15-213

"The course that gives CMU its Zip!"

Machine-Level Programming III: Procedures Sept. 15, 1998

Topics

- Stack-based languages
- Stack frames
- Register saving conventions
- Optimizing to avoid stack frame
- Creating pointers to local variables

Procedure Control Flow

Maintain Return Address in Designated Register (`$26`)

Procedure call:

- `bsr $26, label` Save return addr in `$26`, branch to *`label`*
- `jsr $26, (Ra)` Save return addr in `$26`, jump to address in `Ra`

Return Address Value

- Address of calling instruction + 4

```
0x100: bsr $26, label
0x104: addq $0, $16, $0   # Following instruction
```

- Example `bsr` will set `$26` to `0x104`

Procedure return:

- `ret $31, ($26)` Jump to address in `$26`

Call & Return Code

C Code

```
long int caller()
{
  • • •
  return callee();
}

long int callee()
{
  return 5L;
}
```

Annotated Assembly

```
caller:
          • • •
# save return addr (0x804) in $26
# branch to callee (0x918)
0x800     bsr $26,callee
          • • •
callee:
# return value = 5
0x918     bis $31,5,$0
# jump to addr in $26
0x91c     ret $31,($26),1
```

For Given Procedure Call

- Procedure in which call is made is the "*Caller*"
- Procedure being called is the "*Callee*"

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

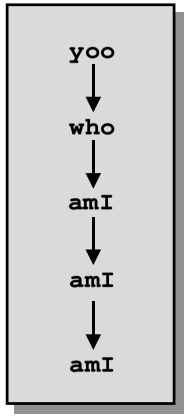
Code Structure

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

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

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

Call Chain



- Procedure `amI` recursive

Alpha Stack Structure

Stack Growth

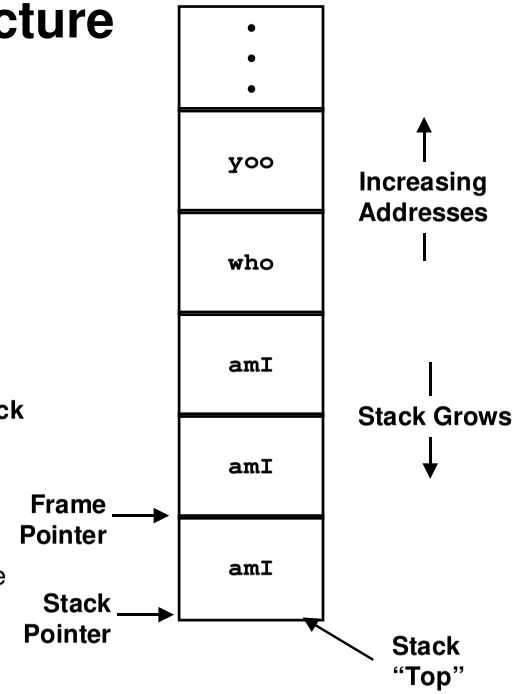
- Toward lower addresses
- Drawn with "top" at bottom

Stack Pointer

- Address of top element on stack
- Use register $30

Frame Pointer

- Top element from caller stack frame
- Usually "virtual"
  - Do not allocate explicit register
  - Computed as offset relative to stack pointer



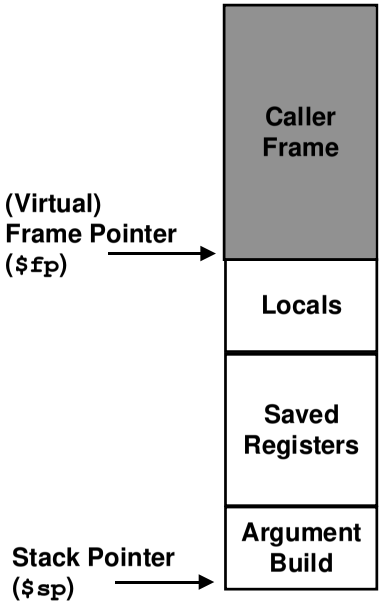
Alpha Stack Frame

Stack Frame ("Top" to Bottom)

- Parameters to called functions
  - Only if too many for registers
- Saved register context
- Storage for local variables

Size Requirements

- Saved state area must be multiple of 16 bytes
- Local area must be multiple of 16 bytes



Alpha Register Convention

General Purpose Registers

- 32 total
- Store integers and pointers
- Fast access: 2 reads, 1 write in single cycle

Usage Conventions

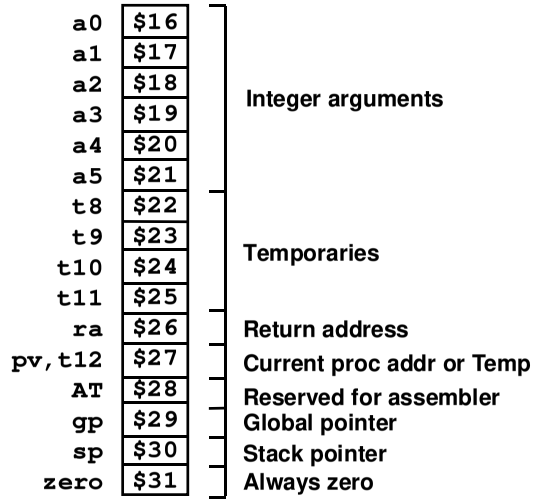
- Established as part of architecture
- Used by all compilers, programs, and libraries

v0	$0	Return value from integer functions
t0	$1	Temporaries (not preserved across procedure calls)
t1	$2	
t2	$3	
t3	$4	
t4	$5	
t5	$6	
t6	$7	
t7	$8	
s0	$9	Callee saved
s1	$10	
s2	$11	
s3	$12	
s4	$13	
s5	$14	
s6, fp	$15	Frame pointer, or callee saved

Registers (cont.)

Important Ones for Now

- `$0` **Return Value**
  - Also used as temp.
- `$1` **Temporary**
  - Unsafe
- `$9…$11` **Callee Save**
  - "Safe" temporaries
- `$16…$17` **Arguments**
- `$26` **Return address**
- `$29` **Global Pointer**
  - Access to global vars.
- `$30` **Stack Pointer**
- `$31` **Constant 0**



Register Saving Conventions

When procedure `yoo` calls `who`:

- `yoo` **is the *caller*,** `who` **is the *callee***

Can Register be Used for Temporary Storage?

```
yoo:
    bis $31, 17, $1
    bsr $26, who
    addq $1, $0, $0
    ret $31, ($26)
```

```
who:
    bis $31, 255, $1
    s4addq $1, $1, $0
    ret $31, ($26)
```

- **Contents of registers `$1` and `$26` overwritten by `who`**

Conventions

- **"Caller Save"**
  - Caller saves temporary in its frame before calling
- **"Callee Save"**
  - Callee saves temporary in its frame before using

Caller Save Version

"Caller Save" Temporary Registers:

- **not guaranteed to be preserved across procedure calls**
- **can be immediately overwritten by a procedure without first saving**
- **if `yoo` wants to preserve a caller-save register across a call to `who`:**
  - **save it on the stack before calling `who`**
  - **restore after `who` returns**

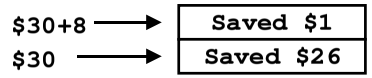
```
yoo:
    • • • # make frame
    bis $31, 17, $1
    # save $26, $1
    stq $26, 0($sp)
    stq $1, 8($sp)
    bsr $26, who
    # restore $26, $1
    ldq $1, 8($sp)
    ldq $26, 0($sp)
    addq $1, $0, $0
    • • • # remove frame
    ret $31, ($26)
```

```
who:
    bis $31, 255, $1
    s4addq $1, $1, $0
    ret $31, ($26)
```


Stack Frame for Caller Save Version

Stack Frame for Procedure `yoo`

- 16 bytes total



- Allocated by decrementing stack pointer

  `lda $sp, -16($sp)`
- Deallocated by incrementing stack pointer

  `addq $sp, 16($sp)`

Stack Frame for Procedure `who`

- None required
- "Leaf" procedure

```
yoo:
    # make frame
    lda $sp, -16($sp)

    • • •

    # remove frame
    addq $sp, 16, $sp
    ret $31, ($26)
```

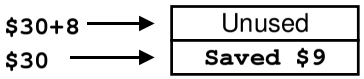
Callee Save Version

Callee Save

- **Must be preserved across procedure calls**
- **If `who` wants to use a callee-save register**
  - Save it on stack upon procedure entry
  - Restore when returning

Stack Frame for Procedure `who`

- 16 bytes total
- To meet size requirements




```
who:
    # make frame
    lda $sp, -16($sp)
    # save $9
    stq $9, 0($sp)
    bis $31, 255, $9
    s4addq $9, $9, $0
    # restore $9
    ldq $9, 0($sp)
    # remove frame
    addq $sp, 16, $sp
    ret $31, ($26)
```


Callee Save Version (Cont.)

Stack Frame for Procedure `yoo`

- 16 bytes total

- Must save **`$9`**
  - Preserve for *its* caller
- Must save **`$26`**
  - Will get overwritten by **`bsr`** instruction

```
yoo:
    # make frame
    lda $sp, 16($sp)
    # save $9, $26
    stq $26, 0($sp)
    stq $9, 8($sp)
    bis $31, 17, $9
    bsr $26, who
    addq $9, $0, $0
    # restore $9, $26
    ldq $26, 0($sp)
    ldq $9, 8($sp)
    # remove frame
    addq $sp, 16($sp)
    ret $31, ($26)
```


Actual Form

Procedure `yoo` uses callee save

```
yoo:
    # make frame
    lda $sp, 16($sp)
    # save $9, $26
    stq $26, 0($sp)
    stq $9, 8($sp)
    bis $31, 17, $9
    bsr $26, who
    addq $9, $0, $0
    # restore $9, $26
    ldq $26, 0($sp)
    ldq $9, 8($sp)
    # remove frame
    addq $sp, 16($sp)
    ret $31, ($26)
```

Procedure `who` uses only caller save

- **Doesn't need to save anything since makes no calls**
- **Doesn't need any stack frame**

```
who:
    bis $31, 255, $1
    s4addq $1, $1, $0
    ret $31, ($26)
```


Procedure Categories

Leaf procedures that do not use stack

- **Do not call other procedures**
- **Can fit all temporaries in caller-save registers**

Leaf procedures that use stack

- **Do not call other procedures**
- **Need stack for temporaries**

Non-leaf procedures

- **Must use stack**
- **at the very least, to save the return address `$26`**
- **Also when need to store array**

Recursive Factorial

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

Complete Assembly

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

```
     .align 3
     .globl rfact
     .ent rfact
rfact:
     ldgp $29,0($27)
rfact..ng:
     lda $30,-16($30)
     .frame $30,16,$26,0
     stq $26,0($30)
     stq $9,8($30)
     .mask 0x4000200,-16
     .prologue 1
     bis $16,$16,$9
     cmple $9,1,$1
     bne $1,$34
     subq $9,1,$16
     bsr $26,rfact..ng
     mulq $0,$9,$0
     br $31,$35
     .align 4
$34:
     bis $31,1,$0
$35:
     ldq $26,0($30)
     ldq $9,8($30)
     addq $30,16,$30
     ret $31,($26),1
     .end rfact
```


Object Vs. Assembly

```
                    rfact:
0x120001210: ldah   gp, 8192(r27)
0x120001214: lda    gp, 28304(gp)

0x120001218: lda    sp, -16(sp)

0x12000121c: stq    r26, 0(sp)
0x120001220: stq    r9, 8(sp)


0x120001224: bis    r16, r16, r9
0x120001228: cmple  r9, 0x1, r1
0x12000122c: bne    r1, 0x120001240
0x120001230: subq   r9, 0x1, r16
0x120001234: bsr    r26, 0x120001218(r31)
0x120001238: mulq   r0, r9, r0
0x12000123c: br     r31, 0x120001244


0x120001240: bis    r31, 0x1, r0

0x120001244: ldq    r26, 0(sp)
0x120001248: ldq    r9, 8(sp)
0x12000124c: addq   sp, 0x10, sp
0x120001250: ret    r31, (r26), 1
```

```
     .align 3
     .globl rfact
     .ent rfact
rfact:
     ldgp $29,0($27)

rfact..ng:
     lda $30,-16($30)
     .frame $30,16,$26,0
     stq $26,0($30)
     stq $9,8($30)
     .mask 0x4000200,-16
     .prologue 1
     bis $16,$16,$9
     cmple $9,1,$1
     bne $1,$34
     subq $9,1,$16
     bsr $26,rfact..ng
     mulq $0,$9,$0
     br $31,$35
     .align 4
$34:
     bis $31,1,$0
$35:
     ldq $26,0($30)
     ldq $9,8($30)
     addq $30,16,$30
     ret $31,($26),1
     .end rfact
```


Rfact Stack

Stack Frame

$26

– Return pointer

$9

– Callee save

Global Pointer

- **Set on first entry to `rfact`**
- **Recursive calls don't need to change**
  - Enter at **`rfact..ng`**

Prologue: Set Up Frame

```
rfact:
    ldgp $29,0($27)
rfact..ng:
    lda $30,-16($30)
    stq $26,0($30)
    stq $9,8($30)
```

Epilogue: Undo Frame

```
$35:
    ldq $26,0($30)
    ldq $9,8($30)
    addq $30,16,$30
    ret $31,($26),1
```


Rfact Body

```
  • • •                 # Prologue
  bis $16,$16,$9        #  $9 = x
  cmple $9,1,$1         #  if (x <= 1)
  bne $1,$34            #   then goto R1
  subq $9,1,$16         #  $16 = x-1
  bsr $26,rfact..ng     #  rfact(x-1)
  mulq $0,$9,$0         #  rval * x
  br $31,$35            #  goto Epilogue
$34:                    # R1:
  bis $31,1,$0          #  Return 1
$35:                    # Epilogue:
```

Registers

$0

– **`rval`** from recursive call

– Return value from this call

$16

– Initially argument **`x`**

– Must set to **`x-1`** when making call

$9

– Hold copy of **`x`**

– To use after recursive call returns

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

Tail Recursion

Tail Recursive Procedure

```
long int t_helper
  (long int x, long 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

```
long int tfact(long 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

```
long int t_helper
  (long int x, long 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

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

Assembly

```
t_helper:
    bis $17,$17,$0    #  $0 = val
$39:                  # start:
    cmple $16,1,$1    #  if x<=1
    bne $1,$37        #  goto done
    mulq $0,$16,$1    #  temp = val*x
    subq $16,1,$16    #  x--
    bis $1,$1,$0      #  val = temp
    br $31,$39        #  goto start
$37:                  # done:
    ret $31,($26),1   #  Return
```


Multi-Way Recursion

```
long int r_prod
  (long int from, long int to)
{
  long int middle;
  long 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;
}
```

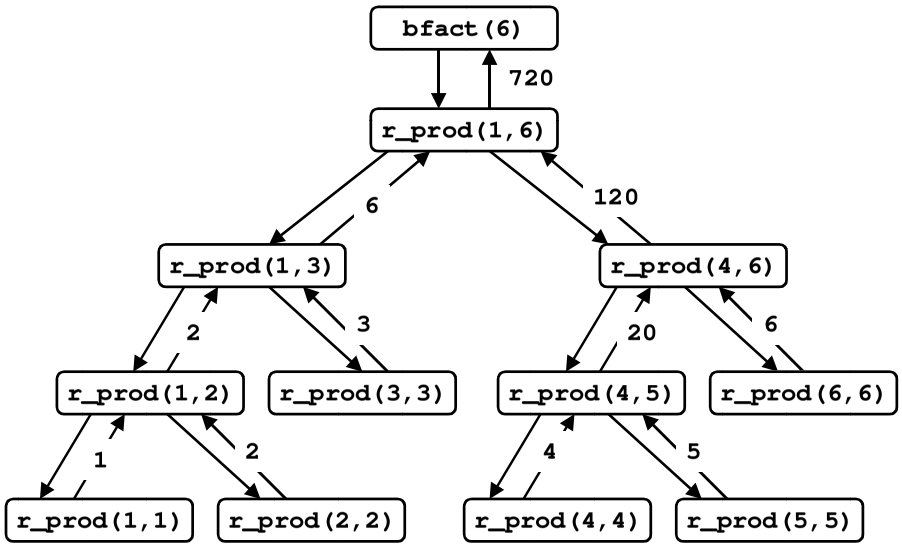
Top-Level Call

```
long int bfact
  (long 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

Saved $11
Saved $10
Saved $9
Saved $26

$26
- Return pointer

$9
- Callee save
- Used to hold **middle**

$10
- Callee save
- Used to hold **prodA**

$11
- Callee save
- Used to hold **to**

```
r_prod..ng:
  • • •              # Prologue
  bis $16,$16,$0     # $0 = from
  bis $17,$17,$11    # $11 = to
  # if !(from<to) goto Epilogue
  cmplt $0,$11,$1
  beq $1,$47
  addq $0,$11,$9
  sra $9,1,$9        # $9 = middle
  bis $9,$9,$17
  # r_prod(from, middle)
  bsr $26,r_prod..ng
  bis $0,$0,$10      # prodA
  addq $9,1,$16      # middle+1
  bis $11,$11,$17
  # r_prod(middle+1, to)
  bsr $26,r_prod..ng
  mulq $10,$0,$0     # prodA*prodB
$47:  • • •          # Epilogue
```


Pointer Code

Recursive Procedure

```
void s_helper
  (long int x,
   long int *accum)
{
  if (x <= 1)
    return;
  else {
    *accum *= x;
    s_helper
        (x-1, accum);
  }
}
```

Top-Level Call

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

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

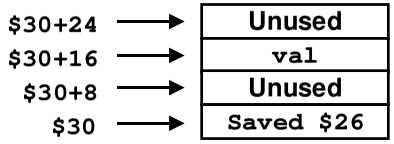
Creating Pointer

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

Body for `sfact`

```
  • • •              # Prologue
  bis $31,1,$1
  stq $1,16($30)     # val = 1
  addq $30,16,$17    # $17 = &val
  bsr $26,s_helper..ng
  ldq $0,16($30)     # return val
  • • •              # Epilogue
```

Using Stack for Local Variable



- **Variable `val` must be stored on stack**
  - Need to create pointer to it
- **Compute pointer as `$sp+16`**
- **Store in `$17` to pass as second argument**

Using Pointer

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

```
  • • •
ldq $1,0($17)    # $1 = *accum
mulq $16,$1,$1   # *accum * x
stq $1,0($17)    # Update *accum
  • • •
```

- Register `$16` holds `x`
- Register `$17` holds `accum`

Mutual Recursion

Top-Level Call

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

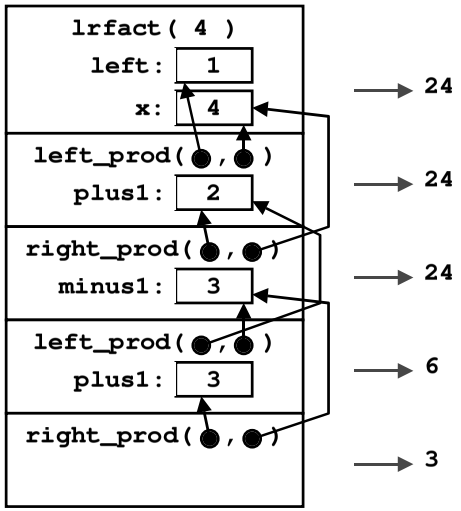
```
long int left_prod
(long int *leftp, long int *rightp)
{
  long int left = *leftp;
  if (left >= *rightp)
    return left;
  else {
    long int plus1 = left+1;
    return left *
      right_prod(&plus1, rightp);
  }
}
```

```
long int right_prod
(long int *leftp, long int *rightp)
{
  long int right = *rightp;
  if (*leftp == right)
    return right;
  else {
    long 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

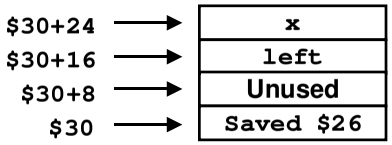


Implementation of `lrfact`

Call to Recursive Routine

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

Stack Frame



Code for Call

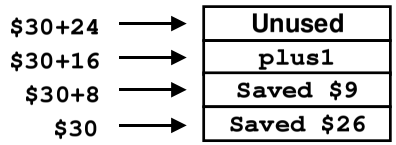
```
stq $16,24($30)  # x on stack
bis $31,1,$1
stq $1,16($30)   # left on stack
addq $30,16,$16  # &left
addq $30,24,$17  # &x
bsr $26,left_prod..ng
```

Implementation of `left_prod`

Call to Recursive Routine

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

Stack Frame



Code for Call

```
ldq $9,0($16)    # left = *leftp
 • • •
addq $9,1,$1     # left+1
stq $1,16($30)   # plus1 on stack
addq $30,16,$16  # &plus1
 # rightp still in $17
jsr $26,right_prod
```


Main Ideas

Can Sometimes Avoid Allocating Stack Frame

- Leaf procedures
- Tail recursion converted into loop

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

- Multi-way
- Mutual