CS2100 COMPUTER ORGANISATION

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Lecture #9

MIPS

Part III: Instruction Formats and Encoding

NUS National University of Singapore | School of Computing

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1. Overview and Motivation

- **Recap:** Assembly instructions will be translated to **machine code** for actual execution
  - This section shows how to translate MIPS assembly code into binary patterns
- Explains some of the “strange facts” from earlier:
  - Why is ***immediate*** limited to 16 bits?
  - Why is ***shift*** amount only 5 bits?
  - etc.
- Prepare us to “build” a MIPS processor in later lectures!

2. MIPS Encoding: Basics

- Each MIPS instruction has a **fixed-length** of 32 bits

  ➔ All relevant information for an operation must be encoded with these bits!

- Additional challenge:
  - To reduce the complexity of processor design, the instruction encodings should be as regular as possible

    ➔ Small number of formats, i.e. as few variations as possible

3. MIPS Instruction Classification

- Instructions are classified according to their operands:
  ➔ Instructions with same operand types have same encoding

R-format (Register format: `op $r1, $r2, $r3`)

- Instructions which use 2 source registers and 1 destination register
- `e.g. add, sub, and, or, nor, slt, etc`
- **Special cases:** `srl, sll`, etc.

I-format (Immediate format: `op $r1, $r2, Immd`)

- Instructions which use 1 source register, 1 immediate value and 1 destination register
- `e.g. addi, andi, ori, slti, lw, sw, beq, bne`, etc.

J-format (Jump format: `op Immd`)

- `j` instruction uses only one immediate value

4. MIPS Registers (Recap)

- For simplicity, register numbers (**`$0`**, **`$1`**, …, **`$31`**) will be used in examples here instead of register names

Name	Register number	Usage
$zero	0	Constant value 0
$v0-$v1	2-3	Values for results and expression evaluation
$a0-$a3	4-7	Arguments
$t0-$t7	8-15	Temporaries
$s0-$s7	16-23	Program variables

Name	Register number	Usage
$t8-$t9	24-25	More temporaries
$gp	28	Global pointer
$sp	29	Stack pointer
$fp	30	Frame pointer
$ra	31	Return address

$at (register 1) is reserved for the assembler.
$k0-$k1 (registers 26-27) are reserved for the operation system.

5. R-Format (1/2)

- Define fields with the following number of bits each:
  - 6 + 5 + 5 + 5 + 5 + 6 = 32 bits

6	5	5	5	5	6

- Each field has a name:

opcode	rs	rt	rd	shamt	funct

- Each field is an independent 5- or 6-bit unsigned integer
  - A 5-bit field can represent any number 0 – 31
  - A 6-bit field can represent any number 0 – 63

5. R-Format (2/2)

Fields	Meaning
`opcode`	- Partially specifies the instruction - Equal to 0 for all R-Format instructions
`funct`	- Combined with opcode exactly specifies the instruction
`rs` (Source Register)	- Specify register containing first operand
`rt` (Target Register)	- Specify register containing second operand
`rd` (Destination Register)	- Specify register which will receive result of computation
`shamt`	- Amount a shift instruction will shift by - 5 bits (i.e. 0 to 31) - Set to 0 in all non-shift instructions

5.1 R-Format: Example (1/3)

MIPS instruction

```
add  $8, $9, $10
```

R-Format Fields	Value	Remarks
`opcode`	0	(textbook pg 94 - 101)
`funct`	32	(textbook pg 94 - 101)
`rd`	8	(destination register)
`rs`	9	(first operand)
`rt`	10	(second operand)
`shamt`	0	(not a shift instruction)

5.1 R-Format: Example (2/3)

MIPS instruction
`add $8, $9, $10`

Note the ordering of the 3 registers

Field representation in decimal:

opcode	rs	rt	rd	shamt	funct
0	9	10	8	0	32

Field representation in binary:

000000	01001	01010	01000	00000	100000

Split into 4-bit groups for hexadecimal conversion:

0000	0001	0010	1010	0100	0000	0010	0000
0_{16}	1_{16}	2_{16}	A_{16}	4_{16}	0_{16}	2_{16}	0_{16}

5.1 R-Format: Example (3/3)

MIPS instruction

```
sll  $8, $9, 4
```

Note the placement of the source register

Field representation in decimal:

opcode	rs	rt	rd	shamt	funct
0	0	9	8	4	0

Field representation in binary:

000000	00000	01001	01000	00100	000000

Split into 4-bit groups for hexadecimal conversion:

0000	0000	0000	1001	0100	0001	0000	0000
0_{16}	0_{16}	0_{16}	9_{16}	4_{16}	1_{16}	0_{16}	0_{16}

5.2 Try It Yourself #1

MIPS instruction

```
add  $10, $7, $5
```

Field representation in decimal:

opcode	rs	rt	rd	shamt	funct
0	7	5	10	0	32

Field representation in binary:

000000	00111	00101	01010	00000	100000

Hexadecimal representation of instruction:

$0\ 0\ E\ 5\ 5\ 0\ 2\ 0_{16}$

6. I-format (1/4)

- What about instructions with immediate values?
  - 5-bit `shamt` field can only represent **0 to 31**
  - Immediates may be much larger than this
    - e.g. `lw`, `sw` instructions require bigger offset

- **Compromise:** Define a new instruction format partially consistent with R-format:
  - If instruction has immediate, then it uses at most 2 registers

6. I-format (2/4)

- Define fields with the following number of bits each:
  - 6 + 5 + 5 + 16 = 32 bits

6	5	5	16

- Again, each field has a name:

opcode	rs	rt	immediate

- Only one field is inconsistent with R-format.
  - **`opcode`**, **`rs`**, and **`rt`** are still in the same locations.

6. I-format (3/4)

- `opcode`
  - Since there is no `funct` field, `opcode` uniquely specifies an instruction
- `rs`
  - specifies the source register operand (if any)
- `rt`
  - specifies register to receive result
  - **note the difference from R-format instructions**

- **Continue on next slide……**

6. I-format (4/4)

- `immediate`:
  - Treated as a ***signed integer***
  - 16 bits → can be used to represent a constant up to 2^{16} different values
  - Large enough to handle:
    - The offset in a typical `lw` or `sw`
    - Most of the values used in the `addi`,`subi`, `slti` instructions

6.1 I-format: Example (1/2)

MIPS instruction

```
addi  $21, $22, -50
```

I-Format Fields	Value	Remarks
`opcode`	**8**	(textbook pg 94 - 101)
`rs`	**22**	(the only source register)
`rt`	**21**	(target register)
`immediate`	**-50**	(in base 10)

6.1 I-format: Example (2/2)

MIPS instruction

```
addi  $21, $22, -50
```

Field representation in decimal:

8	22	21	-50

Field representation in binary:

001000	10110	10101	1111111111001110

Hexadecimal representation of instruction:

$$2\ 2\ D\ 5\ F\ F\ C\ E_{16}$$

6.2 Try It Yourself #2

MIPS instruction

```
lw   $9, 12($8)
```

Field representation in decimal:

opcode	rs	rt	immediate
35	8	9	12

Field representation in binary:

100011	01000	01001	0000000000001100

Hexadecimal representation of instruction:

$8\ D\ 0\ 9\ 0\ 0\ 0\ C_{16}$

6.3 Instruction Address: Overview

- As instructions are stored in memory, they too have addresses
  - Control flow instructions uses these addresses
  - E.g. **`beq`**, **`bne`**, **`j`**
- As instructions are 32-bit long, instruction addresses are word-aligned as well
- **P**rogram **C**ounter (**PC**)
  - A special register that keeps address of instruction being executed in the processor

6.4 Branch: PC-Relative Addressing (1/5)

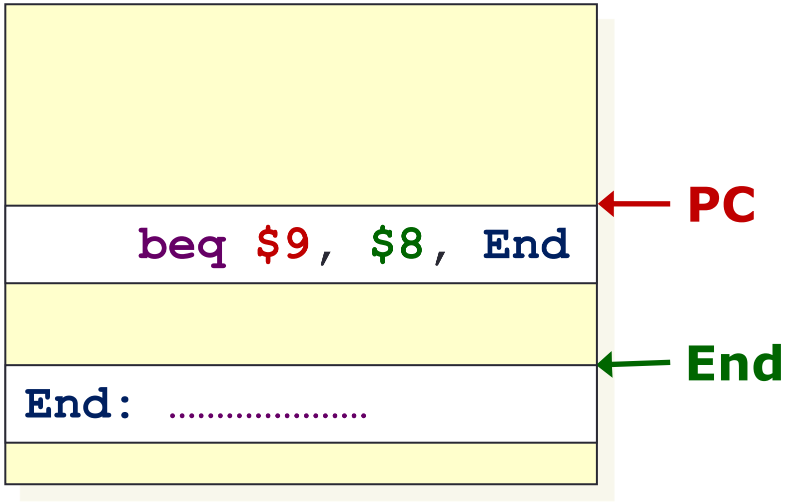
- Use I-Format

opcode	rs	rt	immediate

- **opcode** specifies **beq**, **bne**
- **rs** and **rt** specify registers to compare
- What can **immediate** specify?
  - **Immediate** is only 16 bits
  - Memory address is 32 bits
  - → **immediate** is not enough to specify the entire target address!

6.4 Branch: PC-Relative Addressing (2/5)

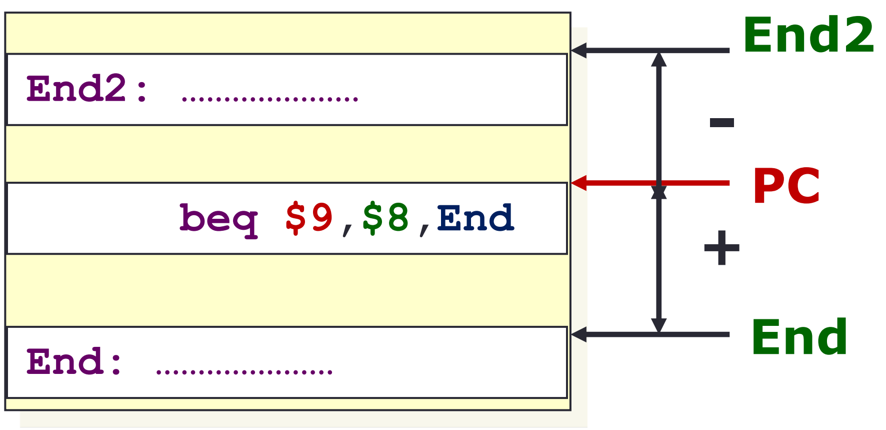
- How do we usually use branches?
  - **Answer:** `if-else`, `while`, `for`
  - Loops are generally **small**:
    - Typically up to 50 instructions
  - Unconditional jumps are done using jump instructions (`j`), not the branches
- **Conclusion:** A branch often changes **PC** by a small amount



6.4 Branch: PC-Relative Addressing (3/5)

- **Solution:**
  - Specify target address **relative to the PC**
- Target address is generated as:
  - PC + the 16-bit **`immediate`** field
  - The **`immediate`** field is a signed two's complement integer

➔ Can branch to ± 2^{15} bytes from the PC:
  - Should be enough to cover most loops



6.4 Branch: PC-Relative Addressing (4/5)

- Can the branch target range be enlarged?
- **Observation:** Instructions are word-aligned
  - Number of bytes to add to the PC will always be a multiple of 4.

  ➔ Interpret the `immediate` as number of words, i.e. automatically multiplied by 4_{10} (100_2)

➔ Can branch to $\pm 2^{15}$ **words** from the PC

- i.e. $\pm 2^{17}$ bytes from the **PC**
- We can now branch 4 times farther!

6.4 Branch: PC-Relative Addressing (5/5)

- Branch calculation:

If the branch is **not taken**:

PC = PC + 4

(**PC + 4** is address of next instruction)

If the branch is **taken**:

PC = (PC + 4) + (`immediate` × 4)

- Observations:
  - **`immediate`** field specifies the number of words to jump, which is the same as the number of instructions to "skip over"
  - **`immediate`** field can be positive or negative
  - Due to hardware design, add **`immediate`** to (PC+4), not to PC (more in later topic)

6.5 Branch: Example (1/3)

```
Loop:  beq  $9, $0, End    # rlt addr: 0
       add  $8, $8, $10    # rlt addr: 4
       addi $9, $9, -1     # rlt addr: 8
       j    Loop           # rlt addr: 12
End:                       # rlt addr: 16
```

- **beq** is an I-Format instruction →

I-Format Fields	Value	Remarks
opcode	4	
rs	9	(first operand)
rt	0	(second operand)
immediate	???	(in base 10)

6.5 Branch: Example (2/3)

```
Loop:  beq  $9, $0, End   # rlt addr: 0
       add  $8, $8, $10   # rlt addr: 4
       addi $9, $9, -1    # rlt addr: 8
       j    Loop          # rlt addr: 12
End:                      # rlt addr: 16
```

- **`immediate`** field:
  - Number of instructions to add to (or subtract from) the PC, starting at the instruction following the branch
  - In **`beq`** case, **`immediate`** **= 3**
  - **End = (PC + 4) + (immediate × 4)**

6.5 Branch: Example (3/3)

```
Loop:  beq  $9, $0, End    # rlt addr: 0
       add  $8, $8, $10    # rlt addr: 4
       addi $9, $9, -1     # rlt addr: 8
       j    Loop           # rlt addr: 12
End:                       # rlt addr: 16
```

Field representation in decimal:

opcode	rs	rt	immediate
4	9	0	3

Field representation in binary:

000100	01001	00000	0000000000000011

6.6 Try It Yourself #3

```
Loop:   beq  $9, $0, End    # rlt addr: 0
        add  $8, $8, $10    # rlt addr: 4
        addi $9, $9, -1     # rlt addr: 8
        beq  $0, $0, Loop   # rlt addr: 12
End:                        # rlt addr: 16
```

- What would be the **`immediate`** value for the second **`beq`** instruction?

Answer: **– 4**

7. J-Format (1/5)

- For branches, PC-relative addressing was used:
  - Because we do not need to branch too far
- For general jumps (`j`):
  - We may jump to anywhere in memory!
- The ideal case is to specify a 32-bit memory address to jump to
  - Unfortunately, we can't (☹ why?)

7. J-Format (2/5)

- Define fields of the following number of bits each:

6 bits	26 bits

- As usual, each field has a name:

`opcode`	`target address`

- Keep `opcode` field identical to R-format and I-format for consistency
- Combine all other fields to make room for larger target address

7. J-Format (3/5)

- We can only specify 26 bits of 32-bit address
- **Optimization:**
  - Just like with branches, jumps will only jump to word-aligned addresses, so last two bits are always `00`
  - So, let's assume the address ends with '`00`' and leave them out

→ Now we can specify **28 bits** of 32-bit address

7. J-Format (4/5)

- Where do we get the other 4 bits?
  - MIPS choose to take the **4 most significant bits from PC+4** (the next instruction after the jump instruction)

  ➔ This means that we cannot jump to anywhere in memory, but it should be sufficient ***most of the time***
- Question:
  - What is the **maximum jump range?** 256MB boundary
- Special instruction if the program straddles 256MB boundary
  - Look up `jr` instruction if you are interested
  - Target address is specified through a register

7. J-Format (5/5)

- **Summary:** Given a **Jump** instruction

32bit PC	opcode	target address
1010………	000010	00001111000011110000111100

Jumps To

1010 00001111000011110000111100 00

1010	00001111000011110000111100	00
Most significant 4bits of PC+4	26bits Target address specified in instruction	Default 2bit "00" for word address

7.1 J-Format: Example

```
Loop:   beq  $9, $0, End   # addr: 8
        add  $8, $8, $10   # addr: 12
        addi $9, $9, -1    # addr: 16
        j    Loop          # addr: 20
End:                       # addr: 24
```

jump target

PC

PC	0000............................10100
Address to jump to	0000............................01000

immediate = **2** (26 bits)

Check your understanding by constructing the new PC value

opcode	target address
000010	00000000000000000000000010

7.2 Branching Far Way

- Given the instruction

  `beq $s0, $s1, L1`

  Assume that the address **`L1`** is farther away from the PC than can be supported by **`beq`** and **`bne`** instructions

- **Challenge:**
  - Construct an equivalent code sequence with the help of unconditional (**`j`**) and conditional branch (**`beq, bne`**) instructions to accomplish this far away branching

8. Addressing Modes (1/3)

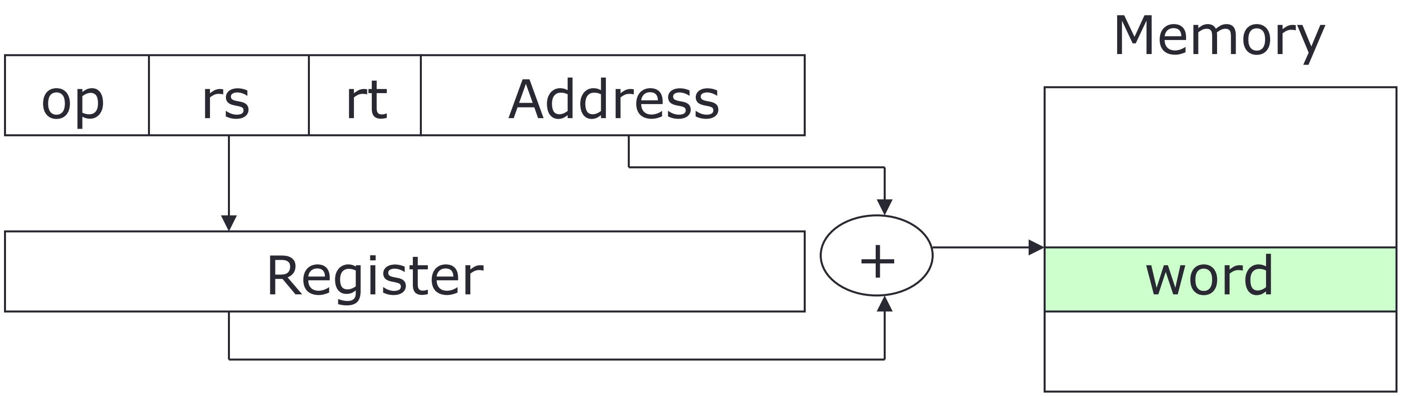
- **Register addressing**: operand is a register

- **Immediate addressing**: operand is a constant within the instruction itself (**`addi`**, **`andi`**, **`ori`**, **`slti`**)

op	rs	rt	immediate

8. Addressing Modes (2/3)

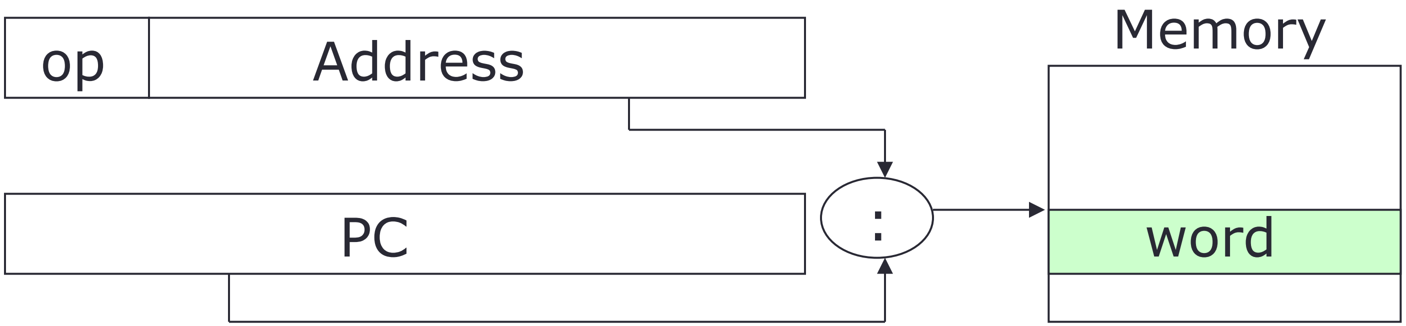
- **Base addressing (displacement addressing)**: operand is at the memory location whose address is sum of a register and a constant in the instruction (`lw, sw`)



8. Addressing Modes (3/3)

- **PC-relative addressing**: address is sum of PC and constant in the instruction (`beq`, `bne`)

- **Pseudo-direct addressing**: 26-bit of instruction concatenated with upper 4-bits of PC (`j`)



Summary (1/2)

- MIPS Instruction:
  32 bits representing a single instruction

R	`opcode`	`rs`	`rt`	`rd`	`shamt`	`funct`
I	`opcode`	`rs`	`rt`	`immediate`		
J	`opcode`	`target address`				

  - Branches and load/store are both I-format instructions; but branches use PC-relative addressing, whereas load/store use base addressing
  - Branches use PC-relative addressing; jumps use pseudo-direct addressing
  - Shifts use R-format, but other immediate instructions (**`addi`**, **`andi`**, **`ori`**) use I-format

Summary (2/2)

MIPS assembly language				
Category	Instruction	Example	Meaning	Comments
Arithmetic	add	`add $s1, $s2, $s3`	`$s1 = $s2 + $s3`	Three operands; data in registers
	subtract	`sub $s1, $s2, $s3`	`$s1 = $s2 - $s3`	Three operands; data in registers
	add immediate	`addi $s1, $s2, 100`	`$s1 = $s2 + 100`	Used to add constants
Data transfer	load word	`lw $s1, 100($s2)`	`$s1` = Memory[`$s2` + 100]	Word from memory to register
	store word	`sw $s1, 100($s2)`	Memory[`$s2` + 100] = $s1	Word from register to memory
	load byte	`lb $s1, 100($s2)`	`$s1` = Memory[`$s2` + 100]	Byte from memory to register
	store byte	`sb $s1, 100($s2)`	Memory[`$s2` + 100] = $s1	Byte from register to memory
	load upper immediate	`lui $s1, 100`	$s1 = 100 * 2^{16}	Loads constant in upper 16 bits
Conditional branch	branch on equal	`beq $s1, $s2, 25`	if (`$s1 == $s2`) go to PC + 4 + 100	Equal test; PC-relative branch
	branch on not equal	`bne $s1, $s2, 25`	if (`$s1 != $s2`) go to PC + 4 + 100	Not equal test; PC-relative
	set on less than	`slt $s1, $s2, $s3`	if (`$s2 < $s3`) `$s1` = 1; else `$s1` = 0	Compare less than; for beq, bne
	set less than immediate	`slti $s1, $s2, 100`	if (`$s2 < 100`) `$s1` = 1; else `$s1` = 0	Compare less than constant
Unconditional jump	jump	`j 2500`	go to 10000	Jump to target address
	jump register	`jr $ra`	go to `$ra`	For switch, procedure return
	jump and link	`jal 2500`	`$ra` = PC + 4; go to 10000	For procedure call

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