

Computer Architecture

Chapter 2: MIPS – part 2

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Adapted from Computer Organization the Hardware/Software Interface – 5th



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
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0	17	18	8	0	32
---	----	----	---	---	----

000000	10001	10010	01000	00000	100000
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$$00000010001100100100000000100000_2 = 02324020_{16}$$

Hexadecimal

- Base 16
 - Compact representation of bit strings
 - 4 bits per hex digit

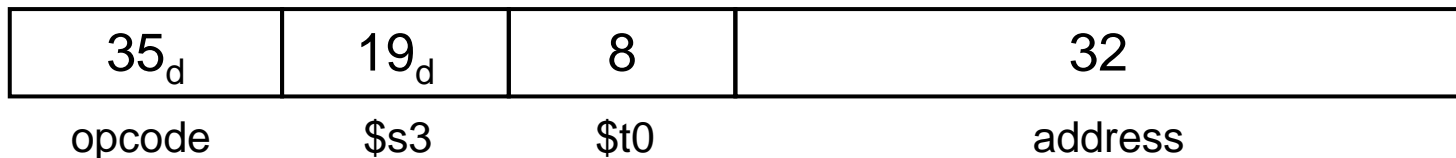
0	0000	4	0100	8	1000	c	1100
1	0001	5	0101	9	1001	d	1101
2	0010	6	0110	a	1010	e	1110
3	0011	7	0111	b	1011	f	1111

- Example: eca8 6420
 - 1110 1100 1010 1000 0110 0100 0010 0000

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
- Example: `lw $t0, 32($s3)`



Design Principle

- *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 Instructions Format Summary

Instr.	Type	op	rs	rt	rd	shamt	function	address
add	R	0	reg	reg	reg	0	32 _d	n.a.
sub	R	0	reg	reg	reg	0	34 _d	n.a.
addi	I	8 _d	reg	reg	n.a.	n.a.	n.a.	constant
lw	I	35 _d	reg	reg	n.a.	n.a.	n.a.	address
st	I	43 _d	reg	reg	n.a.	n.a.	n.a.	address

- R-format: arithmetic instructions
- I-format: data transfer instructions

Example

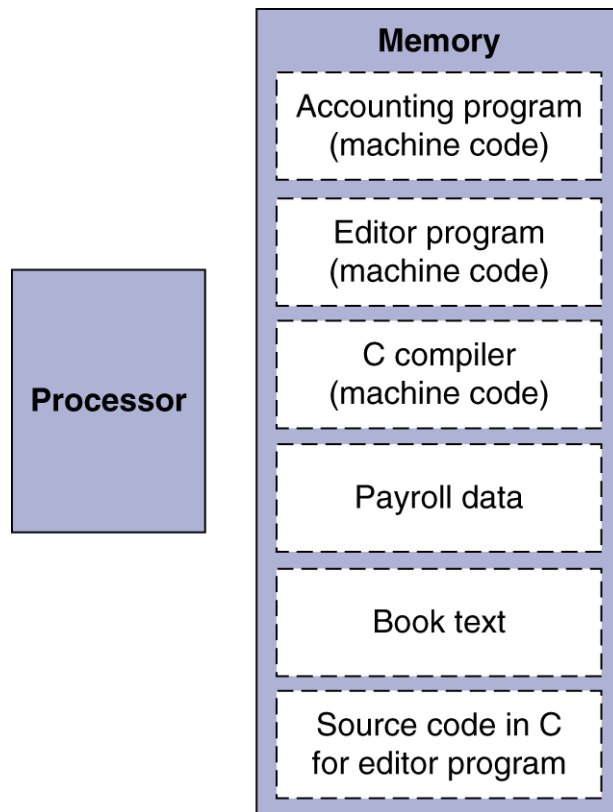
- Write MIPS code for the following C code, then translate the MIPS code to machine code

$A[300] = h + A[300];$

- Assume that $\$t1$ stores the base of array A and $\$s2$ stores h

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

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)

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:

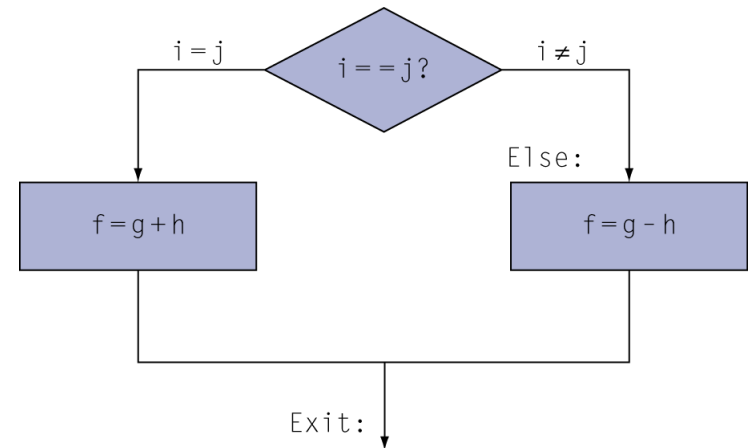
```
if (i==j) f = g+h;  
else f = g-h;
```

– 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;
```

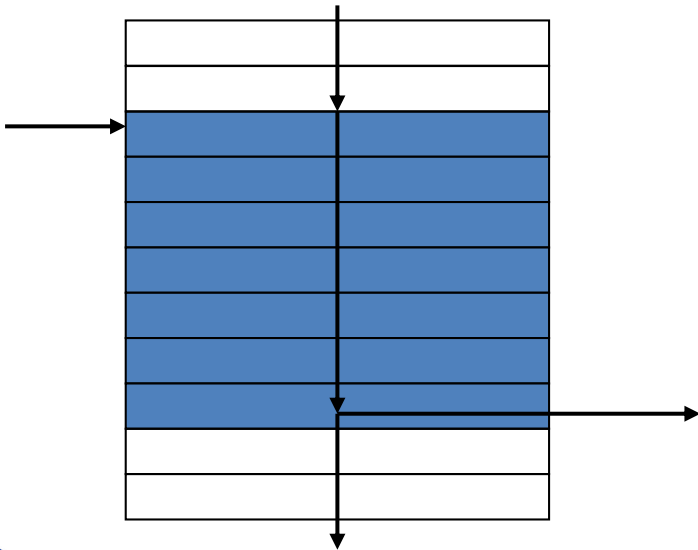
– i in \$s3, k in \$s5, base address of save in \$s6

- 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 `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`
 - $-1 < +1 \Rightarrow \$t0 = 1$
 - `sltu $t0, $s0, $s1 # unsigned`
 - $+4,294,967,295 > +1 \Rightarrow \$t0 = 0$

Procedure Calling

- Steps required
 - Place parameters in registers
 - Transfer control to procedure
 - Acquire storage for procedure
 - Perform procedure's operations
 - Place result in register for caller
 - Return to place of call

Register Usage

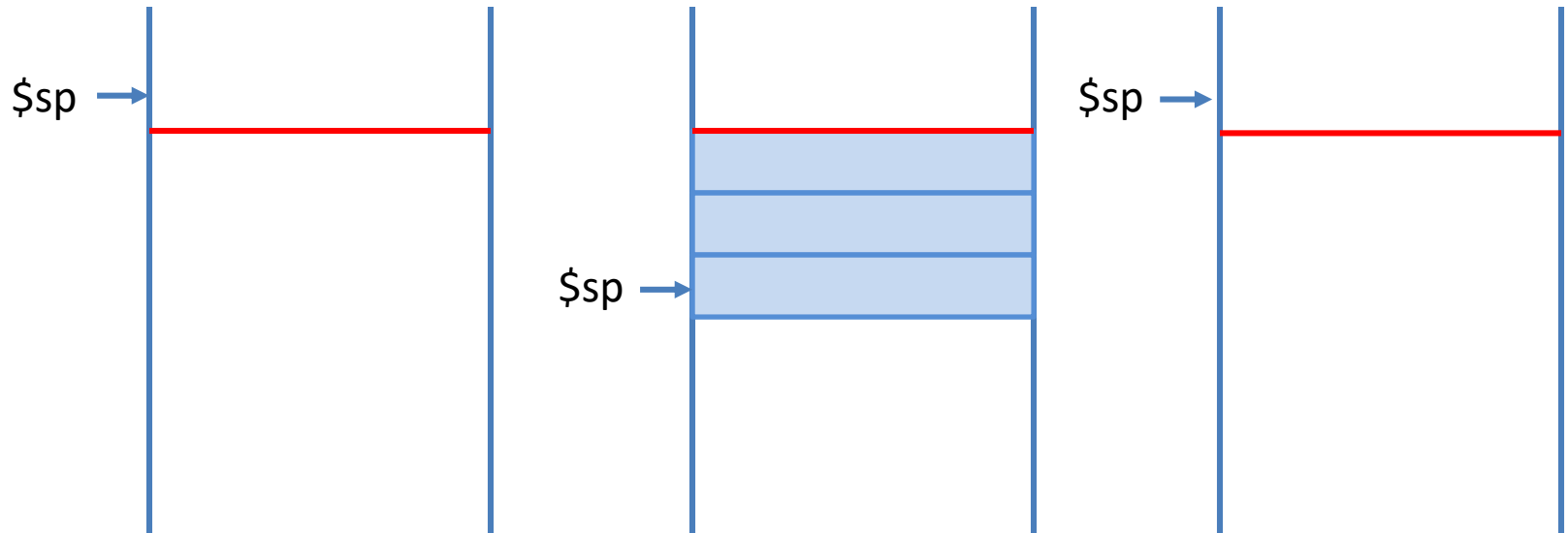
- \$a0 – \$a3: arguments (reg's 4 – 7)
- \$v0, \$v1: result values (reg's 2 and 3)
- \$t0 – \$t9: temporaries
 - Can be overwritten by callee
- \$s0 – \$s7: saved
 - Must be saved/restored by callee
- \$gp: global pointer for static data (reg 28)
- \$sp: stack pointer (reg 29)
- \$fp: frame pointer (reg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

Stack Address Model

High address



Low address

Empty stack

Three elements stack

Empty stack

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

- 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

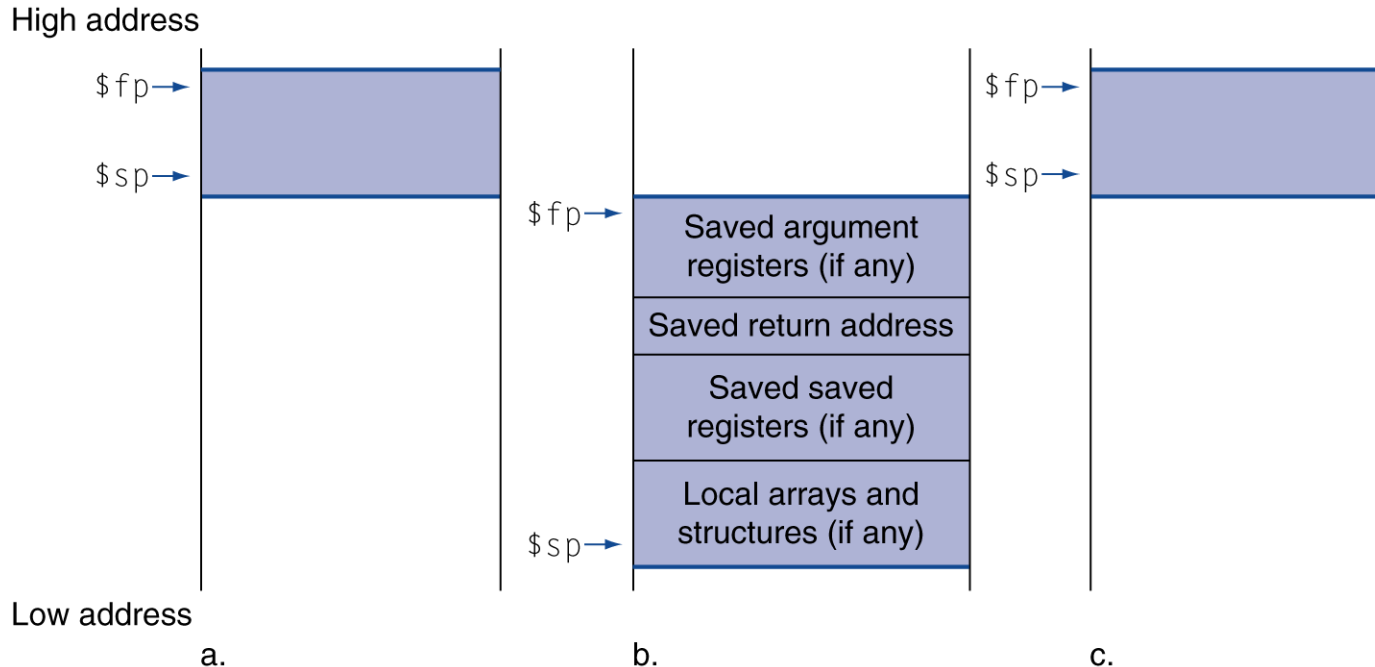
Non-Leaf Procedure Example

- 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   # if so, result is 1
    addi $v0, $zero, 1    #   pop 2 items from stack
    addi $sp, $sp, 8      #   and return
    jr   $ra
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
```

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 \pm offsets into this segment
- Dynamic data: heap
 - E.g., malloc in C, new in Java
- Stack: automatic storage

