MIPS Instruction Set Architecture (2)

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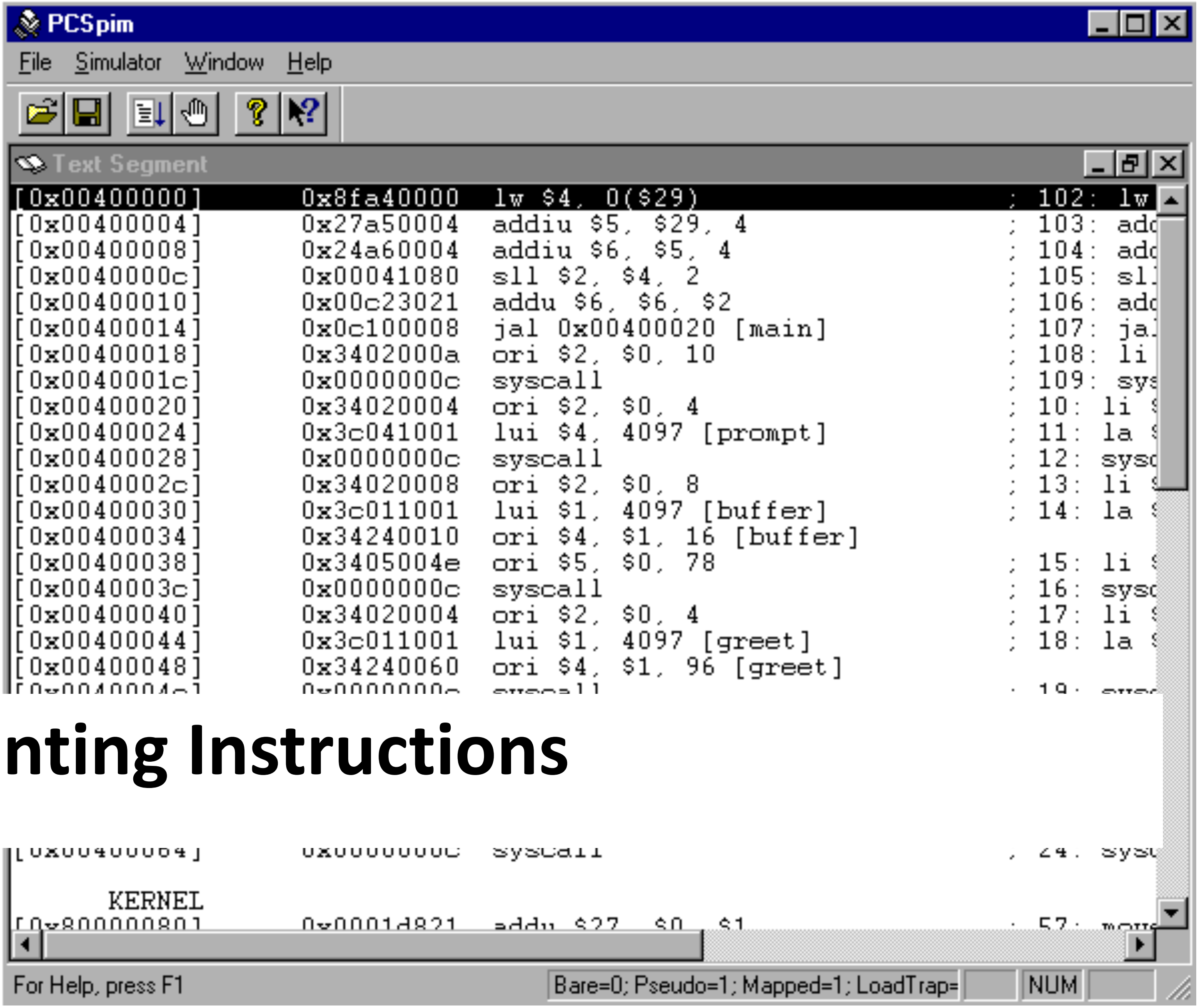
Outline

Textbook: P&H 2.5-2.12 (Except 2.11) – for 4th Ed.
P&H 2.5-2.11 (Except 2.10) – for 5th Ed.

- Representing Instructions
- Logical Operations
- Instructions for Making Decisions
- Supporting Procedures in Computer Hardware
- Communicating with People
- MIPS Addressing for 32-Bit Immediates and Addresses
- Translating and Starting a Program
- Array vs. Pointers – Will not cover (2.14 in 4th Ed.)



```
[0x00400000]    0x8fa40000  lw $4, 0($29)              ; 102: lw
[0x00400004]    0x27a50004  addiu $5, $29, 4           ; 103: ad
[0x00400008]    0x24a60004  addiu $6, $5, 4            ; 104: ad
[0x0040000c]    0x00041080  sll $2, $4, 2              ; 105: sl
[0x00400010]    0x00c23021  addu $6, $6, $2            ; 106: ad
[0x00400014]    0x0c100008  jal 0x00400020 [main]      ; 107: ja
[0x00400018]    0x3402000a  ori $2, $0, 10             ; 108: li
[0x0040001c]    0x0000000c  syscall                    ; 109: sys
[0x00400020]    0x34020004  ori $2, $0, 4              ; 10: li
[0x00400024]    0x3c041001  lui $4, 4097 [prompt]      ; 11: la
[0x00400028]    0x0000000c  syscall                    ; 12: sys
[0x0040002c]    0x34020008  ori $2, $0, 8              ; 13: li
[0x00400030]    0x3c011001  lui $1, 4097 [buffer]      ; 14: la
[0x00400034]    0x34240010  ori $4, $1, 16 [buffer]
[0x00400038]    0x3405004e  ori $5, $0, 78             ; 15: li
[0x0040003c]    0x0000000c  syscall                    ; 16: sys
[0x00400040]    0x34020004  ori $2, $0, 4              ; 17: li
[0x00400044]    0x3c011001  lui $1, 4097 [greet]       ; 18: la
[0x00400048]    0x34240060  ori $4, $1, 96 [greet]
[0x0040004c]    0x0000000c  syscall                    ; 19: sys

[0x00400064]    0x0000000c  syscall                    ; 24: sys

      KERNEL
[0x80000080]    0x0001d821  addu $27, $0, $1           ; 57: mov
```

Representing Instructions

Representing Instructions

- Instructions are encoded in binary
  - Called machine code
- MIPS instructions
  - Encoded as 32-bit instruction words
  - Small number of formats encoding operation code (opcode), register numbers, …
  - Regularity!
- Register numbers
  - $t0 – $t7 are reg's 8 – 15
  - $t8 – $t9 are reg's 24 – 25
  - $s0 – $s7 are reg's 16 – 23

MIPS R-format Instructions

op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

- Instruction fields
  - op: operation code (opcode)
  - rs: first source register number
  - rt: second source register number
  - rd: destination register number
  - shamt: shift amount (00000 for now)
  - funct: function code (extends opcode)

R-format Example

op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

`add $t0, $s1, $s2`

special	$s1	$s2	$t0	0	add
0	17	18	8	0	32
000000	10001	10010	01000	00000	100000

$00000010\ 00110010\ 01000000\ 00100000_2 = 02324020_{16}$

MIPS I-format Instructions

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

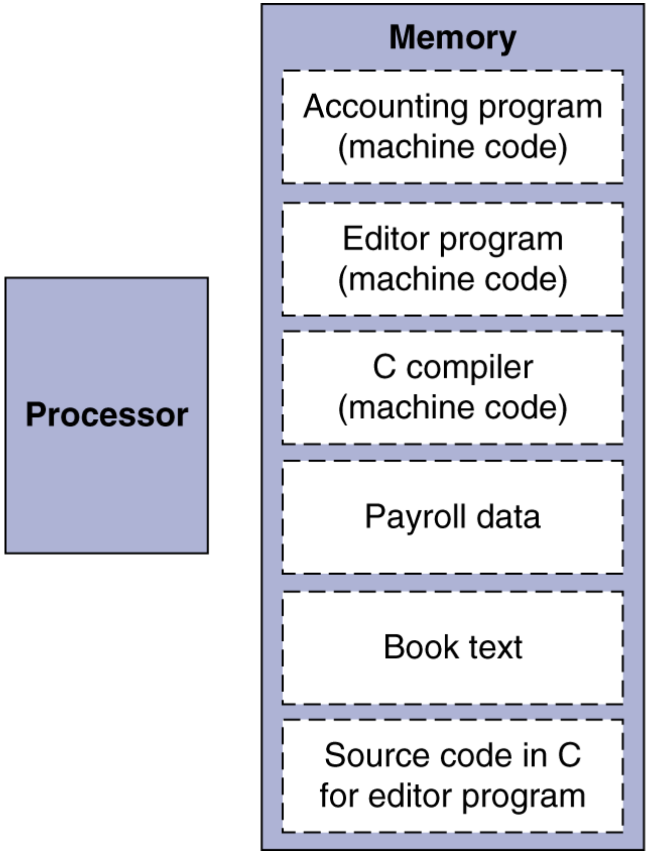
- Immediate arithmetic and load/store instructions
  - rt: destination or source register number
  - Constant: -2^{15} to $+2^{15} - 1$
  - Address: offset added to base address in rs
- *Design Principle 4:* Good design demands good compromises
  - Different formats complicate decoding, but allow 32-bit instructions uniformly
  - Keep formats as similar as possible

MIPS J-format Instructions

op	constant or address
6 bits	26 bits

- Jump instructions (`j` and `jal`)
  - Address: encode 26-bit target address

Stored Program Computers



- Instructions represented in binary, just like data
- Instructions and data stored in memory
- Programs can operate on programs
  - e.g., compilers, linkers, …
- Binary compatibility allows compiled programs to work on different computers
  - Standardized ISAs

Logical Operations

Logical Operations

- Instructions for bitwise manipulation

Operation	C	Java	MIPS
Shift left	<<	<<	`sll`
Shift right	>>	>>	`srl`
Bitwise AND	&	&	`and, andi`
Bitwise OR	|	|	`or, ori`
Bitwise NOT	~	~	`nor`

Useful for extracting and inserting groups of bits in a word

Shift Operations

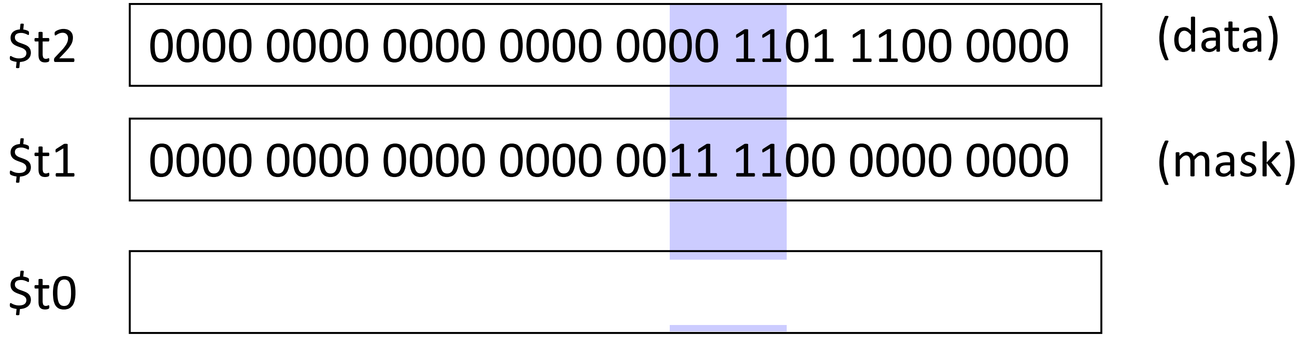
op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

- shamt: how many positions to shift
- Shift left logical
  - Shift left and fill with 0 bits
  - `sll` by *i* bits multiplies by 2^i
- Shift right logical
  - Shift right and fill with 0 bits
  - `srl` by *i* bits divides by 2^i (unsigned only)
  - cf. `sra`: shift right arithmetic

AND Operations

- Useful to mask bits in a word
  - Select some bits, clear others to 0

```
and $t0, $t1, $t2
```



$t2 0000 0000 0000 0000 0000 1101 1100 0000 (data)

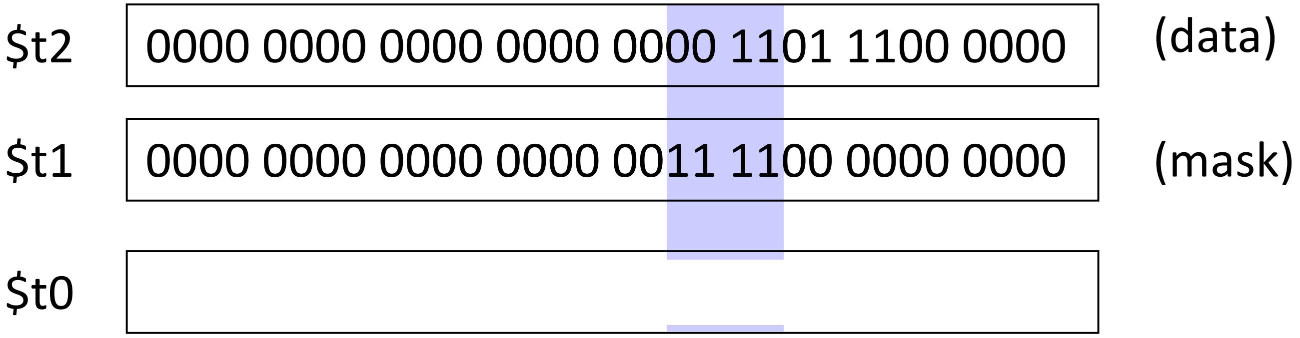
$t1 0000 0000 0000 0000 0011 1100 0000 0000 (mask)

$t0

OR Operations

- Useful to include bits in a word
  - Set some bits to 1, leave others unchanged

```
or $t0, $t1, $t2
```



$t2 0000 0000 0000 0000 0000 1101 1100 0000 (data)

$t1 0000 0000 0000 0000 0011 1100 0000 0000 (mask)

$t0

NOT Operations

- Useful to invert bits in a word
  - Change 0 to 1, and 1 to 0
- MIPS has NOR 3-operand instruction
  - a NOR b == NOT (a OR b)

```
nor $t0, $t1, $zero
```

Register 0:
always read as zero

$t1 0000 0000 0000 0000 0011 1100 0000 0000

$t0 1111 1111 1111 1111 1100 0011 1111 1111

Instructions for Making Decisions

Conditional Operations

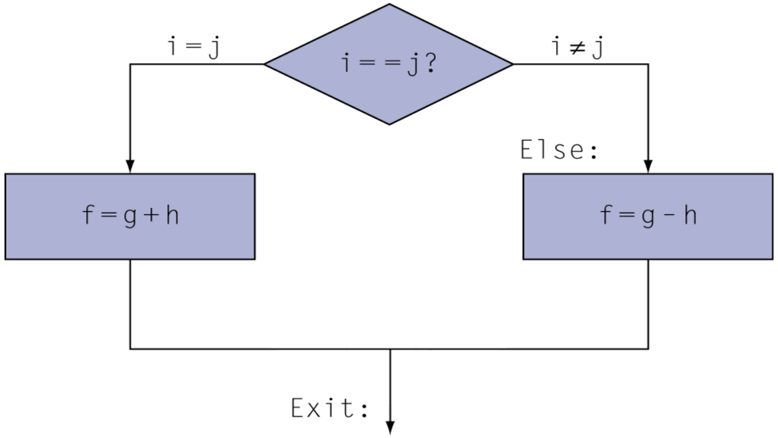
- Branch to a labeled instruction if a condition is true
  - Otherwise, continue sequentially
- `beq rs, rt, L1`
  - if (rs == rt) branch to instruction labeled L1;
- `bne rs, rt, L1`
  - if (rs != rt) branch to instruction labeled L1;
- `j L1`
  - unconditional jump to instruction labeled L1

Compiling If Statements

- C code:

```
if (i==j) f = g+h;
else f = g-h;
```

  - f, g, … in \$s0, \$s1, …
- Compiled MIPS code:



Assembler calculates addresses

Compiling Loop Statements

- C code:

```
while (save[i] == k) i += 1;
```

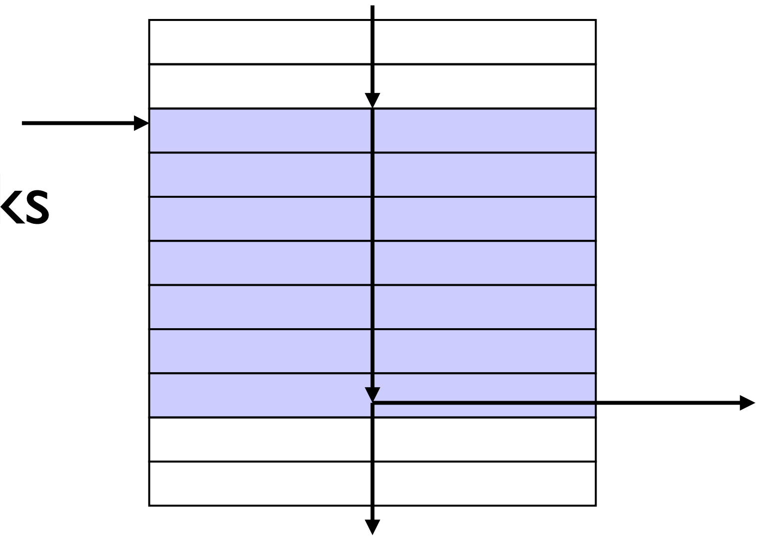
  - i in $s3, k in $s5, address of save in $s6

- Compiled MIPS code:

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

Basic Blocks

- A basic block is a sequence of instructions with
  - No embedded branches (except at end)
  - No branch targets (except at beginning)
- A compiler identifies basic blocks for optimization
- An advanced processor can accelerate execution of basic blocks



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 penalized!
- `beq` and `bne` are the common case
- 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

Supporting Procedures in Computer Hardware

Procedure Calling

- Steps required
  1. Place parameters in registers
  2. Transfer control to procedure
  3. Acquire storage for procedure
  4. Perform procedure's operations
  5. Place result in register for caller
  6. Return to place of call

Register Usage

- $a0 – $a3: arguments (reg's 4 – 7)
- $v0, $v1: result values (reg's 2 and 3)
- $t0 – $t9: temporaries (caller-save reg's)
  - Can be overwritten by callee
- $s0 – $s7: saved (callee-saved reg's)
  - 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)

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

Leaf Procedure Example (Continued)

- MIPS code:

```
leaf_example:
```

```
  addi $sp, $sp, -4
  sw   $s0, 0($sp)
```

Save $s0 on stack

```
  add  $t0, $a0, $a1
  add  $t1, $a2, $a3
  sub  $s0, $t0, $t1
```

Procedure body

```
  add  $v0, $s0, $zero
```

Result

```
  lw   $s0, 0($sp)
  addi $sp, $sp, 4
```

Restore $s0

```
  jr   $ra
```

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 temporaries 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 f;
  else return n * fact(n - 1);
}
```

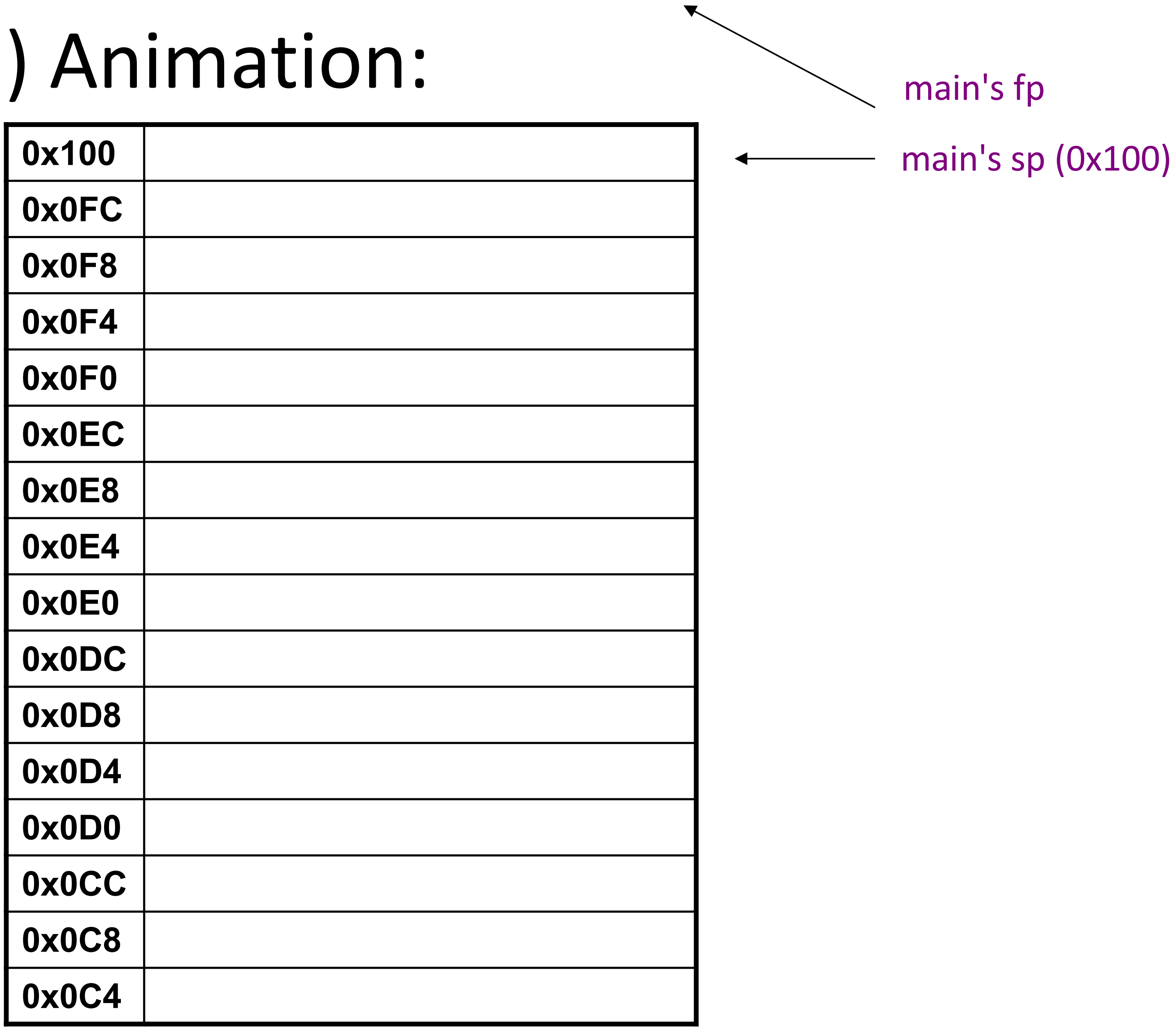
  - Argument n in $a0
  - Result in $v0

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
```

fact() Animation:

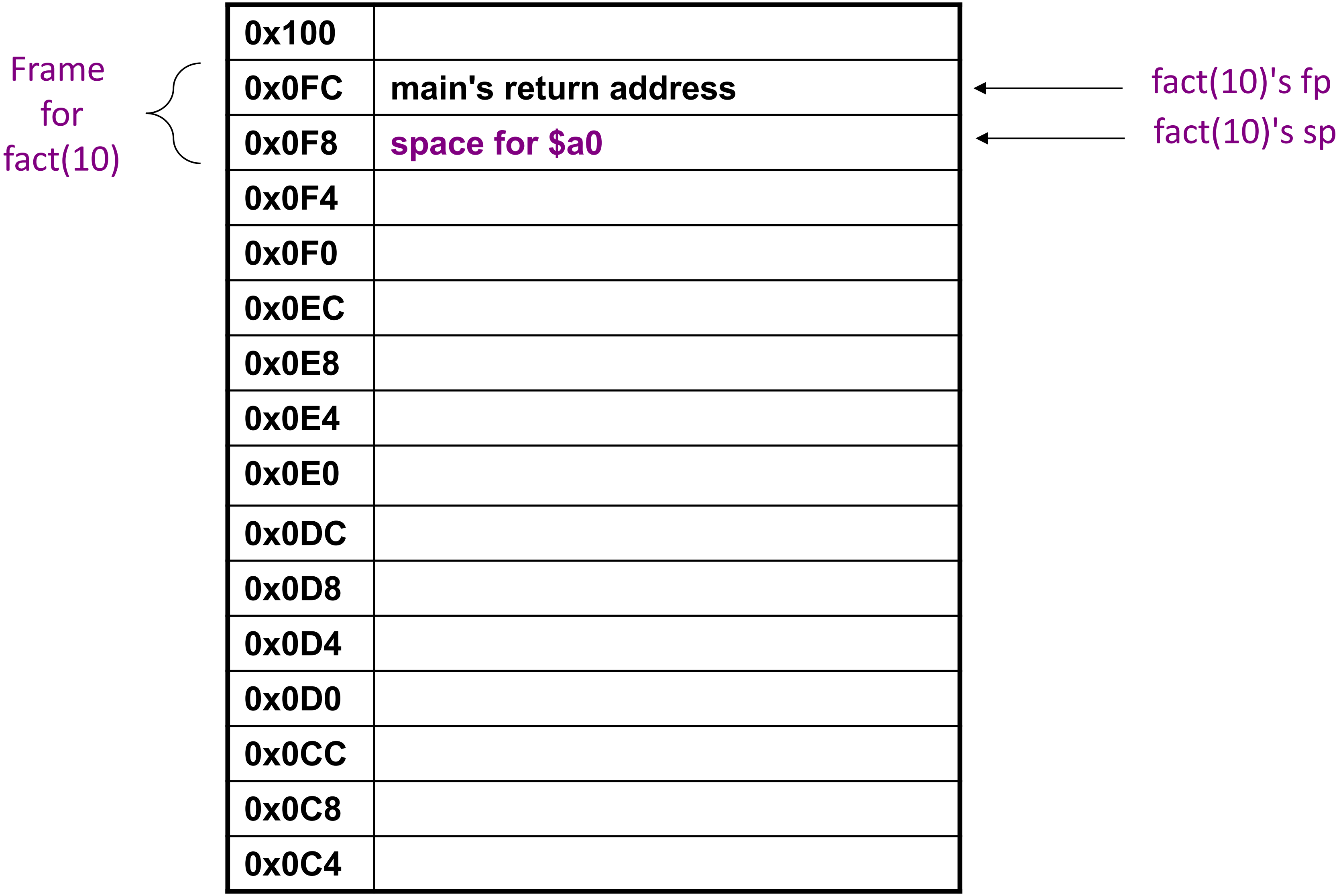


0x100	
0x0FC	
0x0F8	
0x0F4	
0x0F0	
0x0EC	
0x0E8	
0x0E4	
0x0E0	
0x0DC	
0x0D8	
0x0D4	
0x0D0	
0x0CC	
0x0C8	
0x0C4	

main's fp

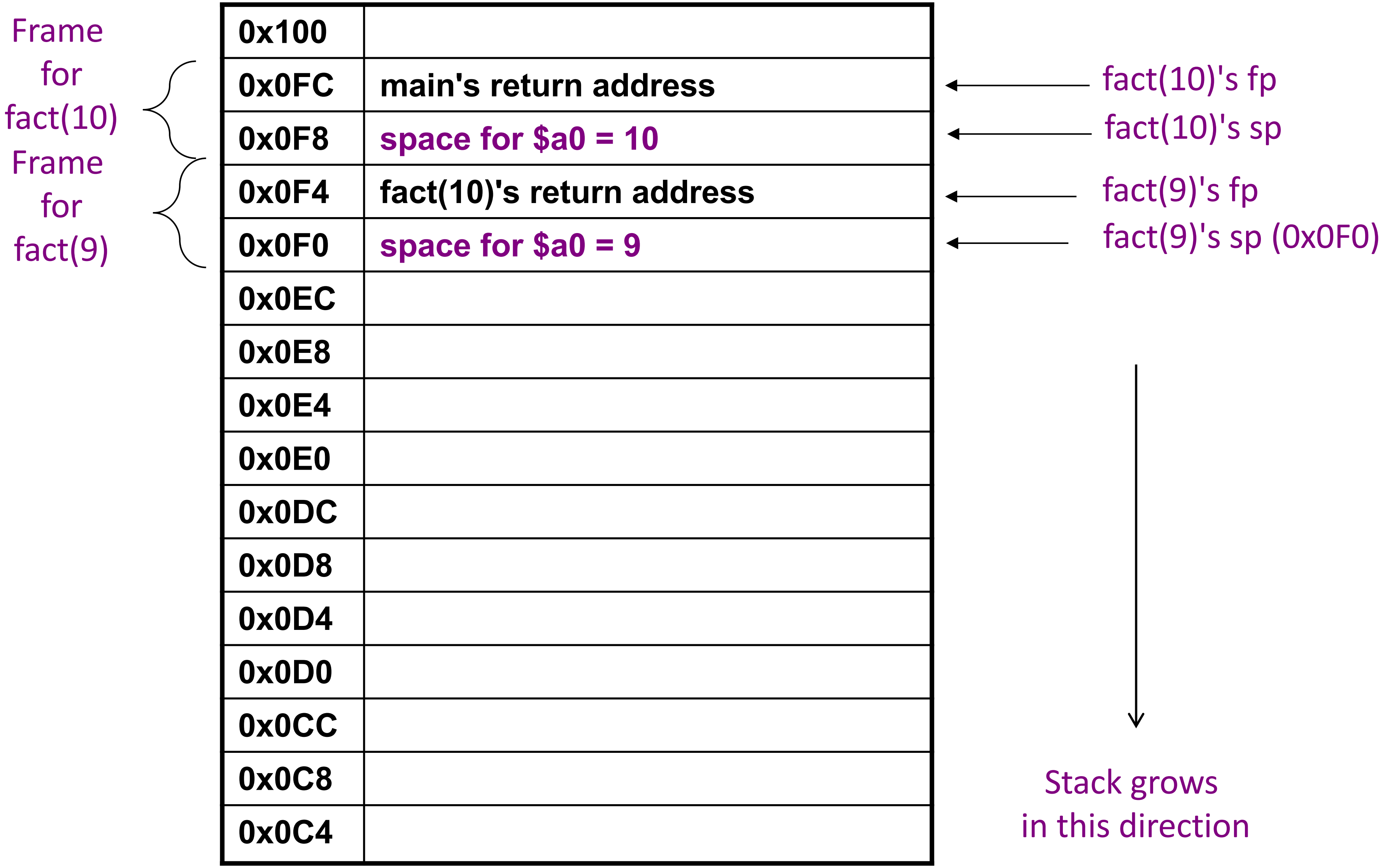
main's sp (0x100)

fact() Animation:



0x100	
0x0FC	main's return address
0x0F8	space for $a0
0x0F4	
0x0F0	
0x0EC	
0x0E8	
0x0E4	
0x0E0	
0x0DC	
0x0D8	
0x0D4	
0x0D0	
0x0CC	
0x0C8	
0x0C4	

fact() Animation:



0x100	
0x0FC	**main's return address**
0x0F8	**space for $a0 = 10**
0x0F4	**fact(10)'s return address**
0x0F0	**space for $a0 = 9**
0x0EC	
0x0E8	
0x0E4	
0x0E0	
0x0DC	
0x0D8	
0x0D4	
0x0D0	
0x0CC	
0x0C8	
0x0C4	

Frame for fact(10)

Frame for fact(9)

fact(10)'s fp

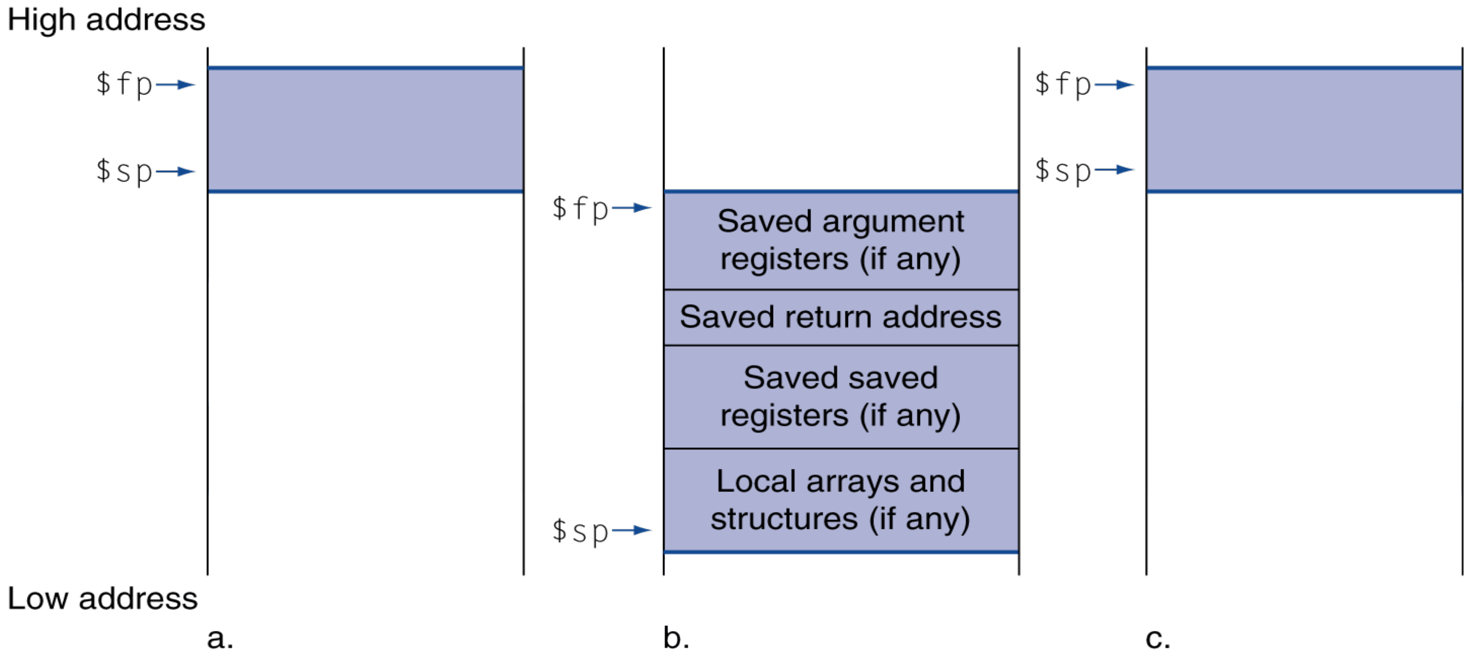
fact(10)'s sp

fact(9)'s fp

fact(9)'s sp (0x0F0)

Stack grows
in this direction

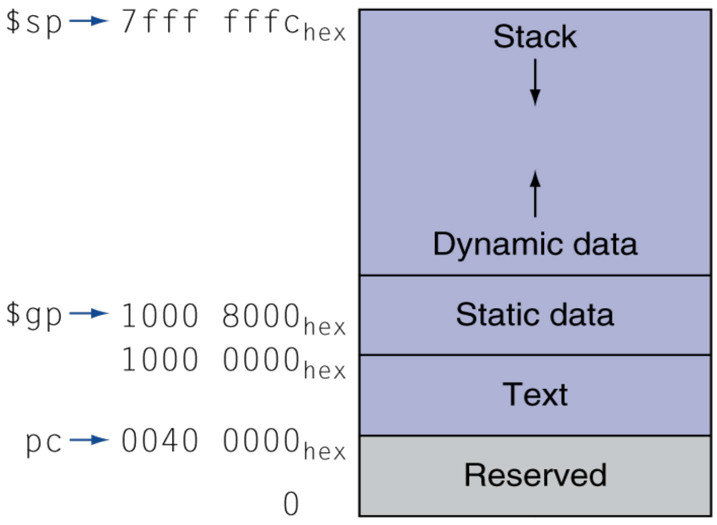
Local Data on the Stack



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

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



Communicating with People (Handling Characters)

Character Data

- 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

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

String Copy Example

- C code (naïve):
  - 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
```

MIPS Addressing for 32-Bit Immediates and Addresses

32-bit Constants

- 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

```
lhi $s0, 61              0000 0000 0111 1101 0000 0000 0000 0000

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

Branch Addressing

- Branch instructions specify
  - Opcode, two registers, target address

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

- Most branch targets are near branch
  - Forward or backward
- PC-relative addressing
  - Target address = PC + offset × 4
  - PC already incremented by 4 by this time

Jump Addressing

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

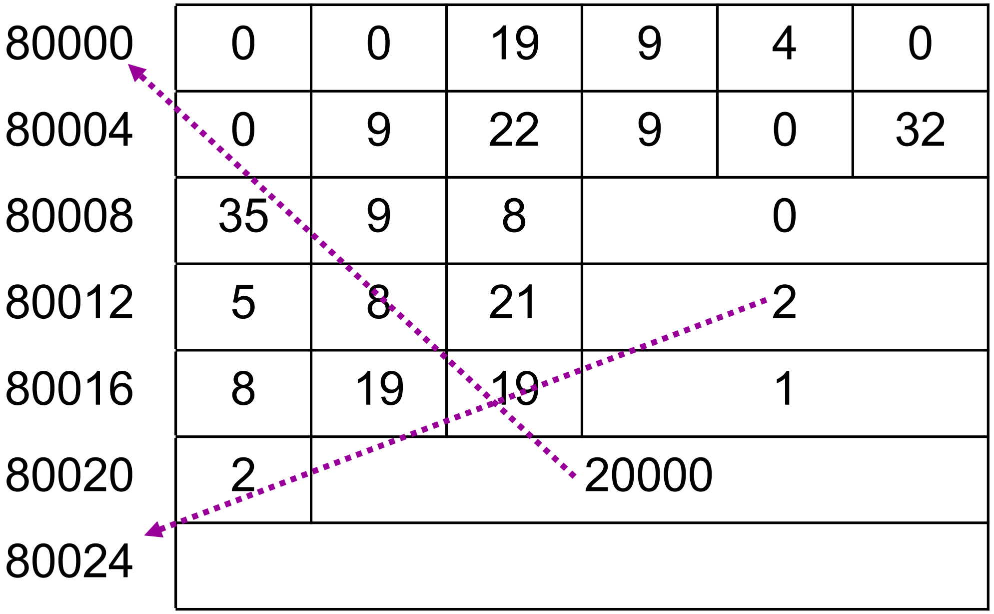
op	address
6 bits	26 bits

- (Pseudo)Direct jump addressing
  - Target address = $PC_{31\ldots28}$: (address $\times$ 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: …
```



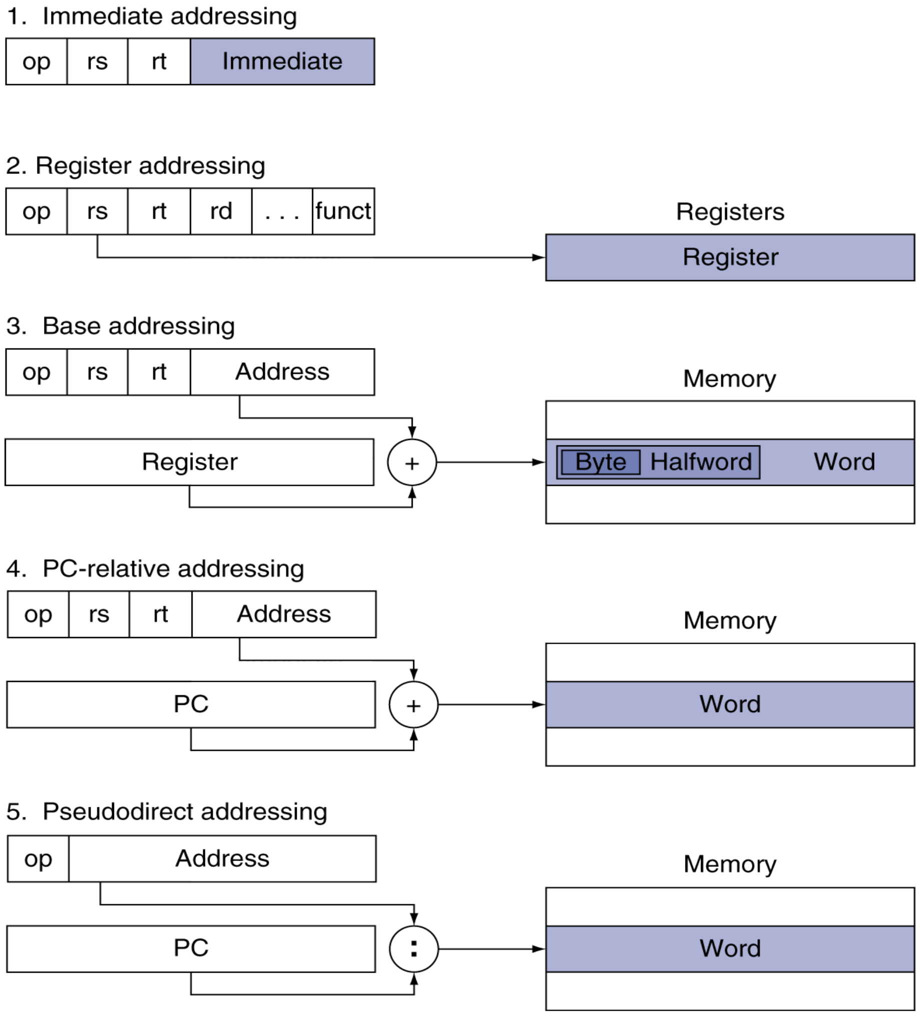
80000	0	0	19	9	4	0
80004	0	9	22	9	0	32
80008	35	9	8	0		
80012	5	8	21	2		
80016	8	19	19	1		
80020	2	20000				
80024						

Branching Far Away

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

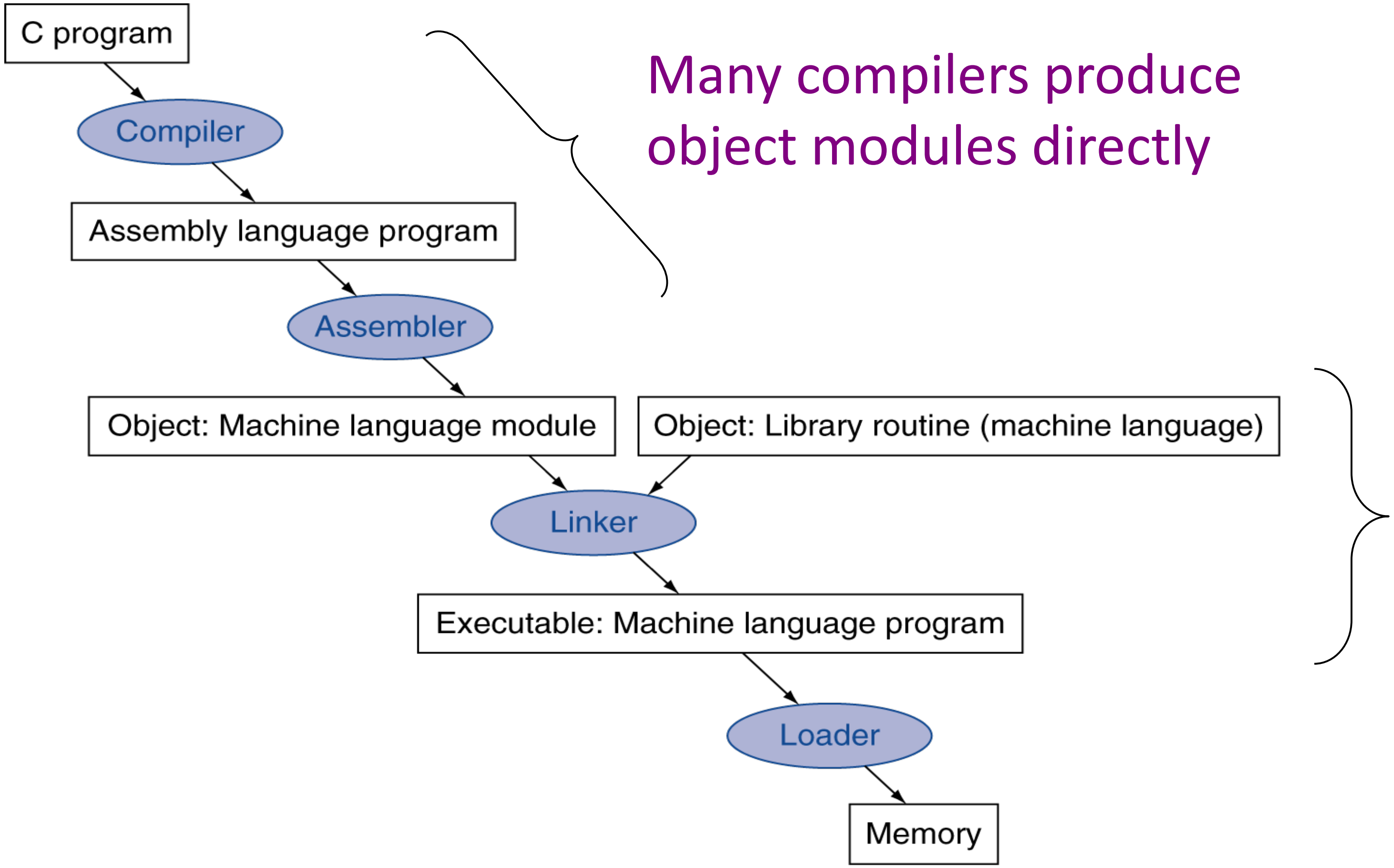
```
          beq $s0,$s1, L1
                ↓
          bne $s0,$s1, L2
          j L1
  L2:     …
```

Addressing Mode Summary



Translating and Starting a Program

Translation and Startup



Many compilers produce object modules directly

Static linking

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

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

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

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

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

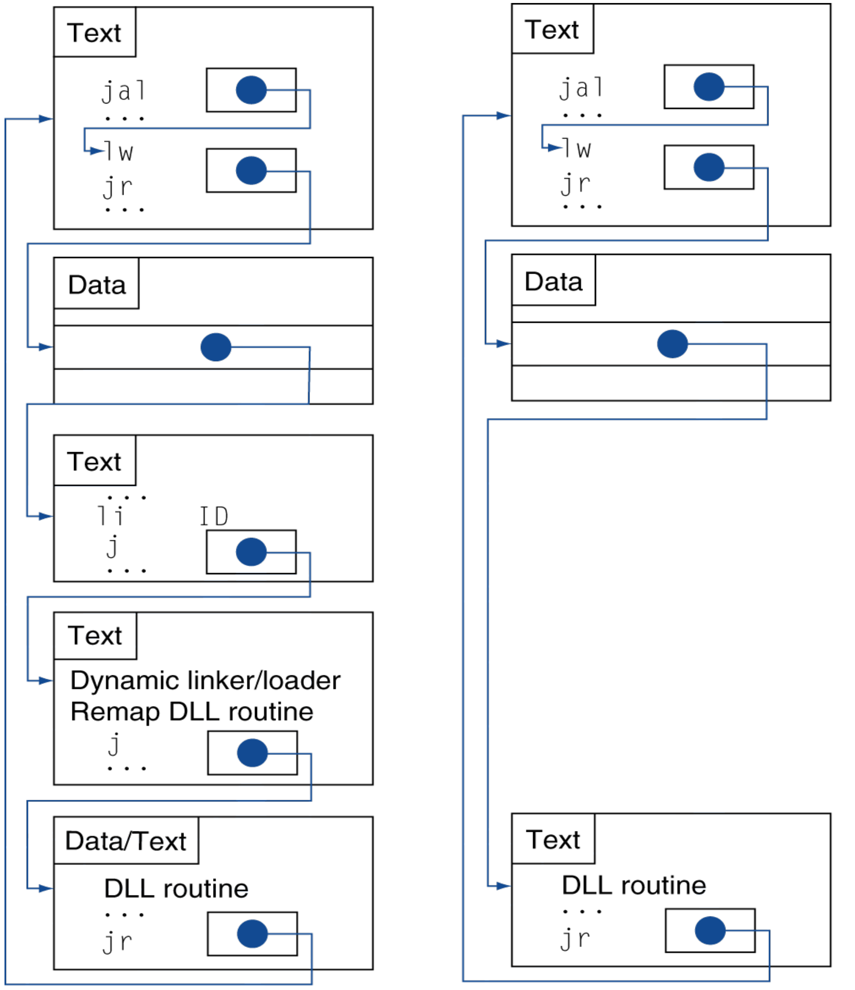
Lazy Linkage

Indirection table

Stub: Loads routine ID, Jump to linker/loader

Linker/loader code

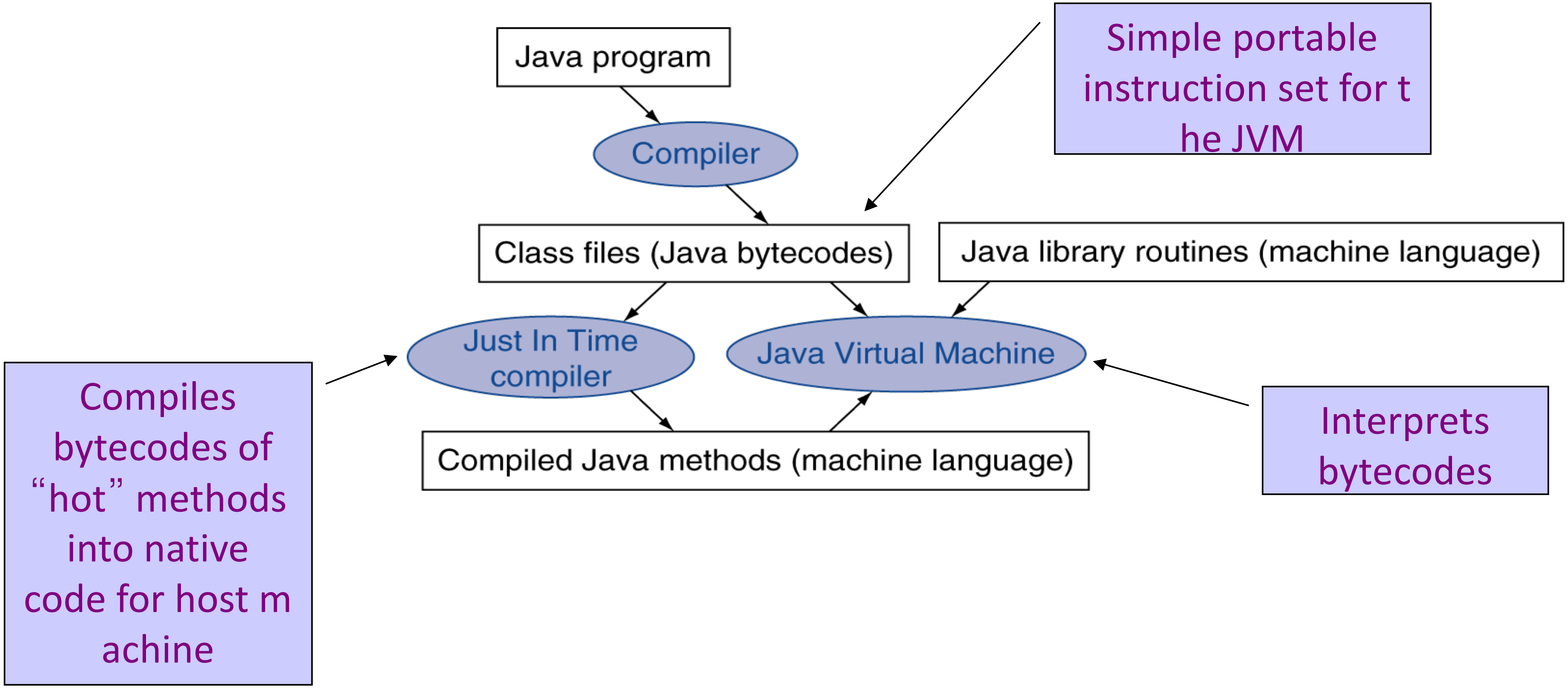
Dynamically mapped code



a. First call to DLL routine

b. Subsequent calls to DLL routine

Starting Java Applications



Simple portable instruction set for the JVM

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

Interprets bytecodes

Array vs. Pointers

Arrays vs. Pointers

- Array indexing involves
  - Multiplying index by element size
  - Adding to array base address
- Pointers correspond directly to memory addresses
  - Can avoid indexing complexity

Example: Clearing and Array

```
clear1(int array[], int size) {
  int i;
  for (i = 0; i < size; i += 1)
    array[i] = 0;
}
```

```
clear2(int *array, int size) {
  int *p;
  for (p = &array[0]; p < &array[size];
       p = p + 1)
    *p = 0;
}
```

```
       move $t0,$zero   # i = 0
loop1: sll $t1,$t0,2    # $t1 = i * 4
       add $t2,$a0,$t1  # $t2 =
                        #   &array[i]
       sw $zero, 0($t2) # array[i] = 0
       addi $t0,$t0,1   # i = i + 1
       slt $t3,$t0,$a1  # $t3 =
                        #   (i < size)
       bne $t3,$zero,loop1 # if (…)
                           # goto loop1
```

```
       move $t0,$a0     # p = & array[0]
       sll $t1,$a1,2    # $t1 = size * 4
       add $t2,$a0,$t1  # $t2 =
                        #   &array[size]
loop2: sw $zero,0($t0)  # Memory[p] = 0
       addi $t0,$t0,4   # p = p + 4
       slt $t3,$t0,$t2  # $t3 =
                        # (p<&array[size])
       bne $t3,$zero,loop2 # if (…)
                           # goto loop2
```

Comparison of Array vs. Ptr

- Multiply “strength reduced” to shift
- Array version requires shift to be inside loop
  - Part of index calculation for incremented i
  - c.f. incrementing pointer
- Compiler can achieve same effect as manual use of pointers
  - Induction variable elimination
  - Better to make program clearer and safer