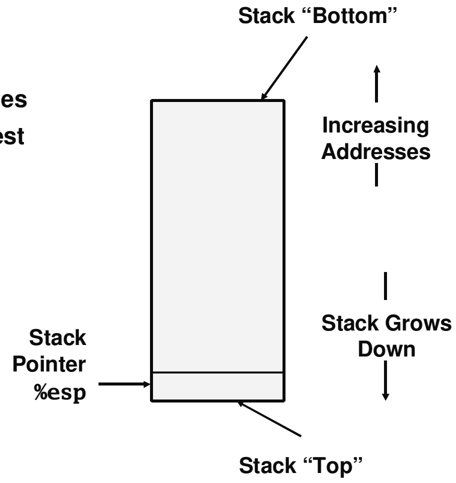
Lecture 5
Machine-Level Programming III: Procedures

Topics

- IA32 stack discipline
- Register saving conventions
- Creating pointers to local variables

IA32 Stack

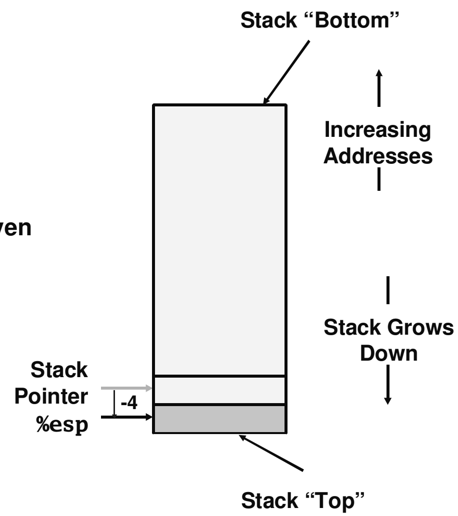
- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register `%esp` indicates lowest stack address
  - address of top element



IA32 Stack Pushing

Pushing

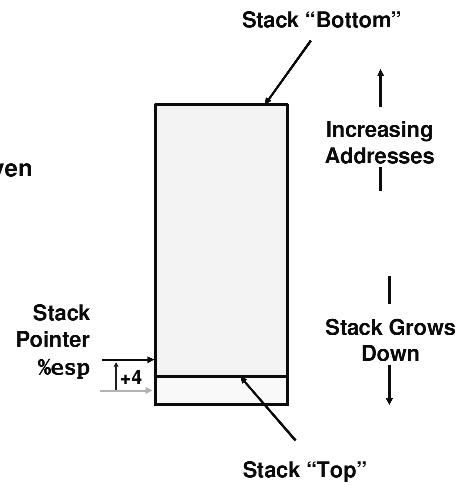
- `pushl` *Src*
- Fetch operand at *Src*
- Decrement `%esp` by 4
- Write operand at address given by `%esp`



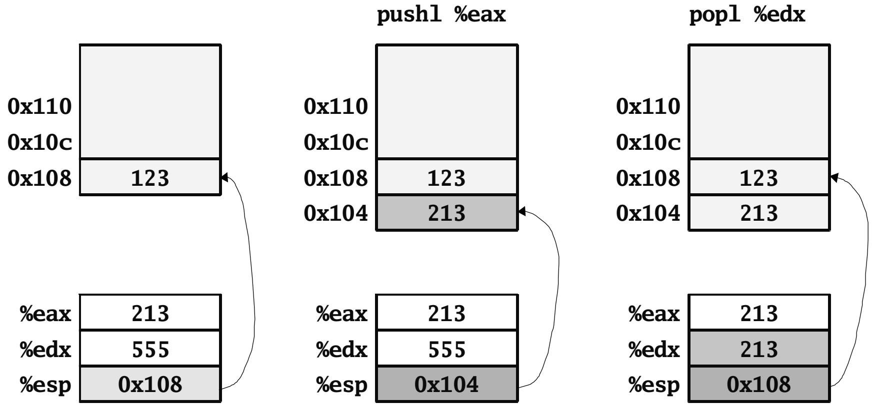
IA32 Stack Popping

Popping

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



Stack Operation Examples



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
```

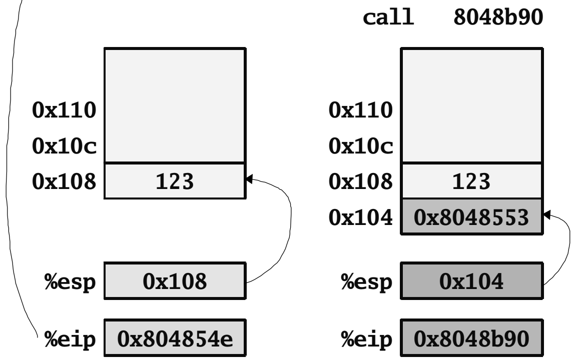
  - Return address = 0x8048553

Procedure return:

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

Procedure Call Example

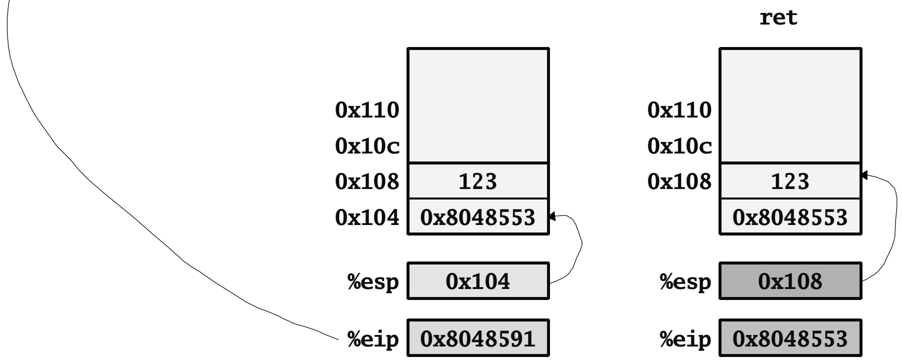
```
804854e: e8 3d 06 00 00     call   8048b90 <main>
8048553: 50                 pushl  %eax
```



`%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, Python
- 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

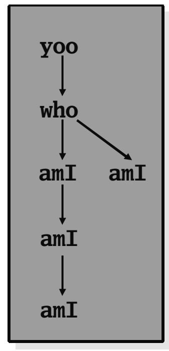
```
yoo(…)
{
  •
  •
  who(…);
  •
  •
}
```

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

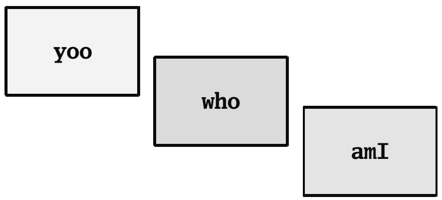
```
amI(…)
{
  •
  •
  amI(…);
  •
  •
}
```

- Procedure `amI` recursive

Call Chain



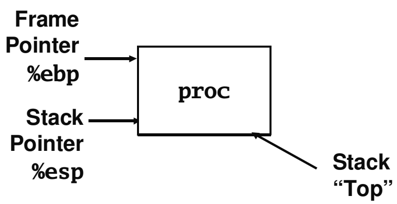
Stack Frames



Contents
- Local variables
- Return information
- Temporary space

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

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

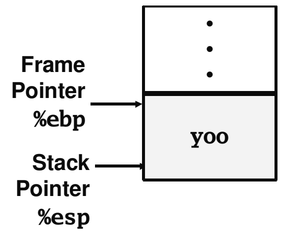


Stack Operation

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

Call Chain

yoo

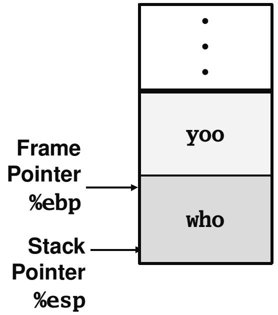


Stack Operation

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

Call Chain

yoo
↓
who

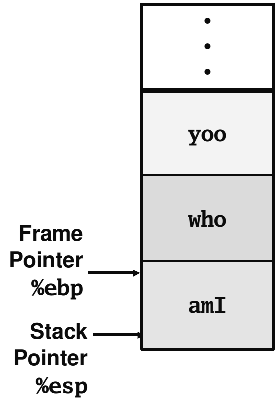


Stack Operation

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

Call Chain

yoo
↓
who
↓
amI

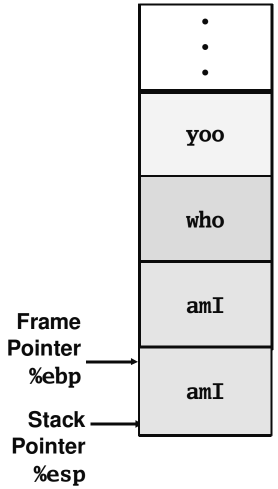


Stack Operation

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

Call Chain

yoo
↓
who
↓
amI
↓
amI

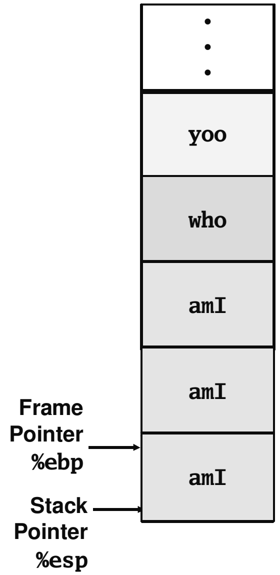


Stack Operation

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

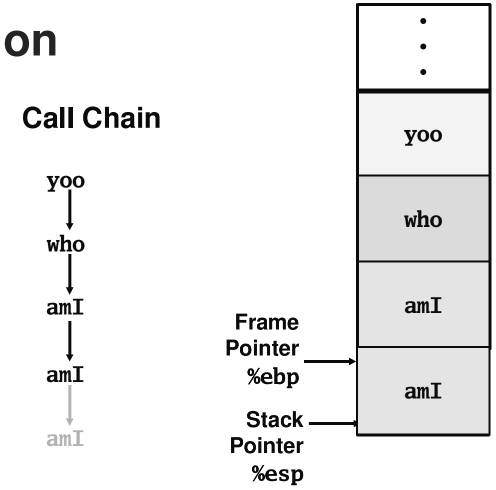
Call Chain

yoo
↓
who
↓
amI
↓
amI
↓
amI



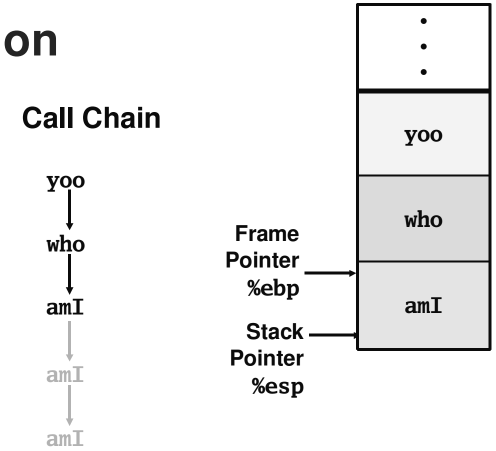
Stack Operation

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



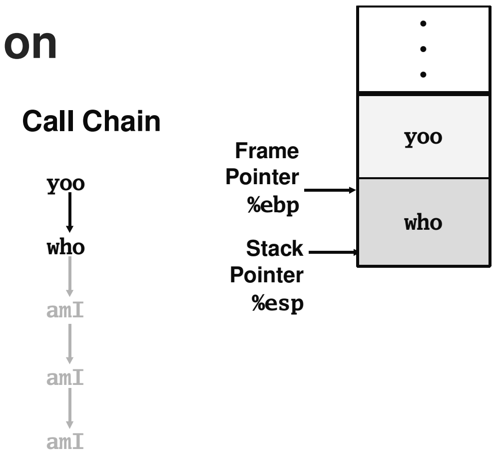
Stack Operation

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



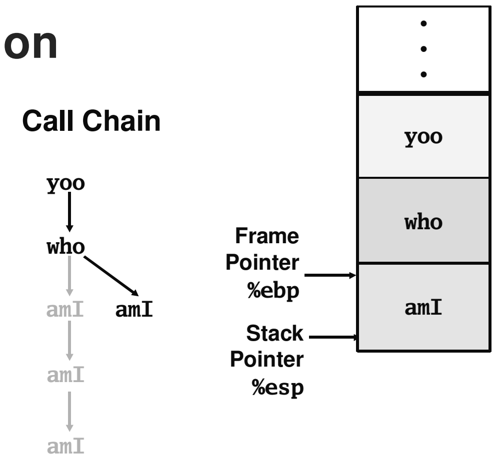
Stack Operation

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



Stack Operation

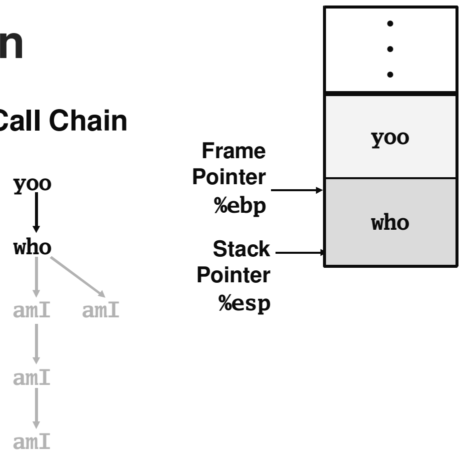
```
amI(…)
{
   •
   •
   •
   •
}
```



Stack Operation

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

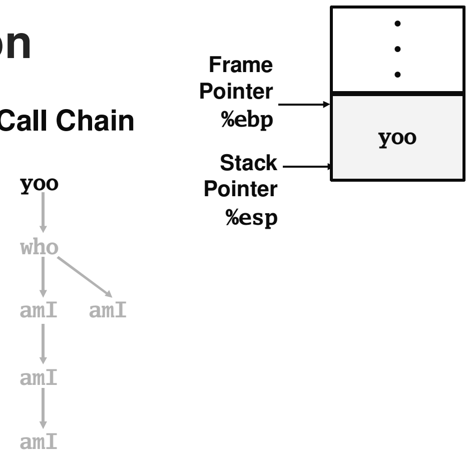
Call Chain



Stack Operation

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

Call Chain



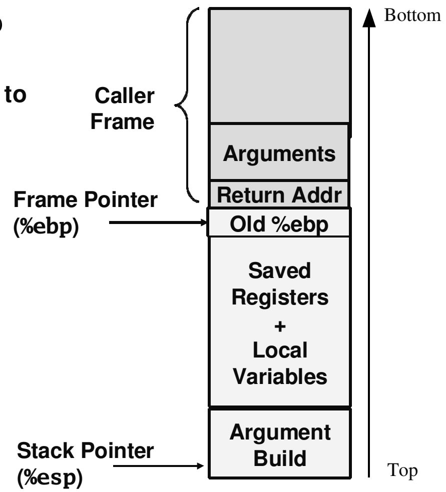
IA32/Linux Stack Frame

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

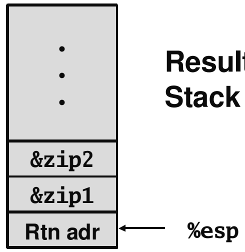
```
int zip1 = 15213;
int zip2 = 91125;

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
    • • •
```

Resulting Stack



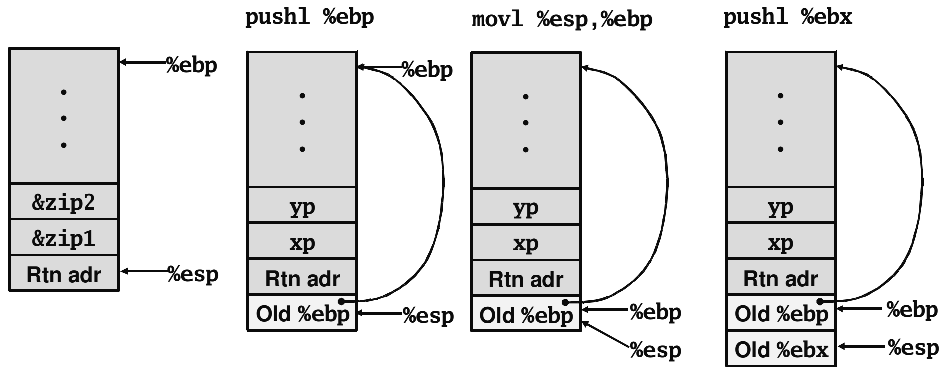
Revisiting swap

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

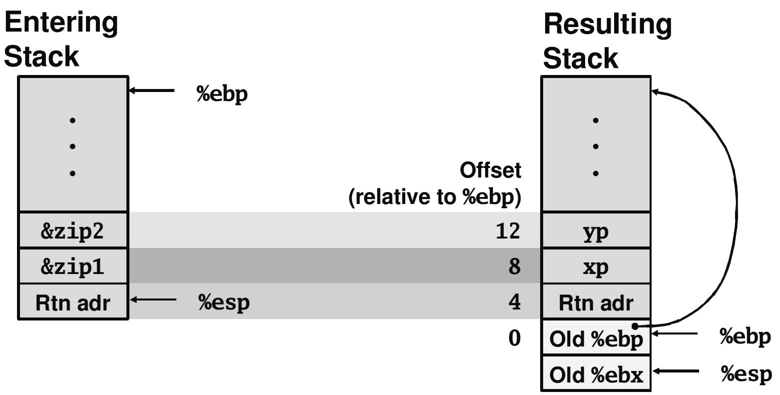
```
swap:
   pushl %ebp               } Set
   movl %esp,%ebp           } Up
   pushl %ebx

   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

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



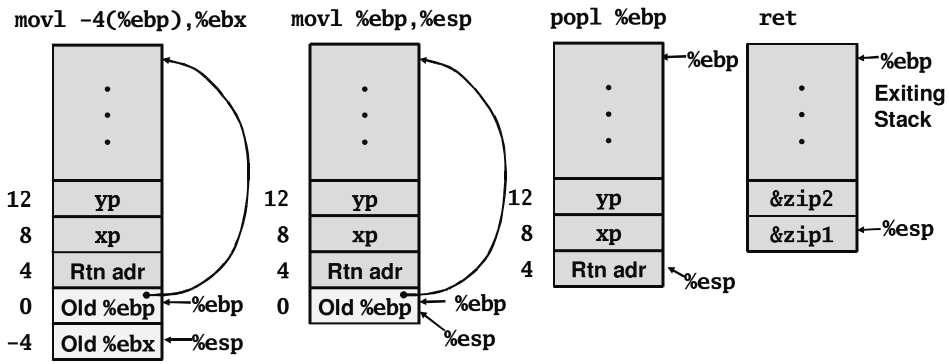
Effect of swap Setup




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


swap Finish

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



Observation

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

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  # Bug!!
    • • •
    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

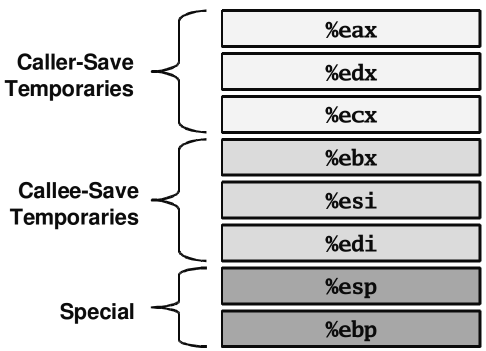
Integer Registers

- 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



Recursive Factorial

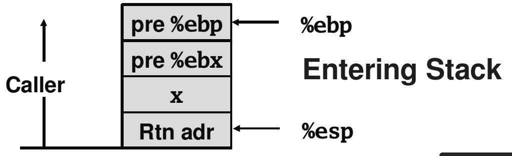
```
int rfact(int x)
{
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

```
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
```

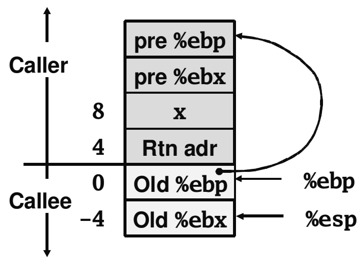
Registers

- %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

Recursion

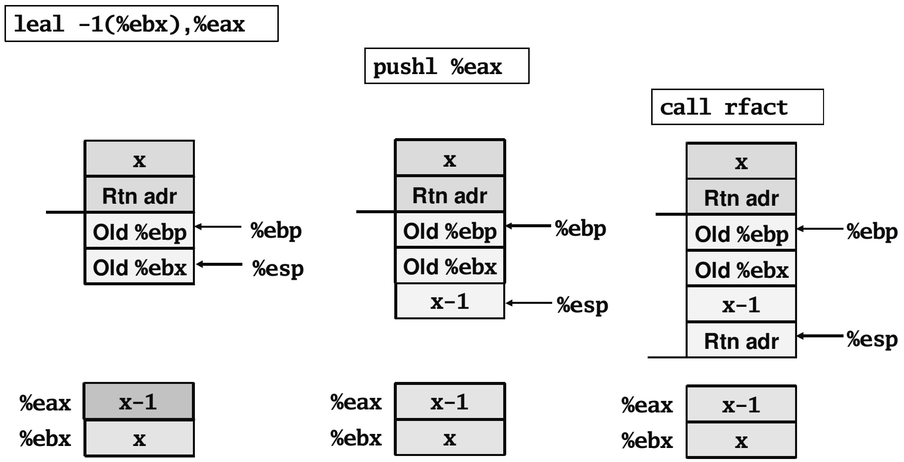
```
  movl 8(%ebp),%ebx   # ebx = x
  cmpl $1,%ebx        # Compare x : 1
  jle .L78            # If <= goto Term
  leal -1(%ebx),%eax  # eax = x-1
  pushl %eax          # Push x-1
  call rfact          # rfact(x-1)
  imull %ebx,%eax     # rval * x
  jmp .L79            # Goto Done
.L78:            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

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

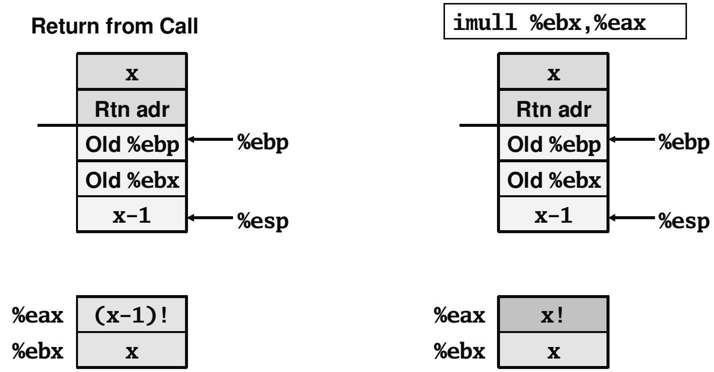
Registers

- %ebx Stored value of x
- %eax
  - Temporary value of x-1
  - Returned value from rfact(x-1)
  - Returned value from this call

Rfact Recursion



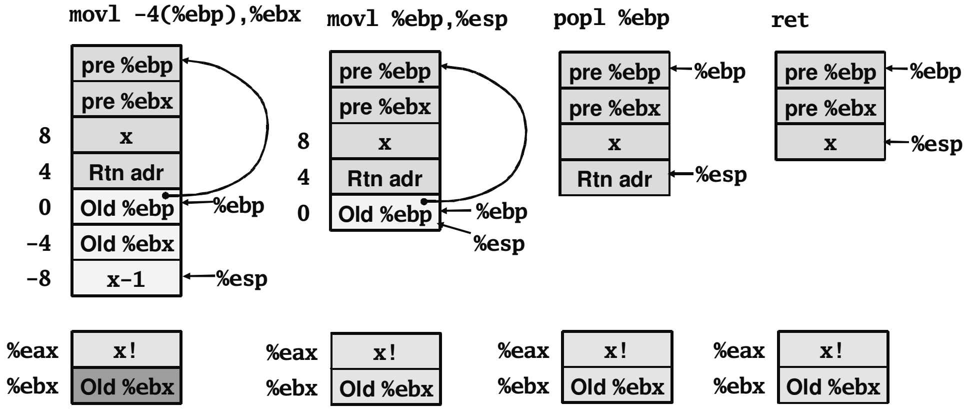
Rfact Result



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

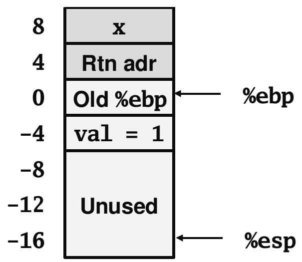
```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- 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;
}
```

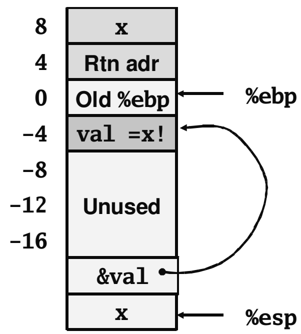

Passing Pointer

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
```

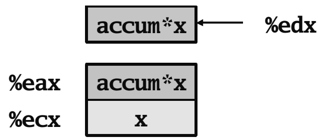
```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

Stack at time of call



Using Pointer

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




```
  • • •
  movl 8(%ebp),%ecx        # x
  movl 12(%ebp),%edx       # *accum
  movl %ecx,%eax           # z = x
  imull (%edx),%eax        # z *= *accum
  movl %eax,(%edx)         # *accum = z
  • • •
```

- Register `%ecx` holds `x`
- Register `%edx` holds pointer to `accum`
  - Use access `(%edx)` to reference memory

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