15-213

"The course that gives CMU its Zip!"

Machine-Level Programming III: Procedures
Sept 19, 2000

Topics

- **IA32 stack discipline**
- **Register saving conventions**
- **Creating pointers to local variables**
- **Stack buffer overflow exploits**
  - finger
  - AIM (AOL Instant Messenger)

IA32 Stack

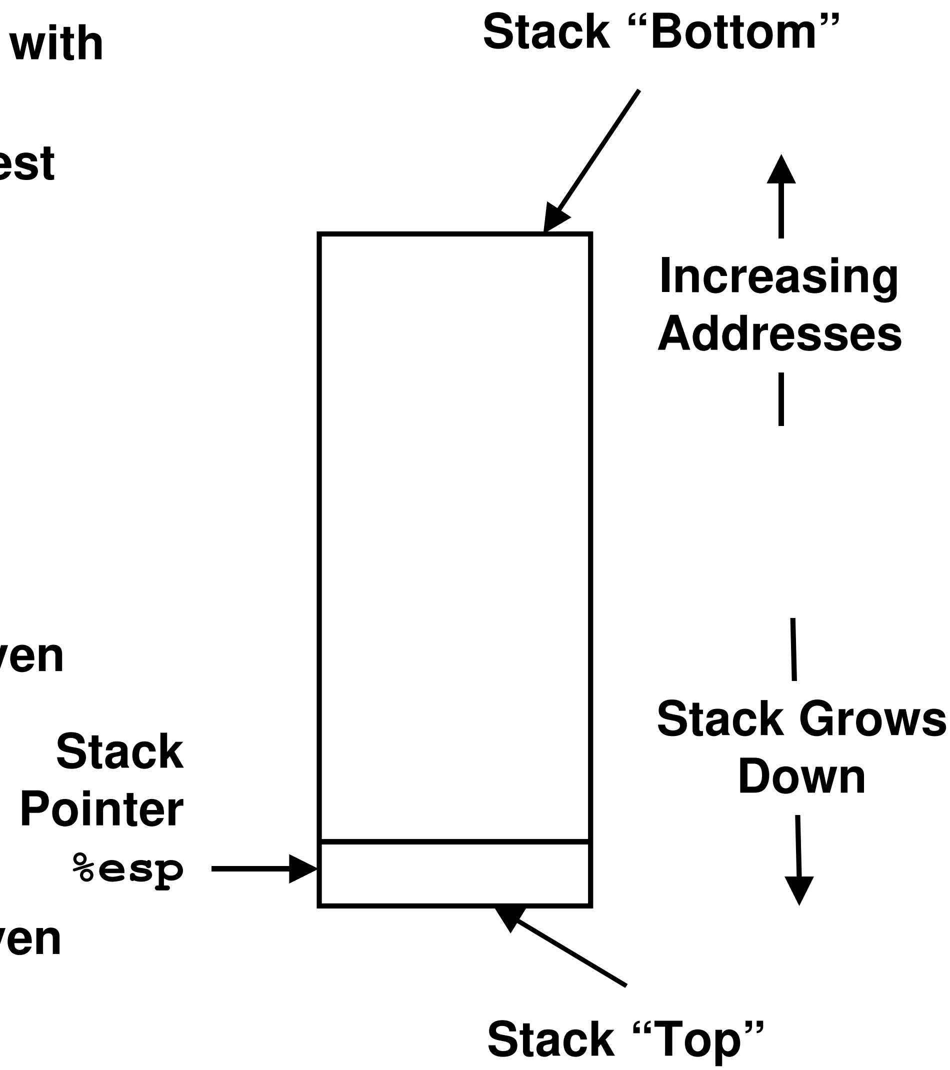
- **Region of memory managed with stack discipline**
- **Register `%esp` indicates lowest allocated position in stack**
  - i.e., address of top element

Pushing

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

Popping

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



Stack Operation Examples

Initial

Address	Stack
0x110	
0x10c	
0x108	123

Register	Value
%eax	213
%edx	555
%esp	0x108

`pushl %eax`

Address	Stack
0x110	
0x10c	
0x108	123
0x104	213

Register	Value
%eax	213
%edx	555
%esp	0x104

`popl %edx`

Address	Stack
0x110	
0x10c	
0x108	123

Register	Value
%eax	213
%edx	213
%esp	0x108

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
```

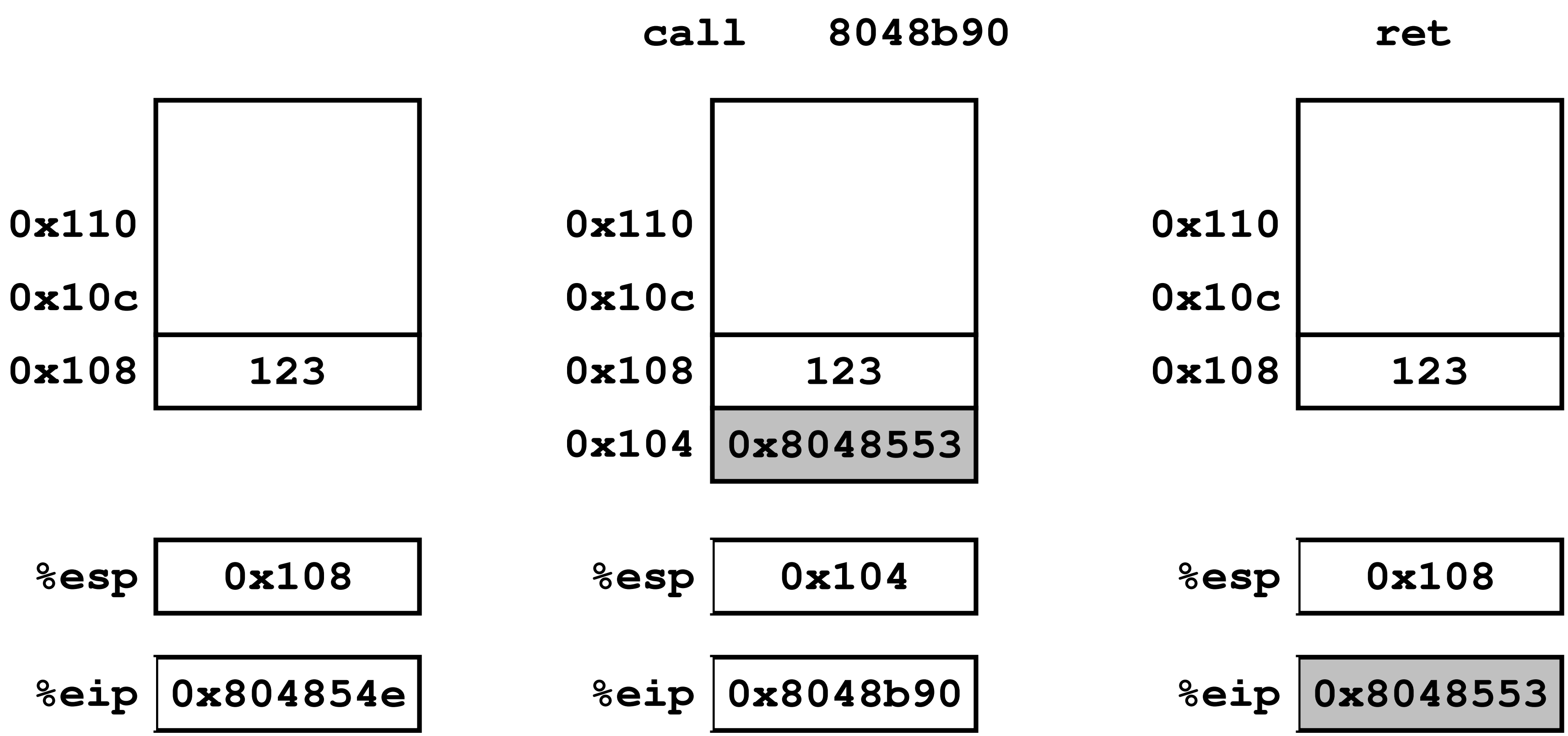
– Return address = **`0x8048553`**

Procedure return:

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

Procedure Call / Return Example

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



`%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

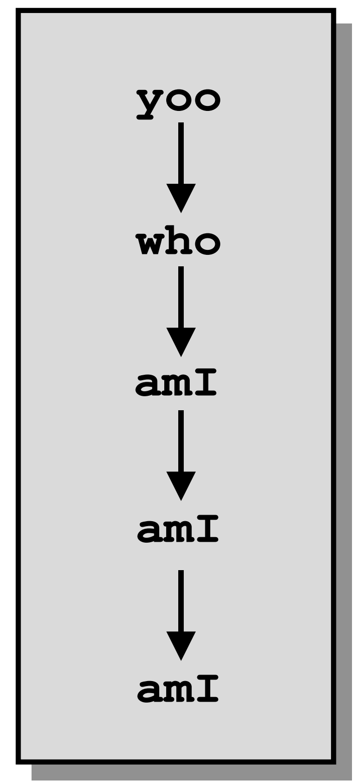
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

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

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

- Procedure `amI` recursive

Call Chain



IA32 Stack Structure

Stack Growth

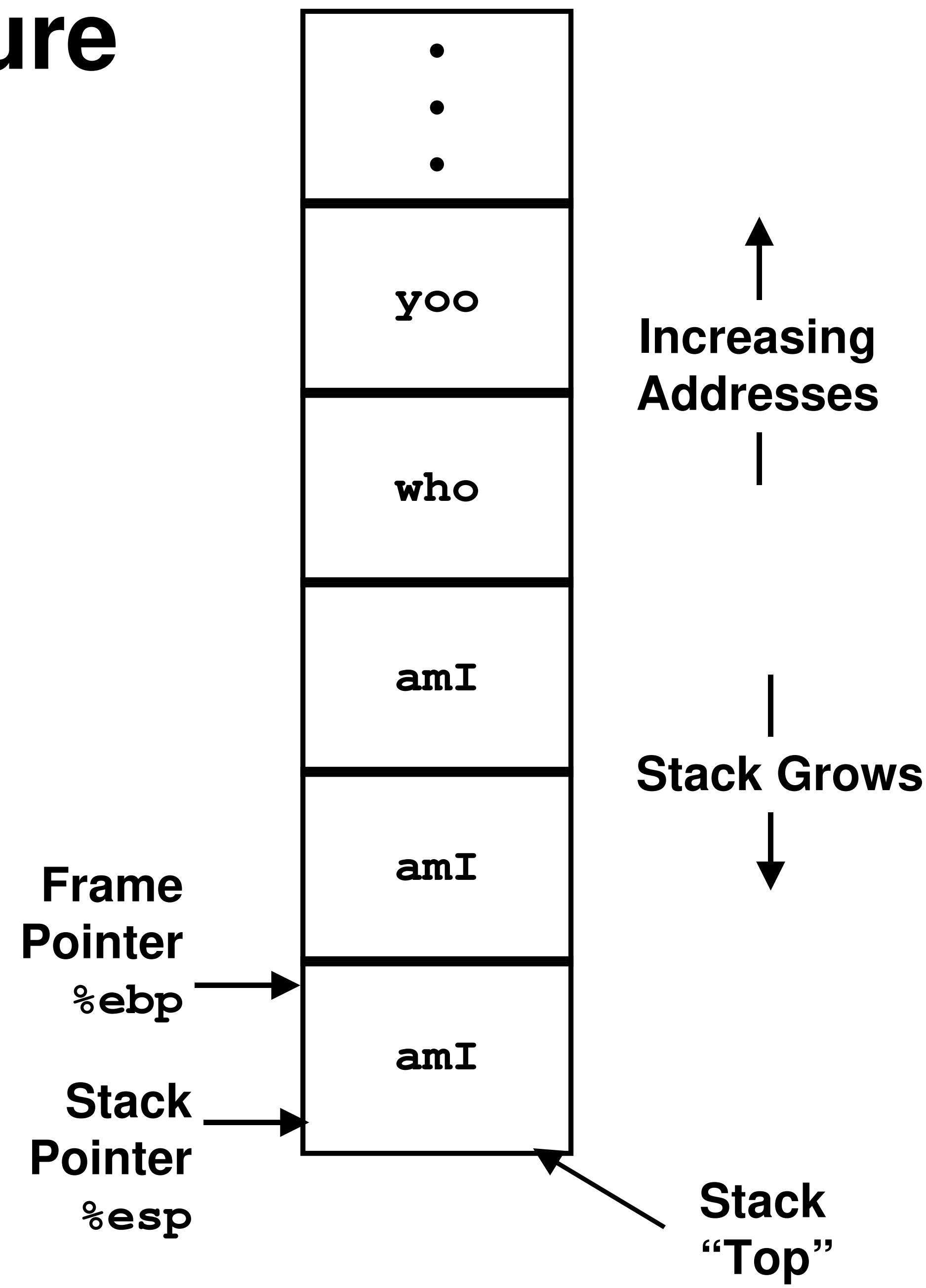
- Toward lower addresses

Stack Pointer

- Address of next available location in stack
- Use register `%esp`

Frame Pointer

- Start of current stack frame
- Use register `%ebp`



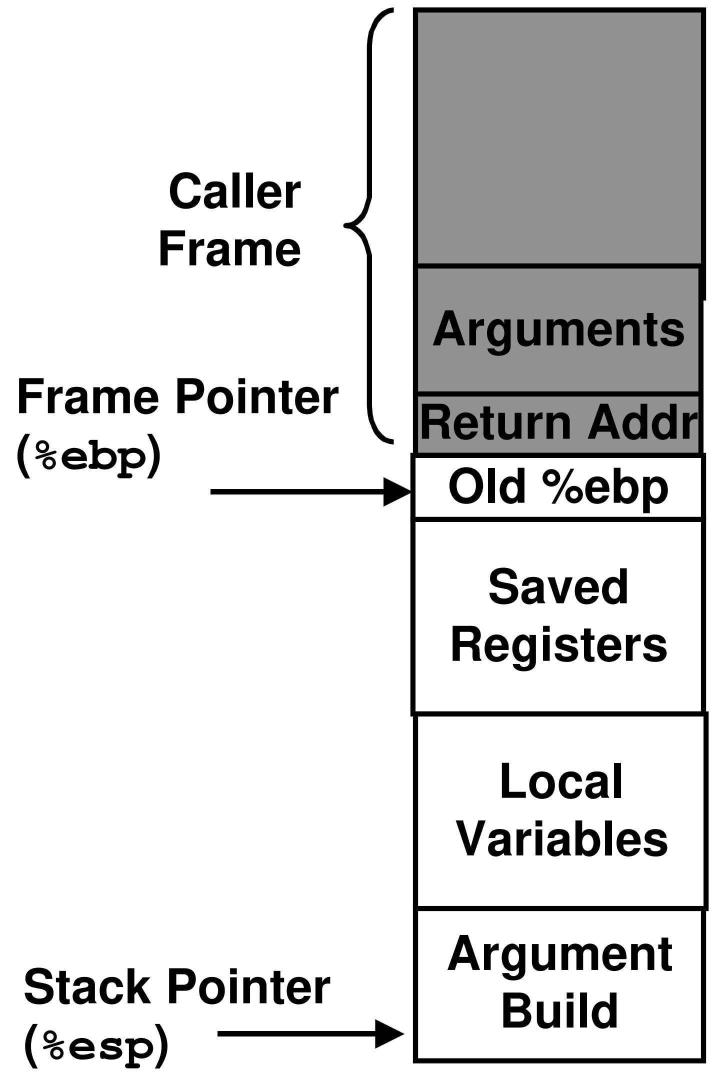
IA32/Linux Stack Frame

Callee Stack Frame ("Top" to Bottom)

- **Parameters for called functions**
- **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**

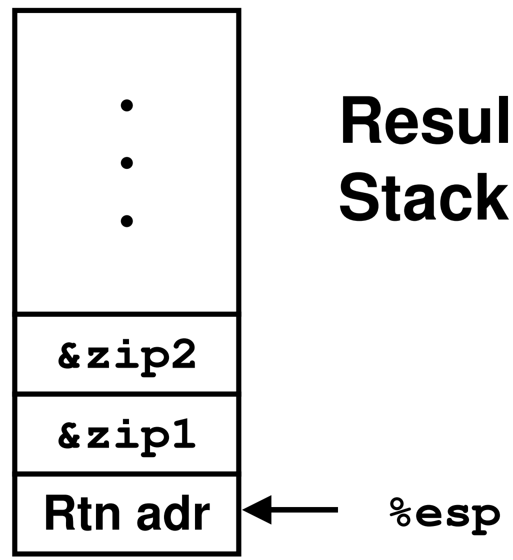


Revisiting `swap`

```
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;
}
```

```
call_swap:
   • • •
   pushl $zip2
   pushl $zip1
   call swap
   • • •
```



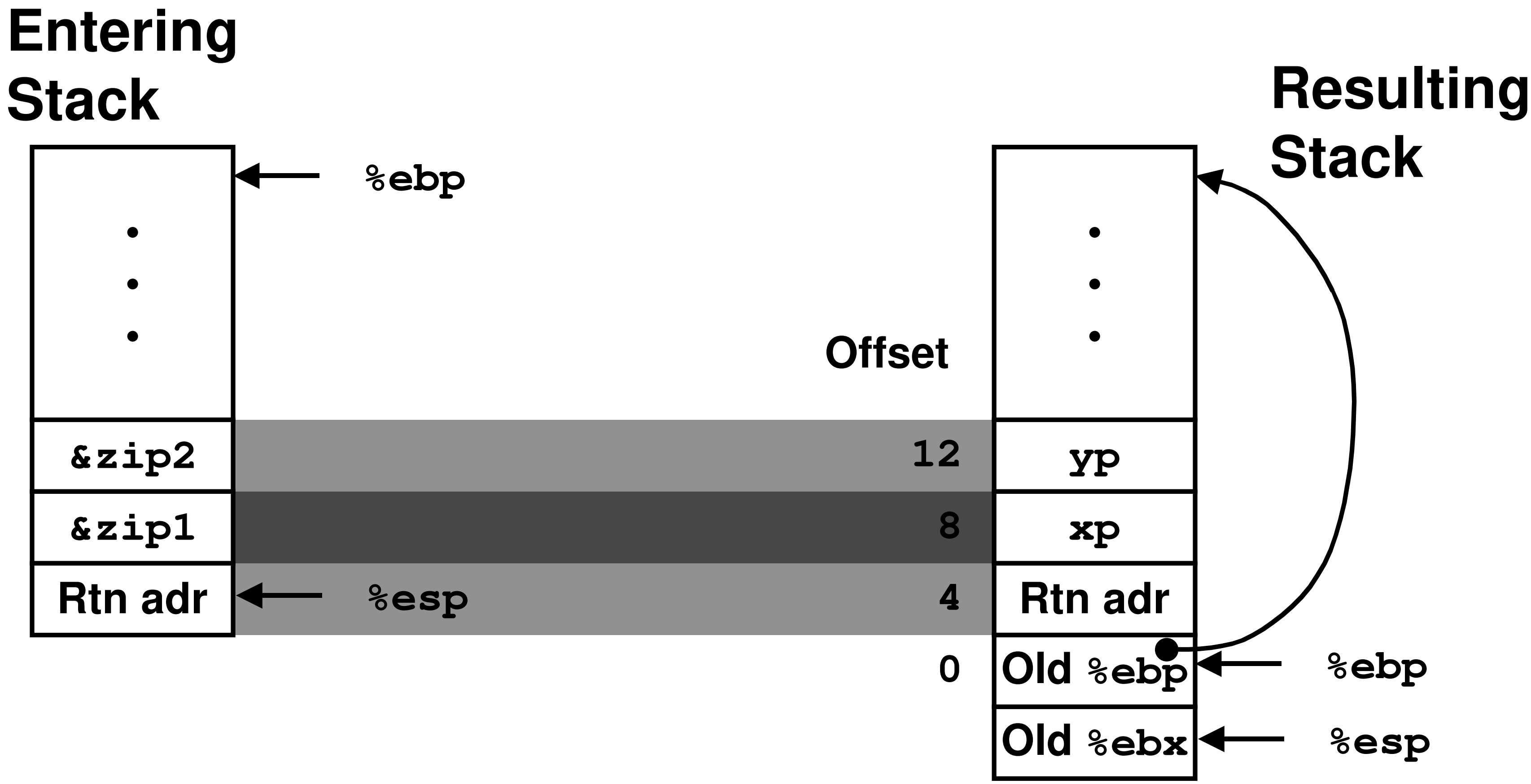
Resulting Stack

Revisiting `swap`

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

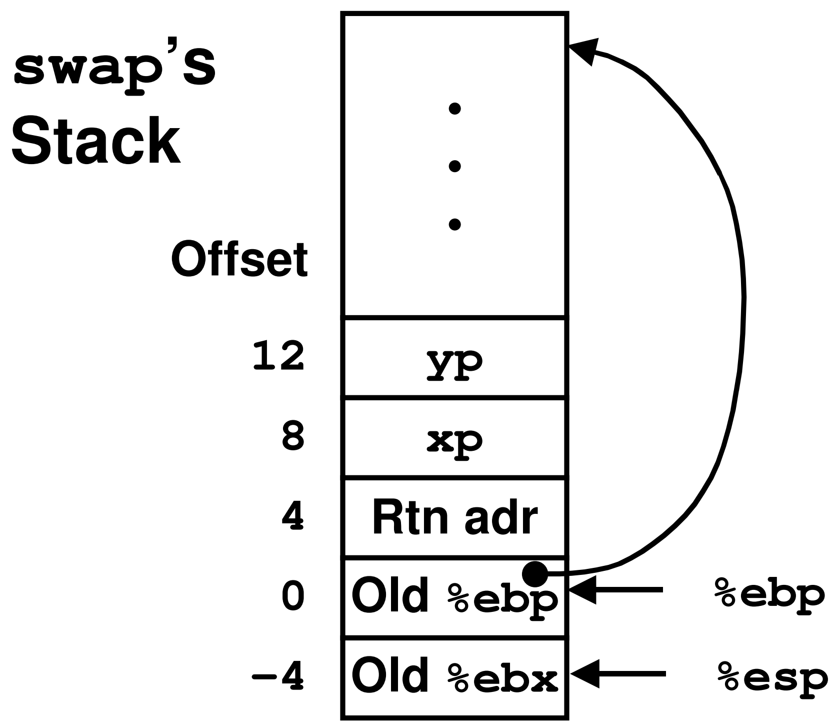
```
swap:
    pushl %ebp              # Set Up
    movl %esp,%ebp
    pushl %ebx

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

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

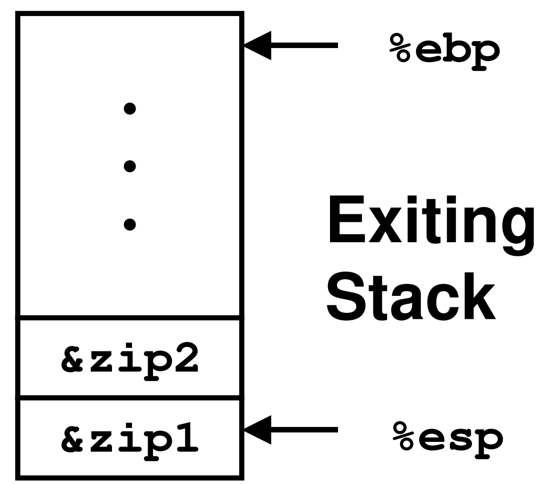
swap Setup




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

`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
   • • •
   ret
```

```
who:
   • • •
   movl 8(%ebp), %edx
   addl $91125, %edx
   • • •
   ret
```

- **Contents of register `%edx` overwritten by `who`**

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

- **Surmised by looking at code examples**

Integer Registers

- **Two have special uses**

  `%ebp`, `%esp`

- **Three managed as callee-save**

  `%ebx`, `%esi`, `%edi`

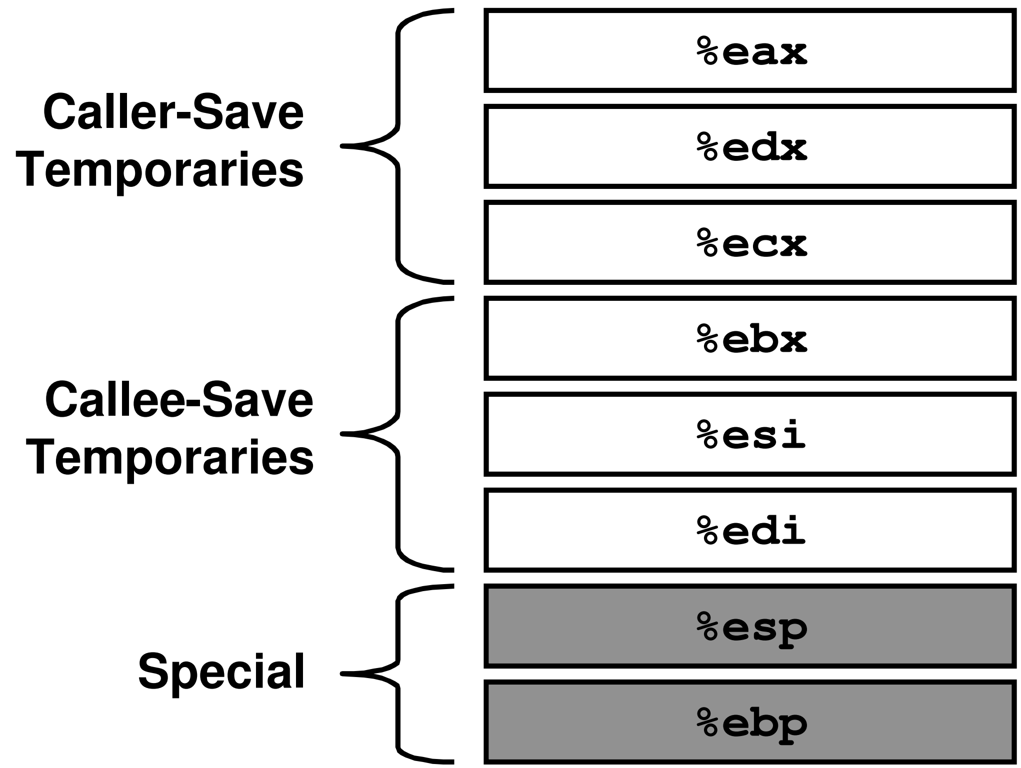
  – Old values saved on stack prior to using

- **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;
}
```

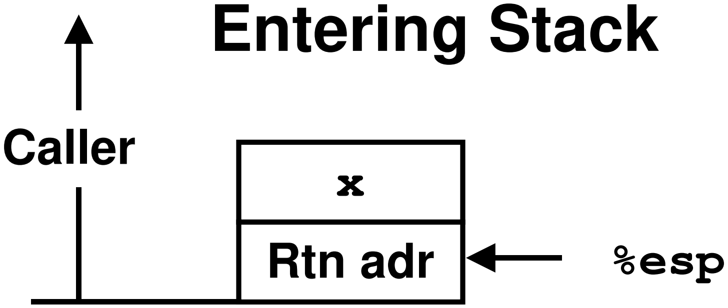
```
.globl rfact
    .type
rfact,@function
rfact:
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
    movl 8(%ebp),%ebx
    cmpl $1,%ebx
    jle .L78
    leal -1(%ebx),%eax
    pushl %eax
    call rfact
    imull %ebx,%eax
    jmp .L79
    .align 4
.L78:
    movl $1,%eax
.L79:
    movl -4(%ebp),%ebx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

Complete Assembly

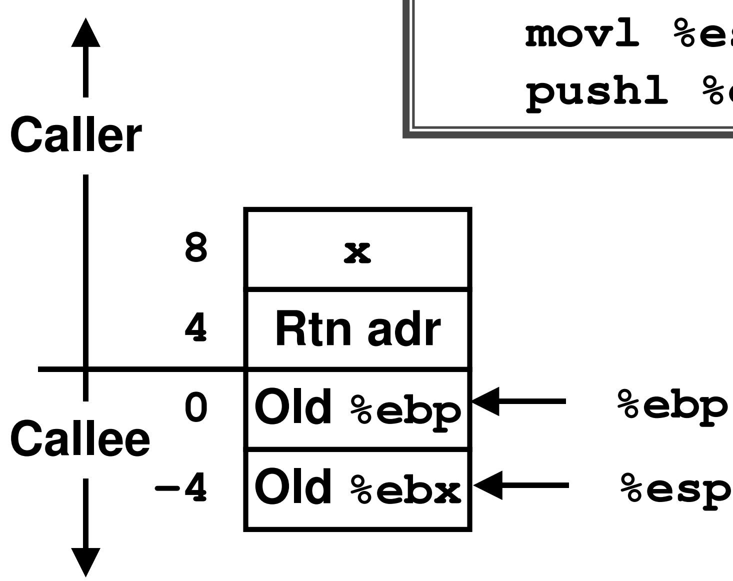
- **Assembler directives**
  - Lines beginning with "`.`"
  - Not of concern to us
- **Labels**
  - `.Lxx`
- **Actual instructions**

Rfact Stack Setup

Entering Stack




```
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:
```

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

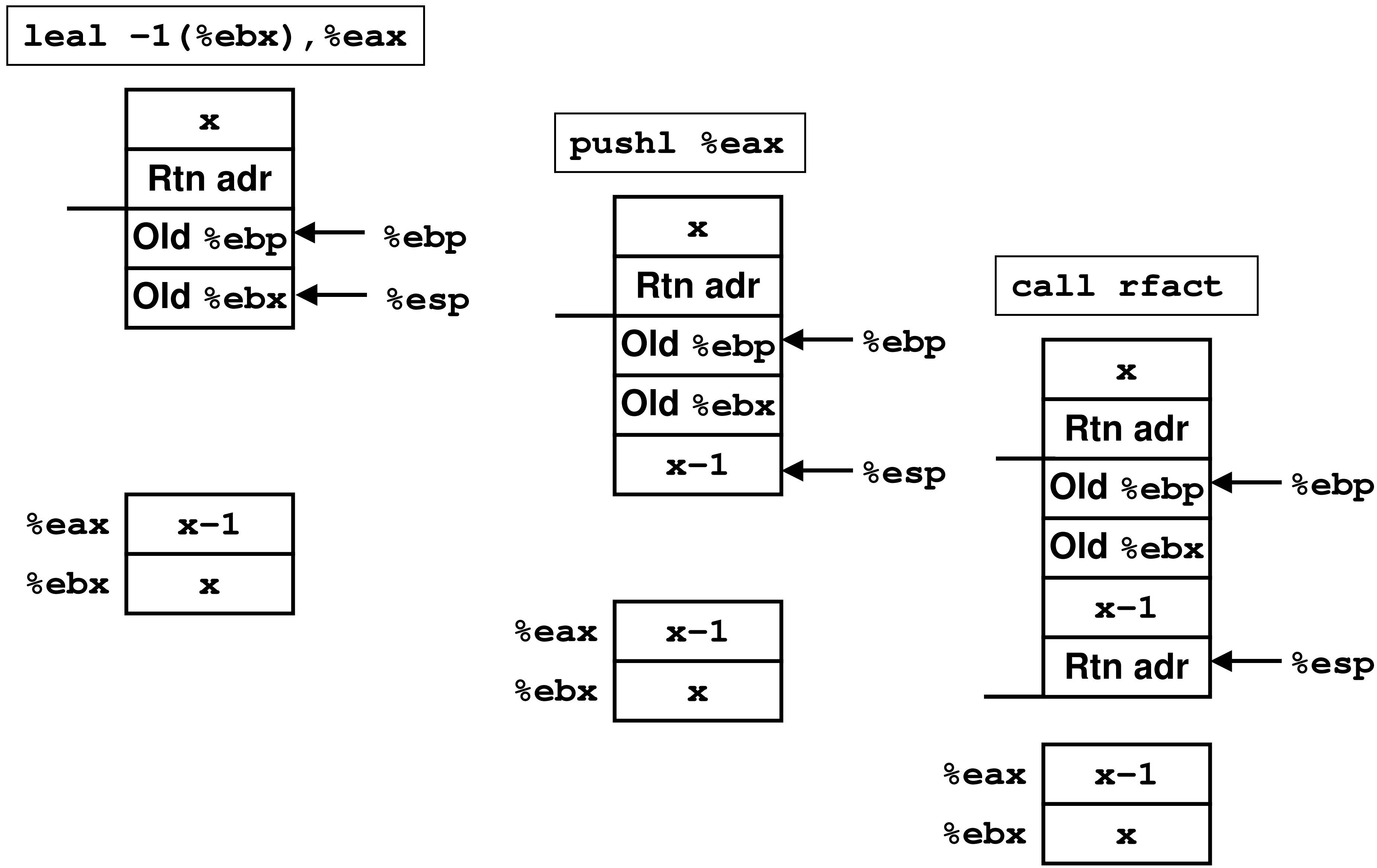
Registers

`$ebx` **Stored value of x**

`$eax`

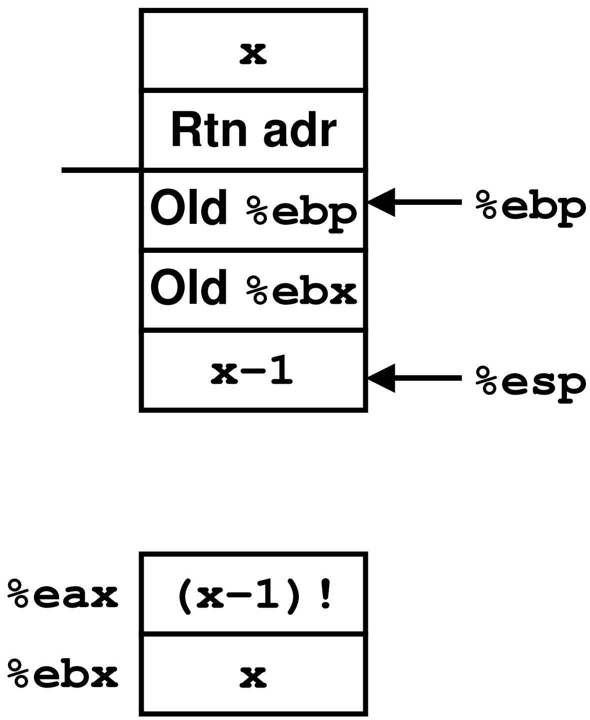
- Temporary value of **`x-1`**
- Returned value from **`rfact(x-1)`**
- Returned value from this call

Rfact Recursion

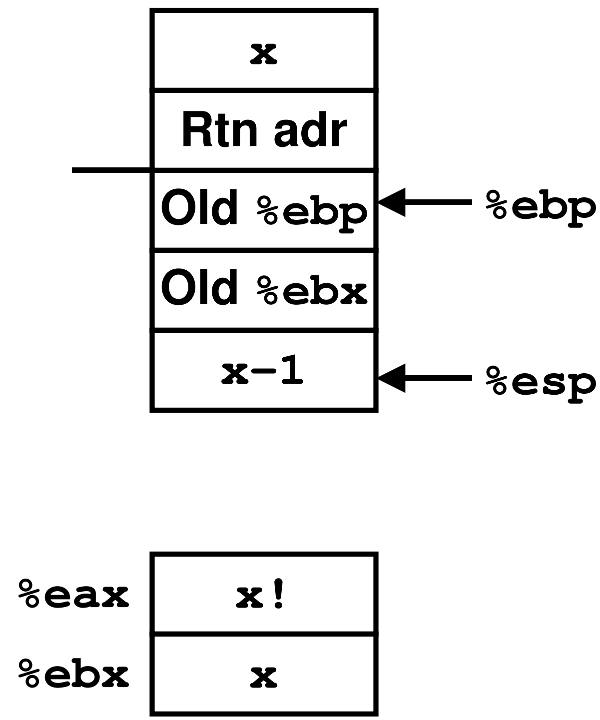


Rfact Result

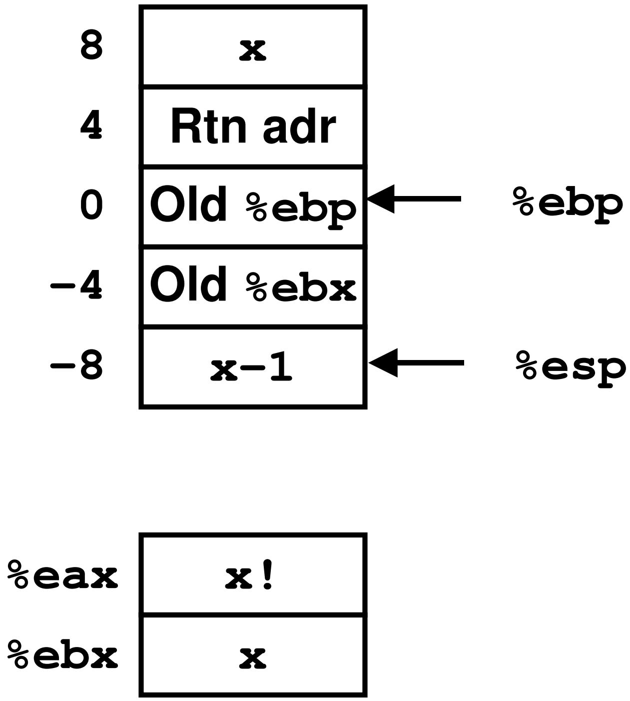
Return from Call



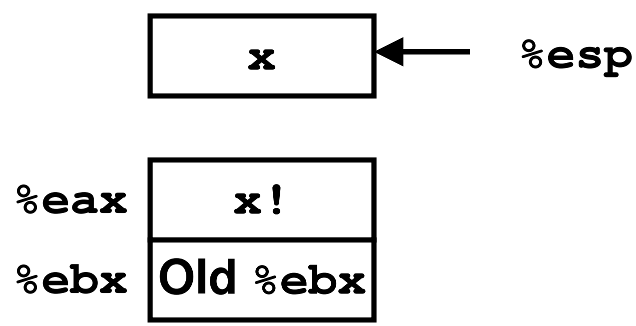

```
imull %ebx,%eax
```



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

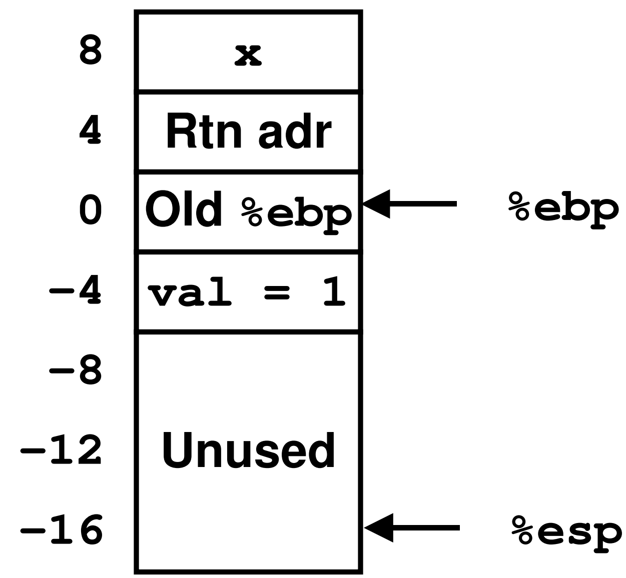
```
int sfact(int x)
{
  int val = 1;
  s_helper(x, &val);
  return val;
}
```

- **Pass pointer to update location**
- **Uses tail recursion**
  - But GCC only partially optimizes it

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;
}
```

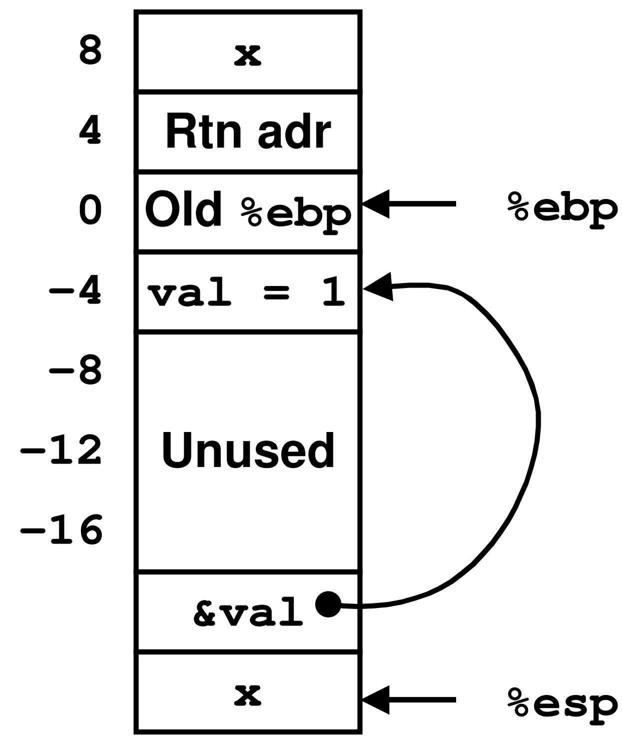
Passing Pointer

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`**
  - Use access `(%edx)` to reference memory

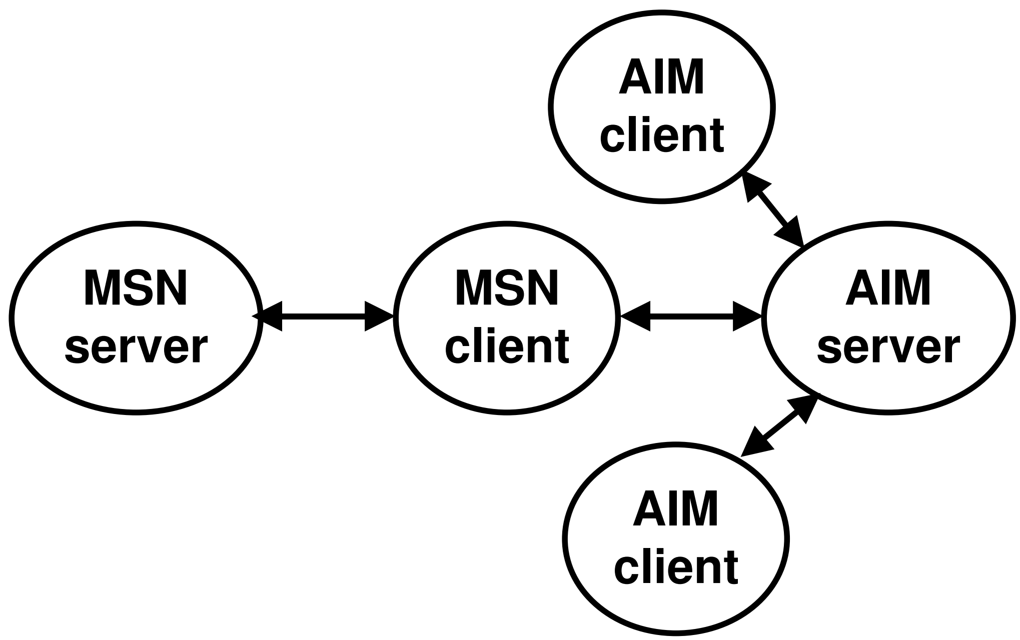
Internet worm and IM War

November, 1988

- Internet Worm attacks thousands of Internet hosts.
- How did it happen?

July, 1999

- Microsoft launches MSN Messenger (instant messaging system).
- Messenger clients can access popular AOL Instant Messaging Service (AIM) servers



Internet Worm and IM War (cont)

August 1999

- **Mysteriously, Messenger clients can no longer access AIM servers.**
- **Even though the AIM protocol is an open, published standard.**
- **Microsoft and AOL begin the IM war:**
  - AOL changes server to disallow Messenger clients
  - Microsoft makes changes to clients to defeat AOL changes.
  - At least 13 such skirmishes.
- **How did it happen?**

The Internet Worm and AOL/Microsoft War were both based on *stack buffer overflow* exploits!

- many Unix functions, such as gets() and strcpy(), do not check argument sizes.
- allows target buffers to overflow.

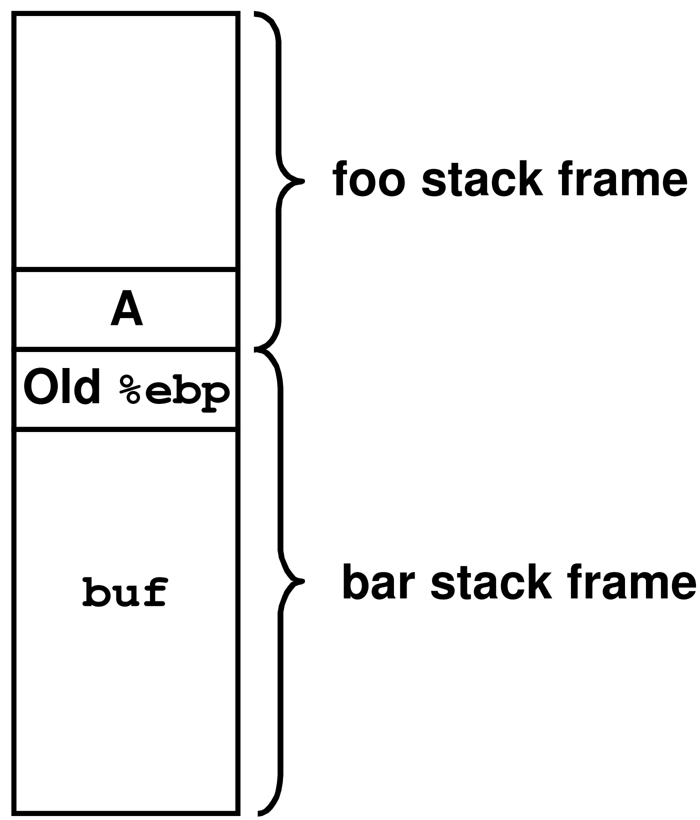
Stack buffer overflows

return address A

```
void foo(){
  bar();
  ...
}
```

```
void bar() {
  char buf[64];
  gets(buf);
  ...
}
```

Stack before call to `gets()`

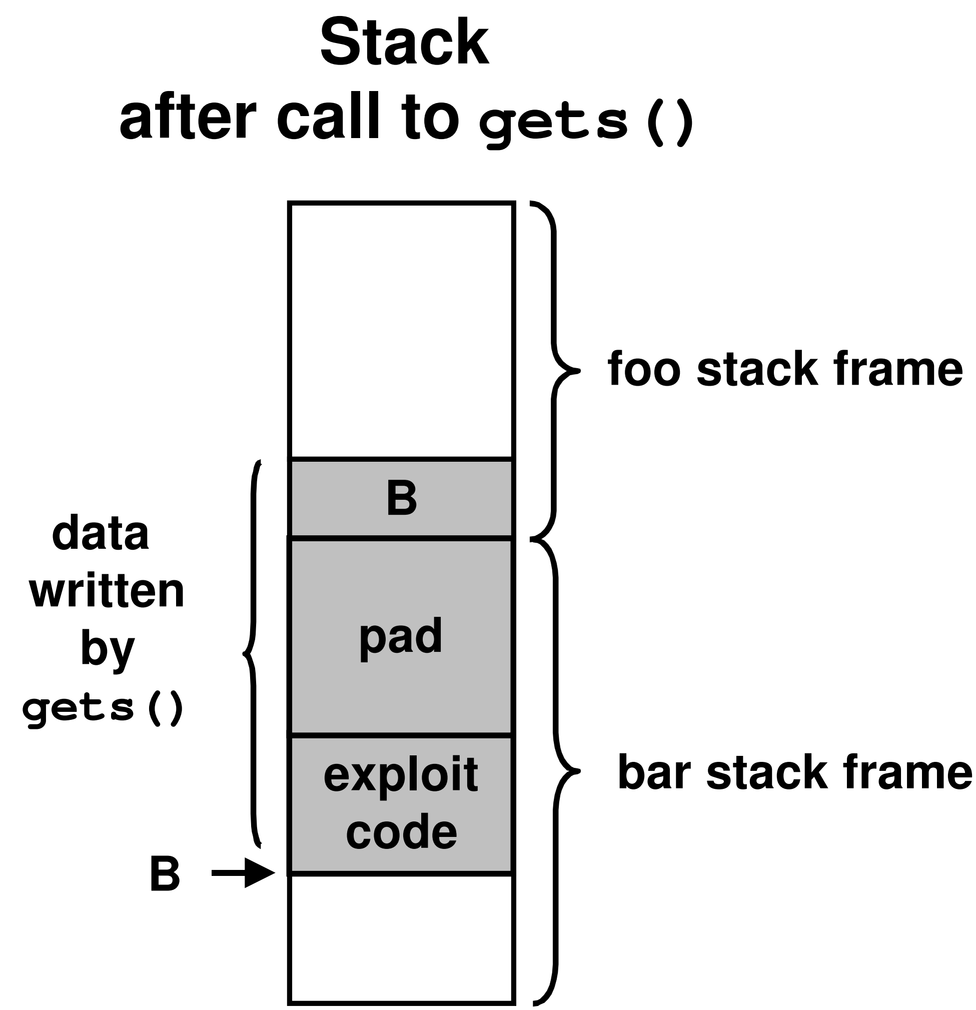


Stack buffer overflows (cont)

return address A

```
void foo(){
  bar();
  ...
}
```

```
void bar() {
  char buf[64];
  gets(buf);
  ...
}
```



When bar() returns, control passes silently to B instead of A!!

Exploits based on buffer overflows

Buffer overflow bugs allow remote machines to execute arbitrary code on victim machines.

Internet worm

- **Early versions of the finger server (fingerd) used `gets()` to read the argument sent by the client:**
  - *`finger droh@cs.cmu.edu`*
- **Worm attacked fingerd client by sending phony argument:**
  - *`finger "exploit code  padding  new return address"`*
  - **exploit code: executed a root shell on the victim machine with a direct TCP connection to the attacker.**

IM War

- **AOL exploited existing buffer overflow bug in AIM clients**
- **exploit code: returned 4-byte signature (the bytes at some location in the AIM client) to server.**
- **When Microsoft changed code to match signature, AOL changed signature location.**

Main Ideas

Stack Provides Storage for Procedure Instantiation

- Save state
- Local variables
- Any variable for which must create pointer

Assembly Code Must Manage Stack

- Allocate / deallocate by decrementing / incrementing stack pointer
- Saving / restoring register state

Stack Adequate for All Forms of Recursion

- Including multi-way and mutual recursion examples in the bonus slides.

Good programmers know the stack discipline and are aware of the dangers of stack buffer overflows.

Free Bonus Slides!

(not covered in lecture)

Topics

- how the stack supports multi-way recursion.
- how the stack supports mutual recursion.

Multi-Way Recursion

```
int r_prod
  (int from, int to)
{
  int middle;
  int prodA, prodB;
  if (from >= to)
    return from;
  middle = (from + to) >> 1;
  prodA = r_prod(from, middle);
  prodB = r_prod(middle+1, to);
  return prodA * prodB;
}
```

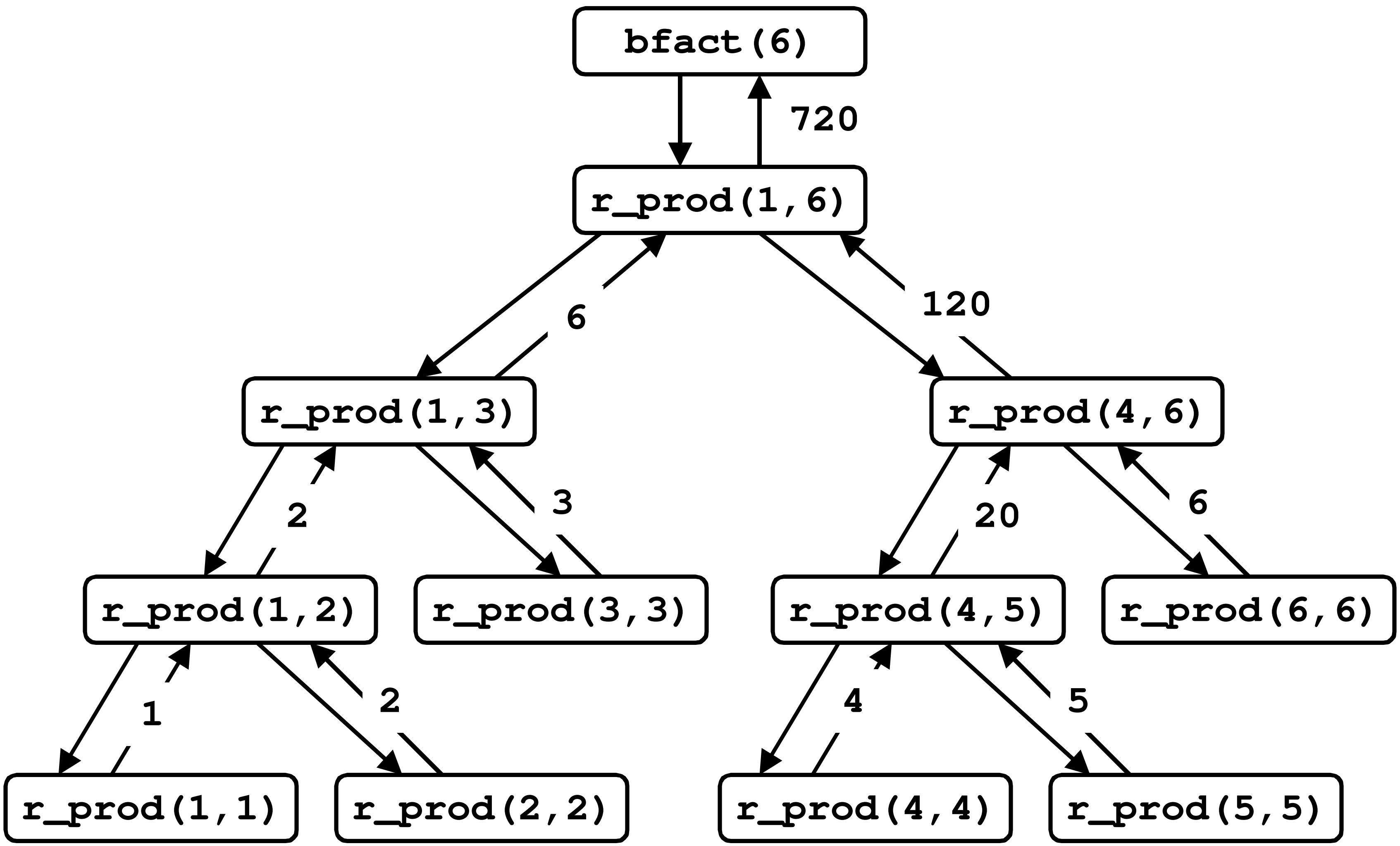
Top-Level Call

```
int bfact(int x)
{
  return r_prod(1,x);
}
```

- **Compute product** $x * (x+1) * \ldots * (y-1) * y$
- **Split into two ranges:**
  - **Left:** $x * (x+1) * \ldots * (m-1) * m$
  - **Right:** $(m+1) * \ldots * (y-1) * y$

    $m = \lfloor (x+y)/2 \rfloor$
- **No real advantage algorithmically**

Binary Splitting Example



Multi-Way Recursive Code

Stack Frame

12	from
8	to
4	Rtn Adr
0	Old $ebp
–4	Old $edi
–8	Old $esi
–12	Old $ebx

$eax

- **from**
- return values

Callee Save Regs.

$ebx	middle
$edi	to
$esi	prodA

```
_r_prod:
   • • •                      # Setup
  movl 8(%ebp),%eax           # eax = from
  movl 12(%ebp),%edi          # edi = to
  cmpl %edi,%eax              # from : to
  jge L8                      # if >= goto done
  leal (%edi,%eax),%ebx # from + to
  sarl $1,%ebx                # middle
  pushl %ebx                  # 2nd arg: middle
  pushl %eax                  # 1st arg: from
  call _r_prod                # 1st call
  pushl %edi                  # 2nd arg: to
  movl %eax,%esi              # esi = ProdA
  incl %ebx                   # middle + 1
  pushl %ebx                  # ... 1st arg
  call _r_prod                # 2nd call
  imull %eax,%esi             # ProdA * ProdB
  movl %esi,%eax              # Return value
L8:                         # done:
   • • •                      # Finish
```

Multi-Way Recursive Code Finish

12	from
8	to
4	Rtn Adr
0	Old $ebp
–4	Old $edi
–8	Old $esi
–12	Old $ebx
–16	Arg 2
–20	Arg 1

```
L8:                          # done:
   leal -12(%ebp),%esp # Set Stack Ptr
   popl %ebx           # Restore %ebx
   popl %esi           # Restore %esi
   popl %edi           # Restore %edi
   movl %ebp,%esp      # Restore %esp
   popl %ebp           # Restore %ebp
   ret                 # Return
```

Stack

- After making recursive calls, still has two arguments on top

Finishing Code

- Moves stack pointer to start of saved register area
- Pops registers

Mutual Recursion

Top-Level Call

```
int lrfact(int x)
{
  int left = 1;
  return
   left_prod(&left, &x);
}
```

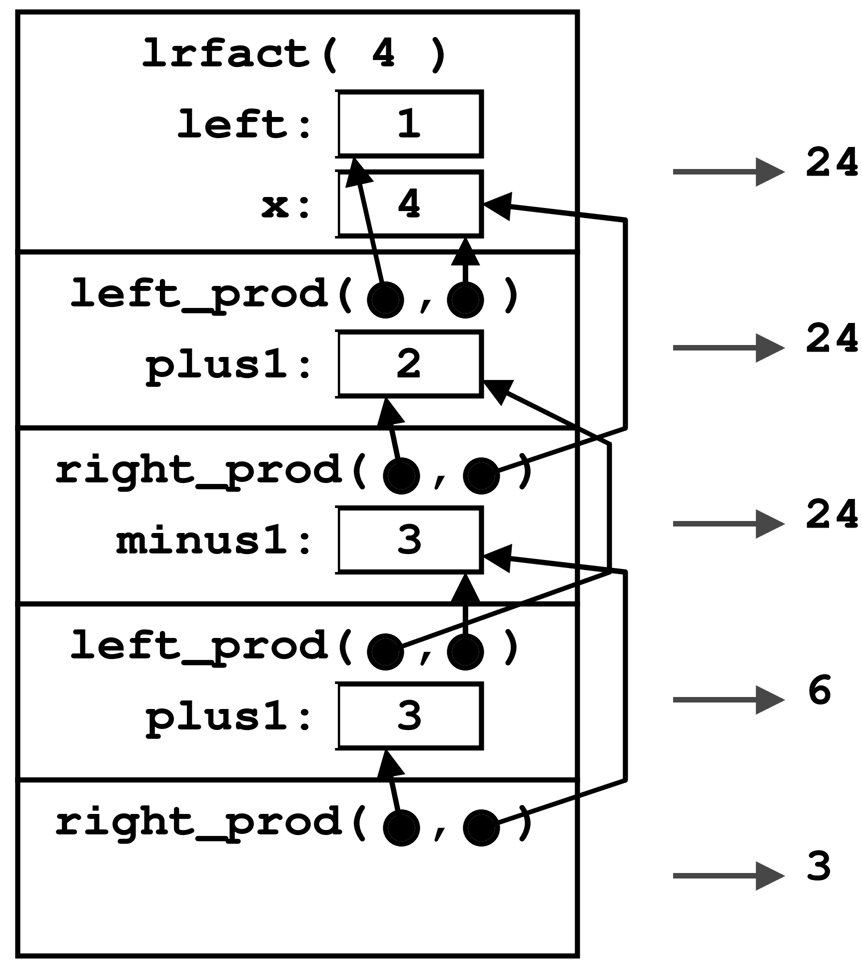
```
int left_prod
(int *leftp, int *rightp)
{
  int left = *leftp;
  if (left >= *rightp)
    return left;
  else {
    int plus1 = left+1;
    return left *
      right_prod(&plus1, rightp);
  }
}
```

```
int right_prod
(int *leftp, int *rightp)
{
  int right = *rightp;
  if (*leftp == right)
    return right;
  else {
    int minus1 = right-1;
    return right *
      left_prod(leftp, &minus1);
  }
}
```

Mutually Recursive Execution Example

Calling

- **Recursive routines pass two arguments**
  - Pointer to own local variable
  - Pointer to caller's local variable

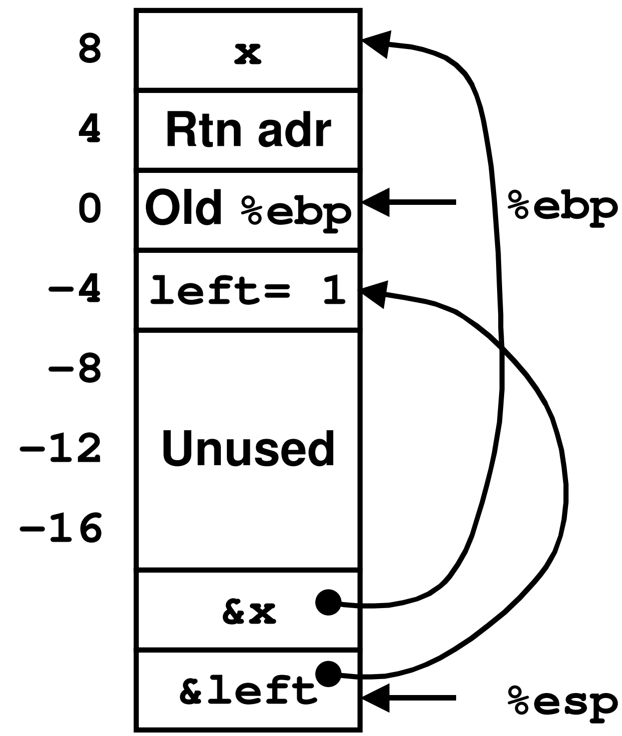


Implementation of `lrfact`

Call to Recursive Routine

```
int left = 1;
return left_prod(&left, &x);
```

Stack at time of call



Code for Call

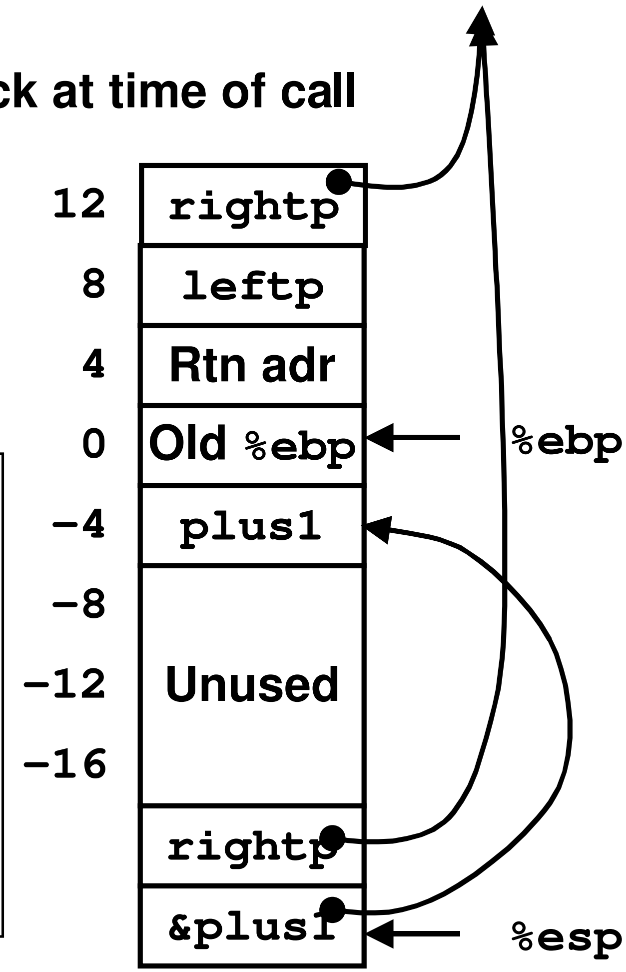
```
leal 8(%ebp),%edx # edx = &x
pushl %edx        # push &x
leal -4(%ebp),%eax# eax = &left
pushl %eax        # push &left
call _left_prod   # Call
```

Implementation of `left_prod`

Call to Recursive Routine

```
int plus1 = left+1;
return left *
  right_prod(&plus1, rightp);
```

Stack at time of call




```
# %ebx holds left
# %edx holds rightp
leal 1(%ebx),%ecx   # left+1
movl %ecx,-4(%ebp)  # Store in plus1
pushl %edx          # Push rightp
leal -4(%ebp),%eax  # &plus1
pushl %eax          # Push &plus1
call _right_prod    # Call
```

Tail Recursion

Tail Recursive Procedure

```
int t_helper
  (int x, int val)
{
  if (x <= 1)
    return val;
  return
    t_helper(x-1, val*x);
}
```

General Form

```
t_helper(x, val)
{
   • • •
  return
   t_helper(Xexpr, Vexpr)
}
```

Top-Level Call

```
int tfact(int x)
{
  return t_helper(x, 1);
}
```

Form

- Directly return value returned by recursive call

Consequence

- Can convert into loop

Removing Tail Recursion

Optimized General Form

```
t_helper(x, val)
{
 start:
   • • •
  val = Vexpr;
  x = Xexpr;
  goto start;
}
```

Resulting Code

```
int t_helper
  (int x, int val)
{
 start:
  if (x <= 1)
    return val;
  val = val*x;
  x = x-1;
  goto start;
}
```

Effect of Optimization

- Turn recursive chain into single procedure
- No stack frame needed
- Constant space requirement
  – Vs. linear for recursive version

Generated Code for Tail Recursive Proc.

Optimized Form

```
int t_helper
  (int x, int val)
{
 start:
  if (x <= 1)
    return val;
  val = val*x;
  x = x-1;
  goto start;
}
```

Code for Loop

```
  # %edx = x
  # %ecx = val
L53:                  # start:
  cmpl $1,%edx           # x : 1
  jle L52                # if <= goto done
  movl %edx,%eax         # eax = x
  imull %ecx,%eax        # eax = val * x
  decl %edx              # x--
  movl %eax,%ecx         # val = val * x
  jmp L53             # goto start
L52:                     # done:
```

Registers

```
$edx  x
$ecx val
```