Machine-Level Programming III: Procedures

CSci 2021: Machine Architecture and Organization
Lecture #11 February 13th, 2015
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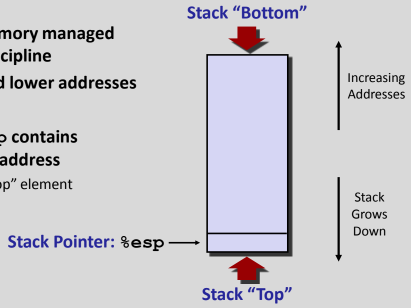
Based on slides originally by:
Randy Bryant, Dave O'Hallaron, Antonia Zhai

Today

- **IA 32 Procedures**
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers
- **X86-64 Procedures**

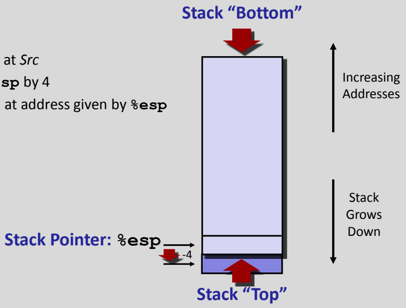
IA32 Stack

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

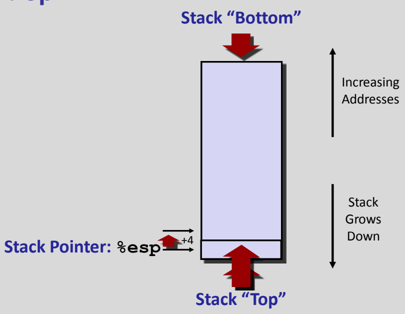


IA32 Stack: Push

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



IA32 Stack: Pop



Procedure Control Flow

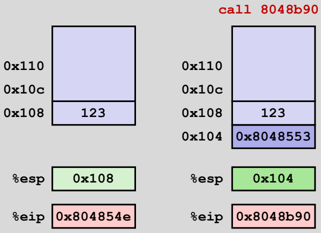
- **Use stack to support procedure call and return**
- **Procedure call: `call label`**
  - Push return address on stack
  - Jump to ***label***
- **Return address:**
  - Address of the next instruction right after call
  - Example from disassembly

```
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

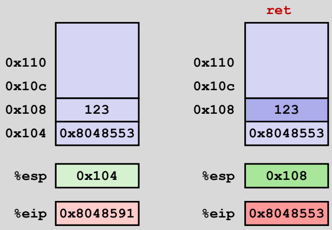
```
804854e:      e8 3d 06 00 00        call    8048b90 <main>
8048553:      50                    pushl   %eax
```



`%eip`: *program counter*

Procedure Return Example

```
8048591:      c3                    ret
```

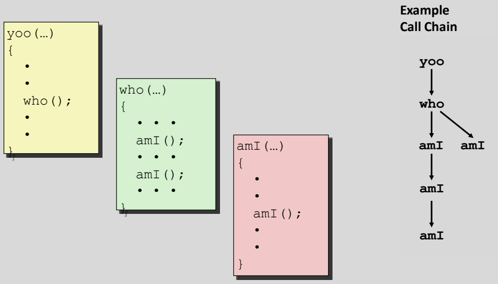


`%eip`: *program counter*

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

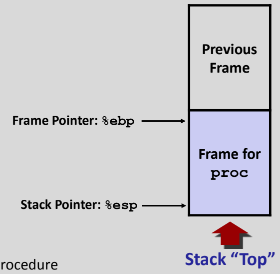
Call Chain Example



Procedure `amI()` is recursive

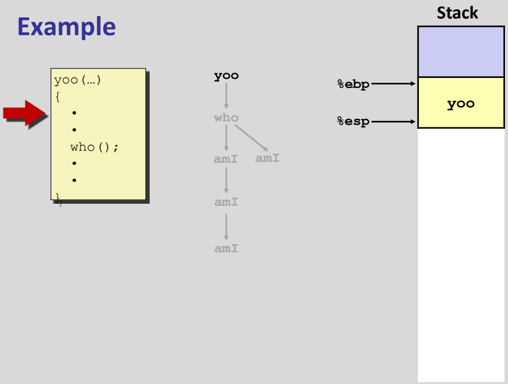
Stack Frames

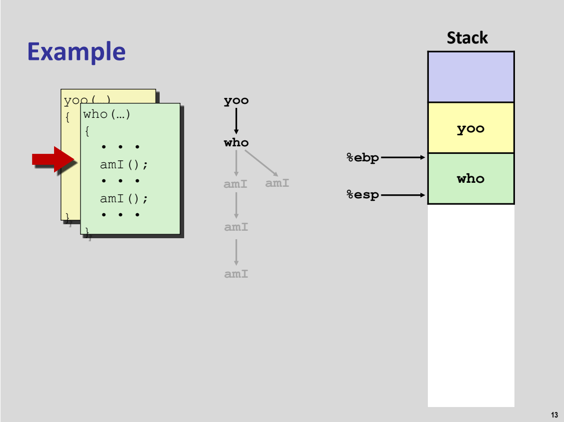
- **Contents**
  - Local variables
  - Return information
  - Temporary space



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

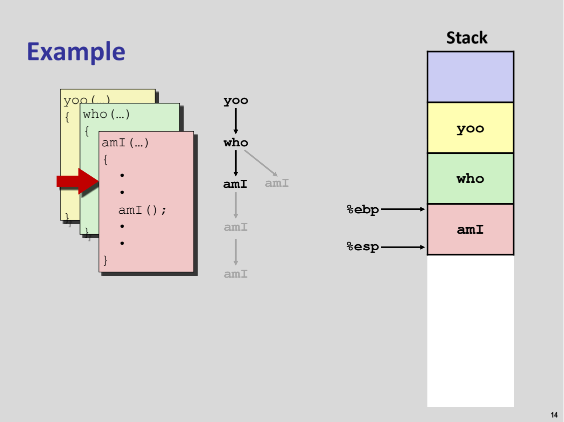
Example





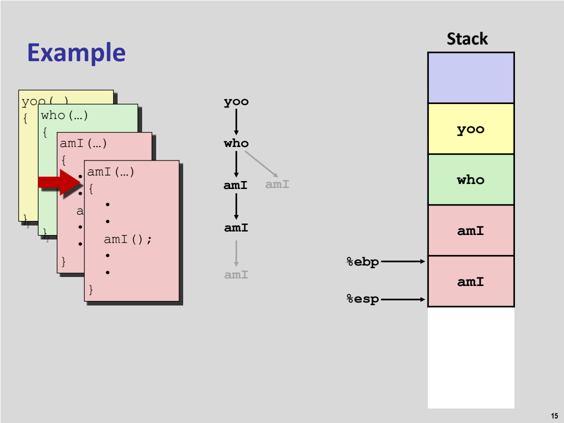
Example

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



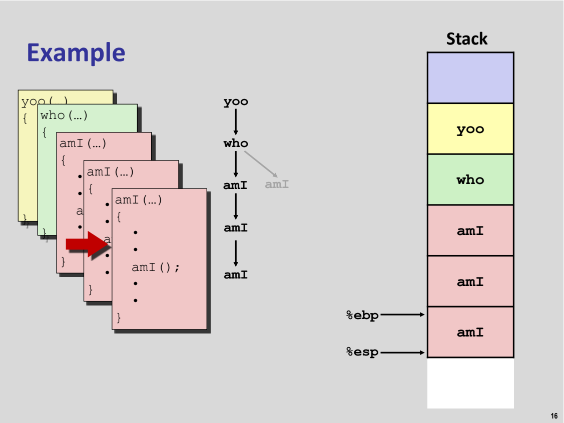
Example

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



Example

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



Example

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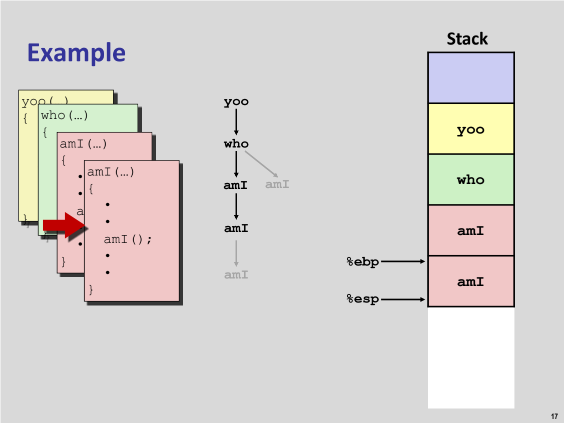
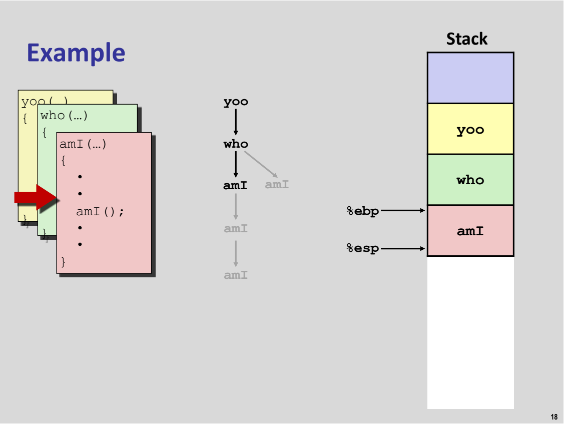



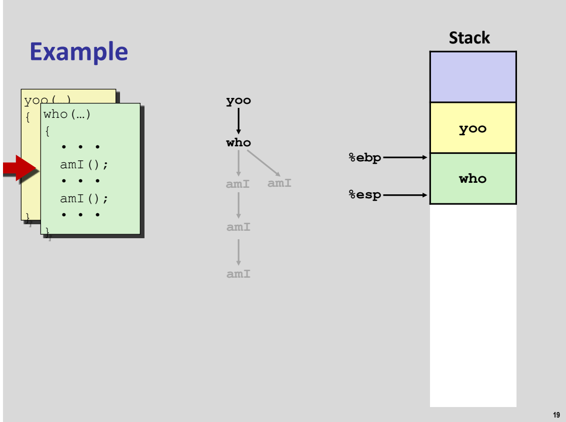
Example

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



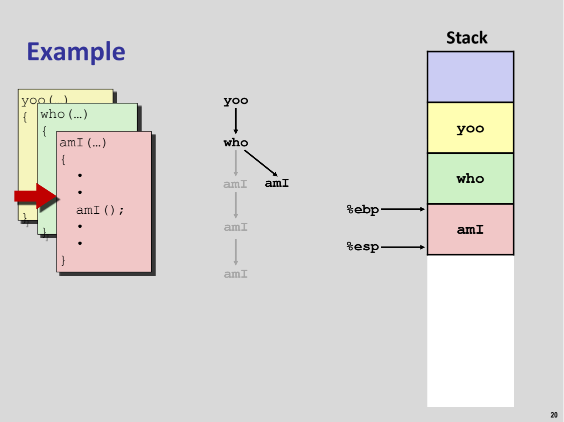
Example

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



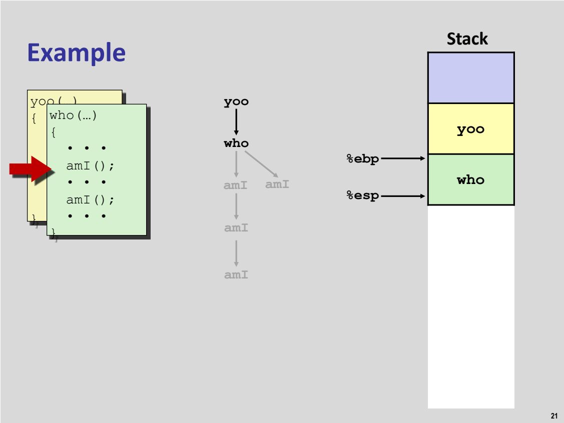
Example

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



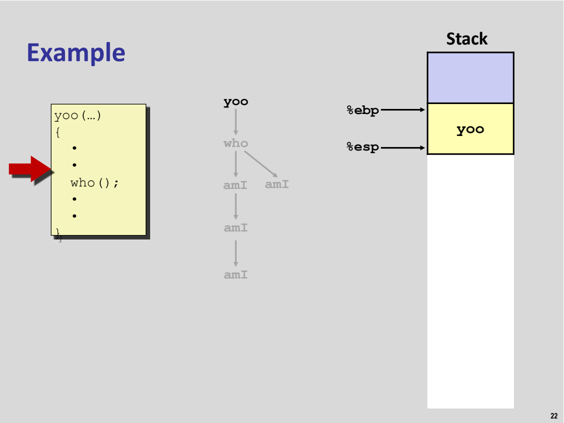
Example

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



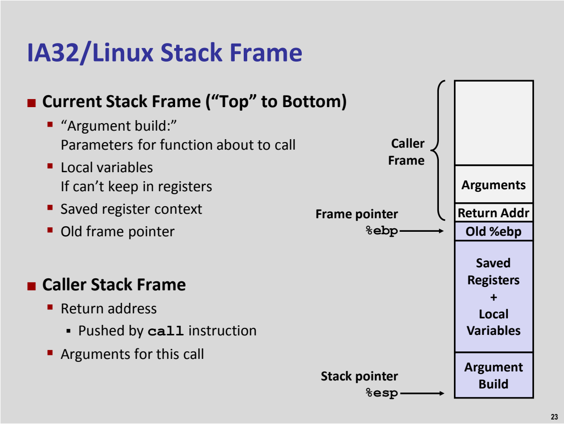
Example

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



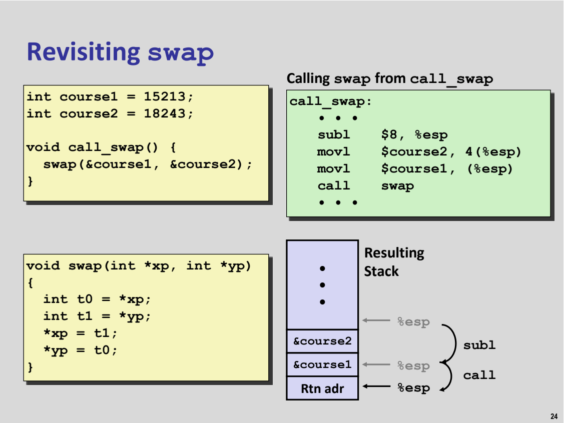
Example

```
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



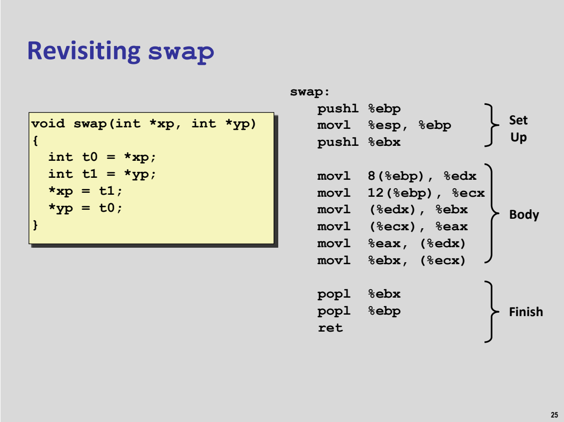
Revisiting swap

```
int course1 = 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`

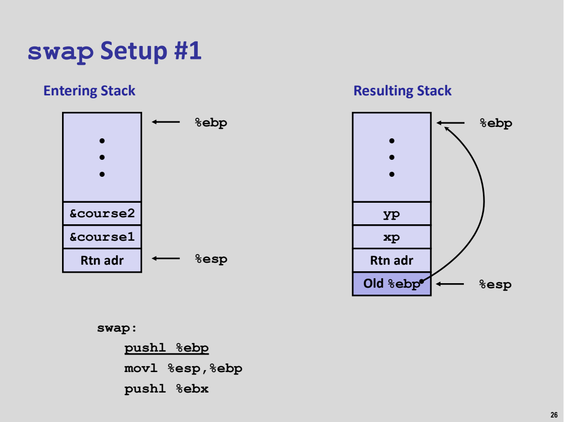
```
call_swap:
   • • •
   subl    $8, %esp
   movl    $course2, 4(%esp)
   movl    $course1, (%esp)
   call    swap
   • • •
```



Revisiting swap

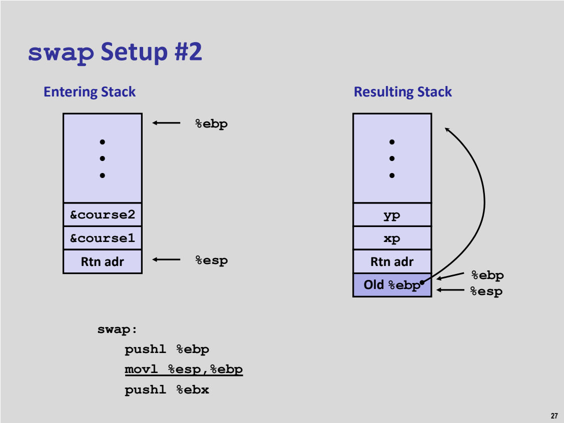
```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
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
```



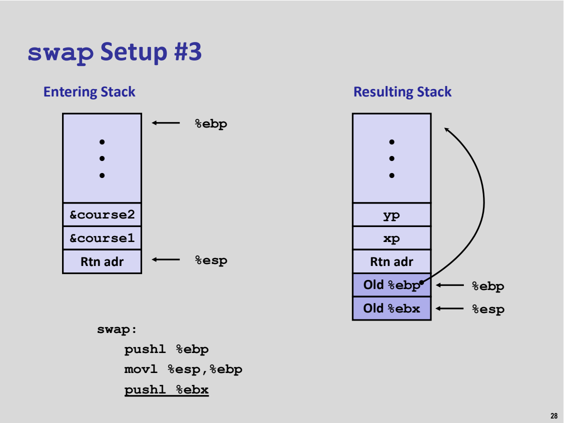
swap Setup #1

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



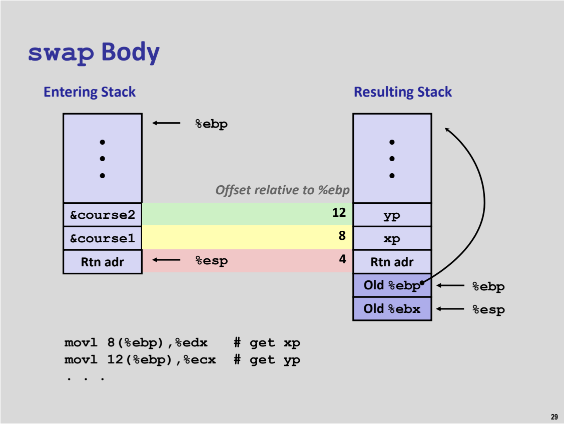
swap Setup #2

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



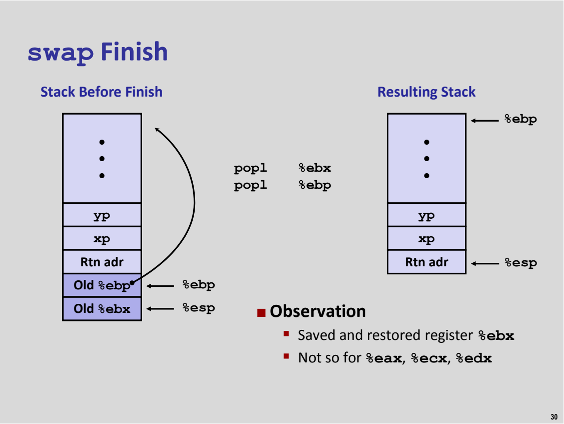
swap Setup #3

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



swap Body

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



swap Finish

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

- **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

- **IA 32 Procedures**
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers
- **X86-64 Procedures**

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
```

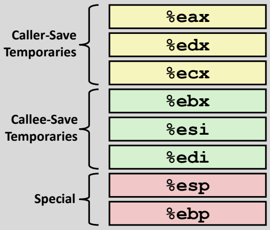
- Contents of register `%edx` overwritten by `who`
- This could be trouble ➞ something should be done!
  - Need some coordination

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 ("scratch")***
    - Caller saves temporary values in its frame before the call
  - ***Callee Save ("preserved")***
    - 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

- **IA 32 Procedures**
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers
- **X86-64 Procedures**

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 %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
```

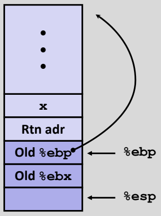
Recursive Call #1

```
/* 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`

`%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`

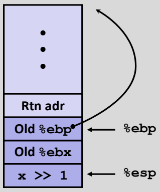
Recursive Call #3

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

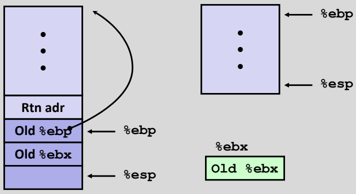
`%ebx` `x`

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

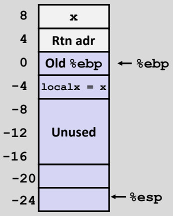
```
/* Increment value by k */
void incrk(int *ip, int k) {
  *ip += k;
}
```

- **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)**



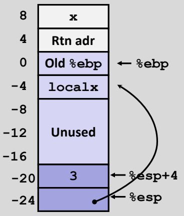
First part of add3

```
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**



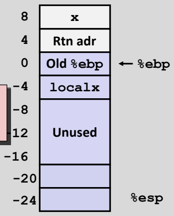
Middle part of add3

```
  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**

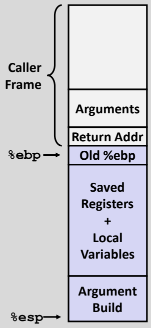


Final part of add3

```
  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



Today

- IA 32 Procedures
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers
- **X86-64 Procedures**

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x86-64 Integer Registers

`%rax`	`%eax`	`%r8`	`%r8d`
`%rbx`	`%ebx`	`%r9`	`%r9d`
`%rcx`	`%ecx`	`%r10`	`%r10d`
`%rdx`	`%edx`	`%r11`	`%r11d`
`%rsi`	`%esi`	`%r12`	`%r12d`
`%rdi`	`%edi`	`%r13`	`%r13d`
`%rsp`	`%esp`	`%r14`	`%r14d`
`%rbp`	`%ebp`	`%r15`	`%r15d`

- Twice the number of registers
- Accessible as 8, 16, 32, 64 bits

---

x86-64 Integer 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

---

x86-64 Registers

- **Arguments passed to functions via registers**
  - If more than 6 integral parameters, then pass rest on stack
  - These registers can be used as caller-saved as well
- **All references to stack frame via stack pointer**
  - Eliminates need to update `%ebp/%rbp`
- **Other Registers**
  - 6 callee saved
  - 2 caller saved
  - 1 return value (also usable as caller saved)
  - 1 special (stack pointer)

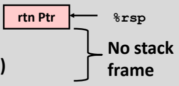
---

x86-64 Long Swap

```
void swap_l(long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
   movq   (%rdi), %rdx
   movq   (%rsi), %rax
   movq   %rax, (%rdi)
   movq   %rdx, (%rsi)
   ret
```

- **Operands passed in registers**
  - First (**`xp`**) in `%rdi`, second (**`yp`**) in `%rsi`
  - 64-bit pointers
- **No stack operations required (except `ret`)**
- **Avoiding stack**
  - Can hold all local information in registers



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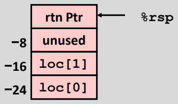
x86-64 Locals in the Red Zone

```
/* Swap, using local array */
void swap_a(long *xp, long *yp)
{
    volatile long loc[2];
    loc[0] = *xp;
    loc[1] = *yp;
    *xp = loc[1];
    *yp = loc[0];
}
```

```
swap_a:
  movq  (%rdi), %rax
  movq  %rax, -24(%rsp)
  movq  (%rsi), %rax
  movq  %rax, -16(%rsp)
  movq  -16(%rsp), %rax
  movq  %rax, (%rdi)
  movq  -24(%rsp), %rax
  movq  %rax, (%rsi)
  ret
```

- **Avoiding Stack Pointer Change**
  - Can hold all information within small window beyond stack pointer



x86-64 NonLeaf without Stack Frame

```
/* Swap a[i] & a[i+1] */
void swap_ele(long a[], int i)
{
    swap(&a[i], &a[i+1]);
}
```

- No values held while swap being invoked
- No callee save registers needed
- `rep` instruction inserted as no-op
  - Based on recommendation from AMD

```
swap_ele:
   movslq %esi,%rsi             # Sign extend i
   leaq   8(%rdi,%rsi,8), %rax  # &a[i+1]
   leaq   (%rdi,%rsi,8), %rdi   # &a[i]  (1st arg)
   movq   %rax, %rsi            # (2nd arg)
   call   swap
   rep                          # No-op
   ret
```

x86-64 Stack Frame Example

```
long sum = 0;
/* Swap a[i] & a[i+1] */
void swap_ele_su
  (long a[], int i)
{
    swap(&a[i], &a[i+1]);
    sum += (a[i]*a[i+1]);
}
```

- Keeps values of `&a[i]` and `&a[i+1]` in callee save registers
- Must set up stack frame to save these registers

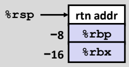
```
swap_ele_su:
   movq    %rbx, -16(%rsp)
   movq    %rbp, -8(%rsp)
   subq    $16, %rsp
   movslq  %esi,%rax
   leaq    8(%rdi,%rax,8), %rbx
   leaq    (%rdi,%rax,8), %rbp
   movq    %rbx, %rsi
   movq    %rbp, %rdi
   call    swap
   movq    (%rbx), %rax
   imulq   (%rbp), %rax
   addq    %rax, sum(%rip)
   movq    (%rsp), %rbx
   movq    8(%rsp), %rbp
   addq    $16, %rsp
   ret
```

Understanding x86-64 Stack Frame

```
swap_ele_su:
   movq    %rbx, -16(%rsp)        # Save %rbx
   movq    %rbp, -8(%rsp)         # Save %rbp
   subq    $16, %rsp              # Allocate stack frame
   movslq  %esi,%rax              # Extend i
   leaq    8(%rdi,%rax,8), %rbx   # &a[i+1] (callee save)
   leaq    (%rdi,%rax,8), %rbp    # &a[i]   (callee save)
   movq    %rbx, %rsi             # 2nd argument
   movq    %rbp, %rdi             # 1st argument
   call    swap
   movq    (%rbx), %rax           # Get a[i+1]
   imulq   (%rbp), %rax           # Multiply by a[i]
   addq    %rax, sum(%rip)        # Add to sum
   movq    (%rsp), %rbx           # Restore %rbx
   movq    8(%rsp), %rbp          # Restore %rbp
   addq    $16, %rsp              # Deallocate frame
   ret
```

Understanding x86-64 Stack Frame

```
movq    %rbx, -16(%rsp)       # Save %rbx
movq    %rbp, -8(%rsp)        # Save %rbp
```



```
subq    $16, %rsp             # Allocate stack frame
```

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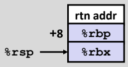

```
movq    (%rsp), %rbx          # Restore %rbx
movq    8(%rsp), %rbp         # Restore %rbp

addq    $16, %rsp             # Deallocate frame
```

Interesting Features of Stack Frame

- **Allocate entire frame at once**
  - All stack accesses can be relative to `%rsp`
  - Do by decrementing stack pointer
  - Can delay allocation, since safe to temporarily use red zone
- **Simple deallocation**
  - Increment stack pointer
  - No base/frame pointer needed

x86-64 Procedure Summary

- **Heavy use of registers**
  - Parameter passing
  - More temporaries since more registers
- **Minimal use of stack**
  - Sometimes none
  - Allocate/deallocate entire block
- **Many optimization choices (tricky to read)**
  - What kind of stack frame to use
  - Various allocation techniques