15-410

"An Experience Like No Other"

Stack Discipline
Jan. 19, 2024

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

Registration

- **15-410**
  - **Still some advisor discussions in the air**
  - **Seems very unlikely everybody qualified will fit**
    - » **Unfortunately, not all qualified students who are graduating this semester seem likely to fit**
- **15-605**
  - **I think enrollment is nearly over**
- **If you're here but not on *any* wait list, see me *right away***
- **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**

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

- **Contact me no later than *today***

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?

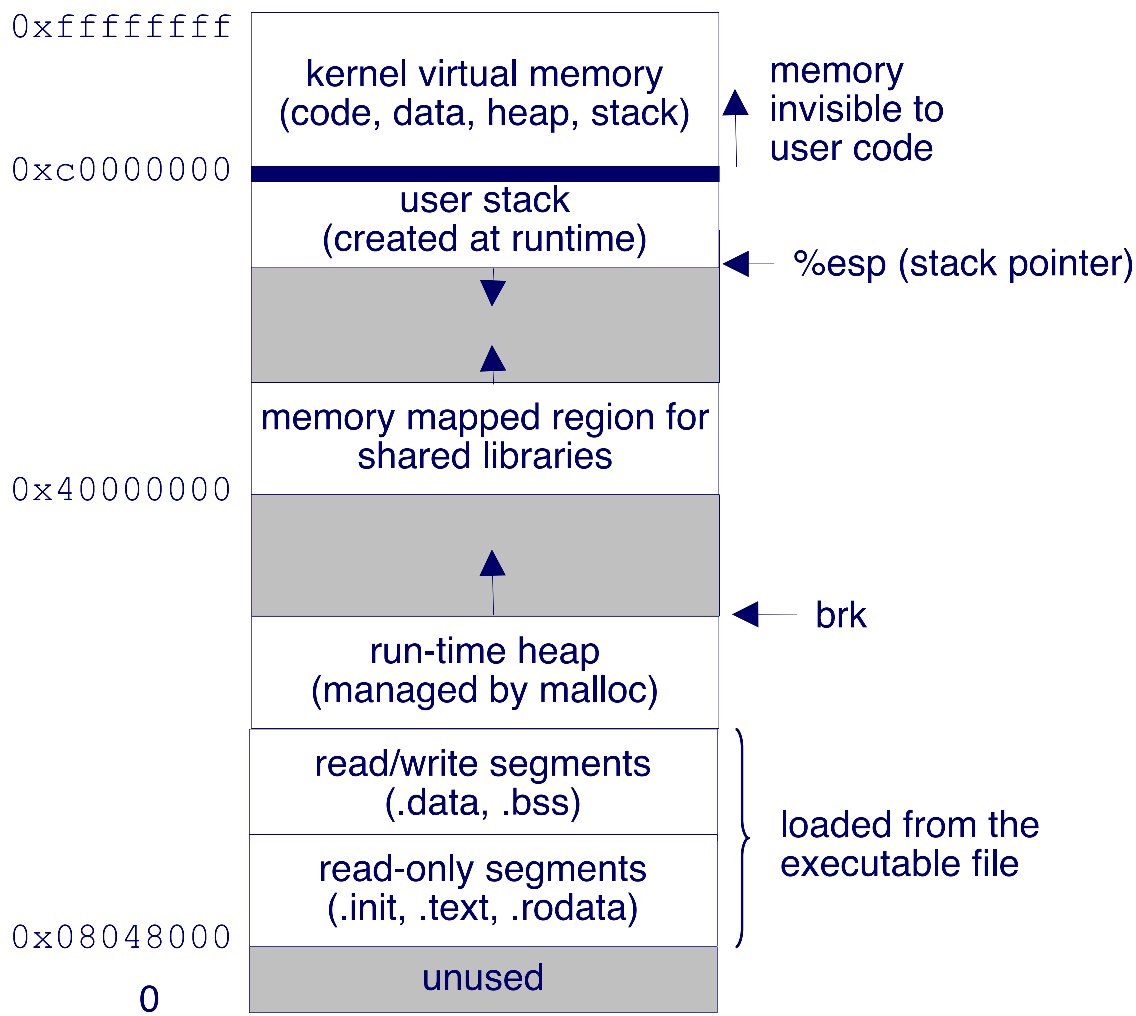
- **x86-64 is *not* simpler for kernel code**
  - **Machine begins in 16-bit mode, then 32, finally 64**
    - » **You don't have time to write 32⇒64 transition code**
    - » **If we gave it to you, it would be a *big* black box**
  - **Interrupts are more complicated**
- **x86-64 is *not* simpler during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

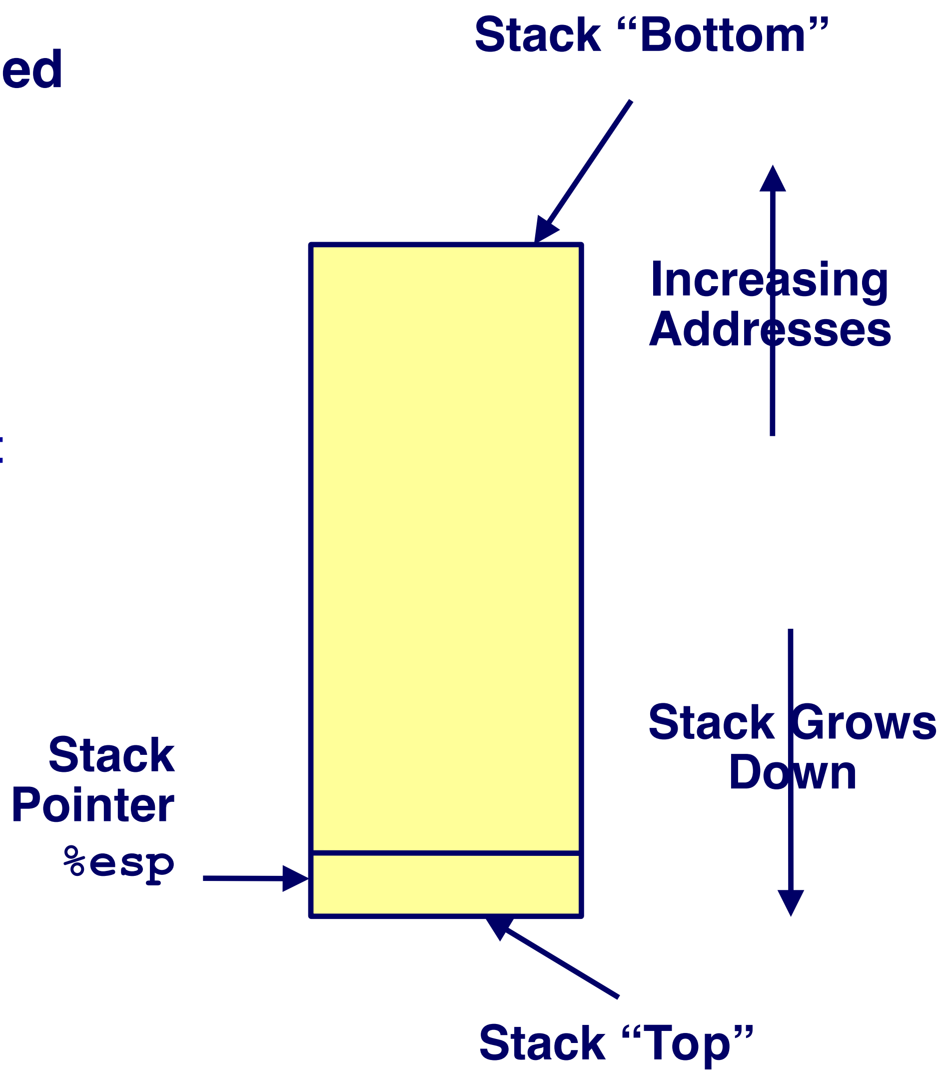


Warning: **numbers specific to Linux 2.x on IA32!!**

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

IA32 Stack

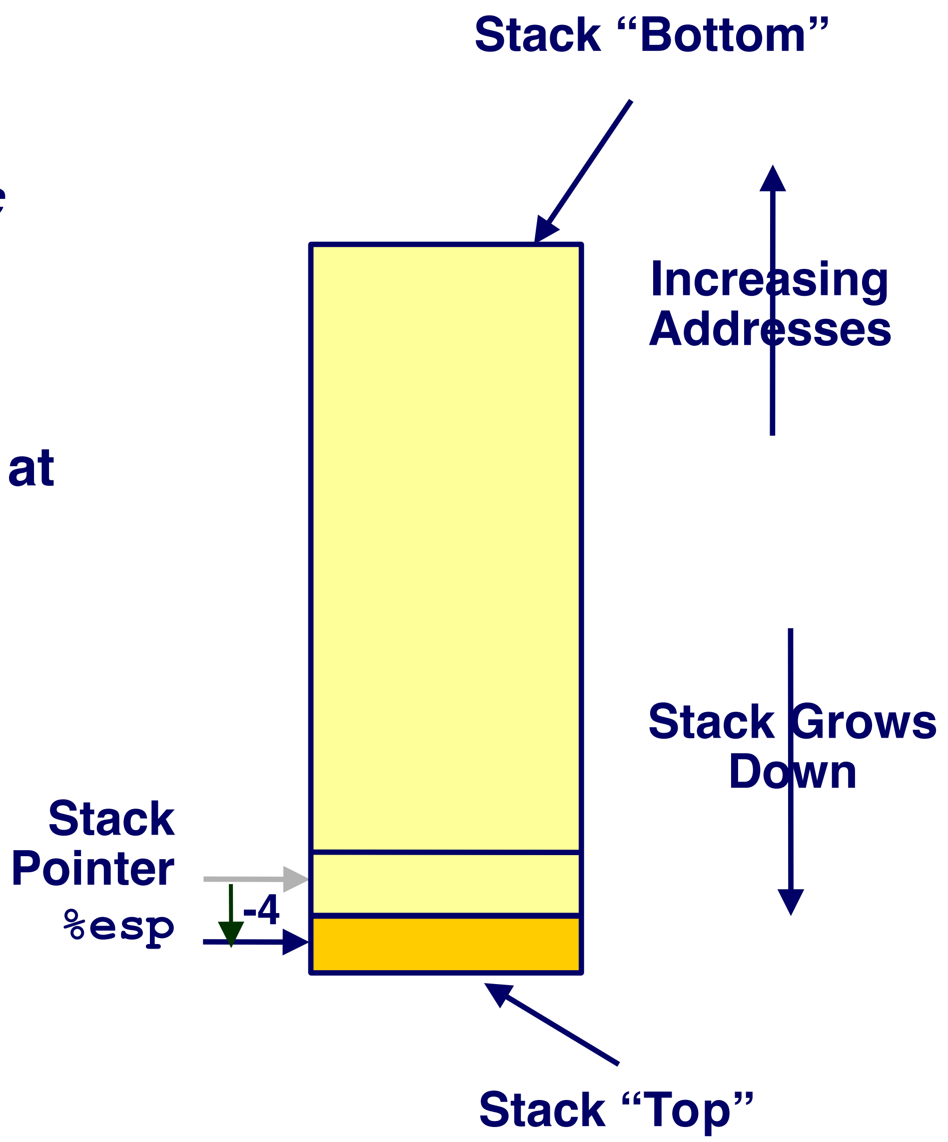
- **Region of memory managed with stack discipline**
- **"Grows" toward lower addresses**
- **Register `%esp` indicates lowest stack address**
  - **address of "top" element**
  - **stack *pointer***



IA32 Stack Pushing

Pushing

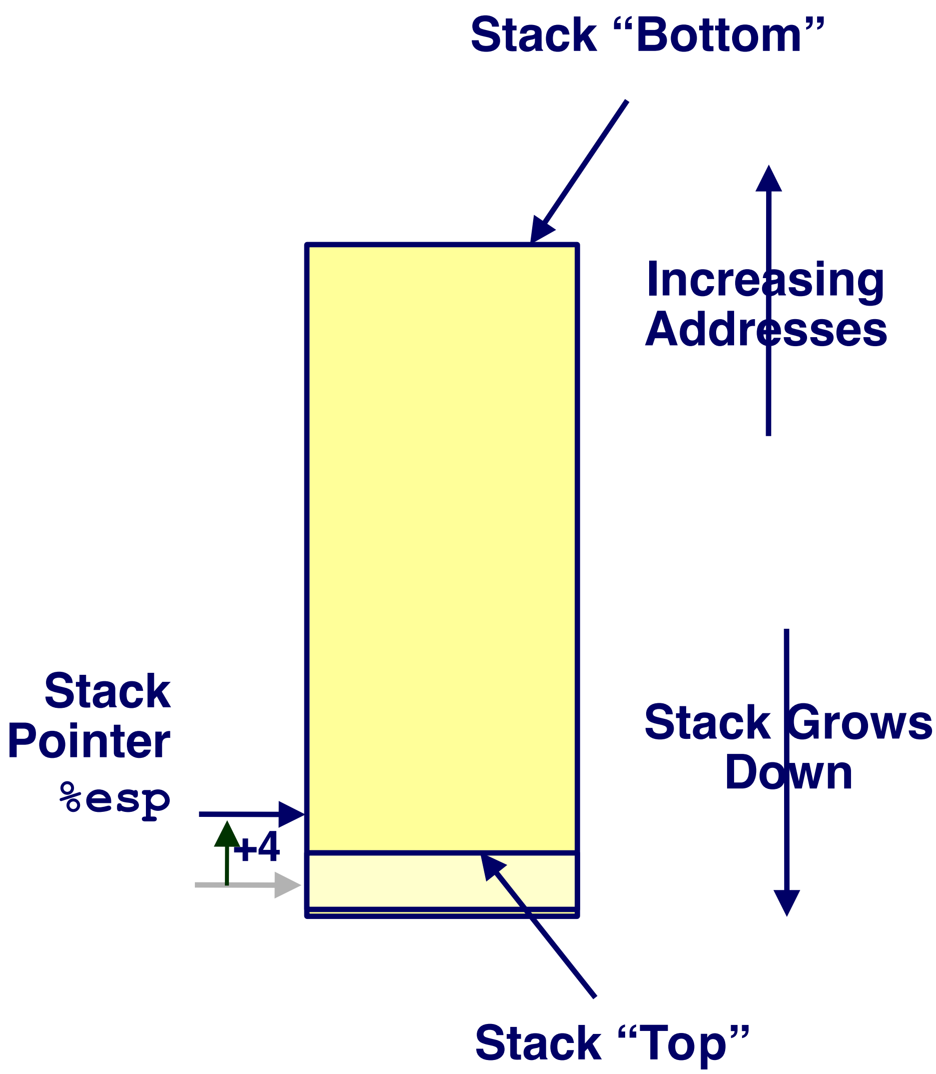
- `pushl` *Src*
- Fetch "operand" from *Src*
  - Maybe a register: %ebp
  - Maybe memory: 8(%ebp)
- Decrement `%esp` by 4
- Store operand in memory at address given by `%esp`



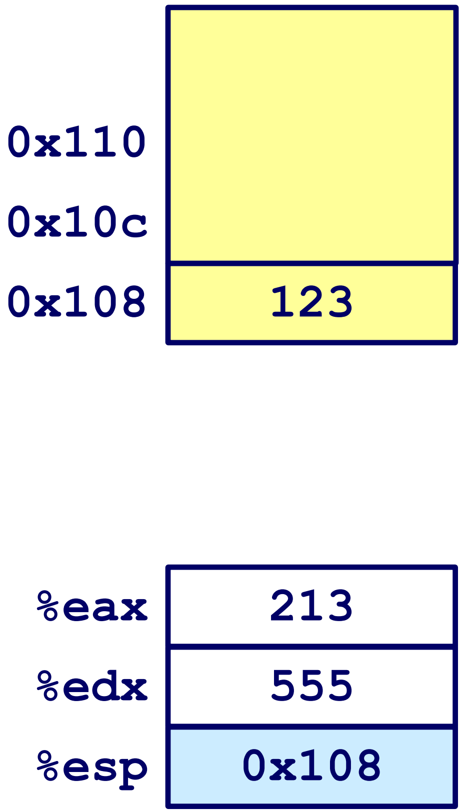
IA32 Stack Popping

Popping

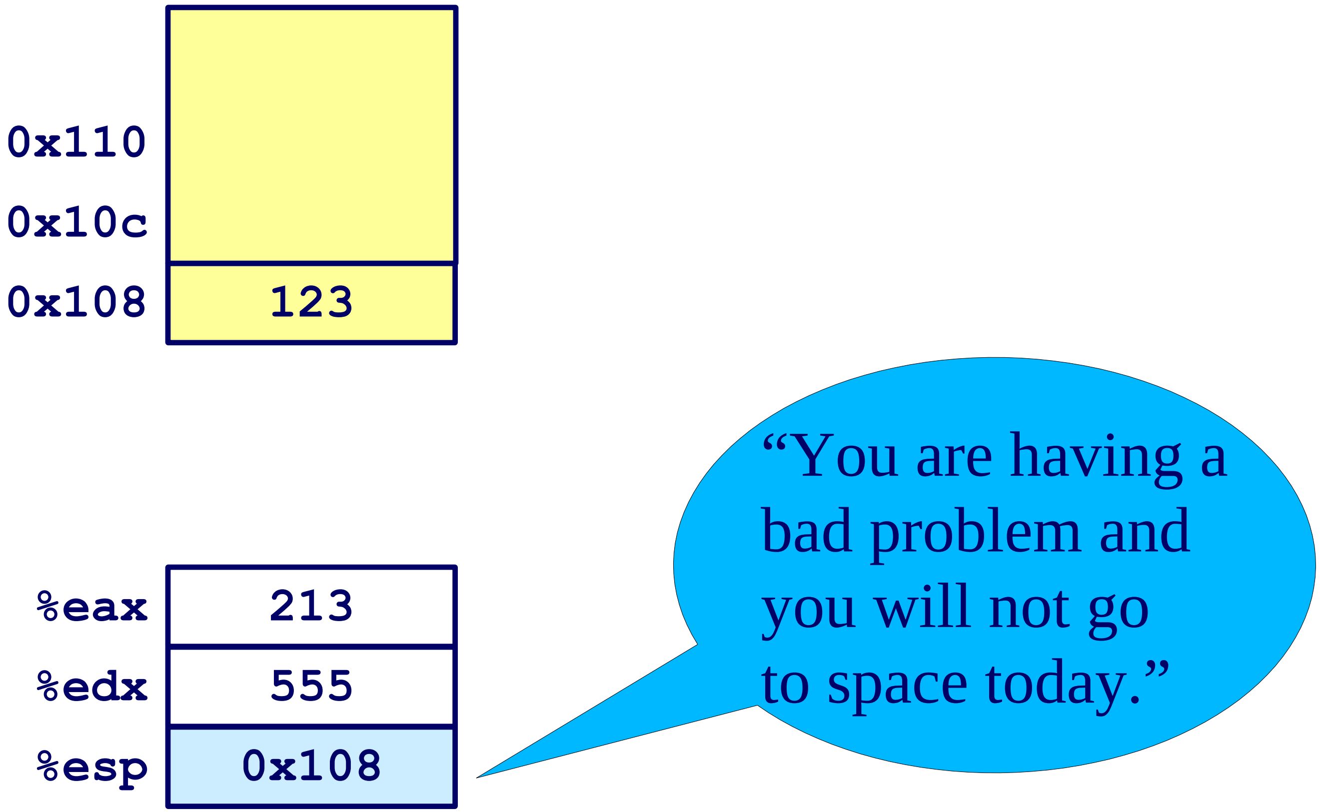
- `popl` *Dest*
- Read memory at address given by `%esp`
- Increment `%esp` by 4
- Store into *Dest* operand



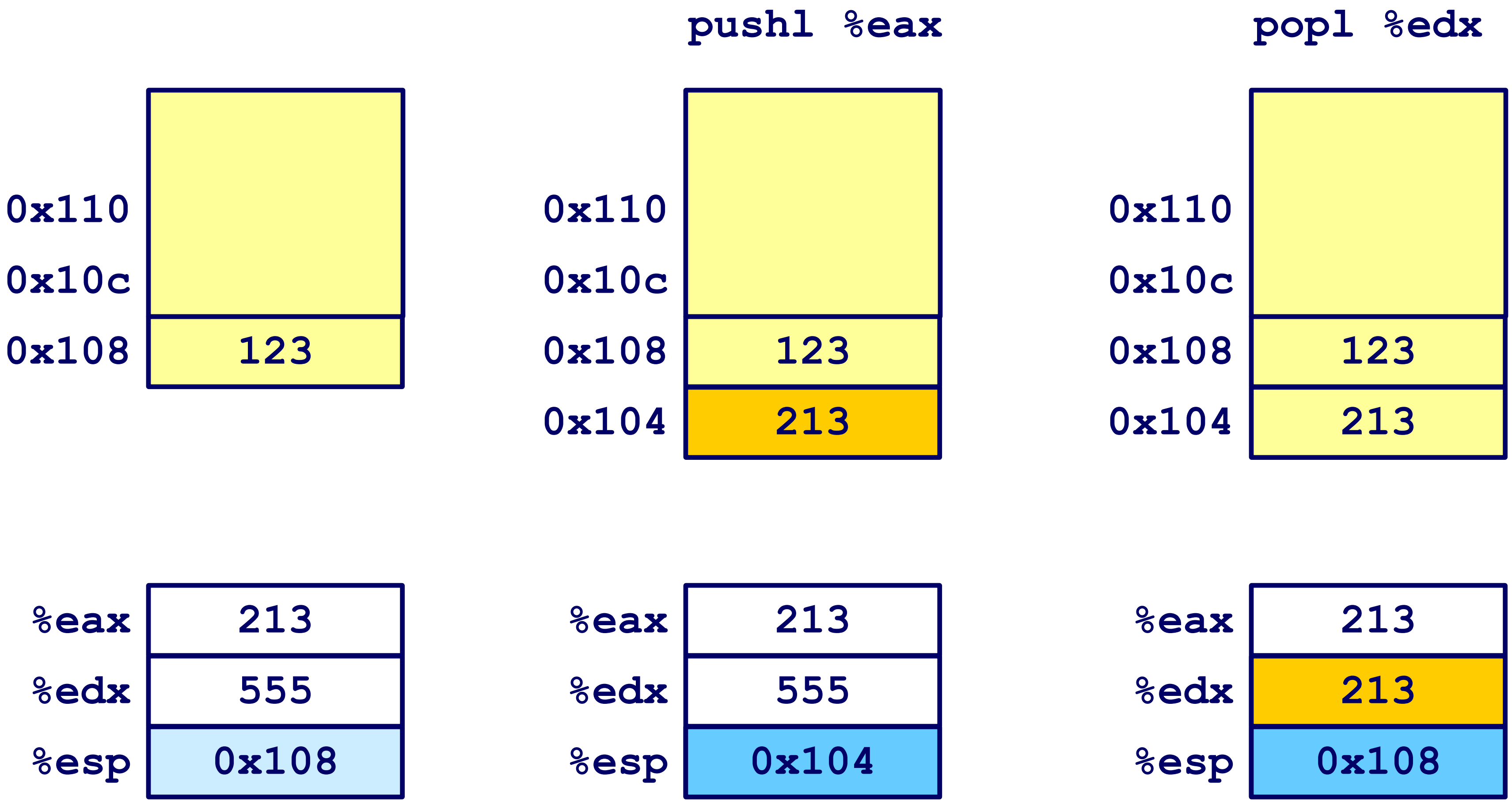
Stack Operation Examples



Stack Operation Examples



Stack Operation Examples



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`

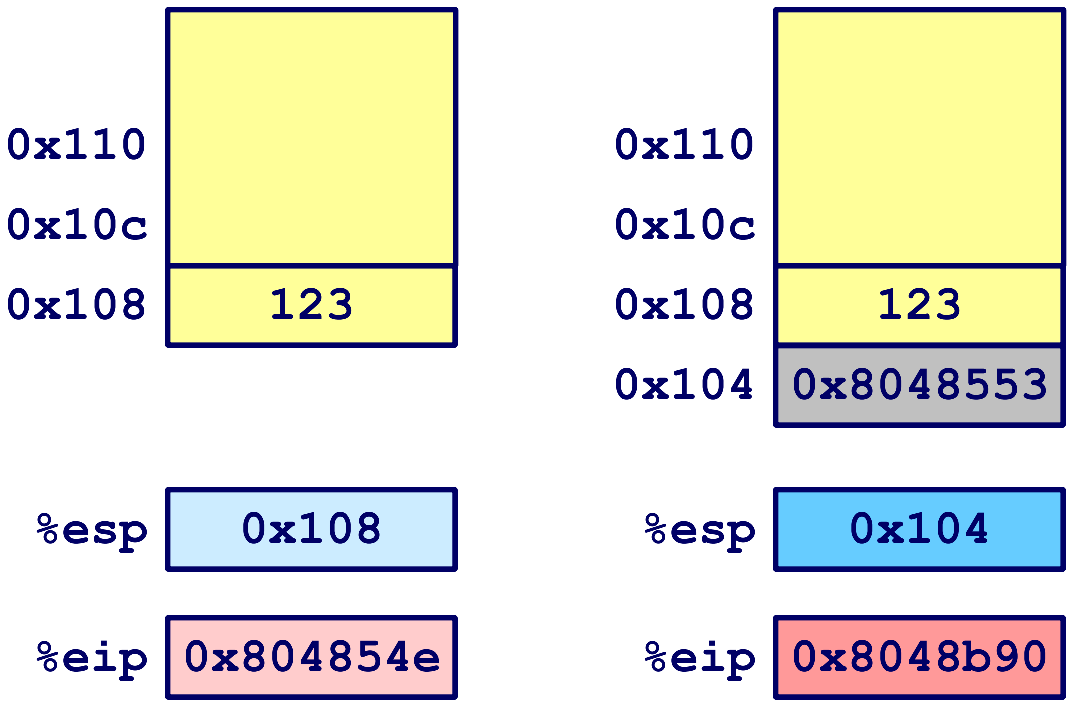
Procedure return:

- `ret` **Pop address from stack;**
  Jump to address

Procedure Call Example

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

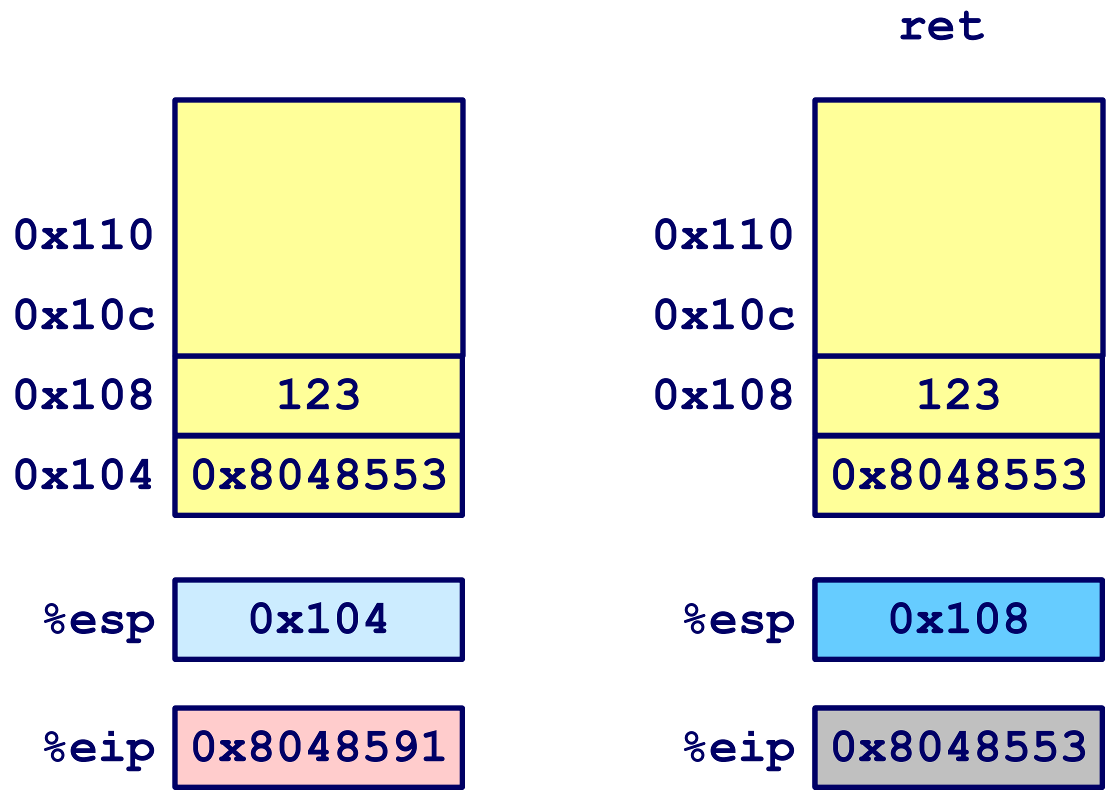
`call    8048b90`



`%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

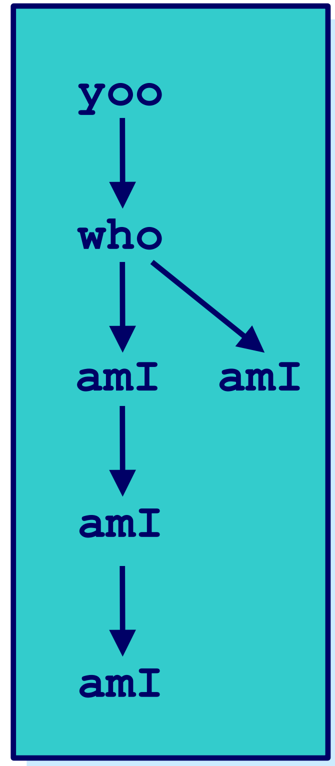
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

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

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

- **Procedure `amI()` recursive**

Call Chain



Stack Frames

Contents

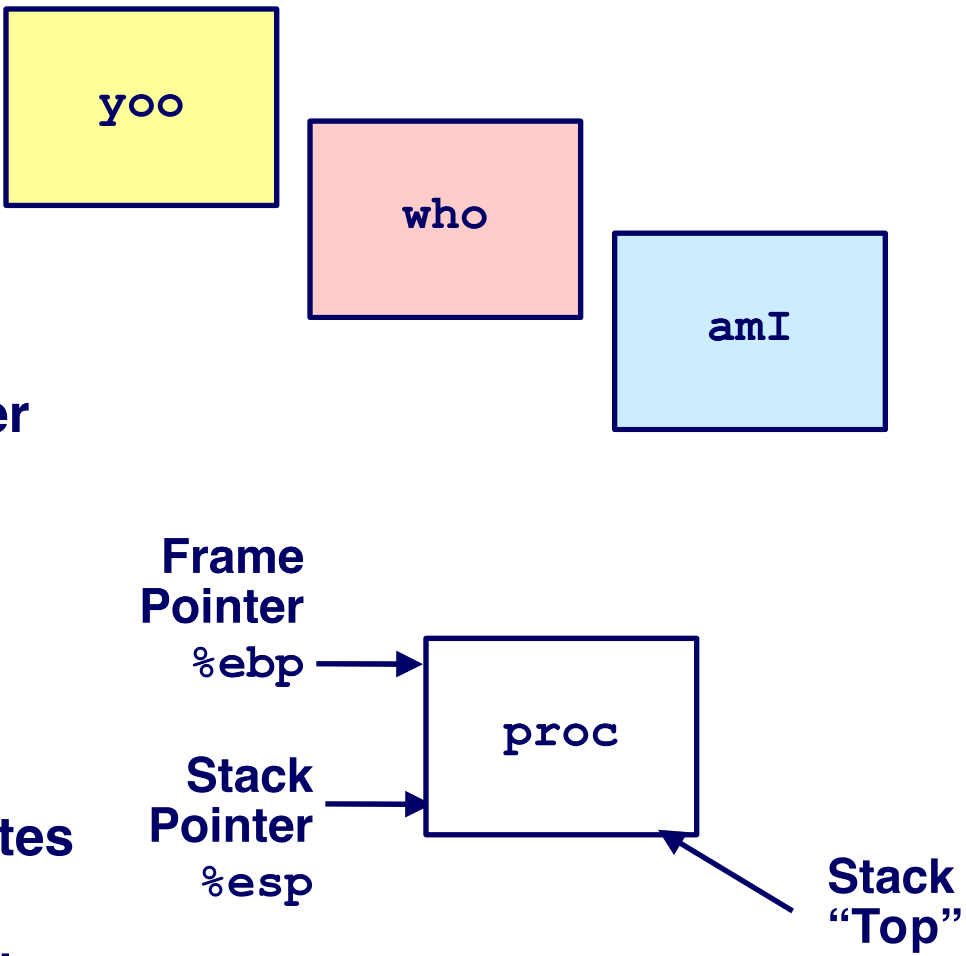
- Local variables
- Return information
- Temporary space

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



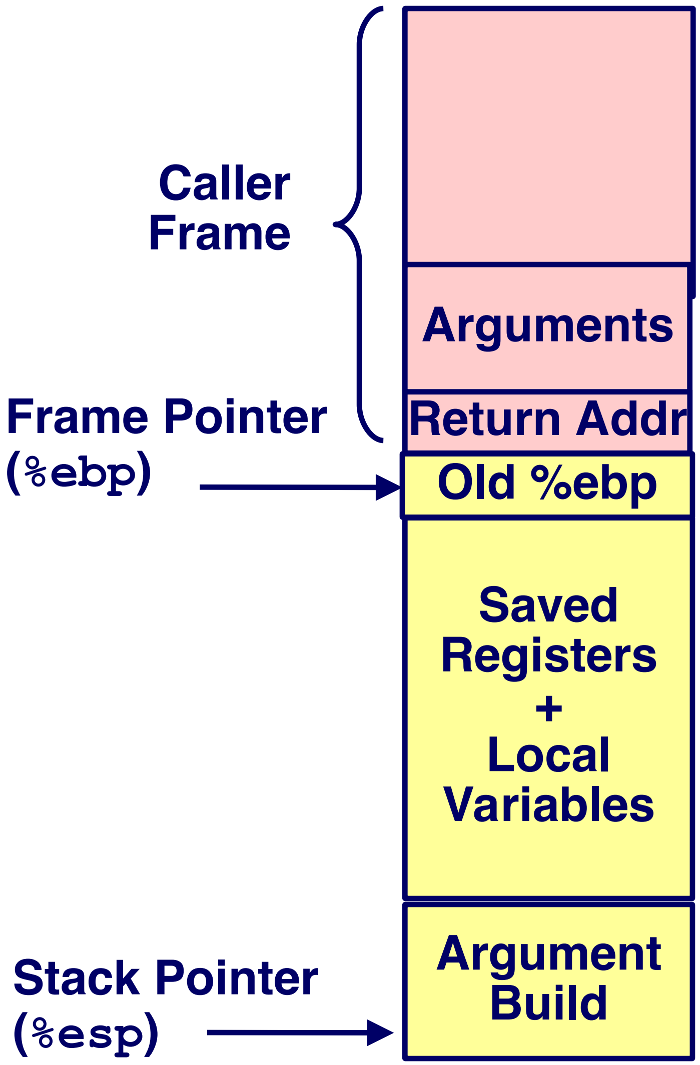
IA32/Linux Stack Frame

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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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
   • • •
```

swap()

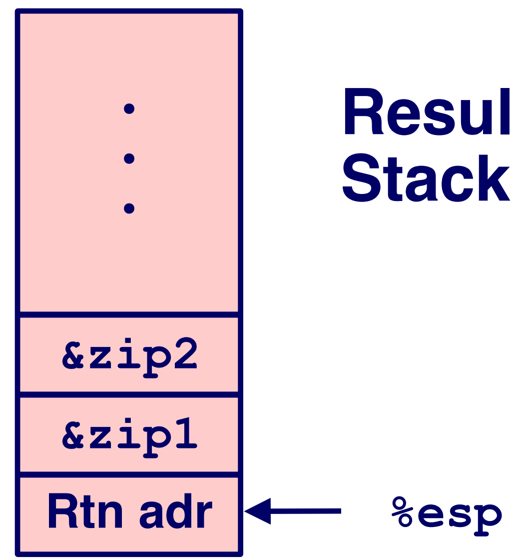
```
int zip1 = 15213;
int zip2 = 91125;

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

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

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

Set Up

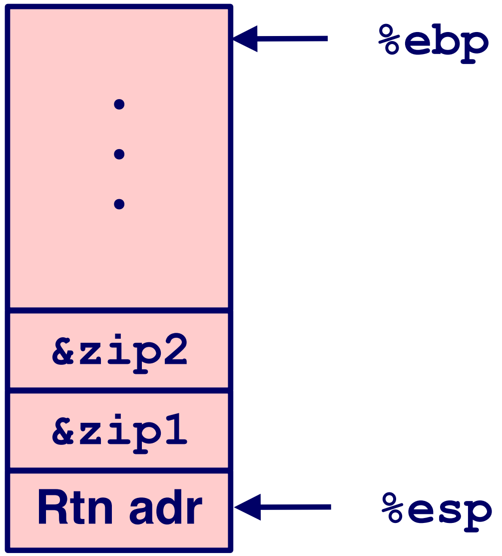
Body

Core

Finish

`swap()` Setup

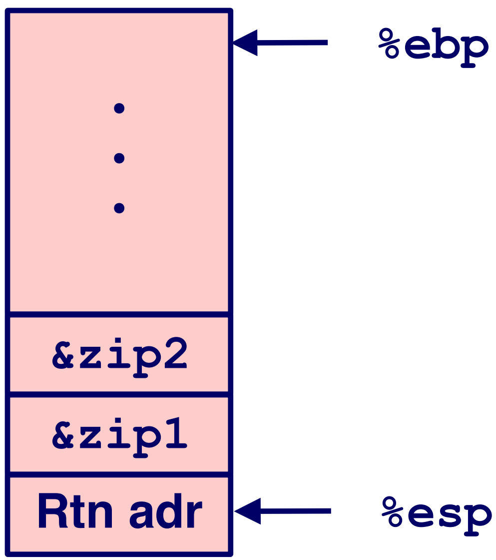
Entering Stack



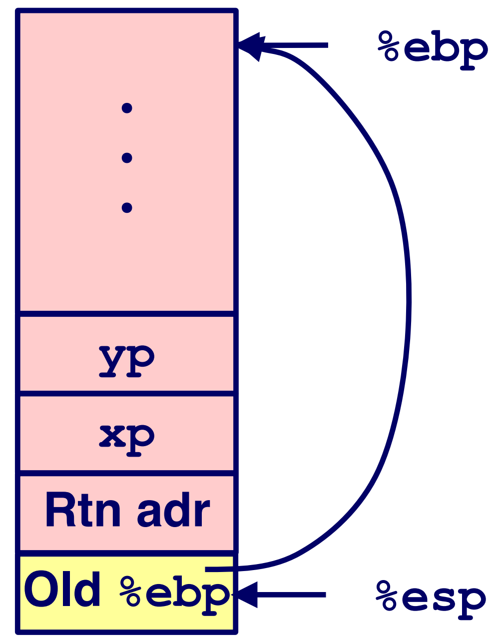

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

`swap()` Setup #1

Entering Stack

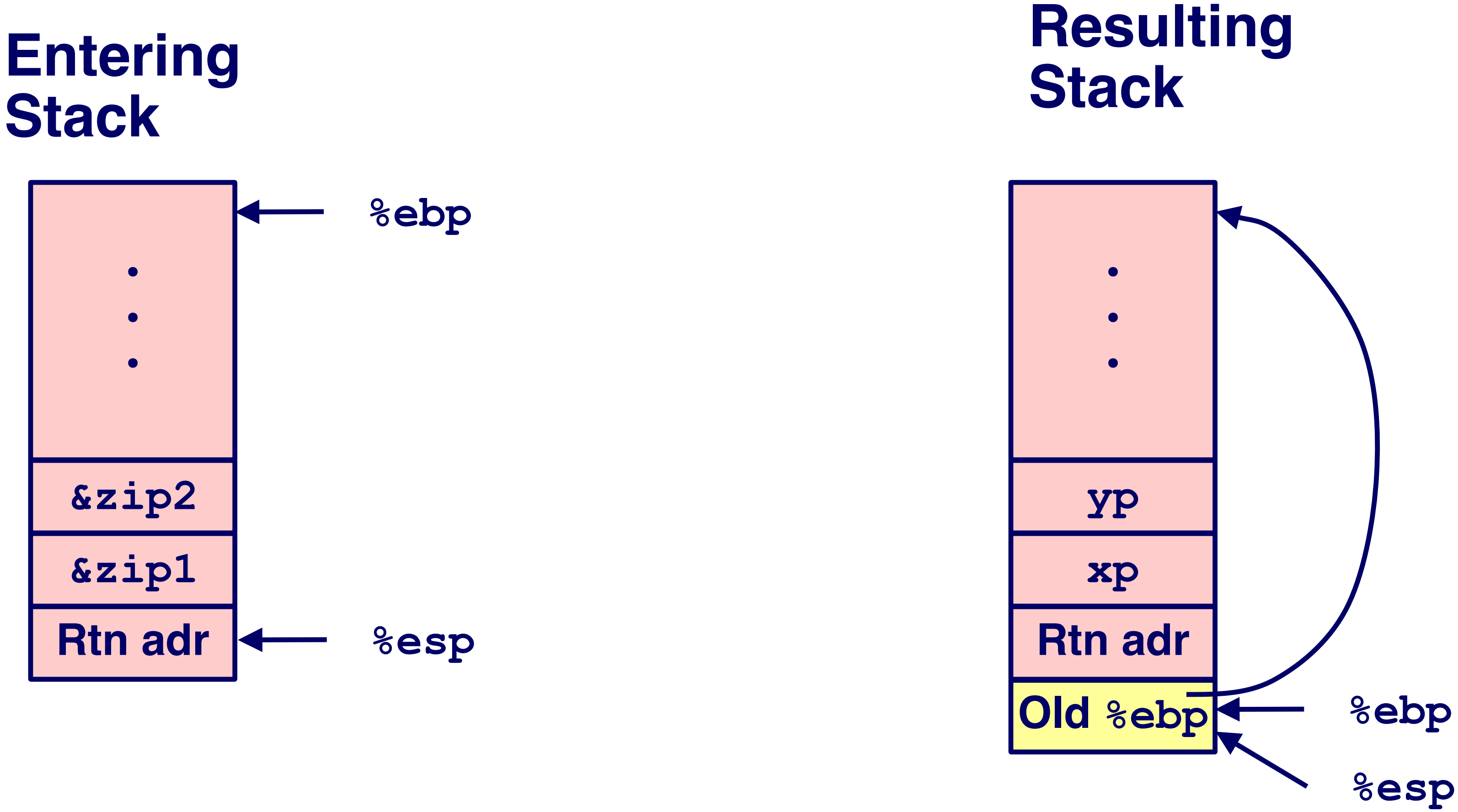


Resulting Stack



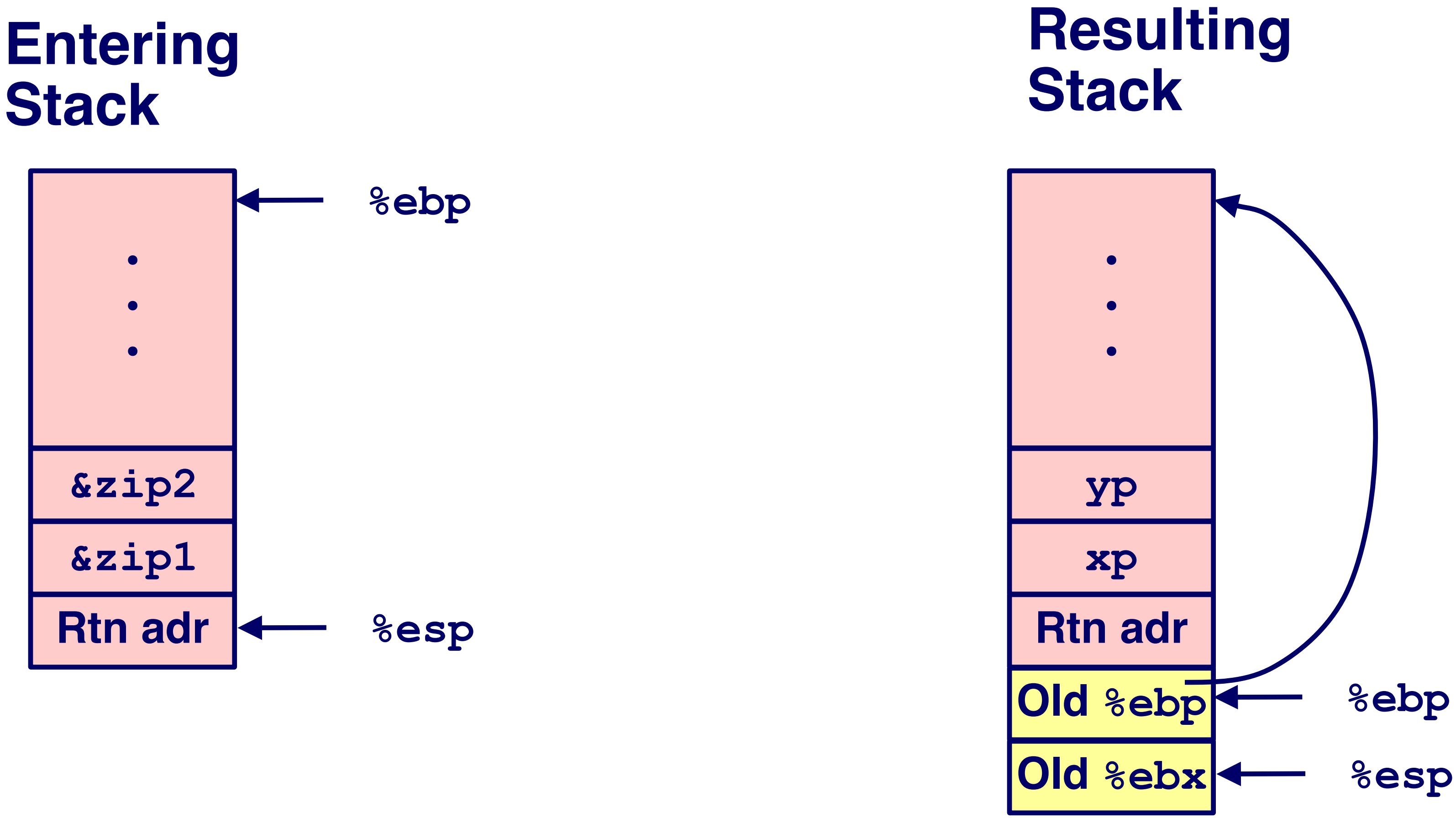

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

`swap()` Setup #2



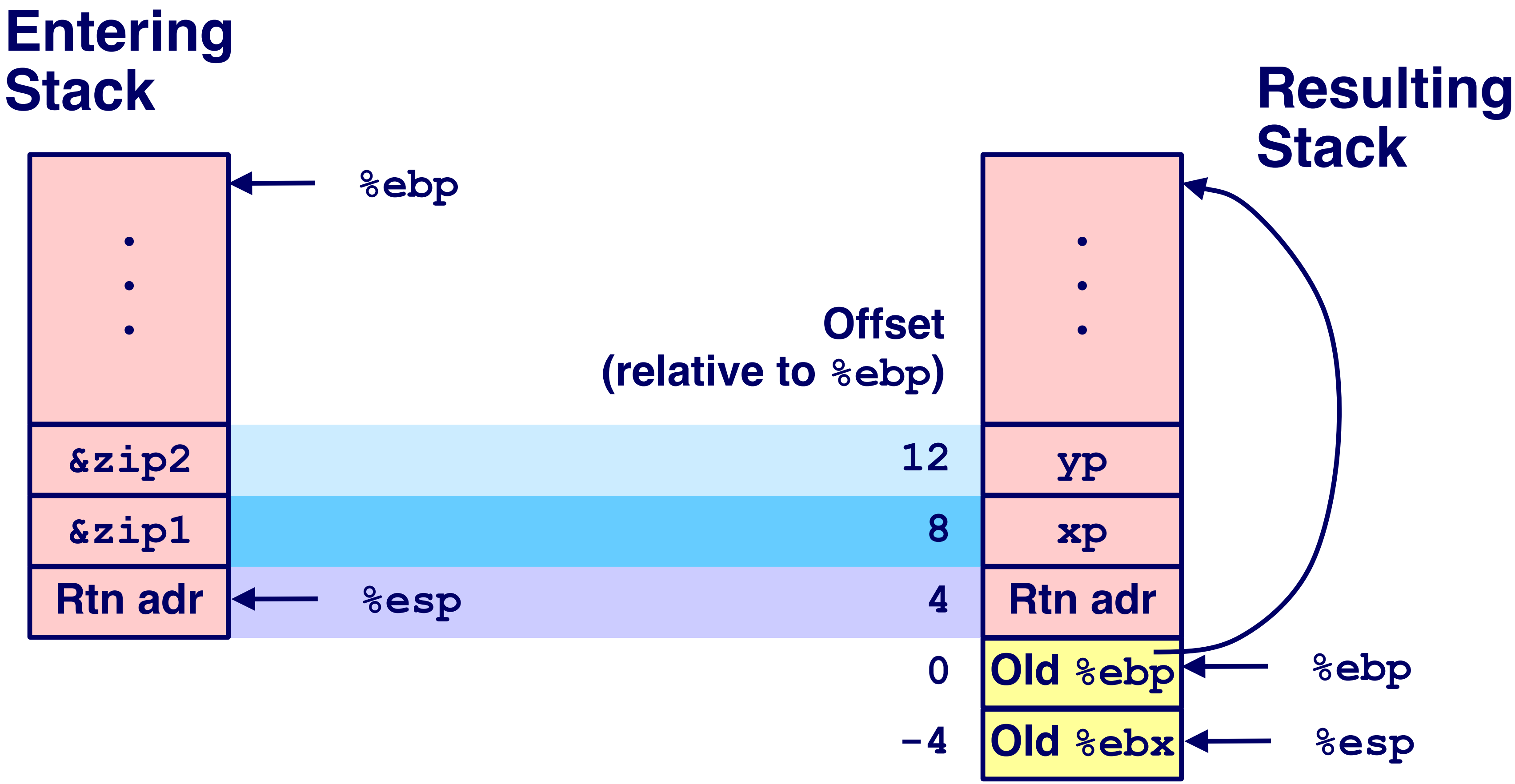

```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

`swap()` Setup #3




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

Effect of swap() Setup

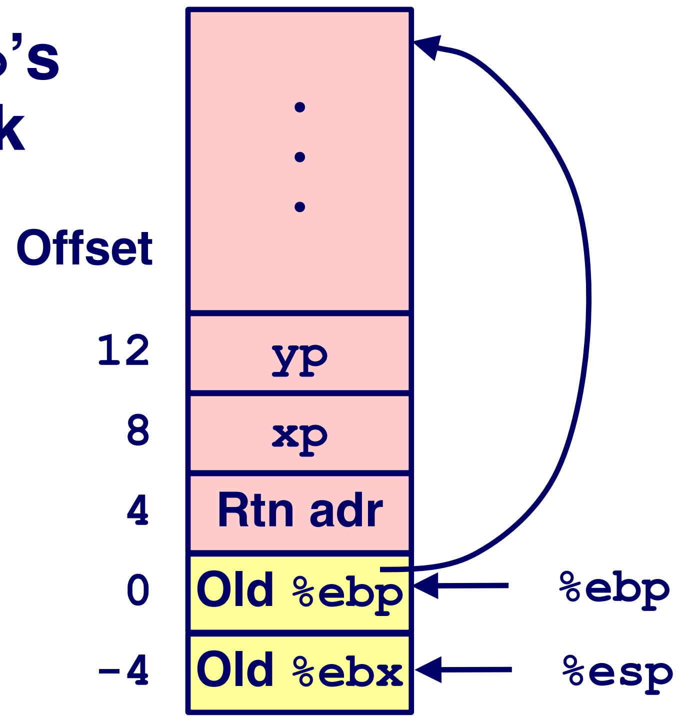


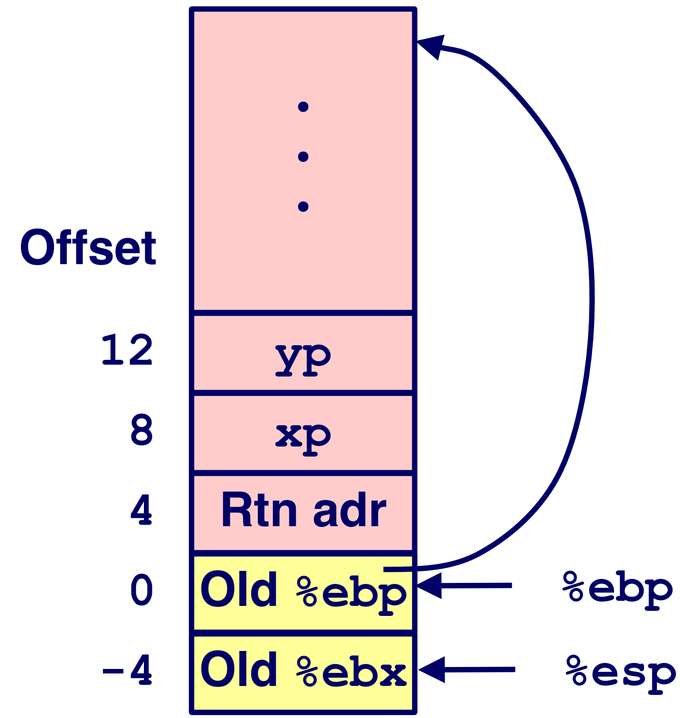

```
movl 12(%ebp),%ecx # get yp
movl 8(%ebp),%edx  # get xp
. . .
```

Body

`swap()` Finish #1

`swap`'s Stack



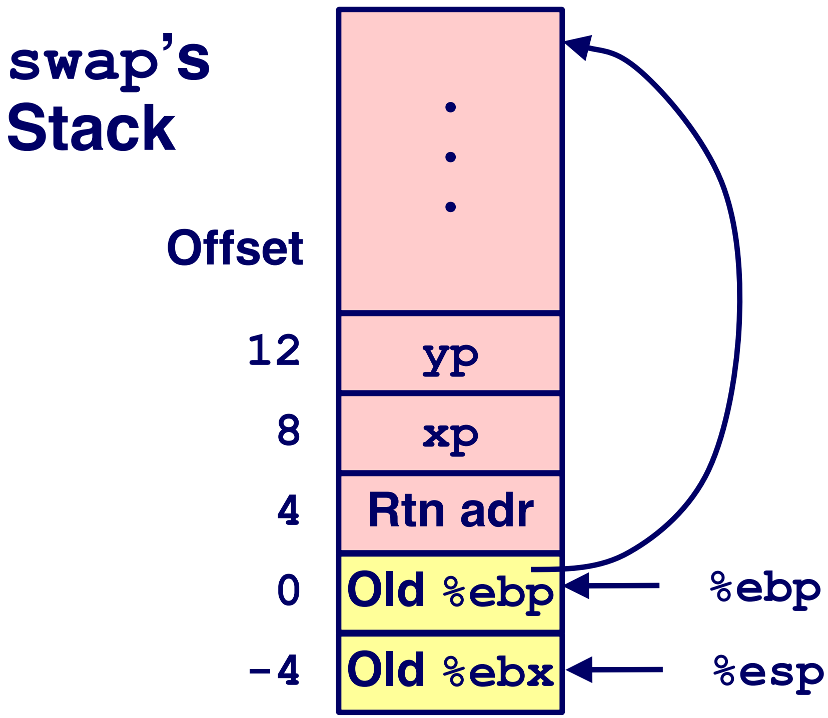


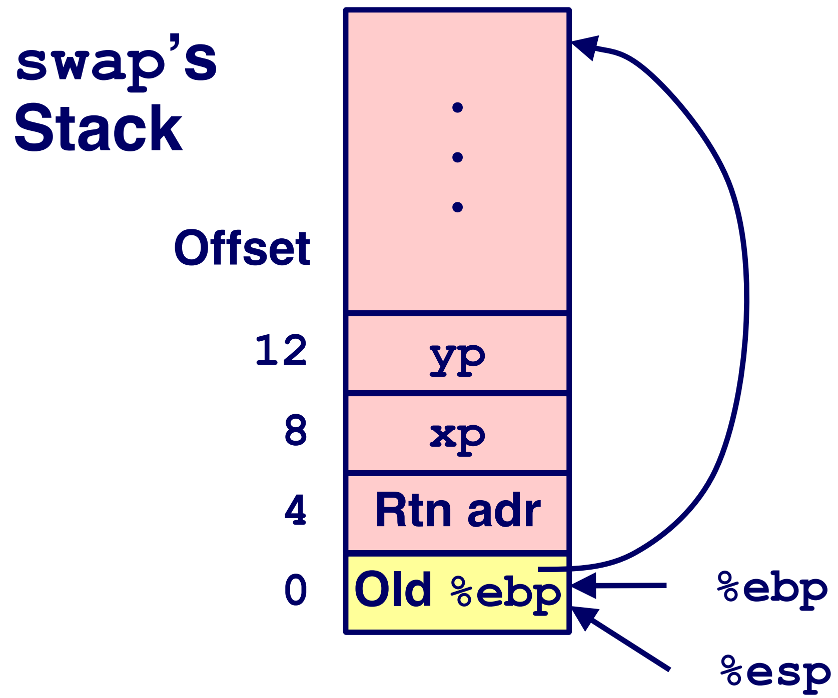

```
movl  -4(%ebp),%ebx
movl  %ebp,%esp
popl  %ebp
ret
```

Observation

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

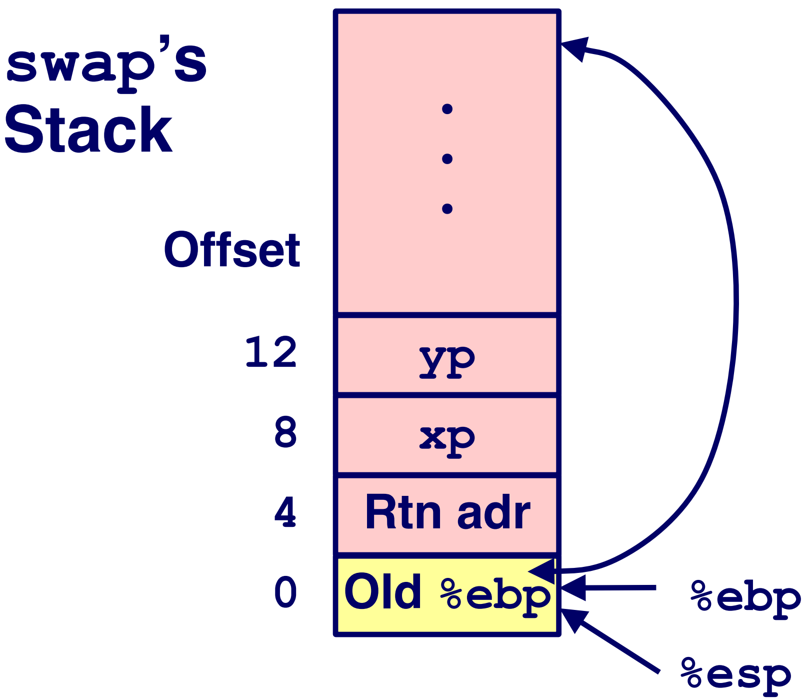
`swap()` Finish #2

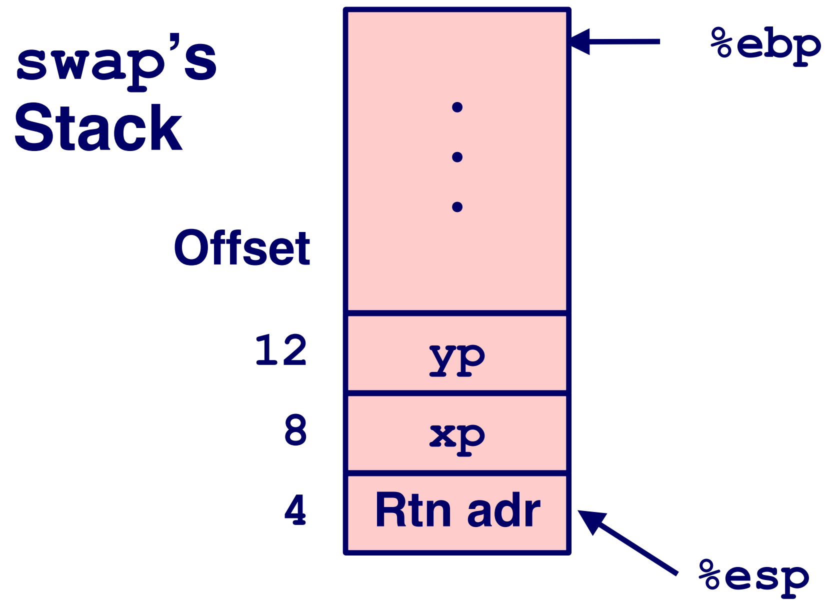





```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

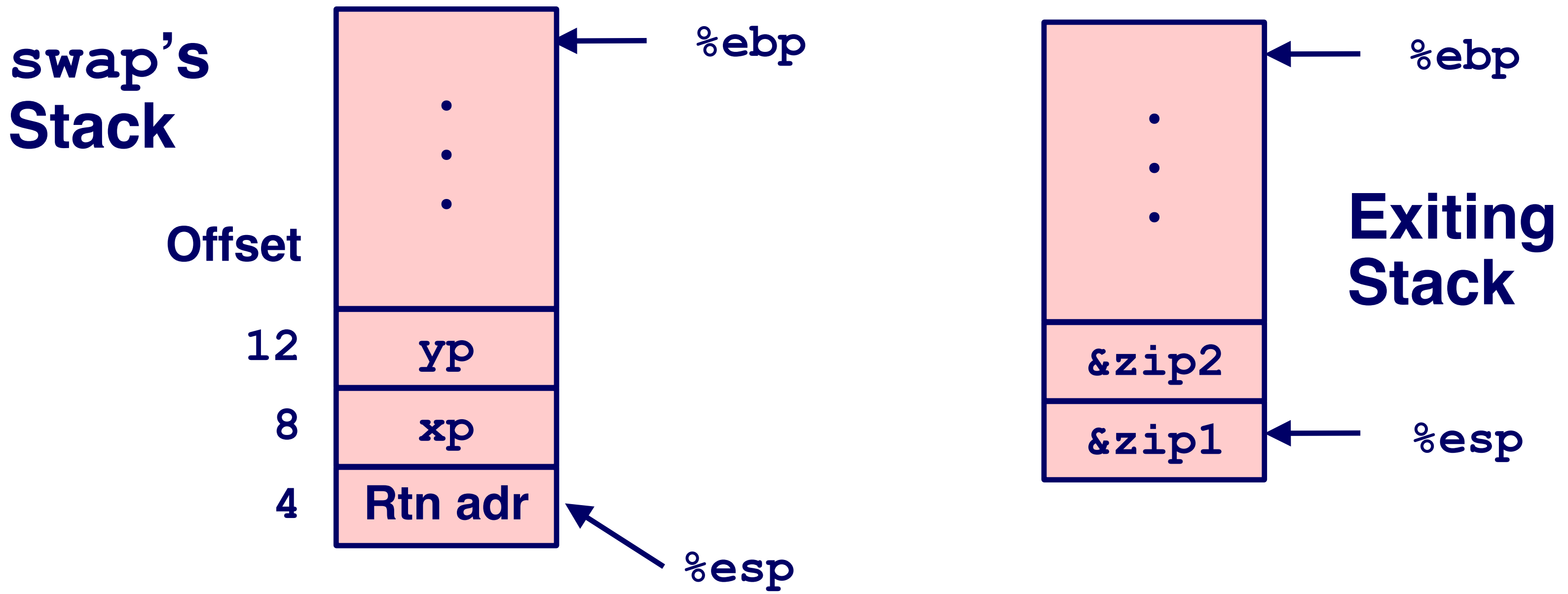
`swap()` Finish #3






```
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

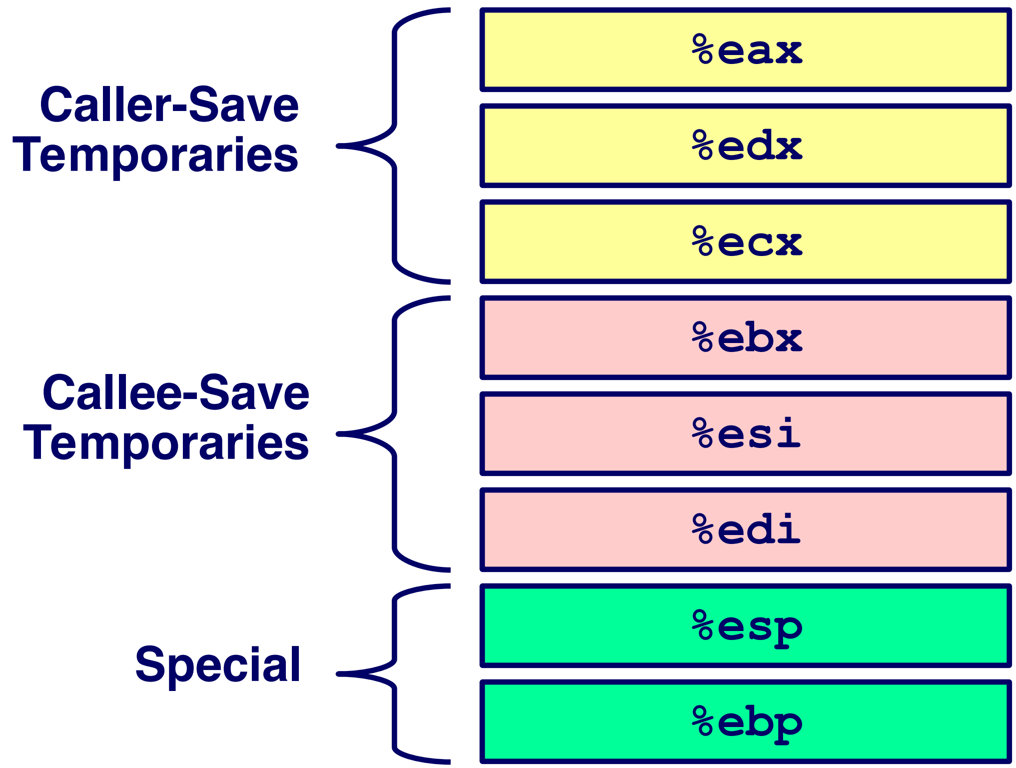
Conventions

- 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**



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?

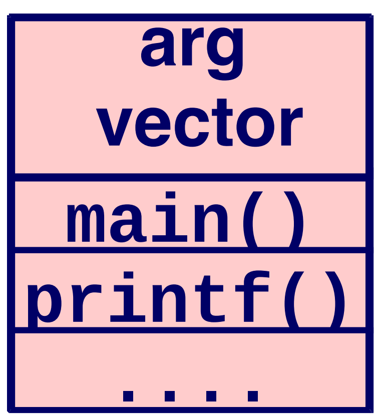
410 students should seek to abolish mystery

- 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"

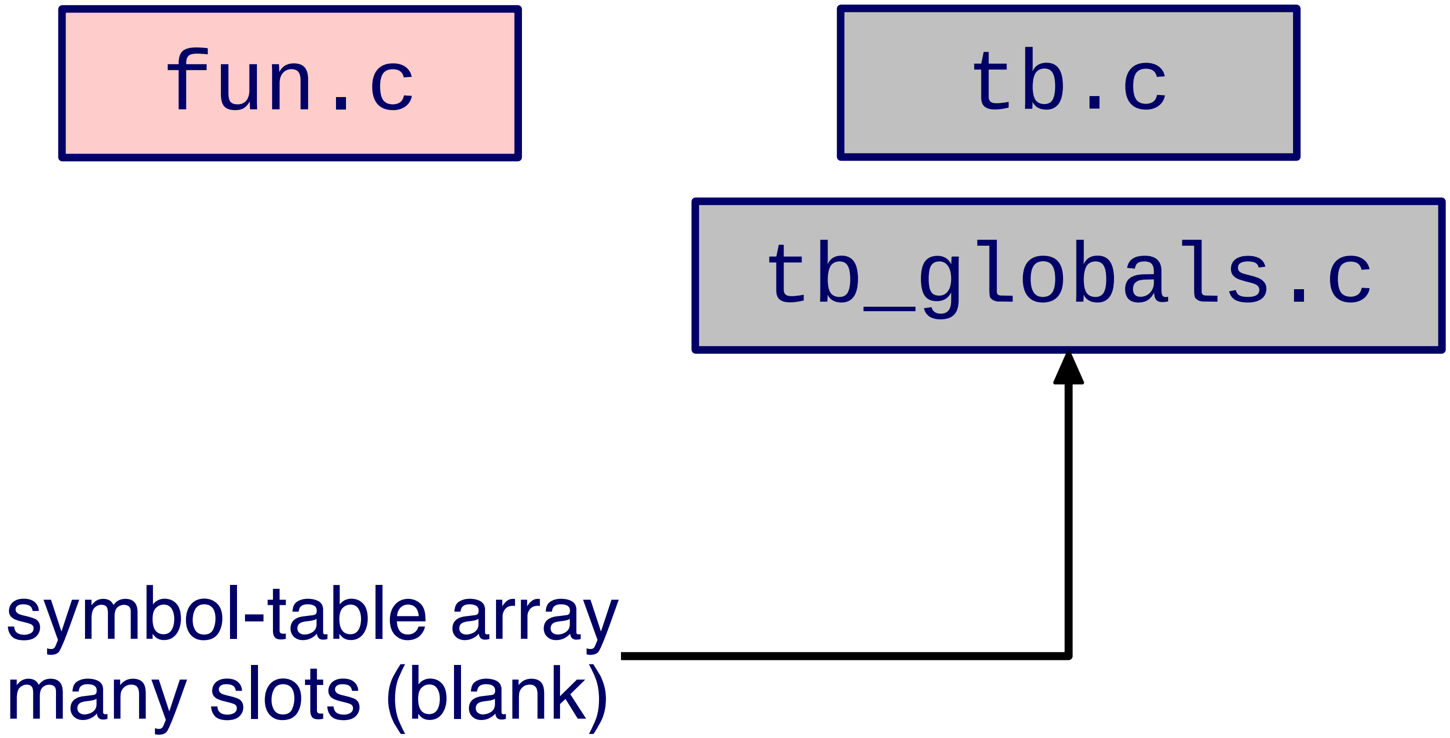
Conceptually easy

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

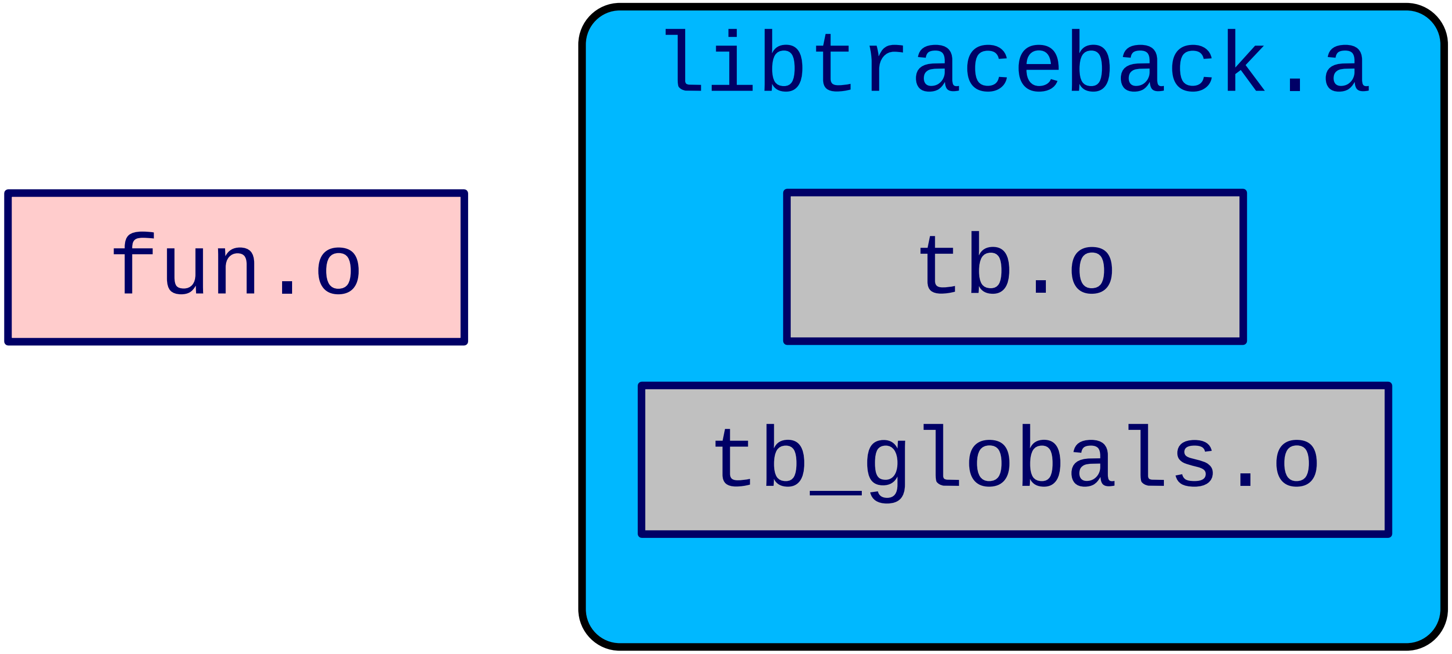
Key questions

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

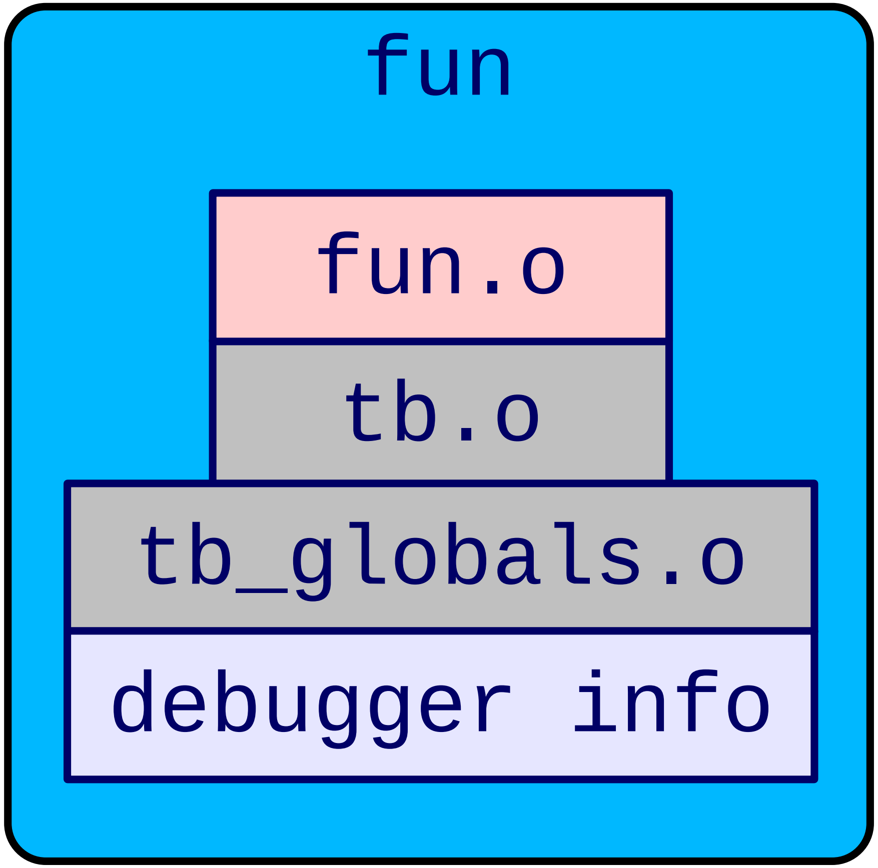
Project 0 “Data Flow”



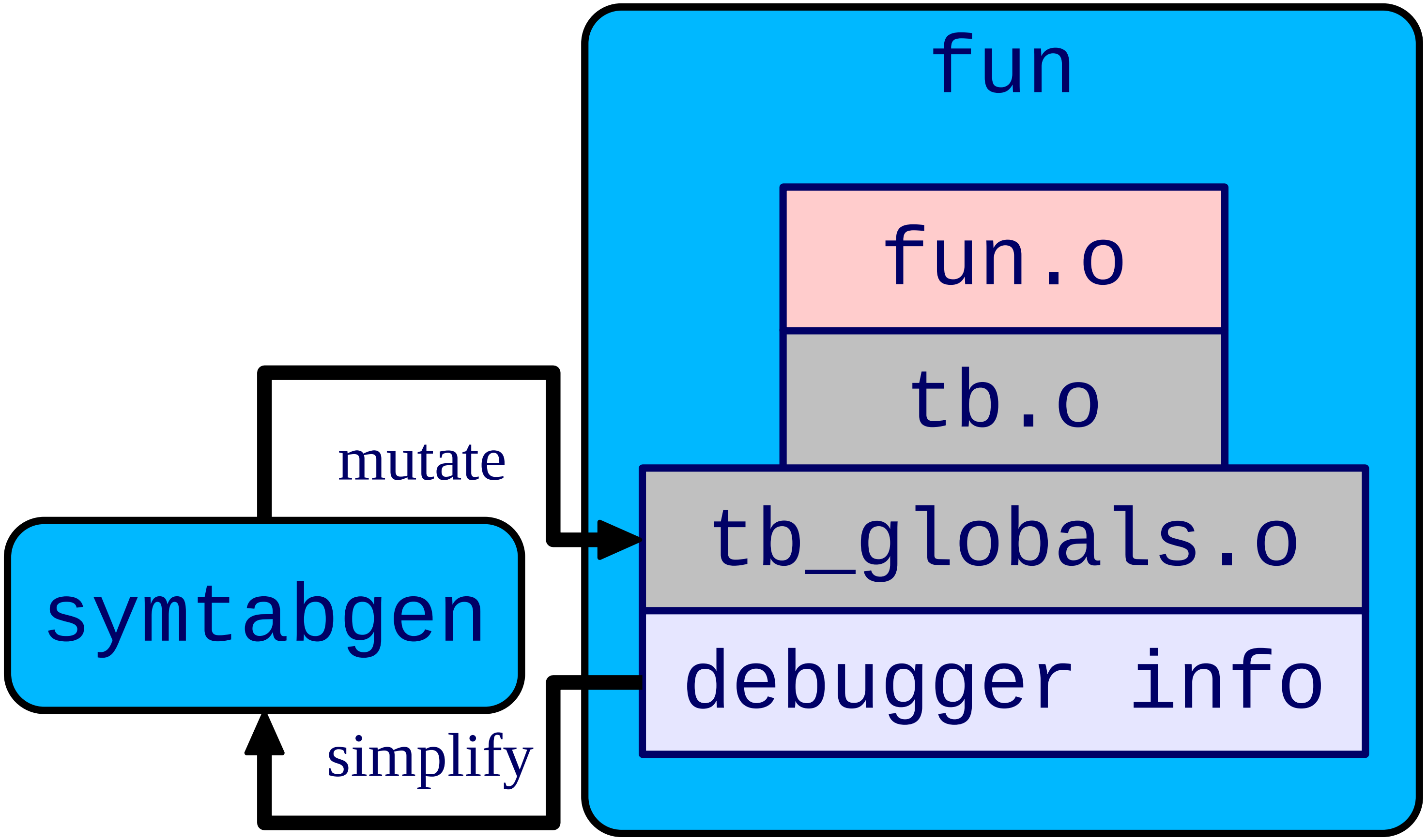
Project 0 “Data Flow” - Compilation



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!