# 15-410

***"Way easier than when we were students"***

# Stack Discipline
# Jan. 14, 2004

**Dave Eckhardt**

**Bruce Maggs**

**Review slides from 15-213 originally developed by Randy Bryant and Dave O'Halloran.**

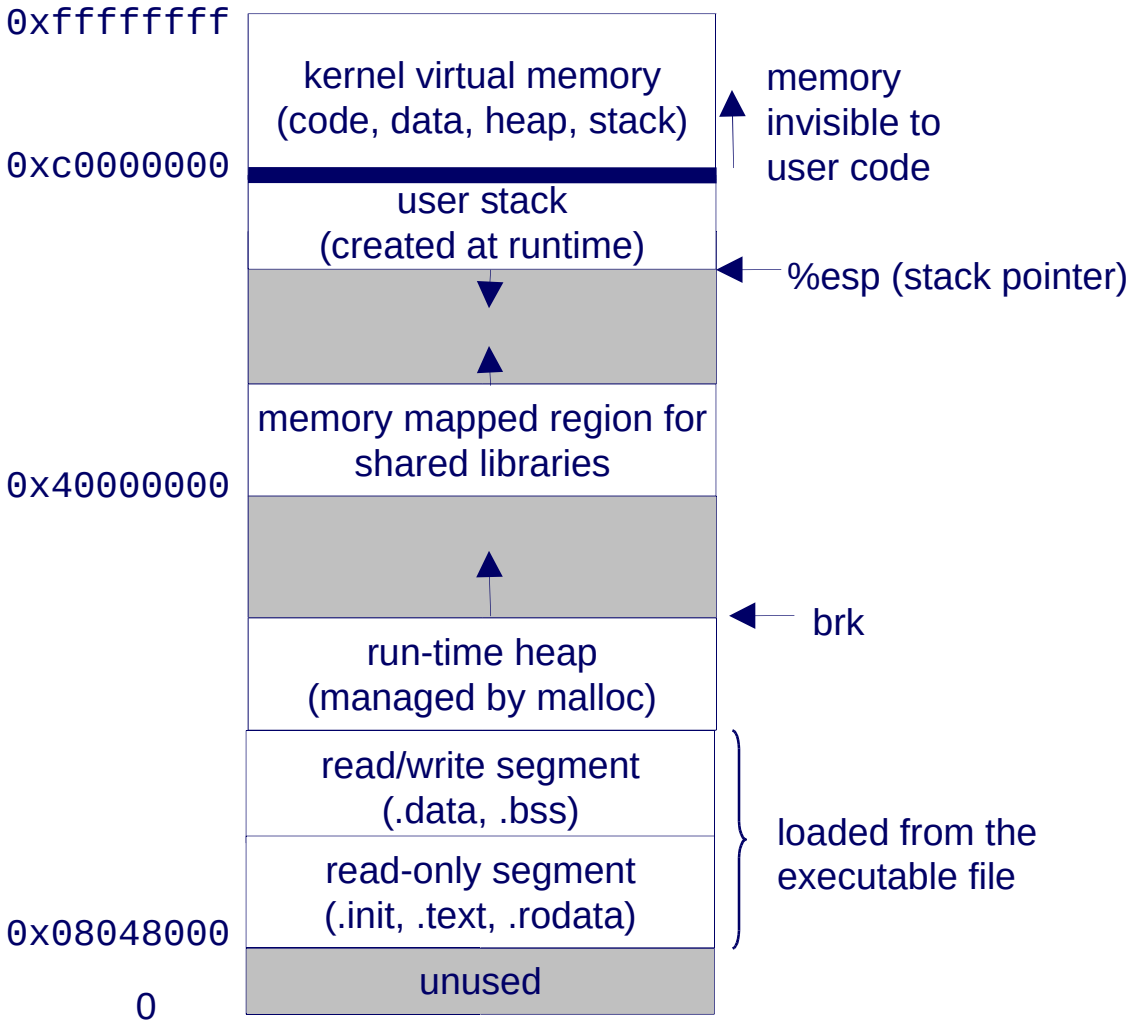
# Outline

## Topics

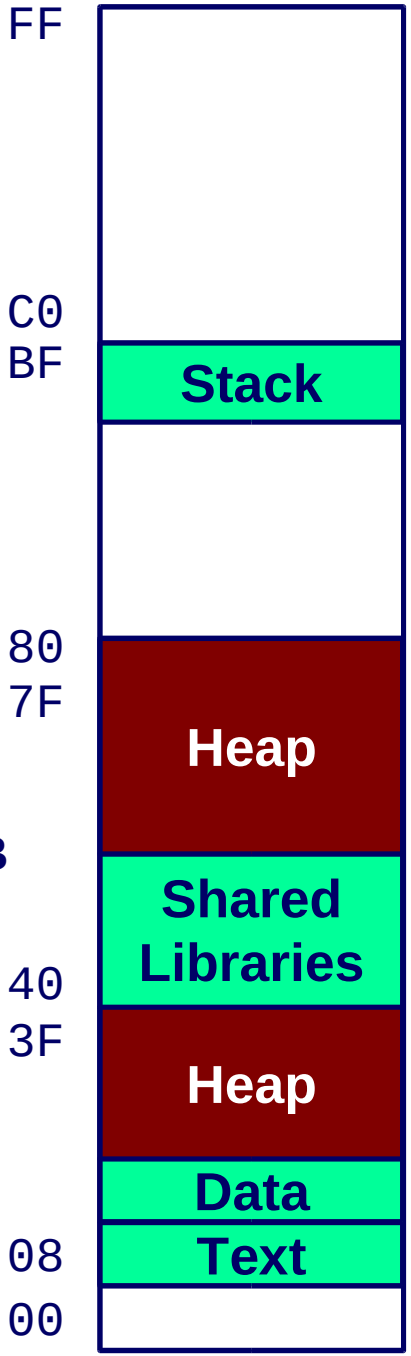
- Process memory model
- IA32 stack organization
- Register saving conventions
- Before & after `main()`
- Project 0

# Private Address Spaces

**Each process has its own private address space.**



# Linux Memory Layout




**Stack**

- Runtime stack (8MB limit)

**Heap**

- Dynamically allocated storage
- When call `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)

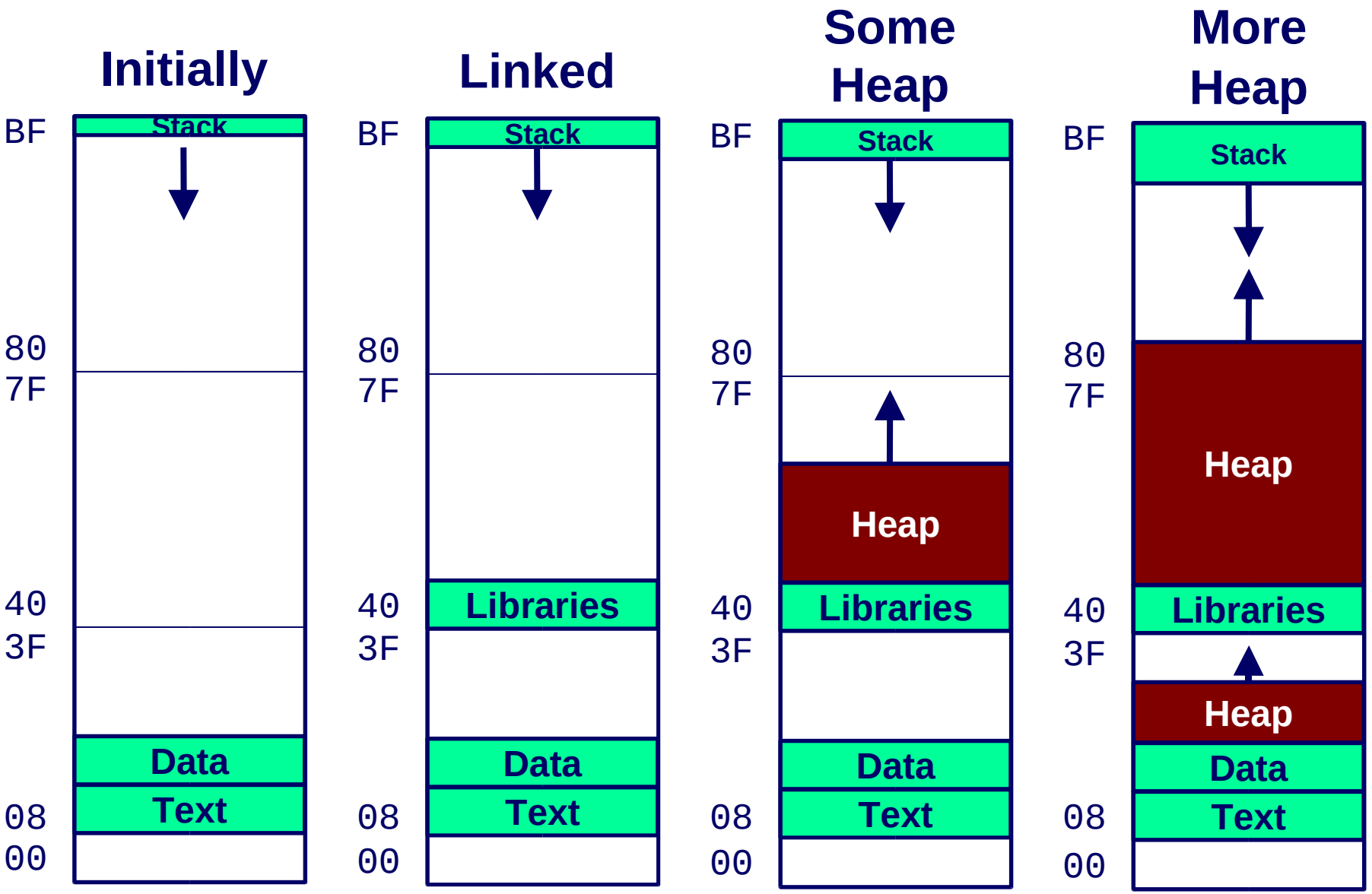
**Data, BSS**

- Statically allocated data
- E.g., arrays & strings declared in code

**Text, RODATA**

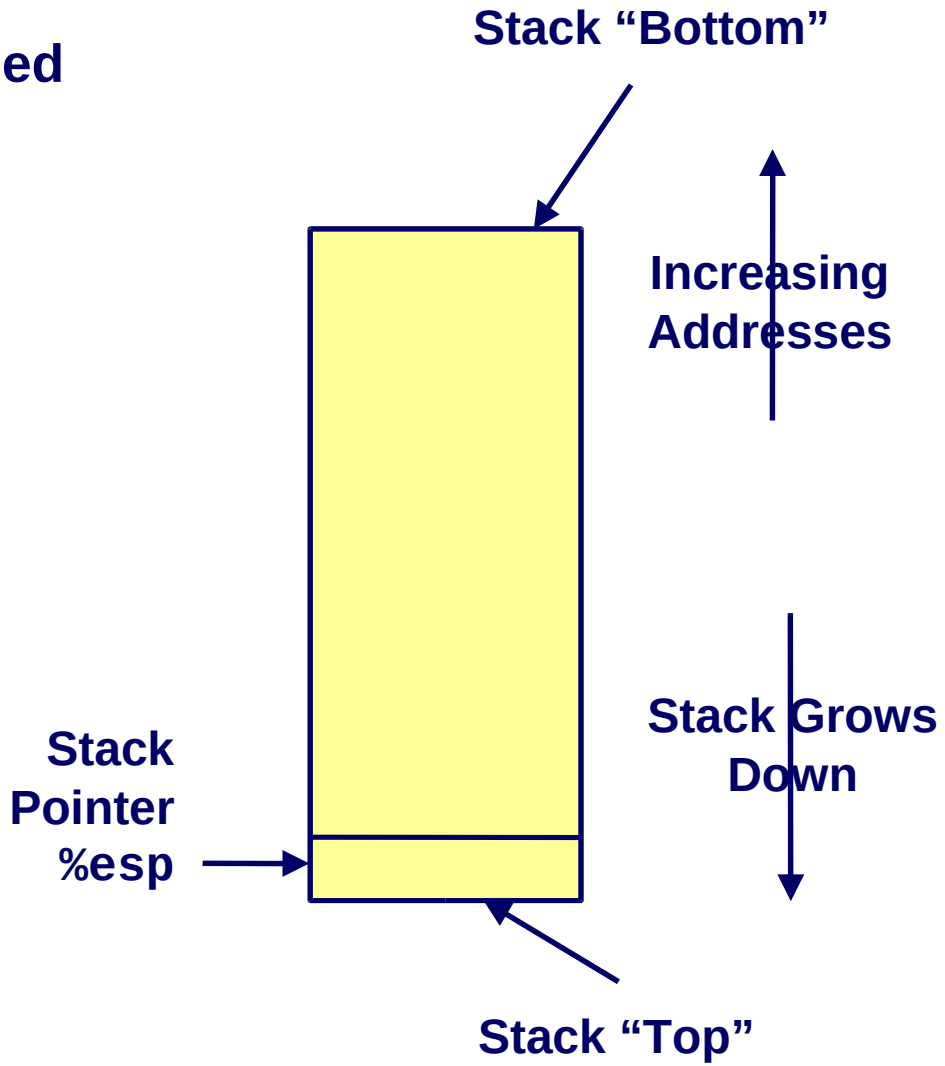
- Text - Executable machine instructions
- RODATA – Read-only (e.g., “const”)

# Linux Memory Allocation



# IA32 Stack

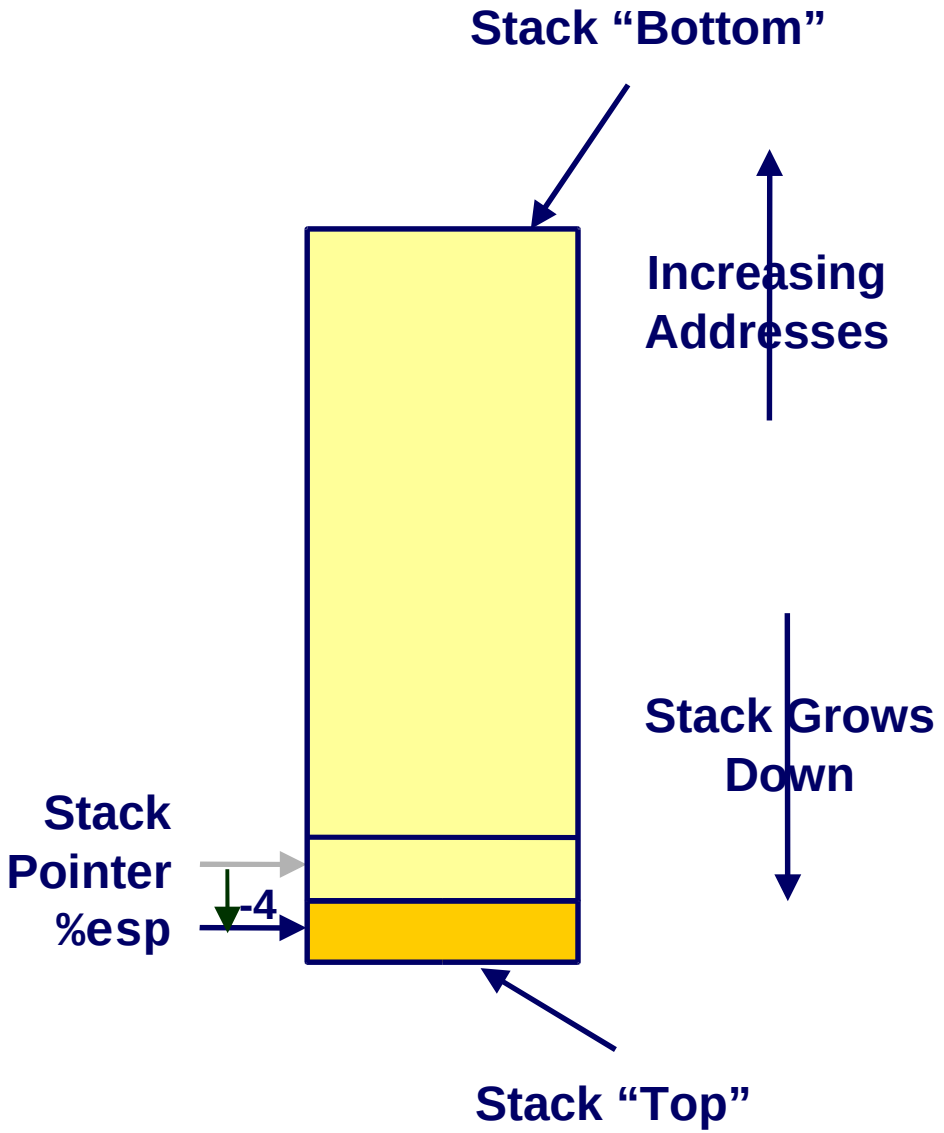
- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register %esp indicates lowest stack address
  - address of top element



# IA32 Stack Pushing

## Pushing

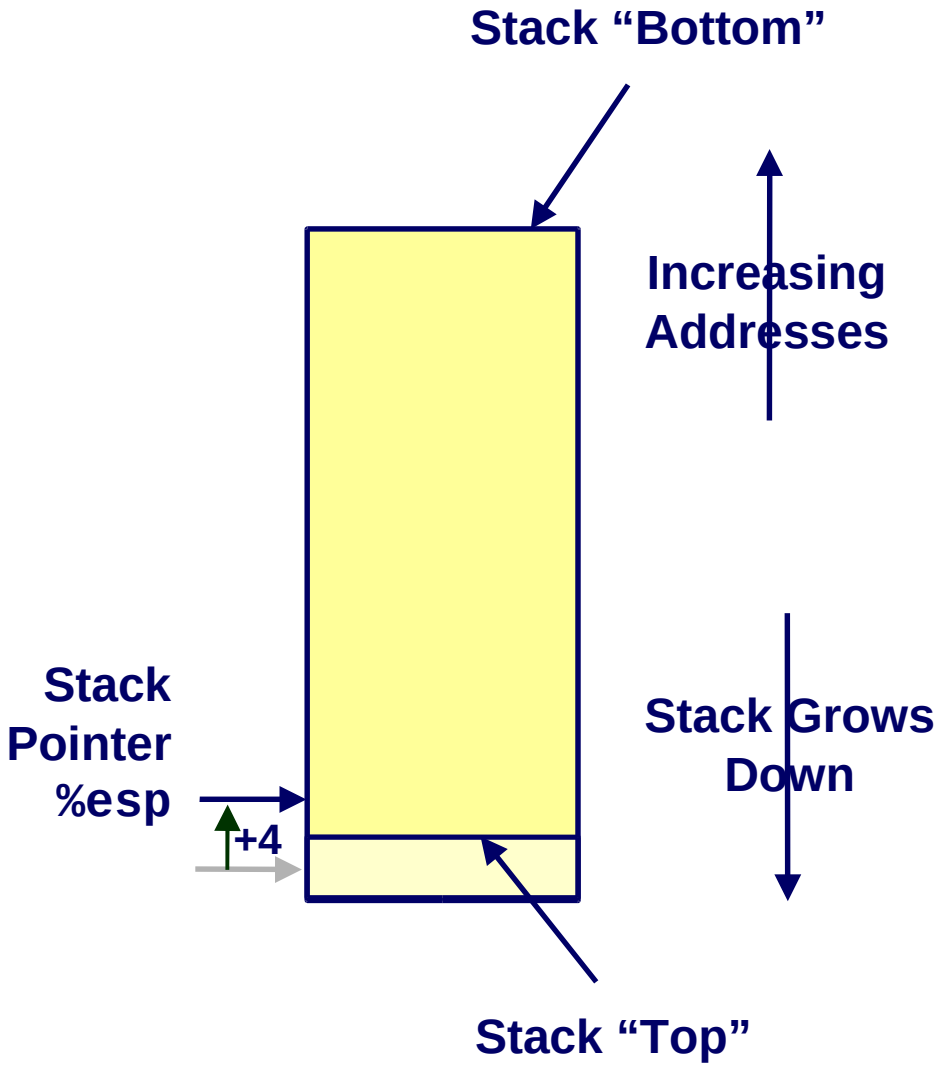
- `pushl` *Src*
- Fetch operand at *Src*
- Decrement %esp by 4
- Write operand at address given by %esp



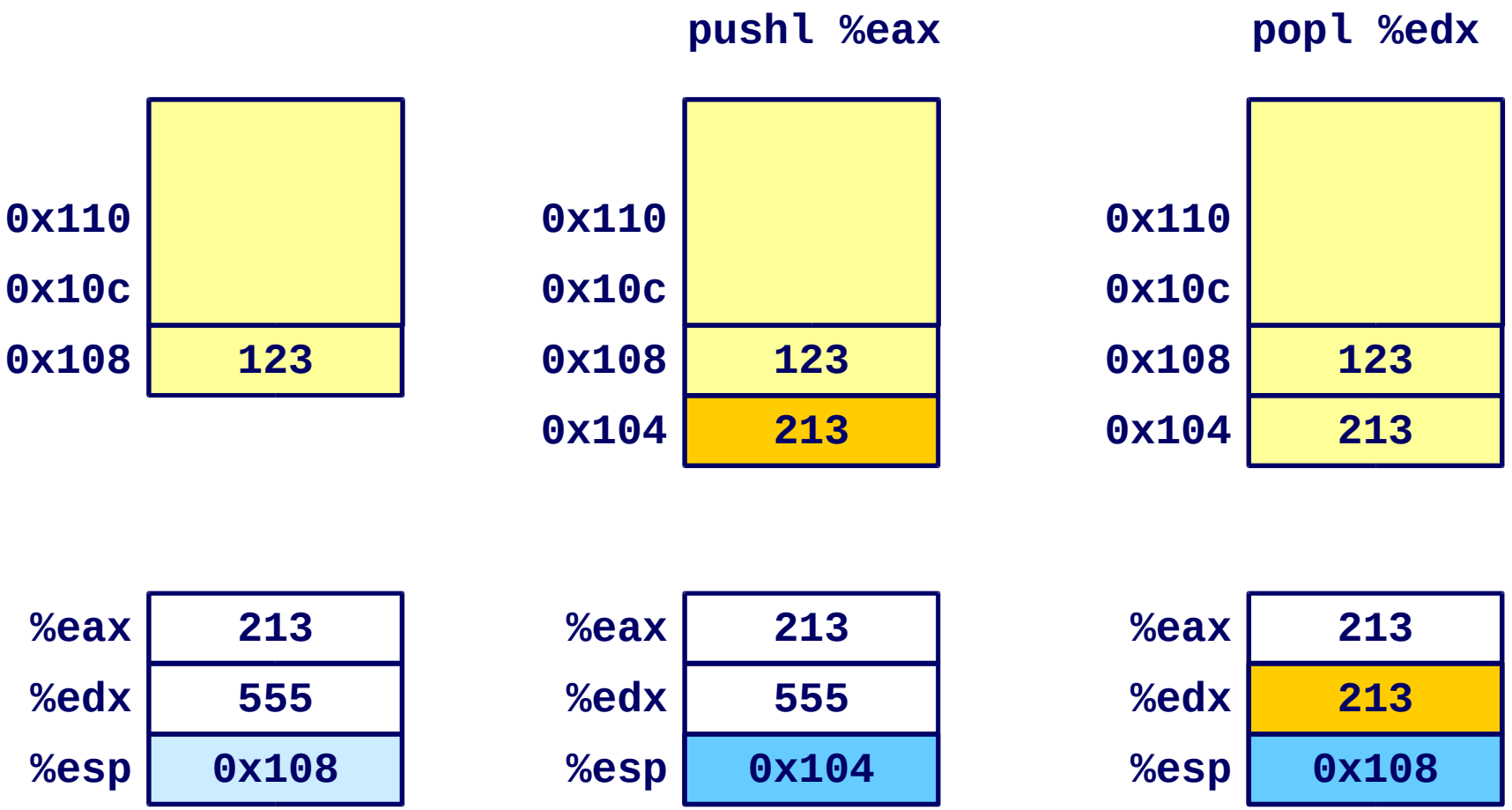
# IA32 Stack Popping

## Popping

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



# Stack Operation Examples



# 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

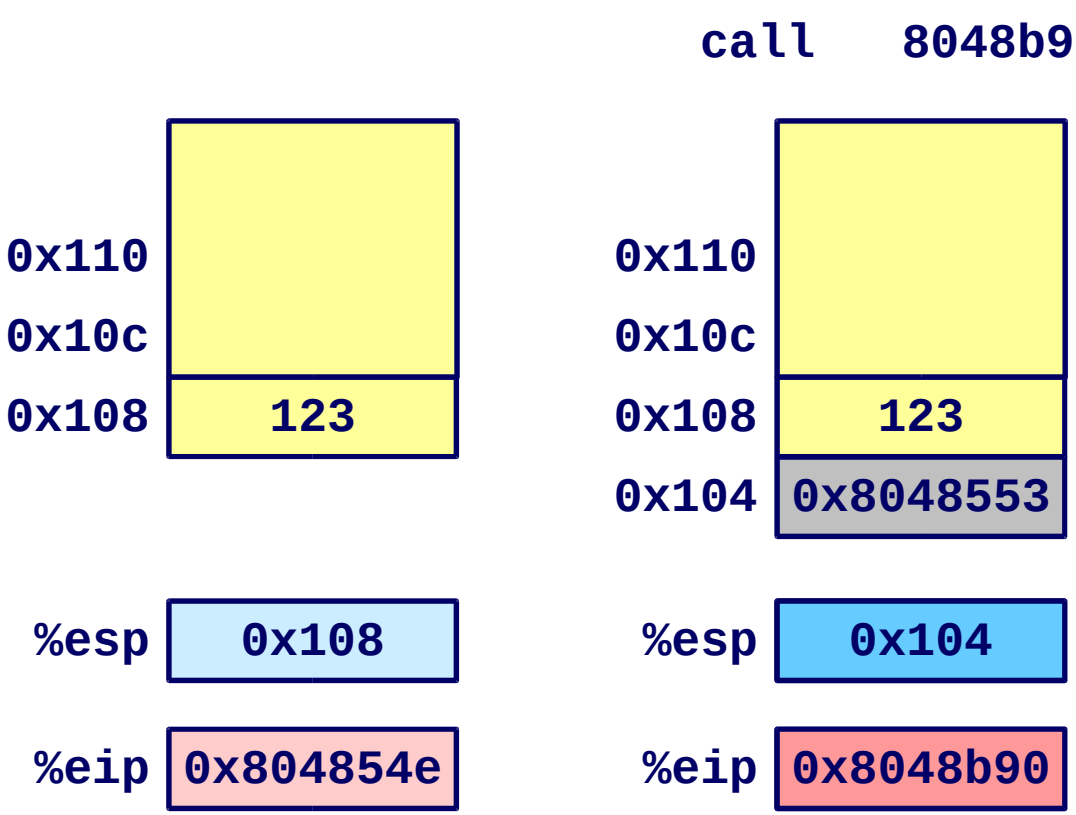
- Address of instruction beyond `call`
- Example from disassembly
- `804854e: e8 3d 06 00 00 call 8048b90 <main>`
- `8048553: 50 pushl %eax`
  - Return address = `0x8048553`

## Procedure return:

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

# Procedure Call Example

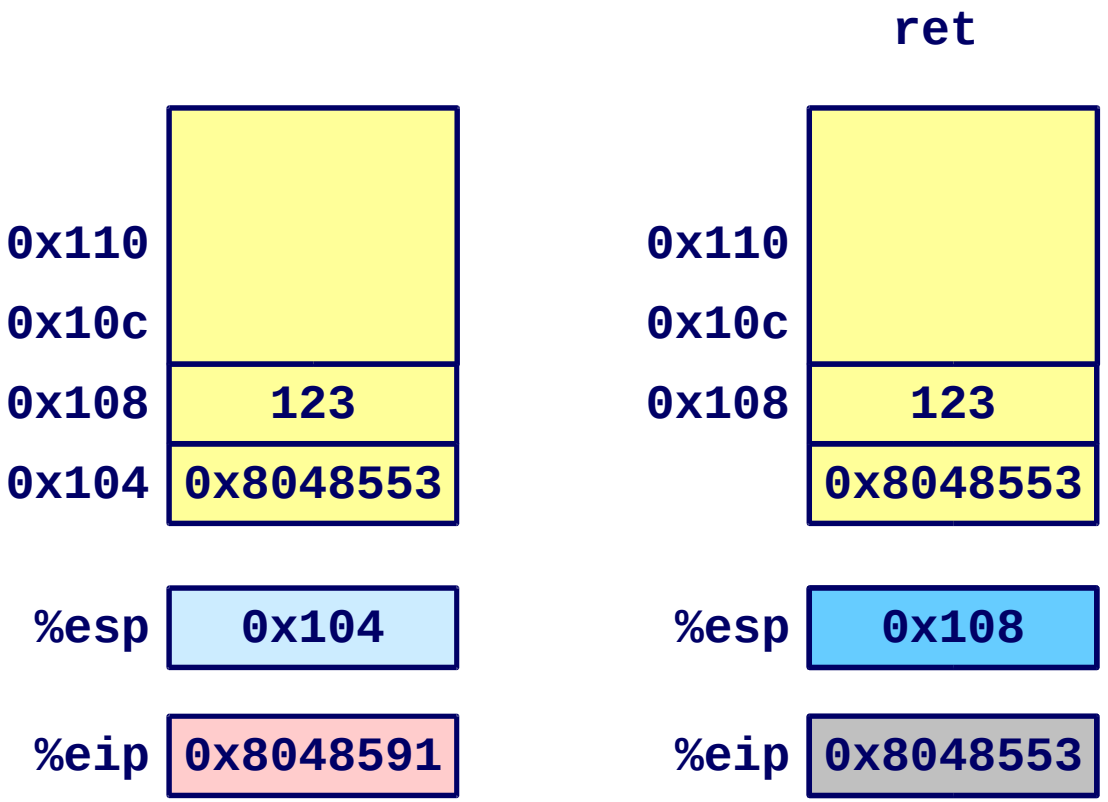
```
804854e:  e8 3d 06 00 00        call   8048b90 <main>
8048553:  50                    pushl  %eax
```




**%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 simultaneous instantiations of single procedure
- Need some place to store state of each instantiation
  - Arguments
  - Local variables
  - Return pointer

## Stack Discipline

- State for given procedure needed for limited time
  - From when called to when return
- Callee returns before caller does

## Stack Allocated in *Frames*

- state for single procedure instantiation

# Call Chain Example

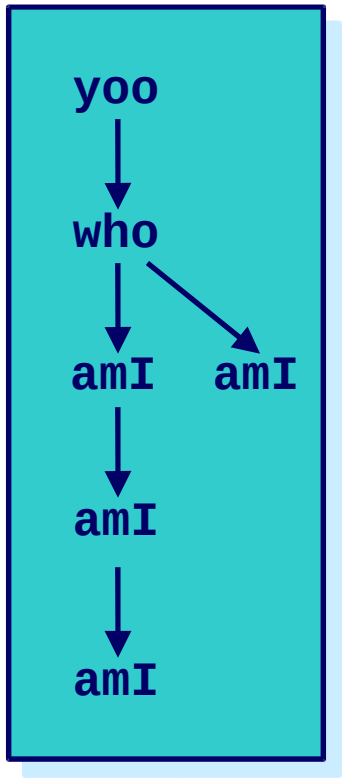
## Code Structure

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

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

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

## Call Chain

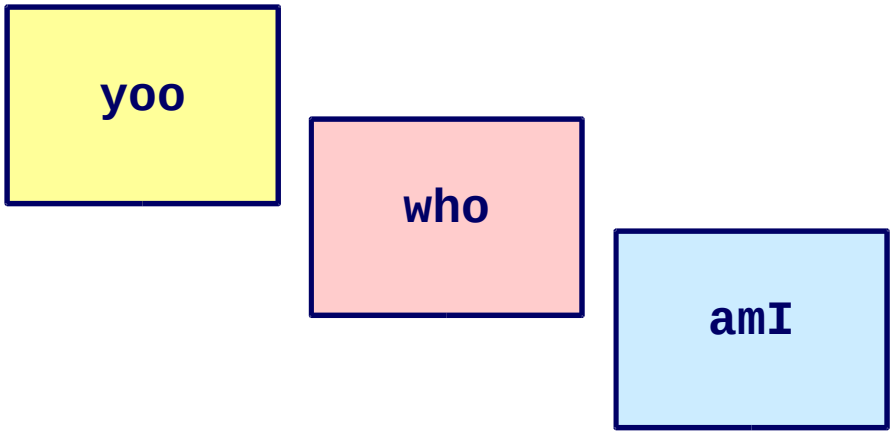



- **Procedure amI recursive**

# Stack Frames

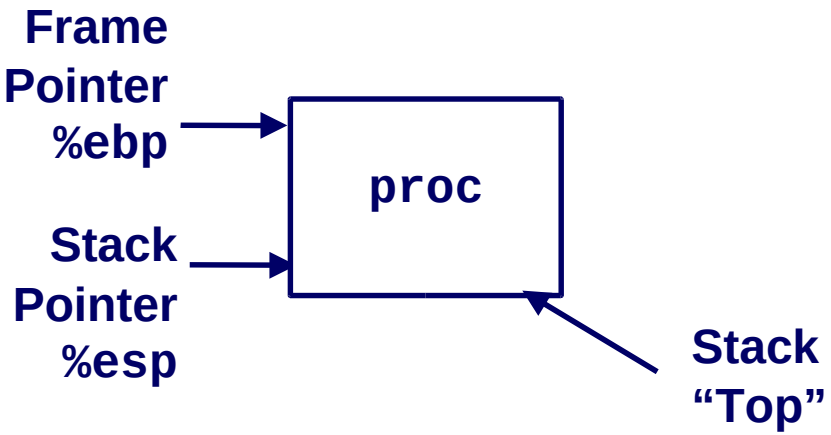
## Contents

- 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

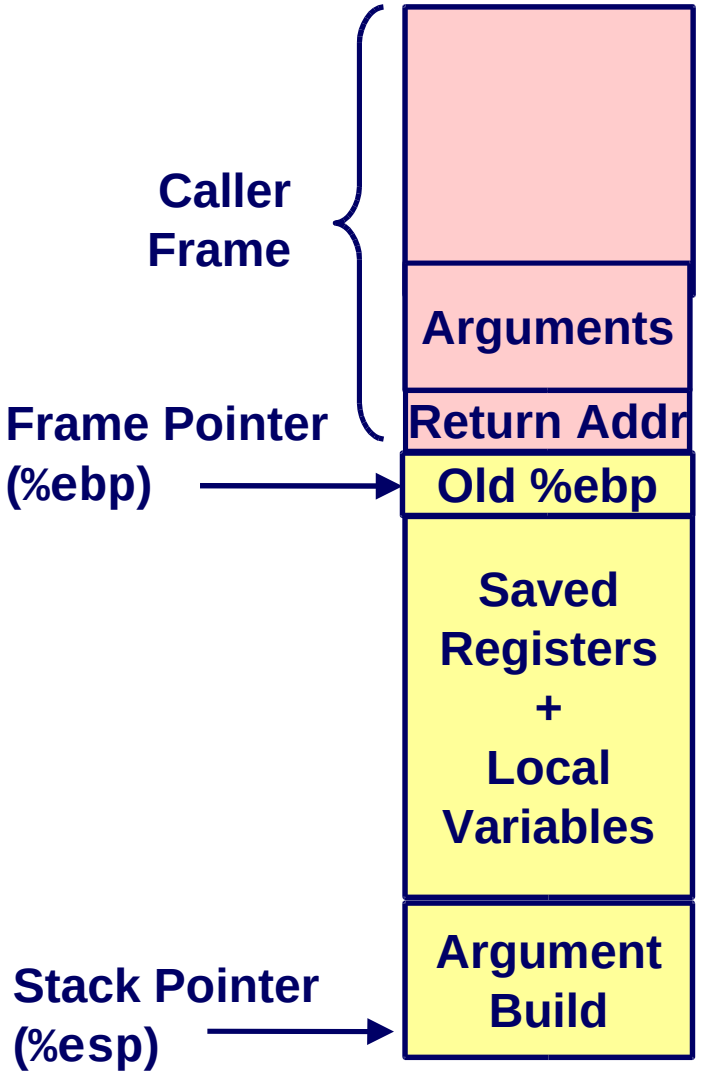
# IA32/Linux Stack Frame

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

- Parameters for function about to call
  - "Argument build"
- Local variables
  - If can't keep in registers
- Saved register context
- Old frame pointer

## Caller Stack Frame

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



# swap

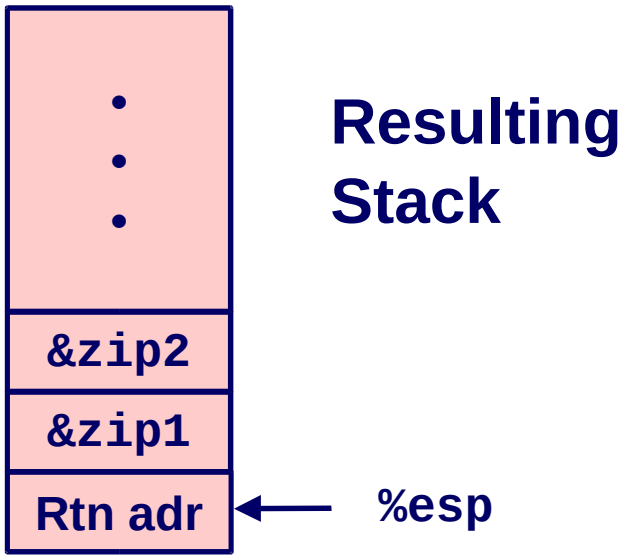
```
int zip1 = 15213;
int zip2 = 91125;

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

    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
```

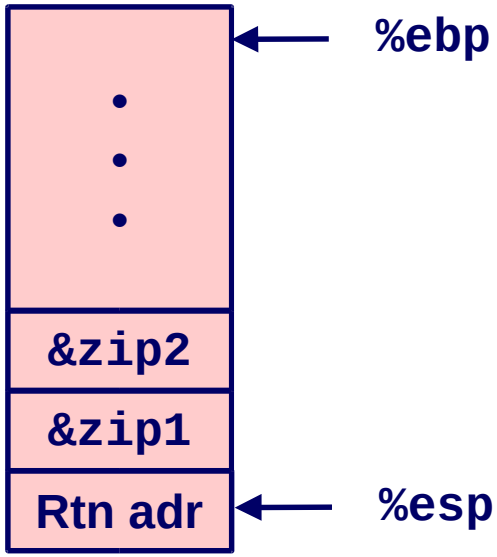
Set Up

Body

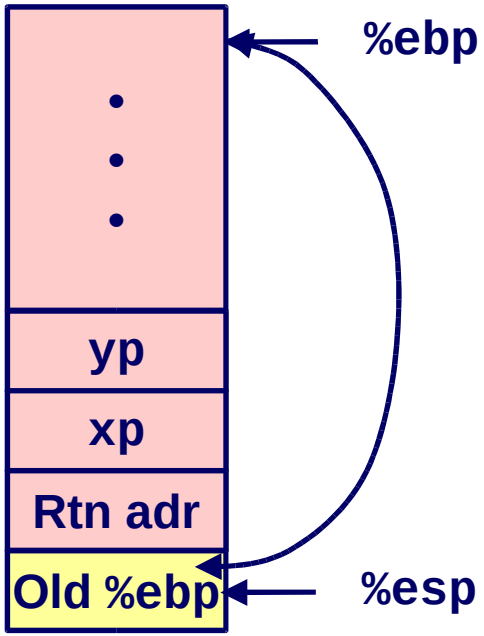
Finish

# swap Setup #1

**Entering Stack**



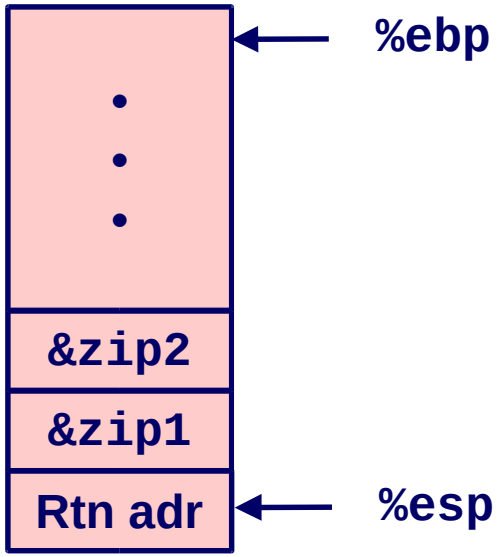

**Resulting Stack**



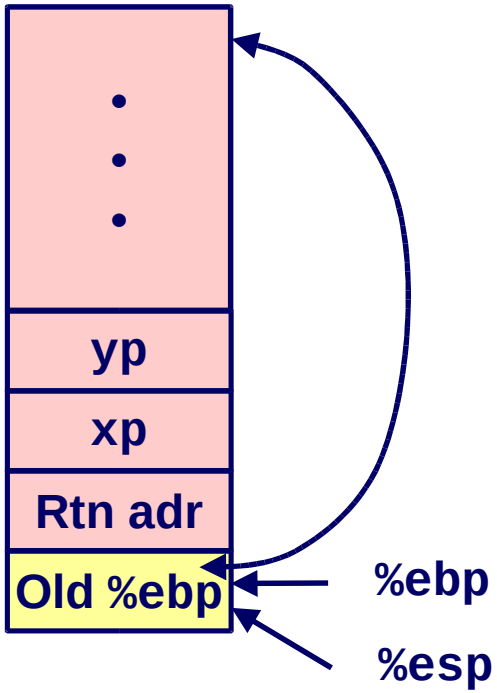

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

# swap Setup #2

**Entering Stack**



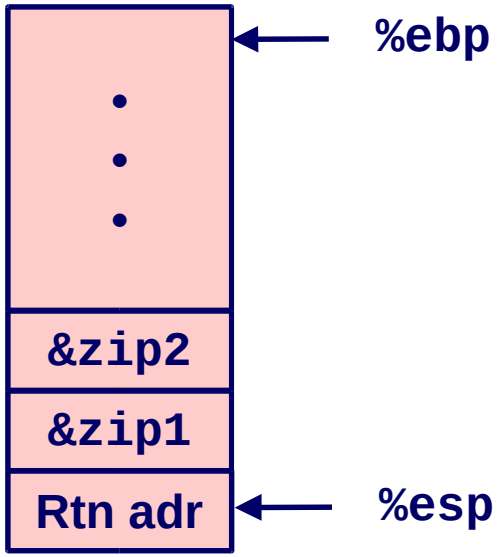

**Resulting Stack**



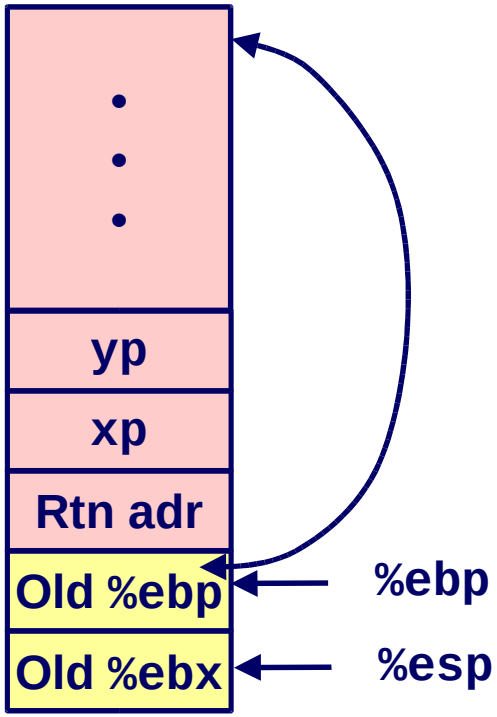

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

# swap Setup #3

**Entering Stack**

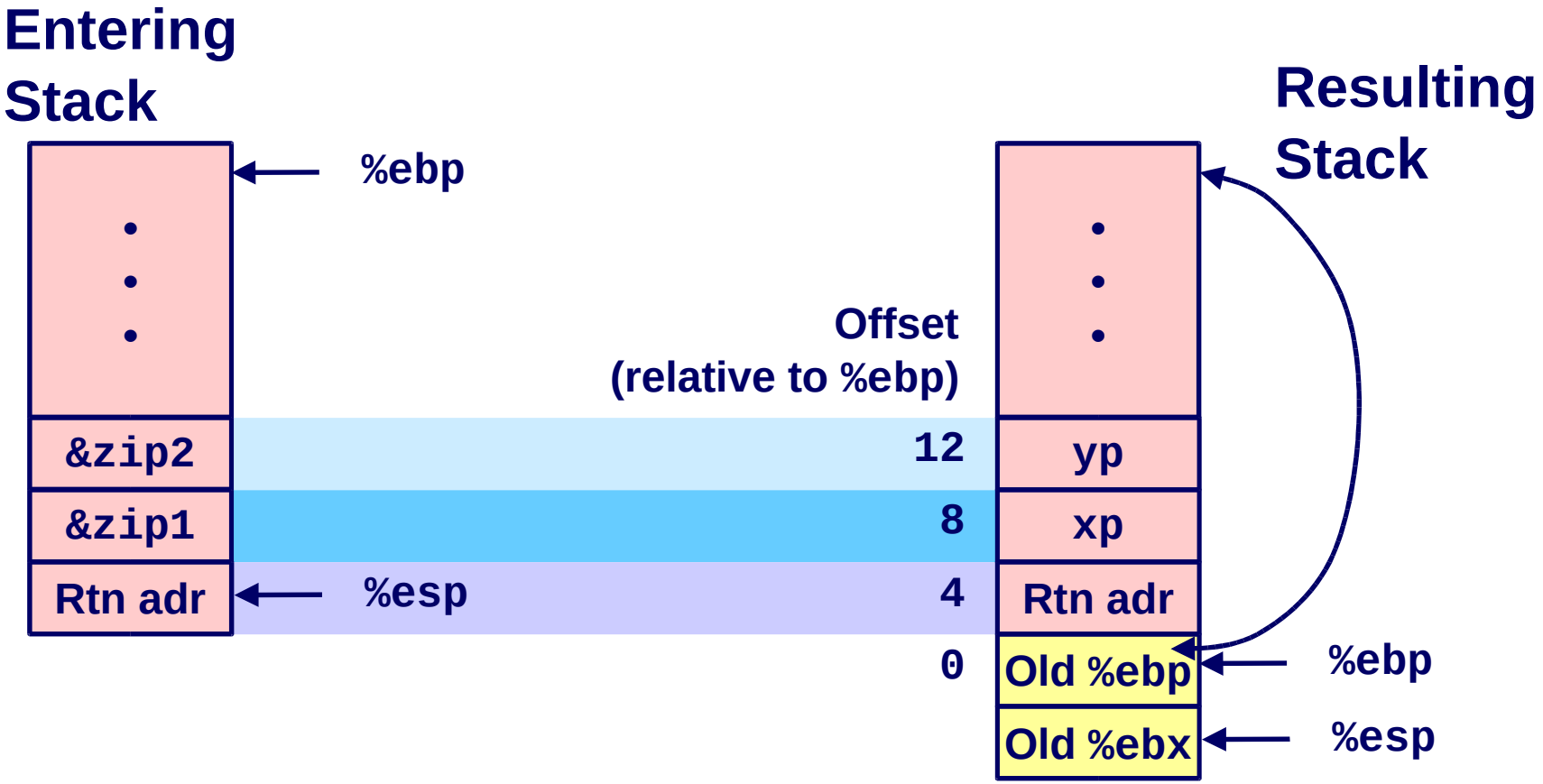



**Resulting Stack**




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

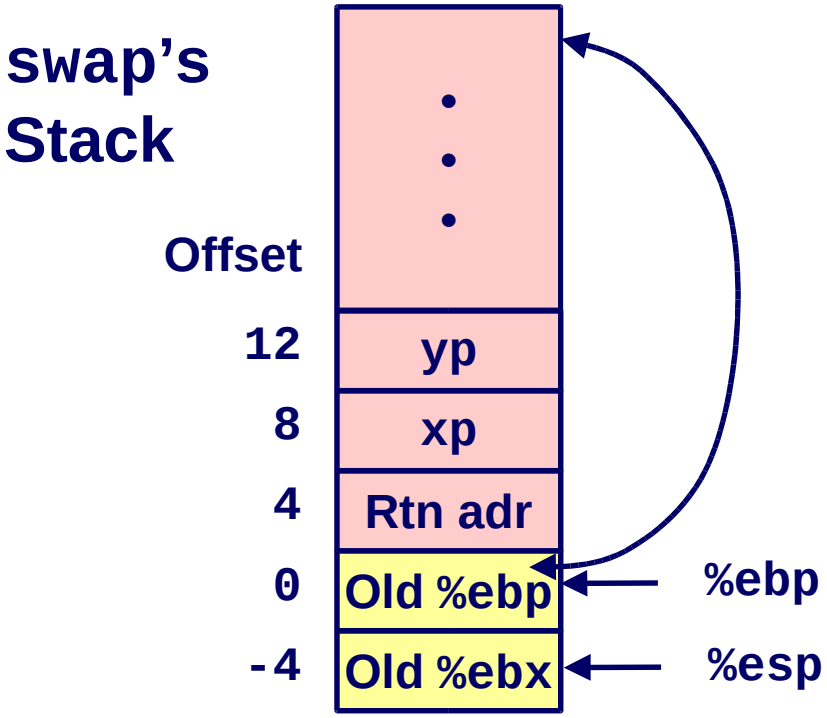
# Effect of swap Setup

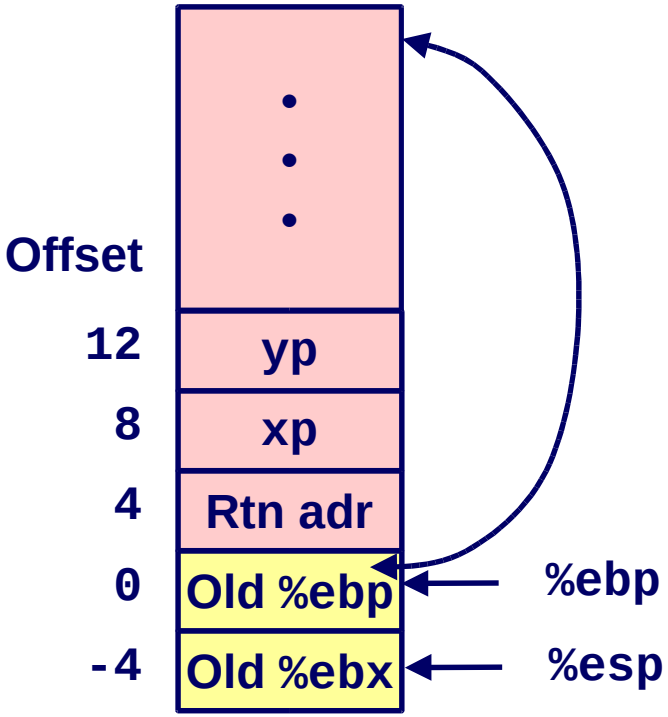



```
movl 12(%ebp),%ecx # get yp
movl 8(%ebp),%edx  # get xp
. . .
```

} Body

# swap Finish #1



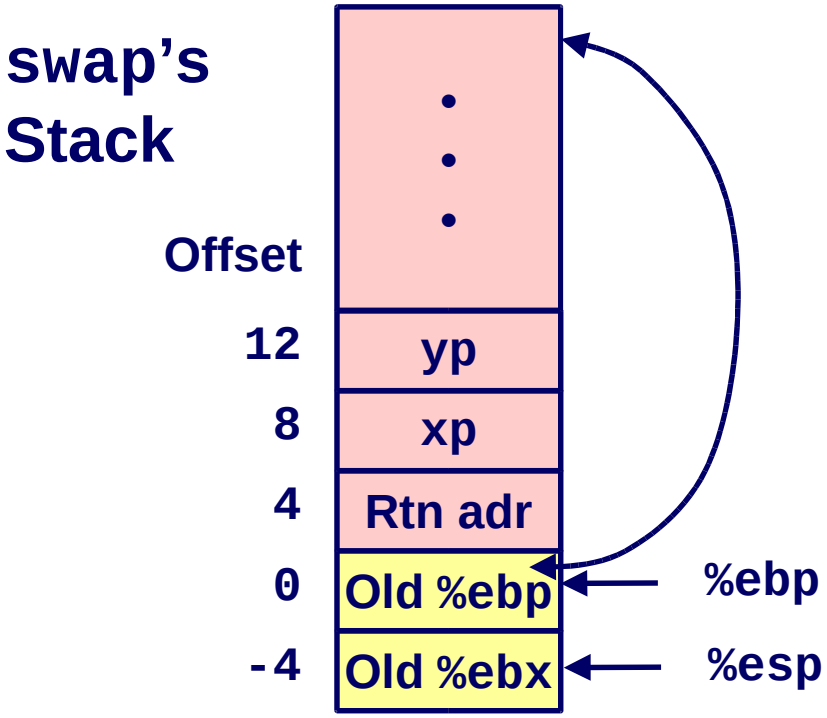



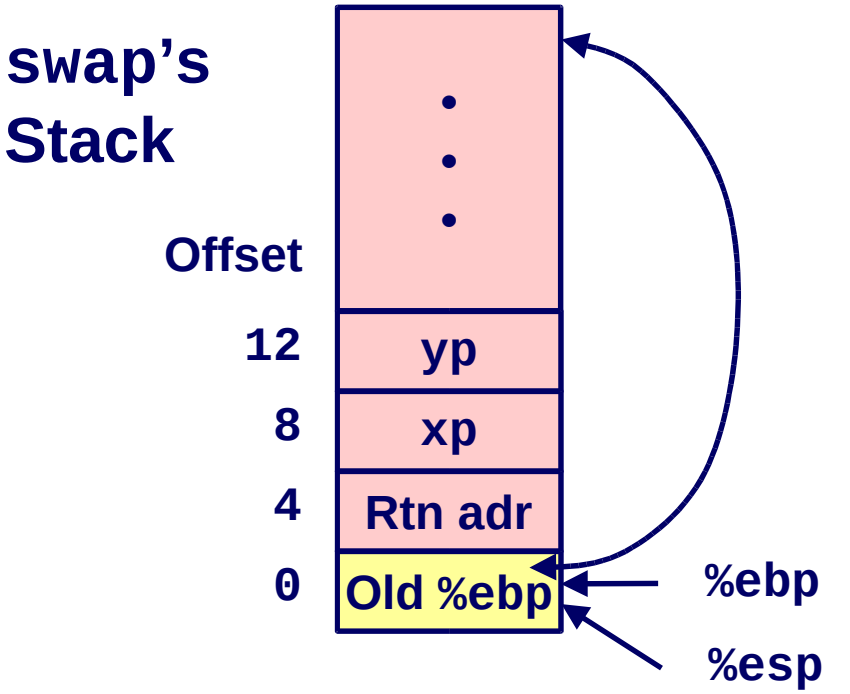

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

## Observation

- Saved & restored register %ebx

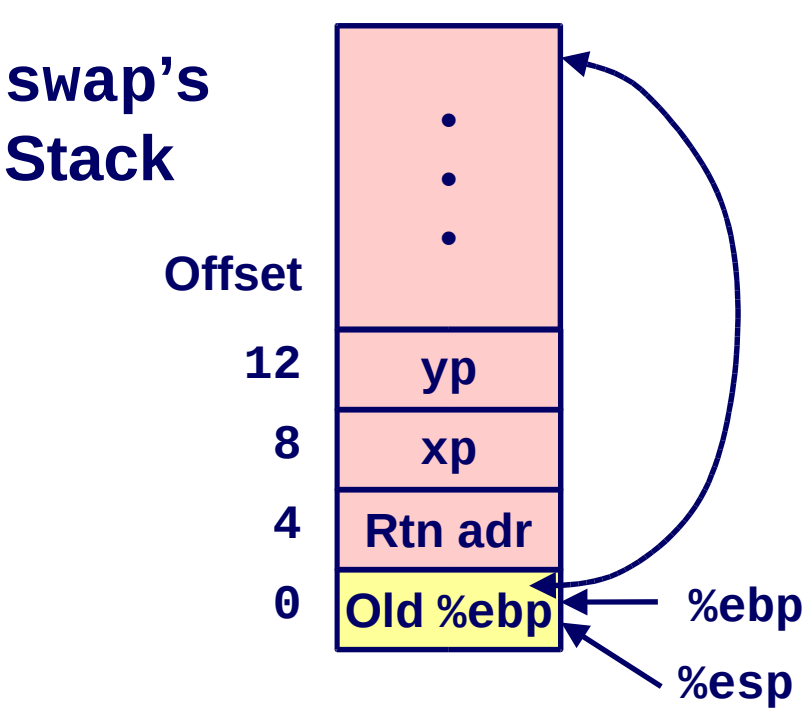
# swap Finish #2

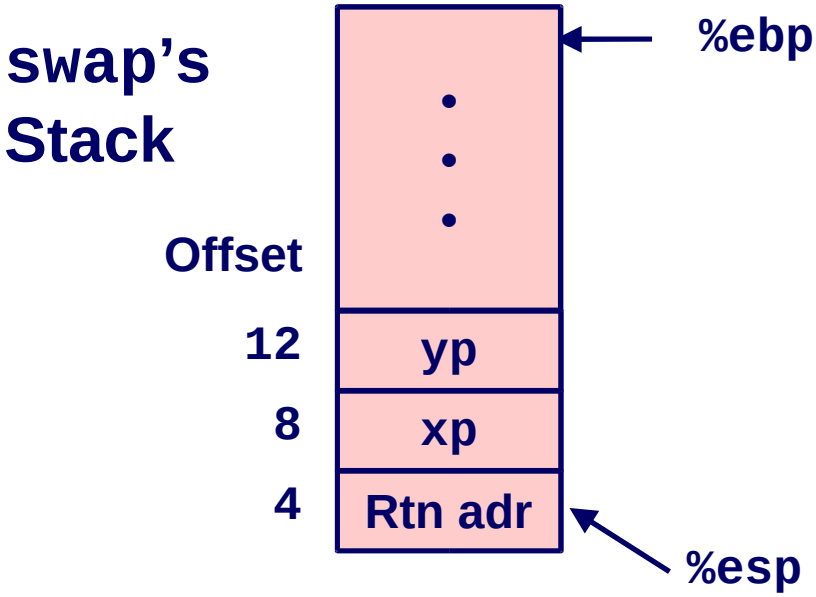



```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

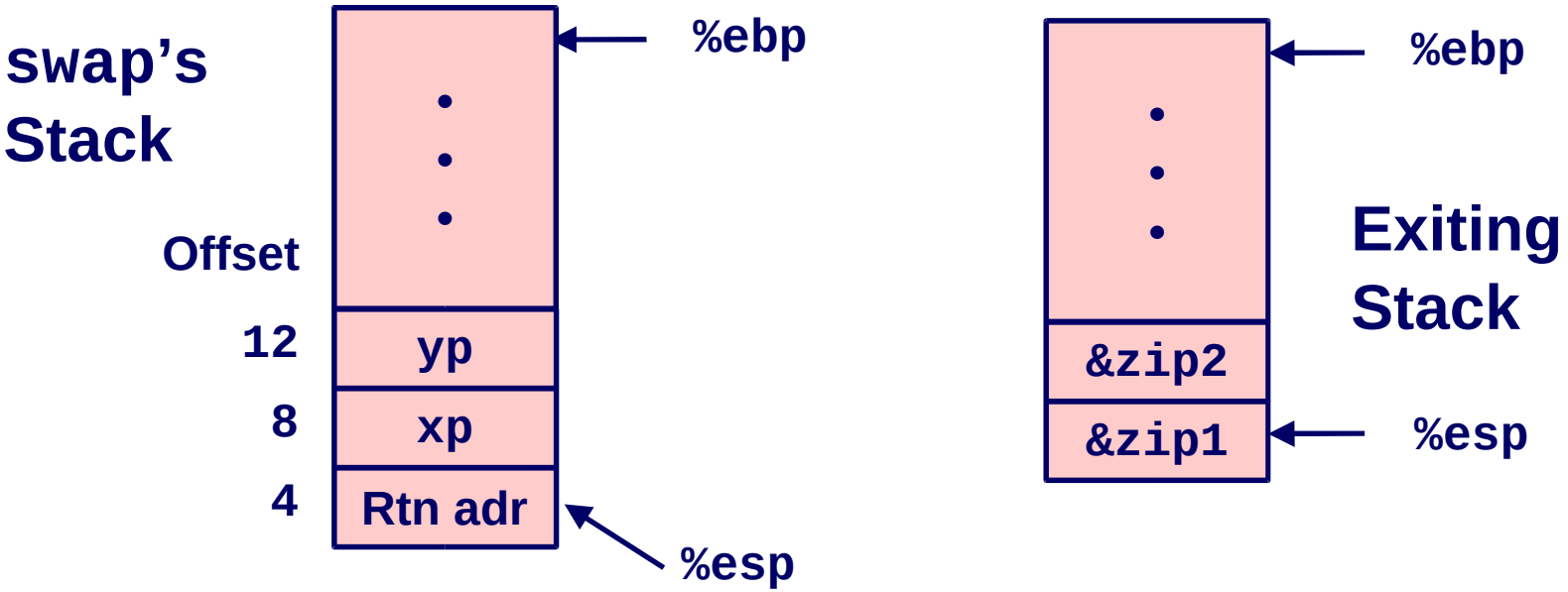
# swap Finish #3




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

# swap Finish #4




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

## Observation

- Saved & restored 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 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 Register be Used for Temporary Storage?**

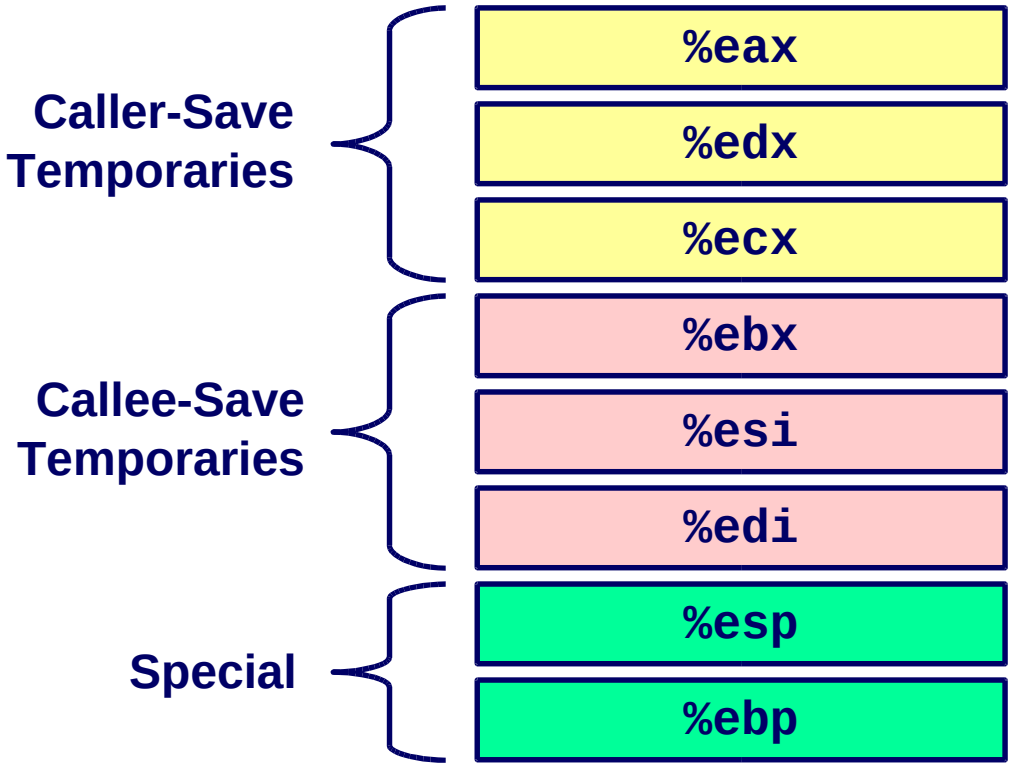
**Conventions**

- **“Caller Save”**
  - **Caller saves temporary in its frame before calling**
- **“Callee Save”**
  - **Callee saves temporary in its frame before using**

# 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 stores returned value



# Stack Summary

## The 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 Combination of Instructions + Conventions

- Call / Ret instructions
- Register usage conventions
  - Caller / Callee save
  - %ebp and %esp
- Stack frame organization conventions

# 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 (1);
}
```

# 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(1)`" ?**

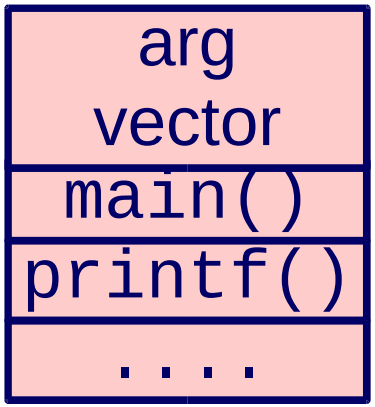
- There's no more program to run...right?
- Where does the 1 go?
- How does it get there?

**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”**



# The Mysterious Parts

**What happens when `main()` does "`return(1)`"???**

- Defined to have same effect as "`exit(1)`"

**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

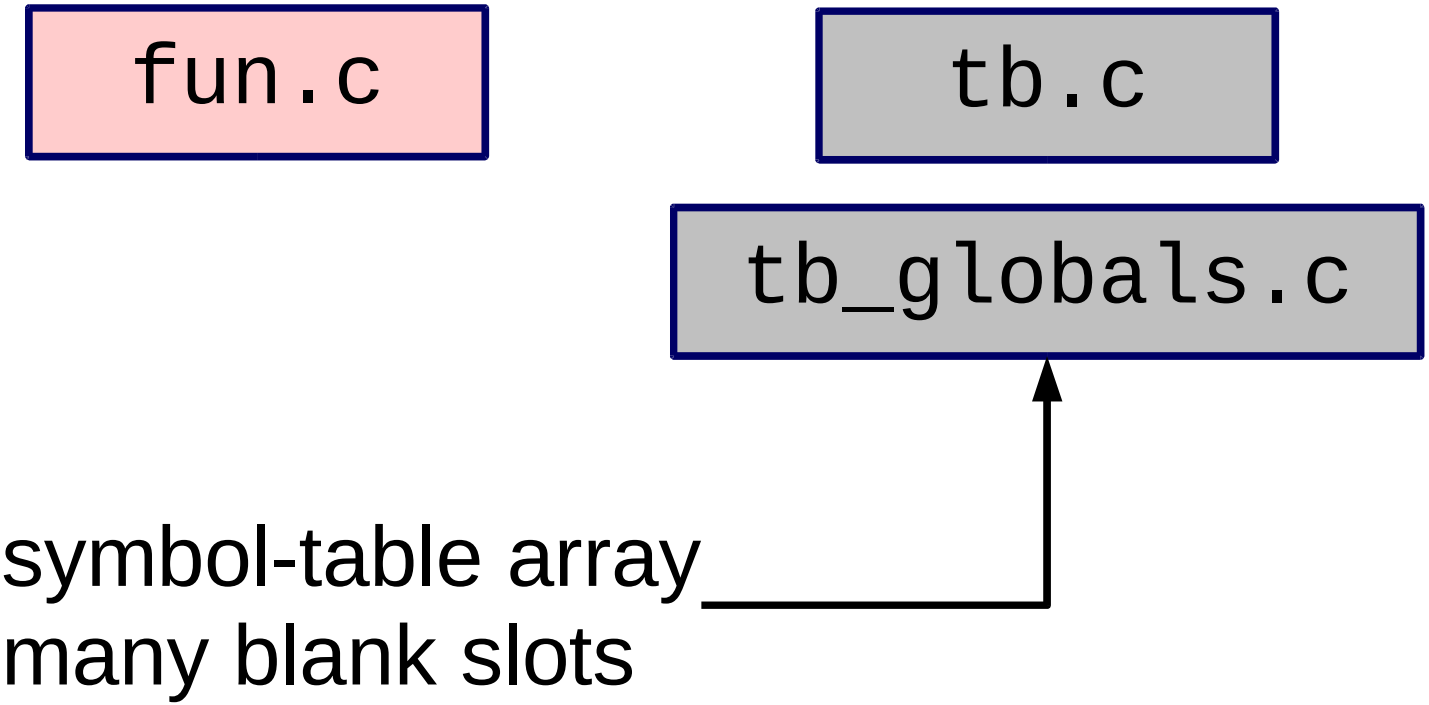
- Can be called by any C function
- Prints stack frames in a symbolic way

```
---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
```

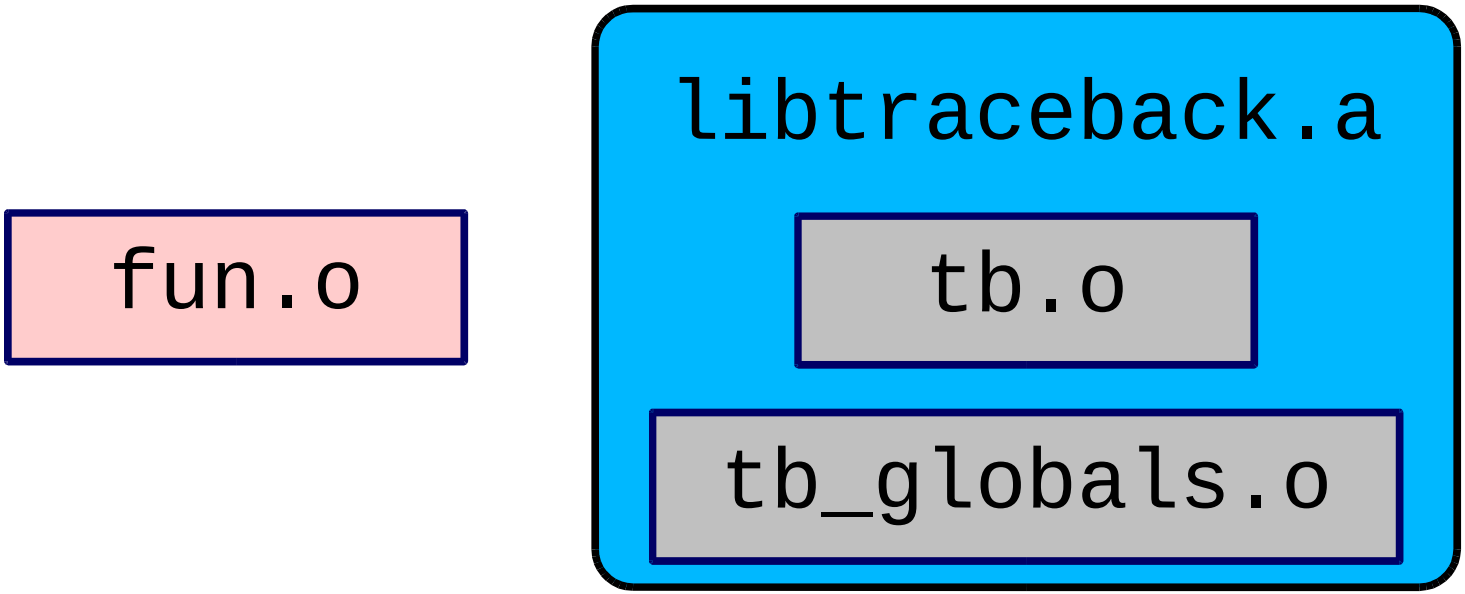
## Key question

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

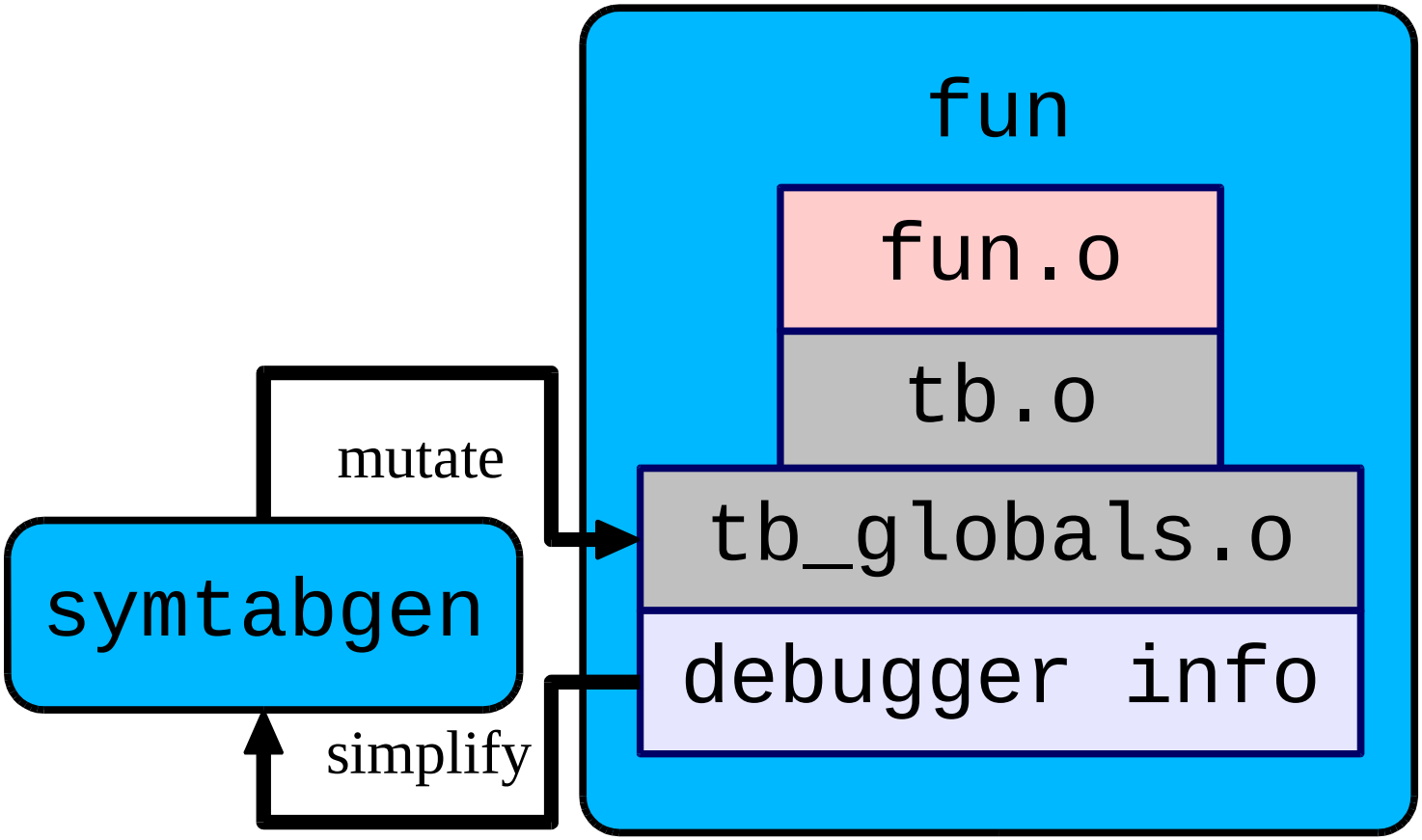
# Project 0 “Data Flow”



# Project 0 “Data Flow”



# Project 0 “Data Flow”



# Summary

**Review of stack knowledge**

**What makes `main()` special**

**Project 0 overview**

**Start interviewing Project 2/3/4 partners!**