

Chapter 2 - part 2

Instructions: Language of the Computer

Sign Extension

- Representing a number using more bits
 - Preserve the numeric value
- In MIPS instruction set
 - `addi`: extend immediate value
 - `lb`, `lh`: extend loaded byte/halfword
 - `beq`, `bne`: extend the displacement
- Replicate the sign bit to the left
 - c.f. unsigned values: extend with 0s
- Examples: 8-bit to 16-bit
 - +2: 0000 0010 => 0000 0000 0000 0010
 - -2: 1111 1110 => 1111 1111 1111 1110

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



- 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

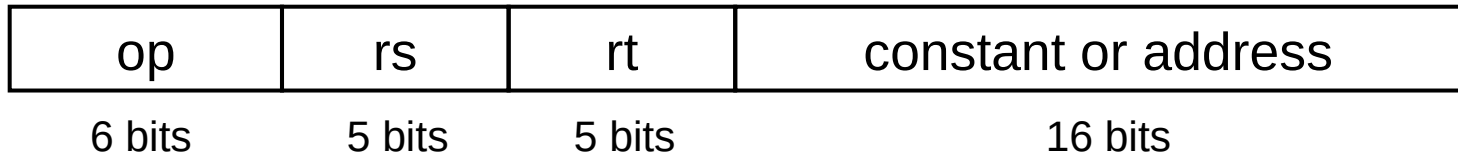
op	rs	rt	rd	shamt	funct
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

add \$t0, \$s1, \$s2

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

$00000010001100100100000000100000_2 = 02324020_{16}$

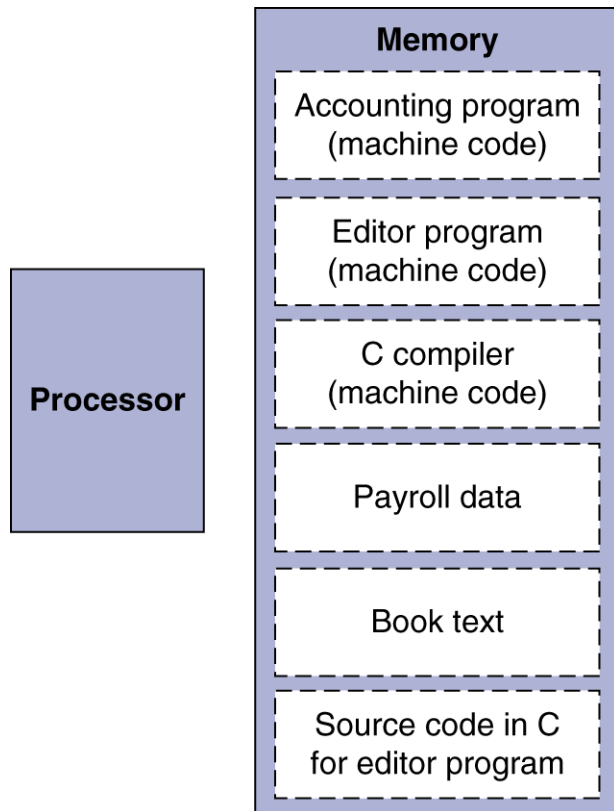
MIPS I-format Instructions



- 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

Stored Program Computers

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, ...
- Binary compatibility allows compiled programs to work on different computers
 - Standardized ISAs

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



- 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)

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
\$t1	0000 0000 0000 0000 0011 1100 0000 0000
\$t0	0000 0000 0000 0000 0000 1100 0000 0000

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
\$t1	0000 0000 0000 0000 0011 1100 0000 0000
\$t0	0000 0000 0000 0000 0011 1101 1100 0000

NOT Operations

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

```
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
```

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

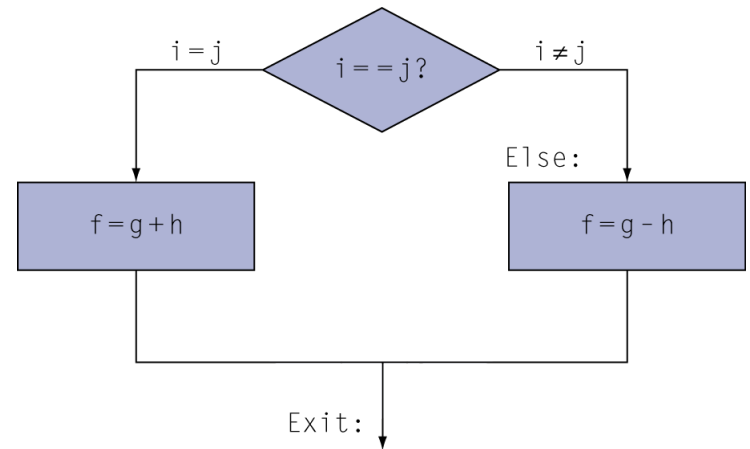
- C code:

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

- f, g, ... in \$s0, \$s1, ...

- Compiled MIPS code:

```
        bne $s3, $s4, Else  
        add $s0, $s1, $s2  
        j   Exit  
Else:   sub $s0, $s1, $s2  
Exit:   ...
```



Assembler calculates addresses

Compiling Loop Statements

- C code:

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

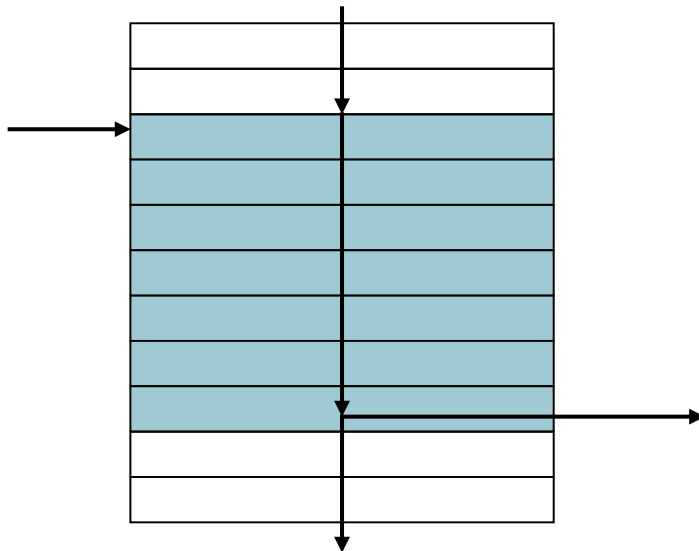
- i in \$s3, k in \$s5, address of save in \$s6

- 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 ($rs < \text{constant}$) $rt = 1$; 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 `b<t`, `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`
 - $-1 < +1 \Rightarrow \$t0 = 1$
 - `sltu $t0, $s0, $s1 # unsigned`
 - $+4,294,967,295 > +1 \Rightarrow \$t0 = 0$

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
 - 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)

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

