Lec 12: Register Calling

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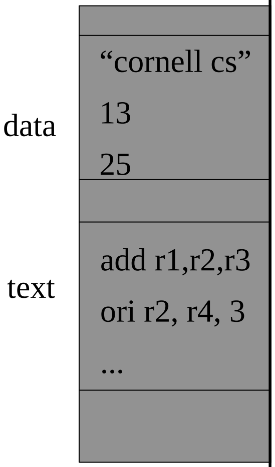
Announcements

- PA 1 is due this Wed
- Ask us questions if in doubt

Program Layout

- Programs consist of segments used for different purposes
  - – Text: holds instructions
  - – Data: holds statically allocated program data such as variables, strings, etc.



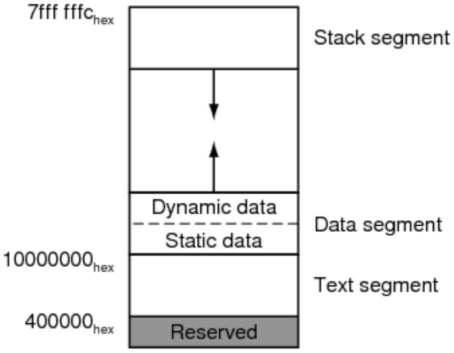
data

“cornell cs”
13
25

text

add r1,r2,r3
ori r2, r4, 3
...

When you run the program



Assembling Programs

```
        .text
        .ent main
main: la $4, Larray
        li $5, 15
        ...
        li $4, 0
        jal exit
        .end main
        .data
Larray:
        .long 51, 491, 3991
```

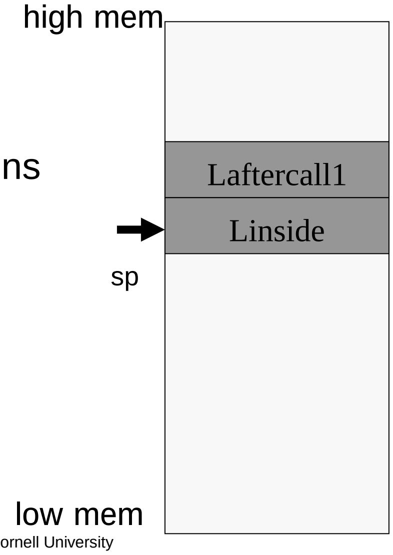
- Programs consist of a mix of instructions, pseudo-ops and assembler directives
- Assembler lays out binary values in memory based on directives

Procedures

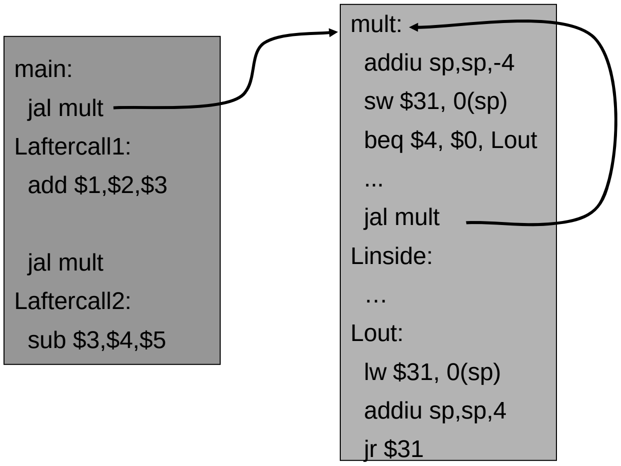
- Enable code to be reused by allowing code snippets to be invoked
- Will need a way to
  - call the routine
  - pass arguments to it
    - fixed length
    - variable length
    - Recursive calls
  - return value to caller
  - manage registers

Call Stacks

- A call stack contains activation records (aka stack frames)
- Each activation record contains
  - the return address for that invocation
  - the local variables for that procedure



Take 3: JAL/JR with Activation Records



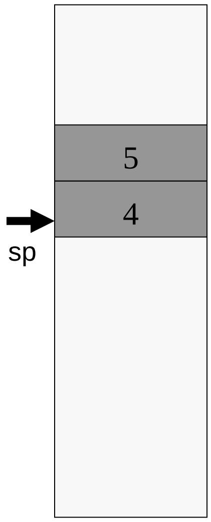
```
main:
  jal mult
Laftercall1:
  add $1,$2,$3

  jal mult
Laftercall2:
  sub $3,$4,$5
```

```
mult:
  addiu sp,sp,-4
  sw $31, 0(sp)
  beq $4, $0, Lout
  ...
  jal mult
Linside:
  …
Lout:
  lw $31, 0(sp)
  addiu sp,sp,4
  jr $31
```

- Stack used to save and restore contents of $31

Many Arguments

```
main:
  li a0, 0
  li a1, 1
  li a2, 2
  li a3, 3
  addiu sp,sp,-8
  li $8, 4
  sw $8, 0(sp)
  li $8, 5
  sw $8, 4(sp)
  jal subf
  // result in v0
```



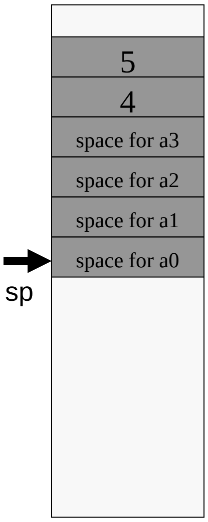
- What if there are more than 4 arguments?
- Use the stack for the additional arguments
  - “spill”

Variable Length Arguments

- Best to use an (initially confusing but ultimately simpler) approach:
  - Pass the first four arguments in registers, as usual
  - Pass the rest on the stack
  - Reserve space on the stack for all arguments, including the first four
- Simplifies functions that use variable-length arguments
  - Store a0-a3 on the slots allocated on the stack, refer to all arguments through the stack

Register Layout on Stack

```
main:
  li a0, 0
  li a1, 1
  li a2, 2
  li a3, 3
  addiu sp,sp,-24
  li $8, 4
  sw $8, 16(sp)
  li $8, 5
  sw $8, 20(sp)
  jal subf
  // result in v0
```



5

4

space for a3

space for a2

space for a1

space for a0

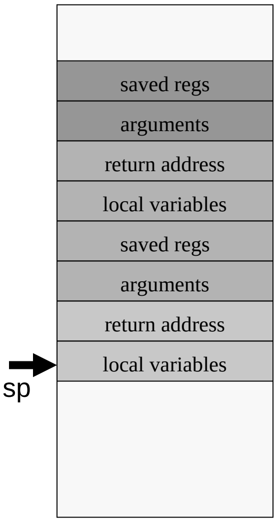
sp

- First four arguments are in registers
- The rest are on the stack
- There is room on the stack for the first four arguments, just in case

Globals and Locals

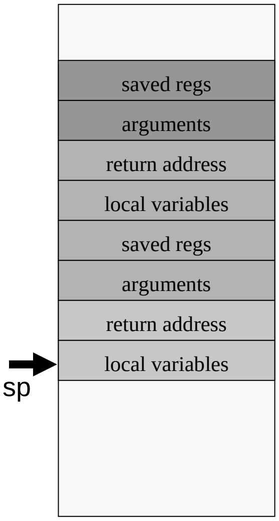
- Global variables are allocated in the “data” region of the program
  - Exist for all time, accessible to all routines
- Local variables are allocated within the stack frame
  - Exist solely for the duration of the stack frame
- Dangling pointers are pointers into a destroyed stack frame
  - C lets you create these, Java does not
  - int *foo() { int a; return &a; }

Frame Layout on Stack



```
blue() {
   pink(0,1,2,3,4,5);
}
pink() {
    orange(10,11,12,13,14);
}
```

Buffer Overflows

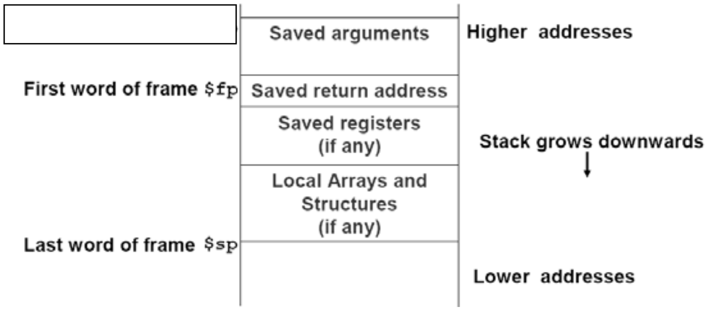


```
blue() {
   pink(0,1,2,3,4,5);
}
pink() {
    orange(10,11,12,13,14);
}
orange() {
          char buf[100];
          gets(buf); // read string, no check
}
```

Frame Pointer

- It is sometimes cumbersome to keep track of location of data on the stack
  – The offsets change as new values are pushed onto and popped off of the stack
- Keep a pointer to the top of the stack frame
  – Simplifies the task of referring to items on the stack
- A frame pointer, $30, aka fp
  – Value of sp upon procedure entry
  – Can be used to restore sp on exit

Frame Pointer



Saved arguments

Higher addresses

First word of frame $fp

Saved return address

Saved registers (if any)

Stack grows downwards

Local Arrays and Structures (if any)

Last word of frame $sp

Lower addresses

Register Usage

- Suppose a routine would like to store a value in a register

- Two options: caller-save and callee-save

- What is tradeoff?
  - If all caller save, could be waste
  - If all callee save, could be waste

- MIPS calling convention supports both
  - Callee-save regs: $16-$23 (s0-s7)
  - Caller-save regs: $8-$15,$24,$25 (t0-t9)

Register Usage

- Callee-save
  - Save it if you modify it
  - Assumes caller needs it
  - Save the previous contents of the register on procedure entry, restore just before procedure return
  - E.g. $31 (what is this?)

- Caller-save
  - Save it if you need it after the call
  - Assume callee can clobber any one of the registers
  - Save contents of the register before proc call
  - Restore after the call

Caller-Save

```
main:
  …
  [use $9 & $8]
  …
  addiu sp,sp,-8
  sw $9, 4(sp)
  sw $8, 0(sp)
  jal mult
  lw $9, 4(sp)
  lw $8, 0(sp)
  addiu sp,sp,8
  …
  [use $9 & $8]
```

- Assume registers are free for the taking
- But other subroutines will do the same
  - must protect values that will be used later
  - save and restore them before and after subroutine invocations
- Pays off if a routine makes few calls to other routines with values that need to be preserved

Callee-Save

```
mult:
  addiu sp,sp,-12
  sw $31,8(sp)
  sw $17, 4(sp)
  sw $16, 0(sp)
            …
  [use $17 and $16]
     …
  lw $31,8(sp)
  lw $17, 4(sp)
  lw $16, 0(sp)
  addiu sp,sp,12
```

- Assume caller is using the registers
- Save on entry, restore on exit
- Pays off if caller is actually using the registers, else the save and restore are wasted

Leaf vs. non-leaf

- Leaf
  - Simple, fast
  - Don’t save registers

- int f(int x, int y) {return (x+y);}

- f:

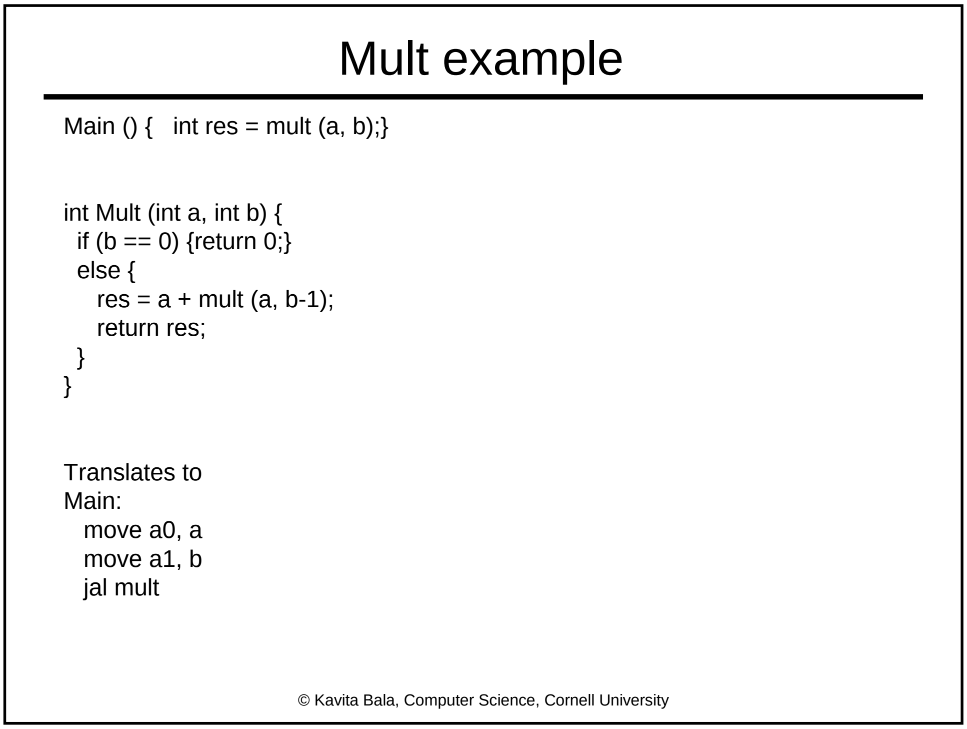
```
add $v0, $a0, $a1    # add x and y
j $ra                # return
nop
```

- Or

```
j $ra
add $v0, $a0, $a1
```

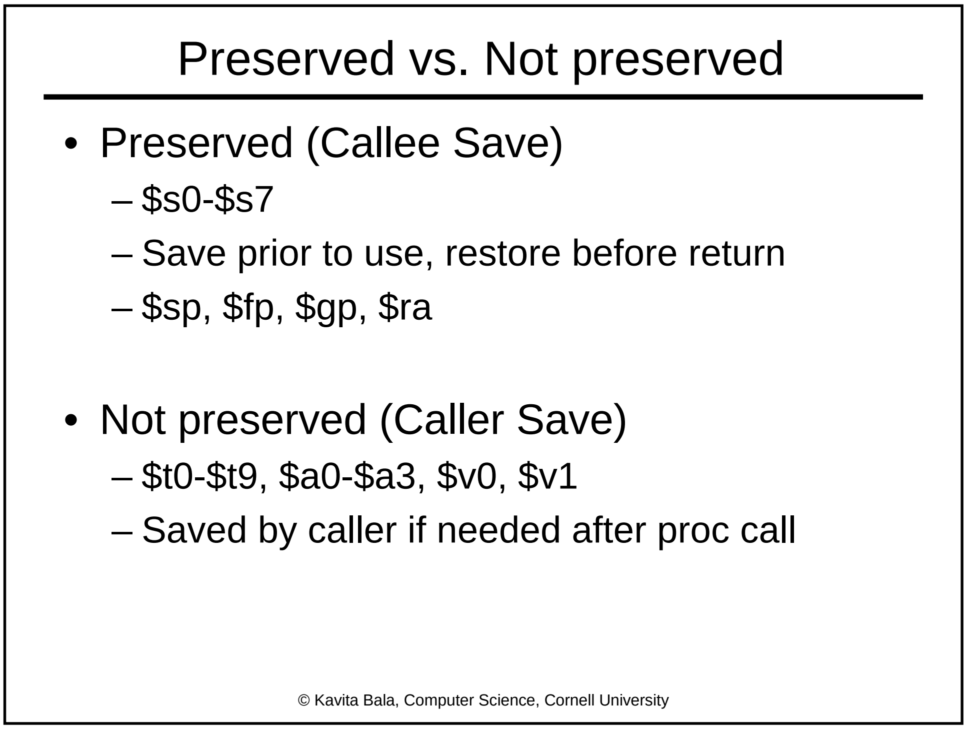
Example

```
f:          beq $a1, $zer0, Done
            nop
            addi $sp, $sp, -12
NotDone: sw $ra, 8($sp)
            sw $a0,4($sp)
            sw $a1,0($sp)
            move $a0, $a0
            subi $a1, $a1, 1
            jal f
            nop
            lw $a0,4(sp)
            lw $a1,0(sp)
            lw $ra,8(sp)
            addi $sp, $sp, 12
            add v0, $a0, $v0
            j Exit
           nop
Done: move $v0, $zero
Exit: return $ra
```



Mult example

```
Main () {   int res = mult (a, b);}


int Mult (int a, int b) {
  if (b == 0) {return 0;}
  else {
     res = a + mult (a, b-1);
     return res;
  }
}


Translates to
Main:
   move a0, a
   move a1, b
   jal mult
```



Preserved vs. Not preserved

- Preserved (Callee Save)
  - $s0-$s7
  - Save prior to use, restore before return
  - $sp, $fp, $gp, $ra

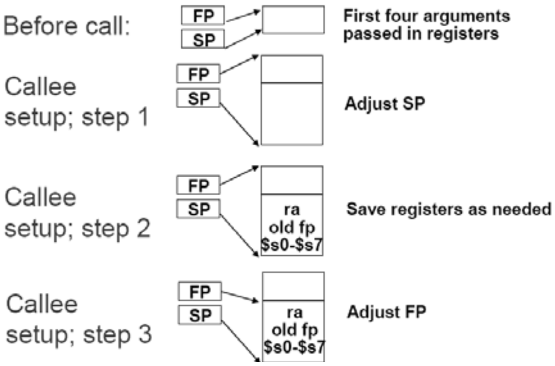
- Not preserved (Caller Save)
  - $t0-$t9, $a0-$a3, $v0, $v1
  - Saved by caller if needed after proc call

MIPS Register Recap

- Return address: $31 (ra)
- Stack pointer: $29 (sp)
- Frame pointer: $30 (fp)
- First four arguments: $4-$7 (a0-a3)
- Return result: $2-$3 (v0-v1)
- Callee-save free regs: $16-$23 (s0-s7)
- Caller-save free regs: $8-$15,$24,$25 (t0-t9)
- Reserved: $26, $27
- Global pointer: $28 (gp)
- Assembler temporary: $1 (at)

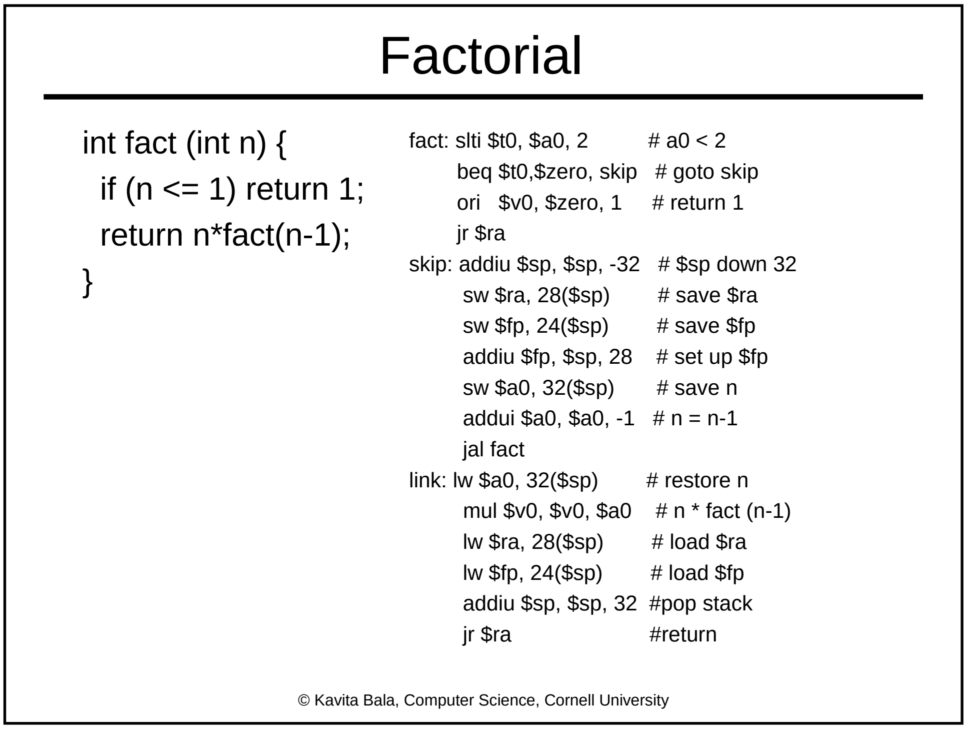
What happens on a call?

- Caller
  - Save caller-saved registers $a0-$a3, $t0-$t9
  - Load arguments in $a0-$a3, rest passed on stack
  - Execute jal
- Callee Setup
  - Allocate memory for new frame ($sp = $sp-frame)
  - Save callee-saved registers $s0-$s7, $fp, $ra
  - Set frame pointer ($fp = $sp-frame-4)
- Callee Return
  - Place return value in $v0 and $v1
  - Restore any callee-saved registers
  - Pop stack ($sp = $sp + frame size)
  - Return by jr $ra



Example

```
f:      slti $t0, $a0, 2
        beq $t0,$zero, skip
        ori   $v0, $zero, 1
        jr $ra
skip: addiu $sp, $sp, -32
         sw $ra, 28($sp)
         sw $fp, 24($sp)
         addiu $fp, $sp, 28
         sw $a0, 32($sp)
         addui $a0, $a0, -1
         jal f
link:  lw $a0, 32($sp)
         mul $v0, $v0, $a0
         lw $ra, 28($sp)
         lw $fp, 24($sp)
         addiu $sp, $sp, 32
         jr $ra                    #return
```



Factorial

```
int fact (int n) {
  if (n <= 1) return 1;
  return n*fact(n-1);
}
```

```
fact: slti $t0, $a0, 2         # a0 < 2
      beq $t0,$zero, skip   # goto skip
      ori   $v0, $zero, 1     # return 1
      jr $ra
skip: addiu $sp, $sp, -32   # $sp down 32
       sw $ra, 28($sp)        # save $ra
       sw $fp, 24($sp)        # save $fp
       addiu $fp, $sp, 28    # set up $fp
       sw $a0, 32($sp)        # save n
       addui $a0, $a0, -1   # n = n-1
       jal fact
link: lw $a0, 32($sp)        # restore n
       mul $v0, $v0, $a0    # n * fact (n-1)
       lw $ra, 28($sp)        # load $ra
       lw $fp, 24($sp)        # load $fp
       addiu $sp, $sp, 32  #pop stack
       jr $ra                       #return
```

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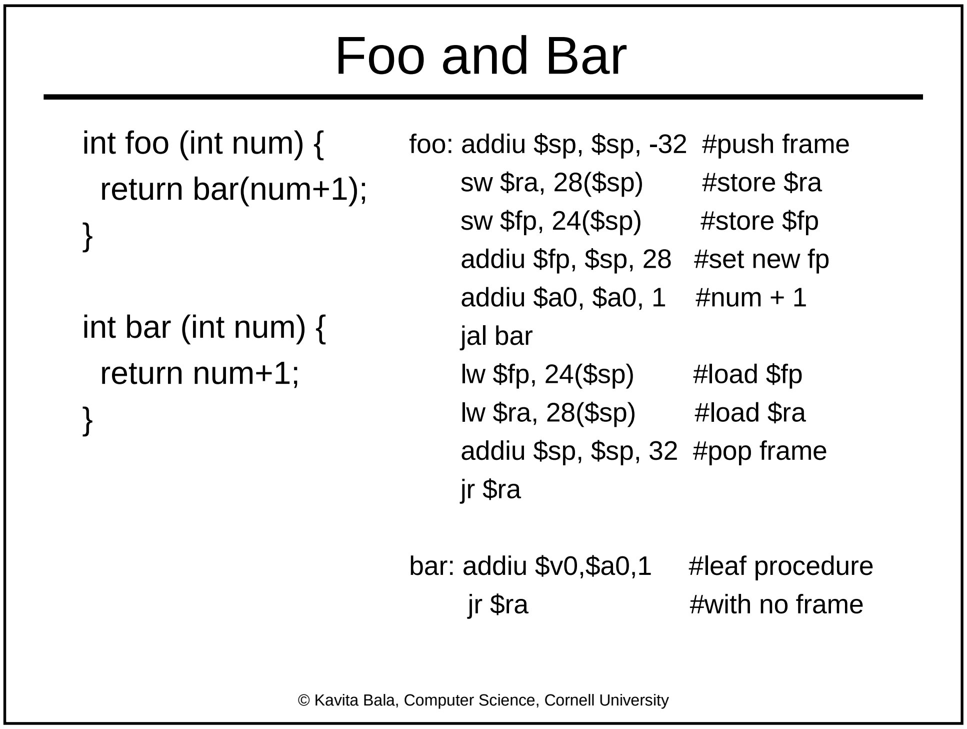

Foo and Bar

```
int foo (int num) {
  return bar(num+1);
}

int bar (int num) {
  return num+1;
}
```

```
foo: addiu $sp, $sp, -32  #push frame
     sw $ra, 28($sp)        #store $ra
     sw $fp, 24($sp)        #store $fp
     addiu $fp, $sp, 28   #set new fp
     addiu $a0, $a0, 1    #num + 1
     jal bar
     lw $fp, 24($sp)       #load $fp
     lw $ra, 28($sp)       #load $ra
     addiu $sp, $sp, 32  #pop frame
     jr $ra

bar: addiu $v0,$a0,1     #leaf procedure
      jr $ra                    #with no frame
```

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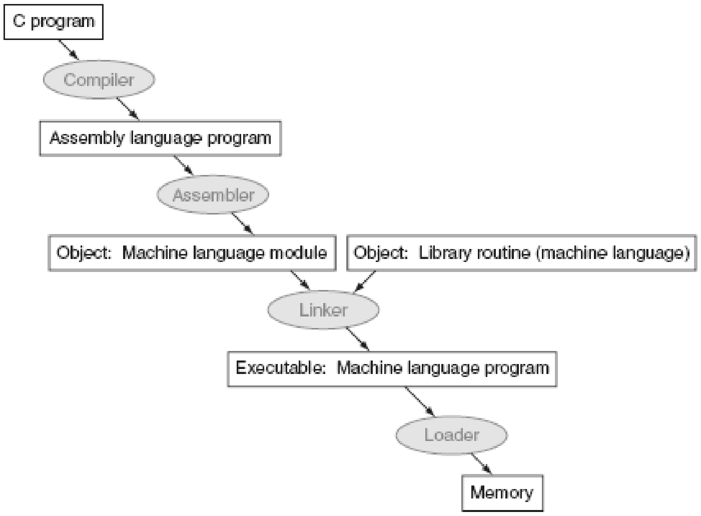
From Assembly to Running


C program
Compiler
Assembly language program
Assembler
Object: Machine language module
Object: Library routine (machine language)
Linker
Executable: Machine language program
Loader
Memory

Big Picture

- Assembler output is obj files
  - Not executable
  - May refer to external symbols
  - Each object file has its own address space
- Linker joins these object files into one executable
- Loader brings it into memory and executes

Object File Generation

- A program is made up of code and data from several object files
- Each object file is generated independently
- Assembler starts at some PC address, e.g. 0, in each object file, generates code as if the program were laid out starting out at location 0x0
- It also generates a symbol table, and a relocation table
  - In case the segments need to be moved

Object file

- Header
  - Size and position of pieces of file
- Text Segment
  - instructions
- Data Segment
  - Static data
- Relocation Information
  - Instructions and data that depend on absolute addresses
- Symbol Table
  - External and unresolved references
- Debugging Information