15-410

"An Experience Like No Other"

IA32 Stack Discipline
Aug 30, 2017

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Slides originally stolen from 15-213

Synchronization

Registration

- The wait list will probably be done today or tomorrow
  - I don't think everybody will fit
- If you're here but not on *any* wait list, see me *right away*
- ECE undergrad: most likely 5/15 will fit (could be more)
- ECE M.S.: 4/7 likely?
- INI: most likely 10/20?
- If you are an M.S. or or Ph.D. student and have not discussed this class with your advisor, do so *today*
  - We will not be registering graduate students without hearing from their advisors
- Some people are being added this morning
  - If you receive mail from an administrator, *please reply the same day*

If you haven't taken 15-213 (A/B, malloc lab ok)

- Contact me no later than *today*

Why Only 32?

You learned x86-64 in 213

- Most machines (even phones!) are 64-bit these days
- x86-64 is simpler than IA32 for user code

Why will 410 be IA32?

- x86-64 is *not* simpler for kernel code
  - Machine begins in 16-bit mode, then 32, finally 64
  - Interrupts are more complicated
- x86-64 is *not* simpler during debugging
  - More registers means more registers to have wrong values
- x86-64 virtual memory is a bit of a drag
  - More steps than x86-32, but not more intellectually stimulating
- There are still a lot of 32-bit machines in the world
  - ...which can boot and run your personal OS

IA32 vs x86-64

Generating IA32 code:

```
gcc –m32 –o hello hello.c
```

Key differences:

- IA32 has only 8 32-bit general purpose registers
- IA32 might use %ebp as a stack frame pointer.

```
gcc –m32 -fno-stack-protector -fno-omit-frame-pointer …
```

- IA32 passes arguments on the stack rather than in registers
- IA32 has different caller/callee-save register conventions

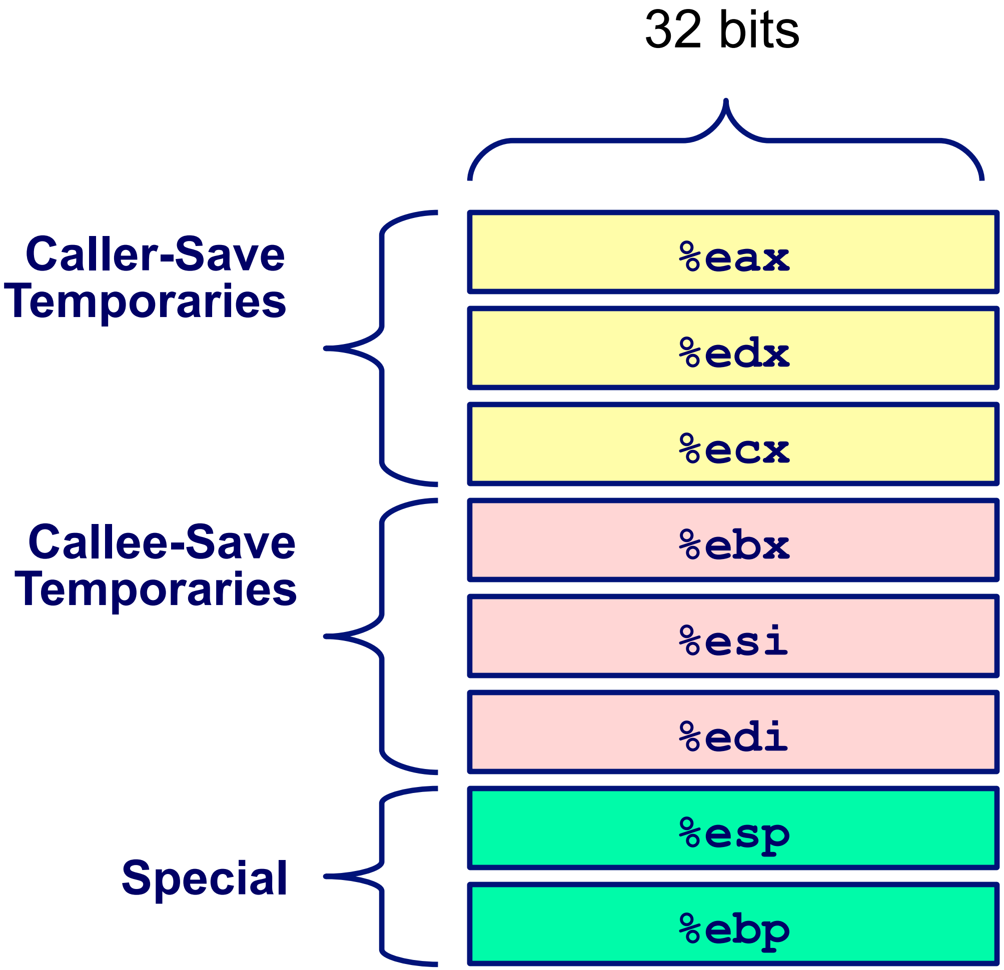
Detailed IA32 Summary:

http://csapp.cs.cmu.edu/3e/waside/waside-ia32.pdf

IA32/Linux Registers

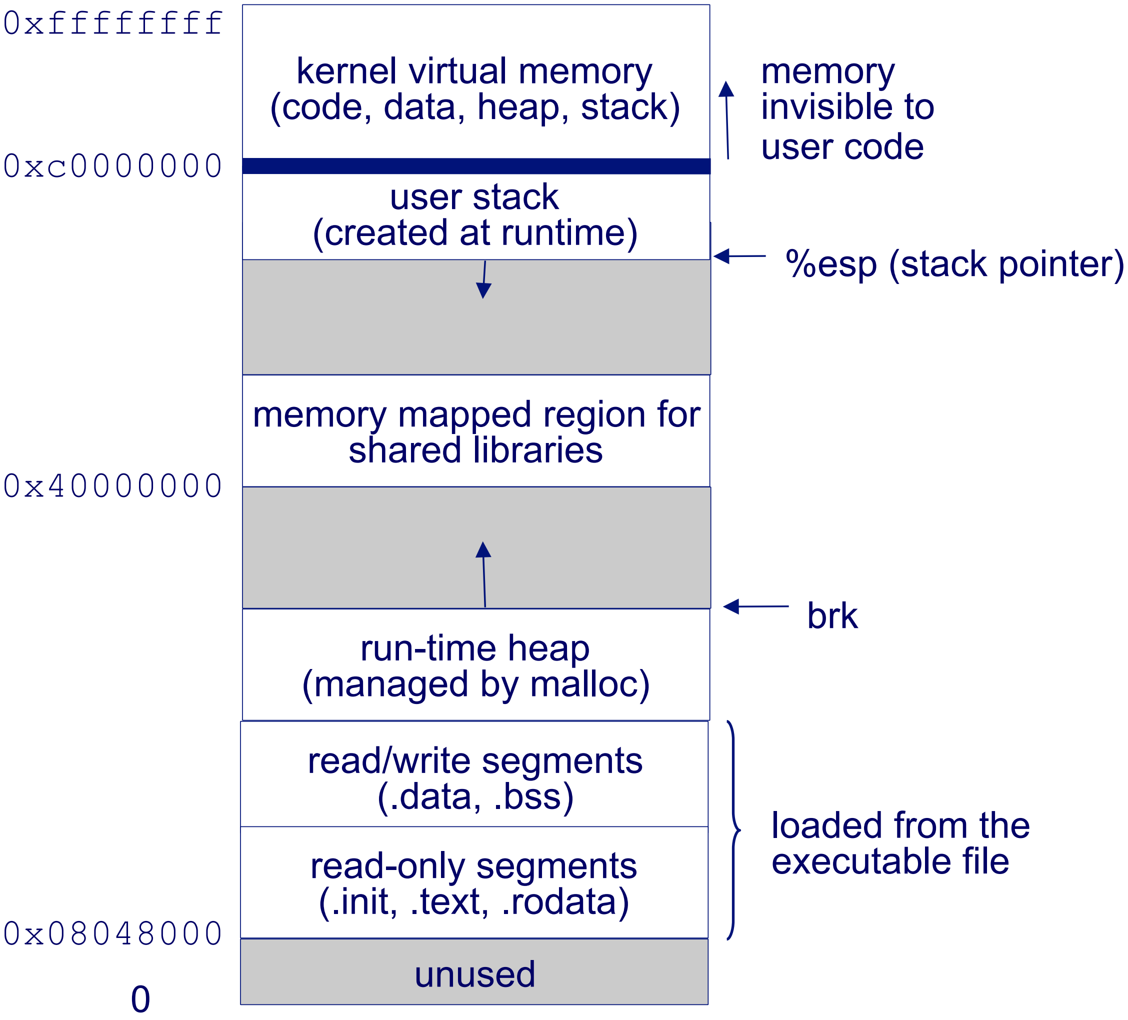
Integer Registers

- Two have special uses
  - `%ebp`, `%esp`
- Three managed as callee-save
  - `%ebx`, `%esi`, `%edi`
  - Old values saved on stack prior to using
- Three managed as caller-save
  - `%eax`, `%edx`, `%ecx`
  - Do what you please, but expect any callee to do so, as well
- Register `%eax` also holds return value



Private Address Spaces

Each process has its own private address space.



0xffffffff

kernel virtual memory (code, data, heap, stack)

memory invisible to user code

0xc0000000

user stack (created at runtime)

%esp (stack pointer)

memory mapped region for shared libraries

0x40000000

brk

run-time heap (managed by malloc)

read/write segments (.data, .bss)

read-only segments (.init, .text, .rodata)

loaded from the executable file

0x08048000

unused

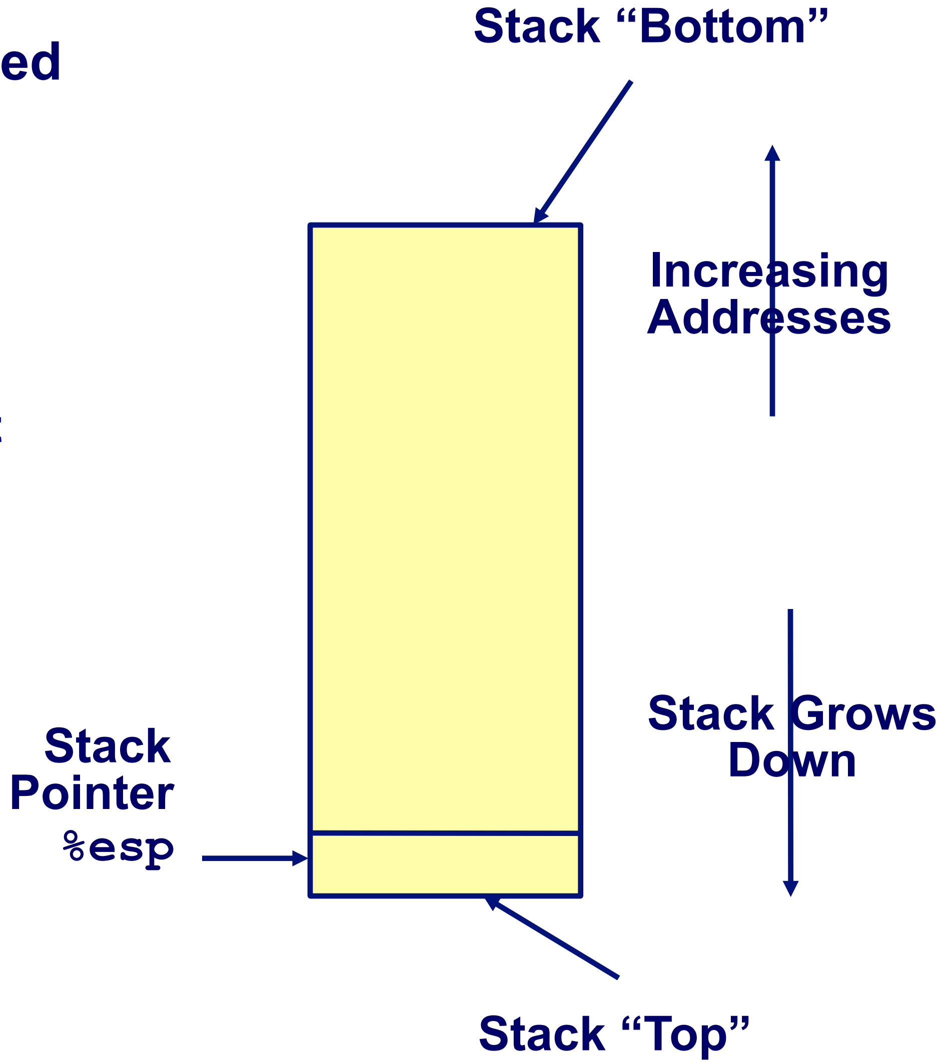
0

Warning: **numbers specific to Linux 2.x on IA32!!**

Warning: **details vary by OS and kernel version!**

IA32 Stack

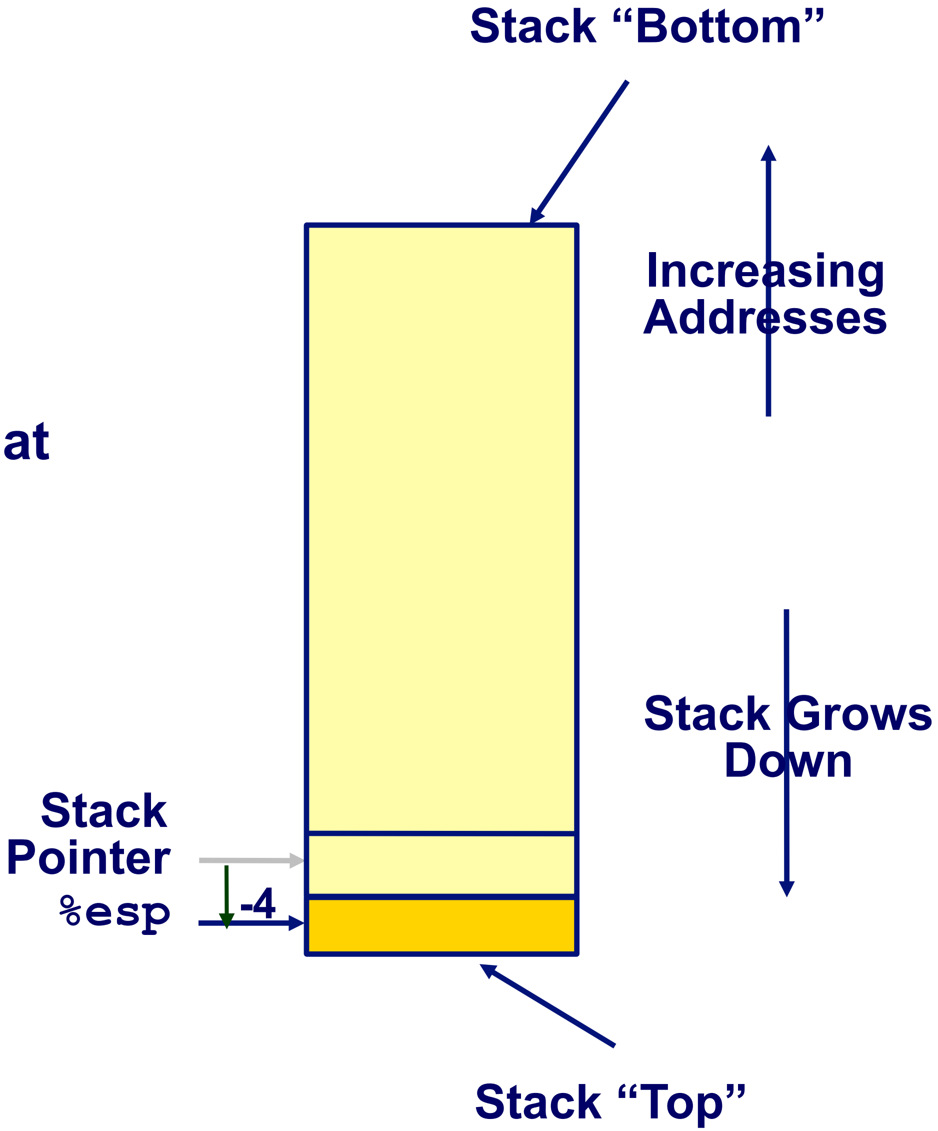
- Region of memory managed with stack discipline
- "Grows" toward lower addresses
- Register `%esp` indicates lowest stack address
  - address of "top" element
  - stack *pointer*



IA32 Stack Pushing

Pushing

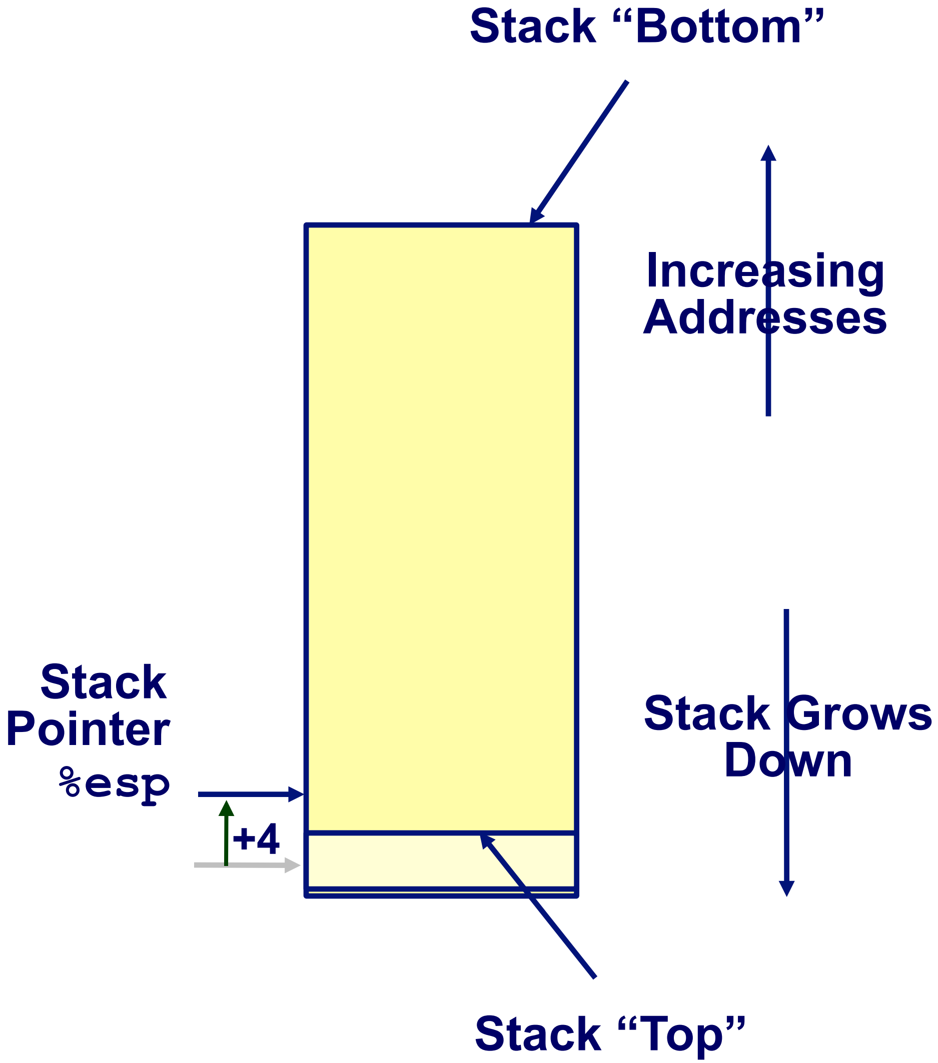
- `pushl` *Src*
- Fetch operand from *Src*
  - Maybe a register: %ebp
  - Maybe memory: 8(%ebp)
- Decrement `%esp` by 4
- Store operand in memory at address given by `%esp`



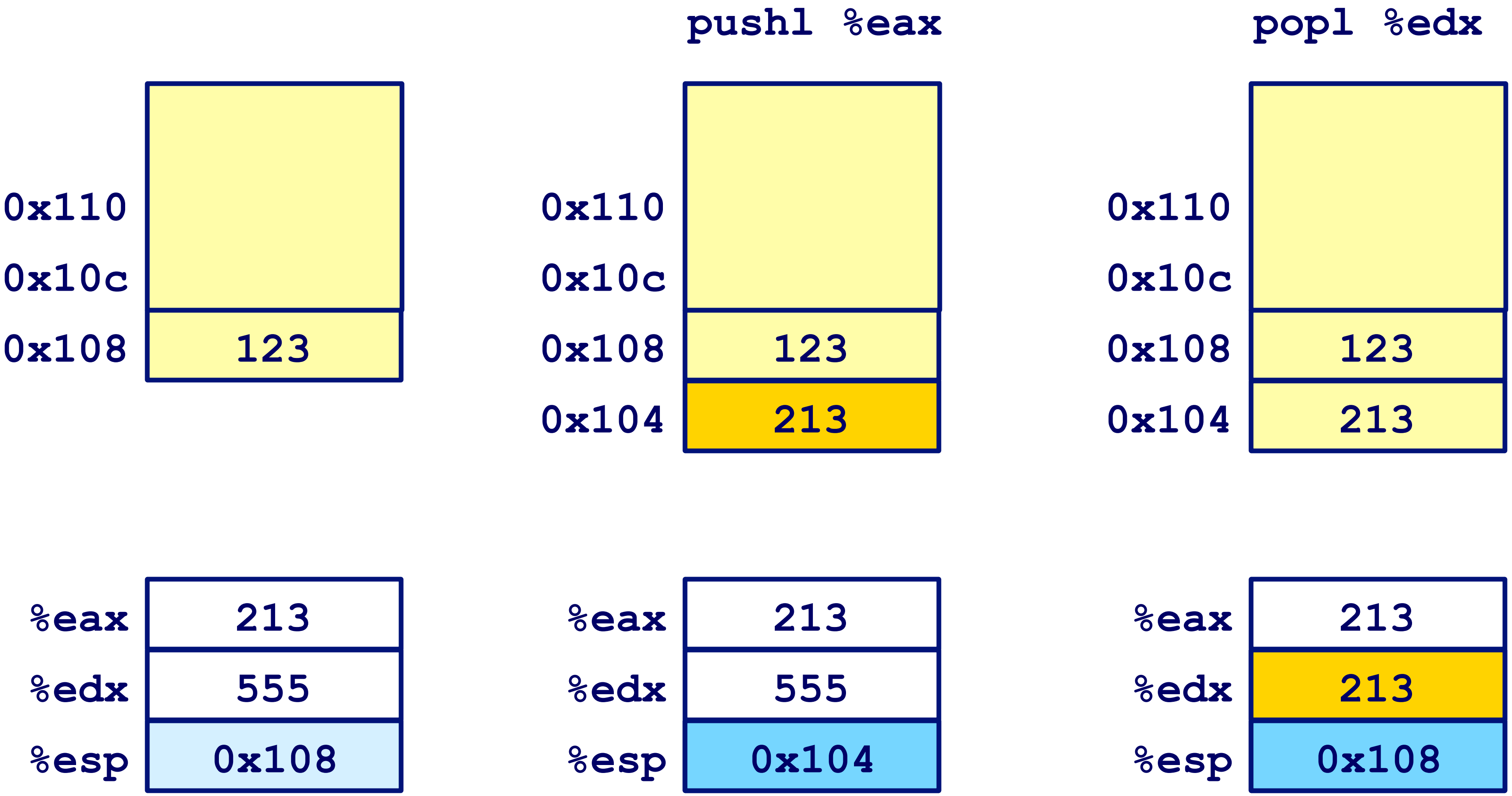
IA32 Stack Popping

Popping

- `popl` *Dest*
- Read memory at address given by `%esp`
- Increment `%esp` by 4
- Store into *Dest* operand



Stack Operation Examples



		pushl %eax	popl %edx
0x110			
0x10c			
0x108	123	123	123
0x104		213	213

%eax	213	213	213
%edx	555	555	213
%esp	0x108	0x104	0x108

Procedure Control Flow

- **Use stack to support procedure call and return**

Procedure call:

```
• call label    Push return address;
                Jump to label
```

"Return address"?

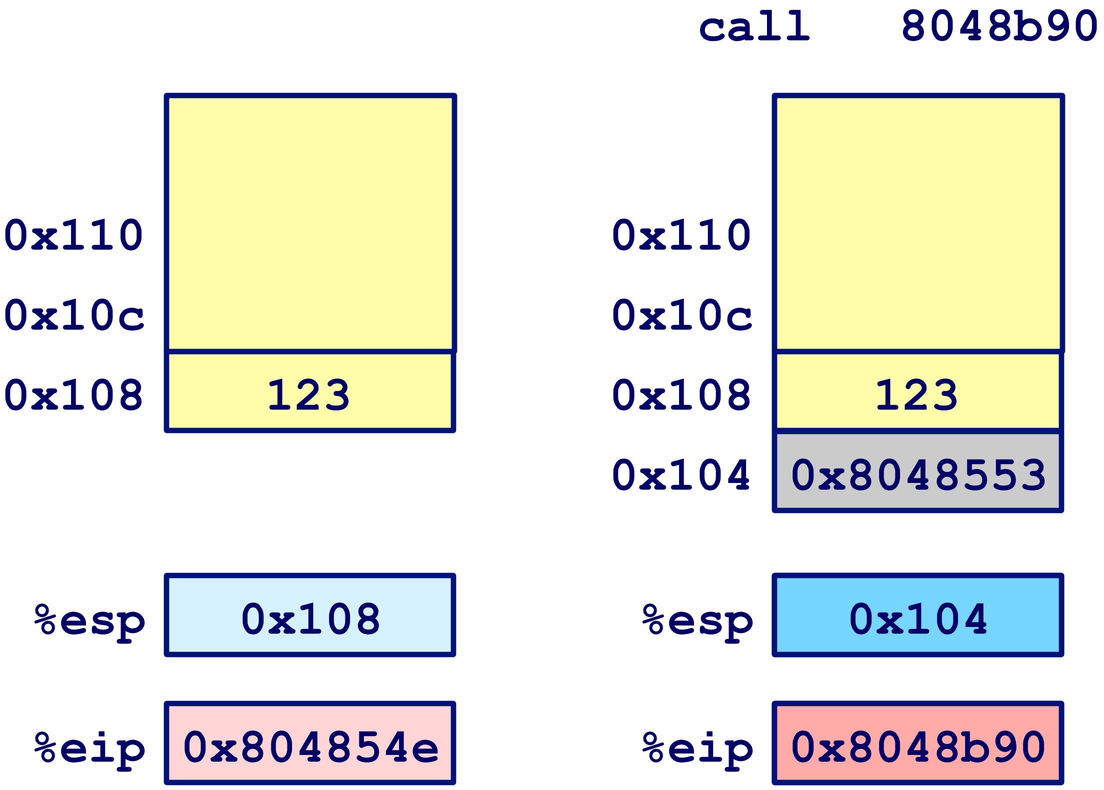
- **Address of instruction *after*** `call`
- **Example from disassembly**
  - `804854e:e8 3d 06 00 00   call   8048b90 <main>`
  - `8048553:50               pushl  %eax`
    - » **Return address =** `0x8048553`

Procedure return:

```
• ret      Pop address from stack;
                Jump to address
```

Procedure Call Example

```
804854e:   e8 3d 06 00 00        call   8048b90 <main>
8048553:   50                    pushl  %eax
```



call 8048b90

0x110

0x10c

0x108 123

%esp 0x108

%eip 0x804854e

0x110

0x10c

0x108 123

0x104 0x8048553

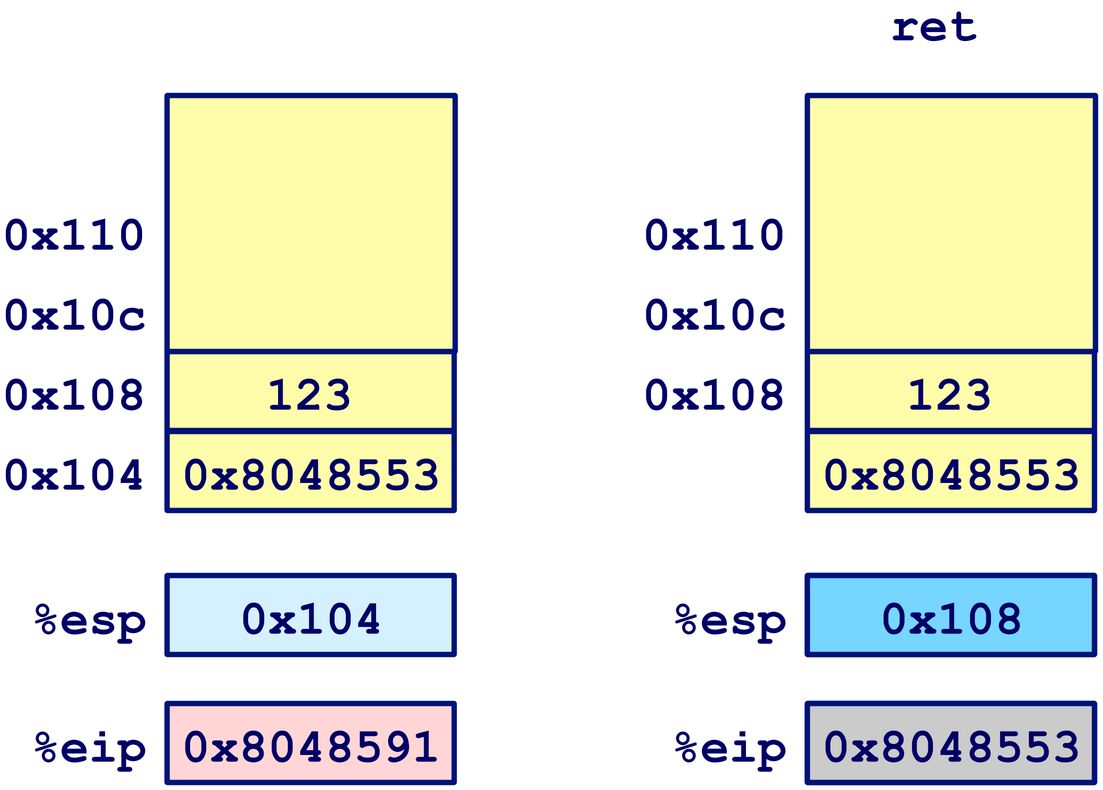
%esp 0x104

%eip 0x8048b90

`%eip` **is program counter**

Procedure Return Example

```
8048591:   c3                    ret
```



`%eip` is program counter

Stack-Based Languages

Languages that support recursion

- e.g., C, Pascal, Java
- Code must be "*reentrant*"
    - Multiple instantiations of a single procedure "live" at same time
- Need some place to store state of each instantiation
    - Arguments
    - Local variables
    - Return pointer (maybe)
    - Weird things (static links, exception handling, …)

Stack discipline – key observation

- State for given procedure needed for limited time
    - From time of call to time of return
- Note: callee returns before caller does

Therefore stack allocated in nested *frames*

- State for single procedure instantiation

Call Chain Example

Code Structure

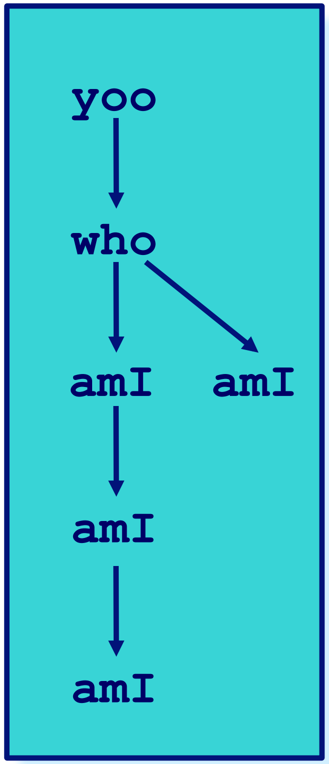
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

```
who(…)
{
    • • •
    amI();
    • • •
    amI();
    • • •
}
```

```
amI(…)
{
     •
     •
     amI();
     •
     •
}
```

- Procedure `amI()` recursive

Call Chain



yoo

who

amI

amI

amI

amI

Stack Frames

Contents

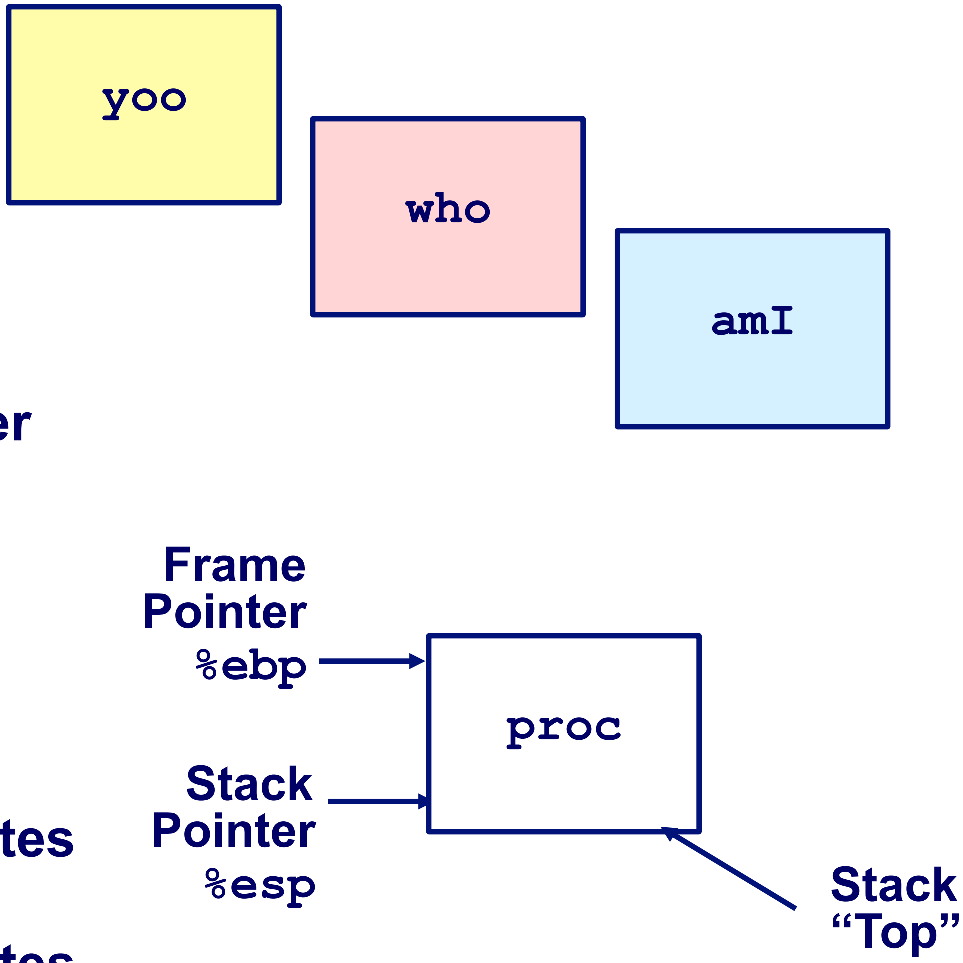
- Local variables
- Return information
- Temporary space

Management

- Space allocated when enter procedure
  - "Set-up" code
- Deallocated when return
  - "Finish" code

Pointers

- Stack pointer `%esp` indicates stack top
- Frame pointer `%ebp` indicates start of current frame



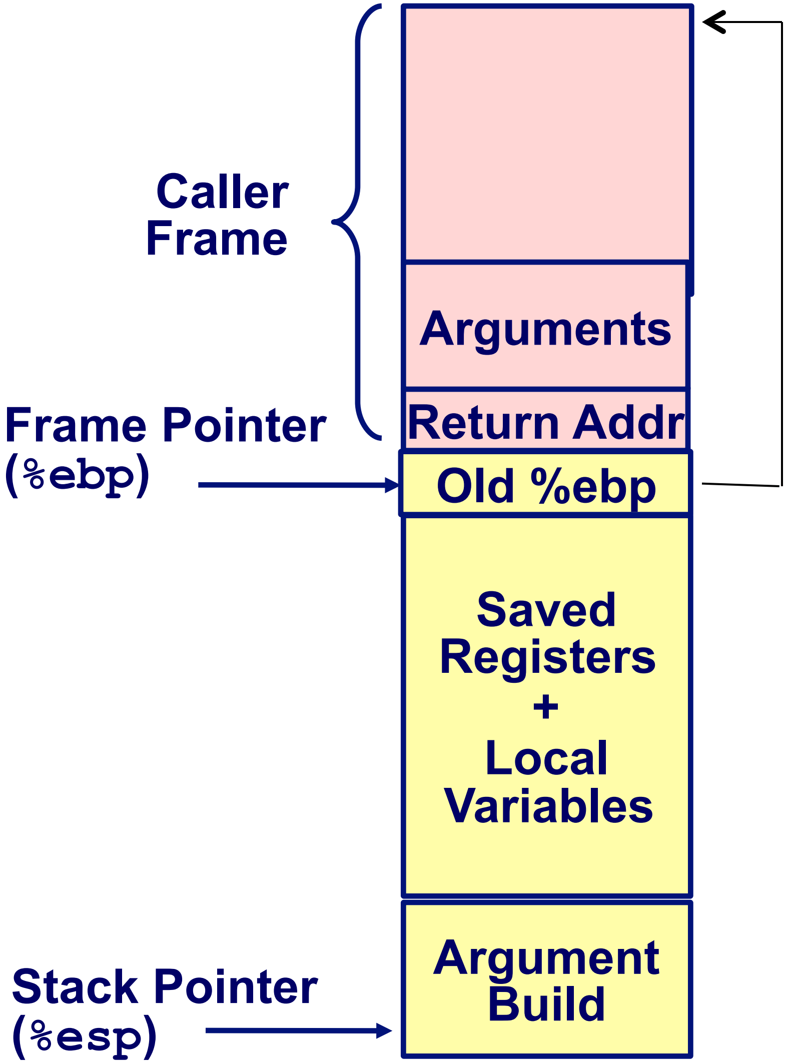
IA32/Linux Stack Frame

Current Stack Frame ("Top" to "Bottom")

- Parameters for function we're about to call
  - "Argument build"
- Local variables
  - If don't all fit in registers
- Caller's saved registers
- Caller's saved frame pointer

Caller's Stack Frame

- Return address
  - Pushed by `call` instruction
- Arguments for this call



swap()

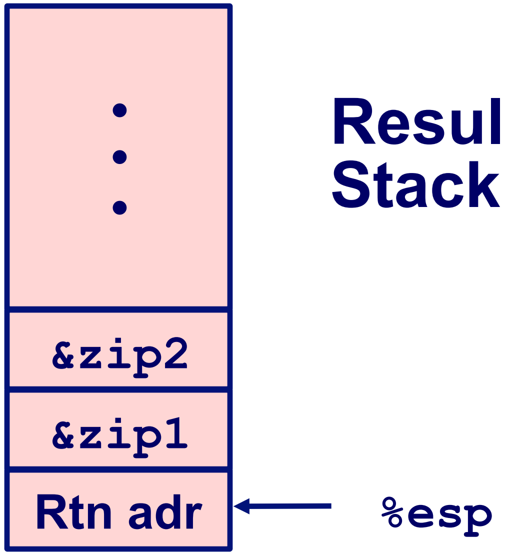
```
int zip1 = 15213;
int zip2 = 91125;

void call_swap()
{
  swap(&zip1, &zip2);
}
```

```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

Calling swap from call_swap

```
call_swap:
    • • •
    pushl $zip2   # Global var
    pushl $zip1   # Global var
    call swap
    • • •
```



Resulting Stack

swap()

```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
   pushl %ebp
   movl %esp,%ebp
   pushl %ebx
```

Set Up

```
   movl 12(%ebp),%ecx
   movl 8(%ebp),%edx
   movl (%ecx),%eax
   movl (%edx),%ebx
   movl %eax,(%edx)
   movl %ebx,(%ecx)
```

Body

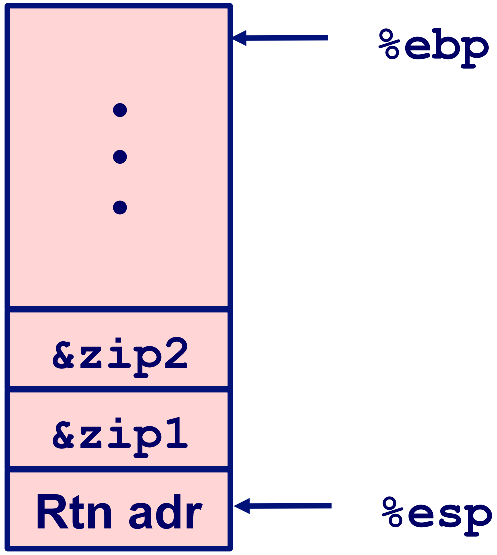
Core

```
   movl -4(%ebp),%ebx
   movl %ebp,%esp
   popl %ebp
   ret
```

Finish

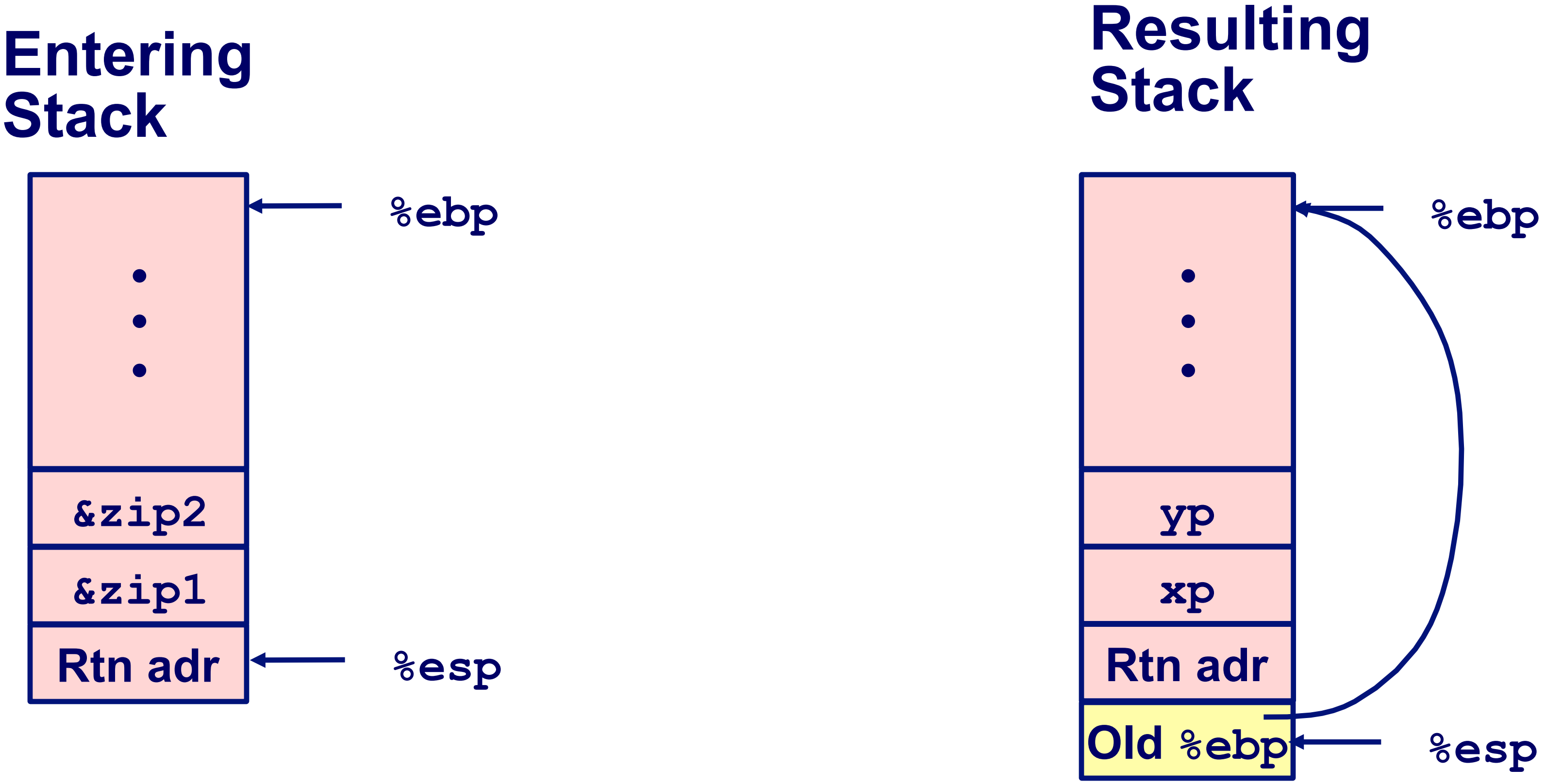
swap() Setup

Entering Stack



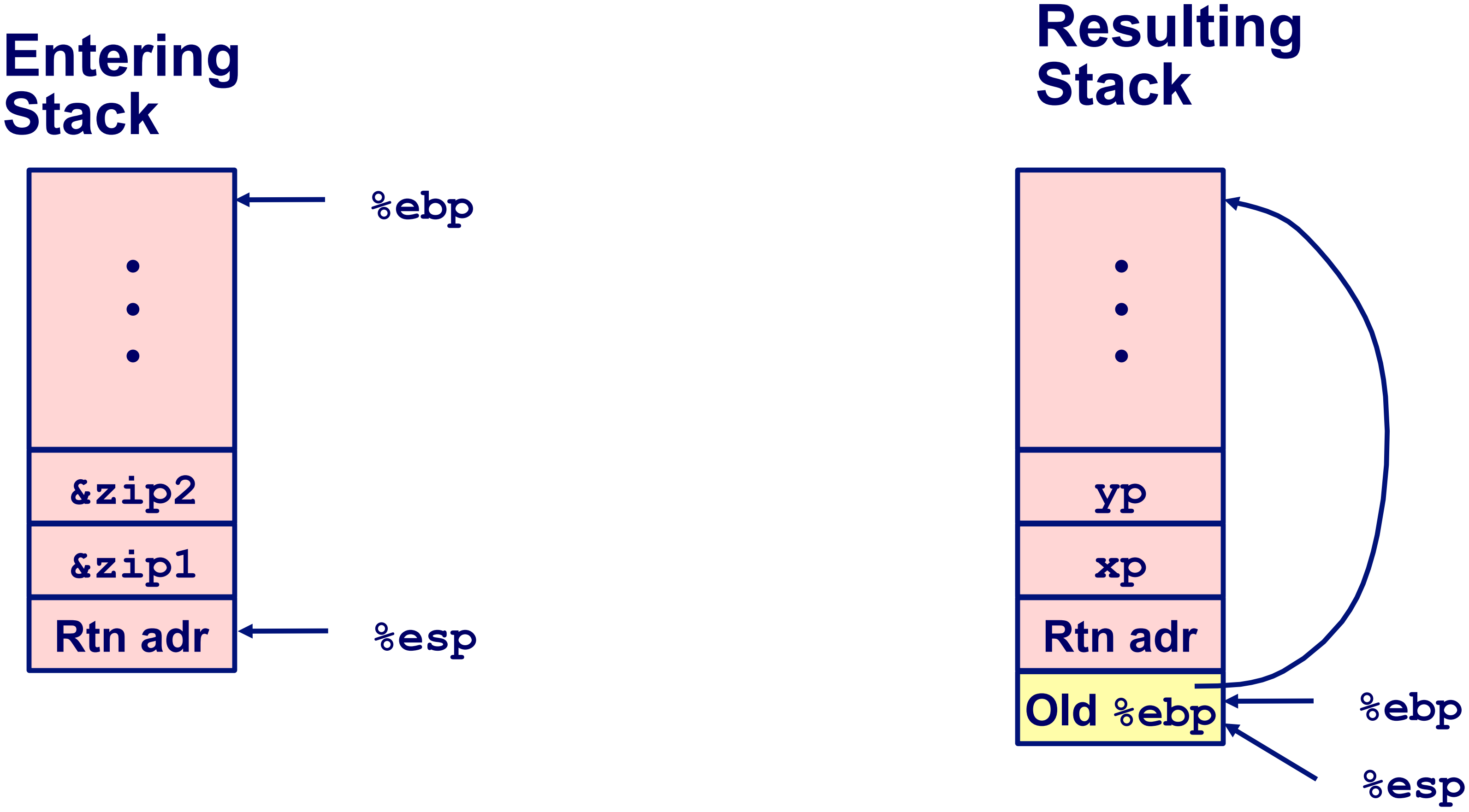
```
swap:
   pushl %ebp
   movl %esp,%ebp
   pushl %ebx
```

swap() Setup #1



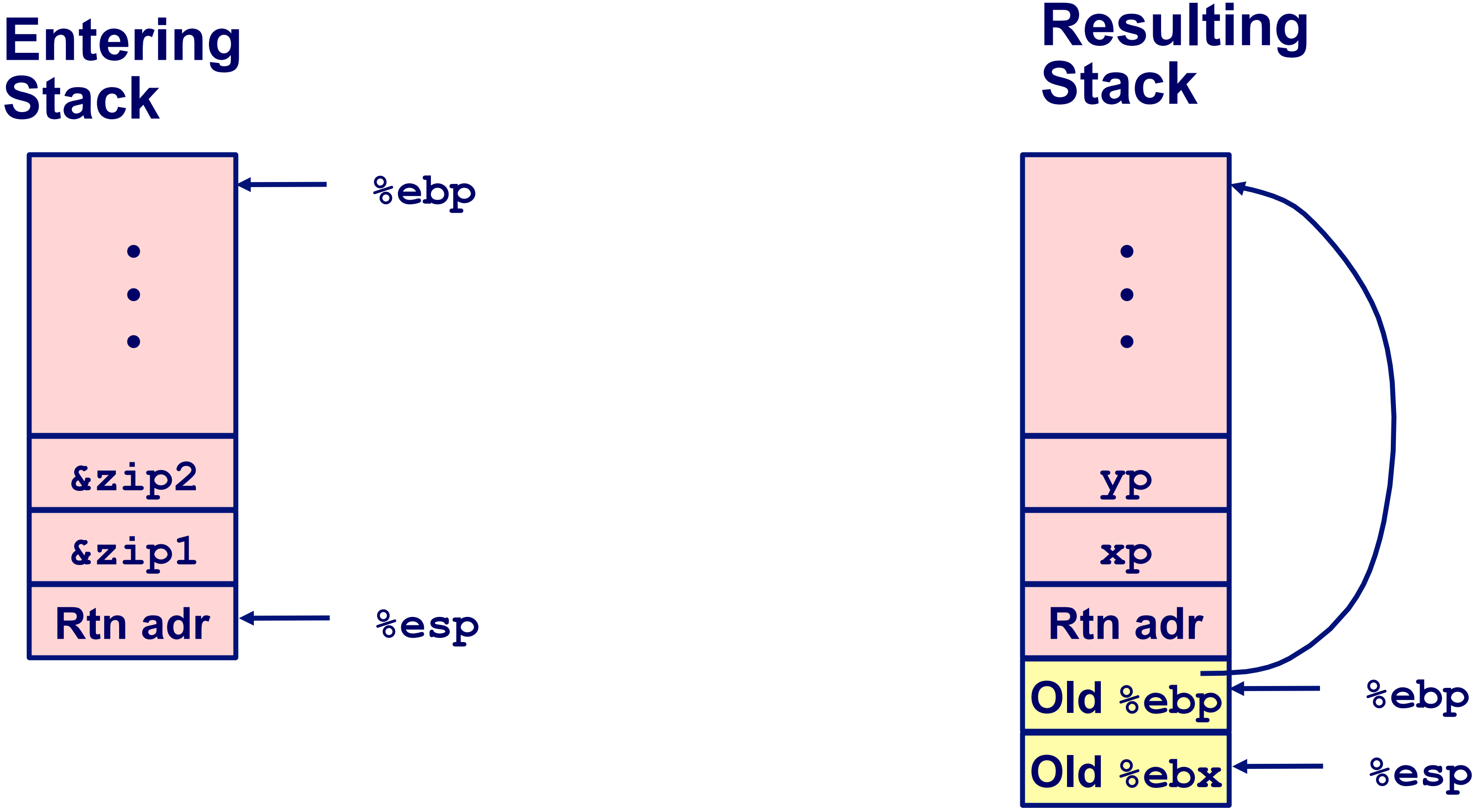
```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

`swap()` Setup #2



```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

swap() Setup #3

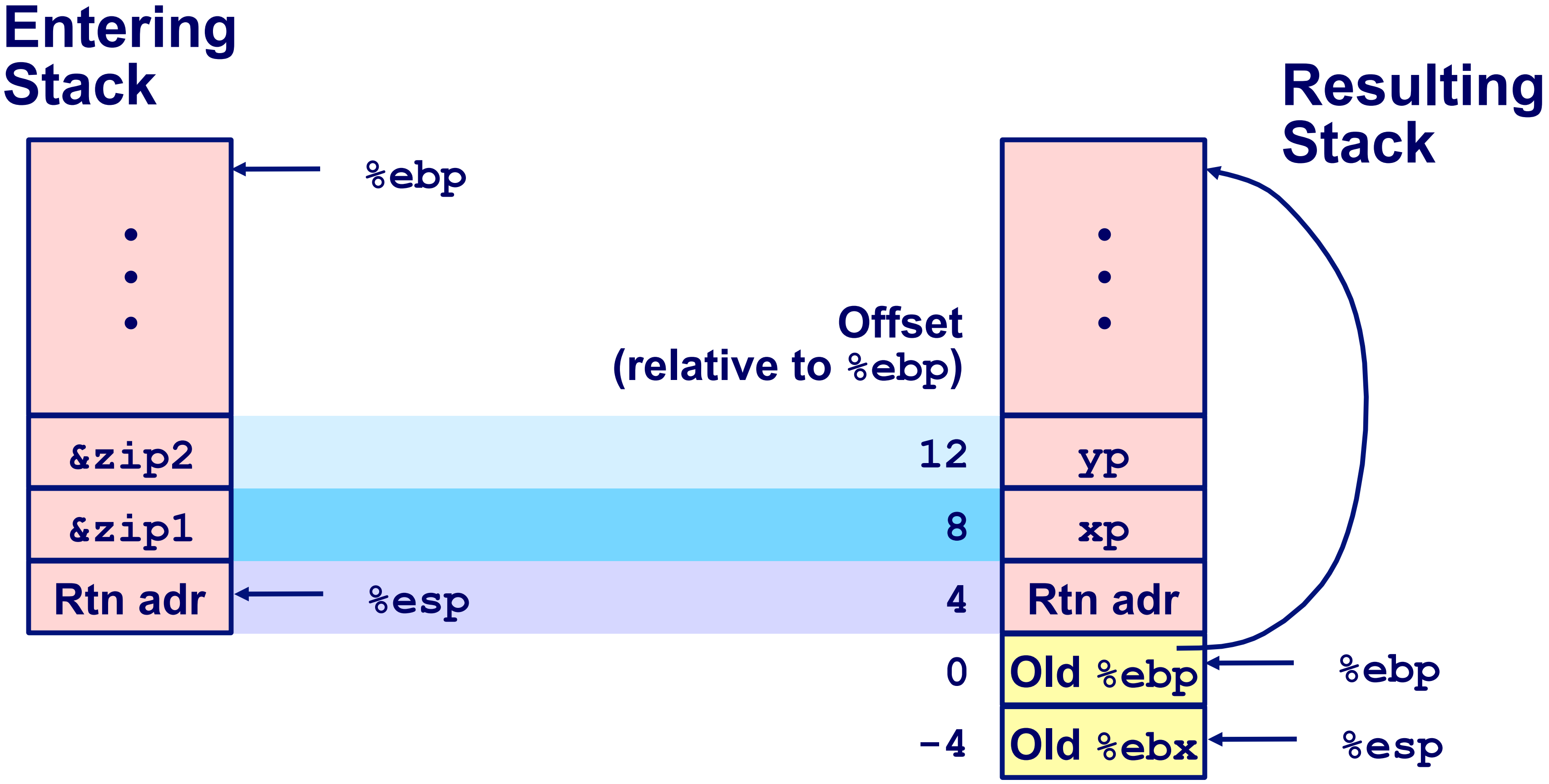


```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

Observation

- Saving caller's register `%ebx`

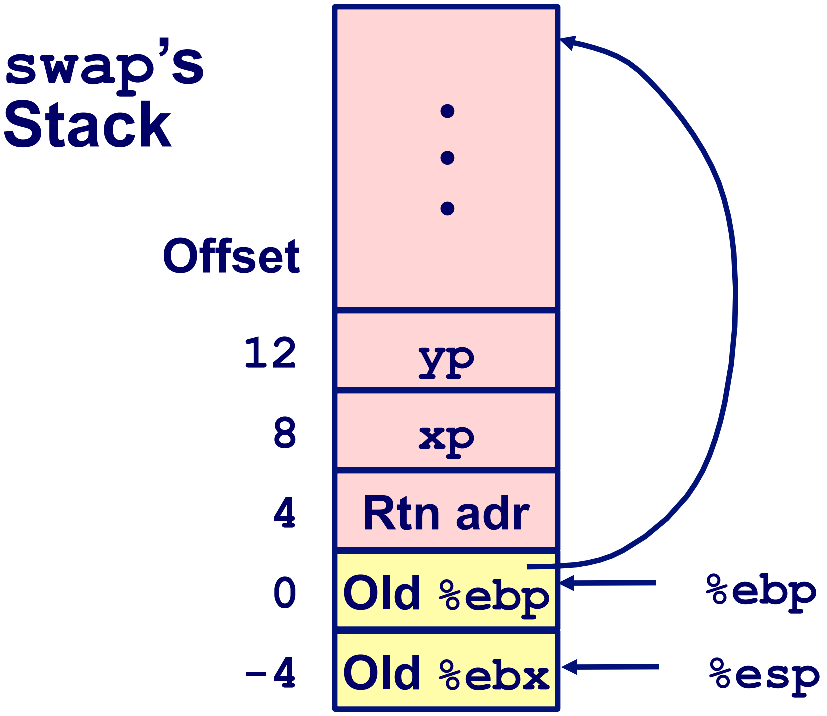
Effect of swap() Setup

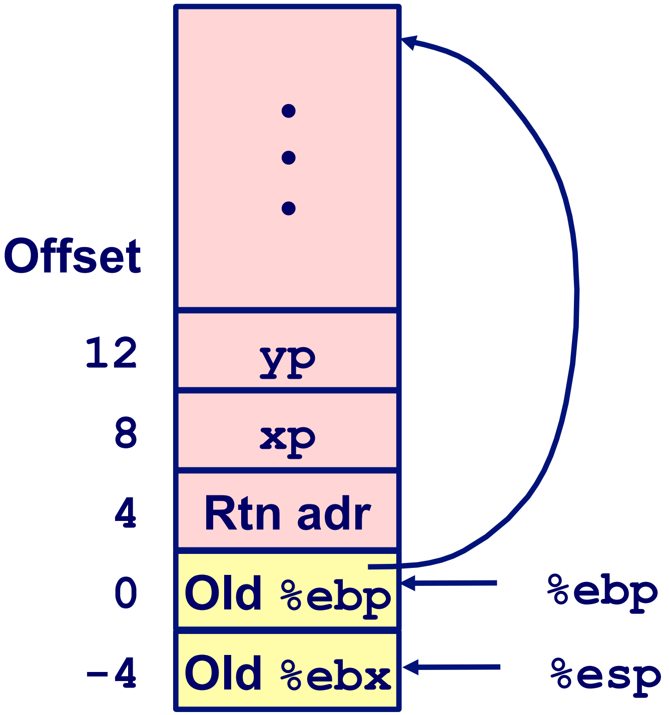


```
movl 12(%ebp),%ecx # get yp
movl 8(%ebp),%edx  # get xp
. . .
```

Body

`swap()` Finish #1



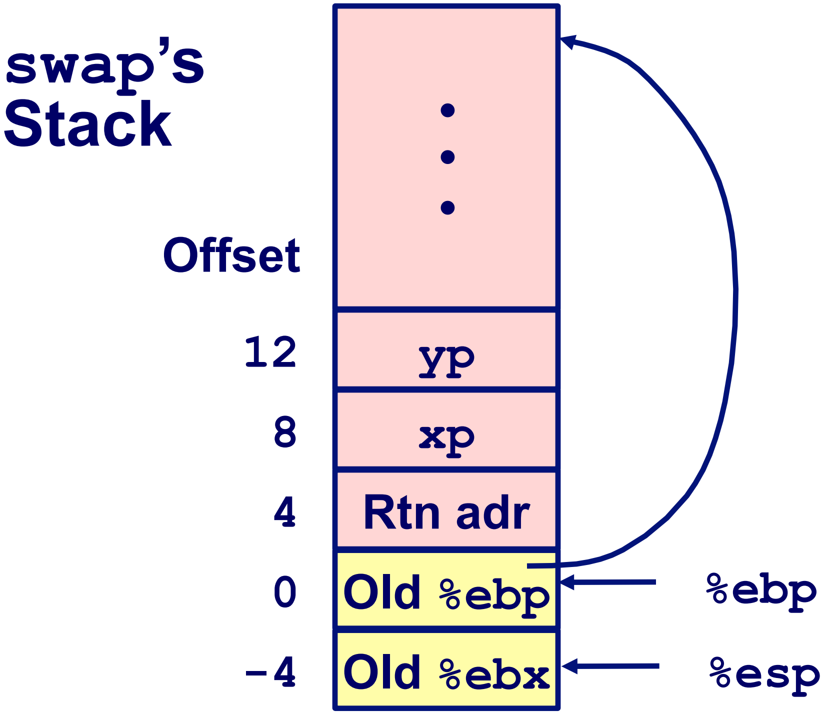


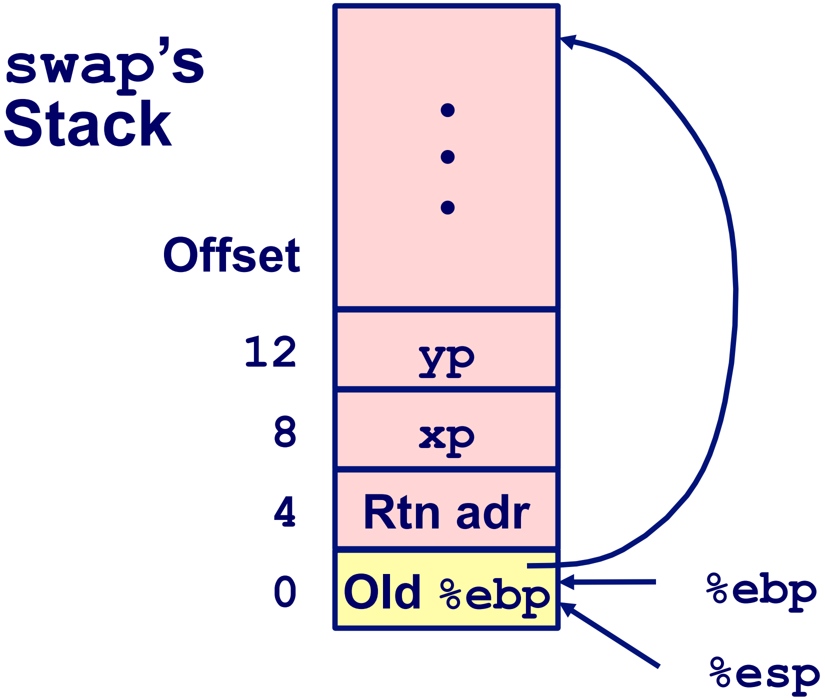
```
movl  -4(%ebp),%ebx
movl  %ebp,%esp
popl  %ebp
ret
```

Observation

- Restoring caller's register `%ebx`

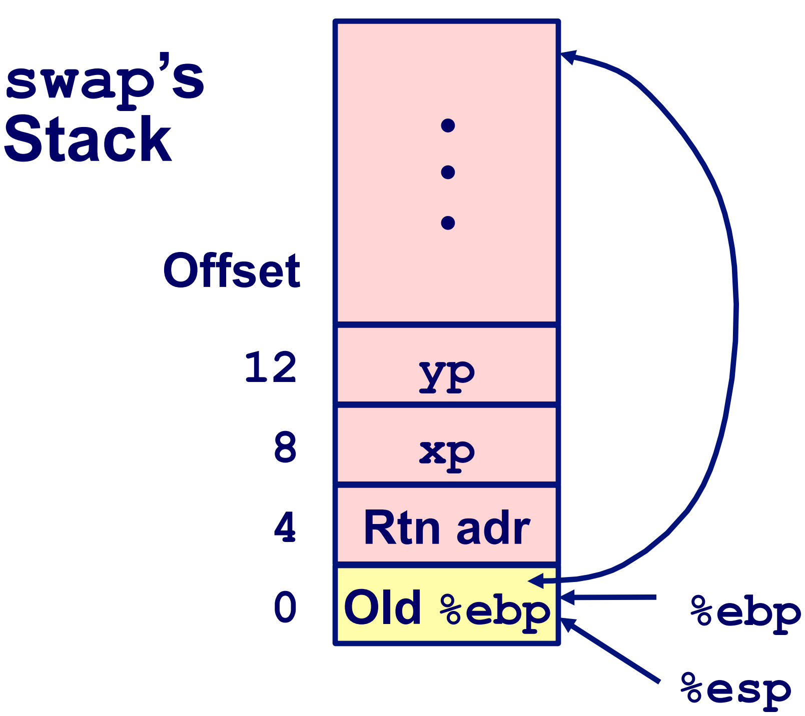
`swap()` Finish #2

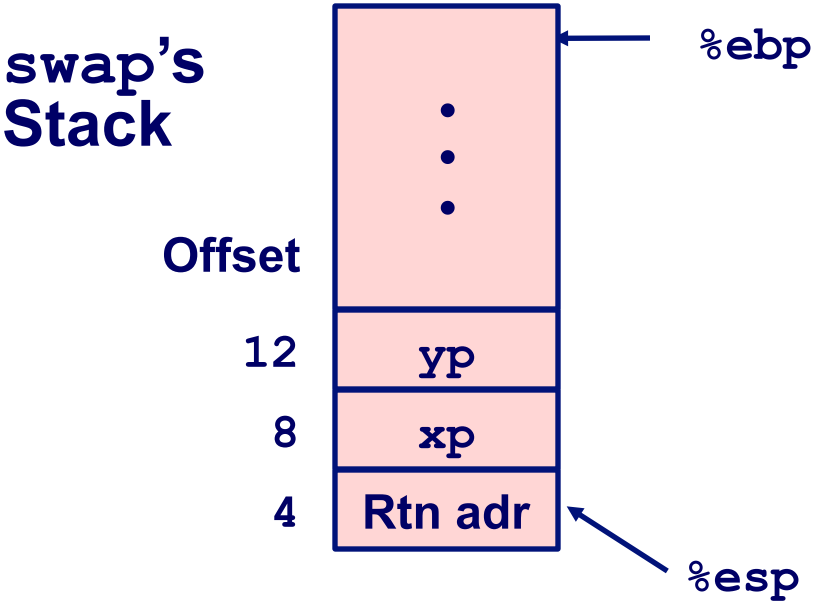




```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

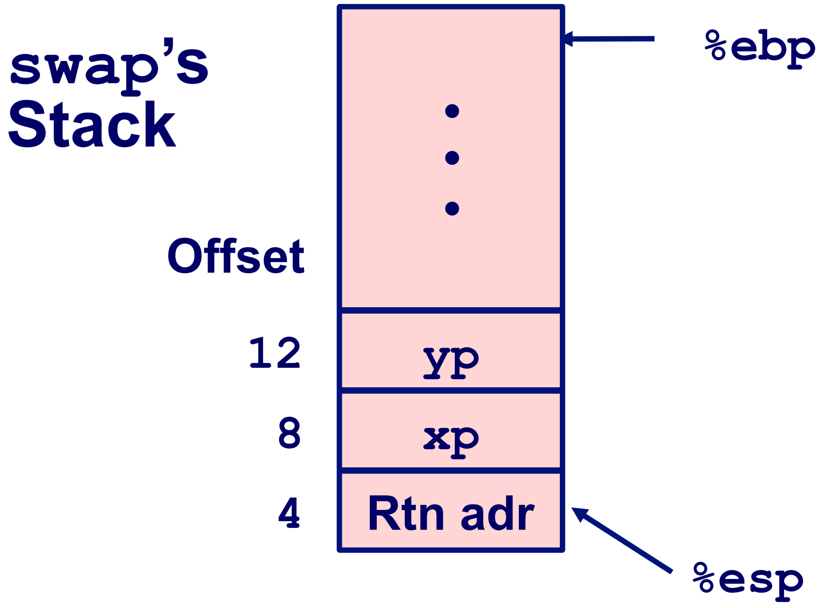
swap() Finish #3

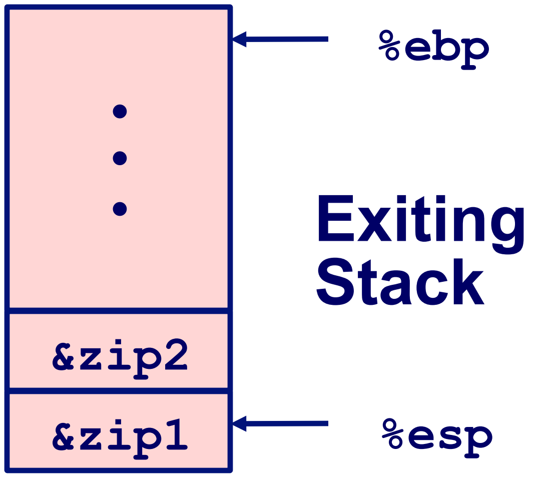




```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

`swap()` Finish #4





```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Observation/query

- Saved & restored caller's register `%ebx`
- Didn't do so for `%eax`, `%ecx`, or `%edx`!

Register Saving Conventions

When procedure `yoo()` calls `who()`:

- `yoo()` is the *caller*, `who()` is the *callee*

Can a register be used for temporary storage?

```
yoo:
    • • •
    movl $15213, %edx
    call who
    addl %edx, %eax
    • • •
    ret
```

```
who:
    • • •
    movl 8(%ebp), %edx
    addl $91125, %edx
    • • •
    ret
```

- Contents of register `%edx` overwritten by `who()`

Register Saving Conventions

When procedure `yoo()` calls `who()`:

- `yoo()` is the *caller*, `who()` is the *callee*

Can a register be used for temporary storage?

Definitions

- "Caller Save" register
  - Caller saves temporary in its frame before calling
- "Callee Save" register
  - Callee saves temporary in its frame before using

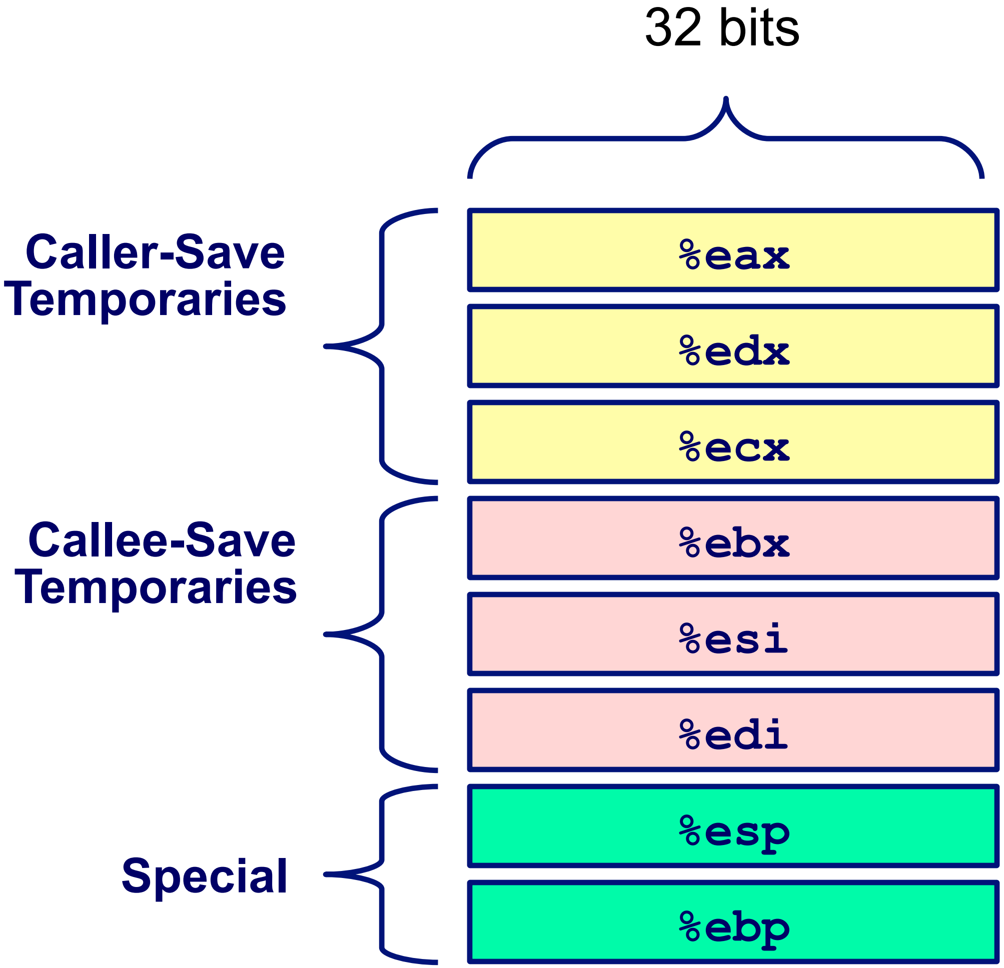
Conventions

- Which registers are caller-save, callee-save?

IA32/Linux Register Usage

Integer Registers

- **Two have special uses**
  - **`%ebp`, `%esp`**
- **Three managed as callee-save**
  - **`%ebx`, `%esi`, `%edi`**
  - **Old values saved on stack prior to using**
- **Three managed as caller-save**
  - **`%eax`, `%edx`, `%ecx`**
  - **Do what you please, but expect any callee to do so, as well**
- **Register `%eax` also holds return value**



Stack Summary

Stack makes recursion work

- Private storage for each *instance* of procedure call
  - Instantiations don't clobber each other
  - Addressing of locals + arguments can be relative to stack positions
- Can be managed by stack discipline
  - Procedures return in inverse order of calls

IA32 procedures: instructions + conventions

- `call` / `ret` instructions mix `%eip`, `%esp` in a fixed way
- Register usage conventions
  - Caller / Callee save
  - `%ebp` and `%esp`
- Stack frame organization conventions
  - Which argument is pushed first

Before & After main()

```
int main(int argc, char *argv[]) {
  if (argc > 1) {
    printf(“%s\n”, argv[1]);
  } else {
    char * av[3] = { 0, 0, 0 };
    av[0] = argv[0];  av[1] = “Fred”;
    execvp(av[0], av);
  }
  return (0);
}
```

The Mysterious Parts

argc, argv

- Strings from one program
- Which part of the memory map are they in?
- How did they get there?

What happens when `main()` does “`return(0)`”???

- There's no more program to run...right?
- Where does the 0 go?
- How does it get there?

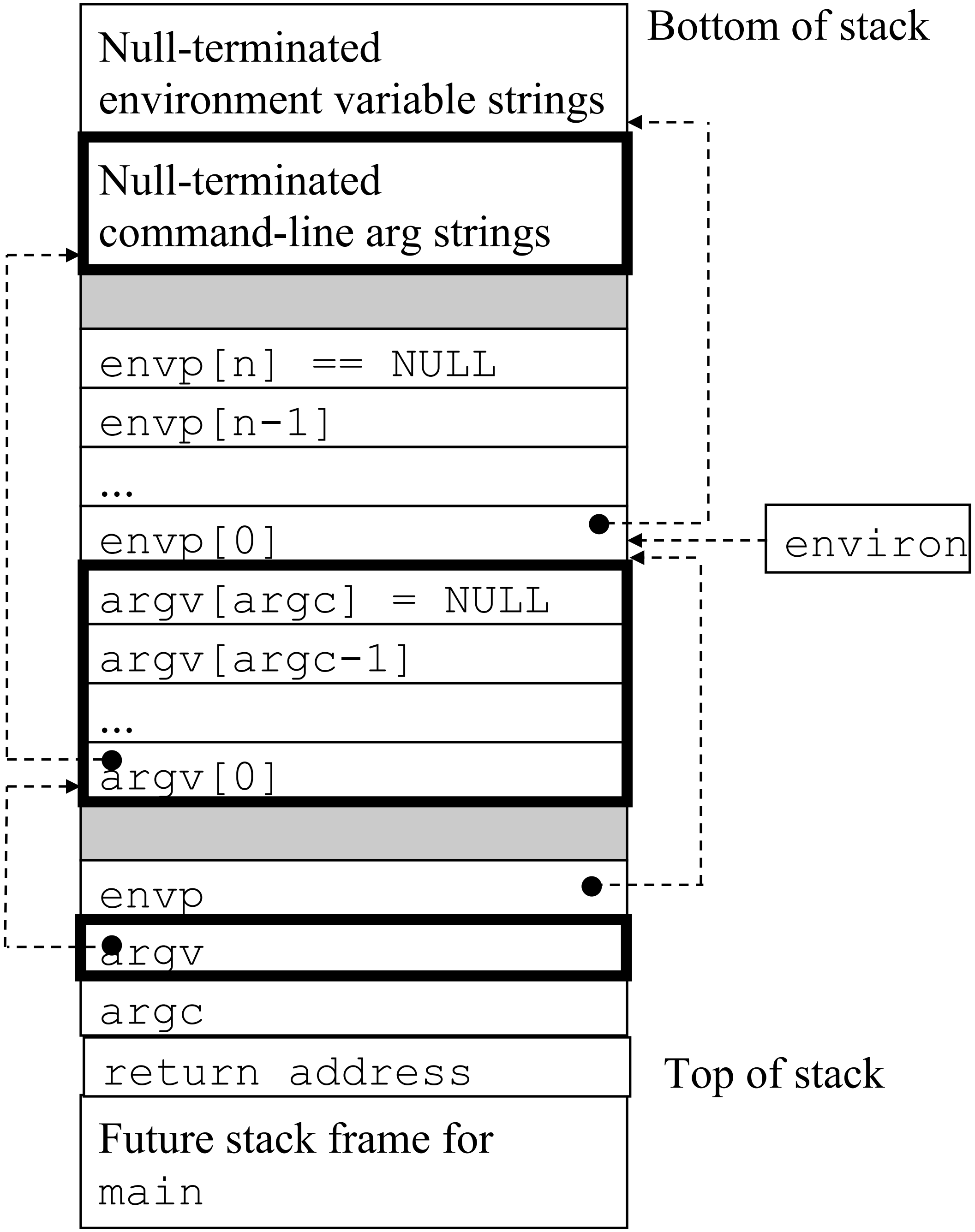
410 students should seek to abolish mystery

The Mysterious Parts

Stack structure when a new program starts

argc, argv, envp

- Come from the program that called **execve**
- Kernel copies strings from old address space to new



The Mysterious Parts

What happens when `main()` does "`return(0)`"?

- Defined by C to have same effect as "`exit(0)`"
- But how??

The Mysterious Parts

What happens when `main()` does "`return(0)`"?

- Defined by C to have same effect as "`exit(0)`"
- But how??

The "main() wrapper"

- Receives argc, argv from OS
- Calls `main()`, then calls `exit()`
- Provided by C library, traditionally in "crt0.s"
- Often has a "strange" name

```
/* not actual code */
void __main(int argc, char *argv[]) {
  exit(main(argc, argv, environ));
}
```

Project 0 - “Stack Crawler”

C/Assembly function

- Can be called by any C function
- Prints stack frames in a symbolic way

```
---Stack Trace Follows---
Function fun3(c='c', d=2.090000), in
Function fun2(f=35.000000), in
Function fun1(count=0), in
Function fun1(count=1), in
Function fun1(count=2), in
...
```

Project 0 - “Stack Crawler”

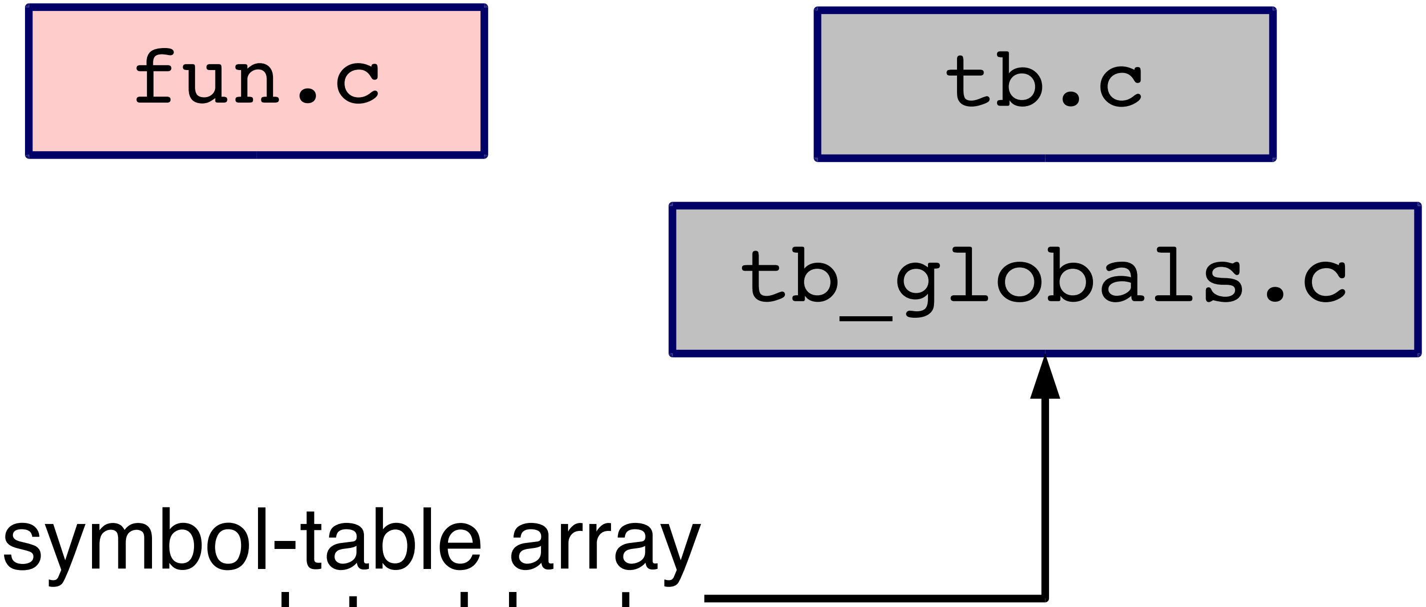
Conceptually easy

- Calling convention specifies layout of stack
- Stack is “just memory” - C happily lets you read & write

Key questions

- How do I know 0x80334720 is “`fun1`”?
- How do I know `fun3()`'s second parameter is called “`d`”?
- How do I know when to stop?

Project 0 “Data Flow”



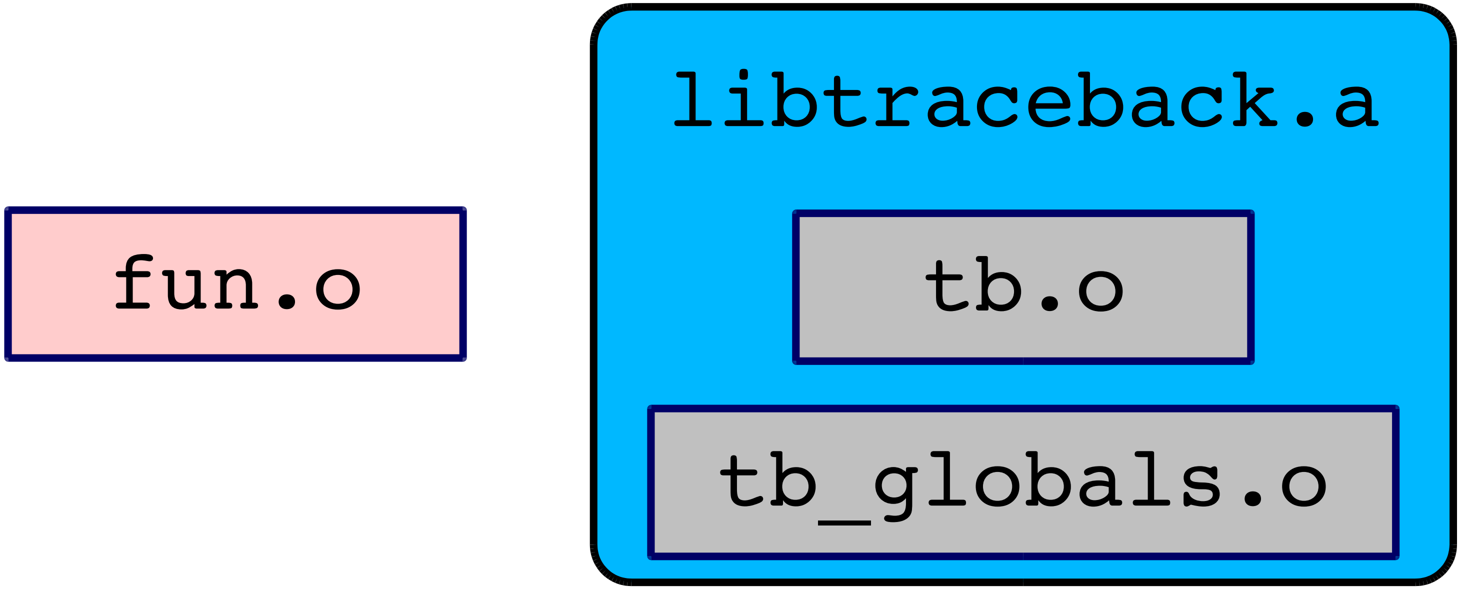
fun.c

tb.c

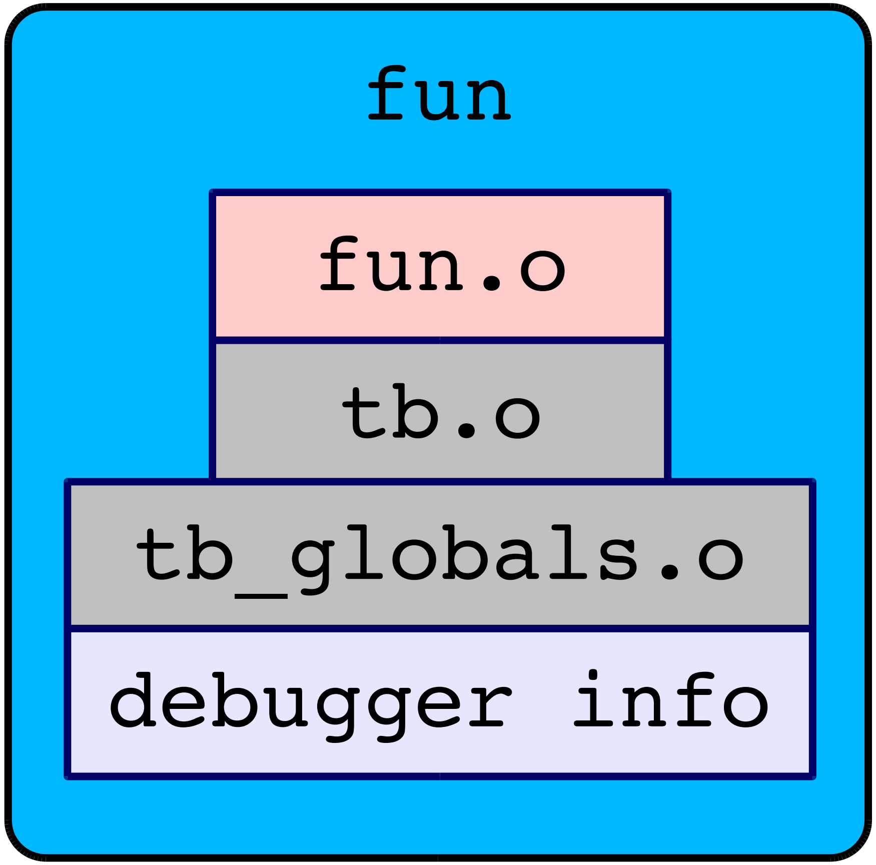
tb_globals.c

symbol-table array
many slots, blank

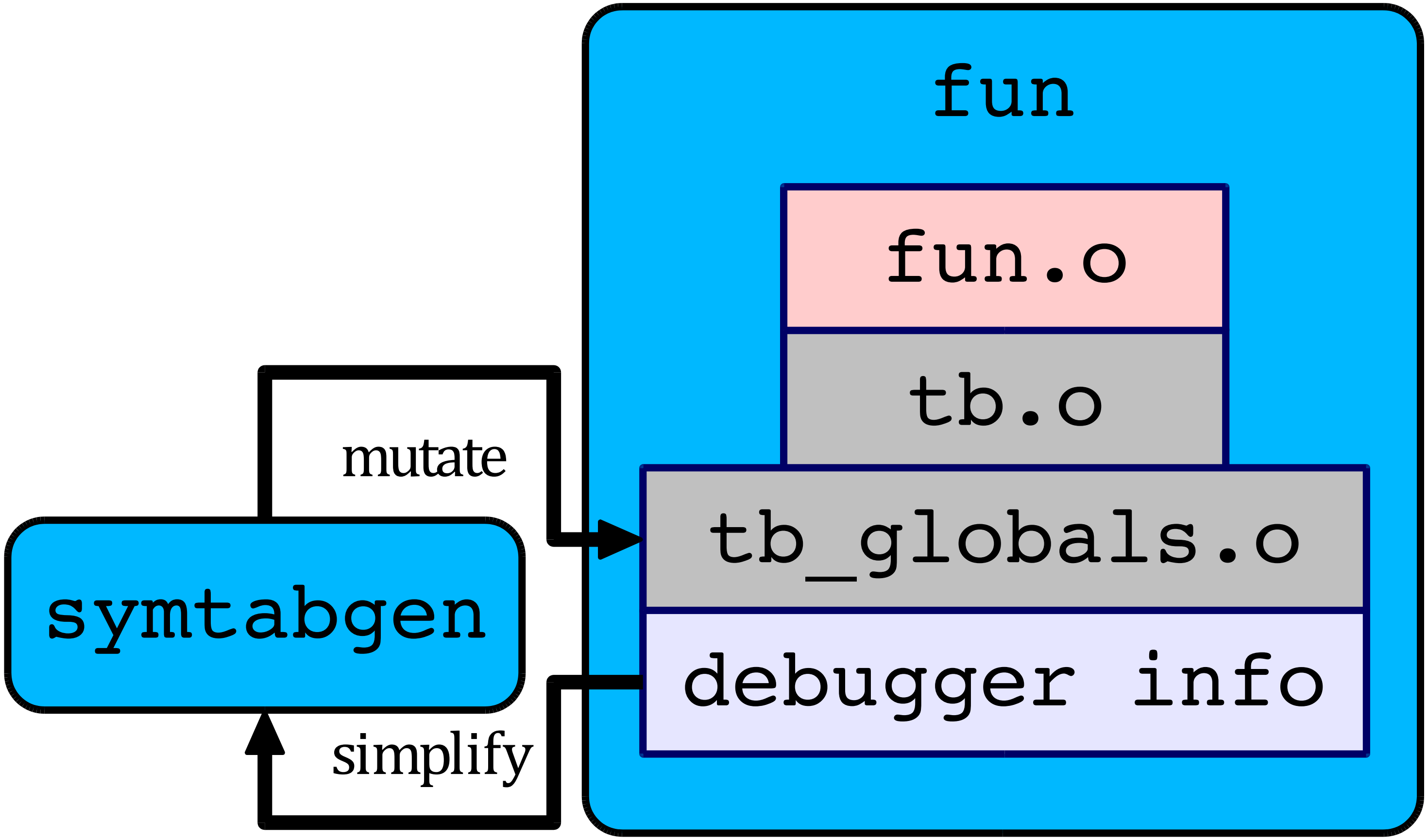
Project 0 “Data Flow” - Compilation



Project 0 “Data Flow” - Linking



Project 0 “Data Flow” - P0 “Post-Linking”



Summary

Review of stack knowledge

What makes `main()` special

Project 0 overview

- Look for handout this evening

Start interviewing Project 2/3/4 partners!

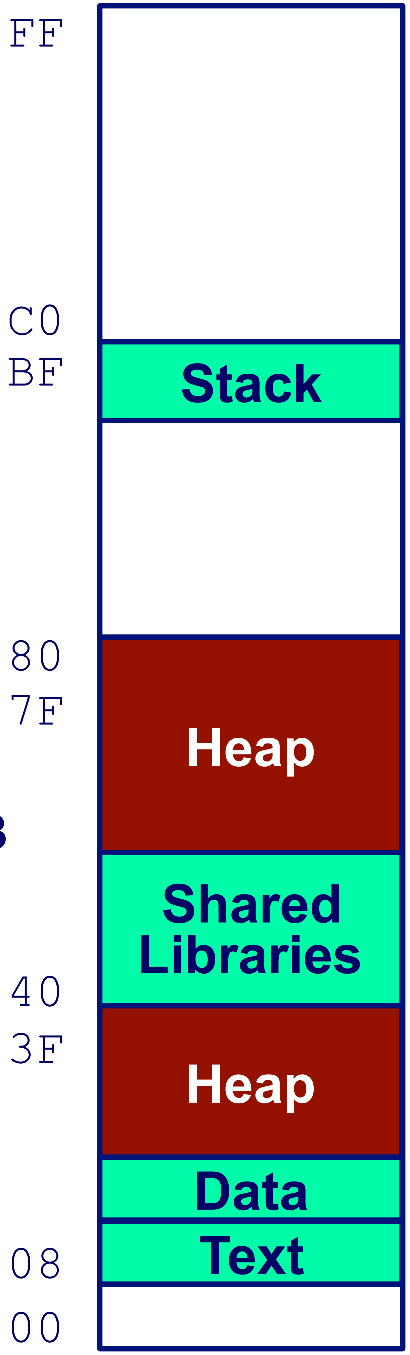
http://csapp.cs.cmu.edu/3e/waside/waside-ia32.pdf

(visit http://csapp.cs.cmu.edu and select “Web Asides”)

Movie Night

"Primer"

- Thursday, August 29th
- 19:30, GHC 4401 ("Rashid Auditorium")
- $1 Pizza
- Presented by `#!/cmu/cc`
- Funded in part by your Student Activities Fee



Upper 2 hex digits of address

Red Hat v. 6.2 ~1920MB memory limit

Linux Memory Layout

Stack

- **Runtime stack (8MB limit by default)**

Heap

- **Dynamically allocated storage**
- **Managed by `malloc()`, `calloc()`, `new`**

Shared/Dynamic Libraries aka Shared Objects

- **Library routines (e.g., `printf()`, `malloc()`)**
- **Linked into object code when first executed**
- **Windows has “DLLs” (semantic differences)**

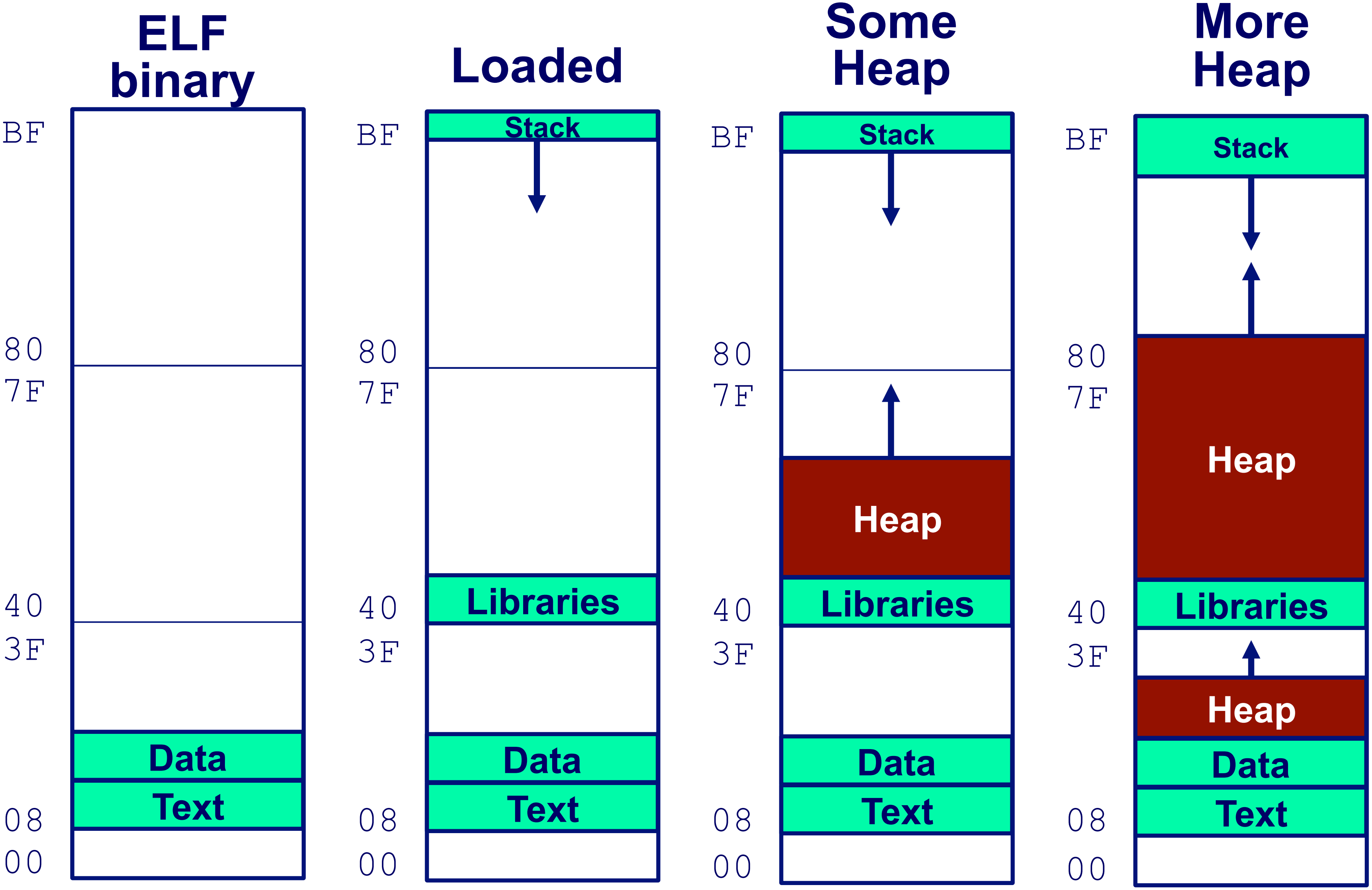
Data, BSS

- **Statically allocated data (BSS starts all-zero)**
- **e.g., arrays & variables declared in code**

Text, RODATA

- **Text - Executable machine instructions**
- **RODATA – Read-only (e.g., “`const`”)**
  - **String literals**

Linux Memory Allocation


ELF binary
Loaded
Some Heap
More Heap
BF
80
7F
40
3F
08
00
Stack
Heap
Libraries
Data
Text