15-410

"An Experience Like No Other"

Stack Discipline
Jan. 14, 2026

Babu Pillai
Dave Eckhardt

Slides originally stolen from 15-213

Synchronization

Reminder: the syllabus has been released!

- **Please read it, carefully, right away**
  - **Please do *not* wait until halfway through P0**

Synchronization

Office hours today?

- I believe so – see the Staff web page
- Don't forget about the syllabus!

Outline

Topics

- Process memory model
- IA32 stack organization
- Register saving conventions
- Before & after `main()`
- Project 0

Why Only 32?

You may have learned x86-64 aka EMT64 aka AMD64

- x86-64 is simpler than x86(-32) for user program code
  - Lots of registers, registers more orthogonal

Why will 410 be x86 / IA32?

Why Only 32?

You may have learned x86-64 aka EMT64 aka AMD64

- x86-64 is simpler than x86(-32) for user program code
  - Lots of registers, registers more orthogonal

Why will 410 be x86 / IA32?

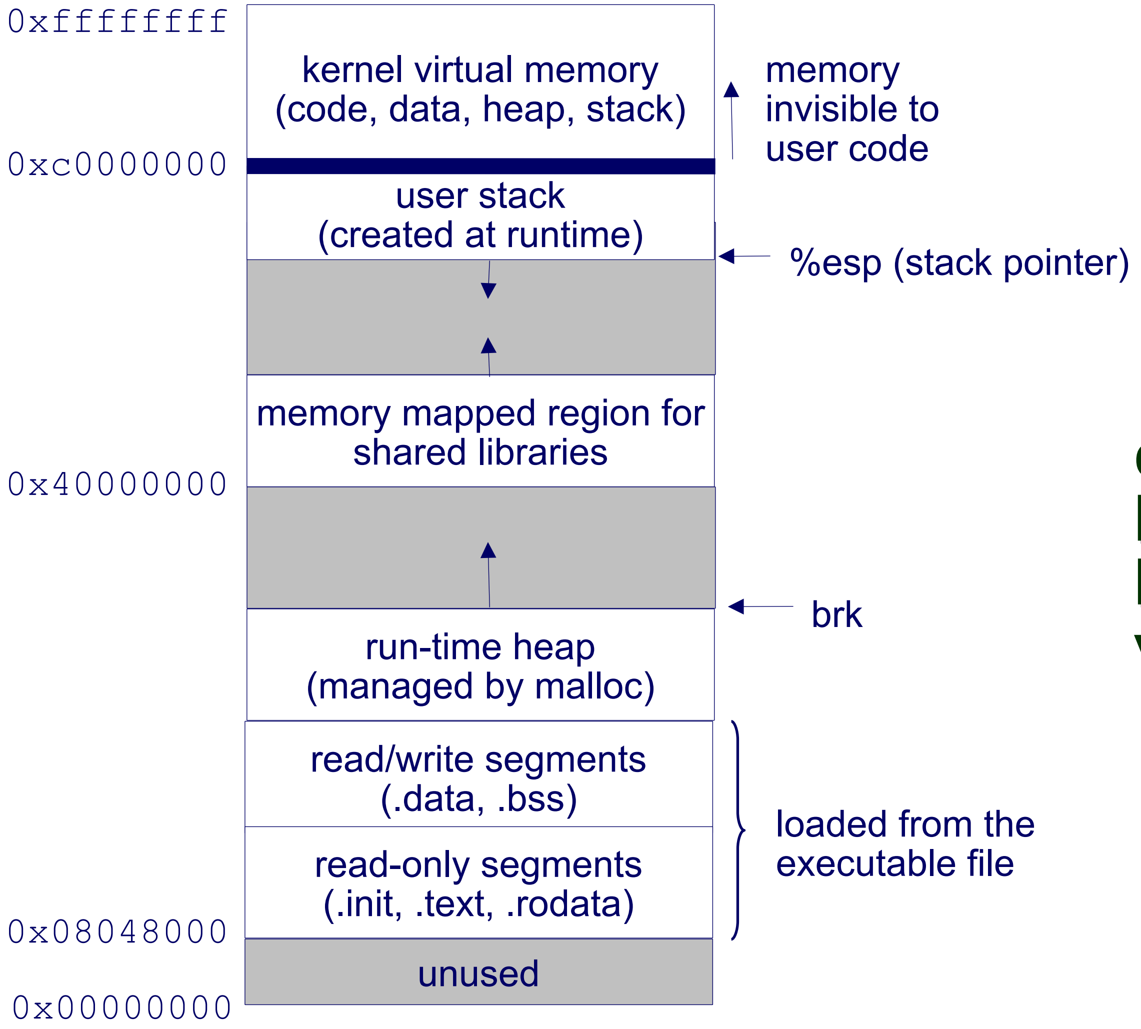
- x86-64 is *not* simpler for kernel code
  - Machine begins in 16-bit mode, then 32, finally 64
    - » You don't have time to write 32⇒64 transition code
    - » If we gave it to you, it would be a *big* black box
  - Interrupts are more complicated
- x86-64 is *not* simpler during debugging
  - More 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

CS:APP 32-bit guide

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

Private Address Spaces

Each process has its own private address space.



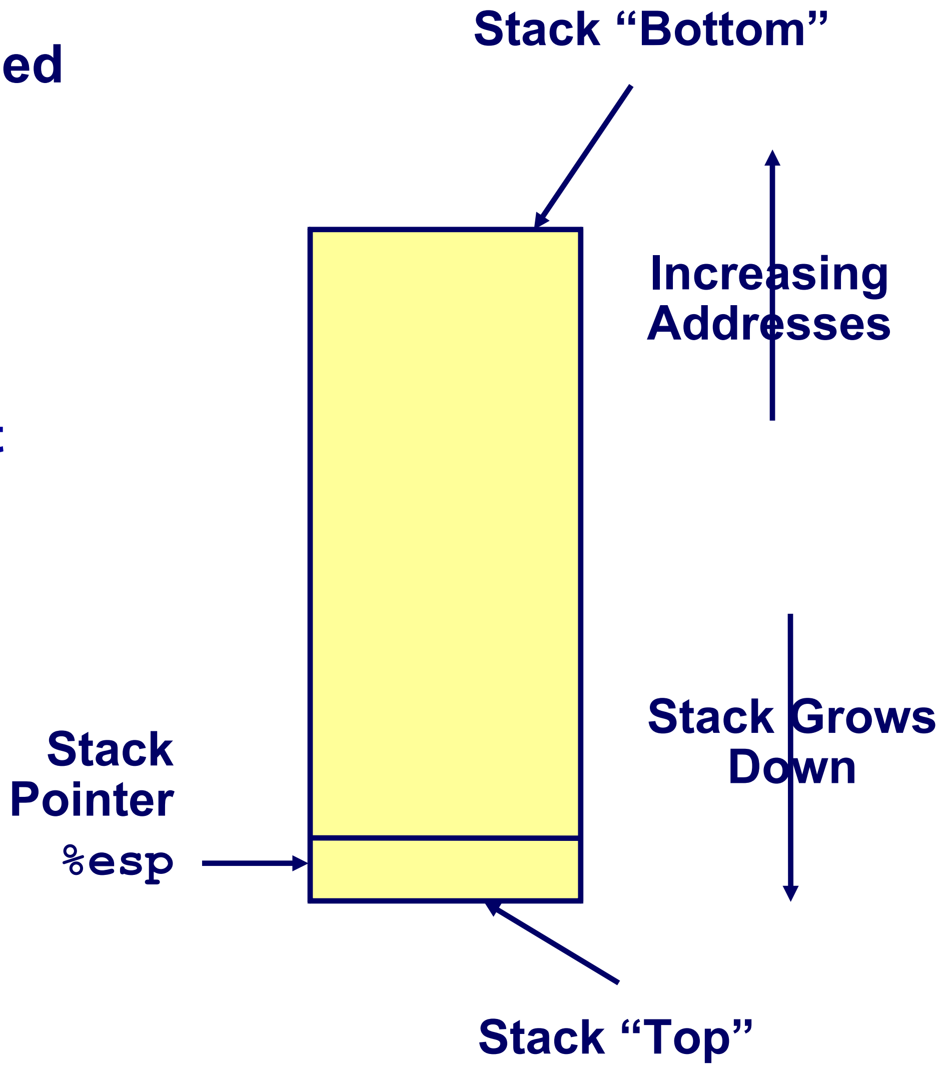
0xffffffff
kernel virtual memory (code, data, heap, stack)
memory invisible to user code
0xc0000000
user stack (created at runtime)
%esp (stack pointer)
memory mapped region for shared libraries
0x40000000
brk
run-time heap (managed by malloc)
read/write segments (.data, .bss)
read-only segments (.init, .text, .rodata)
loaded from the executable file
0x08048000
unused
0x00000000

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

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

IA32 Stack

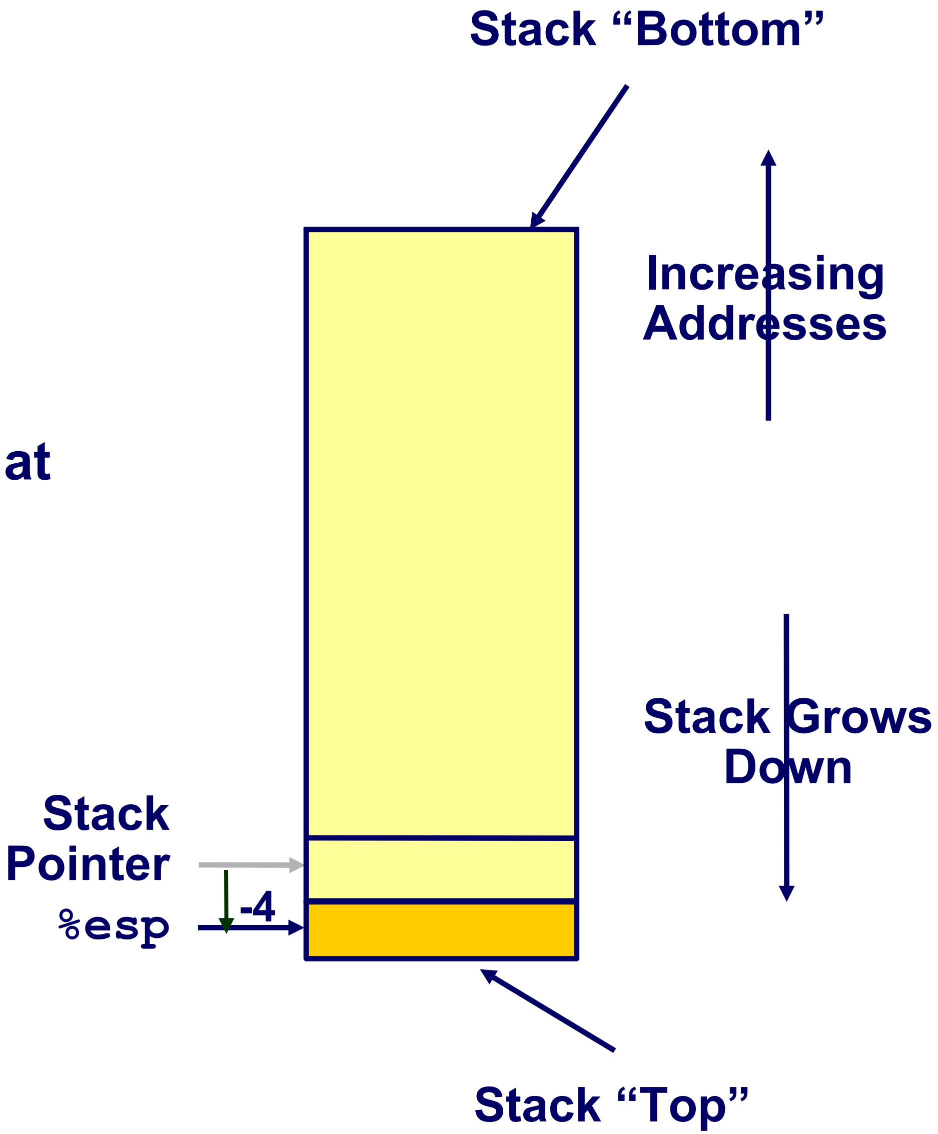
- Region of memory managed with stack discipline
- "Grows" toward lower addresses
- Register `%esp` indicates lowest stack address
  - address of "top" element
  - stack *pointer*



IA32 Stack Pushing

Pushing

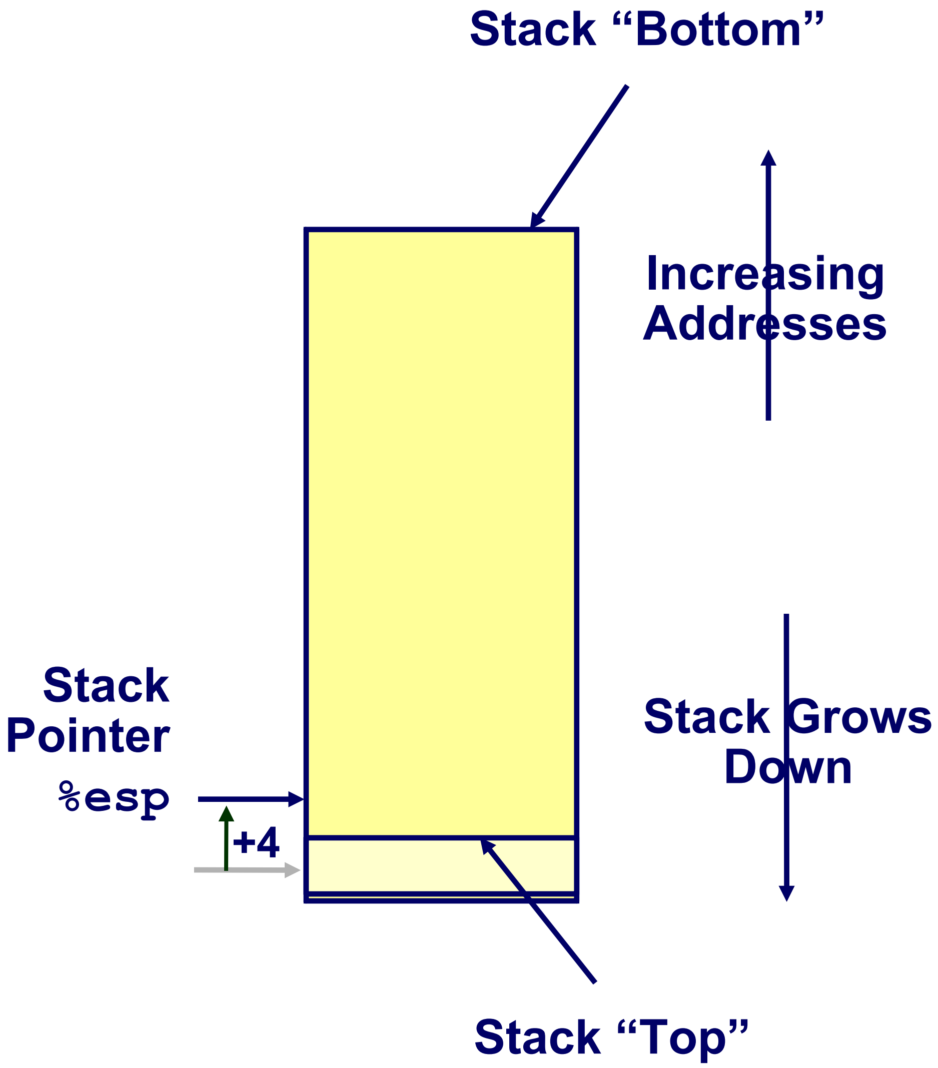
- `pushl` *Src*
- Fetch "operand" from *Src*
  - Maybe a register: %ebp
  - Maybe memory: 8(%ebp)
- Decrement `%esp` by 4
- Store operand in memory at address given by `%esp`



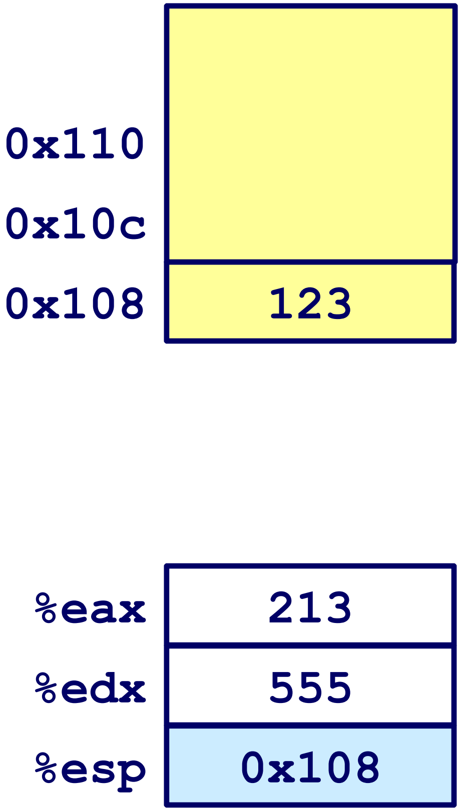
IA32 Stack Popping

Popping

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



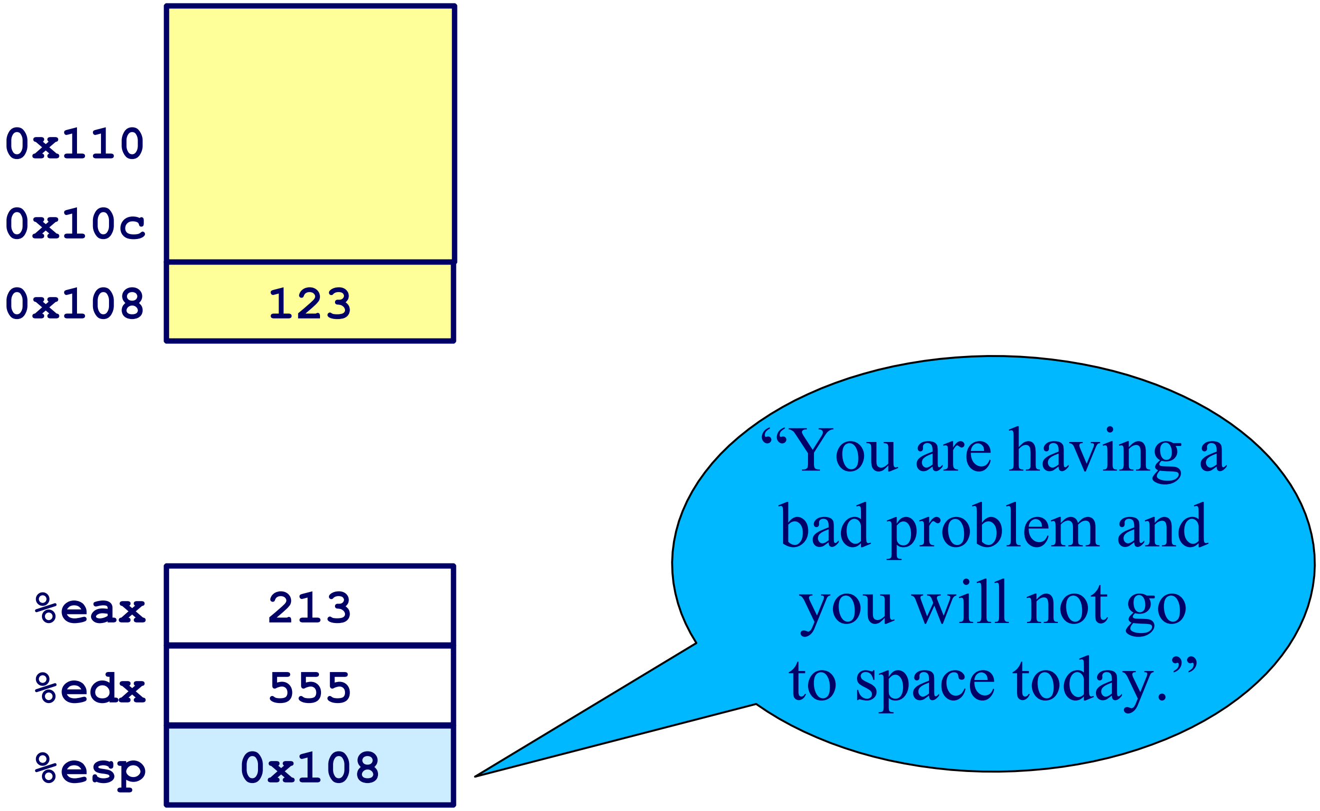
Stack Operation Examples



0x110	
0x10c	
0x108	123

%eax	213
%edx	555
%esp	0x108

Stack Operation Examples

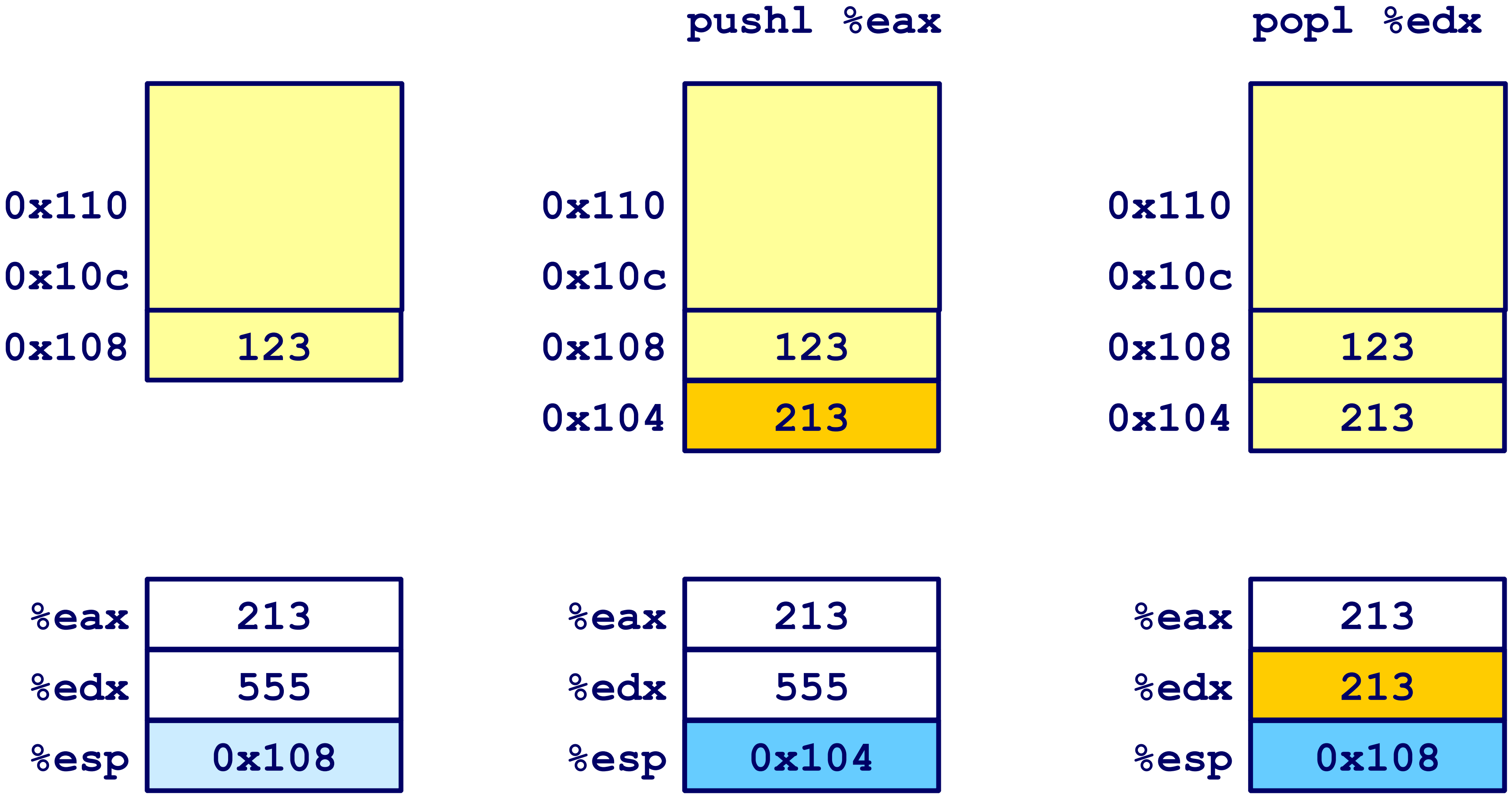


0x110	
0x10c	
0x108	123

%eax	213
%edx	555
%esp	0x108

"You are having a bad problem and you will not go to space today."

Stack Operation Examples



0x110	
0x10c	
0x108	123
%eax	213
%edx	555
%esp	0x108

`pushl %eax`

0x110	
0x10c	
0x108	123
0x104	213
%eax	213
%edx	555
%esp	0x104

`popl %edx`

0x110	
0x10c	
0x108	123
0x104	213
%eax	213
%edx	213
%esp	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
```

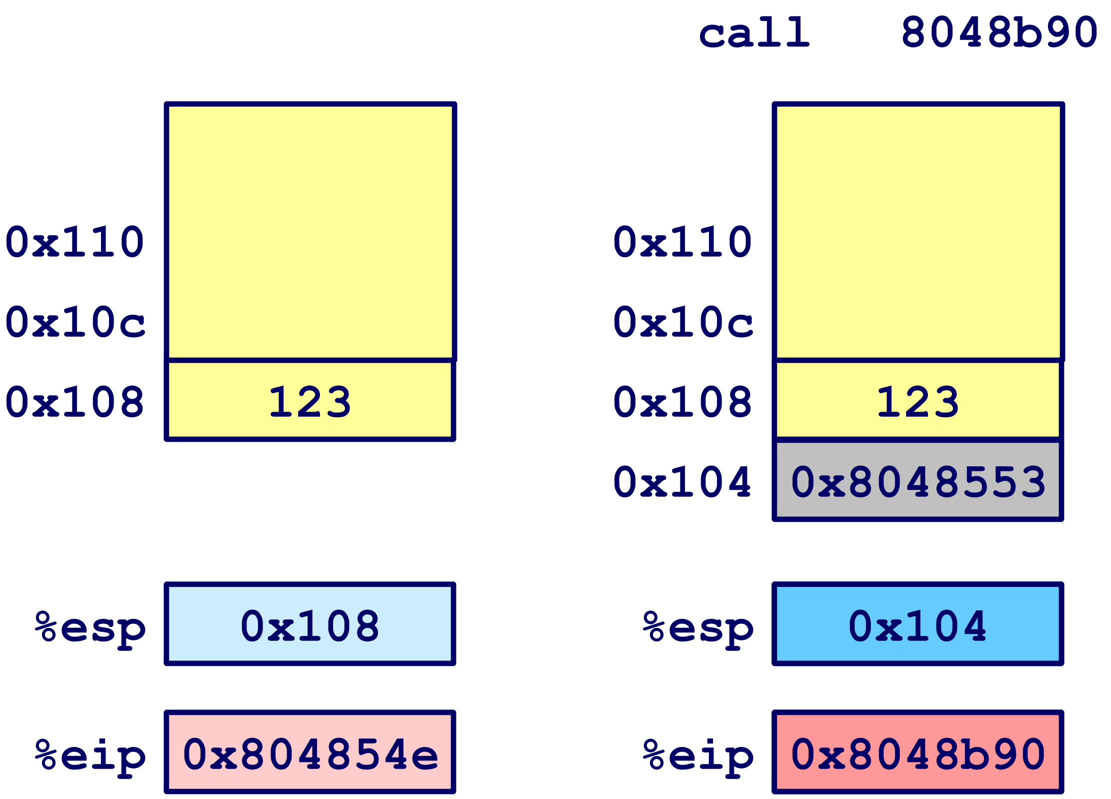
  » **Return address = `0x8048553`**

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
```



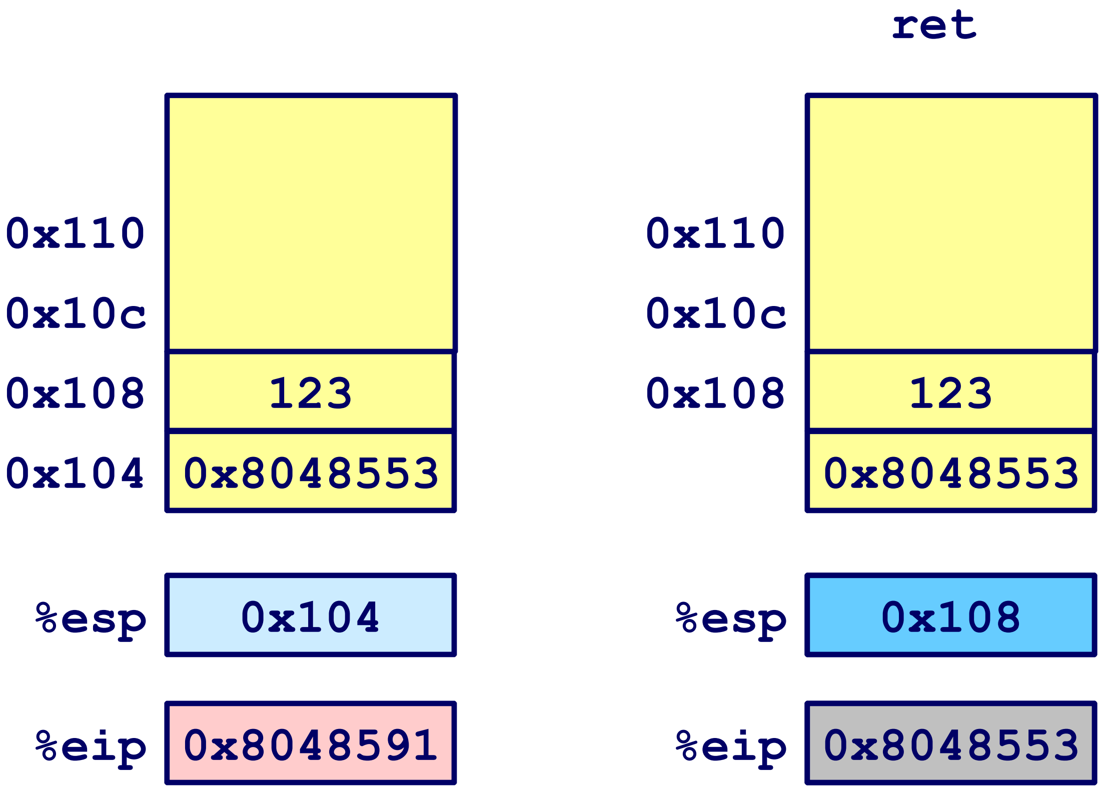
call 8048b90

0x110		0x110	
0x10c		0x10c	
0x108	123	0x108	123
		0x104	0x8048553
%esp	0x108	%esp	0x104
%eip	0x804854e	%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

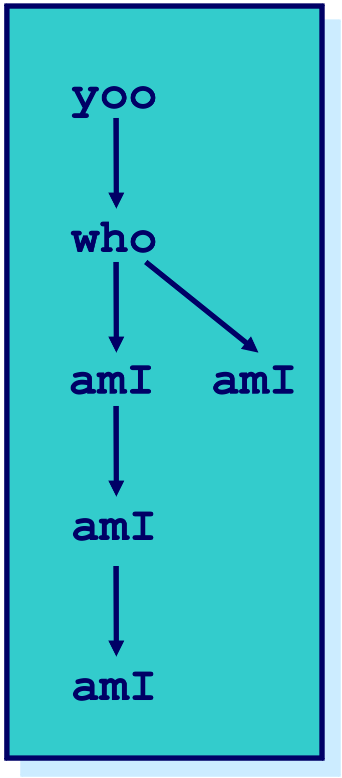
```
yoo(…)
{
•
•
who();
•
•
}
```

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

```
amI(…)
{
•
•
amI();
•
•
}
```

- Procedure `amI()` recursive

Call Chain



Stack Frames

Contents

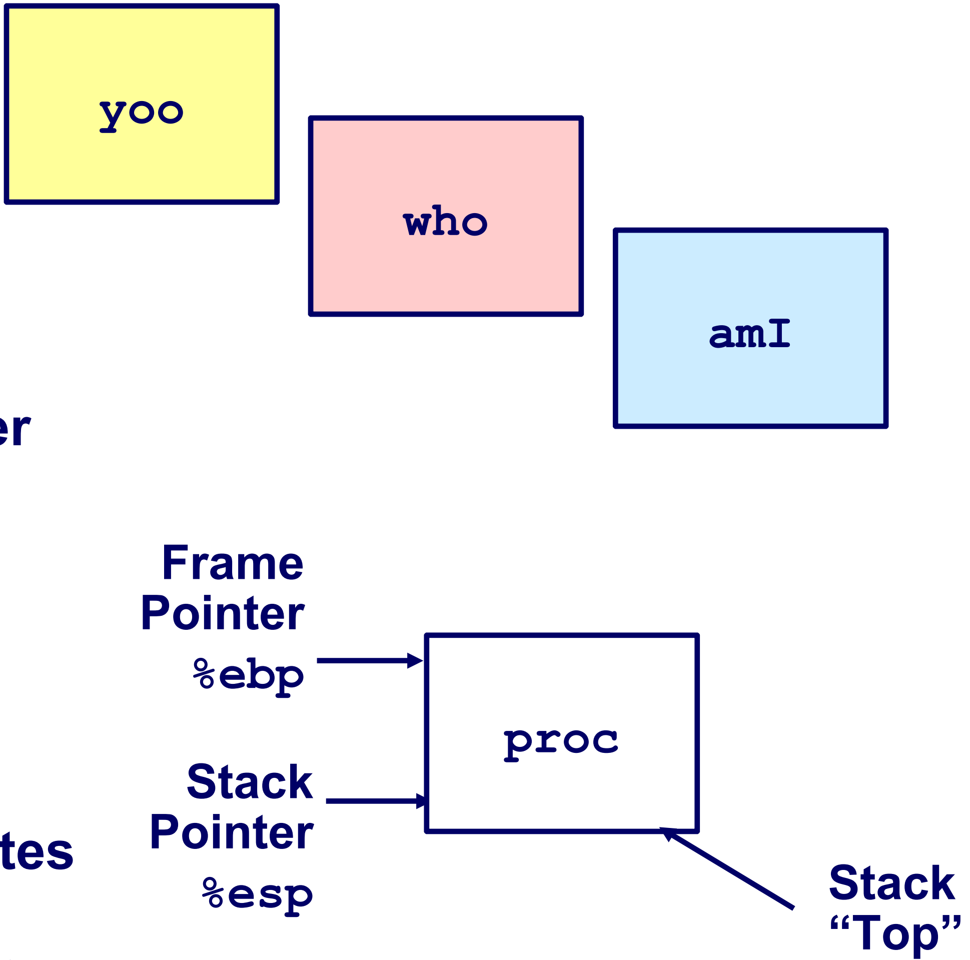
- Local variables
- Return information
- Temporary space

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



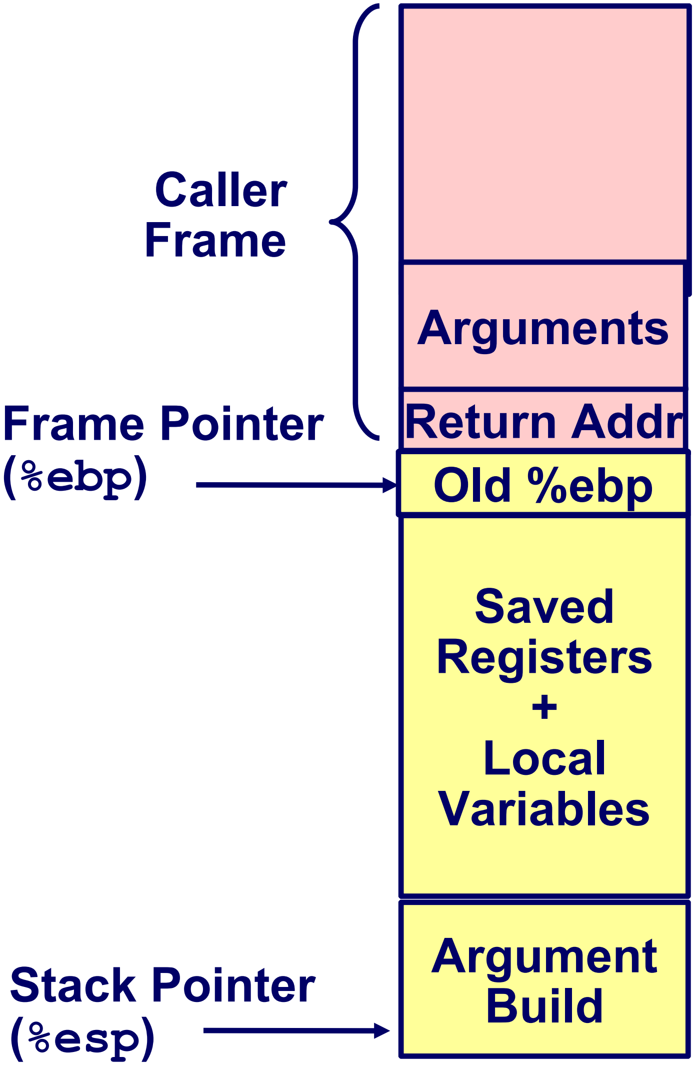
IA32/Linux Stack Frame

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 usl



swap()

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

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;
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{
  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
    • • •
```

swap()

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

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

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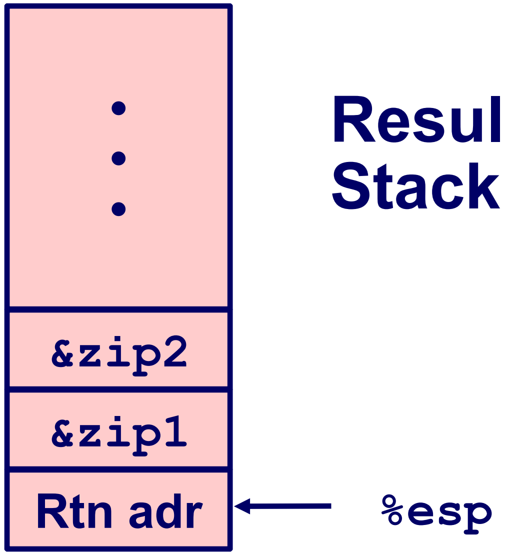

Calling swap from call_swap

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



Resulting Stack

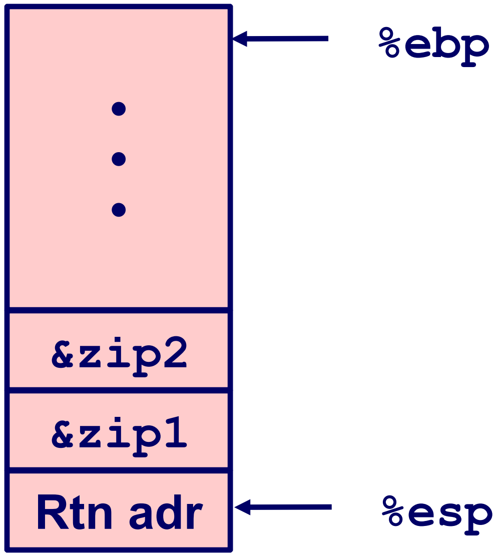
swap()

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

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

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

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

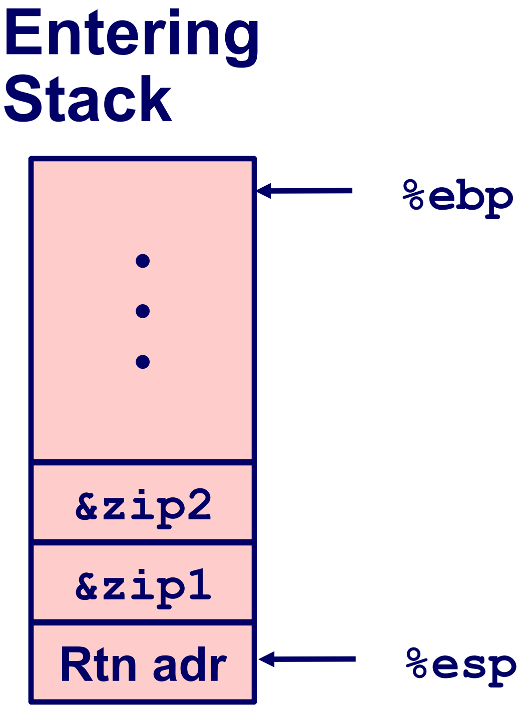
`swap()` Setup

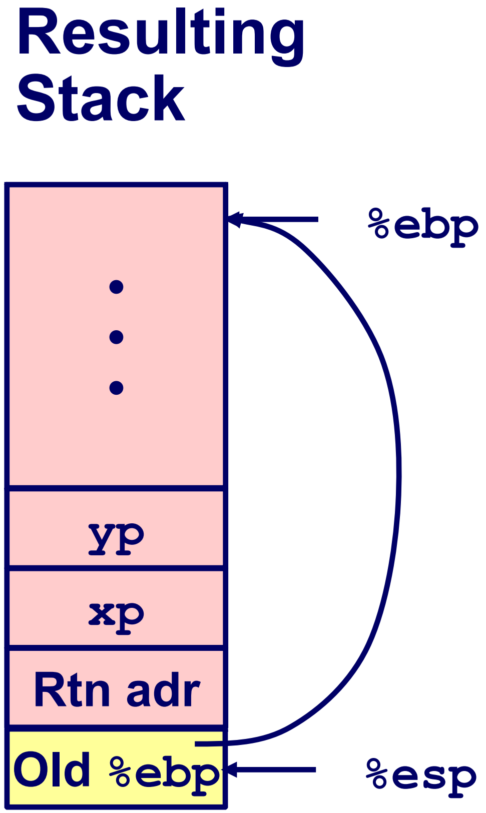
Entering Stack



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

`swap()` Setup #1

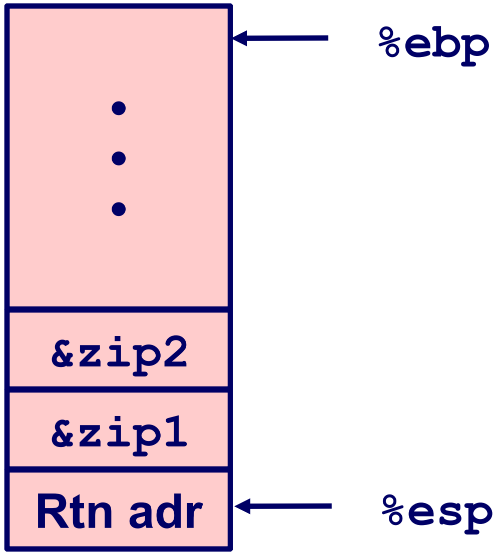




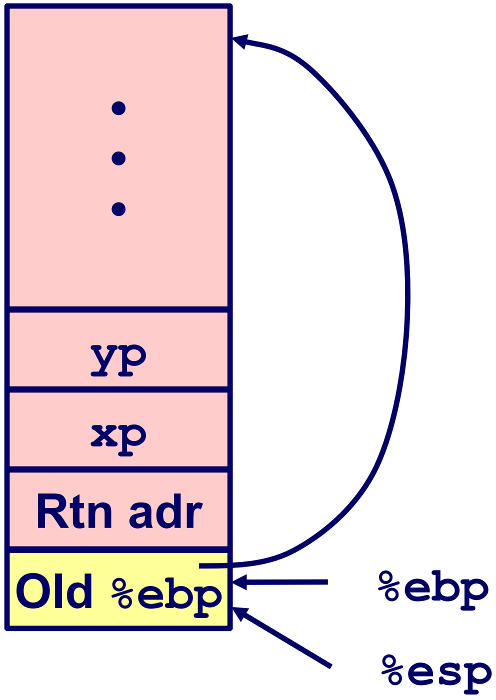
```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

swap() Setup #2

Entering Stack

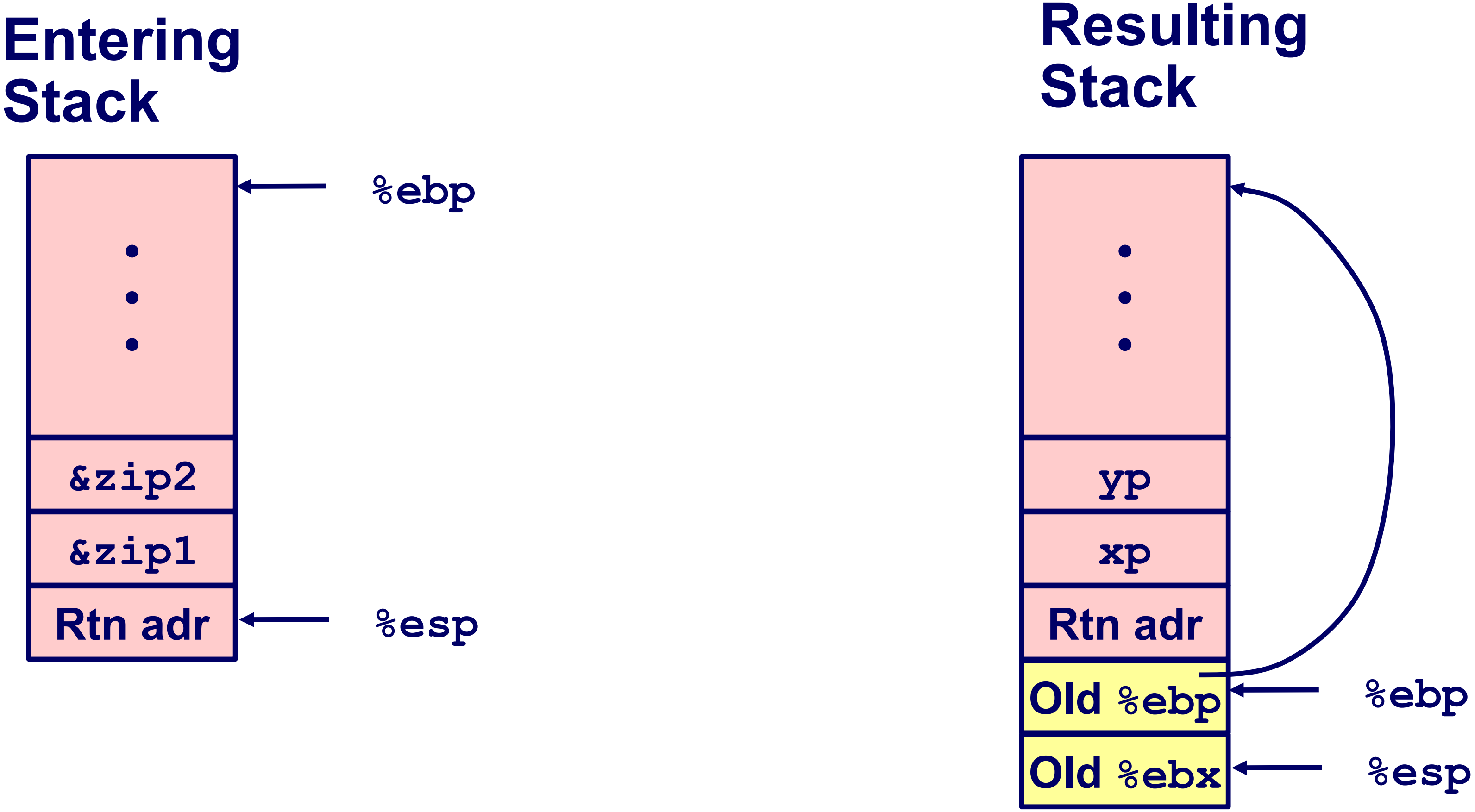


Resulting Stack



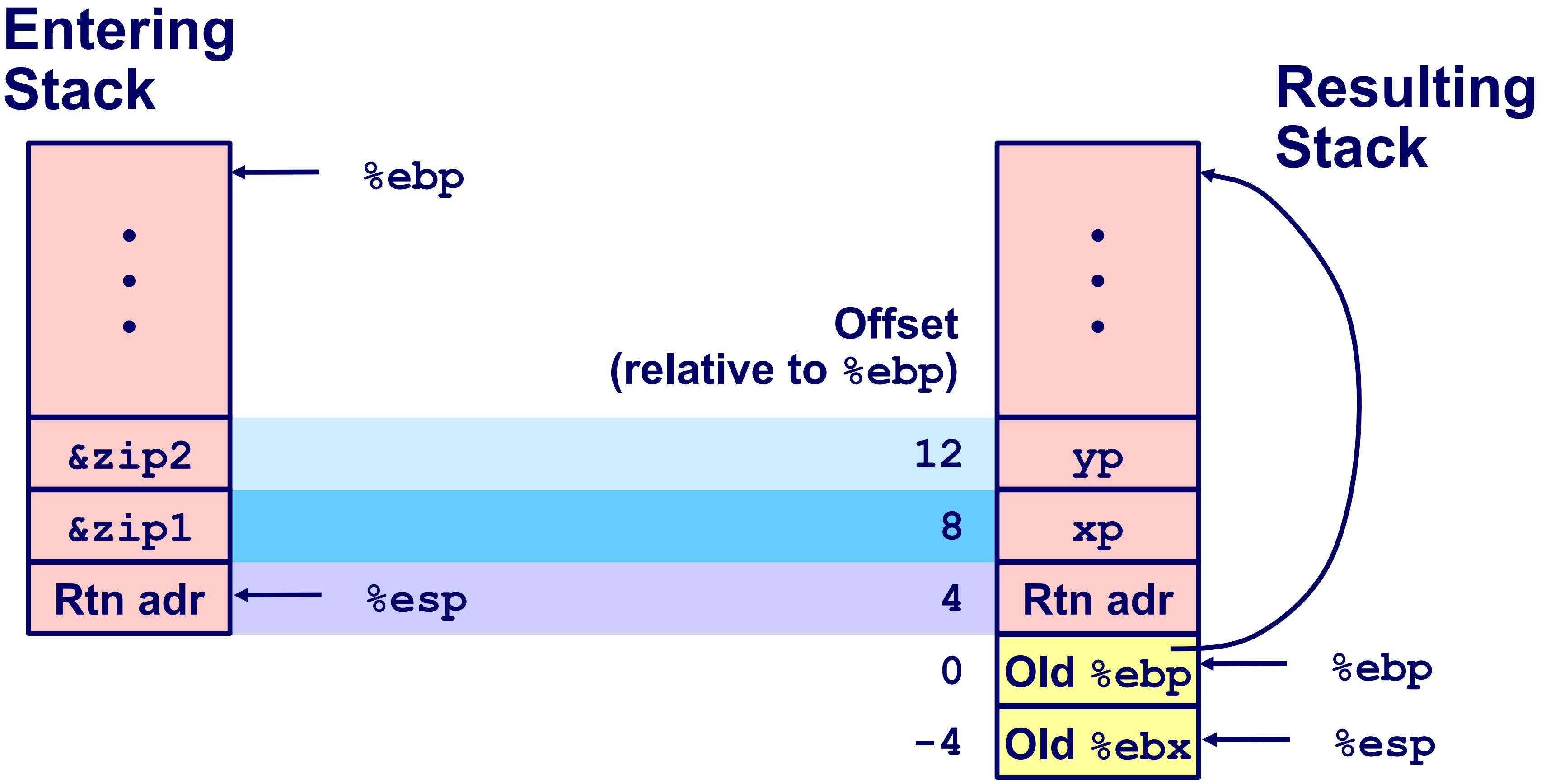
```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

`swap()` Setup #3



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

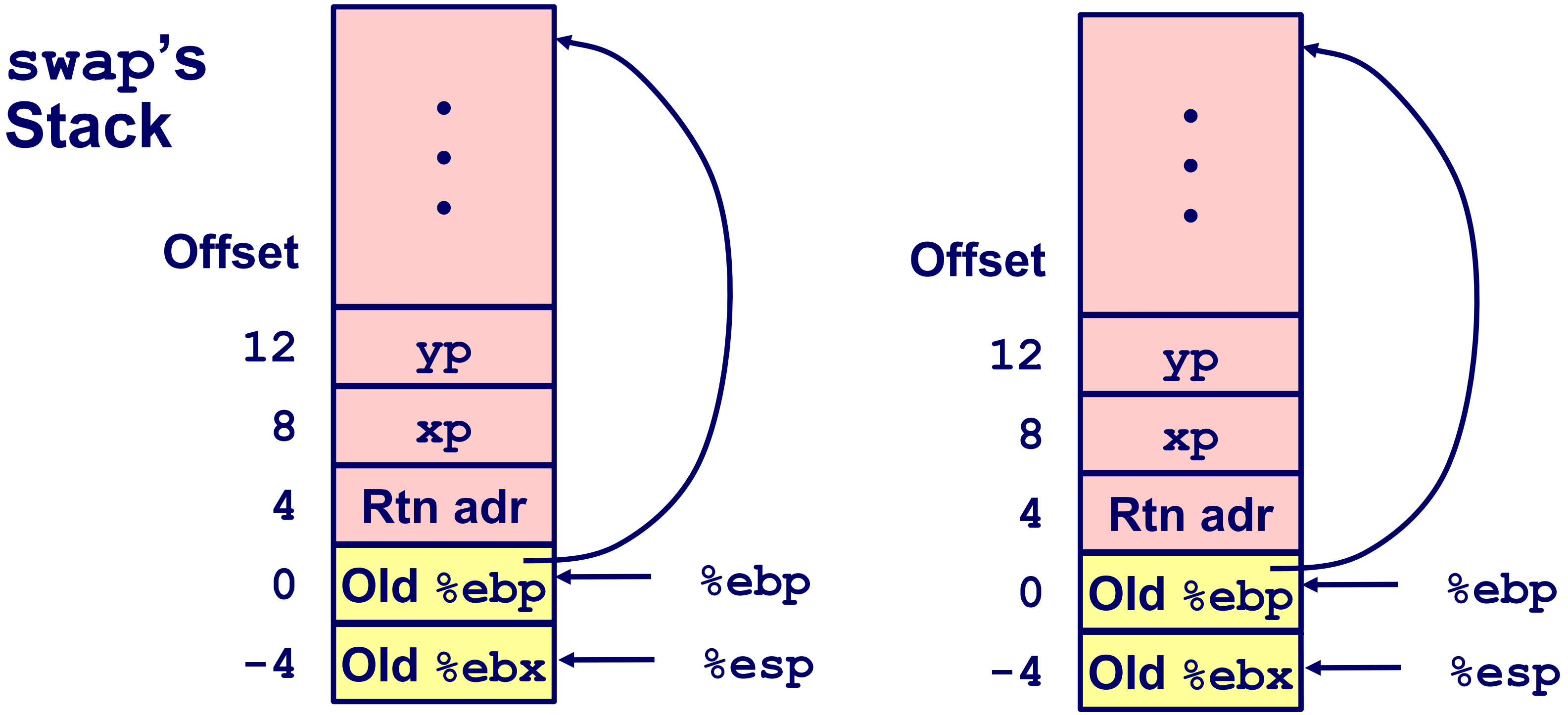
Effect of `swap()` Setup



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

Body

`swap()` Finish #1

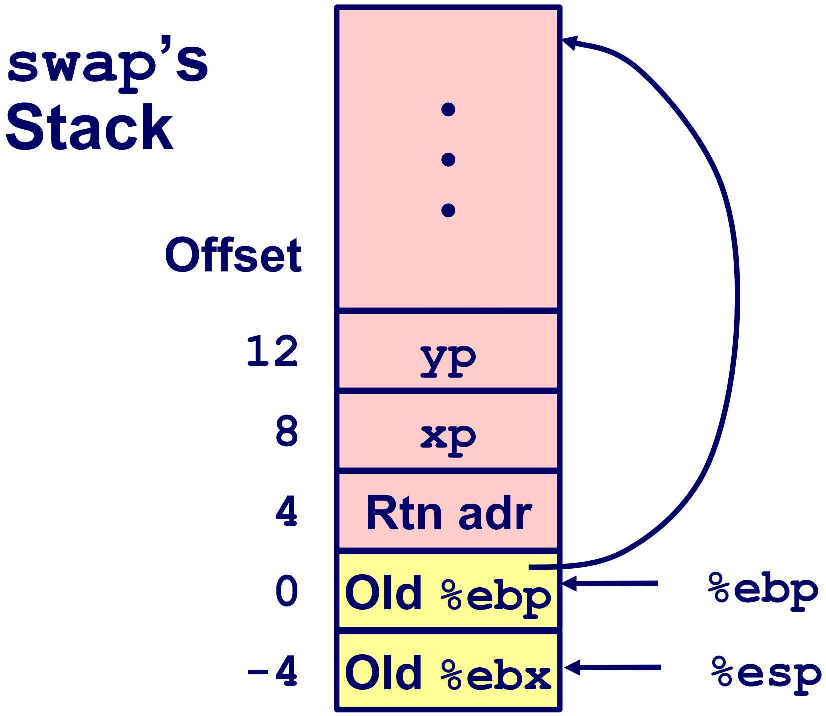


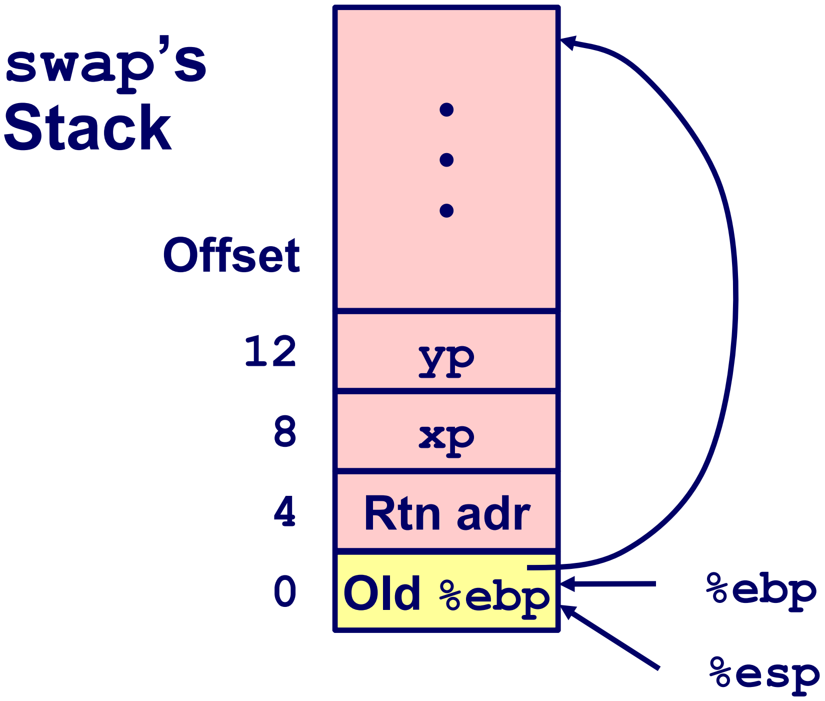
```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Observation

- Restoring saved register `%ebx`
    - "Hold that thought"

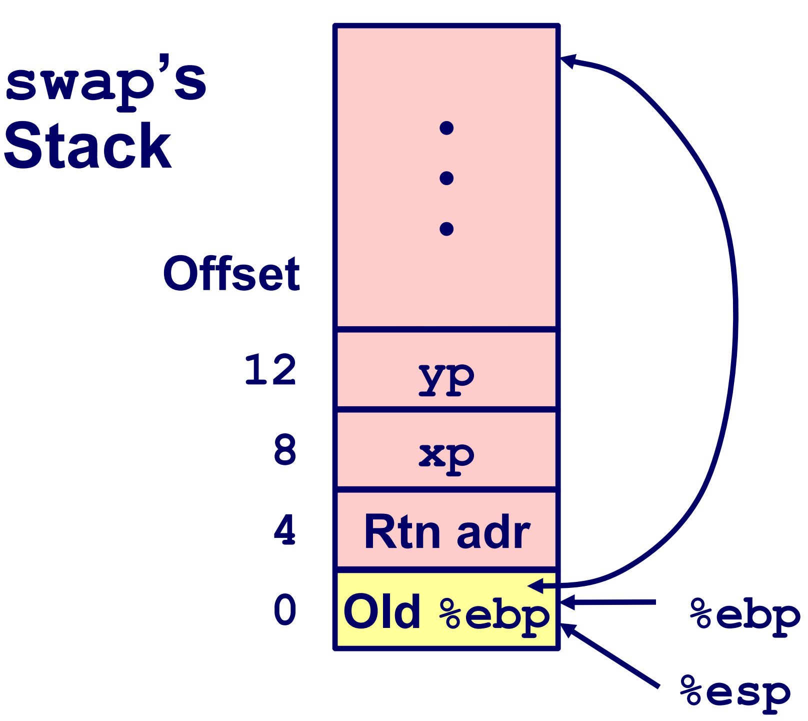
swap() Finish #2

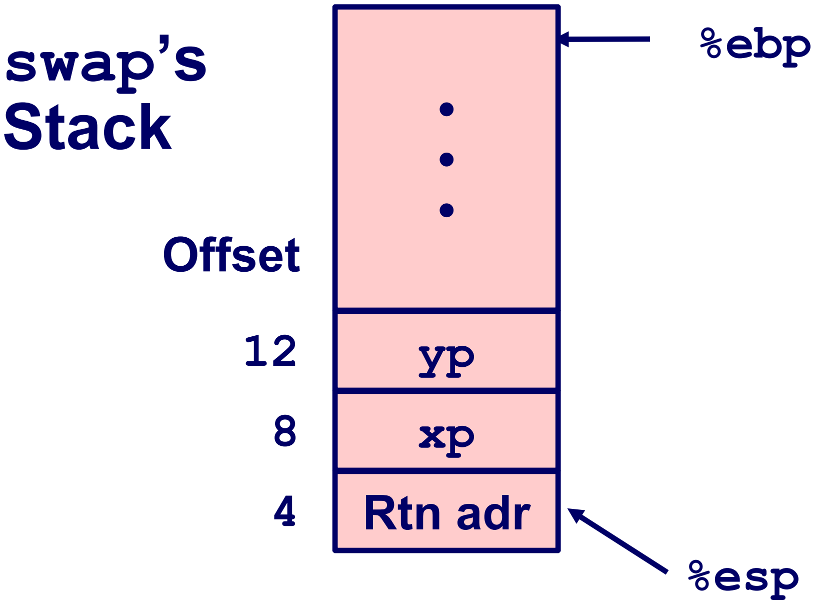




```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

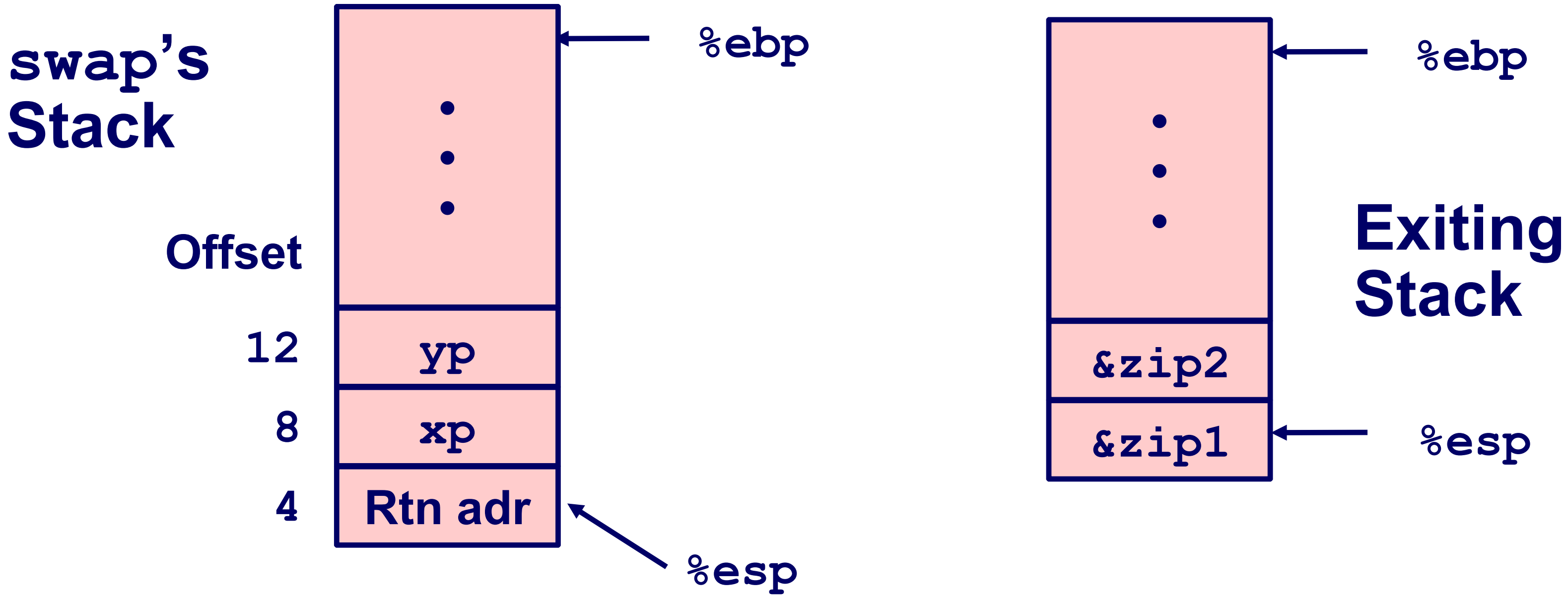
`swap()` Finish #3





```
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

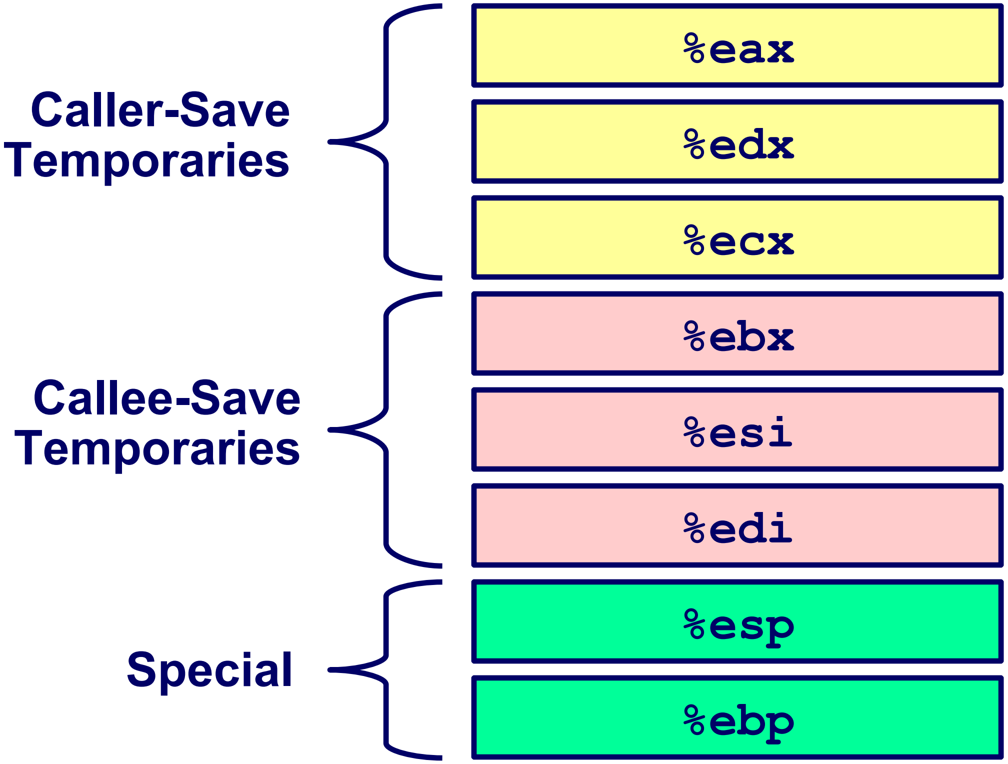
Conventions

- 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



Caller-Save Temporaries

%eax

%edx

%ecx

Callee-Save Temporaries

%ebx

%esi

%edi

Special

%esp

%ebp

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
- Available while another program is running
- 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?

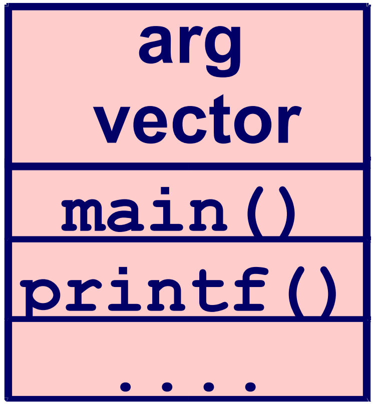
410 students should seek to abolish mystery

- So we will (un)cover each mysterious thing

The Mysterious Parts

argc, argv

- Strings from one program
- Available while another program is running
- Inter-process sharing/information transfer is OS's job
  - OS copies strings from old address space to new in exec()
  - Traditionally placed “below bottom of stack”
  - Other weird things (environment, auxiliary vector) (above argv)



The Mysterious Parts

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

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

The Mysterious Parts

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

- Defined by C standard 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 a legal C function name)

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

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”

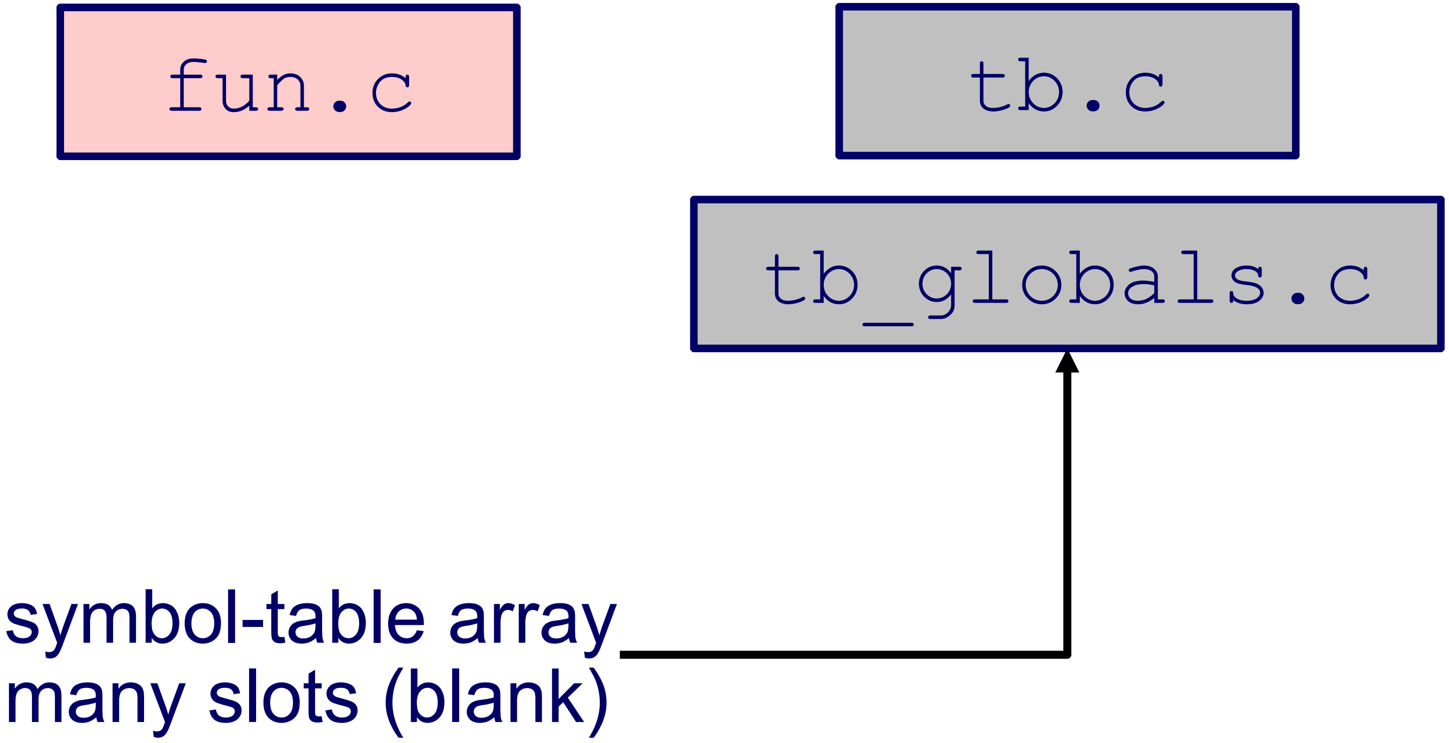
Conceptually easy

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

Key questions

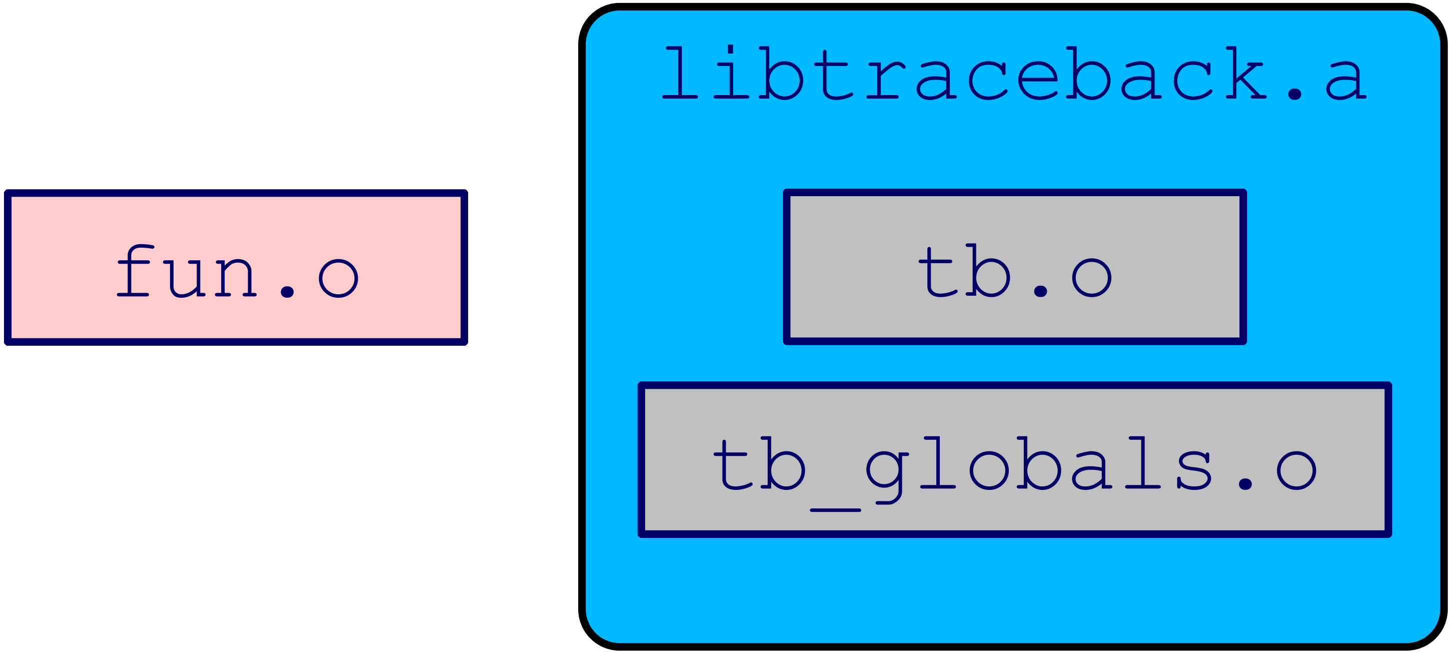
- How do I know 0x80334720 is “`fun1`”?
- How do I know `fun3()`'s second parameter is called “`d`”?

Project 0 “Data Flow”

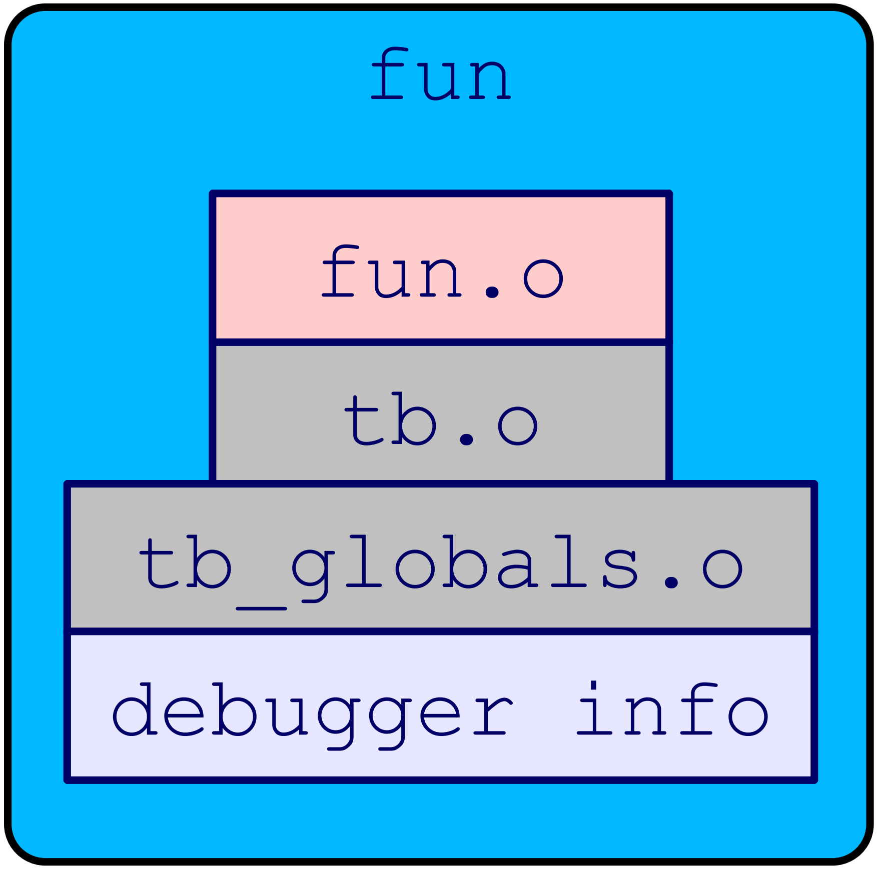


symbol-table array
many slots (blank)

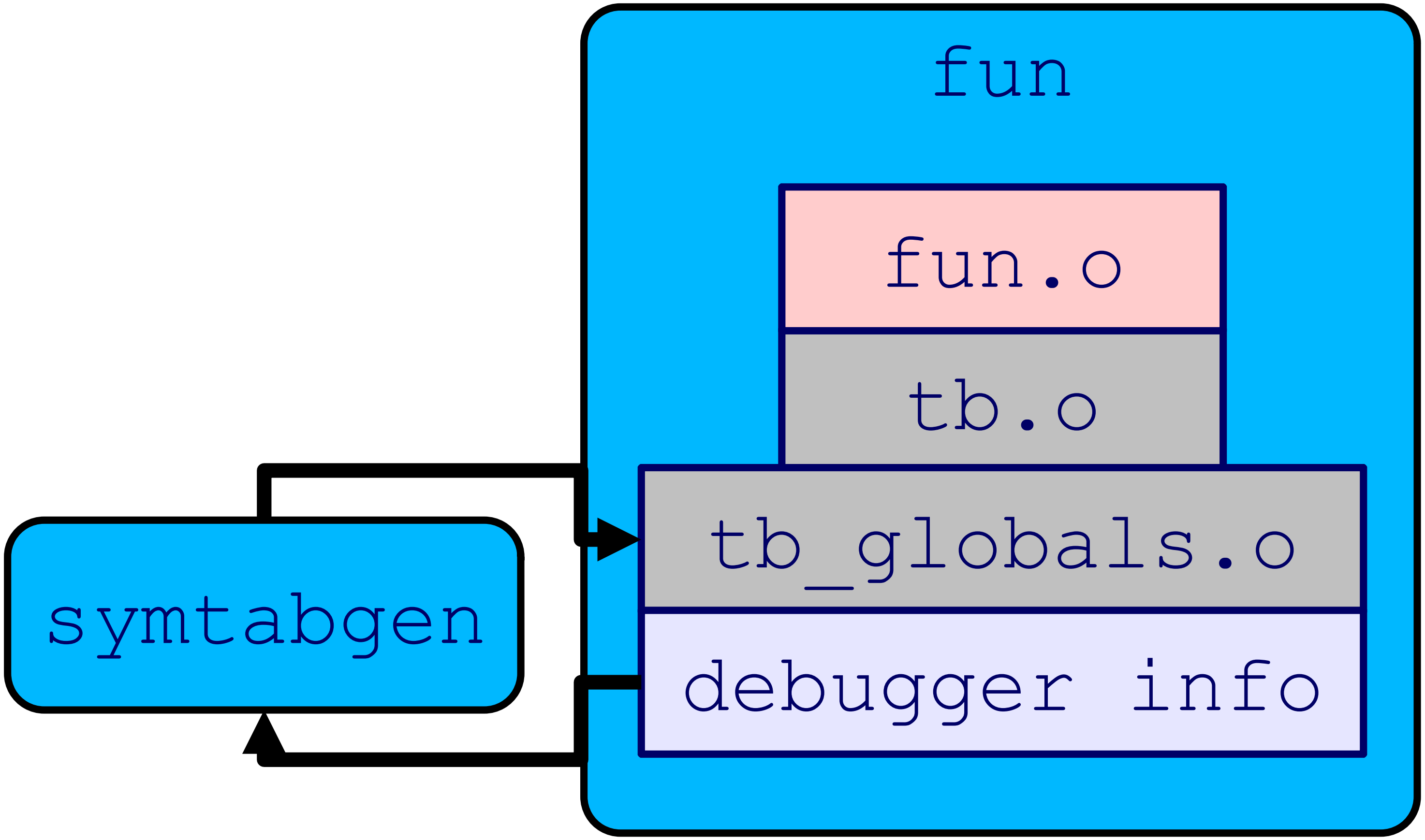
Project 0 “Data Flow” - Compilation



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 afternoon/evening
- Please read *all of the handout* before asking questions!
- Meanwhile, *reading the syllabus* is timely!

Start interviewing Project 2/3/4 partners!