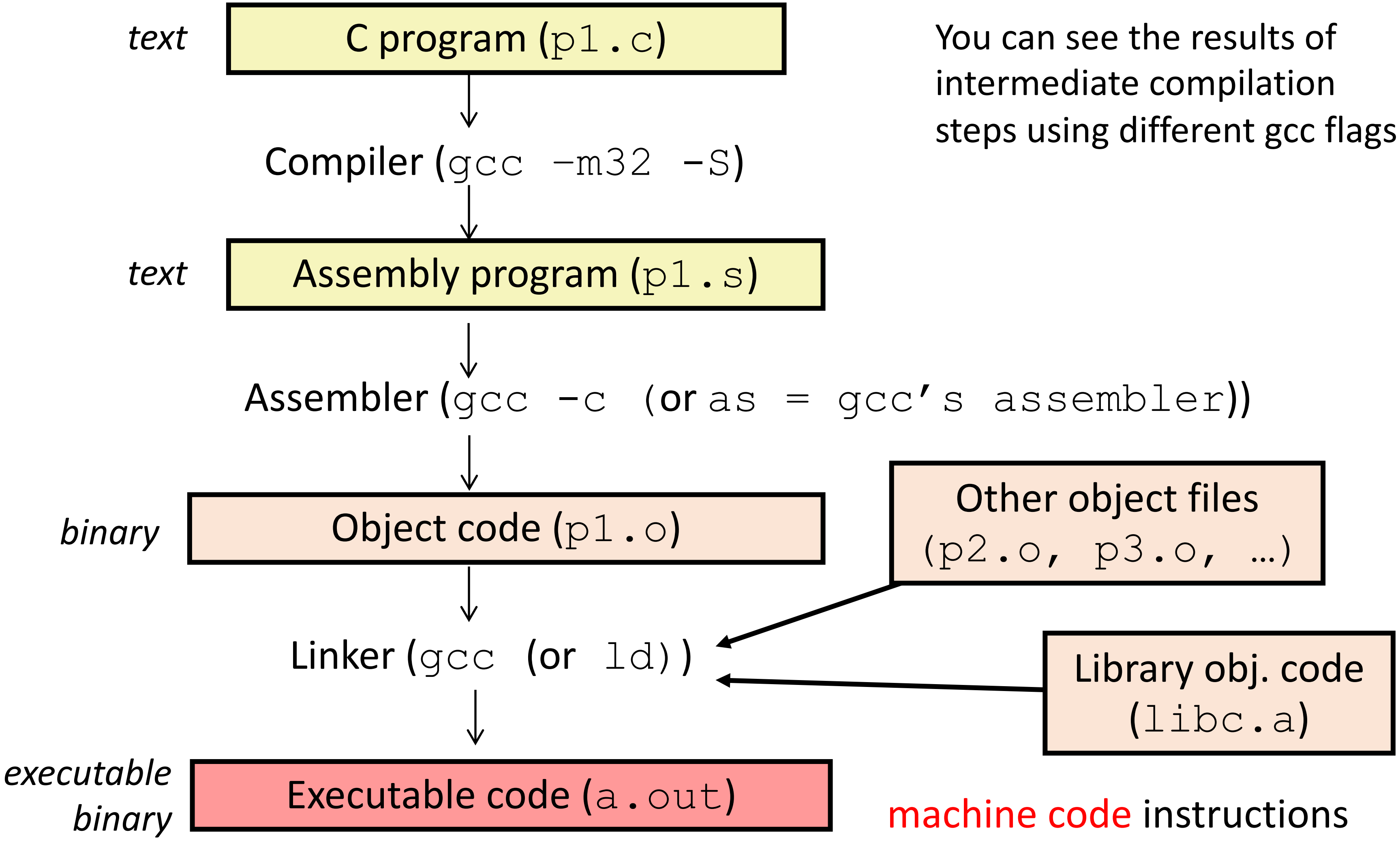
```
int i = 0;
int main()
{
   char *ptr = malloc(sizeof(int));
   char buf[1024]
   int j;
   static int y;
}
```

X86: The De Facto Standard

- Extremely popular for desktop computers
- Alternatives
  - ARM: popular on mobile
  - MIPS: very simple
  - Itanium: ahead of its time
- CISC: 100 distinct opcodes
- Register poor
  - 8 registers of 32 bits
  - only 6 general purpose

- instructions are variable length
  - not aligned at 4 byte boundaries
- lots of backward compatibilities
  - defined in late 70s
  - exploit code that noone pays attention to
- we will use 32 bit because its more convenient.

Compilation Steps (.c to a.out)



text C program (`p1.c`)

Compiler (`gcc -m32 -S`)

text Assembly program (`p1.s`)

Assembler (`gcc -c` (or `as = gcc's assembler`))

binary Object code (`p1.o`)

Other object files (`p2.o, p3.o, …`)

Linker (`gcc` (or `ld`))

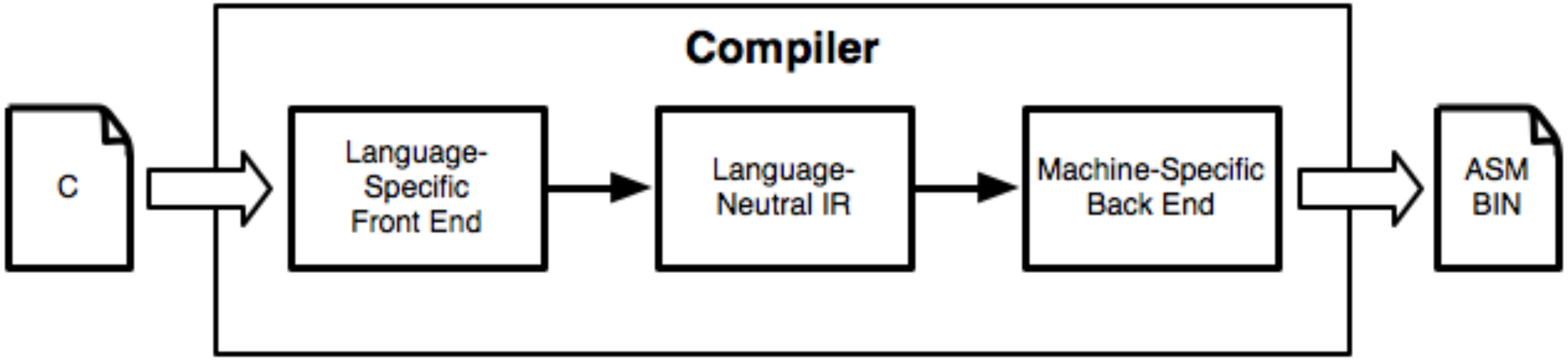
Library obj. code (`libc.a`)

executable binary Executable code (`a.out`)

You can see the results of intermediate compilation steps using different gcc flags

machine code instructions

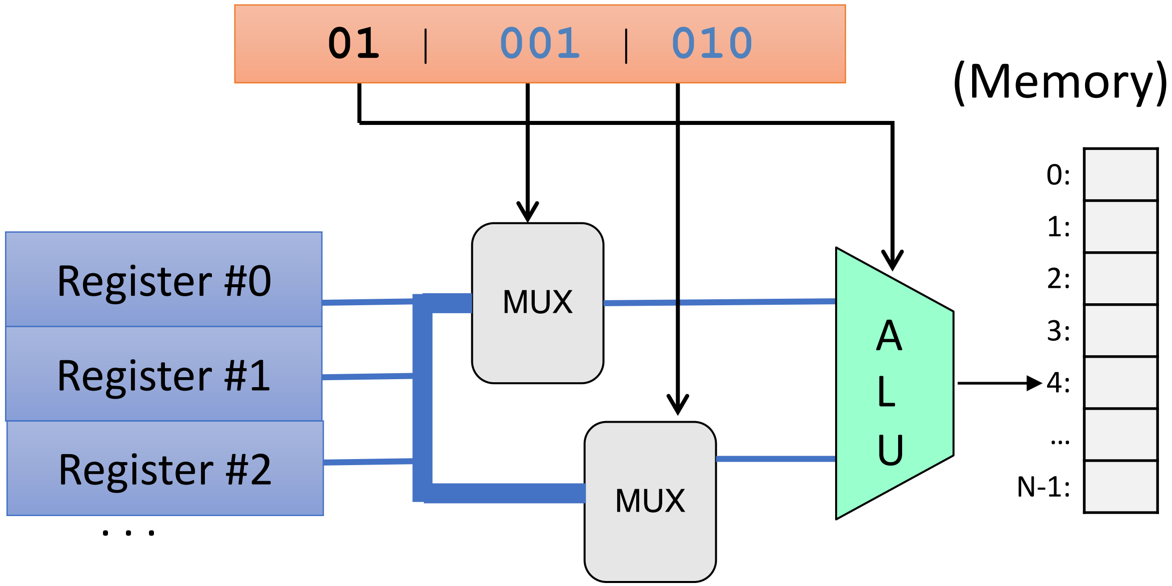
Compilers



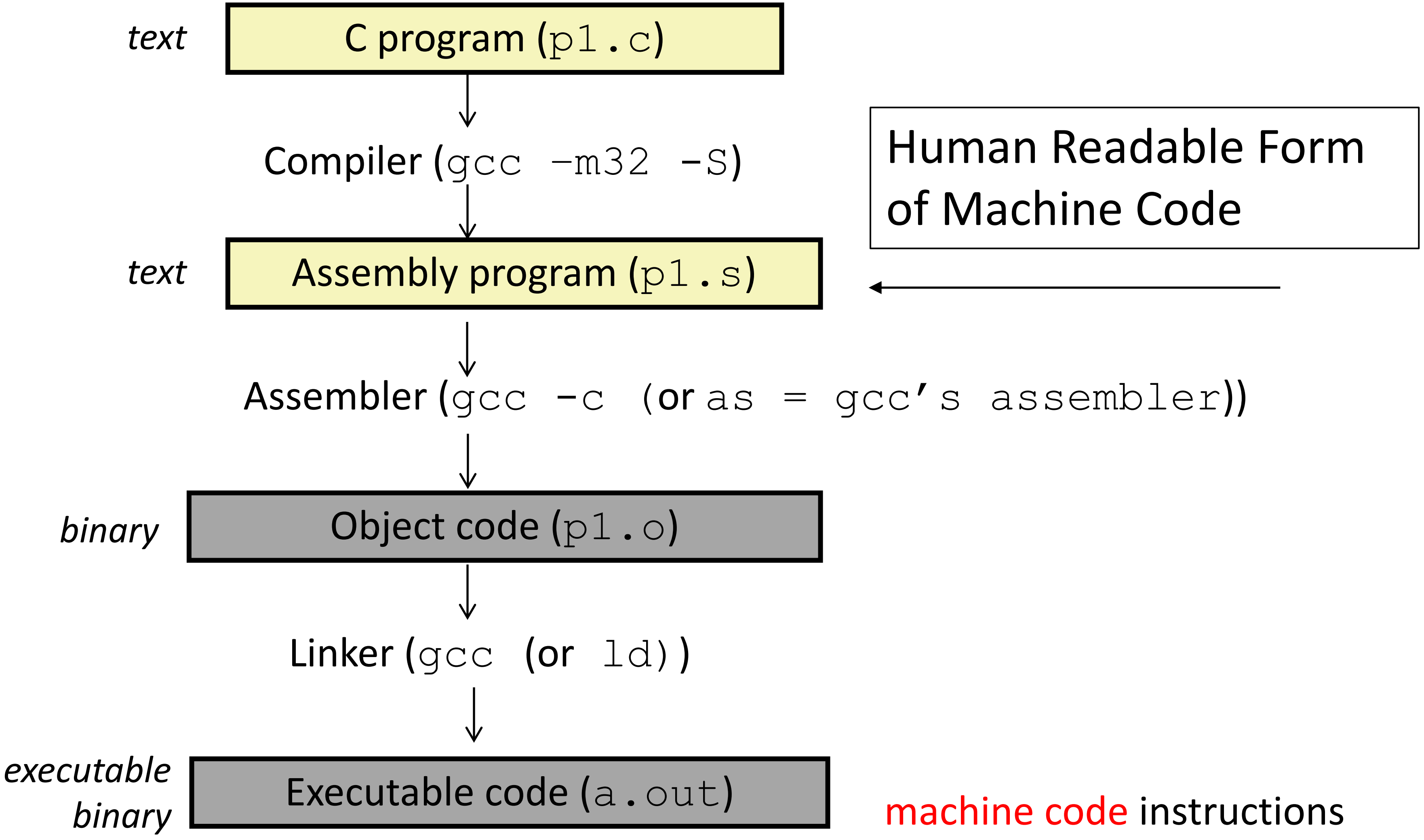
- Computers don't execute source code
  - Instead, they use machine code
- Compilers translate code from a higher level to a lower one
- In this context, C → assembly → machine code

Machine Code

- Binary (0's and 1's) Encoding of ISA Instructions
    - some bits: encode the instruction (opcode bits)
    - others encode operand(s)
        - 01001010 opcode operands
        - 01 001 010 ADD %r1 %r2
    - different bits fed through different CPU circuitry:



Assembly Code



text C program (`p1.c`)

Compiler (`gcc -m32 -S`)

text Assembly program (`p1.s`)

Human Readable Form of Machine Code

Assembler (`gcc -c` (or `as = gcc's assembler`))

binary Object code (`p1.o`)

Linker (`gcc` (or `ld`))

executable binary Executable code (`a.out`)

machine code instructions

What is “assembly”?

```
push %ebp
mov  %esp, %ebp
sub  $16, %esp
movl $10, -8(%ebp)
movl $20, -4(%ebp)
movl -4(%ebp), $eax
addl $eax, -8(%ebp)
movl -8(%ebp), %eax
leave
```

Assembly is the “human readable” form of the instructions a machine can understand.

```
objdump -d a.out
```

Object / Executable / Machine Code

Assembly	**Machine Code (Hexadecimal)**
`push %ebp`	`55`
`mov  %esp, %ebp`	`89 E5`
`sub  $16, %esp`	`83 EC 10`
`movl $10, -8(%ebp)`	`C7 45 F8 0A 00 00 00`
`movl $20, -4(%ebp)`	`C7 45 FC 14 00 00 00`
`movl -4(%ebp), $eax`	`8B 45 FC`
`addl $eax, -8(%ebp)`	`01 45 F8`
`movl -8(%ebp), %eax`	`B8 45 F8`
`leave`	`C9`

Almost a 1-to-1 mapping to Machine Code
Hides some details like num bytes in instructions

Object / Executable / Machine Code

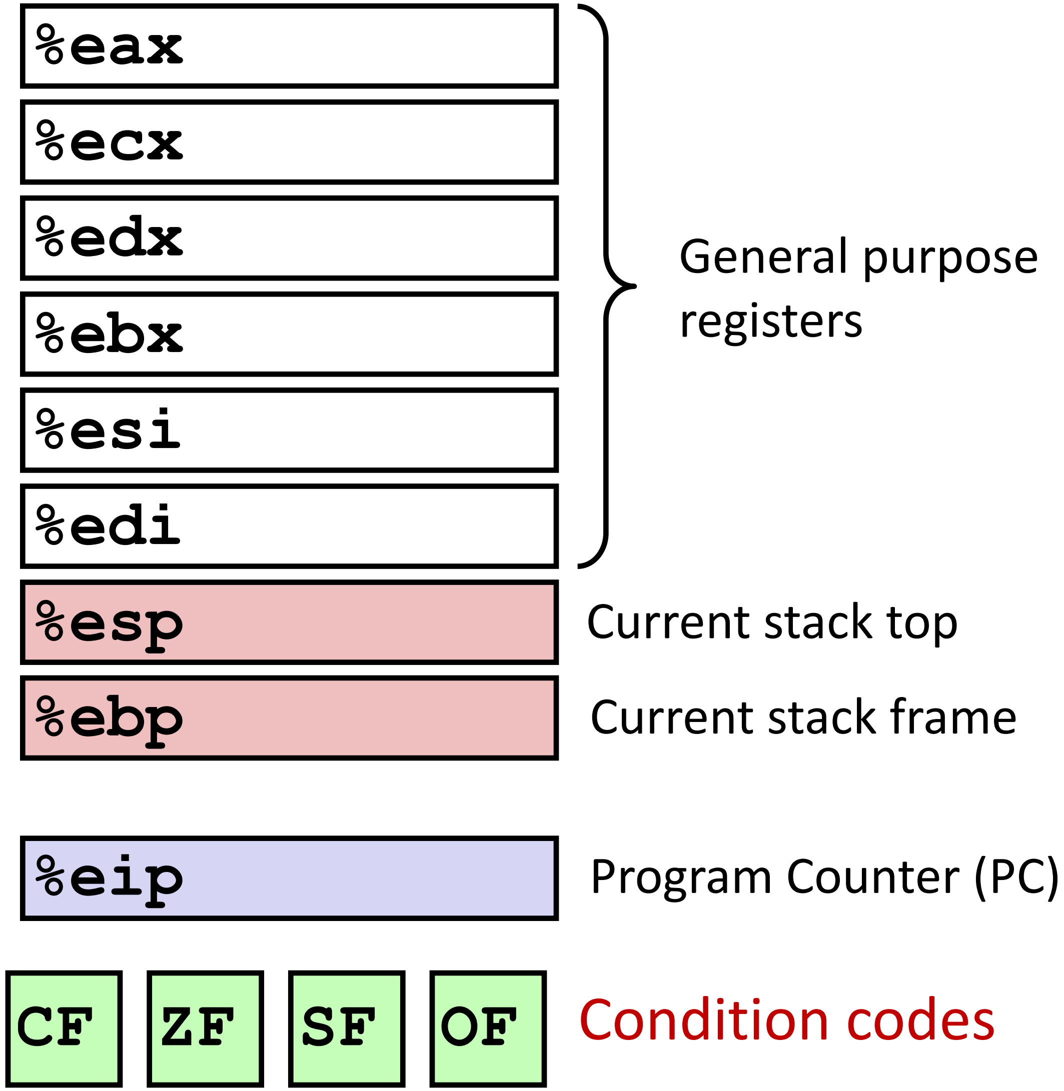
Assembly

```
push %ebp
mov  %esp, %ebp
sub  $16, %esp
movl $10, -8(%ebp)
movl $20, -4(%ebp)
movl -4(%ebp), $eax
addl $eax, -8(%ebp)
movl -8(%ebp), %eax
leave
```

```
int main() {
        int a = 10;
        int b = 20;

        a = a + b;

        return a;
}
```

Processor State in Registers

- Information about currently executing program
  - Temporary data (%eax - %edi)
  - Location of runtime stack (%ebp, %esp)
  - Location of current code control point (%eip, …)
  - Status of recent tests %EFLAGS (CF, ZF, SF, OF)



`%eax`
`%ecx`
`%edx`
`%ebx`
`%esi`
`%edi`

General purpose registers

`%esp` Current stack top

`%ebp` Current stack frame

`%eip` Program Counter (PC)

`CF` `ZF` `SF` `OF` Condition codes

General purpose Registers

Register name
%eax
%ecx
%edx
%ebx
%esi
%edi
%esp
%ebp
%eip
%EFLAGS

`bits: 16 31`	`15 8`	`7 0`
`%eax %ax`	`%ah`	`%al`
`%ecx %cx`	`%ch`	`%cl`
`%edx %dx`	`%dh`	`%dl`
`%ebx %bx`	`%bh`	`%bl`
`%esi %si`		
`%edi %di`		
`%esp %sp`		
`%ebp %bp`		

Six are for instruction operands

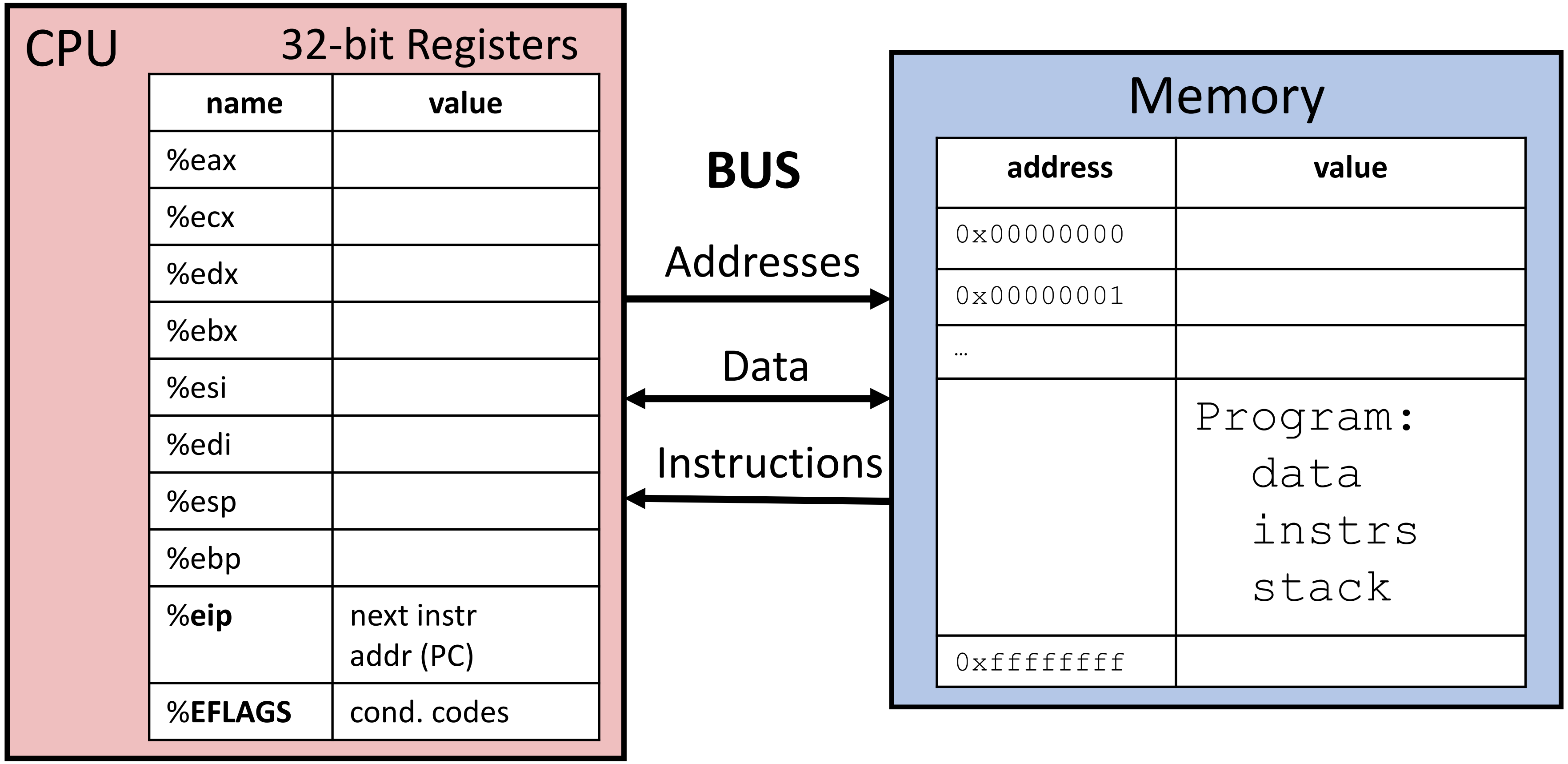
Can store 4 byte data or address value

The low-order 2 bytes %ax is the low-order 16 bits of %eax

Two low-order 1 bytes %al is the low-order 8 bits of %eax

May see their use in ops involving shorts or chars

Assembly Programmer's View of State



CPU

32-bit Registers

name	value
%eax	
%ecx	
%edx	
%ebx	
%esi	
%edi	
%esp	
%ebp	
%eip	next instr addr (PC)
%EFLAGS	cond. codes

BUS

Memory

address	value
`0x00000000`	
`0x00000001`	
…	

	`Program:`
	`data`
	`instrs`
	`stack`

`0xffffffff`	

Registers:

PC: Program counter (%eip)

Condition codes (%EFLAGS)

General Purpose (%eax - %ebp)

Memory:

- Byte addressable array
- Program code and data
- Execution stack

Types of IA32 Instructions

- Data movement
  - Move values between registers and memory
  - Example: movl

- Load: move data from memory to register

- Store: move data from register to memory

Instruction Syntax

Examples:

```
subl $16, %ebx

movl (%eax), %ebx
```

- Instruction ends with data length
- opcode, src, dst
- Constants preceded by $
- Registers preceded by %
- Indirection uses ( )

Addressing Mode: Memory

- Accessing memory requires you to specify which address you want.
  - Put address in a register.
  - Access with () around register name.

- movl (%ecx), %eax
  - Use the address in register ecx to access memory, store result in register eax

Addressing Mode: Memory

- `movl (%ecx), %eax`
  - Use the address in register ecx to access memory, store result in register eax

CPU Registers

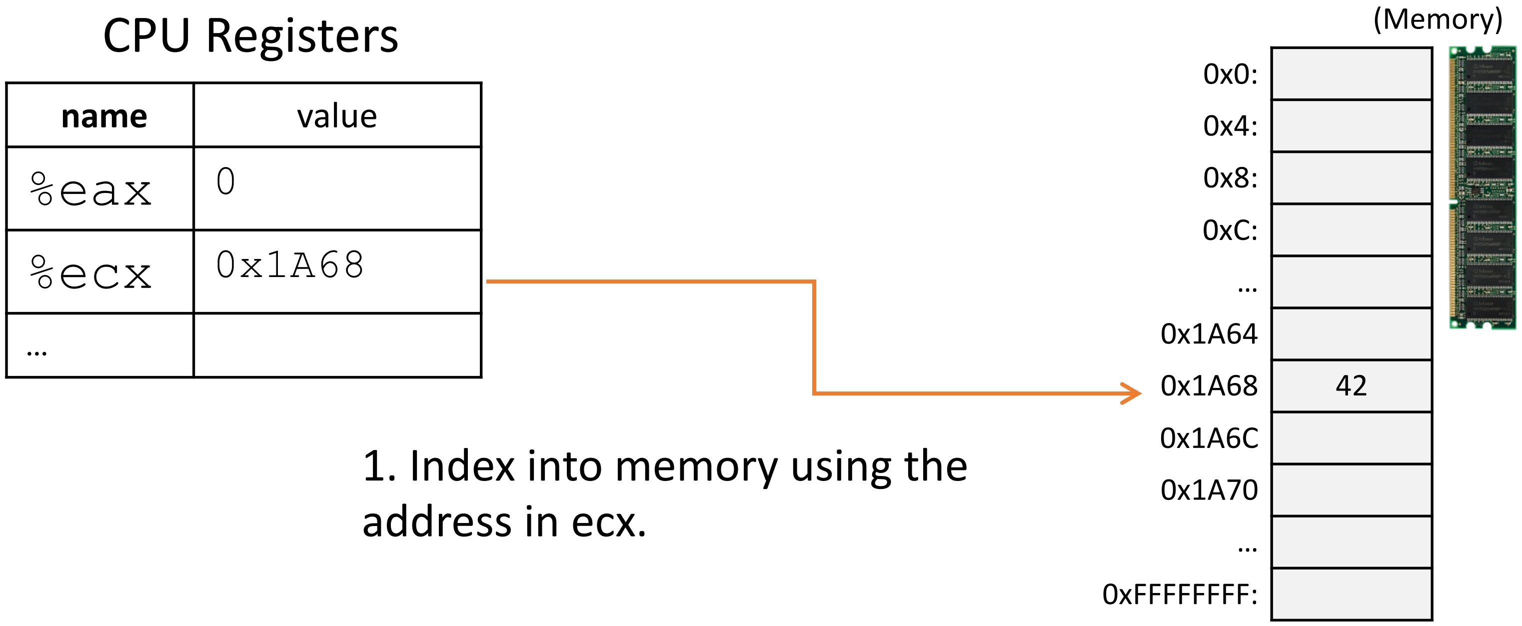
name	value
`%eax`	`0`
`%ecx`	`0x1A68`
…	

(Memory)

0x0:	
0x4:	
0x8:	
0xC:	
…	
0x1A64	
0x1A68	42
0x1A6C	
0x1A70	
…	
0xFFFFFFFF:	

Addressing Mode: Memory

- `movl (%ecx), %eax`
  - Use the address in register ecx to access memory, store result in register eax



CPU Registers

name	value
`%eax`	`0`
`%ecx`	`0x1A68`
…	

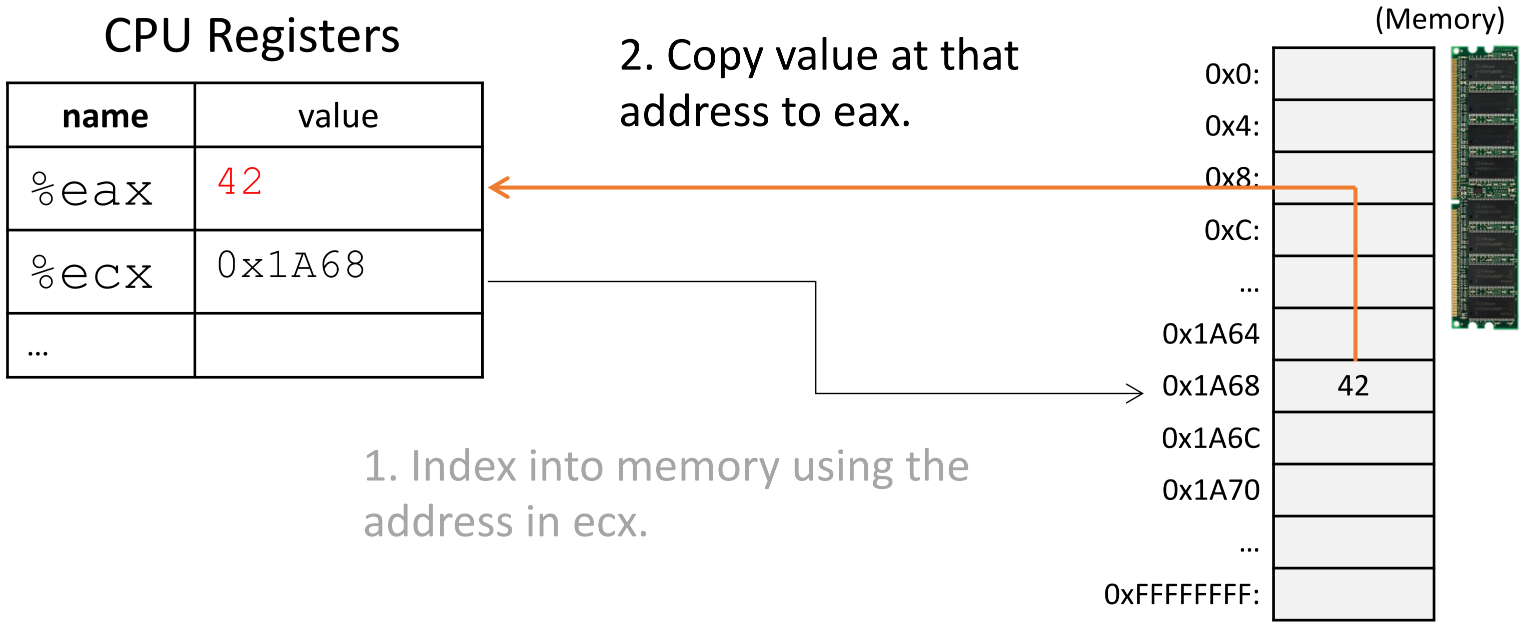
(Memory)

0x0:	
0x4:	
0x8:	
0xC:	
…	
0x1A64	
0x1A68	42
0x1A6C	
0x1A70	
…	
0xFFFFFFFF:	

1. Index into memory using the address in ecx.

Addressing Mode: Memory

- `movl (%ecx), %eax`
  - Use the address in register ecx to access memory, store result in register eax



CPU Registers

name	value
`%eax`	`42`
`%ecx`	`0x1A68`
…	

2. Copy value at that address to eax.

1. Index into memory using the address in ecx.

(Memory)

0x0:	
0x4:	
0x8:	
0xC:	
…	
0x1A64	
0x1A68	42
0x1A6C	
0x1A70	
…	
0xFFFFFFFF:	

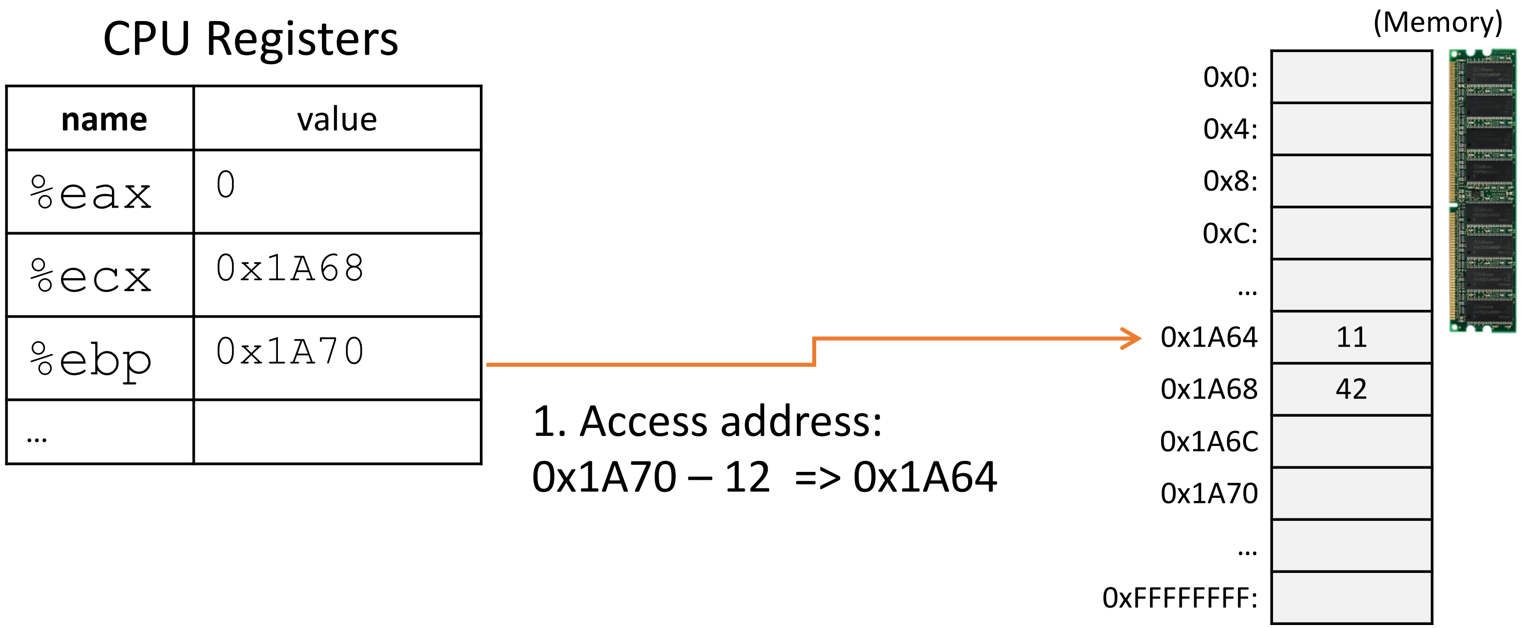
Addressing Mode: Displacement

- Like memory mode, but with constant offset
  - Offset is often negative, relative to %ebp

- `movl -12(%ebp), %eax`
  - Take the address in ebp, subtract twelve from it, index into memory and store the result in eax

Addressing Mode: Displacement

- `movl -12(%ebp), %eax`
  - Take the address in ebp, subtract twelve from it, index into memory and store the result in eax



CPU Registers

name	value
`%eax`	`0`
`%ecx`	`0x1A68`
`%ebp`	`0x1A70`
…	

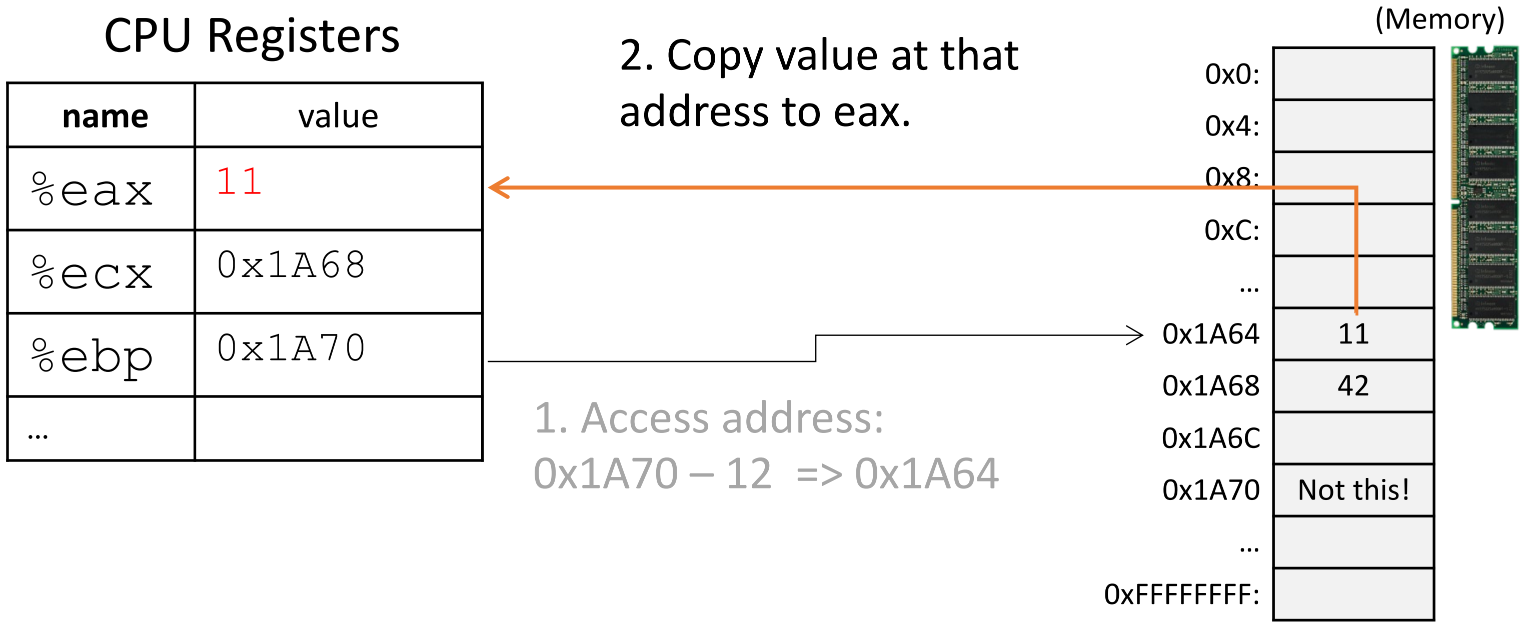
1. Access address:
0x1A70 – 12 => 0x1A64

(Memory)

0x0:	
0x4:	
0x8:	
0xC:	
…	
0x1A64	11
0x1A68	42
0x1A6C	
0x1A70	
…	
0xFFFFFFFF:	

Addressing Mode: Displacement

- `movl -12(%ebp), %eax`
  - Take the address in ebp, subtract three from it, index into memory and store the result in eax



CPU Registers

name	value
`%eax`	`11`
`%ecx`	`0x1A68`
`%ebp`	`0x1A70`
…	

2. Copy value at that address to eax.

1. Access address:
0x1A70 – 12 => 0x1A64

(Memory)

0x0:	
0x4:	
0x8:	
0xC:	
…	
0x1A64	11
0x1A68	42
0x1A6C	
0x1A70	Not this!
…	
0xFFFFFFFF:	

What will memory look like after these instructions?

x is 2 at `%ebp-8`, y is 3 at `%ebp-12`, z is 2 at `%ebp-16`

```
movl -16(%ebp),%eax
sall  $3, %eax
imull $3, %eax
movl -12(%ebp), %edx
addl  -8(%ebp), %edx
addl  %edx, %eax
movl  %eax, -8(%ebp)
```

Registers

name	value
`%eax`	?
`%edx`	?
`%ebp`	**`0x1270`**

Memory

address	value
`0x1260`	2
`0x1264`	3
`0x1268`	2
`0x126c`	
`0x1270`	
…	

What will memory look like after these instructions?

x is 2 at `%ebp-8`, y is 3 at `%ebp-12`, z is 2 at `%ebp-16`

```
movl -16(%ebp),%eax
sall  $3, %eax
imull $3, %eax
movl -12(%ebp), %edx
addl  -8(%ebp), %edx
addl  %edx, %eax
movl  %eax, -8(%ebp)
```

A:

address	value
0x1260	53
0x1264	3
0x1268	24
0x126c	
0x1270	
…	

C:

address	value
0x1260	2
0x1264	16
0x1268	24
0x126c	
0x1270	
…	

B:

address	value
0x1260	53
0x1264	3
0x1268	2
0x126c	
0x1270	
…	

D:

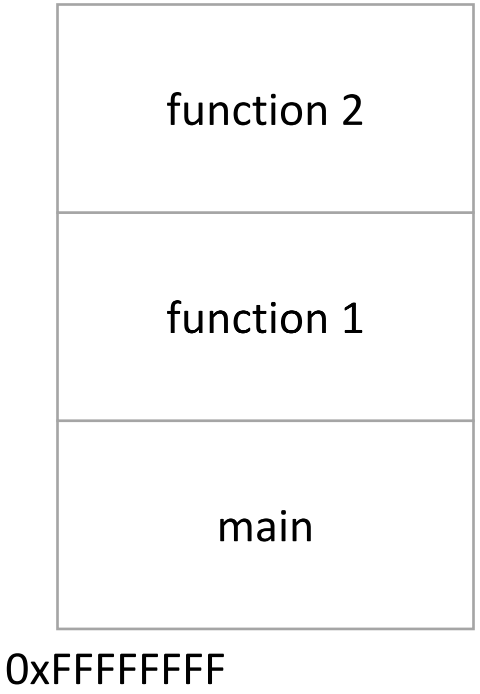
address	value
0x1260	2
0x1264	3
0x1268	53
0x126c	
0x1270	
…	

Stack Frame Contents

- What needs to be stored in a stack frame?
    - Alternatively: What must a function know?

- Local variables
- Previous stack frame base address
- Function arguments
- Return value
- Return address

- Saved registers
- Spilled temporaries



function 2

function 1

main

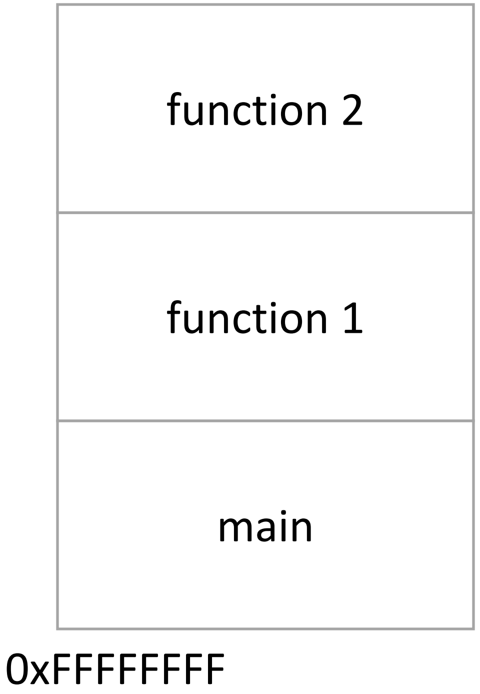
0xFFFFFFFF

Stack Frame Contents

- What needs to be stored in a stack frame?
    - Alternatively: What must a function know?

- Local variables
- Previous stack frame base address
- Function arguments
- Return value
- Return address

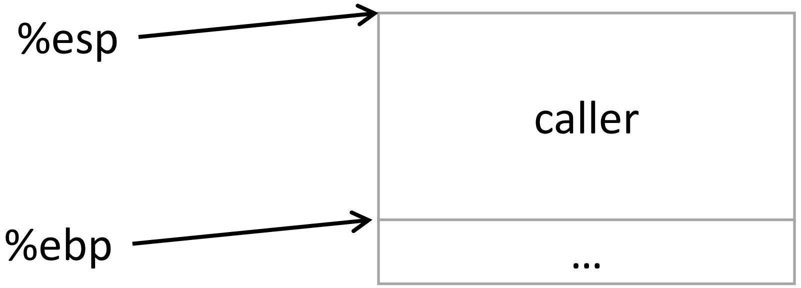
- Saved registers
- Spilled temporaries



Frame Pointer

- Must maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp

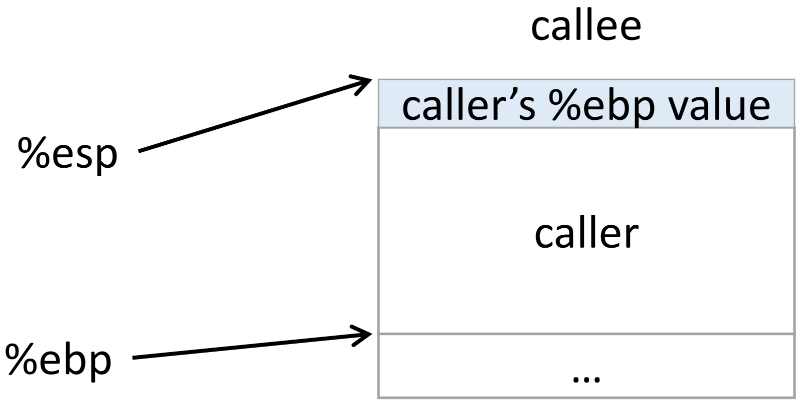
- Must adjust %esp, %ebp on call / return.



Frame Pointer

- Must maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp

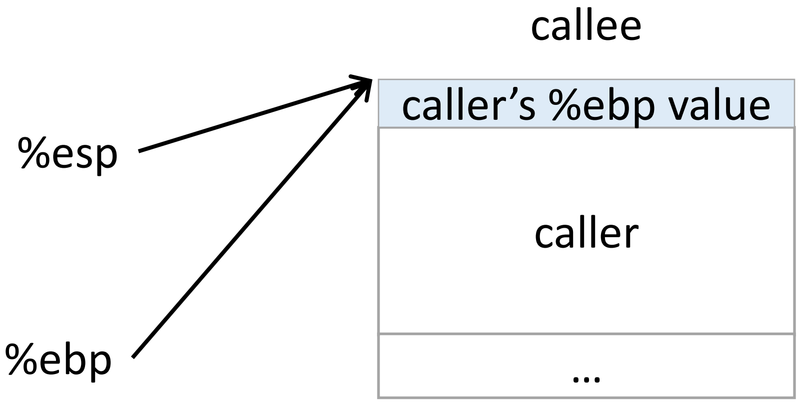
- Immediately upon calling a function:
  - pushl %ebp



Frame Pointer

- Must maintain invariant:
  - The current function’s stack frame is always between the addresses stored in %esp and %ebp

- Immediately upon calling a function:
  - pushl %ebp
  - Set %ebp = %esp

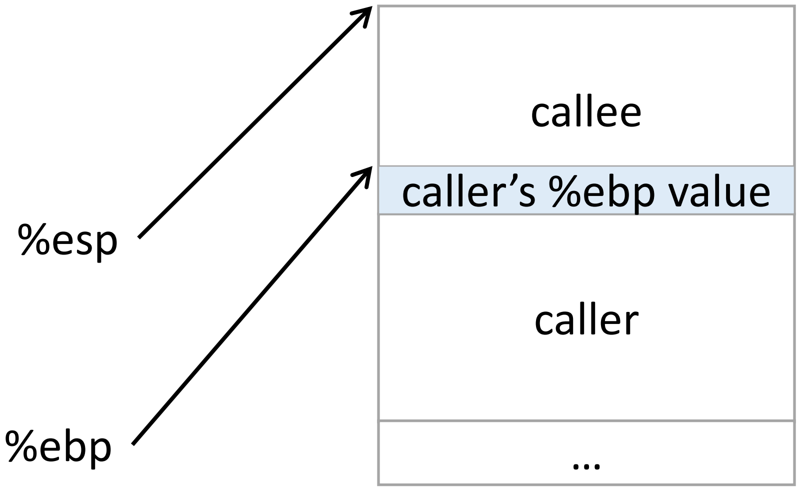


Frame Pointer

- Must maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp

- Immediately upon calling a function:
  - pushl %ebp
  - Set %ebp = %esp
  - Subtract N from %esp

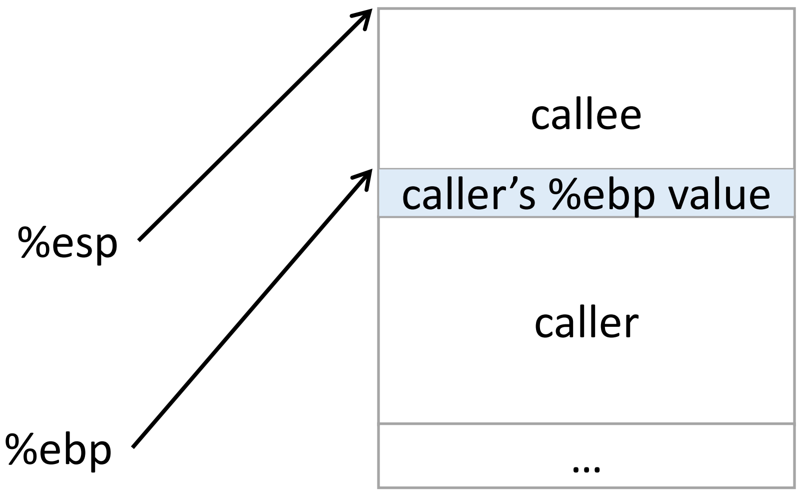
Callee can now execute.



Frame Pointer

- Must maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp

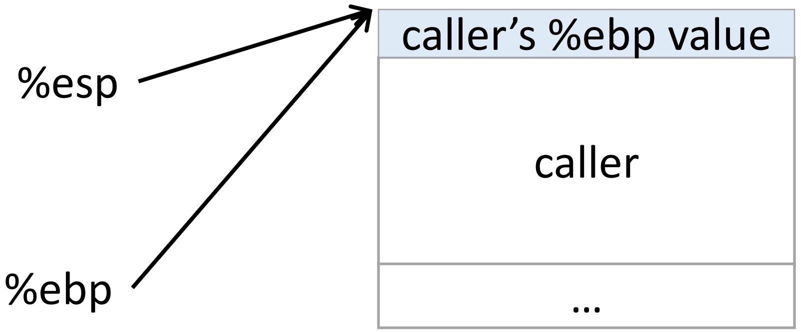
- To return, reverse this:



Frame Pointer

- Must maintain invariant:
    - The current function’s stack frame is always between the addresses stored in %esp and %ebp

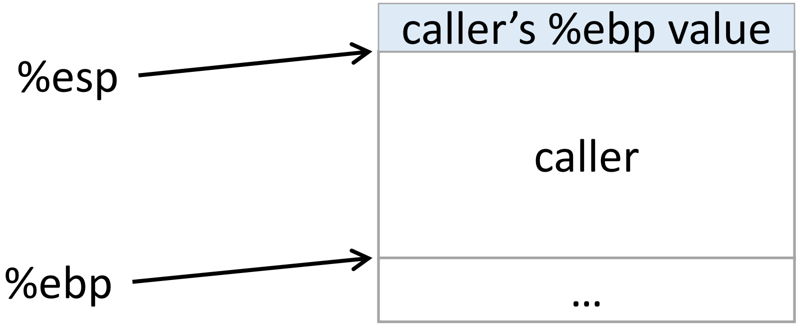
- To return, reverse this:
    - set %esp = %ebp



Frame Pointer

- Must maintain invariant:
  - The current function’s stack frame is always between the addresses stored in %esp and %ebp

- To return, reverse this:
  - set %esp = %ebp
  - popl %ebp

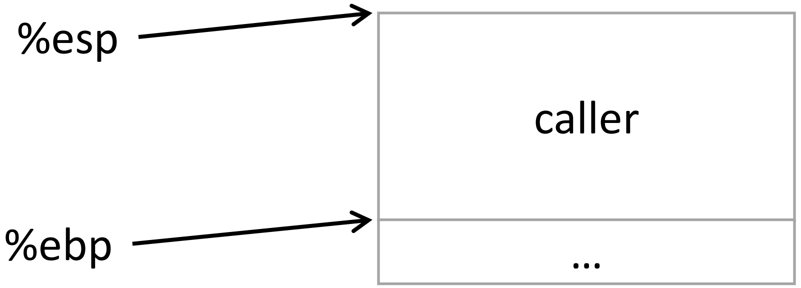


Frame Pointer

- Must maintain invariant:
  - The current function's stack frame is always between the addresses stored in %esp and %ebp

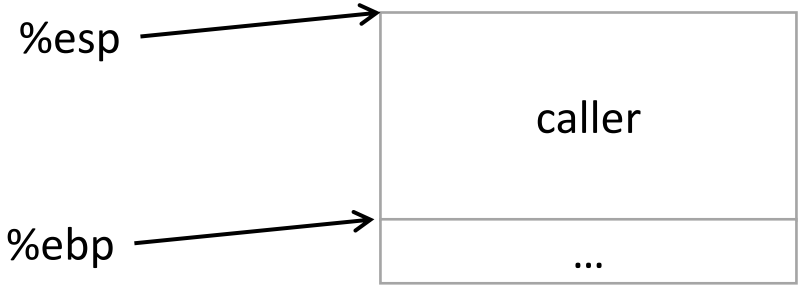
- To return, reverse this:
  - set %esp = %ebp
  - popl %ebp

IA32 has another convenience instruction for this: leave



Back to where we started.

Frame Pointer: Function Call

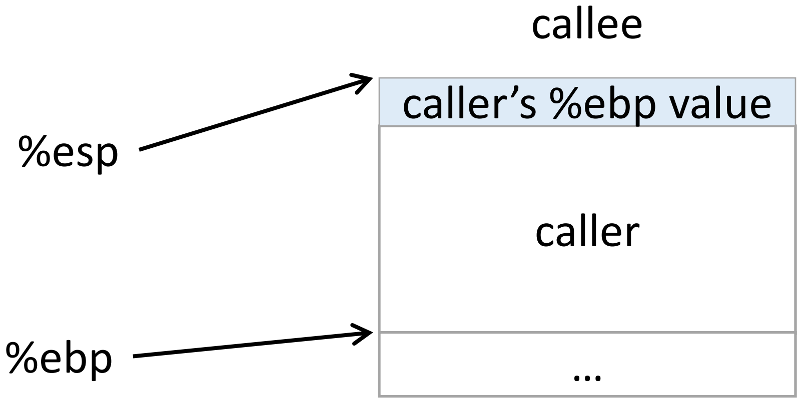

%esp

caller

%ebp

…

Initial state


callee

caller's %ebp value

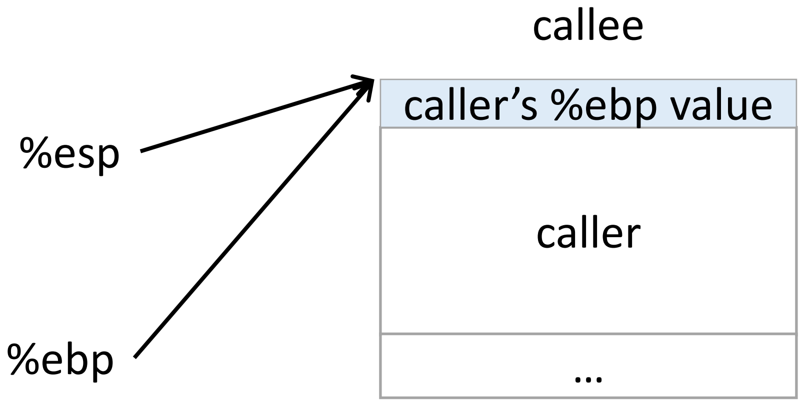
%esp

caller

%ebp

…

pushl %ebp (store caller's frame pointer)


callee

caller's %ebp value

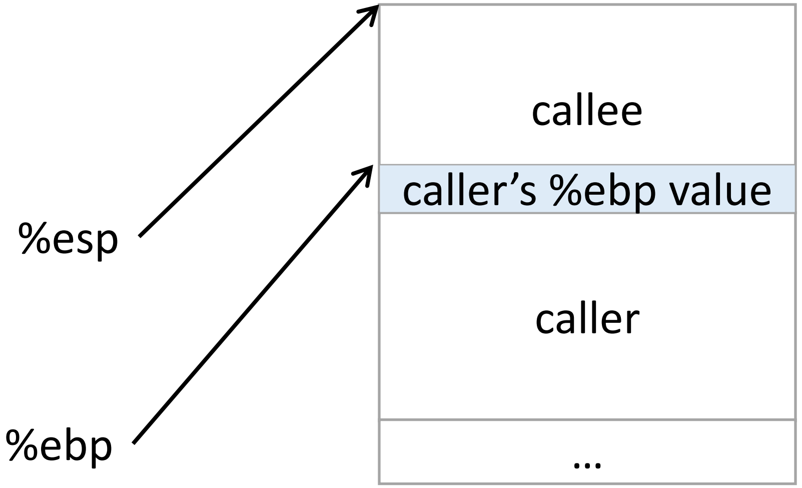
%esp

caller

%ebp

…

movl %esp, %ebp
(establish callee's frame pointer)


callee

caller's %ebp value

%esp

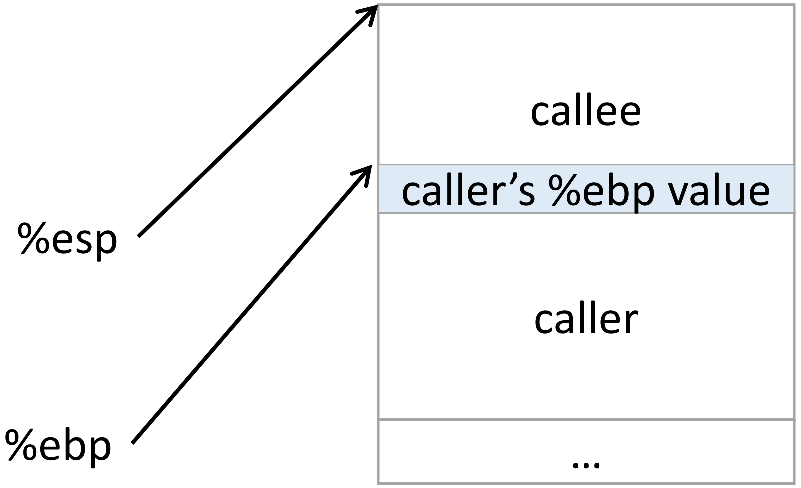
caller

%ebp

…

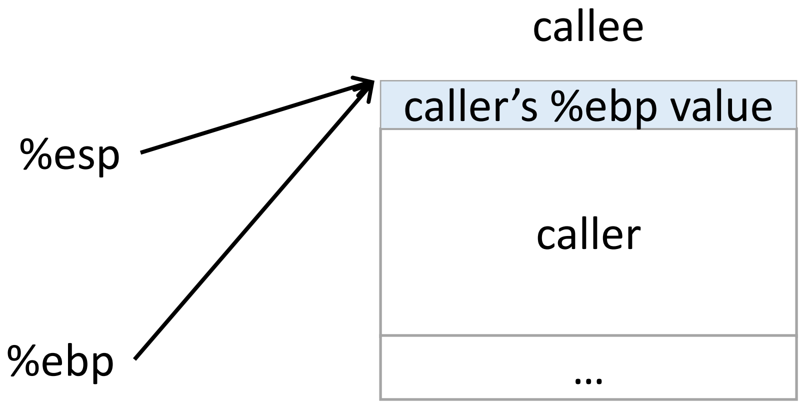
subl $SIZE, %esp
(allocate space for callee's locals)

Frame Pointer: Function Return

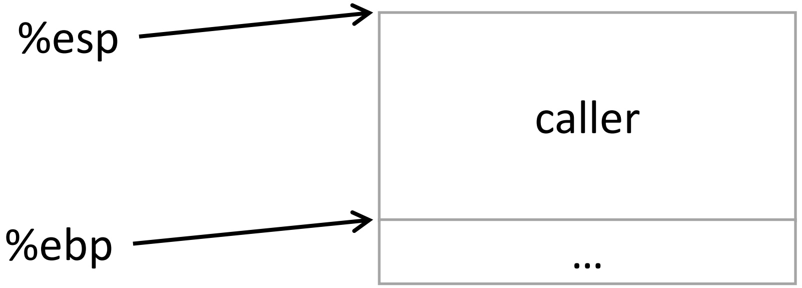


Want to restore caller's frame.

IA32 provides a convenience instruction that does all of this:
`leave`

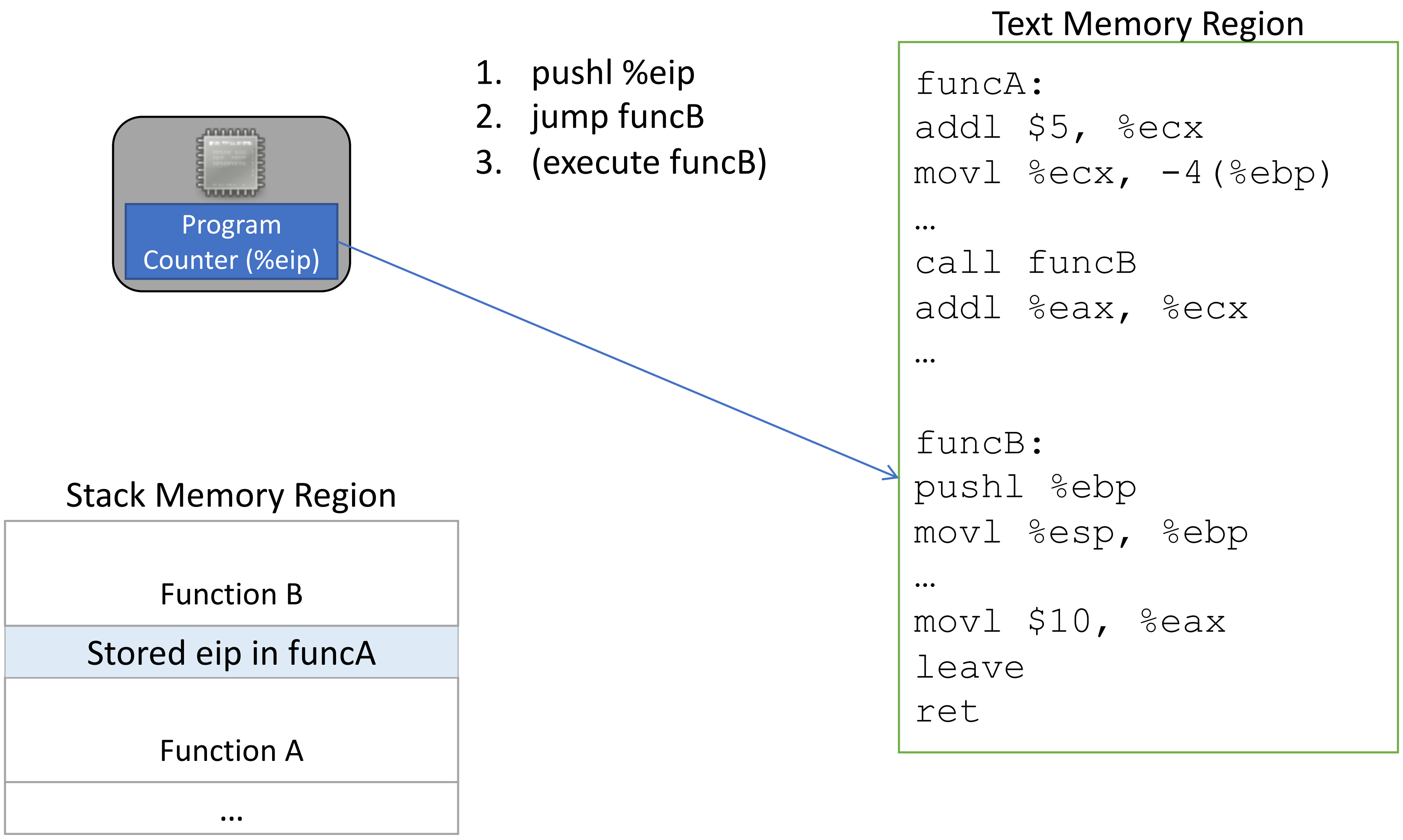


movl %ebp, %esp
(restore caller's stack pointer)



popl %ebp (restore caller's frame pointer)

Functions and the Stack



1. pushl %eip
2. jump funcB
3. (execute funcB)

Text Memory Region

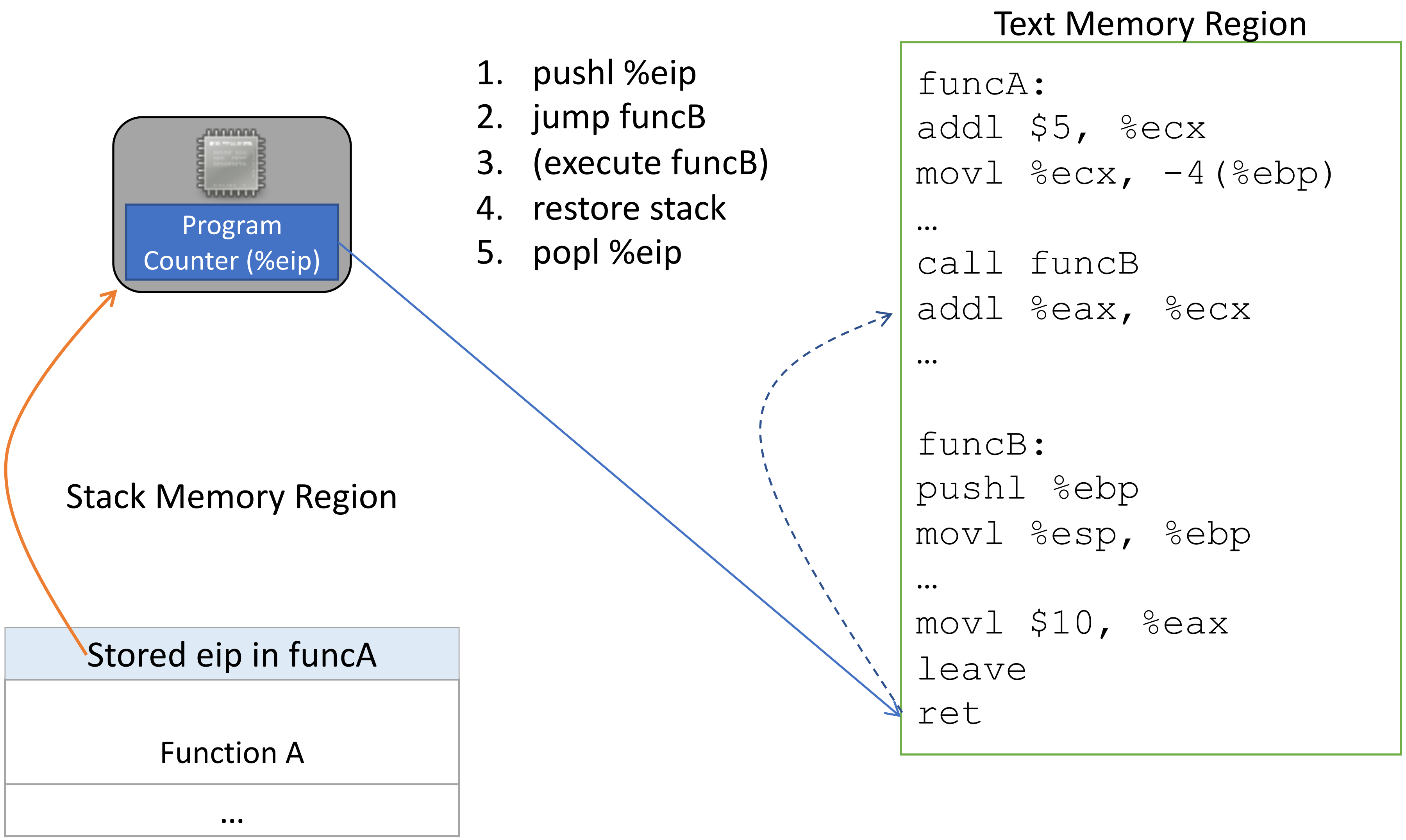
```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Stack Memory Region

Function B
Stored eip in funcA
Function A
…

Functions and the Stack

1. pushl %eip
2. jump funcB
3. (execute funcB)
4. restore stack
5. popl %eip



Program Counter (%eip)

Stack Memory Region

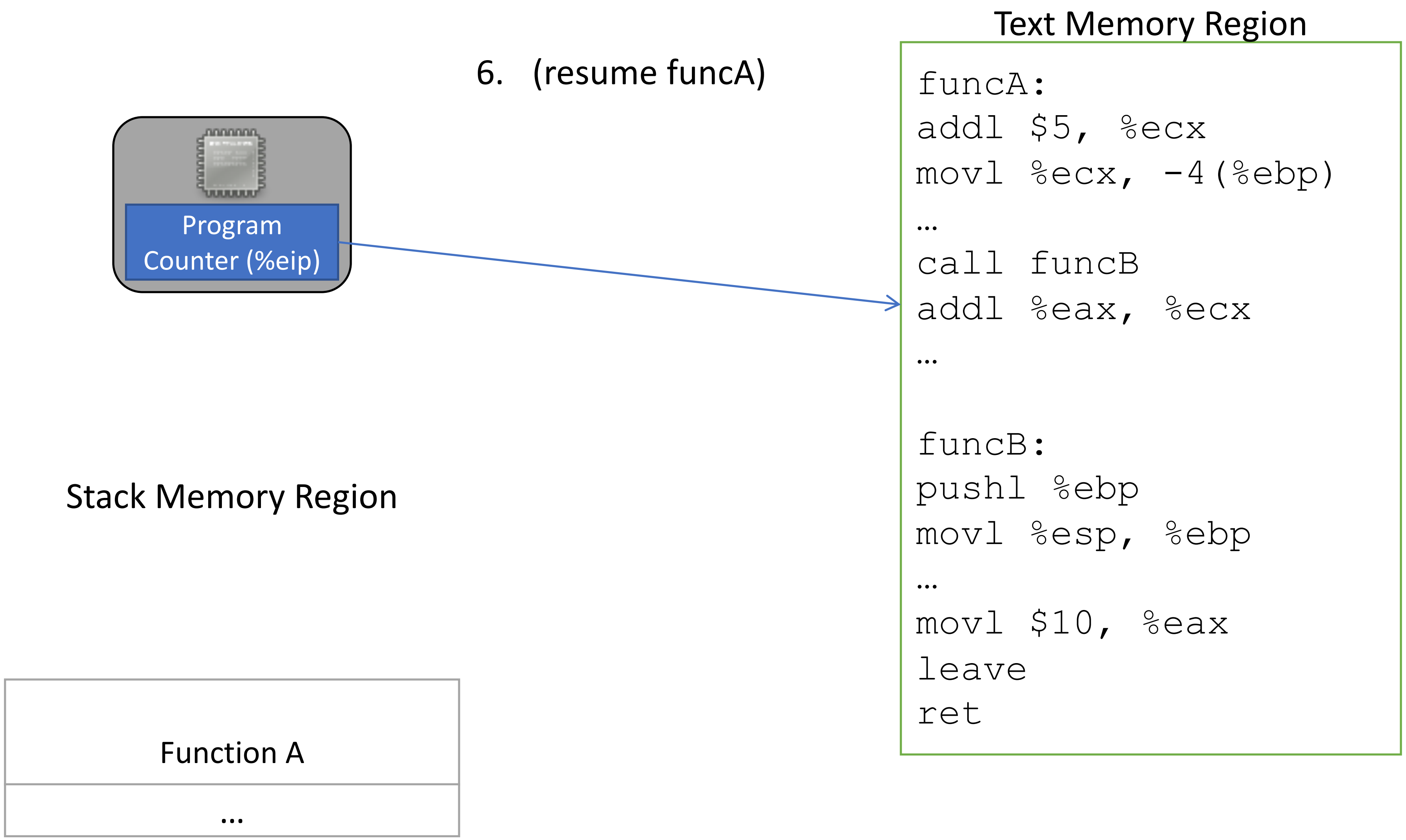
Stored eip in funcA
Function A
…

Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

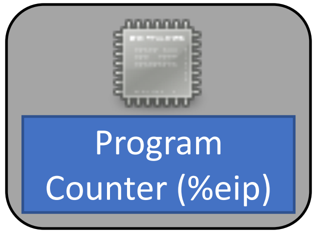
Functions and the Stack

6. (resume funcA)



```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Functions and the Stack

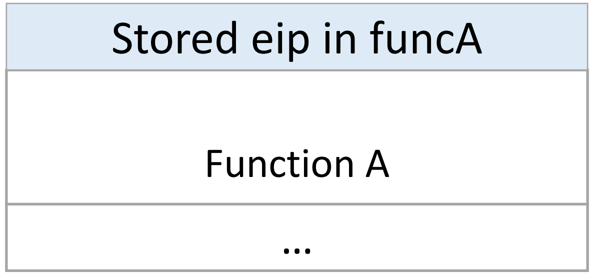


1. pushl %eip
2. jump funcB
3. (execute funcB)
4. restore stack
5. popl %eip
6. (resume funcA)

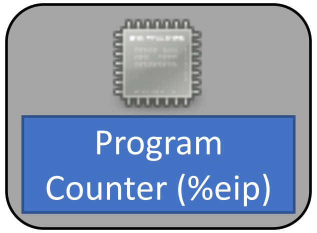
Text Memory Region

```
funcA:
addl $5, %ecx
movl %ecx, -4(%ebp)
…
call funcB
addl %eax, %ecx
…

funcB:
pushl %ebp
movl %esp, %ebp
…
movl $10, %eax
leave
ret
```

Stack Memory Region



Functions and the Stack



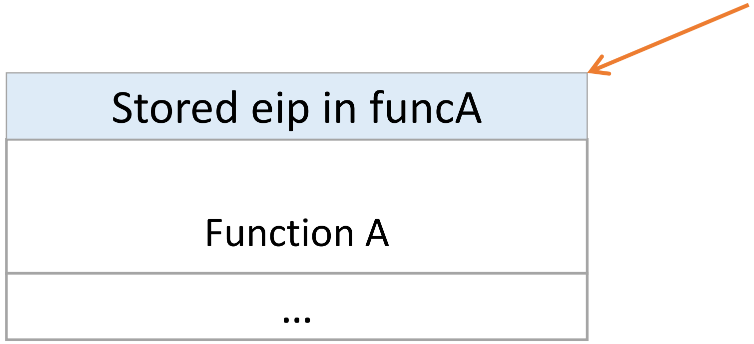
1. pushl %eip
2. jump funcB
3. (execute funcB)
4. restore stack
5. popl %eip
6. (resume funcA)

call

leave

ret

Stack Memory Region



Stored eip in funcA
Function A
…

Return address:

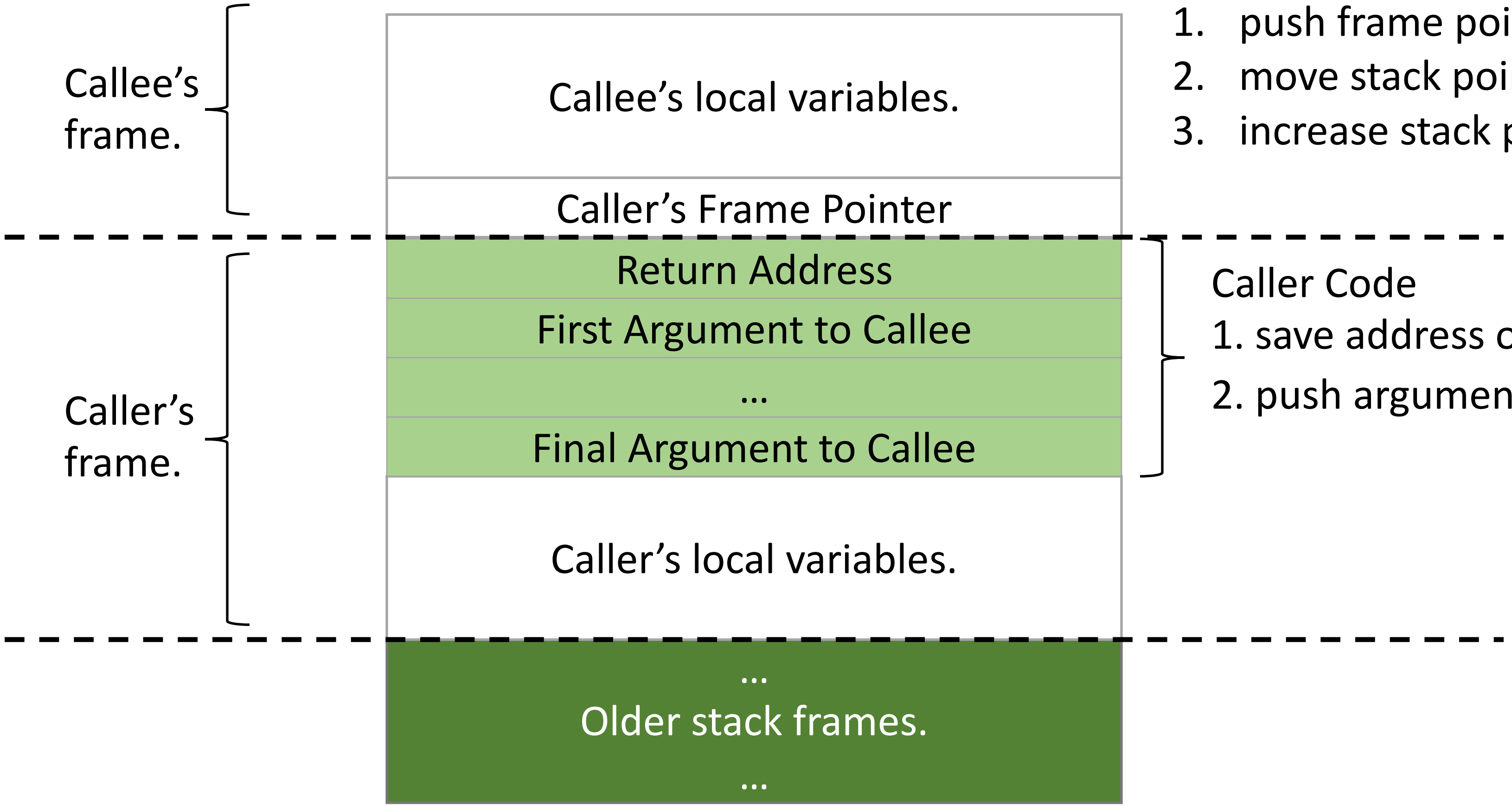
Address of the instruction we should jump back to when we finish (return from) the currently executing function.

Register Convention

- Caller-saved: %eax, %ecx, %edx
  - If the caller wants to preserve these registers, it must save them prior to calling callee
  - callee free to trash these, caller will restore if needed

- Callee-saved: %ebx, %esi, %edi
  - If the callee wants to use these registers, it must save them first, and restore them before returning
  - caller can assume these will be preserved

Putting it all together…



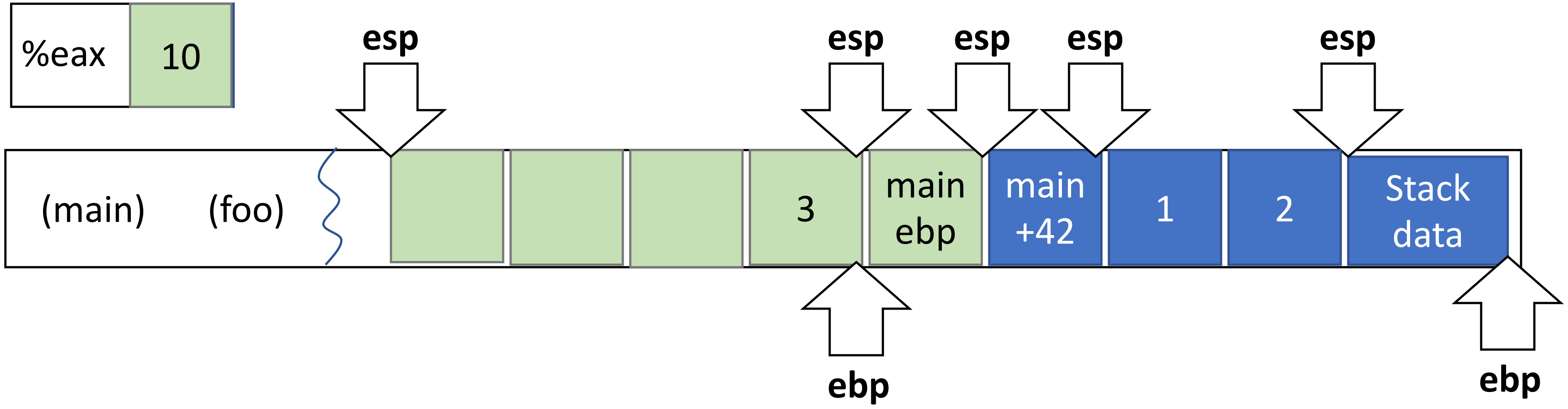
Callee Code

1. push frame pointer
2. move stack pointer to frame pointer
3. increase stack pointer

Caller Code

1. save address of next instruction
2. push arguments

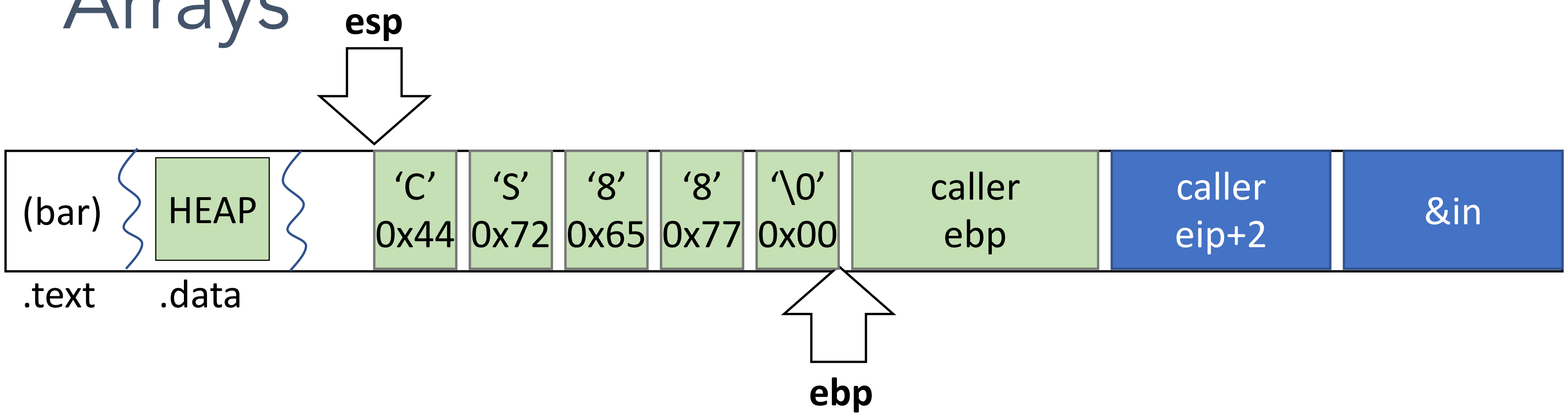
Implementing a function call



```
main:
        …
eip     subl    $8, %esp
eip     movl    $2, 4(%esp)
eip     movl    $1, (%esp)
eip     call    foo
eip     addl    $8, %esp
        …
```

```
foo:
eip     pushl   %ebp
eip     movl    %esp, %ebp
eip     subl    $16, %esp
eip     movl    $3, -4(%ebp)
eip     movl    8(%ebp), %eax
eip     addl    $9, %eax
eip     leave
eip     ret
```

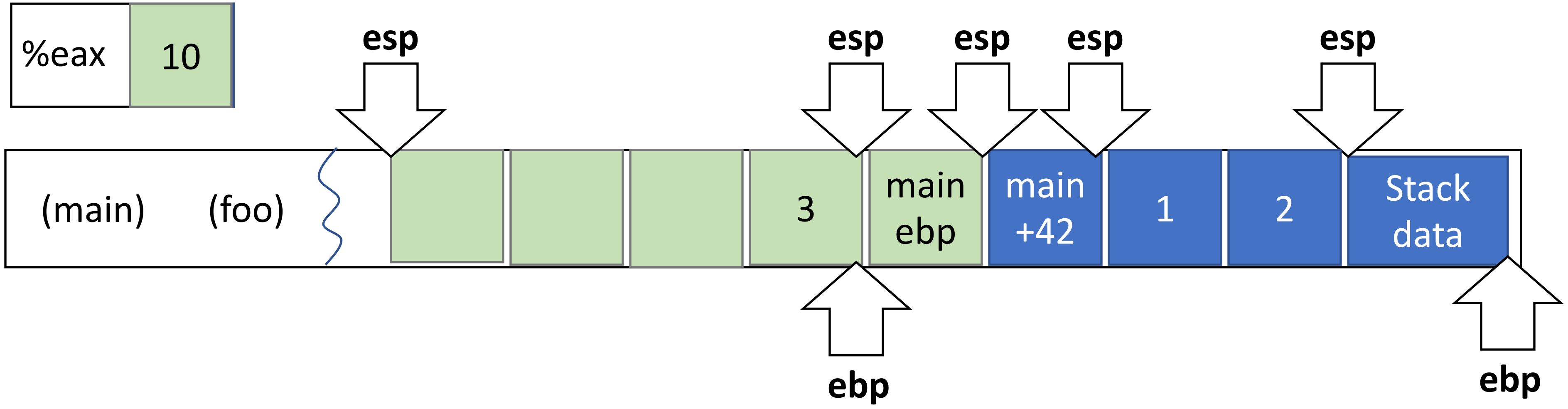
Arrays



```
void bar(char * in){
  char name[5];
  strcpy(name, in);
}
```

```
bar:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $5, %esp
  movl   8(%ebp), %eax
  movl   %eax, 4(%esp)
  leal   -5(%ebp), %eax
  movl   %eax, (%esp)
  call   strcpy
  leave
  ret
```

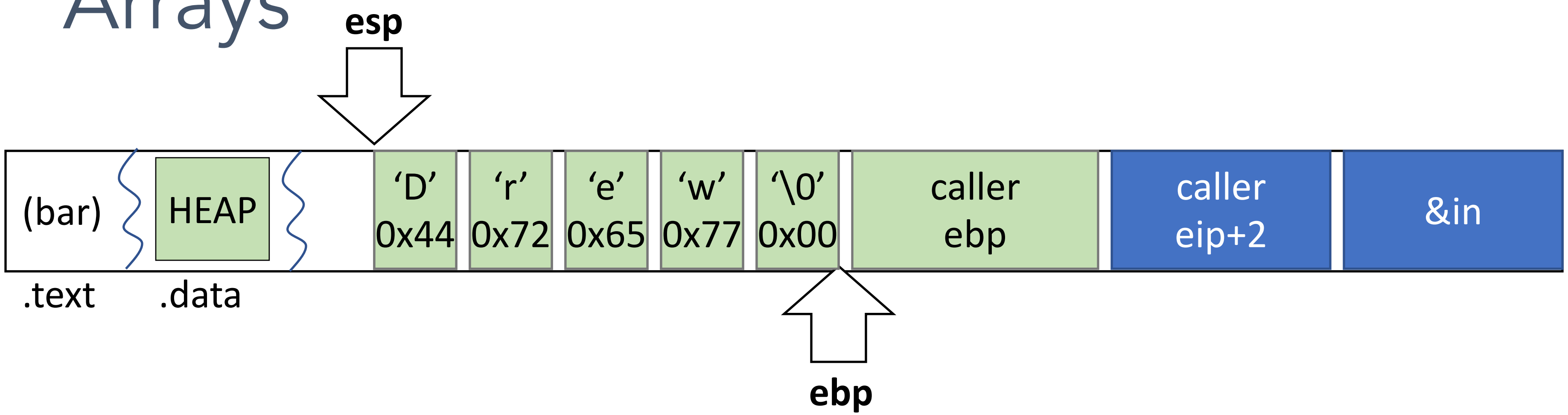
Implementing a function call



```
main:
        …
        subl    $8, %esp
        movl    $2, 4(%esp)
        movl    $1, (%esp)
        call    foo
        addl    $8, %esp
        …
```

```
foo:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    $3, -4(%ebp)
        movl    8(%ebp), %eax
        addl    $9, %eax
        leave
        ret
```

Arrays



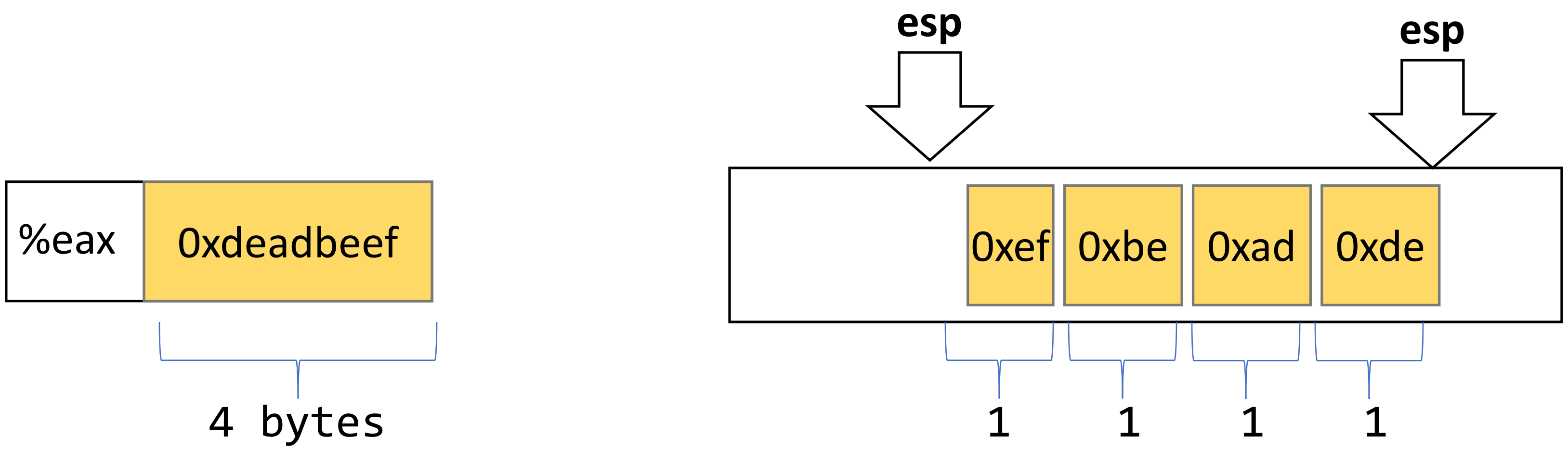
```
void bar(char * in){
  char name[5];
  strcpy(name, in);
}
```

```
bar:
  pushl   %ebp
  movl    %esp, %ebp
  subl    $5, %esp
  movl    8(%ebp), %eax
  movl    %eax, 4(%esp)
  leal    -5(%ebp), %eax
  movl    %eax, (%esp)
  call    strcpy
  leave
  ret
```

Data types / Endianness

- x86 is a little-endian architecture

`pushl %eax`



%eax

0xdeadbeef

4 bytes

esp

esp

0xef

0xbe

0xad

0xde

1

1

1

1

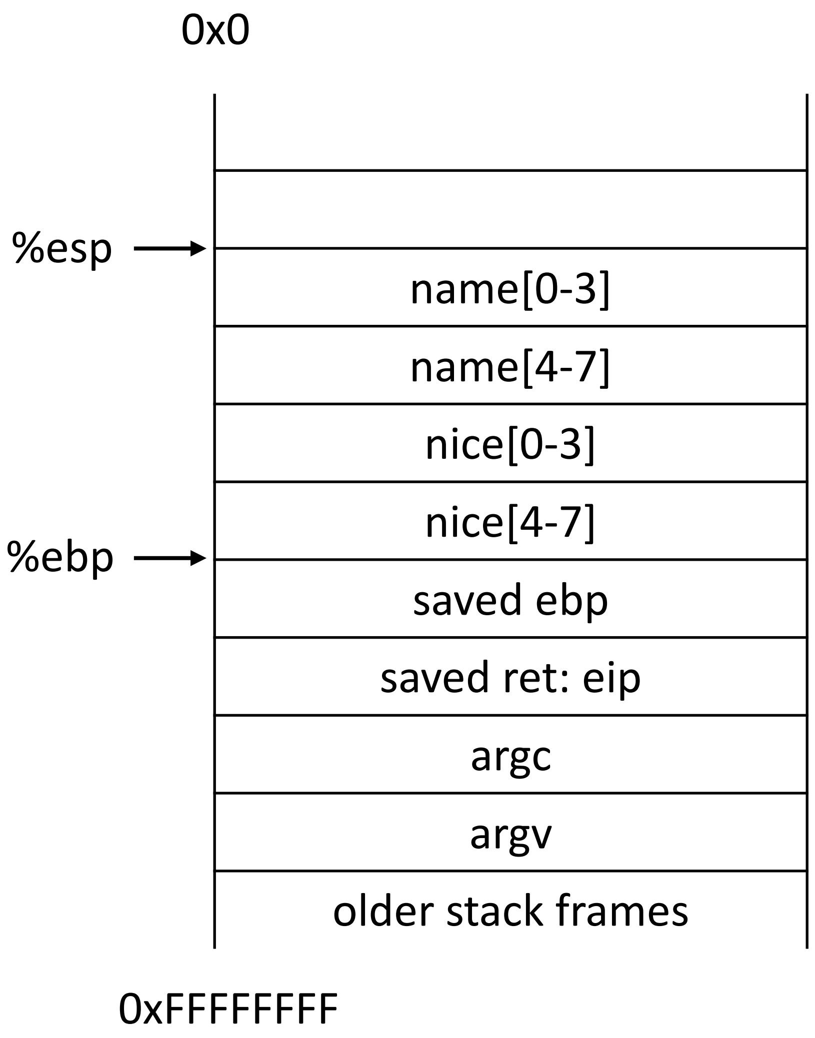
Buffer Overflows

When is a program secure?

- Formal approach: When it does exactly what it should
  - not more
  - not less
- But how do we know what it is supposed to do?

Example 1

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

int main(int argc, char**argv){
   char nice[] = “is nice.”;
   char name[8];
   gets(name);
   printf(“%s %s\n”, name, nice);
   return 0;
}
```

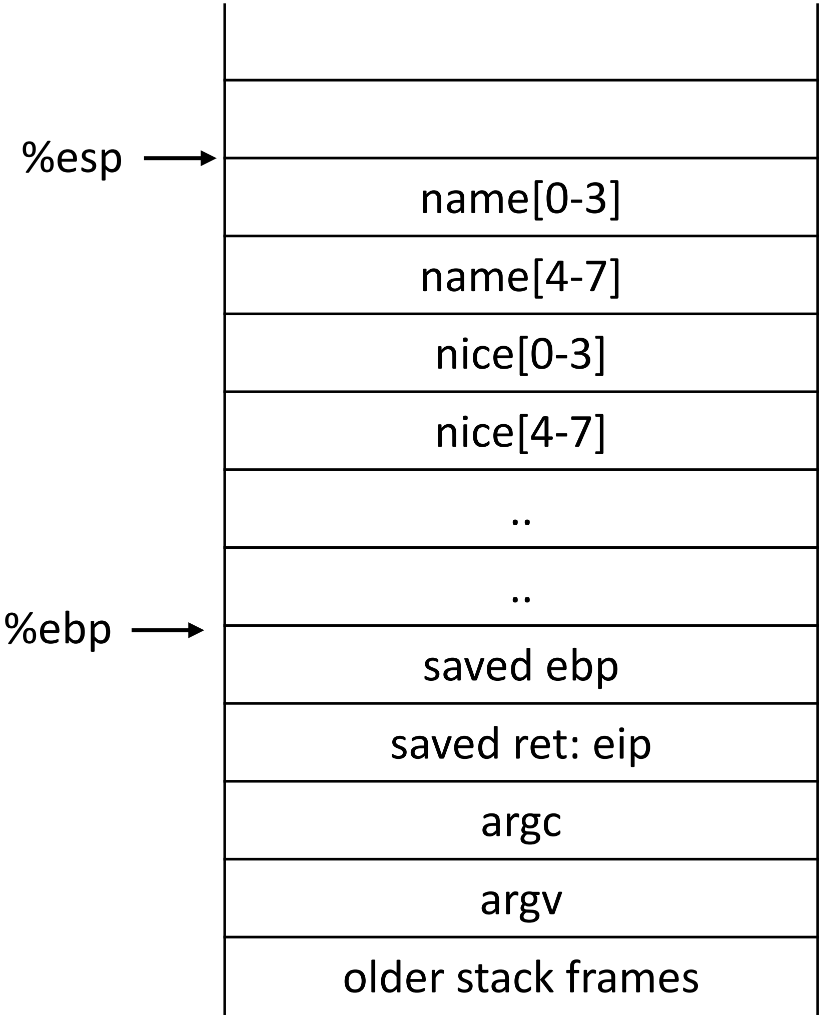


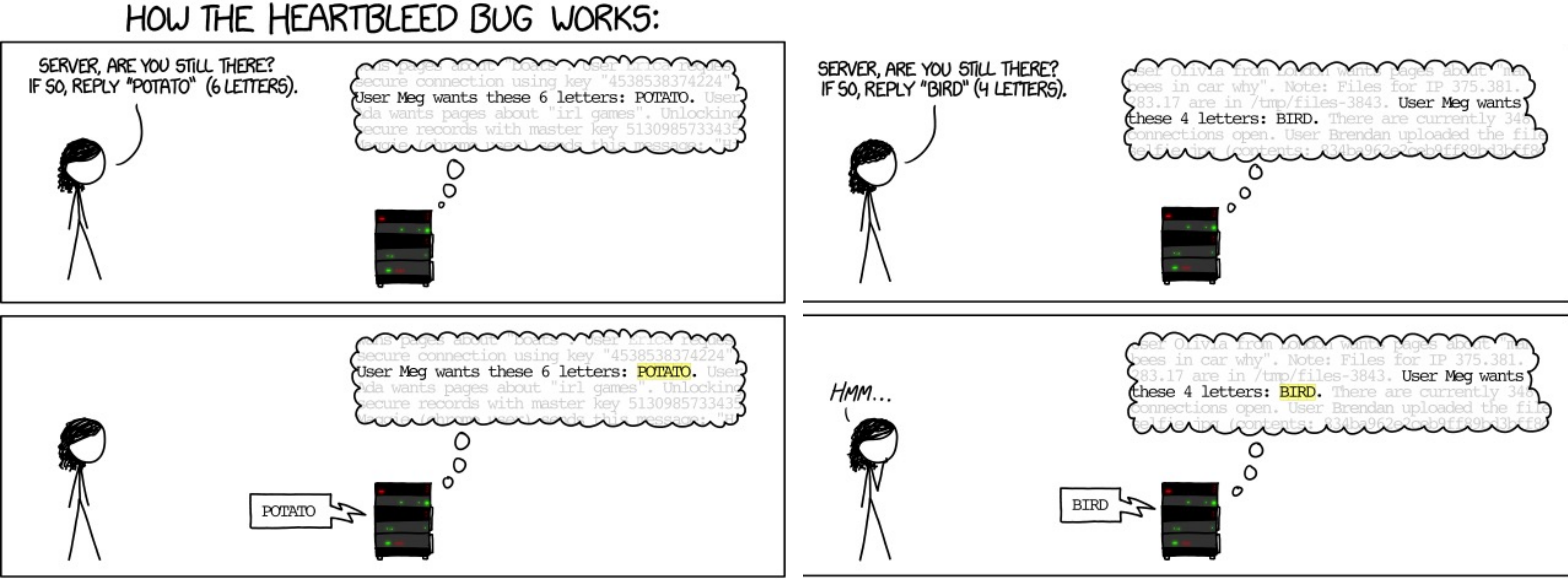
Function call stack

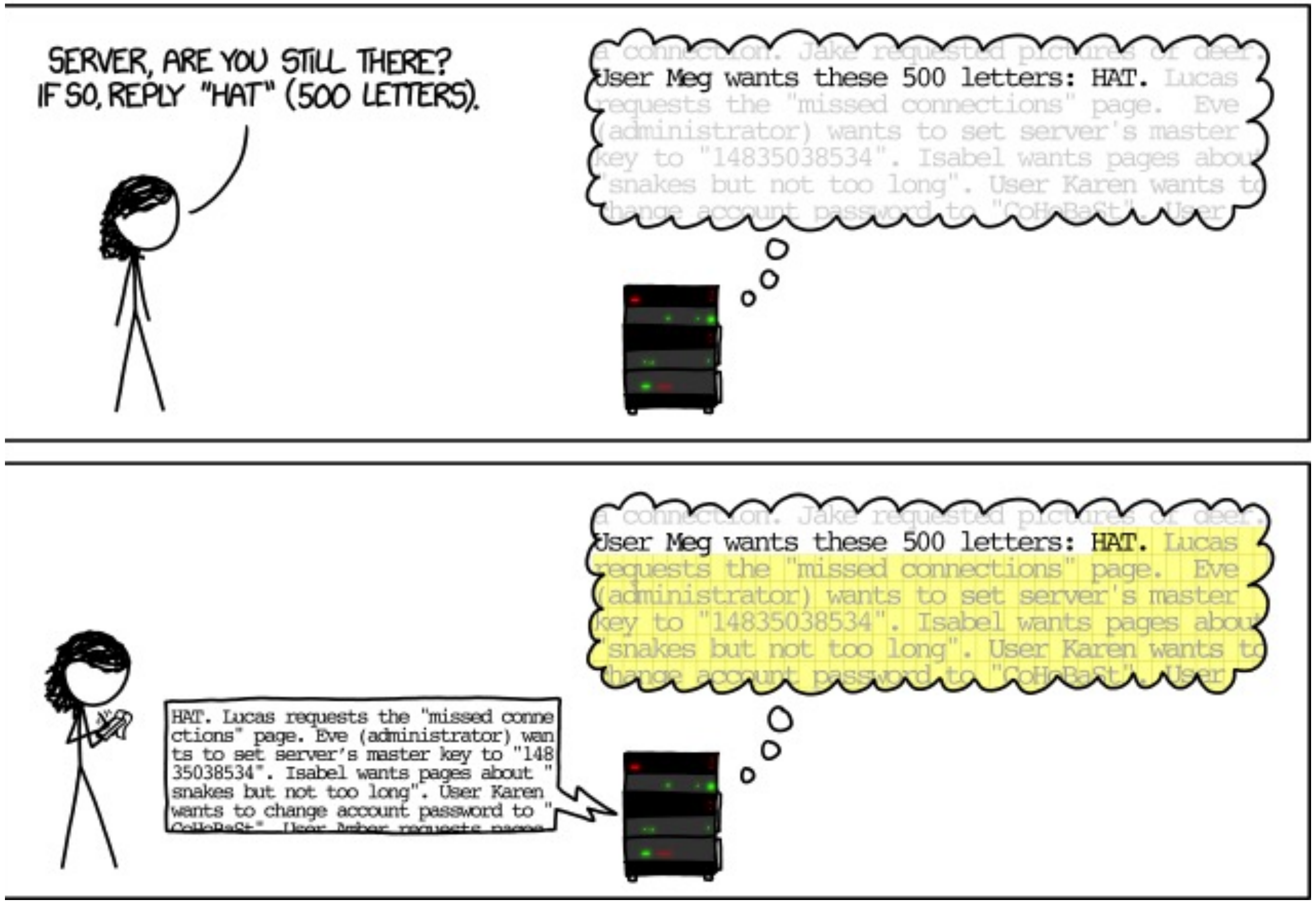
What happens if we <u>read</u> a long name?

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

int main(int argc, char**argv){
   char nice[] = “is nice.”;
   char name[8];
   gets(name);
   printf(“%s %s\n”, name, nice);
   return 0;
}
```

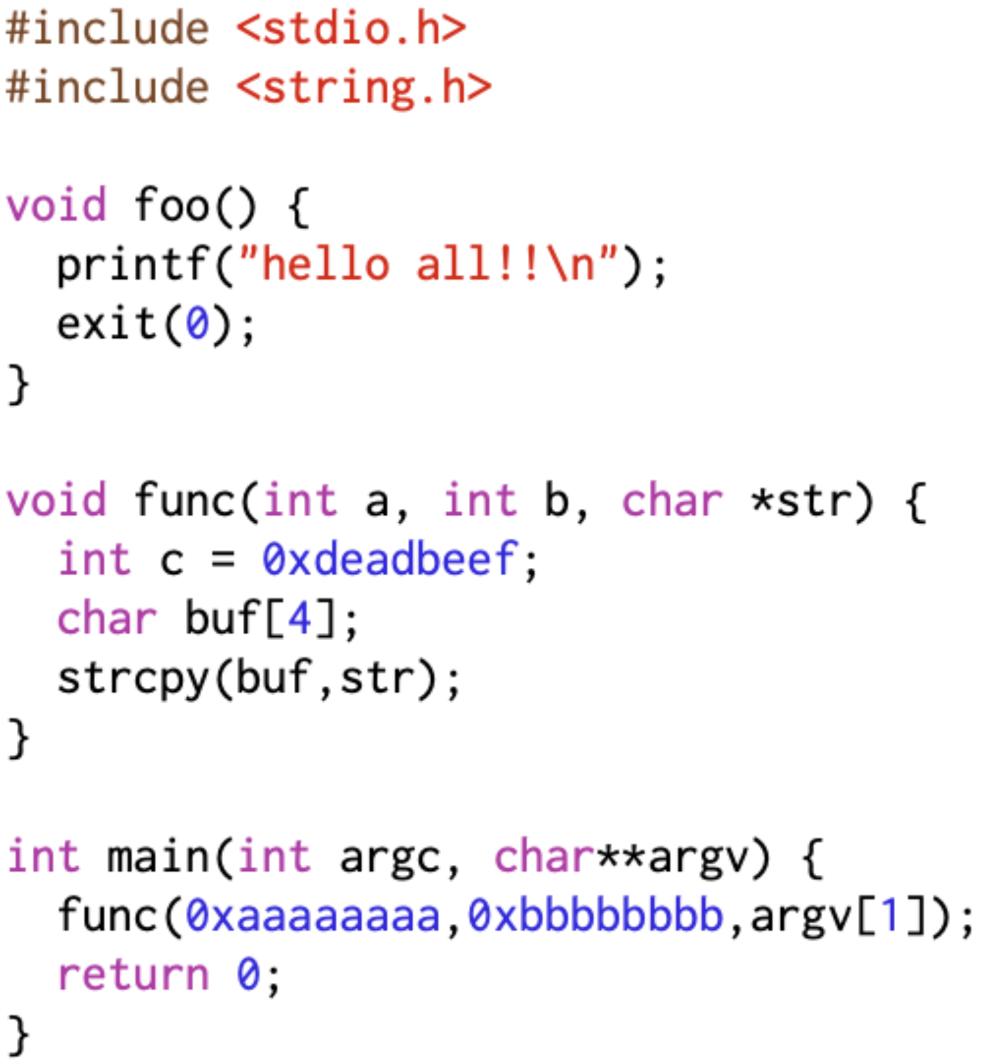
A. Nothing bad will happen
B. Something nonsensical will result
C. Something terrible will result




HOW THE HEARTBLEED BUG WORKS:
SERVER, ARE YOU STILL THERE? IF SO, REPLY "POTATO" (6 LETTERS).
secure connection using key "4538538374224" User Meg wants these 6 letters: POTATO. User Ada wants pages about "irl games". Unlocking secure records with master key 5130985733435
POTATO
SERVER, ARE YOU STILL THERE? IF SO, REPLY "BIRD" (4 LETTERS).
bees in car why". Note: Files for IP 375.381.283.17 are in /tmp/files-3843. User Meg wants these 4 letters: BIRD. There are currently 346 connections open. User Brendan uploaded the file
HMM...
BIRD


SERVER, ARE YOU STILL THERE? IF SO, REPLY "HAT" (500 LETTERS).
a connection. Jake requested pictures of deer. User Meg wants these 500 letters: HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about "snakes but not too long". User Karen wants to change account password to "CoHoBaSt". User
a connection. Jake requested pictures of deer. User Meg wants these 500 letters: HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about "snakes but not too long". User Karen wants to change account password to "CoHoBaSt". User
HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about "snakes but not too long". User Karen wants to change account password to "CoHoBaSt". User Amber requests pages

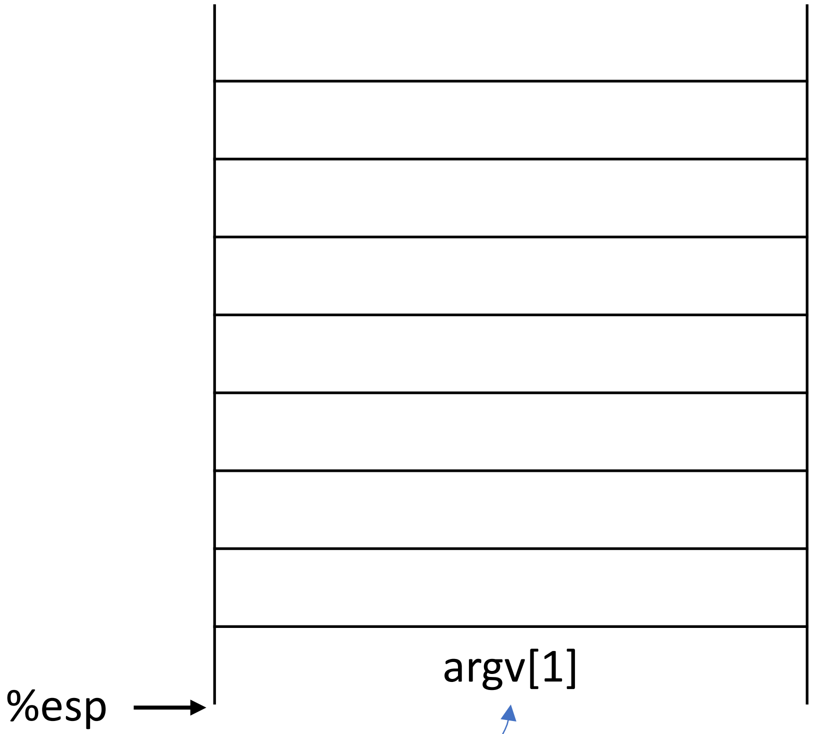
Buffer Overflow example



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

void foo() {
  printf("hello all!!\n”);
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```

Buffer Overflow example

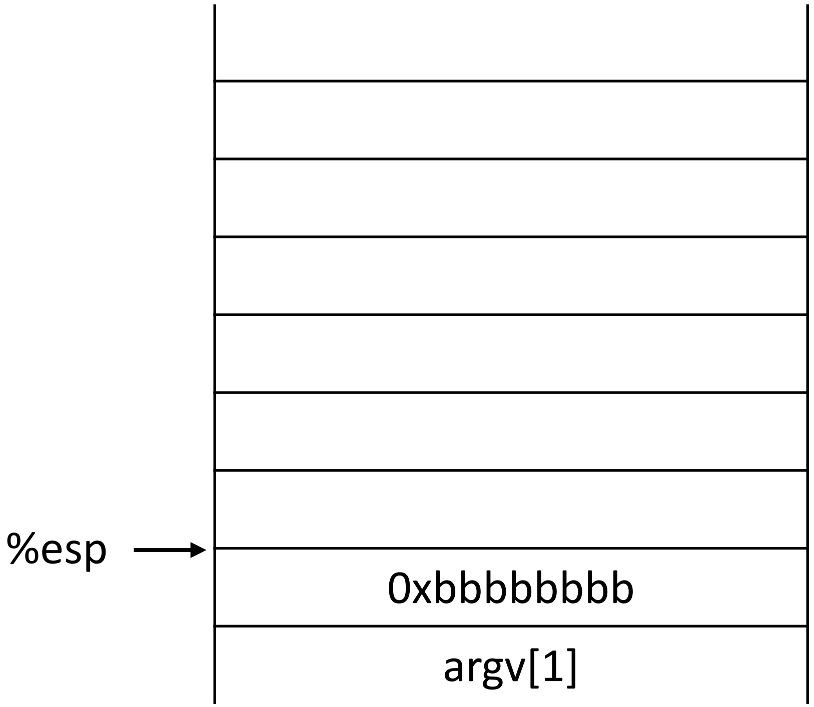
```
#include <stdio.h>
#include <string.h>

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



Load function arguments starting with the last argument

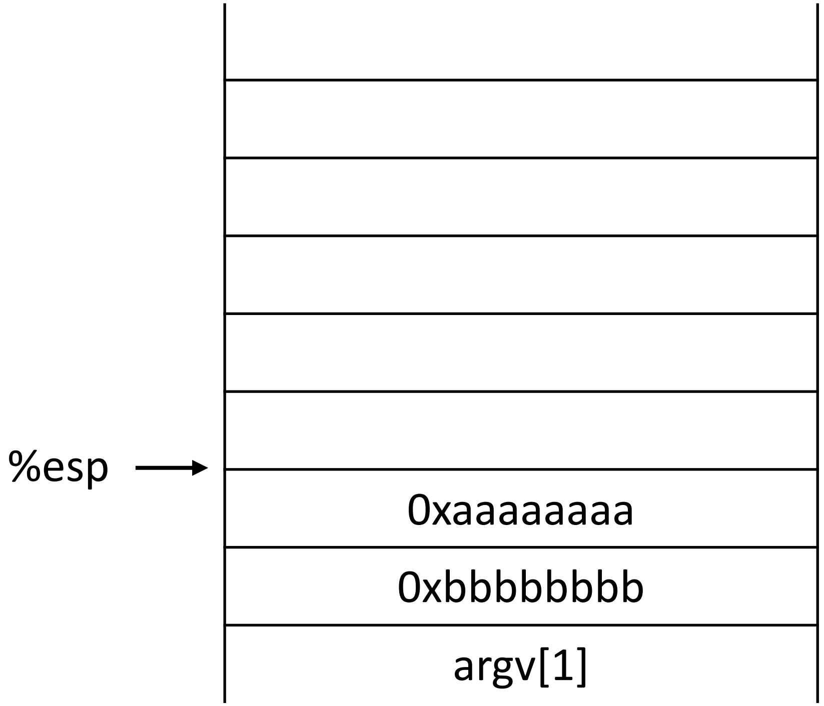
Buffer Overflow example

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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



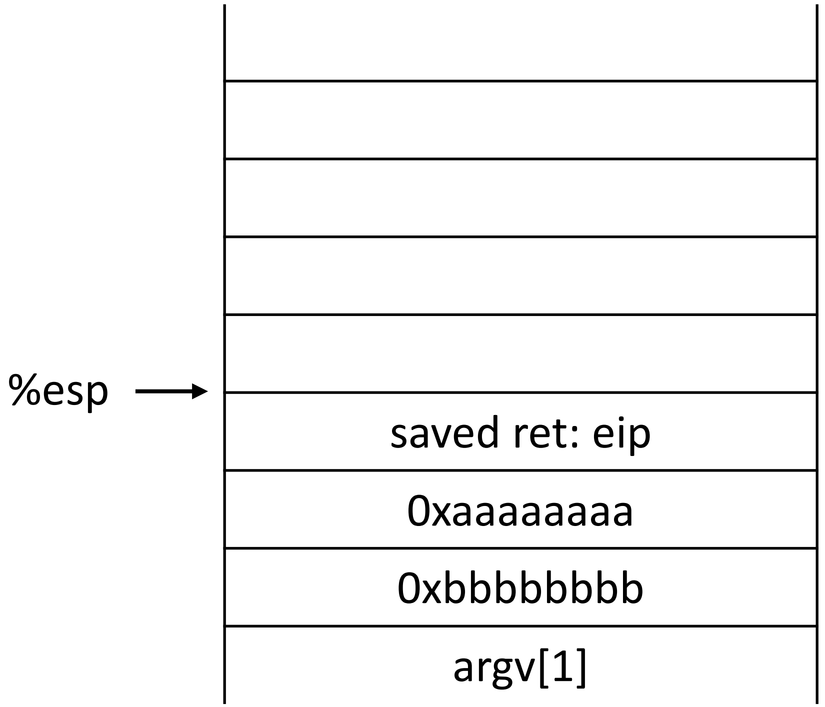
Buffer Overflow example

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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



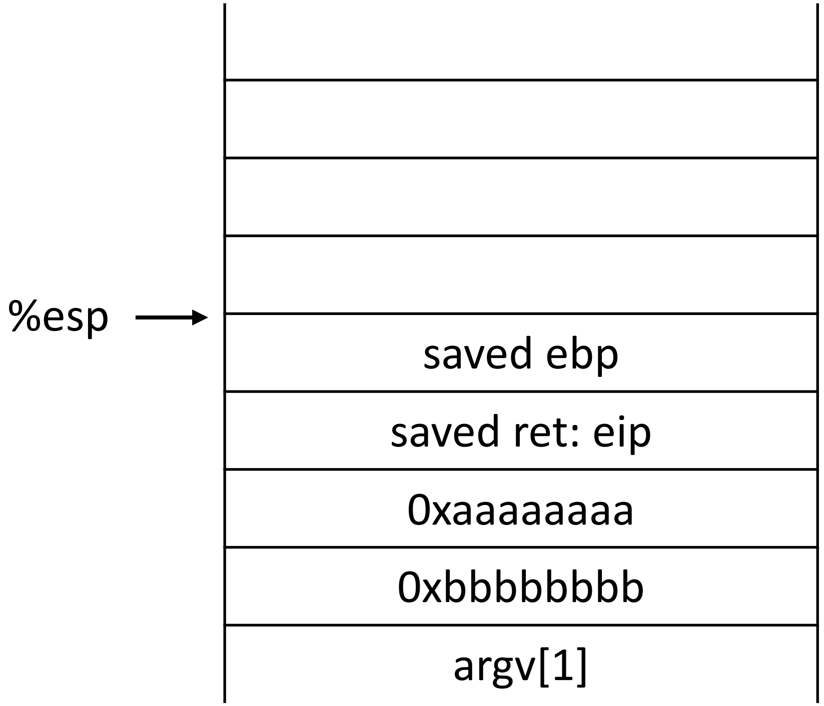
Buffer Overflow example

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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



Buffer Overflow example

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

void foo() {
  printf("hello all!!\n”);
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



%esp

saved ebp

saved ret: eip

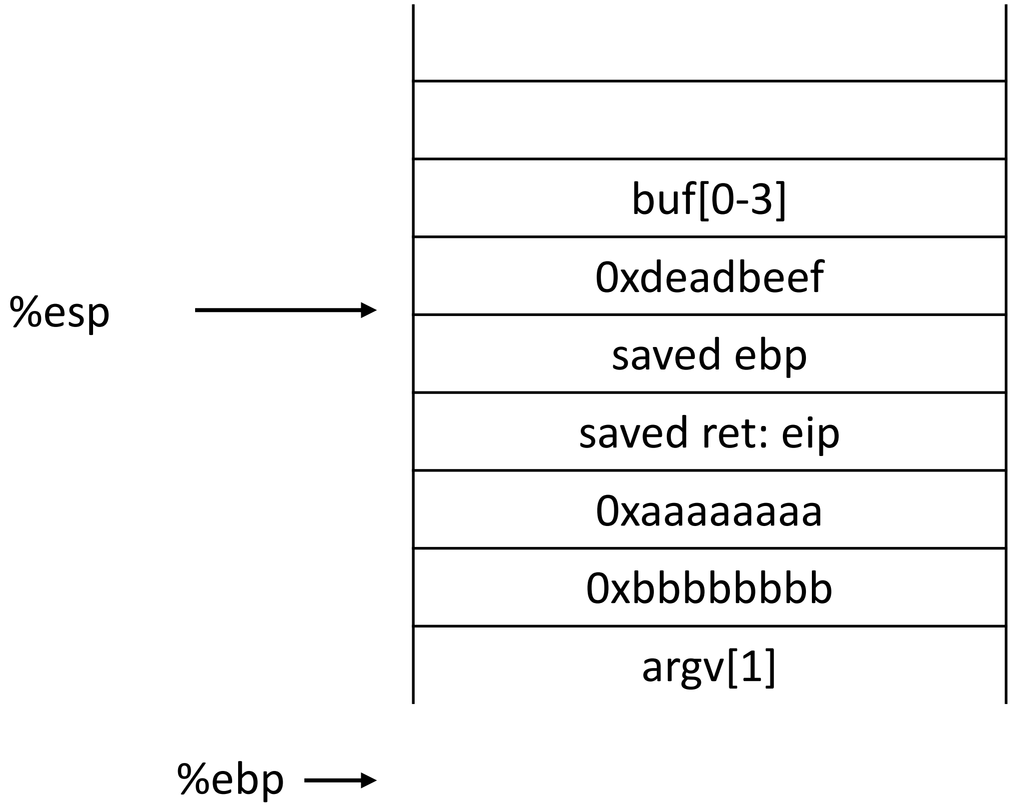
0xaaaaaaaa

0xbbbbbbbb

argv[1]

Buffer Overflow example

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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



%esp

buf[0-3]

0xdeadbeef

saved ebp

saved ret: eip

0xaaaaaaaa

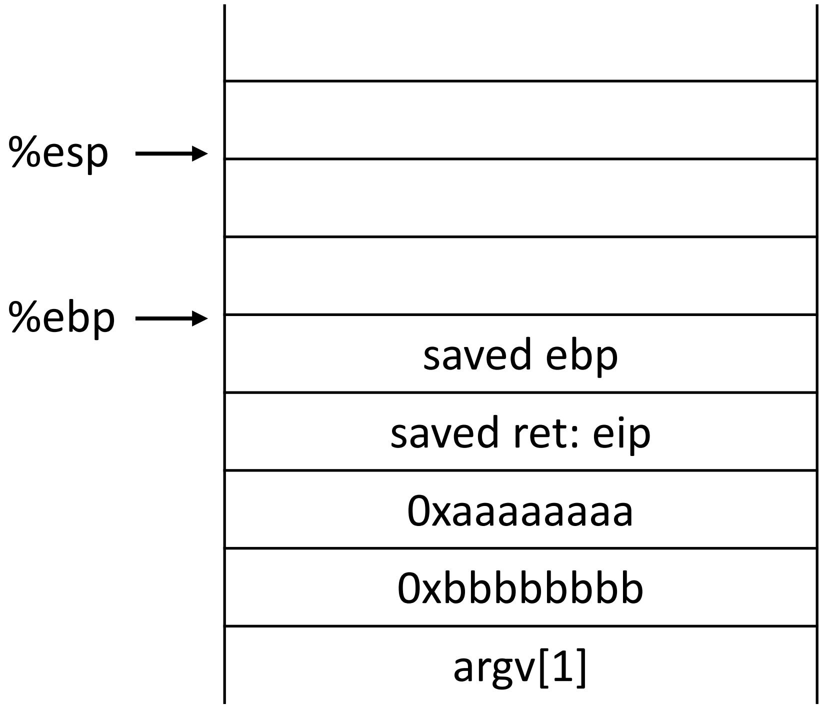
0xbbbbbbbb

argv[1]

%ebp

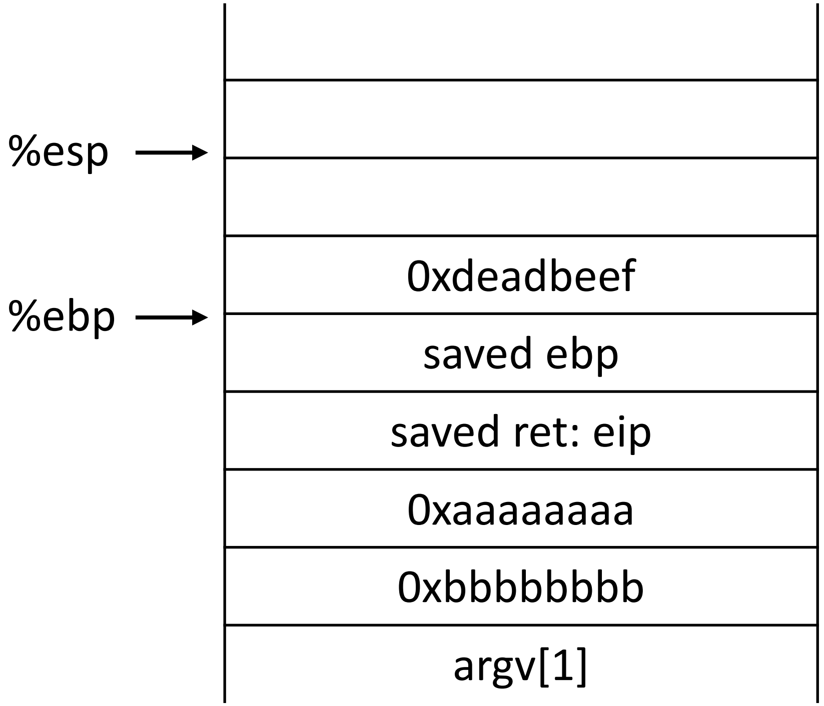
Buffer Overflow example

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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



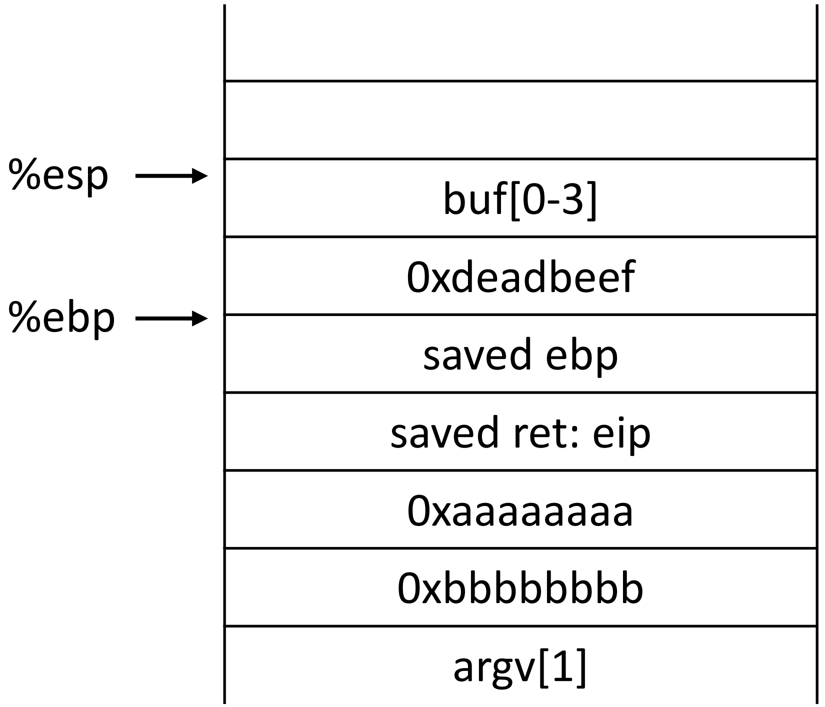
Buffer Overflow example

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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



Buffer Overflow example

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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



%esp → buf[0-3]

0xdeadbeef

%ebp → saved ebp

saved ret: eip

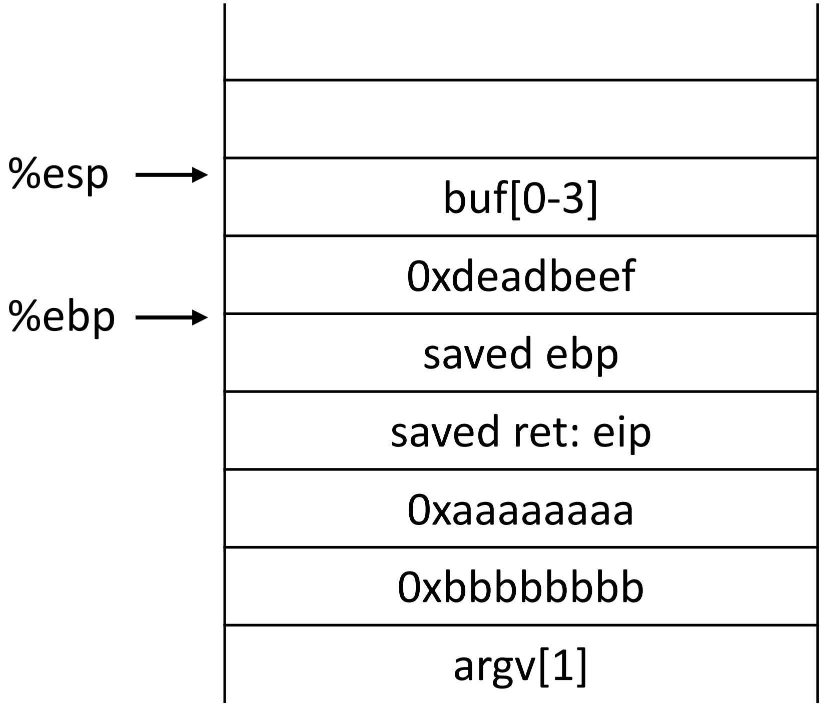
0xaaaaaaaa

0xbbbbbbbb

argv[1]

Buffer Overflow example

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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



%esp → buf[0-3]

0xdeadbeef

%ebp → saved ebp

saved ret: eip

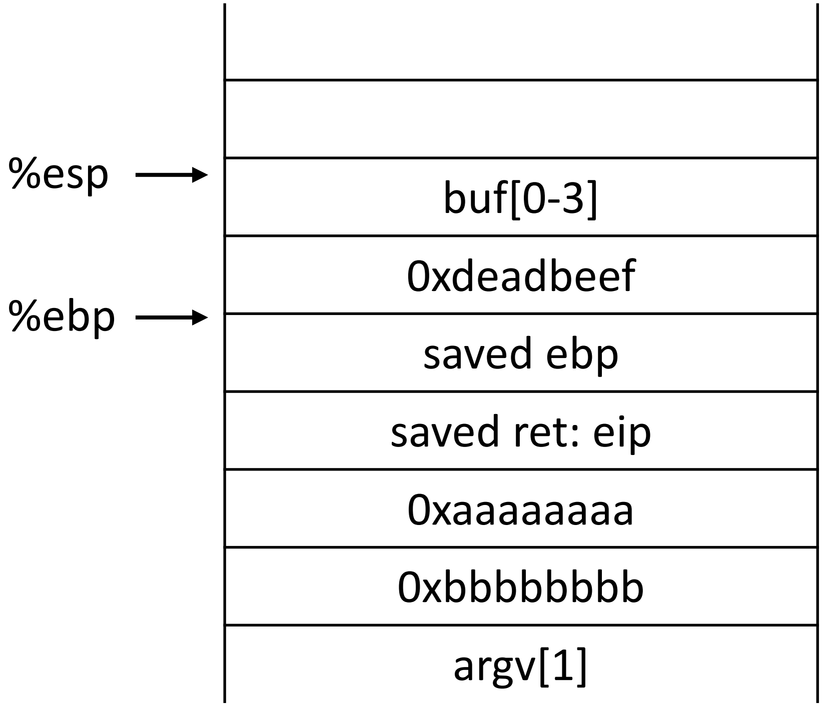
0xaaaaaaaa

0xbbbbbbbb

argv[1]

Buffer Overflow example: If the first input is “AAAAAAAAAAAAAAAA”

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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



%esp →

%ebp →

buf[0-3]

0xdeadbeef

saved ebp

saved ret: eip

0xaaaaaaaa

0xbbbbbbbb

argv[1]

Buffer Overflow example: If the first input is “AAAAAAAAAAAAAAAA”

```
#include <stdio.h>
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  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```
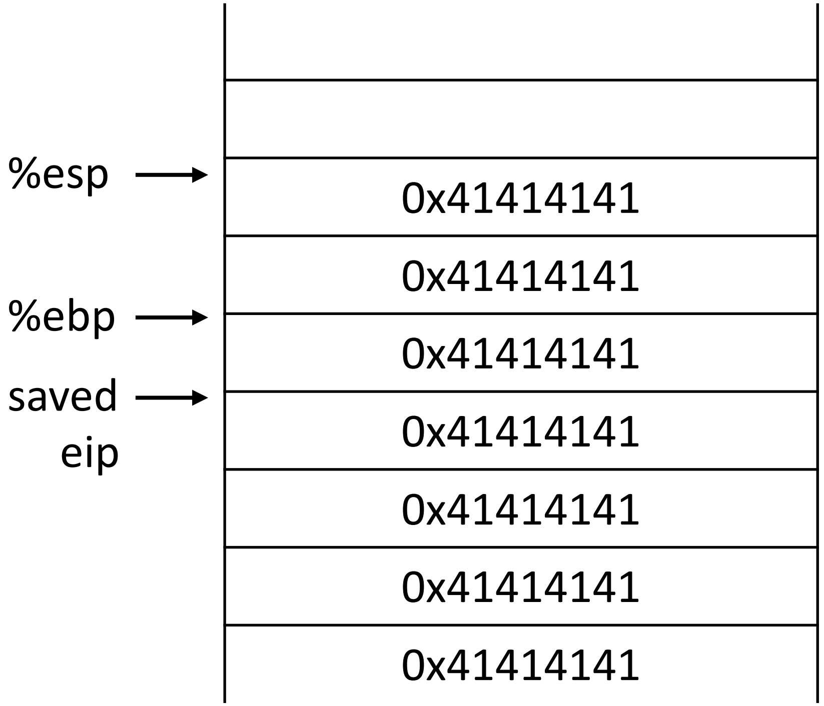
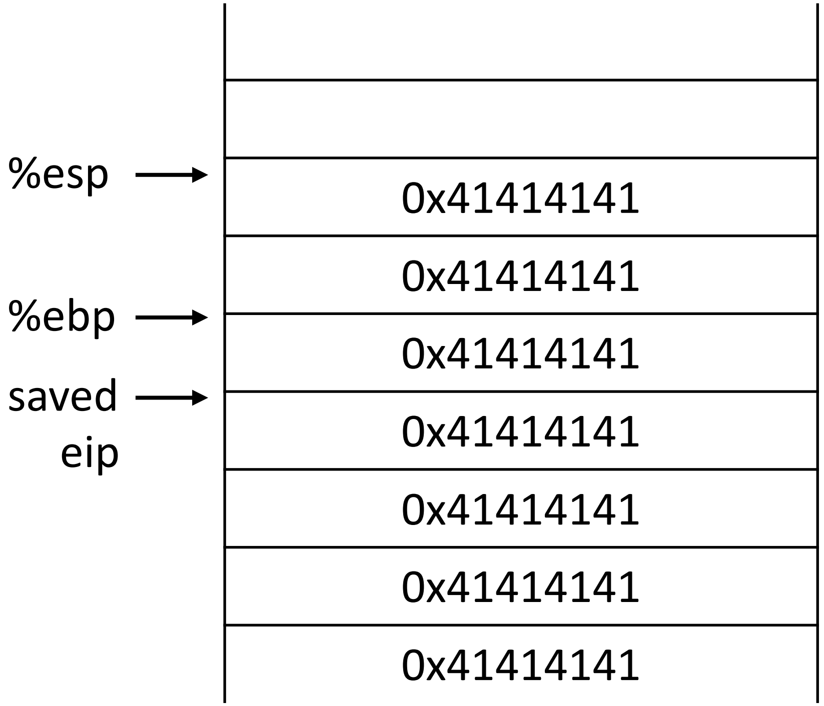



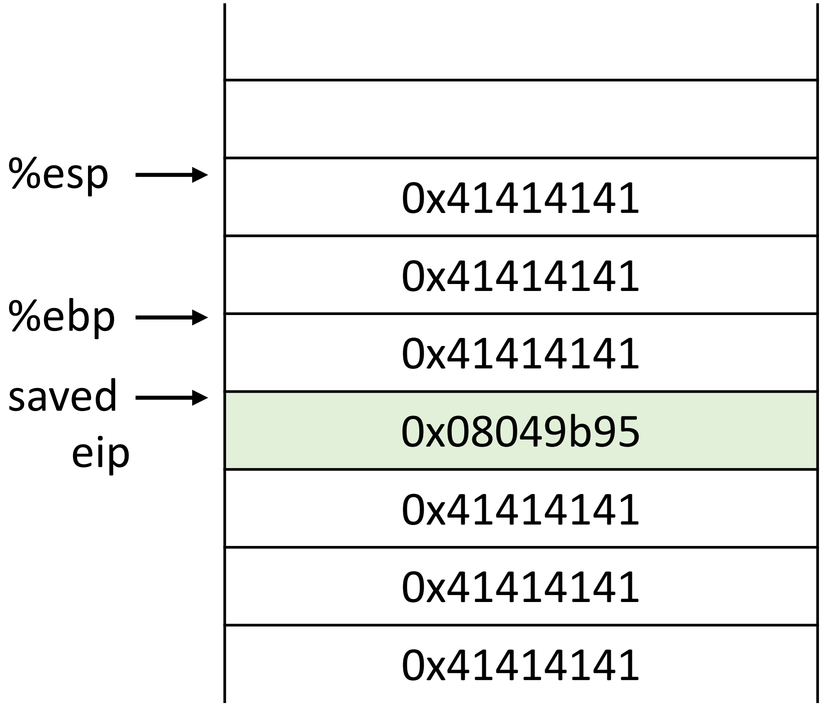
Buffer Overflow example: If the first input is "AAAAAAAAAAAAAAAA"

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

void foo() { 0x08049b95
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



Buffer Overflow example: If the first input is “AAAAAAAAAAAAAAAA”

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

void foo() { 0x08049b95
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



%esp → 0x41414141

0x41414141

%ebp → 0x41414141

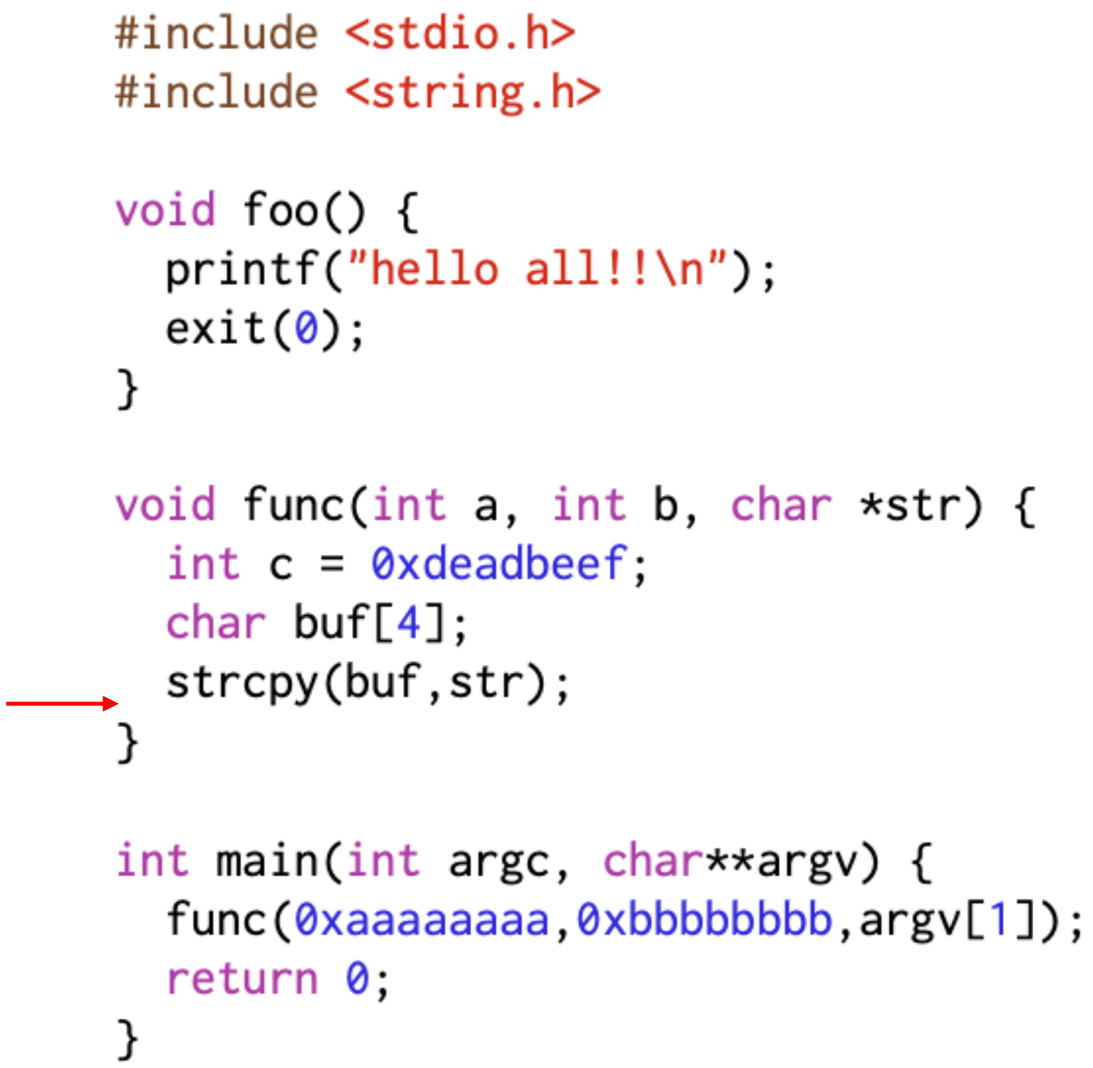
saved eip → 0x08049b95

0x41414141

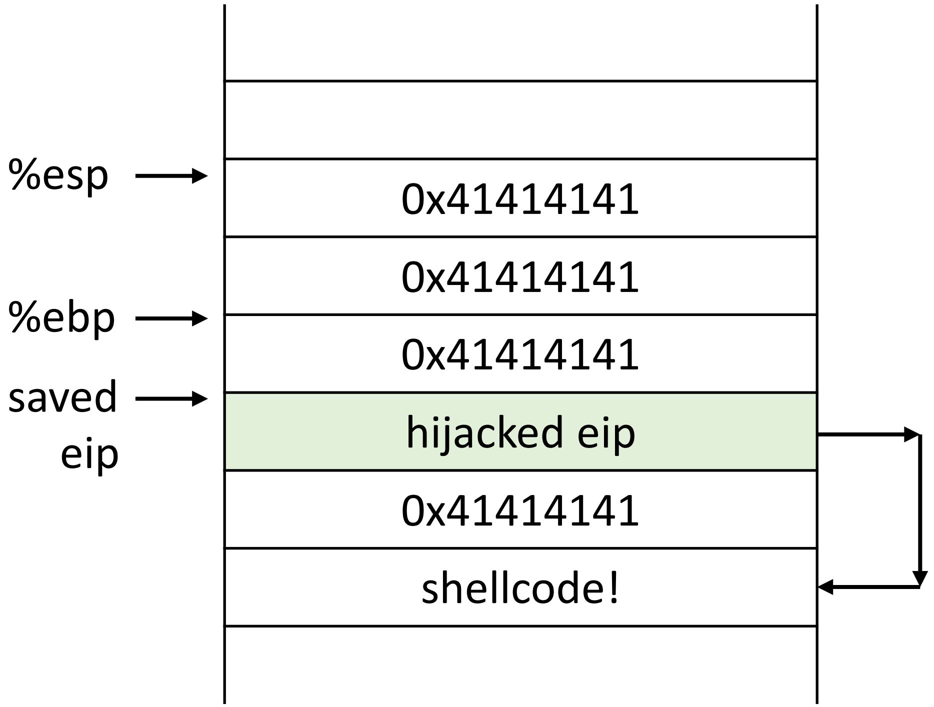
0x41414141

0x41414141

Better Hijacking Control



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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```

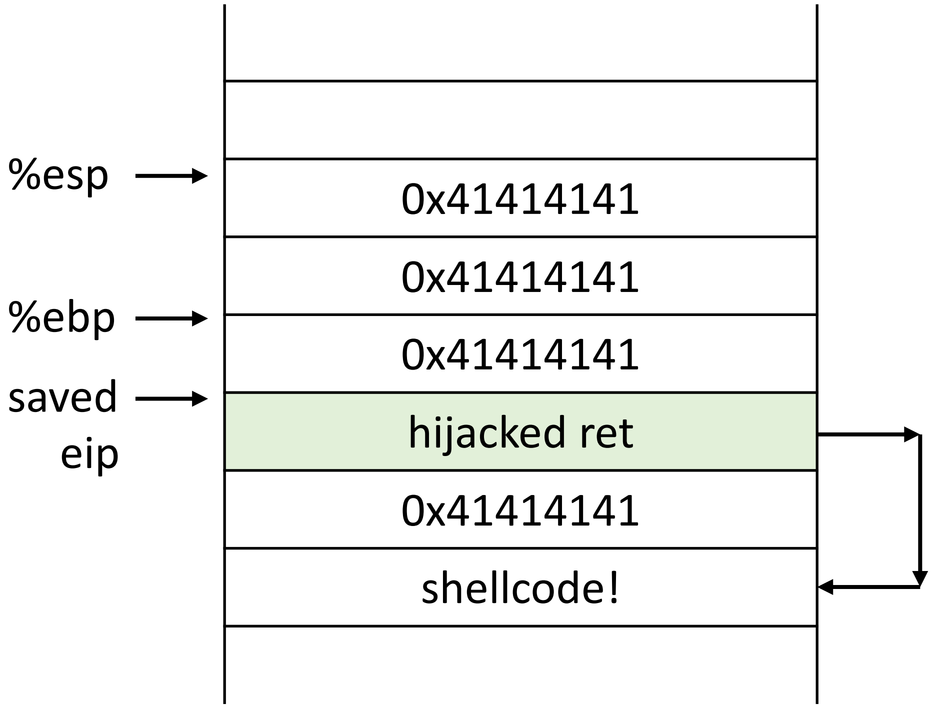


Jump to attacker supplied code where?

- put code in the string
- jump to start of the string

Better Hijacking Control

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

void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(int a, int b, char *str) {
  int c = 0xdeadbeef;
  char buf[4];
  strcpy(buf,str);
}

int main(int argc, char**argv) {
  func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
  return 0;
}
```



%esp

%ebp

saved eip

0x41414141

0x41414141

0x41414141

hijacked ret

0x41414141

shellcode!

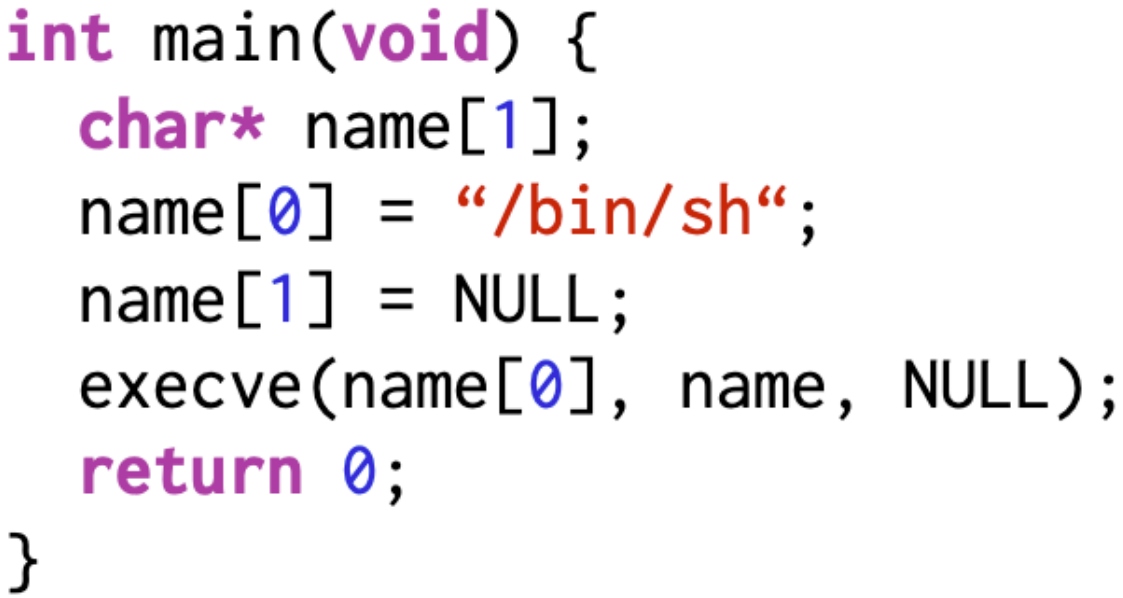
Jump to attacker supplied code where?

- put code in the string
- jump to start of the string

Shellcode

- **Shellcode:** small code fragment that receives initial control in an control flow hijack exploit
    - Control flow hijack: taking control of instruction ptr
- Earliest attacks used shellcode to exec a shell
    - Target a setuid root program, gives you root shell

Shellcode



```
int main(void) {
  char* name[1];
  name[0] = “/bin/sh“;
  name[1] = NULL;
  execve(name[0], name, NULL);
  return 0;
}
```

take the compiled output?

Shellcode

There are some restrictions

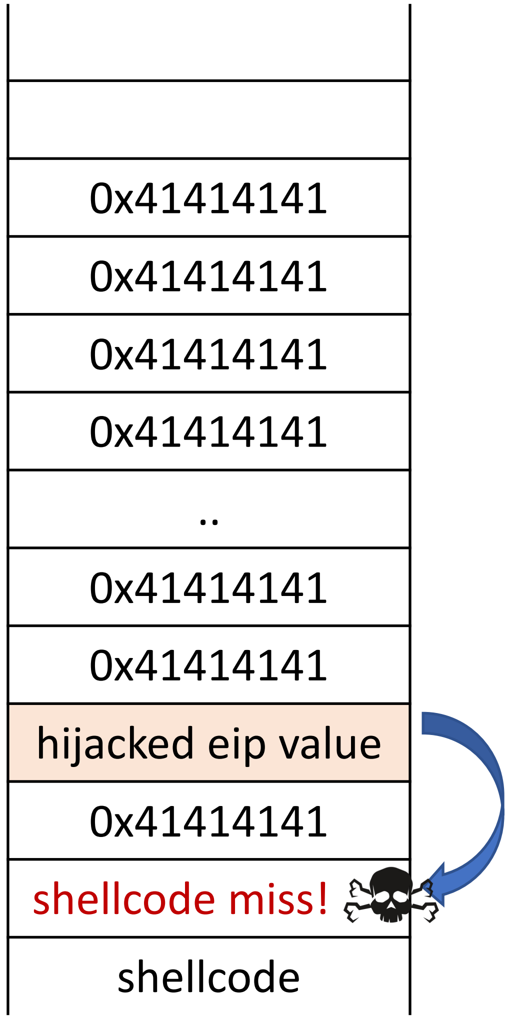
1. Shellcode cannot contain null characters ‘`\0`’
    - Why?
2. If payload is via `gets()` must also avoid line-breaks
    - Why?

Payload is not always robust

Exact address of the shellcode start is not always easy to guess

Miss? Segfault

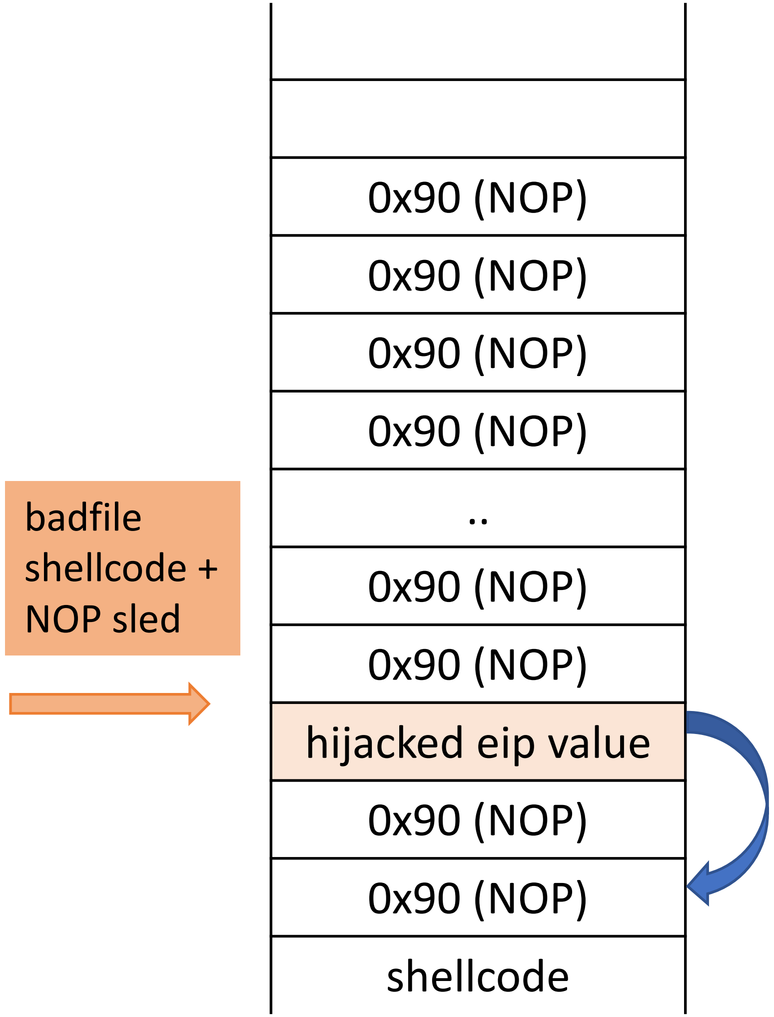
Fix? NOP Sled!



NOP Sled!

- NOP instruction: 0x90
- Instruct eip to move on to the next instruction

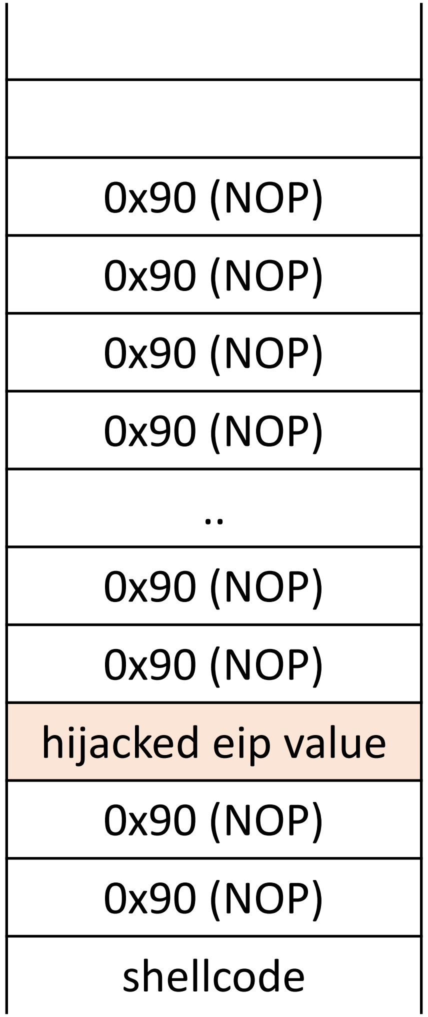
Stack after injecting shellcode and pointing eip to the memory address to a NOP sled leading to the shellcode being executed



Build your very own NOP sled

Information we have

- char buffer[100] <- overflow this buffer
- address of char buffer is 0xffffd88c
- eip = 50 byte offset from char buffer[100]
- shellcode = 20 bytes

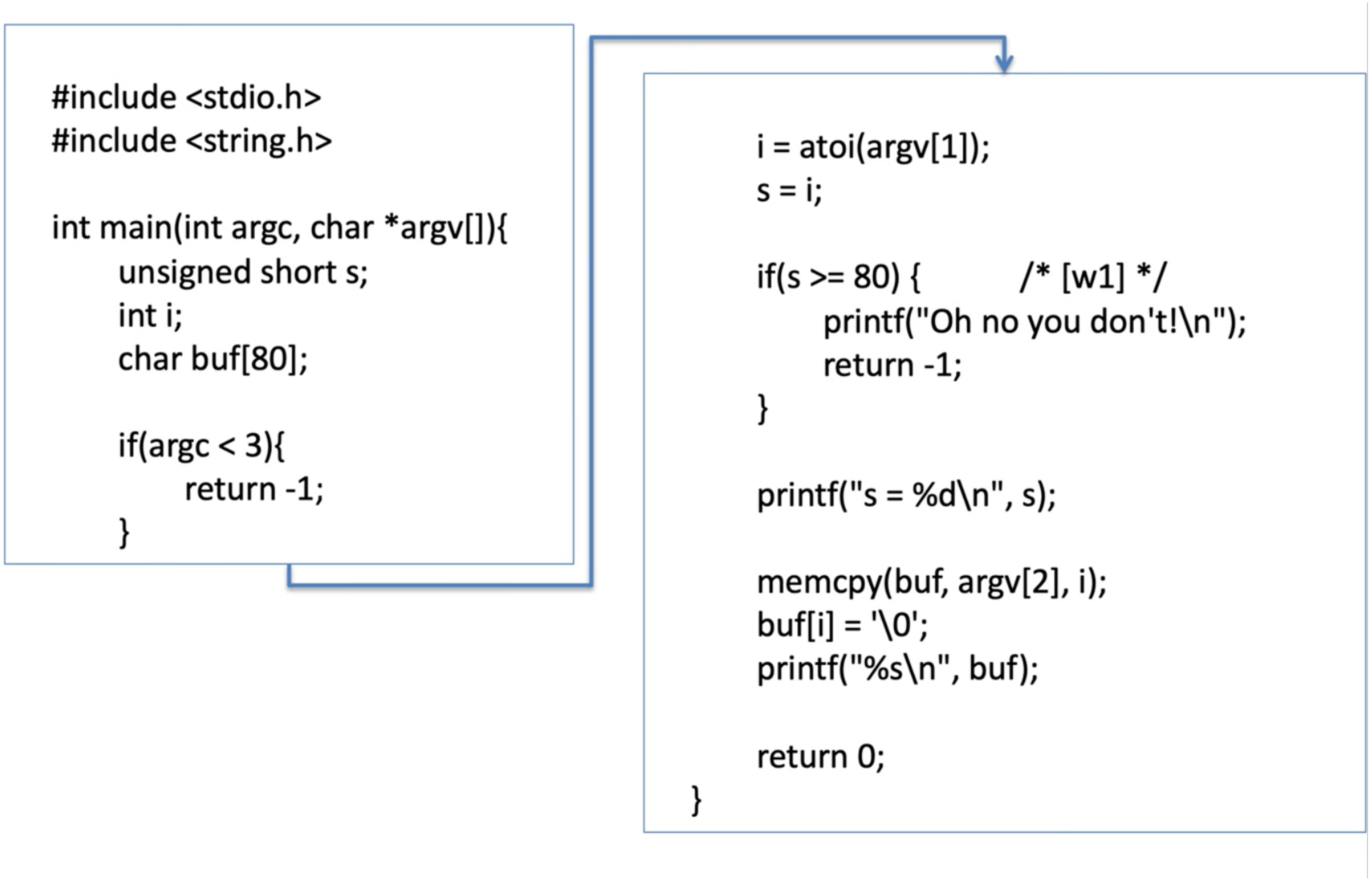


0x90 (NOP)
0x90 (NOP)
0x90 (NOP)
0x90 (NOP)
..
0x90 (NOP)
0x90 (NOP)
hijacked eip value
0x90 (NOP)
0x90 (NOP)
shellcode

Other overflow targets

- Format strings in C
- Heap management structures used by malloc

Integer overflows



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

int main(int argc, char *argv[]){
        unsigned short s;
        int i;
        char buf[80];

        if(argc < 3){
                return -1;
        }

        i = atoi(argv[1]);
        s = i;

        if(s >= 80) {           /* [w1] */
                printf("Oh no you don't!\n");
                return -1;
        }

        printf("s = %d\n", s);

        memcpy(buf, argv[2], i);
        buf[i] = '\0';
        printf("%s\n", buf);

        return 0;
}
```

Integer overflows

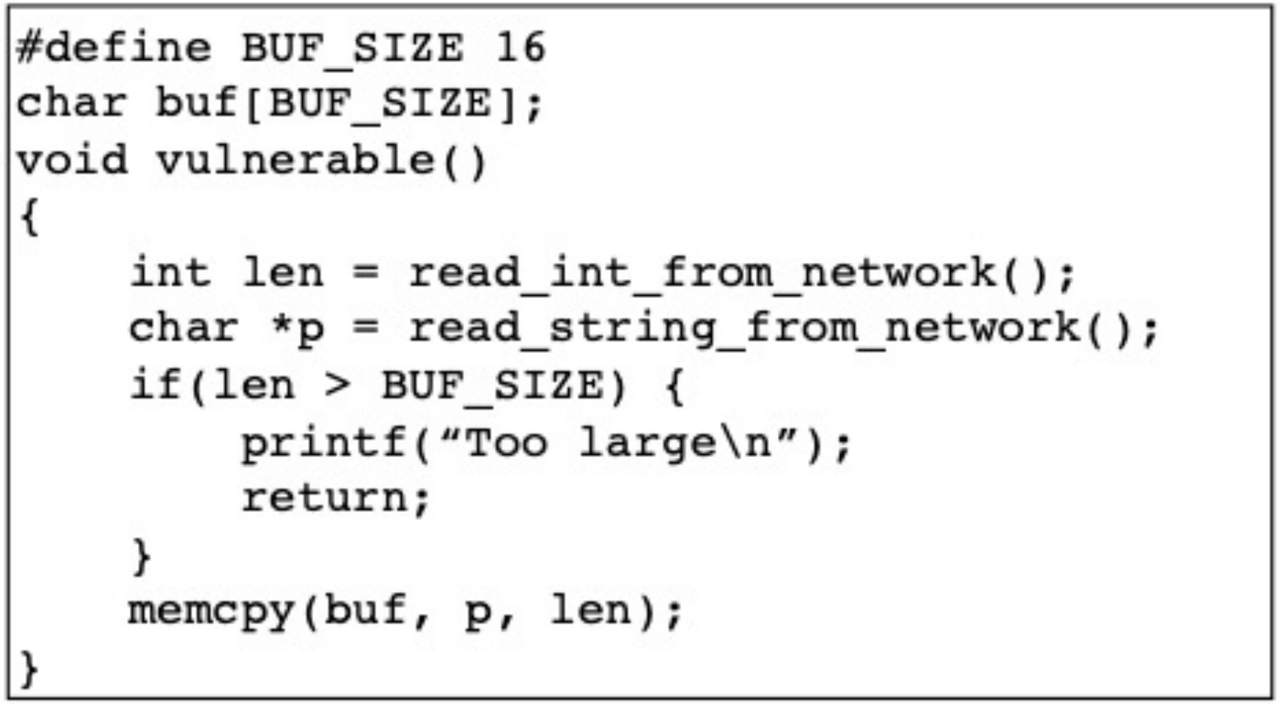
```
#include <stdio.h>
#include <string.h>

int main(int argc, char *argv[]){
    unsigned short s;
    int i;
    char buf[80];

    if(argc < 3){
        return -1;
    }
```

```
    i = atoi(argv[1]);
    s = i;

    if(s >= 80) {          /* [w1] */
        printf("Oh no you don't!\n");
        return -1;
    }

    printf("s = %d\n", s);

    memcpy(buf, argv[2], i);
    buf[i] = '\0';
    printf("%s\n", buf);

    return 0;
}
```

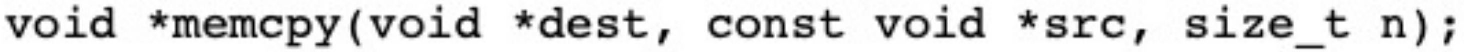
Output

```
$ ./overflow 5 hello
s = 5
hello

$ ./overflow 80 hello
Oh no you don’t

$ ./65536 hello
s = 0
Segmentation fault (core dumped)
```

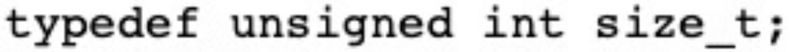
What’s wrong with this code?



```
#define BUF_SIZE 16
char buf[BUF_SIZE];
void vulnerable()
{
    int len = read_int_from_network();
    char *p = read_string_from_network();
    if(len > BUF_SIZE) {
        printf(“Too large\n”);
        return;
    }
    memcpy(buf, p, len);
}
```



```
void *memcpy(void *dest, const void *src, size_t n);
```



```
typedef unsigned int size_t;
```

A. Nothing
B. Buffer overflow
C. Integer overflow
D. Race Condition

Variable arguments in C

- In C, we can define a function with a variable number of arguments

void printf(const char* format,….)

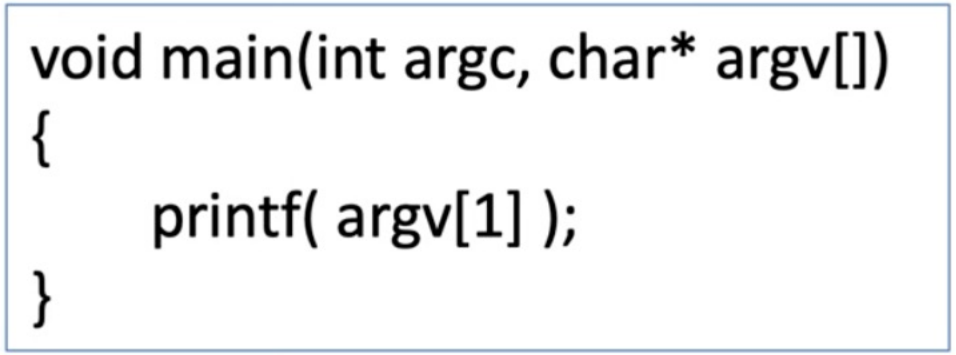
Usage:

printf(“hello world”);

printf(“length of %s = %d \n”, str, str.length());

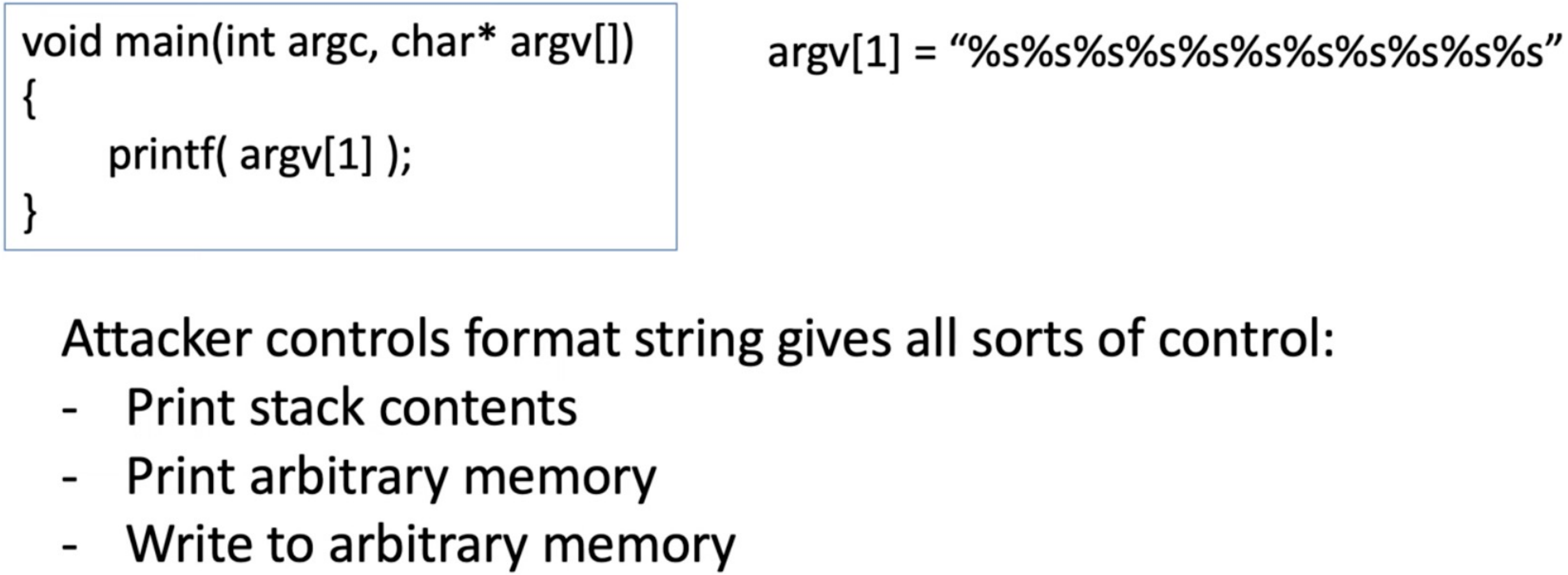
format specification encoded by special % characters

Sloppy use of printf



```
void main(int argc, char* argv[])
{
	printf( argv[1] );
}
```

Sloppy use of printf



```
void main(int argc, char* argv[])
{
      printf( argv[1] );
}
```

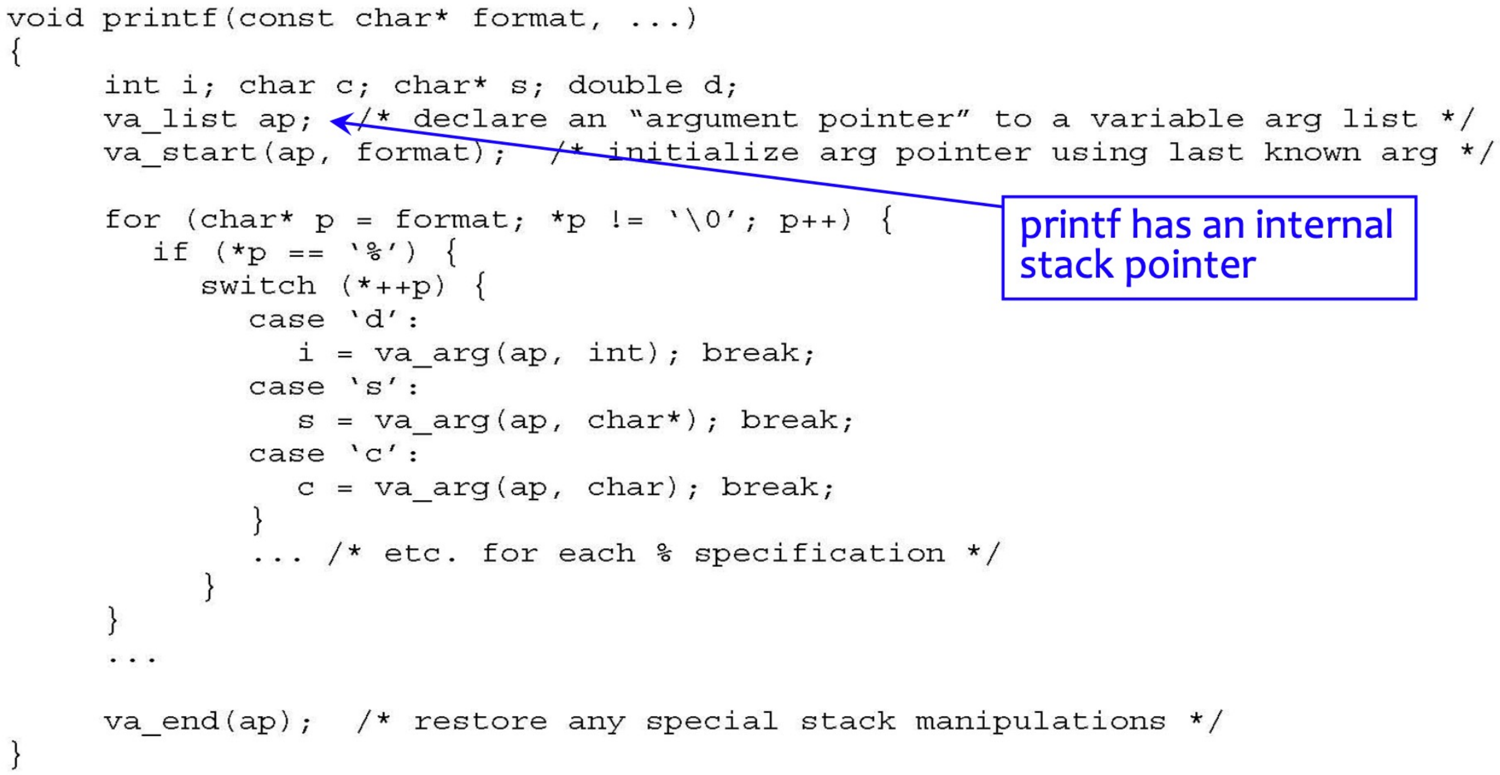
argv[1] = “%s%s%s%s%s%s%s%s%s%s%s”

Attacker controls format string gives all sorts of control:

- Print stack contents
- Print arbitrary memory
- Write to arbitrary memory

Implementation of printf

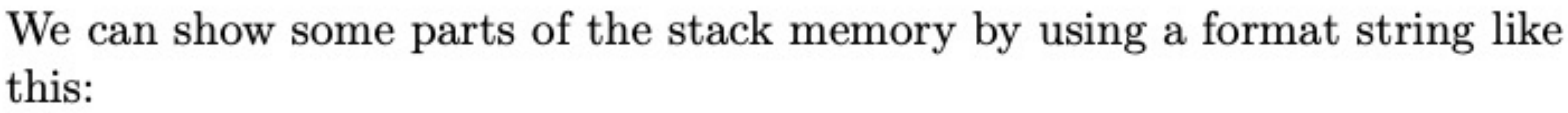
- Special functions va_start, va_arg, va_end
  compute arguments at run-time



```
void printf(const char* format, ...)
{
      int i; char c; char* s; double d;
      va_list ap; /* declare an “argument pointer” to a variable arg list */
      va_start(ap, format);  /* initialize arg pointer using last known arg */

      for (char* p = format; *p != ‘\0’; p++) {
         if (*p == ‘%’) {
            switch (*++p) {
               case ‘d’:
                  i = va_arg(ap, int); break;
               case ‘s’:
                  s = va_arg(ap, char*); break;
               case ‘c’:
                  c = va_arg(ap, char); break;
               }
               ... /* etc. for each % specification */
            }
      }
      ...

      va_end(ap);  /* restore any special stack manipulations */
}
```

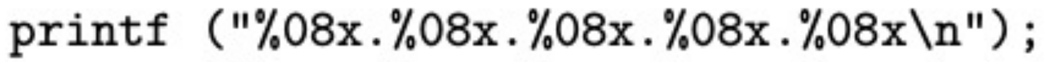
printf has an internal stack pointer

Viewing the stack



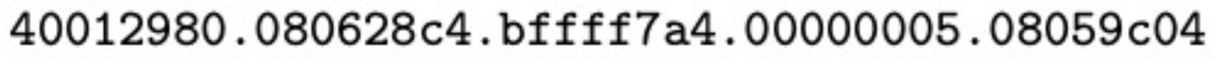
We can show some parts of the stack memory by using a format string like this:

C code



```
printf ("%08x.%08x.%08x.%08x.%08x\n");
```

Output



```
40012980.080628c4.bffff7a4.00000005.08059c04
```

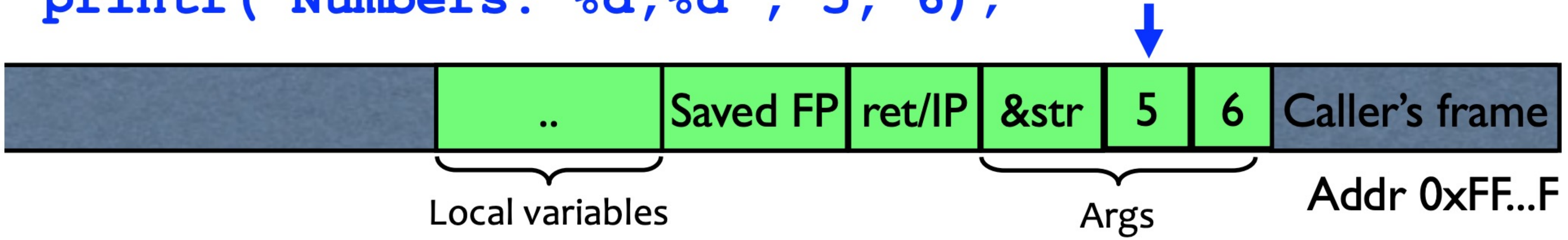
instruct printf:

- retrieve 5 parameters
- display them as 8-digit padded hexademical numbers

Closer look at the stack

```
printf("Numbers: %d,%d", 5, 6);
```

Internal stack pointer starts here



	..	Saved FP	ret/IP	&str	5	6	Caller's frame

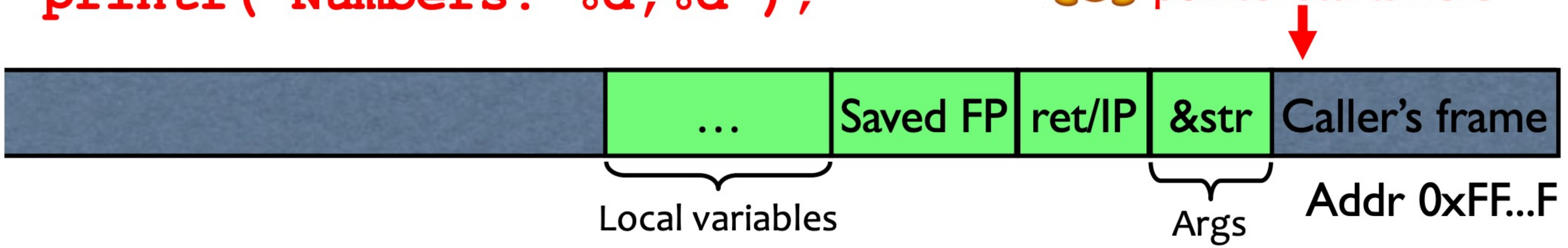
Local variables

Args

Addr 0xFF...F

```
printf("Numbers: %d,%d");
```

😱 Internal stack pointer starts here



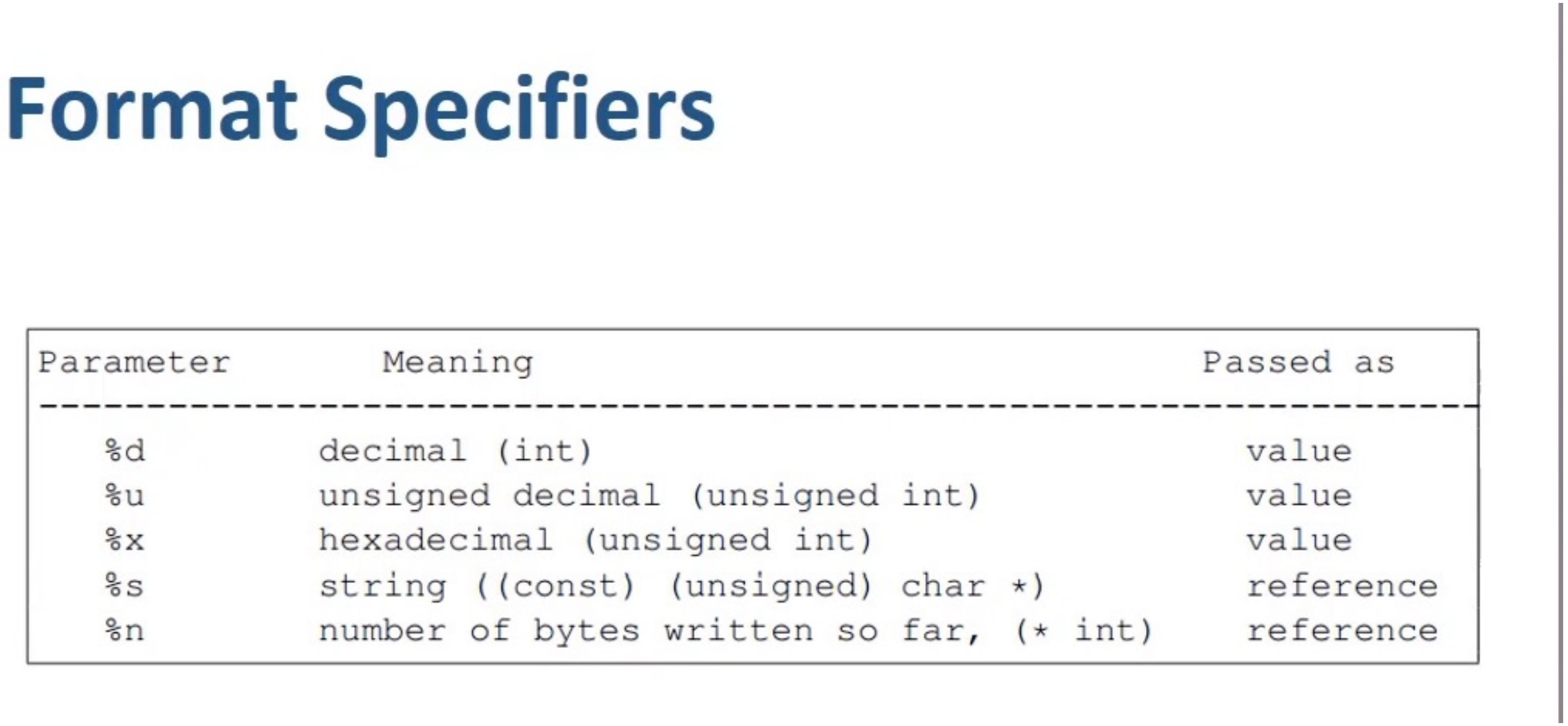
	...	Saved FP	ret/IP	&str	Caller's frame

Local variables

Args

Addr 0xFF...F

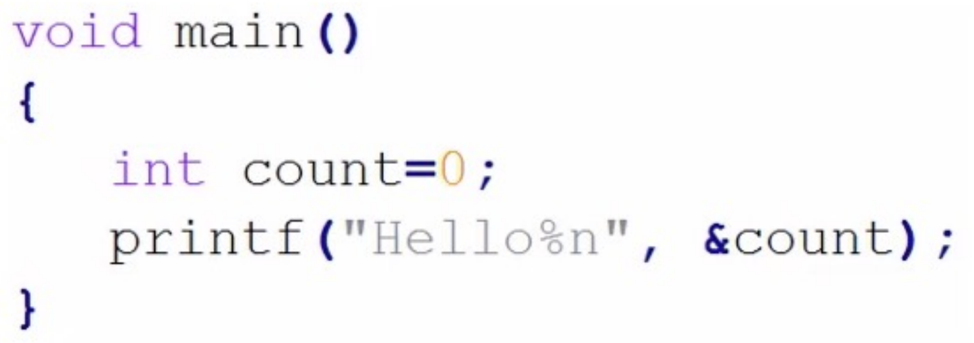
Format specification encoded by special % characters



Format Specifiers

Parameter	Meaning	Passed as
%d	decimal (int)	value
%u	unsigned decimal (unsigned int)	value
%x	hexadecimal (unsigned int)	value
%s	string ((const) (unsigned) char *)	reference
%n	number of bytes written so far, (* int)	reference

The %n format specifier



```
void main()
{
    int count=0;
    printf("Hello%n", &count);
}
```

The %n format specifier

- %n format symbol tells printf to write the number of characters that have been printed

```
printf(“Overflow this!%n”,&myVar);
```

  - Argument of printf is interpeted as destination address
  - This writes 14 into myVar (“Overflow this!” has 14 characters)

- What if printf does not have an argument?

```
char buf[16]=“Overflow this!%n”;
printf(buf);
```

  - Stack location pointed to by printf’s internal stack pointer will be **interpreted as address** into which the number of characters will be written.