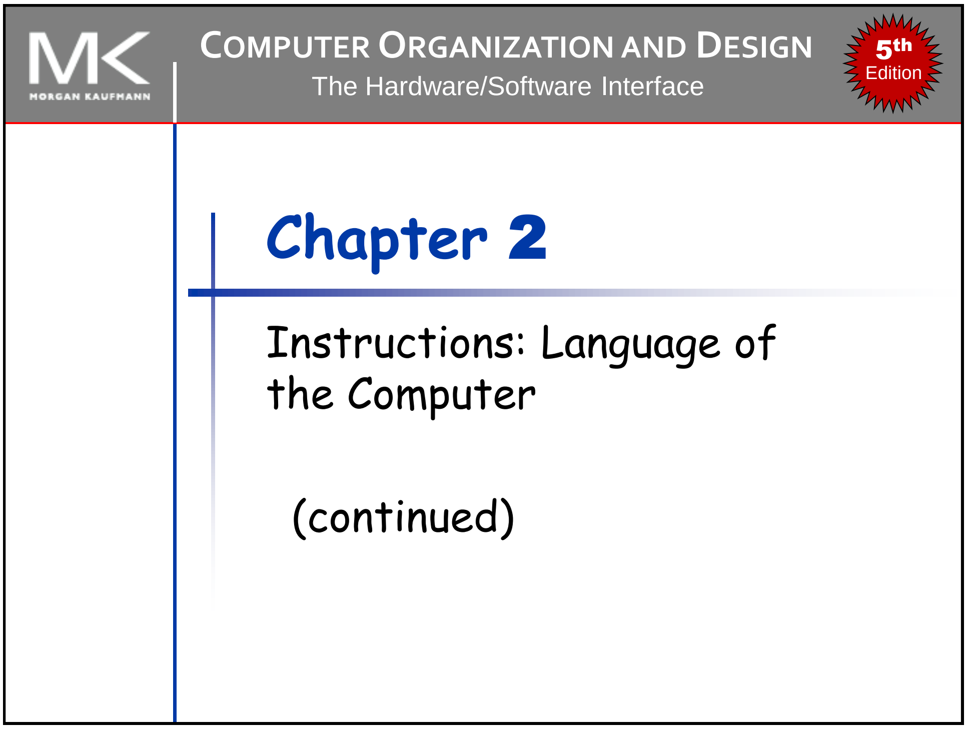


MORGAN KAUFMANN

COMPUTER ORGANIZATION AND DESIGN

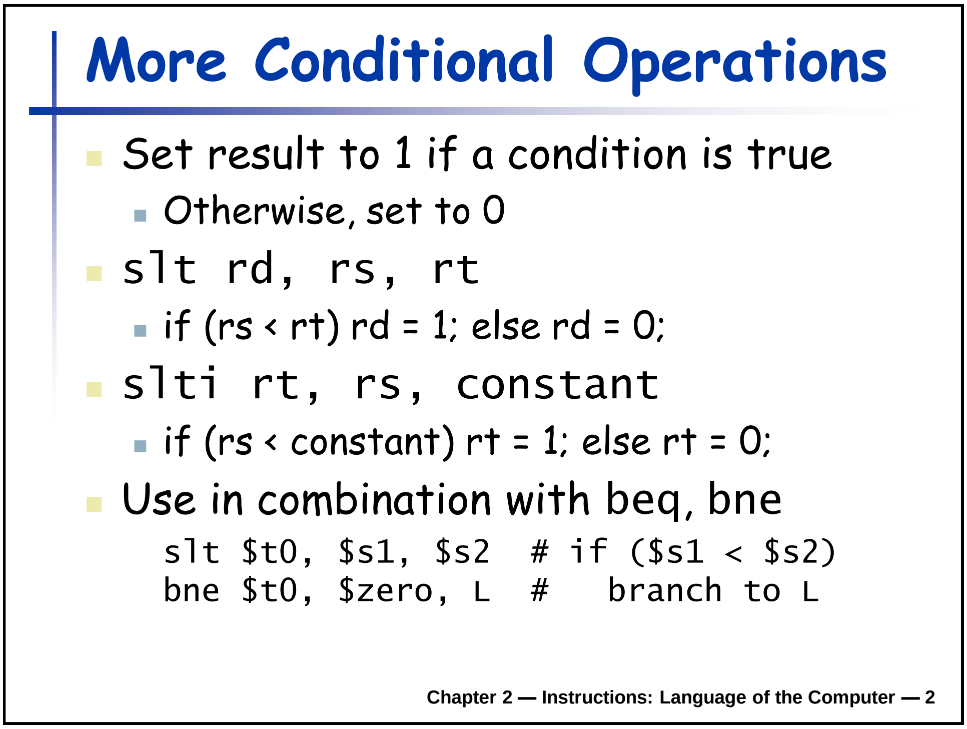
The Hardware/Software Interface

5th Edition

Chapter 2

Instructions: Language of the Computer

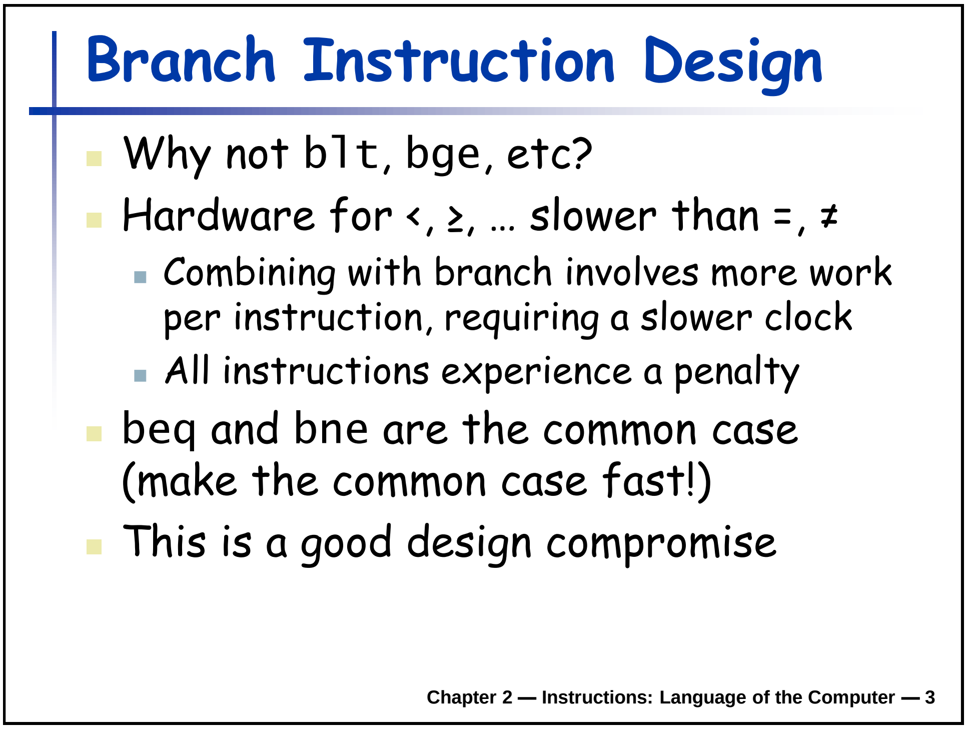
(continued)



More Conditional Operations

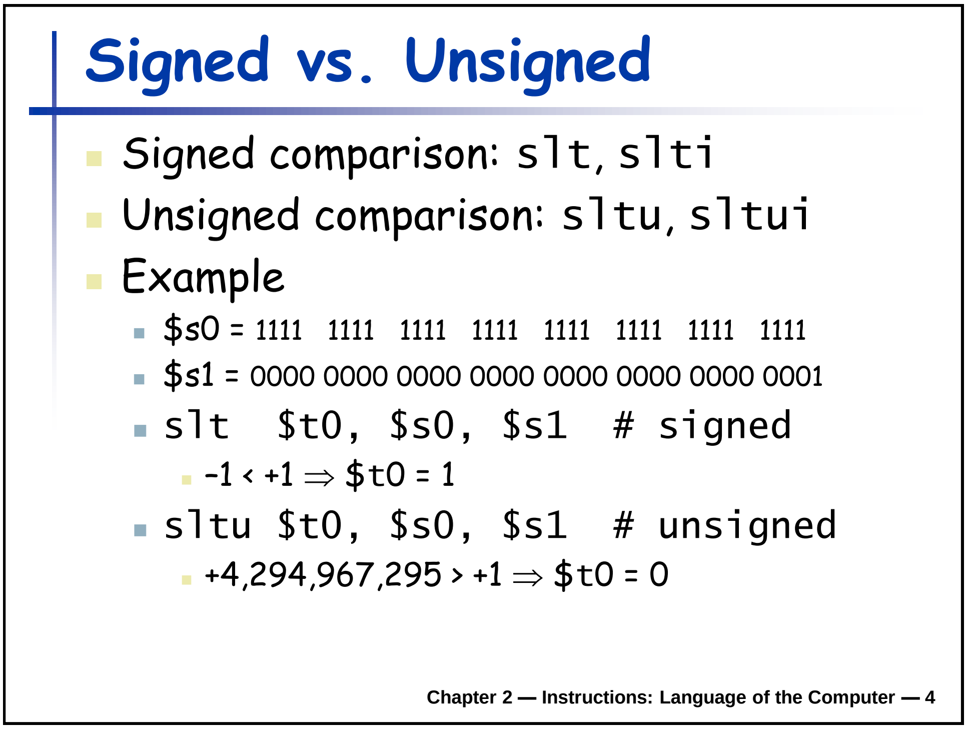
- Set result to 1 if a condition is true
  - Otherwise, set to 0
- `slt rd, rs, rt`
  - if (rs < rt) rd = 1; else rd = 0;
- `slti rt, rs, constant`
  - if (rs < constant) rt = 1; else rt = 0;
- Use in combination with beq, bne

```
slt $t0, $s1, $s2  # if ($s1 < $s2)
bne $t0, $zero, L  #   branch to L
```



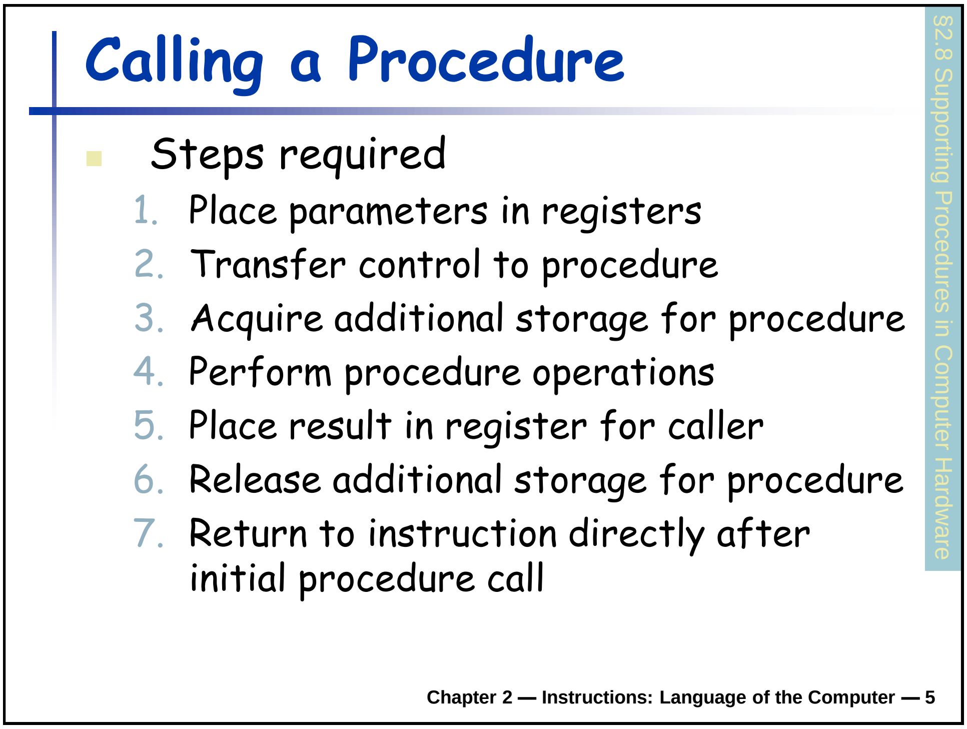
Branch Instruction Design

- Why not `blt`, `bge`, etc?
- Hardware for <, ≥, … slower than =, ≠
  - Combining with branch involves more work per instruction, requiring a slower clock
  - All instructions experience a penalty
- beq and bne are the common case (make the common case fast!)
- This is a good design compromise



Signed vs. Unsigned

- Signed comparison: `slt`, `slti`
- Unsigned comparison: `sltu`, `sltui`
- Example
  - $s0 = 1111 1111 1111 1111 1111 1111 1111 1111
  - $s1 = 0000 0000 0000 0000 0000 0000 0000 0001
  - `slt  $t0, $s0, $s1  # signed`
    - –1 < +1 ⇒ $t0 = 1
  - `sltu $t0, $s0, $s1  # unsigned`
    - +4,294,967,295 > +1 ⇒ $t0 = 0



Calling a Procedure

§2.8 Supporting Procedures in Computer Hardware

- Steps required
  1. Place parameters in registers
  2. Transfer control to procedure
  3. Acquire additional storage for procedure
  4. Perform procedure operations
  5. Place result in register for caller
  6. Release additional storage for procedure
  7. Return to instruction directly after initial procedure call

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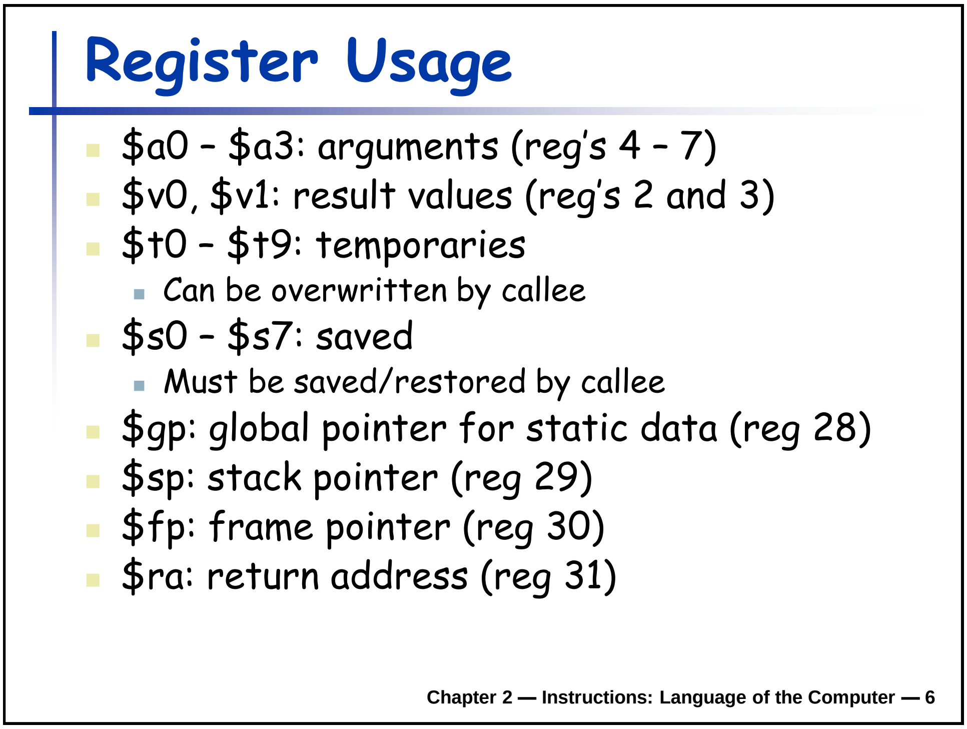

Register Usage

- $a0 – $a3: arguments (reg's 4 – 7)
- $v0, $v1: result values (reg's 2 and 3)
- $t0 – $t9: temporaries
  - Can be overwritten by callee
- $s0 – $s7: saved
  - Must be saved/restored by callee
- $gp: global pointer for static data (reg 28)
- $sp: stack pointer (reg 29)
- $fp: frame pointer (reg 30)
- $ra: return address (reg 31)

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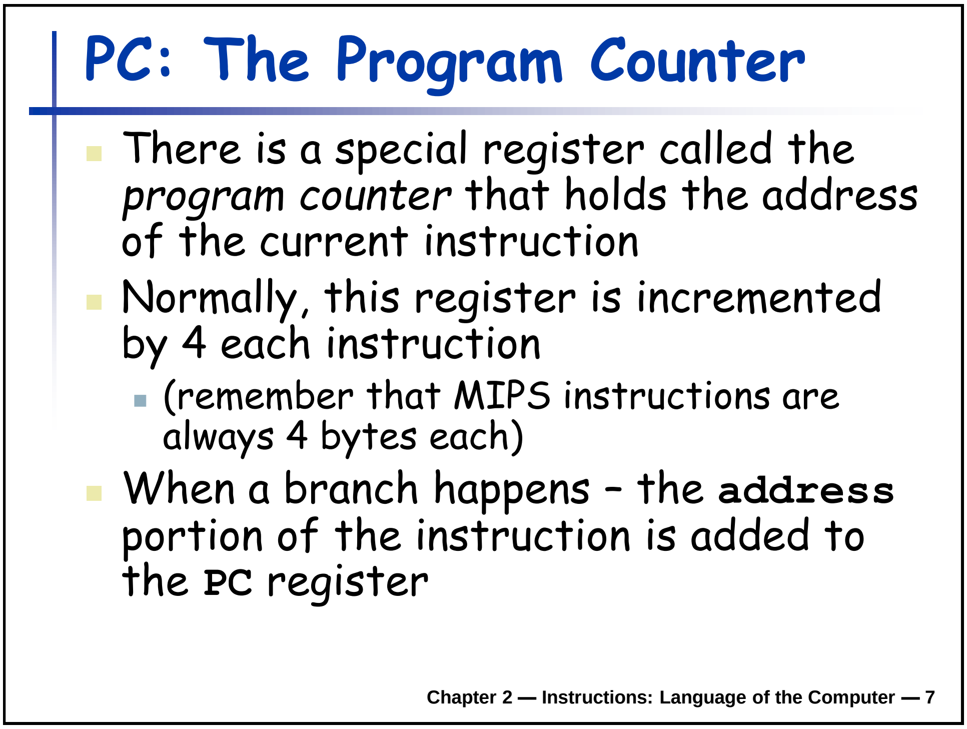
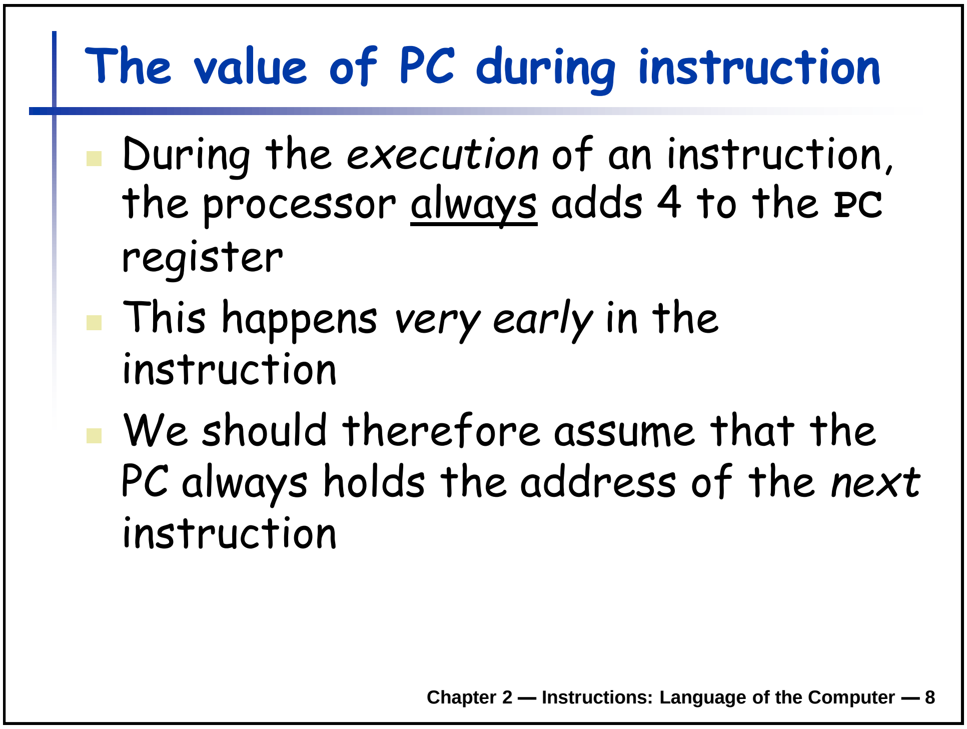


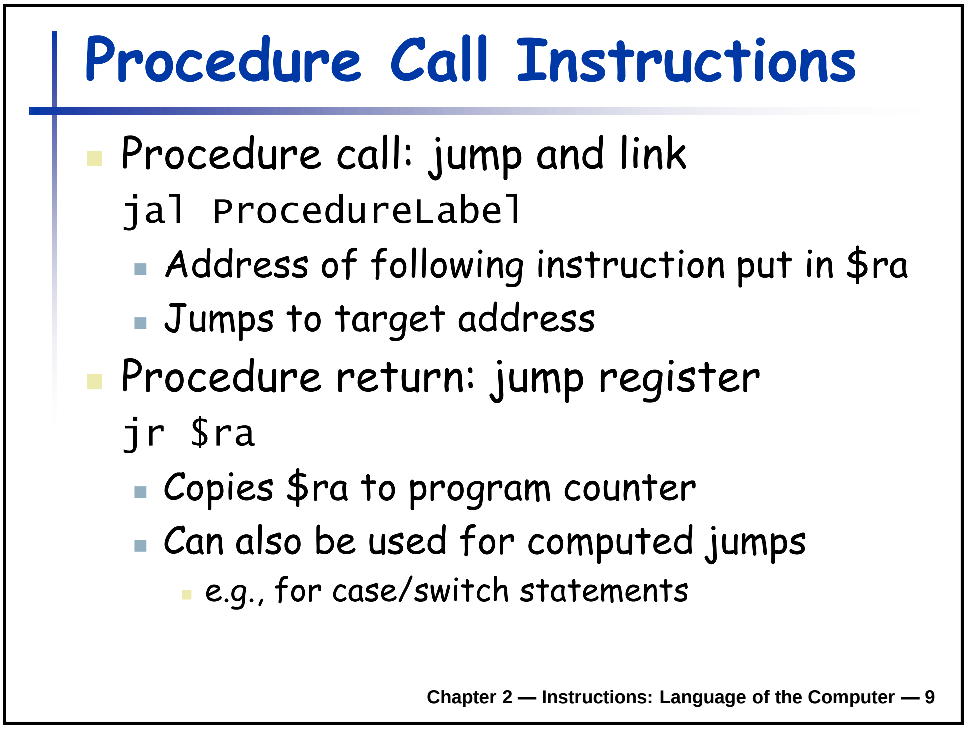
PC: The Program Counter

- There is a special register called the *program counter* that holds the address of the current instruction
- Normally, this register is incremented by 4 each instruction
  - (remember that MIPS instructions are always 4 bytes each)
- When a branch happens – the **`address`** portion of the instruction is added to the **`PC`** register



The value of PC during instruction

- During the *execution* of an instruction, the processor always adds 4 to the **`PC`** register
- This happens *very early* in the instruction
- We should therefore assume that the PC always holds the address of the *next* instruction



Procedure Call Instructions

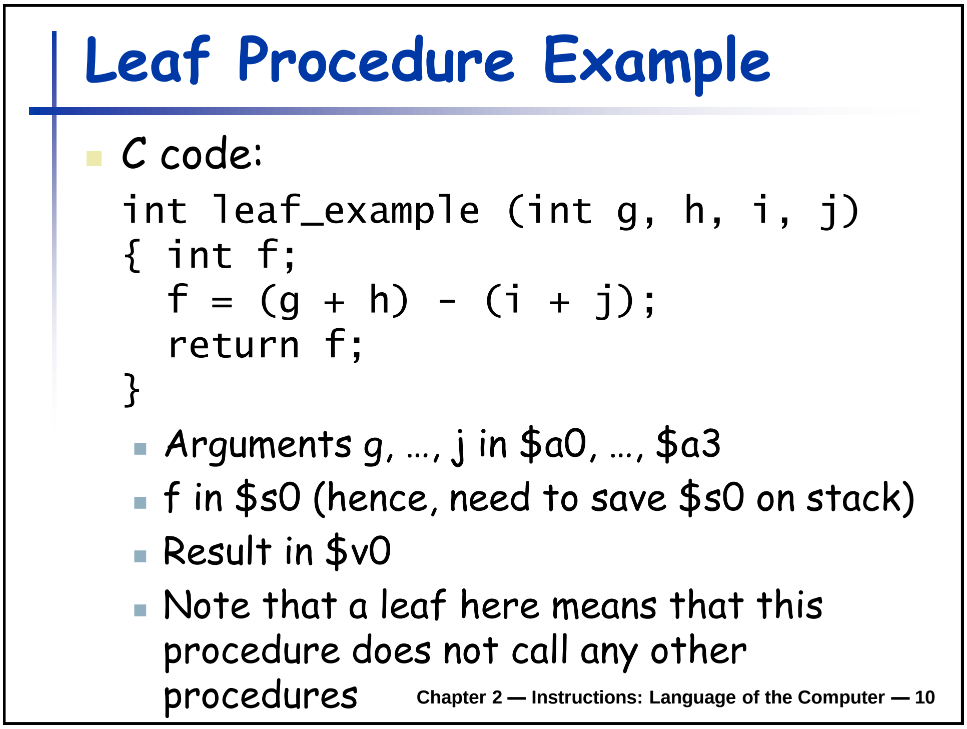
- Procedure call: jump and link

  ```
  jal ProcedureLabel
  ```

  - Address of following instruction put in $ra
  - Jumps to target address
- Procedure return: jump register

  ```
  jr $ra
  ```

  - Copies $ra to program counter
  - Can also be used for computed jumps
    - e.g., for case/switch statements

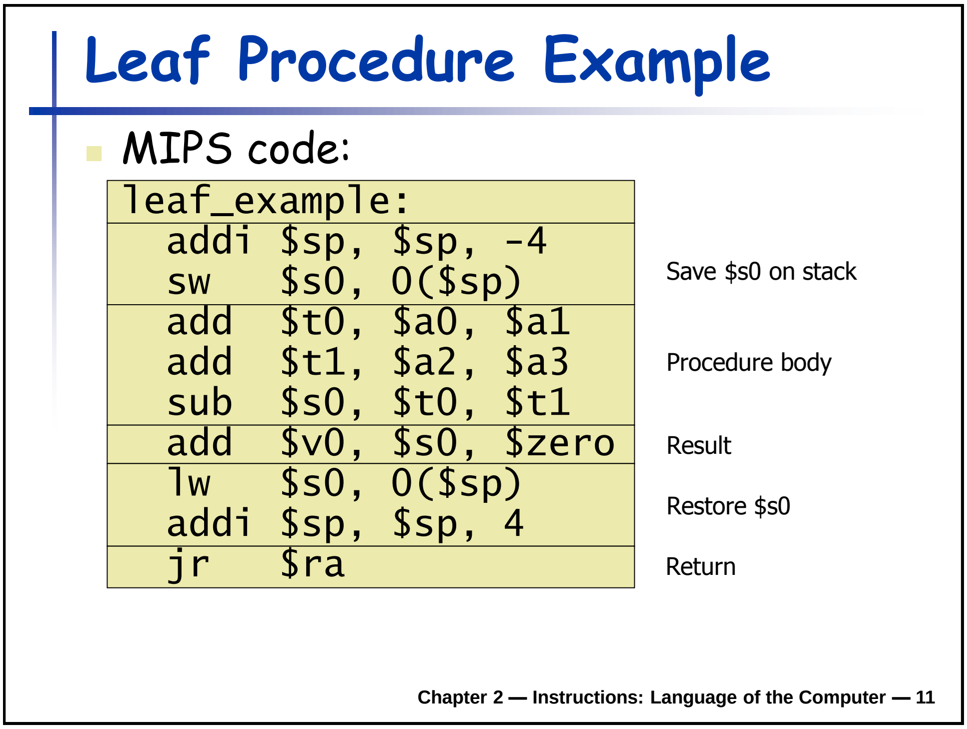


Leaf Procedure Example

- C code:

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

  - Arguments g, …, j in $a0, …, $a3
  - f in $s0 (hence, need to save $s0 on stack)
  - Result in $v0
  - Note that a leaf here means that this procedure does not call any other procedures



Leaf Procedure Example

- MIPS code:

```
leaf_example:
   addi $sp, $sp, -4
   sw   $s0, 0($sp)
   add  $t0, $a0, $a1
   add  $t1, $a2, $a3
   sub  $s0, $t0, $t1
   add  $v0, $s0, $zero
   lw   $s0, 0($sp)
   addi $sp, $sp, 4
   jr   $ra
```

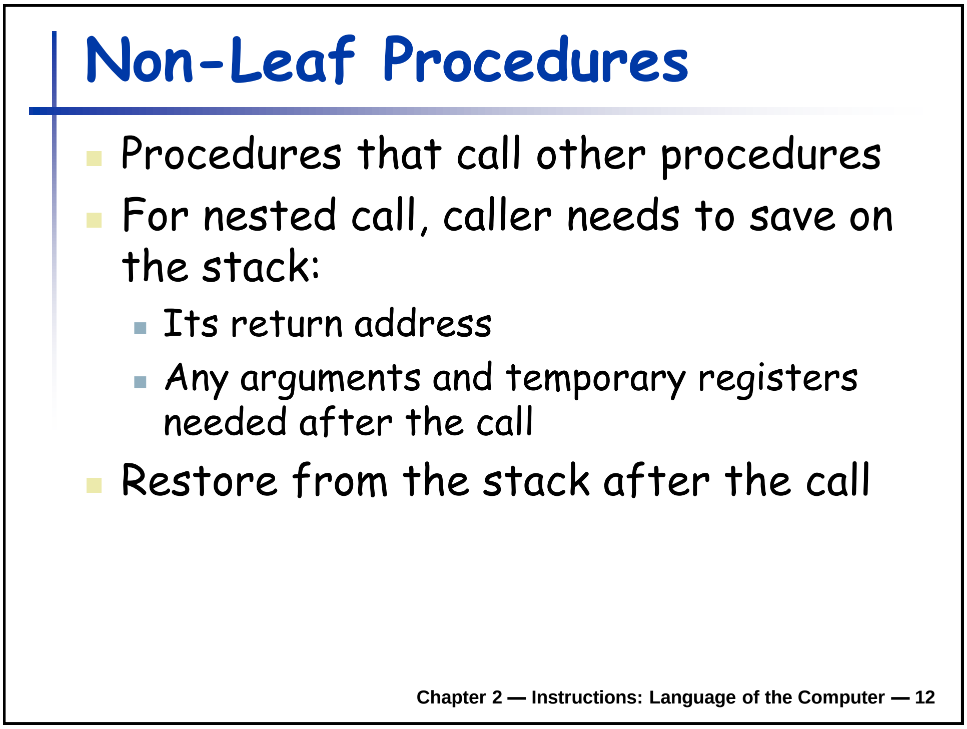
Save $s0 on stack

Procedure body

Result

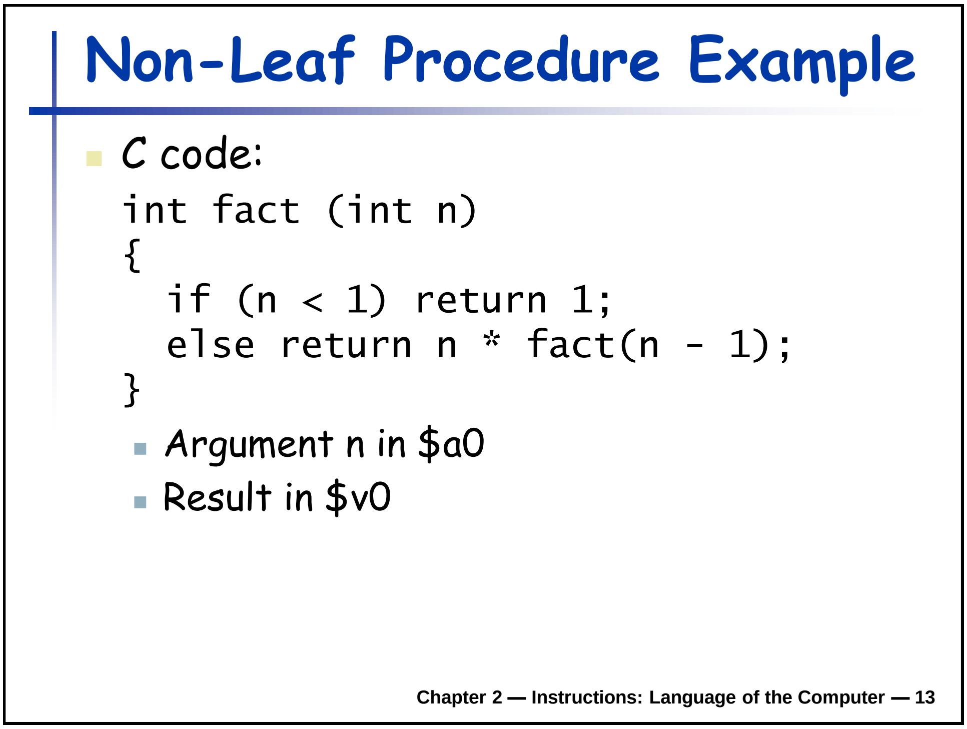
Restore $s0

Return



Non-Leaf Procedures

- Procedures that call other procedures
- For nested call, caller needs to save on the stack:
  - Its return address
  - Any arguments and temporary registers needed after the call
- Restore from the stack after the call



Non-Leaf Procedure Example

- C code:

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

  - Argument n in $a0
  - Result in $v0

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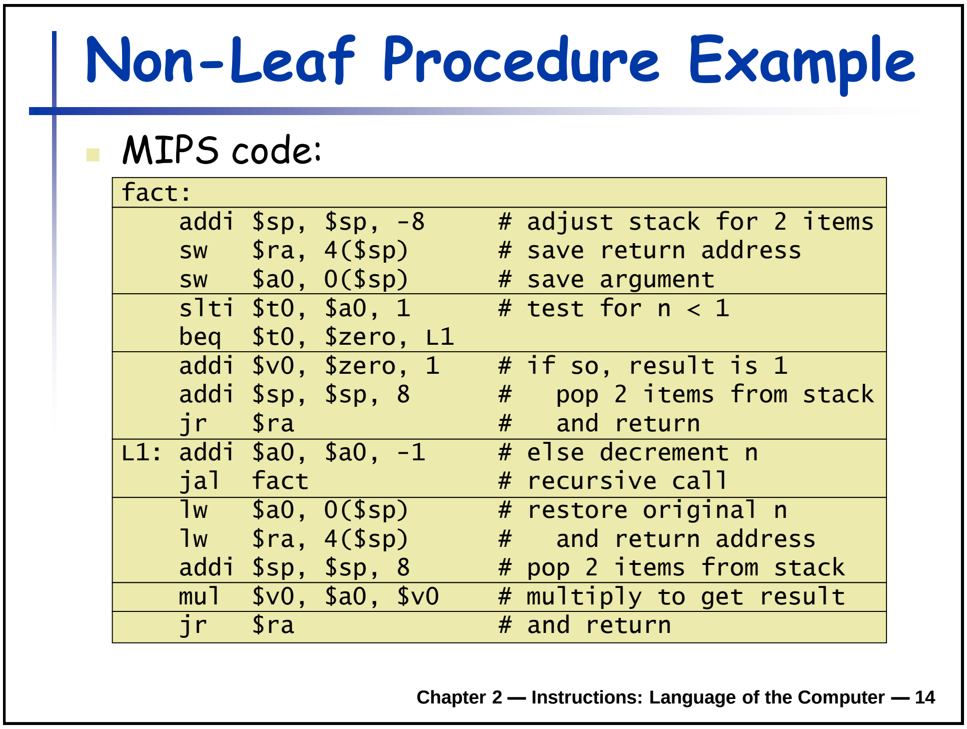

Non-Leaf Procedure Example

- 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      #   pop 2 items from 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
```

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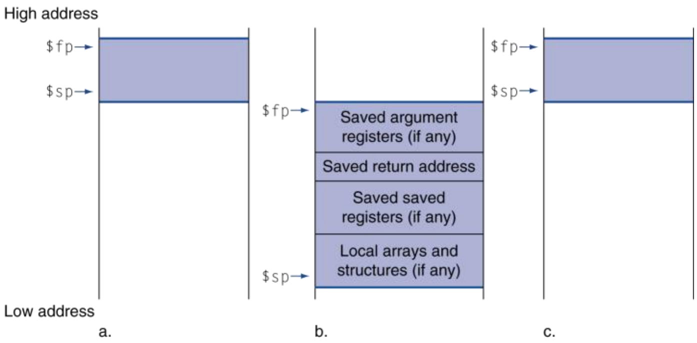
Local Data on the Stack


High address
$fp
$sp
$fp
Saved argument registers (if any)
Saved return address
Saved saved registers (if any)
Local arrays and structures (if any)
$sp
$fp
$sp
Low address
a.
b.
c.

- Local data allocated by callee
  - e.g., C automatic variables
- Procedure frame (activation record)
  - Used by some compilers to manage stack storage

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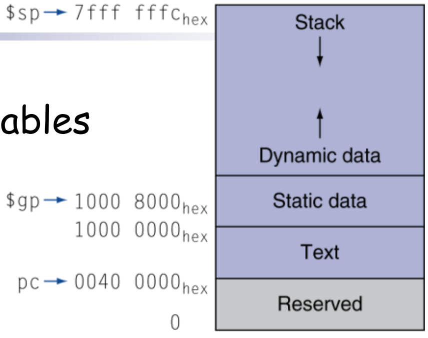
Memory Layout



- Text: program code
- Static data: global variables
  - e.g., static variables in C, constant arrays and strings
  - $gp initialized to address allowing ±offsets into this segment
- Dynamic data: heap
  - E.g., malloc in C, new in Java
- Stack: automatic storage

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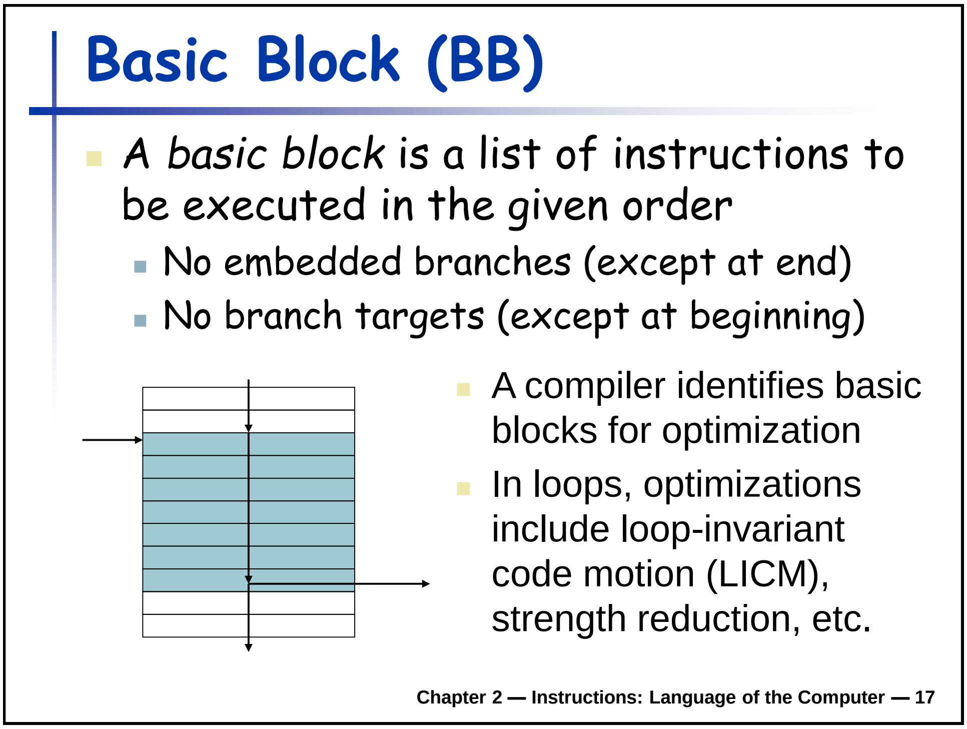

Basic Block (BB)

- A *basic block* is a list of instructions to be executed in the given order
  - No embedded branches (except at end)
  - No branch targets (except at beginning)
- A compiler identifies basic blocks for optimization
- In loops, optimizations include loop-invariant code motion (LICM), strength reduction, etc.

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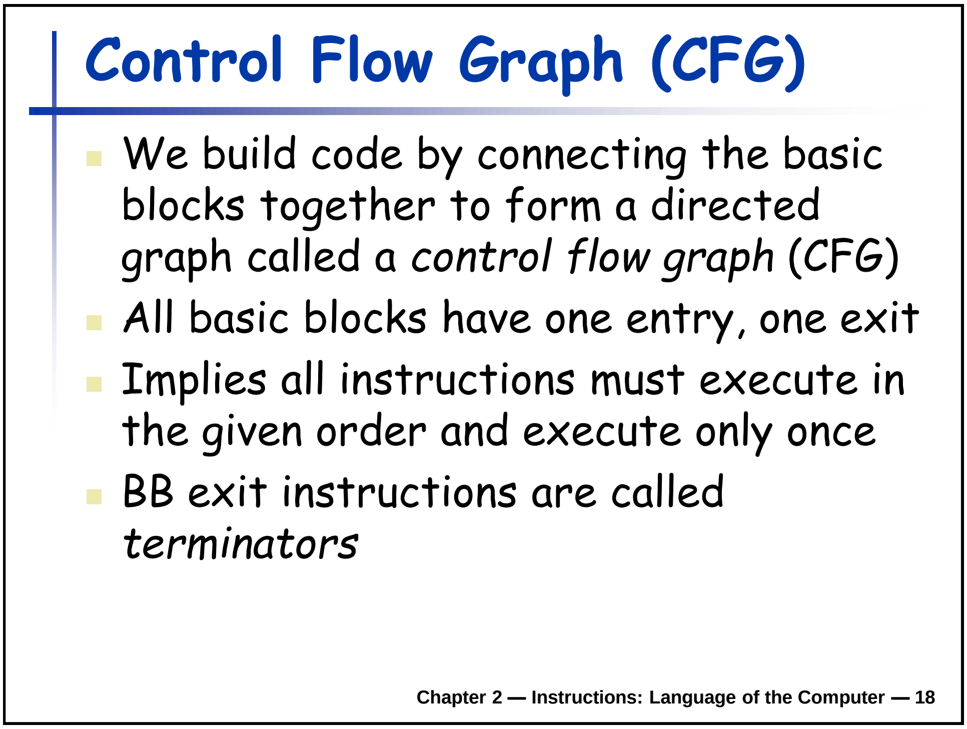

Control Flow Graph (CFG)

- We build code by connecting the basic blocks together to form a directed graph called a *control flow graph* (CFG)
- All basic blocks have one entry, one exit
- Implies all instructions must execute in the given order and execute only once
- BB exit instructions are called *terminators*

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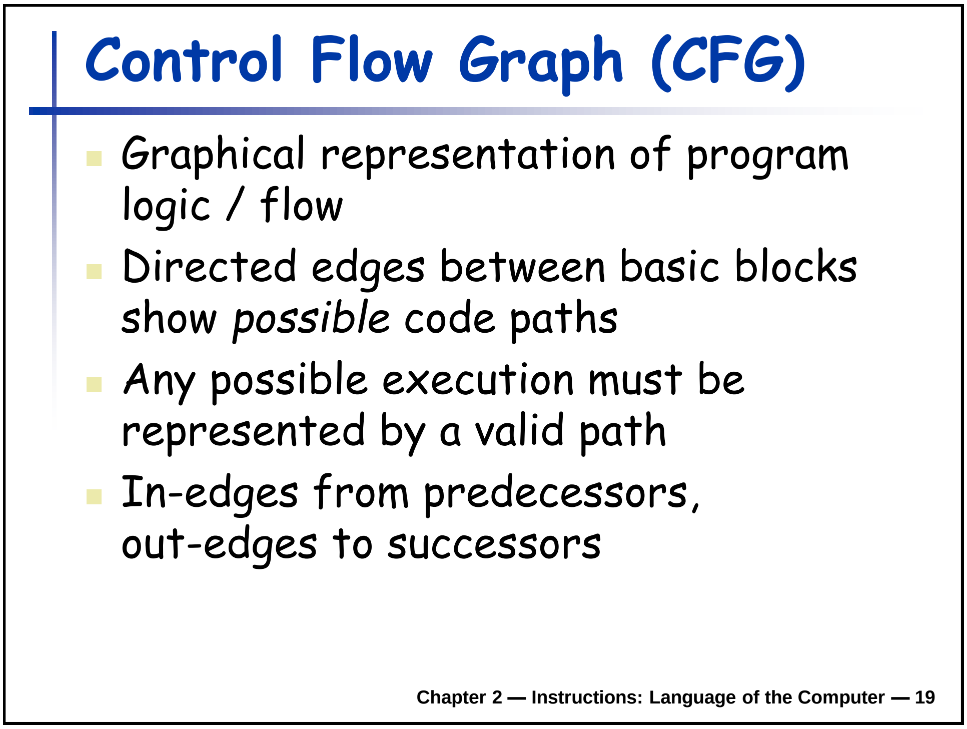
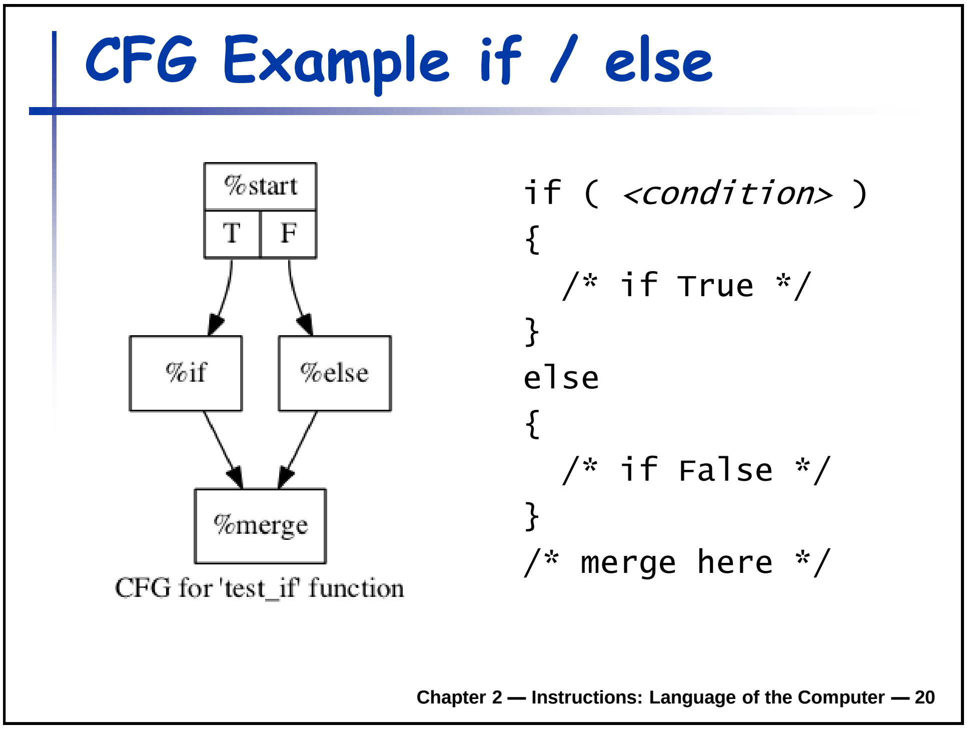


Control Flow Graph (CFG)

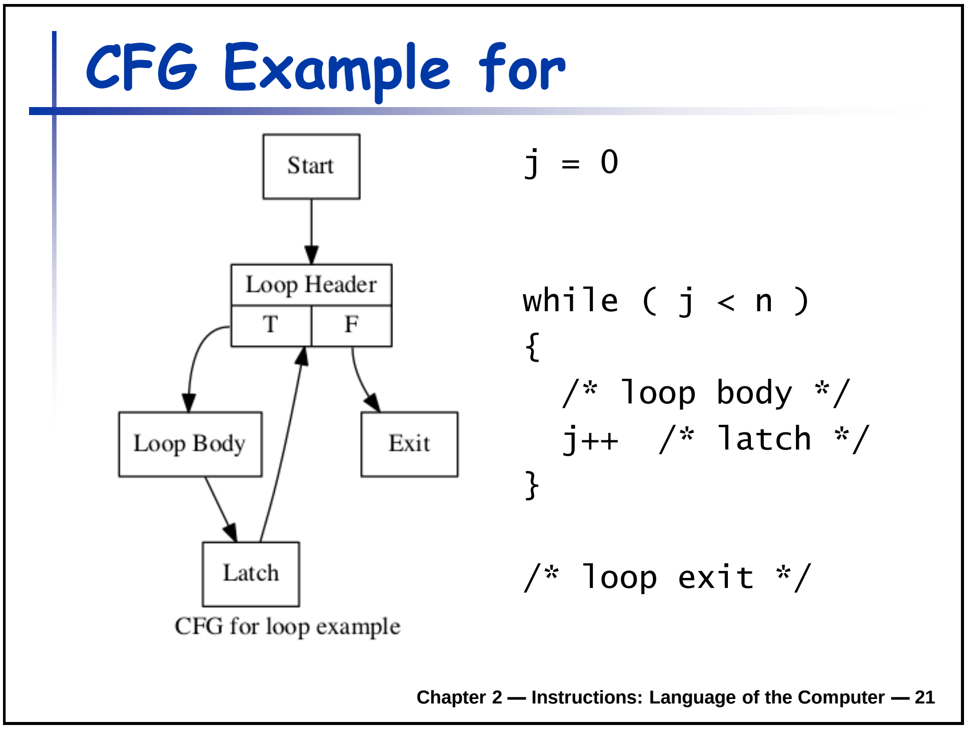
- Graphical representation of program logic / flow
- Directed edges between basic blocks show *possible* code paths
- Any possible execution must be represented by a valid path
- In-edges from predecessors, out-edges to successors



CFG Example if / else

CFG for 'test_if' function

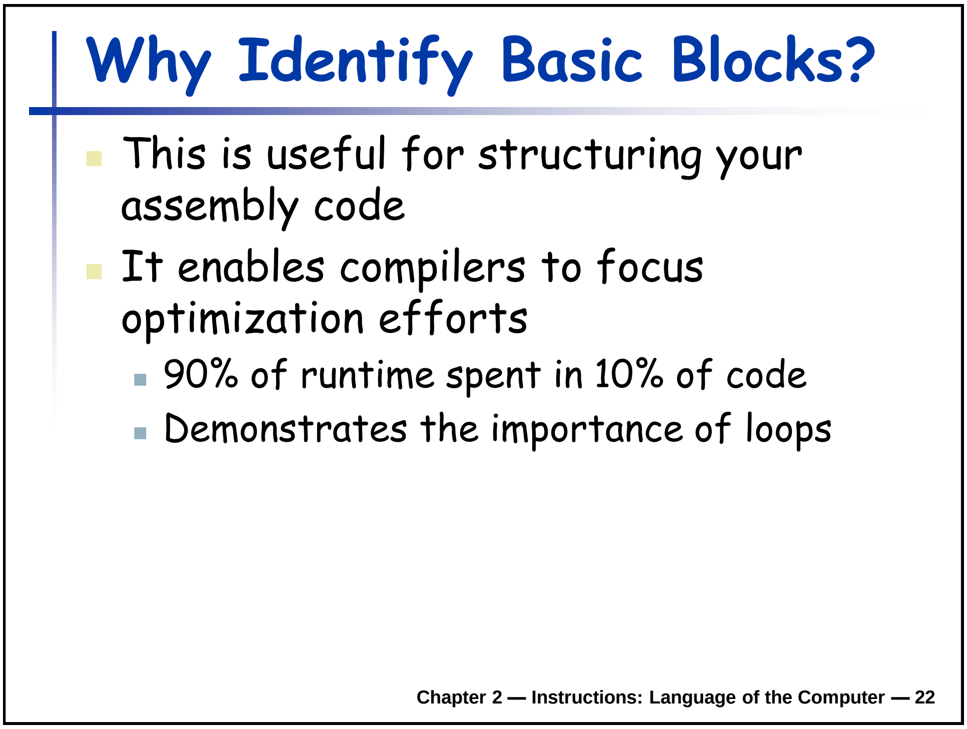
```
if ( <condition> )
{
  /* if True */
}
else
{
  /* if False */
}
/* merge here */
```



CFG Example for

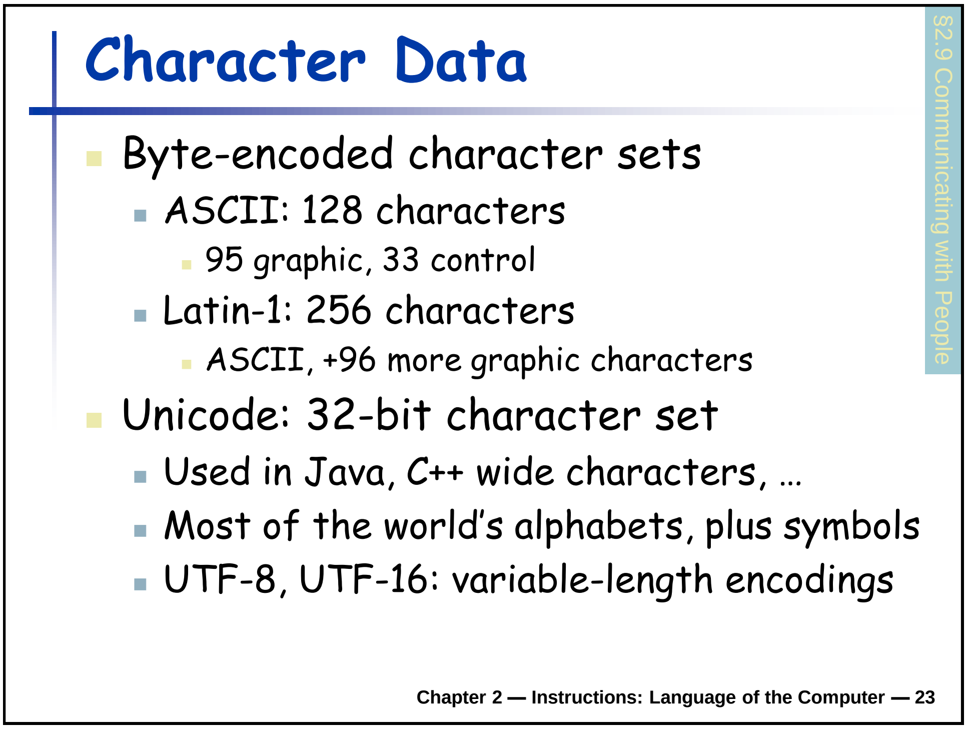
CFG for loop example

```
j = 0


while ( j < n )
{
  /* loop body */
  j++  /* latch */
}

/* loop exit */
```



Why Identify Basic Blocks?

- This is useful for structuring your assembly code
- It enables compilers to focus optimization efforts
  - 90% of runtime spent in 10% of code
  - Demonstrates the importance of loops



Character Data

§2.9 Communicating with People

- Byte-encoded character sets
  - ASCII: 128 characters
    - 95 graphic, 33 control
  - Latin-1: 256 characters
    - ASCII, +96 more graphic characters
- Unicode: 32-bit character set
  - Used in Java, C++ wide characters, …
  - Most of the world's alphabets, plus symbols
  - UTF-8, UTF-16: variable-length encodings

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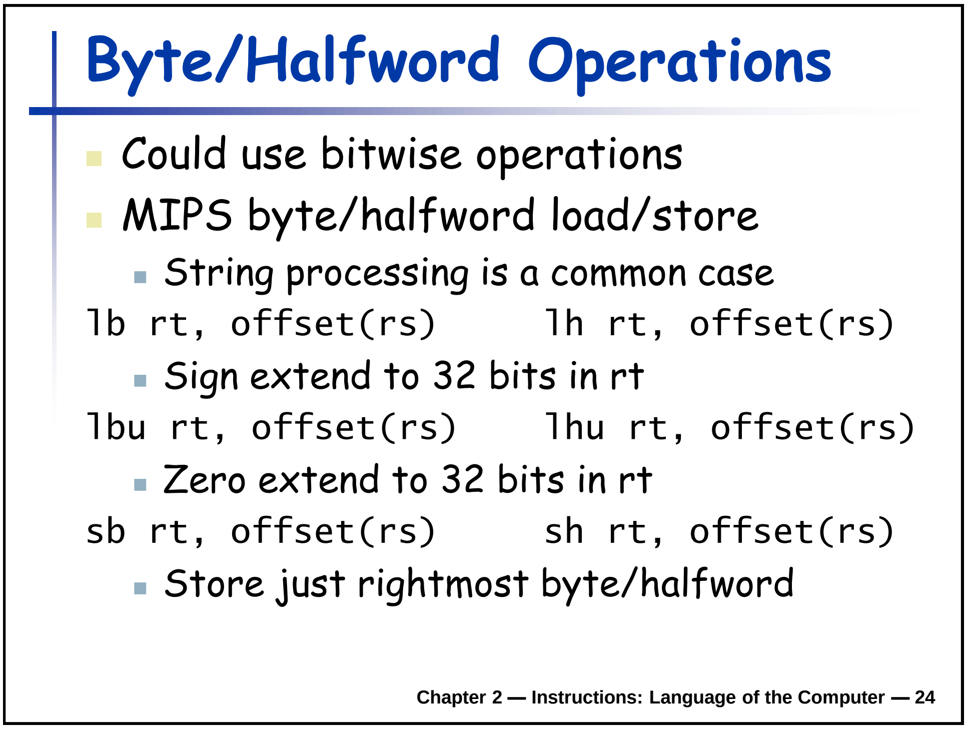

Byte/Halfword Operations

- Could use bitwise operations
- MIPS byte/halfword load/store
  - String processing is a common case

```
lb rt, offset(rs)     lh rt, offset(rs)
```

  - Sign extend to 32 bits in rt

```
lbu rt, offset(rs)    lhu rt, offset(rs)
```

  - Zero extend to 32 bits in rt

```
sb rt, offset(rs)     sh rt, offset(rs)
```

  - Store just rightmost byte/halfword

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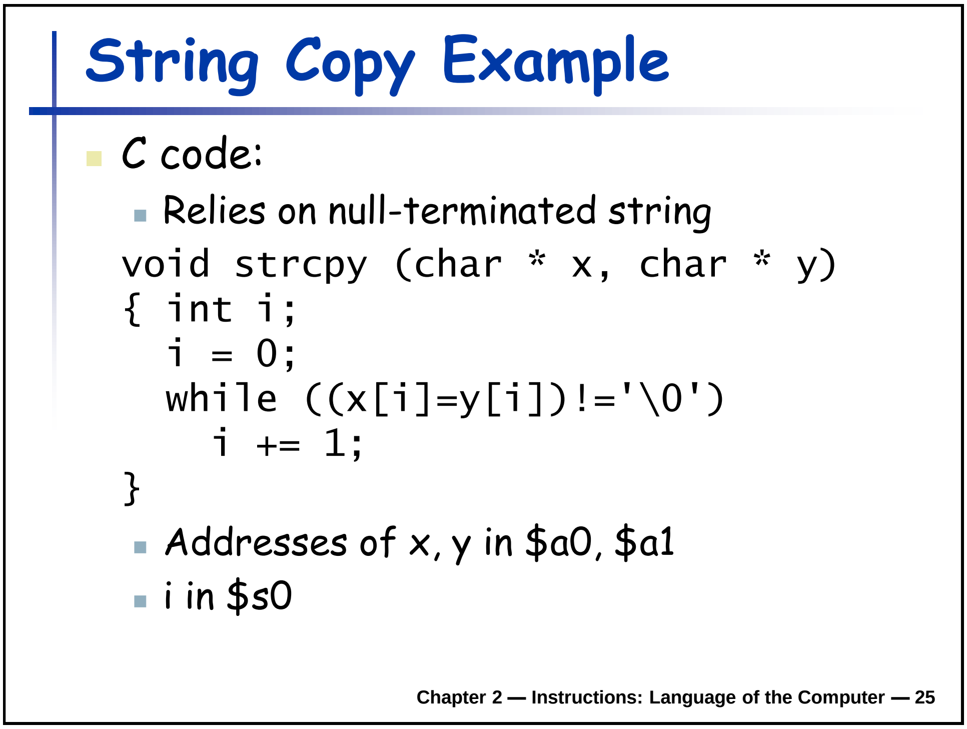
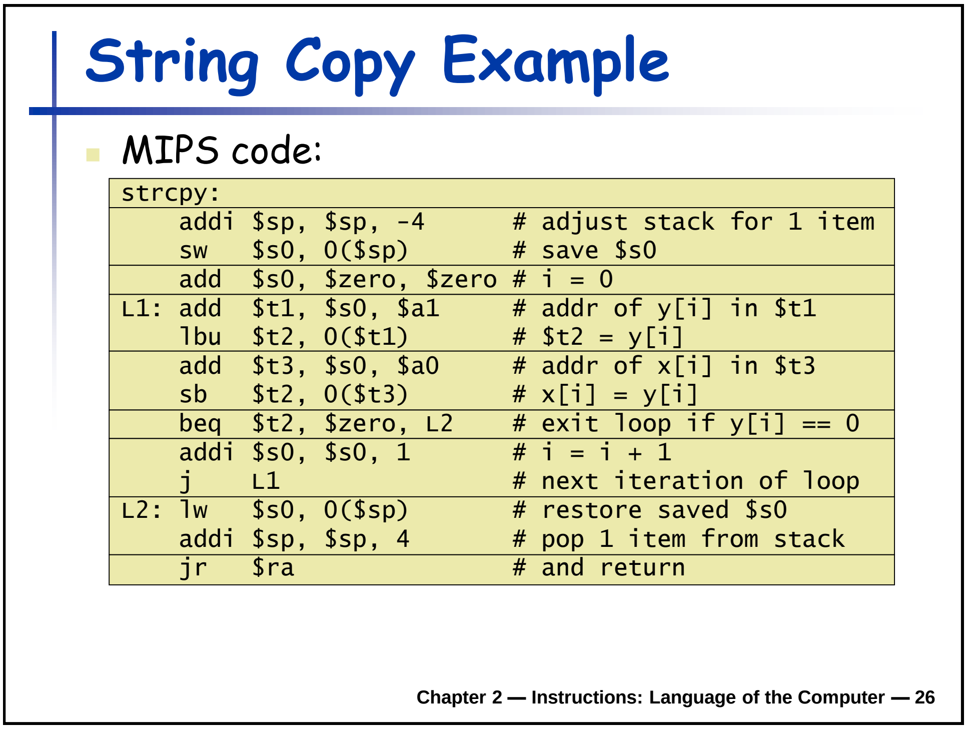


String Copy Example

- C code:
  - Relies on null-terminated string

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

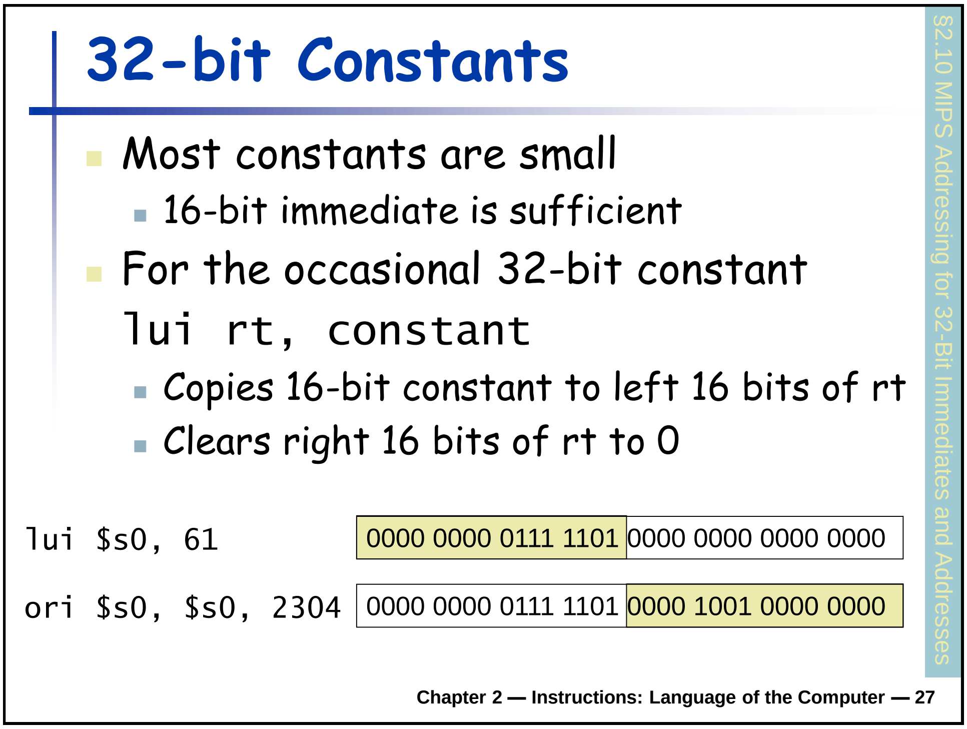
  - Addresses of x, y in $a0, $a1
  - i in $s0



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
```



32-bit Constants

§2.10 MIPS Addressing for 32-Bit Immediates and Addresses

- Most constants are small
  - 16-bit immediate is sufficient
- For the occasional 32-bit constant

  `lui rt, constant`
  - Copies 16-bit constant to left 16 bits of rt
  - Clears right 16 bits of rt to 0

`lui $s0, 61`	0000 0000 0111 1101	0000 0000 0000 0000
`ori $s0, $s0, 2304`	0000 0000 0111 1101	0000 1001 0000 0000

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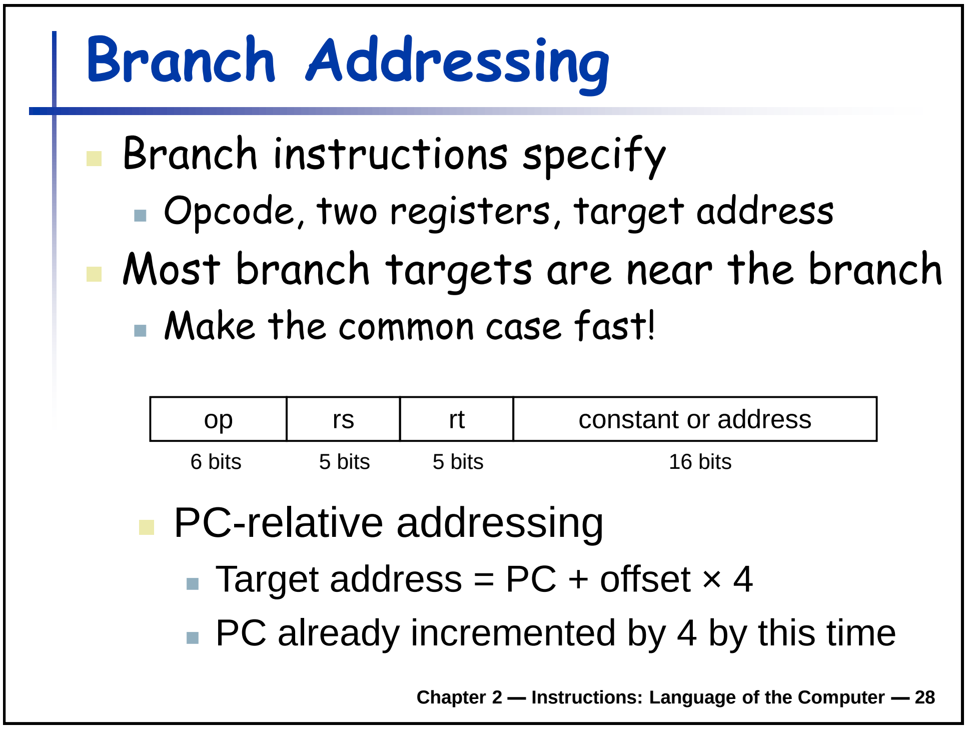

Branch Addressing

- Branch instructions specify
  - Opcode, two registers, target address
- Most branch targets are near the branch
  - Make the common case fast!

op	rs	rt	constant or address
6 bits	5 bits	5 bits	16 bits

- PC-relative addressing
  - Target address = PC + offset × 4
  - PC already incremented by 4 by this time

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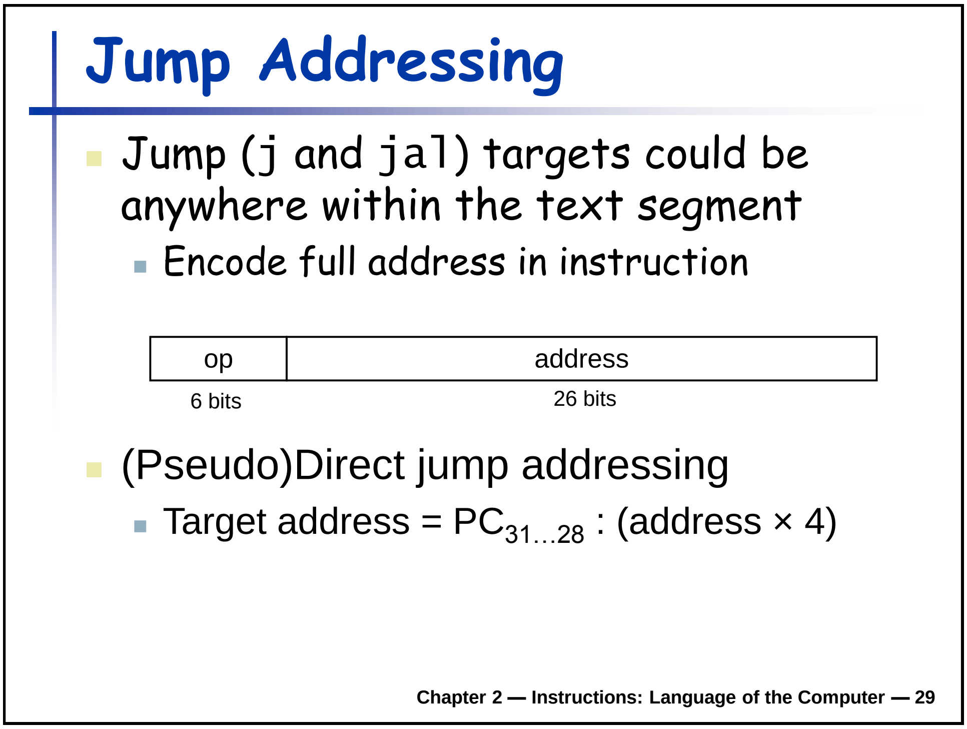
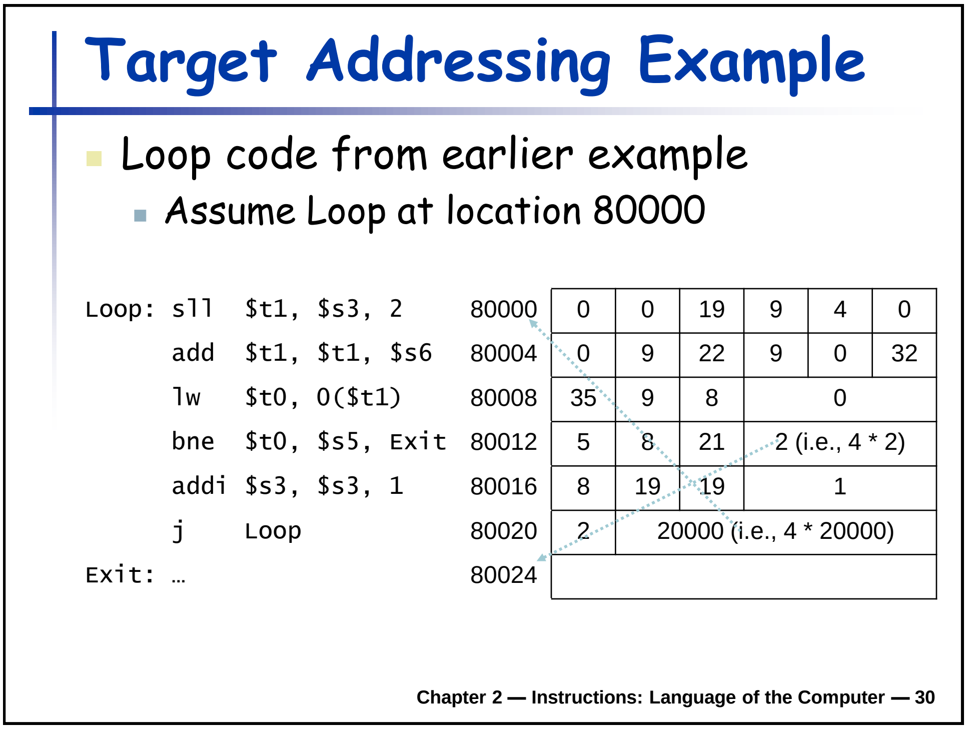


Jump Addressing

- Jump (`j` and `jal`) targets could be anywhere within the text segment
  - Encode full address in instruction

op	address
6 bits	26 bits

- (Pseudo)Direct jump addressing
  - Target address = PC$_{31\ldots28}$: (address × 4)

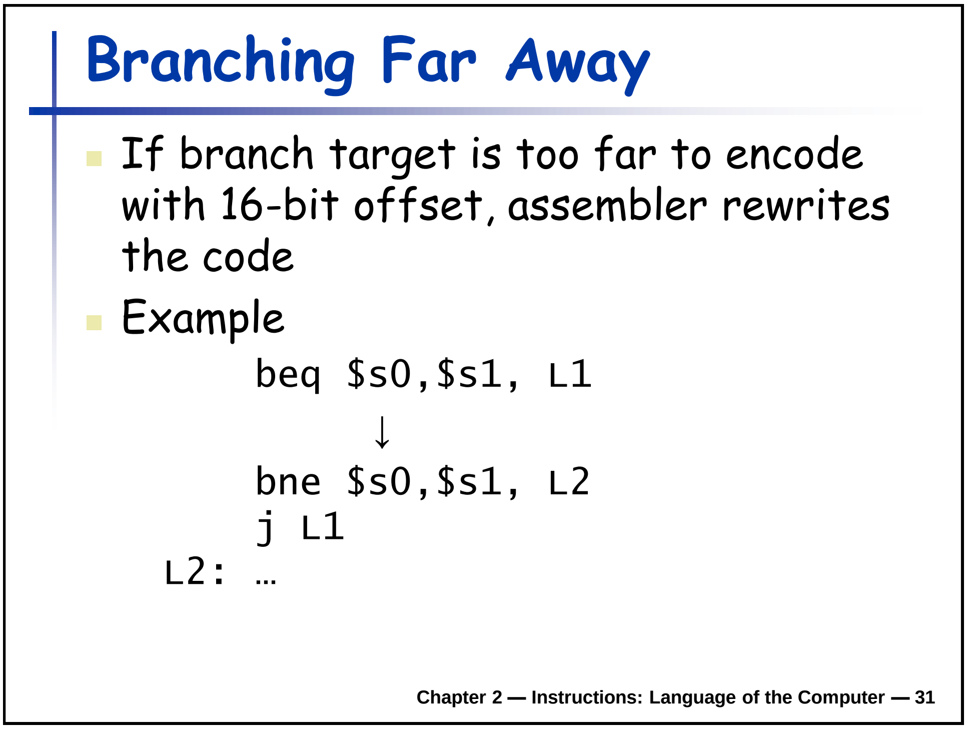


Target Addressing Example

- Loop code from earlier example
  - Assume Loop at location 80000

```
Loop: sll  $t1, $s3, 2
      add  $t1, $t1, $s6
      lw   $t0, 0($t1)
      bne  $t0, $s5, Exit
      addi $s3, $s3, 1
      j    Loop
Exit: …
```

80000	0	0	19	9	4	0
80004	0	9	22	9	0	32
80008	35	9	8	0		
80012	5	8	21	2 (i.e., 4 * 2)		
80016	8	19	19	1		
80020	2	20000 (i.e., 4 * 20000)				
80024						



Branching Far Away

- If branch target is too far to encode with 16-bit offset, assembler rewrites the code
- Example

```
        beq $s0,$s1, L1
                ↓
        bne $s0,$s1, L2
        j L1
    L2: …
```

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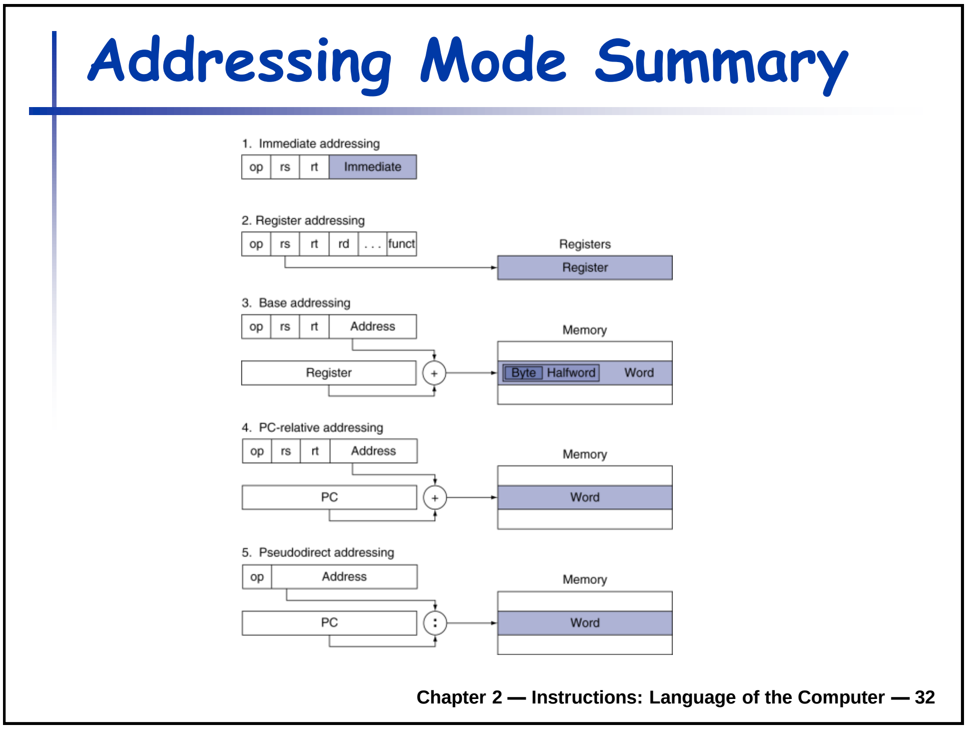

Addressing Mode Summary

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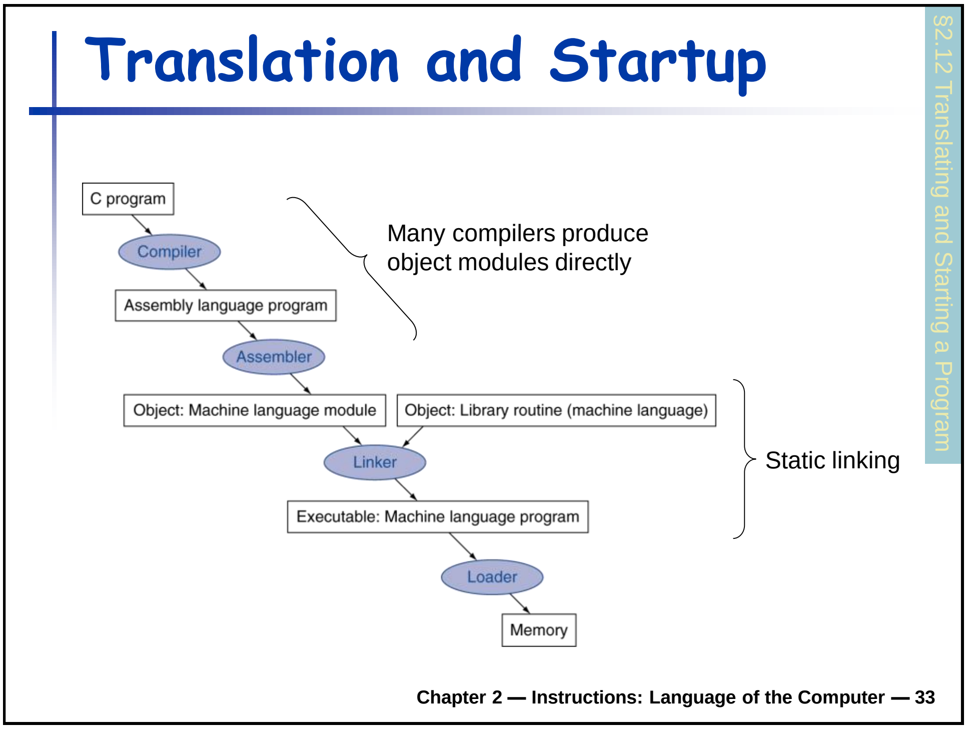

Translation and Startup

§2.12 Translating and Starting a Program

C program

Compiler

Assembly language program

Assembler

Object: Machine language module

Object: Library routine (machine language)

Linker

Executable: Machine language program

Loader

Memory

Many compilers produce object modules directly

Static linking

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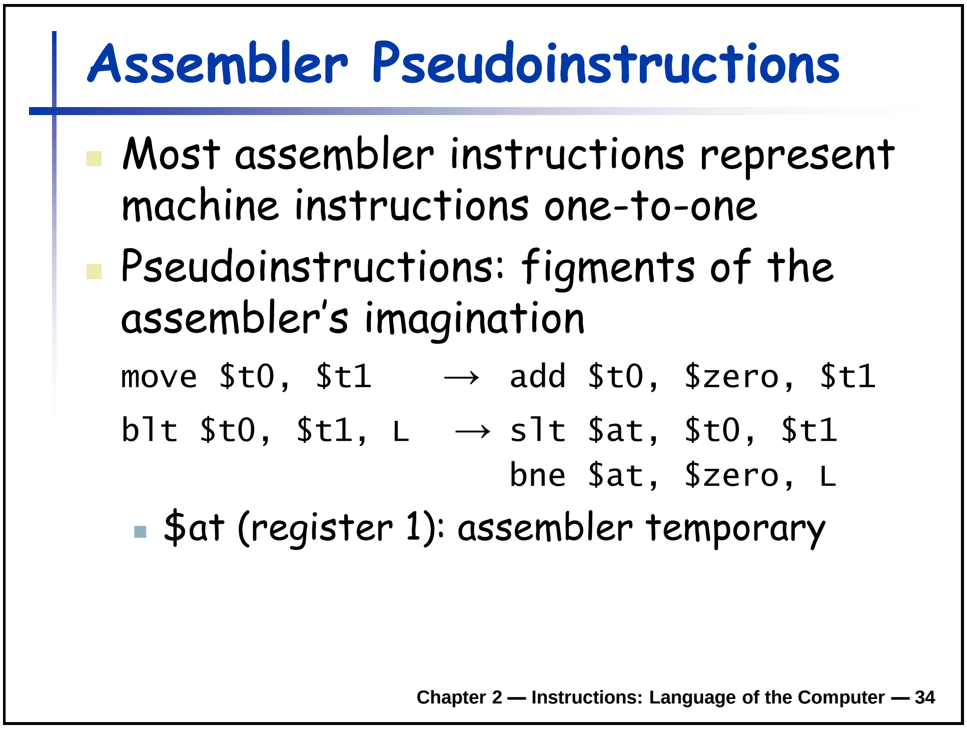

Assembler Pseudoinstructions

- Most assembler instructions represent machine instructions one-to-one
- Pseudoinstructions: figments of the assembler's imagination

```
move $t0, $t1     → add $t0, $zero, $t1
blt $t0, $t1, L   → slt $at, $t0, $t1
                    bne $at, $zero, L
```

  - $at (register 1): assembler temporary

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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

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Linking Object Modules

- Produces an executable image
  1. Merges segments
  2. Resolve labels (determine their addresses)
  3. Patch location-dependent and external refs
- Could leave location dependencies for fixing by a relocating loader
  - But with virtual memory, no need to do this
  - Program can be loaded into absolute location in virtual memory space

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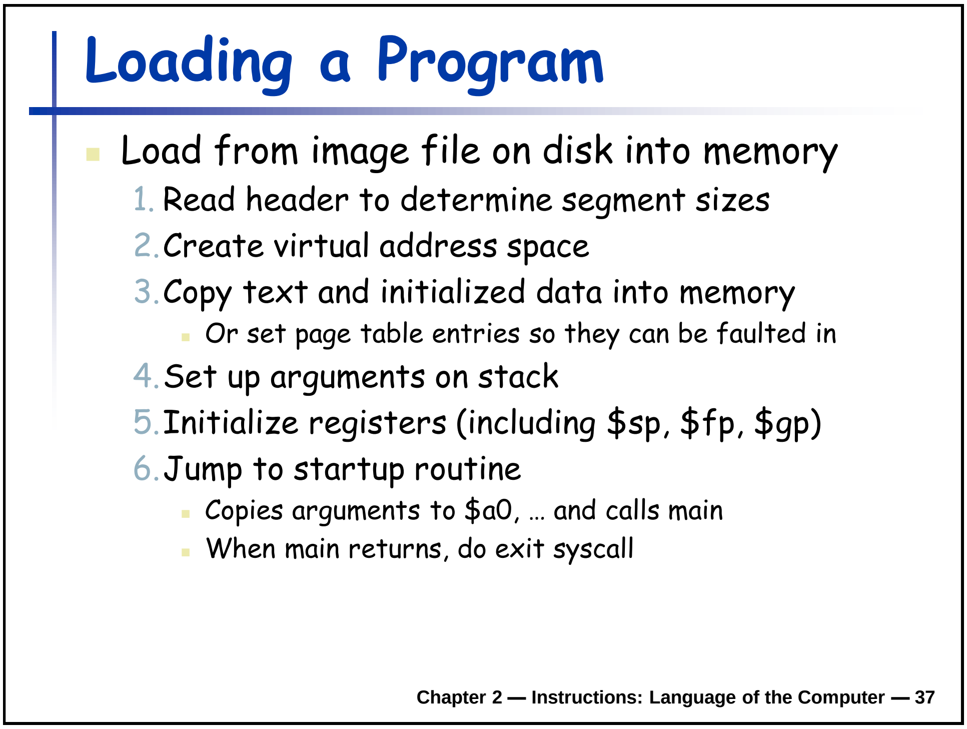

Loading a Program

- 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
     - Or set page table entries so they can be faulted in
  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

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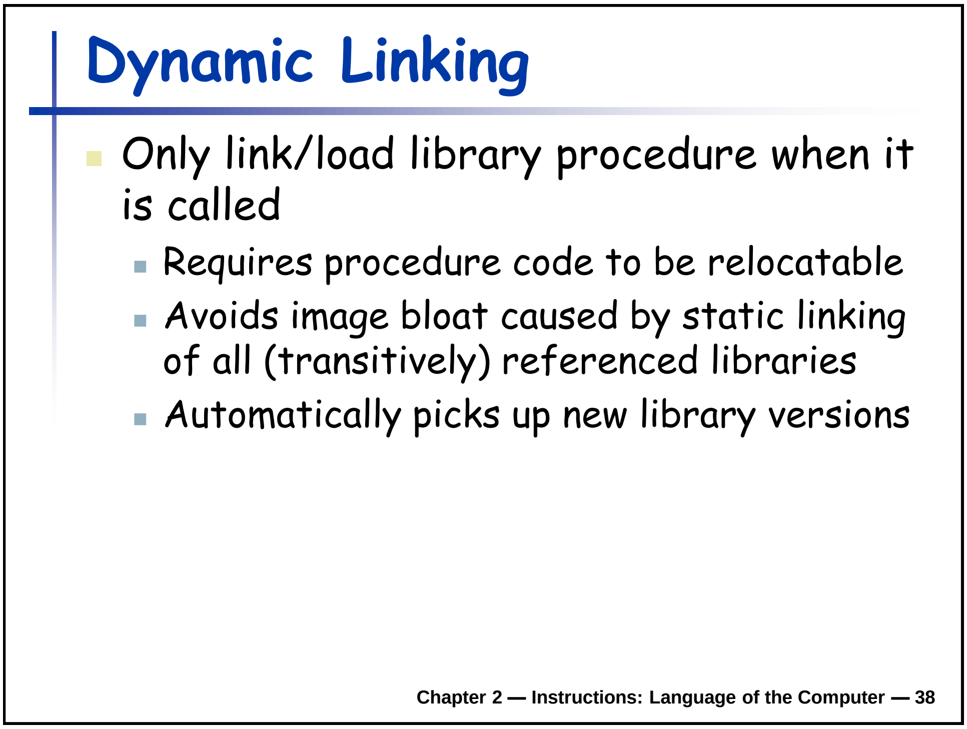

Dynamic Linking

- Only link/load library procedure when it is called
  - Requires procedure code to be relocatable
  - Avoids image bloat caused by static linking of all (transitively) referenced libraries
  - Automatically picks up new library versions

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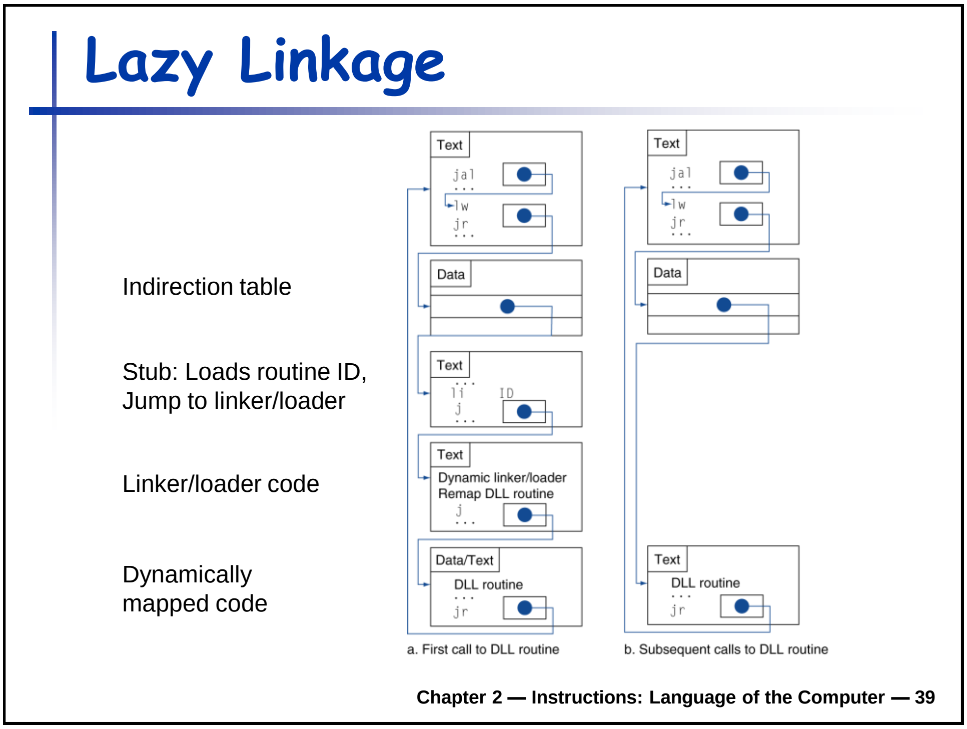

Lazy Linkage

Indirection table

Stub: Loads routine ID,
Jump to linker/loader

Linker/loader code

Dynamically
mapped code

a. First call to DLL routine

b. Subsequent calls to DLL routine

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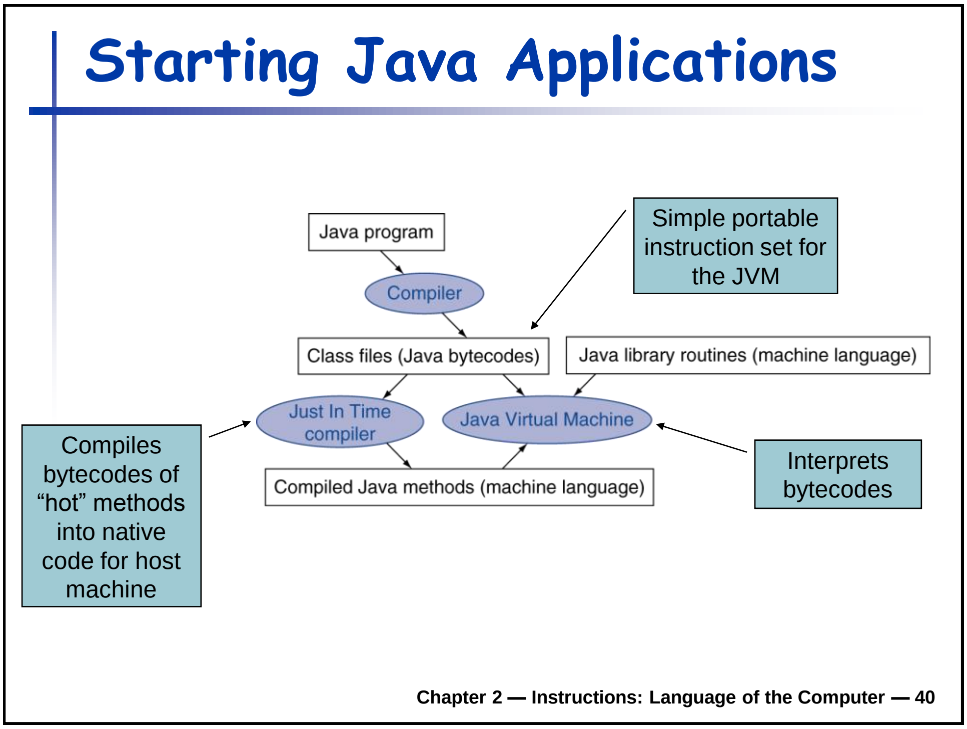

Starting Java Applications

Java program

Compiler

Class files (Java bytecodes)

Java library routines (machine language)

Just In Time compiler

Java Virtual Machine

Compiled Java methods (machine language)

Simple portable instruction set for the JVM

Compiles bytecodes of “hot” methods into native code for host machine

Interprets bytecodes

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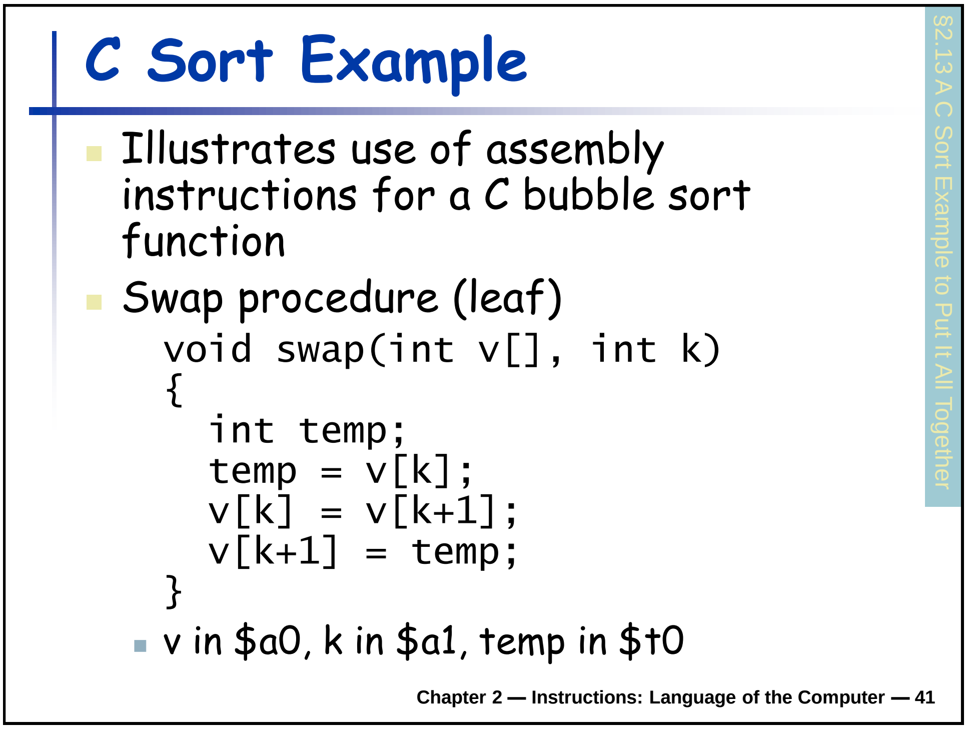


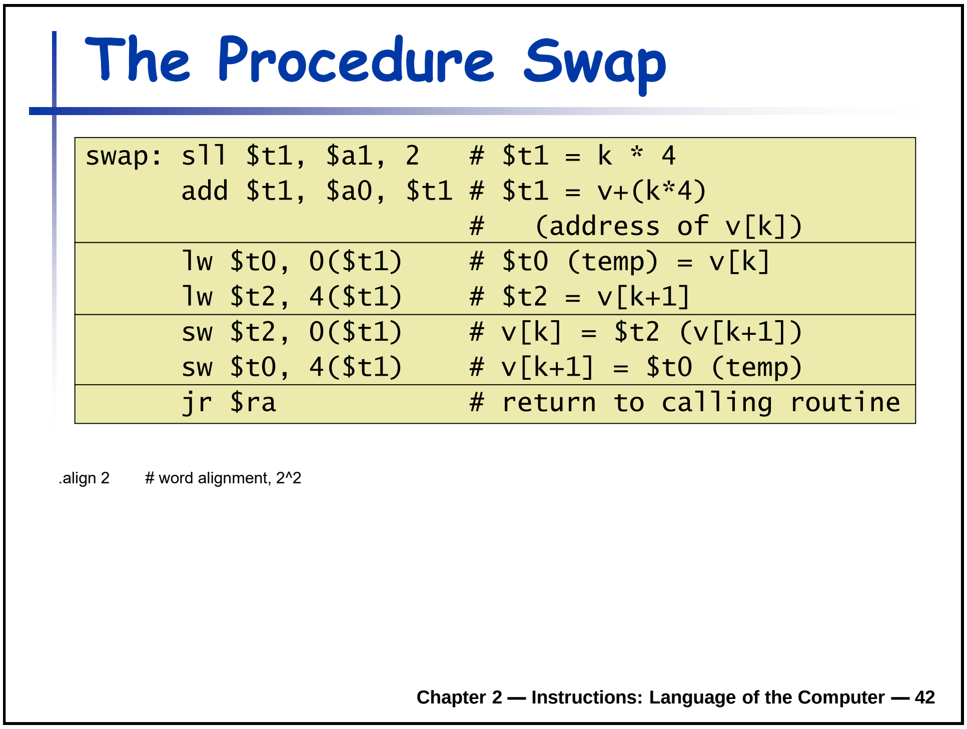
C Sort Example

§2.13 A C Sort Example to Put It All Together

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

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

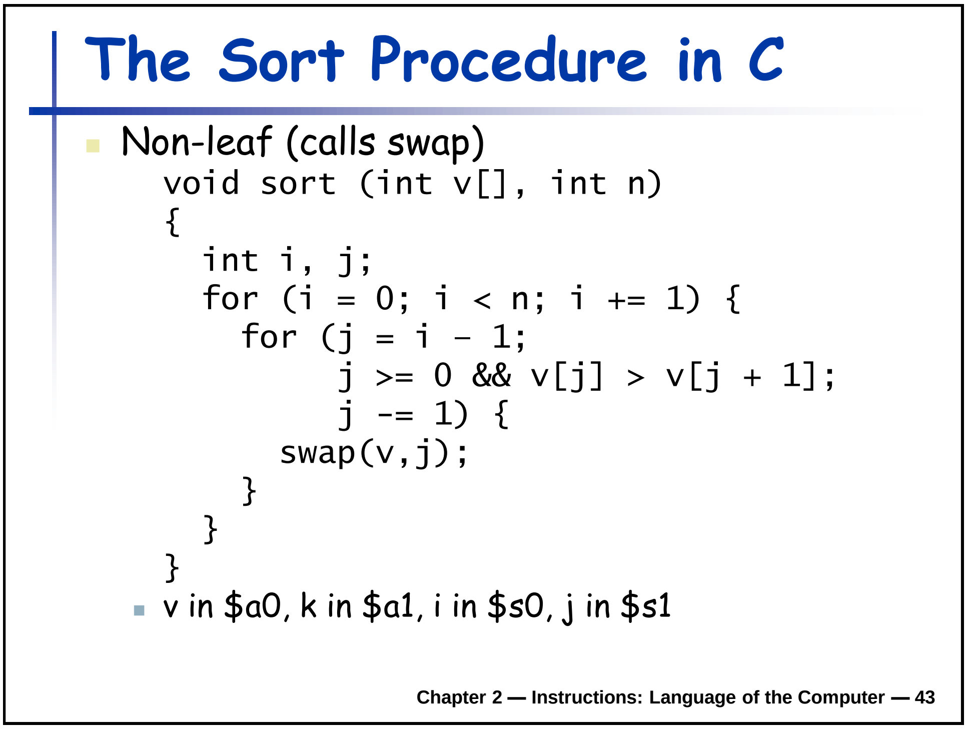
  - v in $a0, k in $a1, temp in $t0



The Procedure 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
```

```
.align 2      # word alignment, 2^2
```



The Sort Procedure in C

- Non-leaf (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, k in $a1, i in $s0, j in $s1

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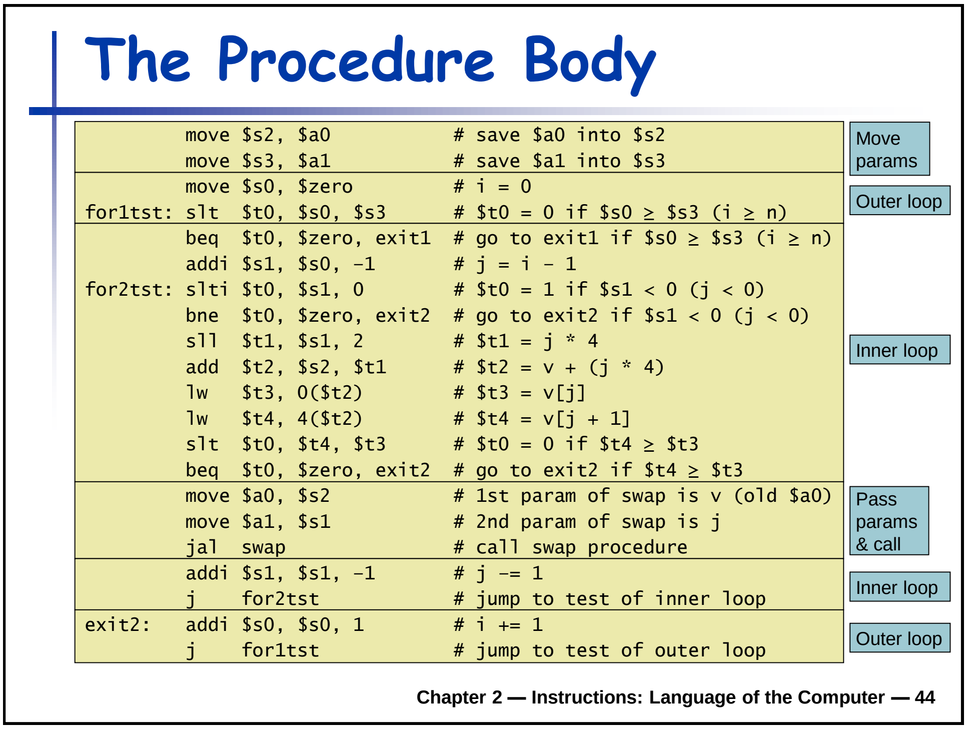

The Procedure Body

```
         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 procedure
         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

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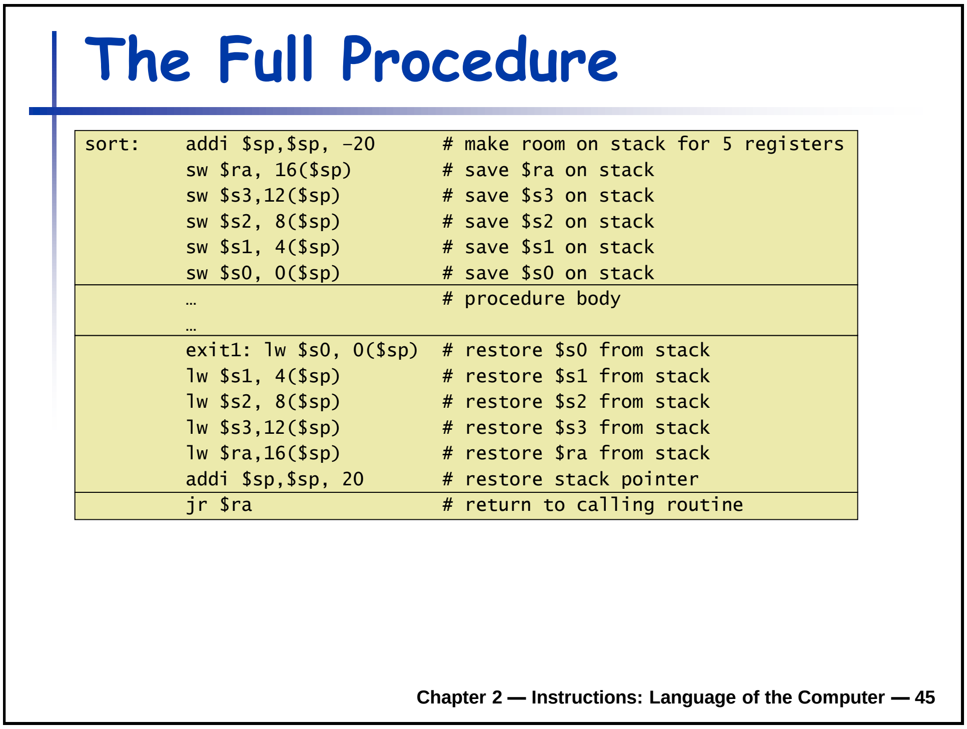

The Full Procedure

```
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
         …                       # procedure 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
```

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