Introduction to Computer Systems

15-213/18-243, fall 2009
6th Lecture, Sep. 10th

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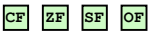
Last Time

- **Complete memory addressing mode**
  - `(%eax), 17(%eax), 2(%ebx, %ecx, 8), …`
- **Arithmetic operations**
  - `subl %eax, %ecx` `# ecx = ecx + eax`
  - `sall $4,%edx` `# edx = edx << 4`
  - `addl 16(%ebp),%ecx` `# ecx = ecx + Mem[16+ebp]`
  - `leal 4(%edx,%eax),%eax` `# eax = 4 + edx + eax`
  - `imull %ecx,%eax` `# eax = eax * ecx`

Last Time

- **x86-64 vs. IA32**
  - Integer registers: **16 x 64-bit** vs. **8 x 32-bit**
  - `movq, addq,` … vs. `movl, addl`, …
  - Better support for passing function arguments in registers

- **Control**
  - Condition code registers
  - Set as side effect or by `cmp, test`
  - Used:
    - Read out by setx instructions (`setg, setle`, …)
    - Or by conditional jumps (`jle .L4, je .L10,` …)



Last Time

- **Do-While loop**

C Code

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

Goto Version

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

- **While-Do loop**

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:
```

or

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


Today

- **For loops**
- **Switch statements**
- **Procedures**

"For" Loop Example: Square-and-Multiply

```
/* Compute x raised to nonnegative power p */
int ipwr_for(int x, unsigned p)
{
  int result;
    for (result = 1; p != 0; p = p>>1) {
      if (p & 0x1)
        result *= x;
      x = x*x;
    }
  return result;
}
```

- **Algorithm**
  - Exploit bit representation: $p = p_0 + 2p_1 + 2^2p_2 + \ldots 2^{n-1}p_{n-1}$
  - Gives: $x^p = z_0 \cdot {z_1}^2 \cdot ({z_2}^2)^2 \cdot \ldots \cdot \underbrace{(\ldots(({z_{n-1}}^2)^2)\ldots)^2}_{n-1 \text{ times}}$
    $z_i = 1$ when $p_i = 0$
    $z_i = x$ when $p_i = 1$
  - Complexity $O(\log p)$

Example

$3^{10} = 3^2 * 3^8$
$= 3^2 * ((3^2)^2)^2$

ipwr Computation

```
/* Compute x raised to nonnegative power p */
int ipwr_for(int x, unsigned p)
{
  int result;
    for (result = 1; p != 0; p = p>>1) {
      if (p & 0x1)
        result *= x;
      x = x*x;
    }
  return result;
}
```

before iteration	result	x=3	p=10
1	1	3	$10=1010_2$
2	1	9	$5=101_2$
3	9	81	$2=10_2$
4	9	6561	$1=1_2$
5	59049	43046721	0

"For" Loop Example

```
int result;
for (result = 1; p != 0; p = p>>1)
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

General Form

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

Test	Init	Update	Body
`p != 0`	`result = 1`	`p = p >> 1`	`{ if (p & 0x1) result *= x; x = x*x; }`

"For" → "While" → "Do-While"

For Version

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

While Version

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

Do-While Version

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

Goto Version

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


For-Loop: Compilation #1

For Version

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

```
for (result = 1; p != 0; p = p>>1)
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

Goto Version

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

```
  result = 1;
  if (p == 0)
    goto done;
loop:
  if (p & 0x1)
    result *= x;
  x = x*x;
  p = p >> 1;
  if (p != 0)
    goto loop;
done:
```


"For" → "While" (Jump-to-Middle)

For Version

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

While Version

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

Goto Version

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


For-Loop: Compilation #2

For Version

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

```
for (result = 1; p != 0; p = p>>1)
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

Goto Version

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

```
  result = 1;
goto middle;
loop:
  if (p & 0x1)
    result *= x;
  x = x*x;
  p = p >> 1;
middle:
  if (p != 0)
    goto loop;
done:
```

Today

- For loops
- **Switch statements**
- Procedures


```
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

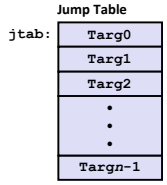
- **Multiple case labels**
  - Here: 5, 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

Jump Table Structure

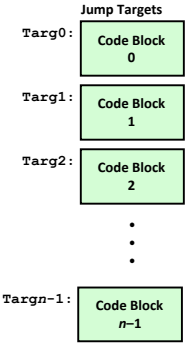
Switch Form

```
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 (IA32)

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

```
Setup:   switch_eg:
           pushl %ebp            # Setup
           movl  %esp, %ebp      # Setup
           pushl %ebx            # Setup
           movl  $1, %ebx
           movl  8(%ebp), %edx
           movl  16(%ebp), %ecx
           cmpl  $6, %edx
           ja    .L61
           jmp   *.L62(,%edx,4)
```

Will disappear Blackboard?

Switch Statement Example (IA32)

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

```
Setup:   switch_eg:
           pushl %ebp            # Setup
           movl  %esp, %ebp      # Setup
           pushl %ebx            # Setup
           movl  $1, %ebx        # w = 1
           movl  8(%ebp), %edx   # edx = x
           movl  16(%ebp), %ecx  # ecx = z
           cmpl  $6, %edx        # x:6
           ja    .L61            # if > goto default
Indirect   jmp   *.L62(,%edx,4)  # goto JTab[x]
jump
```

Jump table

```
.section .rodata
   .align 4
.L62:
   .long   .L61  # x = 0
   .long   .L56  # x = 1
   .long   .L57  # x = 2
   .long   .L58  # x = 3
   .long   .L61  # x = 4
   .long   .L60  # x = 5
   .long   .L60  # x = 6
```


Assembly Setup Explanation

- **Table Structure**
  - Each target requires 4 bytes
  - Base address at `.L62`
- **Jumping**

  Direct: `jmp .L61`
  - Jump target is denoted by label `.L61`

  Indirect: `jmp *.L62(,%edx,4)`
  - Start of jump table: `.L62`
  - Must scale by factor of 4 (labels have 32-bit = 4 Bytes on IA32)
  - Fetch target from effective Address `.L61 + edx*4`
    - Only for $0 \le x \le 6$

Jump table

```
.section .rodata
   .align 4
.L62:
   .long   .L61  # x = 0
   .long   .L56  # x = 1
   .long   .L57  # x = 2
   .long   .L58  # x = 3
   .long   .L61  # x = 4
   .long   .L60  # x = 5
   .long   .L60  # x = 6
```

Jump Table

Jump table

```
.section .rodata
   .align 4
.L62:
  .long   .L61  # x = 0
  .long   .L56  # x = 1
  .long   .L57  # x = 2
  .long   .L58  # x = 3
  .long   .L61  # x = 4
  .long   .L60  # x = 5
  .long   .L60  # x = 6
```

```
   switch(x) {
   case 1:      // .L56
       w = y*z;
       break;
   case 2:      // .L57
       w = y/z;
       /* Fall Through */
   case 3:      // .L58
       w += z;
       break;
   case 5:
   case 6:      // .L60
       w -= z;
       break;
   default:     // .L61
       w = 2;
   }
```


Code Blocks (Partial)

```
switch(x) {
  . . .
case 2:      // .L57
    w = y/z;
    /* Fall Through */
case 3:      // .L58
    w += z;
    break;
  . . .
default:     // .L61
    w = 2;
}
```

```
.L61:  // Default case
  movl  $2, %ebx     # w = 2
  movl  %ebx, %eax   # Return w
  popl  %ebx
  leave
  ret
.L57:  // Case 2:
  movl  12(%ebp), %eax  # y
  cltd                  # Div prep
  idivl %ecx            # y/z
  movl  %eax, %ebx # w = y/z
# Fall through
.L58:  // Case 3:
  addl  %ecx, %ebx # w+= z
  movl  %ebx, %eax # Return w
  popl  %ebx
  leave
  ret
```


Code Blocks (Rest)

```
   switch(x) {
   case 1:      // .L56
       w = y*z;
       break;
     . . .
   case 5:
   case 6:      // .L60
       w -= z;
       break;
     . . .
   }
```

```
.L60: // Cases 5&6:
  subl  %ecx, %ebx  # w -= z
  movl  %ebx, %eax  # Return w
  popl  %ebx
  leave
  ret
.L56: // Case 1:
  movl  12(%ebp), %ebx # w = y
  imull %ecx, %ebx     # w*= z
  movl  %ebx, %eax  # Return w
  popl  %ebx
  leave
  ret
```


x86-64 Switch Implementation

- Same general idea, adapted to 64-bit code
- Table entries 64 bits (pointers)
- Cases use revised code

```
   switch(x) {
   case 1:      // .L50
       w = y*z;
       break;
     . . .
   }
```

```
.L50: // Case 1:
  movq   %rsi, %r8  # w = y
  imulq  %rdx, %r8  # w *= z
  movq   %r8, %rax  # Return w
  ret
```

Jump Table

```
.section .rodata
   .align 8
.L62:
  .quad   .L55  # x = 0
  .quad   .L50  # x = 1
  .quad   .L51  # x = 2
  .quad   .L52  # x = 3
  .quad   .L55  # x = 4
  .quad   .L54  # x = 5
  .quad   .L54  # x = 6
```


IA32 Object Code

- **Setup**
  - Label `.L61` becomes address `0x8048630`
  - Label `.L62` becomes address `0x80488dc`

Assembly Code

```
switch_eg:
  . . .
  ja    .L61           # if > goto default
  jmp   *.L62(,%edx,4) # goto JTab[x]
```

Disassembled Object Code

```
08048610 <switch_eg>:
 . . .
 8048622:  77 0c                  ja     8048630
 8048624:  ff 24 95 dc 88 04 08   jmp    *0x80488dc(,%edx,4)
```


IA32 Object Code (cont.)

- **Jump Table**
  - Doesn't show up in disassembled code
  - Can inspect using GDB

```
gdb asm-cntl
(gdb) x/7xw 0x80488dc
```

    - Examine 7 hexadecimal format "words" (4-bytes each)
    - Use command "`help x`" to get format documentation

```
0x80488dc:
  0x08048630
  0x08048650
  0x0804863a
  0x08048642
  0x08048630
  0x08048649
  0x08048649
```

Disassembled Targets

```
8048630:    bb 02 00 00 00      mov    $0x2,%ebx
8048635:    89 d8               mov    %ebx,%eax
8048637:    5b                  pop    %ebx
8048638:    c9                  leave
8048639:    c3                  ret
804863a:    8b 45 0c            mov    0xc(%ebp),%eax
804863d:    99                  cltd
804863e:    f7 f9               idiv   %ecx
8048640:    89 c3               mov    %eax,%ebx
8048642:    01 cb               add    %ecx,%ebx
8048644:    89 d8               mov    %ebx,%eax
8048646:    5b                  pop    %ebx
8048647:    c9                  leave
8048648:    c3                  ret
8048649:    29 cb               sub    %ecx,%ebx
804864b:    89 d8               mov    %ebx,%eax
804864d:    5b                  pop    %ebx
804864e:    c9                  leave
804864f:    c3                  ret
8048650:    8b 5d 0c            mov    0xc(%ebp),%ebx
8048653:    0f af d9            imul   %ecx,%ebx
8048656:    89 d8               mov    %ebx,%eax
8048658:    5b                  pop    %ebx
8048659:    c9                  leave
804865a:    c3                  ret
```


Matching Disassembled Targets

0x08048630
0x08048650
0x0804863a
0x08048642
0x08048630
0x08048649
0x08048649

```
8048630:    bb 02 00 00 00      mov
8048635:    89 d8               mov
8048637:    5b                  pop
8048638:    c9                  leave
8048639:    c3                  ret
804863a:    8b 45 0c            mov
804863d:    99                  cltd
804863e:    f7 f9               idiv
8048640:    89 c3               mov
8048642:    01 cb               add
8048644:    89 d8               mov
8048646:    5b                  pop
8048647:    c9                  leave
8048648:    c3                  ret
8048649:    29 cb               sub
804864b:    89 d8               mov
804864d:    5b                  pop
804864e:    c9                  leave
804864f:    c3                  ret
8048650:    8b 5d 0c            mov
8048653:    0f af d9            imul
8048656:    89 d8               mov
8048658:    5b                  pop
8048659:    c9                  leave
804865a:    c3                  ret
```


x86-64 Object Code

- **Setup**
  - Label **.L61** becomes address **0x0000000000400716**
  - Label **.L62** becomes address **0x0000000000400990**

Assembly Code

```
switch_eg:
  . . .
  ja    .L55            # if > goto default
  jmp   *.L56(,%rdi,8)  # goto JTab[x]
```

Disassembled Object Code

```
0000000000400700 <switch_eg>:
 . . .
  40070d:  77 07                ja     400716
  40070f:  ff 24 fd 90 09 40 00 jmpq   *0x400990(,%rdi,8)
```


x86-64 Object Code (cont.)

- **Jump Table**
  - Can inspect using GDB

```
gdb asm-cntl
(gdb) x/7xg 0x400990
```

  - Examine 7 hexadecimal format "giant words" (8-bytes each)
  - Use command "**help x**" to get format documentation

```
0x400990:
  0x0000000000400716
  0x0000000000400739
  0x0000000000400720
  0x000000000040072b
  0x0000000000400716
  0x0000000000400732
  0x0000000000400732
```


Sparse Switch Example

```
/* Return x/111 if x is multiple
   && <= 999.  -1 otherwise */
int div111(int x)
{
  switch(x) {
  case   0: return 0;
  case 111: return 1;
  case 222: return 2;
  case 333: return 3;
  case 444: return 4;
  case 555: return 5;
  case 666: return 6;
  case 777: return 7;
  case 888: return 8;
  case 999: return 9;
  default: return -1;
  }
}
```

- Not practical to use jump table
  - Would require 1000 entries
- Obvious translation into if-then-else would have max. of 9 tests

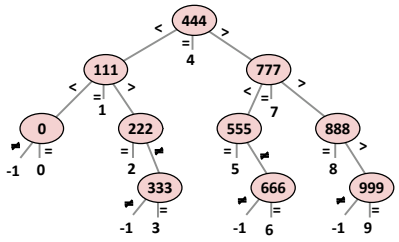
Sparse Switch Code (IA32)

```
    movl 8(%ebp),%eax  # get x
    cmpl $444,%eax     # x:444
    je L8
    jg L16
    cmpl $111,%eax     # x:111
    je L5
    jg L17
    testl %eax,%eax    # x:0
    je L4
    jmp L14

    . . .
```

- Compares x to possible case values
- Jumps different places depending on outcomes

```
    . . .
L5:
    movl $1,%eax
    jmp L19
L6:
    movl $2,%eax
    jmp L19
L7:
    movl $3,%eax
    jmp L19
L8:
    movl $4,%eax
    jmp L19
    . . .
```

Sparse Switch Code Structure



- Organizes cases as binary tree
- Logarithmic performance

Summarizing

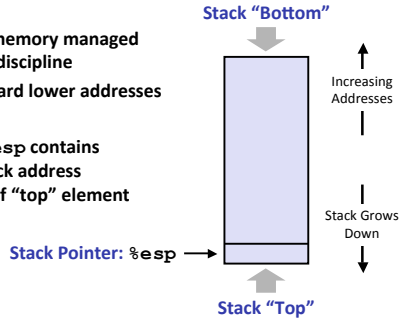
- **C Control**
  - if-then-else
  - do-while
  - while, for
  - switch
- **Assembler Control**
  - Conditional jump
  - Conditional move
  - Indirect jump
  - Compiler
  - Must generate assembly code to implement more complex control
- **Standard Techniques**
  - IA32 loops converted to do-while form
  - x86-64 loops use jump-to-middle
  - Large switch statements use jump tables
  - Sparse switch statements may use decision trees (not shown)
- **Conditions in CISC**
  - CISC machines generally have condition code registers

Today

- For loops
- Switch statements
- **Procedures**

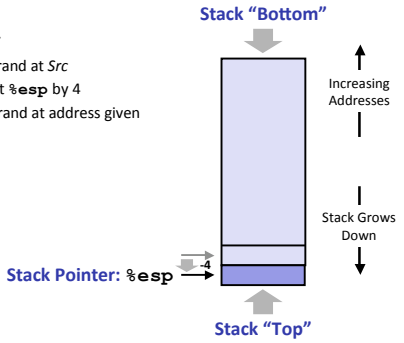
IA32 Stack

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



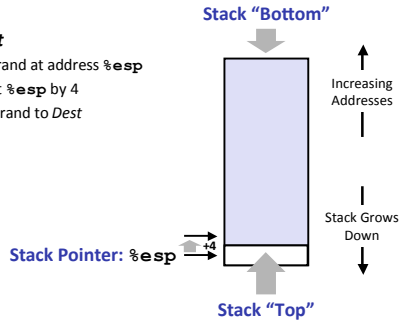
IA32 Stack: Push

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



IA32 Stack: Pop

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



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 instruction beyond `call`
  - Example from disassembly

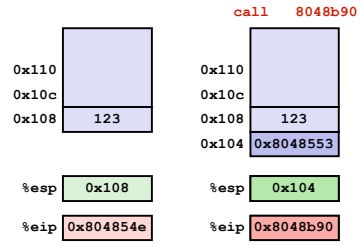
```
804854e:  e8 3d 06 00 00    call   8048b90 <main>
8048553:  50                pushl  %eax
```

  - Return address = `0x8048553`
- **Procedure return: `ret`**
  - Pop address from stack
  - Jump to address

Think: `popl %eip`

Procedure Call Example

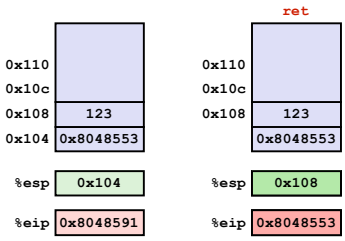
```
804854e:  e8 3d 06 00 00    call   8048b90 <main>
8048553:  50                pushl  %eax
```



`%eip`: program counter

Procedure Return Example

```
8048591:  c3                ret
```

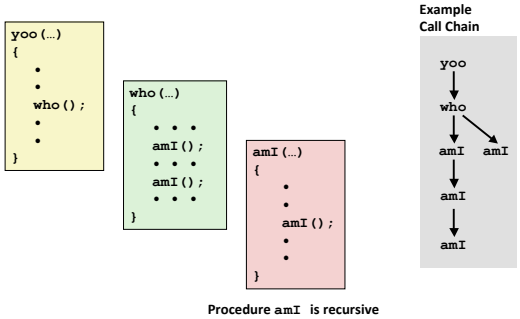


`%eip`: program counter

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

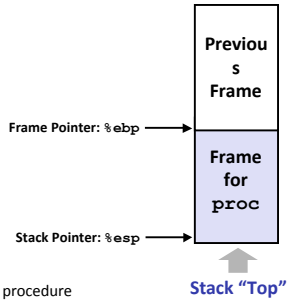
Call Chain Example



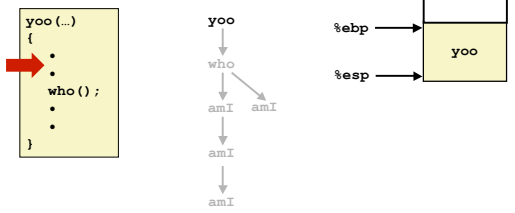
Procedure `amI` is recursive

Stack Frames

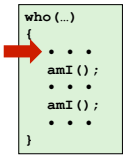
- **Contents**
  - Local variables
  - Return information
  - Temporary space
- **Management**
  - Space allocated when enter procedure
    - "Set-up" code
  - Deallocated when return
    - "Finish" code

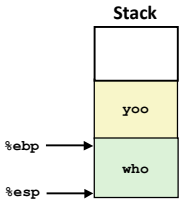


Example

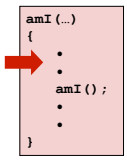


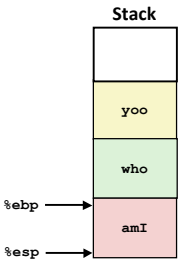
Example



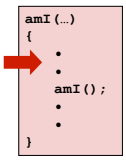


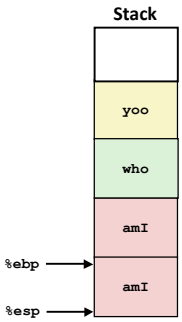
Example



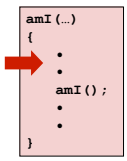


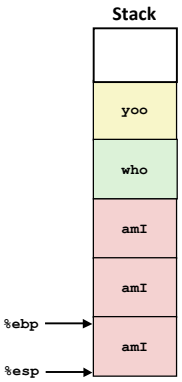
Example



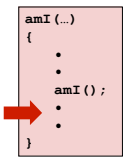


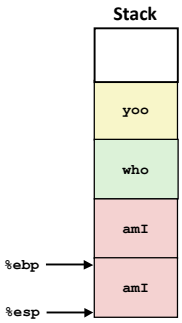
Example



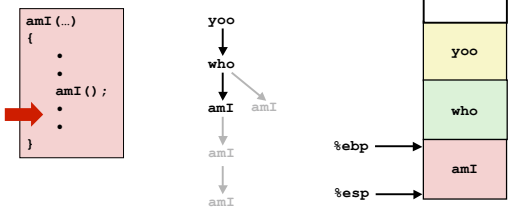


Example

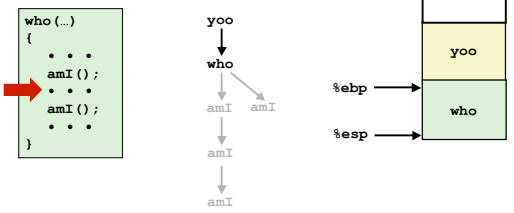




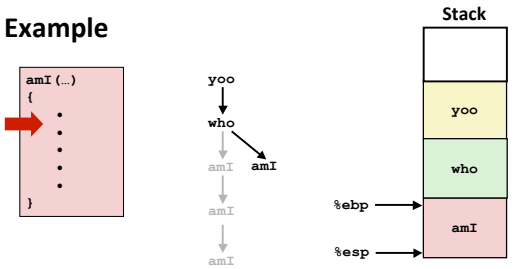
Example



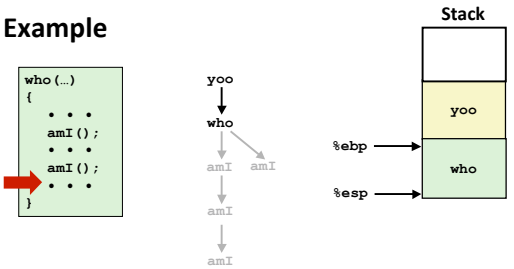
Example



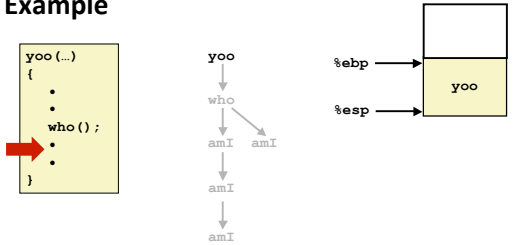
Example



Example

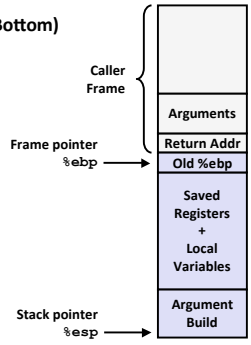


Example



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



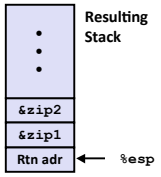
Revisiting swap

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

void call_swap()
{
  swap(&zip1, &zip2);
}
```

Calling swap from call_swap

```
call_swap:
    • • •
    pushl $zip2   # Global Var
    pushl $zip1   # Global Var
    call swap
    • • •
```

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



Revisiting swap

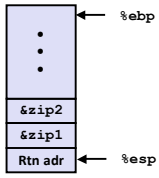
```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

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

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

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

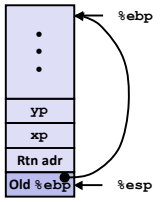
Do on blackboard?

swap Setup #1

Entering Stack



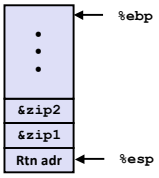
Resulting Stack

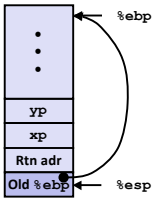



```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```


swap Setup #1

Entering Stack

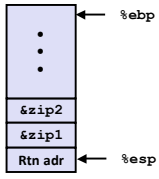




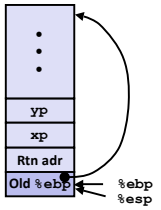

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```


swap Setup #1

Entering Stack



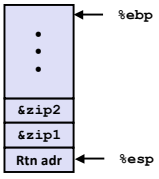
Resulting Stack

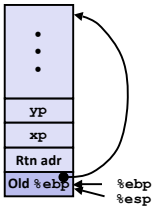



```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```


swap Setup #1

Entering Stack

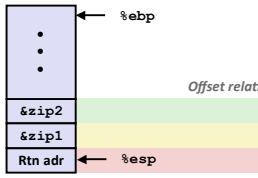





```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

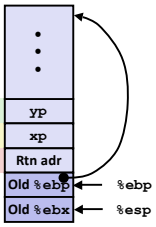
swap Setup #1

Entering Stack



Offset relative to %ebp

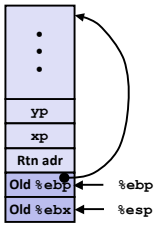
Resulting Stack



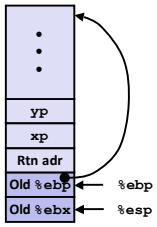

```
movl 12(%ebp),%ecx # get yp
movl 8(%ebp),%edx  # get xp
. . .
```


swap Finish #1

swap's Stack



Resulting Stack

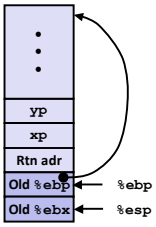


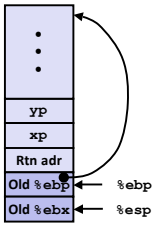

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Observation: Saved and restored register %ebx

swap Finish #2

swap's Stack

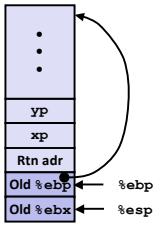




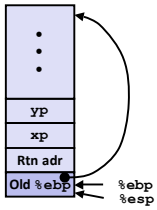

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```


swap Finish #2

swap's Stack



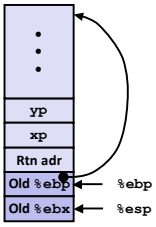
Resulting Stack

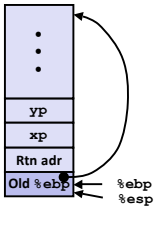



```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```


swap Finish #2

swap's Stack

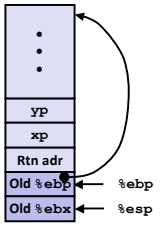




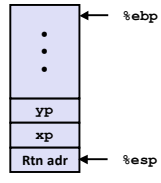

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```


swap Finish #3

swap's Stack



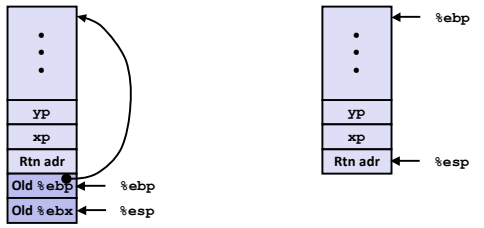
Resulting Stack




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

swap Finish #4

swap's Stack

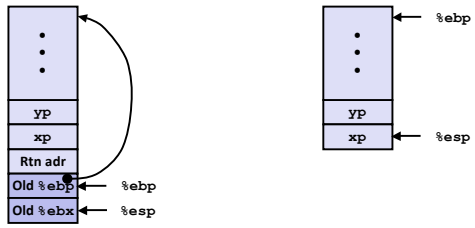



```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```


swap Finish #4

swap's Stack

Resulting Stack




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

- **Observation**
  - Saved & restored register `%ebx`
  - Didn't do so for `%eax`, `%ecx`, or `%edx`

Disassembled swap

```
080483a4 <swap>:
 80483a4:   55          push   %ebp
 80483a5:   89 e5       mov    %esp,%ebp
 80483a7:   53          push   %ebx
 80483a8:   8b 55 08    mov    0x8(%ebp),%edx
 80483ab:   8b 4d 0c    mov    0xc(%ebp),%ecx
 80483ae:   8b 1a       mov    (%edx),%ebx
 80483b0:   8b 01       mov    (%ecx),%eax
 80483b2:   89 02       mov    %eax,(%edx)
 80483b4:   89 19       mov    %ebx,(%ecx)
 80483b6:   5b          pop    %ebx
 80483b7:   c9          leave
 80483b8:   c3          ret
```

Calling Code

```
 8048409:   e8 96 ff ff ff    call 80483a4 <swap>
 804840e:   8b 45 f8          mov  0xfffffff8(%ebp),%eax
```


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
```

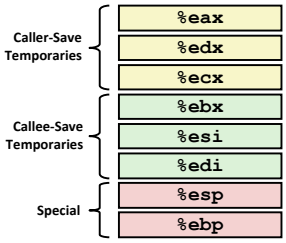
  - Contents of register `%edx` overwritten by `who`

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

- `%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



Recursive Factorial

```
int rfact(int x)
{
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

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

```
.globl rfact
    .type
rfact,@function
rfact:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
    movl 8(%ebp),%ebx
    cmpl $1,%ebx
    jle .L78
    leal -1(%ebx),%eax
    pushl %eax
    call rfact
    imull %ebx,%eax
    jmp .L79
    .align 4
.L78:
    movl $1,%eax
.L79:
    movl -4(%ebp),%ebx
    movl %ebp,%esp
    popl %ebp
    ret
```


Pointer Code

Recursive Procedure

```
void s_helper
  (int x, int *accum)
{
  if (x <= 1)
    return;
  else {
    int z = *accum * x;
    *accum = z;
    s_helper (x-1,accum);
  }
}
```

Top-Level Call

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- **Pass pointer to update location**

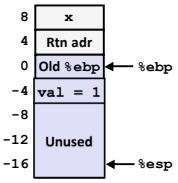
Creating & Initializing Pointer

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- Variable `val` must be stored on stack
  - Because: Need to create pointer to it
- Compute pointer as `-4(%ebp)`
- Push on stack as second argument

Initial part of `sfact`

```
_sfact:
   pushl %ebp
   movl %esp,%ebp
   subl $16,%esp
   movl 8(%ebp),%edx
   movl $1,-4(%ebp)
```



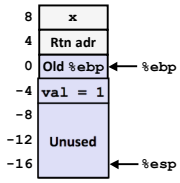
Creating & Initializing Pointer

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- Variable `val` must be stored on stack
  - Because: Need to create pointer to it
- Compute pointer as `-4(%ebp)`
- Push on stack as second argument

Initial part of `sfact`

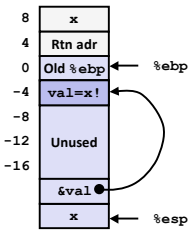
```
_sfact:
   pushl %ebp          # Save %ebp
   movl %esp,%ebp      # Set %ebp
   subl $16,%esp       # Add 16 bytes
   movl 8(%ebp),%edx   # edx = x
   movl $1,-4(%ebp)    # val = 1
```



Passing Pointer

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

Stack at time of call



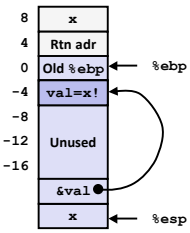
Calling `s_helper` from `sfact`

```
   leal -4(%ebp),%eax
   pushl %eax
   pushl %edx
   call s_helper
   movl -4(%ebp),%eax
   • • •
```


Passing Pointer

```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

Stack at time of call



Calling `s_helper` from `sfact`

```
   leal -4(%ebp),%eax  # Compute &val
   pushl %eax          # Push on stack
   pushl %edx          # Push x
   call s_helper       # call
   movl -4(%ebp),%eax  # Return val
   • • •               # Finish
```

IA 32 Procedure 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
  - 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