Digital Logic Design + Computer Architecture

Sayandeep Saha

Assistant Professor
Department of Computer Science and Engineering
Indian Institute of Technology Bombay

Instruction Set Architecture

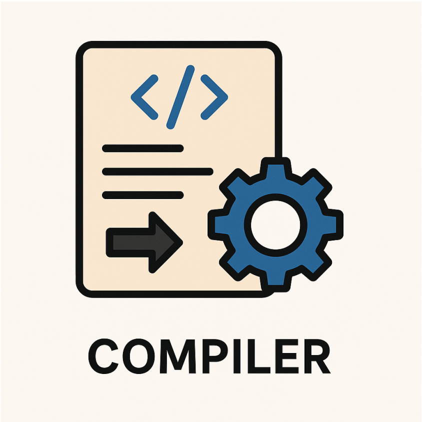
How to talk to a Computer?

- **Computers can be given "instructions"**
- We have a set of instructions for every computer — called **instruction set**
- **When you write a program, you write instructions..**
  - More details later…
- Every instruction some hardware circuit implemented inside the processor to get its job done.
- **Instruction Set Architecture**: specifies the set of instructions a processor understands, their encoding, how they access memory etc…

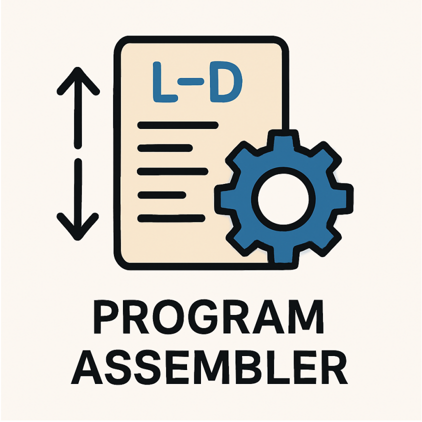
Image generated by ChatGPT

What happens when you write a program

- **Say we write:**
  - a = b + c;



- There is a software program called **compiler**
  - Takes our code and encodes in terms of the instructions available for the computer
  - `add reg1, reg2, reg3`



- There is another program called **assembler** which converts the instruction (sequence) to bits
- 0101110000110101

Image generated by ChatGPT

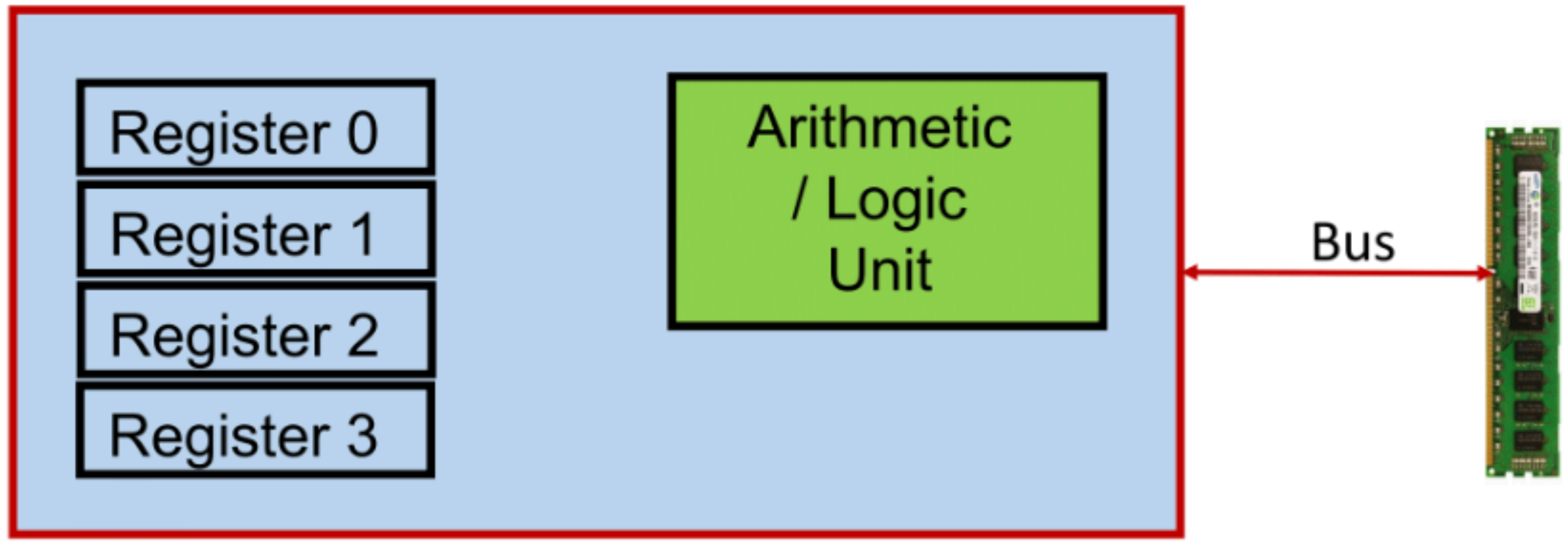
How to talk to a Computer?

- **Instruction Set Architecture**: specifies the set of instructions a processor understands, their encoding, how they access memory etc…
  - **End of the day even your ChatGPT is a sequence of instructions** (many billions or trillions).
- Instruction set is basically an **abstraction layer**
  - **Hides the complexity of hardware from the software designers,**
  - **Interfaces the software and hardware.**

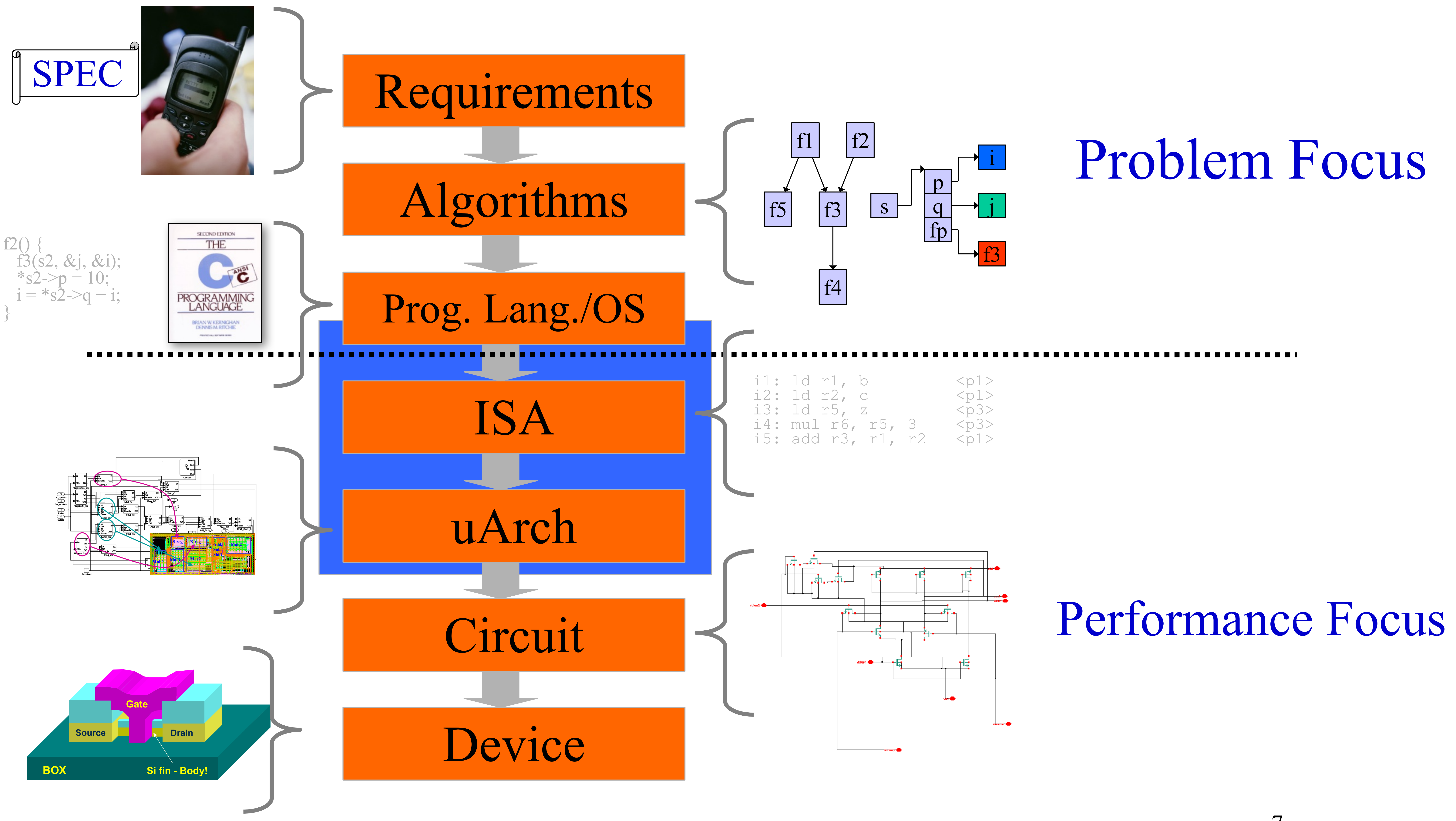
Image generated by ChatGPT

Let's get into the processor a bit

- It is a sequential circuit with a **limited** number of registers.
- It interacts with an external "memory".
- Every instruction operates on some **operands** and generate results.
- Results and operands are stored in **registers**.
- **But they can also be in memory as the number of registers are limited**
- Note that typically such memory (called **DRAM** or **Dynamic Random Access Memory)** is **off chip —outside the processor**
- **To operate, you have to bring the data from memory and store the results back**

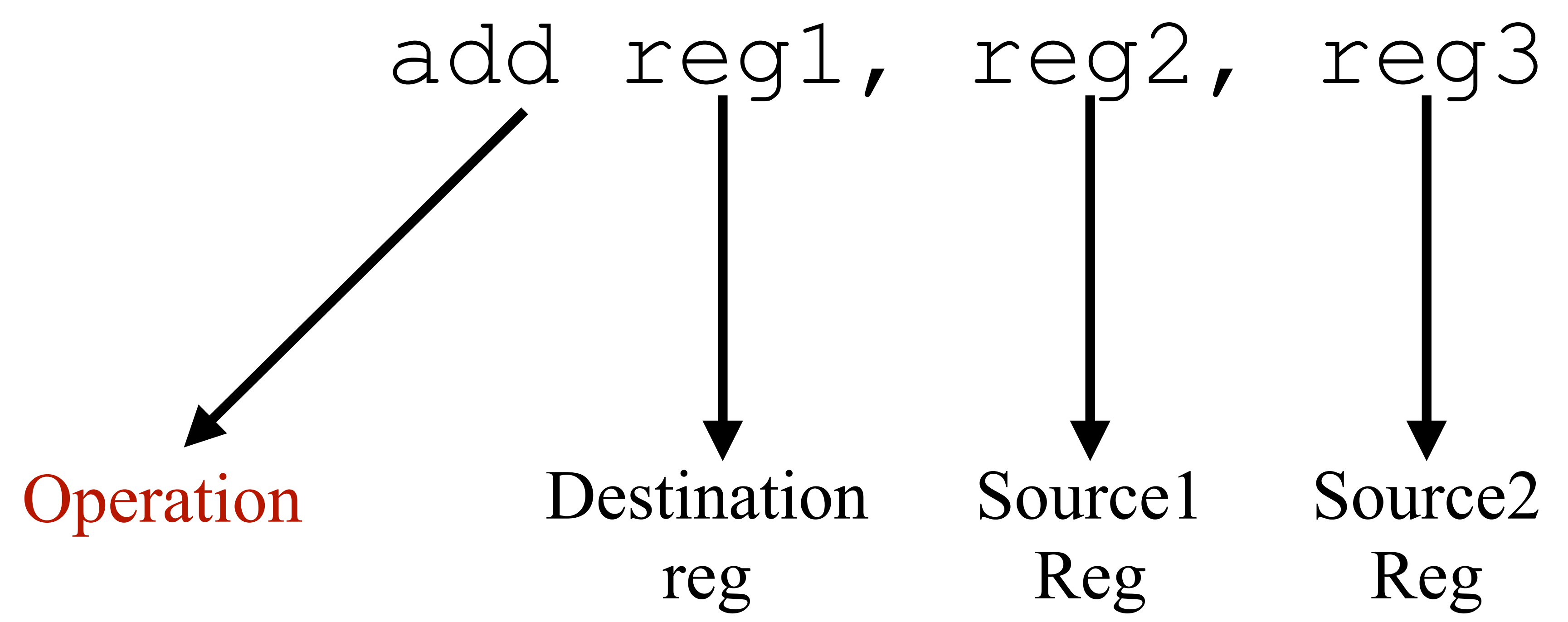


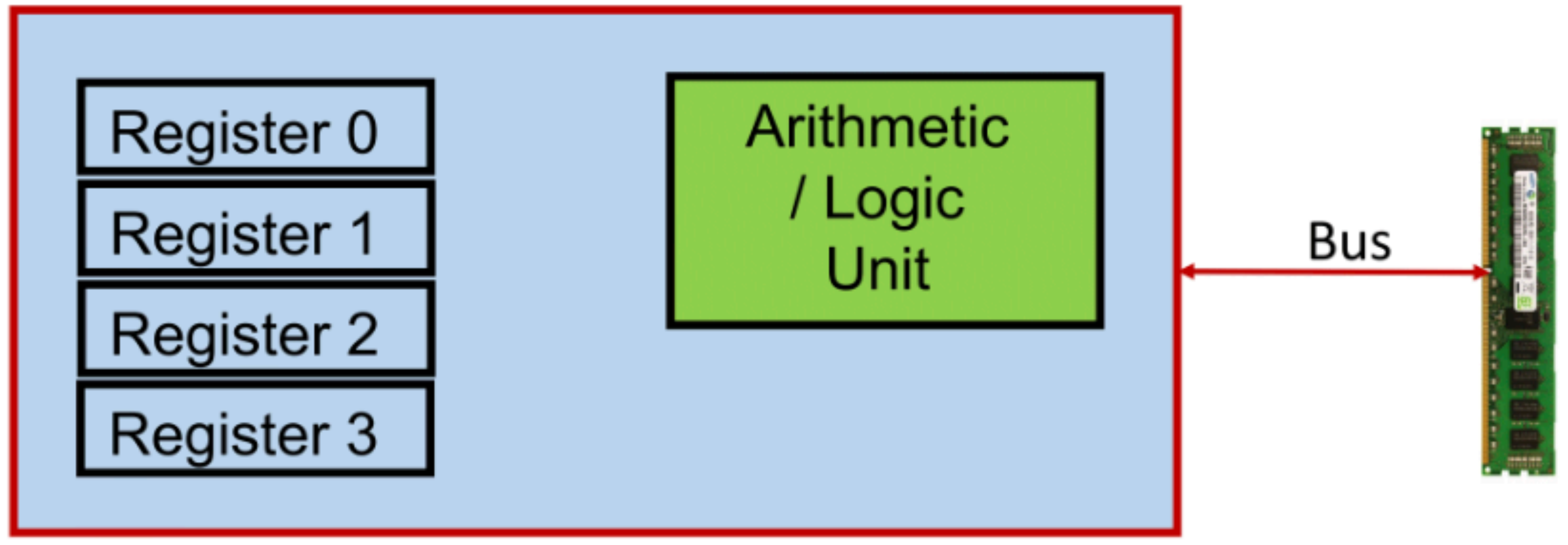
The Big Picture



Dissection of an Instruction

- Let’s focus on the simplistic view of the processor





- Most of the arithmetic/logical instructions can take this form — not all though

Instruction Set Architectures (ISA)

- There are many…
  - Intel uses **X86**
  - Apple uses a version of **AArch64** (ARM)
  - The entire world of embedded processors like ST-Microelectronics uses ARM
  - Now **RISC-V** is becoming a mainstream trend.
  - We shall study MIPS — a simple to understand ISA

Instruction Set Architectures (ISA)

- We shall study MIPS — a simple to understand ISA
    - Great for beginning…
    - Similar to ARM
    - Still in use in the embedded devices
        - Your smart card
        - Modems
        - Bitcoin-wallets

Now let's write some MIPS

- We shall name the registers as `$0`, `$1`, or `$a0`, `$g1` etc…
- Now we shall try something a bit more complex…

```
add reg1, reg2, reg3
        ↓
add $0, $1, $2
```

Now let's write some MIPS

- Let's compute: `a = b+c-d`
- No idea? — get idea :P

```
add reg1, reg2, reg3
        ↓
add $0, $1, $2
```

Now let's write some MIPS

- Let's compute: `a = b+c-d`
- Assume we have add and sub instructions taking two sources and one destination register

```
add $0, $1, $2

sub $0, $1, $2
```

Now let's write some MIPS

- Let's compute: `a = b+c-d`
- Assume we have add and sub instructions taking two sources and one destination register

```
add $0, $1, $2

sub $0, $1, $2
```

- First' let's simplify :
  - `t = b+c`
  - `a = t-d`

- **Observe**: I use a temporary register…

- Now, I can map to instructions..
  - `add $r0, $r1, $r2 //t = b+c`
  - `sub $d0, $r0, $r3 //a = t-d`

Now let's write some MIPS

- Let's try: `f = (g+h)-(i+j)`

Now let's write some MIPS

- Let's try: `f = (g+h)-(i+j)`

  - `add $r0, $r1, $r2 //x = g+h`
  - `add $r3, $r4, $r5 //y = i+j`
  - `Sub $r0, $r0, $r3 //f = x-y`

- **Food of thought**: Well, do I really need to reuse registers???

Ok…A Few MIPS Details…

- We have 32 registers in the processor
  - So we have to reuse registers, no other option…
  - Typically, registers are 32-bits…
- But why don't we have infinite number of registers
  - Well, every piece of register is a real hardware…

- **But**: Why 32??

Ok…A Few MIPS Details…

- We have 32 registers in the processor
  - So we have to reuse registers, no other option…
  - Typically, registers are 32-bits…
  - Each instruction also encoded in 32 bits

- **But**: Why 32??

- But why don't we have infinite number of registers
  - Well, every piece of register is a real hardware…

The choice depends on several factors, like the speed of the execution, the usage and size of memory, the size of code, the encoding and decoding of instructions….**It's not a random choice**…

Immediate Instructions…

- `b = a + 7`

```
addi $r0, $r1, 7
```

- We don't need a register for the constant…
  - Can you tell me why?? Just guess…

Immediate Instructions…

- `b = a + 7`

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addi $r0, $r1, 7
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- We don't need a register for the constant…
  - Can you tell me why?? Just guess…

- `i` stands for 'immediate'
- The constant is in **2's complement form and of 16 bits.**
- **Question: Do I need a `subi` instruction??**

Zero Is Very Special in Our Life…

- MIPS has a register which is called `$zero`
    - It stores 0
    - What is the purpose?
        - Well, a lot…you will see
    - A simple use of `$zero`

```
add $r1, $r0, $zero  // a = b
```

- But again, why???

Zero Is Very Special in Our Life…

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```
add $r1, $r0, $zero  // a = b
```

- But again, why??? — just not needed

a=b….The Pseudo-Instructions

- You can still write…

```
move $r1, $r0  // a = b
```

- But it is a pseudo-instruction
- Internally it converts to `add`
- Once again an engineering choice
- There are many such pseudo-instructions. See:

https://en.wikibooks.org/wiki/MIPS_Assembly/Pseudoinstructions

Logical Instructions

- Your good old Boolean algebra

sll, srl, and, or, nor, andi, ori etc

No not instruction ☺, well not is nor with one operand=0

- Remember: **These are bitwise operations…**
  - **Treats the operands as bit strings instead of numbers**

Logical Instructions

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- Remember: **These are bitwise operations…**
  - **Treats the operands as bit strings instead of numbers**

Critical Thinking…

- We have seen that constants are 16 bits…
- But registers are 32-bits…
- How to store a 32-bit constant in a register???
  - Let’s say the constant is:
    - 11110000000000001111111111111111
    - In Hex: 0xF000FFFF
- **Info**: You have the following new instruction:
  - `lui $r0, const // loads cosnt in the upper 16 bits of the register $r0`

Critical Thinking…

- Think, how the data will be represented inside your register…

1111000000000000	1111111111111111

MSB LSB

- Initially The register `$r0` is at (simplifying assumption…does not matter)

0000000000000000	0000000000000000

MSB LSB

- Now do: `lui $r0, 0xF000`

1111000000000000	0000000000000000

MSB LSB

- **Now do,** `addi $r0, 0xFFFF`

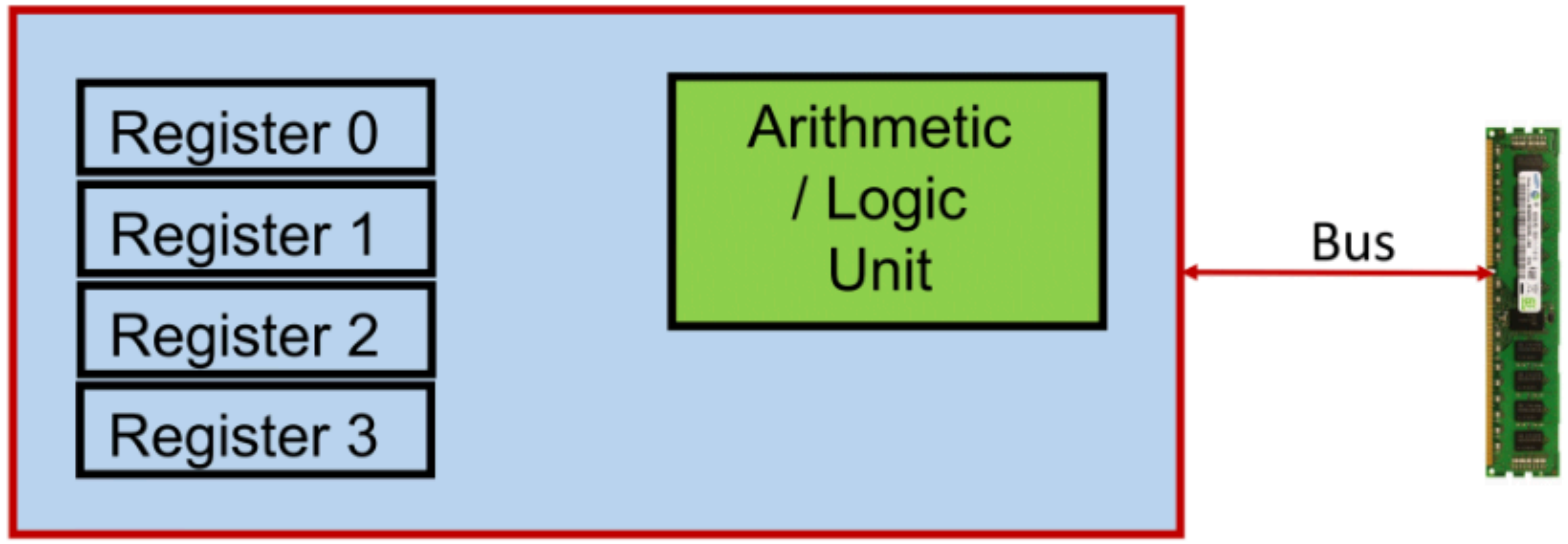
- You can also do `ori`

1111000000000000	1111111111111111

MSB LSB

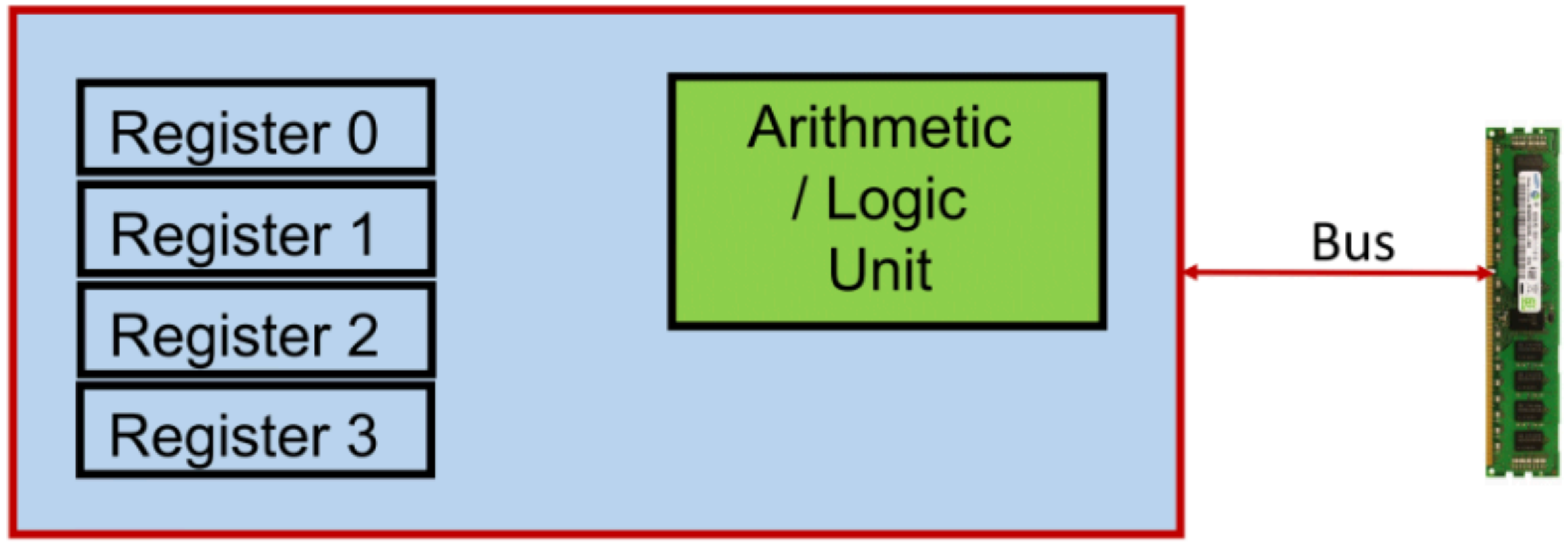
How to Use Your Memory??

- Recall, that MIPS only have 32 registers.
- Have you ever cared about counts while declaring variables in your program? — No way…
- Then how things work?
    - How can every program fits itself in 32 registers?



How to Use Your Memory??

- **Solution**:
  - Just store things in an external memory
  - Fetch the data to registers whenever it is required
  - Store the results after processing.
  - But still something is missing here…What is that??



How to Use Your Memory??

- Name this person?

How to Use Your Memory??

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  - John Luis von Neumann

How to Use Your Memory??

- In the old days, "programming" involved actually changing a machine's physical configuration:
  - by flipping switches or connecting wires.
  - Memory only stored data that was being operated on.
- Then around 1944, **John von Neumann and others got the idea to encode instructions in a format that could be stored in memory just like data. — Stored program paradigm**
  - The processor interprets and executes instructions from memory

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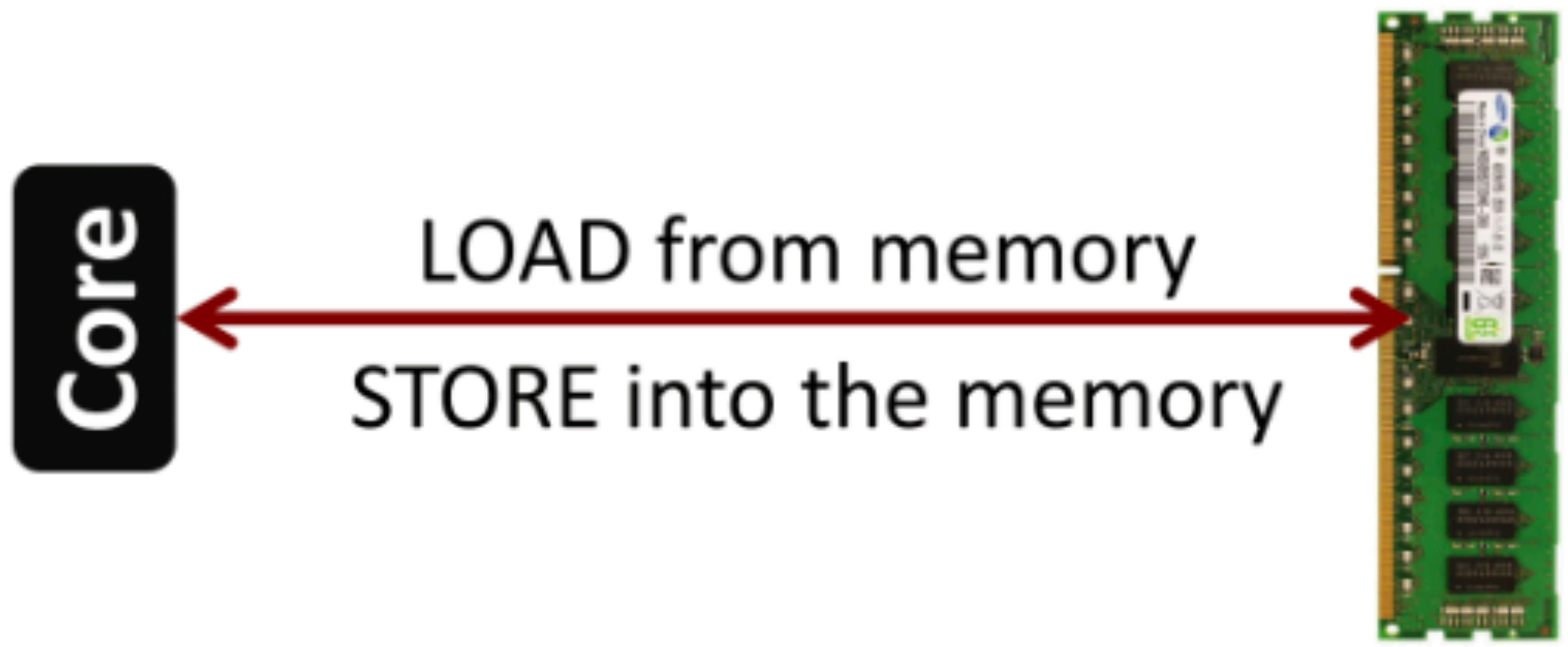
Memory Instructions

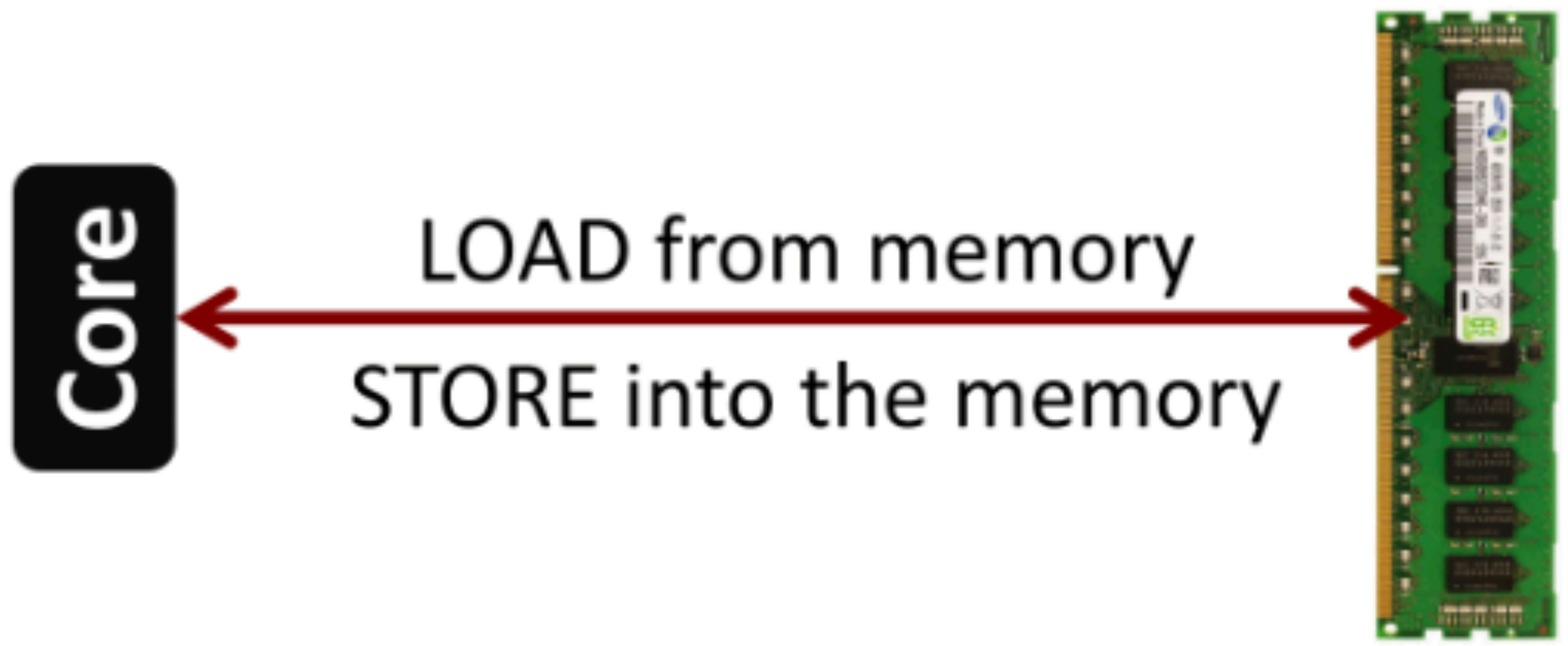
- **Load-Store Architecture**:
  - Load your data to process
  - Store it back…
- Instructions are handled in a slightly different manner….will come to that…




```
lw $t0, 1($a0)     # $t0 = Memory[$a0 + 1]
sw $t0, 1($a0)     # Memory[$a0 + 1] = $t0
```

Memory Instructions

- **Load-Store Architecture**:
  - Load your data to process
  - Store it back…
- Instructions are handled in a slightly different manner….will come to that…
- But, a critical question:
  - How do you know where to find the data inside memory?

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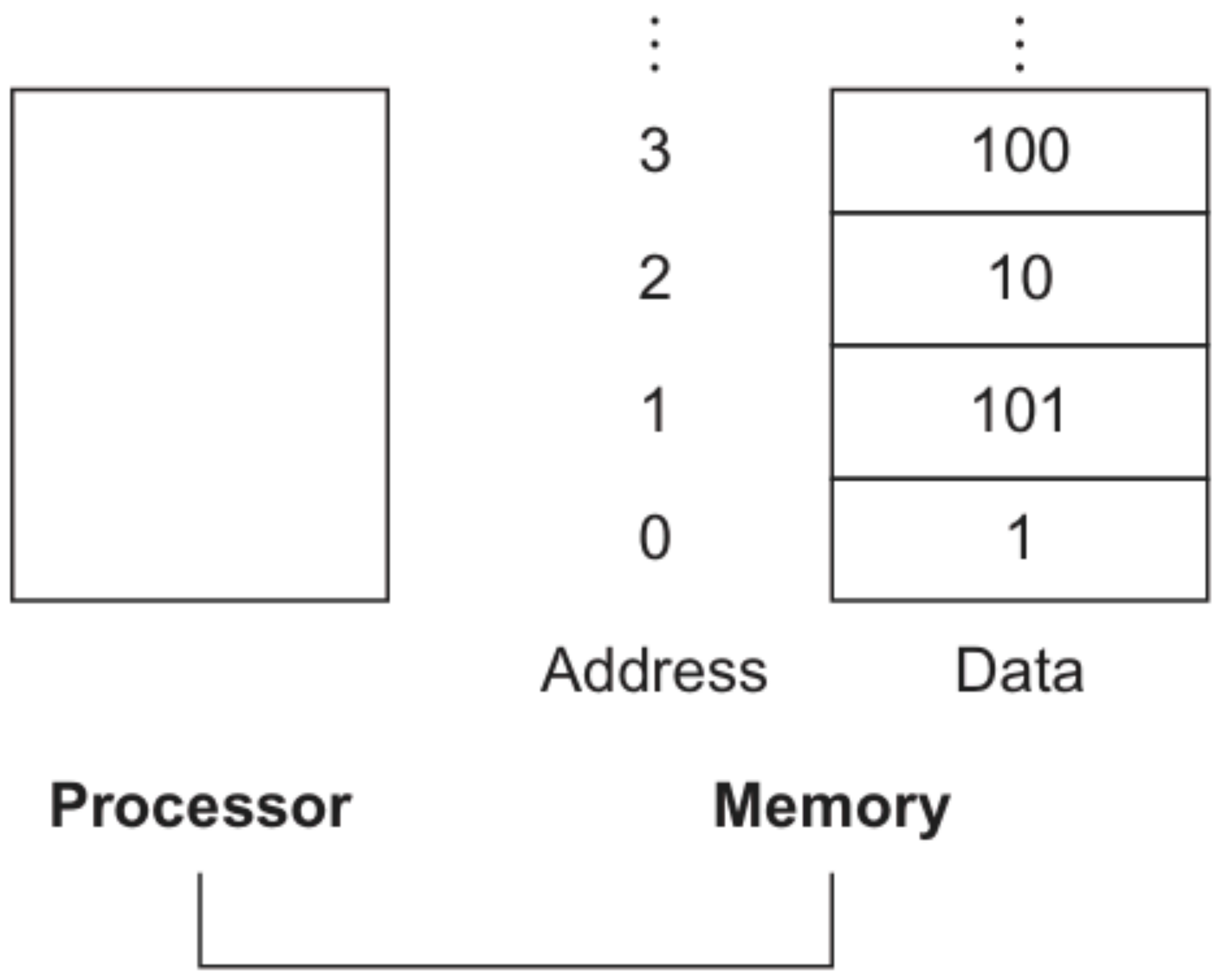
Memory Instructions

- But, a critical question:
  - How do you know where to find the data inside memory?
    - Memory has addresses
    - Think it like a large contiguous array…
    - **Every byte in memory has an unique address**
      - **Byte-addressable**
  - **BTW, each address is 32-bit in MIPS**



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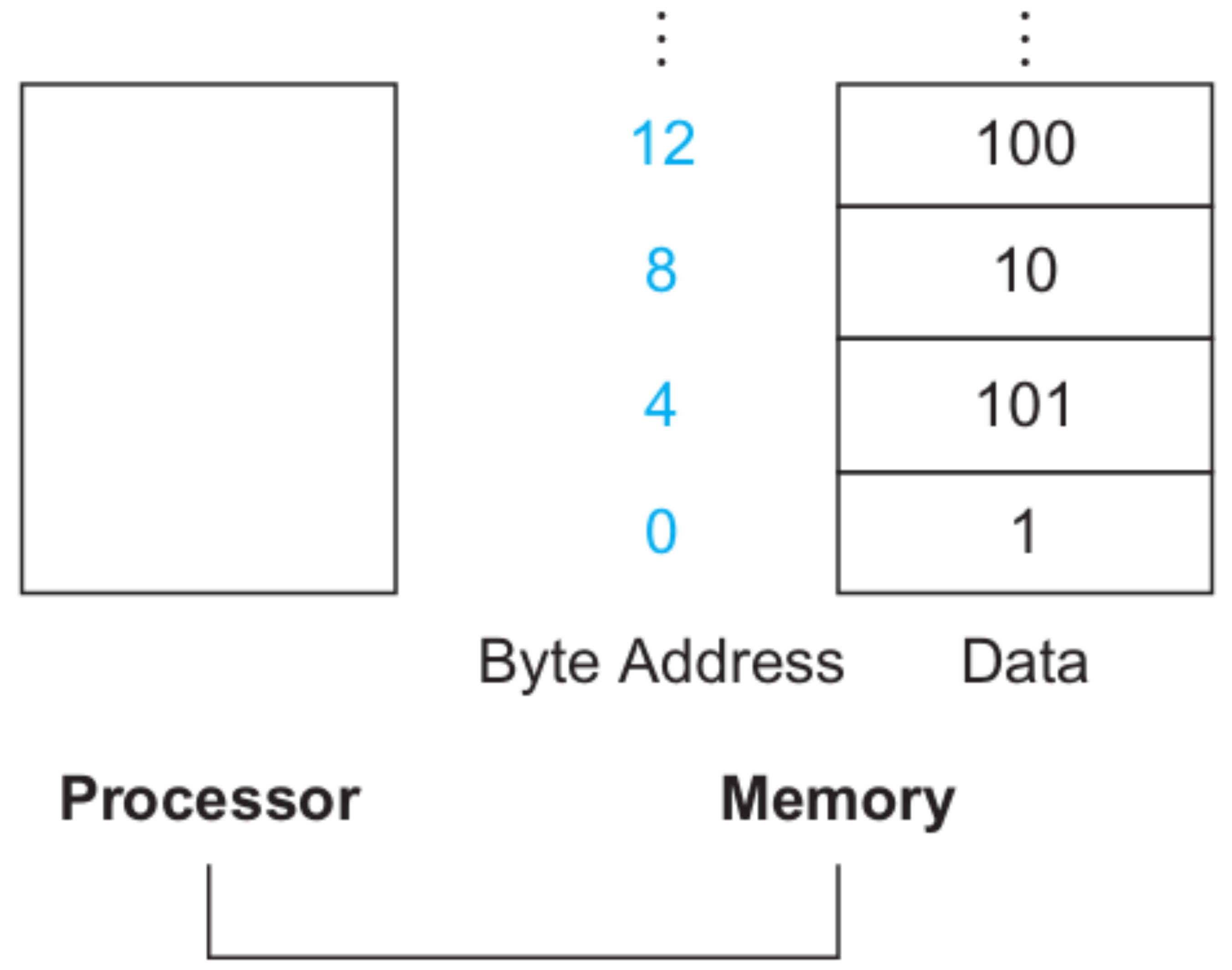

- The `lw` is interpreted as "load word"
  - MIPS also have other variants like "load byte" (`lb`)
- Data comes in `$t0`.
- But what is the 1(`$a0`) part signify?
  - `$a0` is the *base address* of the location you want to read from memory
  - 1 is called the *offset*.
- But why don't you read directly?

Memory Instructions

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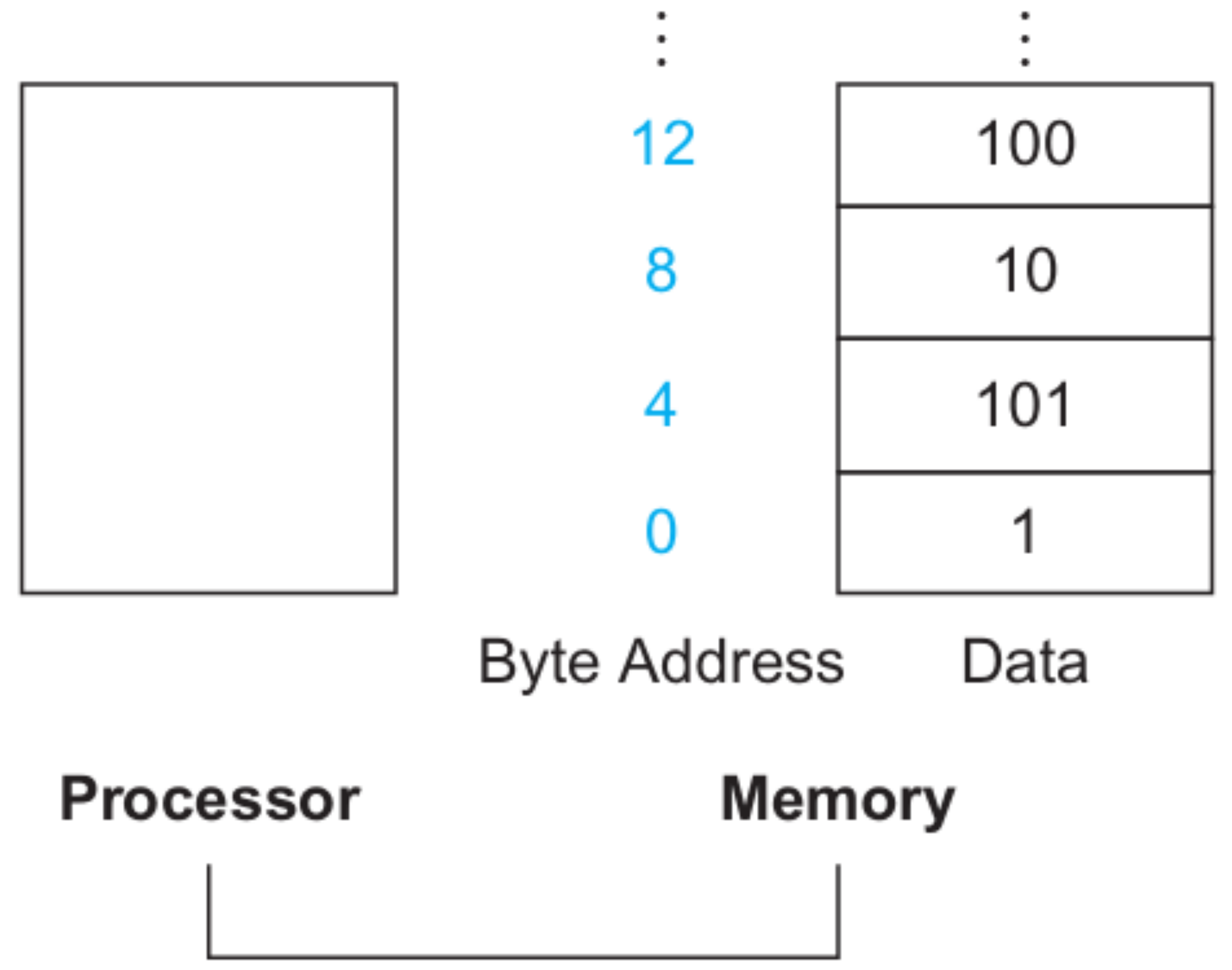
- But why don't you read directly?
  - Again a design choice, to ease compilation, programming, and hardware design…

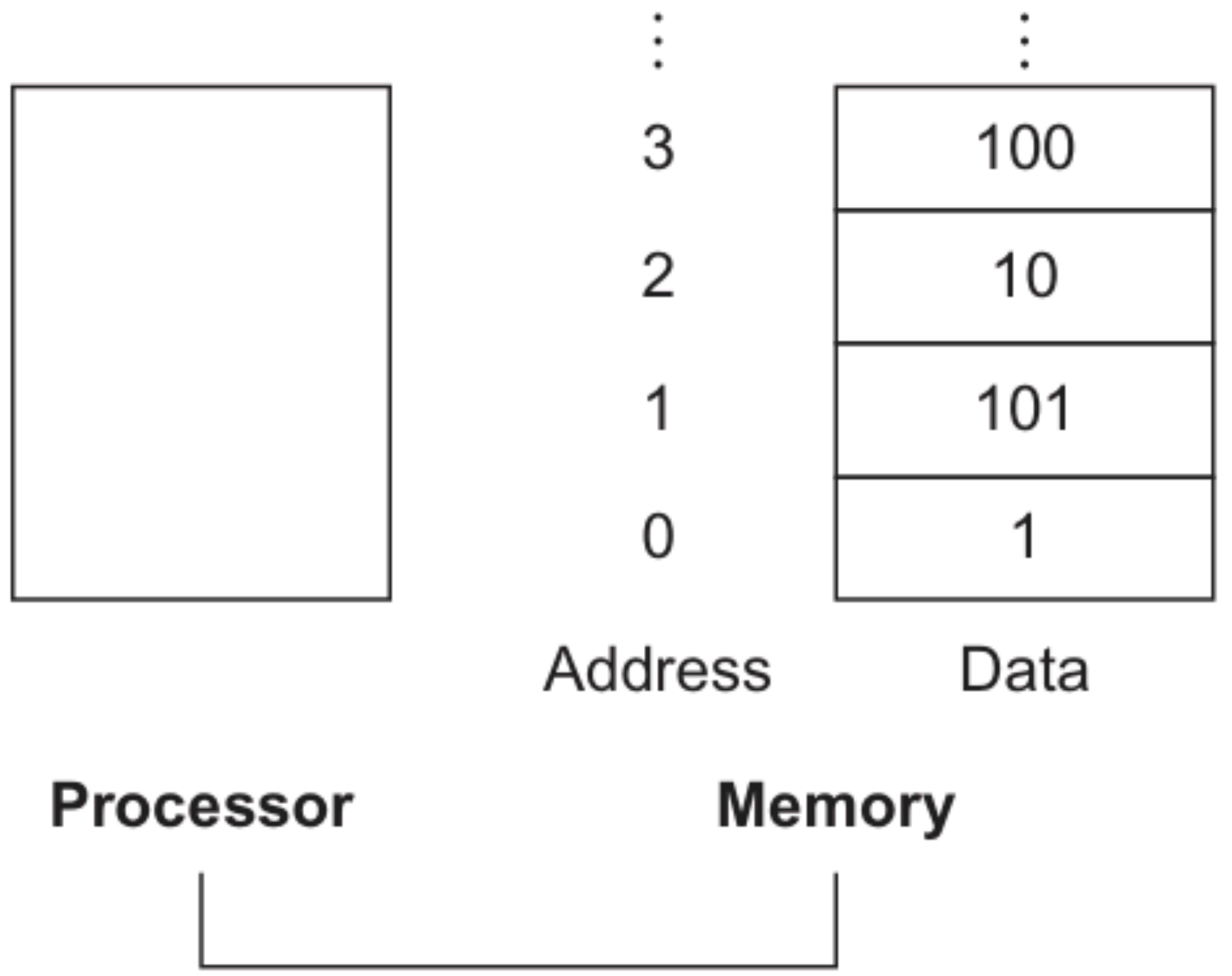


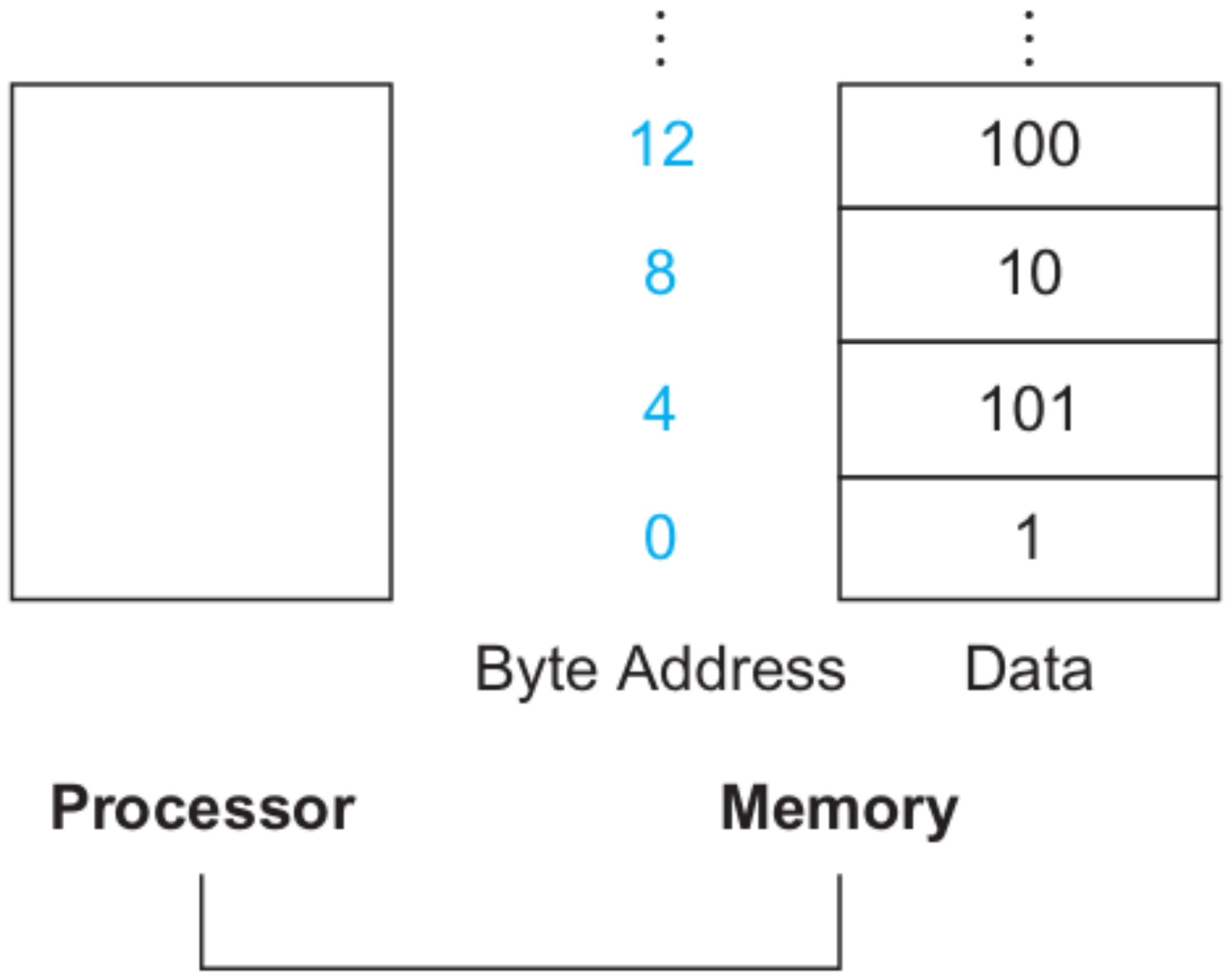
Memory Instructions: Word vs. Byte

```
lw $t0, 1($s0)          lb $t0, 1($s0)
```

- `lw` is interpreted as "load word"
- `lb` is "load byte"
- For the lw, we need the base+offset ($s0 + 1) to be **always divisible by 4 — word alignment**
- Why?
- Nothing such for lb

- **What Lies Beneath?**
  - `lb` just read the byte in the calculated address
  - `lw` reads four consecutive bytes starting from the calculated address.
- Why word alignment — again, it simplifies hardware OS, compiler….





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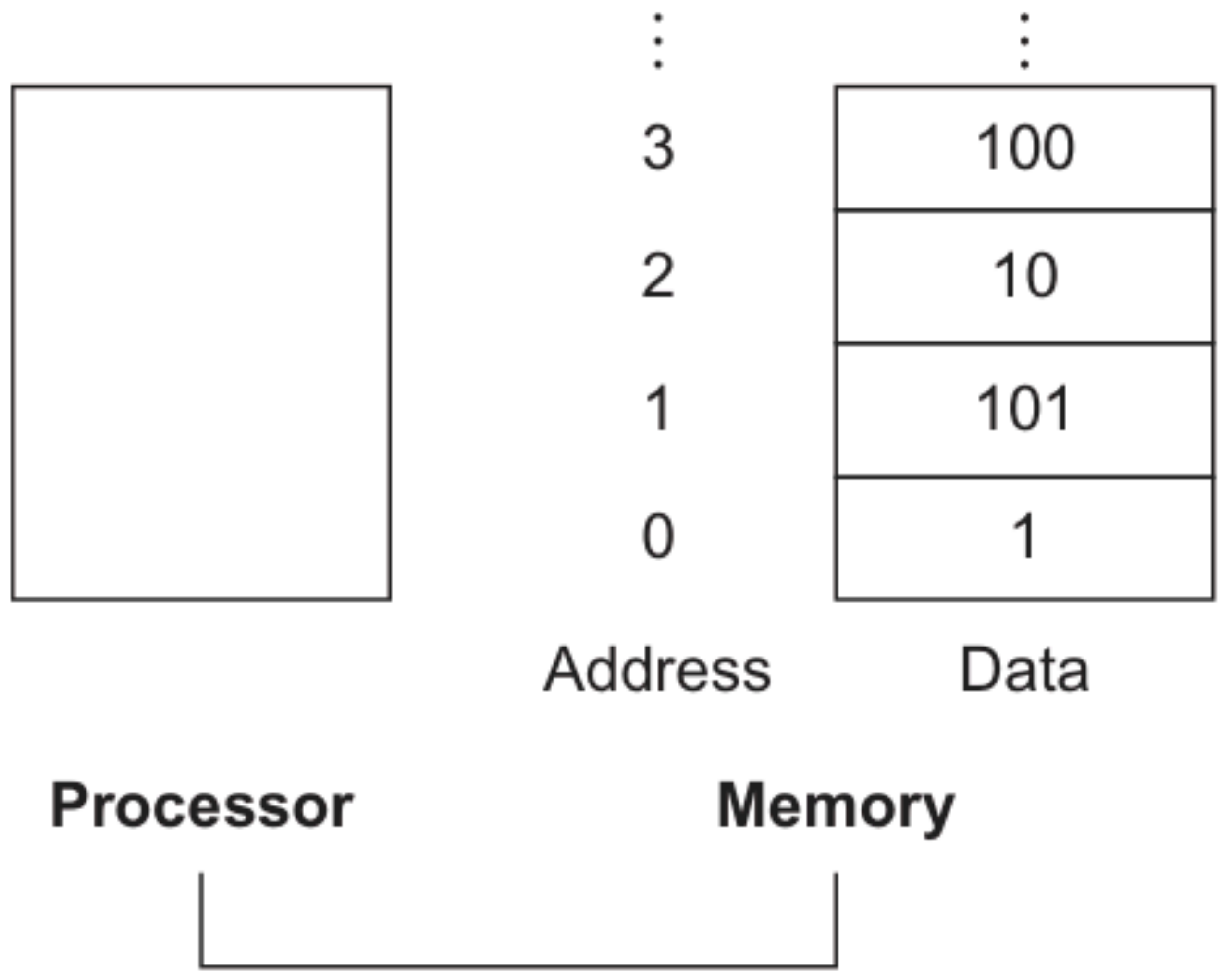
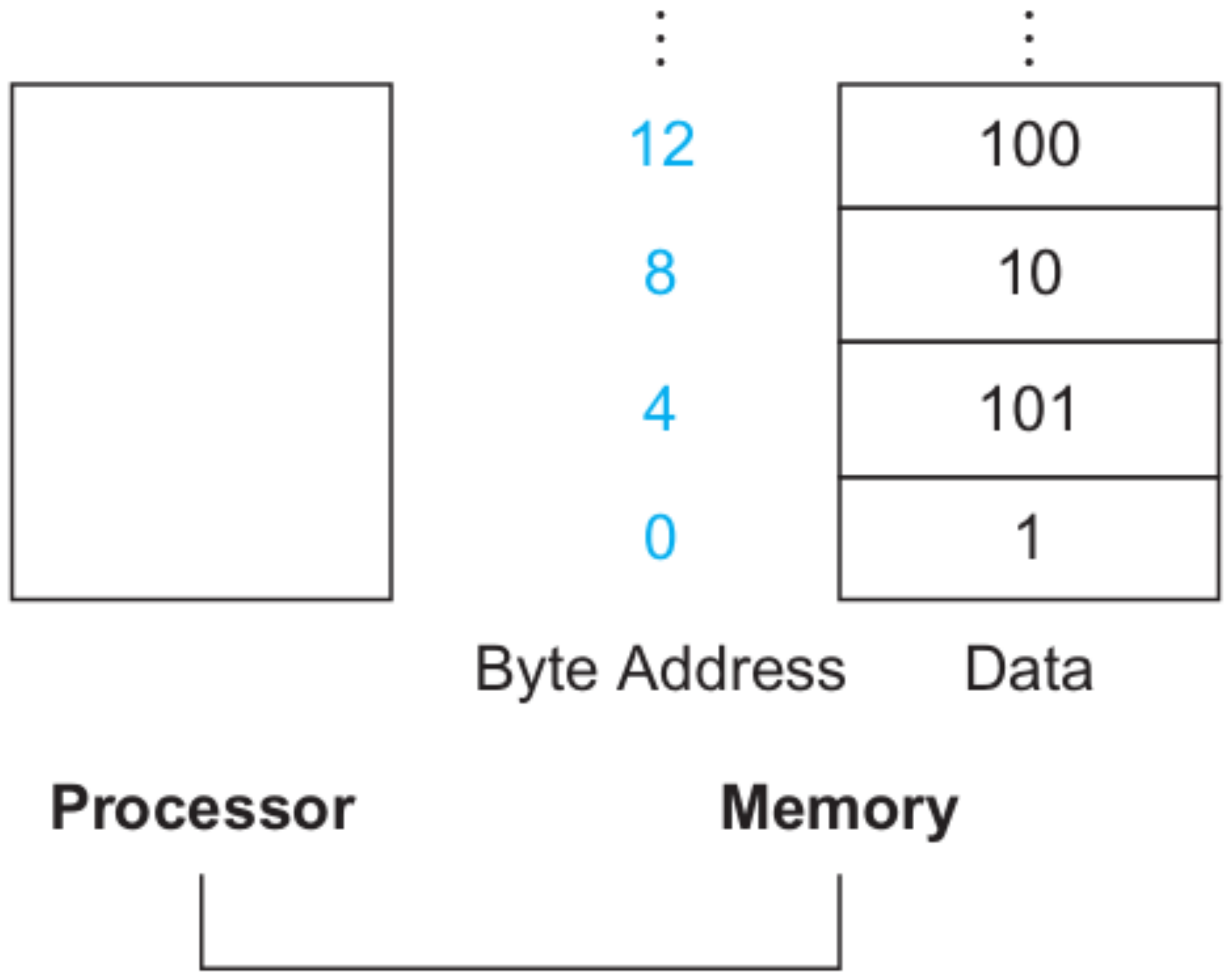
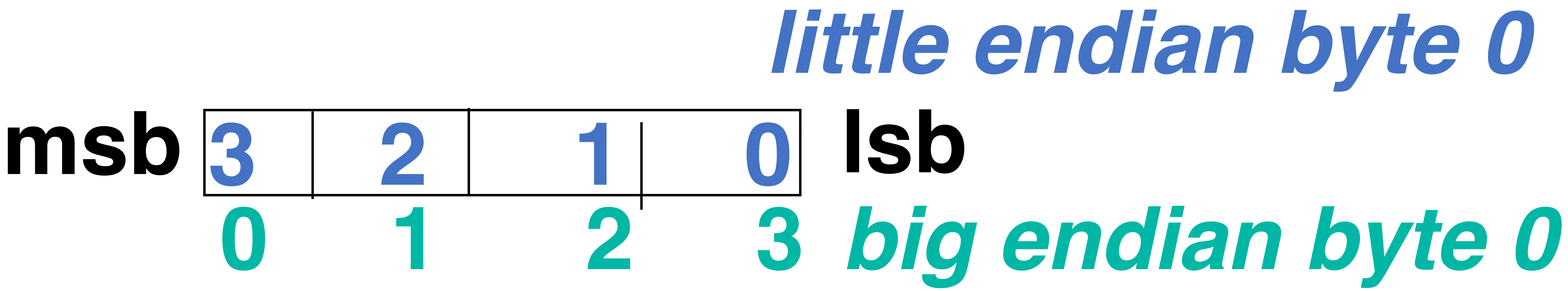




Endianness (Byte ordering within a word)

- Big Endian: address of most significant byte = word address (xx00 = Big end of word), MIPS

- Little Endian: address of least significant byte = word address (xx00 = Little end of word), x86



Just for an example, do not take it for granted …

```
unsigned int i = 1;
char *c = (char*)&i;  // reading the LSB
Printf (“%d”, *c);
```

```
unsigned int i = 12345678;
char *c = (char*)&i;
Printf (“%d”, *c);
```

```
unsigned int i = 1;
char *c = (char*)&i;  // reading the LSB
Printf (“%d”, *c);
```

Little endian: 1

Big endian: 0

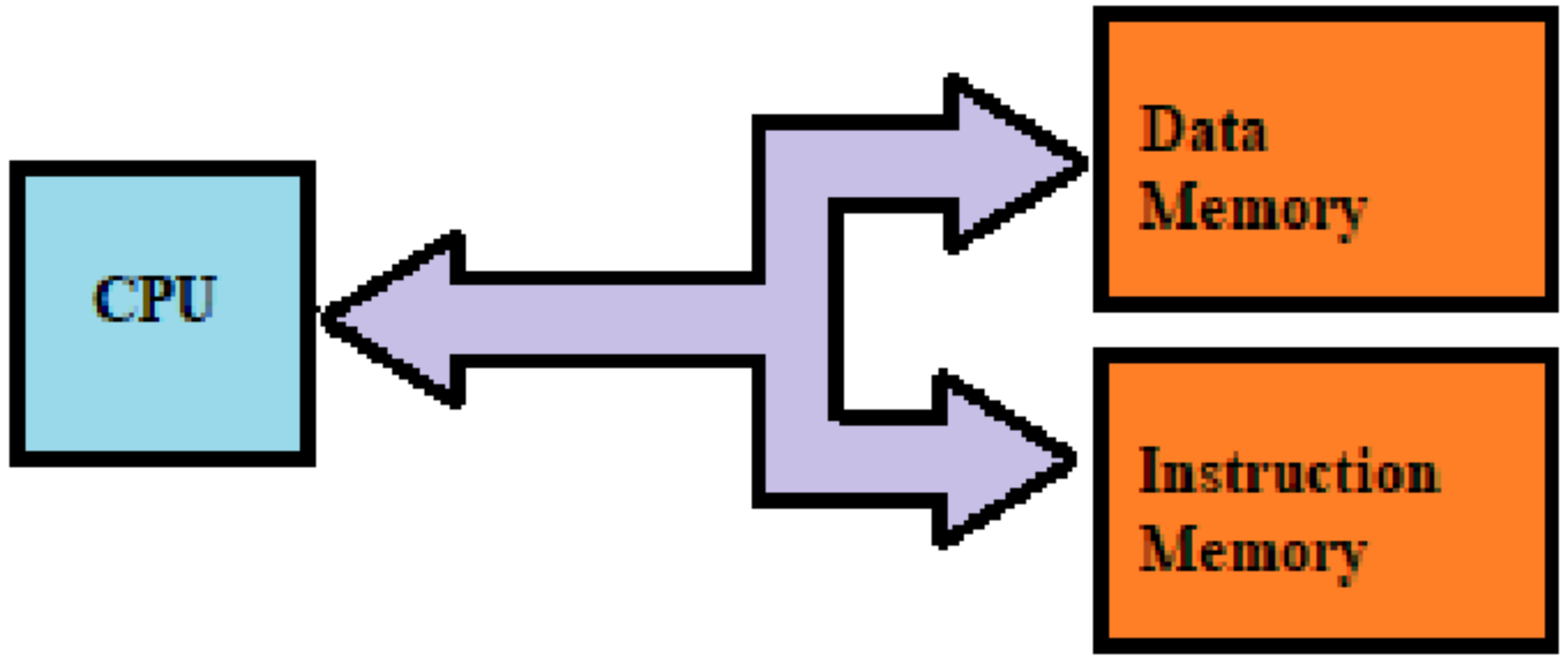
```
unsigned int i = 12345678;
char *c = (char*)&i;
Printf (“%d”, *c);
```

Little endian: 78

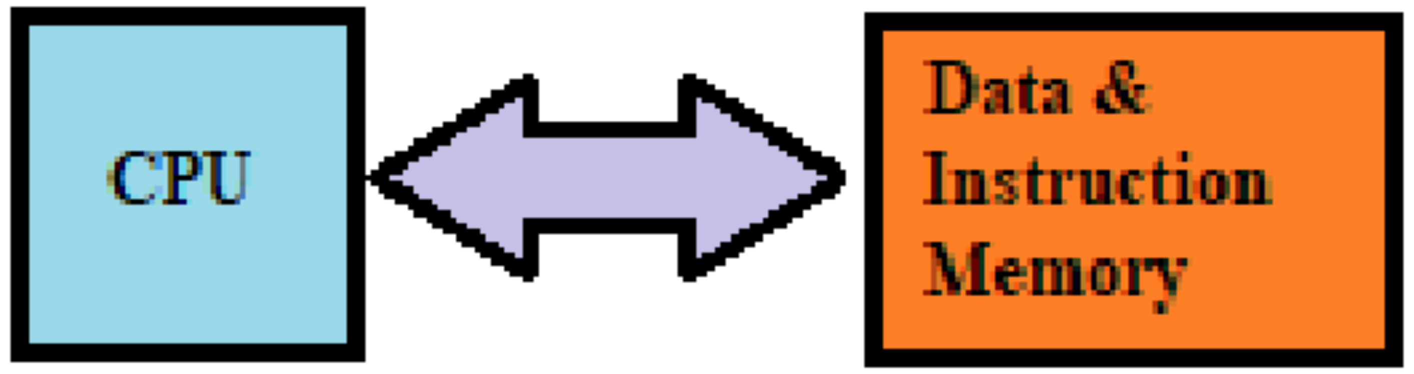
Big endian: 12

Another Important Point…

- Ok, **Von Neumann** said, data and code both are stored in the same memory.
  - In practice, this may lead to an issue — at a specific interval of time, **you can either fetch a data or an instruction**.
    - Affects parallelisation
- **What if you separate the data and instruction memory and buses?**
  - That is called **Harvard Architecture.**
  - Modern commercial systems use a combination of both
    - RAM stores both instruction and data
    - But there are other intermediate memory (**caches**) which are separated for instruction and data



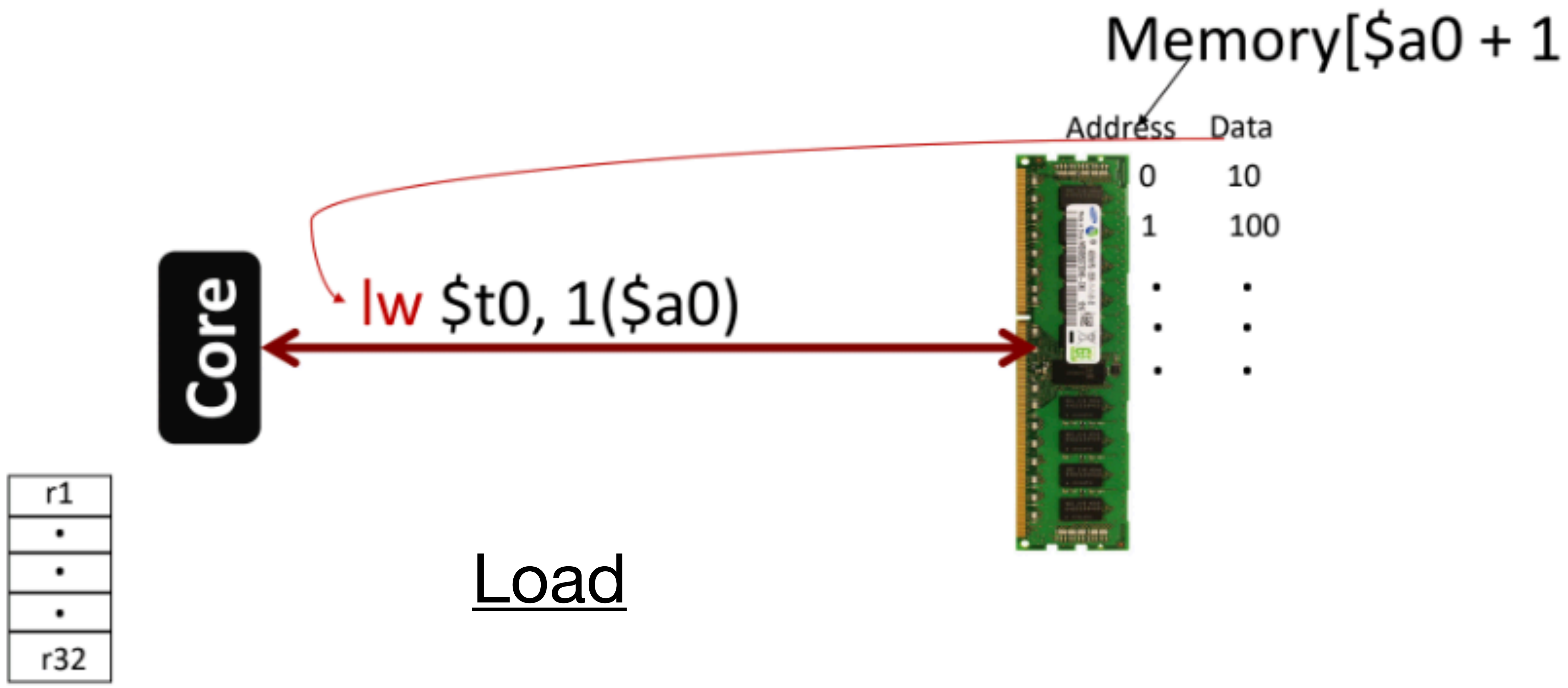
a)



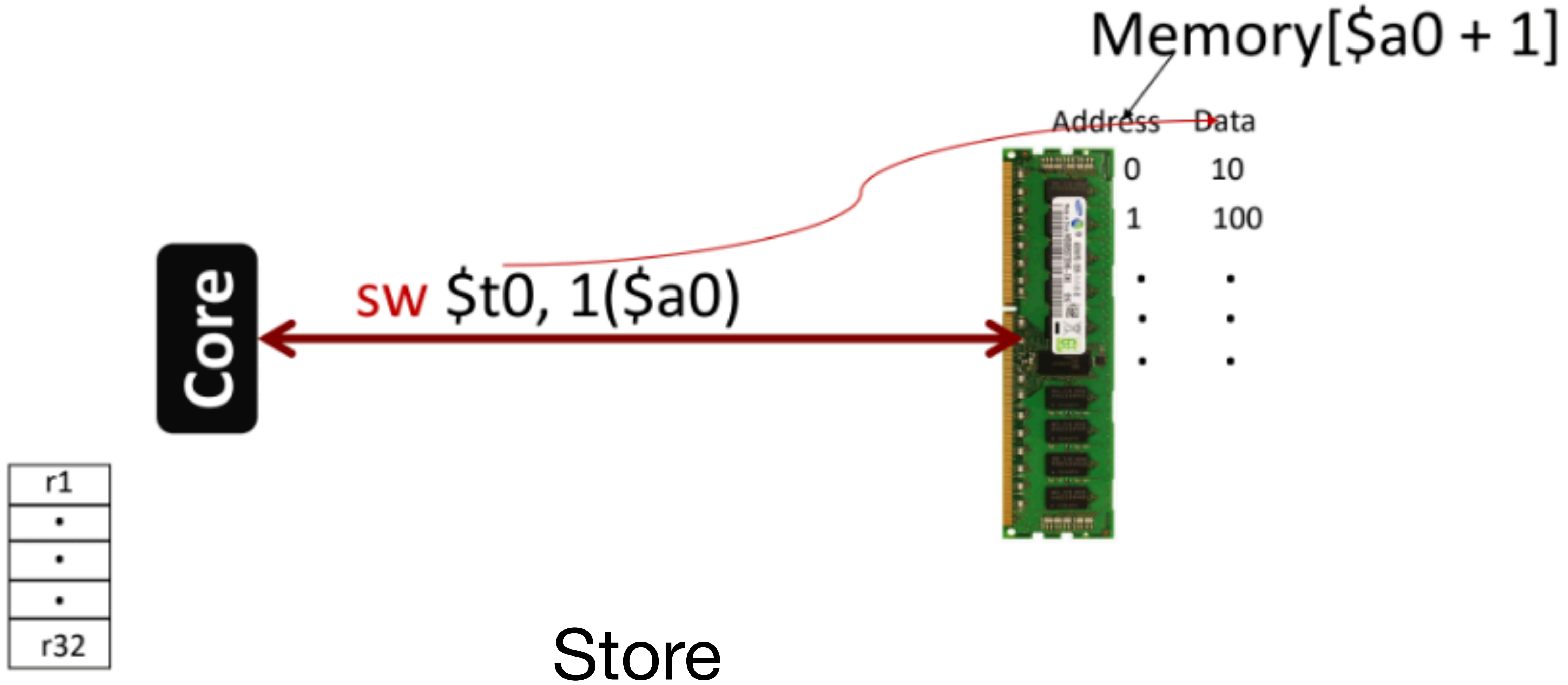
b)

Source: Internet

Load, Store Cheatsheet



Load



Store

Program Counter

Points to the next instruction in the memory to be fetched

g = h + A [8];

PCX: lw $t0, 8($3) # A[8]
PCY: add $s1, $s2, $t0 # g = h + t0

PCY = PCX+4

Load+Store+Instruction-fetch

Summary…

- Data and instructions at the same place
- Registers are limited — 32 bit wide
- Instructions are 32 bit wide
- Registers are accessed by names
- Memory is accessed by addresses

Decision Making…

- If, else statements in your program…
  - How they are interpreted as instructions??

beq (branch equals to) and
bne (branch not equals to)

beq $t0, $t1, L1
bne $t0, $t1, L1

Decision Making…

beq $t0, $t1, L1

goto L1 (statements labeled as L1) if $t0 equals $t1

bne $t0, $t1, L1

goto L1 (statements labeled as L1) if $t0 does not equal to $t1

Simple Example…

- Let's compile:
  - `if (i == j) f = g + h; else f = g - h;`

Assume:

`$s0` has `i`, `$s1` has `j`, `$s2` has `g`, `$s3` has `h`, `$s4` has `f`

Unconditional Jump

jumps to a specific label

```
     beq $s0, $s1, if_equal     # if i == j, jump to if_equal
     sub $s4, $s2, $s3          # else: f = g - h
     j end_if                   # jump to end
if_equal:
     add $s4, $s2, $s3          # f = g + h
end_if:
```

Decision Making…

- So you can check conditions:
  - `If (x = 0)..`
  - `If (x != 0)..`
  - `If (x = y)..`
  - `If (x != y)…`
- But how about the following code??

```
if (a < b)

  c=1
else
  c=0
```

Decision Making…

```
if (a < b)

  c=1
else
  c=0
```

- Set on less than (`slt`)
  - `slt     $t0, $s3, $s4    # $t0 = 1 if $s3 < $s4`

    `slti    $t0,$s2,10       # $t0 = 1 if $s2 < 10`

- After using `slt`, we can use the `beq` or `bne`

Simple Example…

- Let's compile:
  - `if (i < j) f = g + h; else f = g - h;`

Assume:

`$s0` has `i`, `$s1` has `j`, `$s2` has `g`, `$s3` has `h`, `$s4` has `f`

```
    slt $t0, $s0, $s1         # $t0 = 1 if i < j
    beq $t0, $zero, ELSE      # if $t0 == 0, i >= j, jump to ELSE
    add $s4, $s2, $s3         # f = g + h
    j END_IF                  # jump to END_IF
ELSE:
    sub $s4, $s2, $s3         # f = g - h
END_IF:
```

Dealing With Loops

- Let's first see how we deal with **arrays**…
  - `f = h + A[8]`

Assume:

- `$t0` has `A[8]`, `$s5` has base address of the array A, `$s4` has `f`, `$s3` has `h`
- Also assume "`A[8]`" as `uint8_t` (a byte)

```
lbu $t0, 8($s5)            # Load word A[8] with byte offset
add $s4, $s3, $t0          # f = h + A[8]
```

- But what is "`A[8]`" is `int (4 bytes)?????`

```
lw $t0, 32($s5)            # Load A[8], 8 * 4 = 32 (word)offset
add $s4, $s3, $t0          # f = h + A[8]
```

Dealing With Loops

- Let’s consider:
  - `while (A[i] > k) i = i+1;`

Performs left logical shift by two bits..why??

<u>Assume:</u>

`$s0` has `i,`

`$t1` has address of `A[i]`

`$t2` has `A[i]`

`$s6` has `k`

```
LOOP:
 sll $t1, $s0, 2                # $s0 = i, i*4 for word offset
 add $t1, $s5, $t1              # Compute address A[i]
 lw $t2, 0($t1)                 # Load A[i] (integer)
 slt $t3, $t2, $s6              # $t3 = 1 if A[i] < k
 bne $t3, $zero, END_LOOP       # if A[i] < k, exit loop
 addi $s0, $s0, 1               # i = i + 1
 j LOOP
END_LOOP:
```

Dealing With Loops

- What happens if:
  - `while (A[i] == k) i = i+1;`

<u>Assume:</u>

`$s0` has `i`,

`$t1` has address of `A[i]`

`$t2` has `A[i]`

`$s6` has `k`

Dealing With Loops

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<u>Assume:</u>

`$s0` has `i`,

`$t1` has address of `A[i]`

`$t2` has `A[i]`

`$s6` has `k`

```
  LOOP:
    sll $t1, $s0, 2          # $s0 = i, i*4 for word offset
    add $t1, $s5, $t1        # Compute address A[i]
    lw $t2, 0($t1)           # Load A[i] (integer)
    bne $t2, $s6, END_LOOP   # if A[i] != k, exit loop
    addi $s0, $s0, 1         # i = i + 1
    j LOOP
END_LOOP:
```

More on Jumping…

- What happens if:
  - `while (A[i] == k) i = i+1;`

Assume:

`$s0` has `I,`

`$t1` has address of `A[i]`

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`$s6` has `k`

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- Normally:
  - PC, PC+4, PC+8,….
  - But jump instruction loads a new value to the PC
    - It’s the offset in the program where the exception should divert (the label is basically that)

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- Normally:
  - PC, PC+4, PC+8,….
  - But jump instruction loads a new value to the PC
    - It’s the offset in the program where the exception should divert (the label is basically that)
  - But jumping is even more exotic…Let’s see why

More on Jumping…

More on Jumping…Working with Functions

```
int sum(int a, int b)
{
     int c=a+b;
     return c;
}
void main (void)
{
     int i=1;
     int j=2;
     int k = sum(i,j);
    // …..
}
```

Function call jumps to a location in your code

- **Caller**: One who calls the function
- **Callee**: The function which is being called

- **Anatomy of a Function Call**:
  - Put parameters in a place where the function can access them.
  - Transfer control to the function.
  - Acquire the storage resources needed for the function.
  - Perform the desired task.
  - Put the result value in a place where the caller program can access it.
  - Return control to the point of origin, since a function can be called from several points in a program.

Working with Functions — The MIPS Case

- **<u>MIPS Support for Function Call</u>**:
  - `$a0–$a3`: four argument registers in which to pass parameters
  - `$v0–$v1`: two value registers in which to return values
  - `$ra`: one **return address** register to return to the point of origin

- **<u>Ways of Jumping..</u>**:
  - `jal Label`: Jump and link
  - `jr $ra`: Jump back to the return address stored in `$ra`

Working with Functions — The MIPS Case

- **<u>Ways of Jumping..</u>**:
  - `jal Label`:
    - First, save `PC+4` in `$ra`
    - The instruction to be executed next is at `Label`
  - `jr $ra`: Jump back to the return address stored in `$ra` `(PC + 4)`

Working with Functions — The MIPS Case

Complete Picture

```
int sum(int a)
{
    int c=a+4;
    return c;
}
void main (void)
{
    int i=2;
    int k = sum(i);
}
```

```
sum:
 PC+100: addi $v0, $a0, 4      # c = a + 4, return in $v0
 PC+104: jr $ra                # return to PC+12

main:
 PC+4:   li $a0, 2             # i = 2
 PC+8:   jal sum               # call sum(i); $ra = PC+12
 PC+12:  addi $s1, $v0, 0      # k = return value (k = 6)
```