ARCOS Group

uc3m | Universidad Carlos III de Madrid

Lesson 3 (I)
Fundamentals of assembler programming

Computer Structure
Bachelor in Computer Science and Engineering

Contents

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

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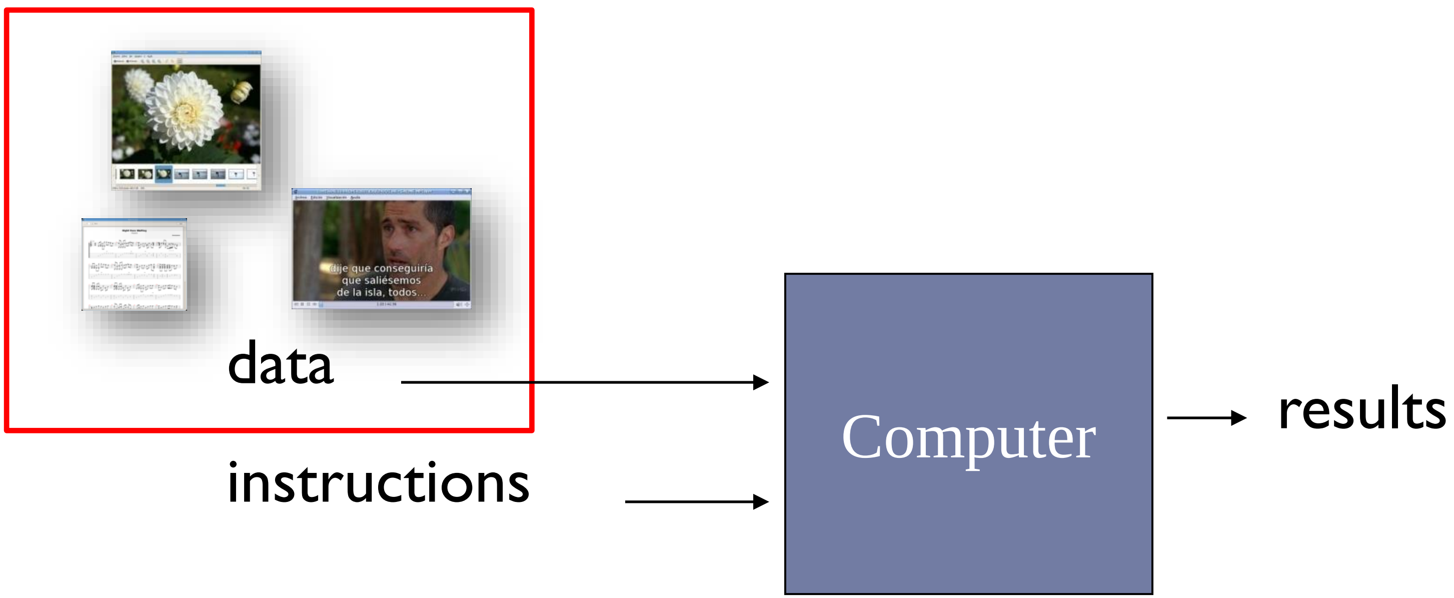
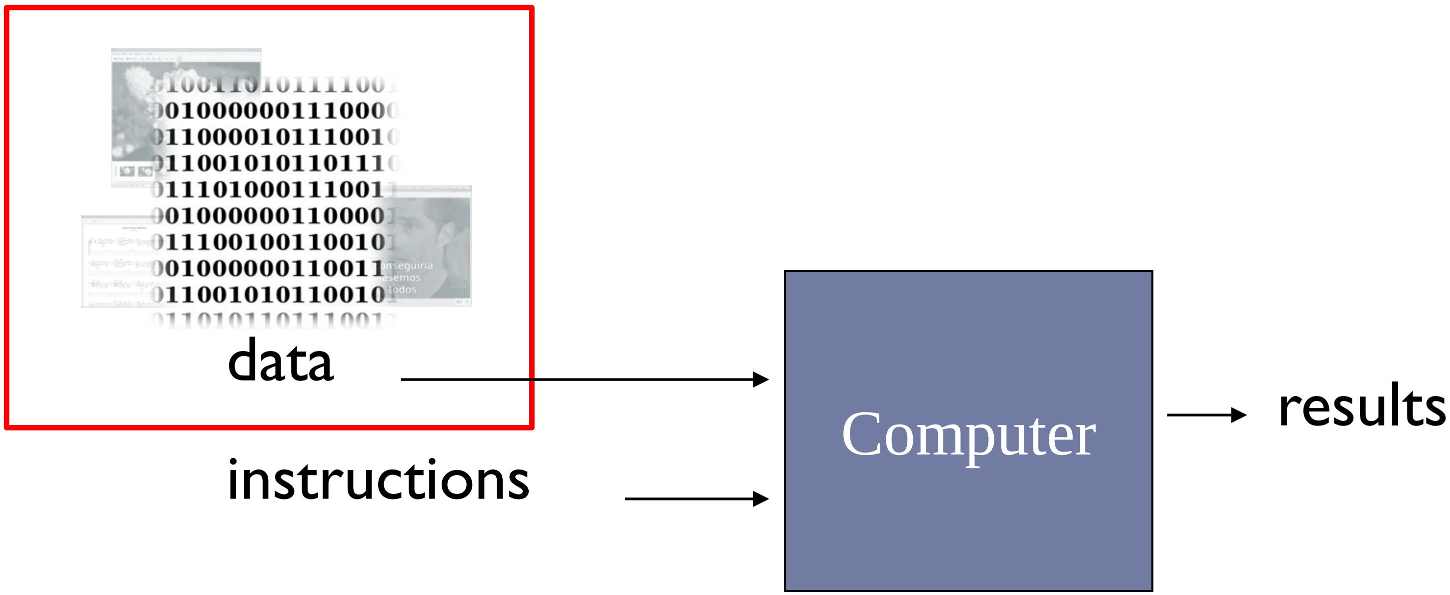
Types of information: instructions and data

- Data representation…



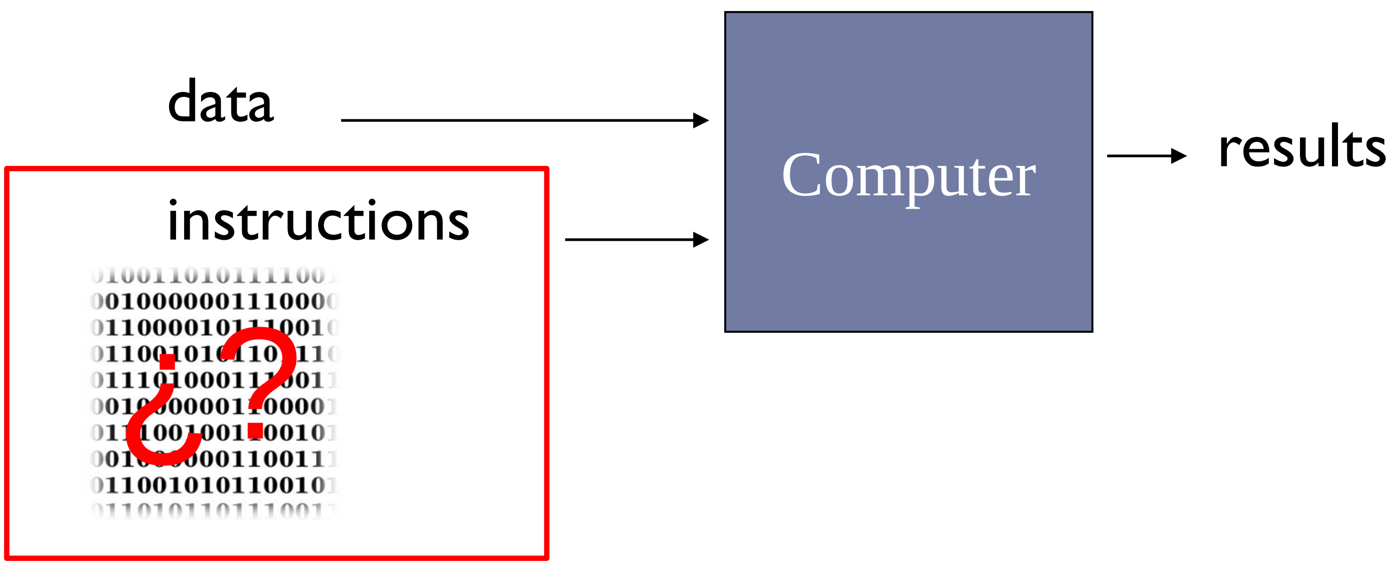
Types of information: instructions and data

- Binary data representation.



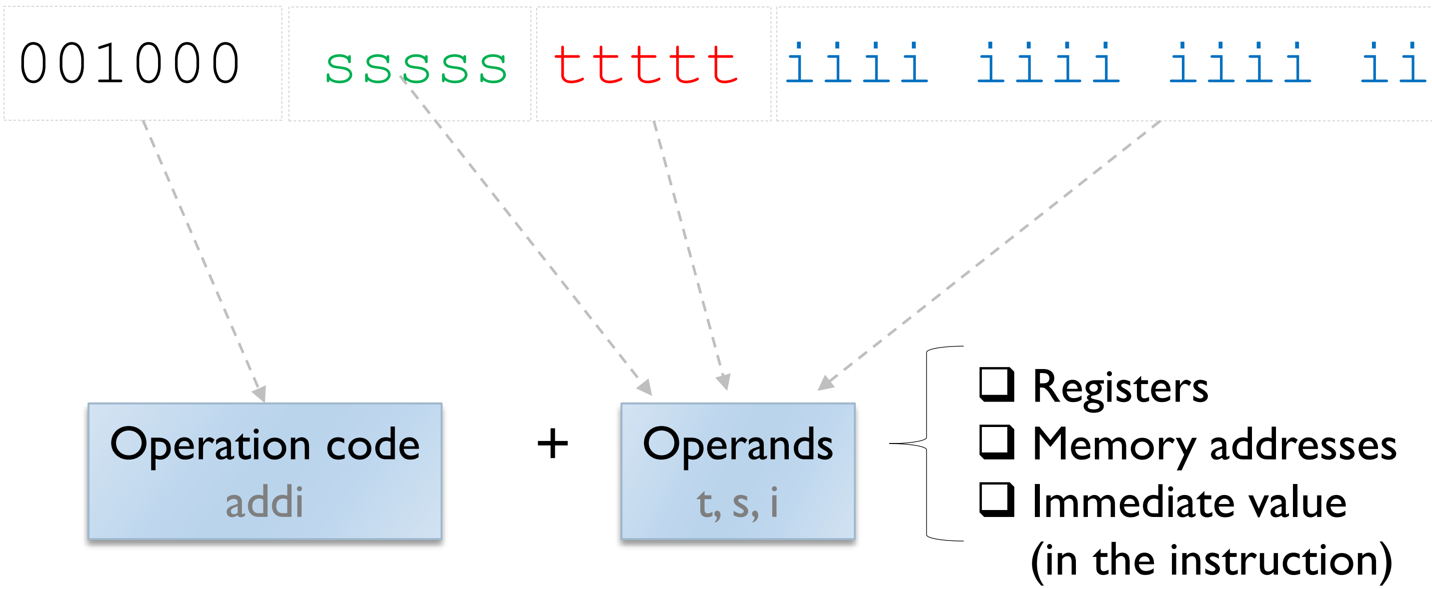
Types of information: instructions and data

- What about the instructions?



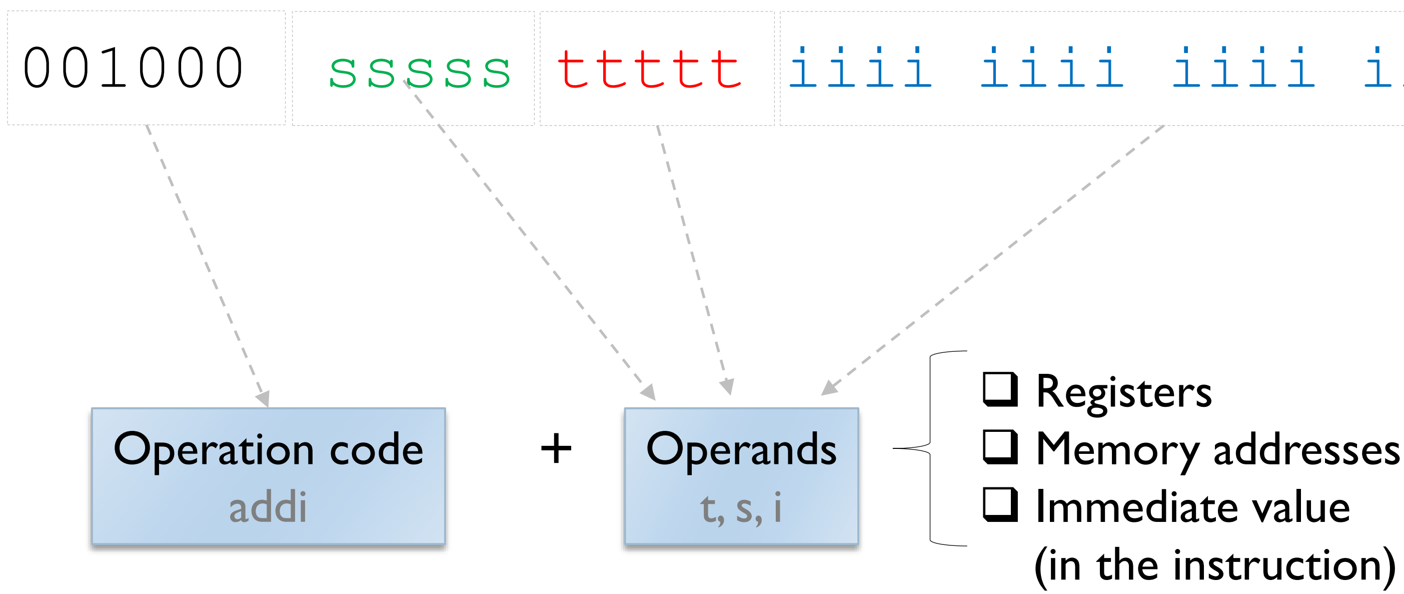
Machine instruction

- Machine instruction: elementary operation that can be executed directly by the processor.
- Example of instruction in MIPS:
  - Sum of a register (s) with an immediate value (i) and the result of the sum is stored in register (t).



Properties of machine instructions

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



Information contained in a machine instruction

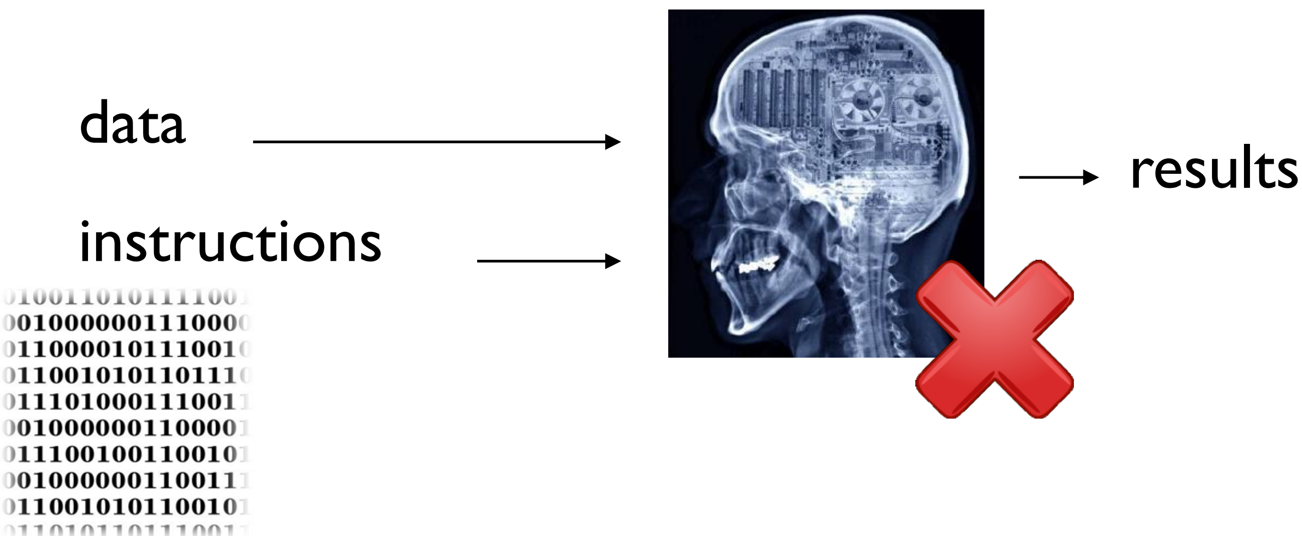
- The operation to be performed.
- Where the operands are located:
  - In registers
  - In memory
  - In the instruction itself (immediate)
- Where to leave the results (as operand)
- A reference to the next instruction to be executed
  - Implicitly: the following instruction
    - A program is a consecutive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

Operation code (addi) + **Operands** (t, s, i)

Operands:
- ❑ Registers
- ❑ Memory addresses
- ❑ Immediate value (in the instruction)

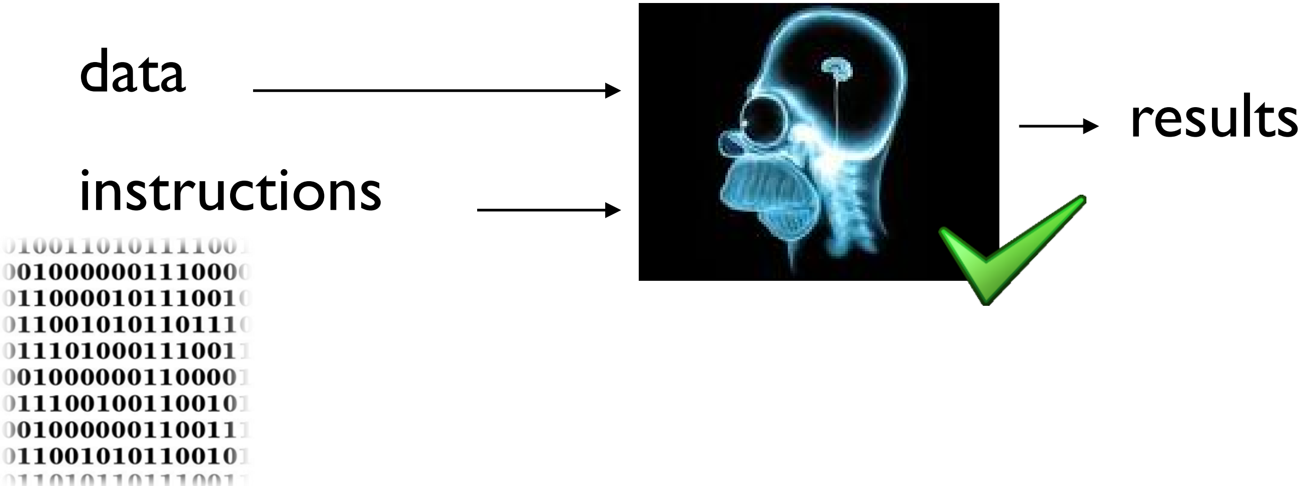
Machine instructions

- There are not complex instructions…



Machine instructions

- … but very simple tasks…



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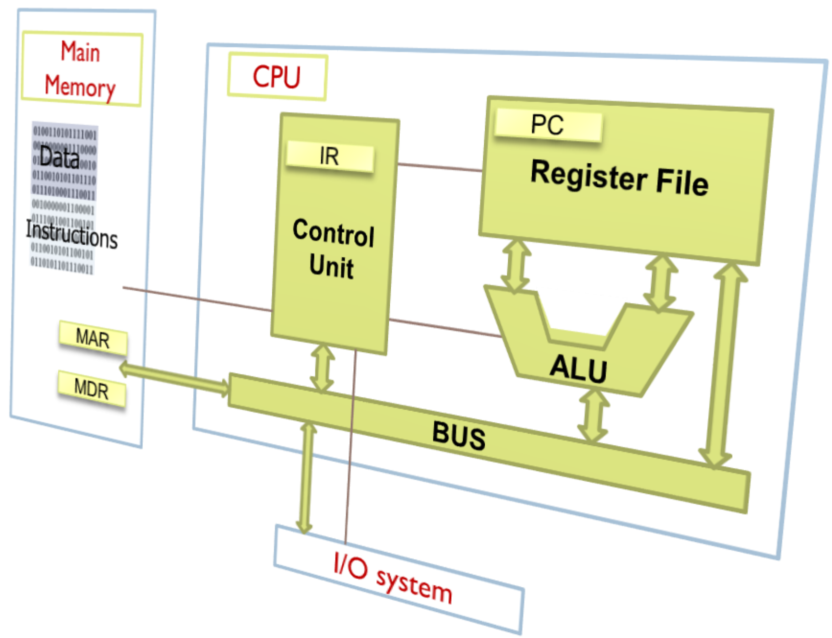
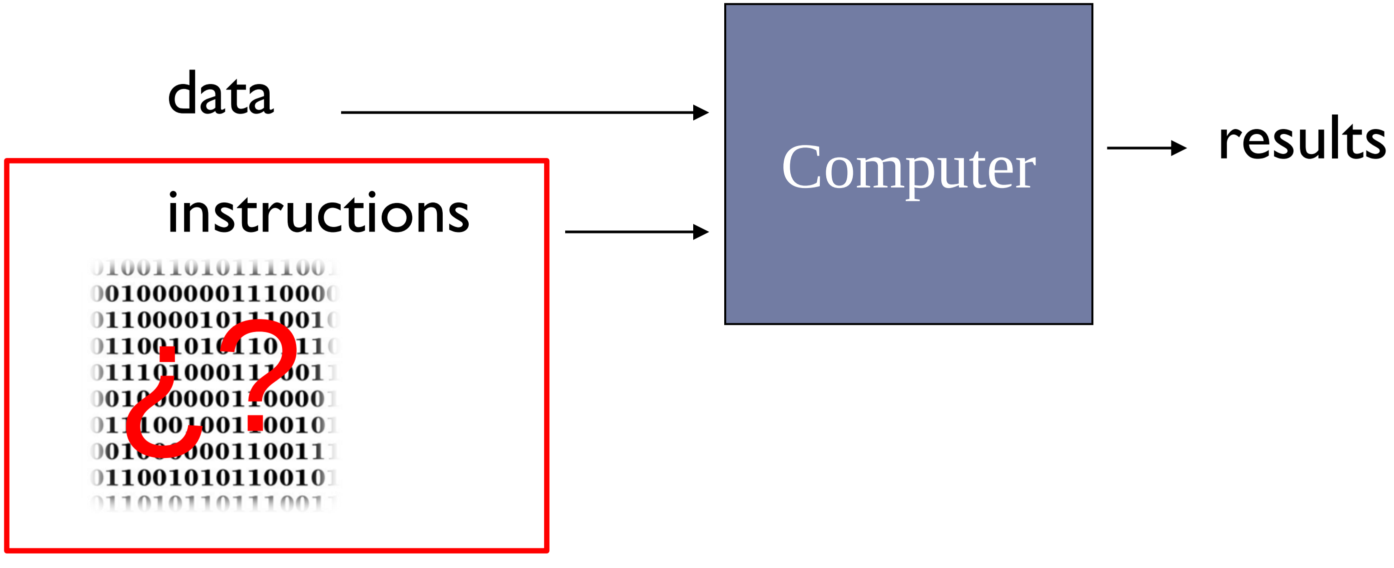
Machine instructions

- … performed by the processor:
  - Data transfers
  - Arithmetic
  - Logical
  - Conversion
  - Input/Output
  - System Control
  - Flow control



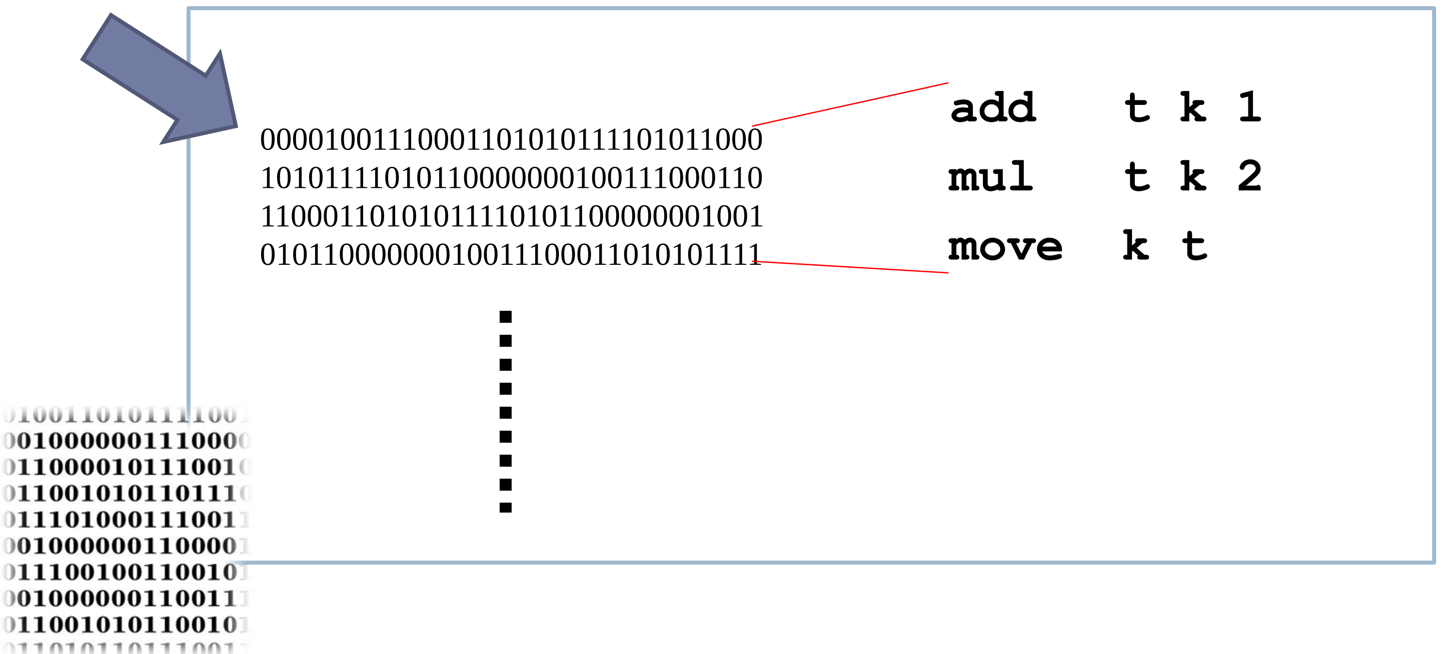
Types of information: instructions and data

- What about the instructions?



Definition of program

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



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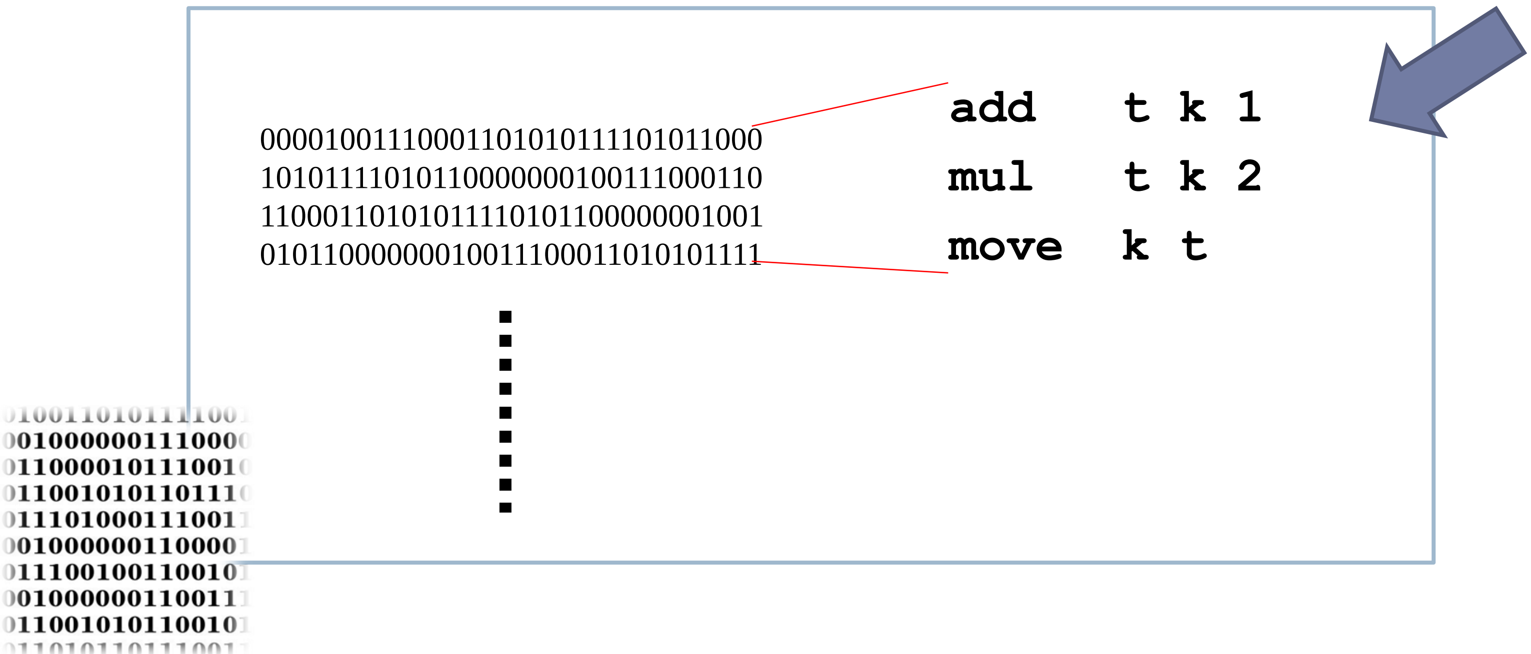
Assembly language definition

- **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`

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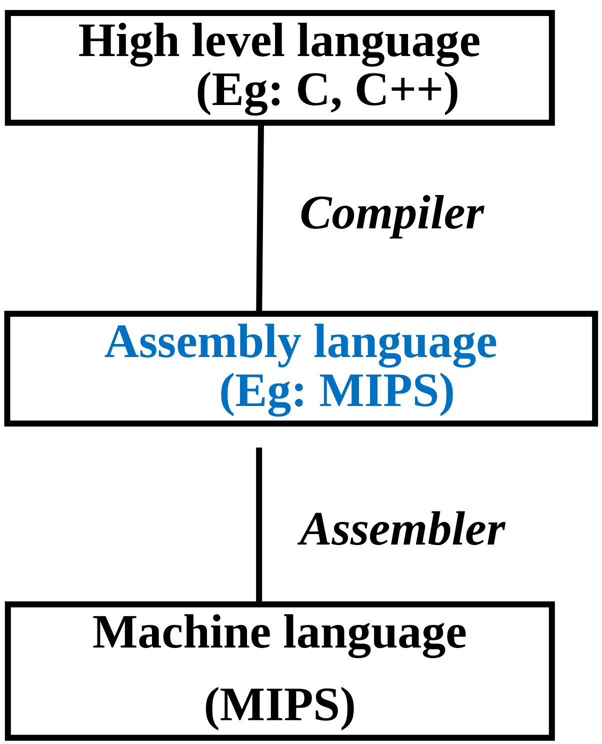
Languages levels



temp = v[k];

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

v[k+1] = temp;

```
lw    $t0, 0($2)
lw    $t1, 4($2)
sw    $t1, 0($2)
sw    $t0, 4($2)
```

```
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)

- Operations:
  - Arithmetic, logic, transfer, control, control, etc.
- 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.
- Memory addressing:
  - Most of them use byte addressing
  - They provide instructions for accessing multi-byte elements from a given position

Characteristics of an instruction set (2/2)

- Addressing modes:
  - They specify where and how to access operands (register, memory or the instruction itself)
- Flow control instructions:
  - Unconditional jumps
  - Conditional jumps
  - Procedure calls
- Format and coding of the instruction set:
  - Fixed or variable length instructions
    - 80x86: variable (from 1 up to 18 bytes)
    - MIPS, ARM: fixed

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Programming model of a computer

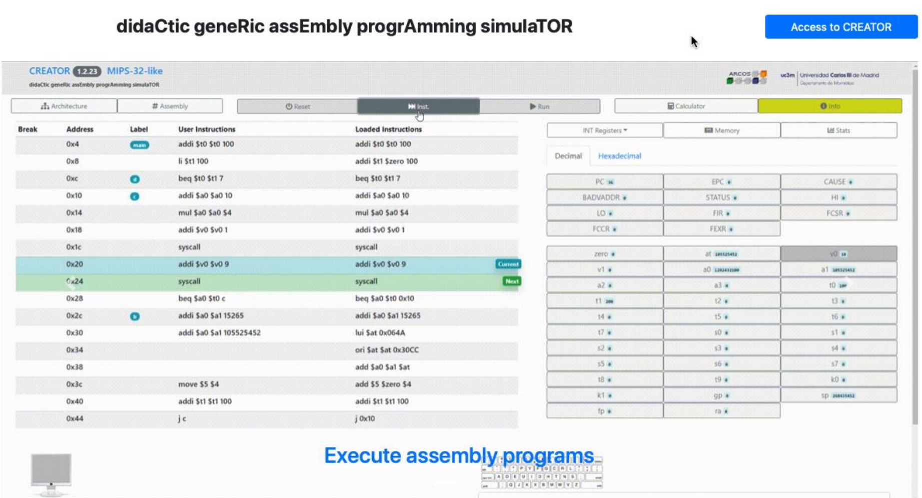
- A computer offers a programming model that consists of:
  - Instruction set (assembly language)
    - ISA: *Instruction Set Architecture*
    - An instruction includes:
      - Operation code
      - Other elements: registers, memory address, numbers
  - Storing elements
    - Registers
    - Memory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

Motivation to learn assembly

```
#include <stdio.h>

#define PI 3.1416
#define RADIUS 20

int main ()
{
    register int l;

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

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

Motivation to use CREATOR simulator

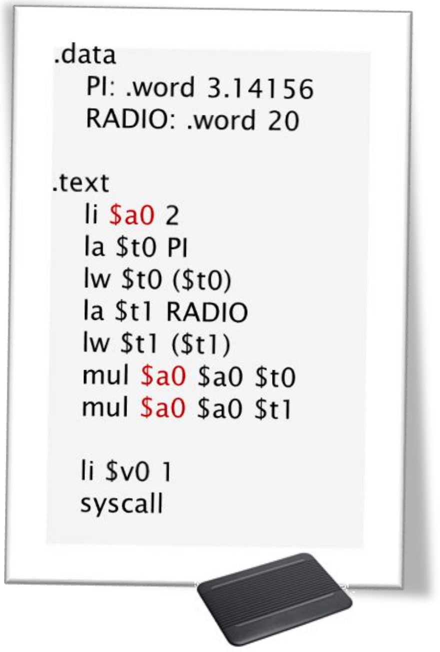


https://creatorsim.github.io/

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

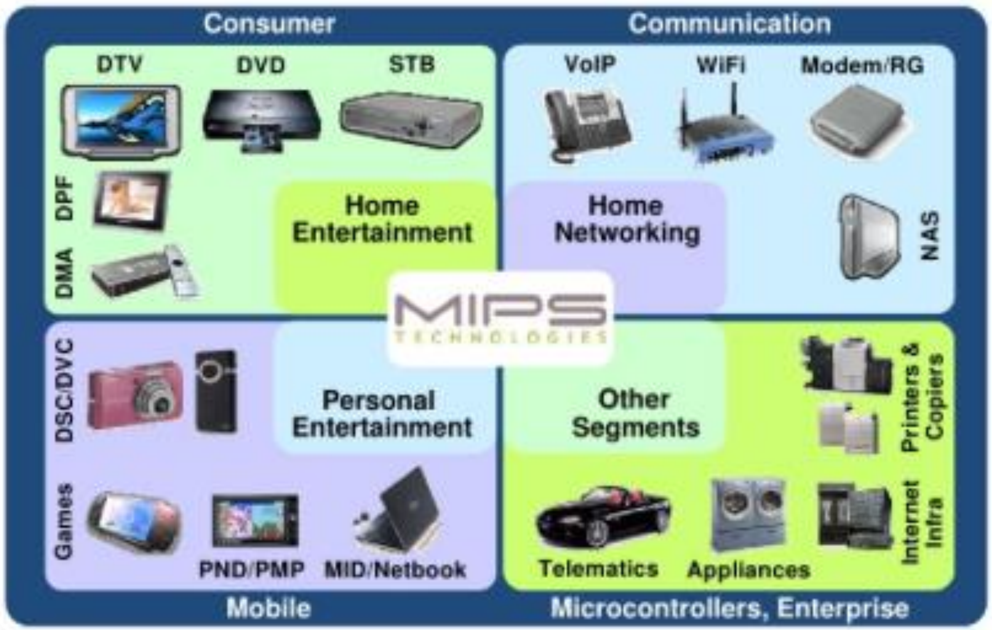
Goals

- 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



Example assembler: MIPS 32

- RISC (Reduced Instruction Set Computer) Processor
- Examples of RISC processors:
  - MIPS, ARM, RISC-V



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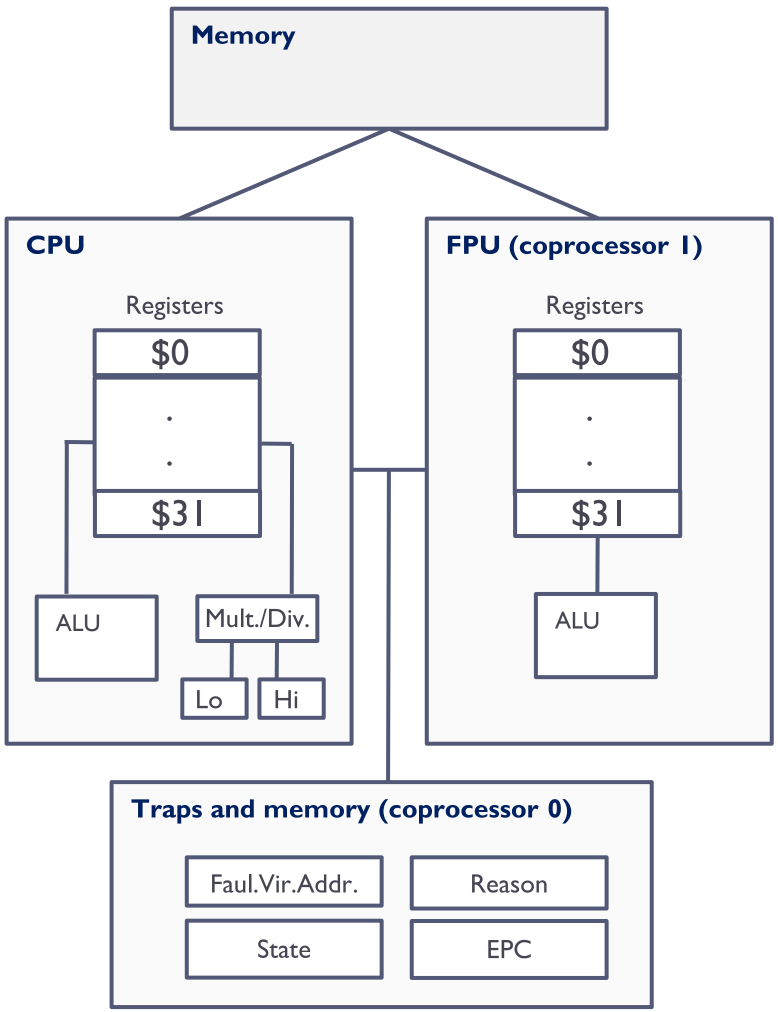
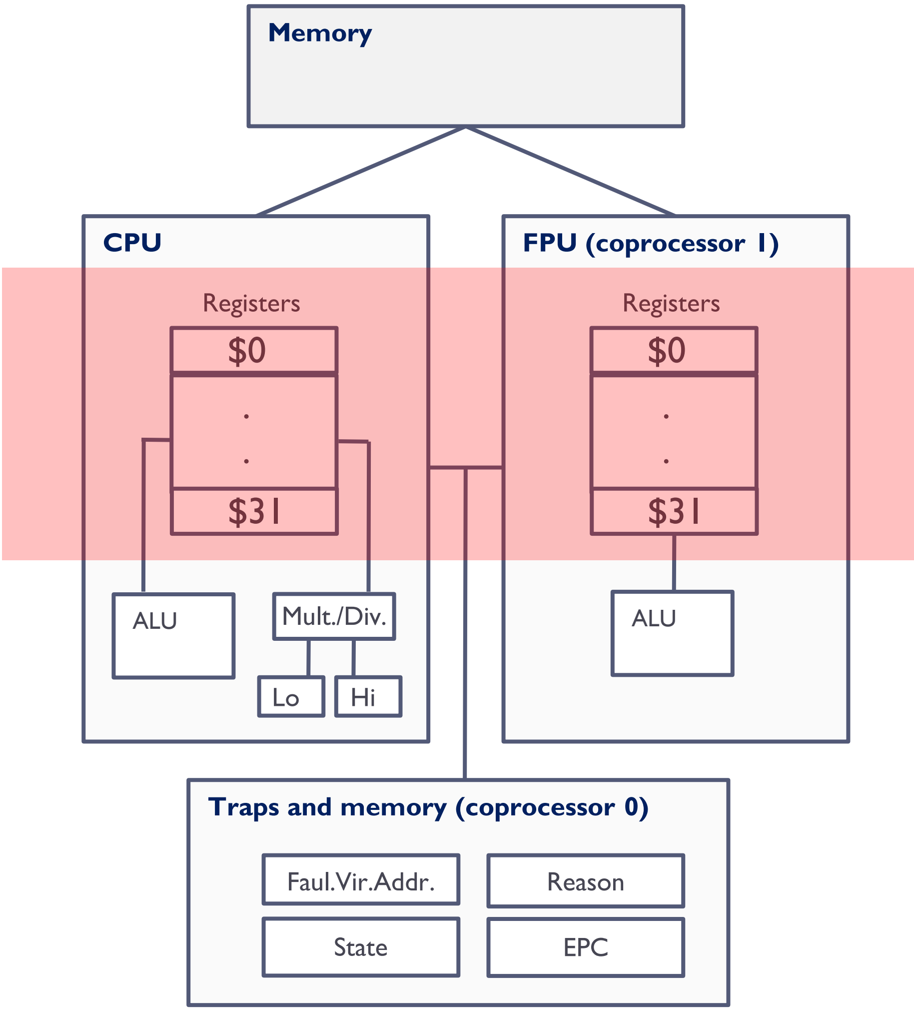
MIPS architecture



- MIPS 32
  - 32 bits processor
  - RISC type
  - CPU + auxiliary coprocessors
- Coprocessor 0
  - exceptions, interrupts and virtual memory system
- Coprocessor 1
  - FPU (floating point unit)

http://es.wikipedia.org/wiki/MIPS_(procesador)

MIPS architecture



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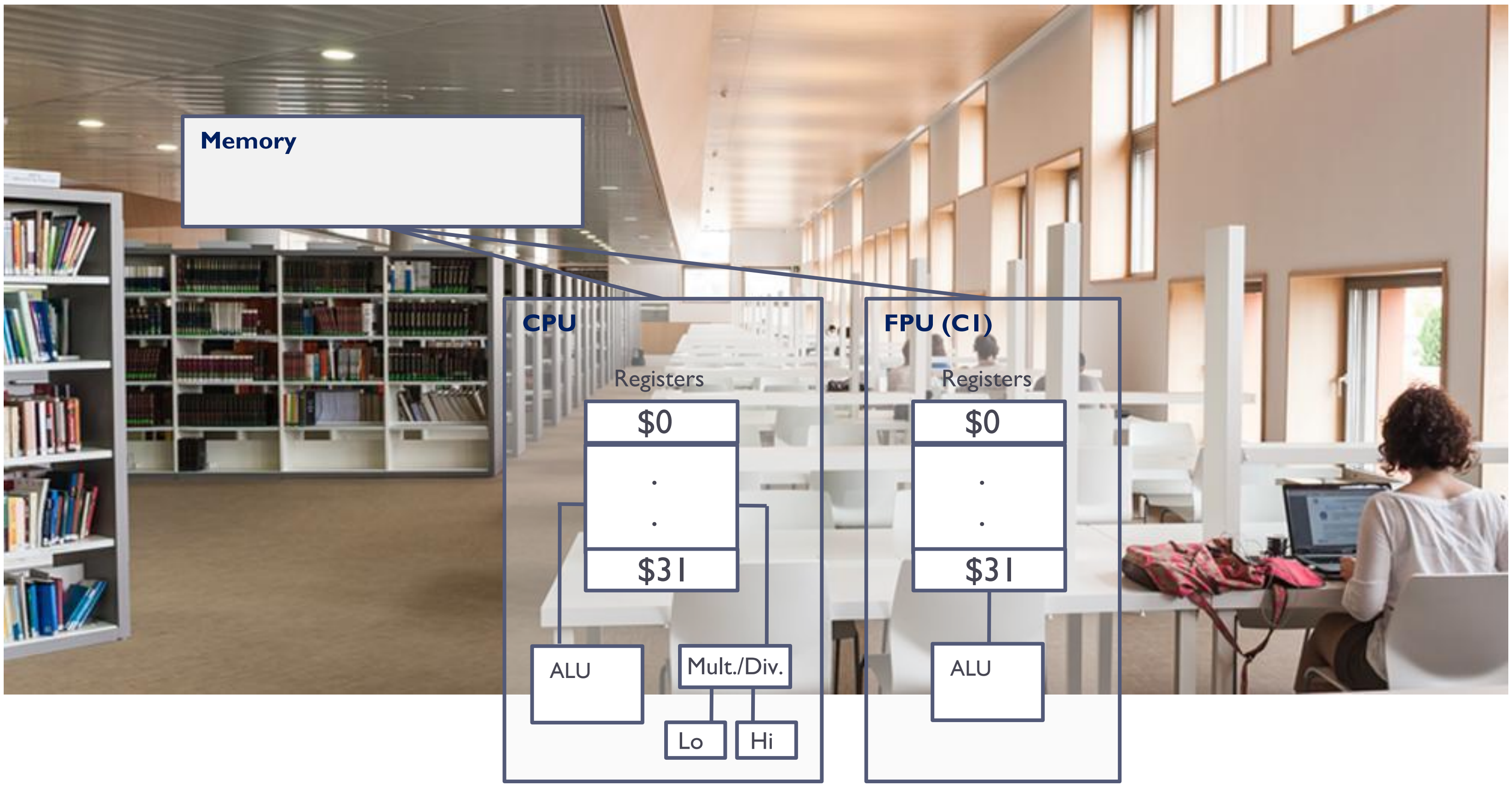

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Register File (integers)

Symbolic name	Number	Usage
$zero	$0	Constant 0
$at	$1	Reserved for assembler
$v0, $v1	$2, $3	Results of functions
$a0, ..., $a3	$4, …, $7	Function arguments
$t0, ..., $t7	$8, …, $15	Temporary (NO preserved across calls)
$s0, ..., $s7	$16, ..., $23	Saved temporary (preserved across calls)
$t8, $t9	$24, $25	Temporary (NO preserved across calls)
$k0, $k1	$26, $27	Reserved for operating system
$gp	$28	Pointer to global area
$sp	$29	Stack pointer
$fp	$30	Frame pointer
$ra	$31	Return address (used by function calls)

- There are 32 registers
  - Size: 4 bytes (1 word)
  - Used a $ at the beginning
- Use convention:
  - Reserved
  - Arguments
  - Results
  - Temporary
  - Pointers

Register File (floating point)

Symbolic name	Usage
$f0…$f3	Results (like $v…)
$f4…$f11	Temporals (like $t…)
$f12…$f15	Arguments (like $a…)
$f16…$f19	Temporals (like $t…)
$f20…$f31	Reserved (like $sv…)

- There are 32 registers
  - Size: 4 bytes (1 word)
  - Used a $ at the beginning
- Can be used:
  - Simple precision (32 registers)
  - Double precision (16 registers)
    - Two consecutives registers are combined into a single double
    - ($f0, $f1) ($f2,$f3) …

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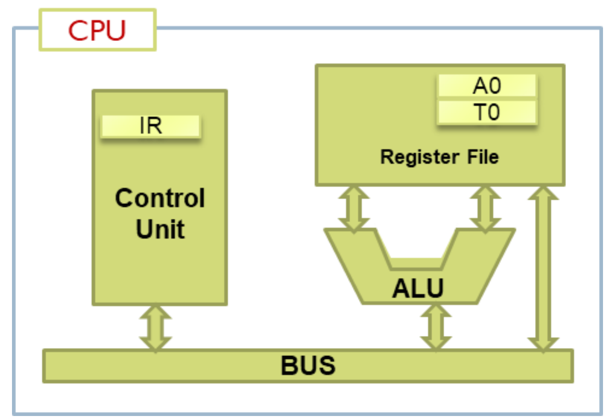
Data transfer

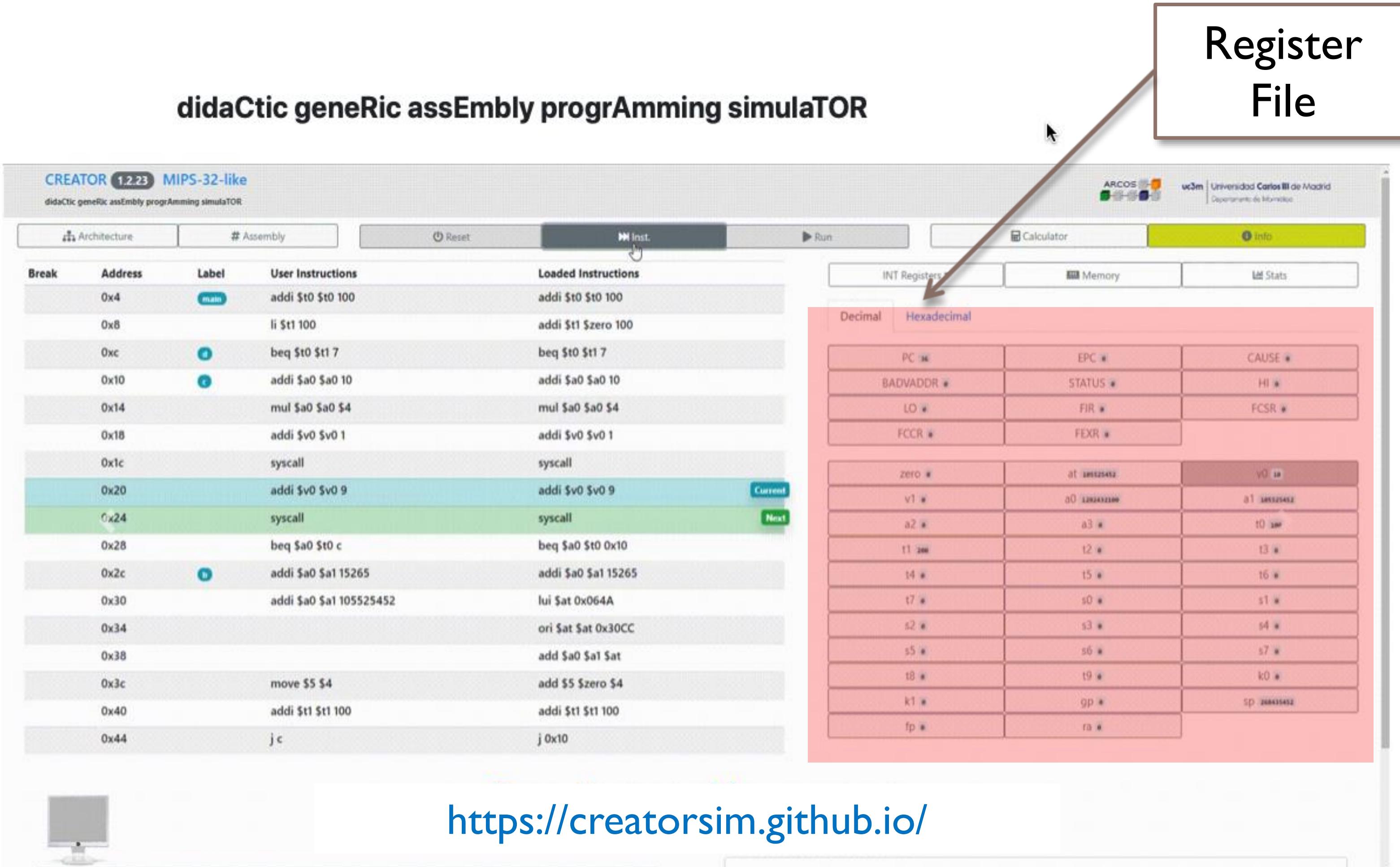
- Copy data:
  - Between registers
  - Between registers and memory (later)
- Examples:
  - Immediate load
    (store a value in a register)
    - li $t0 5 # $t0 ← 5
  - Register to register
    - move $a0 $t0 # $a0 ← $t0




```
move  $a0 $t0    # BR[$a0] = BR[$t0]
li        $t0 1  # BR[$t0] = IR(li,$t0,1)
```

CREATOR

didaCtic geneRic assEmbly progrAmming simulaTOR



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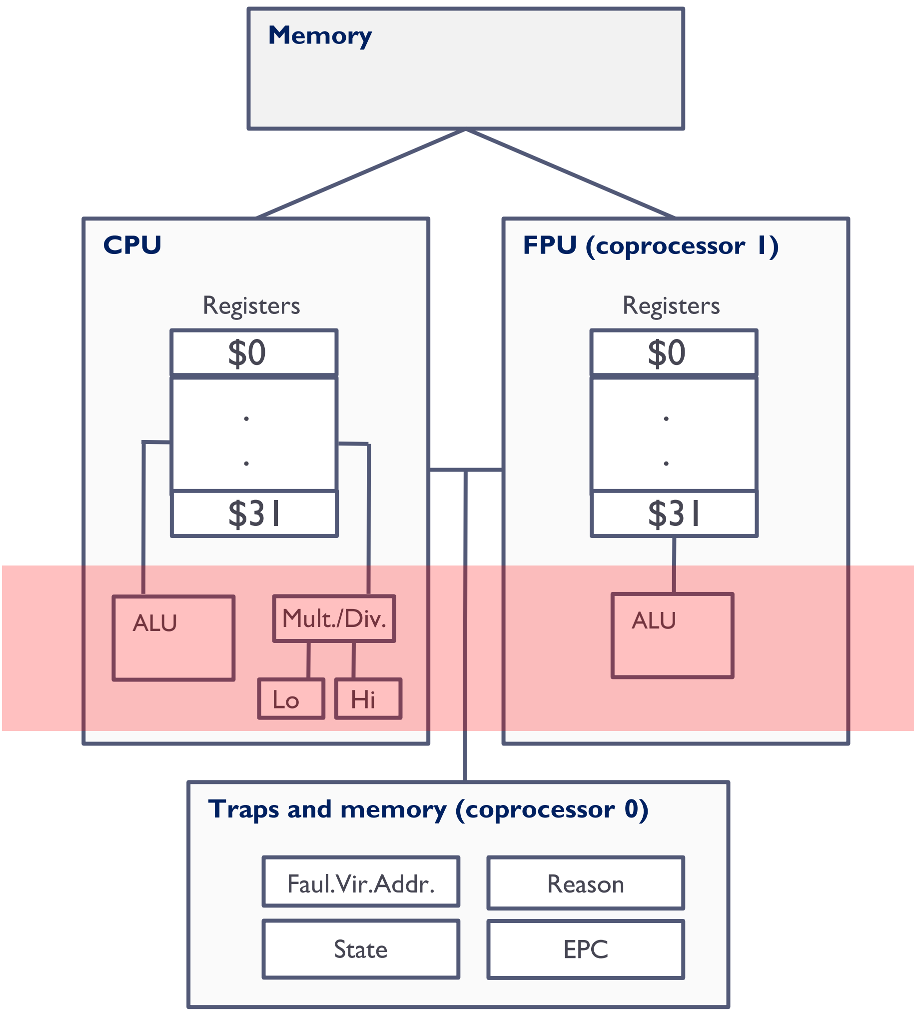
MIPS architecture



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Arithmetic instructions

- Integer operations (ALU) or floating-point operations (FPU)
- Examples (ALU):
  - Addition
    add $t0, $t1, $t2 $t0 = $t1 + $t2 Add with overflow
    addi $t0, $t1, 5 $t0 = $t1 + 5 Add with overflow
    addu $t0, $t1, $t2 $t0 = $t1 + $t2 Add without overflow
  - Subtraction
    sub $t0 $t1 1
  - Multiplication
    mul $t0 $t1 $t2
  - Division
    div $t0, $t1, $t2 $t0 = $t1 / $t2 Integer division
    rem $t0, $t1, $t2 $t0 = $t1 % $t2 Remainder

Example

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

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

```
li $t0, 5
li $t1, 7
li $t2, 8


add $t1, $t1, $t2
mul $t3, $t1, $t0
```

Example

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

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

```
li $t0, 5
li $t1, 7
li $t2, 8
li $t3 10

sub $t4, $t1, $t3
mul $t4, $t4, $t0
add $t4, $t4, $t2
li  $t5, -1
mul $t4, $t4, $t5
```

Types of arithmetic operations

- Pure binary or two's complement arithmetic

- Examples:
  - Signed sum (ca2)
    add $t0 $t1 $t2
  - Immediate signed sum
    addi $t0 $t1 -5
  - Unsigned sum (binary)
    addu $t0 $t1 $t2
  - Immediate unsigned sum
    addiu $t0 $t1 2

- Without **overflow**:

```
li $t0 0x7FFFFFFF
li $t1 5
addu $t0 $t0 $t1
```

- With **overflow**:

```
li $t0 0x7FFFFFFF
li $t1 1
add $t0 $t0 $t1
```

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
```


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CREATOR

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
```

→

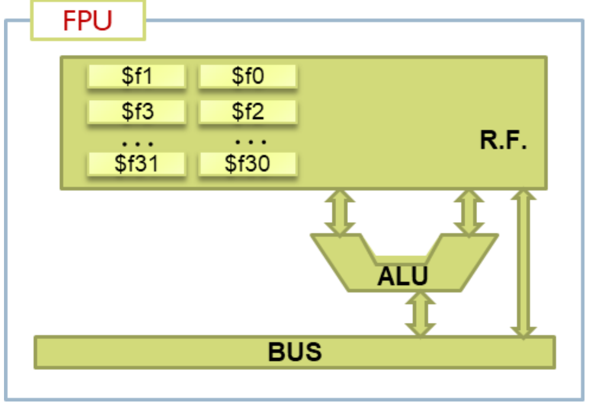
```
li $t1 5
li $t2 7
li $t3 8

addi  $t4 $t2 -10
mul   $t4 $t4 $t1
add   $t4 $t4 $t3
mul   $t4 $t4 -1
```

Arithmetic: IEEE 754

- IEEE 754 floating point arithmetic on the FPU
- Examples:
  - Simple precision add
    add.s $f0 $f1 $f4

    f0 = f1 + f4
  - Double precision add
    add.d $f0 $f2 $f4

    (f0,f1) = (f2,f3) + (f4,f5)

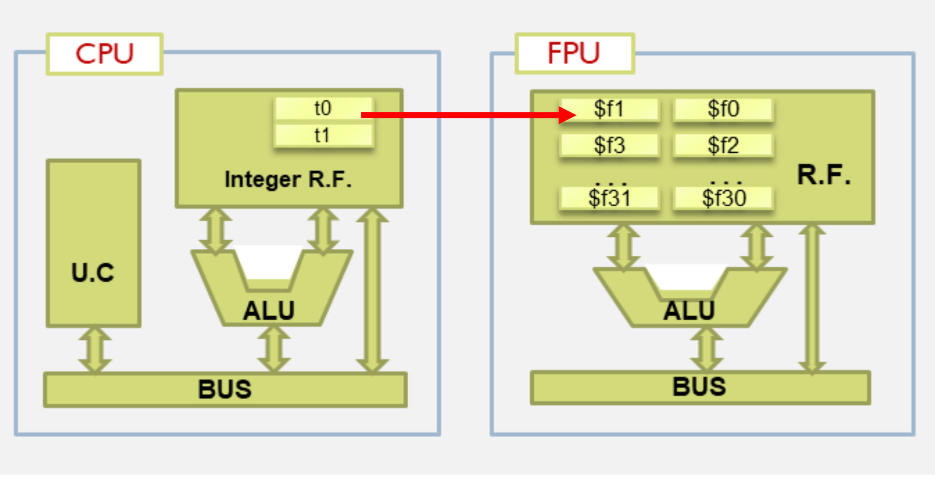


  - Load the float value 8.0 in register $f4:
    li.s $f4, 8.0
  - Load the double value 12.4 in registers ($f2, $f3):
    li.d $f2, 12.4
  - Others: add.s, sub.s, mul.s, div.s, abs.s, bclt, bclf, …

Data transfer: IEEE 754

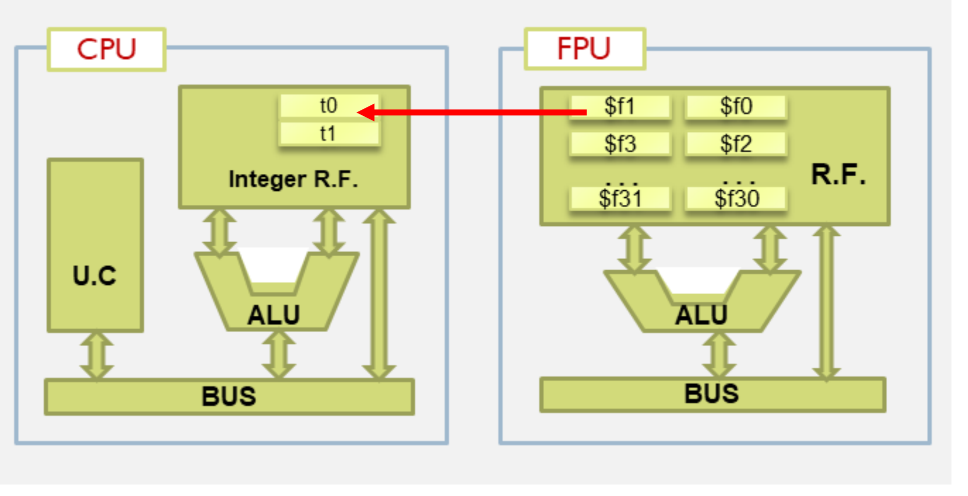
```
mtc1  $t0   $f1
```

- Move To Coprocessor 1 (FPU)




```
mfc1  $t0   $f1
```

- Move From Coprocessor 1 (FPU)



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Conversion operations

- `cvt.s.w  $f2 $f1`
  - Convert from integer ($f1) to single precision ($f2)
- `cvt.w.s  $f2 $f1`
  - Convert from single precision ($f1) to integer ($f2)
- `cvt.d.w  $f2 $f0`
  - Convert from integer ($f0) to double precision ($f2)
- `cvt.w.d  $f2 $f0`
  - Convert from double precision ($f0) to integer ($f2)
- `cvt.d.s  $f2 $f0`
  - Convert from single precision ($f0) to double ($f2,$f3)
- `cvt.s.d  $f2 $f0`
  - Convert from double precision ($f0) to single ($f2)

Example

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

longitud = PI * radio;
```

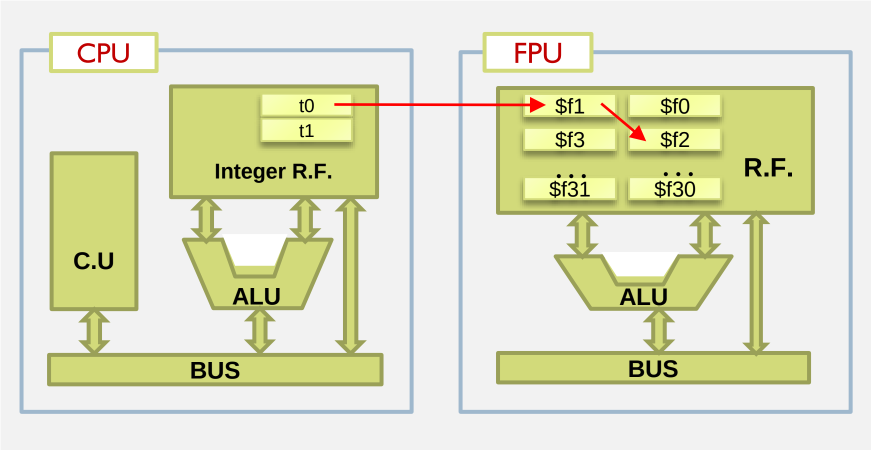
```
.text
.globl main
 main:

   li.s      $f0   3.1415
   li        $t0 4
```

Example

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

longitud = PI * radio;
```




```
.text
.globl main
 main:

  li.s      $f0  3.1415
  li        $t0 4

  mtc1      $t0 $f1    # 4ca2
  cvt.s.w   $f2 $f1    # 4ieee754
  mul.s     $f0 $f2 $f1
```

Logical instructions

- Boolean operations:
  - NOT
    `not $t0 $t1          ($t0 = ! $t1)`
  - AND
    `and $t0 $t1 $t2      ($t0 = $t1 & $t2)`
  - OR
    `or  $t0 $t1 $t2      ($t0 = $t1 |  $t2)`
    `ori $t0 $t1 80       ($t0 = $t1 |  80)`
  - XOR
    `xor $t0 $t1 $t2      ($t0 = $t1 ^ $t2)`

```
NOT  10
     --
     01

     1100
AND  1010
     ----
     1000

     1100
OR   1010
     ----
     1110

     1100
XOR  1010
     ----
     0110
```

Example

```
li $t0, 5
li $t1, 8


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

What is the value of $t2?

Example (solution)

```
li $t0, 5
li $t1, 8


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

What is the value of $t2?

	000 …. 0101	$t0
	000 ….. 1000	$t1
and	000 ….. 0000	$t2

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Exercise

```
li $t0, 5
li $t1, 0x007FFFFF



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

What does an "and" with 0x007FFFFF allow to do?

Exercise (solution)

```
li $t0, 5
li $t1, 0x007FFFFF


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

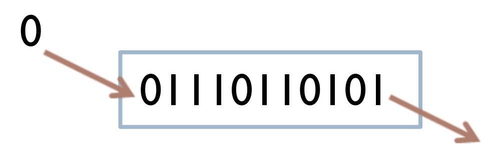
What does an "and" with 0x007FFFFF allow to do?

Obtain the 23 least significant bits

The constant used for bit selection is called a mask.

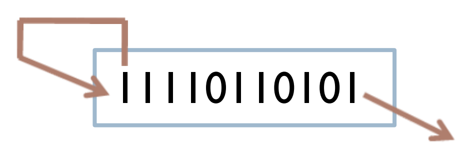
Shift instructions

- Bits movement
- Examples:
  - Shift right logical
    srl $t0 $t0 4 ($t0 = $t0 >> 4 bits)



  - Shift left logical
    sll $t0 $t0 5 ($t0 = $t0 << 5 bits)

  - Shift right arithmetic
    sra $t0 $t0 2 ($t0 = $t0 >> 2 bits)



Example

```
li $t0, 5
li $t1, 6

sra $t0, $t1, 1
```

- What is the value of $t0?

```
srl $t0, $t1, 1
```

- What is the value of $t0?

Example (solution)

```
li $t0, 5
li $t1, 6

sra $t0, $t1, 1
```

- What is the value of $t0?

  000 …. 0110 $t1
  shift one bit to right (/2)
  000 ….. 0011 $t0

```
srl $t0, $t1, 1
```

- What is the value of $t0?

  000 …. 0110 $t1
  Shit one bit to left (x2)
  000 ….. 1100 $t0

Rotations

- Bits movement
- Example:
  - Rotate left
    rol $t0 $t0 4   rotate 4 bits

  - Rotate right
    ror $t0 $t0 5   rotate 5 bits

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

move $t1 $t0
rol  $t1 $t1 1
and  $t1 $t1 0x00000001
```

Comparison instructions

- seq $t0, $t1, $t2

  if ($t1 == $t2) $t0 = 1; else $t0 = 0 # set if equal
- sneq $t0, $t1, $t2

  if ($t1 !=$t2) $t0 = 1; else $t0 = 0 # set if no equal
- sge $t0, $t1, $t2

  if ($t1 >= $t2) $t0 = 1; else $t0 = 0 # set if greater or equal
- sgt $t0, $t1, $t2

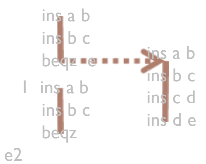
  if ($t1 > $t2) $t0 = 1; else $t0 = 0 # set if greater than
- sle $t0, $t1, $t2

  if ($t1 <= $t2) $t0 = 1; else $t0 = 0 # set if less or equal
- slt $t0, $t1, $t2

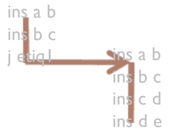
  if ($t1 < $t2) $t0 = 1; else $t0 = 0 # set if less than

Branch instructions

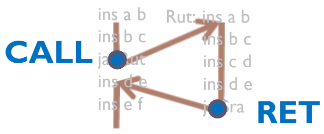
- Change the sequence of instructions to be executed
- Several types:
  - Conditional branches:
    - Branch if value match condition
    - E.g.: bne $t0 $t1 etiqueta1



  - Unconditional branches:
    - Always branch
      E.g.: j etiqueta2

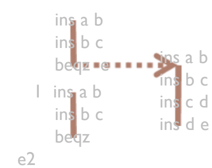


  - Function calls:
    - Branch with return
    - E.g.: jal subrutina1 …… jr $ra



Branch instructions

- Change the sequence of instructions to be executed
- Several types:
  - Conditional branches:
    - Branch if value match condition
    - E.g.: bne $t0 $t1 etiqueta1




```
beq    $t0  $t1  etiq1   # go to etiq1 if $t0  = $t1
bne    $t0  $t1  etiq1   # go to etiq1 if $t0 != $t1
beqz   $t1       etiq1   # go to etiq1 if $t1  = 0
bnez   $t1       etiq1   # go to etiq1 if $t1 != 0
bgt    $t0  $t1  etiq1   # go to etiq1 if $t0 >  $t1
bge    $t0  $t1  etiq1   # go to etiq1 if $t0 >= $t1
blt    $t0  $t1  etiq1   # go to etiq1 if $t0 <  $t1
ble    $t0  $t1  etiq1   # go to etiq1 if $t0 <= $t1
```

Control flow structures if…(1/2)

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


if (b2 == 8) {
    b1 = 0;
}
 ...
```

```
      li    $t0 4 # b1
      li    $t1 2 # b2
      li    $t2 8

      bne   $t1 $t2 end1
      li    $t0 0

end1: ...
```

Control flow structures if-else ...(2/2)

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

if (a < b)
{
    // action 1
}
else
{
    // action 2
}
```

```
      li   $t1 1
      li   $t2 2

      blt $t1 $t2 then1
else1: ...
      # action 2
      b end1

then1: ...
      # action 1

end1: ...
```

Control flow structures
while

```
int i;

i=0;
while (i < 10)
{
    /* action */
    i = i + 1 ;
}
```

```
        li   $t0 0
        li   $t1 10
while2: bge $t0 t1 end2
        # action
        addi $t0 $t0 1
        b while2
end2:    ...
```

Exercise

- Calculate 1 + 2 + 3 + …. + 10 and result in $t1

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

- Calculate 1 + 2 + 3 + …. + 10 and result in $t1

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

```
        li   $t0 0
        li   $t1 0
        li   $t2 10
while:  bge  $t0 t2 end
        add  $t1 $t1 $t0
        addi $t0 $t0 1
        b    while
end:    ...
```

Exercise

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

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

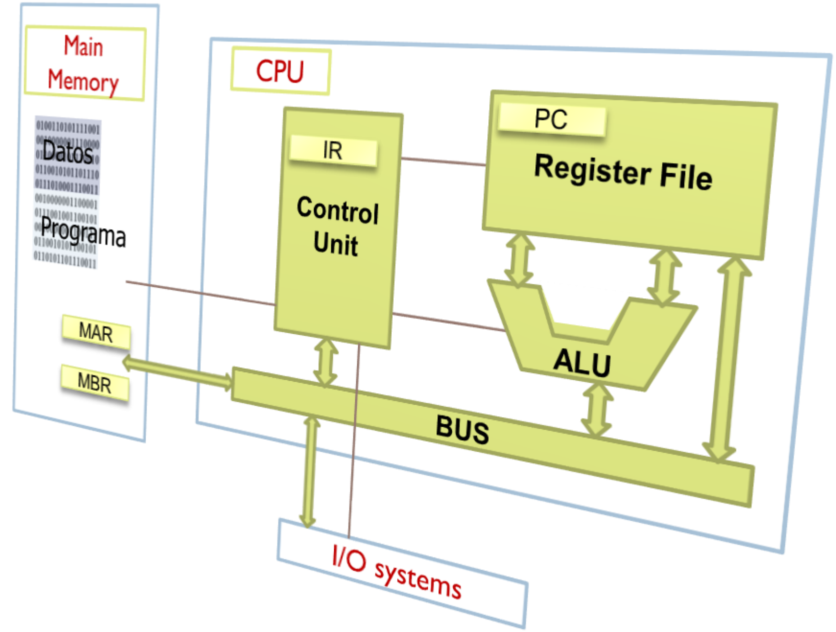
Exercise (solution)

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

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

```
         li   $t0 0     #i
         li   $t1 45    #n
         li   $t2 32
         li   $t3 0     #s
while1:  bge  $t0 t2 end1
         and  $t4 $t1 1
         add  $t3 $t3 $t4
         srl  $t1 $t1 1
         addi $t0 $t0 1
         b    while1
end1:    ...
```

Types of instructions



- Data transfer
- Arithmetic
- Logical
- Shifting
- Rotation
- Comparison
- 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.

Example

- Calculate the number of 1's of a `int` in C/Java

Another solution :

```
int count[256] = {0,1,1,2,1,2,2,3,1, . . .8};
int i;
int c = 0;

for (i = 0; i <4; i++) {
     c =  count[n & 0xFF];
     s = s + c;
     n = n >> 8;
}
printf(”There is  %d\n", c);
```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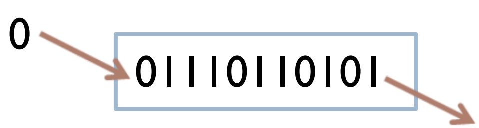
Example

- Obtain the 16 first bits of a register ($t0) and store them in the 16 last bits of other register ($t1)

Solution

- Obtain the 16 first bits of a register ($t0) and store them in the 16 last bits of other register ($t1)

```
srl  $t1,  $t0,  16
```



Shift 16 bits to right

Compilation process

High level language	Assembly language	Binary language

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 $v0 1
    syscall
```

Binary language

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

Example

- Determine if the number stored in $t2 is even. If $t2 is even the program stores 1 in $t1, else stores 0 in $t1

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Solution

- Determine if the number stored in $t2 is even. If $t2 is even the program stores 1 in $t1, else stores 0 in $t1

```
       li  $t2  9
       li  $t1  2
       rem $t1  $t2  $t1     # remainder
       beq $t1  $0  then     # cond.
else:  li $t1 0
       b end                  # uncond.
then:  li $t1 1
end:  ...
```

Example

- Determine if the number stored in $t2 is even. If $t2 is even the program stores 1 in $t1, else stores 0 in $t1. In this case, analyze the last bit

Solution

- Determine if the number stored in $t2 is even. If $t2 is even the program stores 1 in $t1, else stores 0 in $t1. In this case, analyze the last bit

```
        li  $t2 9
        li  $t1 1
        and $t1  $t2  $t1    # get the last bit
        beq $t1 $0  then     # cond.
else:   li $t1 0
        b end                 # uncond.
then:   li $t1 1
end:    ...
```


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Example

- Calculate a^n
  - a in $t0
  - n in $t1
  - Result in $t2

```
a=8
n=4;
i=0;
p = 1;
while (i < n)
{
   p = p * a
   i = i + 1 ;
}
```

Solution

- Calculate a^n
  - a in $t0
  - n in $t1
  - Result in $t2

```
a=8
n=4;
i=0;
p = 1;
while (i < n)
{
  p = p * a
  i = i + 1 ;
}
```

```
          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
```


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