

15-410

“An Experience Like No Other”

Stack Discipline
Aug. 27, 2008

Dave Eckhardt

Slides originally stolen from 15-213

Movie Night

“War Games”

- **Thursday, August 28th**
- **19:00, Wean 7500**
- **\$1 pizza contribution**
- **Presented by the CMU Computer Club**

Synchronization

Registration

- If you're here but not registered, please make sure you're at least on the waiting list *today*

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

- Contact us no later than *today*

Mid-Term Exam

- Two plausible days
- When I ask you to fill out the web form, please do so *promptly*

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

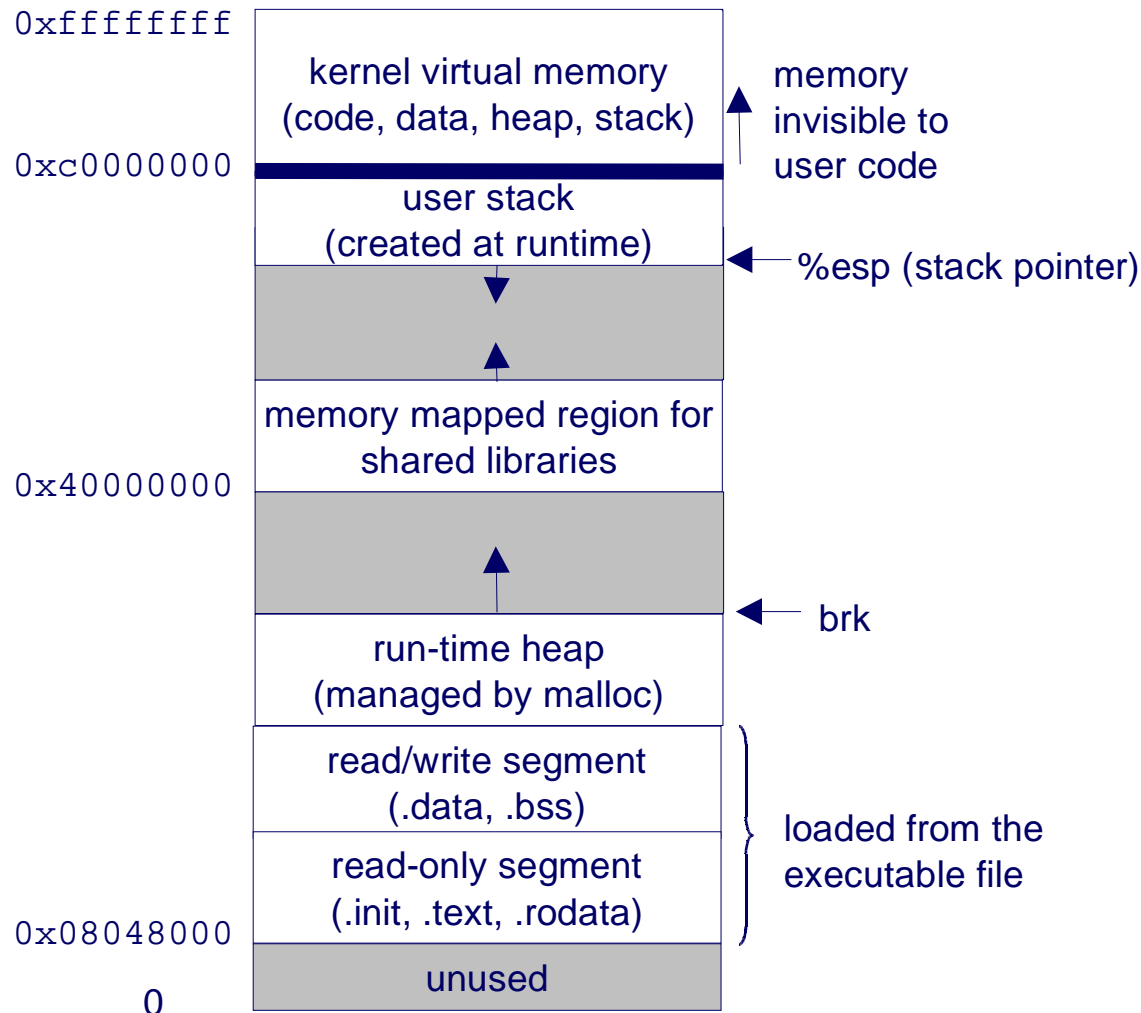
- x86-64 is simpler than x86(-32) for user program code
 - Lots of registers, registers more orthogonal

Why will 410 be x86 / IA32?

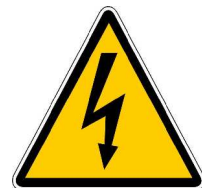
- x86-64 is *not* simpler for kernel code
 - Machine begins in 16-bit mode, then 32, finally 64
 - You don't have time to write 32⇒64 transition code
 - If we gave it to you, it would be a *big* black box
 - More registers means more registers to have wrong values
- There are still a lot more 32-bit machines in the world
 - ...which can boot and run your personal OS

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!

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

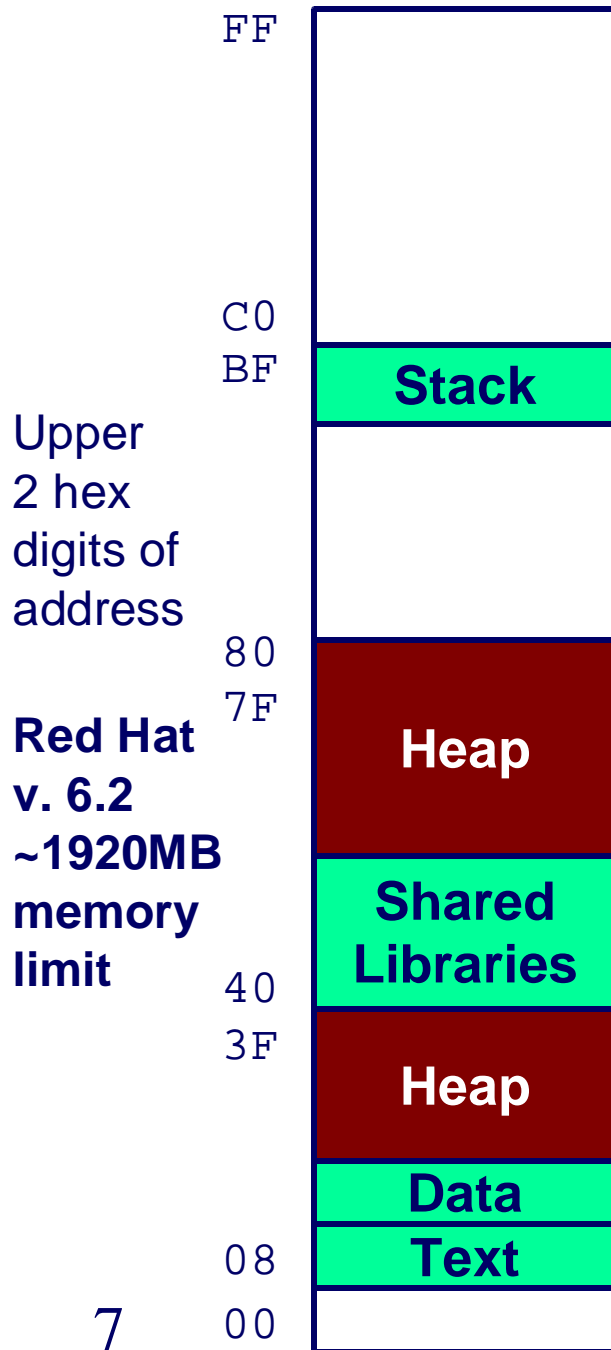
- Library routines (e.g., `printf()`, `malloc()`)
- Linked into object code when first executed
- Windows has “DLLs” (semantic differences)

Data, BSS

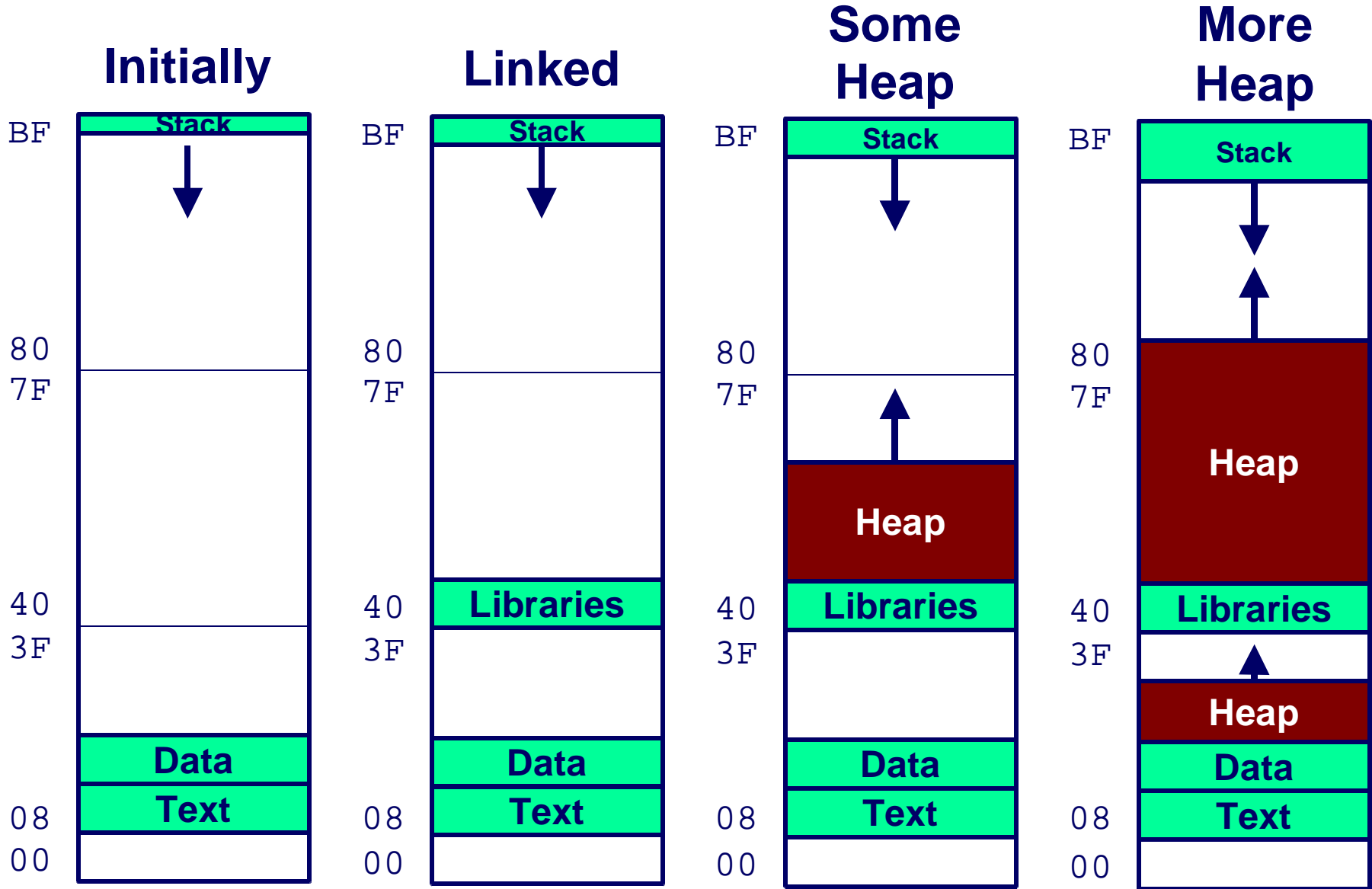
- Statically allocated data (BSS starts all-zero)
- e.g., arrays & variables declared in code

Text, RODATA

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



Linux Memory Allocation

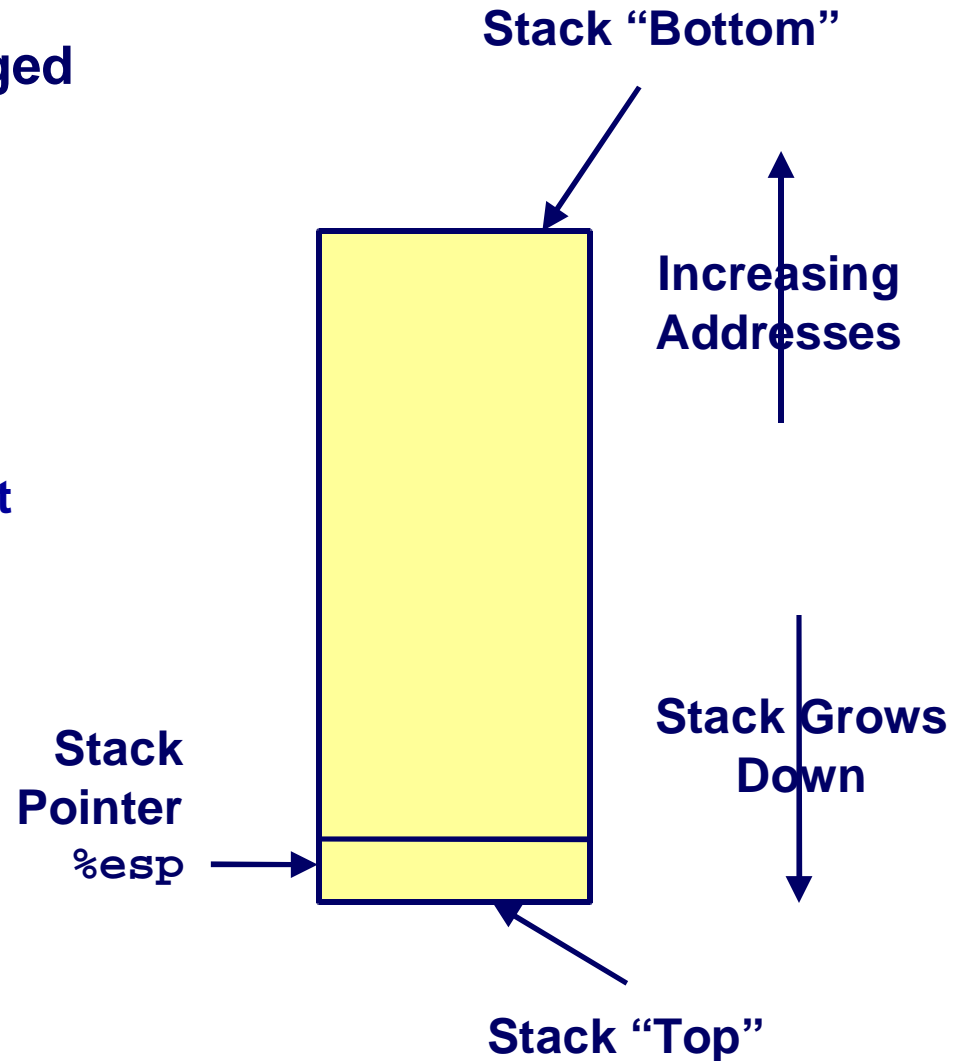


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15-410, F'08

IA32 Stack

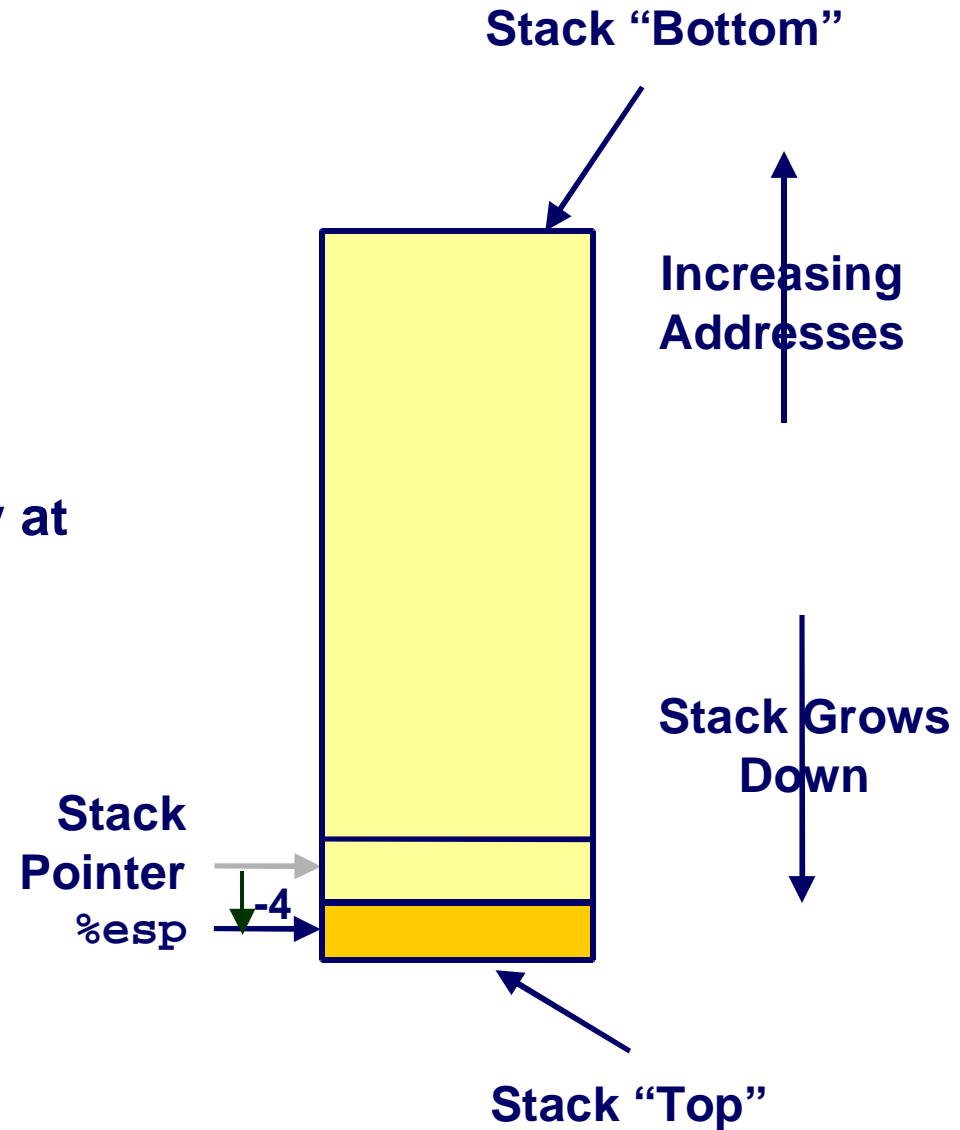
- Region of memory managed with stack discipline
- “Grows” toward lower addresses
- Register `%esp` indicates lowest stack address
 - address of “top” element
 - stack *pointer*



IA32 Stack Pushing

Pushing

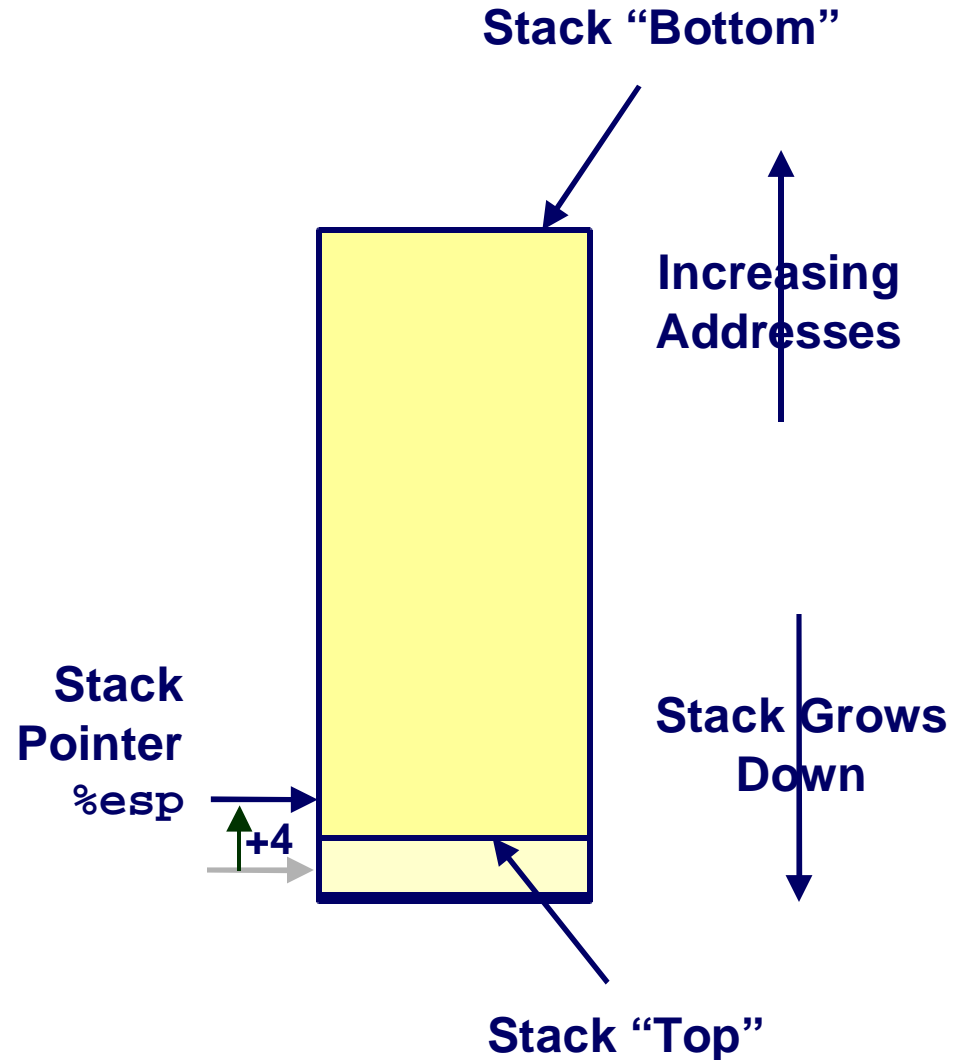
- `pushl Src`
- Fetch operand from *Src*
 - A register: `%ebp`
 - Memory: `8(%ebp)`
- Decrement `%esp` by 4
- Store operand in memory at address given by `%esp`



IA32 Stack Popping

Popping

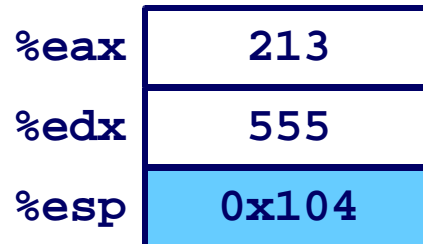
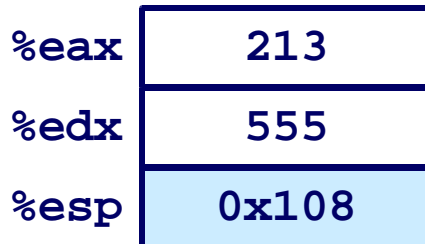
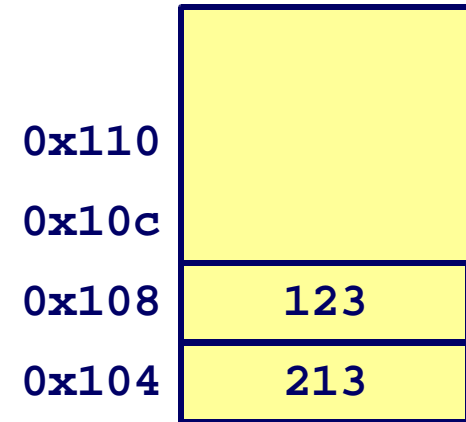
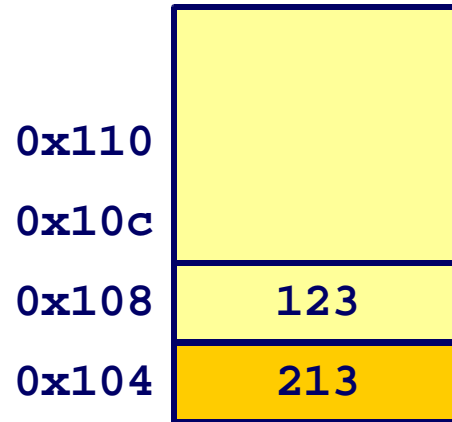
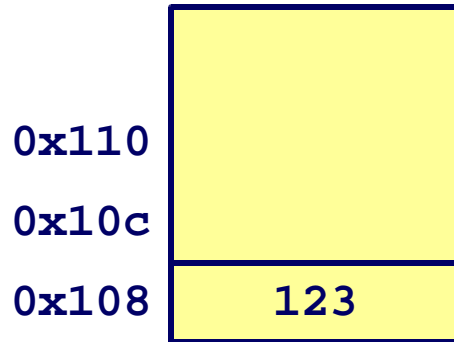
- `popl Dest`
- Read operand at address given by `%esp`
- Increment `%esp` by 4
- Write to `Dest`



Stack Operation Examples

`pushl %eax`

`popl %edx`



Procedure Control Flow

- Use stack to support procedure call and return

Procedure call:

- `call label` Push return address on stack; Jump to *label*

Return address value

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

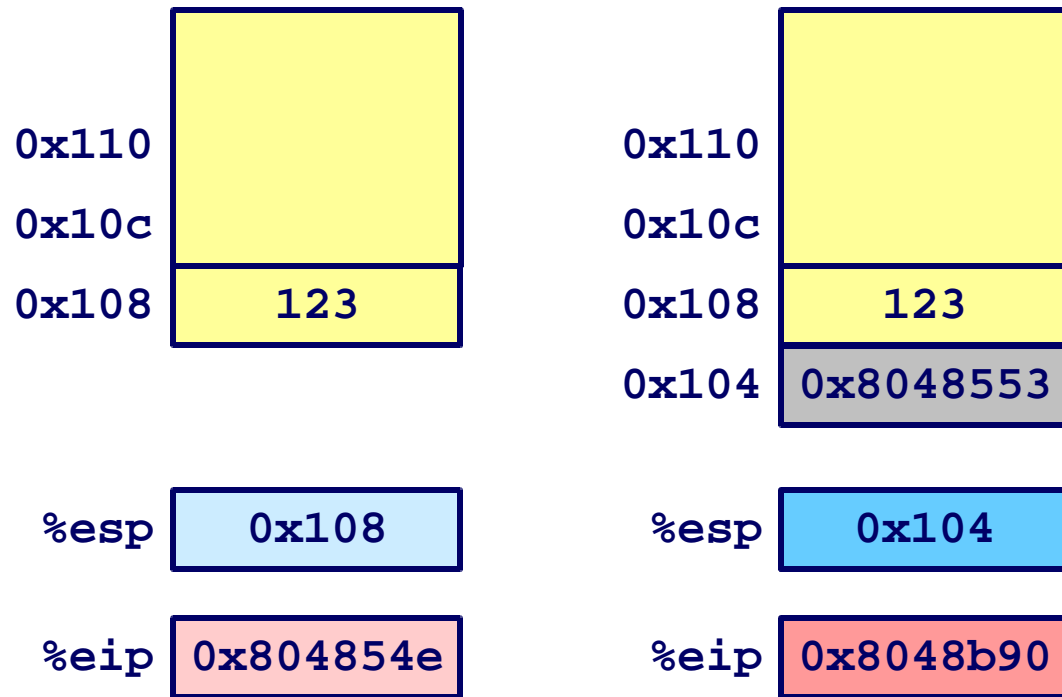
Procedure return:

- `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

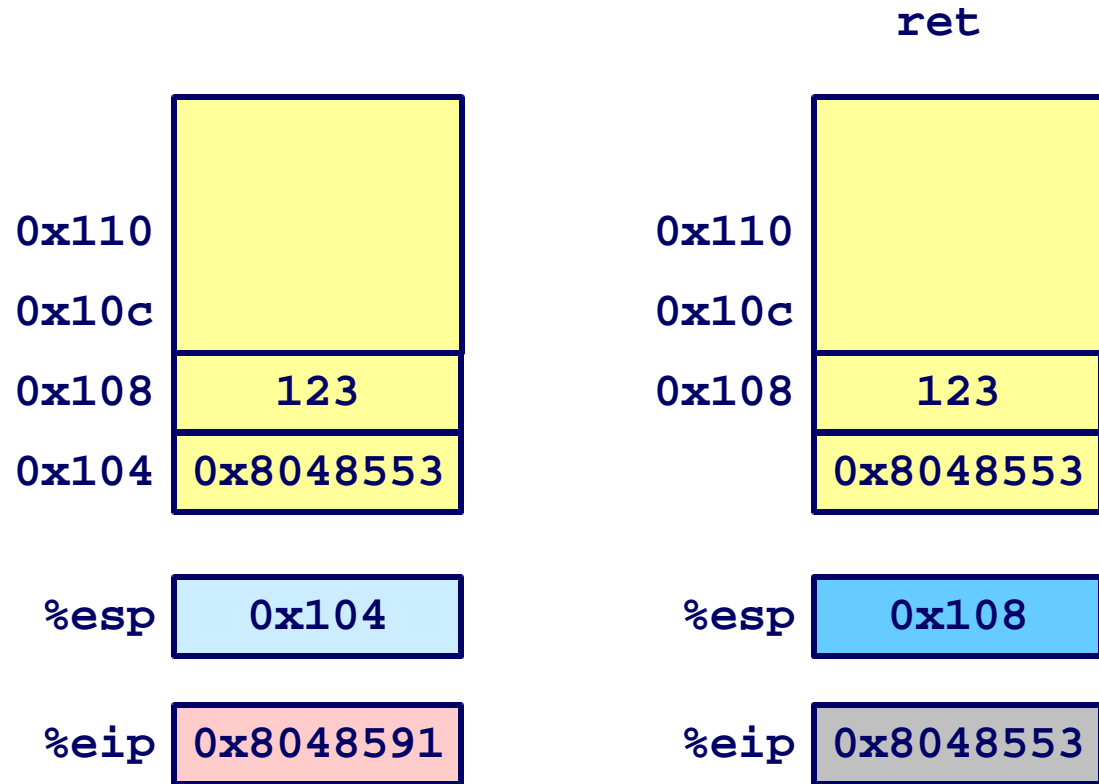


%eip is program counter

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

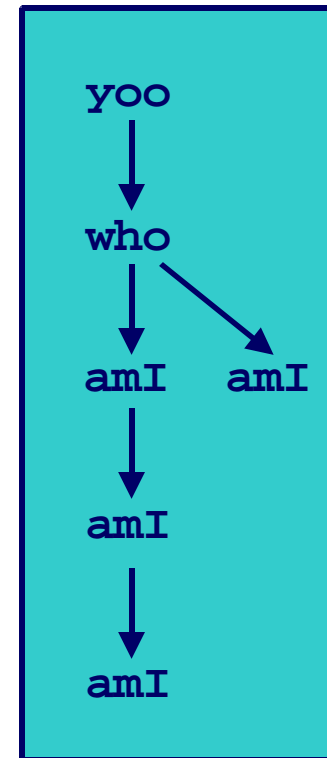
```
yoo (...)  
{  
  •  
  •  
  who ( ) ;  
  •  
  •  
}
```

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

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

- Procedure `amI ()` recursive

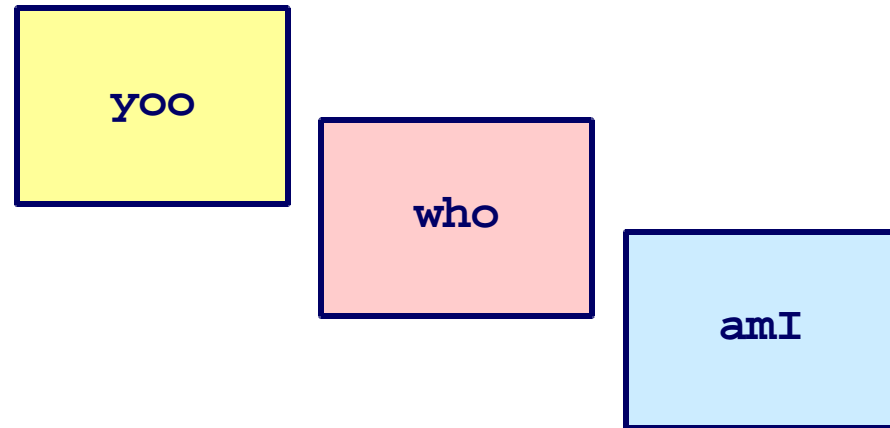
Call Chain



Stack Frames

Contents

- Local variables
- Return information
- Temporary space

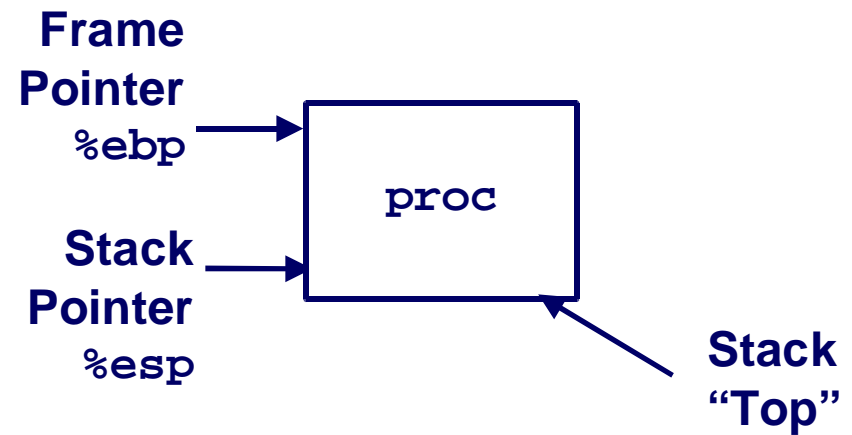


Management

- 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



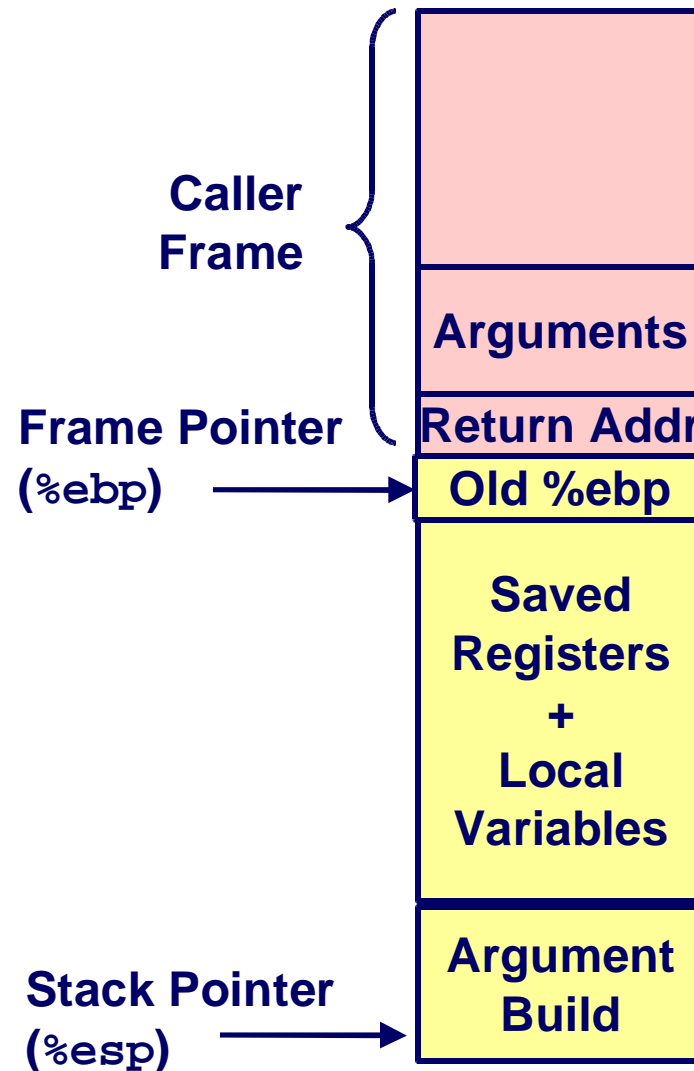
IA32/Linux Stack Frame

Current Stack Frame (“Top” to “Bottom”)

- Parameters for function 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 ()

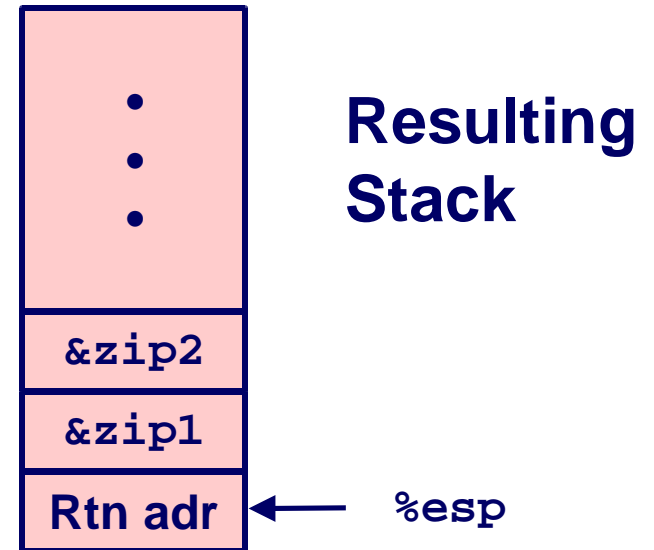
```
int zip1 = 15213;
int zip2 = 91125;

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
    . . .
```



swap ()

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

swap:

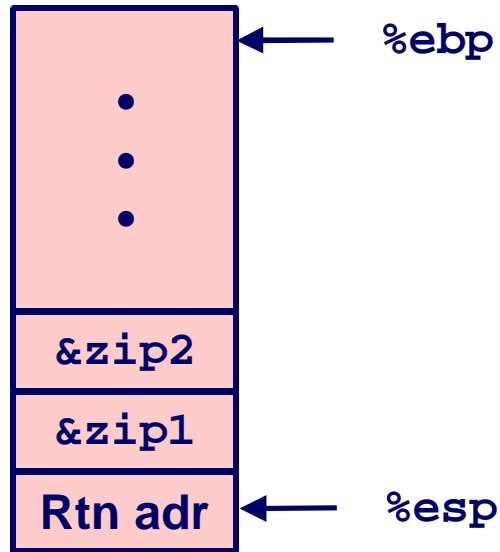
```
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
} Set Up

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

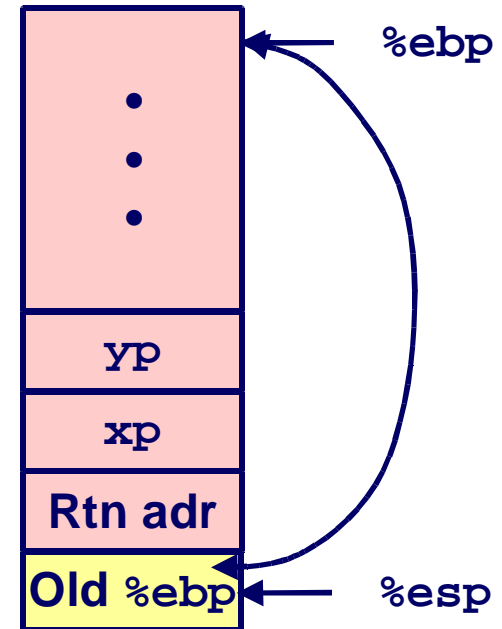
    movl -4(%ebp),%ebx
    movl %ebp,%esp
    popl %ebp
    ret
} Finish
```

swap () Setup #1

Entering Stack



Resulting Stack

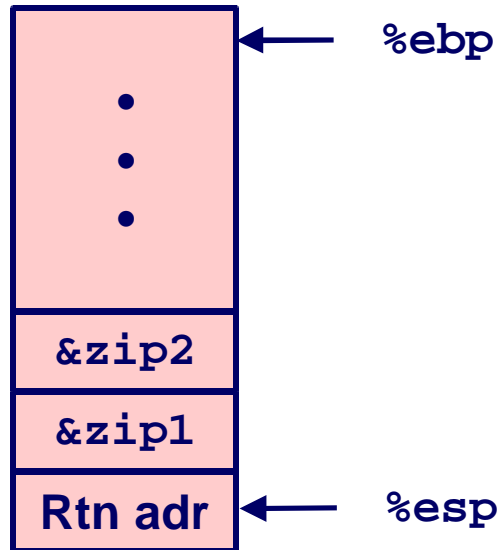


swap:

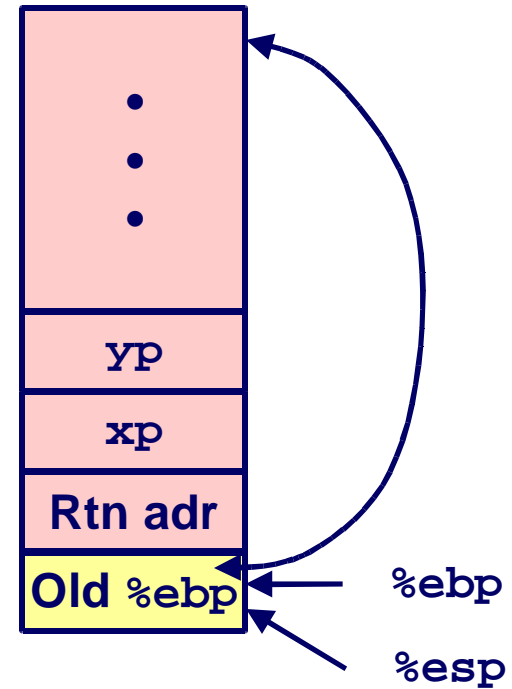
```
pushl %ebp  
movl %esp,%ebp  
pushl %ebx
```

swap () Setup #2

Entering Stack



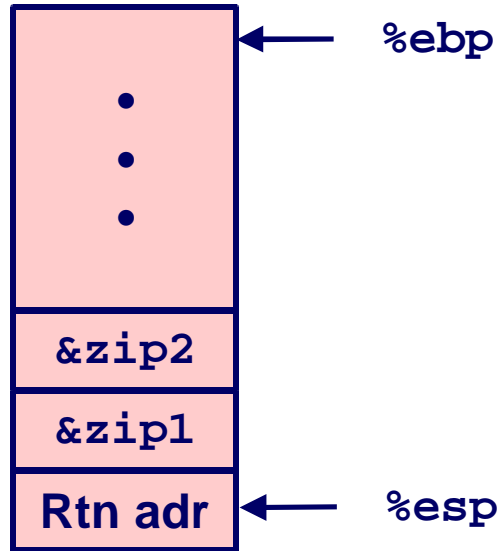
Resulting Stack



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

swap () Setup #3

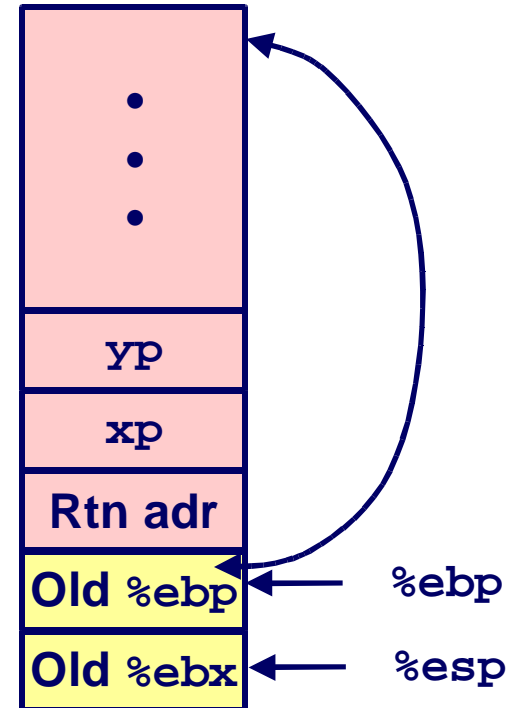
Entering Stack



`swap:`

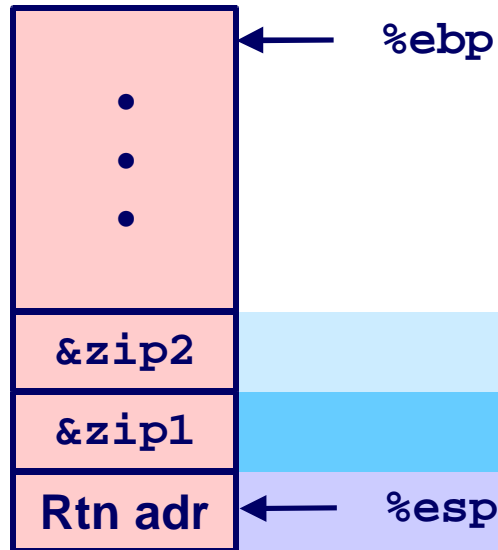
```
    pushl %ebp  
    movl %esp,%ebp  
    pushl %ebx
```

Resulting Stack



Effect of swap () Setup

Entering Stack



Offset
(relative to %ebp)

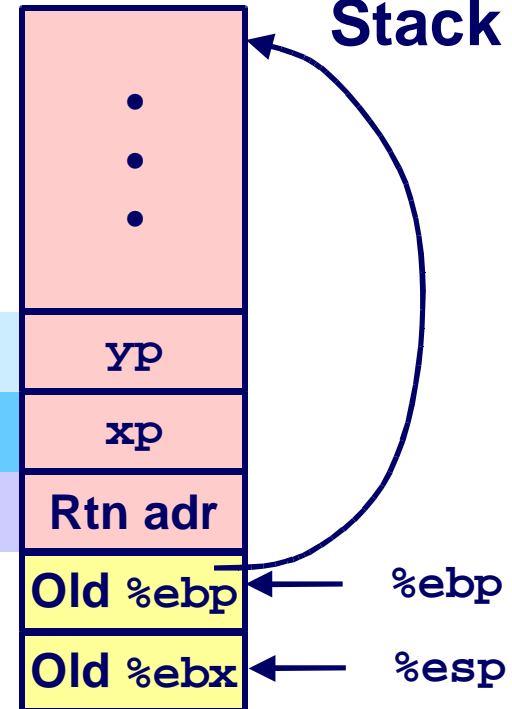
12

8

4

0

Resulting Stack

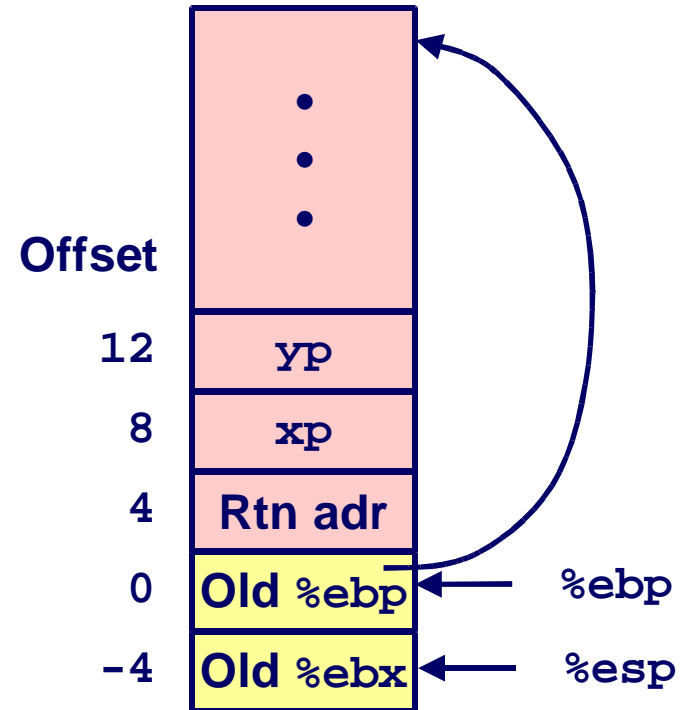
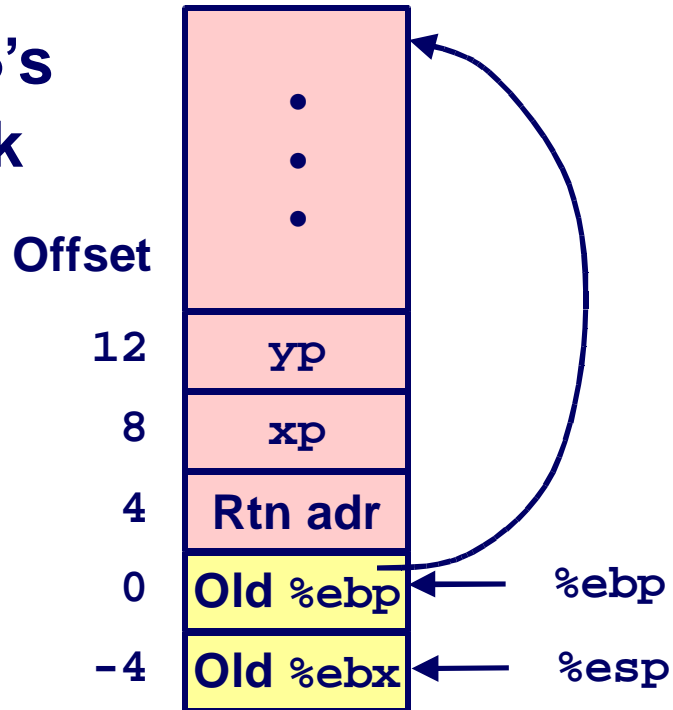


```

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

swap () Finish #1

swap's
Stack

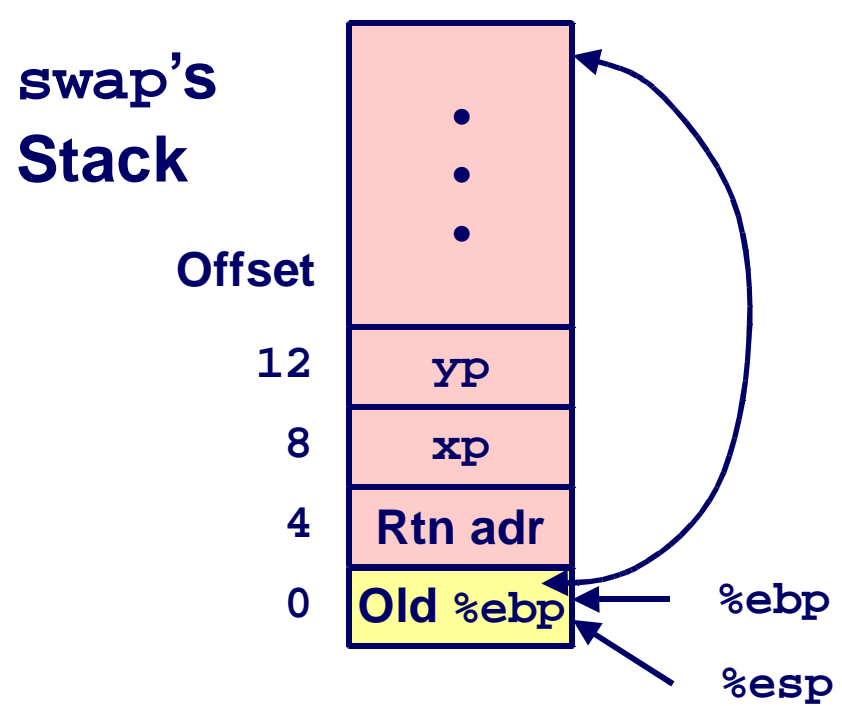
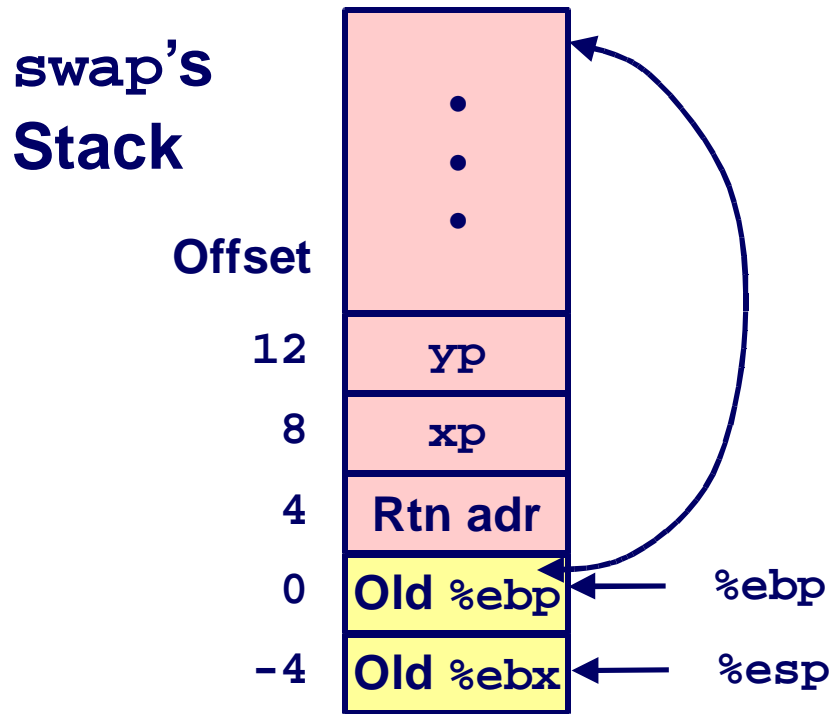


```
movl -4(%ebp), %ebx  
movl %ebp, %esp  
popl %ebp  
ret
```

Observation

- Saved & restored register %ebx

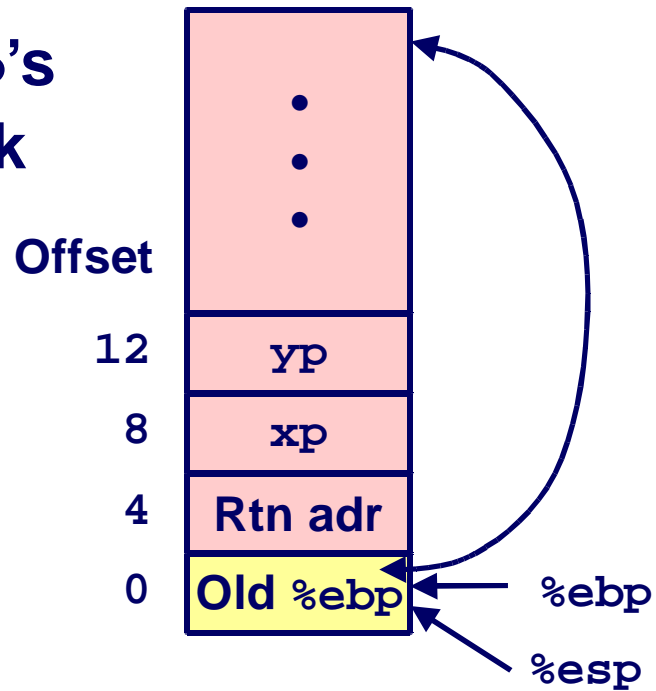
swap () Finish #2



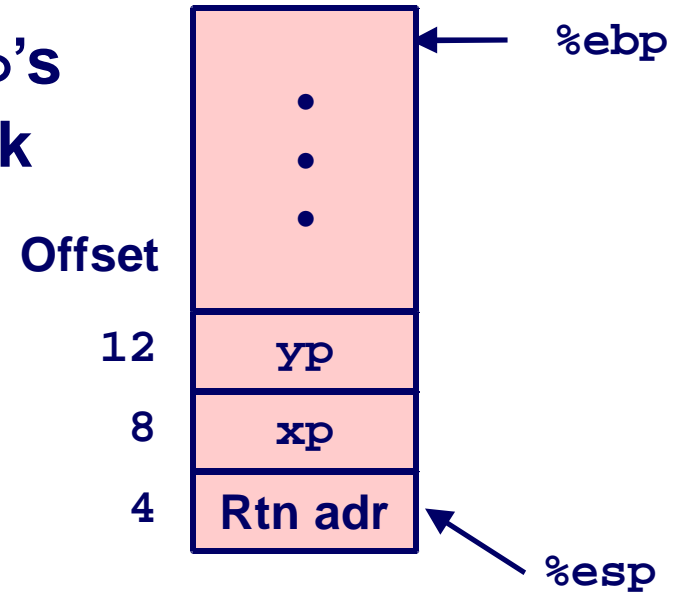
```
movl -4(%ebp),%ebx  
movl %ebp,%esp  
popl %ebp  
ret
```

swap () Finish #3

swap's
Stack

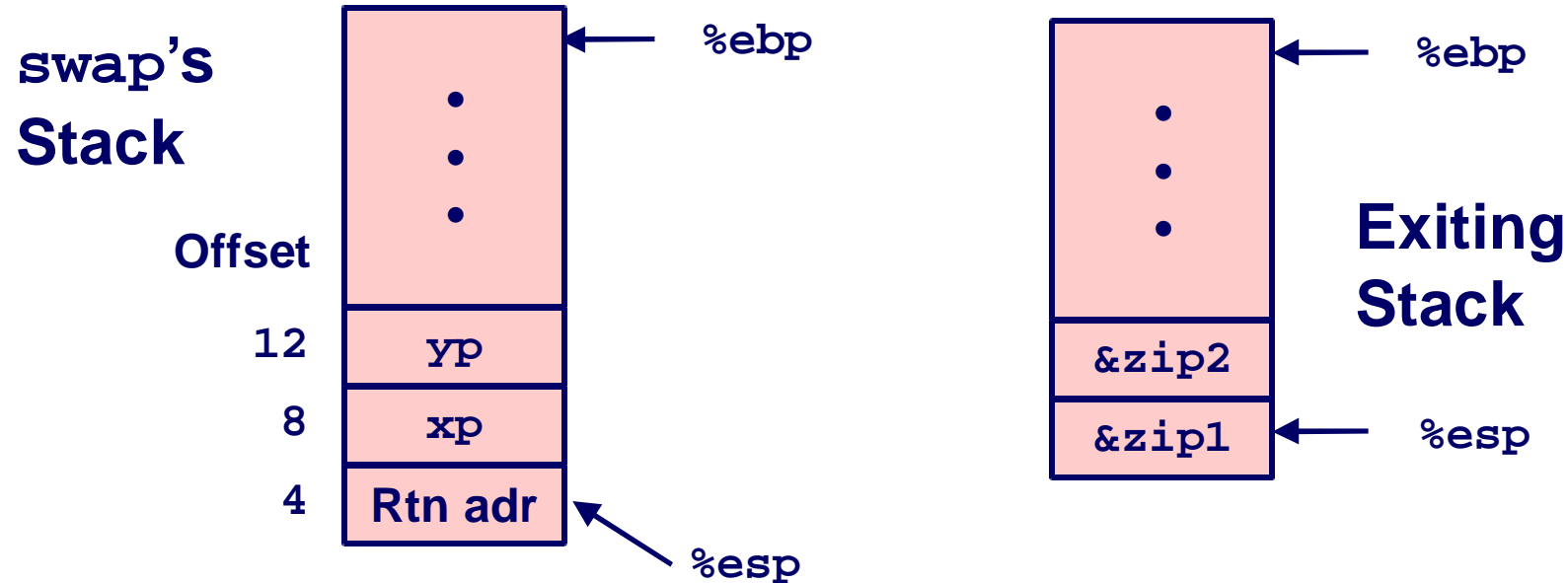


swap's
Stack



```
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

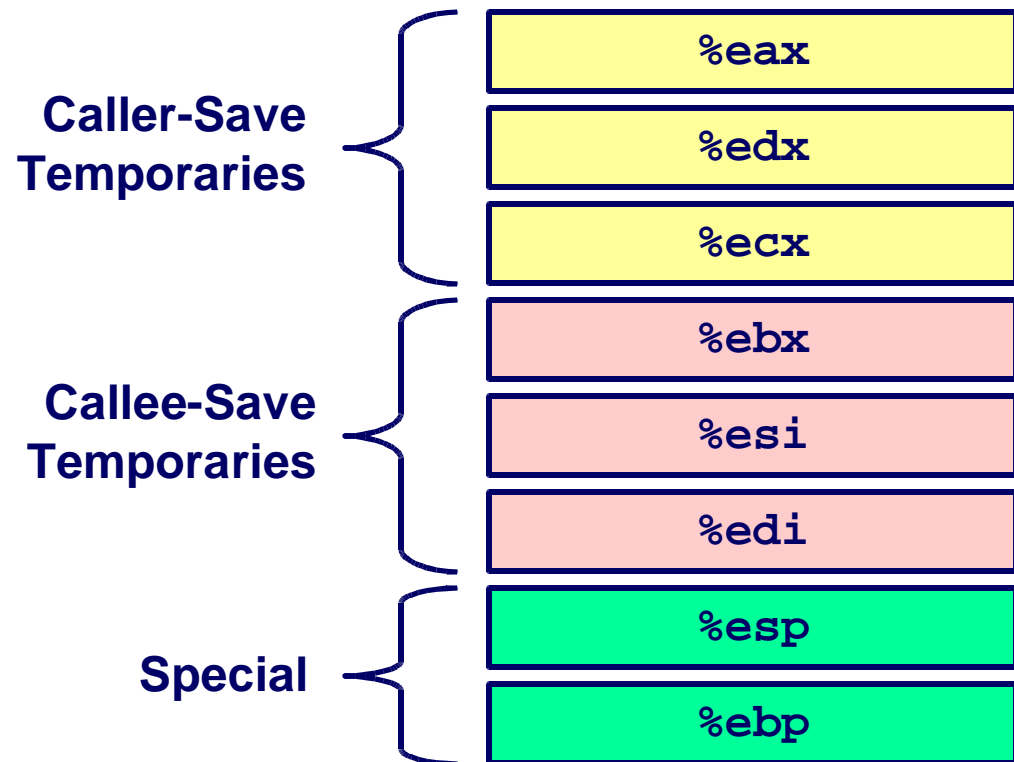
Conventions

- 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)`”???

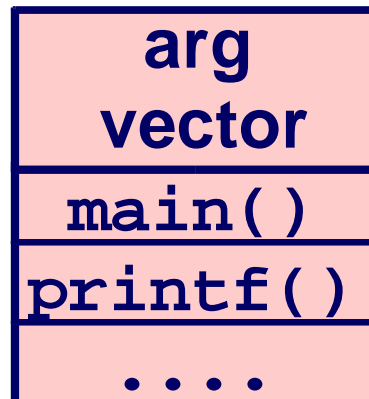
- There's no more program to run...right?
- Where does the 0 go?
- How does it get there?

410 students should seek to abolish mystery

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 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));  
}
```

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=2.090000d), in

Function fun2(f=35.000000f), in

Function fun1(count=0), in

Function fun1(count=1), in

Function fun1(count=2), in

...

Project 0 - “Stack Crawler”

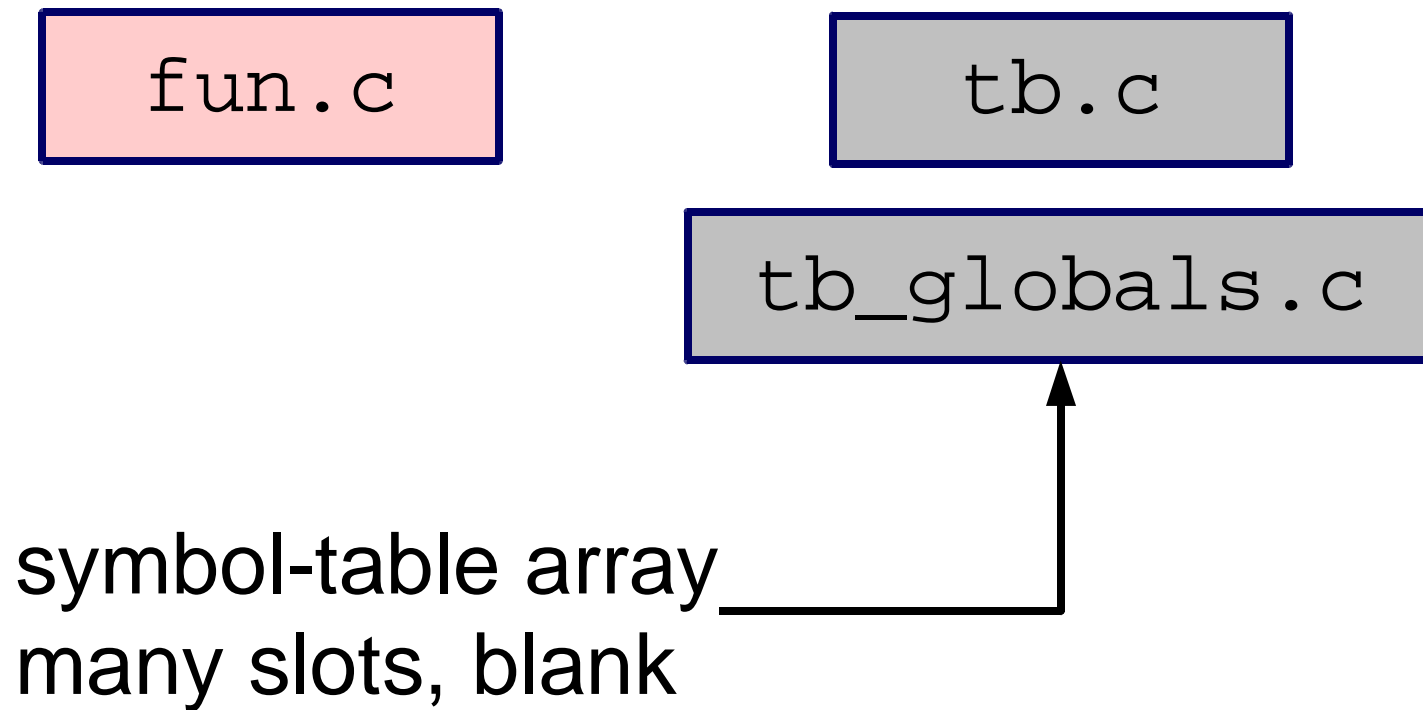
Conceptually easy

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

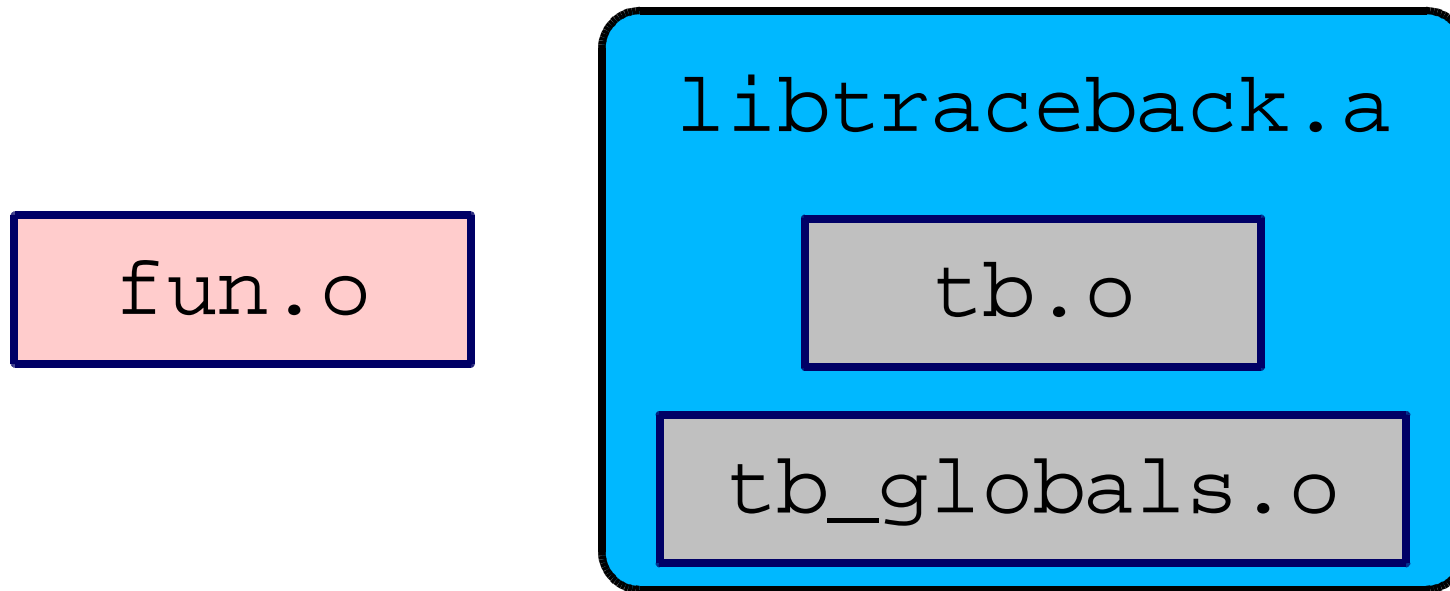
Key questions

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

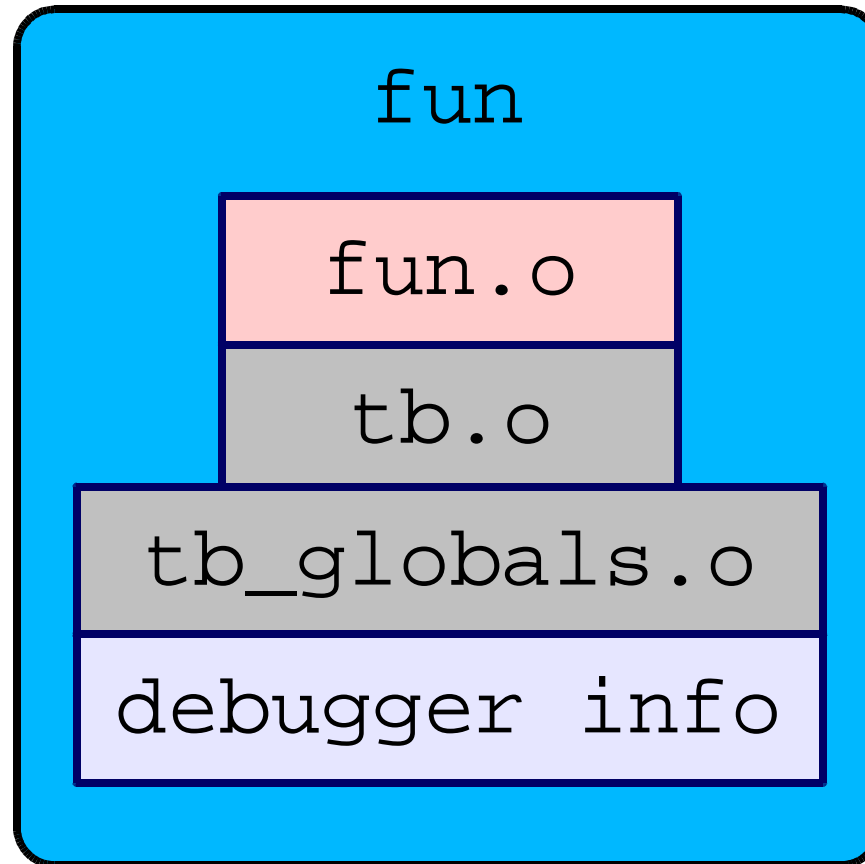
Project 0 “Data Flow”



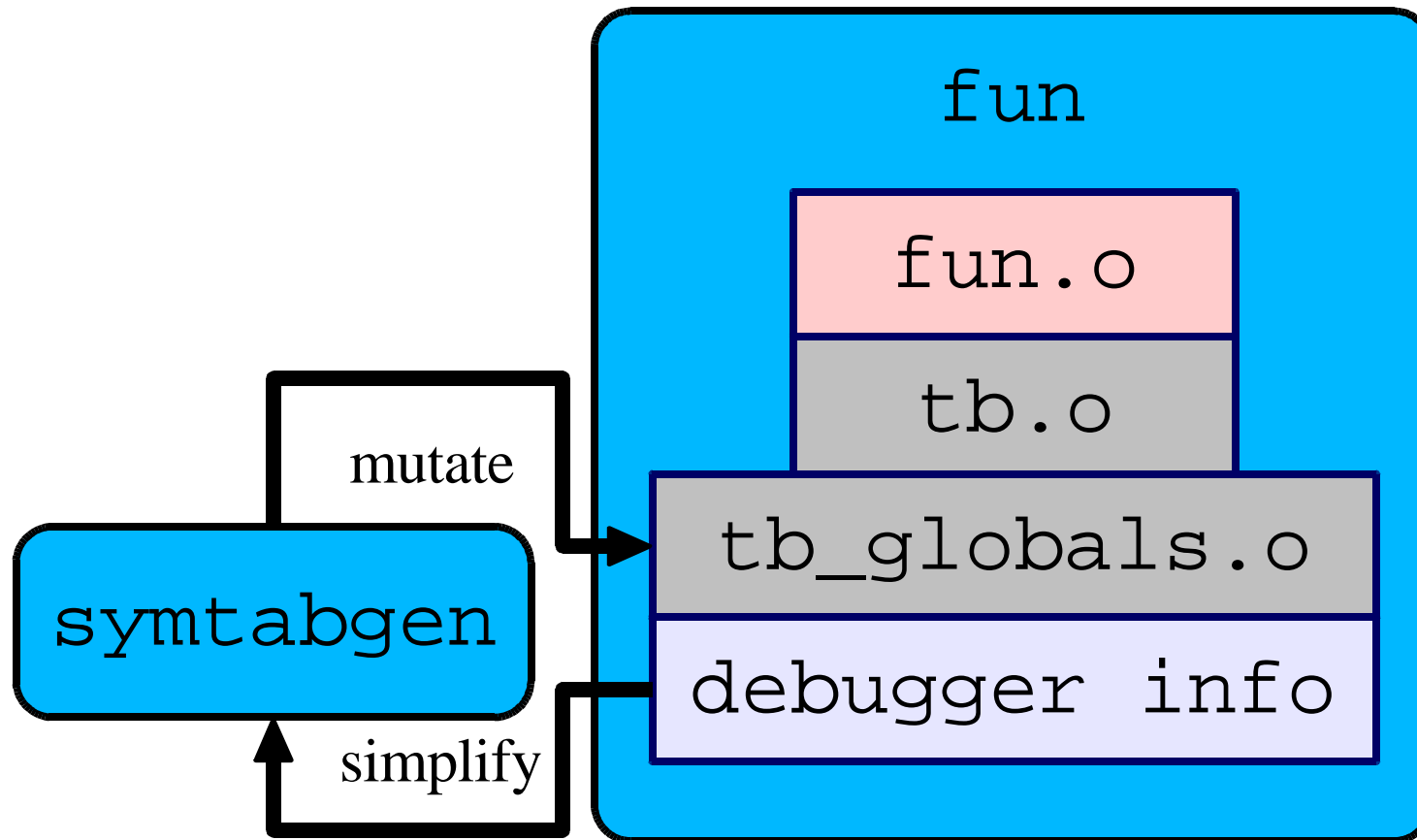
Project 0 “Data Flow” - Compilation



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 evening

Start interviewing Project 2/3/4 partners!