UNM SCHOOL of ENGINEERING
Department of Computer Science

Machine-Level Programming III: Switch Statements and Procedures

CS 341: Intro. to Computer Architecture & Organization

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Today

- Switch statements
- IA 32 Procedures
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

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:       // .L3
       w = y*z;
       break;
     . . .
   }
```

```
.L3:
  movq    %rdx, %rax
  imulq   %rsi, %rax
  ret
```

Jump Table

```
  .section .rodata
  .align 8
.L7:
  .quad     .L2     # x = 0
  .quad     .L3     # x = 1
  .quad     .L4     # x = 2
  .quad     .L5     # x = 3
  .quad     .L2     # x = 4
  .quad     .L6     # X = 5
  .quad     .L6     # x = 6
```

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
```

Summarizing

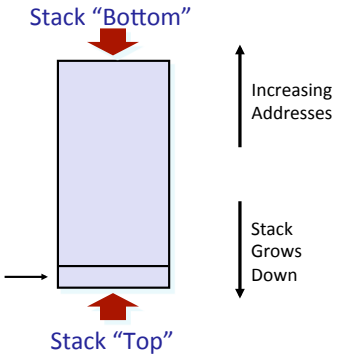
- C Control
  - if-then-else
  - do-while
  - while, for
  - switch
- Assembler Control
  - Conditional jump
  - Conditional move
  - Indirect jump
  - Compiler generates code sequence to implement more complex control
- Standard Techniques
  - Loops converted to do-while form
  - Large switch statements use jump tables
  - Sparse switch statements may use decision trees

Today

- Switch statements
- IA 32 Procedures
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

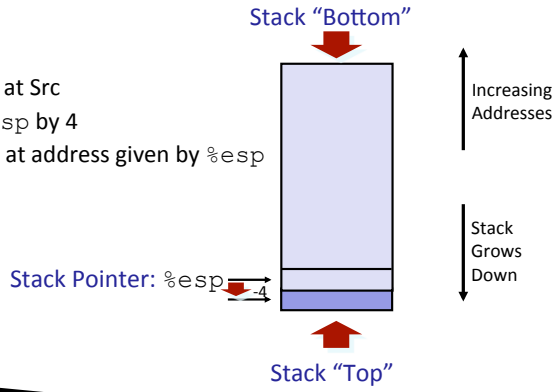
IA32 Stack

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

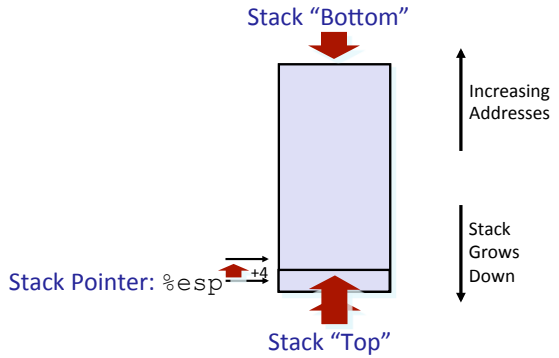


IA32 Stack: Push

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



IA32 Stack: Pop



Procedure Control Flow

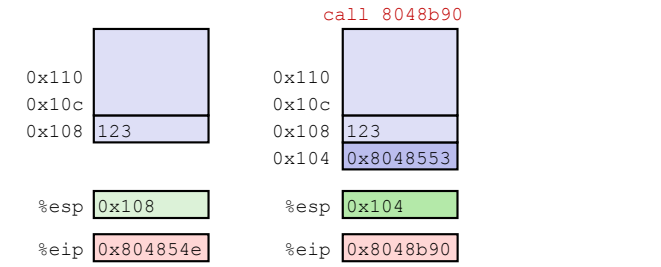
- Use stack to support procedure call and return
- Procedure call: **`call label`**
  - Push return address on stack
  - Jump to label
- Return address:
  - Address of the next instruction right after call
  - Example from disassembly

```
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

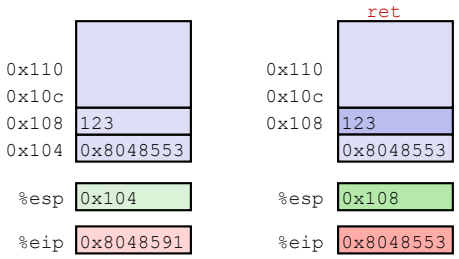
```
804854e:  e8 3d 06 00 00     call   8048b90 <main>
8048553:  50                 pushl  %eax
```



`%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

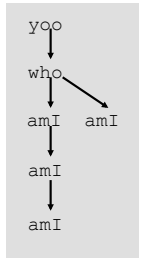
```
yoo(…)
{
  •
  •
  who();
  •
  •
}
```

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

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

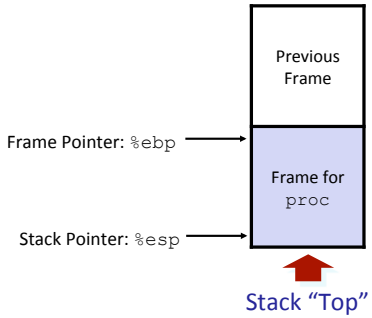
Procedure `amI()` is recursive

Example Call Chain

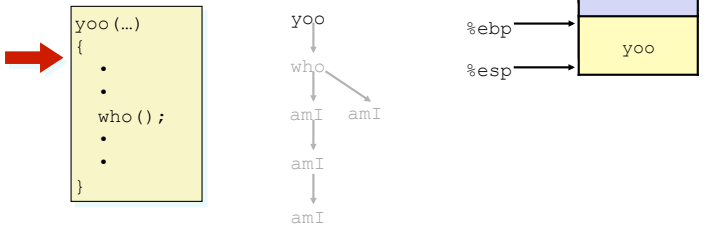


Stack Frames

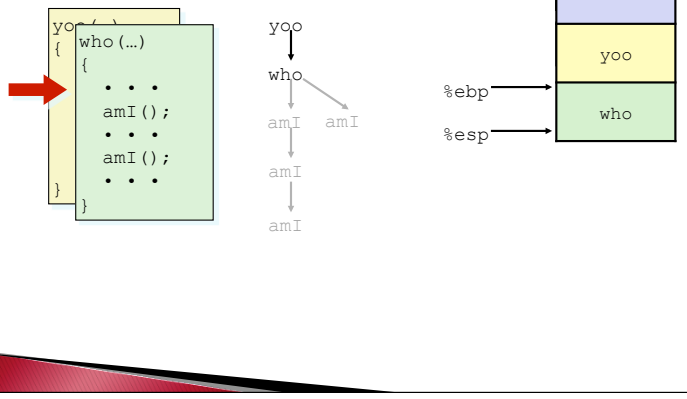
- Contents
  - Local variables
  - Return information
  - Temporary space
- Management
  - Space allocated when enter procedure
    - "Set-up" code
  - Deallocated when return
    - "Finish" code



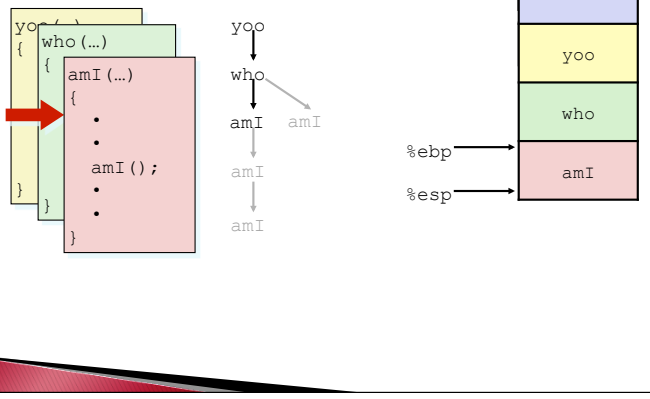
Example



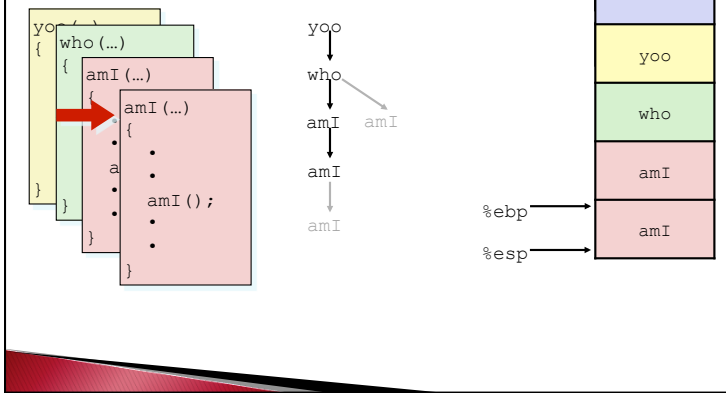
Example



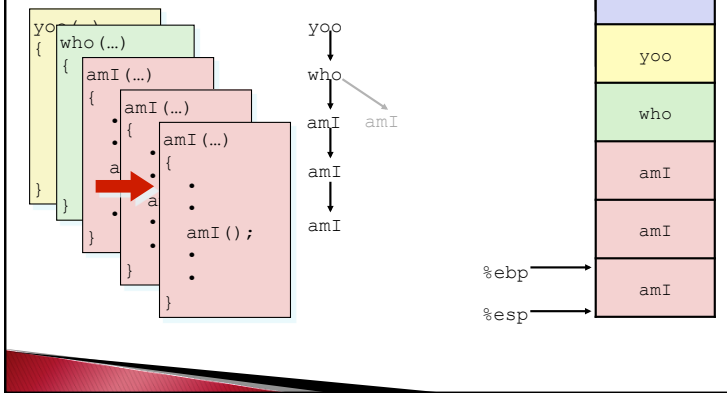
Example



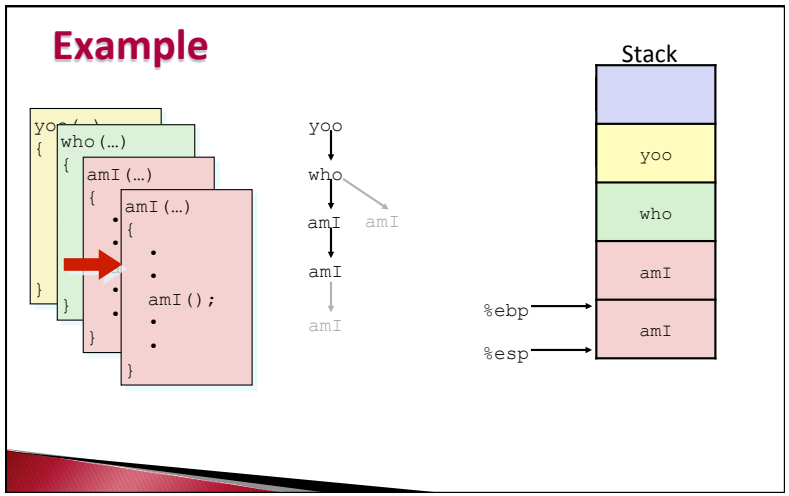
Example



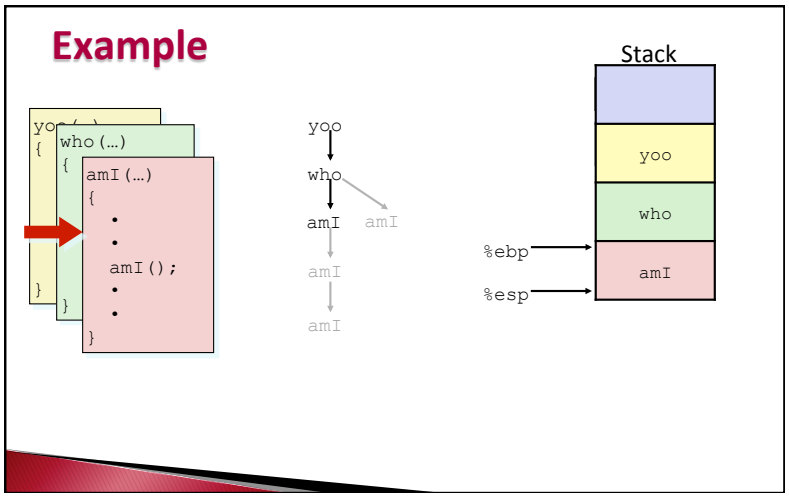
Example



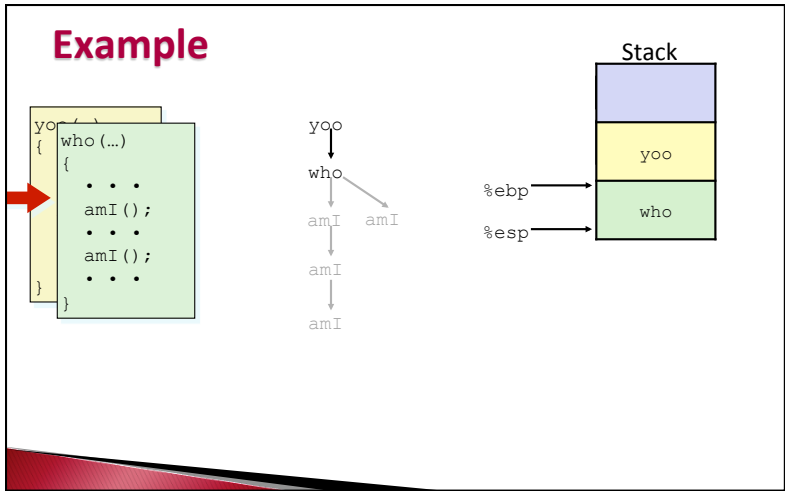
Example



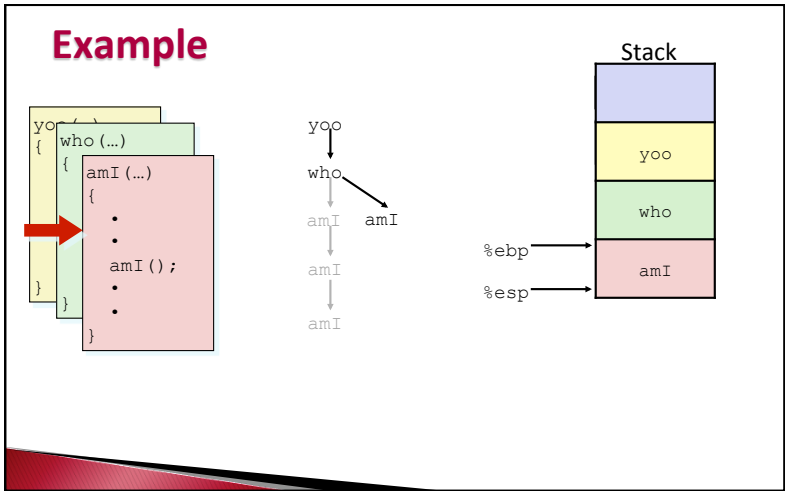
Example



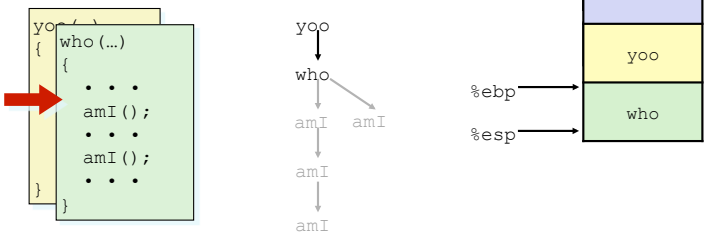
Example



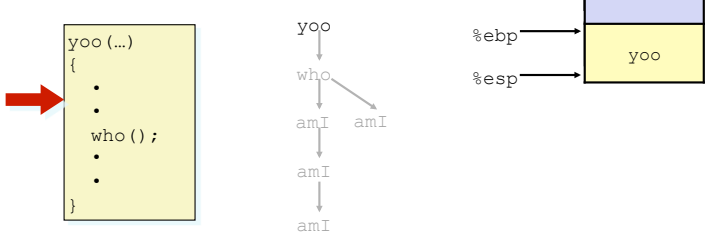
Example



Example

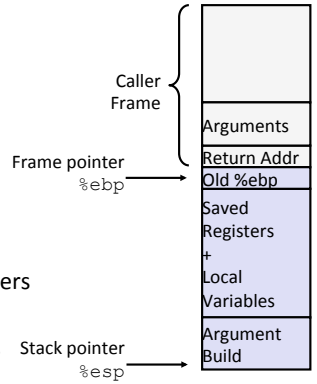


Example



IA32/Linux Stack Frame

- Caller Stack Frame
  - Return address
    - Pushed by `call` instruction
  - Arguments for this call
- Callee Stack Frame
  - Old frame pointer
  - Local variables: If can't keep in registers
  - Saved register context
  - "Argument build": callee parameters



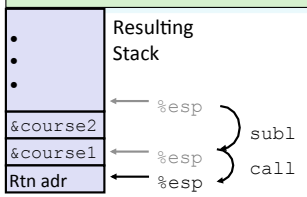
Revisiting `swap`

```
int course1 = 15213;
int course2 = 18243;

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

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

Calling `swap` from `call_swap`

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



Revisiting swap

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

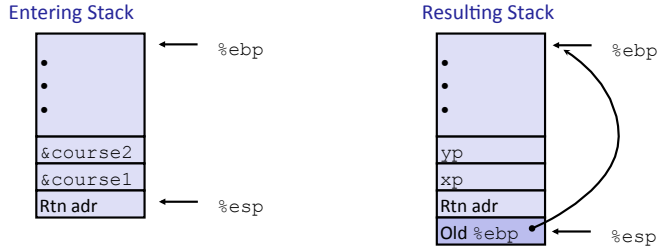
```
swap:
    pushl %ebp
    movl  %esp, %ebp
    pushl %ebx

    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

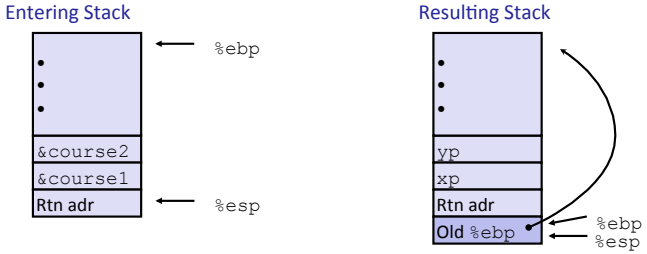
Finish

swap Setup #1



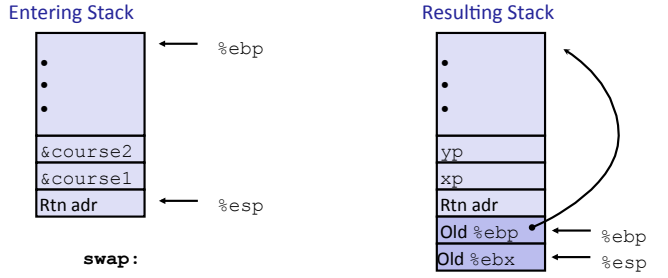

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #2



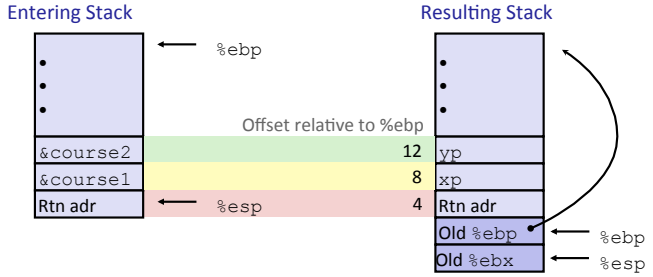

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #3



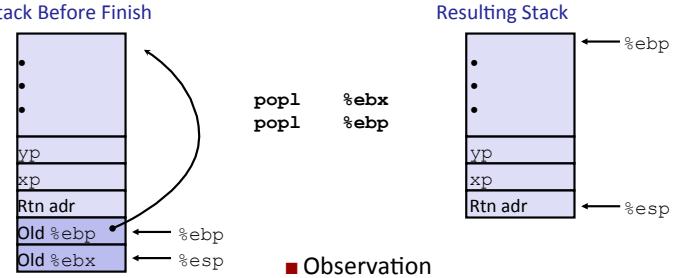

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Body




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

swap Finish



- 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
```

Today

- Switch statements
- **IA 32 Procedures**
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

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 $18243, %edx
    • • •
    ret
```

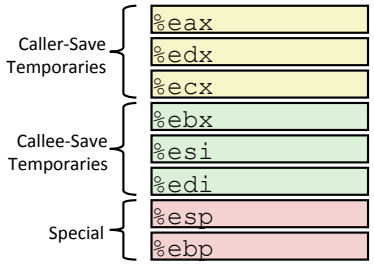
  - Contents of register `%edx` overwritten by `who`
  - This could be trouble ➙ something should be done!
    - Need some coordination

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
  - Restored to original values upon exit from procedure



Today

- Switch statements
- IA 32 Procedures
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

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
```

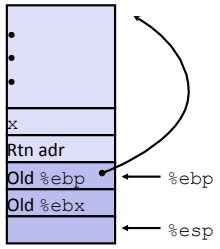
- Registers
  - %eax, %edx used without first saving
  - %ebx used, but saved at beginning & restored at end

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

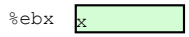


Recursive Call #2

```
/* 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

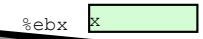


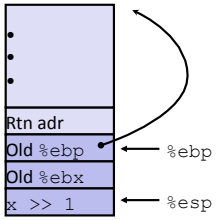
Recursive Call #3

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

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



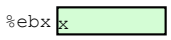


Recursive Call #4

```
/* 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

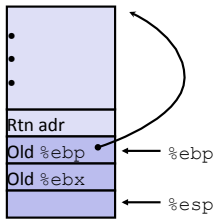


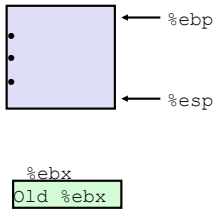
Recursive Call #5

```
/* 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

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**

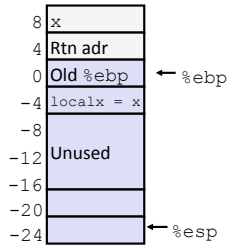
Creating and Initializing Local Variable

```
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
```



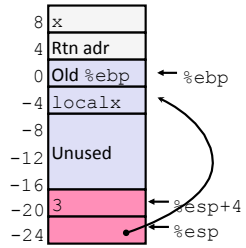
Creating Pointer as Argument

```
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
  call incrk
```



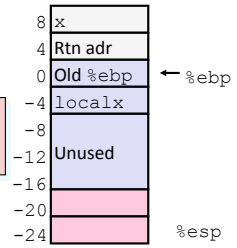
Retrieving local variable

```
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