

ARCOS Group

uc3m | Universidad **Carlos III** de Madrid

L3: Fundamentals of assembler programming Computer Structure

Bachelor in Computer Science and Engineering
Bachelor in Applied Mathematics and Computing
Dual Bachelor in Computer Science and Engineering and Business Administration

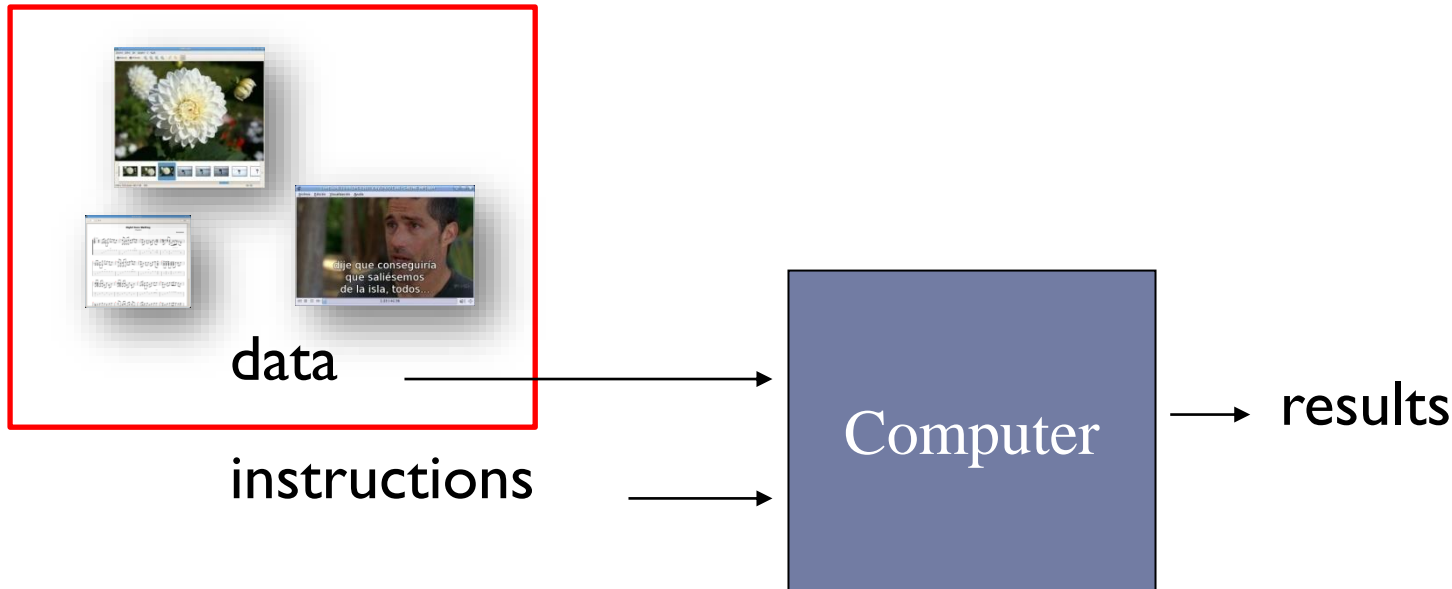


Contents

1. Basic concepts on assembly programming
 1. Motivations and goals
 2. Introduction to RISC-V32
2. RISC-V32 assembly language, memory model and data representation
3. Instruction formats and addressing modes
4. Procedure calls and stack convention

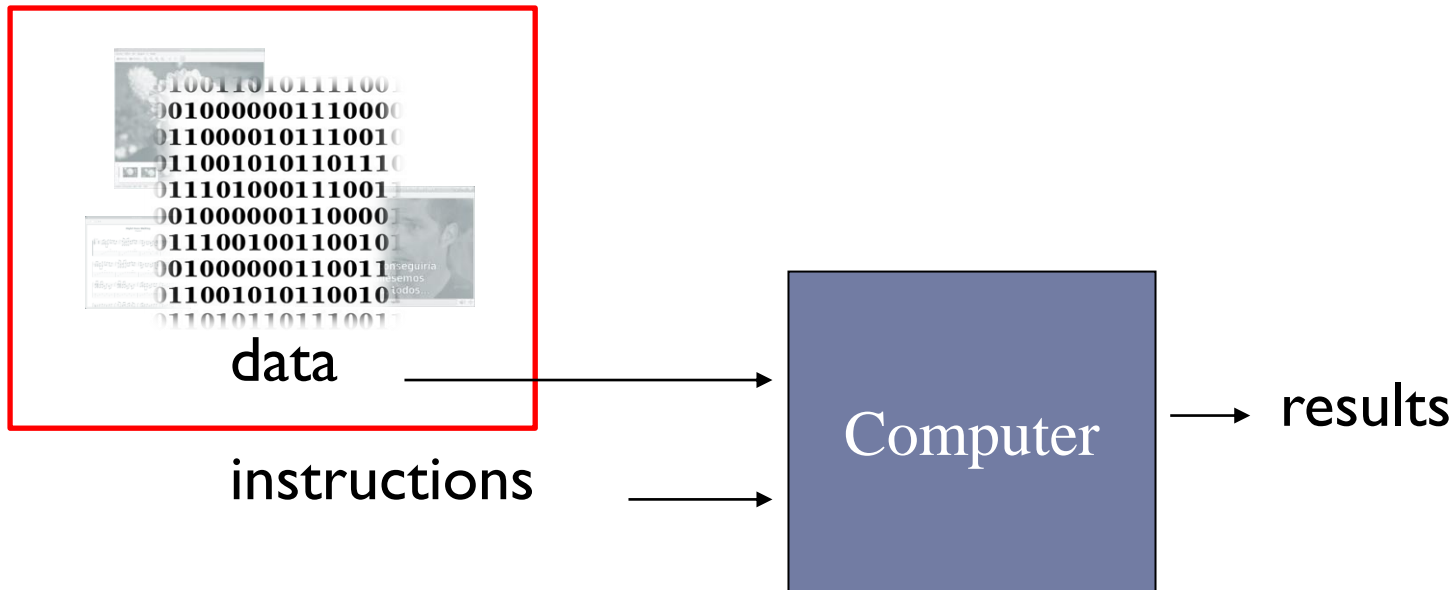
Types of information: instructions and data

► Data representation...



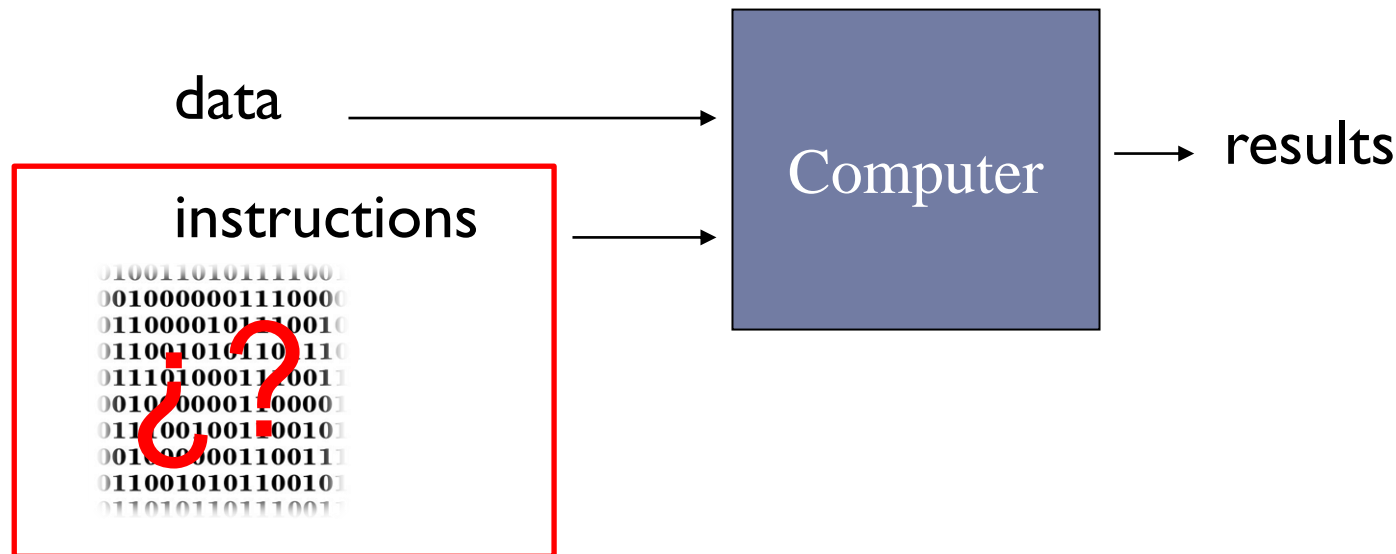
Types of information: instructions and data

► Binary data representation.



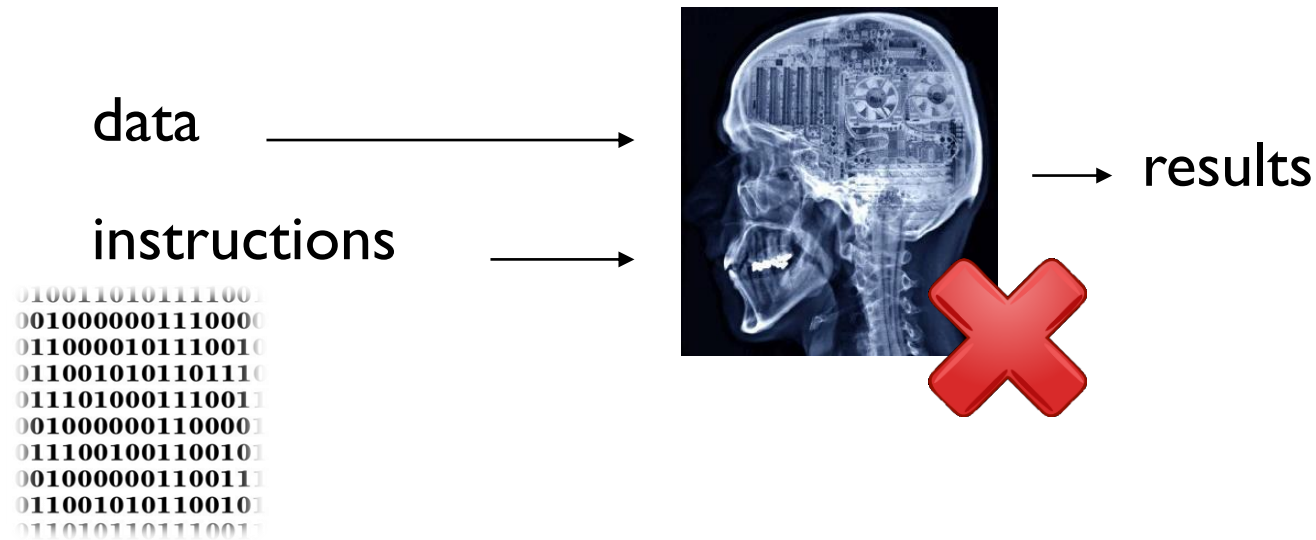
Types of information: instructions and data

- ▶ What about the instructions?
 - ▶ Machine instructions, properties and format



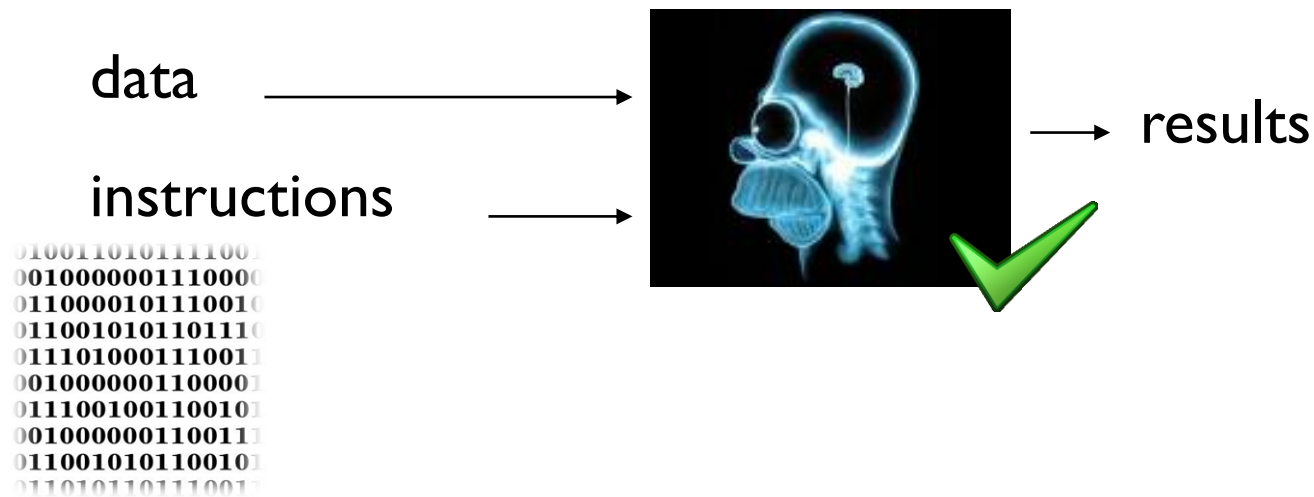
Machine instructions

- ▶ There are not complex instructions...



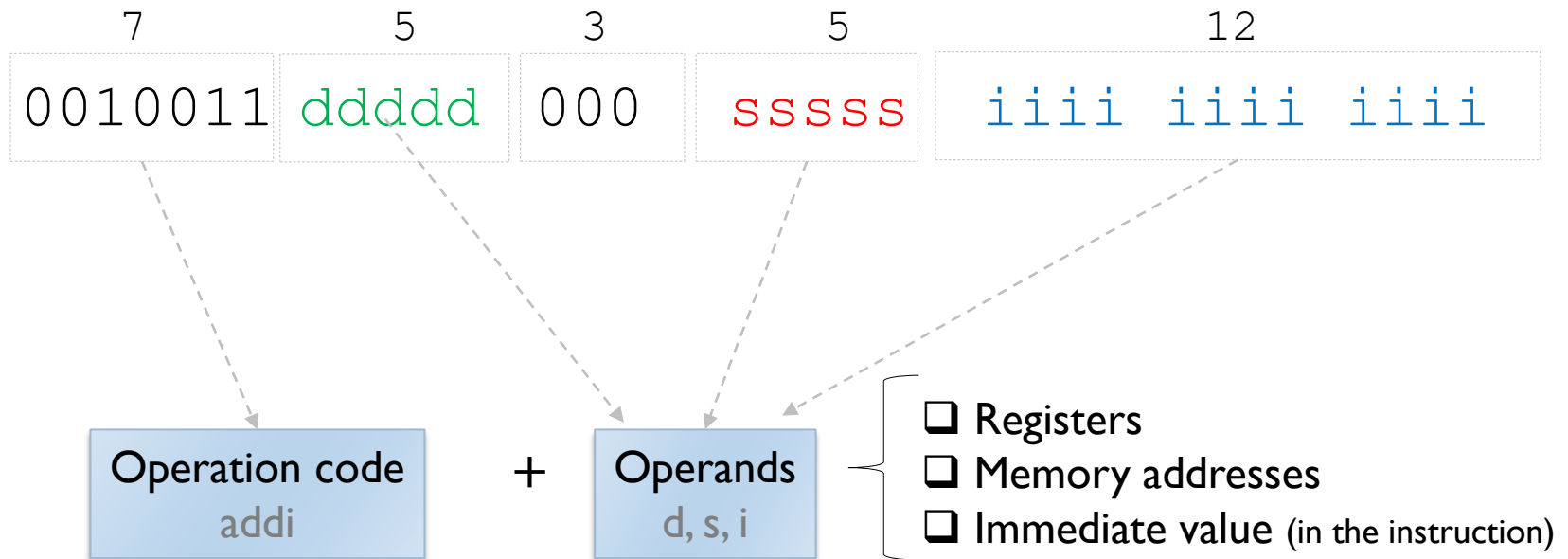
Machine instructions

- ▶ ... but very simple tasks...



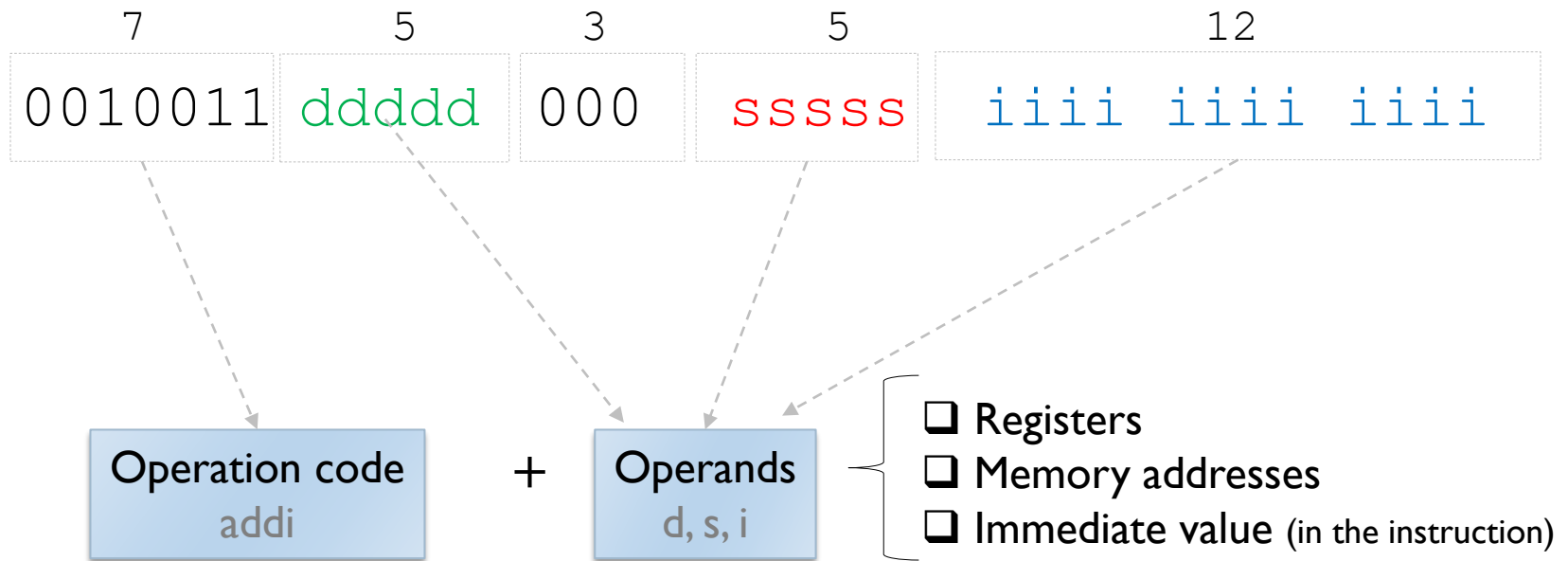
Machine instruction: definition

- ▶ **Machine instruction:** elementary operation that can be executed directly by the processor.
- ▶ **Example:** instruction of immediate add (addi) for 32 bits
 - ▶ $(d) = \text{register } (s) + \text{immediate value } (i)$



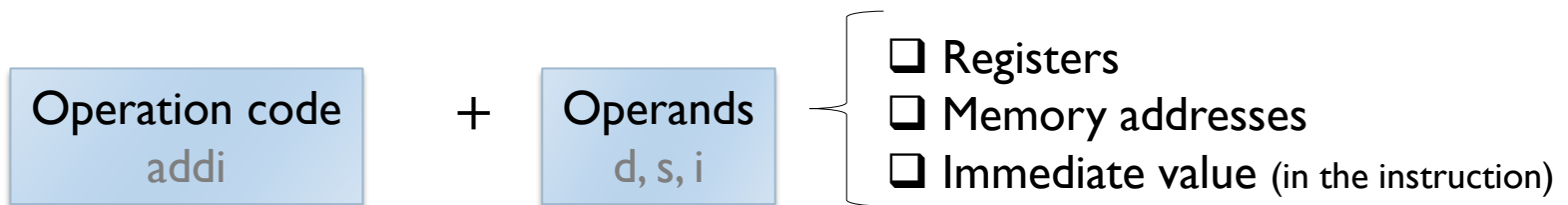
Machine instruction: properties

- ▶ Perform a **single, simple task**
- ▶ Operate on a **fixed number of operands**
- ▶ **Include all** the **information necessary** for its **execution**



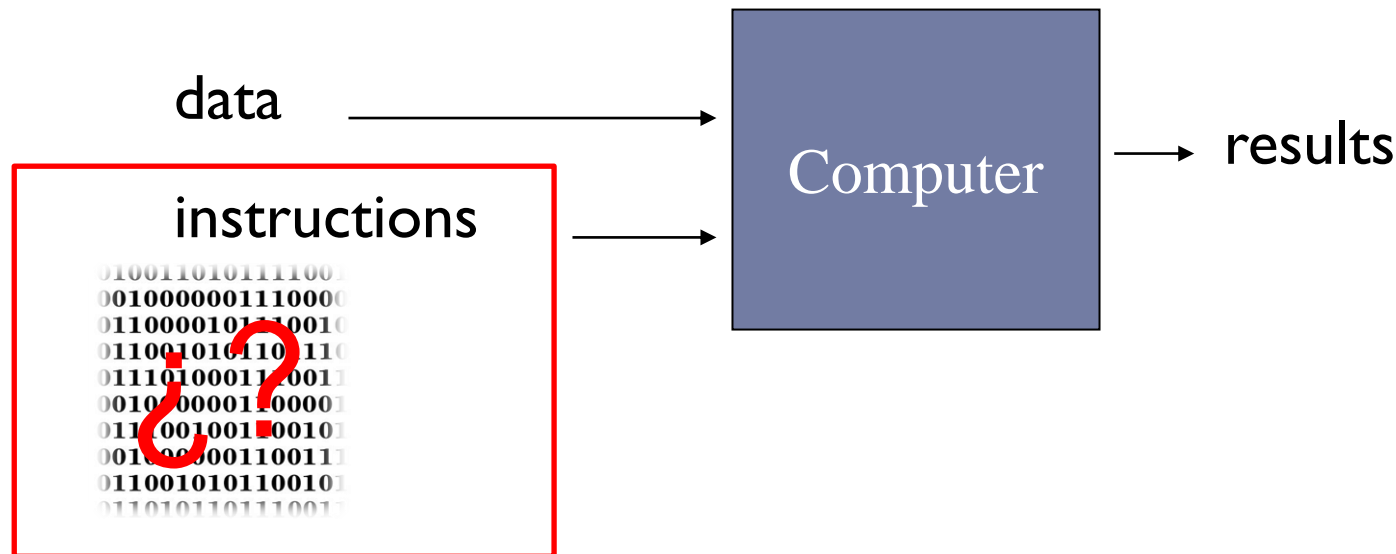
Machine instruction: included information

- ▶ The **operation to be performed**.
- ▶ Where the **operands** are located:
 - ▶ In registers
 - ▶ In memory
 - ▶ In the instruction itself (immediate)
- ▶ Where to leave the **results** (as operand)
- ▶ A reference to the **next instruction** to be executed
 - ▶ Implicitly: the following instruction
 - ▶ A program is a consecutive sequence of machine instructions.
 - ▶ Explicitly in branching instructions (as operand)



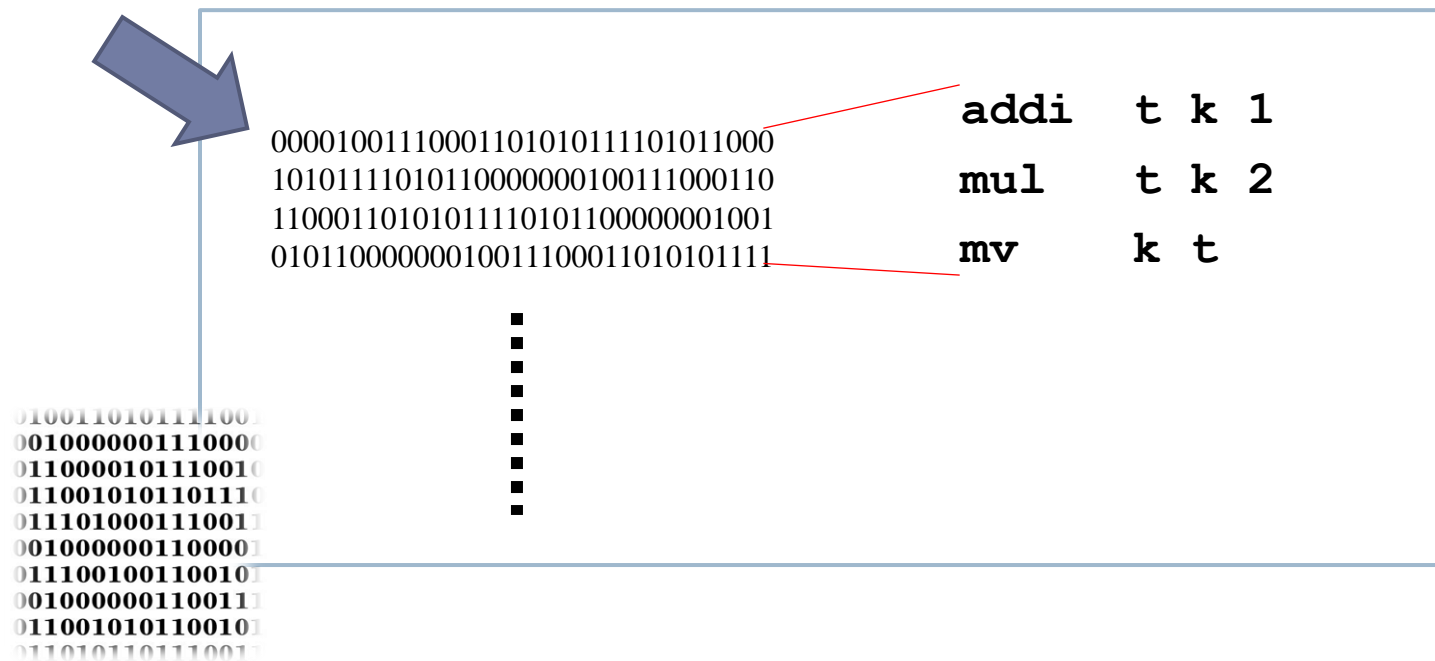
Types of information: instructions and data

- ▶ What about the instructions?
 - ▶ Program, assembly language, ISA



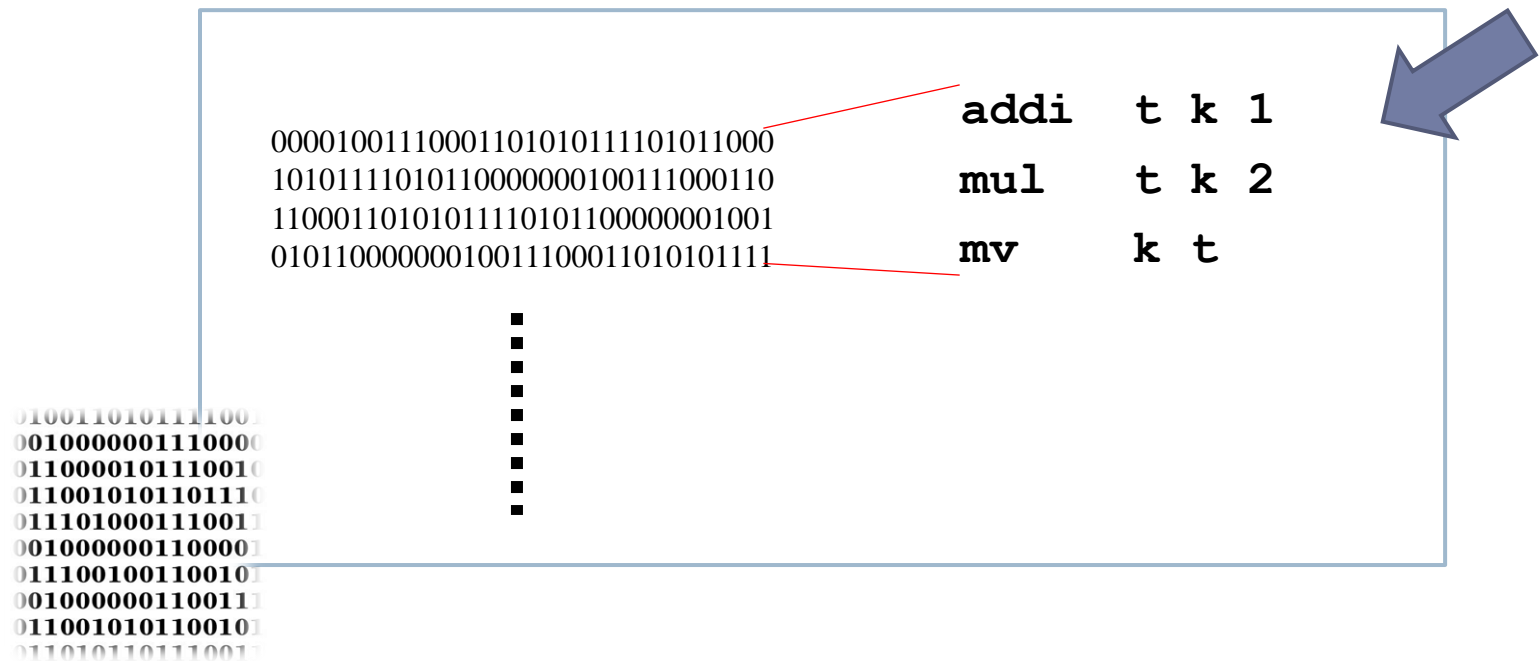
Definition of program

- **Program:** Ordered sequence of machine instructions that are executed by default in order.



Assembly language definition

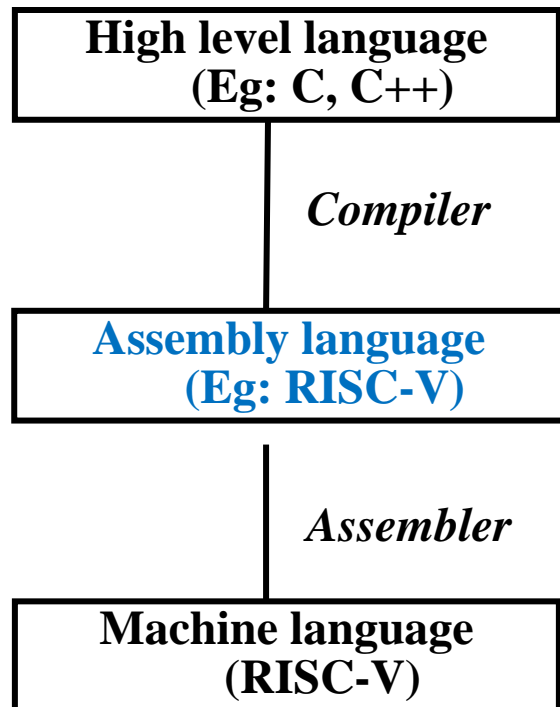
- **Assembly language:** programmer-readable language that is **the most direct representation of architecture-specific machine code.**



Assembly language definition

- ▶ **Assembly language:** programmer-readable language that is **the most direct representation of architecture-specific machine code.**
- ▶ Uses symbolic codes to represent instructions
 - ▶ `add` – addition
 - ▶ `lw` – Load a memory data
- ▶ Uses symbolic codes for data and references
 - ▶ `t0` – register
- ▶ There is an assembly instruction per machine instruction
 - ▶ `add t1, t2, t3`

Languages levels



```
temp = v[k];  
v[k] = v[k+1];  
v[k+1] = temp;
```

```
lw    t0, 0(x2)  
lw    t1, 4(x2)  
sw    t1, 0(x2)  
sw    t0, 4(x2)
```

```
0000 1001 1100 0110 1010 1111 0101 1000  
1010 1111 0101 1000 0000 1001 1100 0110  
1100 0110 1010 1111 0101 1000 0000 1001  
0101 1000 0000 1001 1100 0110 1010 1111
```

Instruction sets

- ▶ **Instruction Set Architecture (ISA)**
 - ▶ Instruction set of a processor
 - ▶ Boundary between hardware and software
- ▶ **Examples:**
 - ▶ 80x86
 - ▶ ARM
 - ▶ MIPS
 - ▶ RISC-V
 - ▶ PowerPC
 - ▶ Etc.

Characteristics of an instruction set (1 / 2)

- ▶ **Format and coding of the instruction set:**
 - ▶ Fixed or variable length instructions
 - ▶ 80x86: variable (from 1 up to 18 bytes)
 - ▶ MIPS, ARM: fixed
- ▶ **Operands:**
 - ▶ Registers, memory, the instruction itself
- ▶ **Type and size of operands:**
 - ▶ bytes: 8 bits
 - ▶ integers: 16, 32, 64 bits
 - ▶ floating-point numbers: single precision, double precision, etc.
- ▶ **Addressing modes:**
 - ▶ They specify where and how to access operands (register, memory or the instruction itself)

Characteristics of an instruction set (2/2)

- ▶ **Operations:**
 - ▶ Arithmetic, logic, transfer, control, control, etc.
- ▶ **Flow control instructions:**
 - ▶ Unconditional jumps
 - ▶ Conditional jumps
 - ▶ Procedure calls
- ▶ **Memory addressing:**
 - ▶ Most of them use byte addressing
 - ▶ They provide instructions for accessing multi-byte elements from a given position

Programming model of a computer

- ▶ A computer offers a programming model that consists of:
 - ▶ **Instruction set (assembly language)**
 - ▶ *ISA: Instruction Set Architecture*
 - ▶ An instruction includes:
 - Operation code
 - Other elements: registers, memory address, numbers
 - ▶ **Storing elements**
 - ▶ Registers
 - ▶ Memory
 - ▶ Registers of I/O controllers
 - ▶ **Execution modes**

Motivation to learn assembly

High-level language

```
#include <stdio.h>

#define PI 3.1416
#define RADIO 20

int main ( )
{
    int l;

    l=2*PI*RADIO;
    printf("long: %d\n",l) ;
    return (0);
}
```



Assembly language

```
.data
PI: .word 3.14156
RADIO: .word 20

.text
li a0 2
la t0 PI
lw t0 ($t0)
la t1 RADIO
lw t1 (t1)
mul a0 a0 t0
mul a0 a0 t1

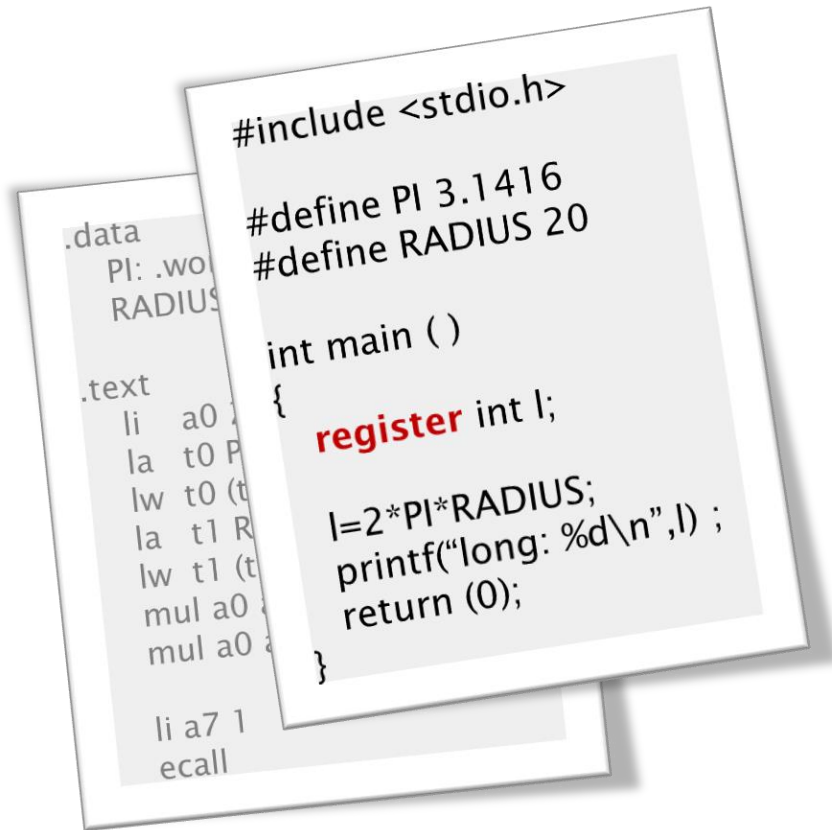
li a7 1
ecall
```



Machine language

```
0100110101111001
0010000001110000
0110000101110010
0110010101101110
0111010001110011
0010000001100001
0111001001100101
0010000001100111
0110010101100101
0110101101110011
```

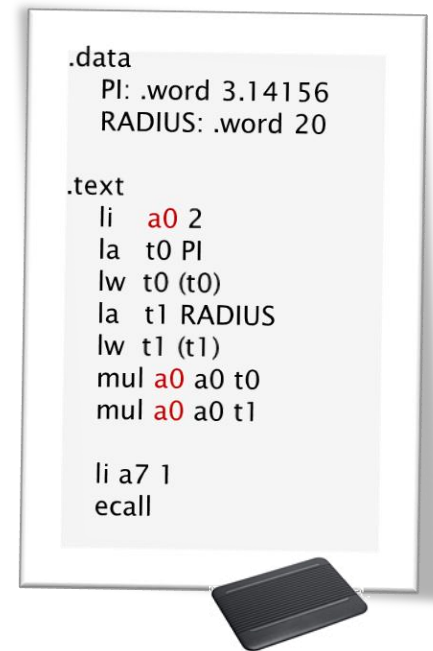
Motivation to learn assembly



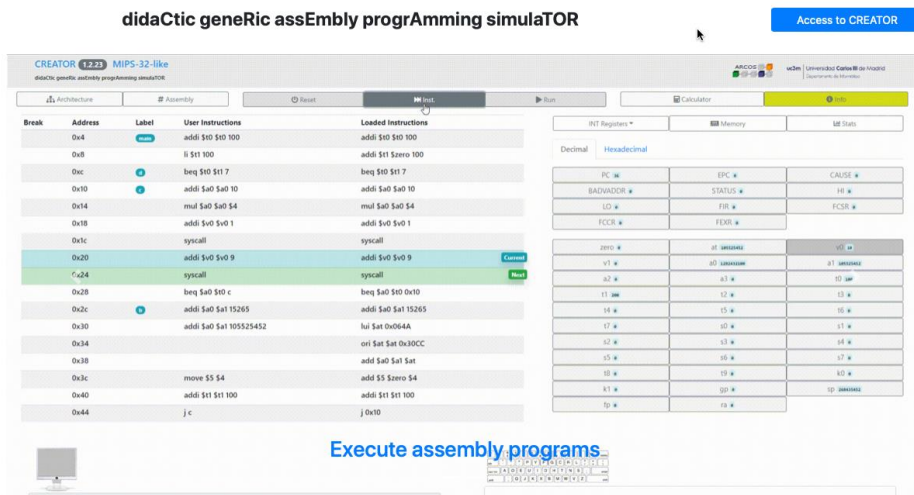
- ▶ Understand how high-level languages are executed
 - ▶ C, C++, Python, Java, ...
- ▶ Analyze the execution time of high-level instructions.
- ▶ Useful in specific domains:
 - ▶ Compilers
 - ▶ Operating Systems
 - ▶ Games
 - ▶ Embedded systems
 - ▶ Etc.

Goals

- ▶ Know how the elements of a high-level assembly language are represented.:
 - ▶ Data types (int, char, ...)
 - ▶ Control structures (if, while, ...)
- ▶ Be able to write small programs in assembler



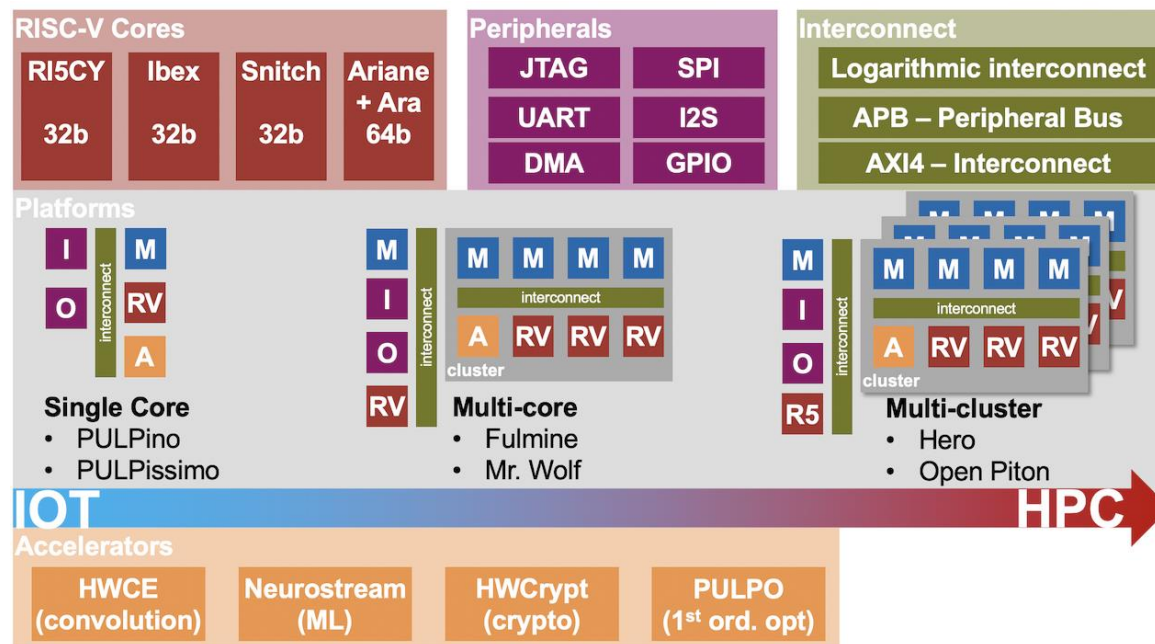
Motivation to use CREATOR simulator



- ▶ CREATOR: didaCtic geneRic assEmbly progrAmming simulaTOR
- ▶ CREATOR can simulate MIPS₃₂ and RISC-V architectures
- ▶ CREATOR can be executed from Firefox, Chrome, Edge or Safari

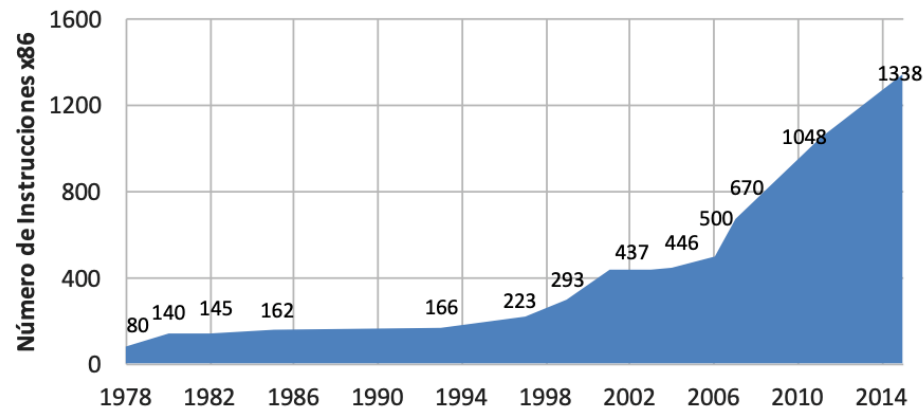
Motivations to use RISC-V

- RISC processor (*Reduced Instruction Set Computer*)
- Examples of RISC processors:
 - RISC-V, ARM, MIPS, etc.



Advantages of using RISC-V

- ▶ Open hardware architecture:
 - ▶ Allows anyone to design, manufacture and sell RISC-V chips and software
- ▶ Small and simple set of instructions
 - ▶ RV32I -> ~47 instructions, RV32IMAF -> ~76
 - ▶ Difference with x86 architecture instructions



Guía Práctica de RISC-V.
David Patterson y Andrew Waterman

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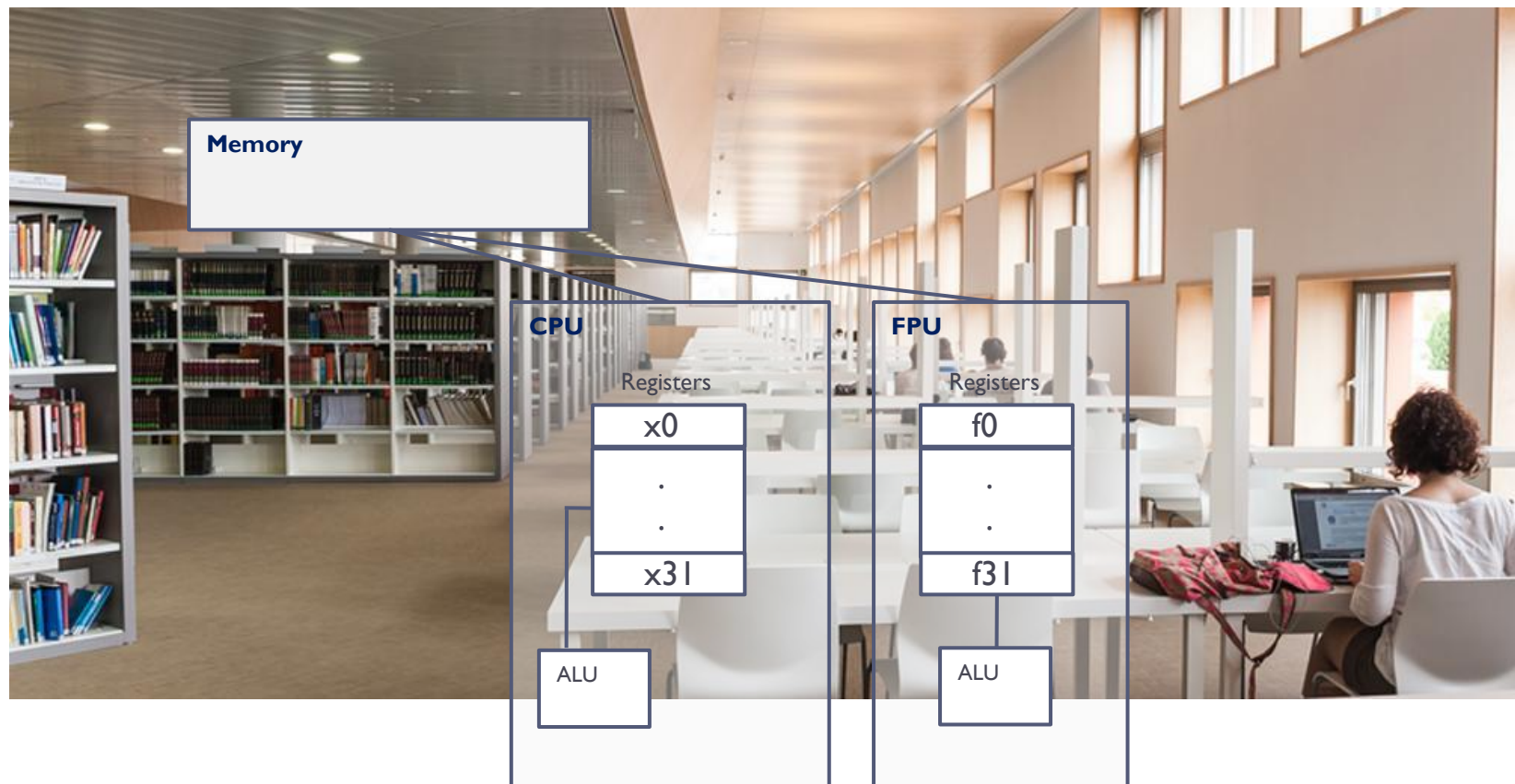
RISC-V instruction set

- ▶ **Instruction sets:**
 - ▶ RV32I: Set of instructions on integers. 32 bits
 - ▶ RV64I: Set of instructions on integers. 64 bits
 - ▶ RV128I: Set of instructions about integers. 128 bits
- ▶ **On each of them there are different extensions:**
 - ▶ M: instructions for integer multiplication and division
 - ▶ F: instructions for single-precision floating point
 - ▶ D: double precision floating-point instructions
 - ▶ G: Includes M, F and D
 - ▶ Q: quadruple-precision floating-point instructions
 - ▶ Etc.
- ▶ **Example: RV64IF: RISC-V 64-bits processor with simple-precision floating-point instructions**

RISC-V instruction sets to be described

- ▶ **Instruction sets:**
 - ▶ **RV32I:** Set of instructions on integers. 32 bits
 - ▶ **RV64I:** Set of instructions on integers. 64 bits
 - ▶ **RV128I:** Set of instructions on integers. 128 bits
- ▶ **Each of them has different extensions:**
 - ▶ **M:** instructions for integer multiplication and division
 - ▶ **F:** instructions for single-precision floating point
 - ▶ **D:** double precision floating-point instructions

RISC-V register file



CREATOR

didaCtic geneRc assEmbly progrAMming simulaTOR

Register
file

CREATOR 1.2.23 MIPS-32-like
didaCtic geneRc assEmbly progrAMming simulaTOR

Architecture # Assembly Reset Inst. Run Calculator Info

Break	Address	Label	User Instructions	Loaded Instructions
	0x4	start	addi \$t0 \$t0 100	addi \$t0 \$t0 100
	0x8		li \$t1 100	addi \$t1 \$zero 100
	0xc		beq \$t0 \$t1 7	beq \$t0 \$t1 7
	0x10		addi \$a0 \$a0 10	addi \$a0 \$a0 10
	0x14		mul \$a0 \$a0 \$4	mul \$a0 \$a0 \$4
	0x18		addi \$v0 \$v0 1	addi \$v0 \$v0 1
	0x1c		syscall	syscall
	0x20		addi \$v0 \$v0 9	addi \$v0 \$v0 9
	0x24		syscall	syscall
	0x28		beq \$a0 \$t0 c	beq \$a0 \$t0 0x10
	0x2c		addi \$a0 \$a1 15265	addi \$a0 \$a1 15265
	0x30		addi \$a0 \$a1 105525452	lui \$at 0x064A
	0x34			ori \$at \$at 0x30CC
	0x38			add \$a0 \$a1 \$at
	0x3c		move \$5 \$4	add \$5 \$zero \$4
	0x40		addi \$t1 \$t1 100	addi \$t1 \$t1 100
	0x44		j c	j 0x10

INT Registers Memory Mem Stats

Decimal Hexadecimal

PC	EPC	CAUSE
BADVADDR	STATUS	HI
LO	FIR	FCSR
FCR	FEXR	
zero	a1	v0
v1	a0	a1
a2	a3	t0
t1	t2	t3
t4	t5	t6
t7	s0	s1
s2	s3	s4
s5	s6	s7
t8	t9	k0
k1	gp	sp
fp	ra	

<https://creatorsim.github.io/>

Register File (integers)

ABI Name	Number	Uso
zero	x0	Constant 0
ra	x1	Return address (routines)
sp	x2	Stack pointer
gp	x3	Global pointer
tp	x4	Thread pointer
t0...t2	x5...x7	Temporary (NON-kept between calls)
s0/fp	x8	Temporary (kept between calls) / Frame stack pointer
s1	x9	Temporary (kept between calls)
a0...a1	x10...x11	Input argument for routines/returned values
a2...a7	x12...x17	Input argument for routines
s2...s11	x18...x27	Temporary (kept between calls)
t3...t6	x28...x31	Temporary (<u>NON</u> -kept between calls)

- ▶ There are 32 registers
 - ▶ Size of 4 bytes (one word)
 - ▶ Dual name:
 - ▶ Logical: ABI name (*Application Binary Interface*)
 - ▶ Numeric: starting with **x** at the beginning
- ▶ Use agreement
 - ▶ Reserved
 - ▶ Arguments
 - ▶ Results
 - ▶ Temporary
 - ▶ Pointers

Data transfer (integer registers)

- ▶ Copy data:
 - ▶ Between registers
 - ▶ Between registers and memory (later)

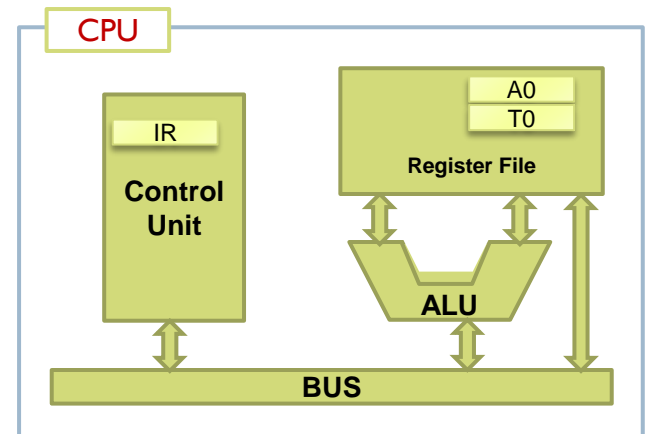
- ▶ Examples:

- ▶ Copy from register to register

`mv a0 t0`

- ▶ Immediate load

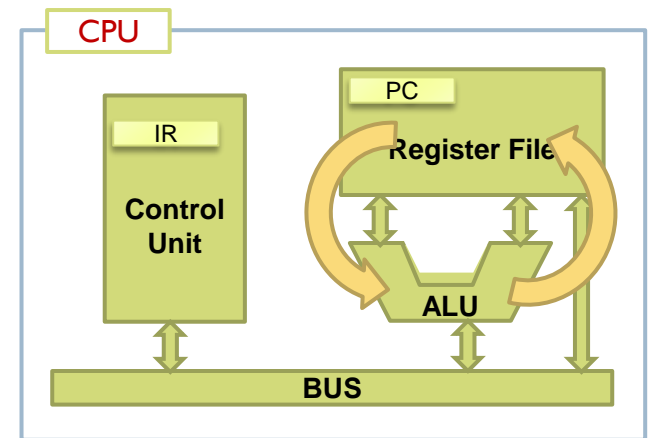
`li t0 5`



```
mv    a0 t0    # a0 ← t0
li    t0 5      # t0 ← 000....00101
```


Arithmetic instructions (integer registers)

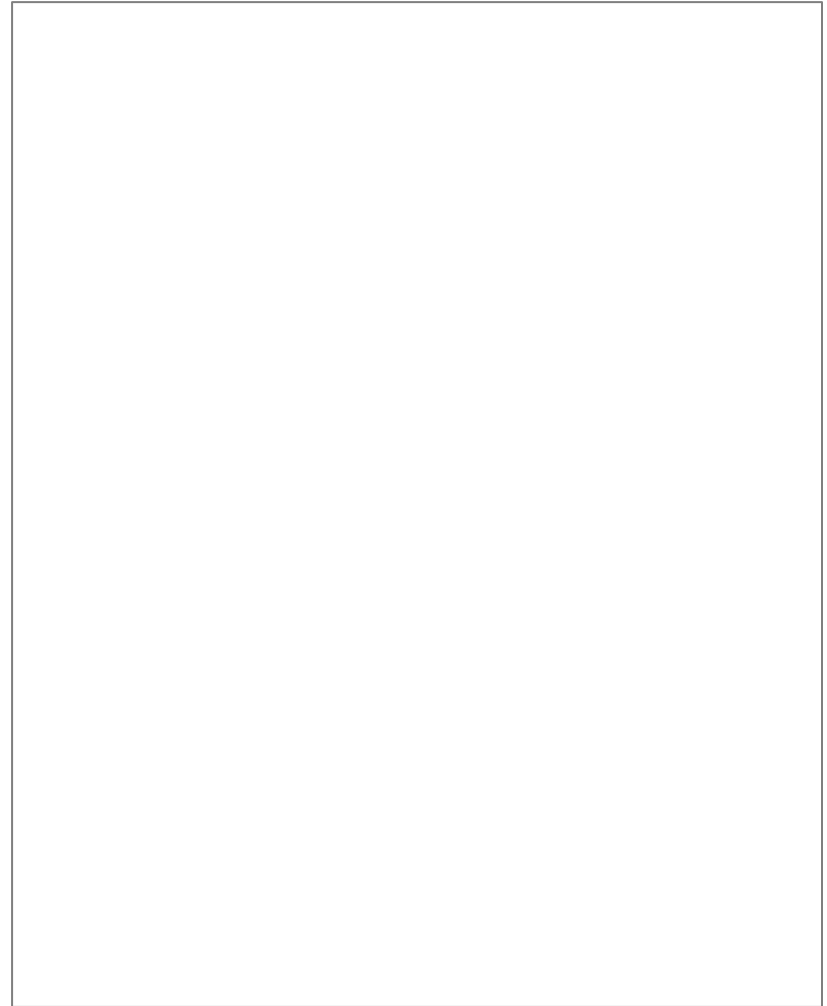
- ▶ Performs the **arithmetic integer operations in two complement**.
- ▶ Examples (ALU):
 - ▶ Addition
 - `add t0 t1 t2` $\# t0 \leftarrow t1 + t2$
 - `addi t0 t1 5` $\# t0 \leftarrow t1 + 5$
 - ▶ Subtraction
 - `sub t0 t1 t2` $\# t0 \leftarrow t1 - t2$
 - ▶ Multiplication
 - `mul t0 t1 t2` $\# t0 \leftarrow t1 * t2$
 - ▶ Integer division (5 / 2=2)
 - `div t0 t1 t2` $\# t0 \leftarrow t1 / t2$
 - ▶ Division remainder (5 % 2=1)
 - `rem t0 t1 t2` $\# t0 \leftarrow t1 \% t2$



Example

```
int a = 5;  
int b = 7;  
int c = 8;  
int i;
```

```
i = a * (b + c)
```



Example

```
int a = 5;  
int b = 7;  
int c = 8;  
int i;
```

```
i = a * (b + c)
```

```
li  t1 5  
li  t2 7  
li  t3 8
```

```
add  t4 t2 t3  
mul  t4 t4 t1
```

Exercise

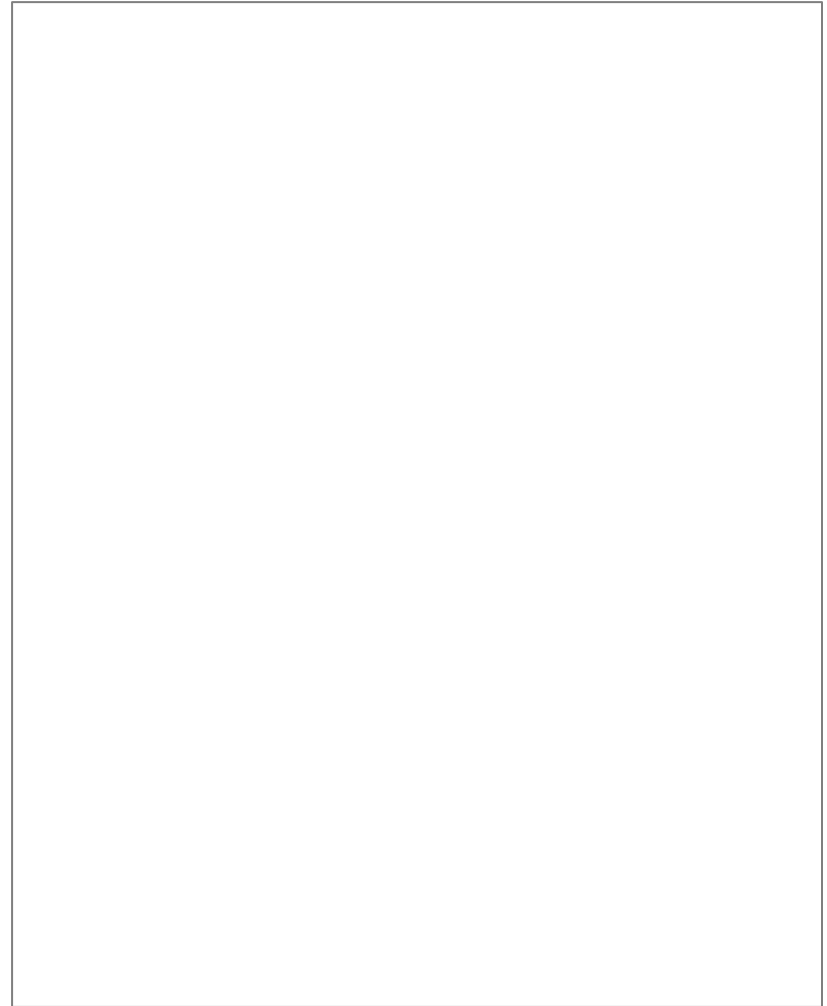
```
int a = 5;
```

```
int b = 7;
```

```
int c = 8;
```

```
int i;
```

```
i = -(a * (b - 10) + c)
```



Exercise (solution)

```
int a = 5;  
int b = 7;  
int c = 8;  
int i;
```

```
i = -(a * (b - 10) + c)
```

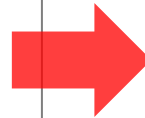
```
li  t1 5  
li  t2 7  
li  t3 8
```

```
li    t0 10  
sub   t4  t2  t0  
mul   t4  t4  t1  
add   t4  t4  t3  
li    t0 -1  
mul   t4  t4  t0
```

Exercise

```
li t1 5  
li t2 7  
li t3 8
```

```
li    t0 10  
sub   t4 t2 t0  
mul   t4 t4 t1  
add   t4 t4 t3  
li    t0 -1  
mul   t4 t4 t0
```

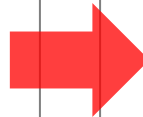


**Can be performed by using
less instrucciones?**

Exercise (solution)

```
li t1 5  
li t2 7  
li t3 8
```

```
li    t0 10  
sub   t4 t2 t0  
mul   t4 t4 t1  
add   t4 t4 t3  
li    t0 -1  
mul   t4 t4 t0
```



```
li t1 5  
li t2 7  
li t3 8
```

```
addi   t4 t2 -10  
mul    t4 t4 t1  
add    t4 t4 t3  
add    t4 x0 t4
```

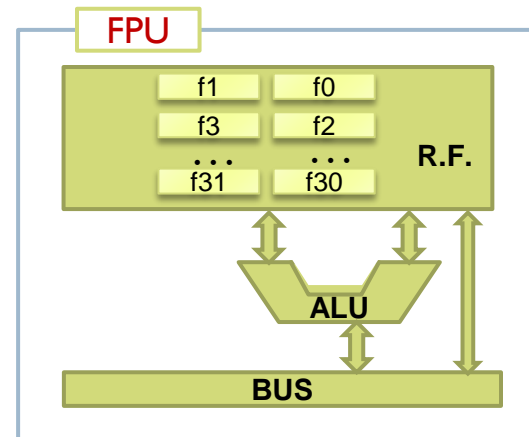
Register File (floating-point)

ABI Name	Name	Usage
ft0...ft7	f0 ... f7	Temporals (like t...)
fs0...fs1	f8 ... f9	There are saved (like s...)
fa0...fa1	f10 ... f11	Arguments/return (like a...)
fa2...fa7	f12 ... f17	Arguments (like a...)
fs2...fs11	f18 ... f27	There are saved (like s...)
ft8...ft11	f28 ... f31	Temporals (like t...)

- ▶ There are 32 registers
- ▶ The ft0 register does not have its value set to 0.
- ▶ In the single precision extension, the registers are 32 bits (4 bytes).
- ▶ In the double precision extension, the registers are 64 bits (8 bytes) and can store:
 - ▶ Single precision values in the lower 32 bits of the register
 - ▶ Double precision values in the 64 bits of the register

Floating-point register file

- ▶ There are 32 floating-point registers in addition to the integer registers:
 - ▶ From f0 to f31
- ▶ Copy registers (.s .d):
 - ▶ `fmv.s rd rs` # `rd = rs`
- ▶ Common arithmetic operations (.s .d):
 - ▶ `fadd.s rd rs1 rs2` # `rd = rs1 + rs2`
 - ▶ `fsub.s rd rs1 rs2` # `rd = rs1 - rs2`
 - ▶ `fmul.s rd rs1 rs2` # `rd = rs1 * rs2`
 - ▶ `fdiv.s rd rs1 rs2` # `rd = rs1 / rs2`
 - ▶ `fmin.s rd rs1 rs2` # `rd = min(rs1, rs2)`
 - ▶ `fmax.s rd rs1 rs2` # `rd = max(rs1, rs2)`
 - ▶ `fsqrt.s rd rs1` # `rd = sqrt(rs1)`
 - ▶ `fmadd.s rd rs1 rs2 rs3` # `rd = rs1 x rs2 + rs3`
 - ▶ `fmsub.s rd rs1 rs2 rs3` # `rd = rs1 x rs2 - rs3`
 - ▶ `fabs.s rd rs` # `rd = |rs|`
 - ▶ `fneg.s rd rs` # `rd = -rs`

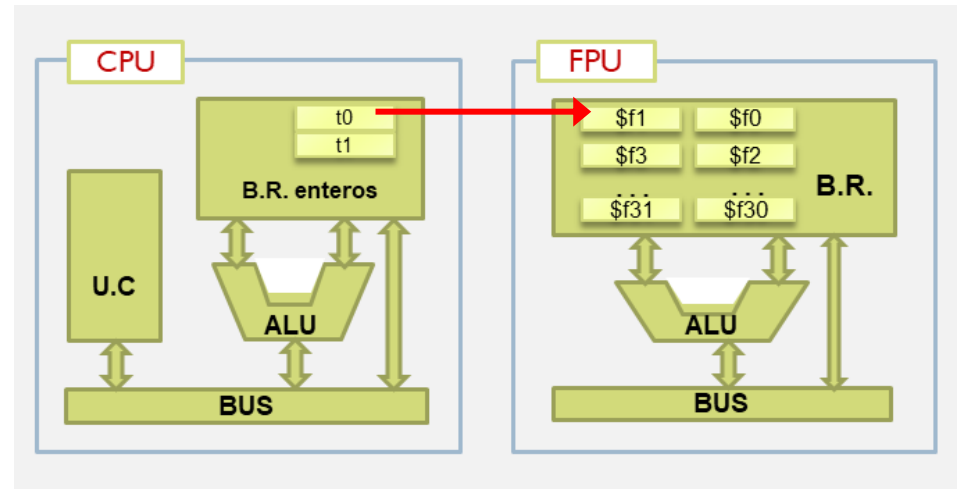


Copy instructions

(integer registers \leftrightarrow floating-point registers)

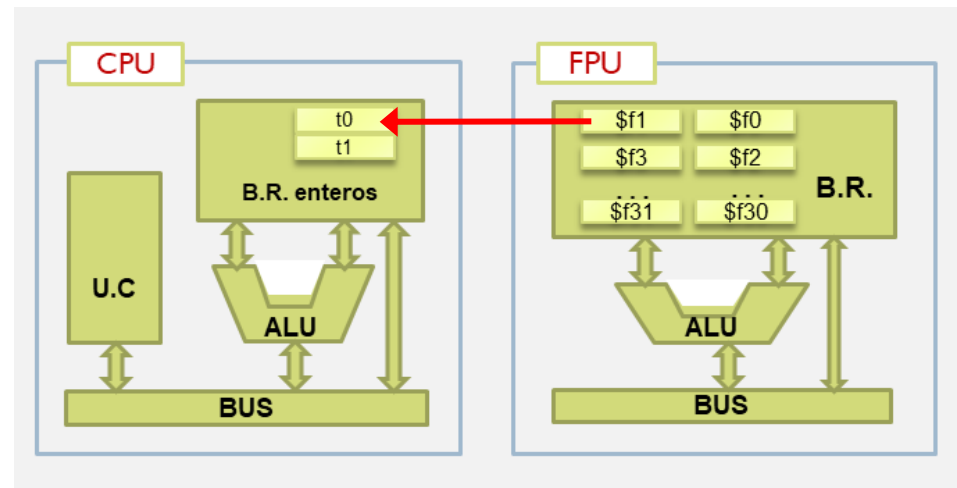
`fmv.w.x rd rs`

- Copy from integer register `rs` to a floating register `rd` (*single precision*)



`fmv.x.w rd rs`

- Copy from floating register `rs` (*single precision*) to a integer register `rd`



Conversion operations (1/3)

integer \leftrightarrow simple precision

► `fcvt.w.s rd, rs`

- Convert from simple precision (value in floating register `rs`) to a 32-bit integer 32 **with** sign (integer register `rd`).

► `fcvt.wu.s rd, rs`

- Convert from simple precision (value in floating register `rs`) to a 32-bit integer 32 **withou** sign (integer register `rd`).

► `fcvt.s.w rd, rs`

- Convert a 32-bit integer 32 **with** sign (value in integer register `rs`) to a simple precision (floating register `rd`).

► `fcvt.s.wu rd, rs`

- Convert a 32-bit integer 32 **without** sign (value in integer register `rs`) to a simple precision (floating register `rd`).

Conversion operations (2/3)

integer \leftrightarrow double precision

► `fcvt.w.d rd, rs`

- Convert from double precision (value in floating register `rs`) to a 32-bit integer 32 **with** sign (integer register `rd`).

► `fcvt.wu.d rd, rs`

- Convert from double precision (value in floating register `rs`) to a 32-bit integer 32 **without** sign (integer register `rd`).

► `fcvt.d.w rd, rs`

- Convert a 32-bit integer 32 **with** sign (value in integer register `rs`) to a double precision (floating register `rd`).

► `fcvt.d.wu rd, rs1`

- Convert a 32-bit integer 32 **without** sign (value in integer register `rs`) to a double precision (floating register `rd`).

Conversion operations (3/3)

double precision \leftrightarrow simple precision

▶ `fcvt.s.d rd, rs1`

- ▶ Convert from double precision (value in floating register rs) to simple precision (floating register rd).

▶ `fcvt.d.s rd, rs`

- ▶ Convert from simple precision (value in floating register rs) to double precision (floating register rd).

Classification of floating-point numbers

- ▶ `fclass.s rd, rs1` (simple precision)
- ▶ `fclass.d rd, rs1` (double precision)
- ▶ Save in `rd` the type of the floating-point number of the register `rs1`:

Value in rd	Meaning
0	-Inf
1	Negative normalized number
2	Negative non-normalized number
3	-0
4	+0
5	Positive non-normalized number
6	Positive normalized number
7	+Inf
8	NaN (non-quiet)
9	NaN (quiet)

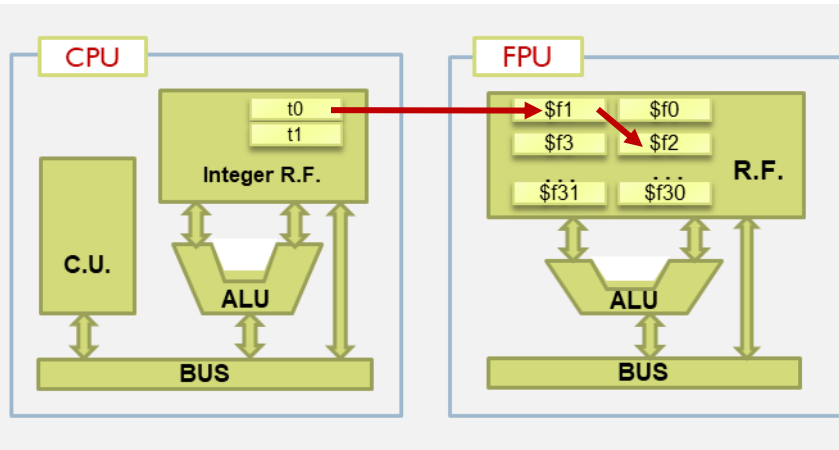
Example

```
float PI    = 3,1415;
int  radio = 4;
float length;

length = PI * radio;
```

```
.text
main:
```

```
li t0, 0x40490E56
    # does not exist li.s
    # 0x40490E56 is the
    # representation IEEE754
    # in hexadecimal for 3.1415
fmv.w.x ft0, t0    # ft0 ← t0
li      t1  4      # 4 in Ca2
fcvt.s.w ft1, t1    # 4 in ieee754
fmul.s  ft0, ft0, ft1
```



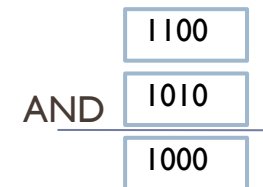
Logical instructions

- ▶ **Boolean** operations

- ▶ **Examples:**

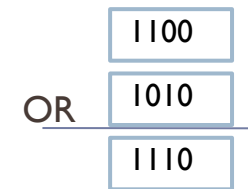
- ▶ **AND**

`and t0 t1 t2` ($t0 = t1 \& t2$)
`andi t0 t1 t2` ($t0 = t1 \& t2$)



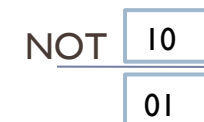
- ▶ **OR**

`or t0 t1 t2` ($t0 = t1 | t2$)
`ori t0 t1 80` ($t0 = t1 | 80$)



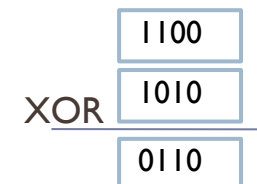
- ▶ **NOT**

`not t0 t1` ($t0 = ! t1$)
`xori t0 t1 -1`



- ▶ **XOR**

`xor t0 t1 t2` ($t0 = t1 \wedge t2$)

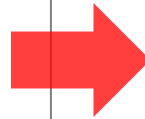


Exercise

```
li t0, 5
```

```
li t1, 8
```

```
and t2, t1, t0
```



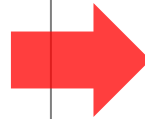
What will be the value of t2?

Exercise (solution)

```
li t0, 5
```

```
li t1, 8
```

```
and t2, t1, t0
```



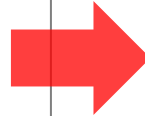
```
00...0101    t0
```

```
00...1000    t1
```

```
and  00...0000    t2
```

Exercise

```
li t0, 5  
li t1, 0x007FFFFFFF  
  
and t2, t1, t0
```

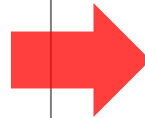


What does an "and" with
0x007FFFFFFF allow to do?

Exercise (solution)

```
li t0, 5
li t1, 0x007FFFFFFF

and t2, t1, t0
```



What does an "and" with
0x007FFFFFFF allow to do?

Obtain the 23 least
significant bits

The constant used for bit
selection is called a
mask.

Shift instructions

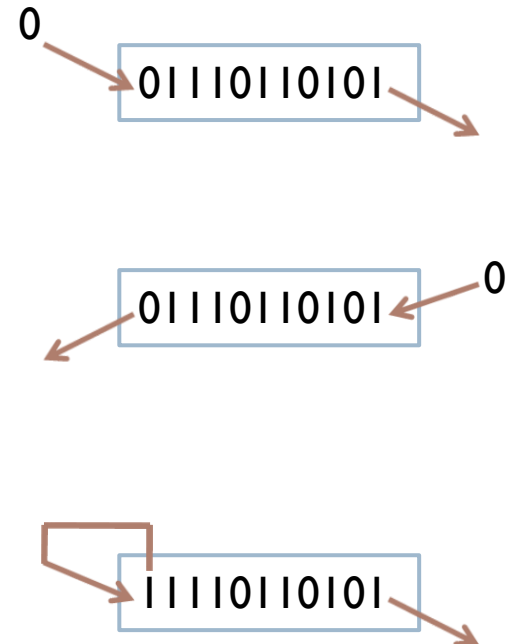
- ▶ Bits movement

- ▶ Examples:

- ▶ Shift right **logical**
`srl t0 t0 4` ($t0 = t0 \gg 4$ bits)

- ▶ Shift left **logical**
`sll t0 t0 5` ($t0 = t0 \ll 5$ bits)

- ▶ Shift right **arithmetic**
`sra t0 t0 2` ($t0 = t0 \gg 2$ bits)



Exercise (solution)

```
li t0, 5
```

```
li t1, 6
```

```
srai t0, t1, 1
```



- What is the value of t0?

000 0110 t1

shift one bit to right (/2)

000 0011 t0

```
slli t0, t1, 1
```



- What is the value of \$t0?

000 0110 t1

Shift one bit to left (x2)

000 1100 t0

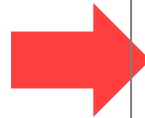
Exercise

Make a program that detects the sign of a stored number t0 and leaves in t1 a 1 if it is negative and a 0 if it is positive.



Exercise (solution)

Make a program that detects the sign of a stored number t0 and leaves in t1 a 1 if it is negative and a 0 if it is positive.



```
li    t0 -3  
srli  t1 t0 31
```


Comparison instructions (integer registers)

- ▶ `slt rd, rs1, rs2` if ($s(rs1) < s(rs2)$) $rd = 1$; else $rd = 0$
- ▶ `sltu rd, rs1, rs2` if ($u(rs1) < u(rs2)$) $rd = 1$; else $rd = 0$
- ▶ `slti rd, rs1, 5` if ($s(rs1) < s(5)$) $rd = 1$; else $rd = 0$
- ▶ `sltiu rd, rs1, 5` if ($u(rs1) < u(5)$) $rd = 1$; else $rd = 0$
- ▶ `seqz rd, rs1` if ($rs1 == 0$) $rd = 1$; else $rd = 0$
- ▶ `snez rd, rs1` if ($rs1 != 0$) $rd = 1$; else $rd = 0$
- ▶ `sgtz rd, rs1` if ($rs1 > 0$) $rd = 1$; else $rd = 0$
- ▶ `sltz rd, rs1` if ($rs1 < 0$) $rd = 1$; else $rd = 0$

Comparison instructions (floating-point registers)

► Simple precision

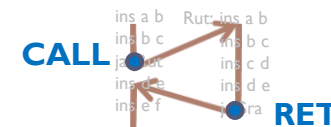
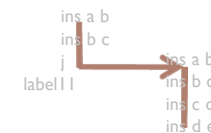
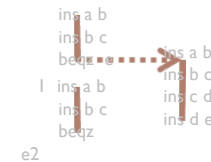
- `feq.s rd, rs1, rs2` if (`rs1 == rs2`) `rd = 1`; else `rd = 0`
- `fle.s rd, rs1, rs2` if (`rs1 <= rs2`) `rd = 1`; else `rd = 0`
- `flt.s rd, rs1, rs2` if (`rs1 < rs2`) `rd = 1`; else `rd = 0`

► Double precision:

- `feq.d rd, rs1, rs2` if (`rs1 == rs2`) `rd = 1`; else `rd = 0`
- `fle.d rd, rs1, rs2` if (`rs1 <= rs2`) `rd = 1`; else `rd = 0`
- `flt.d rd, rs1, rs2` if (`rs1 < rs2`) `rd = 1`; else `rd = 0`

Control flow

- ▶ Change the sequence of instructions to be executed
- ▶ Several types:
 - ▶ Conditional branches:
 - ▶ Branch if value match condition
 - ▶ E.g.: `bne t0 t1 label1`
 - ▶ Unconditional branches:
 - ▶ Always branch
 - E.g.: `j etiqueta2`
 - ▶ Function calls:
 - ▶ Branch with return
 - ▶ E.g.: `jal ra subrutina1 jr ra`



Branch instructions

- ▶ Conditional (only with integer registers):

- ▶ `beq t0 t1 label1` # jump to label1 if `t0 == t1`
 - ▶ `bne t0 t1 label1` # jump to label1 if `t0 != t1`
 - ▶ `blt t0 t1 label1` # jump to label1 if `t0 < t1`
 - ▶ `bltu t0 t1 label1` # jump to label1 if `t0 < t1` (unsigned)
 - ▶ `bge t0 t1 label1` # jump to label1 if `t0 >= t1`
 - ▶ `bgeu t0 t1 label1` # jump to label1 if `t0 >= t1` (unsigned)
- (as pseudo-instructions)
- ▶ `bgt t0 t1 label1` # jump to label1 if `t0 > t1`
 - ▶ `ble t0 t1 label1` # jump to label1 if `t0 <= t1`

Branch instructions

jump label

► Conditional (only with integer registers):

- **beq** **t0** **t1** **label1** # jump to label1 if t0 == t1
- **bne** **t0** **t1** **label1** # jump to label1 if t0 != t1
- **blt** **t0** **t1** **label1** # jump to label1 if t0 < t1
- **bltu** **t0** **t1** **label1** # jump to label1 if t0 < t1 (unsigned)
- **bge** **t0** **t1** **label1** # jump to label1 if t0 >= t1
- **bgeu** **t0** **t1** **label1** # jump to label1 if t0 >= t1 (unsigned)

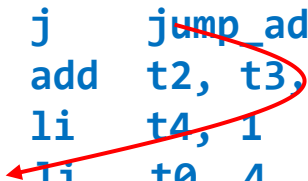
- **bgt** **t0** **t1** **label1** # jump to label1 if t0 > t1
- **ble** **t0** **t1** **label1** # jump to label1 if t0 <= t1

► Unconditional:

- **j** **label1** # jump to label1. Equivalent to **beq x0 x0 label1**

label1 refers to an instruction (represents a memory address where the instruction is located) which is skipped:

```
add  t1, t2, t3
j     jump_addr
add  t2, t3, t4
li   t4, 1
jump_addr: li t0, 4
```



Control flow if

beq	t1 = t0
bne	t1 != t0
bge	t1 >= t0
ble	t0 <= t1
blt	t1 < t0
bgt	t0 > t1

```
int a=1;
int b=2;

main ()
{
    if (a < b) {
        a = b;
    }
    ...
}
```

Control flow if

CREATOR

beq	t1 = t0
bne	t1 != t0
bge	t1 >= t0
ble	t0 <= t1
blt	t1 < t0
bgt	t0 > t1

```
int a=1;
int b=2;

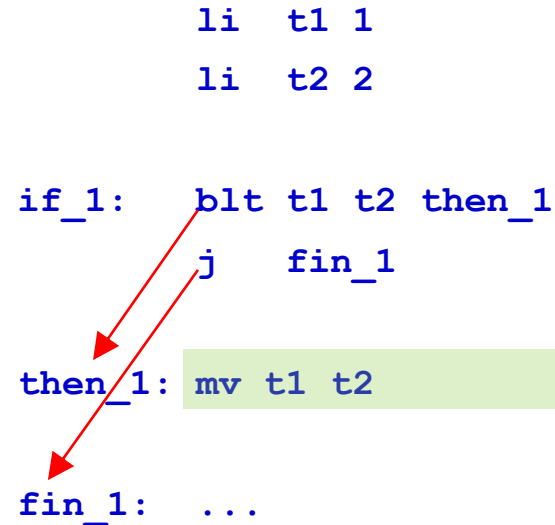
main ()
{
    if (a < b) {
        a = b;
    }
    ...
}
```

```
li    t1 1
li    t2 2

if_1: blt t1 t2 then_1
      j    fin_1

then_1: mv t1 t2

fin_1: ...
```



Control flow if

CREATOR

beq	t1 = t0
bne	t1 != t0
bge	t1 >= t0
ble	t0 <= t1
blt	t1 < t0
bgt	t0 > t1

```
int a=1;
int b=2;

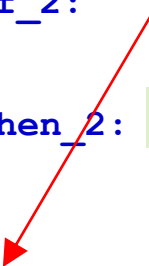
main ()
{
    if (a < b) {
        a = b;
    }
    ...
}
```

```
li    t1 1
li    t2 2

if_2: bge t1 t2 fin_2

then_2: mv t1 t2

fin_2: ...
```



Control flow if-else

CREATOR

beq	t1 = t0
bne	t1 != t0
bge	t1 >= t0
ble	t0 <= t1
blt	t1 < t0
bgt	t0 > t1

```
int a=1;
```

```
int b=2;
```

```
main ()
```

```
{
```

```
  if (a < b){
```

```
    // action 1
```

```
  } else {
```

```
    // action 2
```

```
  }
```

```
}
```

```
li t1 1
```

```
li t2 2
```

```
if_3: bge t1 t2 else_3
```

```
then_3: # action 1
```

```
j fi_3
```

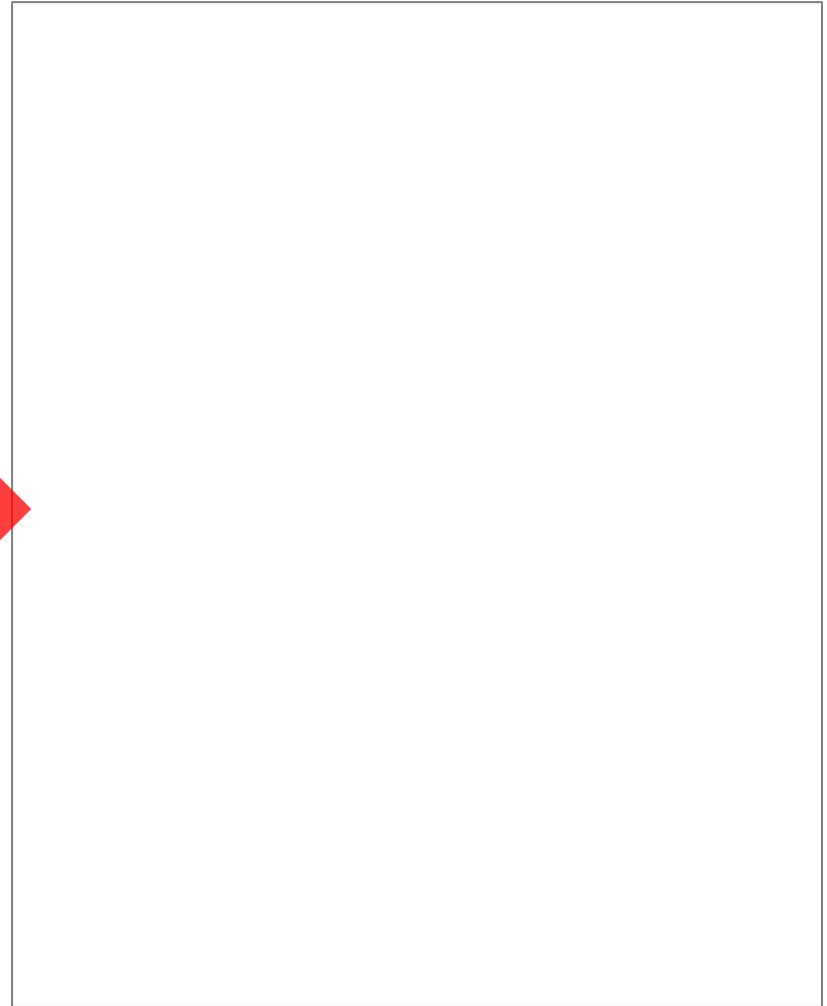
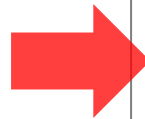
```
else_3: # action 2
```

```
fi_3: ...
```

Exercise

```
int b1 = 4;  
int b2 = 2;
```

```
if (b2 == 8) {  
    b1 = 1;  
}  
...
```



Exercise (solution)

```
int b1 = 4;  
int b2 = 2;
```

```
if (b2 == 8) {  
    b1 = 1;  
}  
...
```



```
li    t0 4  
li    t1 2  
li    t2 8  
  
bne   t0 t2 fin1  
li    t1 1  
fin1: ...
```

Branches with floating-point numbers

Jump to label if
ft1 < ft2

```
flr t0, ft1, ft2  
bne t0, x0, label  
.  
.  
.  
label:
```

Control flow while

beq	t1 = t0
bne	t1 != t0
bge	t1 >= t0
ble	t0 <= t1
blt	t1 < t0
bgt	t0 > t1

```
int i;

main ()
{
    i=0;
    while (i < 10) {

        /* action */
        i = i + 1 ;
    }
}
```

Control flow while

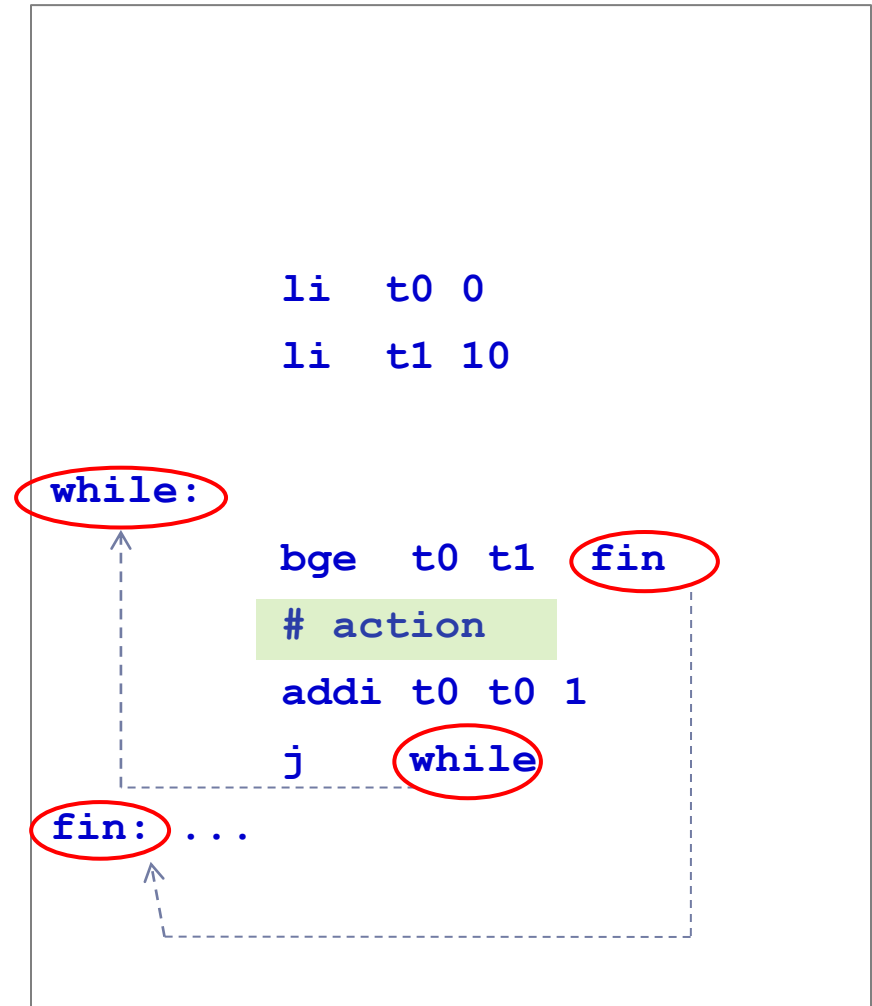
CREATOR

beq	t1 = t0
bne	t1 != t0
bge	t1 >= t0
ble	t0 <= t1
blt	t1 < t0
bgt	t0 > t1

```
int i;

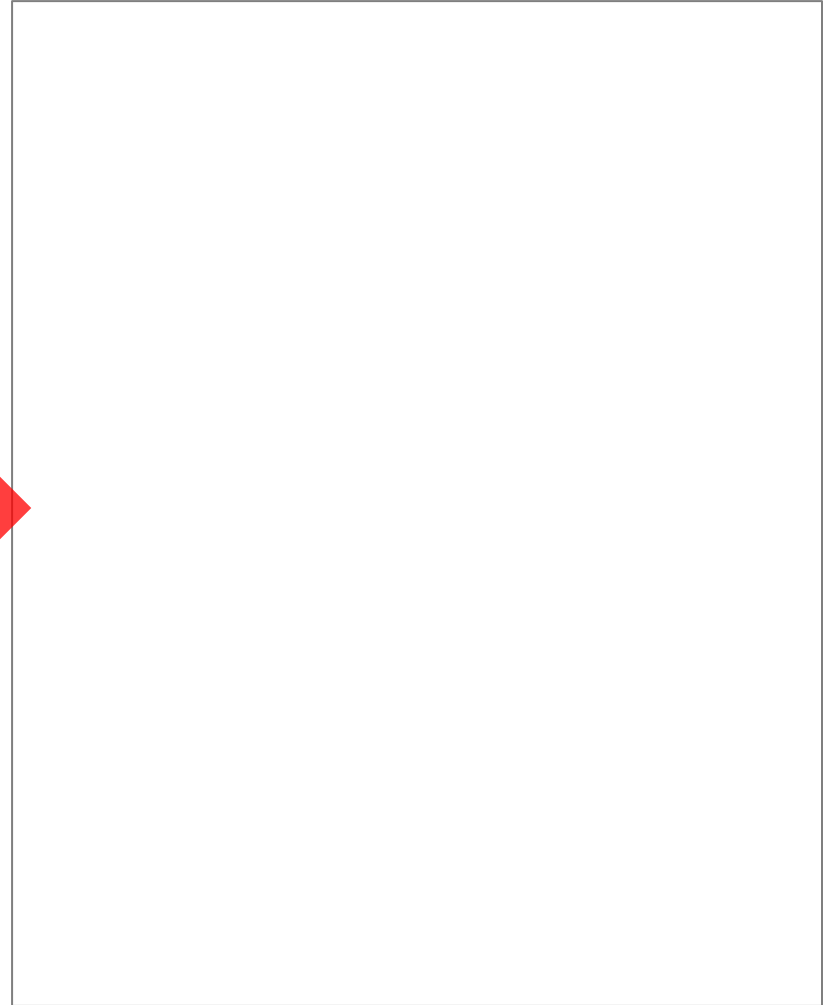
main ()
{
    i=0;
    while (i < 10) {

        /* action */
        i = i + 1 ;
    }
}
```



Exercise

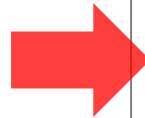
Make a program that
calculates the sum of
the first ten numbers
and leaves this value in
register a0



Exercise (solution)

Make a program that calculates the sum of the first ten numbers and leaves this value in register a0

$$1 + 2 + 3 + \dots + 10$$



```
li  a0 0
add a0 a0 1
add a0 a0 2
add a0 a0 3
add a0 a0 4
add a0 a0 5
add a0 a0 6
add a0 a0 7
add a0 a0 8
add a0 a0 9
```

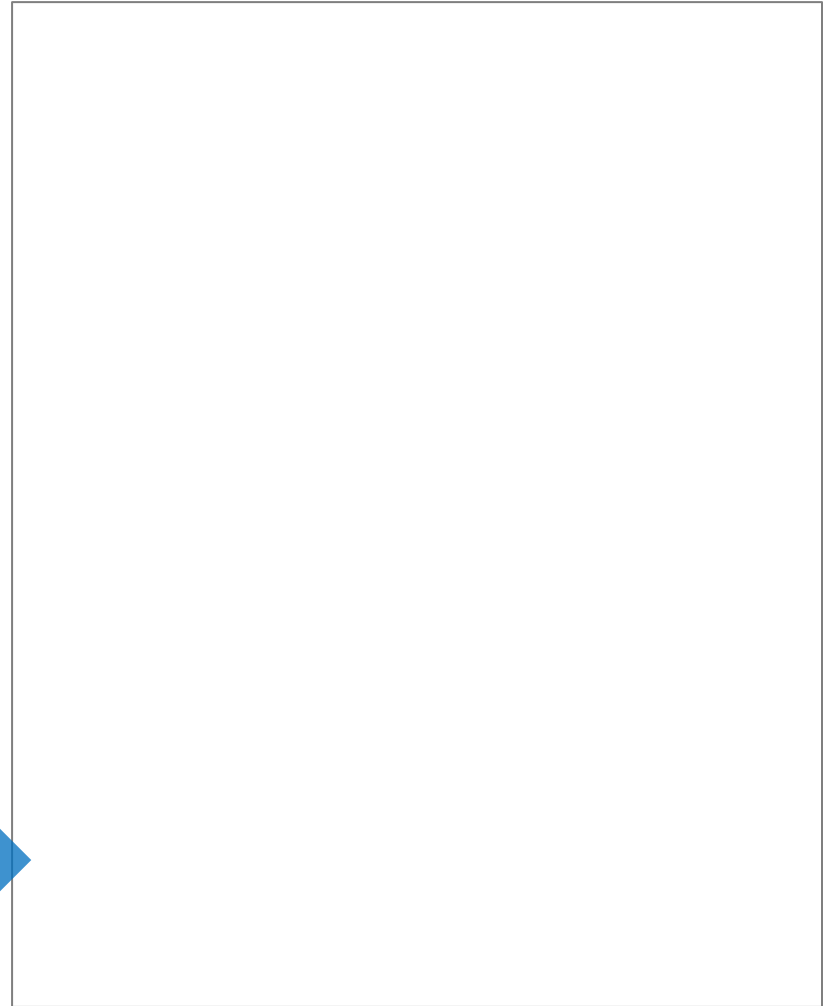
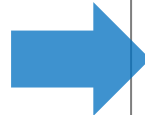
No valid
;-)

Exercise (solution)

Make a program that
calculates the sum of
the first ten numbers
and leaves this value in
register a0



```
int i, s;  
  
s=0;  
i=0;  
while (i <= 10)  
{  
    s = s + i ;  
    i = i + 1 ;  
}
```



Exercise (solution)

Make a program that calculates the sum of the first ten numbers and leaves this value in register a0



```
int i, s;

s=0;
i=0;
while (i <= 10)
{
    s = s + i ;
    i = i + 1 ;
}
```



```
li t0 0
li a0 0
li t2 10

while1:
    bgt t0 t2 fin1
    add a0 a0 t0
    addi t0 t0 1
    j while1

fin1:
```

Exercise

- ▶ Calculate the number of 1's of a register (t0).
Result in t3.

Exercise (solution)

- Calculate the number of 1's of a register (t0).
Result in t3.

```
i = 0;
n = 45;  # number
s = 0;
while (i < 32)
{
    b = first bit of n
    s = s + b;
    shift the contents of
    of n one bit to the
    right
    i = i + 1 ;
}
```

Exercise (solution)

- Calculate the number of 1's of a register (t0).
Result in t3.

```
i = 0;
n = 45;  # number
s = 0;
while (i < 32)
{
    b = first bit of n
    s = s + b;
    shift the contents of
    of n one bit to the
    right
    i = i + 1 ;
}
```

```
i = 0;
n = 45;  # number
s = 0;
while (i < 32)
{
    b = n & 1;
    s = s + b;
    n = n >> 1;
    i = i + 1 ;
}
```

Exercise (solution)

- Calculate the number of 1's of a register (t0).
Result in t3.

```

i = 0;
n = 45;  # number
s = 0;
while (i < 32)
{
    b = n & 1;
    s = s + b;
    n = n >> 1;
    i = i + 1 ;
}

```

```

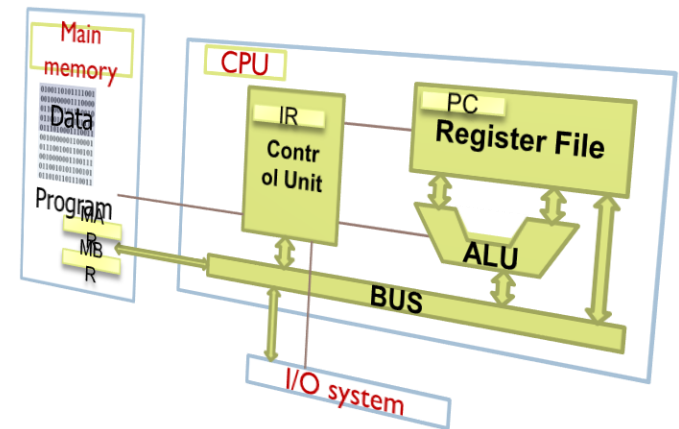
        li    t0, 0    #i
        li    t1, 45   #n
        li    t2, 32
        li    t3, 0    #s
while:   bge   t0, t2, fin
        andi  t4, t1, 1
        add   t3, t3, t4
        srli  t1, t1, 1
        addi  t0, t0, 1
        j     while
fin:     ...

```

Types of instructions

summary

- ▶ Data transfer
- ▶ Arithmetic
- ▶ Logical
- ▶ Shifting and rotation
- ▶ Comparison
- ▶ Control flow (branches, ...)
- ▶ Conversion
- ▶ Input/output
- ▶ System calls



Typical faults

1) Poorly designed program

- ▶ Does not do what is requested
- ▶ Incorrectly does what is requested

2) Programming directly in assembler

- ▶ Do not code in pseudo-code the algorithm to be implemented

3) Write unreadable code

- ▶ Do not tabulate the code
- ▶ Do not comment the assembly code or make reference to the algorithm initially proposed.

ARCOS Group

uc3m | Universidad **Carlos III** de Madrid

L3: Fundamentals of assembler programming Computer Structure

Bachelor in Computer Science and Engineering
Bachelor in Applied Mathematics and Computing
Dual Bachelor in Computer Science and Engineering and Business Administration

