Machine-Level Programming III: IA32 Procedures

CS-281: Introduction to Computer Systems

Instructor:
Thomas C. Bressoud

Denison University

Switch Statement Example

```
long switch_eg
   (long x, long y, long z)
{
    long w = 1;
    switch(x) {
    case 1:
        w = y*z;
        break;
    case 2:
        w = y/z;
        /* Fall Through */
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;
    }
    return w;
}
```

- Multiple case labels
  - Here: 5 & 6
- Fall through cases
  - Here: 2
- Missing cases
  - Here: 4

Jump Table Structure

Switch Form

```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1
    • • •
  case val_n-1:
    Block n–1
}
```

Jump Table

```
jtab: Targ0
      Targ1
      Targ2
        •
        •
        •
      Targn-1
```

Jump Targets

```
Targ0:   Code Block 0
Targ1:   Code Block 1
Targ2:   Code Block 2
   •
   •
   •
Targn-1: Code Block n–1
```

Approximate Translation

```
target = JTab[x];
goto *target;
```


Switch Statement Example (IA32)

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

What range of values takes default?

Setup:

```
switch_eg:
   pushl   %ebp             # Setup
   movl    %esp, %ebp       # Setup
   movl    8(%ebp), %eax    # %eax = x
   cmpl    $6, %eax         # Compare x:6
   ja      .L2              # If unsigned > goto default
   jmp     *.L7(,%eax,4)    # Goto *JTab[x]
```

Note that **w** not initialized here

Switch Statement Example (IA32)

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

Jump table

```
.section    .rodata
  .align 4
.L7:
  .long     .L2 # x = 0
  .long     .L3 # x = 1
  .long     .L4 # x = 2
  .long     .L5 # x = 3
  .long     .L2 # x = 4
  .long     .L6 # x = 5
  .long     .L6 # x = 6
```

Setup:

```
switch_eg:
   pushl   %ebp            # Setup
   movl    %esp, %ebp      # Setup
   movl    8(%ebp), %eax   # eax = x
   cmpl    $6, %eax        # Compare x:6
   ja      .L2             # If unsigned > goto default
   jmp     *.L7(,%eax,4)   # Goto *JTab[x]
```

Indirect jump

Assembly Setup Explanation

- **Table Structure**
  - Each target requires 4 bytes
  - Base address at **.L7**

- **Jumping**
  - **Direct: jmp .L2**
  - Jump target is denoted by label .L2

  - **Indirect: jmp *.L7(,%eax,4)**
  - Start of jump table: **.L7**
  - Must scale by factor of 4 (labels have 32-bits = 4 Bytes on IA32)
  - Fetch target from effective Address **.L7 + eax*4**
    - Only for $0 \le \mathbf{x} \le 6$

Jump table

```
.section    .rodata
  .align 4
.L7:
  .long     .L2 # x = 0
  .long     .L3 # x = 1
  .long     .L4 # x = 2
  .long     .L5 # x = 3
  .long     .L2 # x = 4
  .long     .L6 # x = 5
  .long     .L6 # x = 6
```

Jump Table

Jump table

```
.section   .rodata
  .align 4
.L7:
  .long    .L2 # x = 0
  .long    .L3 # x = 1
  .long    .L4 # x = 2
  .long    .L5 # x = 3
  .long    .L2 # x = 4
  .long    .L6 # x = 5
  .long    .L6 # x = 6
```

```
switch(x) {
case 1:        // .L3
     w = y*z;
     break;
case 2:        // .L4
     w = y/z;
     /* Fall Through */
case 3:        // .L5
     w += z;
     break;
case 5:
case 6:        // .L6
     w -= z;
     break;
default:       // .L2
     w = 2;
}
```


Handling Fall-Through

```
long w = 1;
   . . .
switch(x) {
   . . .
case 2:
     w = y/z;
     /* Fall Through */
case 3:
     w += z;
     break;
   . . .
}
```

```
case 3:
        w = 1;
        goto merge;
```

```
     case 2:
         w = y/z;
```

```
merge:
         w += z;
```

Code Blocks (Partial)

```
switch(x) {
case 1:       // .L3
      w = y*z;
      break;
 . . .
case 3:       // .L5
    w += z;
    break;
  . . .
default:      // .L2
    w = 2;
}
```

```
.L2:                 # Default
   movl  $2, %eax    # w = 2
   jmp   .L8         # Goto done

.L5:                 # x == 3
   movl  $1, %eax    # w = 1
   jmp   .L9         # Goto merge

.L3:                 # x == 1
   movl  16(%ebp), %eax  # z
   imull 12(%ebp), %eax  # w = y*z
   jmp   .L8          # Goto done
```


Denison University

Code Blocks (Rest)

```
switch(x) {
  . . .
  case 2:   // .L4
      w = y/z;
      /* Fall Through */
  merge:    // .L9
      w += z;
      break;
  case 5:
  case 6:   // .L6
      w -= z;
      break;
}
```

```
.L4:                 # x == 2
   movl  12(%ebp), %edx
   movl  %edx, %eax
   sarl  $31, %edx
   idivl 16(%ebp)    # w = y/z

.L9:                 # merge:
   addl  16(%ebp), %eax # w += z
   jmp   .L8         # goto done

.L6:                 # x == 5, 6
   movl  $1, %eax         # w = 1
   subl  16(%ebp), %eax # w = 1-z
```

Switch Code (Finish)

```
return w;
```

```
.L8:                # done:
   popl  %ebp
   ret
```

- **Noteworthy Features**
  - Jump table avoids sequencing through cases
    - Constant time, rather than linear
  - Use jump table to handle holes and duplicate tags
  - Use program sequencing to handle fall-through
  - Don't initialize w = 1 unless really need it

IA32 Object Code

- **Setup**
  - Label `.L2` becomes address `0x8048422`
  - Label `.L7` becomes address `0x8048660`

Assembly Code

```
switch_eg:
  . . .
  ja     .L2            # If unsigned > goto default
  jmp    *.L7(,%eax,4)  # Goto *JTab[x]
```

Disassembled Object Code

```
08048410 <switch_eg>:
 . . .
 8048419:77 07                ja     8048422 <switch_eg+0x12>
 804841b:ff 24 85 60 86 04 08 jmp    *0x8048660(,%eax,4)
```

IA32 Object Code (cont.)

- **Jump Table**
  - Doesn't show up in disassembled code
  - Can inspect using GDB
  - `gdb switch`
  - `(gdb) x/7xw 0x8048660`
    - Examine 7 hexadecimal format "words" (4-bytes each)
    - Use command "`help x`" to get format documentation

```
0x8048660:    0x08048422    0x08048432    0x0804843b    0x08048429
0x8048670:    0x08048422    0x0804844b    0x0804844b
```


IA32 Object Code (cont.)

- **Deciphering Jump Table**

```
0x8048660:    0x08048422    0x08048432    0x0804843b    0x08048429
0x8048670:    0x08048422    0x0804844b    0x0804844b
```

Address	Value	x
0x8048660	0x8048422	0
0x8048664	0x8048432	1
0x8048668	0x804843b	2
0x804866c	0x8048429	3
0x8048670	0x8048422	4
0x8048674	0x804844b	5
0x8048678	0x804844b	6

Disassembled Targets

```
8048422:   b8 02 00 00 00       mov    $0x2,%eax
8048427:   eb 2a                jmp    8048453 <switch_eg+0x43>
8048429:   b8 01 00 00 00       mov    $0x1,%eax
804842e:   66 90                xchg   %ax,%ax # noop
8048430:   eb 14                jmp    8048446 <switch_eg+0x36>
8048432:   8b 45 10             mov    0x10(%ebp),%eax
8048435:   0f af 45 0c          imul   0xc(%ebp),%eax
8048439:   eb 18                jmp    8048453 <switch_eg+0x43>
804843b:   8b 55 0c             mov    0xc(%ebp),%edx
804843e:   89 d0                mov    %edx,%eax
8048440:   c1 fa 1f             sar    $0x1f,%edx
8048443:   f7 7d 10             idivl  0x10(%ebp)
8048446:   03 45 10             add    0x10(%ebp),%eax
8048449:   eb 08                jmp    8048453 <switch_eg+0x43>
804844b:   b8 01 00 00 00       mov    $0x1,%eax
8048450:   2b 45 10             sub    0x10(%ebp),%eax
8048453:   5d                   pop    %ebp
8048454:   c3                   ret
```


Matching Disassembled Targets

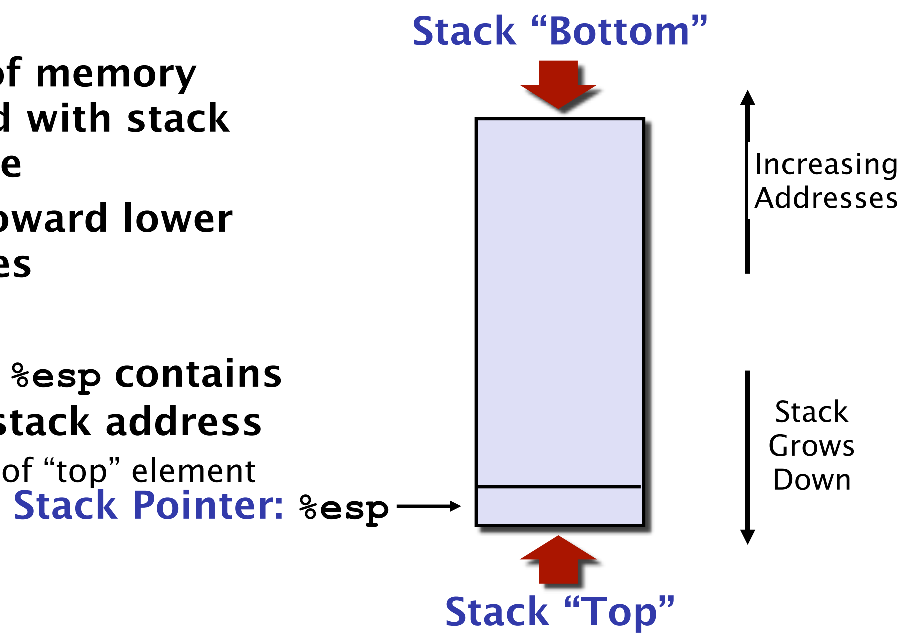
Value
0x8048422
0x8048432
0x804843b
0x8048429
0x8048422
0x804844b
0x804844b

```
8048422:   mov    $0x2,%eax
8048427:   jmp    8048453 <switch_eg+0x43>
8048429:   mov    $0x1,%eax
804842e:   xchg   %ax,%ax
8048430:   jmp    8048446 <switch_eg+0x36>
8048432:   mov    0x10(%ebp),%eax
8048435:   imul   0xc(%ebp),%eax
8048439:   jmp    8048453 <switch_eg+0x43>
804843b:   mov    0xc(%ebp),%edx
804843e:   mov    %edx,%eax
8048440:   sar    $0x1f,%edx
8048443:   idivl  0x10(%ebp)
8048446:   add    0x10(%ebp),%eax
8048449:   jmp    8048453 <switch_eg+0x43>
804844b:   mov    $0x1,%eax
8048450:   sub    0x10(%ebp),%eax
8048453:   pop    %ebp
8048454:   ret
```

IA32 Stack

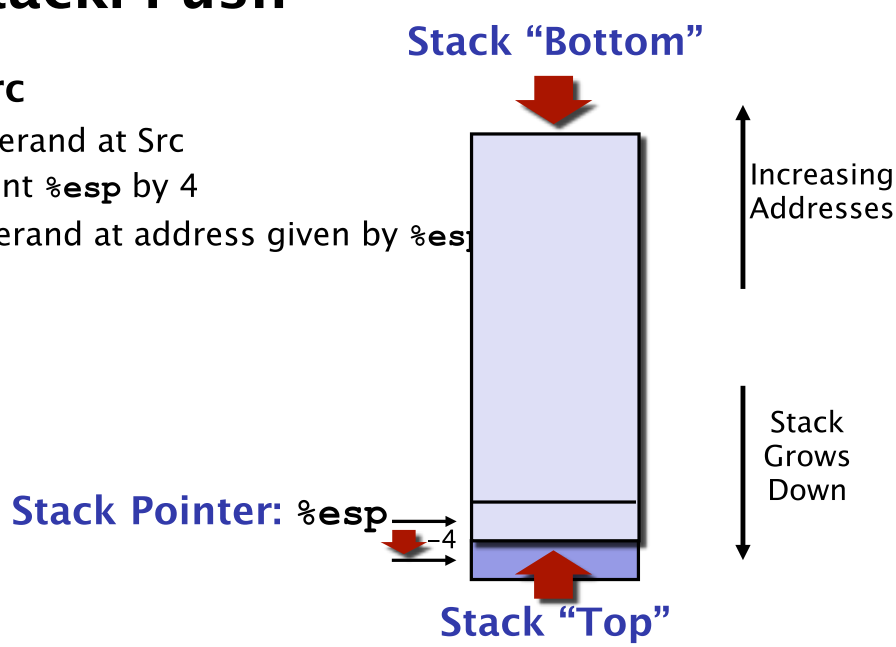
- **Region of memory managed with stack discipline**
- **Grows toward lower addresses**

- **Register `%esp` contains lowest stack address**
  - address of "top" element

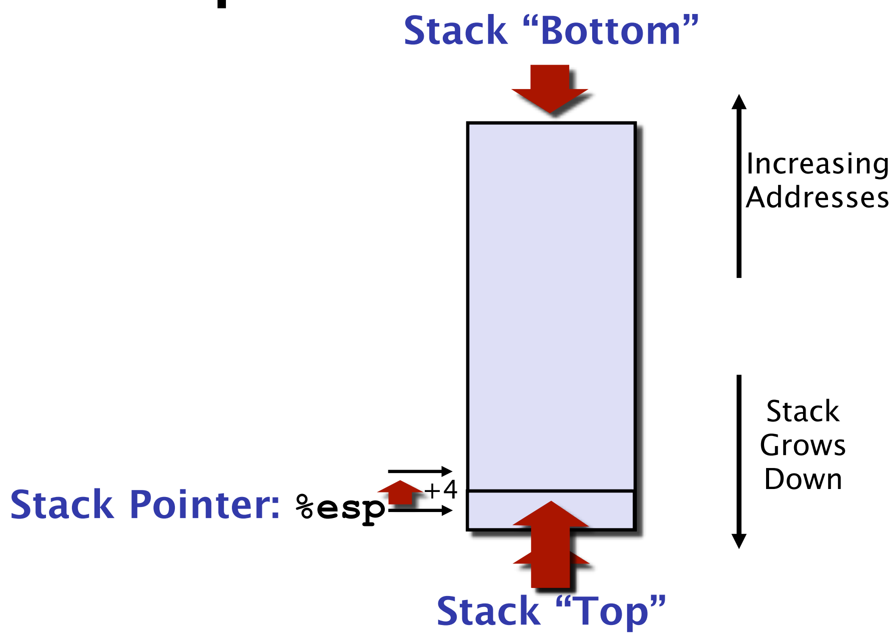


IA32 Stack: Push

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



IA32 Stack: Pop



Procedure Control Flow

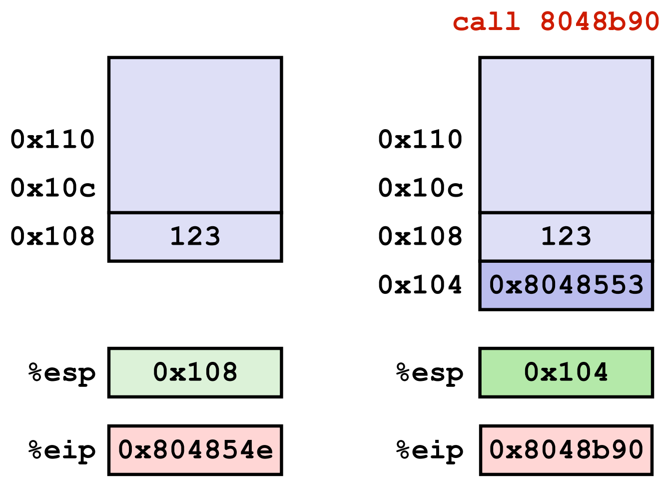
- **Use stack to support procedure call and return**
- **Procedure call: `call label`**
  - Push return address on stack
  - Jump to **label**
- **Return address:**
  - Address of the next instruction right after call
  - Example from disassembly

```
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

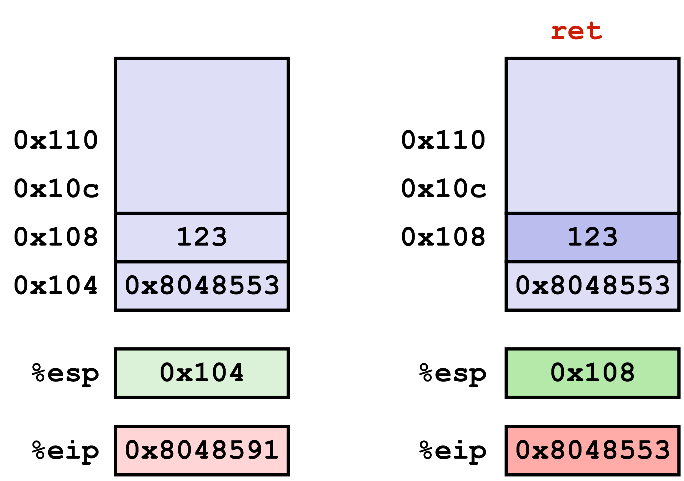
```
804854e:      e8 3d 06 00 00          call    8048b90 <main>
8048553:      50                      pushl   %eax
```



%eip: program counter

Procedure Return Example

```
8048591:      c3                      ret
```



%eip: 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

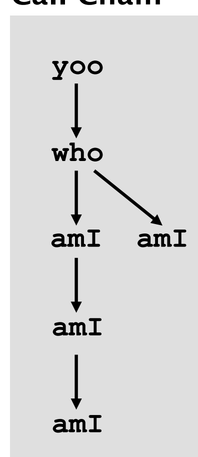
Call Chain Example

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

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

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

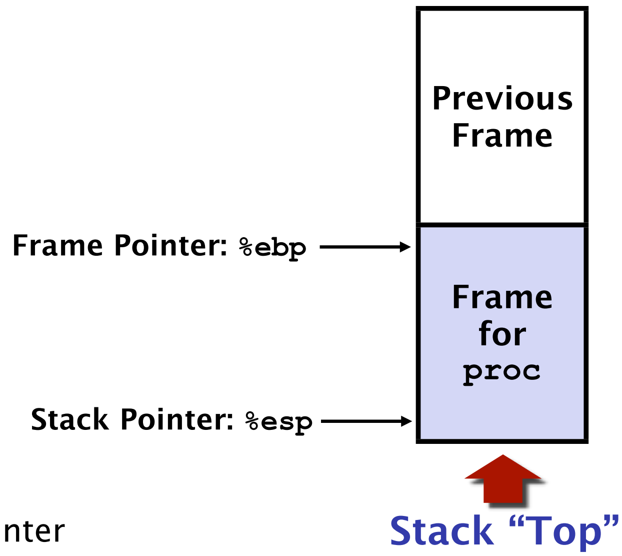
Example Call Chain



Procedure `amI()` is recursive

Stack Frames

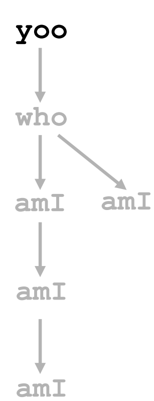
- **Contents**
  - Local variables
  - Return information
  - Temporary space

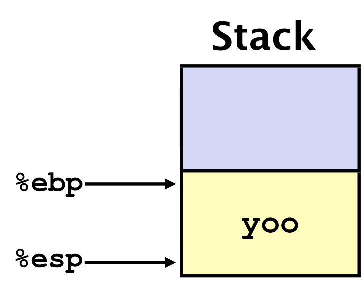


- **Management**
  - Space allocated when enter procedure
    - "Set-up" code
  - Deallocated when return
    - "Finish" code

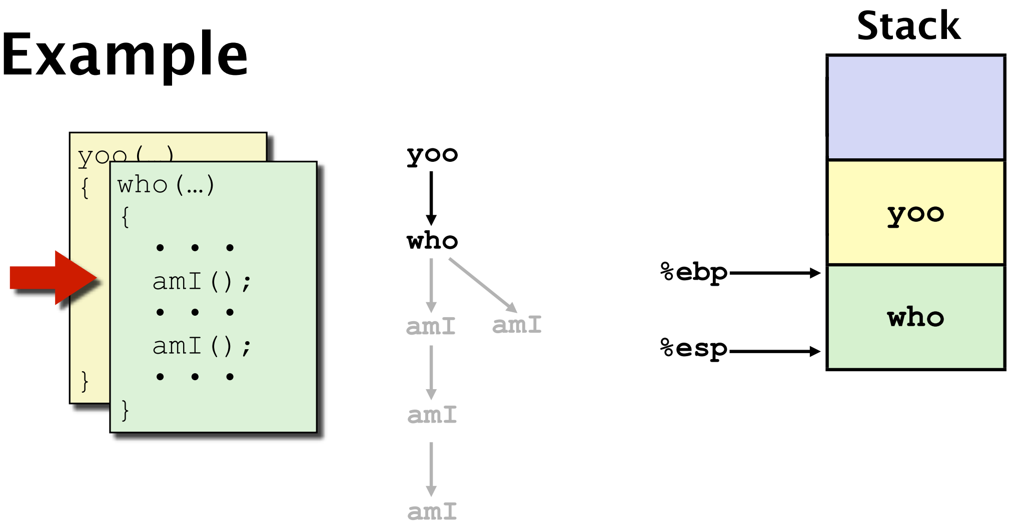
Example

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

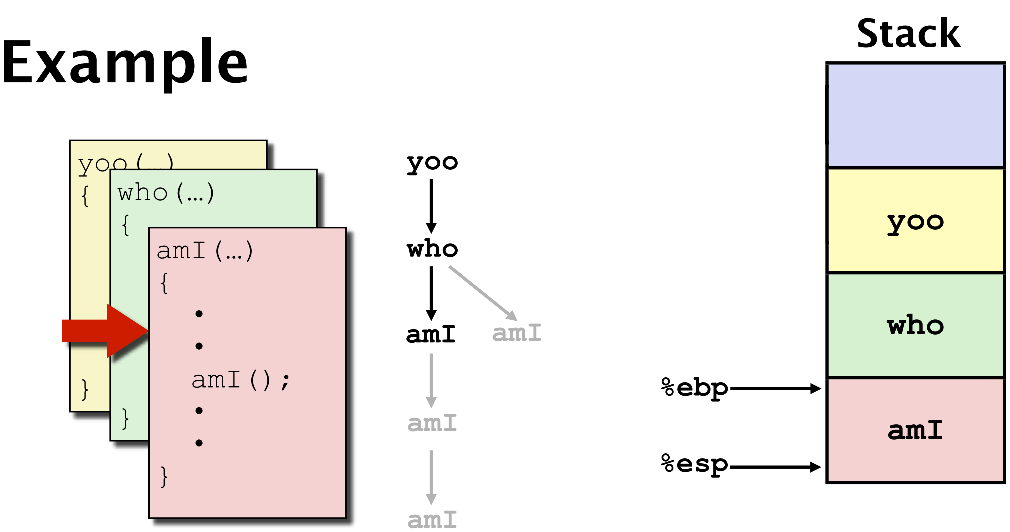




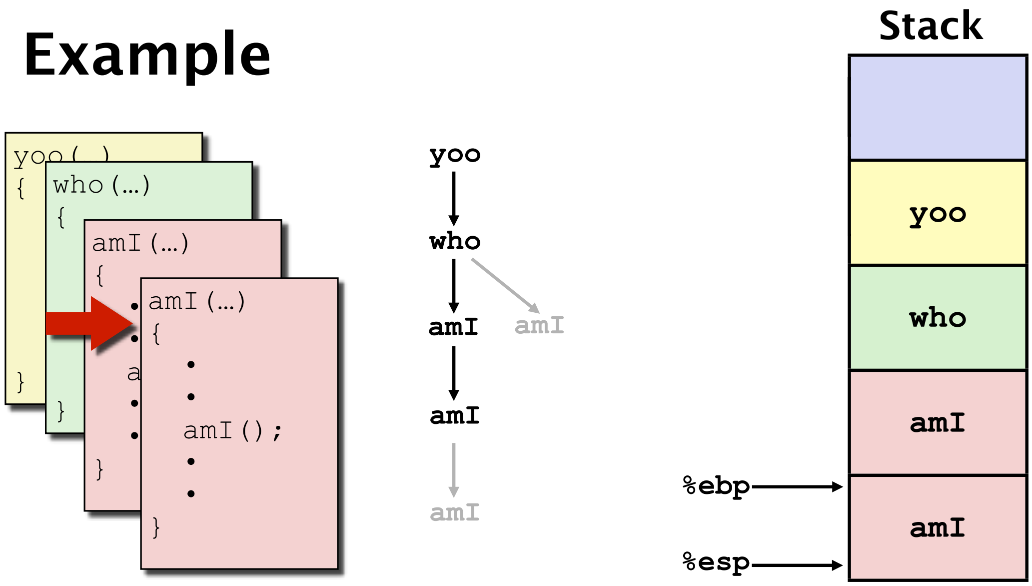
Example



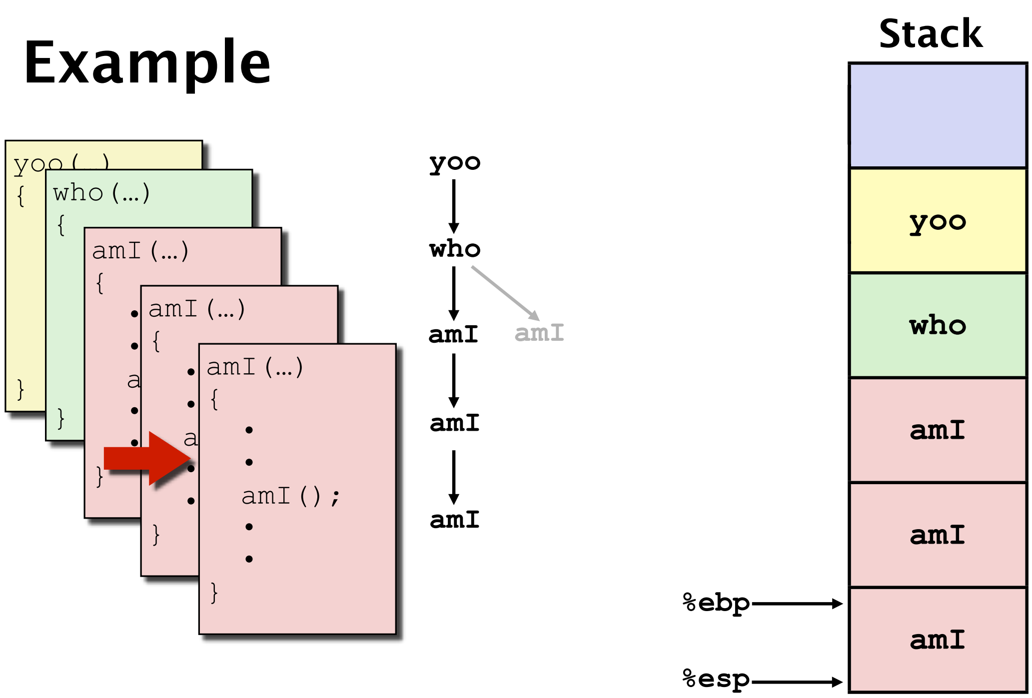
Example



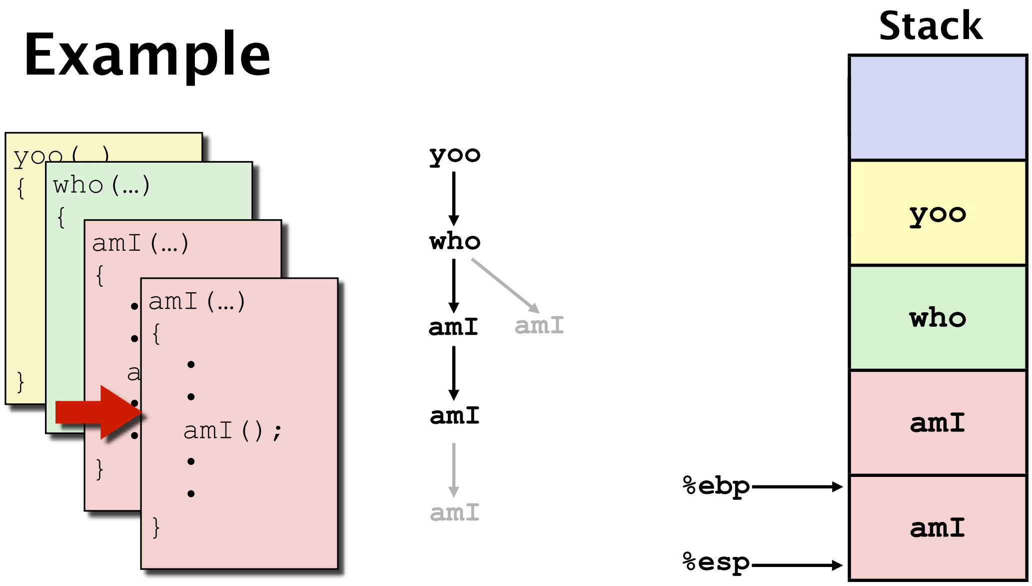
Example



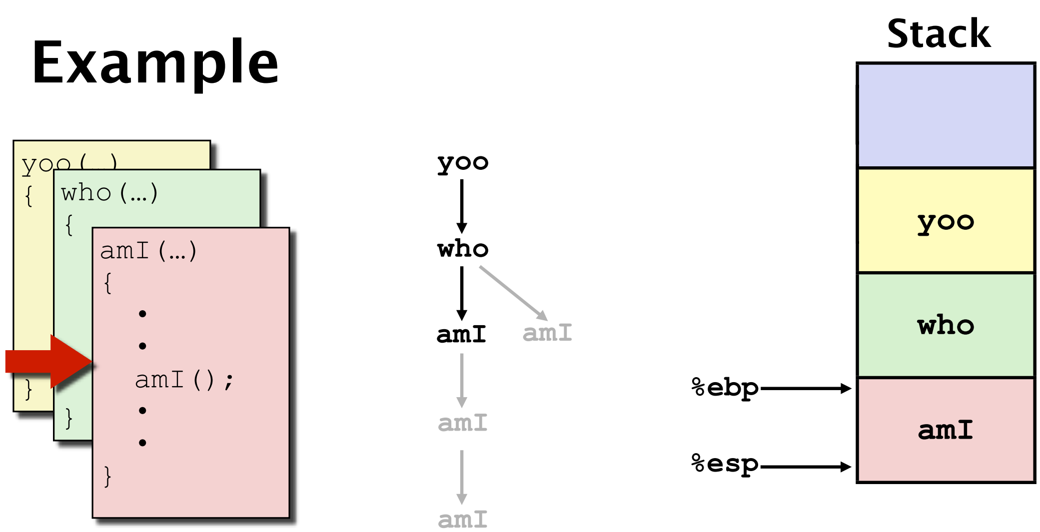
Example



Example

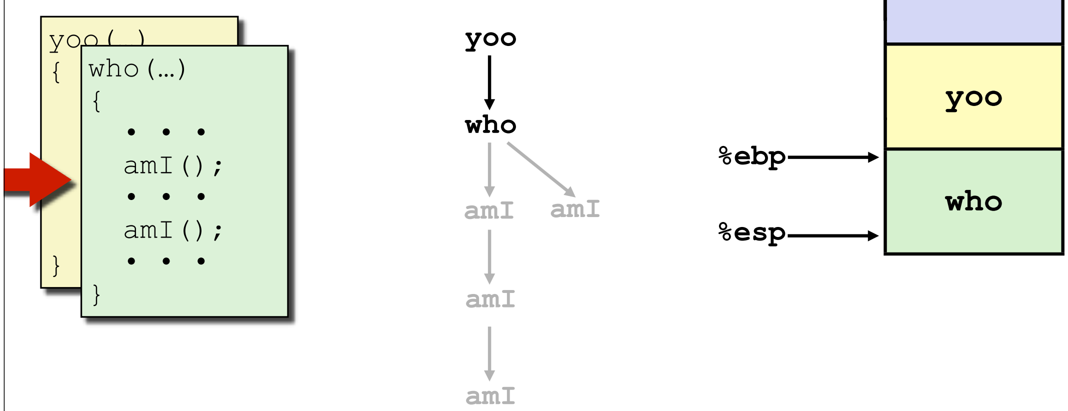


Example



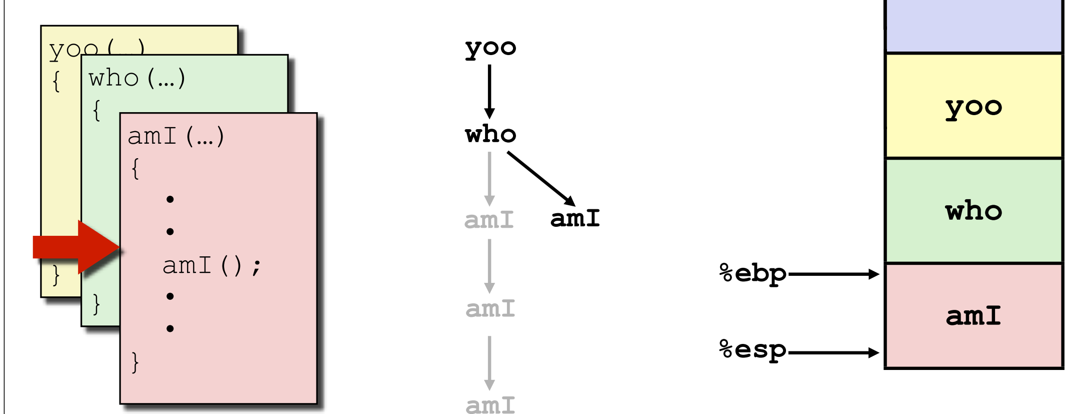
Example

Stack



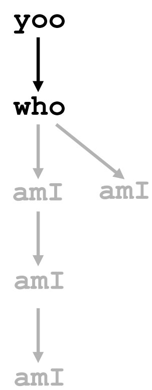
Example

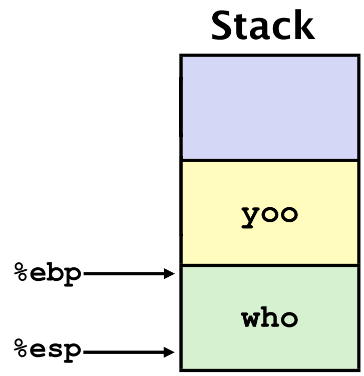
Stack



Example

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

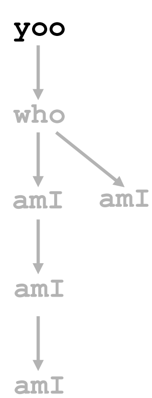


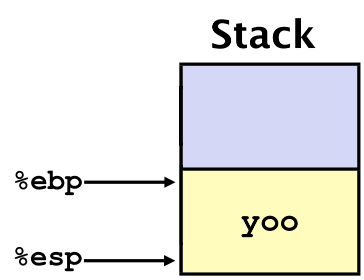


Denison University

Example

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

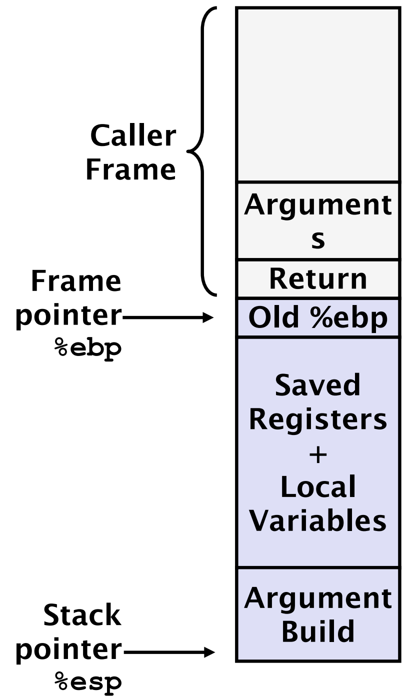




IA32/Linux Stack Frame

- **Current Stack Frame ("Top" to Bottom)**
  - "Argument build:"
    Parameters for function about to call
  - 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



Revisiting `swap`

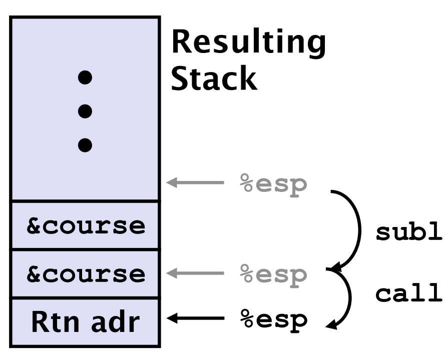
```
int course1 = 281;
int course2 = 271;

void call_swap() {
  swap(&course1, &course2);
}
```

Calling `swap` from `call_swap`

```
call_swap:
    • • •
    subl    $8, %esp
    movl    $course2, 4(%esp)
    movl    $course1, (%esp)
    call    swap
    • • •
```

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



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

    popl  %ebx
    popl  %ebp
    ret
```

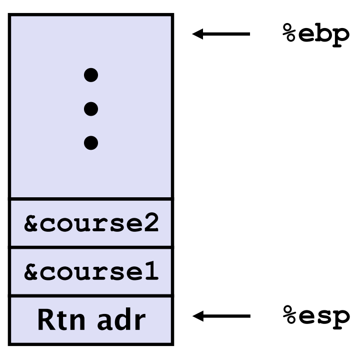
Set Up

Body

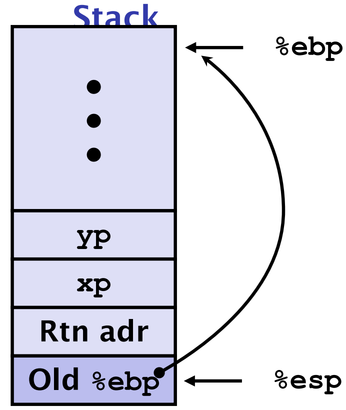
Finish

swap Setup #1

Entering Stack



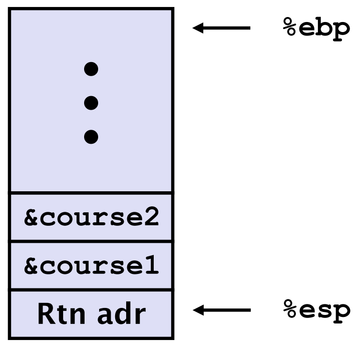
Resulting Stack



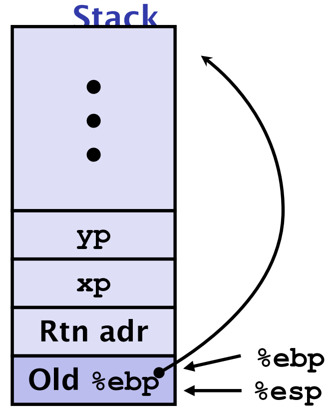

```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

swap Setup #2

Entering Stack



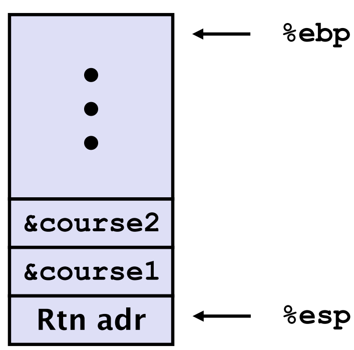
Resulting Stack



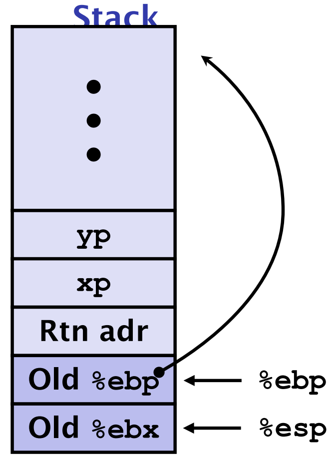

```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```


swap Setup #3

Entering Stack



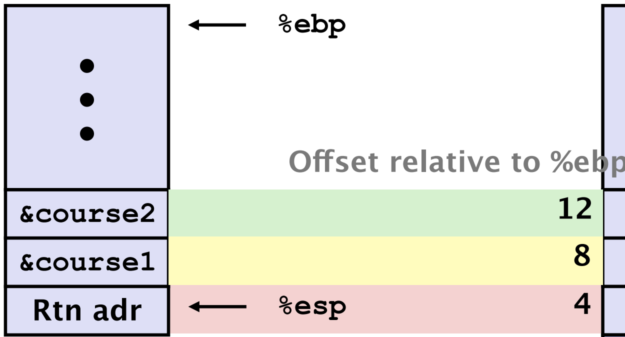
Resulting Stack



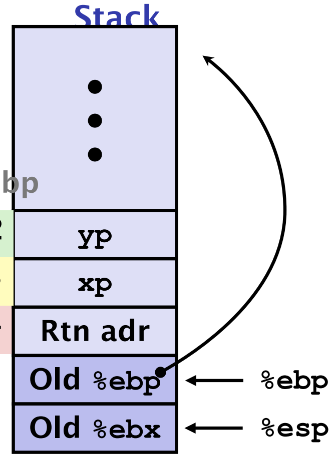

```
swap:
    pushl %ebp
    movl  %esp,%ebp
    pushl %ebx
```

swap Body

Entering Stack



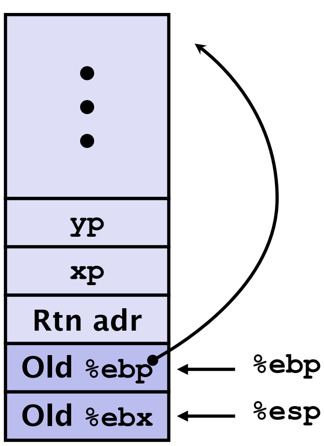
Resulting Stack




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

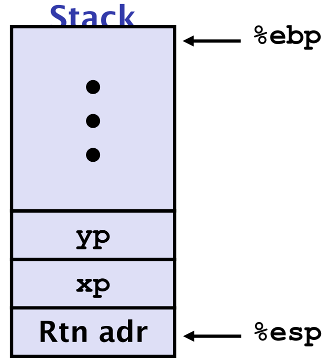

swap Finish

Stack Before Finish




```
popl     %ebx
popl     %ebp
```

Resulting Stack



- **Observation**
  - Saved and restored register **%ebx**
  - Not so for **%eax**, **%ecx**, **%edx**

Disassembled swap

```
08048384 <swap>:
 8048384:   55                        push   %ebp
 8048385:   89 e5                     mov    %esp,%ebp
 8048387:   53                        push   %ebx
 8048388:   8b 55 08                  mov    0x8(%ebp),%edx
 804838b:   8b 4d 0c                  mov    0xc(%ebp),%ecx
 804838e:   8b 1a                     mov    (%edx),%ebx
 8048390:   8b 01                     mov    (%ecx),%eax
 8048392:   89 02                     mov    %eax,(%edx)
 8048394:   89 19                     mov    %ebx,(%ecx)
 8048396:   5b                        pop    %ebx
 8048397:   5d                        pop    %ebp
 8048398:   c3                        ret
```

Calling Code

```
 80483b4:  movl   $0x8049658,0x4(%esp) # Copy &course2
 80483bc:  movl   $0x8049654,(%esp)    # Copy &course1
 80483c3:  call   8048384 <swap>       # Call swap
 80483c8:  leave                       # Prepare to return
 80483c9:  ret                         # Return
```


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 $281, %edx
    call who
    addl %edx, %eax
   • • •
    ret
```

```
who:
   • • •
    movl 8(%ebp), %edx
    addl $271, %edx
   • • •
    ret
```

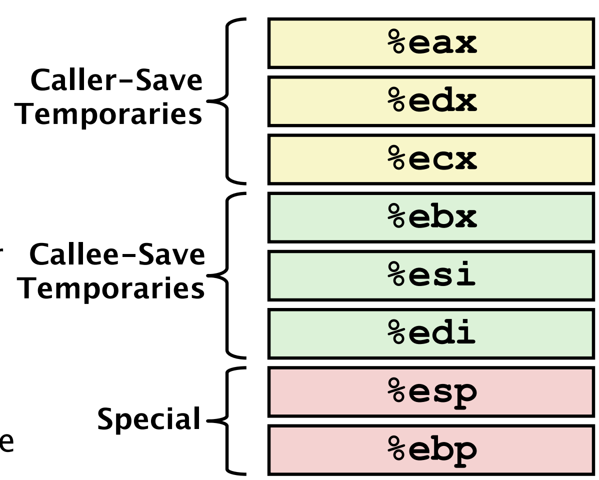
  - Contents of register `%edx` overwritten by `who`
  - This could be trouble → something should be done!
    - Need some coordination

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 values in its frame before the call
  - **"Callee Save"**
    - Callee saves temporary values in its frame before using

IA32/Linux+Windows Register Usage

- **`%eax, %edx, %ecx`**
  - Caller saves prior to call if values are used later
- **`%eax`**
  - also used to return integer value
- **`%ebx, %esi, %edi`**
  - Callee saves if wants to use them
- **`%esp, %ebp`**
  - special form of callee save



Recursive Function

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
pcount_r:
    pushl  %ebp
    movl   %esp, %ebp
    pushl  %ebx
    subl   $4, %esp
    movl   8(%ebp), %ebx
    movl   $0, %eax
    testl  %ebx, %ebx
    je   .L3
    movl   %ebx, %eax
    shrl   %eax
    movl   %eax, (%esp)
    call   pcount_r
    movl   %ebx, %edx
    andl   $1, %edx
    leal   (%edx,%eax), %eax
.L3:
    addl   $4, %esp
    popl   %ebx
    popl   %ebp
    ret
```

- **Registers**
  - `%eax`, `%edx` used without first saving
  - `%ebx` used, but saved at beginning & restored at end

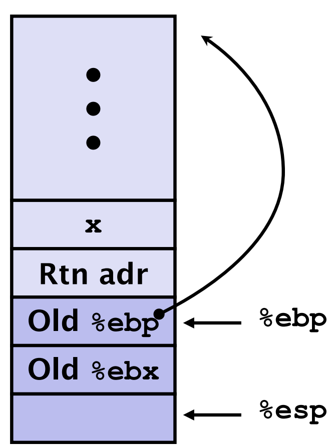
Recursive Call #1

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
pcount_r:
    pushl %ebp
    movl   %esp, %ebp
    pushl %ebx
    subl   $4, %esp
    movl   8(%ebp), %ebx
     • • •
```

- **Actions**
  - Save old value of `%ebx` on stack
  - Allocate space for argument to recursive call
  - Store x in `%ebx`

`%ebx` x



Recursive Call #2

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
  • • •
  movl   $0, %eax
  testl  %ebx, %ebx
  je     .L3
  • • •
.L3:
  • • •
  ret
```

- **Actions**
  - If x == 0, return
    - with `%eax` set to 0

`%ebx` | `x`

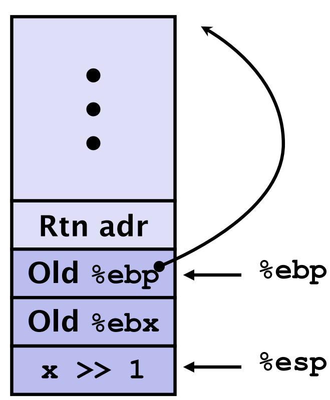
Recursive Call #3

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
  • • •
  movl   %ebx, %eax
  shrl   %eax
  movl   %eax, (%esp)
  call   pcount_r
  • • •
```

- **Actions**
  - Store x >> 1 on stack
  - Make recursive call
- **Effect**
  - `%eax` set to function result
  - `%ebx` still has value of x

`%ebx` | `x`

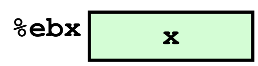


Recursive Call #4

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
  • • •
movl    %ebx, %edx
andl    $1, %edx
leal   (%edx,%eax), %eax
  • • •
```

- **Assume**
  - `%eax` holds value from recursive call
  - `%ebx` holds x



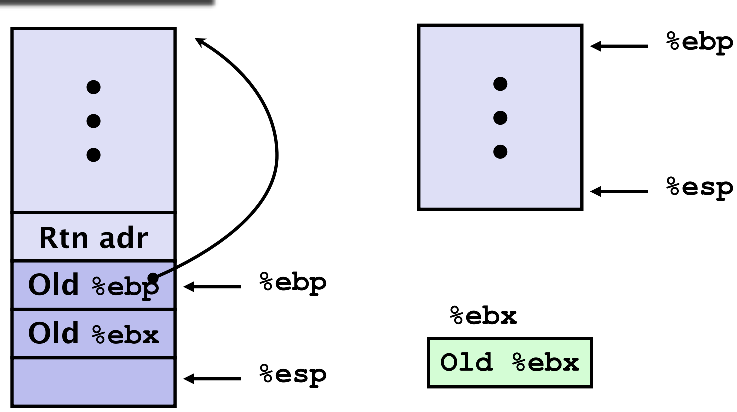
- **Actions**
  - Compute (x & 1) + computed value
- **Effect**

Recursive Call #5

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
      • • •
L3:
     addl$4, %esp
     popl%ebx
     popl%ebp
     ret
```

- **Actions**
  - Restore values of `%ebx` and `%ebp`
  - Restore `%esp`



Observations About Recursion

- **Handled Without Special Consideration**
  - Stack frames mean that each function call has private storage
    - Saved registers & local variables
    - Saved return pointer
  - Register saving conventions prevent one function call from corrupting another's data
  - Stack discipline follows call / return pattern
    - If P calls Q, then Q returns before P
    - Last-In, First-Out
- **Also works for mutual recursion**
  - P calls Q; Q calls P

Pointer Code

Generating Pointer

```
/* Compute x + 3 */
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

Referencing Pointer

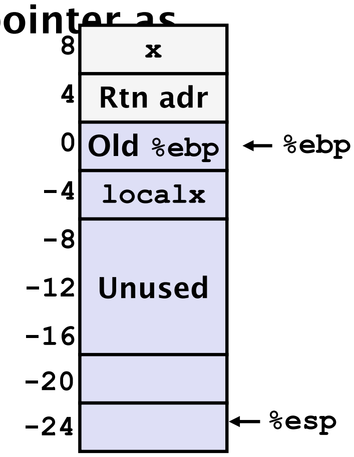
```
/* Increment value by k */
void incrk(int *ip, int k) {
  *ip += k;
}
```

- **`add3` creates pointer and passes it to `incrk`**

Creating and Initializing Local Variable

```
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

- **Variable localx must be stored on stack**
  - Because: Need to create pointer to it
- **Compute pointer as -4(%ebp)**



First part of `add3`

```
add3:
   pushl              %ebp
   movl %esp, %ebp
   subl $24, %esp         # Alloc. 24 bytes
   movl 8(%ebp), %eax
   movl %eax, -4(%ebp)# Set localx to x
```

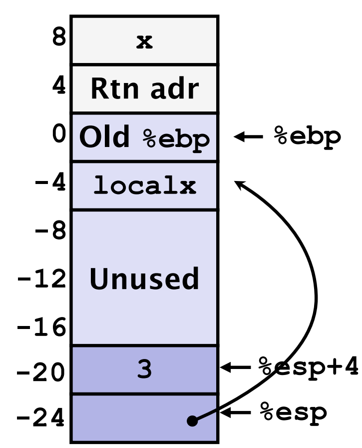

Creating Pointer as Argument

```
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

- **Use leal instruction to compute address of localx**

Middle part of `add3`

```
   movl $3, 4(%esp)      # 2nd arg = 3
   leal -4(%ebp), %eax# &localx
   movl %eax, (%esp)     # 1st arg =
&localx
```



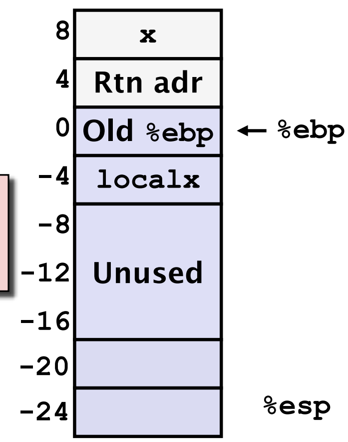
Retrieving local variable

```
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

- Retrieve localx from stack as return value

Final part of add3

```
  movl -4(%ebp), %eax # Return val= localx
  leave
  ret
```



IA 32 Procedure Summary

- Important Points
  - Stack is the right data structure for procedure call / return
    - If P calls Q, then Q returns before P
- Recursion (& mutual recursion) handled by normal calling conventions
  - Can safely store values in local stack frame and in callee-saved registers
  - Put function arguments at top of stack
  - Result return in `%eax`
- `Pointers are addresses of values`
  - `On stack or global`