# CS 33

## Machine Programming (4)

# Conditional-Branch Example

```
int absdiff(int x, int y)
{
    int result;
    if (x > y) {
      result = x-y;
    } else {
      result = y-x;
    }
    return result;
}
```

```
absdiff:
    movl    %esi, %eax
    cmpl    %esi, %edi
    jle     .L6
    subl    %eax, %edi
    movl    %edi, %eax
    jmp     .L7
.L6:
    subl %edi, %eax
.L7:
    ret
```

Body1

Body2a

Body2b

x in %edi

y in %esi

# Conditional-Branch Example (Cont.)

```
int goto_ad(int x, int y)
{
  int result;
  if (x <= y) goto Else;
  result = x-y;
  goto Exit;
Else:
  result = y-x;
Exit:
  return result;
}
```

```
absdiff:
    movl    %esi, %eax
    cmpl    %esi, %edi
    jle     .L6
    subl    %eax, %edi
    movl    %edi, %eax
    jmp .L7
.L6:
    subl %edi, %eax
.L7:
    ret
```

Body1

Body2a

Body2b

- C allows “goto” as means of transferring control
  - closer to machine-level programming style
- Generally considered bad coding style

# General Conditional-Expression Translation

## C Code

```
val = Test ? Then_Expr : Else_Expr;
```

```
val = x>y ? x-y : y-x;
```

## Goto Version

```
  nt = !Test;
  if (nt) goto Else;
  val = Then_Expr;
  goto Done;
Else:
  val = Else_Expr;
Done:
  . . .
```

- Test is expression returning integer
  - == 0 interpreted as false
  - ≠ 0 interpreted as true
- Create separate code regions for then & else expressions
- Execute appropriate one

# "Do-While" Loop Example

## C Code

```
int pcount_do(unsigned x)
{
  int result = 0;
  do {
    result += x & 0x1;
    x >>= 1;
  } while (x);
  return result;
}
```

## Goto Version

```
int pcount_do(unsigned x)
{
  int result = 0;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
  return result;
}
```

- Count number of 1's in argument x ("popcount")
- Use conditional branch either to continue looping or to exit loop

# "Do-While" Loop Compilation

## Goto Version

```
int pcount_do(unsigned x)  {
  int result = 0;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
  return result;
}
```

**Registers:**

| | |
|---|---|
| %edi | x |
| %eax | result |

```
    movl   $0, %eax      #   result = 0
.L2:       # loop:
    movl   %edi, %ecx
    andl   $1, %ecx      #   t = x & 1
    addl   %ecx, %eax    #   result += t
    shrl   %edi          #   x >>= 1
    jne    .L2           #   if !0, goto loop
```

# General "Do-While" Translation

**C Code**

```
do
   Body
   while (Test);
```

**Goto Version**

```
loop:
   Body
   if (Test)
      goto loop
```

- **Body:**

```
{
   Statement1;
   Statement2;
      …
   Statementn;
}
```

- **Test returns integer**
  - **= 0 interpreted as false**
  - **≠ 0 interpreted as true**

# "While" Loop Example

## C Code

```
int pcount_while(unsigned x) {
  int result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

## Goto Version

```
int pcount_do(unsigned x)  {
  int result = 0;
  if (!x) goto done;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
done:
  return result;
}
```

- **Is this code equivalent to the do-while version?**
  - **must jump out of loop if test fails**

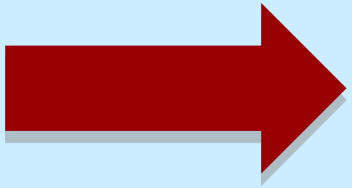
# General "While" Translation

**While version**

```
while (Test)
  Body
```

**Do-While Version**

```
  if (!Test)
    goto done;
  do
    Body
    while(Test);
done:
```



**Goto Version**

```
  if (!Test)
    goto done;
loop:
  Body
  if (Test)
    goto loop;
done:
```

# “For” Loop Example

## C Code

```
#define WSIZE 8*sizeof(int)
int pcount_for(unsigned x) {
  int i;
  int result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  return result;
}
```

- **Is this code equivalent to other versions?**

# “For” Loop Form

## General Form

```
for (Init; Test; Update)
    Body
```

```
for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
}
```

**Init**

```
i = 0
```

**Test**

```
i < WSIZE
```

**Update**

```
i++
```

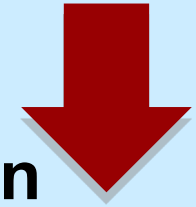
**Body**

```
{
  unsigned mask = 1 << i;
  result += (x & mask) != 0;
}
```

# "For" Loop → While Loop

**For Version**

```
for (Init; Test; Update)
    Body
```



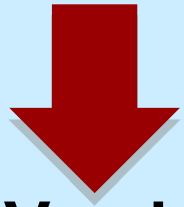
**While Version**

```
Init;
while (Test) {
    Body
    Update;
}
```

# "For" Loop → … → Goto

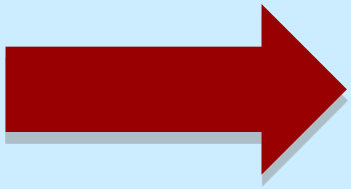
## For Version

```
for (Init; Test; Update)
    Body
```

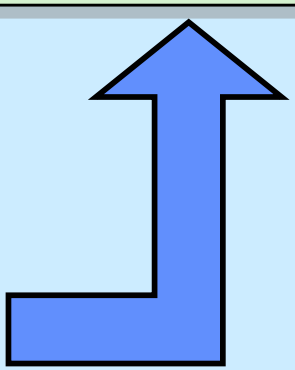


## While Version

```
Init;
while (Test) {
    Body
    Update;
}
```



```
  Init;
  if (!Test)
    goto done;
do
  Body
  Update
  while(Test);
done:
```



```
  Init;
  if (!Test)
    goto done;
loop:
  Body
  Update
  if (Test)
    goto loop;
done:
```

# "For" Loop Conversion Example

## C Code

```
#define WSIZE 8*sizeof(int)
int pcount_for(unsigned x) {
  int i;
  int result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  return result;
}
```

**Initial test can be optimized away**

## Goto Version

```
int pcount_for_gt(unsigned x) {
  int i;
  int result = 0;
  i = 0;                          Init
  if (!(i < WSIZE))               !Test
    goto done;
 loop:
  {                               Body
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  i++;                            Update
  if (i < WSIZE)                  Test
    goto loop;
 done:
  return result;
}
```

```
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;
}
```

# Switch-Statement Example

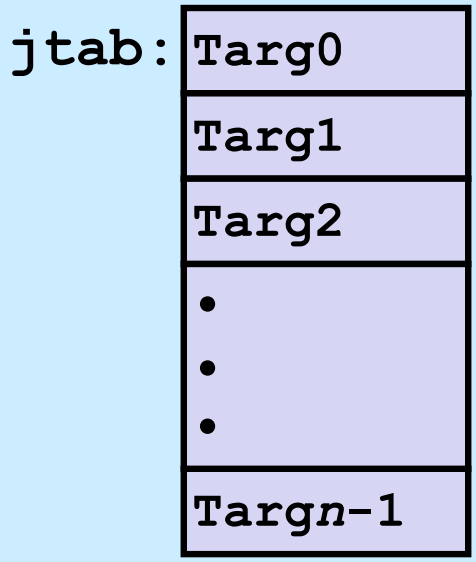
- **Multiple case labels**
  - **here: 5 & 6**
- **Fall-through cases**
  - **here: 2**
- **Missing cases**
  - **here: 4**

# Jump-Table Structure

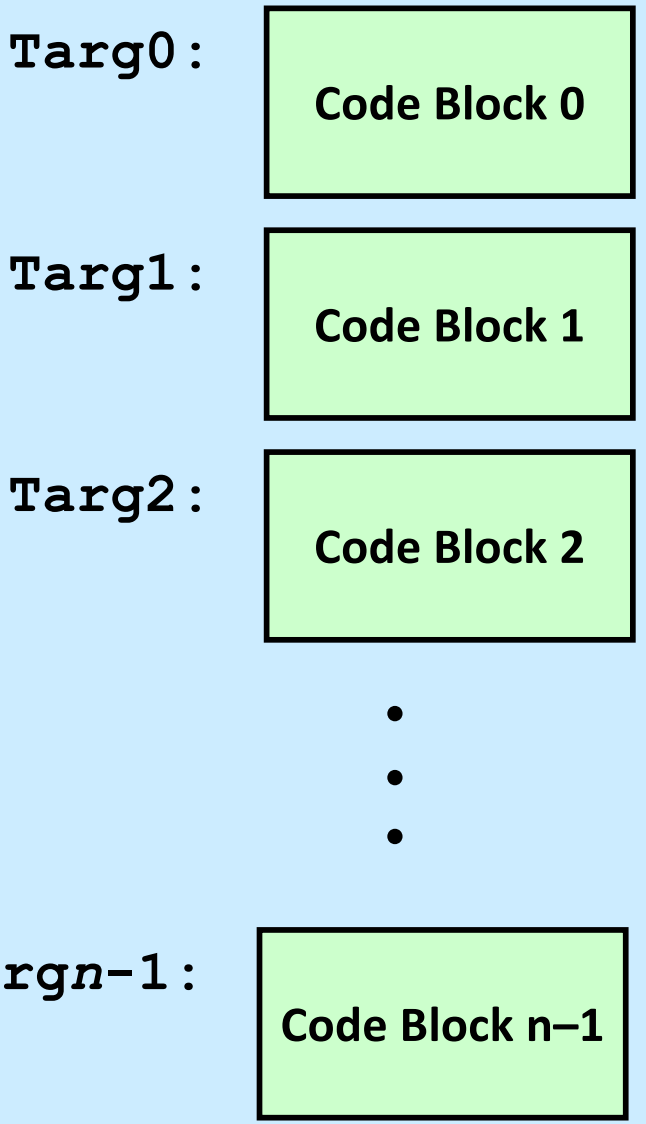
**Switch Form**

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

**Jump Table**




**Jump Targets**




**Approximate Translation**

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

# Switch-Statement Example (x86-64)

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

**What range of values is covered by the default case?**

**Setup:**

```
  switch_eg:
     ...      # Setup
     movq     %rdx, %rcx       # %rcx = z
     cmpq     $6, %rdi         # Compare x:6
     ja       .L8              # If unsigned > goto default
     jmp      *.L7(,%rdi,8)    # Goto *JTab[x]
```

Note that w not initialized here

# Switch-Statement Example

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

**Jump table**

```
.section    .rodata
  .align 4
.L7:
  .quad     .L8  # x = 0
  .quad     .L3  # x = 1
  .quad     .L4  # x = 2
  .quad     .L9  # x = 3
  .quad     .L8  # x = 4
  .quad     .L6  # x = 5
  .quad     .L6  # x = 6
```

**Setup:**

```
switch_eg:
    ...     # Setup
    movq    %rdx, %rcx      # %rcx = z
    cmpq    $6, %rdi        # Compare x:6
    ja      .L8             # If unsigned > goto default
    jmp     *.L7(,%rdi,8)   # Goto *JTab[x]
```

Indirect jump

# Assembly-Setup Explanation

- **Table structure**
  - each target requires 8 bytes
  - base address at `.L7`

Jump table

```
.section   .rodata
  .align 4
.L7:
  .quad    .L8 # x = 0
  .quad    .L3 # x = 1
  .quad    .L4 # x = 2
  .quad    .L9 # x = 3
  .quad    .L8 # x = 4
  .quad    .L6 # x = 5
  .quad    .L6 # x = 6
```

- **Jumping**

  direct: `jmp .L8`
  - jump target is denoted by label `.L8`

  indirect: `jmp *.L7(,%rdi,8)`
  - start of jump table: `.L7`
  - must scale by factor of 8 (labels have 8 bytes on x86-64)
  - fetch target from effective address `.L7 + rdi*8`
    - » only for $0 \le x \le 6$

# Jump Table

**Jump table**

```
.section   .rodata
  .align 4
.L7:
  .quad    .L8 # x = 0
  .quad    .L3 # x = 1
  .quad    .L4 # x = 2
  .quad    .L9 # x = 3
  .quad    .L8 # x = 4
  .quad    .L6 # x = 5
  .quad    .L6 # x = 6
```

```
switch(x) {
case 1:          // .L3
     w = y*z;
     break;
case 2:          // .L4
     w = y/z;
     /* Fall Through */
case 3:          // .L9
     w += z;
     break;
case 5:
case 6:          // .L6
     w -= z;
     break;
default:         // .L8
     w = 2;
}
```

# Code Blocks (Partial)

```
switch(x) {
case 1:          // .L3
      w = y*z;
      break;
 . . .
case 5:          // .L6
case 6:          // .L6
    w -= z;
    break;
default:         // .L8
    w = 2;
}
```

```
.L3:     # x == 1
  movl  %rsi, %rax  # y
  imulq %rdx, %rax  # w = y*z
  ret
.L6:                # x == 5, x == 6
  movl  $1, %eax # w = 1
  subq  %rdx, %rax   # w -= z
  ret
.L8:                # Default
  movl  $2, %eax # w = 2
  ret
```

# Handling Fall-Through

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

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

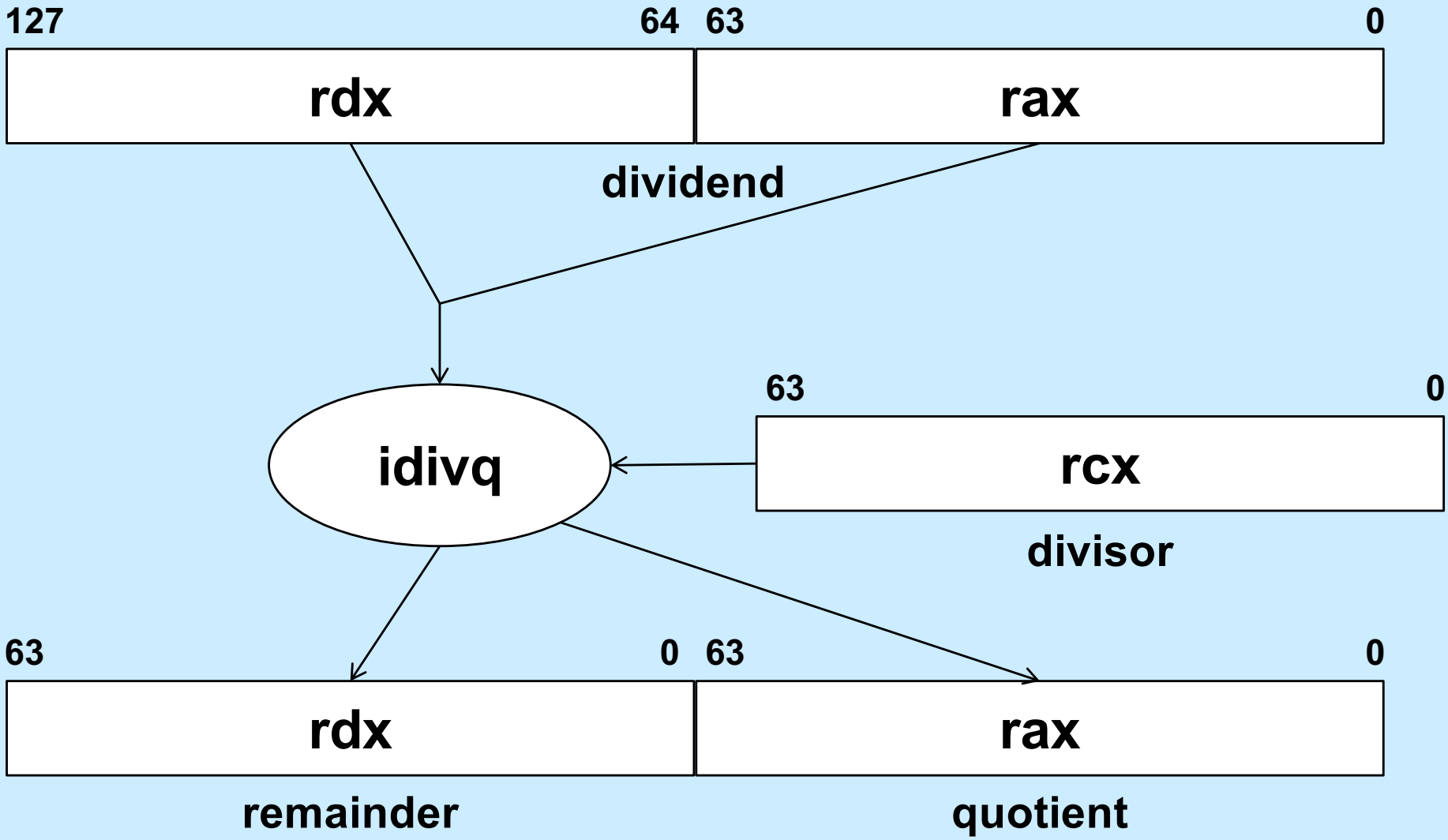
```
     case 3:
          w = 1;
merge:
          w += z;
```

# Code Blocks (Rest)

```
  switch(x) {
    . . .
    case 2:  // .L4
        w = y/z;
        /* Fall Through */
    case 3:  // .L9
        w += z;
        break;
    . . .
}
```

```
.L4:    # x == 2
  movq  %rsi, %rax
  movq  %rsi, %rdx
  sarq  $63, %rdx
  idivq %rcx      # w = y+z
  jmp   .L5
.L9:    # x == 3
  movl  $1, %eax # w = 1
.L5:    # merge:
  addq  %rcx, %rax # w += z
  ret
```

# idivq



# x86-64 Object Code

- **Setup**
  - label `.L8` becomes address `0x4004e5`
  - label `.L7` becomes address `0x4005c0`

**Assembly code**

```
switch_eg:
  . . .
   ja      .L8             # If unsigned > goto default
   jmp     *.L7(,%rdi,8)   # Goto *JTab[x]
```

**Disassembled object code**

```
00000000004004ac <switch_eg>:
 . . .
 4004b3:  77 30           ja     4004e5 <switch_eg+0x39>
 4004b5:  ff 24 fd c0 05 40 00  jmpq    *0x4005c0(,%rdi,8)
```

# x86-64 Object Code (cont.)

- **Jump table**
  - **doesn't show up in disassembled code**
  - **can inspect using gdb**

```
gdb switch
(gdb) x/7xg 0x4005c0
```

    - » **examine 7 hexadecimal format "giant" words (8-bytes each)**
    - » **use command "`help x`" to get format documentation**

```
0x4005c0:       0x00000000004004e5      0x00000000004004bc
0x4005d0:       0x00000000004004c4      0x00000000004004d3
0x4005e0:       0x00000000004004e5      0x00000000004004dc
0x4005f0:       0x00000000004004dc
```

# x86-64 Object Code (cont.)

- **Deciphering jump table**

```
0x4005c0:    0x00000000004004e5    0x00000000004004bc
0x4005d0:    0x00000000004004c4    0x00000000004004d3
0x4005e0:    0x00000000004004e5    0x00000000004004dc
0x4005f0:    0x00000000004004dc
```

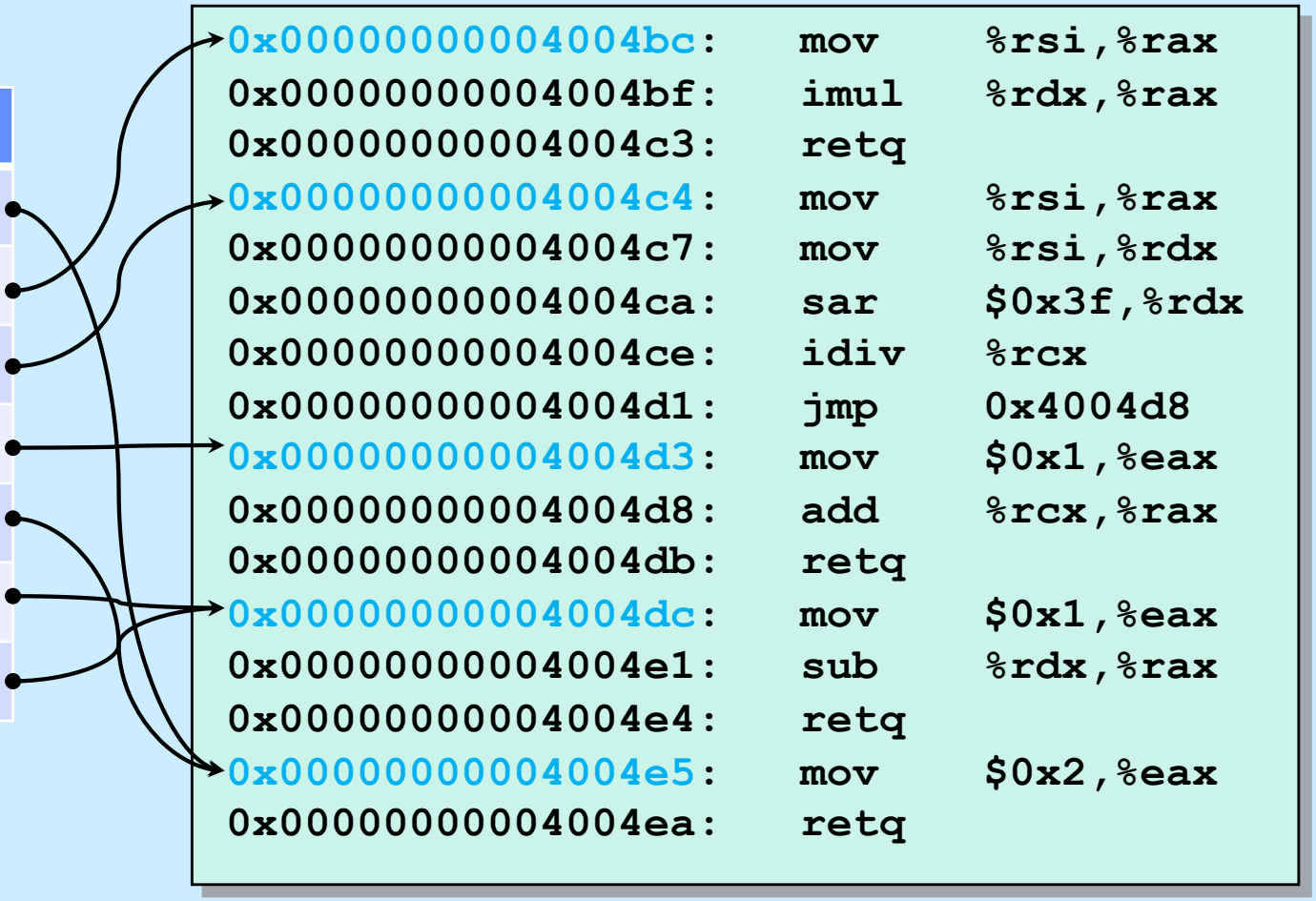
| Address | Value | x |
|---|---|---|
| 0x4005c0 | 0x4004e5 | 0 |
| 0x4005c8 | 0x4004bc | 1 |
| 0x4005d0 | 0x4004c4 | 2 |
| 0x4005d8 | 0x4004d3 | 3 |
| 0x4005e0 | 0x4004e5 | 4 |
| 0x4005e8 | 0x4004dc | 5 |
| 0x4005f0 | 0x4004dc | 6 |

# Disassembled Targets

```
(gdb) disassemble 0x4004bc,0x4004eb
 Dump of assembler code from 0x4004bc to 0x4004eb
   0x00000000004004bc <switch_eg+16>:   mov    %rsi,%rax
   0x00000000004004bf <switch_eg+19>:   imul   %rdx,%rax
   0x00000000004004c3 <switch_eg+23>:   retq
   0x00000000004004c4 <switch_eg+24>:   mov    %rsi,%rax
   0x00000000004004c7 <switch_eg+27>:   mov    %rsi,%rdx
   0x00000000004004ca <switch_eg+30>:   sar    $0x3f,%rdx
   0x00000000004004ce <switch_eg+34>:   idiv   %rcx
   0x00000000004004d1 <switch_eg+37>:   jmp    0x4004d8 <switch_eg+44>
   0x00000000004004d3 <switch_eg+39>:   mov    $0x1,%eax
   0x00000000004004d8 <switch_eg+44>:   add    %rcx,%rax
   0x00000000004004db <switch_eg+47>:   retq
   0x00000000004004dc <switch_eg+48>:   mov    $0x1,%eax
   0x00000000004004e1 <switch_eg+53>:   sub    %rdx,%rax
   0x00000000004004e4 <switch_eg+56>:   retq
   0x00000000004004e5 <switch_eg+57>:   mov    $0x2,%eax
   0x00000000004004ea <switch_eg+62>:   retq
```

# Matching Disassembled Targets

| Value | x |
|---|---|
| 0x4004e5 | 0 |
| 0x4004bc | 1 |
| 0x4004c4 | 2 |
| 0x4004d3 | 3 |
| 0x4004e5 | 4 |
| 0x4004dc | 5 |
| 0x4004dc | 6 |



# Quiz 1

## What C code would you compile to get the following assembler code?

```
        movq    $0, %rax
.L2:
        movq    %rax, a(,%rax,8)
        addq    $1, %rax
        cmpq    $10, %rax
        jne     .L2
        ret
```

```
long a[10];
void func() {
  long i;
  for (i=0; i<10; i++)
    a[i]= 1;
}
```

a

```
long a[10];
void func() {
  long i=0;
  while (i<10)
    a[i]= i++;
}
```

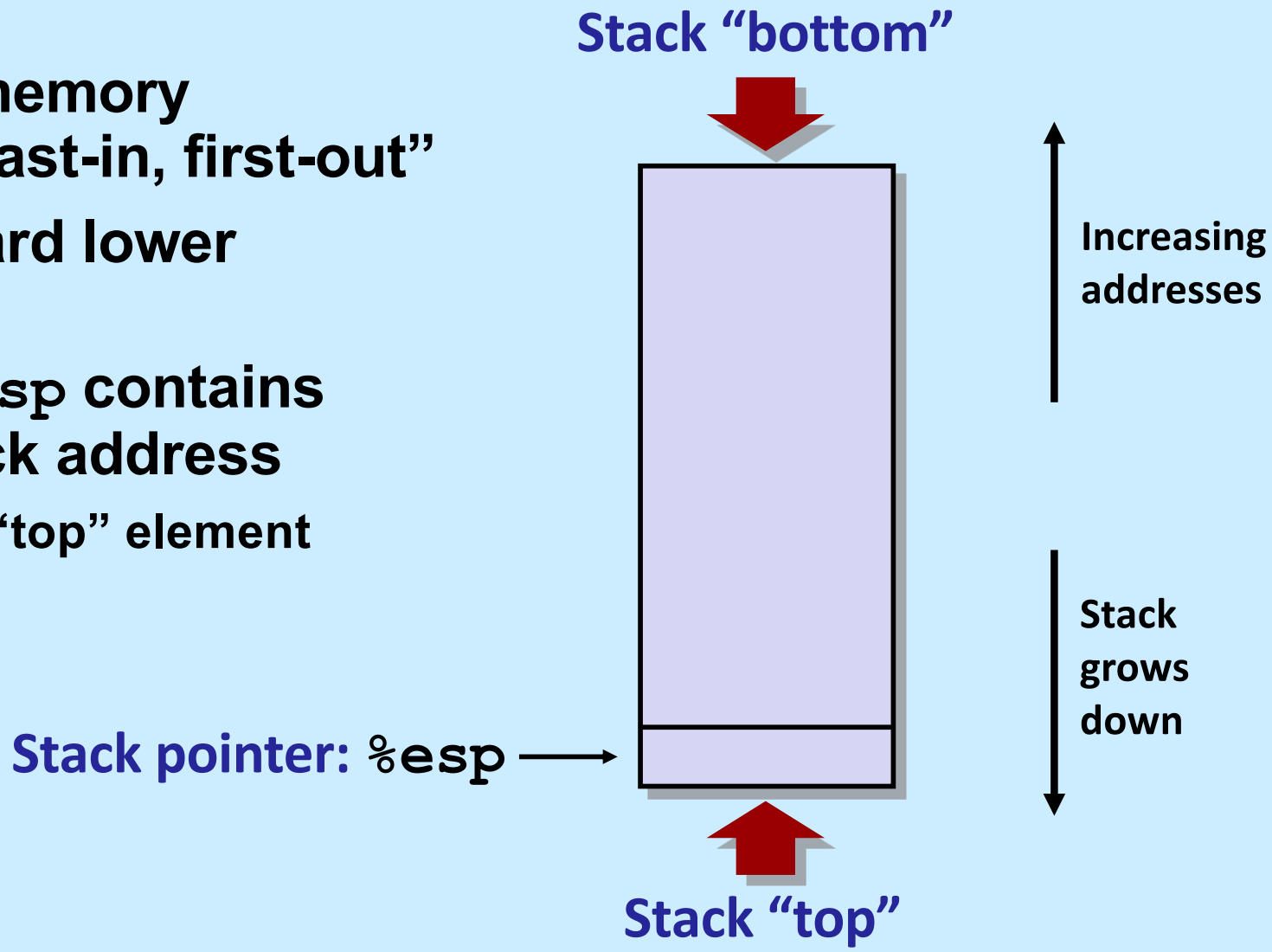
b

```
long a[10];
void func() {
  long i=0;
  switch (i) {
case 0:
    a[i] = 0;
    break;
default:
    a[i] = 10
  }
}
```

c

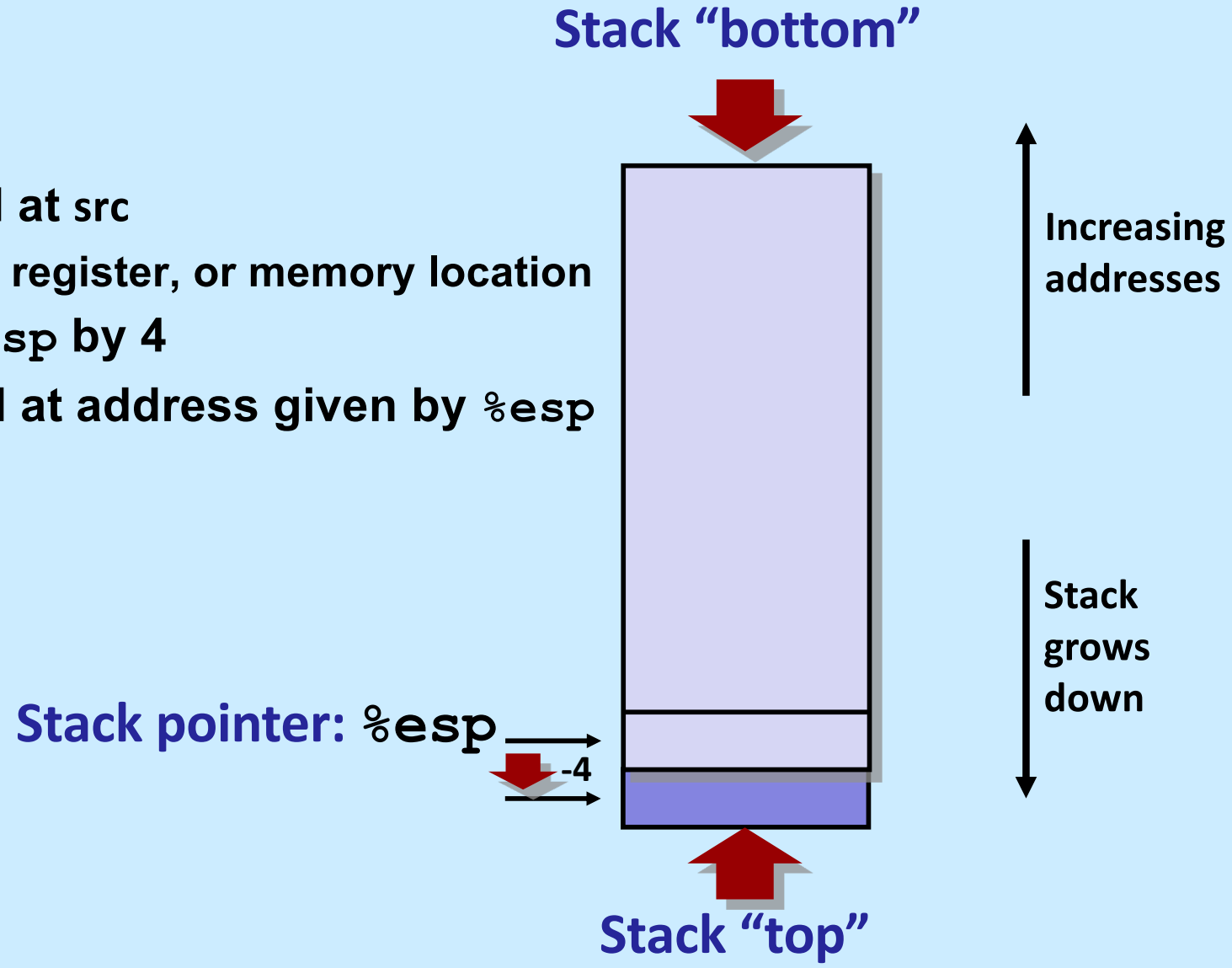
# IA32 Stack

- Region of memory managed "last-in, first-out"
- Grows toward lower addresses
- Register `%esp` contains lowest stack address
  - address of "top" element



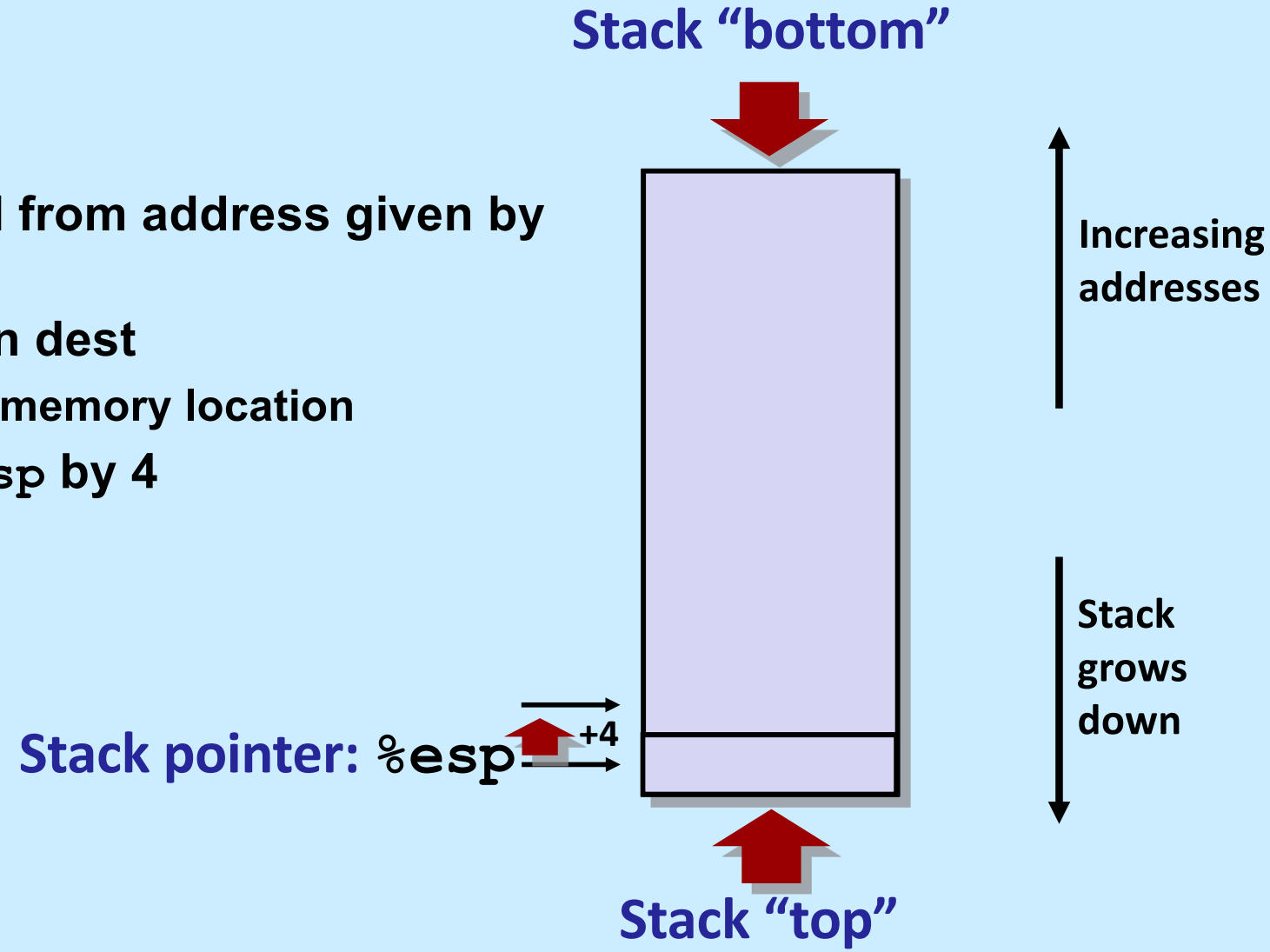
# IA32 Stack: Push

- `pushl` *`src`*
  - fetch operand at src
    - » immediate, register, or memory location
  - decrement `%esp` by 4
  - store operand at address given by `%esp`

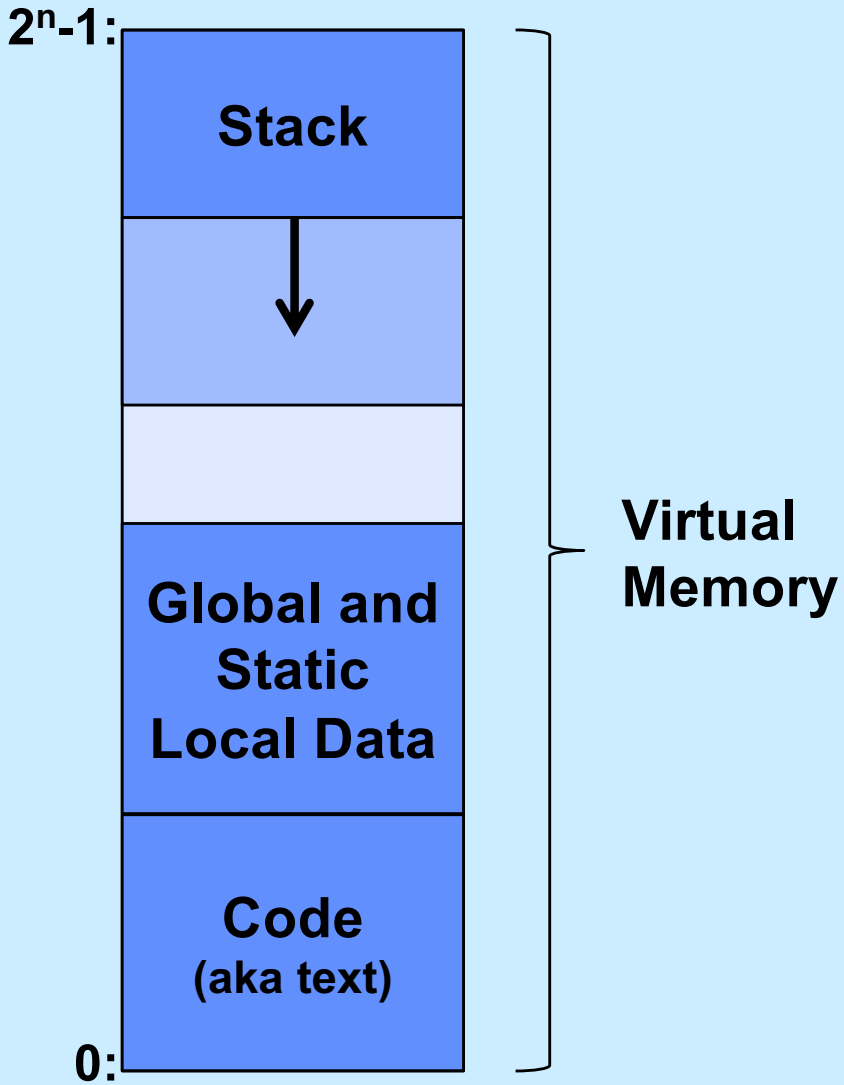


# IA32 Stack: Pop

- `popl` *`dest`*
  - fetch operand from address given by %esp
  - put operand in dest
    - » register or memory location
  - increment `%esp` by 4



# Digression (Again): Where Stuff Is (Roughly)



# Function Control Flow

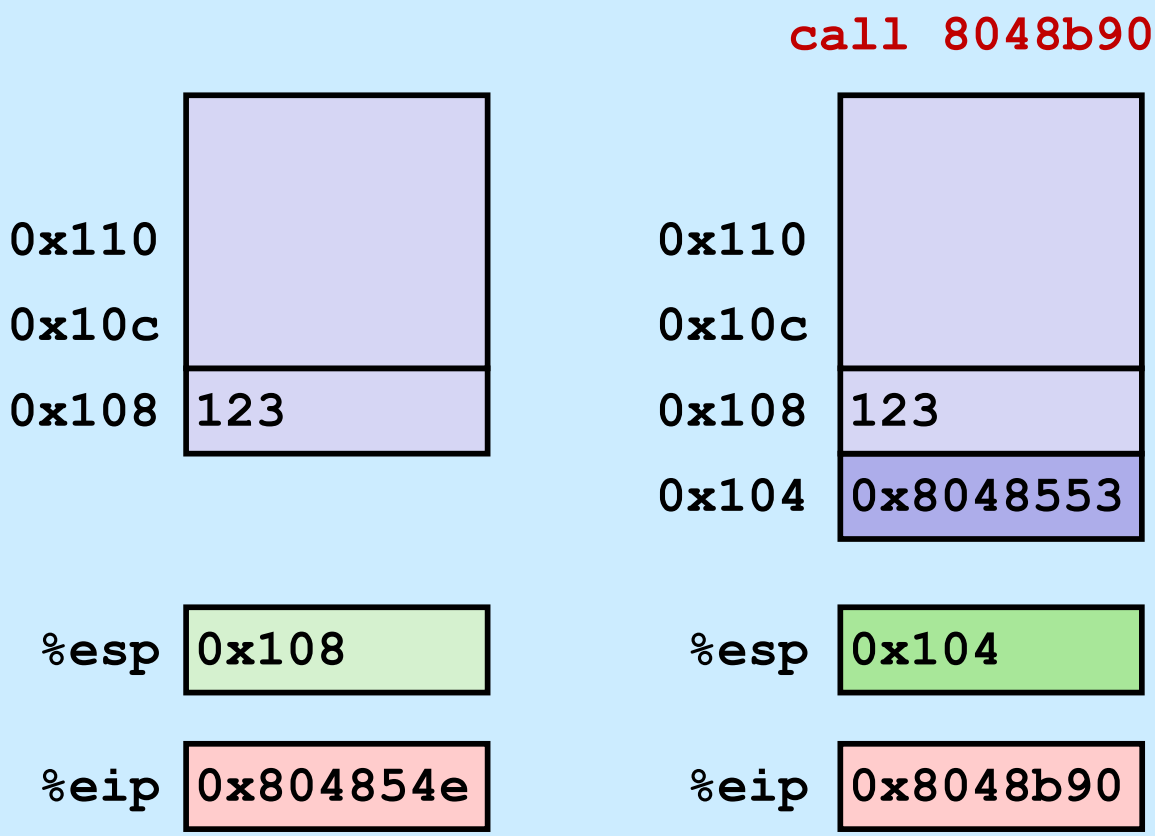
- Use stack to support function call and return
- Function call: `call sub`
  - push return address on stack
  - jump to sub
- Return address:
  - address of the next instruction after call
  - example from disassembly

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

  - return address = `0x8048553`
- Function return: `ret`
  - pop address from stack
  - jump to address

# Function Call

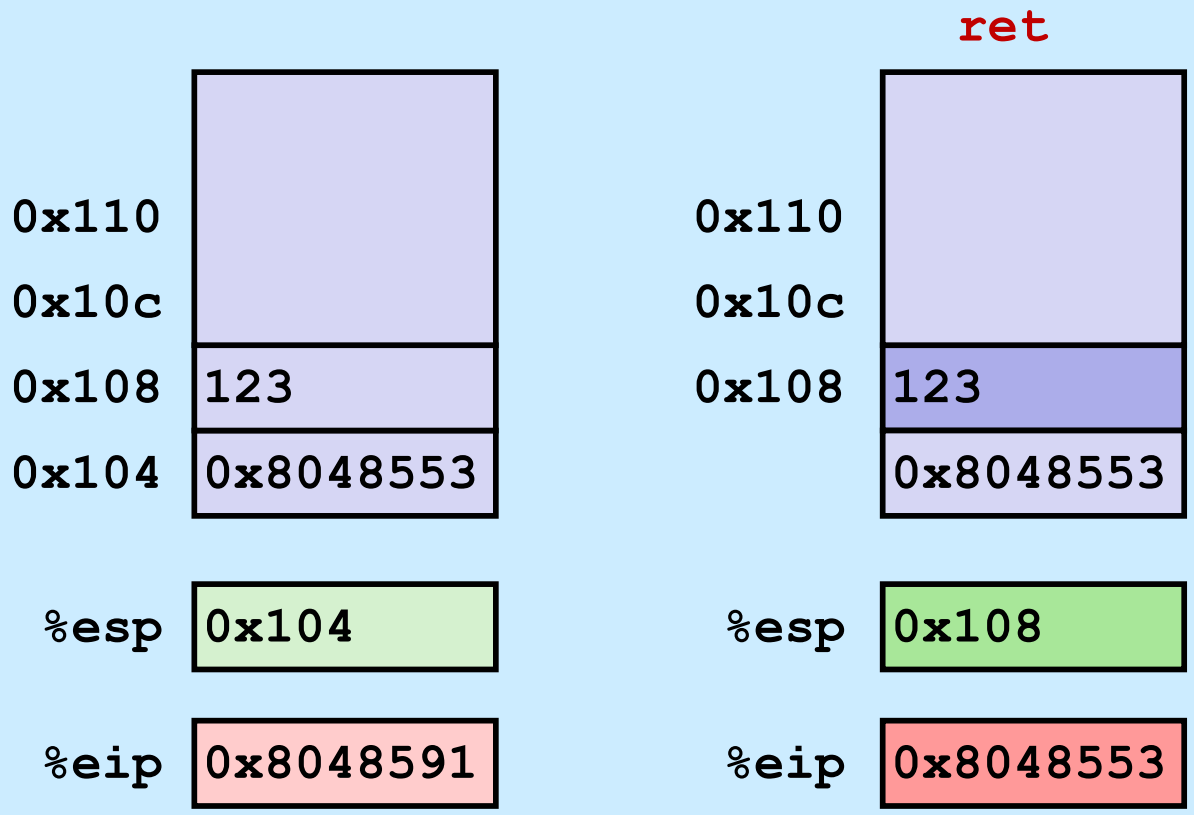
```
804854e:      e8 3d 06 00 00         call   8048b90 <sub>
8048553:      50                     pushl  %eax
```




*%eip:* program counter

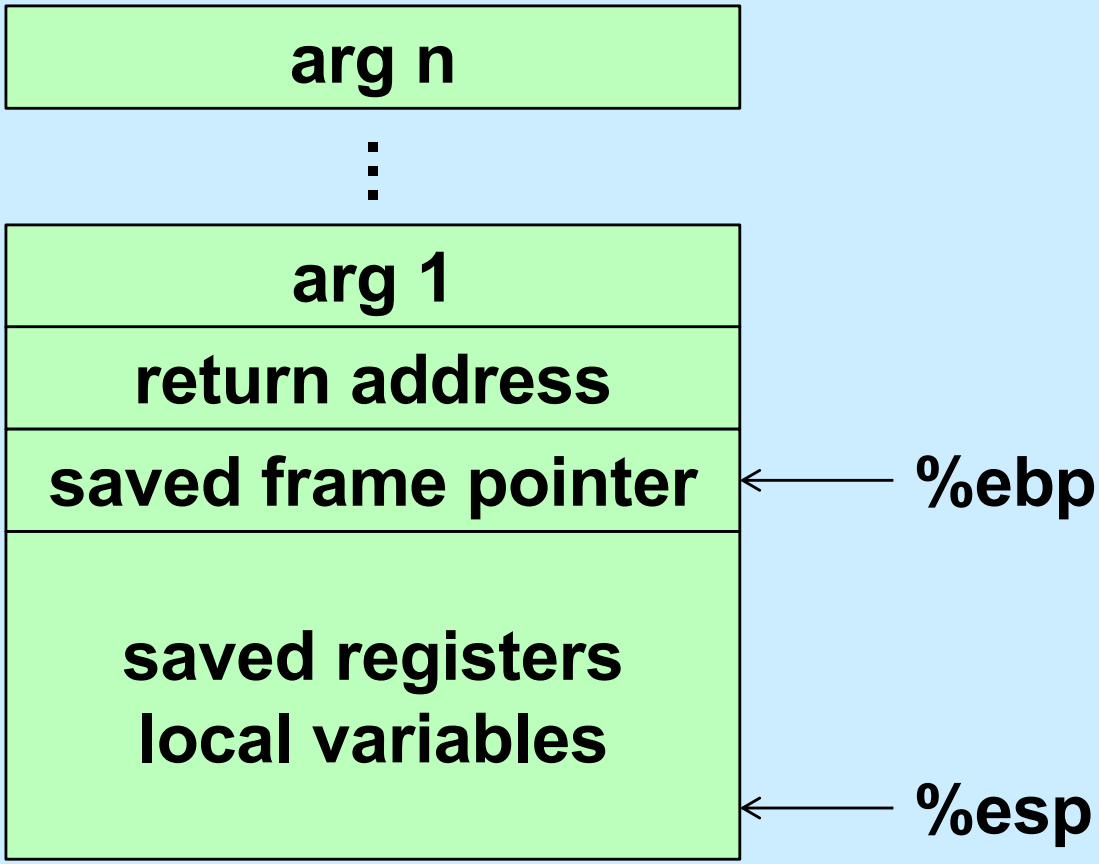
# Function Return

```
8048591:      c3                          ret
```




*%eip:* program counter

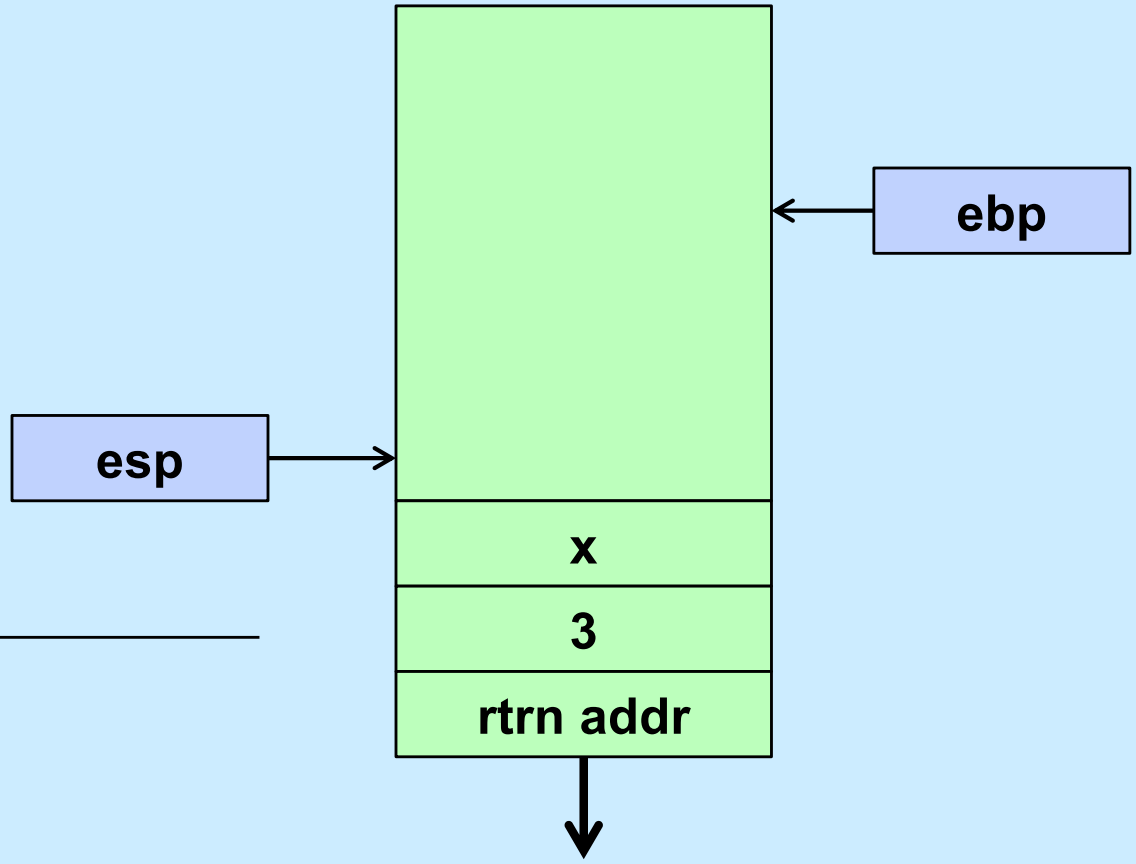
# The IA32 Stack Frame



# Passing Arguments

```
int x;
int res;
int main() {
   ...
   res = subr(3, x);
   ...
}
```

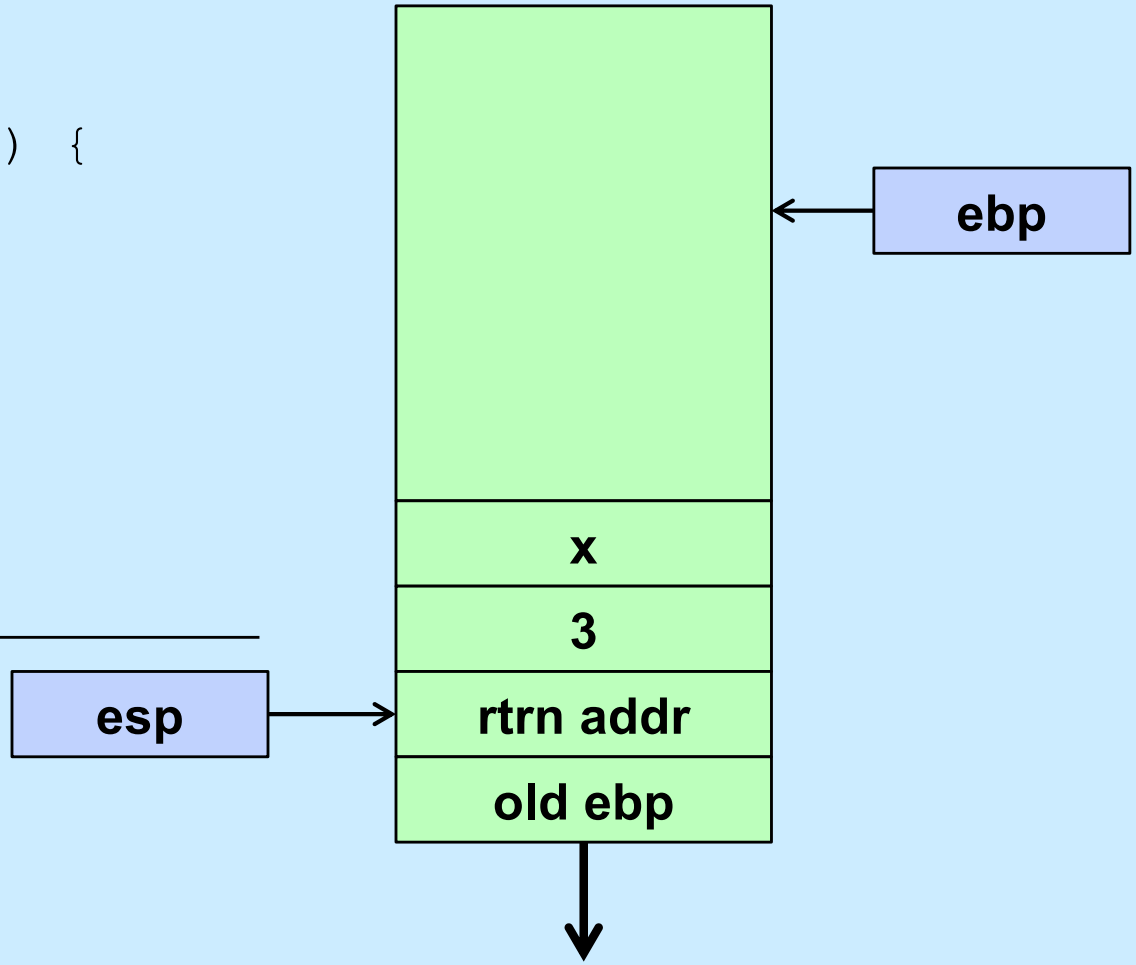
```
main:
   ...
   pushl x
   pushl $3
   call subr
   movl %eax,res
   ...
```



# Retrieving Arguments

```
int subr(int a, int b) {
  return a + b;
}
```

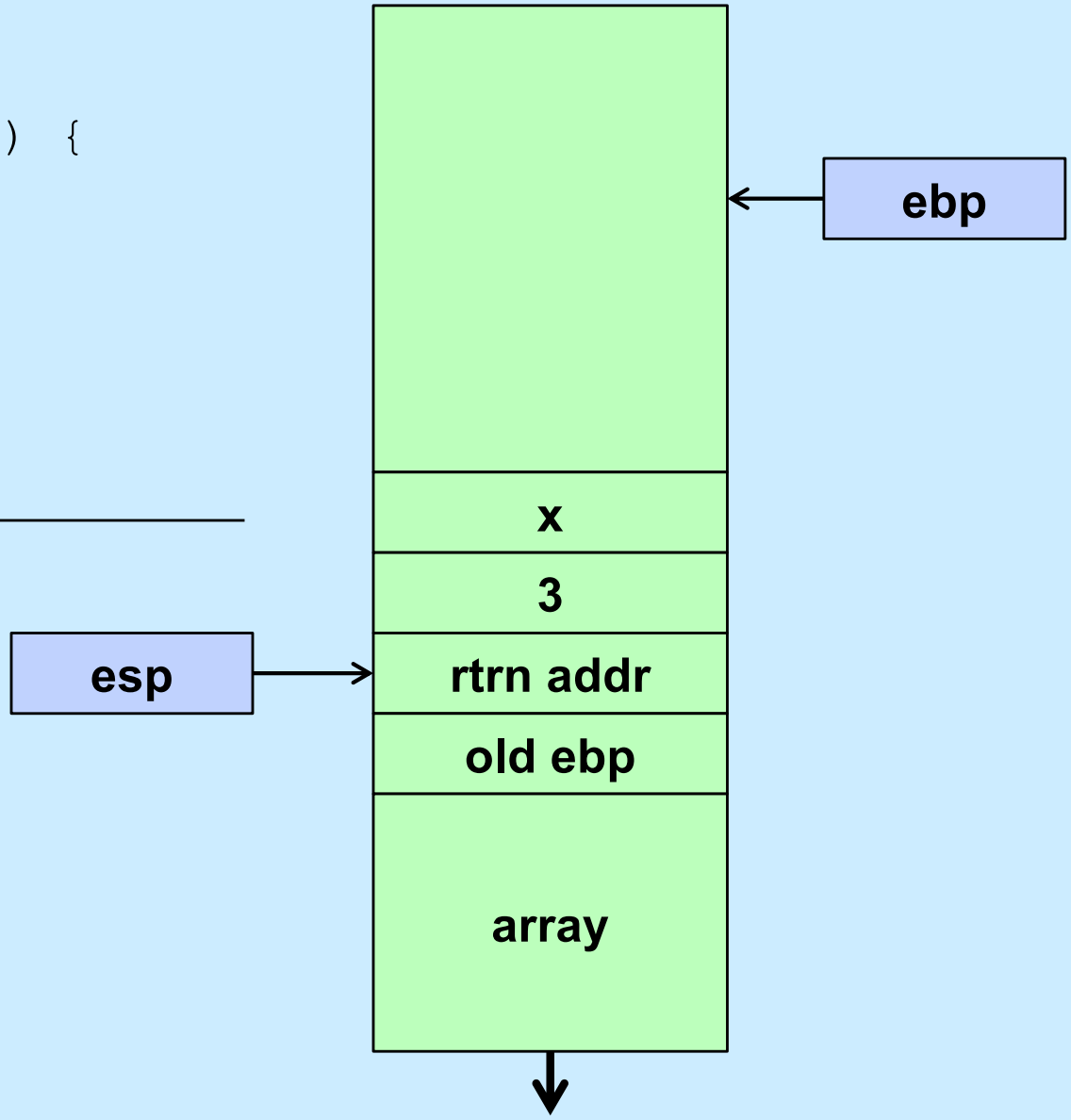
```
subr:
  pushl %ebp
  movl %esp, %ebp
  movl 12(%ebp), %eax
  addl 8(%ebp), %eax
  popl %ebp
  ret
```



# Space for Local Variables

```
int subr(int a, int b) {
  int array[20];
  ...
}
```

```
subr:
  pushl %ebp
  movl %esp, %ebp
  subl $80, %esp
  ...
  addl $80, %esp
  popl %ebp
  ret
```



# Register-Saving Conventions

- When function `yoo` calls `who`:
  - `yoo` is the caller
  - `who` is the callee
- Can registers be used for temporary storage?

```
yoo:
    • • •
    movl $33, %edx
    call who
    addl %edx, %eax
    • • •
    ret
```

```
who:
    • • •
    movl 8(%ebp), %edx
    addl $32, %edx
    • • •
    ret
```

  - contents of register `%edx` overwritten by `who`
  - this could be trouble: something should be done!
    - » need some coordination

# Register-Saving Conventions

- When function `yoo` calls `who`:
  - `yoo` is the caller
  - `who` is the callee
- Can registers be used for temporary storage?
- Conventions
  - "caller save"
    - » caller saves registers containing temporary values on stack before the call
    - » restores them after call
  - "callee save"
    - » callee saves registers on stack before using
    - » restores them before returning

# 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
  - restored to original values upon exit from function

# Register-Saving Example

```
yoo:
    ...
    movl $33, %edx
    pushl %edx
    call who
    popl %edx
    addl %edx, %eax
    ...
    ret
```

```
who:
    ...
    pushl %ebx
    ...
    movl 4(%ebp), %ebx
    addl %53, %ebx
    movl 8(%ebp), %edx
    addl $32, %edx
    ...
    popl %ebx
    ...
    ret
```

# Recursive Function

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

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

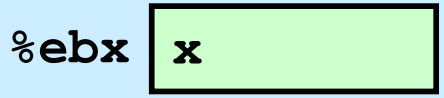
```
pcount_r:
    pushl  %ebp
    movl   %esp, %ebp
    pushl  %ebx
    subl   $4, %esp
    movl   8(%ebp), %ebx
    movl   $0, %eax
    testl  %ebx, %ebx
    je     .L3
    movl   %ebx, %eax
    shrl   $1, %eax
    movl   %eax, (%esp)
    call   pcount_r
    movl   %ebx, %edx
    andl   $1, %edx
  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

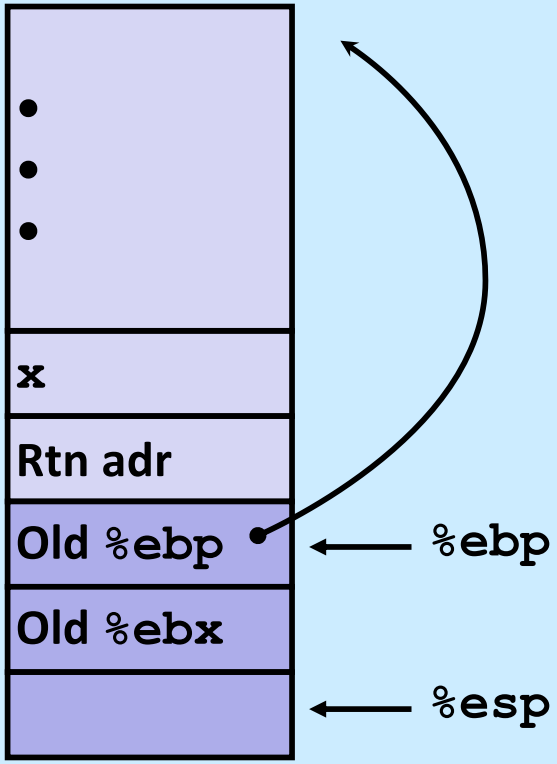
# Recursive Call #1

```
/* 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`**



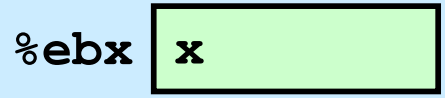



# Recursive Call #2

```
/* 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**

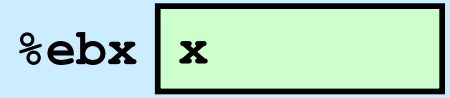


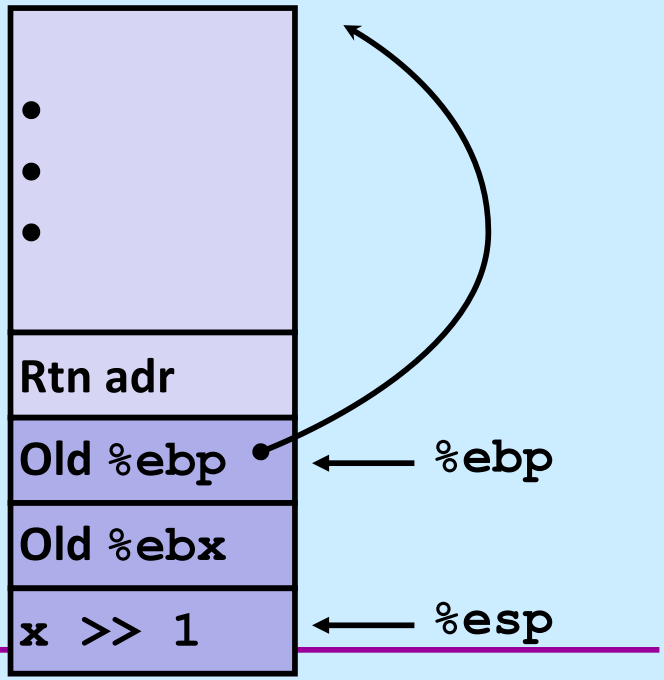
# Recursive Call #3

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

```
  • • •
movl   %ebx, %eax
shrl   $1, %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



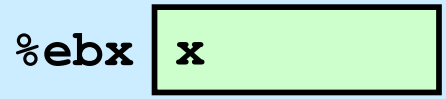



# Recursive Call #4

```
/* 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**
  - **`%eax` set to function result**

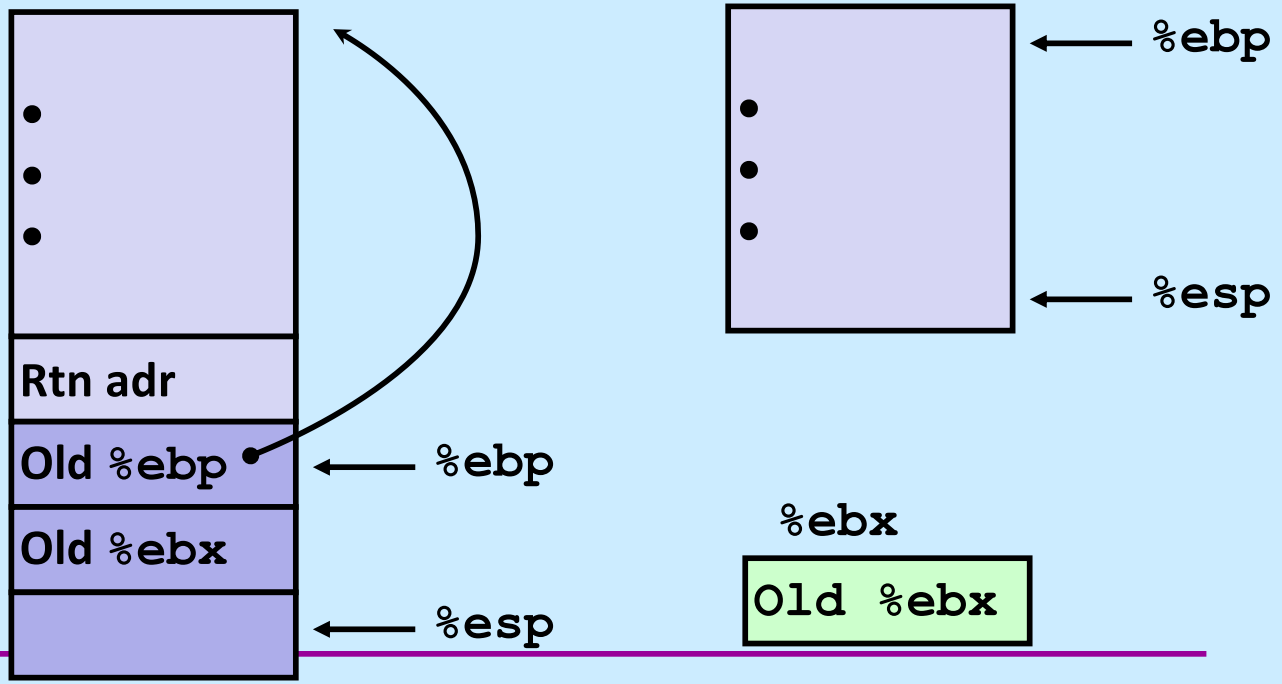


# Recursive Call #5

```
/* 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

# Why Bother with a Frame Pointer?

- It (%rbp) points to the beginning of the stack frame
  - making it easy for people to figure out where things are in the frame
  - but people don't execute the code ...
- The stack pointer always points somewhere within the stack frame
  - it moves about, but the compiler knows where it is pointing
    - » a local variable might be at 8(%rsp) for one instruction, but at 16(%rsp) for a subsequent one
    - » tough for people, but easy for the compiler
- Thus the frame pointer is superfluous
  - it can be used as a general-purpose register

# x86-64 General-Purpose Registers: Usage Conventions

| | | | |
|---|---|---|---|
| `%rax` | Return value | `%r8` | Argument #5 |
| `%rbx` | Callee saved | `%r9` | Argument #6 |
| `%rcx` | Argument #4 | `%r10` | Caller saved |
| `%rdx` | Argument #3 | `%r11` | Caller Saved |
| `%rsi` | Argument #2 | `%r12` | Callee saved |
| `%rdi` | Argument #1 | `%r13` | Callee saved |
| `%rsp` | Stack pointer | `%r14` | Callee saved |
| `%rbp` | Callee saved | `%r15` | Callee saved |