

ARCOS Group

uc3m | Universidad **Carlos III** de Madrid

Lesson 3 (III)

Fundamentals of assembler programming

Computer Structure
Bachelor in Computer Science and Engineering



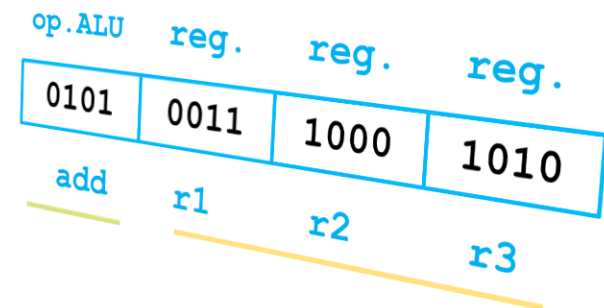
Contents

- ▶ Basic concepts on assembly programming
- ▶ MIPS32 assembly language, memory model and data representation
- ▶ Instruction formats and addressing modes
- ▶ Procedure calls and stack convention

Information of an instruction

▶ The instructions:

- ▶ Its size is **adjusted to one word or multiples words**
- ▶ They are **divided in fields**:
 - ▶ Operation to do
 - ▶ Operands
 - There can be implicit operands



▶ The **instruction format**:

- ▶ Form of representation of an instruction composed of fields of binary numbers:
 - ▶ The field size limits the number of values to encode

Information of an instruction

- ▶ **Instruction set** based on very **few formats**:
 - ▶ Each instruction belongs to one of this available formats
- ▶ **Example: 3 instruction formats in MIPS**

Type R
arithmetic



Type I
Immediate
transfer



Type J
branches



Instruction and pseudoinstruction in MIPS32

- ▶ An assembly instruction corresponds to a machine instruction
 - ▶ A machine instruction occupies 32 bits
 - ▶ Example: `addi $t1, $t1, 2`
- ▶ A pseudo-assembler instruction corresponds to one or several machine instructions.
 - ▶ Example 1:
 - ▶ The instruction: `move reg2, reg1`
 - ▶ It is equivalent to: `add reg2, $zero, reg1`
 - ▶ Example 2:
 - ▶ The instruction : `li $t1, 0x00800010`
 - ▶ It does not fit in 32 bits, but it can be used as a pseudoinstruction.
 - ▶ It is equivalent to:
 - `lui $t1, 0x0080`
 - `ori $t1, $t1, 0x0010`

Instruction fields

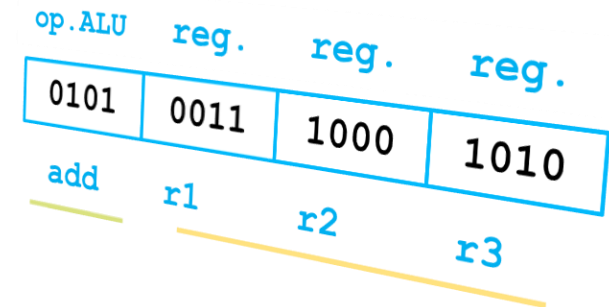
▶ Each field encodes:

▶ Operation (Operation code)

- ▶ Instruction and format used

▶ Operands

- ▶ Location of operands
- ▶ Location for results
- ▶ Location of next instruction (*in branches*)
 - Implicit: $PC \leftarrow PC + '4'$ (next instruction)
 - Explicit: j 0x01004 (PC modified)



Locations of operands

1. In the instruction

li \$t0 0x123

2. In registers (processor)

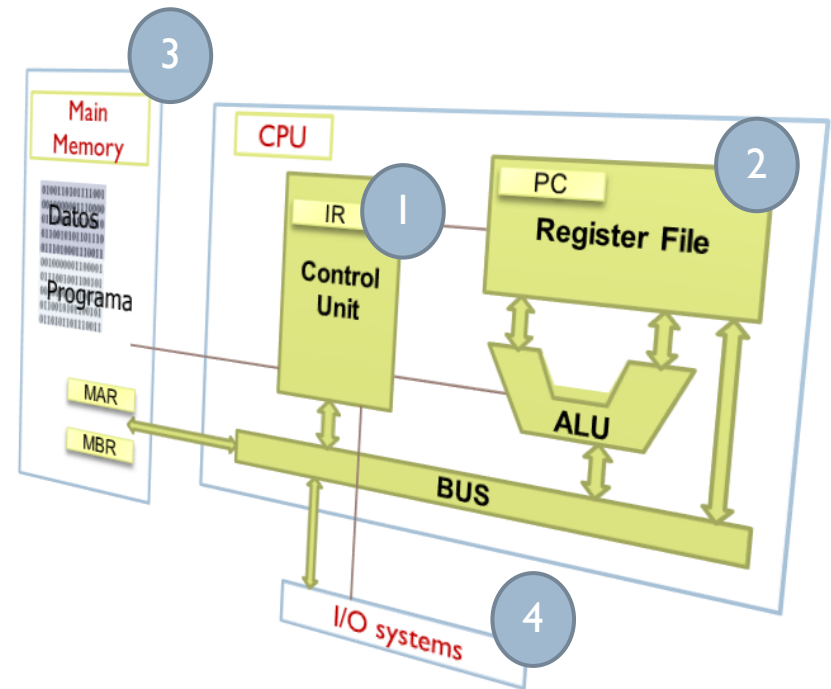
li \$t0 0x123

3. Main memory

lw \$t0 address

4. Input/output modules

in \$t0 0xFEB



Kinds of ways to said the locations of operands: addressing modes

1. In the instruction

li \$t0 0x123

2. In registers (processor)

li \$t0 0x123

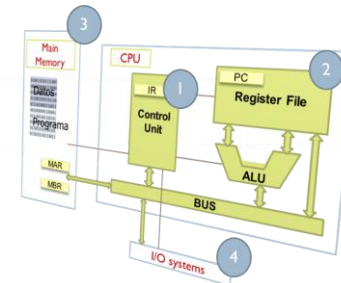
3. Main memory

lw \$t0

address

4. Input/output modules

in \$t0 0xFEB



- **Number** representing an address
- **Symbolic label** representing an address
- **(register)**: represents the address stored in the register
- **num(register)**: represents the address obtained by adding num with the address stored in the register
- **label + num**: represents the address obtained by adding label with num

Contents

- ▶ Basic concepts on assembly programming
- ▶ MIPS32 assembly language, memory model and data representation
- ▶ Instruction formats and **addressing modes**
- ▶ Procedure calls and stack convention

Addressing modes

▶ Procedure that allows to localize the operands

▶ Types:

▶ Implicit

▶ Immediate

▶ Direct {

- To register
- To memory

▶ Indirect {

- To register
- To memory

▶ Relative {

- To index register
- Base register
- To PC
- To stack

Addressing modes in MIPS

- ▶ Immediate value

- ▶ Direct

- ▶ To memory address

- ▶ To register \$r

- ▶ Indirect

- ▶ To memory

- ▶ To register (\$r)

- ▶ Relative to

- register offset(\$r)

- stack offset(\$sp)

- PC beq ... label l

Addressing modes

▶ Procedure that allows to localize the operands

▶ Types:

▶ **Implicit**

▶ **Immediate**

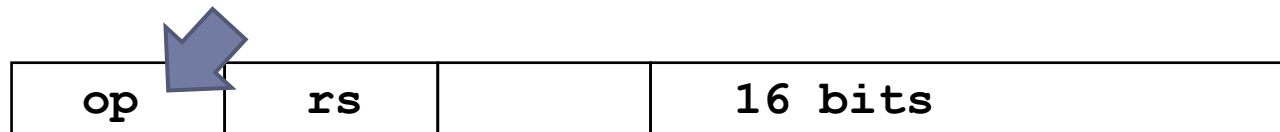
▶ Direct {
• **To register**
• **To memory**

▶ Indirect {
• To register
• To memory

▶ Relative {
• To index register
• Base register
• To PC
• To stack

Implicit addressing

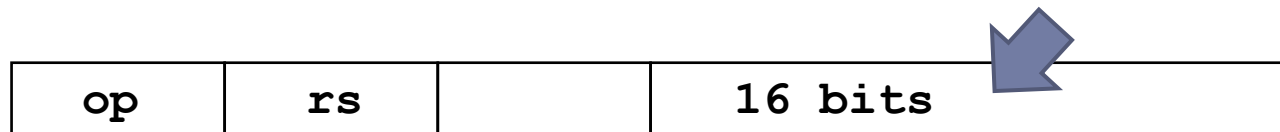
- ▶ The operand is not encoded in one field of instruction.
- ▶ Example (mips32): **beqz \$a0 label**
 - ▶ If \$a0 is zero, then branch to label
 - ▶ \$a0 is an operand, \$zero is the other one



- ▶ G/B
 - ▶ Good: It is fast because no extra memory access is required.
 - ▶ Good: Instructions shorter
 - ▶ Bad: limited options

Immediate addressing

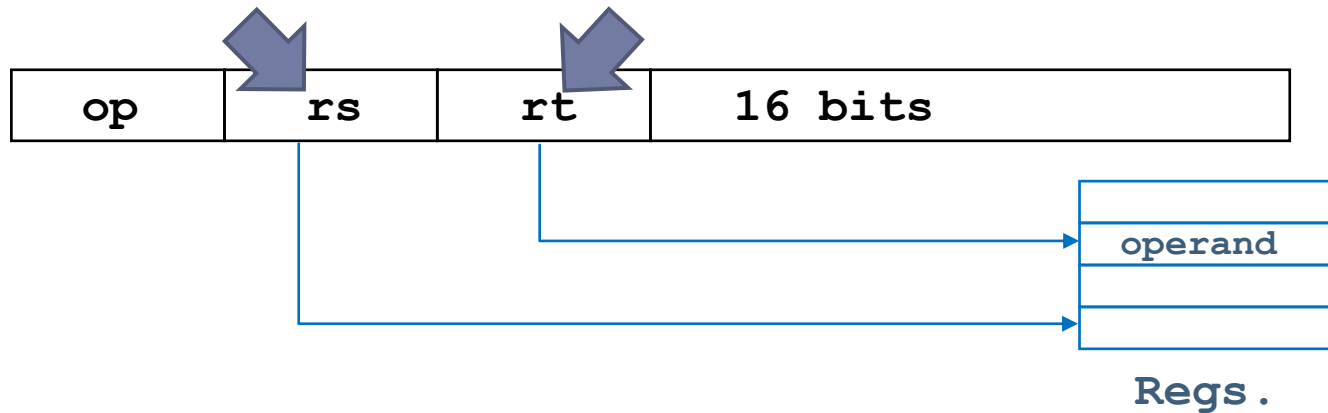
- ▶ Operand is in one field of the instruction of instruction.
- ▶ Example (mips32): `li $a0 0x25`
 - ▶ Load 0x25 in register \$a0
 - ▶ 0x25 is the immediate value



- ▶ G/B
 - ▶ Good: It is fast because no extra memory access is required.
 - ▶ Bad: not always fits within a word
 - ▶ `li $t1, 0x00800010`
 - ▶ Equivalent to:
 - ▶ `lui $t1, 0x0080`
 - ▶ `ori $t1, $t1, 0x0010`

Register addressing

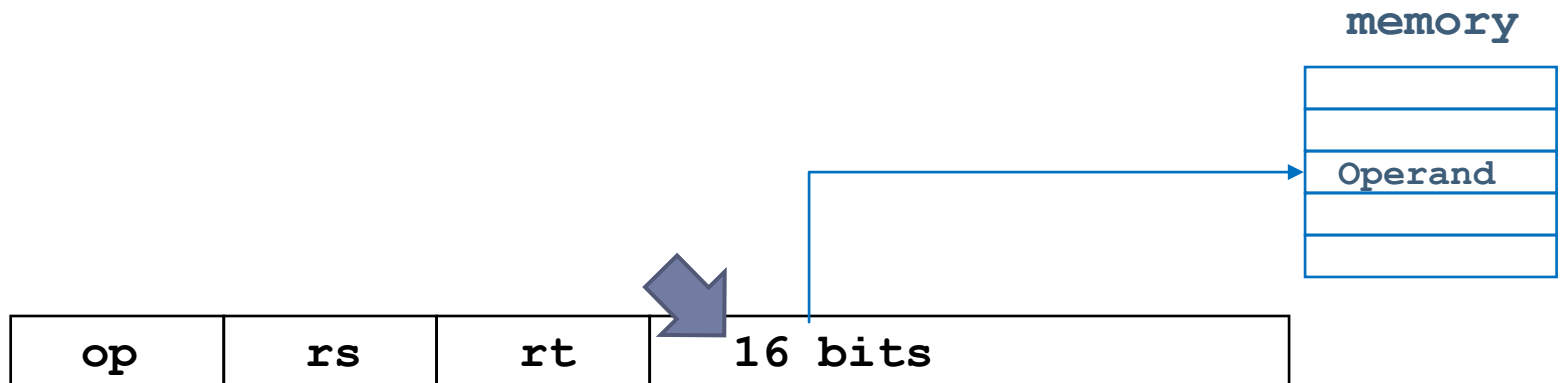
- ▶ Operand is in a register.
- ▶ Example (MIPS): `move $a0 $a1`
 - ▶ \$a0 and \$a1 are encoded in the instruction



- ▶ G/B:
 - ▶ Good: Faster access (no extra memory access required)
 - ▶ Good: Small address field
 - ▶ Bad: limited number of registers

Direct addressing

- ▶ Operand in memory. The instruction encodes the address.
- ▶ Example (MIPS): `lw $t1, 0xFFF0`
 - ▶ Load in \$t1 the word stored in address `0xFFF0`



- ▶ G/B:
 - ▶ Good: capacity is bigger than register file
 - ▶ Bad: memory access time is larger than register access time
 - ▶ Bad: large fields => large instructions

Addressing modes

▶ Procedure that allows to localize the operands

▶ Types:

▶ Implicit

▶ Immediate

▶ Direct {
• To register
• To memory

▶ Indirect {
• **To register**
• **To memory**

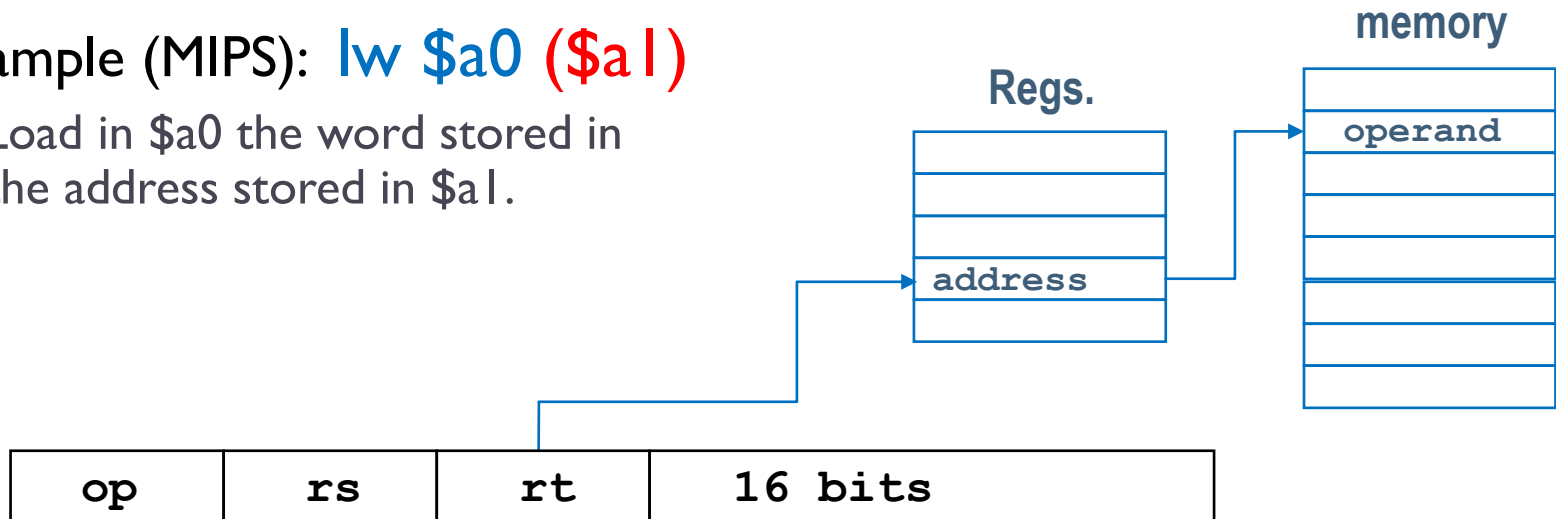
▶ Relative {
• To index register
• Base register
• To PC
• To stack

Register indirect addressing

- ▶ The instruction has the register where the address is stored

- ▶ Example (MIPS): `lw $a0 ($a1)`

- ▶ Load in \$a0 the word stored in the address stored in \$a1.



- ▶ G/B:

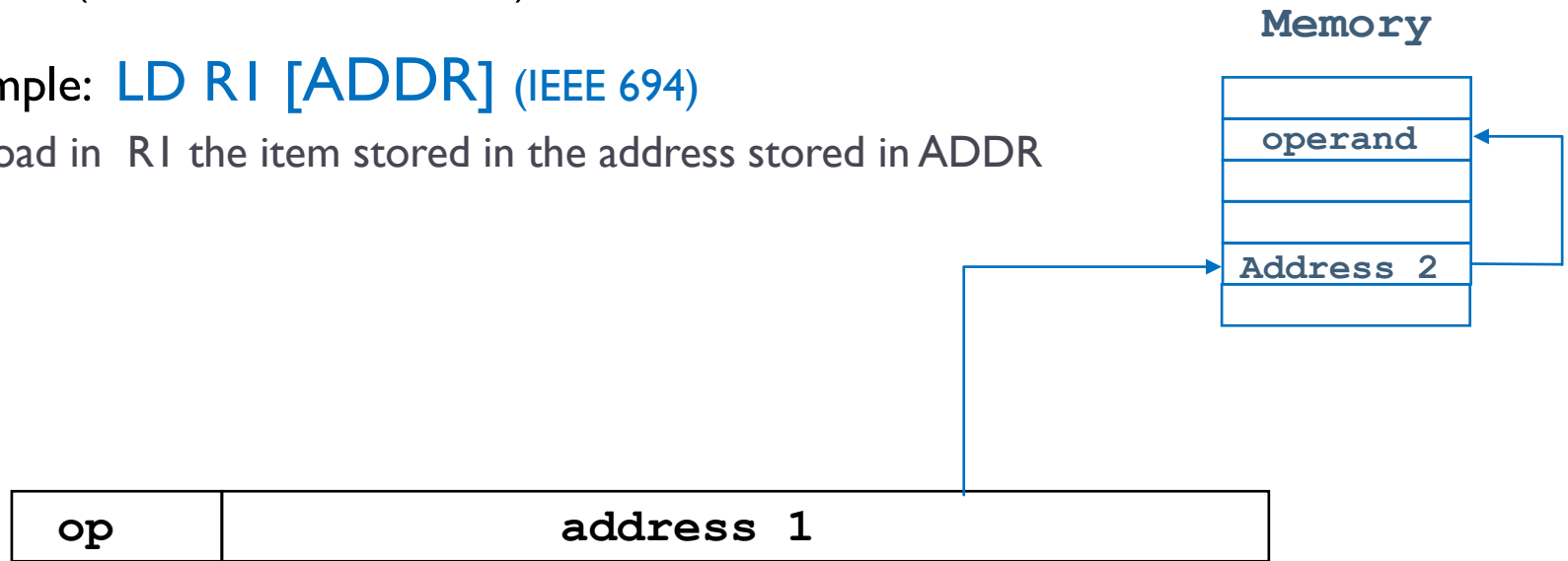
- ▶ Good: Small fields
 - ▶ Good: address in a register can addressing the entire memory (32-bits registers)
 - ▶ Bad: extra memory access (slow execution)

Indirect addressing

- ▶ The instruction has the address where the operand address is stored (not available in MIPS)

- ▶ Example: **LD RI [ADDR]** (IEEE 694)

- ▶ Load in RI the item stored in the address stored in ADDR



- ▶ G/B:

- ▶ Bad: several memory accesses are required
 - ▶ Bad: slower instructions
 - ▶ Good: large address space, addressing can be multilevel (e.g.: [[[.RI]]])

Addressing modes

▶ Procedure that allows to localize the operands

▶ Types:

▶ Implicit

▶ Immediate

▶ Direct {

- To register
- To memory

▶ Indirect {

- To register
- To memory

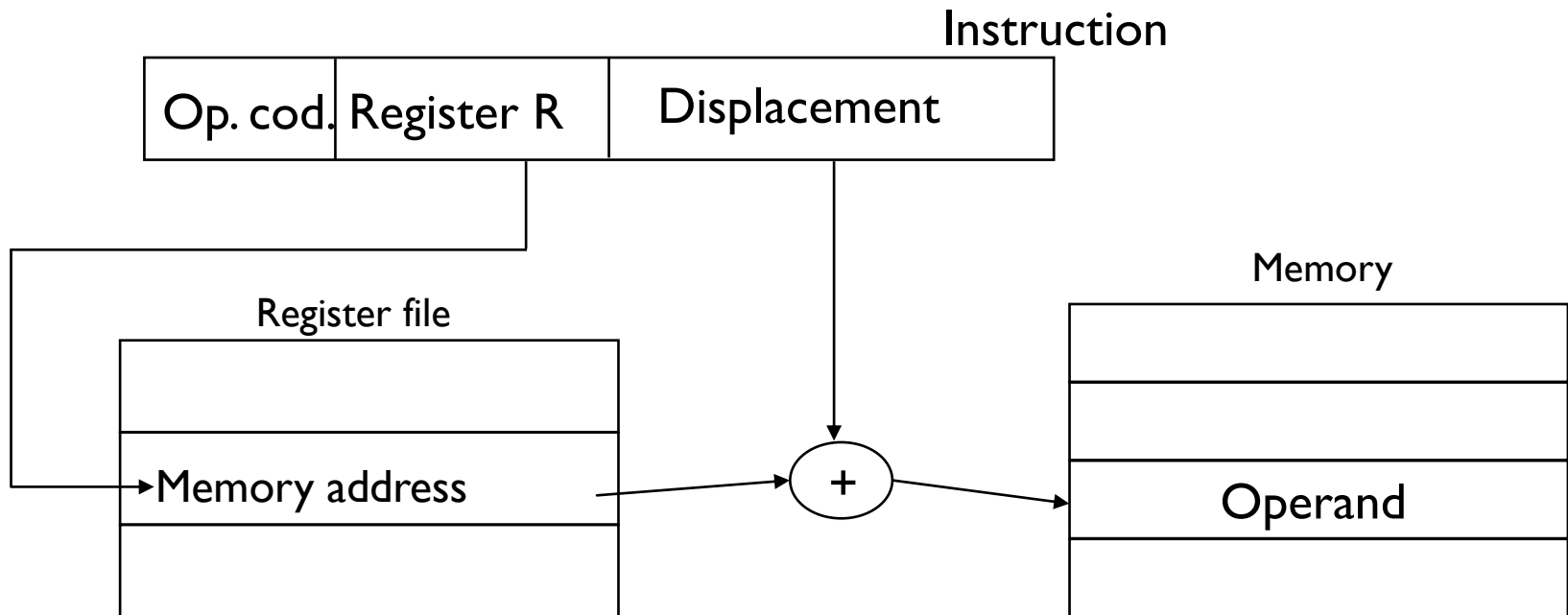
▶ Relative {

- **To index register**
- **Base register**
- **To PC**
- **To stack**

Base-register addressing

Example: `lw $a0 12($t1)`

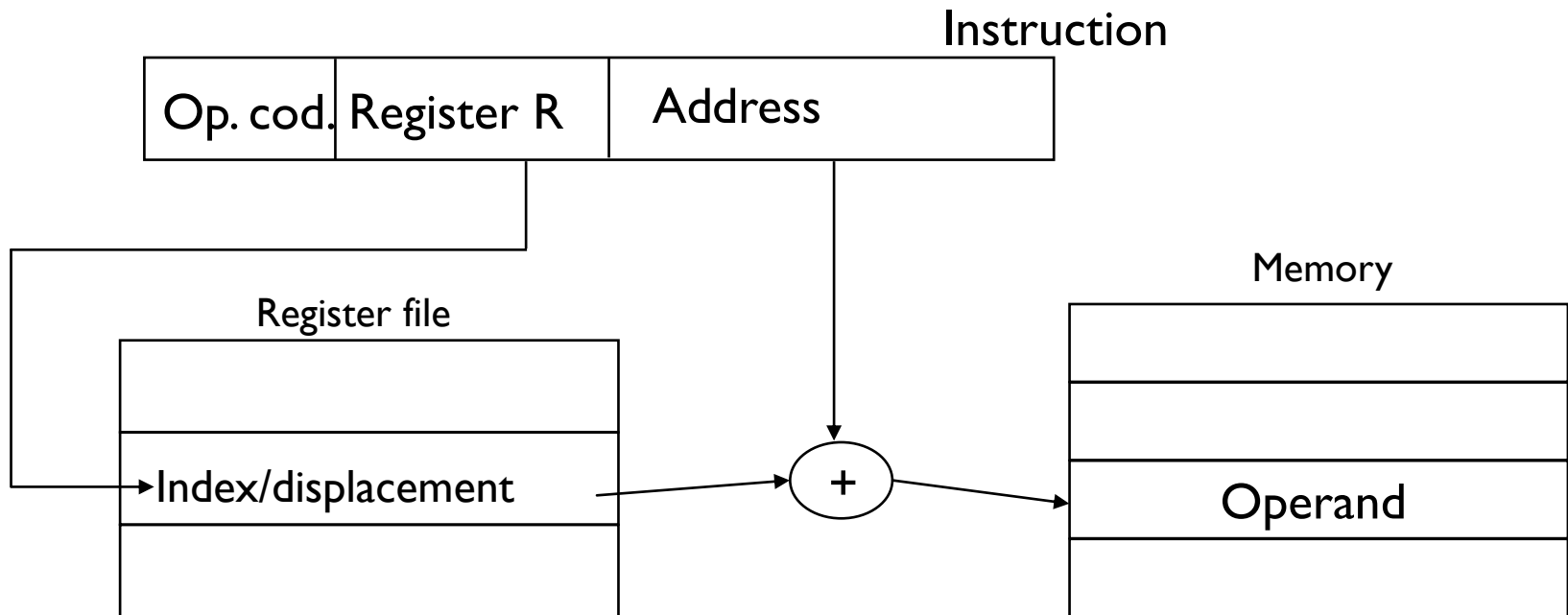
- ❑ Load in `$a0` the word stored in address: `$t1 + 12`
- ❑ `$t1` represents the base address



Index-register addressing

Example: `lw $a0 address($t1)`

- ❑ Load in \$a0 the word stored in address: $\$t1 + \text{address}$
- ❑ \$t1 represents an index (offset from address)



Example (base/index)

```
int v[5] ;
```

```
main ( )
```

```
{
```

```
    v[3] = 5 ;
```

```
    v[4] = 8 ;
```

```
}
```

```
.data
v: .space 20    # 5int*4bytes/int
```

```
.text
```

```
.globl main
```

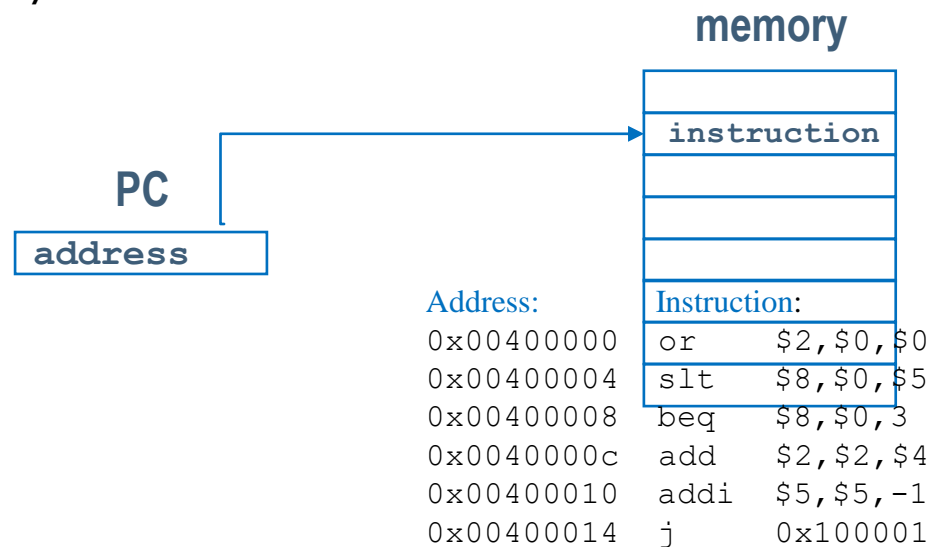
```
main:
```

```
    la $t0, v
    li $t1, 5
    sw $t1, 12($t0)
```

```
    la $t0, 16
    li $t1, 8
    sw $t1, v($t0)
```

PC-relative addressing

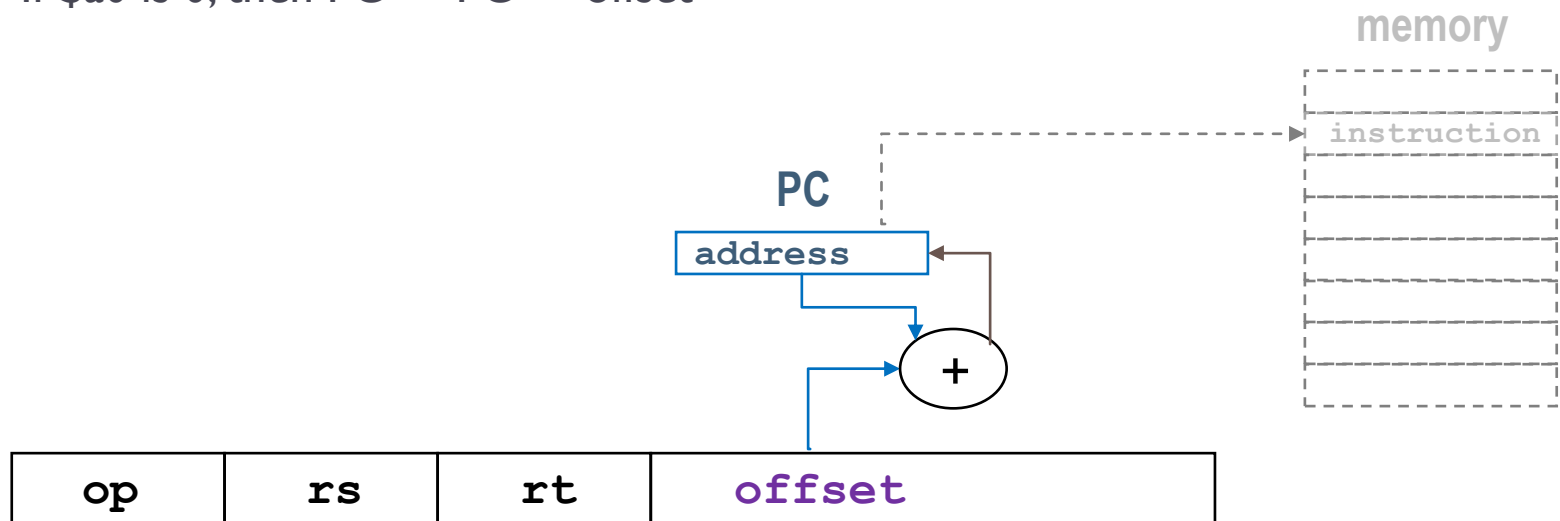
- ▶ The program counter (PC):
 - ▶ Registers of 32 bits (4 bytes) in a 32-bits computer.
 - ▶ PC stores the address of the next instruction to be executed
 - ▶ Points to a word (4 bytes) in memory with the instruction to be executed
 - ▶ PC in a 32-bits computer is updated by default as $PC = PC + 4$



PC-relative addressing

▶ Example: `beqz $a0 label`

- ▶ The assembler encode label as the **offset** from the beqz instruction to the memory position associated to **label**.
 - ▶ Label encoded as displacement (address \rightarrow # instructions to jump)
- ▶ If `$a0` is 0, then $PC \leftarrow PC + \text{"offset"}$



PC-relative addressing in MIPS

- ▶ Instruction `beq $9, $0, label` is encoded as:



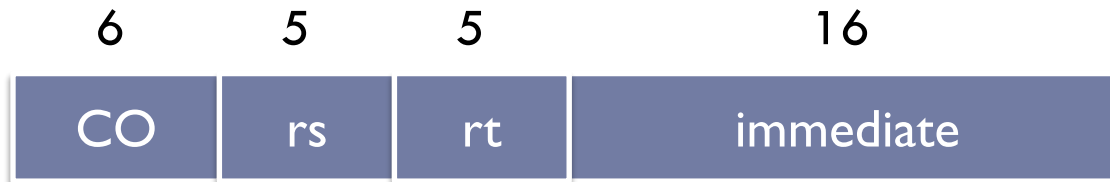
- ▶ When `$t0 == $l`, what is the value for `end` label?

```
loop:    beq    $t0,$l, end
         add    $t8,$t4,$t4
         addi   $t0,$0,-1
         j      loop
end:     ...
```

- ▶ Label must be encoded in an “immediate” field

PC-relative addressing in MIPS

- ▶ Instruction `beq $9, $0, label` is encoded as:



- ▶ When `$t0 == $1`, **end** is 3 (“number of instructions to skip”)

```
loop:    beq    $t0, $1, end
```

```
        ...
```

```
end:    ...
```

- ▶ Reasons:

- ▶ When an instruction is going to be executed, PC has the addresss of next instruction in memory
- ▶ When the condition in satisfied: $PC = PC + (label * 4)$

Use in loops

```
        li    $t0 8
        li    $t1 4
        li    $t2 1
        li    $t4 0
while:   bge   $t4 $t1 end
        mul   $t2 $t2 $t0
        addi  $t4 $t4 1
        b     while
end:     move  $t2 $t4
```

- ▶ **end** represents the address where the instruction `move` is stored
- ▶ **while** represents the address where the instruction `bge` is stored

Use in loops

```
        li    $t0 8
        li    $t1 4
        li    $t2 1
        li    $t4 0
while:   bge   $t4 $t1 end
        mul   $t2 $t2 $t0
        addi  $t4 $t4 1
        b     while
end:     move  $t2 $t4
```

Address	Content
0x0000100	li \$t0 8
0x0000104	li \$t1 4
0x0000108	li \$t2 1
0x000010C	li \$t4 0
0x0000110	bge \$t4 \$t1 end
0x0000114	mul \$t2 \$t2 \$t0
0x0000118	addi \$t4 \$t4 1
0x000011C	b while
0x0000120	move \$t2 \$t4

Use in loops

```
        li    $t0 8
        li    $t1 4
        li    $t2 1
        li    $t4 0
while:   bge   $t4 $t1 end
        mul   $t2 $t2 $t0
        addi  $t4 $t4 1
        b     while
end:     move  $t2 $t4
```

- **end** encoded as displacement relative to current PC => **3**
 $PC = PC + 3 * 4$
- **while** encoded as displacement relative to current PC => **-4**
 $PC = PC + (-4) * 4$

Address	Content
0x0000100	li \$t0 8
0x0000104	li \$t1 4
0x0000108	li \$t2 1
0x000010C	li \$t4 0
0x0000110	bge \$t4 \$t1 end
0x0000114	mul \$t2 \$t2 \$t0
0x0000118	addi \$t4 \$t4 1
0x000011C	b while
0x0000120	move \$t2 \$t4

Use in loops

```
        li    $t0 8
        li    $t1 4
        li    $t2 1
        li    $t4 0
while:   bge   $t4 $t1 end
        mul   $t2 $t2 $t0
        addi  $t4 $t4 1
        b     while
end:     move  $t2 $t4
```

- **end** encoded as displacement relative to current PC => **3**
 $PC = PC + 3 * 4$
- **while** encoded as displacement relative to current PC => **-4**
 $PC = PC + (-4) * 4$

Address	Content
0x0000100	li \$t0 8
0x0000104	li \$t1 4
0x0000108	li \$t2 1
0x000010C	li \$t4 0
0x0000110	bge \$t4 \$t1 3
0x0000114	mul \$t2 \$t2 \$t0
0x0000118	addi \$t4 \$t4 1
0x000011C	b -4
0x0000120	move \$t2 \$t4

Differences between b and j instructions

- Instruction j address



Branch address \Rightarrow $PC = \text{address}$

- Instruction b displacement

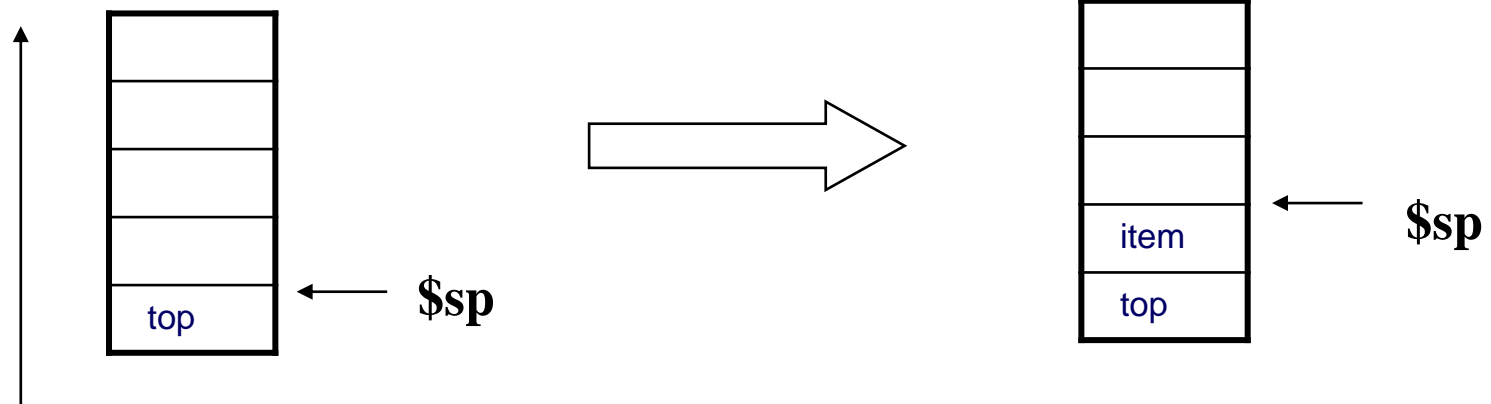


Branch address \Rightarrow $PC = PC + \text{displacement}$

Stack addressing

PUSH Reg

Push the content of a register (item)

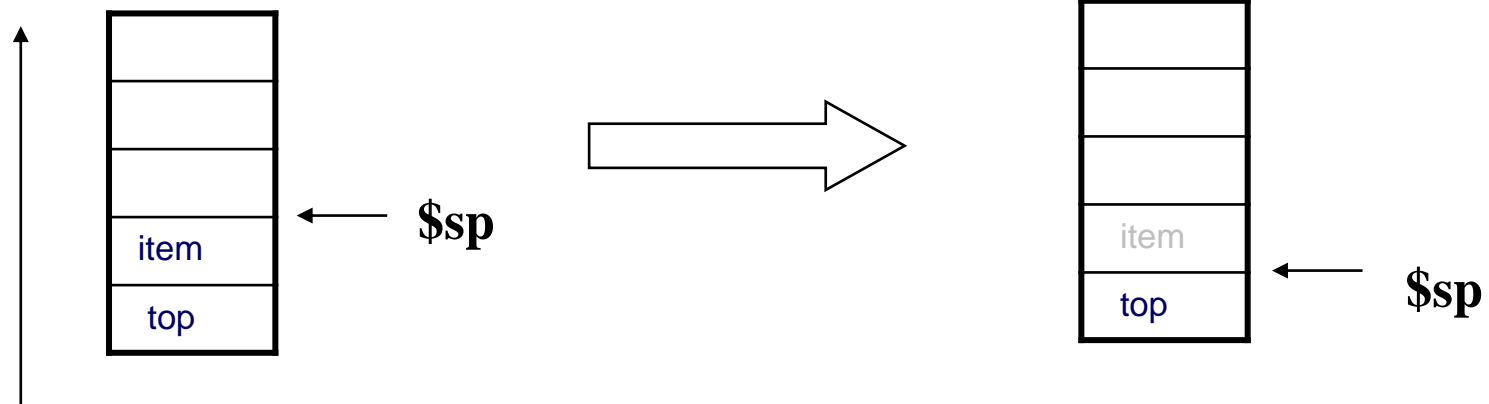


Stack grows to lower memory addresses

Stack addressing

POP Reg

Pop the top of the stack (item)
Copy the element in a Reg



Stack grows to lower memory addresses

Stack addressing

- ▶ MIPS does not have PUSH or POP instructions
 - ▶ The stack pointer (\$sp) is visible
 - ▶ We assume that \$sp points to the last element in the stack
 - ▶ Push -> allocate new word + store a value
 - ▶ Pop -> retrieve a value + deallocate a word

PUSH \$t0

```
sub $sp, $sp, 4  
sw $t0, ($sp)
```

POP \$t0

```
lw $t0, ($sp)  
add $sp, $sp, 4
```

Examples of addressing types

- ▶ `la $t0 label` **immediate**
 - ▶ The second operand is an address
 - ▶ But this address is not accessed, the address is the operand
- ▶ `lw $t0 label` **direct**
 - ▶ The second operand is an address
 - ▶ A memory access is required to obtain the final operand
- ▶ `bne $t0 $t1 label` **PC-relative**
 - ▶ Last operand represents a displacement
 - ▶ Label is encoded as a number that represents a displacement relative to PC

Contents

- ▶ Basic concepts on assembly programming
- ▶ MIPS32 assembly language, memory model and data representation
- ▶ **Instruction formats** and addressing modes
- ▶ Procedure calls and stack convention

Instruction format

- ▶ A machine instruction is divided in **fields**
- ▶ A machine instruction includes:
 - ▶ Operation code
 - ▶ Operands
 - ▶ How the operands are represented
 - ▶ Results
 - ▶ Address of the next instruction
- ▶ Example in MIPS:

Type R
arithmetic



Instruction format

- ▶ The **format** specifies, for each field in the instruction:
 - ▶ The meaning of each field
 - ▶ The number of bits of each field
 - ▶ How is encoded each field
 - ▶ binary, 1's complement, displacement w.r.t. ...
- ▶ Usually:
 - ▶ Very few formats in order to simplify the control unit design.
 - ▶ Fields of the same type have the same length.
 - ▶ Operation code is the first field (of first word)

Format length

- ▶ The **format length** is number of bits to encode the instruction
 - ▶ The size of an instruction is usually one word, but there can be instructions of several words
 - ▶ In MIPS32 the size of all instructions is one word (32 bits)
- ▶ Two types:
 - ▶ **Fixed/Unique length:**
 - ▶ All instructions with the same size
 - ▶ Examples:
 - MIPS32 (32 bits), PowerPC (32 bits), ...
 - ▶ **Variable length:**
 - ▶ Different instructions can have different sizes
 - ▶ How to know the instruction length? → Op. code
 - ▶ Examples:
 - IA32 (Intel processors): variable number of bytes

Operation code

- ▶ **Fixed size:**

- ▶ n bits $\rightarrow 2^n$ operation codes
- ▶ m operation codes $\rightarrow \log_2 m$ bits.

- ▶ **Extension fields**

- ▶ MIPS (arithmetic-logic instructions)
- ▶ $Op = 0$; The instruction is encoded in `func`

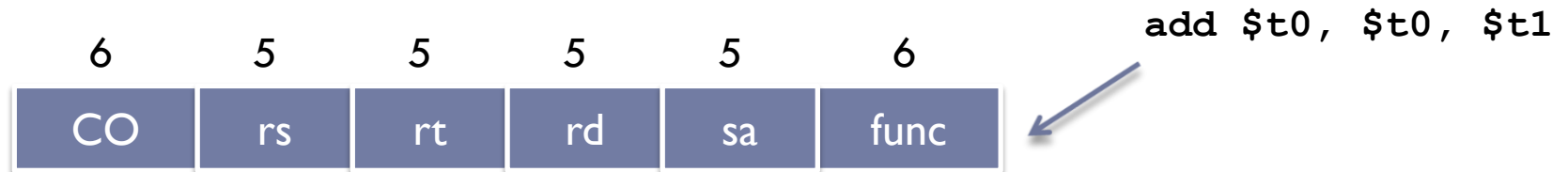
Type R
arithmetic



- ▶ **Variable sizes:**

- ▶ More frequent instructions = shorter sizes

Example: MIPS instruction formats

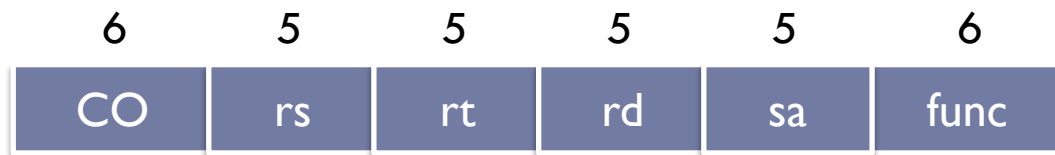


Example of MIPS formats

■ MIPS Instruction:

❑ `add $8, $9, $10`

❑ Format:



Decimal representation:

0	9	10	8	0	32
---	---	----	---	---	----

Binary representation

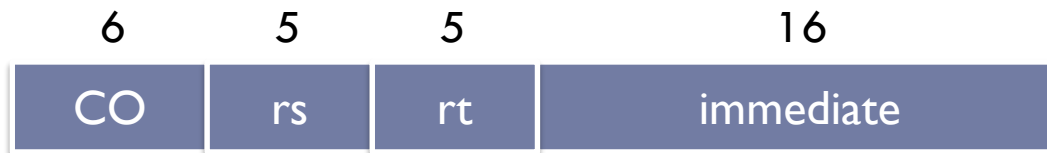
000000	01001	01010	01000	00000	100000
--------	-------	-------	-------	-------	--------

Example of MIPS formats

■ MIPS Instruction:

❑ `addi $21, $22, -50`

❑ Format:



Decimal representation:

8	22	21	-50
---	----	----	-----

Binary representation

001000	10110	10101	1111111111001110
--------	-------	-------	------------------

How to use the addi instruction with 32 bits values?

- ▶ **What happens when this instruction is used in a program?**

- ▶ `addi $t0, $t0, 0xABABCD`

- ▶ The immediate value has 32 bits.

- This instruction cannot be encoded in one word (32 bits)

How to use the addi instruction with 32 bits values?

- ▶ **What happens when this instruction is used in a program?**

- ▶ `addi $t0, $t0, 0xABABCD`

- ▶ The immediate value has 32 bits.

- This instruction cannot be encoded in one word (32 bits)

- ▶ **Solution:**

- ▶ This instruction is translated to:

- ```
lui $at, 0xABAB
ori $at, $at, 0xCDCD
add $t0, $t0, $at
```

- ▶ The `$at` is reserved to the assembler

# Example

---

- ▶ A 16-bit computer has an instruction set of 60 instructions and a register bank with 8 registers.
- ▶ Define the format of this instruction: **ADDx R1 R2 R3**, where R1, R2 and R3 are registers.

# Solution

---

word-> 16 bits  
60 instructions  
8 registers (in RB)  
ADDx R1(reg.), R2(reg.), R3(reg.)

## ► Word of 16 bits

16 bits

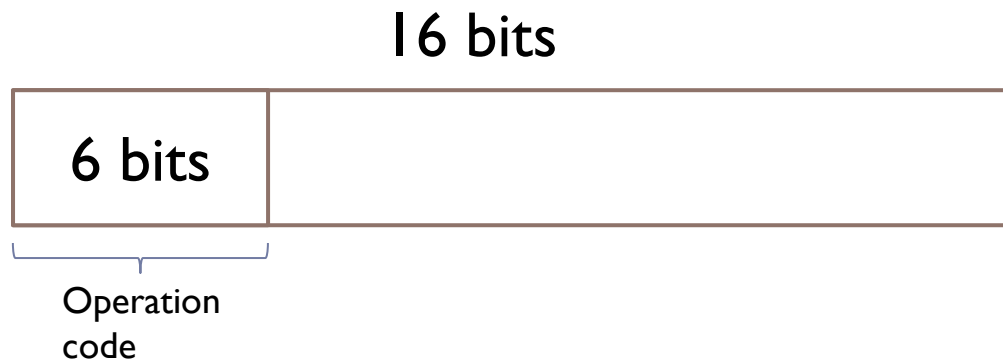




# Solution

word-> 16 bits  
60 instructions  
8 registers (in RB)  
ADDx R1(reg.), R2(reg.), R3(reg.)

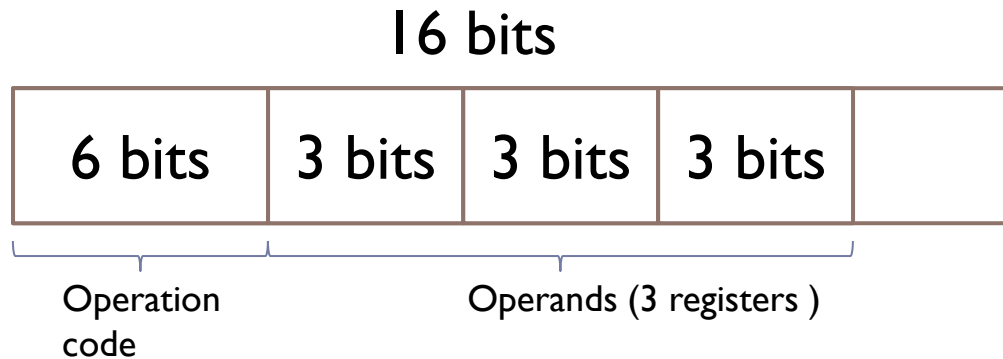
- ▶ To encode 60 instructions, 6 bits are required for the operation code



# Solution

word-> 16 bits  
60 instructions  
8 registers (in RB)  
ADDx R1(reg.), R2(reg.), R3(reg.)

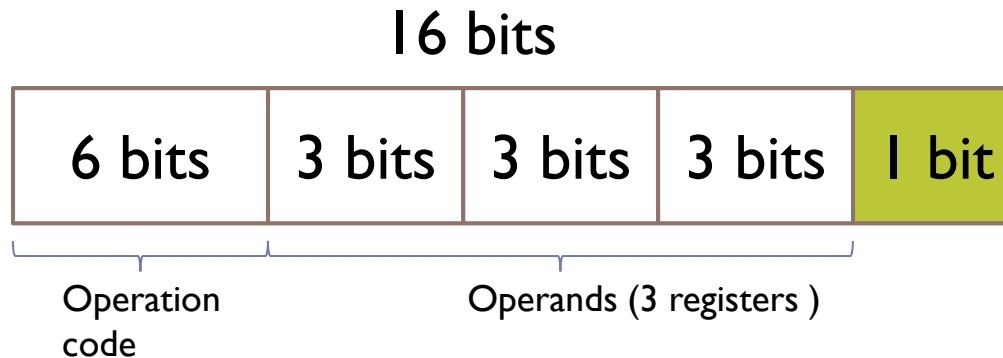
- ▶ To encode 8 registers, 3 bits are required



# Solution

word-> 16 bits  
60 instructions  
8 registers (in RB)  
ADDx R1(reg.), R2(reg.), R3(reg.)

- Spare one bit ( $16 - 6 - 3 - 3 - 3 = 1$ )



# Instruction sets

---

- ▶ There are different ways for the **classification** of the instructions sets.
- ▶ For example:
  - ▶ By complexity of the instruction set
    - ▶ CISC vs RISC
  - ▶ By available execution modes

# CISC-RISC

---

- ▶ CISC: *Complex Instruction Set Architecture* (<http://es.wikipedia.org/wiki/RISC>)
  - ▶ Many instructions
  - ▶ Complex instructions
  - ▶ Irregular design
- ▶ RISC: *Reduced Instruction Set Code* (<http://es.wikipedia.org/wiki/CISC>)
  - ▶ Simple instructions
  - ▶ Very few instructions
  - ▶ Instructions with fixed size
  - ▶ Many registers
  - ▶ Most of instructions use registers
  - ▶ Parameters are passed using registers
  - ▶ Pipelined architectures

# Execution modes

---

- ▶ The execution modes indicates the number of operands and the type of operands that can be specified in an instruction.
  - ▶ 0 addresses → Stack.
    - PUSH 5; PUSH 7; ADD
  - ▶ 1 address → Accumulator register.
    - ADD RI →  $AC \leftarrow AC + RI$
  - ▶ 2 addresses → Registers, Register-memory, Memory-memory.
    - ADD .R0, .RI ( $R0 \leftarrow R0 + RI$ )
  - ▶ 3 addresses → Registers, Register-memory, memory-memory.
    - ADD .R0, .RI, .R2

ARCOS Group

**uc3m** | Universidad **Carlos III** de Madrid

# Lesson 3 (III)

## Fundamentals of assembler programming

Computer Structure  
Bachelor in Computer Science and Engineering

