Digital Logic Design + Computer Architecture

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Instruction Set Architecture

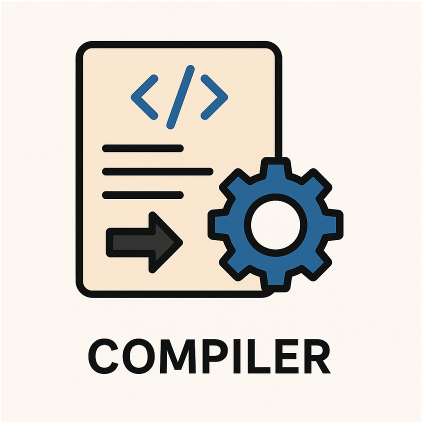
How to talk to a Computer?

- **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…

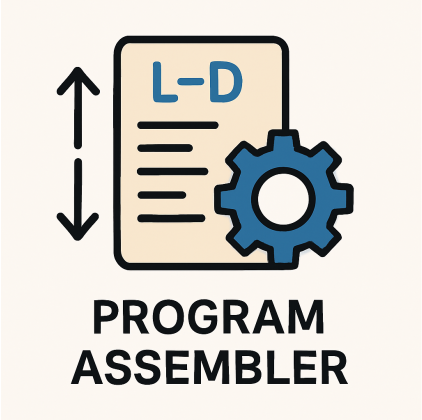
Image generated by ChatGPT

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

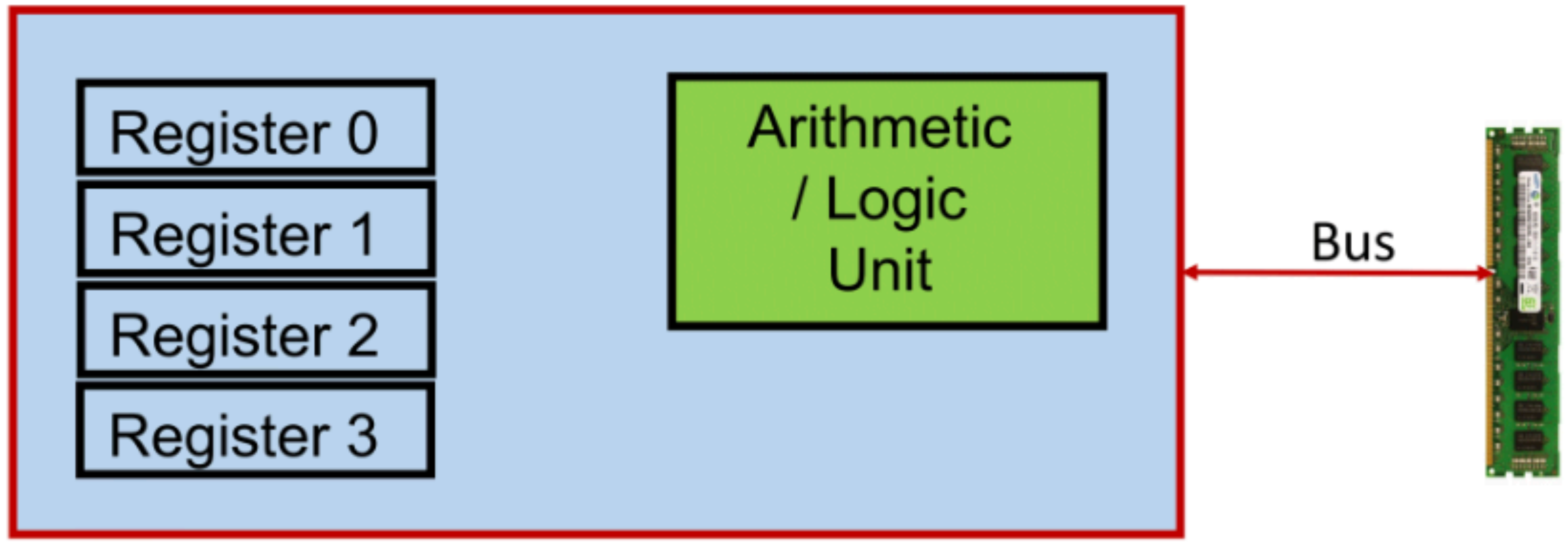
How to talk to a Computer?

- **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.**

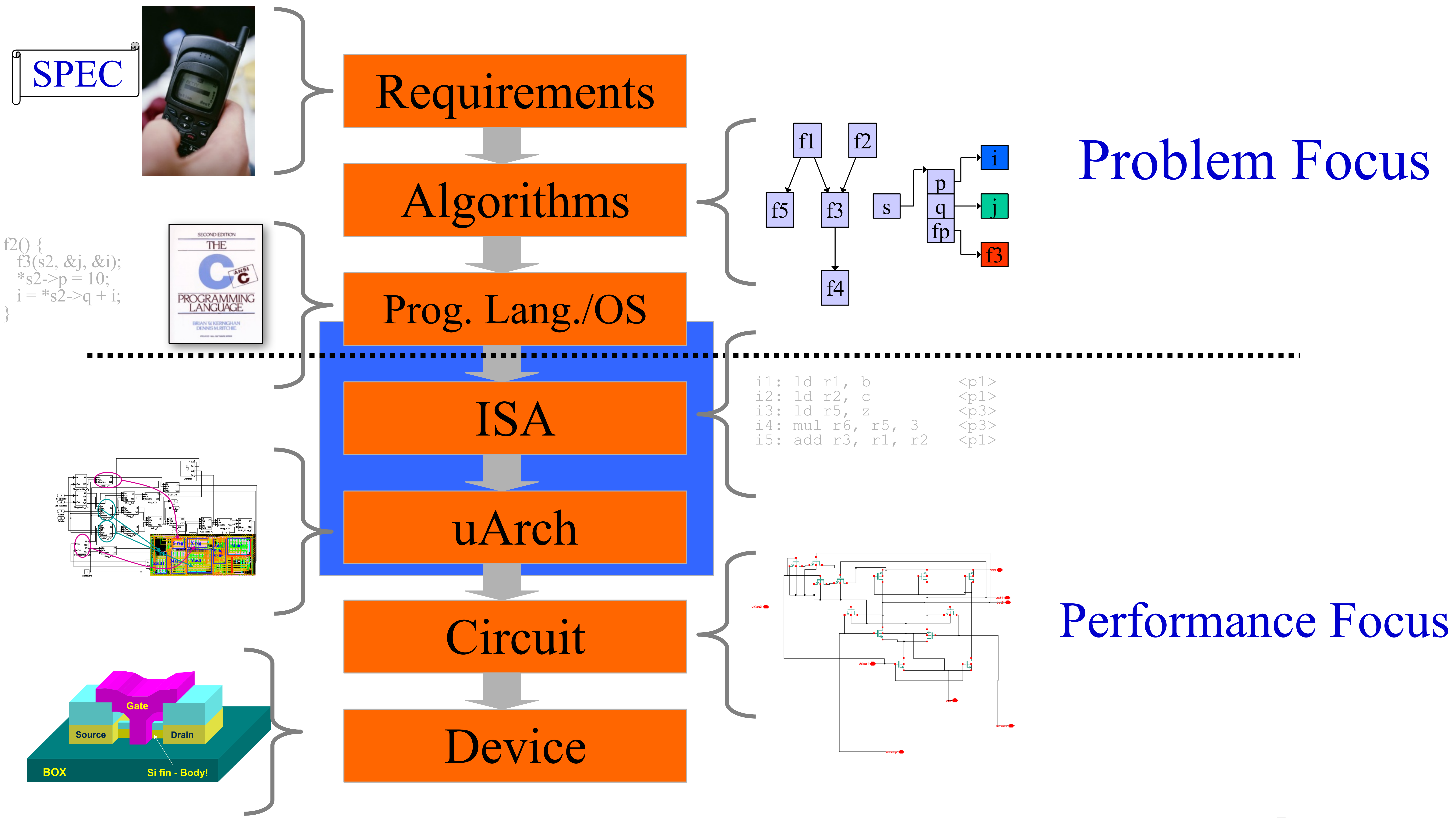
Image generated by ChatGPT

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**

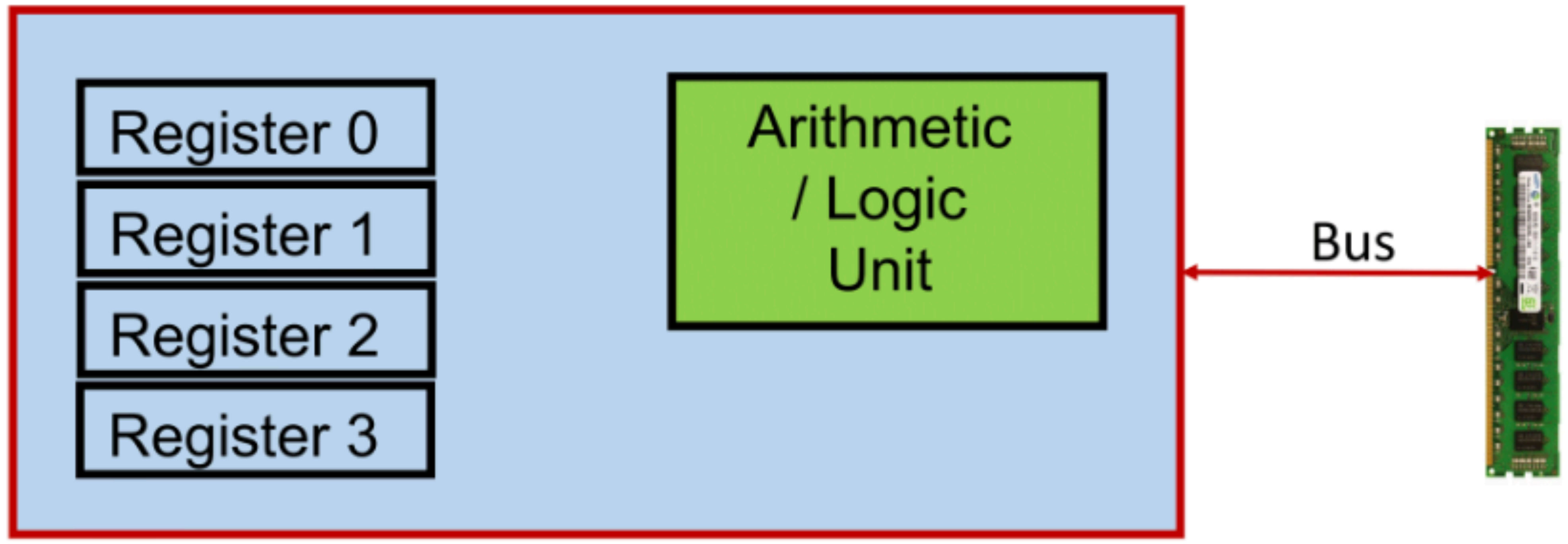


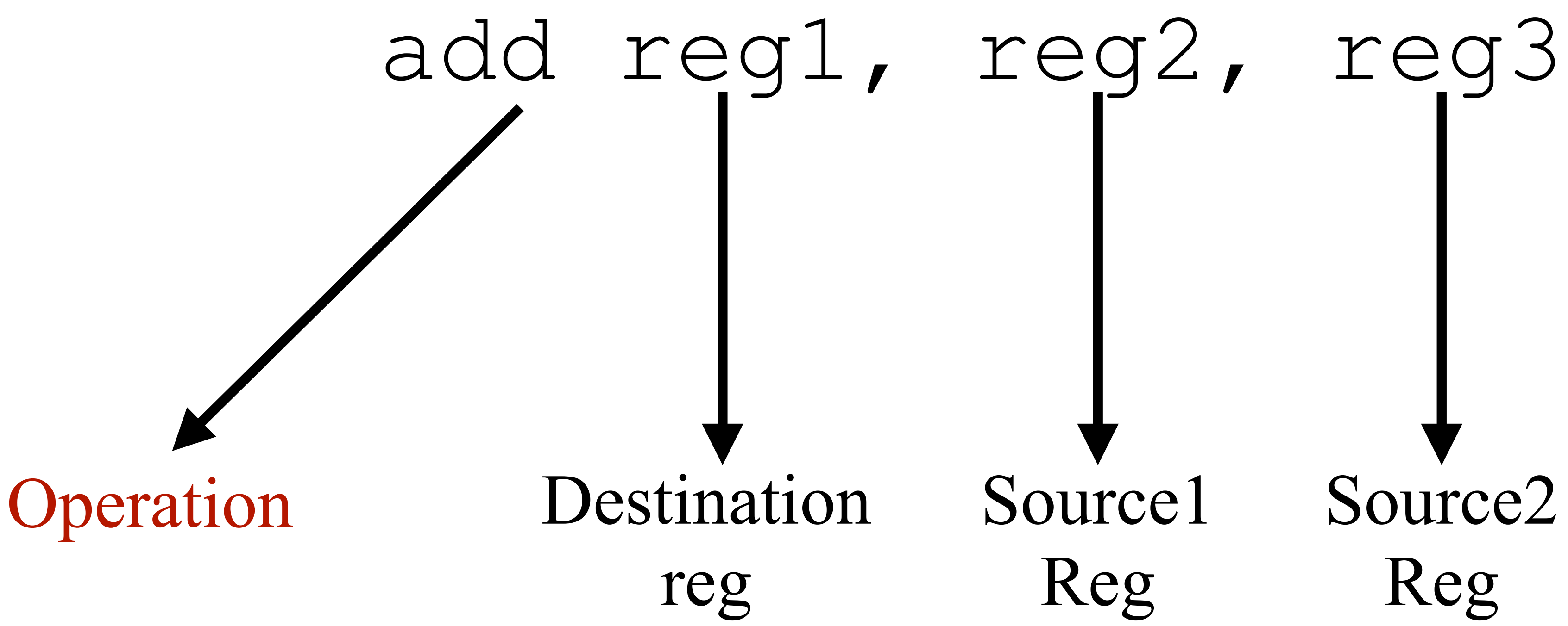
The Big Picture



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
```

- 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: <u>Do I need a `subi` instruction??</u>**

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???

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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`

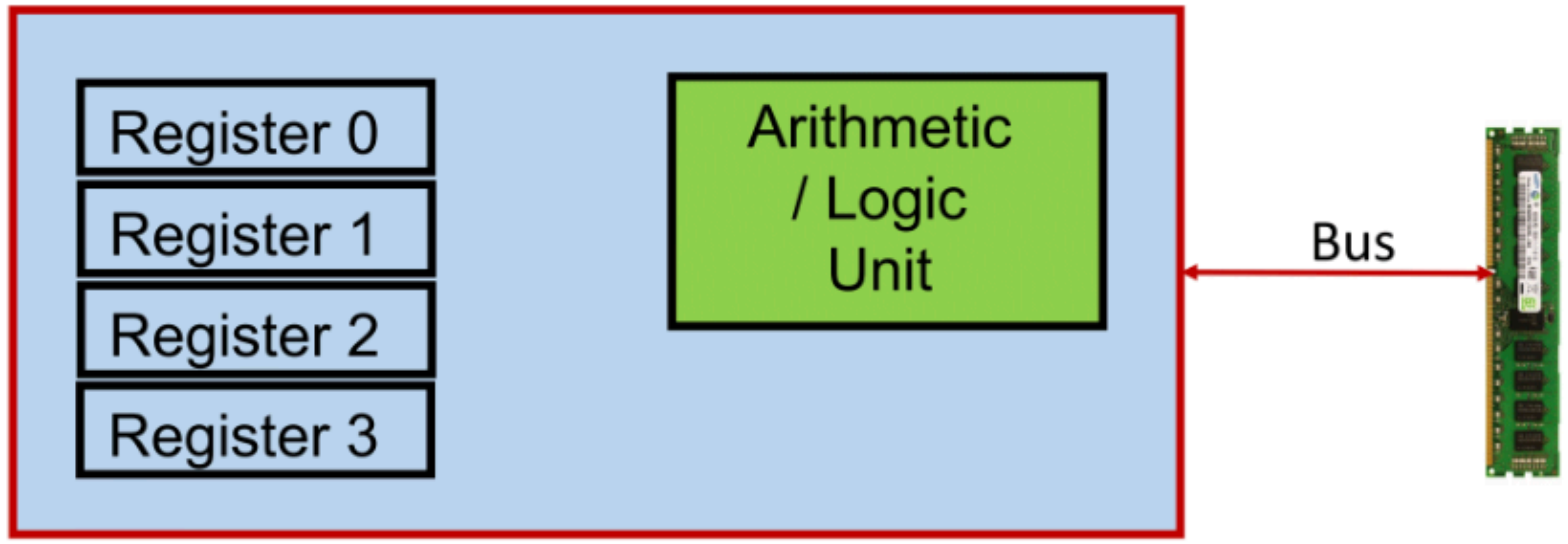
1111000000000000	1111111111111111

MSB LSB

- You can also do `ori`

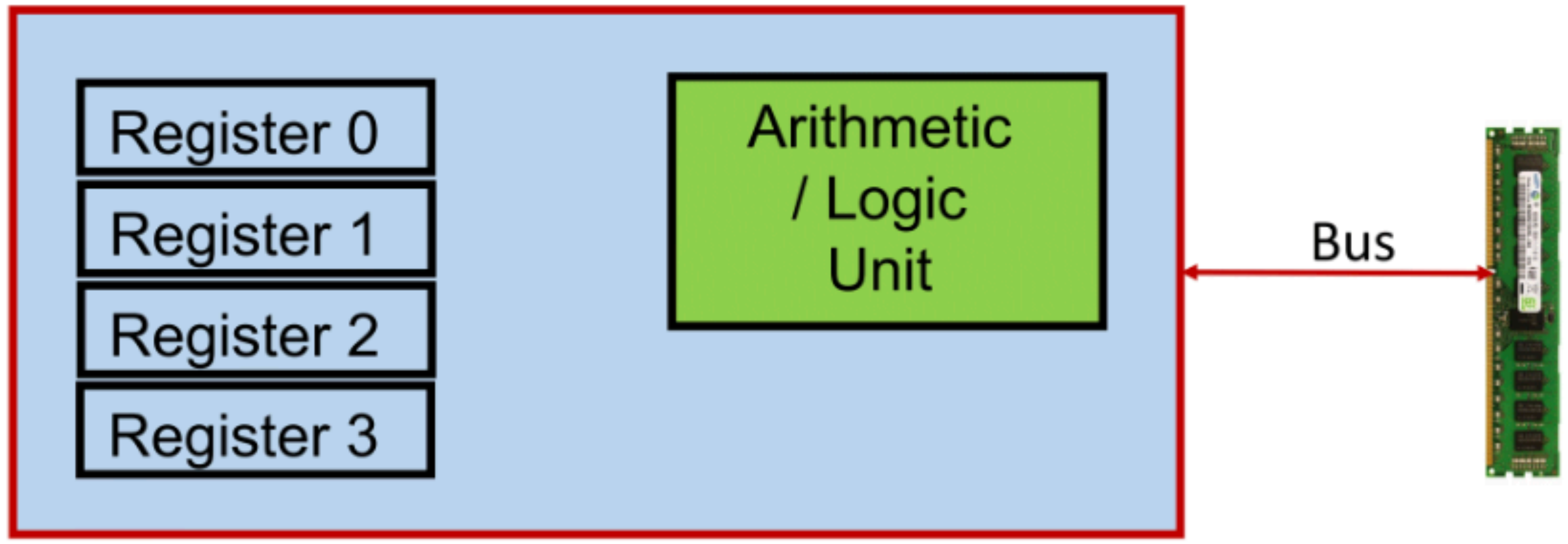
How to Use Your Memory??

- 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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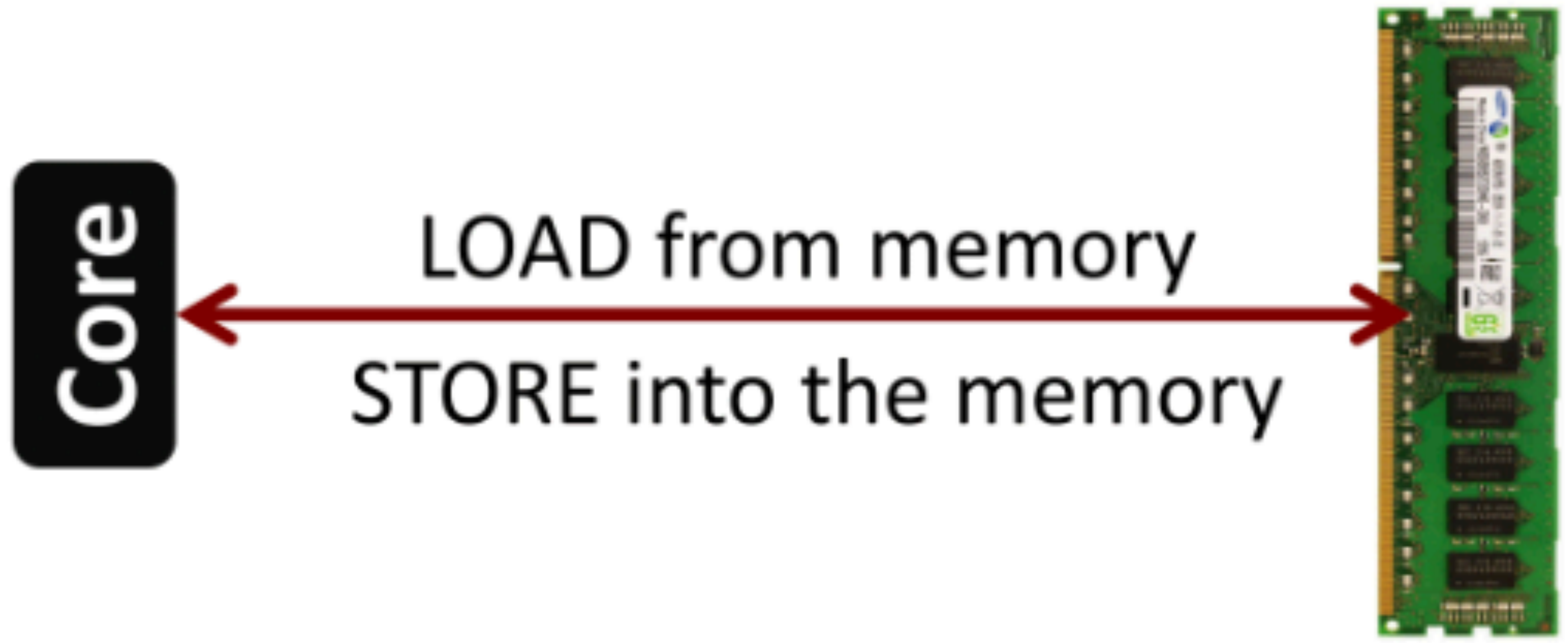
Memory Instructions

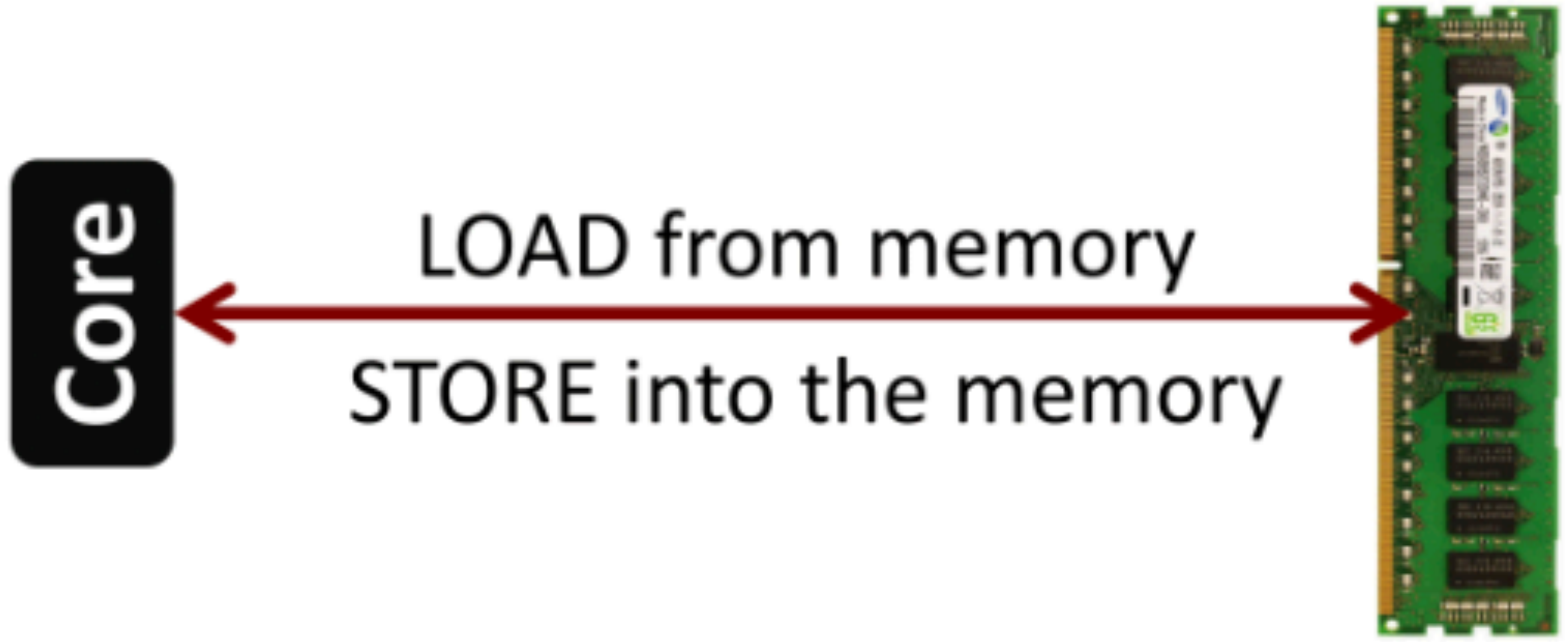
- **Load-Store Architecture**:
  - Load your data to process
  - Store it back…
- Instructions are handled in a slightly different manner….will come to that…




```
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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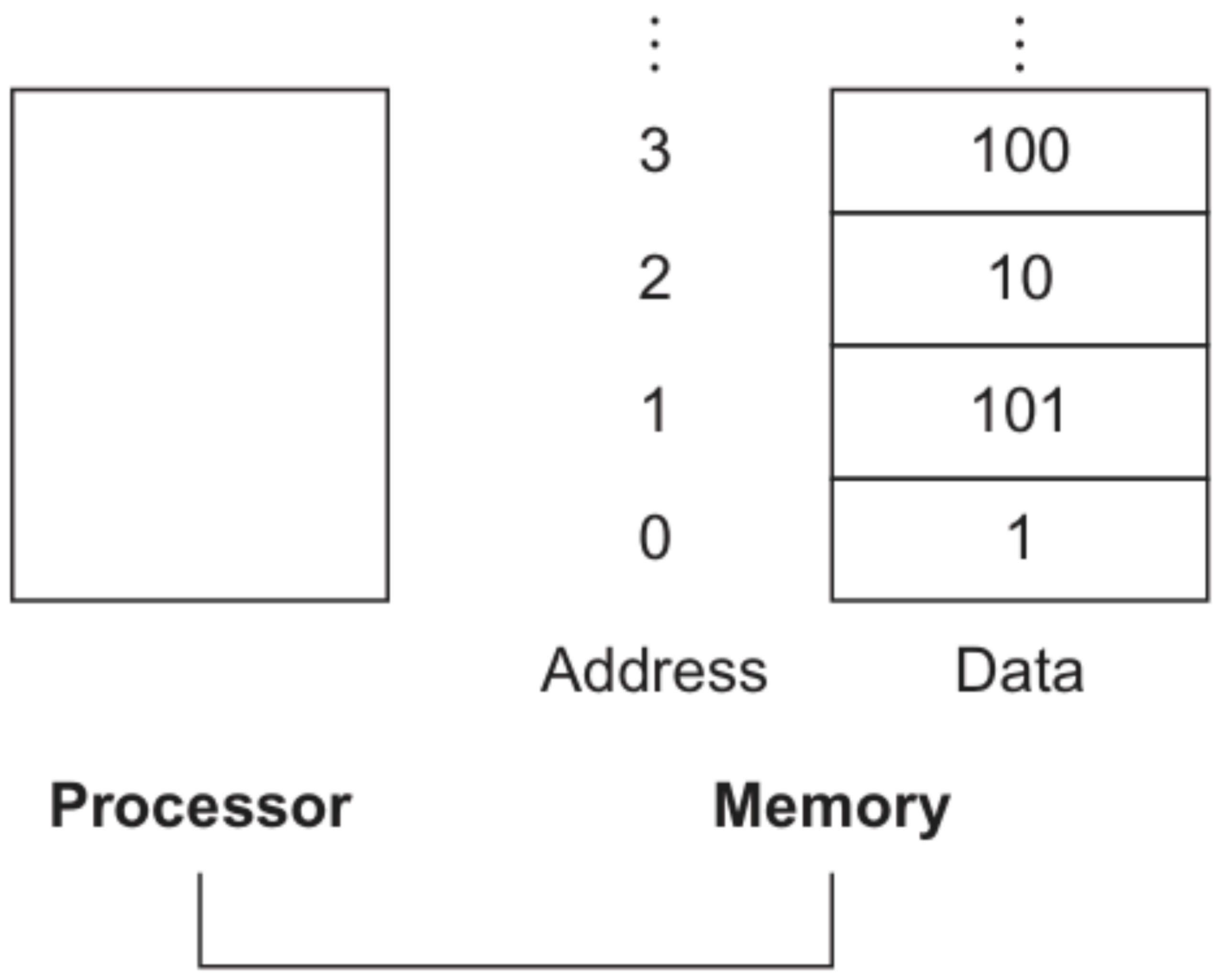
Memory Instructions

- 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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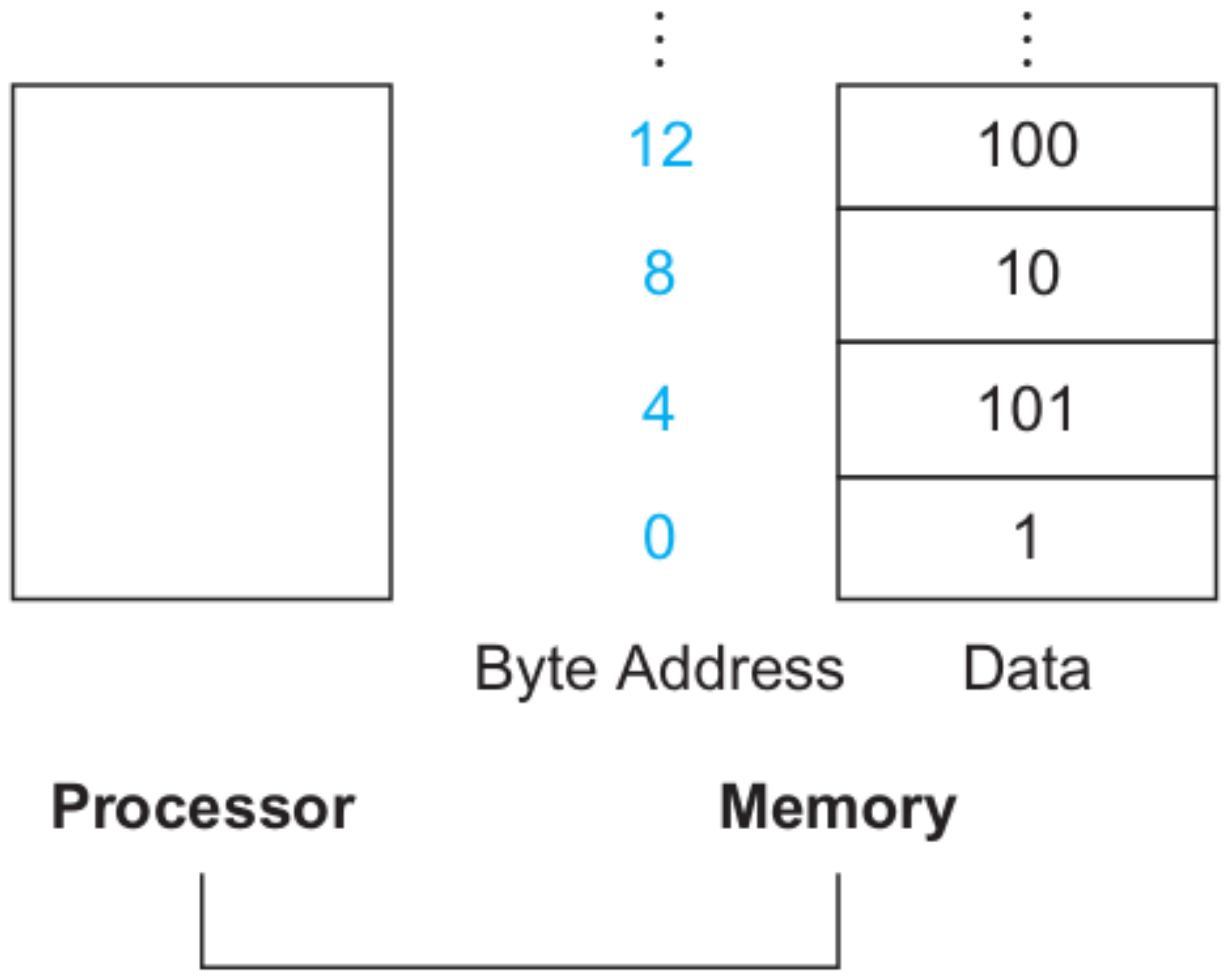

- The `lw` is interpreted as "load word"
  - MIPS also have other variants like "load byte" (`lb`)
- Data comes in `$t0`.
- But what is the 1(`$a0`) part signify?
  - `$a0` is the *base address* of the location you want to read from memory
  - 1 is called the *offset*.
- But why don't you read directly?

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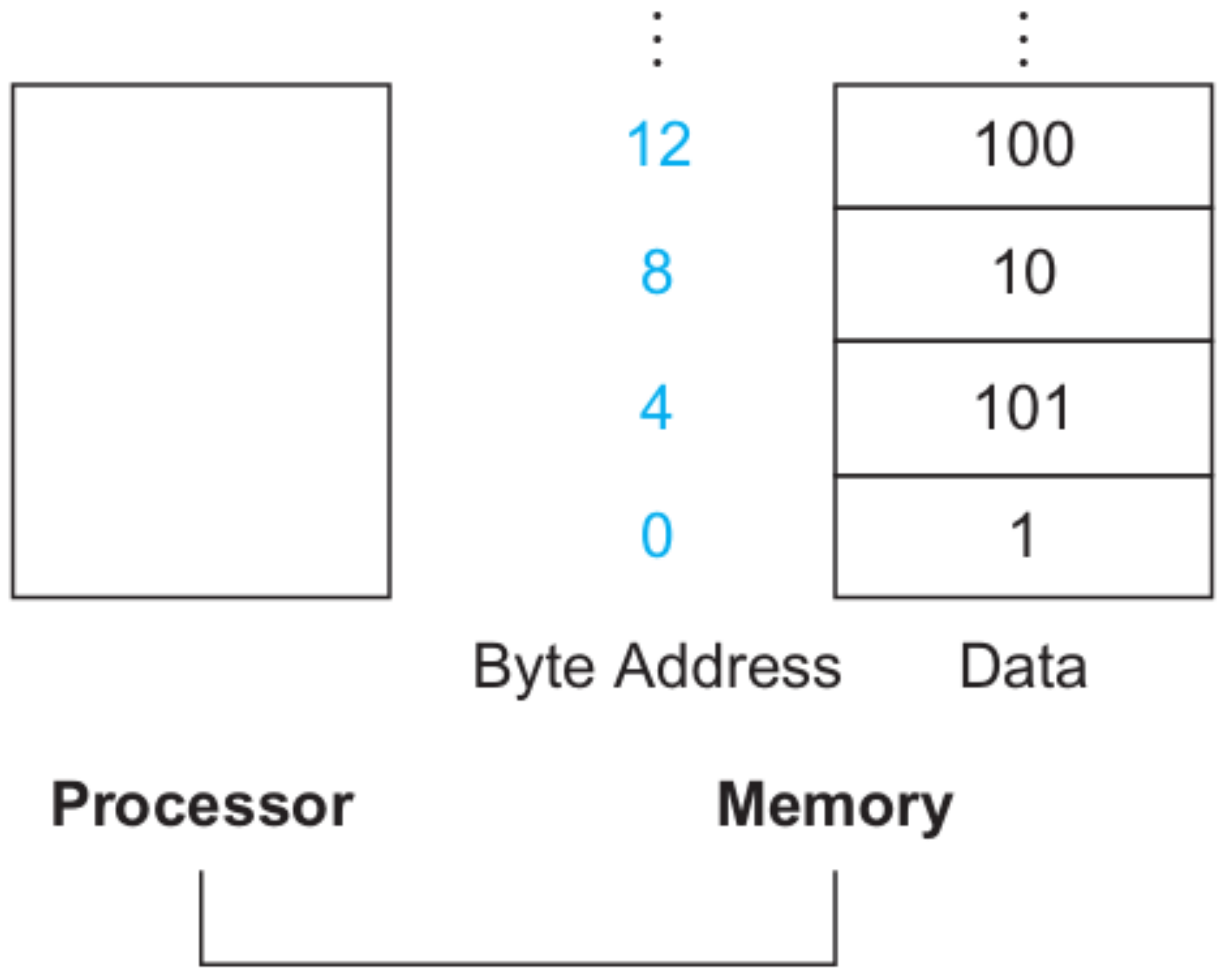
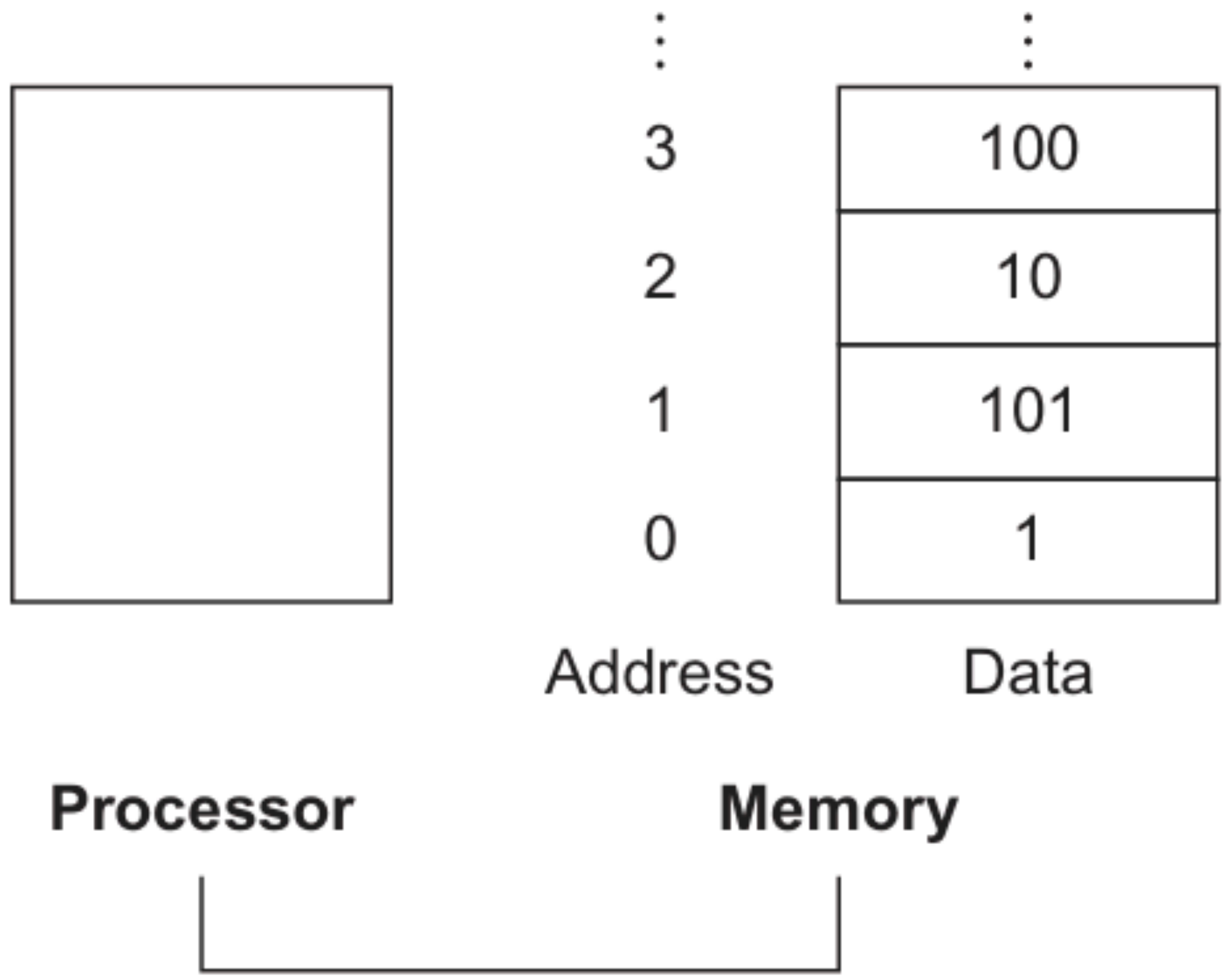
- But why don't you read directly?
  - Again a design choice, to ease compilation, programming, and hardware design…

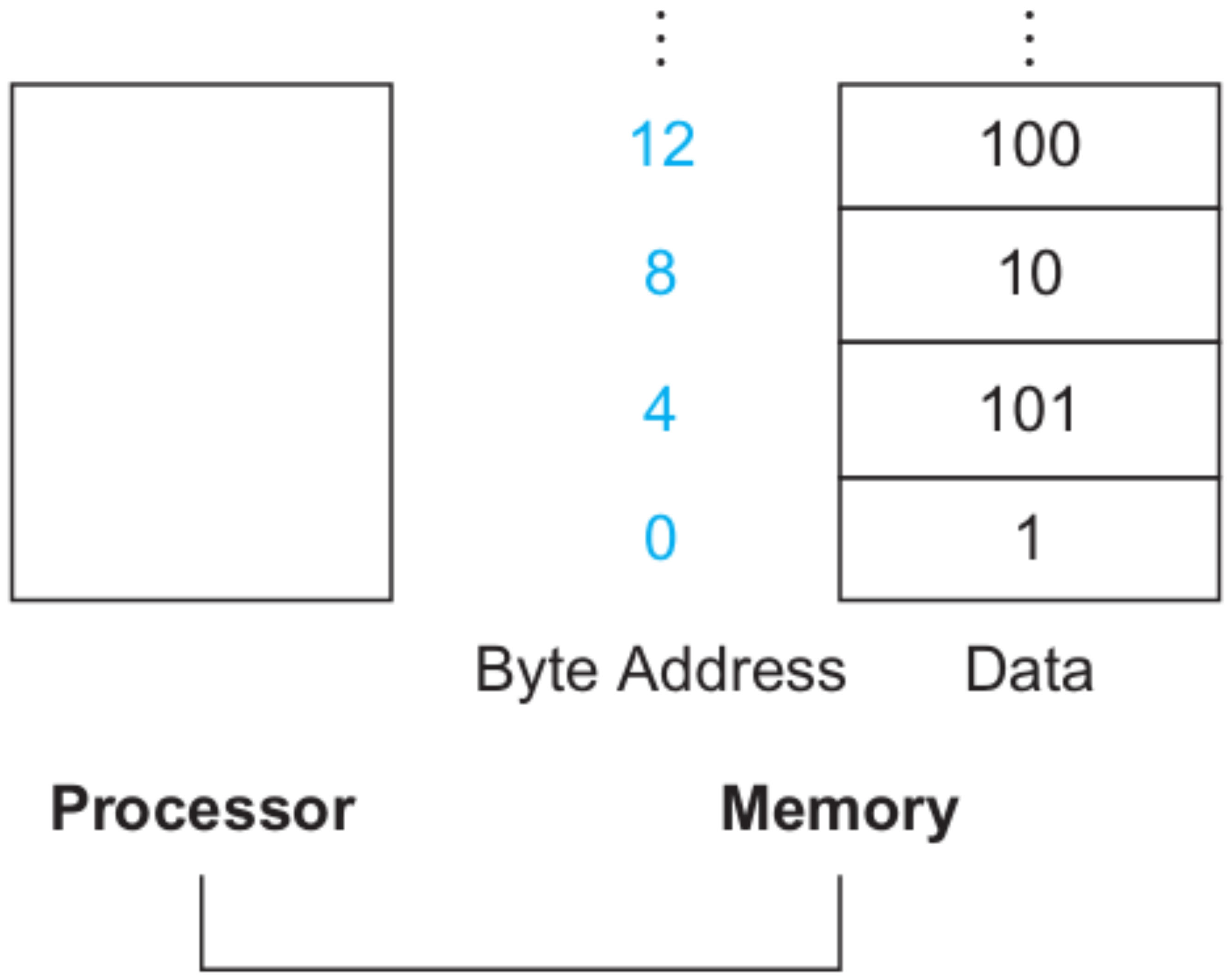


Memory Instructions: Word vs. Byte

```
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….





Memory Instructions: Word vs. Byte

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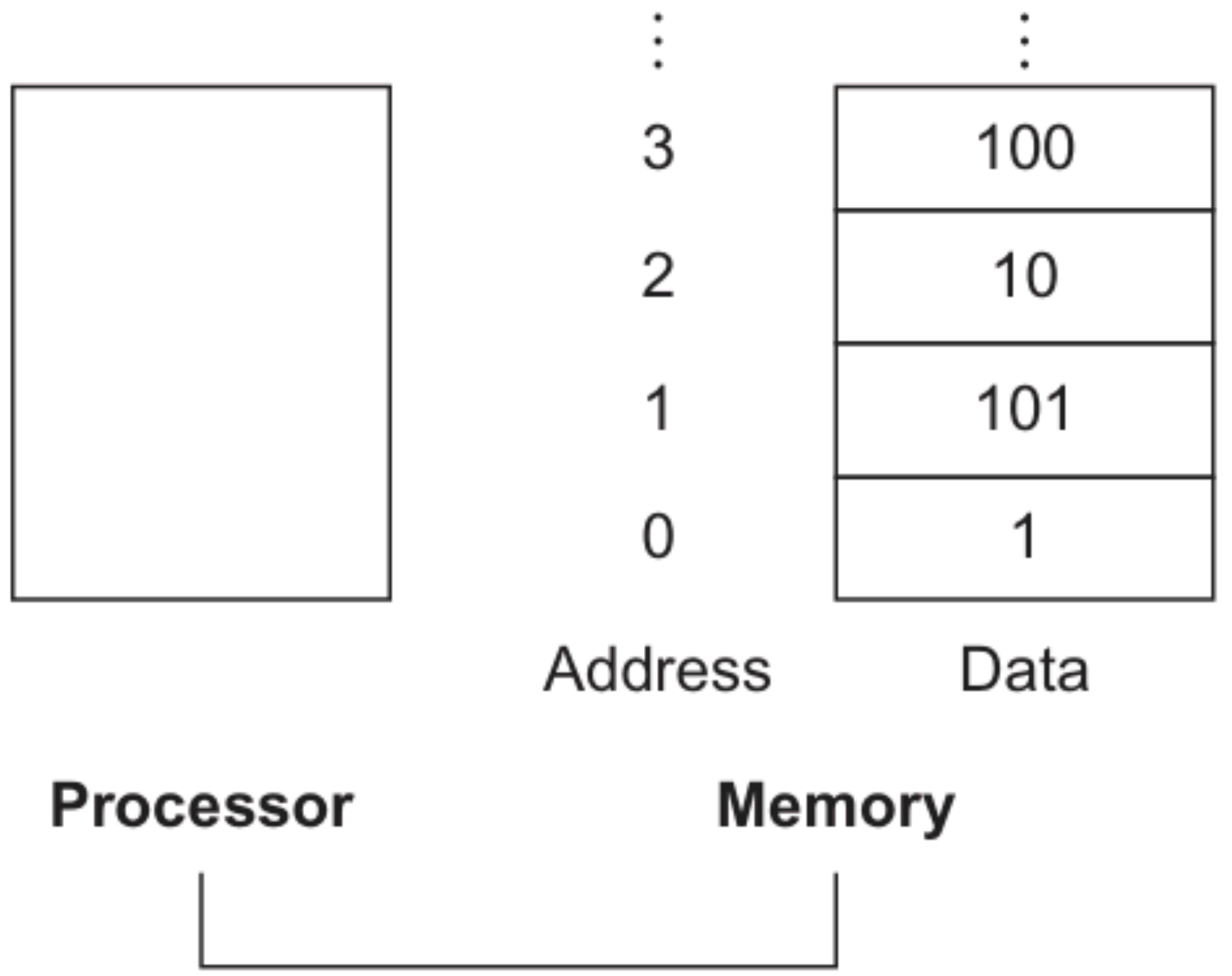
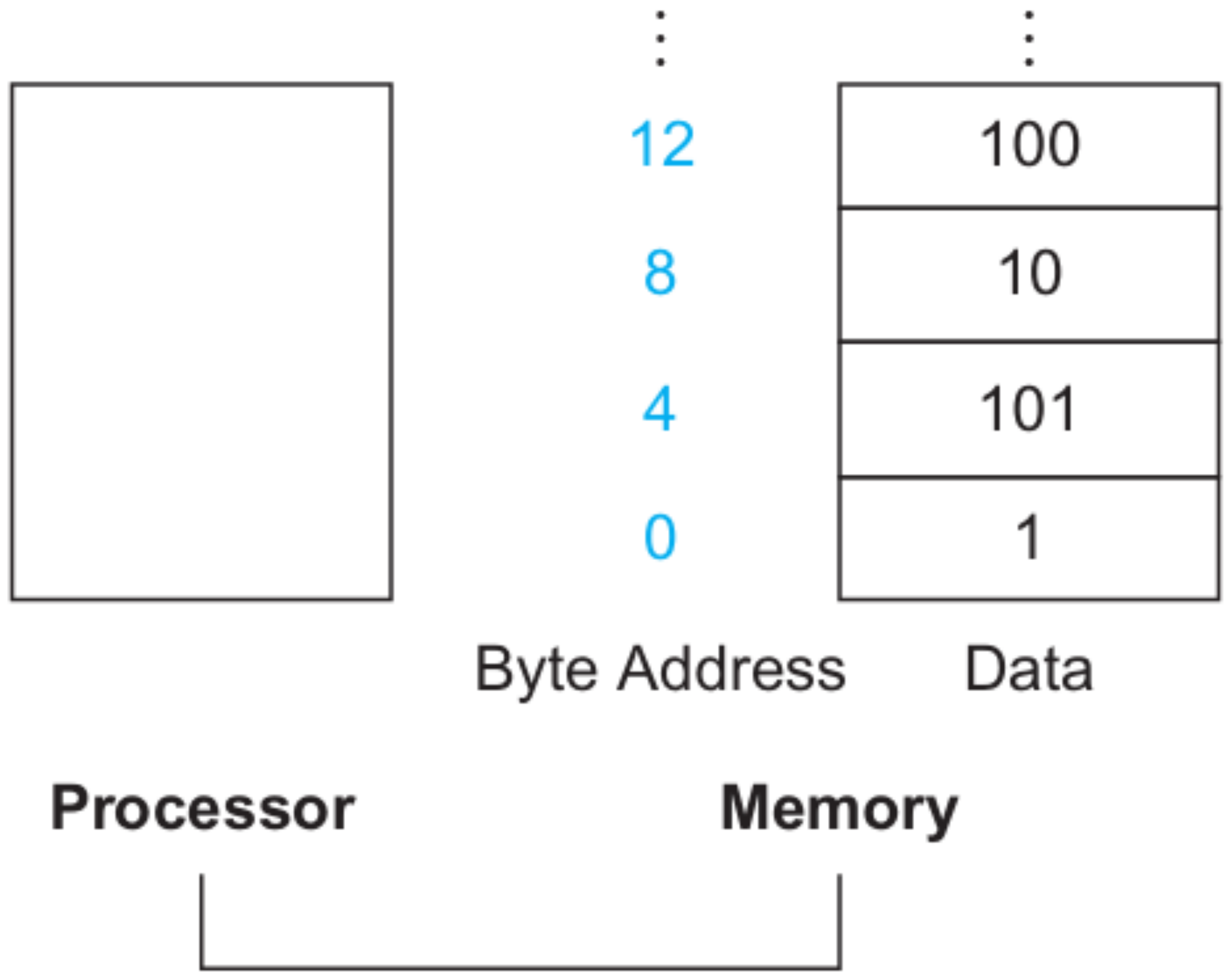
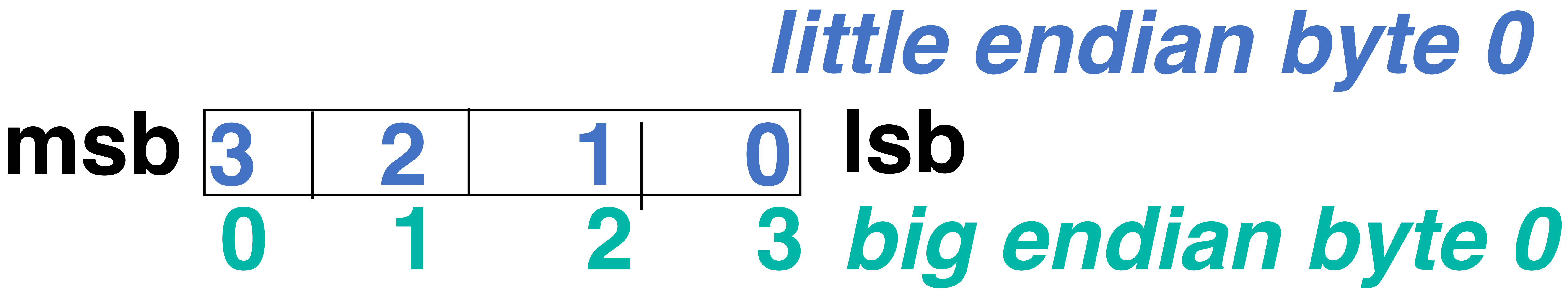




Endianness (Byte ordering within a word)

- 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

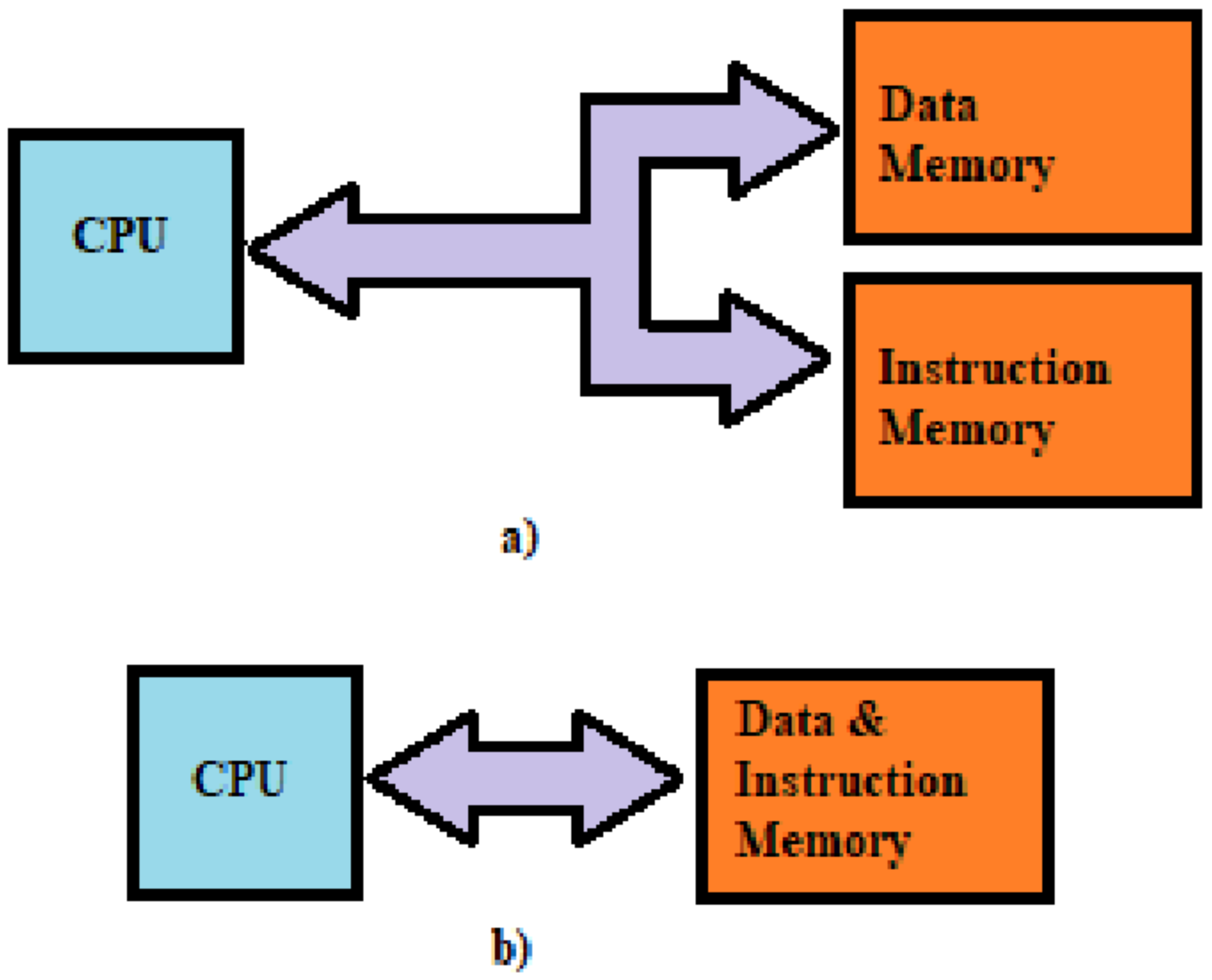
```
unsigned int i = 12345678;
char *c = (char*)&i;
Printf (“%d”, *c);
```

Little endian: 78

Big endian: 12

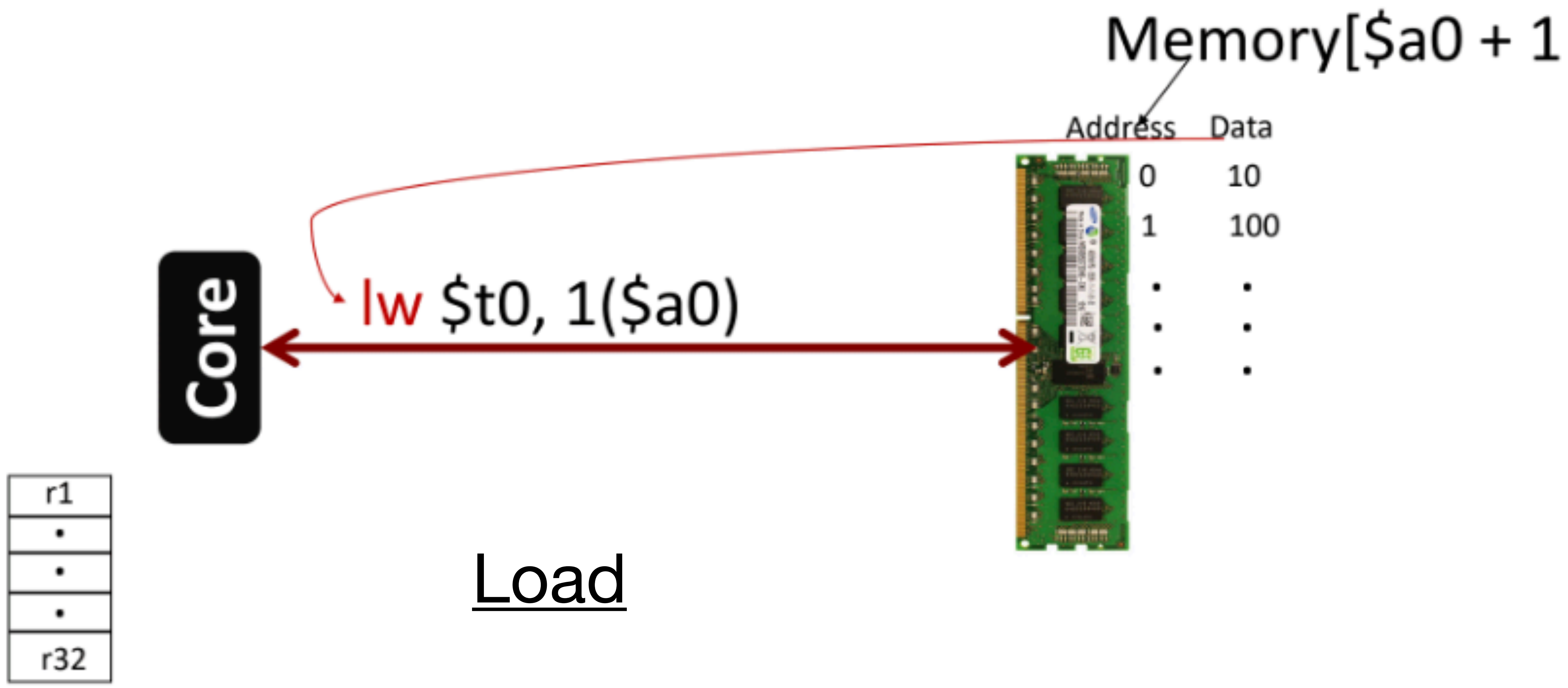
Another Important Point…

- 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

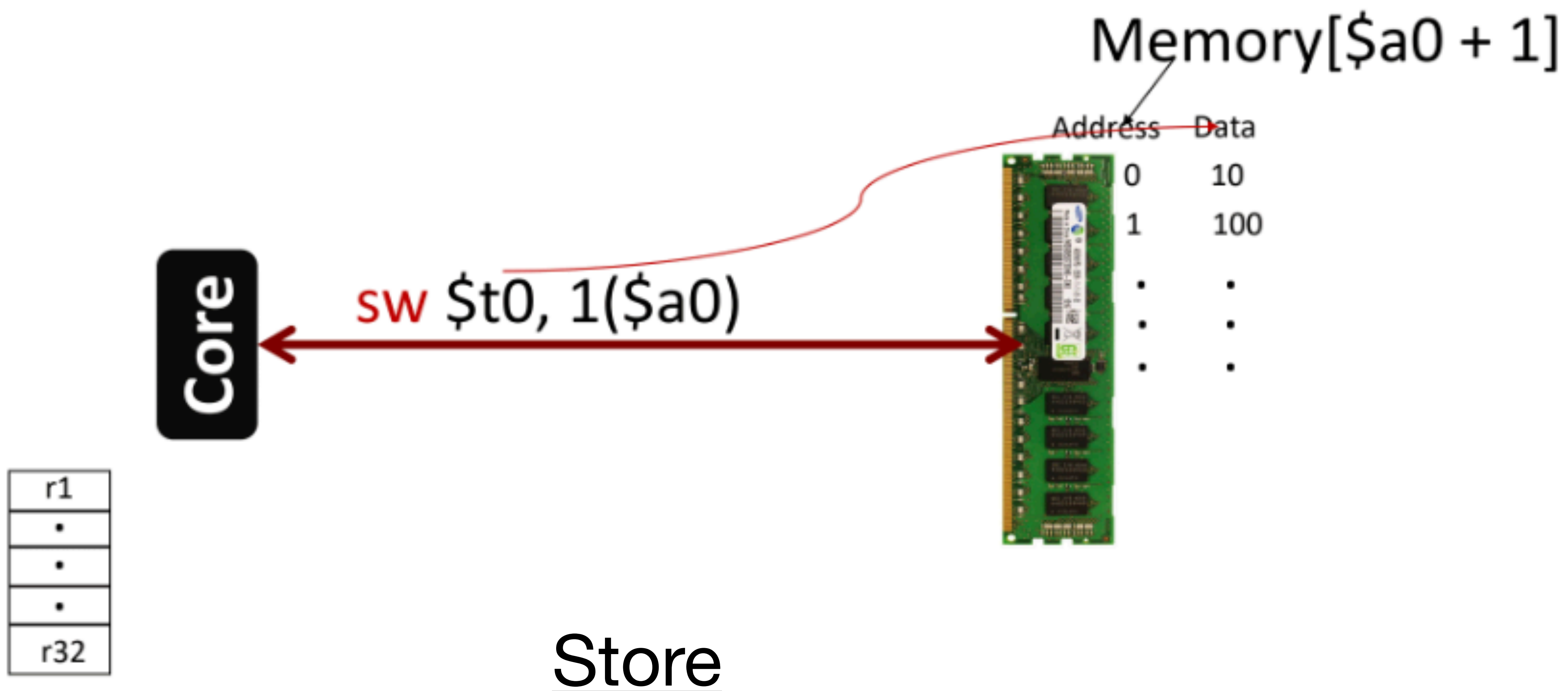


Source: Internet

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`

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`$s6` has `k`

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  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;`

<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:
```

- 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)

More on Jumping…

- 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`

```
LOOP:
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  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:
```

- 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

- **<u>Anatomy of a Function Call</u>**:
  - 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

- **MIPS Support for Function Call**:
  - `$a0–$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

- **Ways of Jumping..**:
  - `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)
```

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`

Functions — More Parameters

- What if there are more than 4 parameters?
- What if the function needs more registers (beyond two return registers) to operate?
- **Remember**: caller must have its state restored after callee finishes.

```
int leaf_example (int g, int h, int i, int j, int k)
{
    int f;
    f = (g + h) - (i + j) + k;
    return f;
    }

    void main (void)
{
     int g=2;
     int h=3;
     int i=1;
     int j=1;
     int k=3;
     int l = leaf_example(g,h,i,j,k);
}
```

Functions — More Parameters

What is this trick?

```
int leaf_example (int g, int h, int i, int j,
int k)
{
    int f;
    f = (g + h) - (i + j) + k;
    return f;
    }

    void main (void)
{
     int g=2;
     int h=3;
     int i=1;
     int j=1;
     int k=3;
     int l = leaf_example(g,h,i,j,k);
}
```

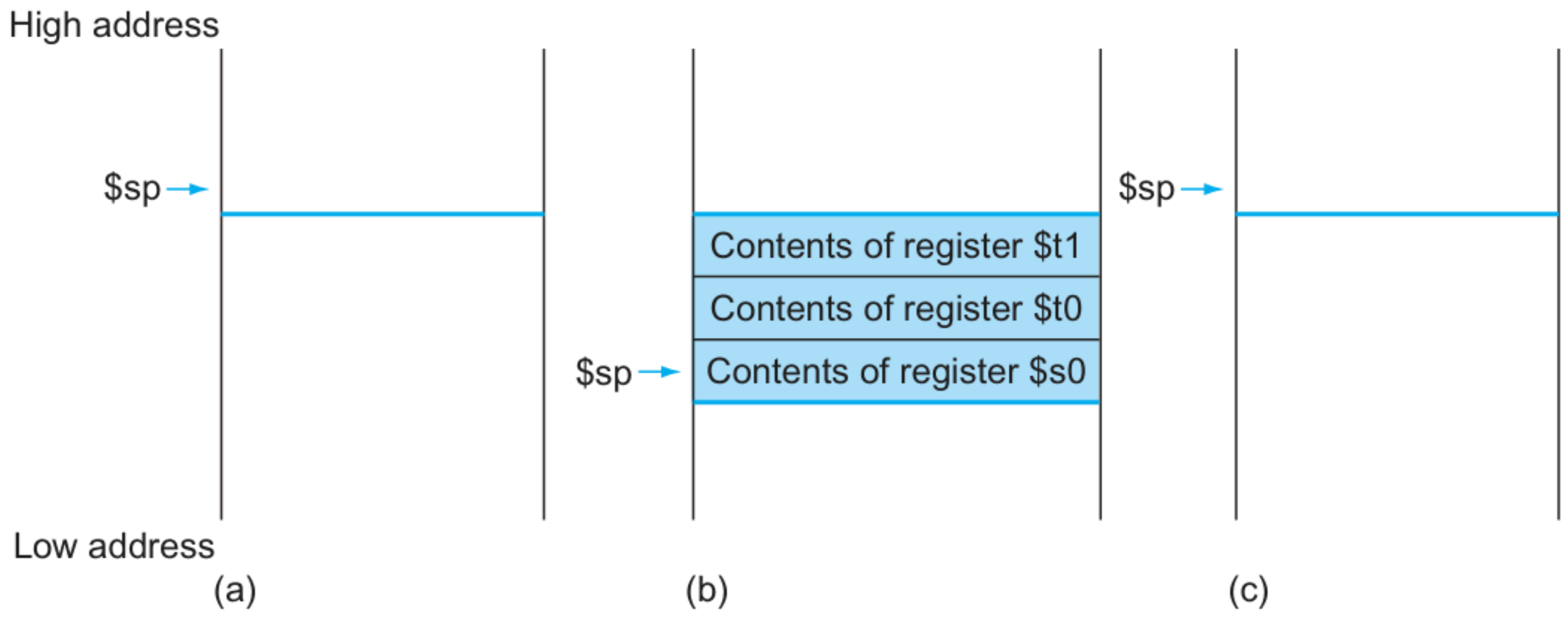
```
leaf_example:
    addi $sp, $sp, -8          # make space for s0, t0
    sw $s0, 4($sp)             # save s0
    sw $t0, 0($sp)             # save t0

    add $s0, $a0, $a1          # s0 = g + h
    add $t0, $a2, $a3          # t0 = i + j
    sub $v0, $s0, $t0          # v0 = (g + h) - (i + j)
    add $v0, $v0, $t2          # v0 += k (f = ... + k)

    lw $t0, 0($sp)             # restore t0
    lw $s0, 4($sp)             # restore s0
    addi $sp, $sp, 8           # deallocate stack
    jr $ra                     # return
```

Stack — What is it?

- A region in DRAM
- Grows in the lower direction
- Push and Pop are the main operations
- **Stack pointer**: A special register
  - A value denoting the most recently allocated address in a stack that shows where registers should be spilled or where old register values can be found.



Functions — More Parameters

- **MIPS Support for Function Call**:
  - We need registers beyond `$a3`
    - Use other registers `$s0`, `$t0`
    - But the caller function might be already have some values in them.
    - **Solution**: store them in memory (stack) before using in the function.
      - Restore back before exiting
  - This idea of saving registers is called **register spilling**

What is this trick?

```
leaf_example:
    addi $sp, $sp, -8            # make space for s0, t0
    sw $s0, 4($sp)               # save s0
    sw $t0, 0($sp)               # save t0

    add $s0, $a0, $a1            # s0 = g + h
    add $t0, $a2, $a3            # t0 = i + j
    sub $v0, $s0, $t0            # v0 = (g + h) - (i + j)
    add $v0, $v0, $t2            # v0 += k (f = ... + k)

    lw $t0, 0($sp)               # restore t0
    lw $s0, 4($sp)               # restore s0
    addi $sp, $sp, 8             # deallocate stack
    jr $ra                       # return
```

Nested Procedures

```
main(){
a = a + f1(a);
}
f1(a) {
        a = a -  f2(a);  return a;}
f2(a) {
        a = a + f3(a); return a;}
f3(a) {
        a = a + 1;      return a;}
```

```
f1:
    f2's argument in $a0 to $a3
            jal f2
```

Nested Procedures

```
f1:
    f2's argument in $a0 to $a3
    jal f2
…
f2:
    f3's argument in $a0 to $a3
    jal f3
…
```

Nested Procedures

```
f1:
  PC:    f2's argument in $a0 to $a3
  PC+4: jal f2                    // $ra = PC+8
…
f2:
  PC+100: f3's argument in $a0 to $a3
  PC+104: jal f3              // $ra = PC+108
                                                f3: …
…                                                 jr $ra
```

Nested Procedures

```
f1:
  PC:   f2's argument in $a0 to $a3
  PC+4: jal f2                    // $ra = PC+8
…
f2:
  PC+100: f3's argument in $a0 to $a3
  PC+104: jal f3            // $ra = PC+108
  jr $ra ☹     Oh no!!                          f3: …
…                                                    jr $ra
```

Nested Procedures

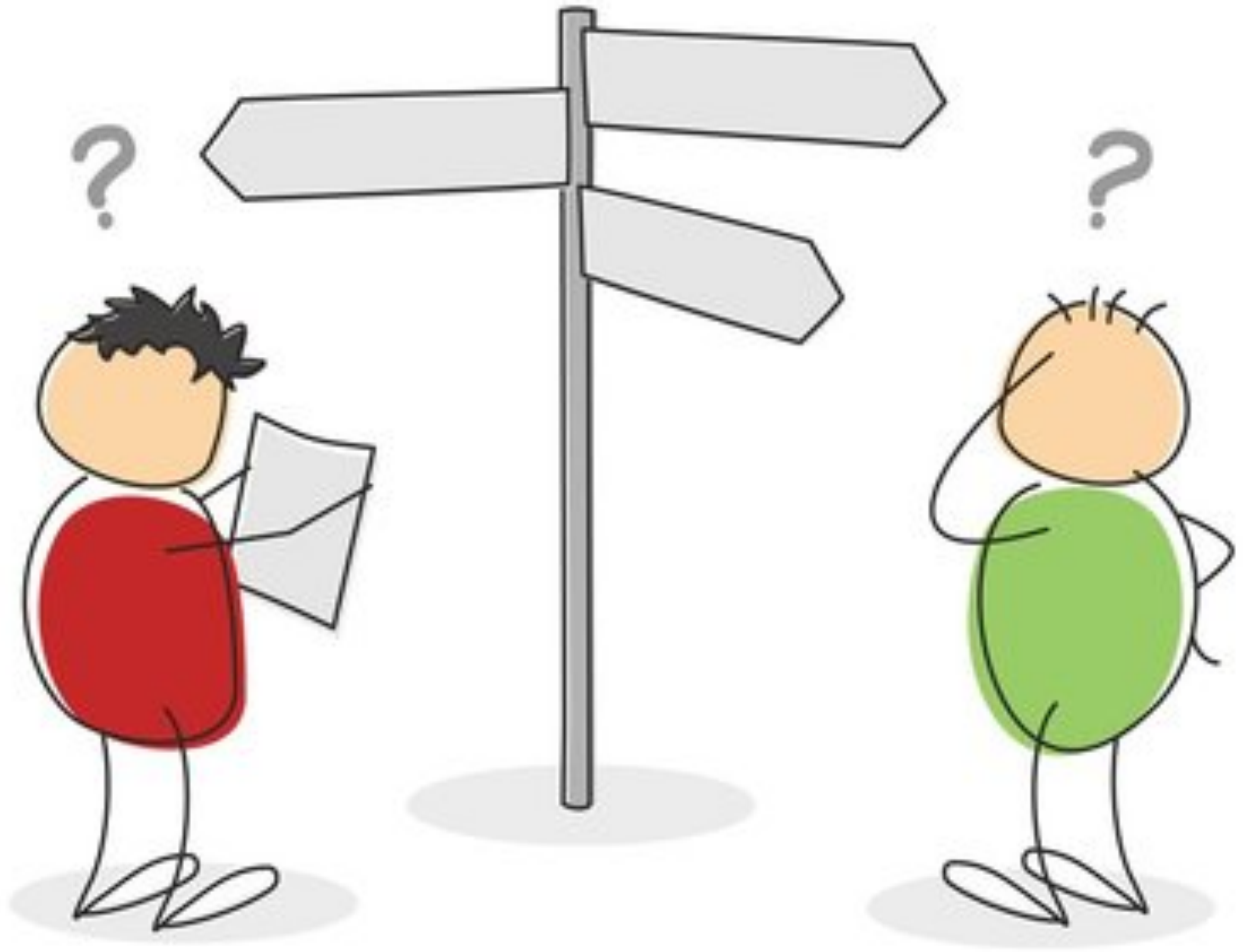
caller registers

callee registers

Why?

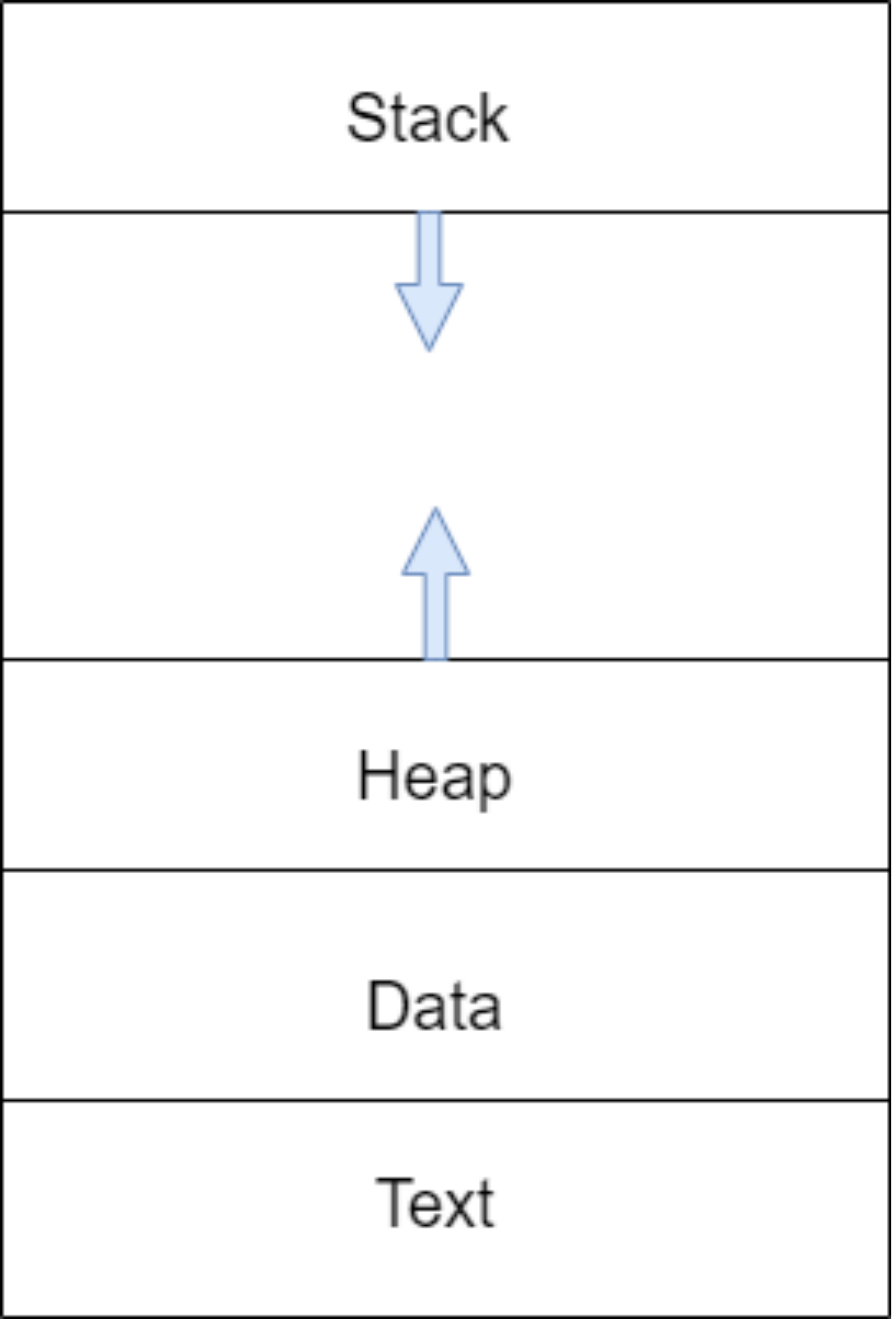
Callee does not know, registers used by callers, can be many callers too

Caller does not know the callee's plan ☺



What to do?

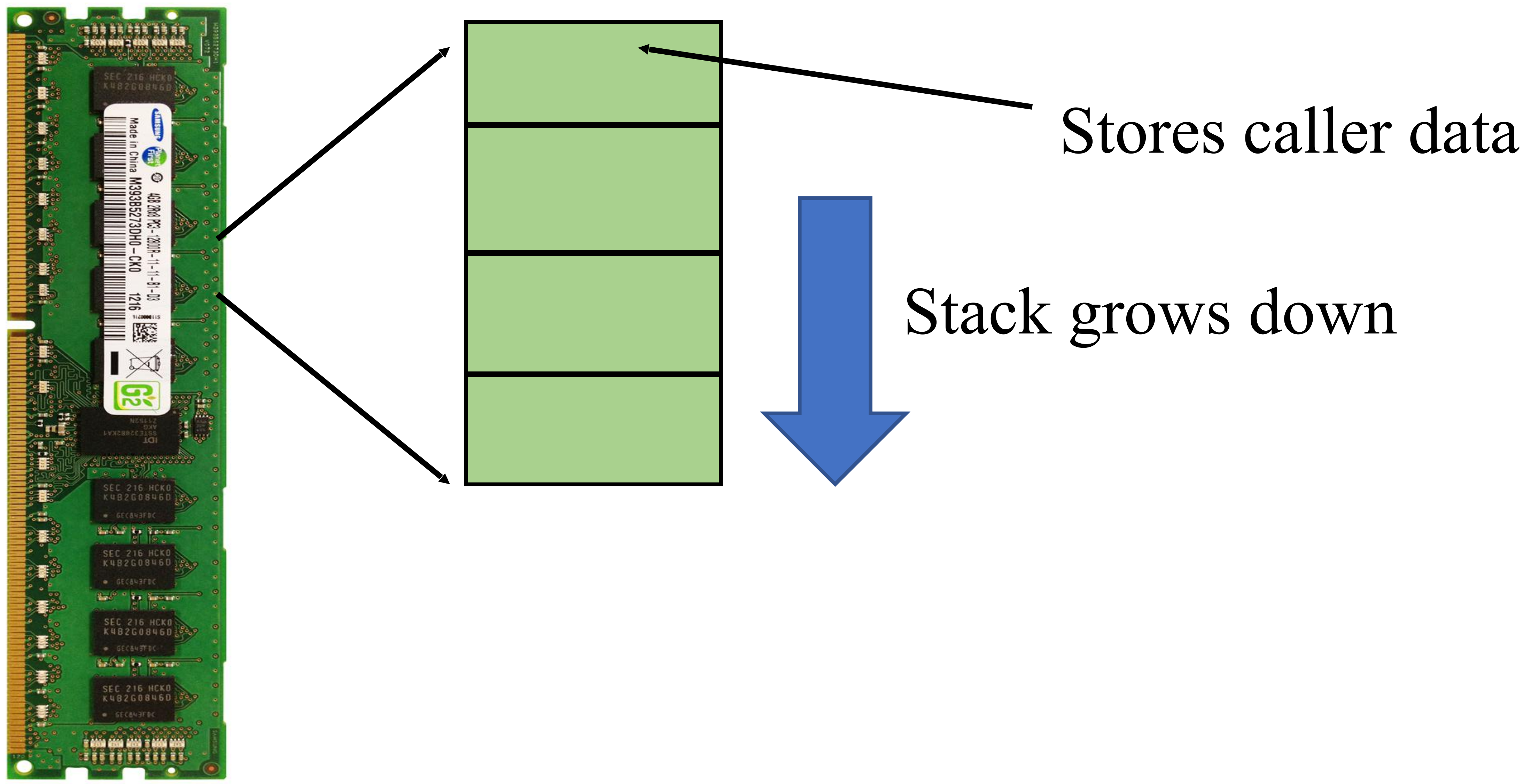
- Push all the other registers that must be preserved onto the stack
  - Caller pushes any argument registers (`$a0–$a3`) or temporary registers (`$t0–$t9`) that are needed after the call.
  - Callee pushes the return address register `$ra` and any saved registers (`$s0–$s7`) used by the callee.
  - The $sp is adjusted to account for the number of registers put on the stack.
  - Everything is restored after the call



The loaded program

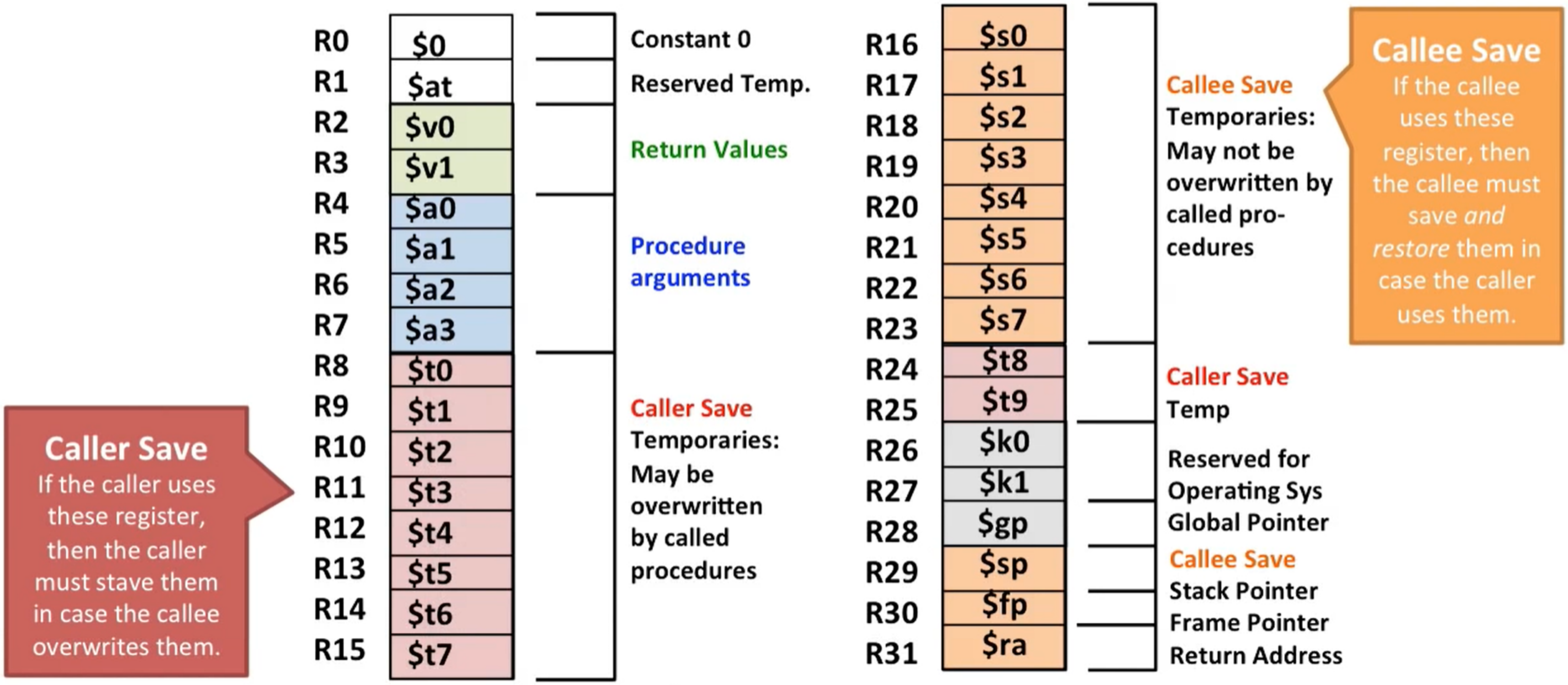
- System program that loads the executable into the memory.
- Every executable has a text, heap/stack data segments

MIPS way of handling it:
The Stack (part of DRAM, for each function call)

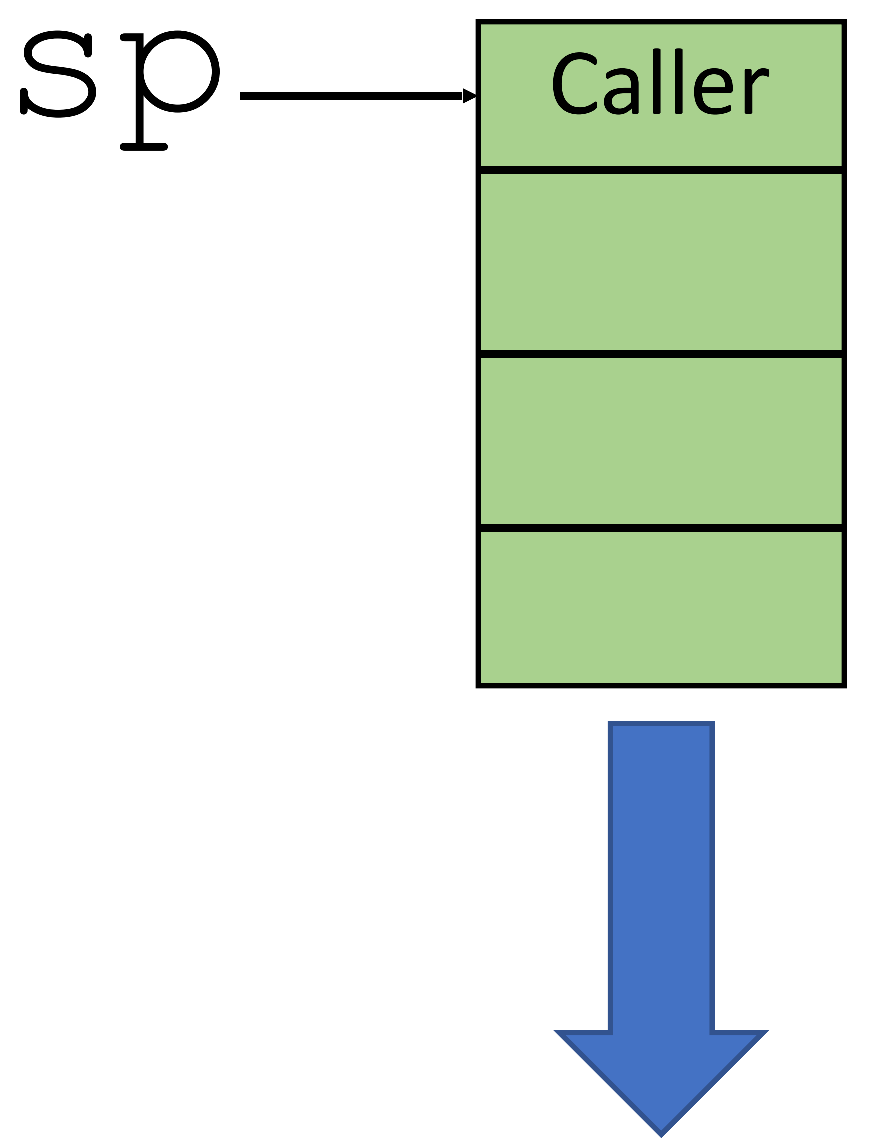


`$sp` (stack pointer) points to the address where stack ends

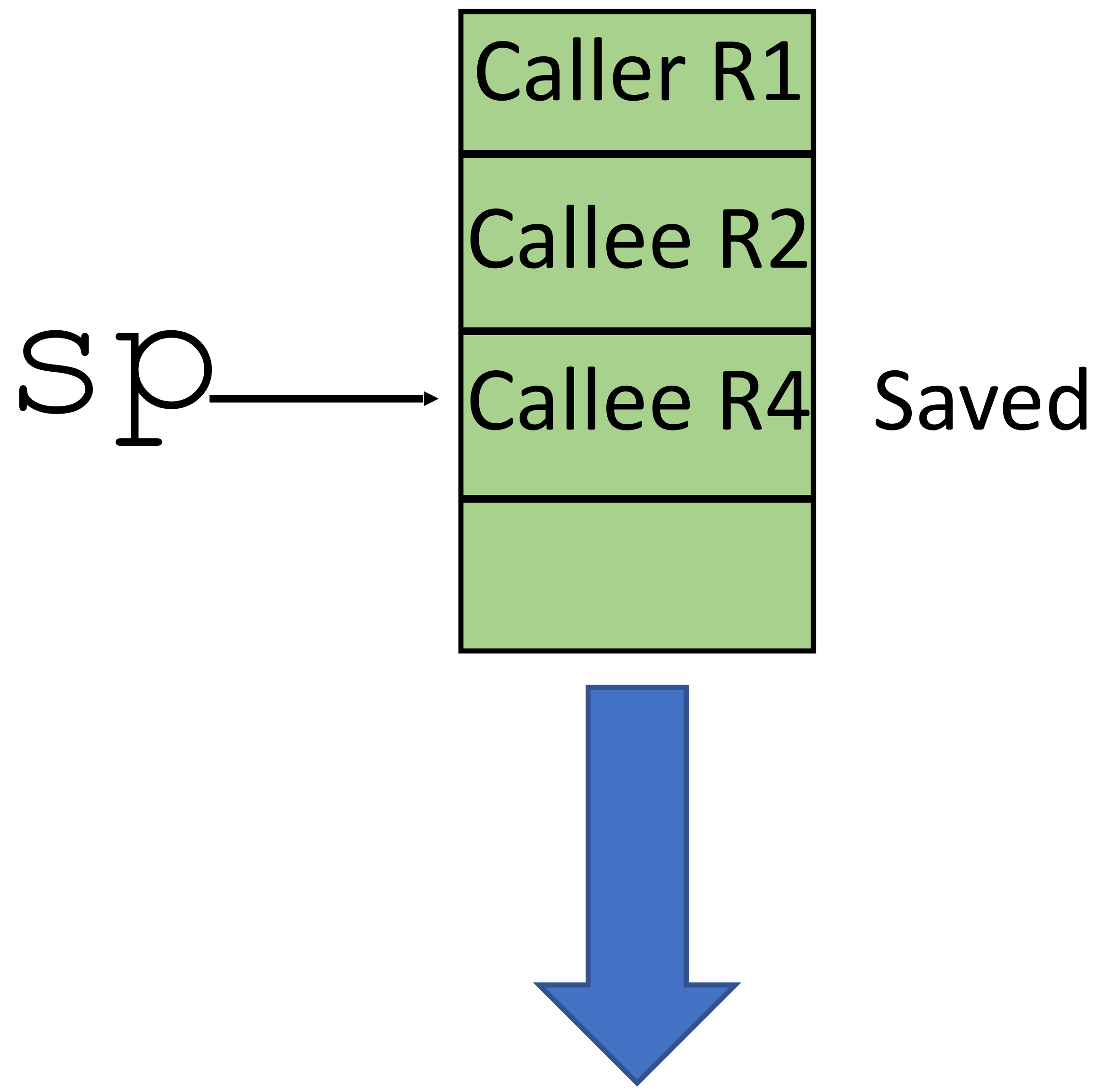
One per function, private memory area, else the same problem ☹


R0 $0 Constant 0
R1 $at Reserved Temp.
R2 $v0
R3 $v1
Return Values
R4 $a0
R5 $a1
R6 $a2
R7 $a3
Procedure arguments
R8 $t0
R9 $t1
R10 $t2
R11 $t3
R12 $t4
R13 $t5
R14 $t6
R15 $t7
Caller Save
Temporaries:
May be overwritten by called procedures
Caller Save
If the caller uses these register, then the caller must stave them in case the callee overwrites them.
R16 $s0
R17 $s1
R18 $s2
R19 $s3
R20 $s4
R21 $s5
R22 $s6
R23 $s7
Callee Save
Temporaries:
May not be overwritten by called pro-cedures
Callee Save
If the callee uses these register, then the callee must save and restore them in case the caller uses them.
R24 $t8
R25 $t9
Caller Save
Temp
R26 $k0
R27 $k1
Reserved for Operating Sys
R28 $gp Global Pointer
Callee Save
R29 $sp Stack Pointer
R30 $fp Frame Pointer
R31 $ra Return Address

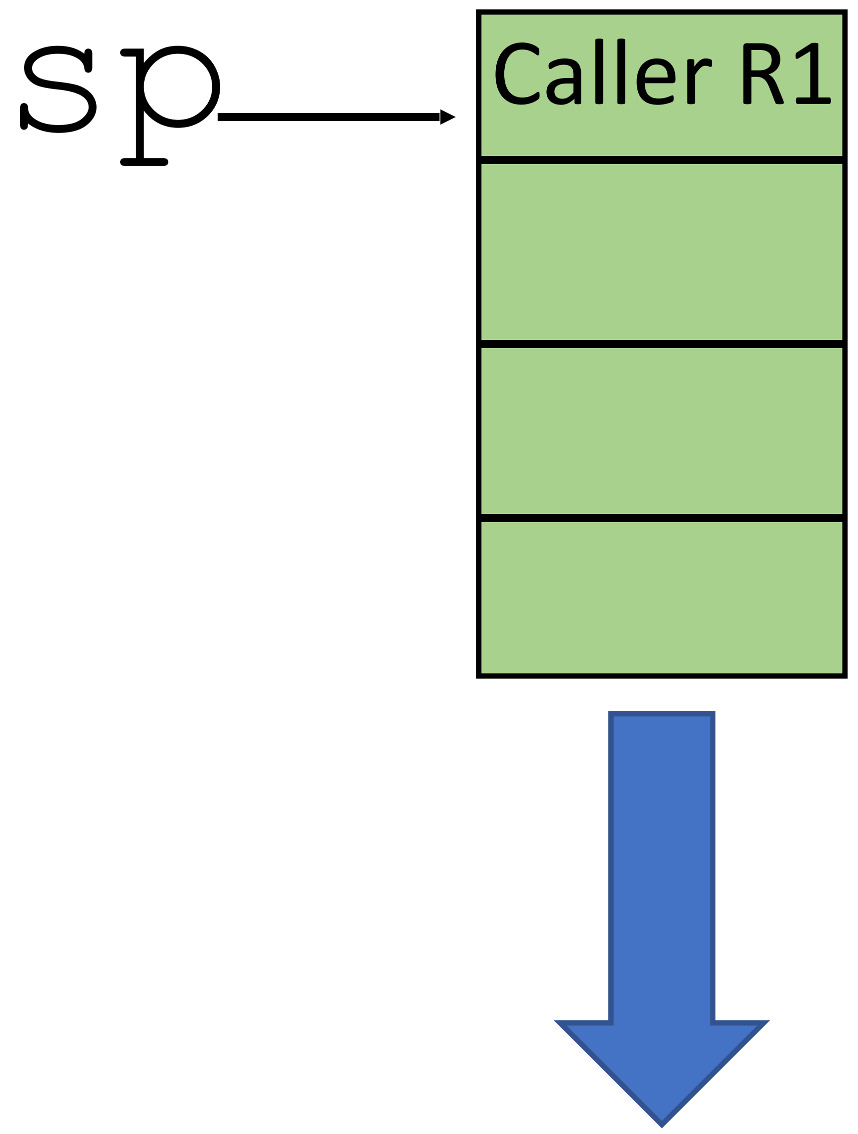
MIPS way of handling it: Before function call



MIPS way of handling it: Function call is ON

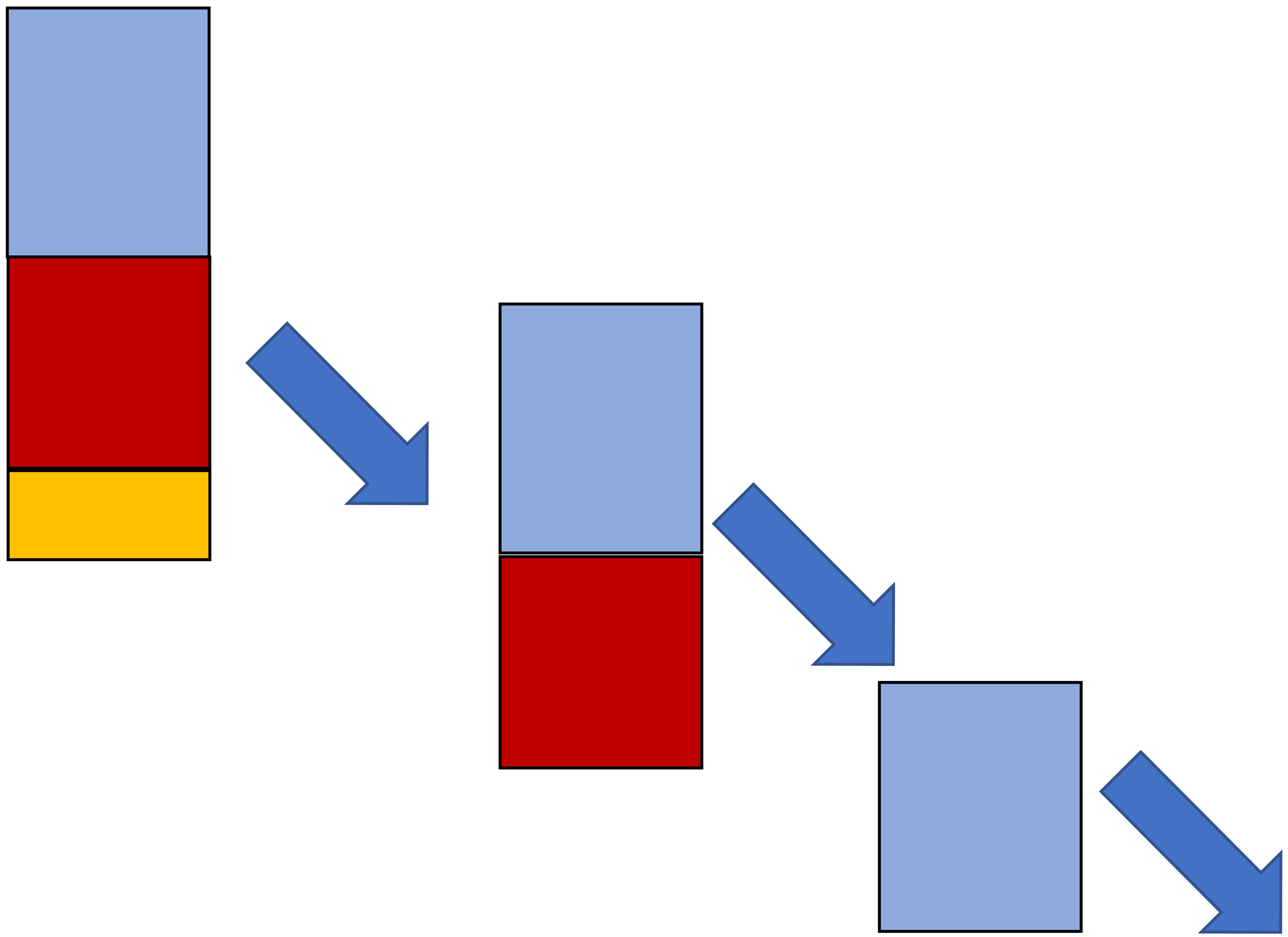


MIPS way of handling it: After the function call



Nested Functions (Remember main() is a function too ☺)

```
CS230 // jal cs230
{
    CS330 // jal cs330
     {
        CS430 // jal cs430
         {
         } //jr
     } //jr
} // jr
```



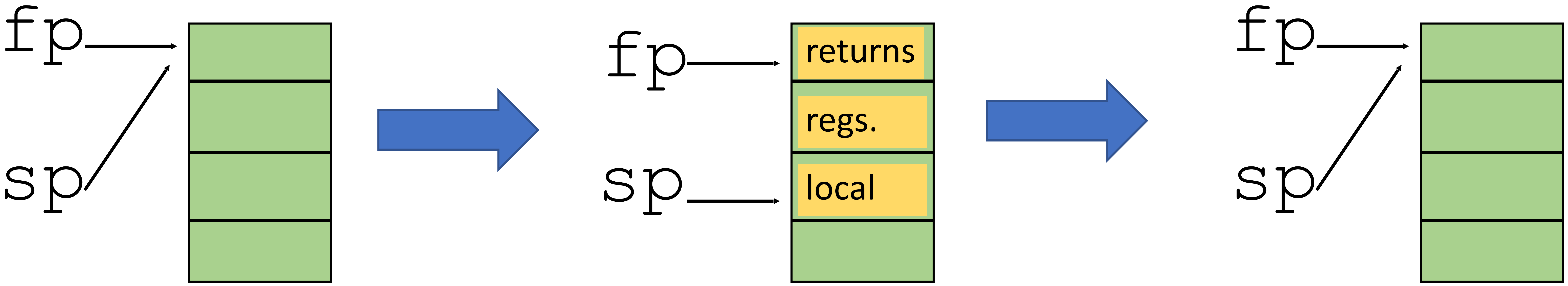
The final one: Frame pointer

- Stack also stores local variables and data structures (local arrays and structures) for a function along with the return address(es).

- Frame pointer ($fp) will get incremented and decremented based on the local arguments used.

The final one: Frame pointer

Frame pointer: Points to local variables and saved registers. Points to the highest address in the function frame. Stays there throughout the procedure. Stack pointer, moves around.



A Complete Example: Recursion

```c
int fact (int n) {
  if (n < 1) return (1);
  else return (n * fact(n - 1)); }
```

1

```
fact:
    addi $sp, $sp, -8           # make space for ra and n
    sw $ra, 4($sp)              # save return address
    sw $a0, 0($sp)              # save n

    slti $t0, $a0, 1            # t0 = 1 if n < 1
    beq $t0, $zero, RECURSE     # if n >= 1, do recursion

    li $v0, 1                   # base case: return 1
    addi $sp, $sp, 8            # deallocate stack
    jr $ra                      # return

RECURSE:
    addi $a0, $a0, -1           # n - 1
    jal fact                    # recursive call

    lw $a0, 0($sp)              # restore n
    mul $v0, $a0, $v0           # n * fact(n - 1)
    lw $ra, 4($sp)              # restore return address
    addi $sp, $sp, 8            # deallocate stack
    jr $ra                      # return
```

A Complete Example: Recursion

```
int fact (int n) {
  if (n < 1) return (1);
  else return (n * fact(n - 1)); }
```

```
fact:
1   addi $sp, $sp, -8           # make space for ra and n
    sw $ra, 4($sp)              # save return address
    sw $a0, 0($sp)              # save n

    slti $t0, $a0, 1            # t0 = 1 if n < 1
    beq $t0, $zero, RECURSE     # if n >= 1, do recursion

    li $v0, 1                   # base case: return 1
    addi $sp, $sp, 8            # deallocate stack
    jr $ra                      # return

RECURSE:
2   addi $a0, $a0, -1           # n - 1
    jal fact                    # recursive call

    lw $a0, 0($sp)              # restore n
    mul $v0, $a0, $v0           # n * fact(n - 1)
    lw $ra, 4($sp)              # restore return address
    addi $sp, $sp, 8            # deallocate stack
    jr $ra                      # return
```

A Complete Example: Recursion

```
int fact (int n) {
  if (n < 1) return (1);
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```

```
fact:
1   addi $sp, $sp, -8          # make space for ra and n
    sw $ra, 4($sp)             # save return address
    sw $a0, 0($sp)             # save n

    slti $t0, $a0, 1           # t0 = 1 if n < 1
    beq $t0, $zero, RECURSE    # if n >= 1, do recursion

3   li $v0, 1                  # base case: return 1
    addi $sp, $sp, 8           # deallocate stack
    jr $ra                     # return

RECURSE:
2   addi $a0, $a0, -1          # n - 1
    jal fact                   # recursive call

    lw $a0, 0($sp)             # restore n
    mul $v0, $a0, $v0          # n * fact(n - 1)
    lw $ra, 4($sp)             # restore return address
    addi $sp, $sp, 8           # deallocate stack
    jr $ra                     # return
```

A Complete Example: Recursion

```
int fact (int n) {
  if (n < 1) return (1);
  else return (n * fact(n - 1)); }
```

- Do you notice something unusual??

```
fact:
1   addi $sp, $sp, -8          # make space for ra and n
    sw $ra, 4($sp)             # save return address
    sw $a0, 0($sp)             # save n

    slti $t0, $a0, 1           # t0 = 1 if n < 1
    beq $t0, $zero, RECURSE    # if n >= 1, do recursion

3   li $v0, 1                  # base case: return 1
    addi $sp, $sp, 8           # deallocate stack
    jr $ra                     # return

RECURSE:
2   addi $a0, $a0, -1          # n - 1
    jal fact                   # recursive call

4   lw $a0, 0($sp)             # restore n
    mul $v0, $a0, $v0          # n * fact(n - 1)
    lw $ra, 4($sp)             # restore return address
    addi $sp, $sp, 8           # deallocate stack
    jr $ra                     # return
```

A Complete Example: Recursion

```
int fact (int n) {
  if (n < 1) return (1);
  else return (n * fact(n - 1)); }
```

- Can you tell me why there I do not `lw` the `$ra` in the base case???
  - `$ra` does not change in the base case

```
fact:
1   addi $sp, $sp, -8          # make space for ra and n
    sw $ra, 4($sp)             # save return address
    sw $a0, 0($sp)             # save n

    slti $t0, $a0, 1           # t0 = 1 if n < 1
    beq $t0, $zero, RECURSE    # if n >= 1, do recursion

3   li $v0, 1                  # base case: return 1
    addi $sp, $sp, 8           # deallocate stack
    jr $ra                     # return

RECURSE:
2   addi $a0, $a0, -1          # n - 1
    jal fact                   # recursive call

4   lw $a0, 0($sp)             # restore n
    mul $v0, $a0, $v0          # n * fact(n - 1)
    lw $ra, 4($sp)             # restore return address
    addi $sp, $sp, 8           # deallocate stack
    jr $ra                     # return
```

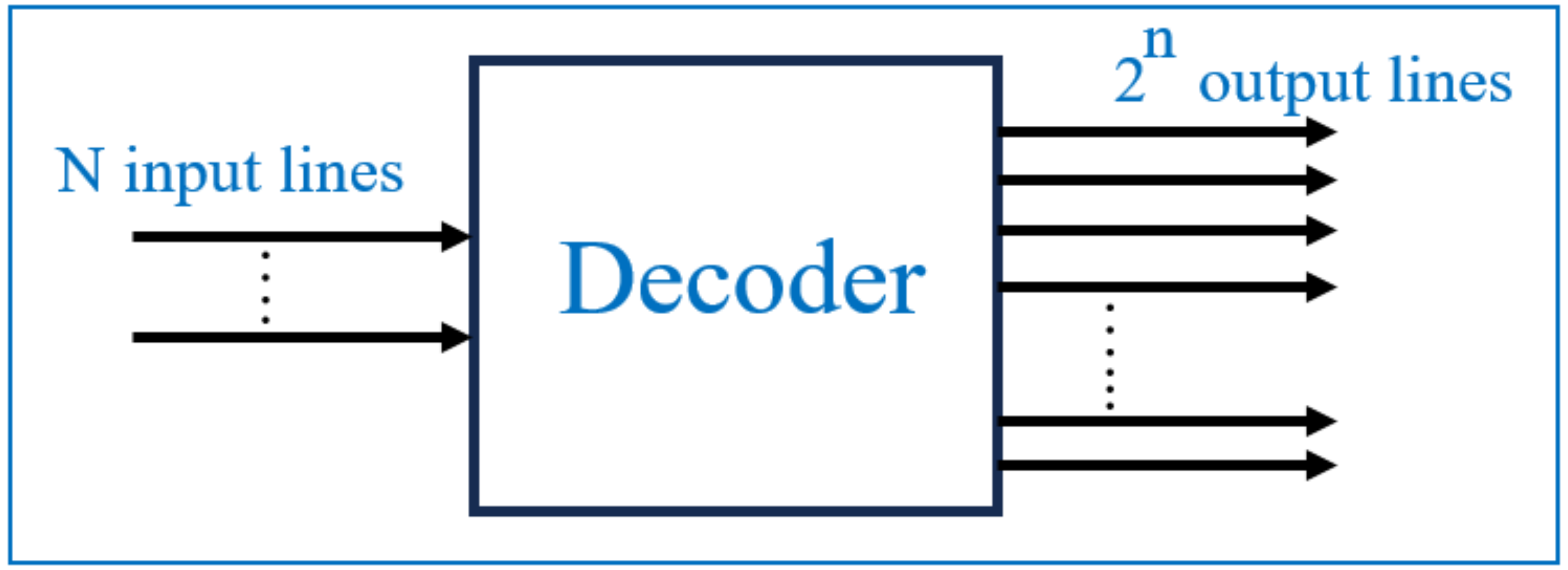
Interpreting Instructions

Why to Interpret?

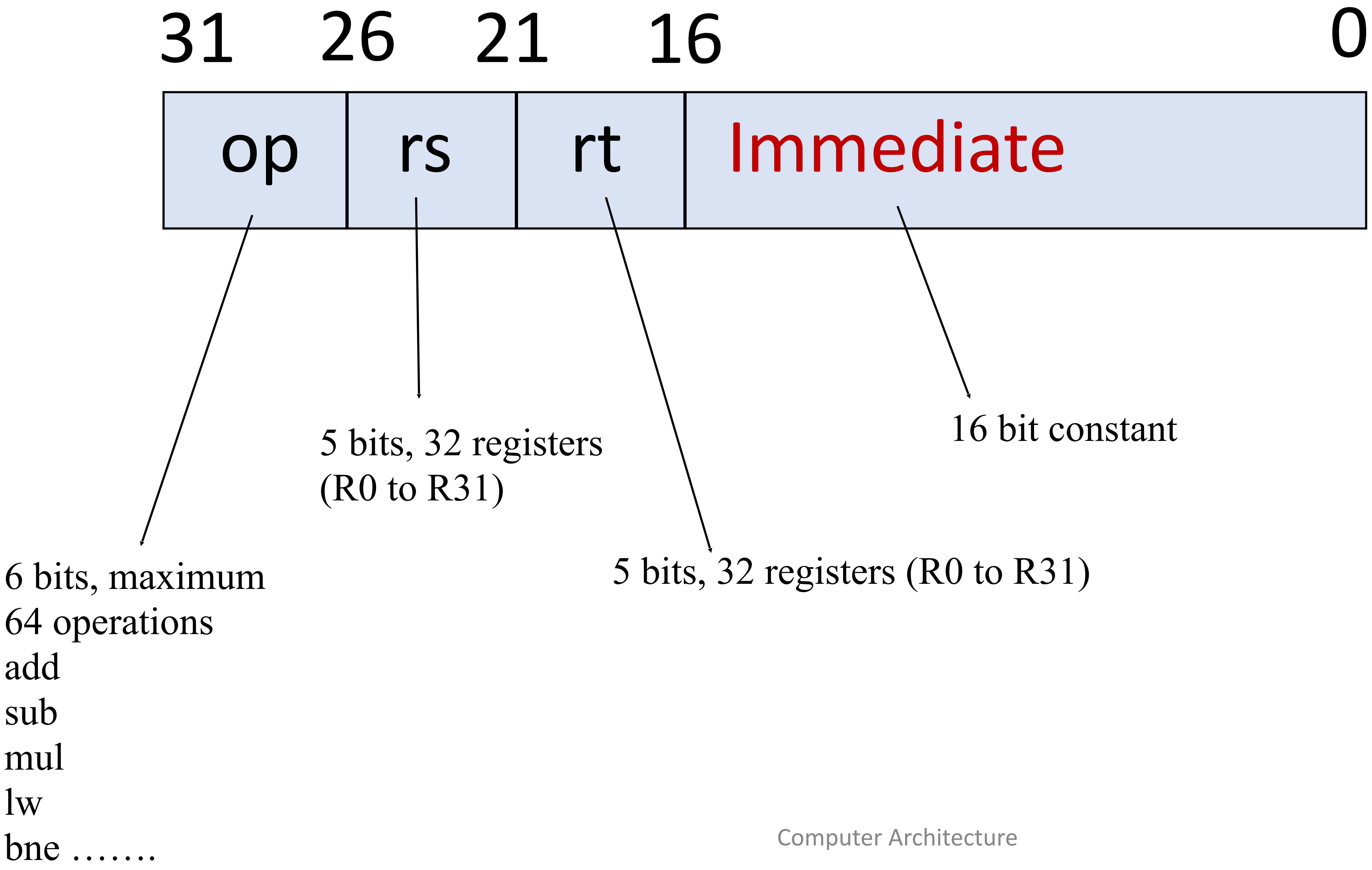
- Everything is a string of bits…
- Instructions are 32 bit strings
- How do the hardware know what is `$lw` and what is `$addi`
  - Unique bit string for each of them
- But how does the machine interpret them?

Decode it …

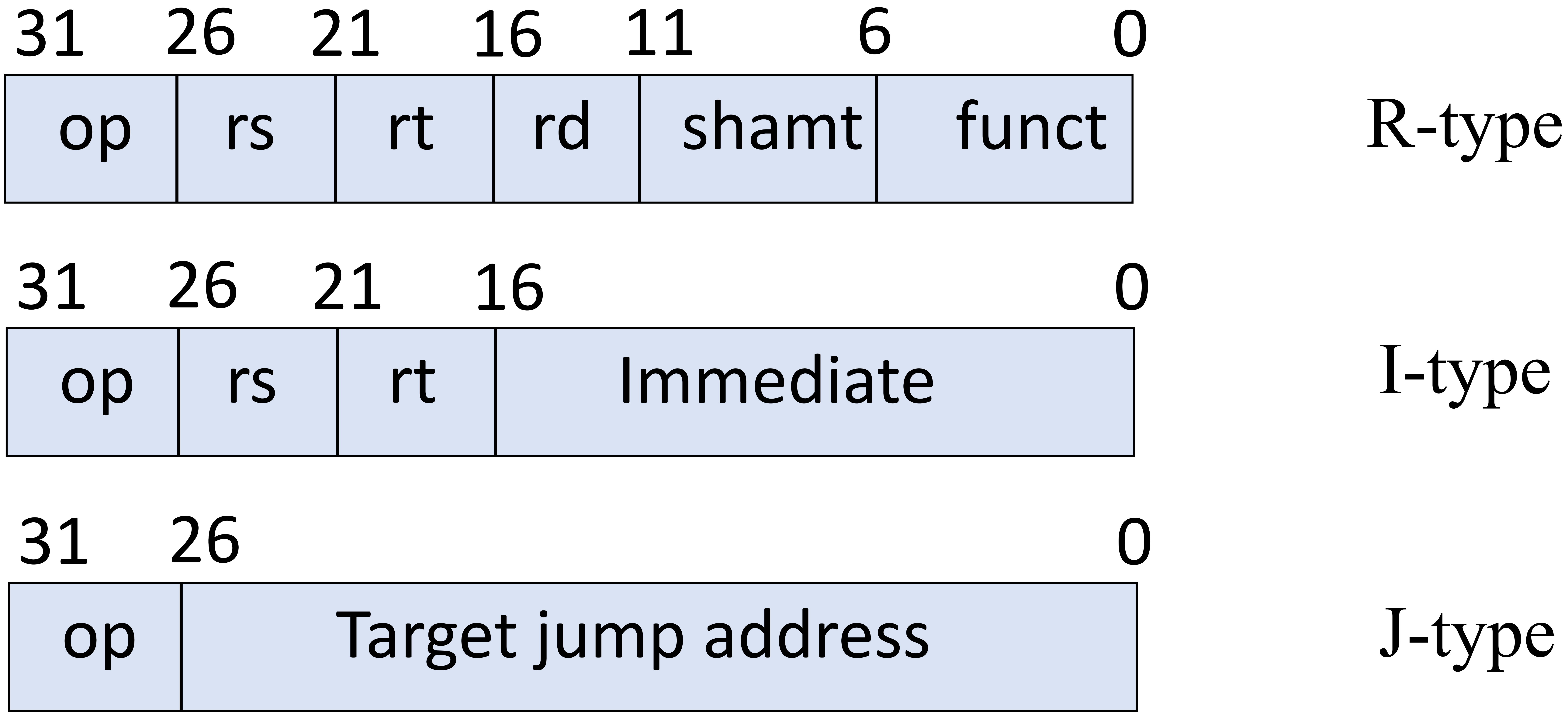
- Everything is a string of bits…
- Instructions are 32 bit strings
- How do the hardware know what is `$lw` and what is `$addi`
  - Unique bit string for each of them
- But how does the machine interpret them?



Instruction Decoding



Let's have a look



Good design demands good compromises

Instruction	Format	op	rs	rt	rd	shamt	funct	address
add	R	0	reg	reg	reg	0	32	n.a.
sub	R	0	reg	reg	reg	0	34	n.a.
addi	I	8	reg	reg	n.a.	n.a.	n.a.	constant
lw	I	35	reg	reg	n.a.	n.a.	n.a.	address
sw	I	43	reg	reg	n.a.	n.a.	n.a.	address

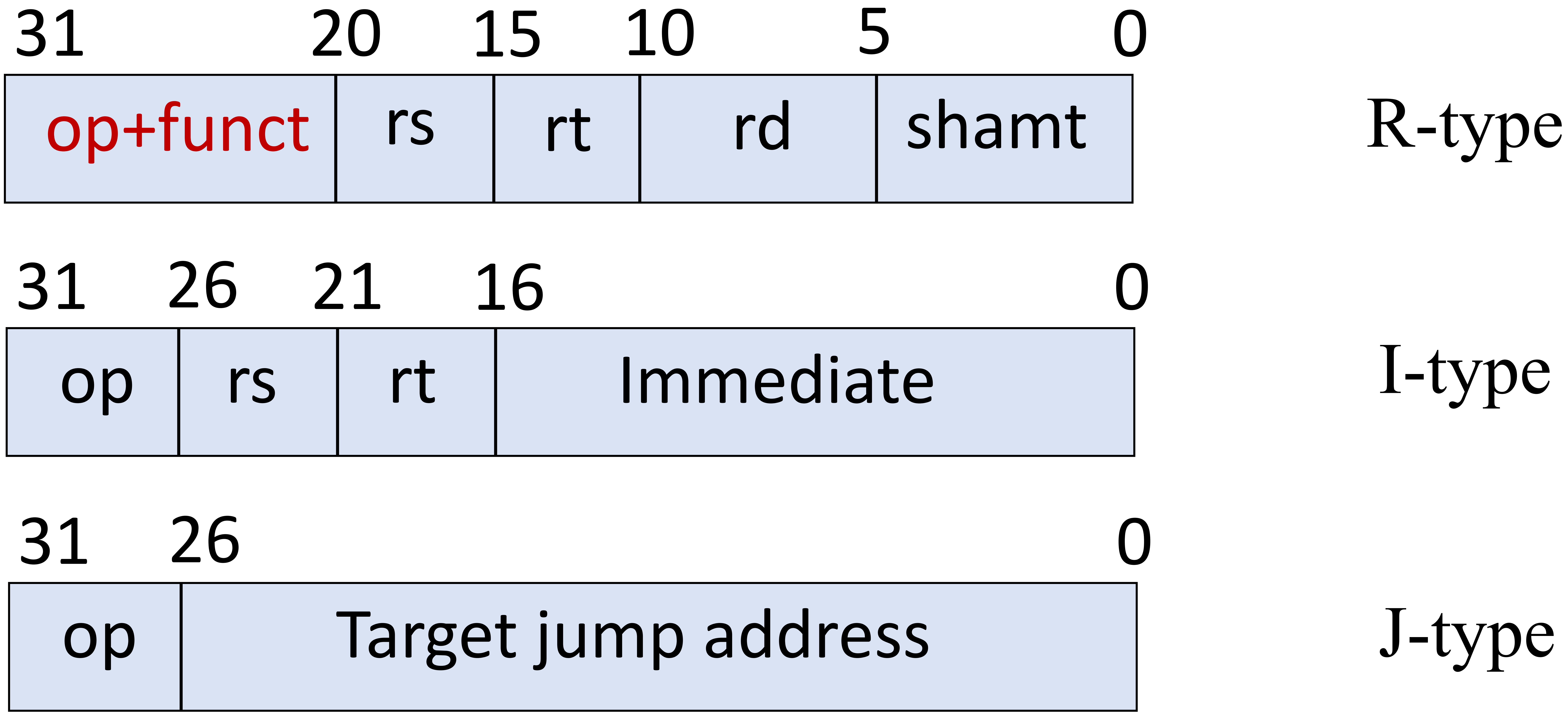
→ (op) tells how to treat the last set of fields:
three fields or one field, still why funct ☹

MIPS encoding Anatomy

op	rs	rt	rd	shamt	funct

Why this field?
Wastage of space ☹

Why not?


31 20 15 10 5 0
op+funct
rs
rt
rd
shamt
R-type
31 26 21 16 0
op
rs
rt
Immediate
I-type
31 26 0
op
Target jump address
J-type

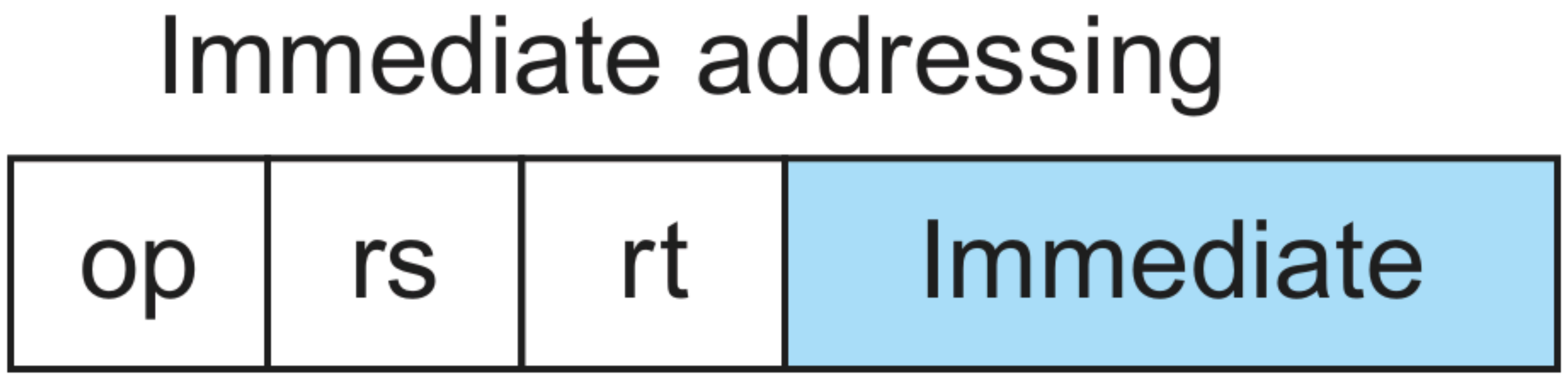
Potential Causes: Simple is The Best

- Every instruction looks the same
- Same number of bits for the **op** for all the instruction
- All the fields starts from the same location
- Uniform treatment for all instructions make the decoder hardware simple:
  - Believe me, you can save some MUXs

Addressing Modes

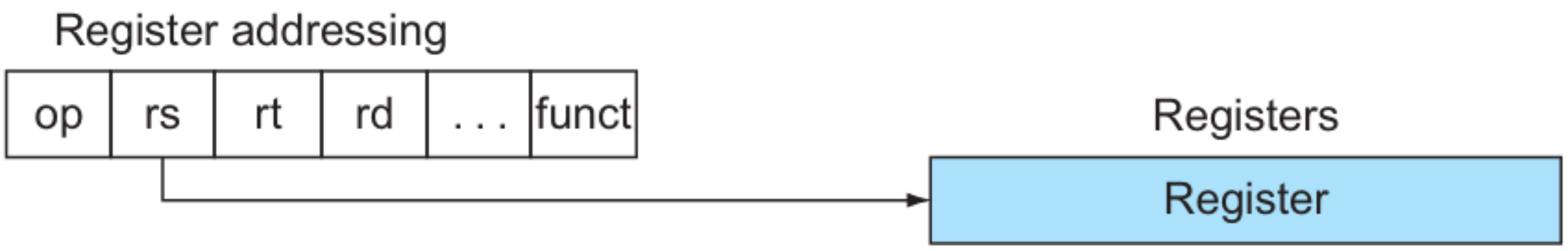
- Where is your data??

Addressing Modes



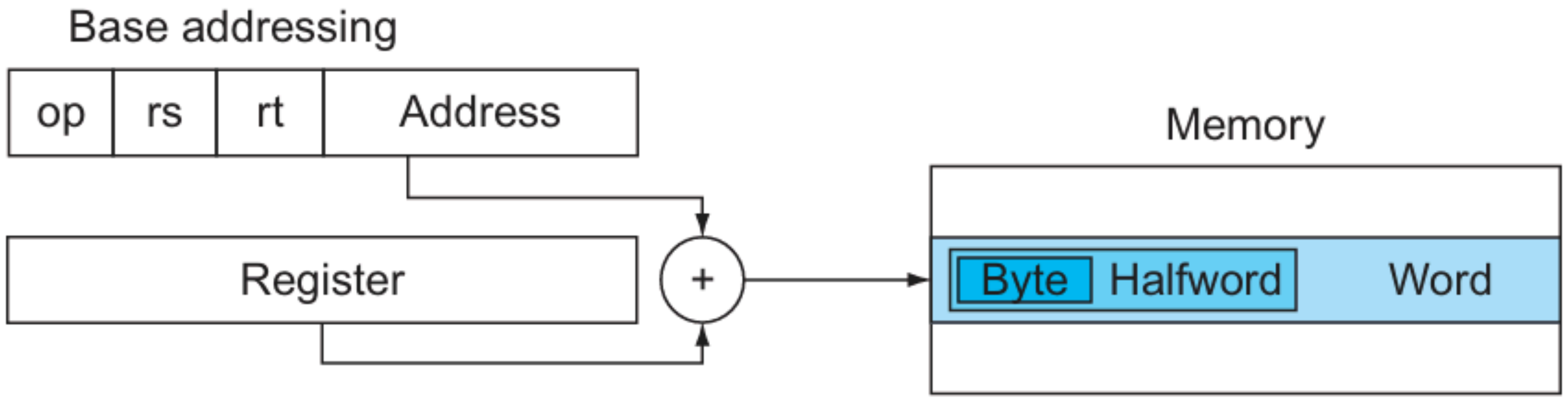
- Data is packed within instruction
- `addi $t0, $t0, 3`

Addressing Modes



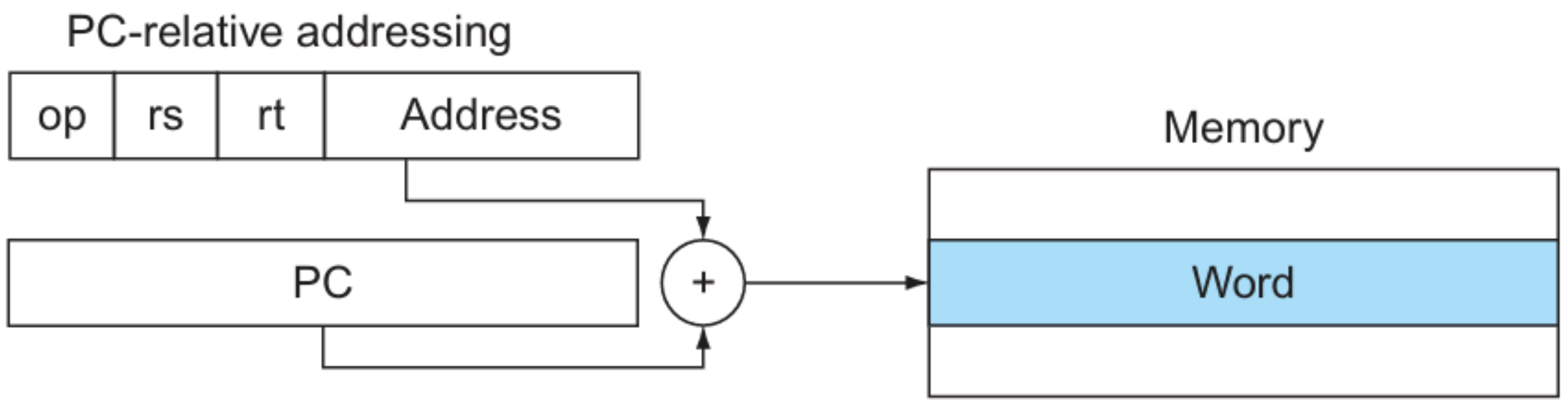
- Data is inside a register
- `add $t0, $t1, $s0`

Addressing Modes



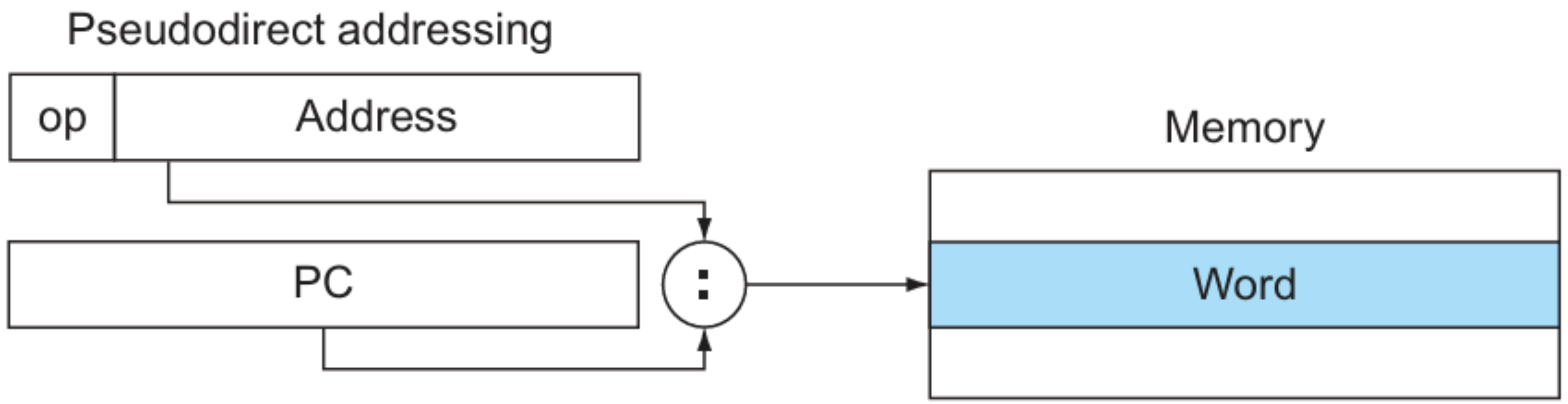
- Data is in memory
- Address is the sum of a register value + offset specified in the instruction.
- `lw $t0, 4($s0), lw $t0,($s0)`
- `lw/sw` have many versions for accessing byte halfword and word.
- Great for accessing arrays, structures, and with pointers

Addressing Modes



- Conditional branches
- The address field basically specifies an offset
- Adds a 16-bit address (sign extended to 26 bit and shifted left by 2 bits) to the PC
- `beq $t0, $zero, RECURSE`

Addressing Modes



- Again for branching
- `jal label`
- Concatenates a 26-bit address shifted left 2 bits with the 4 upper bits of the PC
    - Why?

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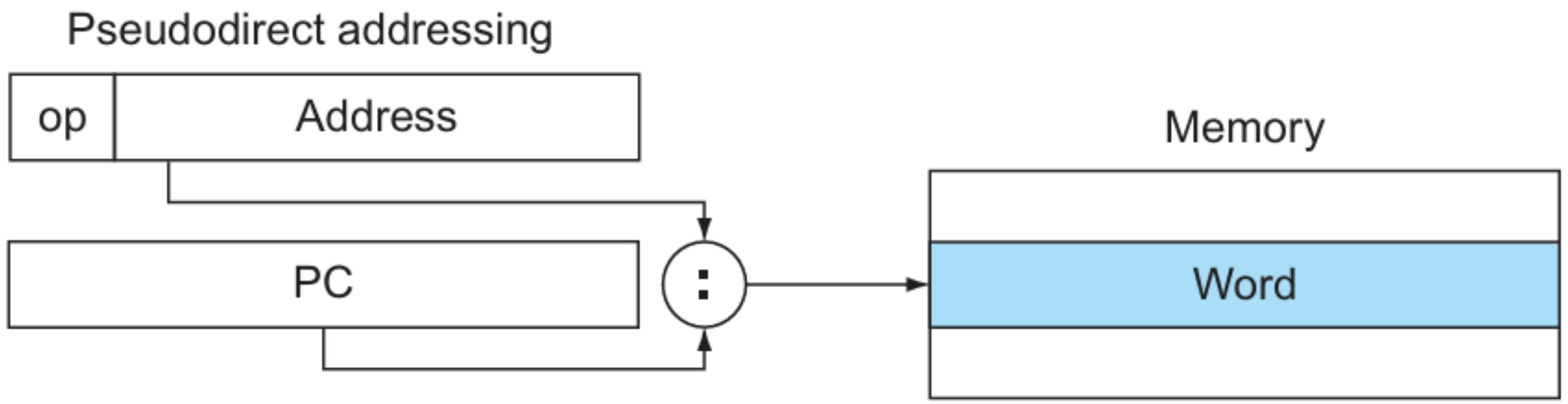

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- Concatenates a 26-bit address shifted left 2 bits with the 4 upper bits of the PC
  - Why?
  - Remember word alignment of memory??????
    - 26 shifted by 2 bit is 28 bits with two zeros at the end — always divisible by 4
    - You can address 2^{28} bits = 256 MB
    - Add the upper 4 bits of PC — can access several 256 MB chunks..

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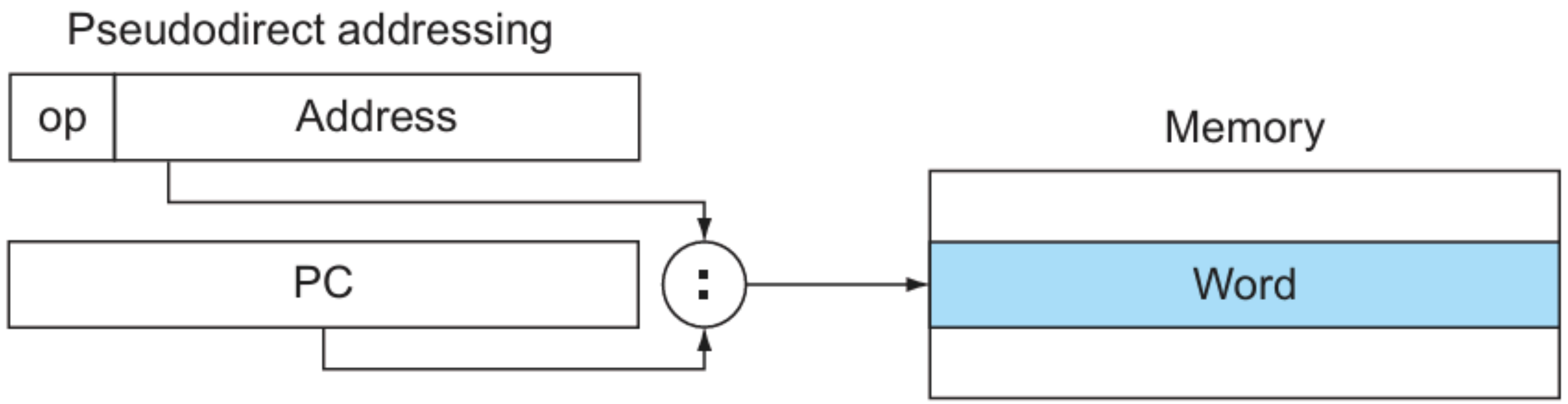

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