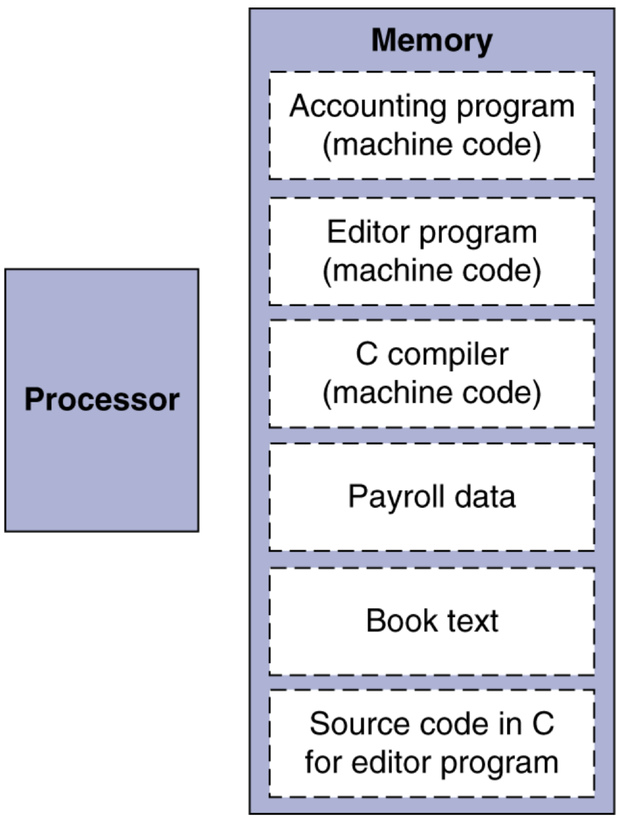
Topic 3

Assembly Programming
- Function (Procedure) Call

Stored Program

The BIG Picture



- Instructions represented in binary, just like data
- Instructions and data stored in memory
- Programs can operate on programs
  - e.g., compilers, linkers, …

Program Counter (PC)

- Each instruction is stored as a word in program memory
  - has an address
  - when labeled, the label is equal to the address
- PC holds address of an instruction to be executed
  - 32 bits register
  - Usually increased by 4
- PC is a special register in CPU
  - Different from the registers in register file

Program Counter (PC)

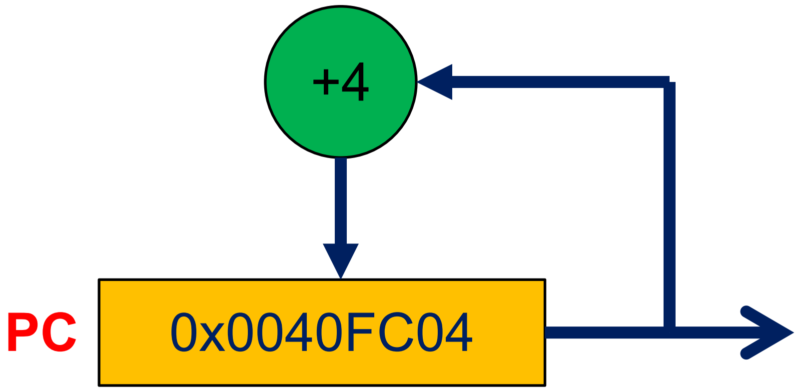
PC 0x0040FC00 →

Address	Content
.	.
.	.
.	.
0x0040FC00	add
0x0040FC04	addi
0x0040FC08	slt
0x0040FC0C	beq
0x0040FC10	j
.	.
.	.
.	.

“add” instruction is to be executed by CPU

Program stored in memory

Program Counter (PC)

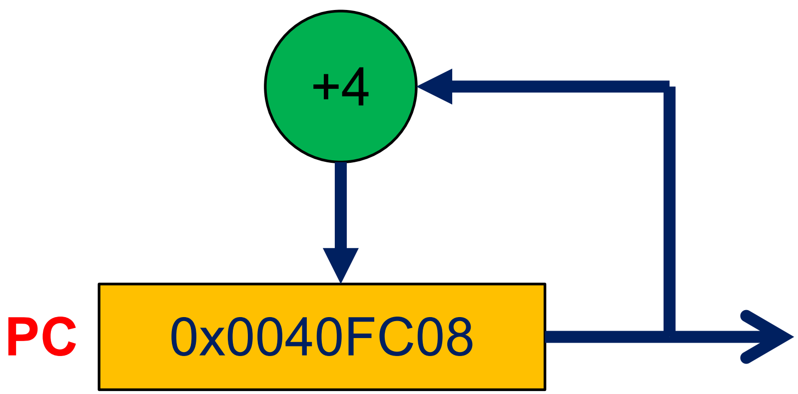


Address	Content
.	.
.	.
.	.
0x0040FC00	add
0x0040FC04	addi
0x0040FC08	slt
0x0040FC0C	beq
0x0040FC10	j
.	.
.	.
.	.

"addi" instruction is to be executed by CPU

Program stored in memory

Program Counter (PC)



Address	Content
.	.
.	.
.	.
0x0040FC00	add
0x0040FC04	addi
0x0040FC08	slt
0x0040FC0C	beq
0x0040FC10	j
.	.
.	.
.	.

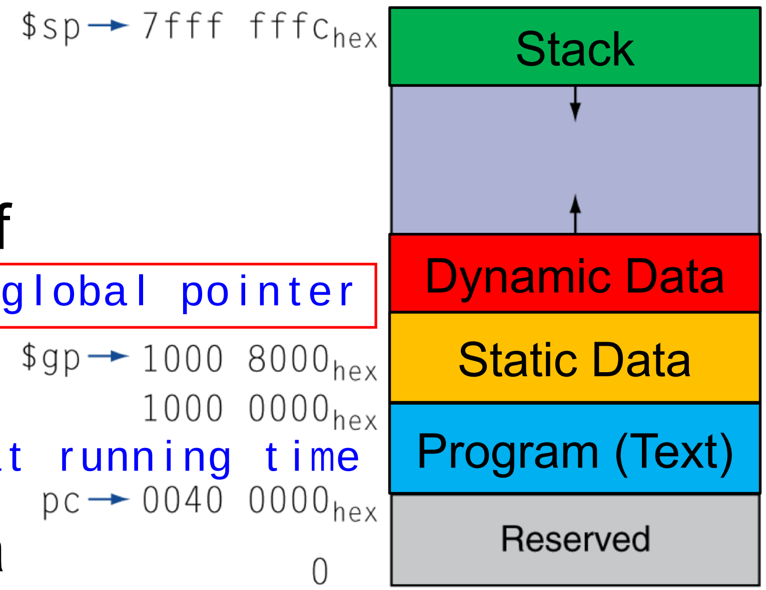
“slt” instruction is to be executed by CPU

Program stored in memory

Memory Layout

- Text: program code
  - PC initialized to 0x00400000
- Static data: global/static variables
  - $gp initialized to the middle of this segment, 0x10008000 allowing ±offset
- Dynamic data: heap
  - E.g., malloc in C, new in Java
- Stack: storage for temporary variable in functions
  - $sp initialized to 0x7ffffffc, growing towards low address

static pointer



global pointer

created at running time

Function Calling

- Used to improve reusability and manageability
- Steps of function call operation
  1. Place parameters in parameter registers
  2. Transfer control to the function
  3. Acquire storage for the function in stack
  4. Perform function's operations
  5. Place results in result register(s) for caller
  6. Release storage release the memory even in stack
  7. Return to the place before the function call

Function Call Instructions

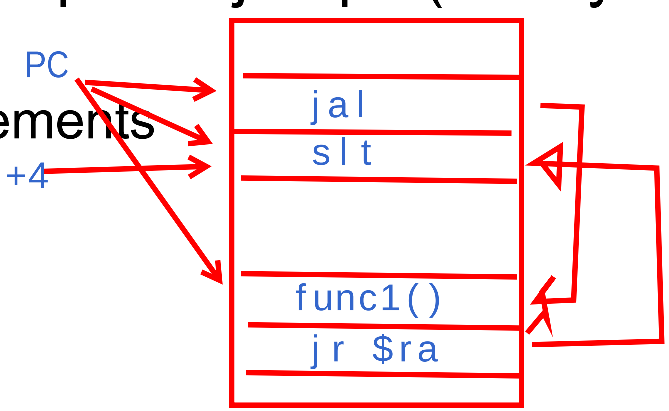
- Function call operations: jump and link

  `jal FunctionLabel (J-type)`

  - \$ra = PC+4; Address of following instruction put in \$ra
  - PC = target address PC = the 1st instruction of func()1
- Function return operations: jump register

  `jr $ra (R-type)`

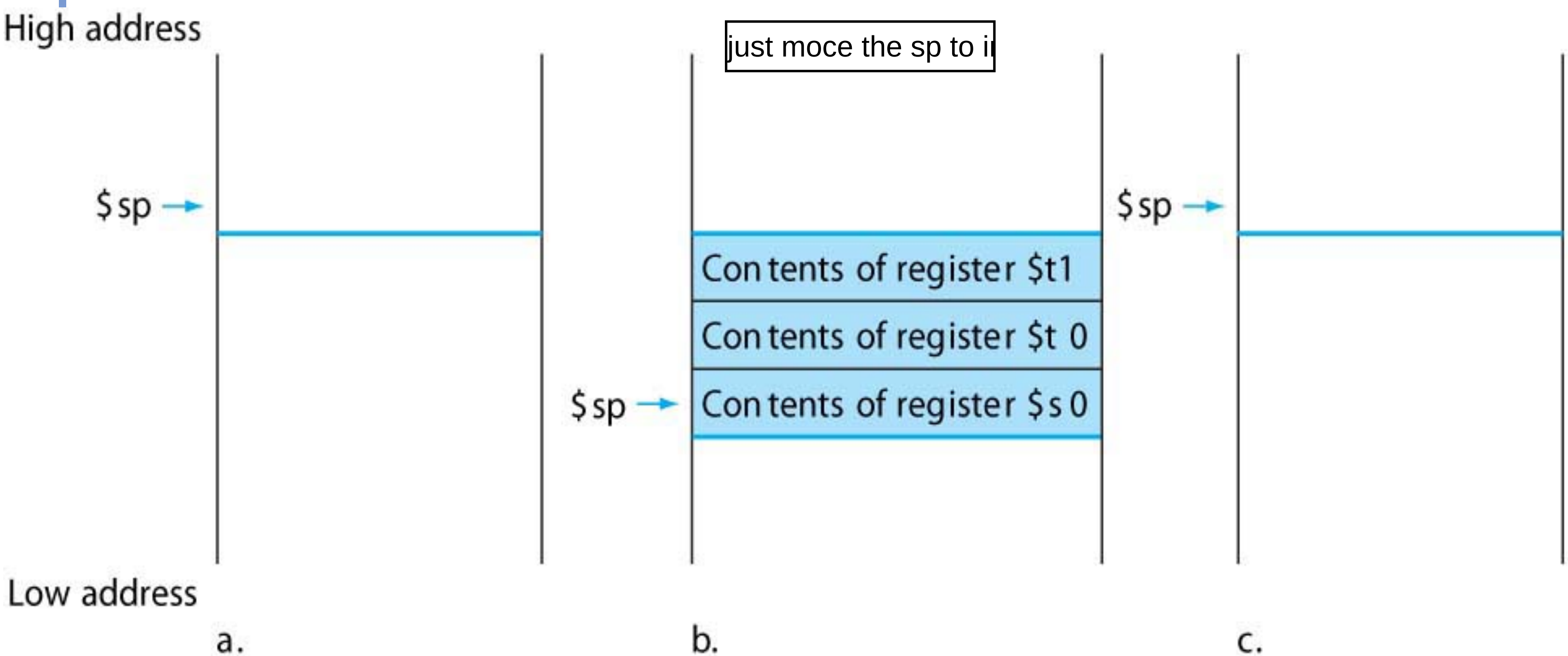
  - PC = \$ra; Copies \$ra to program counter
  - Can also be used for computed jumps (to any other register)
    - e.g., for case/switch statements



Register Usage

- $zero: constant 0 (reg 0)
- $at: Assembler Temporary (reg 1)
- $v0, $v1: result values (reg's 2 and 3) pass result out of the func
- $a0 – $a3: arguments (reg's 4 – 7) parameters
- $t0 – $t9: temporaries (reg's 8 – 15)
  - Can be overwritten by callee
- $s0 – $s7: saved (reg's 16 – 23)
  - Must be saved/restored by callee
- $t8, $t9: temporaries (reg's 24 and 25)
- $k0, $k1: reserved for OS kernel (reg's 26 and 27)
- $gp: global pointer for static data (reg 28)
- $sp: stack pointer (reg 29)
- $fp: frame pointer (reg 30)
- $ra: return address (reg 31)

Uses of Stack in Function Call



Before calling

During function
- **For storing important registers**
- **For temporary variables**

After calling
- **Important registers restored**
- **Temporary variables destroyed**

Leaf Function

- Functions that don't call other functions
- C code:

```
int leaf_example (int g, h, i, j)
{ int f;
  f = (g + h) - (i + j);
  return f;}
```

- Assumptions:
  - Arguments g, …, j in \$a0, …, \$a3
  - f in \$s0 (need to save \$s0 before it's overwritten)
  - Result in \$v0

Leaf Function Example

- MIPS code

```
leaf_example:                              create 3 words
  addi $sp, $sp, -12   #create spaces on stack
  sw   $t1, 8($sp)     #store data on stack
  sw   $t0, 4($sp)
                                           push: data -> stack
  sw   $s0, 0($sp)
  add  $t0, $a0, $a1                   Unnecessary
  add  $t1, $a2, $a3
  sub  $s0, $t0, $t1
  add  $v0, $s0, $zero          use v0/v1 to pass result out  of the function
  lw   $s0, 0($sp)     #restore data from stack
                                           pop: data <= stack
  lw   $t0, 4($sp)
  lw   $t1, 8($sp)
  addi $sp, $sp, 12    #destroy spaces on stack
  jr   $ra             #return from function
```

String Copy Example

- C code:
  - Assuming null-terminated string

```
void strcpy (char x[], char y[])
{ int i;
  i = 0;
  while ((x[i]=y[i])!='\0')
    i += 1;
}
```

  - Base addresses of x, y in $a0, $a1
  - i in $s0

String Copy Example

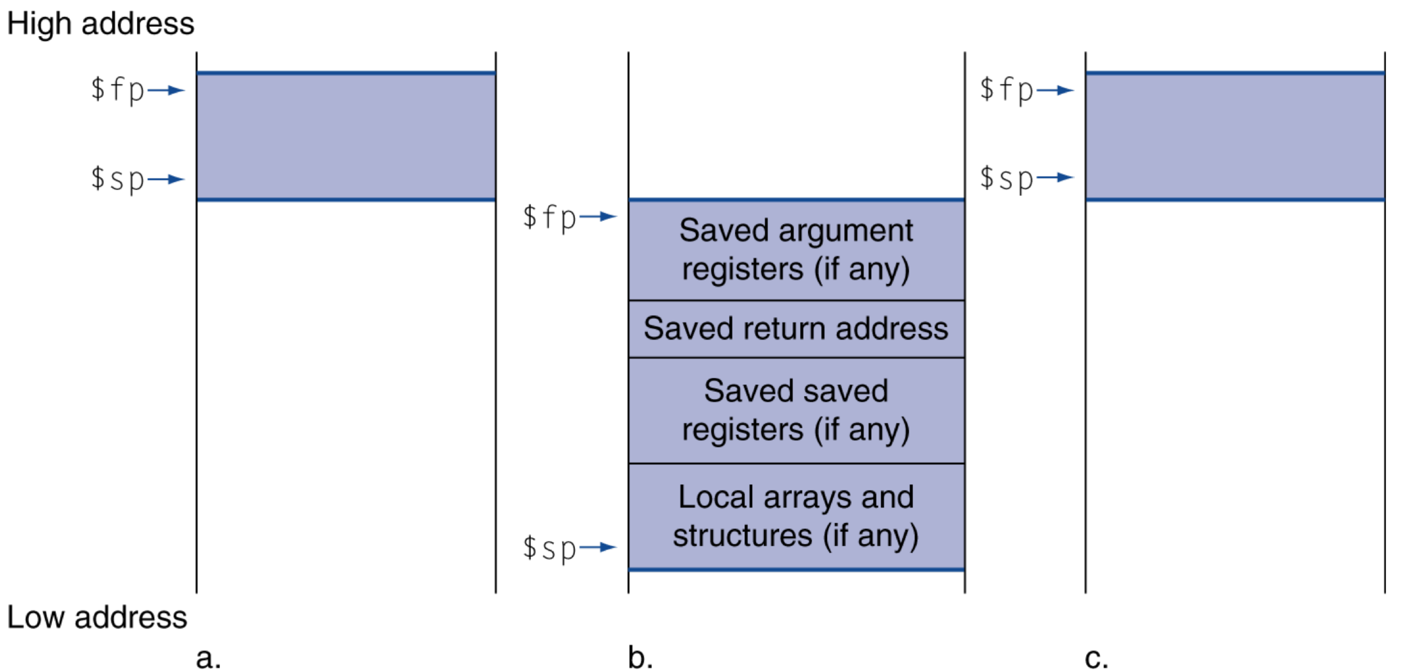
- MIPS code:

```
strcpy:
     addi $sp, $sp, -4       # adjust stack for 1 item
     sw   $s0, 0($sp)        # save $s0
     add  $s0, $zero, $zero  # i = 0
L1:  add  $t1, $s0, $a1      # addr of y[i] in $t1
     lbu  $t2, 0($t1)        # $t2 = y[i]
     add  $t3, $s0, $a0      # addr of x[i] in $t3
     sb   $t2, 0($t3)        # x[i] = y[i]
     beq  $t2, $zero, L2     # exit loop if y[i] == 0
     addi $s0, $s0, 1        # i = i + 1
     j    L1                 # next iteration of loop
L2:  lw   $s0, 0($sp)        # restore saved $s0
     addi $sp, $sp, 4        # pop 1 item from stack
     jr   $ra                # and return
```

Non-Leaf Functions

- Functions that call other functions
- For nested call, caller needs to save on the stack: $ra needs to ne pr
  - Its return address
  - Any arguments and temporaries needed after the call
- Restore from the stack after the call

Local Data on the Stack



- Function frame (activation record)
  - Saved registers
  - Local data allocated by function
- Two pointers manages stack
  - $sp manages frames
  - $fp manages elements in each frame frame pointer

Non-Leaf Function Example

- C code:

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

  - Argument n in $a0
  - Result in $v0

Non-Leaf Function Example

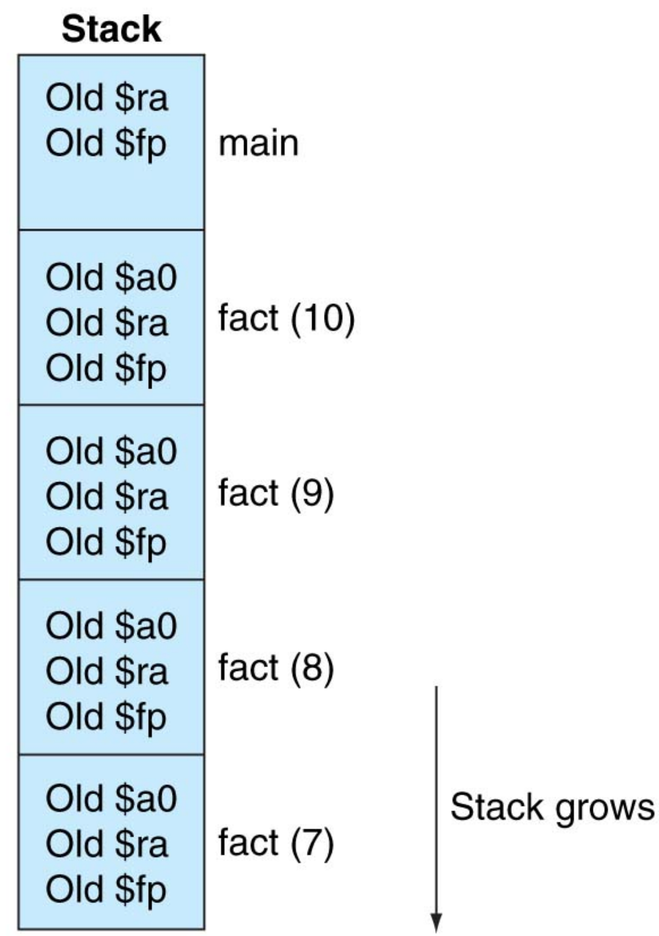
both will be ov

- MIPS code:

```
fact:
    addi $sp, $sp, -8     # adjust stack for 2 items
    sw   $ra, 4($sp)      # save return address
    sw   $a0, 0($sp)      # save argument
    slti $t0, $a0, 1      # test for n < 1
    beq  $t0, $zero, L1
    addi $v0, $zero, 1    # if so, result is 1
    addi $sp, $sp, 8      #   release stack
    jr   $ra              #   and return
L1: addi $a0, $a0, -1     # else decrement n
    jal  fact             # recursive call
    lw   $a0, 0($sp)      # restore original n
    lw   $ra, 4($sp)      #   and return address
    addi $sp, $sp, 8      # pop 2 items from stack
    mul  $v0, $a0, $v0    # multiply to get result
    jr   $ra              # and return
```

Usage of Stack Frames

- `fact (int n)` is a function, can be called recursively
- Note: $fp wasn't used in previous example



Function Calling Convention

- Three places in function calling when conventions apply
  - Immediately before the function is called
  - In function, but before it starts executing
  - Immediately before the function finishes

Function Calling Convention

- Before the function is called
  - Pass arguments to \$a0-\$a3
    - more arguments on stack
  - Save registers that should be saved by caller,
    - such as \$a0-\$a3 (non-leaf function), \$t0-\$t9 (if necessary)
  - `jal`

Function Calling Convention

- Before function starts executing
  - Allocate memory of frame’s size
    - by moving $sp downwords for frame’s size
  - Save registers that should be saved by the function in the frame, before they are overwritten
    - $s0-$s7 (if to be used), $fp (if used), $ra (non-leaf function),
  - Establish $fp (if desired), $fp = $sp + frame’s size – 4

Function Calling Convention

- Before function finishes
  - If necessary, place function result to $v0, $v1
  - Restore registers saved by the function
    - Pop from frame
  - Destroy stack frame by moving $sp upword
  - `jr $ra`

C Sort Example

- Illustrates use of assembly instructions for a C bubble sort function
- Swap function (leaf)

```
void swap(int v[], int k)
{
  int temp;
  temp = v[k];
  v[k] = v[k+1];
  v[k+1] = temp;
}
```

  - v in $a0, k in $a1, temp in $t0

The Function Swap

```
swap: sll $t1, $a1, 2   # $t1 = k * 4
      add $t1, $a0, $t1 # $t1 = v+(k*4)
                        #   (address of v[k])
      lw $t0, 0($t1)    # $t0 (temp) = v[k]
      lw $t2, 4($t1)    # $t2 = v[k+1]
      sw $t2, 0($t1)    # v[k] = $t2 (v[k+1])
      sw $t0, 4($t1)    # v[k+1] = $t0 (temp)
      jr $ra            # return to calling routine
```

The Sort Function in C

- Non-leaf function (calls swap)

```
void sort (int v[], int n)
{
  int i, j;
  for (i = 0; i < n; i += 1) {
    for (j = i – 1;
         j >= 0 && v[j] > v[j + 1];
         j -= 1) {
      swap(v,j);
    }
  }
}
```

  - v in \$a0, n in \$a1, i in \$s0, j in \$s1

The Full Function

```
sort: addi $sp,$sp, -20       # make room on stack for 5
                              # registers
      sw $ra, 16($sp)         # save $ra on stack
      sw $s3,12($sp)          # save $s3 on stack
      sw $s2, 8($sp)          # save $s2 on stack
      sw $s1, 4($sp)          # save $s1 on stack
      sw $s0, 0($sp)          # save $s0 on stack
      …                       # function body
      …
exit1:lw $s0, 0($sp)          # restore $s0 from stack
      lw $s1, 4($sp)          # restore $s1 from stack
      lw $s2, 8($sp)          # restore $s2 from stack
      lw $s3,12($sp)          # restore $s3 from stack
      lw $ra,16($sp)          # restore $ra from stack
      addi $sp,$sp, 20        # restore stack pointer
      jr $ra                  # return to calling routine
```

The Function Body

```
          move $s2, $a0           # save $a0 into $s2
          move $s3, $a1           # save $a1 into $s3
          move $s0, $zero         # i = 0
for1tst:  slt  $t0, $s0, $s3      # $t0 = 0 if $s0 ≥ $s3 (i ≥ n)
          beq  $t0, $zero, exit1  # go to exit1 if $s0 ≥ $s3 (i ≥ n)
          addi $s1, $s0, –1       # j = i – 1
for2tst:  slti $t0, $s1, 0        # $t0 = 1 if $s1 < 0 (j < 0)
          bne  $t0, $zero, exit2  # go to exit2 if $s1 < 0 (j < 0)
          sll  $t1, $s1, 2        # $t1 = j * 4
          add  $t2, $s2, $t1      # $t2 = v + (j * 4)
          lw   $t3, 0($t2)        # $t3 = v[j]
          lw   $t4, 4($t2)        # $t4 = v[j + 1]
          slt  $t0, $t4, $t3      # $t0 = 0 if $t4 ≥ $t3
          beq  $t0, $zero, exit2  # go to exit2 if $t4 ≥ $t3
          move $a0, $s2           # 1st param of swap is v (old $a0)
          move $a1, $s1           # 2nd param of swap is j
          jal  swap               # call swap function
          addi $s1, $s1, –1       # j –= 1
          j    for2tst            # jump to test of inner loop
exit2:    addi $s0, $s0, 1        # i += 1
          j    for1tst            # jump to test of outer loop
```

Move params

Outer loop

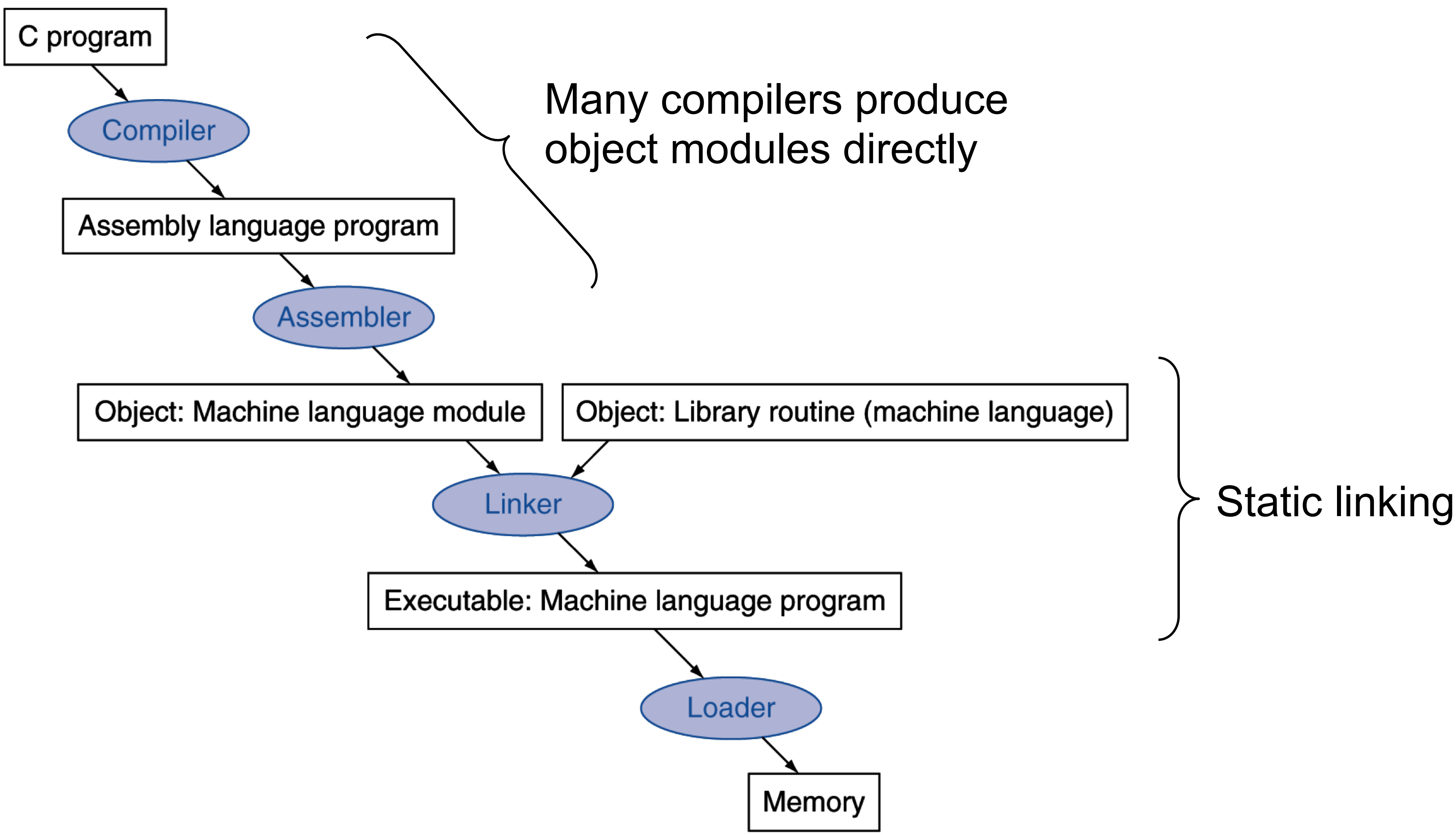
Inner loop

Pass params & call

Inner loop

Outer loop

Translation and Startup



Producing an Object Module

- Assembler (or compiler) translates program into machine instructions
- Provides information for building a complete program from the pieces
  - *Header*: described contents of object module
  - *Text segment*: translated instructions
  - *Static data segment*: data allocated for the life of the program
  - *Relocation info*: for contents that depend on absolute location of loaded program
  - *Symbol table*: global definitions and external refs
  - *Debug info*: for associating with source code

Example of Object Modules

```
int X[100], Y[100];
Procedure_A(int m)
{ m = X[0];
   ...
   Procedure_B(…);
   ...
}
```

```
lw $a0, offset1($gp)
jal Procedure_B
...
```

```
Procedure_B(int n)
{ Y[0] = n;
   ...
   Procedure_A(…);
   ...
}
```

```
sw $a1, offset2($gp)
jal Procedure_A
...
```

- m and n are parameters to the C functions
- Array X and Y are global variables
- By default \$gp = 1000 8000$_{hex}$

Example of Object Modules

Object file header			
	Name	Procedure A	
	Text size	100_{hex}	
	Data size	20_{hex}	
Text segment	Address	Instruction	
	0	lw $a0, 0($gp)	
	4	jal 0	
	…	…	
Data segment	0	(X)	
	…	…	
Relocation information	Address	Instruction type	Dependency
	0	lw	X
	4	jal	B
Symbol table	Label	Address	
	X	---	
	B	---	

Object file header			
	Name	Procedure B	
	Text size	200_{hex}	
	Data size	30_{hex}	
Text segment	Address	Instruction	
	0	sw $a1, 0($gp)	
	4	jal 0	
	…	…	
Data segment	0	(Y)	
	…	…	
Relocation information	Address	Instruction type	Dependency
	0	sw	Y
	4	jal	A
Symbol table	Label	Address	
	Y	---	
	A	---	

Linking Object Modules

- Produces an executable image
  1. Merges segments
  2. Resolve labels (determine their addresses)
  3. Patch location-dependent and external references

Example of Linked Objects

Executable File Header		
	Text size	300_{hex}
	Data size	50_{hex}
Text Segment	Address	Instruction
	$0040\ 0000_{hex}$	lw \$a0, 8000_{hex}(\$gp)
	$0040\ 0004_{hex}$	jal 40 0100_{hex}
	…	…
	$0040\ 0100_{hex}$	sw \$a1, 8020_{hex}(\$gp)
	$0040\ 0104_{hex}$	jal 40 0000_{hex}
	…	…
Data Segment	Address	
	$1000\ 0000_{hex}$	(X)
	…	…
	$1000\ 0020_{hex}$	(Y)
	…	…

Loading a Program

- Load from image file on disk into memory
  1. Read header to determine segment sizes
  2. Create virtual address space
  3. Copy text and initialized data into memory
  4. Set up arguments on stack
  5. Initialize registers (including \$sp, \$fp, \$gp)
  6. Jump to startup routine
     - Copies arguments to \$a0, … and calls main
     - When main returns, do `exit` syscall

Dynamic Linking

- Only link/load library function when it is called
  - Requires function code to be relocatable
  - Avoids big executable caused by static linking of all referenced libraries
    - Some of them may be never used
  - Automatically picks up new library versions

MIPS R2000 Assembly Language

- Appendix B.10