15-213

"The course that gives CMU its Zip!"

Machine-Level Programming III: Procedures
Sept. 11, 2008

IA32

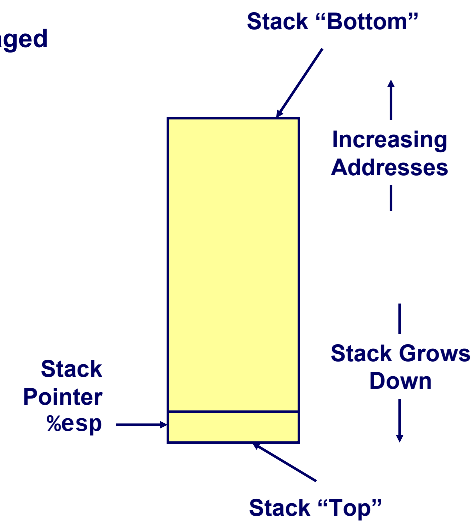
- stack discipline
- Register saving conventions
- Creating pointers to local variables

x86-64

- Argument passing in registers
- Minimizing stack usage
- Using stack pointer as only reference

IA32 Stack

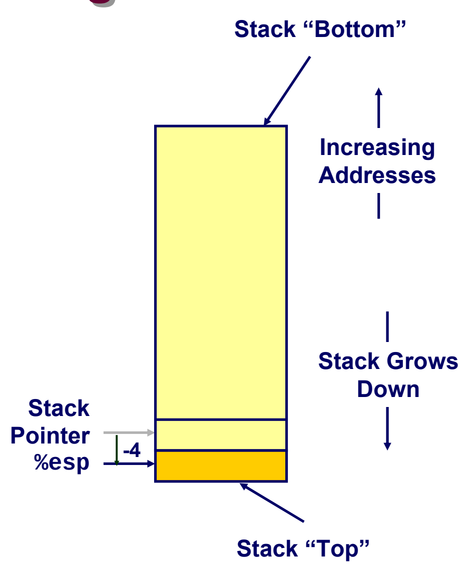
- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register %esp indicates lowest stack address
  - address of top element



IA32 Stack Pushing

Pushing

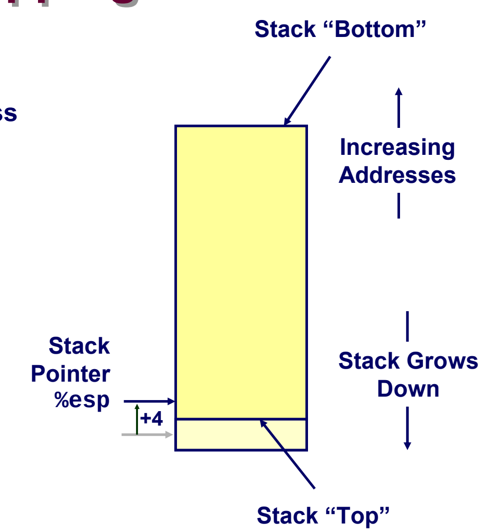
- `pushl` *Src*
- Fetch operand at *Src*
- Decrement %esp by 4
- Write operand at address given by %esp



IA32 Stack Popping

Popping

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

- Address of instruction beyond `call`
- Example from disassembly

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

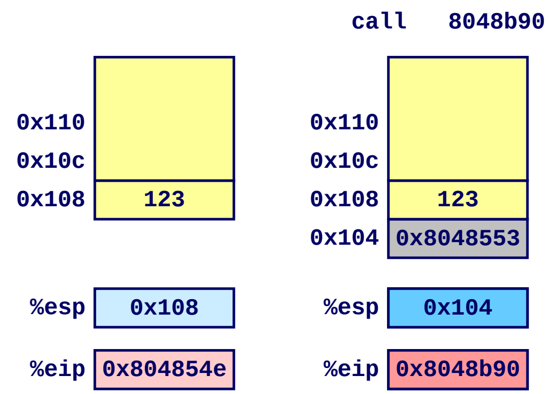
  - Return address = `0x8048553`

Procedure return:

- `ret`   Pop address from stack; Jump to address

Procedure Call Example

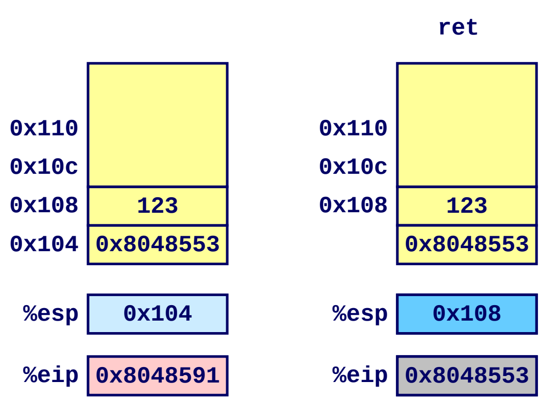
```
804854e:  e8 3d 06 00 00      call   8048b90 <main>
8048553:  50                  pushl  %eax
```



`%eip` is program counter

Procedure Return Example

```
8048591:   c3                 ret
```



`%eip` is 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

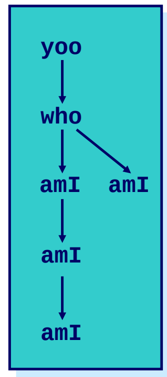
Code Structure

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

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

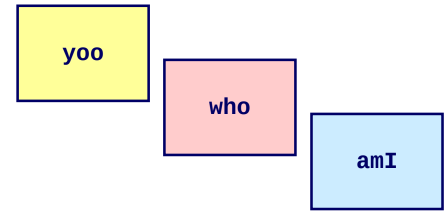
```
amI(…)
{
    •
    •
    amI();
    •
    •
}
```

Call Chain



- Procedure `amI` recursive

Stack Frames



Contents

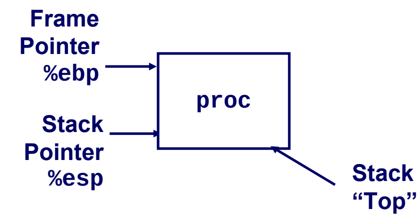
- Local variables
- Return information
- Temporary space

Management

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

Pointers

- Stack pointer `%esp` indicates stack top
- Frame pointer `%ebp` indicates start of current frame

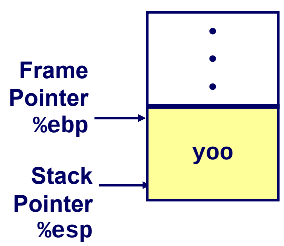


Stack Operation

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

Call Chain

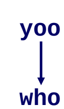
yoo

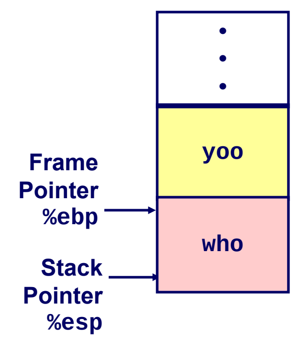


Stack Operation

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

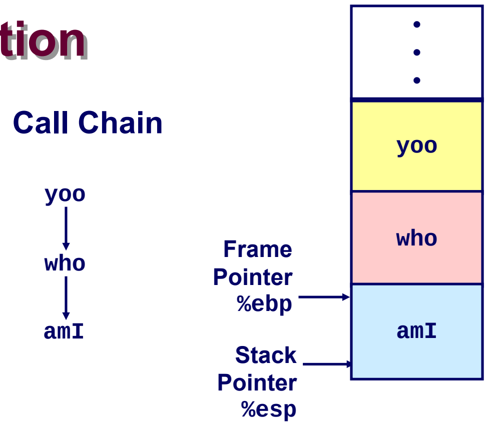
Call Chain





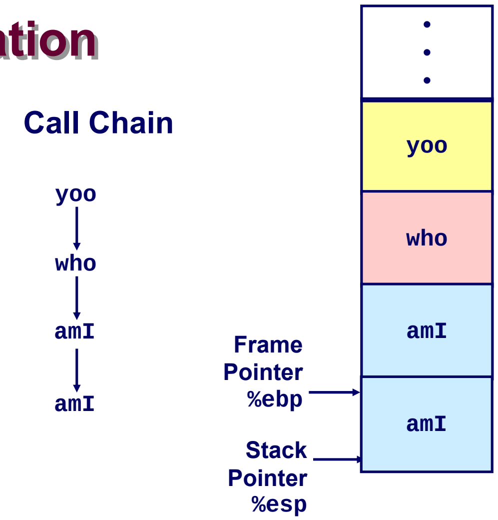
Stack Operation

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



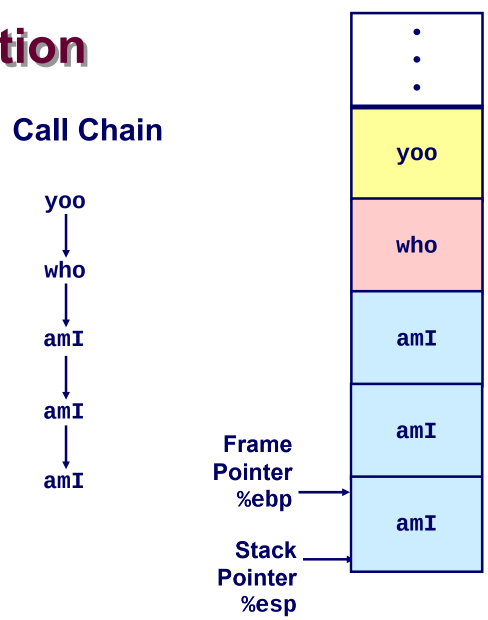
Stack Operation

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



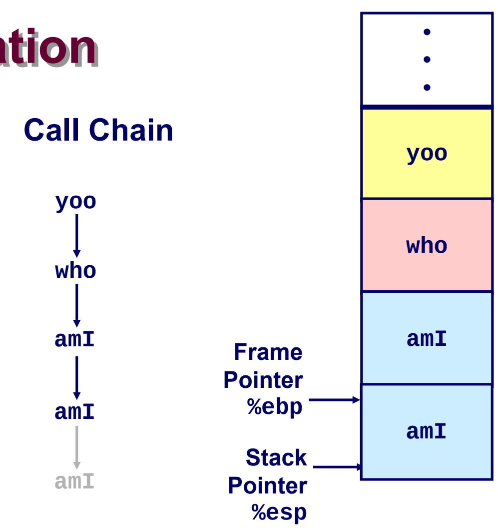
Stack Operation

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



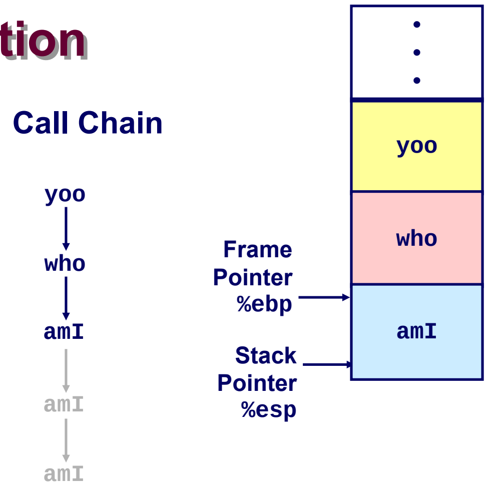
Stack Operation

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



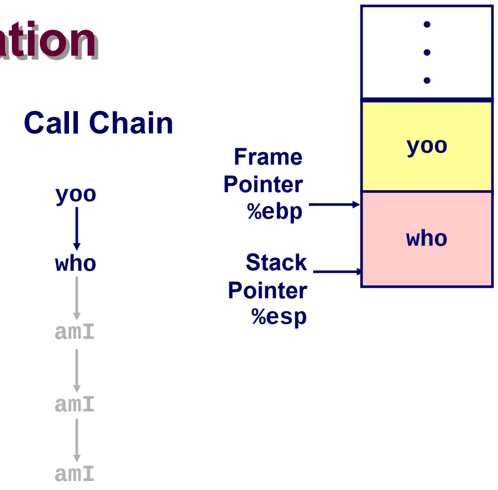
Stack Operation

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



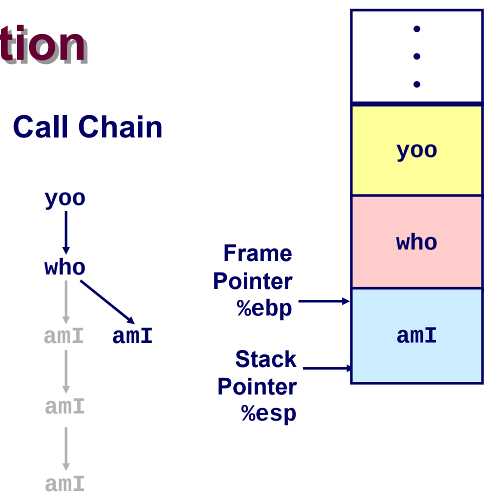
Stack Operation

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



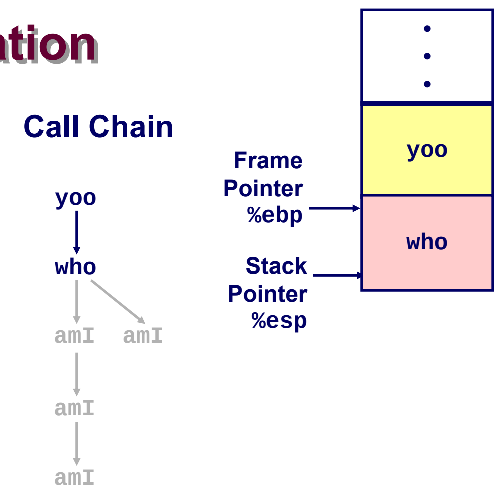
Stack Operation

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



Stack Operation

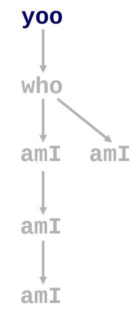
```
who(…)
{
   • • •
   amI();
   • • •
   amI();
   • • •
}
```

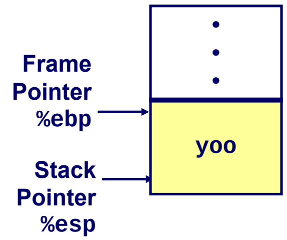


Stack Operation

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

Call Chain





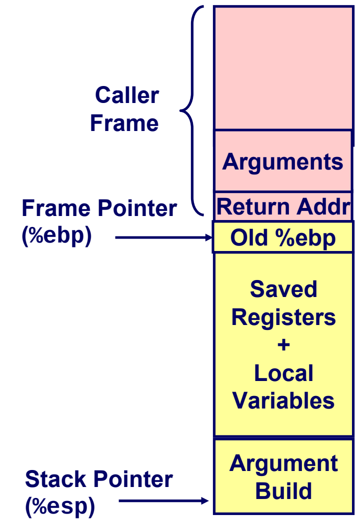
IA32/Linux Stack Frame

Current Stack Frame ("Top" to Bottom)

- Parameters for function about to call
  - "Argument build"
- 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



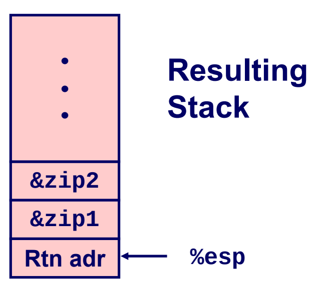
Revisiting swap

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

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

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

Calling swap from `call_swap`

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

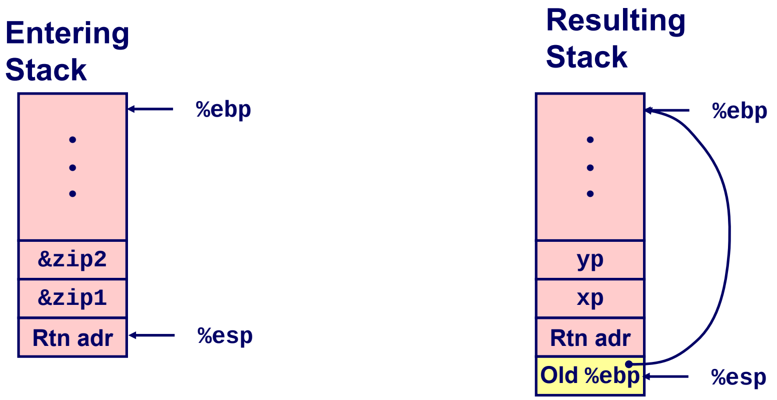


Revisiting swap

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

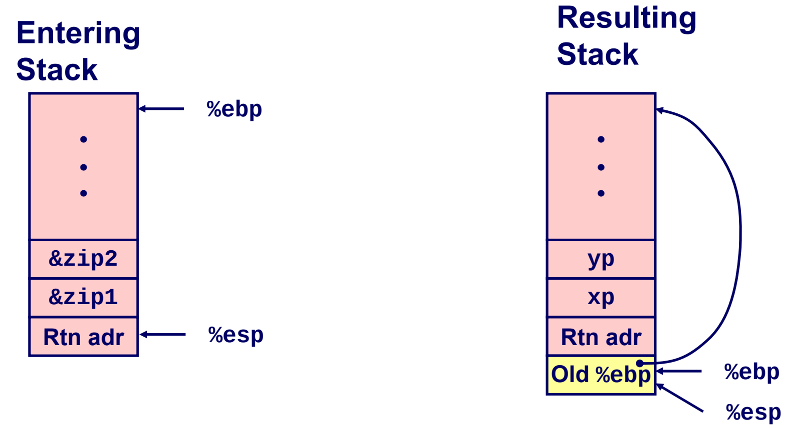
```
swap:
   pushl %ebp
   movl %esp,%ebp          Set
   pushl %ebx              Up

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

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

swap Setup #1



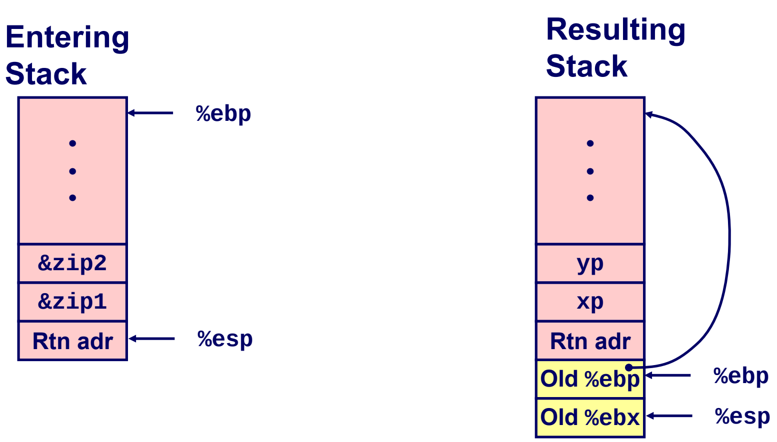

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```


swap Setup #2



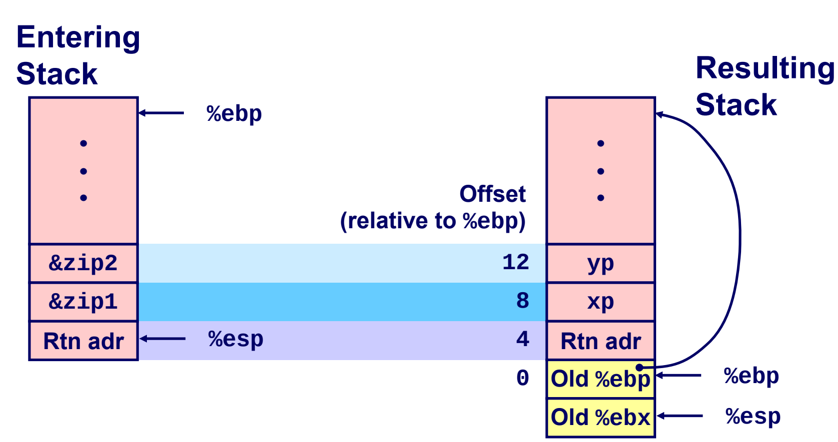

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```


swap Setup #3




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

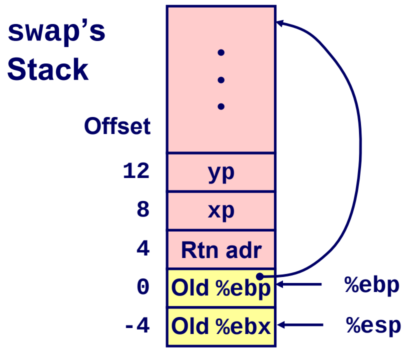

Effect of swap Setup




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

Body

swap Finish #1

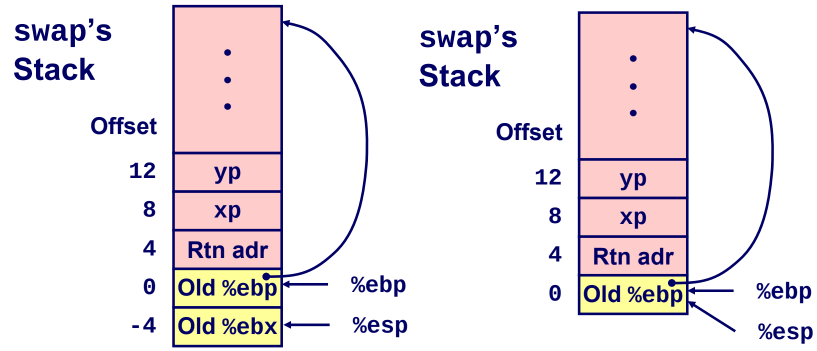



```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Observation

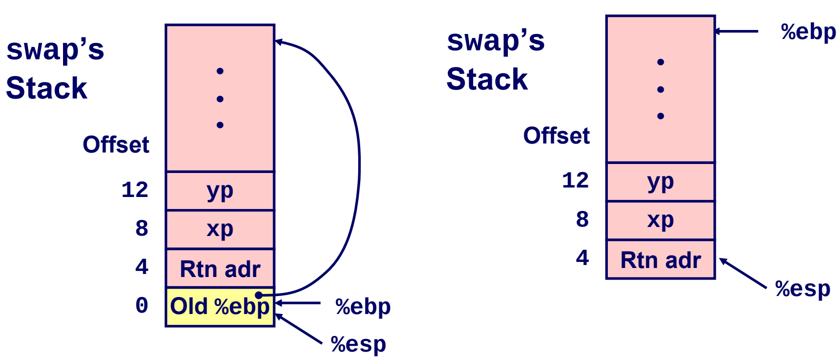
- Saved & restored register %ebx

swap Finish #2



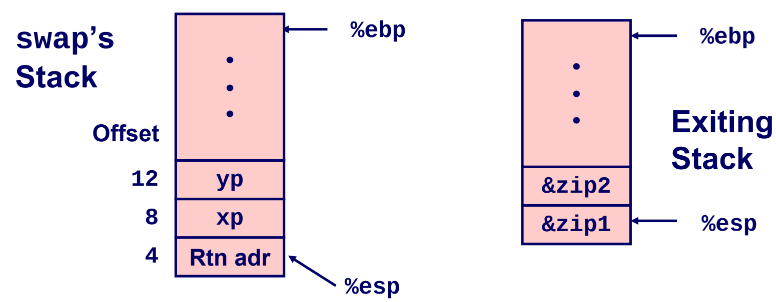

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```


swap Finish #3




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


swap Finish #4




```
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

Integer Registers

- Two have special uses
  - %ebp, %esp
- Three managed as callee-save
  - %ebx, %esi, %edi
    - Old values saved on stack prior to using
- Three managed as caller-save
  - %eax, %edx, %ecx
    - Do what you please, but expect any callee to do so, as well
- Register %eax also stores returned value

Caller-Save Temporaries	%eax
	%edx
	%ecx
Callee-Save Temporaries	%ebx
	%esi
	%edi
Special	%esp
	%ebp

Recursive Factorial

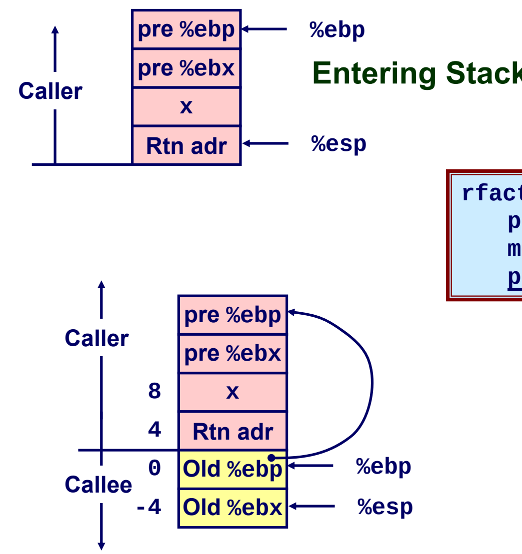
```
int rfact(int x)
{
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

```
.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
```

Registers

- %eax used without first saving
- %ebx used, but save at beginning & restore at end

Rfact Stack Setup




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


Rfact Body

```
  movl 8(%ebp),%ebx   # ebx = x
  cmpl $1,%ebx        # Compare x : 1
  jle .L78            # If <= goto Term
  leal -1(%ebx),%eax  # eax = x-1
  pushl %eax          # Push x-1
  call rfact          # rfact(x-1)
  imull %ebx,%eax     # rval * x
  jmp .L79            # Goto done
.L78:                 # Term:
  movl $1,%eax        # return val = 1
.L79:                 # Done:
```

Recursion (leal … imull)

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

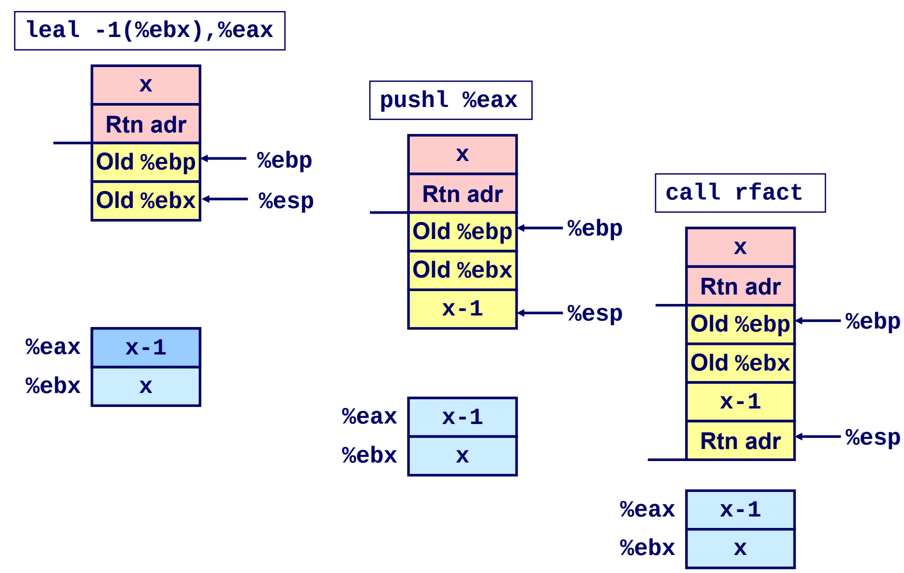
Registers

%ebx Stored value of x

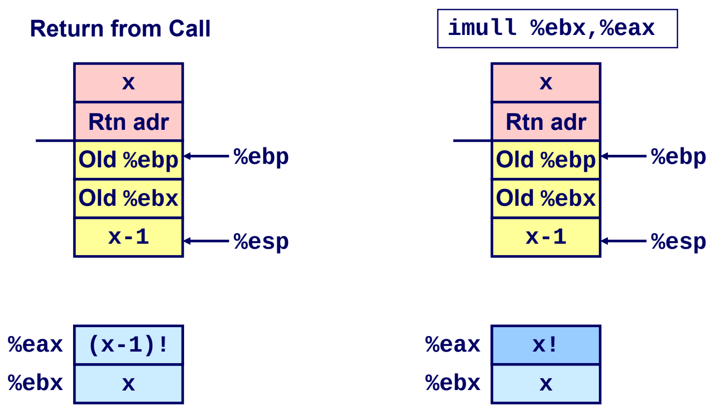
%eax

- Temporary value of x-1
- Returned value from rfact(x-1)
- Returned value from this call

Rfact Recursion



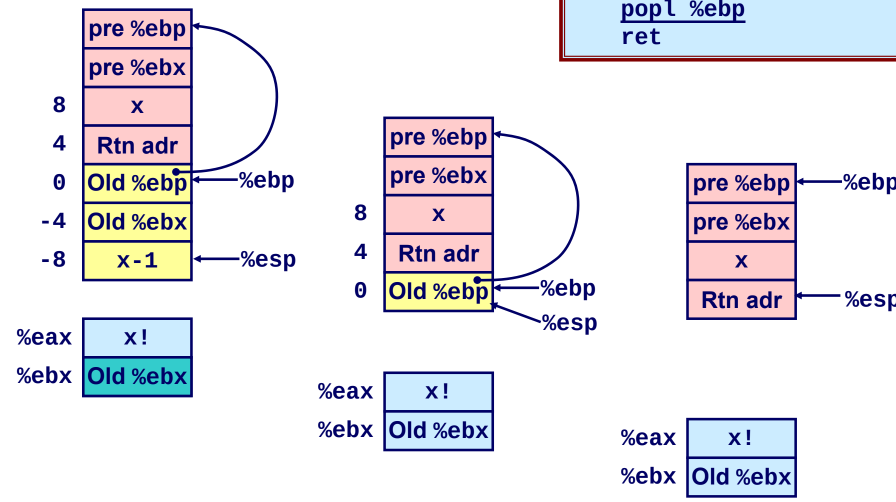
Rfact Result



Assume that `rfact(x-1)` returns `(x-1)!` in register `%eax`

Rfact Completion

```
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

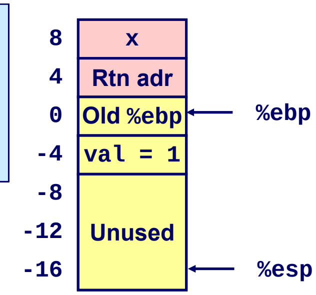
```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- Pass pointer to update location

Creating & Initializing Pointer

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
```



Using Stack for Local Variable

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

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

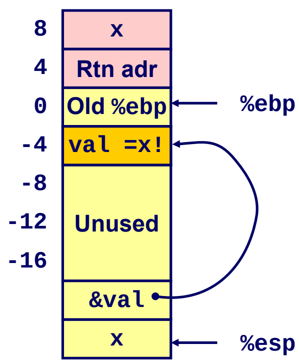
Passing Pointer

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
```

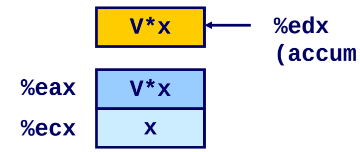
```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

Stack at time of call



Using Pointer

```
void s_helper
  (int x, int *accum)
{
  • • •
    int z = *accum * x;
    *accum = z;
  • • •
}
```




```
    • • •
    movl %ecx,%eax      # z = x
    imull (%edx),%eax   # z *= *accum
    movl %eax,(%edx)    # *accum = z
    • • •
```

- Register %ecx holds x
- Register %edx holds accum
  - Assume memory initally has value V
  - Use access (%edx) to reference memory

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
- Can be 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

x86-64 General Purpose 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, or 64 bits

x86-64 Register Conventions

%rax	Return Value	%r8	Argument #5
%rbx	Callee Saved	%r9	Argument #6
%rcx	Argument #4	%r10	Callee Saved
%rdx	Argument #3	%r11	Used for linking
%rsi	Argument #2	%r12	C: 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

Other Registers

- 6+1 callee saved
- 2 or 3 have special uses

x86-64 Long Swap

```
void swap(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

Avoiding Stack

- Can hold all local information in registers

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

	rtn Ptr	← %rsp
−8	unused	
−16	loc[1]	
−24	loc[0]	

x86-64 NonLeaf without Stack Frame

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

- No values held while swap being invoked
- No callee save registers needed

```
swap_ele_se:
  movslq %esi,%rsi            # Sign extend i
  leaq   (%rdi,%rsi,8), %rdi  # &a[i]
  leaq   8(%rdi), %rsi        # &a[i+1]
  call   swap                 # swap()
  incq   scount(%rip)         # scount++;
  ret
```


x86-64 Call using Jump

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

- When swap executes `ret`, it will return from `swap_ele`
- Possible since swap is a "tail call"

```
swap_ele:
  movslq %esi,%rsi            # Sign extend i
  leaq   (%rdi,%rsi,8), %rdi  # &a[i]
  leaq   8(%rdi), %rsi        # &a[i+1]
  jmp    swap                 # swap()
```


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];
}
```

```
swap_ele_su:
  movq    %rbx, -16(%rsp)
  movslq  %esi,%rbx
  movq    %r12, -8(%rsp)
  movq    %rdi, %r12
  leaq    (%rdi,%rbx,8), %rdi
  subq    $16, %rsp
  leaq    8(%rdi), %rsi
  call    swap
  movq    (%r12,%rbx,8), %rax
  addq    %rax, sum(%rip)
  movq    (%rsp), %rbx
  movq    8(%rsp), %r12
  addq    $16, %rsp
  ret
```

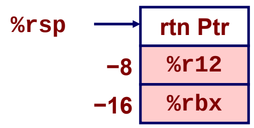
- Keeps values of a and i in callee save registers
- Must set up stack frame to save these registers

Understanding x86-64 Stack Frame

```
swap_ele_su:
  movq    %rbx, -16(%rsp)     # Save %rbx
  movslq  %esi,%rbx           # Extend & save i
  movq    %r12, -8(%rsp)      # Save %r12
  movq    %rdi, %r12          # Save a
  leaq    (%rdi,%rbx,8), %rdi  # &a[i]
  subq    $16, %rsp           # Allocate stack frame
  leaq    8(%rdi), %rsi       #     &a[i+1]
  call    swap                # swap()
  movq    (%r12,%rbx,8), %rax  # a[i]
  addq    %rax, sum(%rip)     # sum += a[i]
  movq    (%rsp), %rbx        # Restore %rbx
  movq    8(%rsp), %r12       # Restore %r12
  addq    $16, %rsp           # Deallocate stack frame
  ret
```

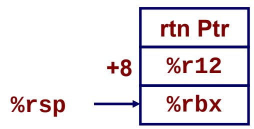
Stack Operations

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

movq  %r12, -8(%rsp)   # Save %r12
```




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

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

movq  8(%rsp), %r12    # Restore %r12
```




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

x86-64 Procedure Summary

Heavy Use of Registers

- Parameter passing
- More temporaries

Minimal Use of Stack

- Sometimes none
- Allocate/deallocate entire block

Many Tricky Optimizations

- What kind of stack frame to use
- Calling with jump
- Various allocation techniques