CS2100 COMPUTER ORGANISATION

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Lecture #9

MIPS

Part III: Instruction Formats and Encoding

https://app.sli.do/event/tXUVc12jFmMftmXWVXZdJr

Lecture #9: MIPS Part 3: Instruction Formats

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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!

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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

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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

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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.

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5. R-Format (1/2)

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

- Each field has a name:

- 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

NOTE:
There are only 32 registers, so 5 bits for each register is enough. Similarly, it is enough for **`shamt`** field since shifting 32 bits clears the entire register.

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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

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5.1 R-Format: Example (1/3)

MIPS instruction

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

NOTE:
Find the value of `opcode` and `funct` from the MIPS green sheet that contains all information.

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)

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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}

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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}

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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:

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

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5. R-Format: Summary

MIPS instruction

```
arith  $rd, $rs, $rt
```

NOTE:
`opcode` is always 0
`shamt` is always 0
`arith` is arithmetic operation

opcode	rs	rt	rd	shamt	funct
0	rs	rt	rd	0	XX

MIPS instruction

```
shift  $rd, $rt, shamt
```

NOTE:
`opcode` is always 0
`rs` is always 0
`shift` is shift operation

opcode	rs	rt	rd	shamt	funct
0	0	rt	rd	shamt	XX

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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

NOTE:
The reason why we want to keep some fields in the same position (e.g., **`opcode`**) is that by looking at the *binary*, we can quickly identify the instruction format.
Also, we ensure that retrieving **`rs`** and **`rt`** will be consistent across R-format and I-format.

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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.

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

NOTE:
We merge **rd**, **shamt** and **funct** to form a 16-bit field used for a constant value (**immediate**).
That is, 5 + 5 + 6 = 16 bits. Just nice!

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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……**

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6. I-format (4/4)

- **`immediate`**:
  - Treated as a ***signed integer***
    - ***Except*** for bitwise operations (**`andi`**, **`ori`**, **`xori`**)
  - 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`**, **`slti`** instructions

NOTE:
This should answer why we ***cannot*** put 32-bit constants in the instruction. Because the instruction itself is only 32-bit wide. So we can only use parts of it. Plus, we still need to encode **`opcode`**, **`rs`** and **`rt`**.

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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)

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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:

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

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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:

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

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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

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

- Use I-Format

- **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!

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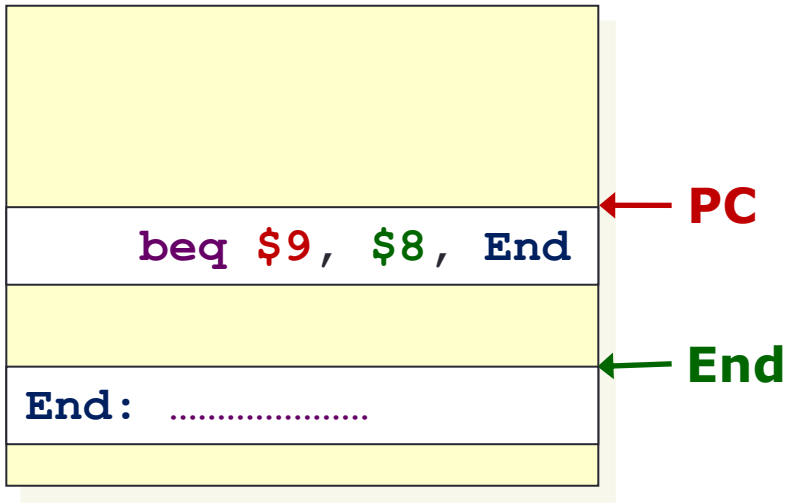
6.4 Branch: PC-Relative Addressing (2/5)

- 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



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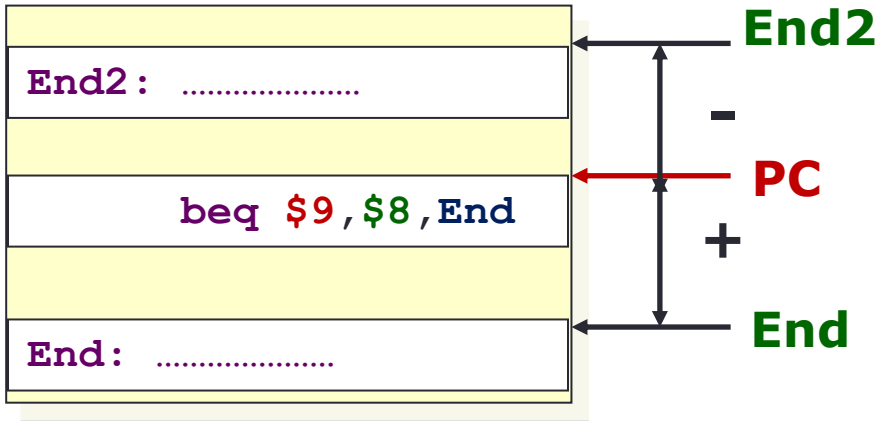
6.4 Branch: PC-Relative Addressing (3/5)

- **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



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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 ± 2^{15} **words** from the PC

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

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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)

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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)

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6.5 Branch: Example (2/3)

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)

```
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)**

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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

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6.6 Try It Yourself #3

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)

```
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**

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6. I-Format: Summary

MIPS instruction

`arith $rt, $rs, C16`$_{2s}$

NOTE:
`C16`$_{2s}$ is in 2s complement
`arith` is arithmetic operation

MIPS instruction

`ld/st $rt, C16`$_{2s}$`($rs)`

NOTE:
`C16`$_{2s}$ is in 2s complement
`ld/st` is a load or store operation

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6. I-Format: Summary

MIPS instruction

```
logic  $rt, $rs, C16
```

NOTE:
`C16` is raw binary (*no negative*)
`logic` is logical operation (*bitwise operation*)

MIPS instruction

```
branch $rs, $rt, label
```

NOTE:
`branch` is a branch operation
`label` is converted to number first (*PC-relative addressing*)

NOTE:
please note the position of `rs` and `rt` here.
The first register is NOT `rt` but is `rs` instead!

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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?)

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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

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7. J-Format (3/5)

- We can only specify 26 bits of 32-bit address
- **Optimisation:**
  - Just like with branches, jumps will only jump to word-aligned addresses, so last 2 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

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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

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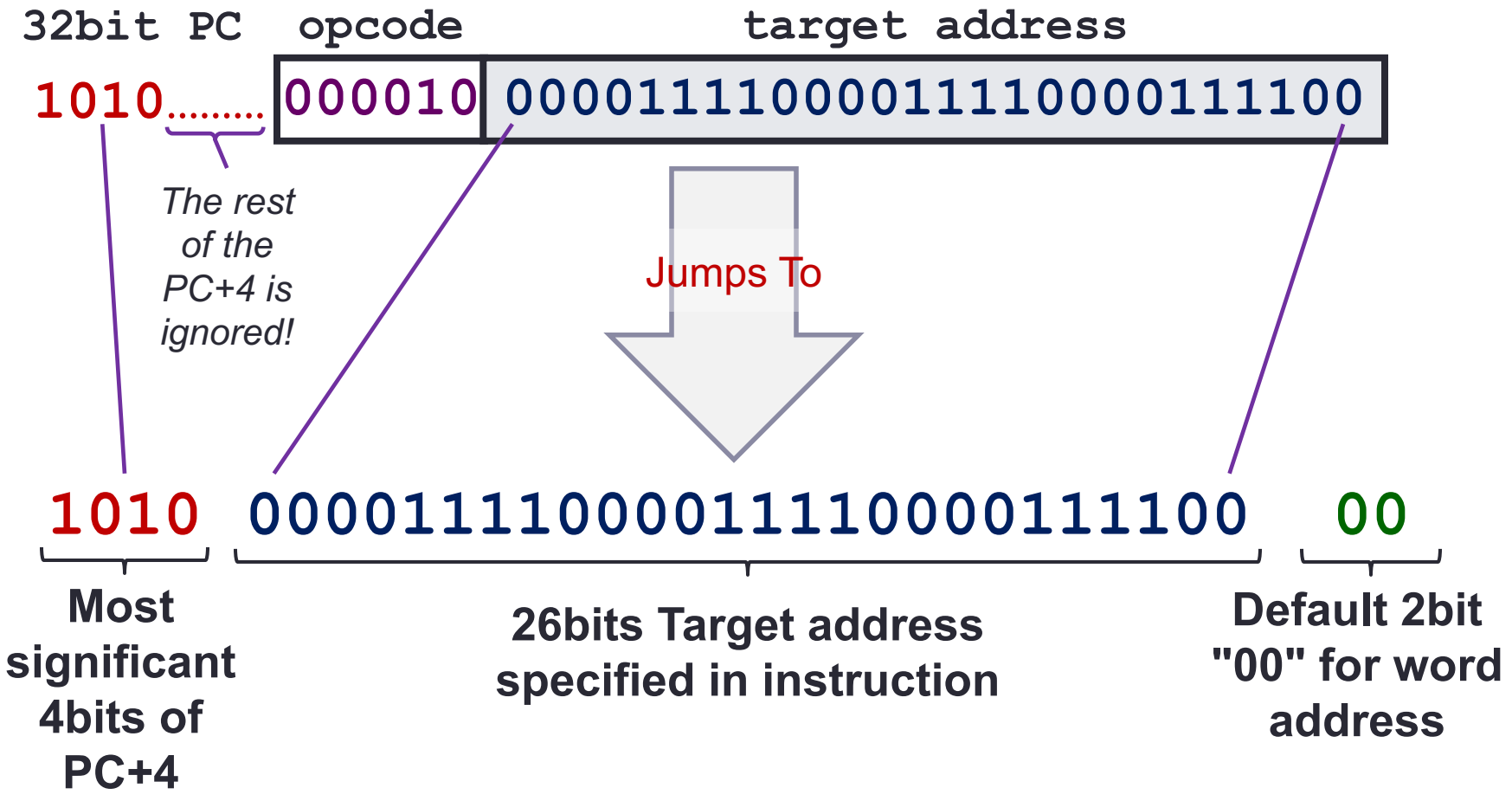
7. J-Format (5/5)

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



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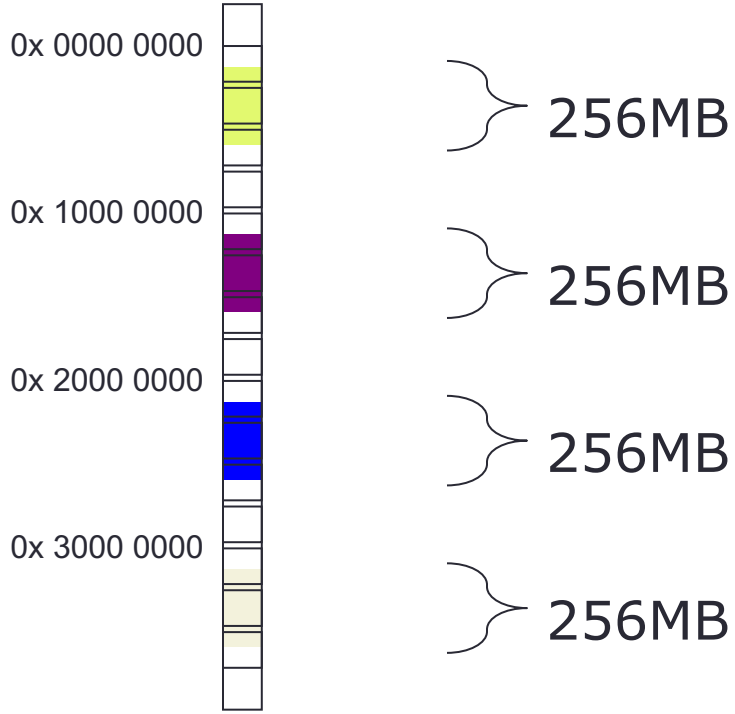
7. 256MB Boundary

- Due to the use of the first 4-bits from the PC (*i.e., the memory address of the currently executed instruction*), we can only jump within our ***block***.

- If you are at the top of the boundary, you ***cannot*** jump up.
- If you are at the bottom of the boundary, you ***cannot*** jump down.
- Can you figure out the address of the *top* and the *bottom*? (*discuss in forum*)



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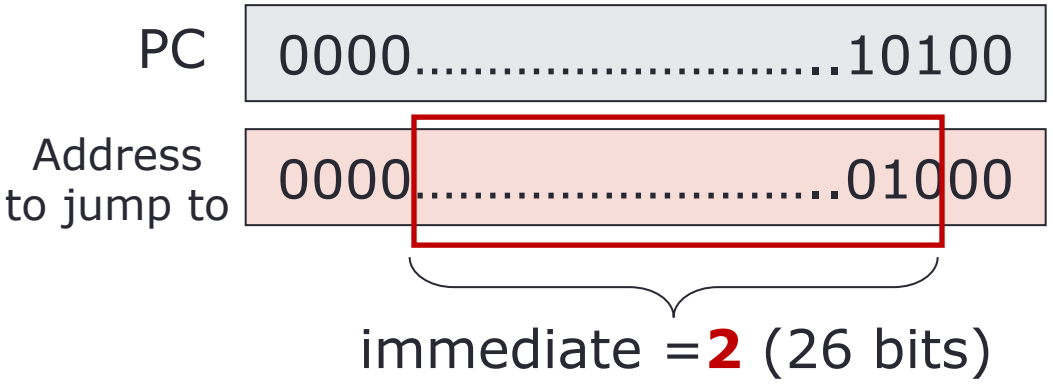
7.1 J-Format: Example

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



Check your understanding by constructing the new PC value

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7.2 Branching Far Way

- Given the instruction

  ```
  beq $s0, $s1, L1
  ```

  Assume that the address `L1` is farther away from the PC than what 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

NOTE:
Discuss in forum

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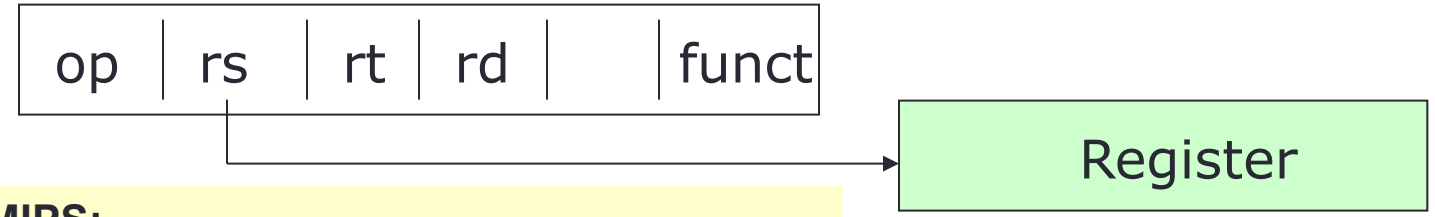
8. Addressing Modes (1/3)

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



MIPS:
`add`, `sub`, `and`, `or`, `xor`, `nor`, `slt`, `sll`, `srl`

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

MIPS:
`addi`, `andi`, `ori`, `xori`, `slti`

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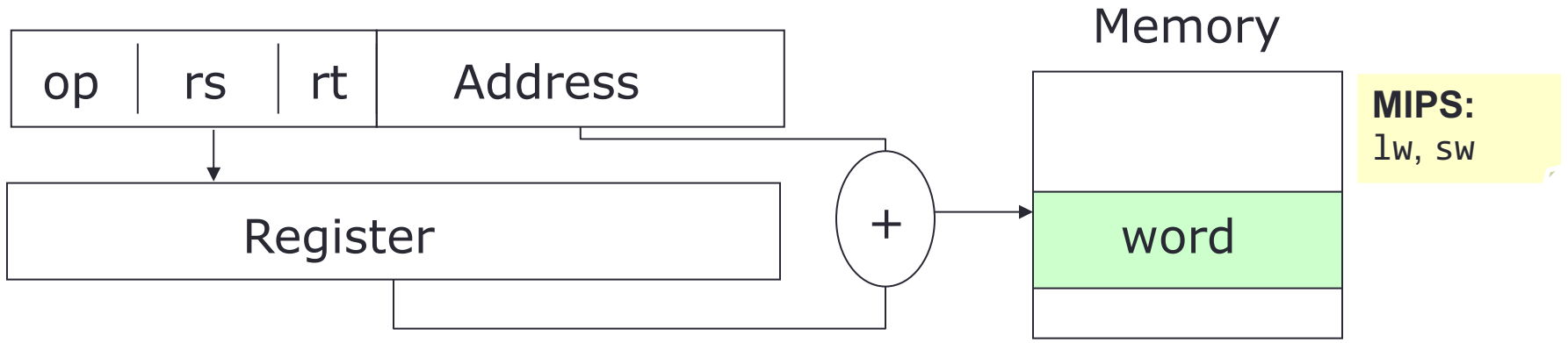
8. Addressing Modes (2/3)

- **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`)



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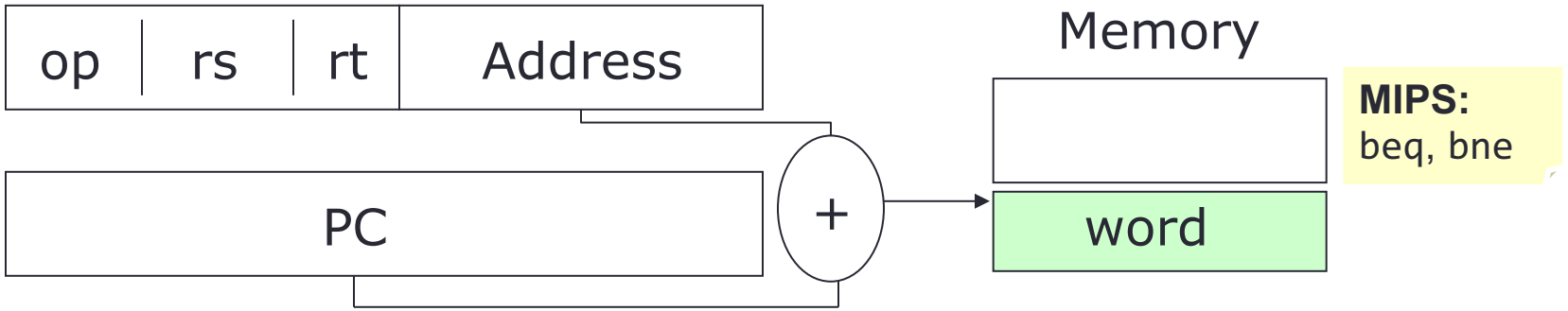
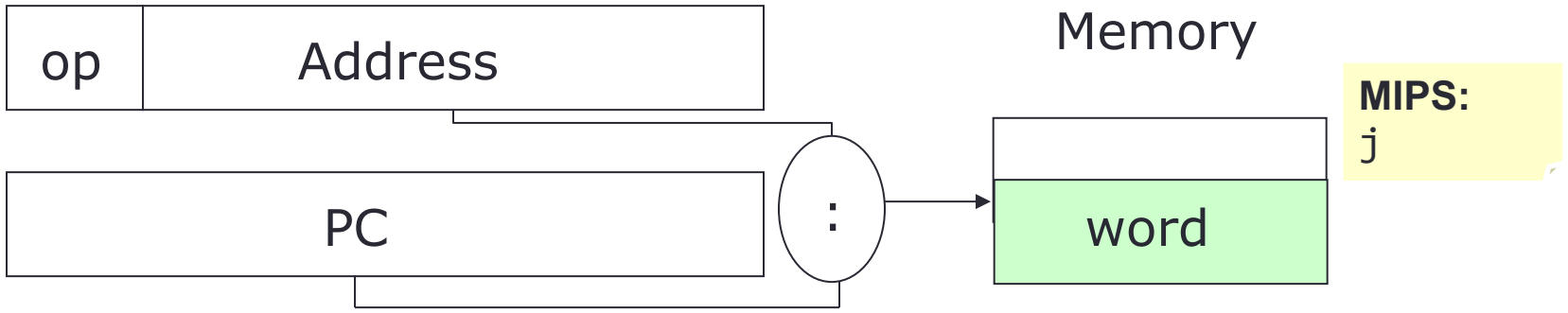
8. Addressing Modes (3/3)

- **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`)



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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

IN OTHER WORDS:
beq, **bne**: ignore PC, count displacement
j: use PC, ignore displacement

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Summary (2/2)

MIPS assembly language				
Category	Instruction	Example	Meaning	Comments
	add	`add $s1, $s2, $s3`	`$s1 = $s2 + $s3`	Three operands; data in registers
Arithmetic	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
	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
Data transfer	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
	branch on equal	`beq $s1, $s2, 25`	if (`$s1 == $s2`) go to PC + 4 + 100	Equal test; PC-relative branch
Conditional 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
	jump	`j 2500`	go to 10000	Jump to target address
Uncondi-	jump register	`jr $ra`	go to `$ra`	For switch, procedure return
tional jump	jump and link	`jal 2500`	`$ra` = PC + 4; go to 10000	For procedure call

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