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

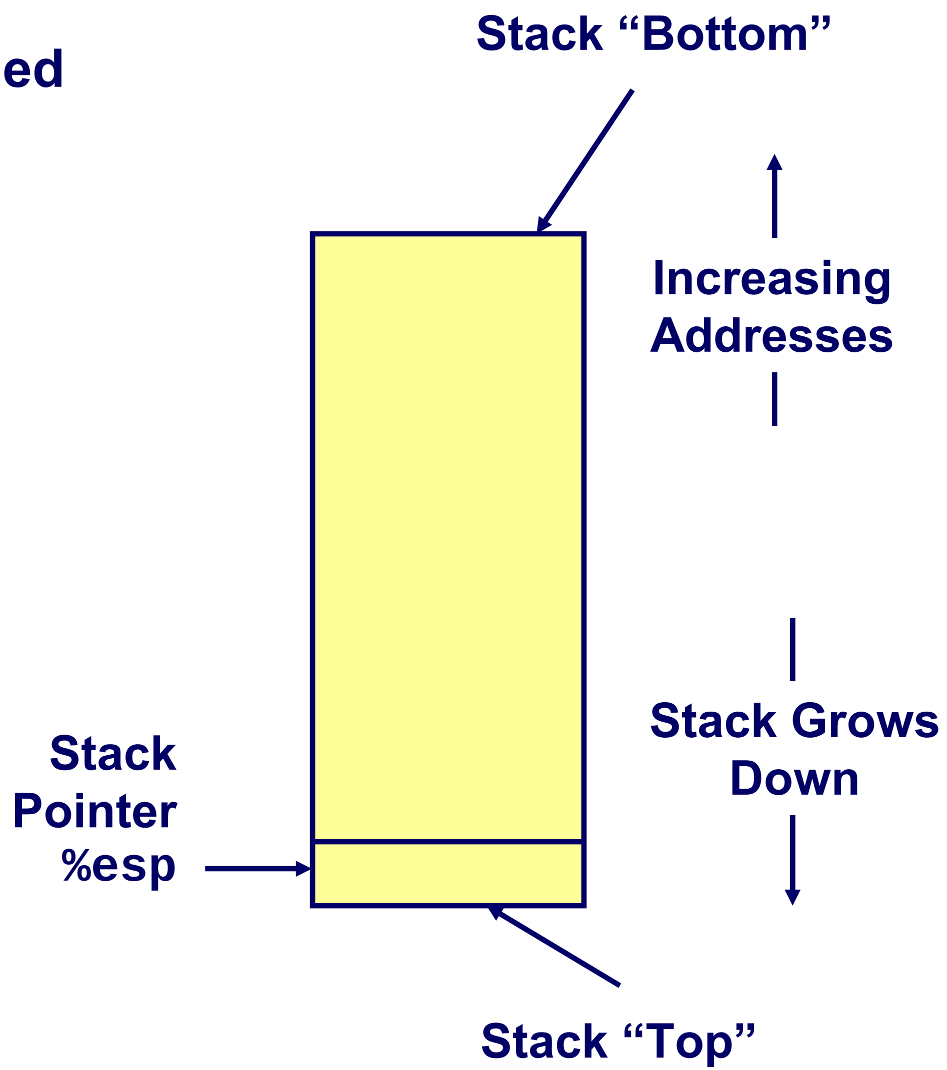
x86-64

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

`class06.ppt`

IA32 Stack

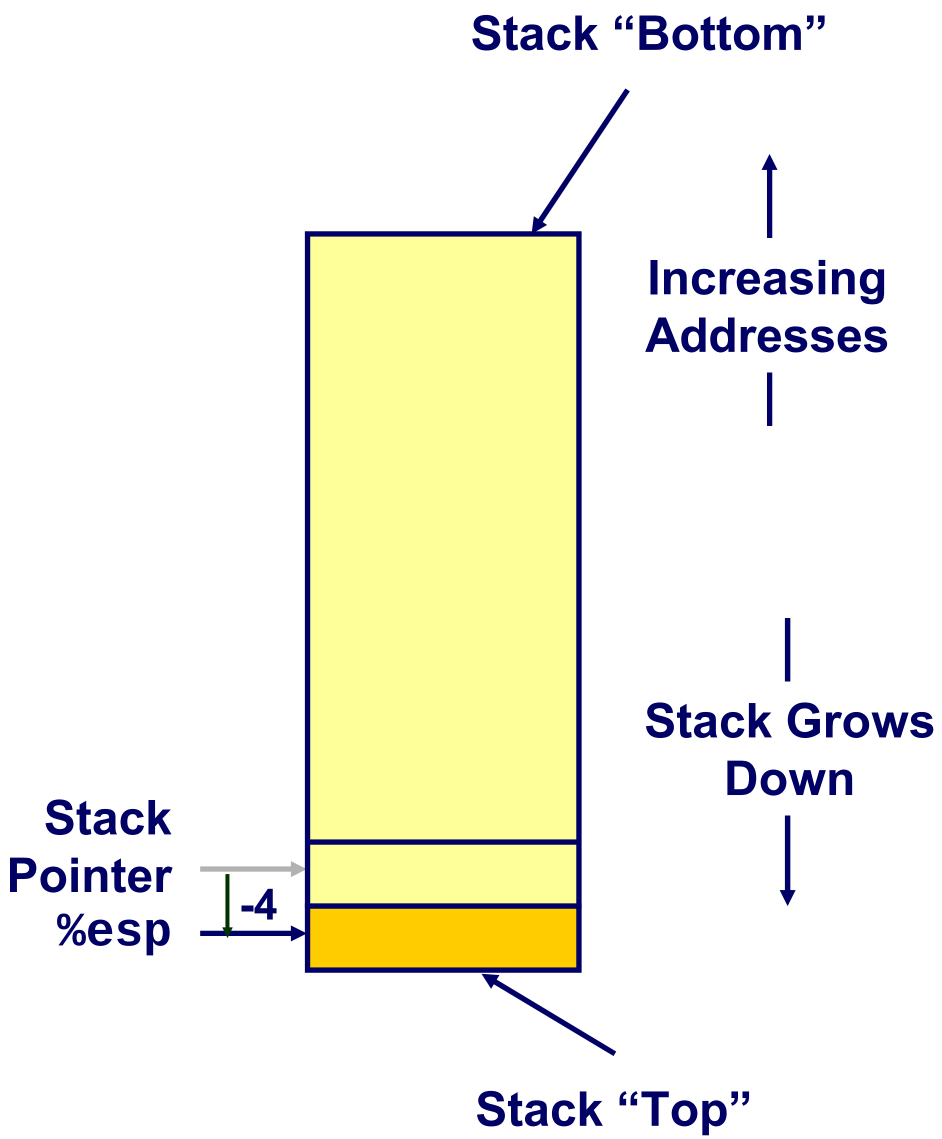
- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register %esp indicates lowest stack address
  - address of top element



IA32 Stack Pushing

Pushing

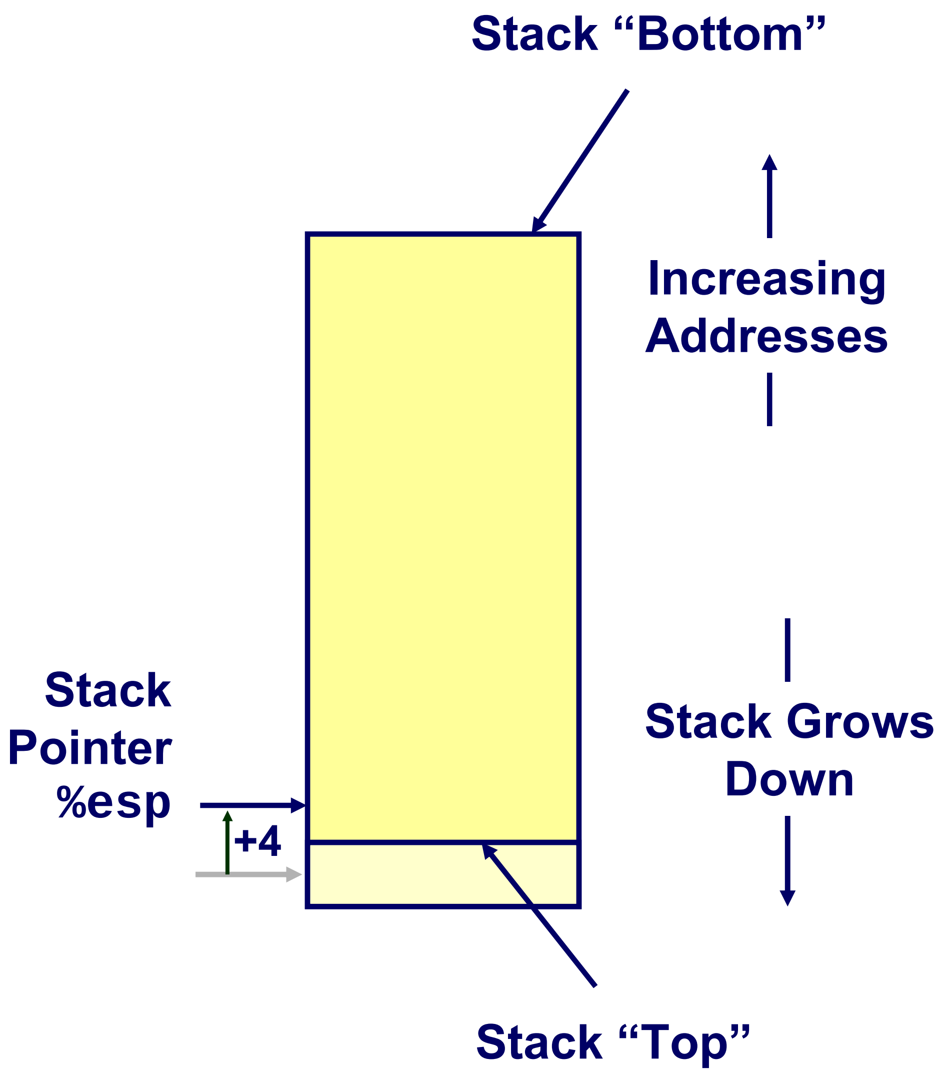
- `pushl` *Src*
- Fetch operand at *Src*
- Decrement %esp by 4
- Write operand at address given by %esp



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`

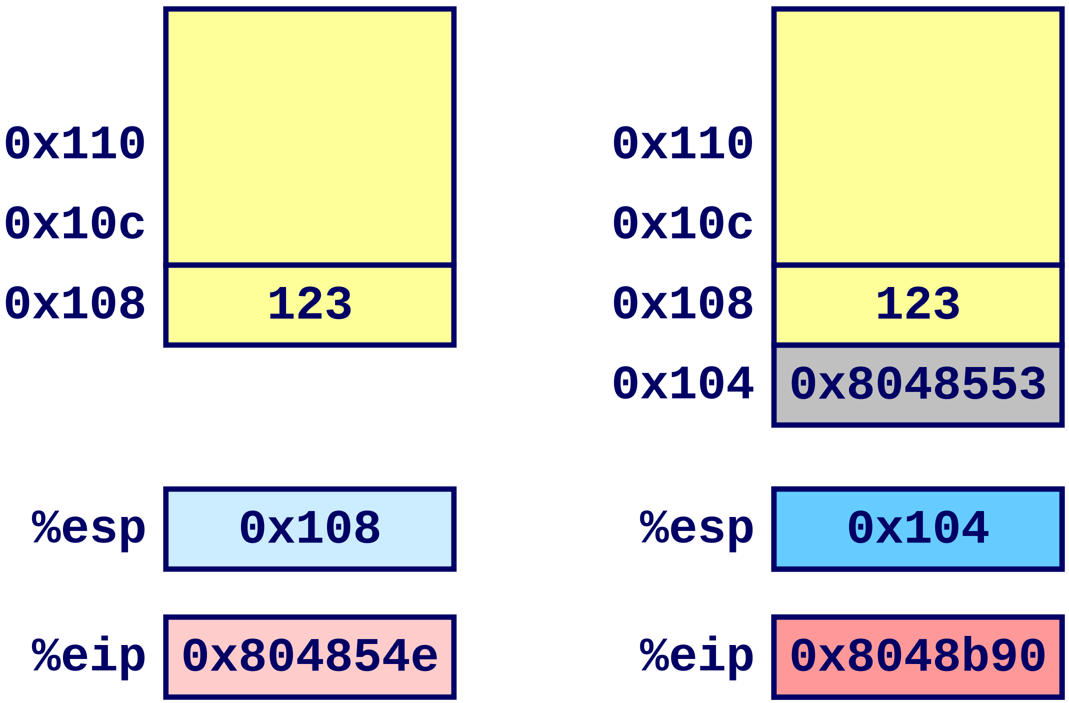
Procedure return:

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

Procedure Call Example

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

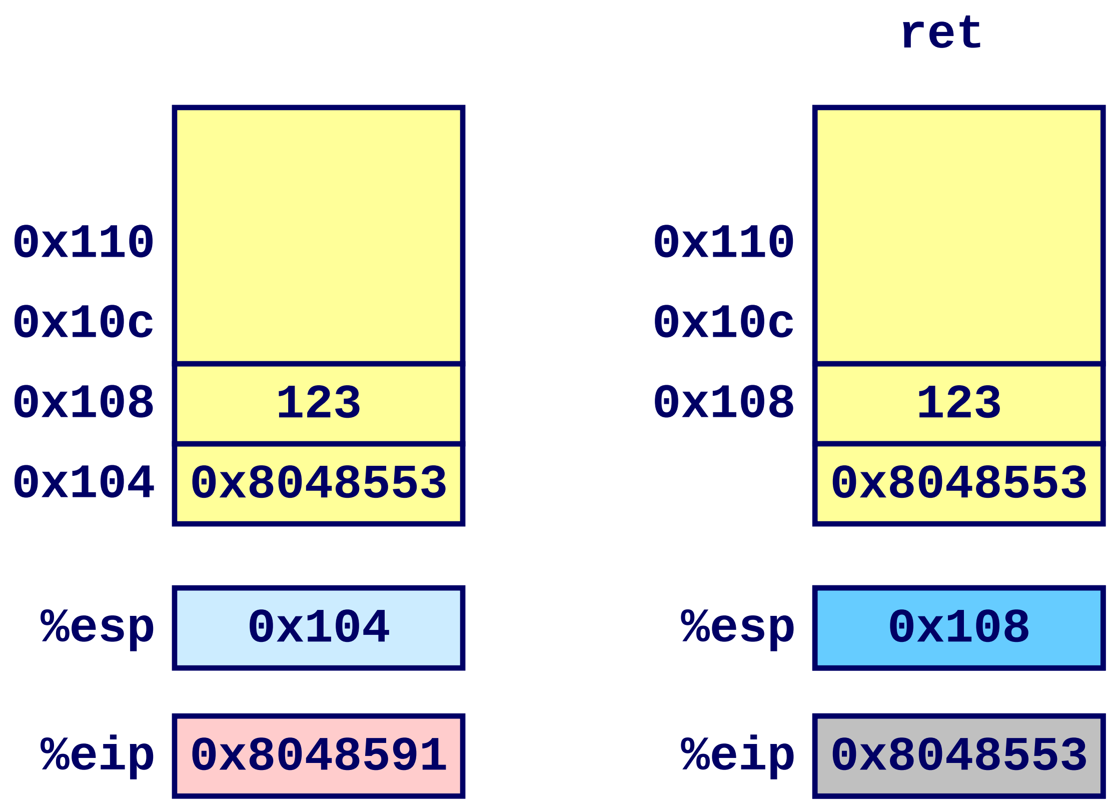
`call   8048b90`



`%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

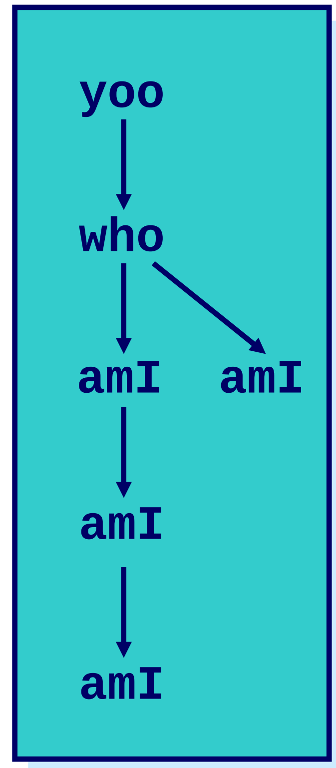
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

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

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

- Procedure `amI` recursive

Call Chain



Stack Frames

Contents

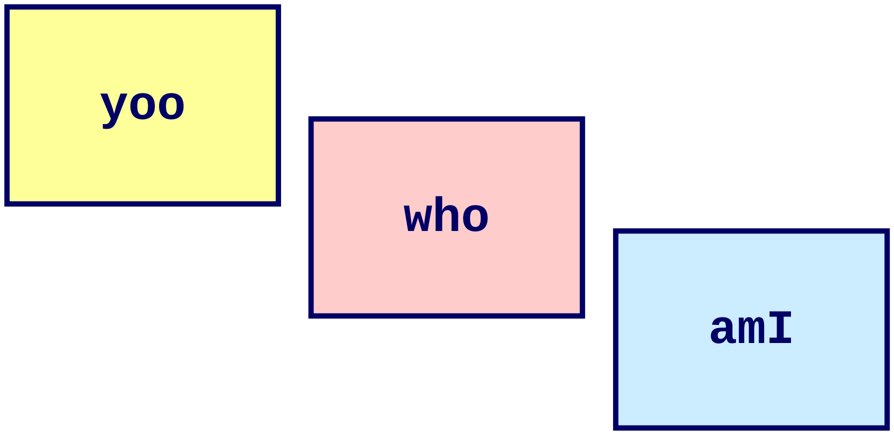
- Local variables
- Return information
- Temporary space

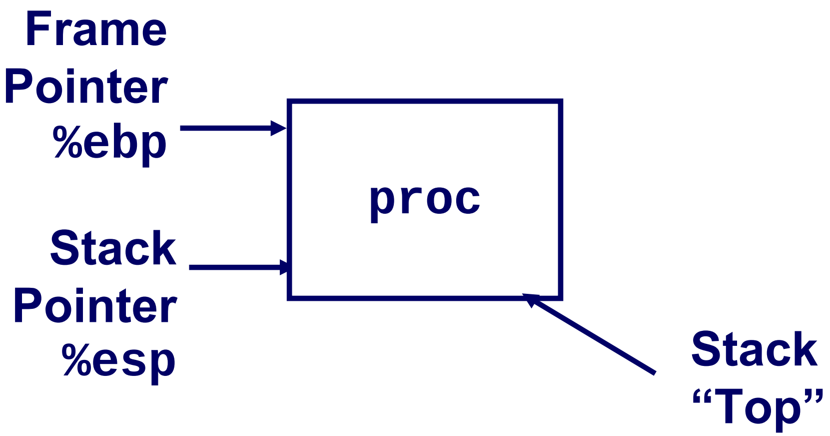
Management

- 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



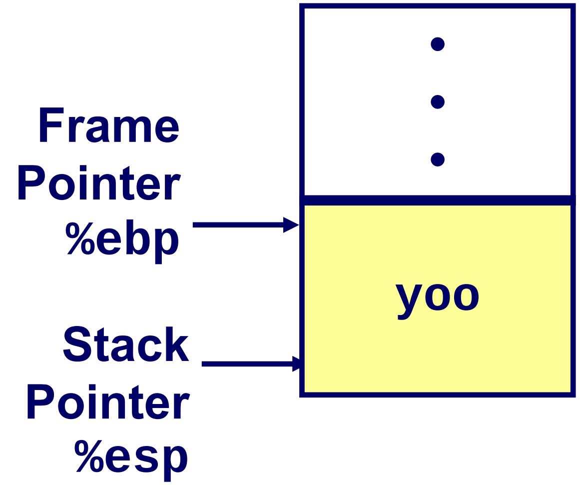


Stack Operation

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

Call Chain

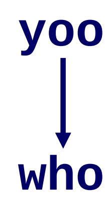
yoo

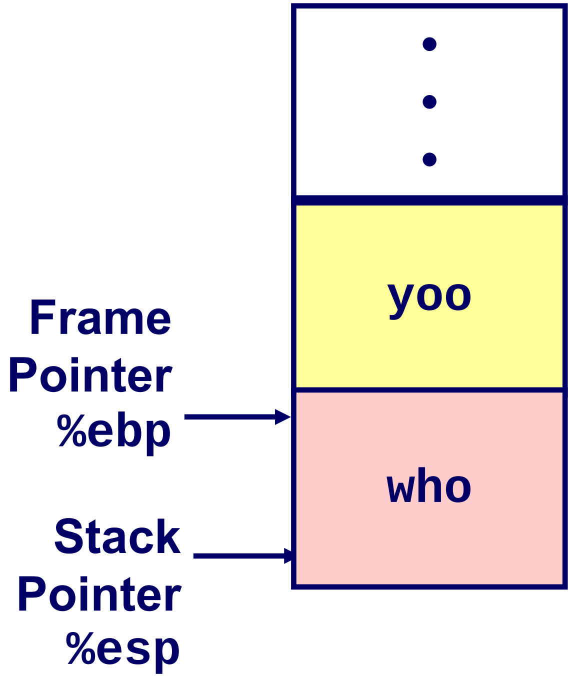


Stack Operation

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

Call Chain

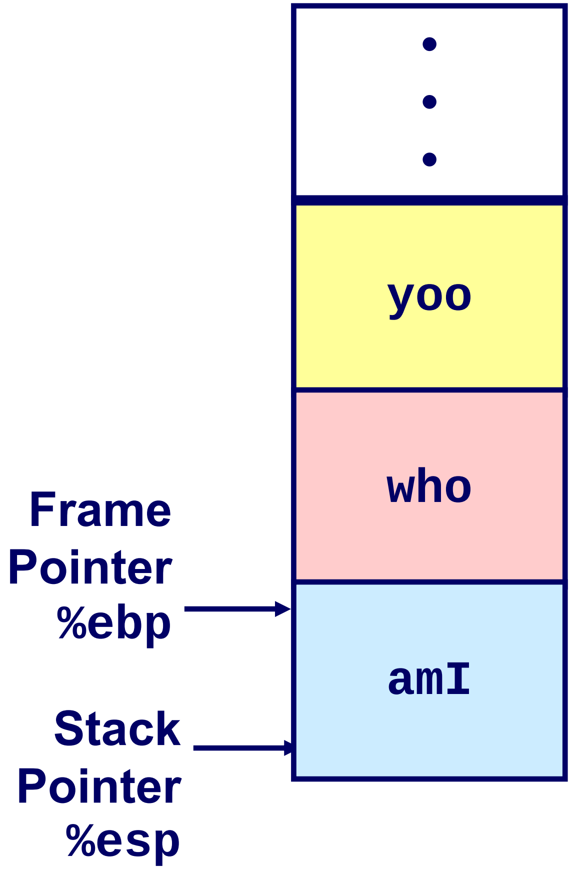




Stack Operation

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

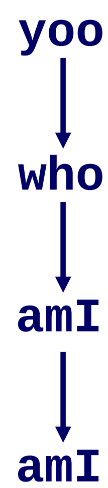
Call Chain

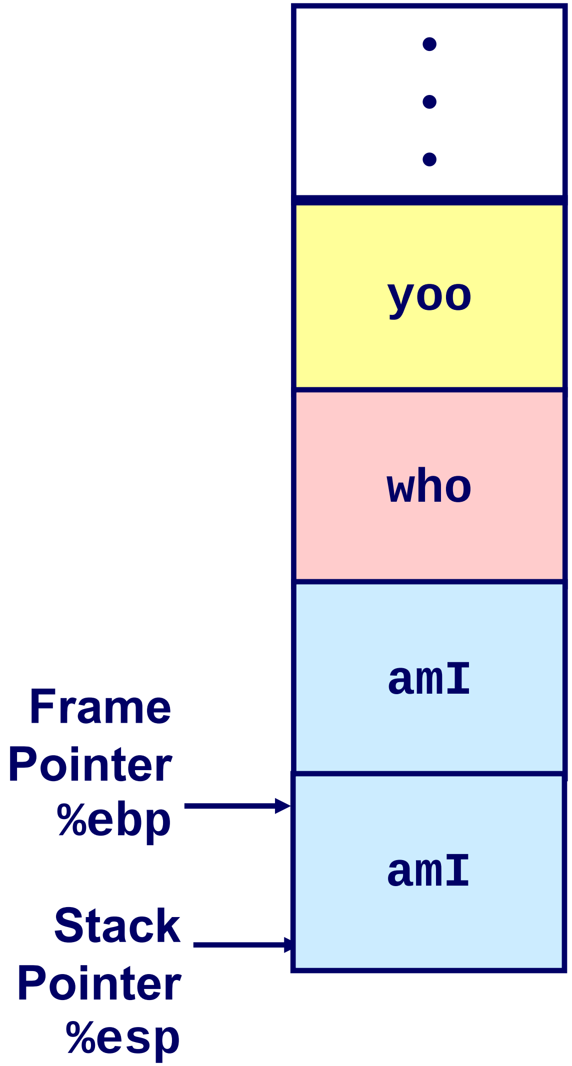


Stack Operation

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

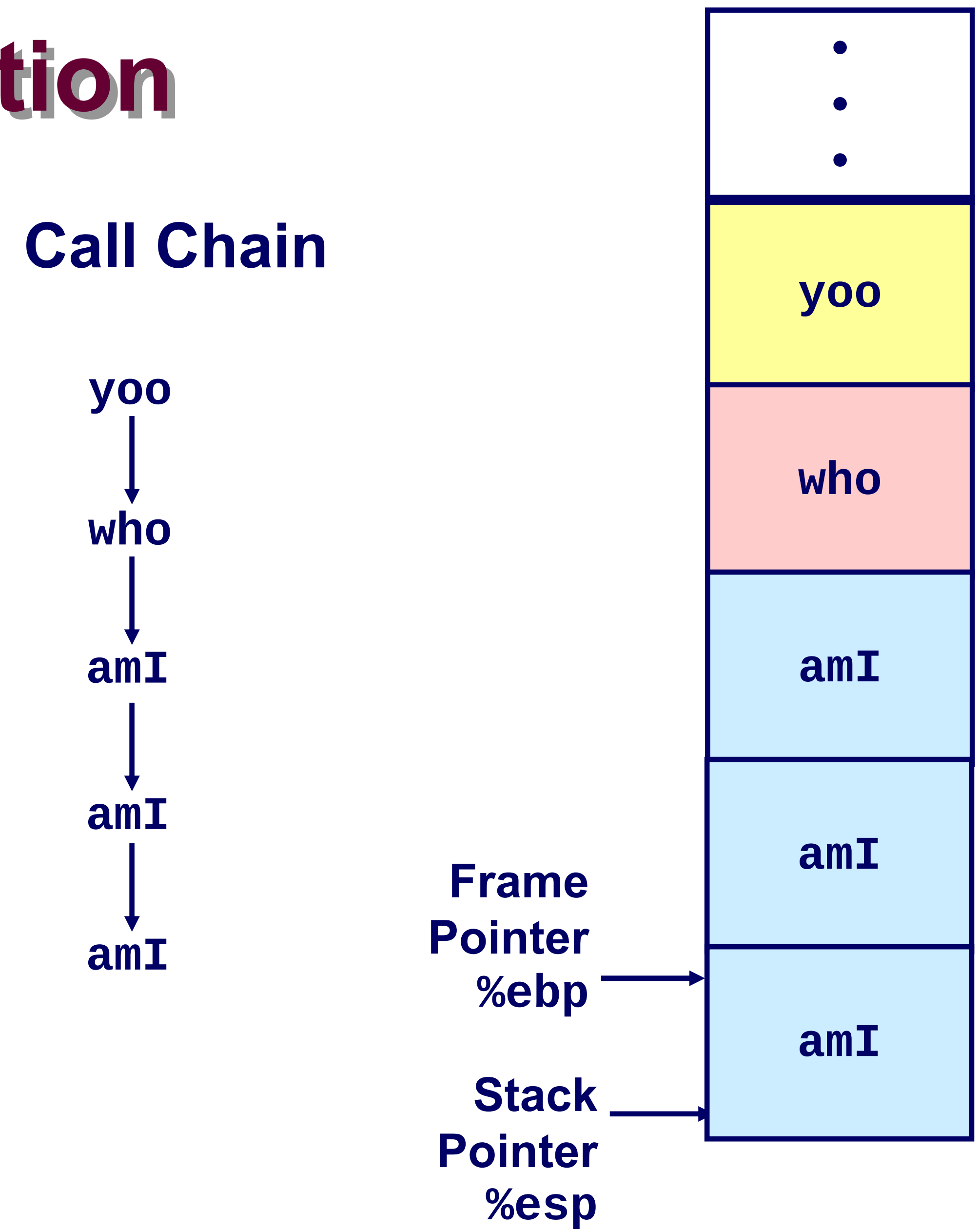
Call Chain





Stack Operation

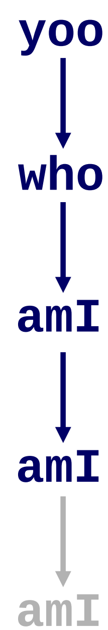
```
amI(…)
{
  •
  •
    amI();
  •
  •
}
```

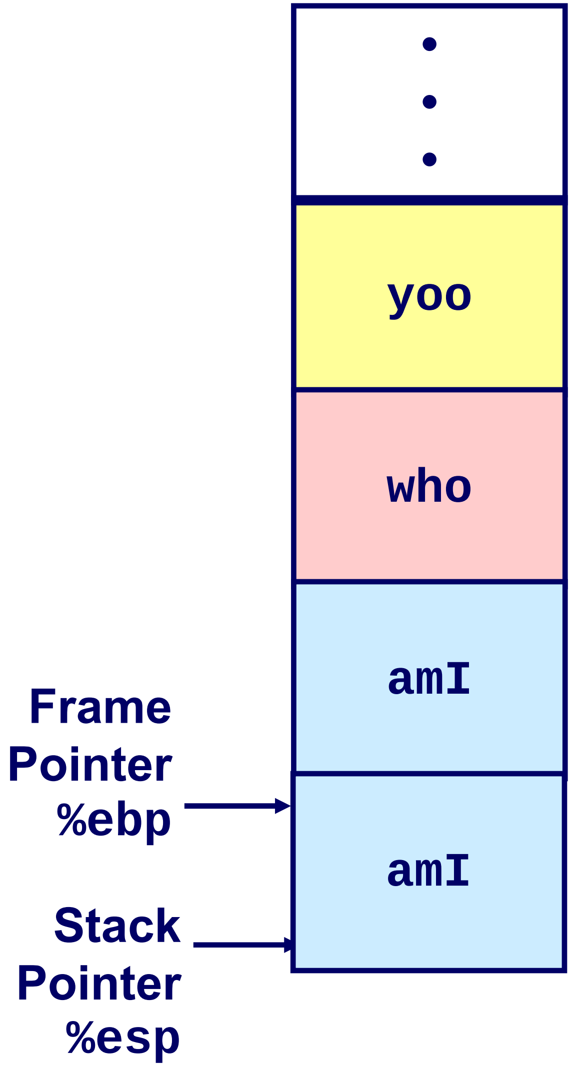


Stack Operation

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

Call Chain

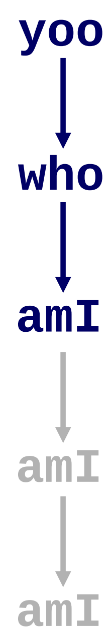


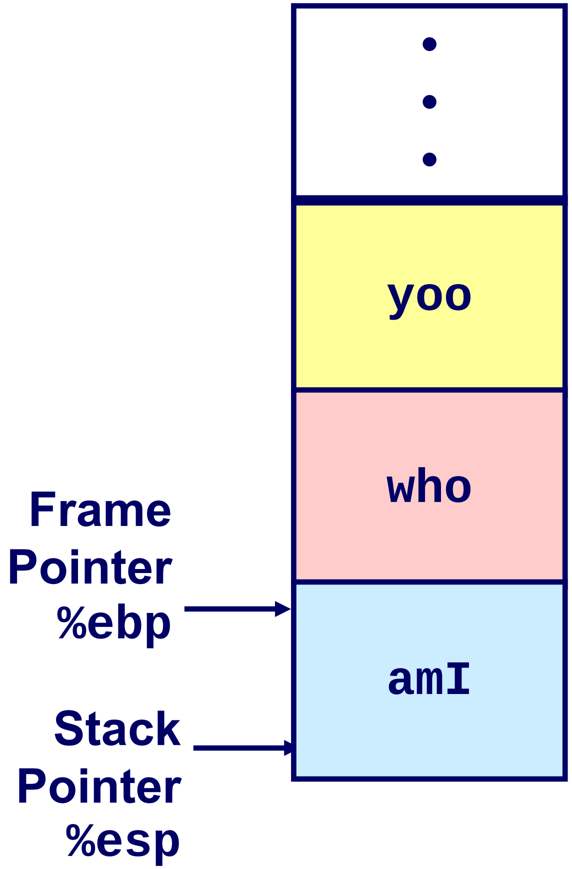


Stack Operation

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

Call Chain

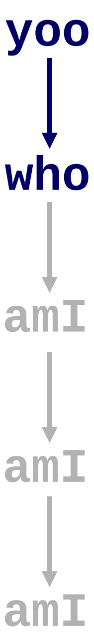


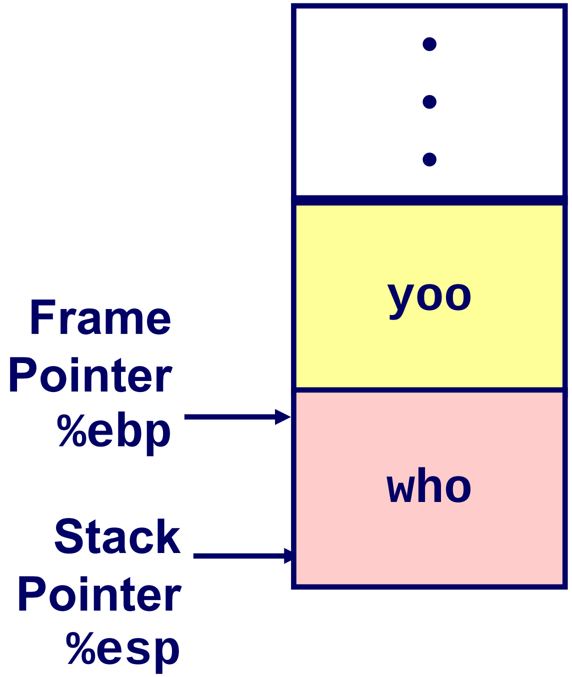


Stack Operation

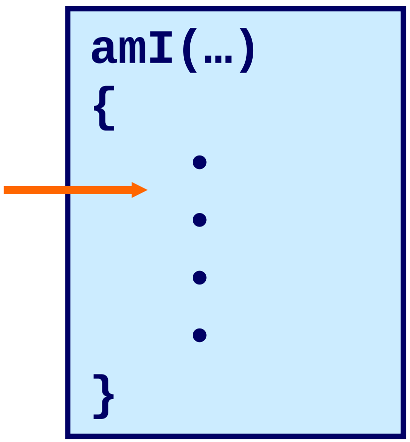
```
who(…)
{
   • • •
   amI();
   • • •
   amI();
   • • •
}
```

Call Chain

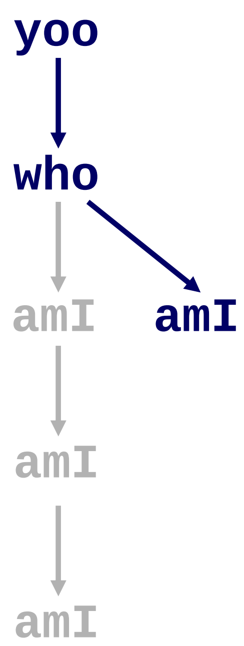


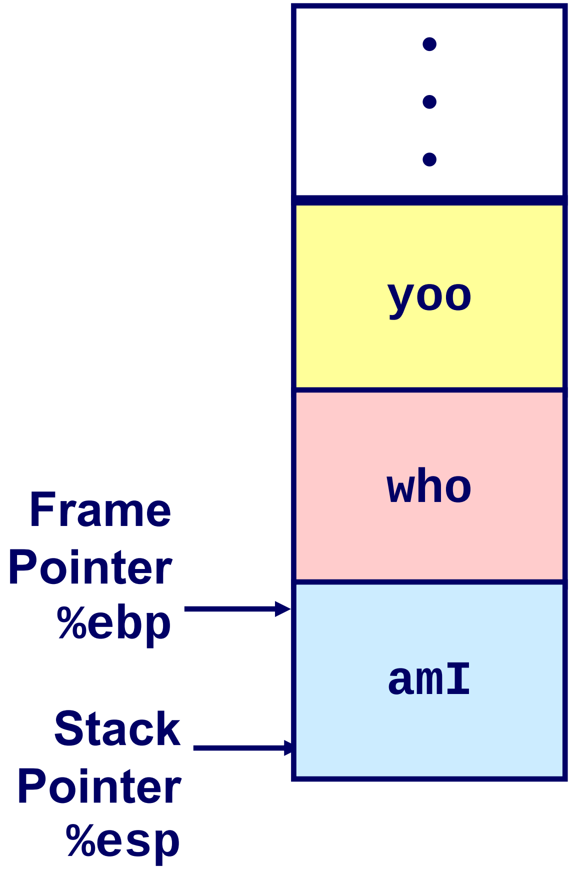


Stack Operation



Call Chain

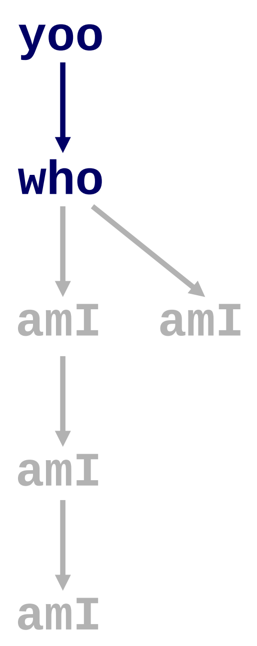


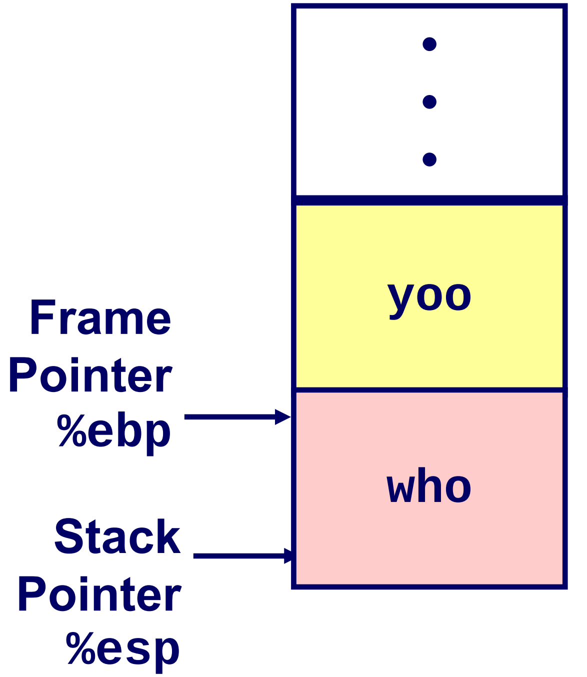


Stack Operation

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

Call Chain

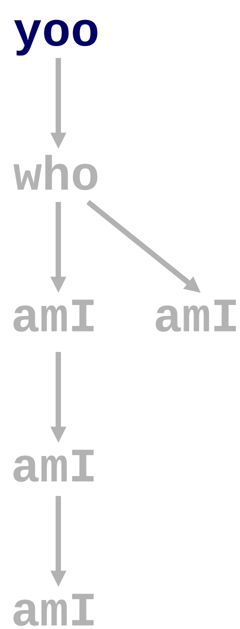


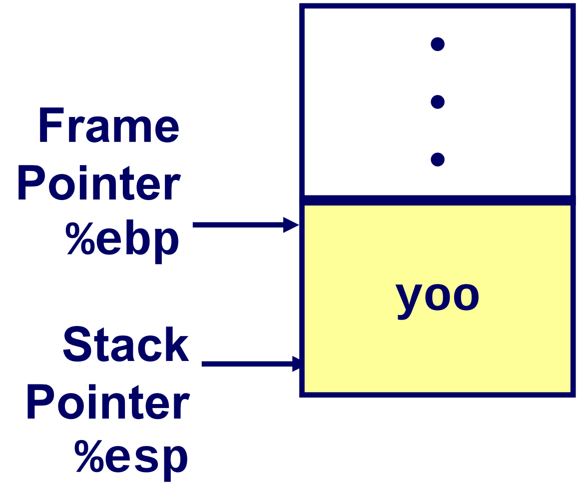


Stack Operation

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

Call Chain





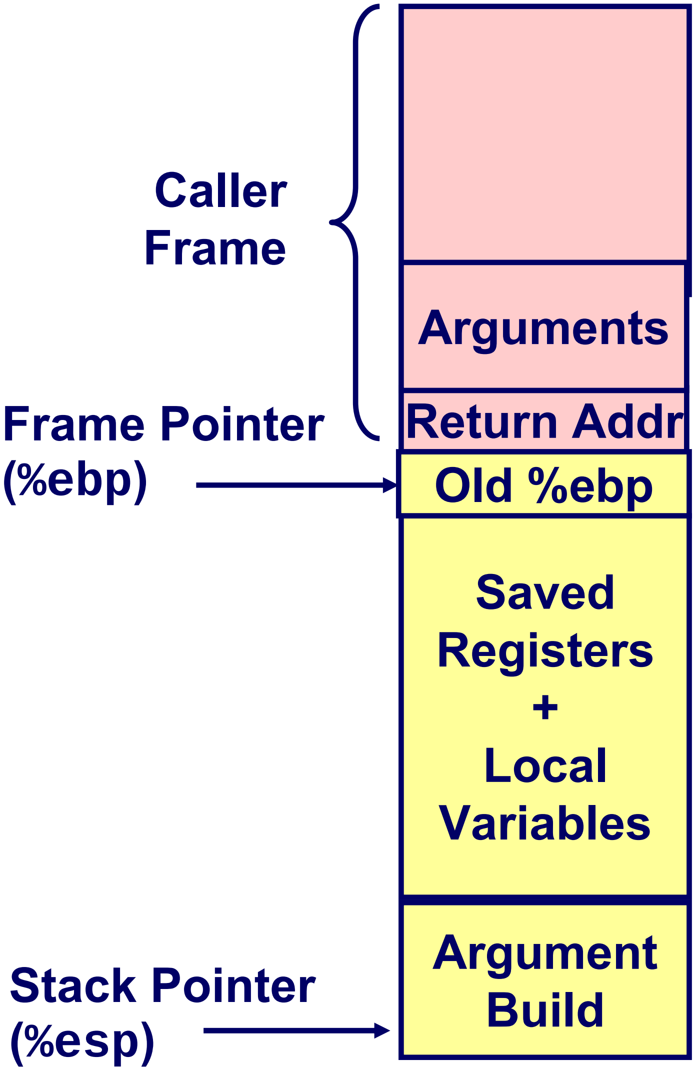
IA32/Linux Stack Frame

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

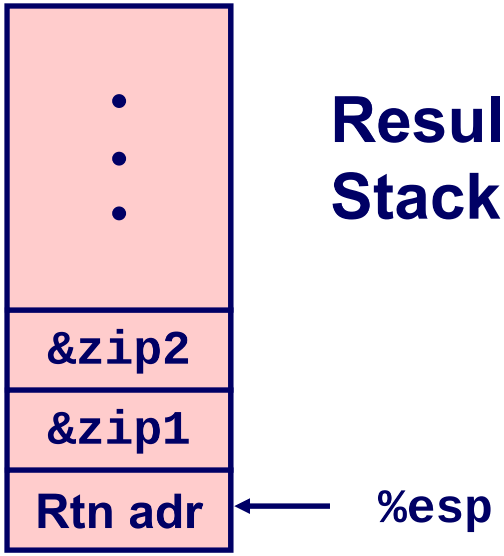
```
int zip1 = 15213;
int zip2 = 91125;

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;
}
```

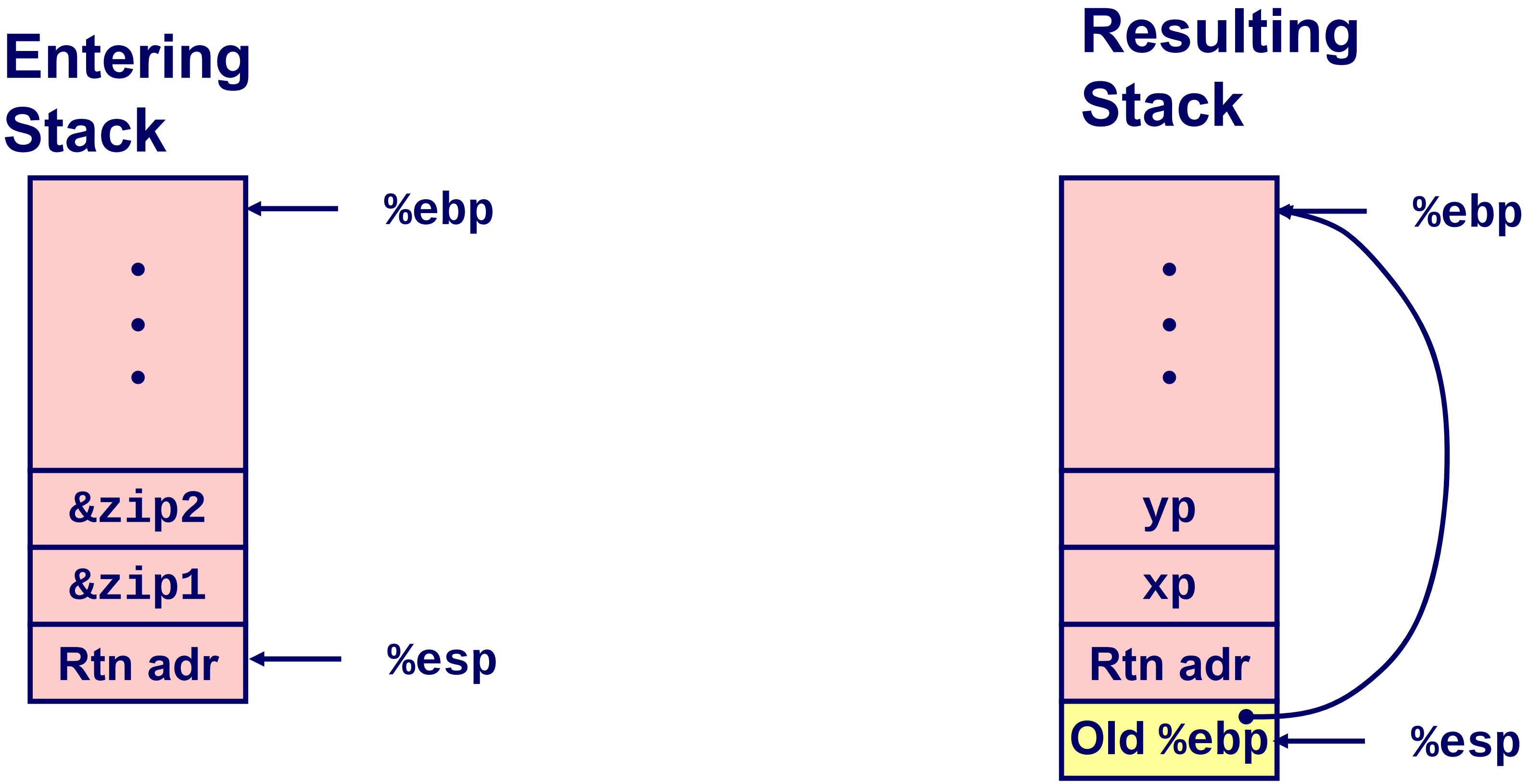
```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx

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

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

Set Up

Body

Finish

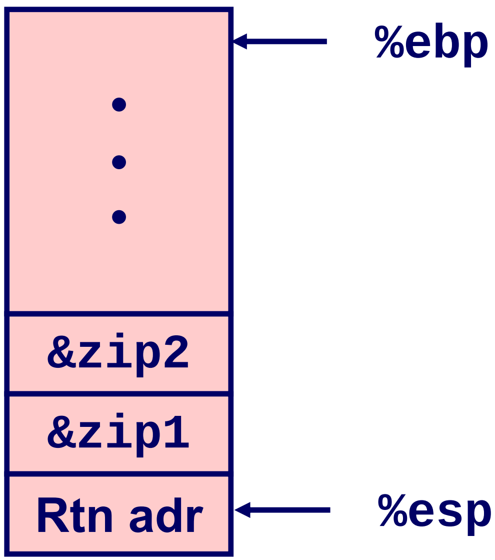
swap Setup #1



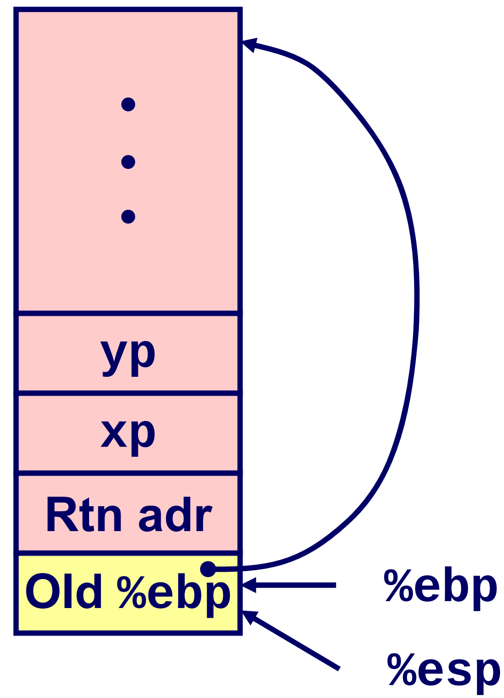

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #2

Entering Stack



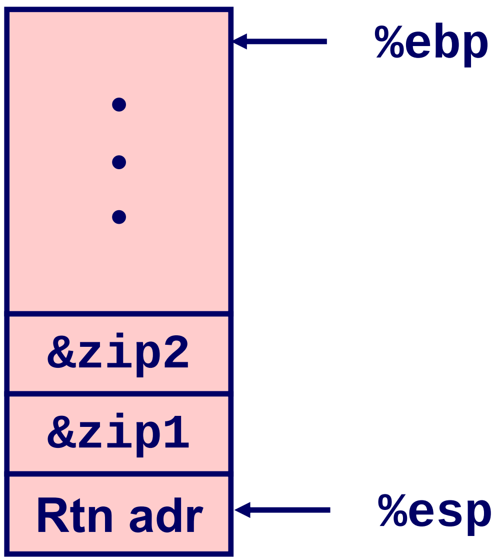
Resulting Stack



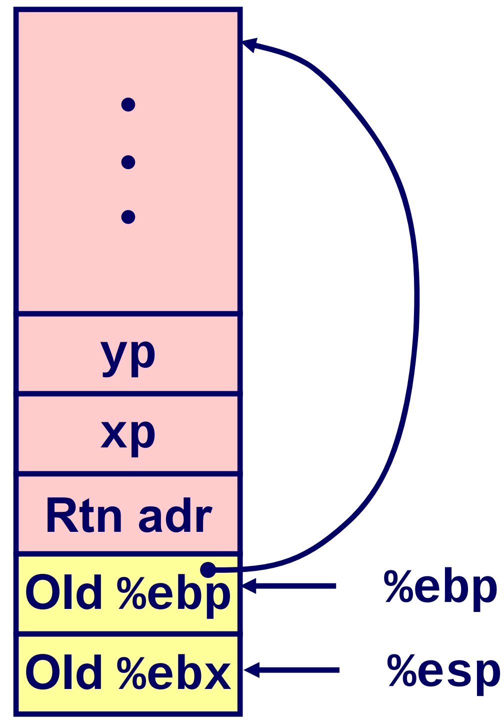

```
swap:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

swap Setup #3

Entering Stack

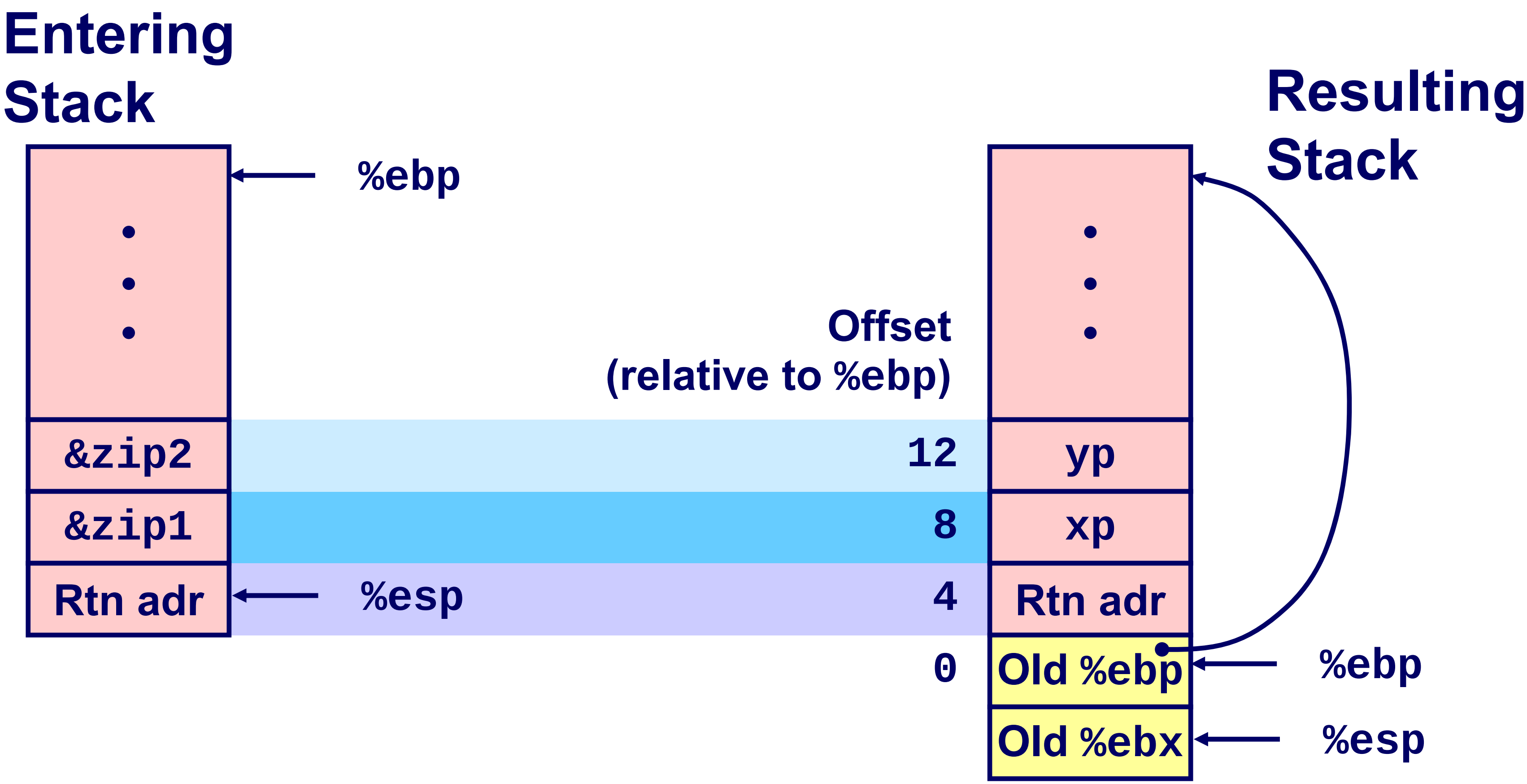


Resulting Stack




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

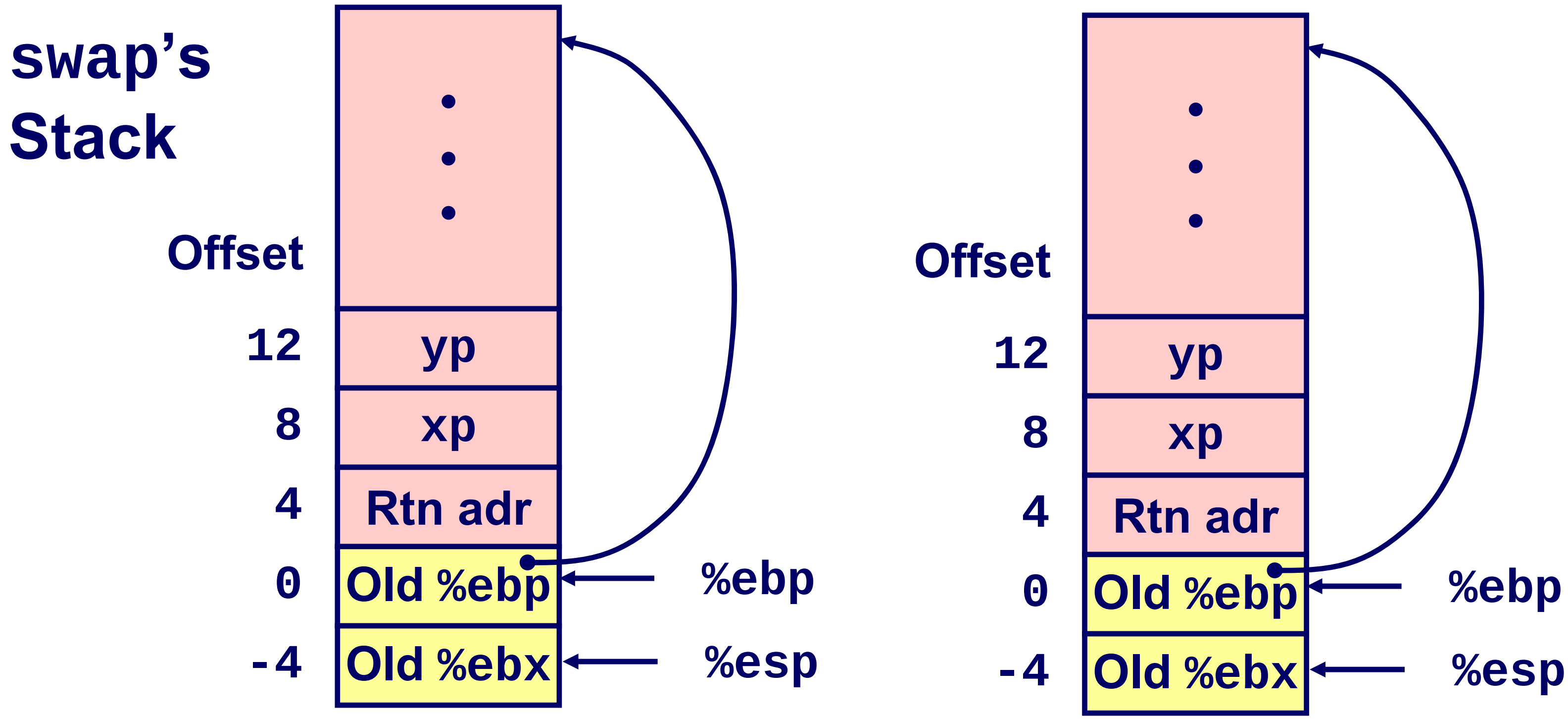
Effect of swap Setup




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

Body

swap Finish #1

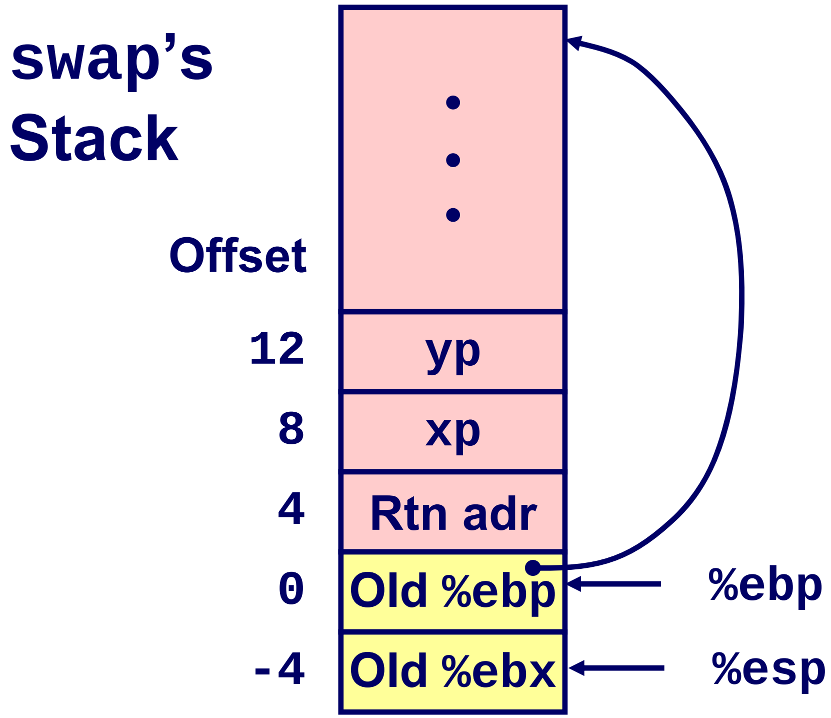


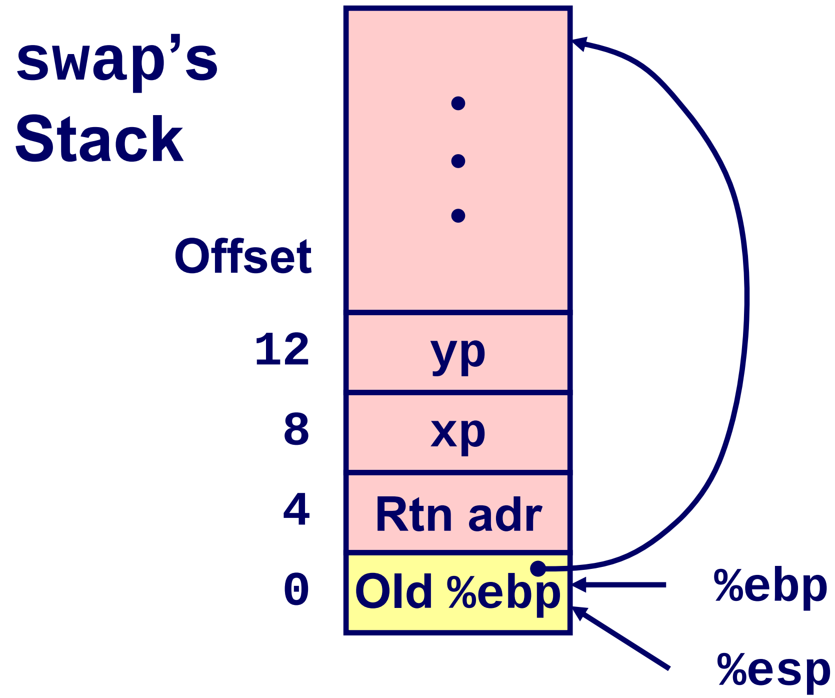

```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Observation

- Saved & restored register %ebx

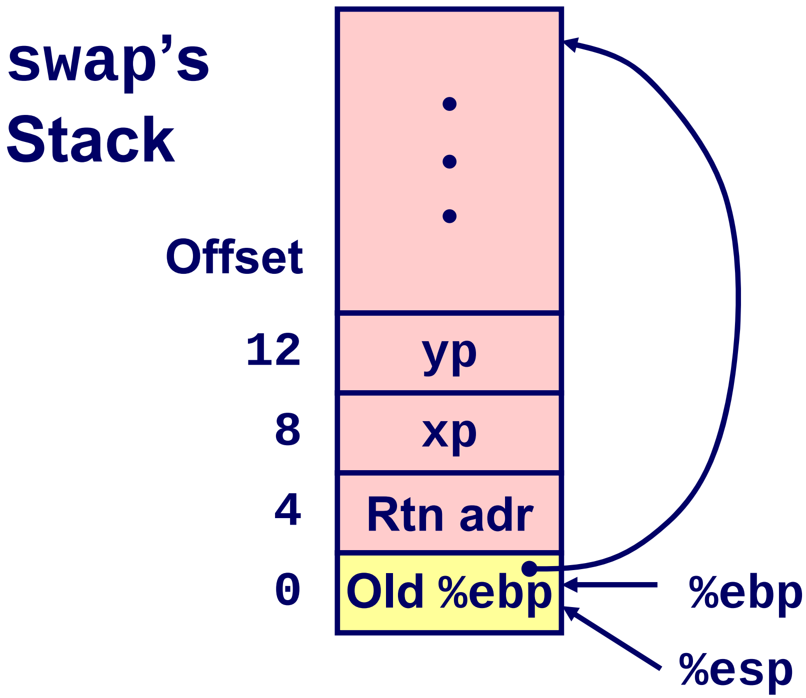
swap Finish #2

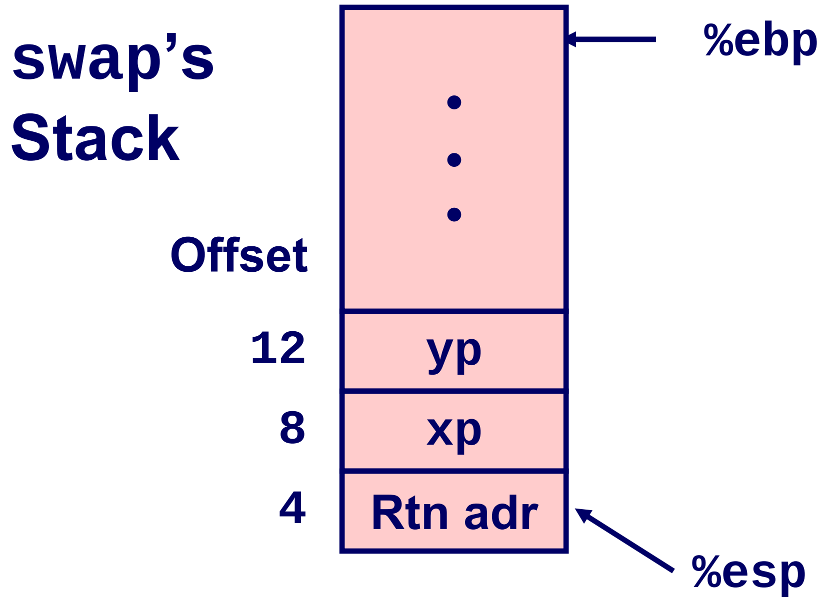





```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

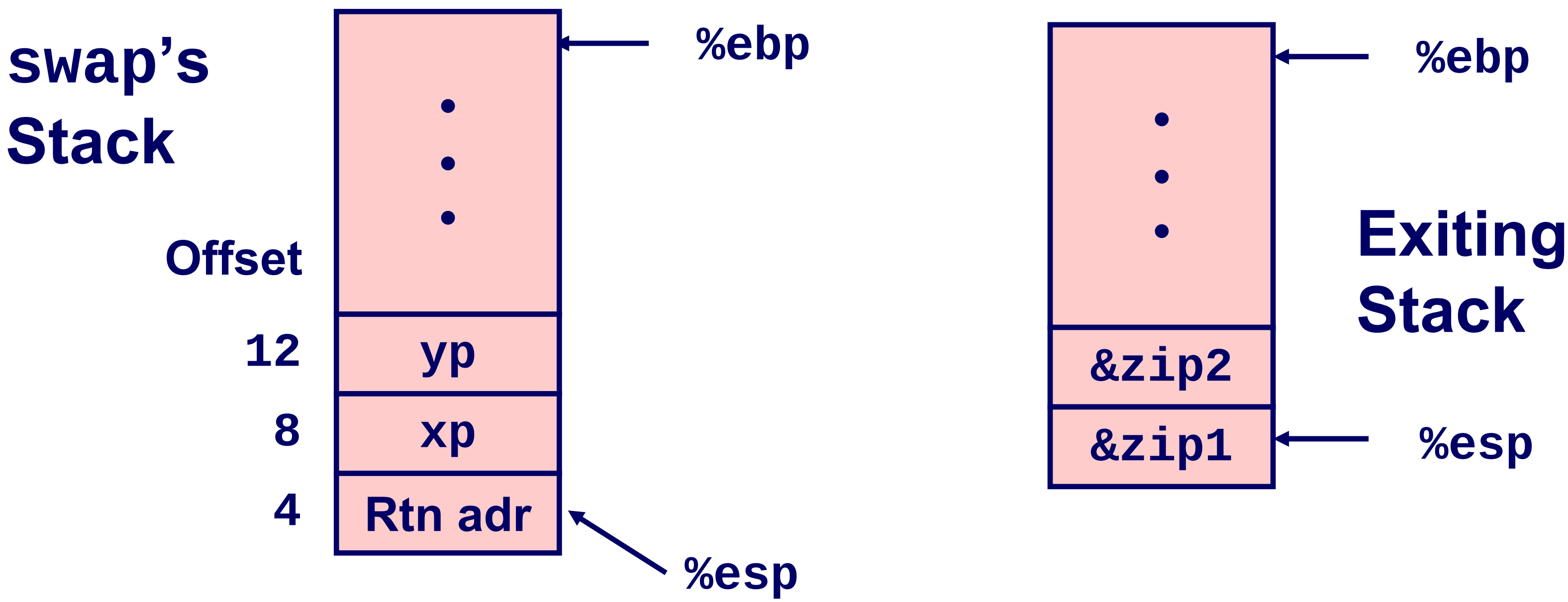
swap Finish #3






```
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?

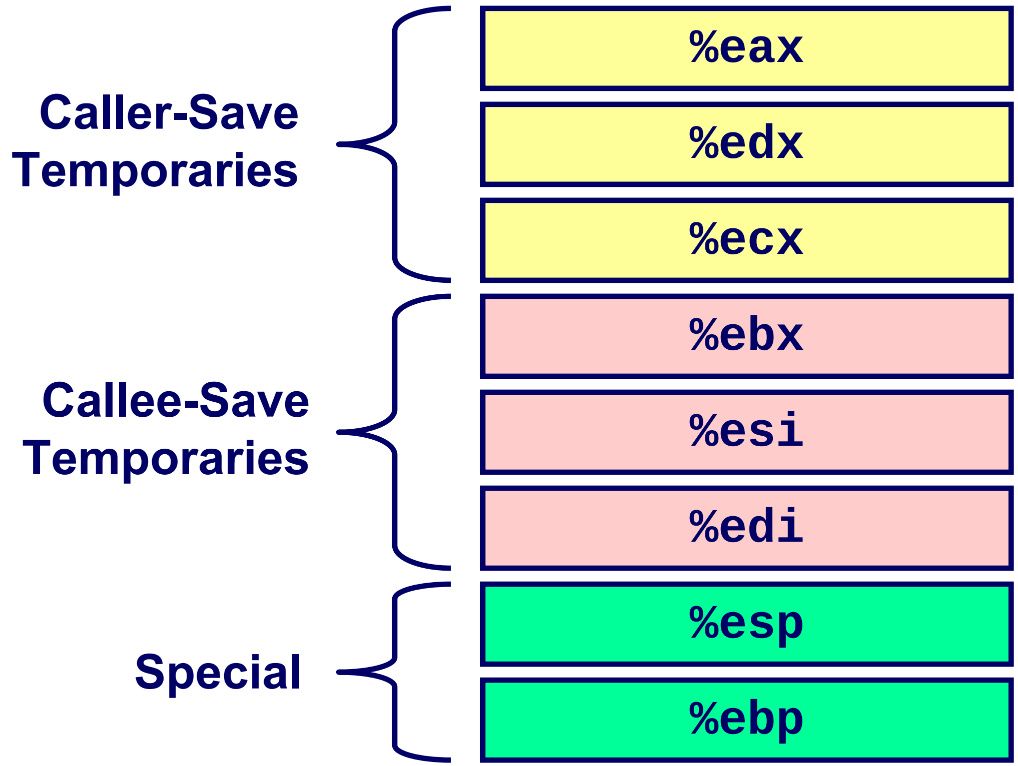
Conventions

- "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



Recursive Factorial

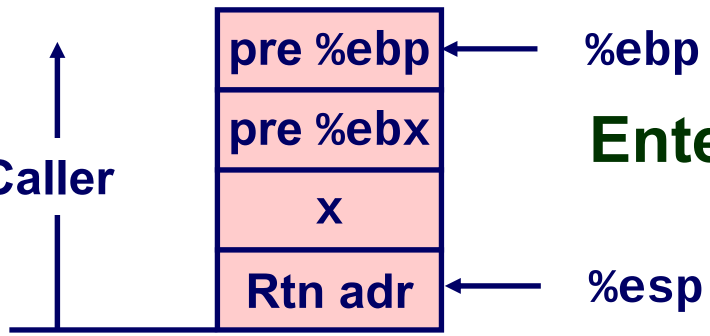
```
int rfact(int x)
{
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

Registers

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

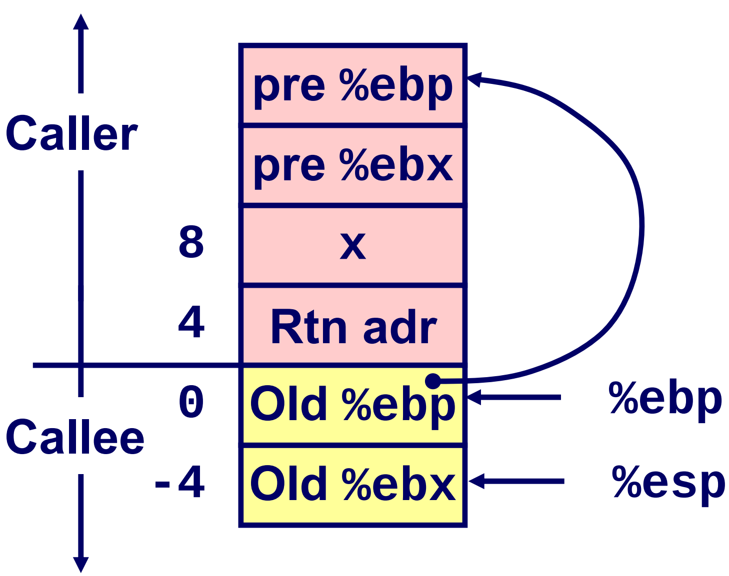
```
.globl rfact
    .type
rfact,@function
rfact:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
    movl 8(%ebp),%ebx
    cmpl $1,%ebx
    jle .L78
    leal -1(%ebx),%eax
    pushl %eax
    call rfact
    imull %ebx,%eax
    jmp .L79
    .align 4
.L78:
    movl $1,%eax
.L79:
    movl -4(%ebp),%ebx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

Rfact Stack Setup



Entering Stack

```
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

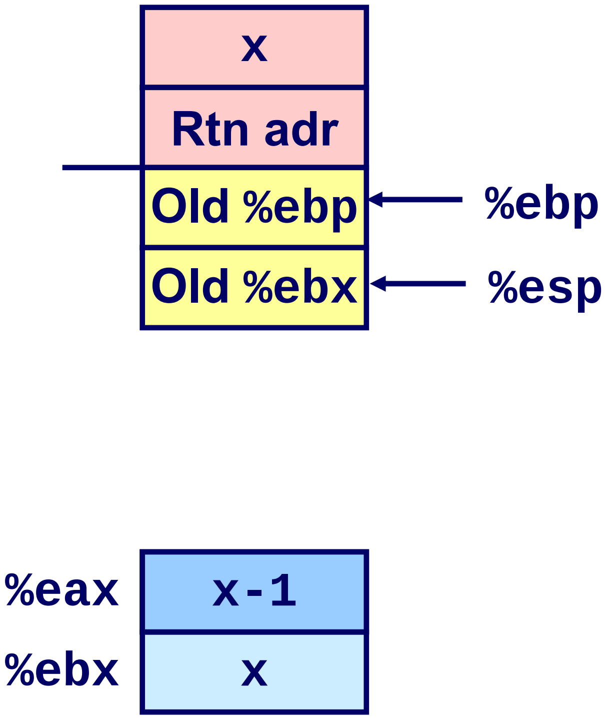
`%ebx` Stored value of x

`%eax`

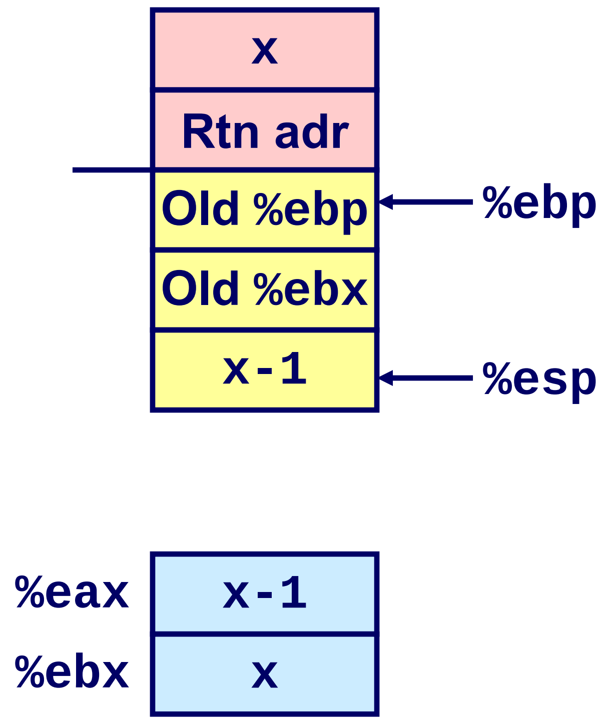
- Temporary value of `x-1`
- Returned value from `rfact(x-1)`
- Returned value from this call

Rfact Recursion

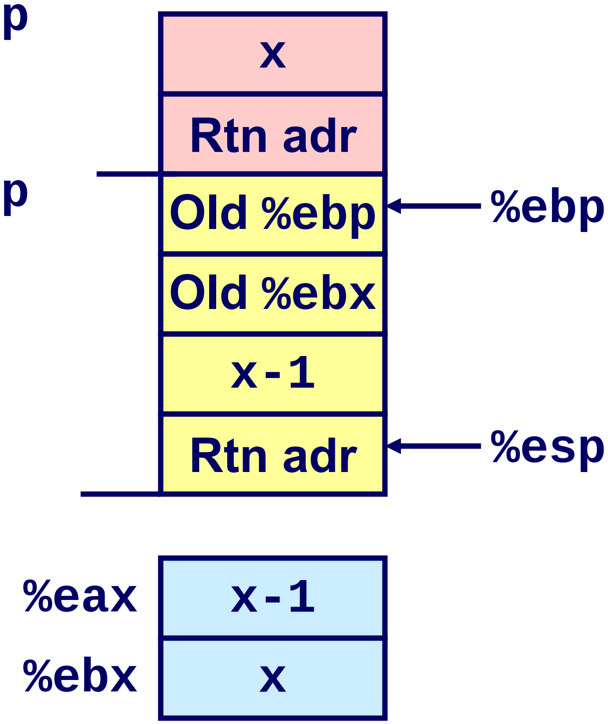
```
leal -1(%ebx),%eax
```




```
pushl %eax
```

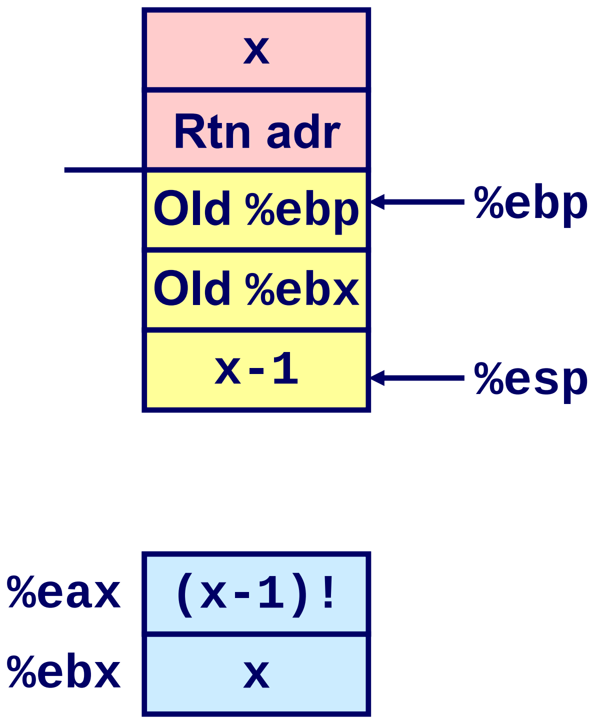



```
call rfact
```



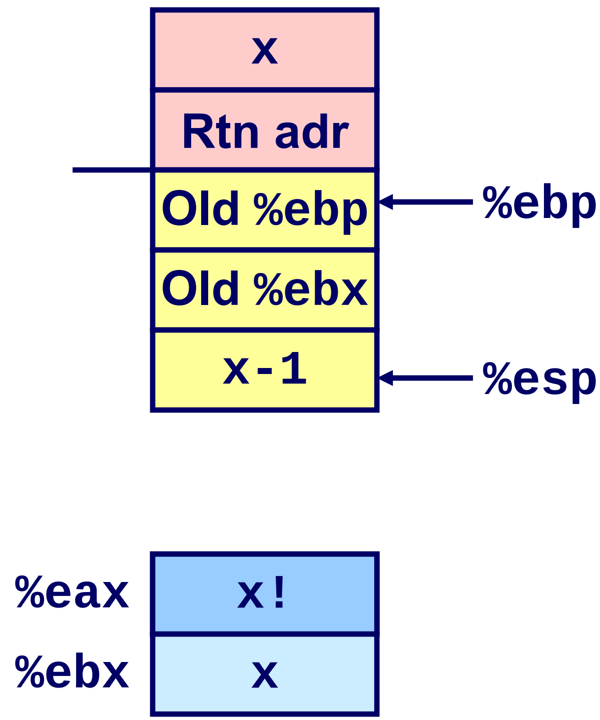
Rfact Result

Return from Call



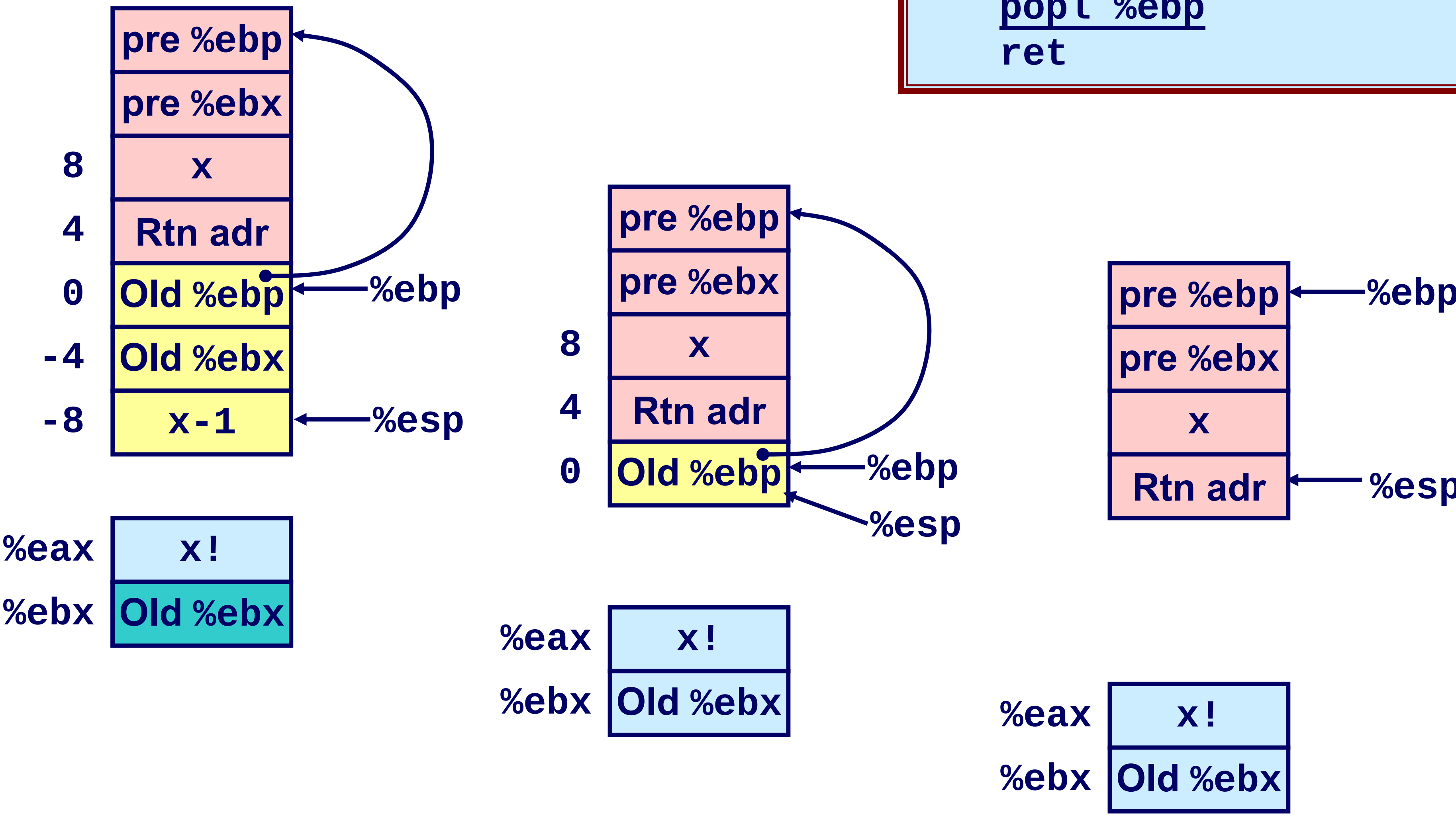
Assume that `rfact(x-1)` returns `(x-1)!` in register %eax

```
imull %ebx,%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

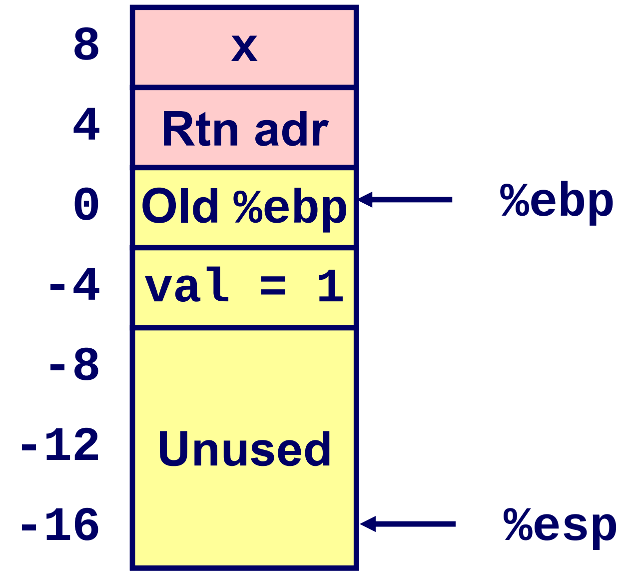
```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- **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;
}
```

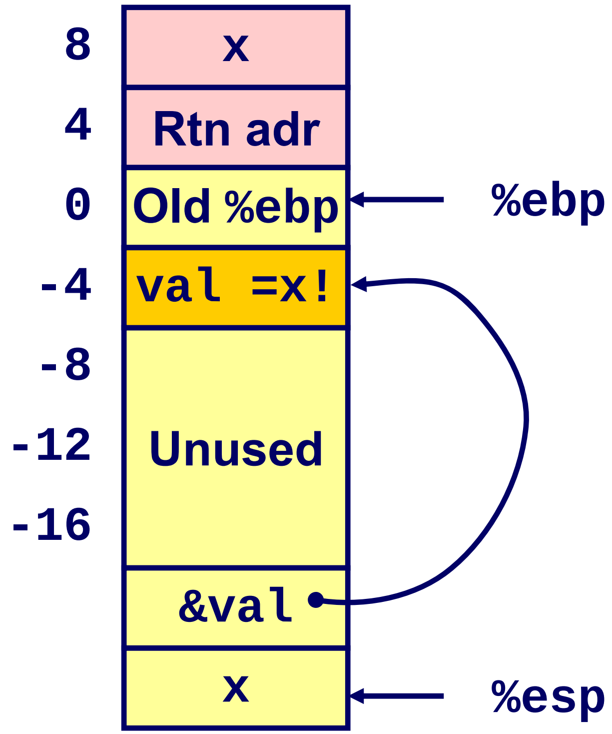
Passing Pointer

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
```

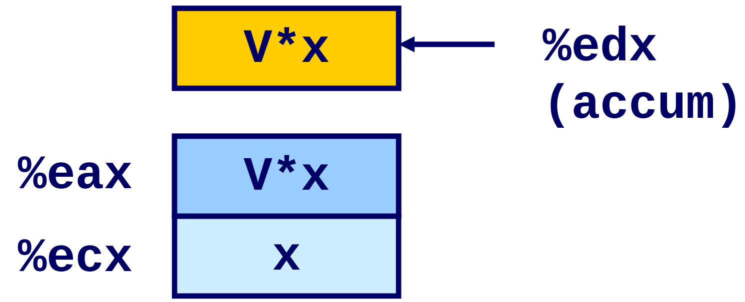
```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

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

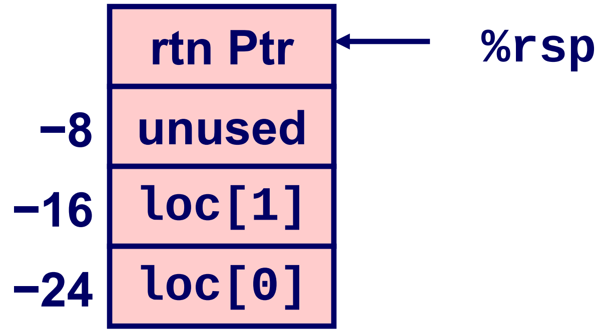
x86-64 Locals in the Red Zone

```
/* 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



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
```

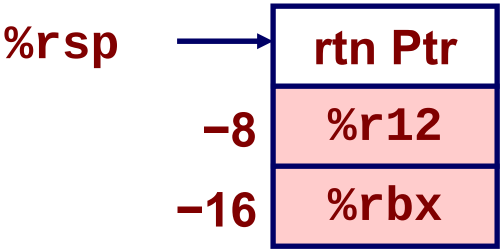
- Keeps values of `a` and `i` in callee save registers
- Must set up stack frame to save these registers

Understanding x86-64 Stack Frame

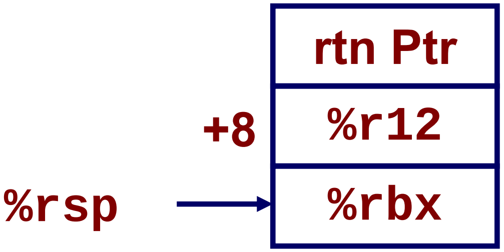
```
swap_ele_su:
  movq    %rbx, -16(%rsp)   # Save %rbx
  movslq  %esi,%rbx         # Extend & save i
  movq    %r12, -8(%rsp)    # Save %r12
  movq    %rdi, %r12        # Save a
  leaq    (%rdi,%rbx,8), %rdi  # &a[i]
  subq    $16, %rsp         # Allocate stack frame
  leaq    8(%rdi), %rsi     #     &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