CSCI2510 Computer Organization
Lecture 09:
Basic Processing Unit

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Basic Functional Units of a Computer

I/O		Memory	Processor / CPU
Input	**Output**		**Registers** / **Arithmetic and Logic Unit** / **Control**
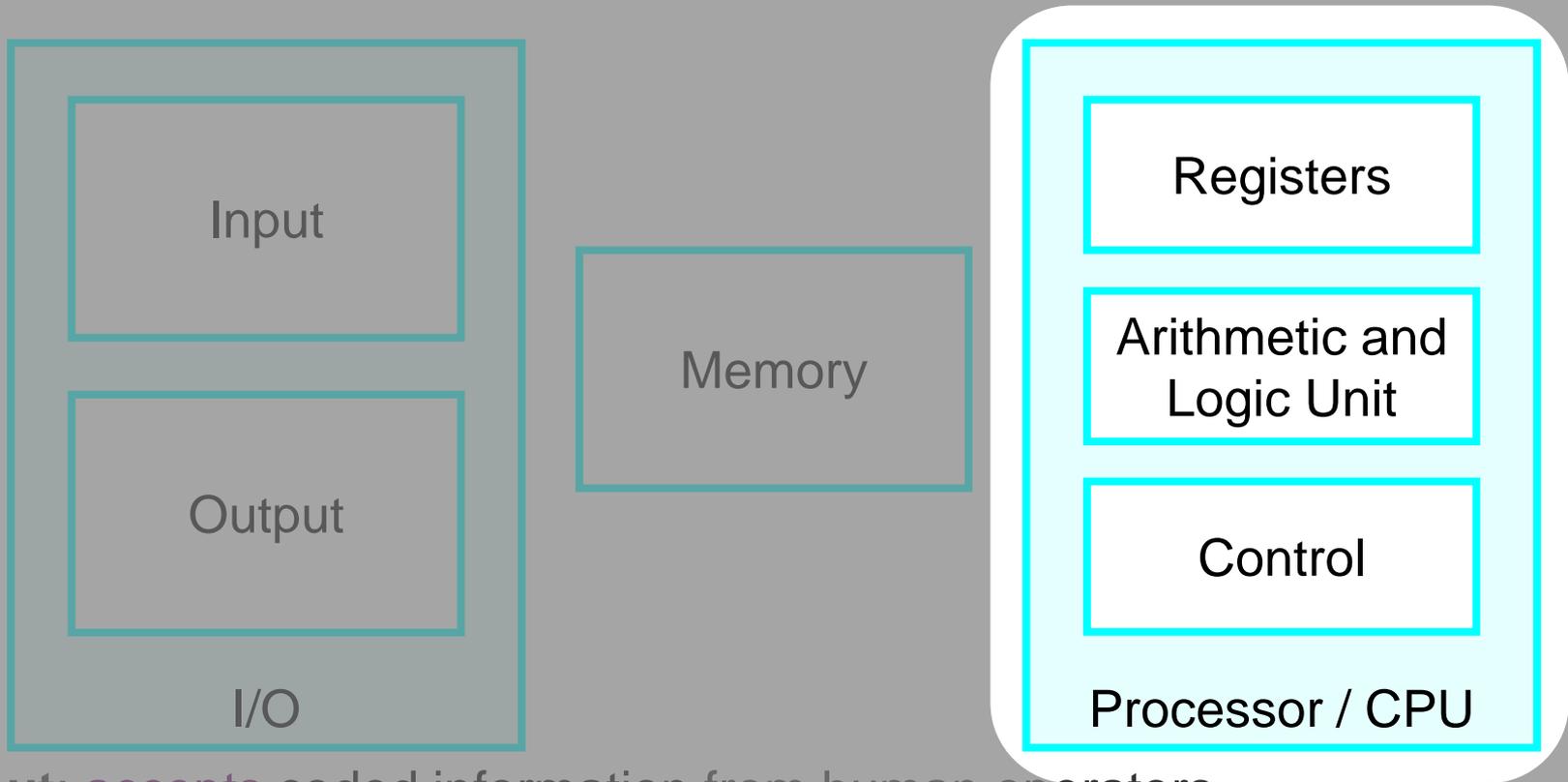
- **Input**: accepts coded information from human operators.
- **Memory**: stores the received information for later use.
- **Processor**: executes the instructions of a program stored in the memory.
- **Output**: reacts to the outside world.
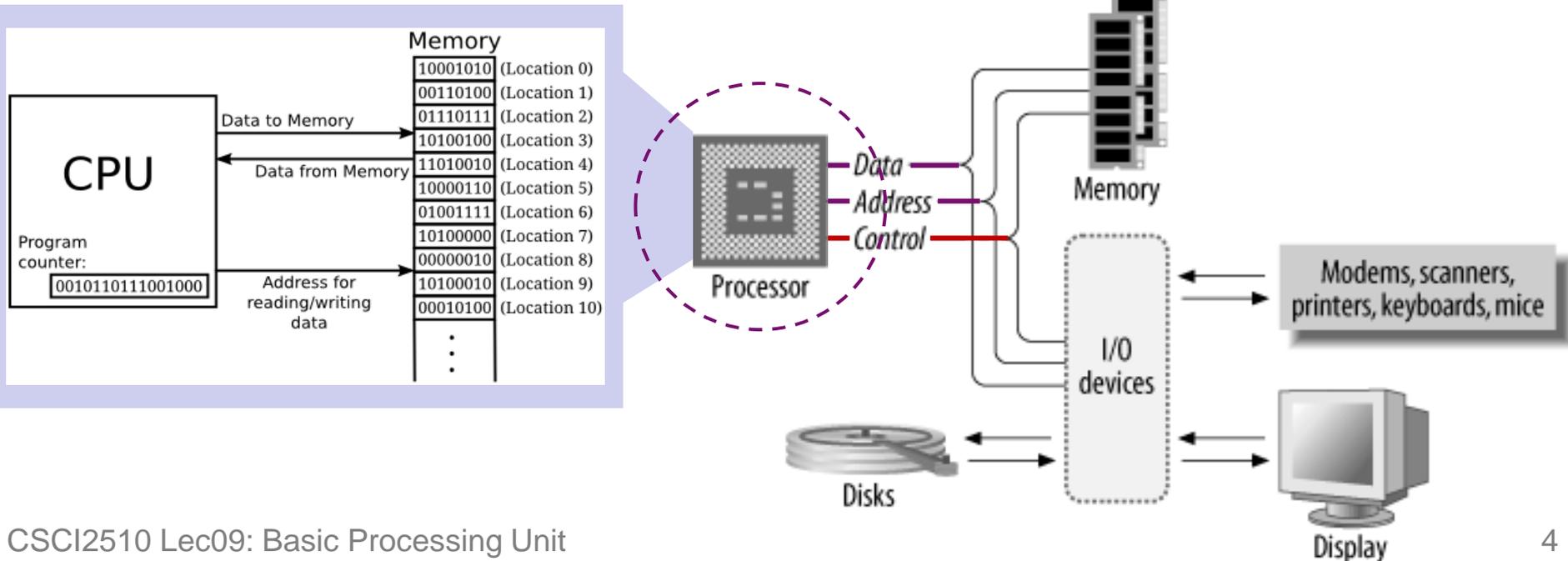- **Control**: coordinates all these actions.

Outline

- Processor Internal Structure

- Instruction Execution

  - Fetch Phase

  - Execute Phase

- Execution of A Complete Instruction
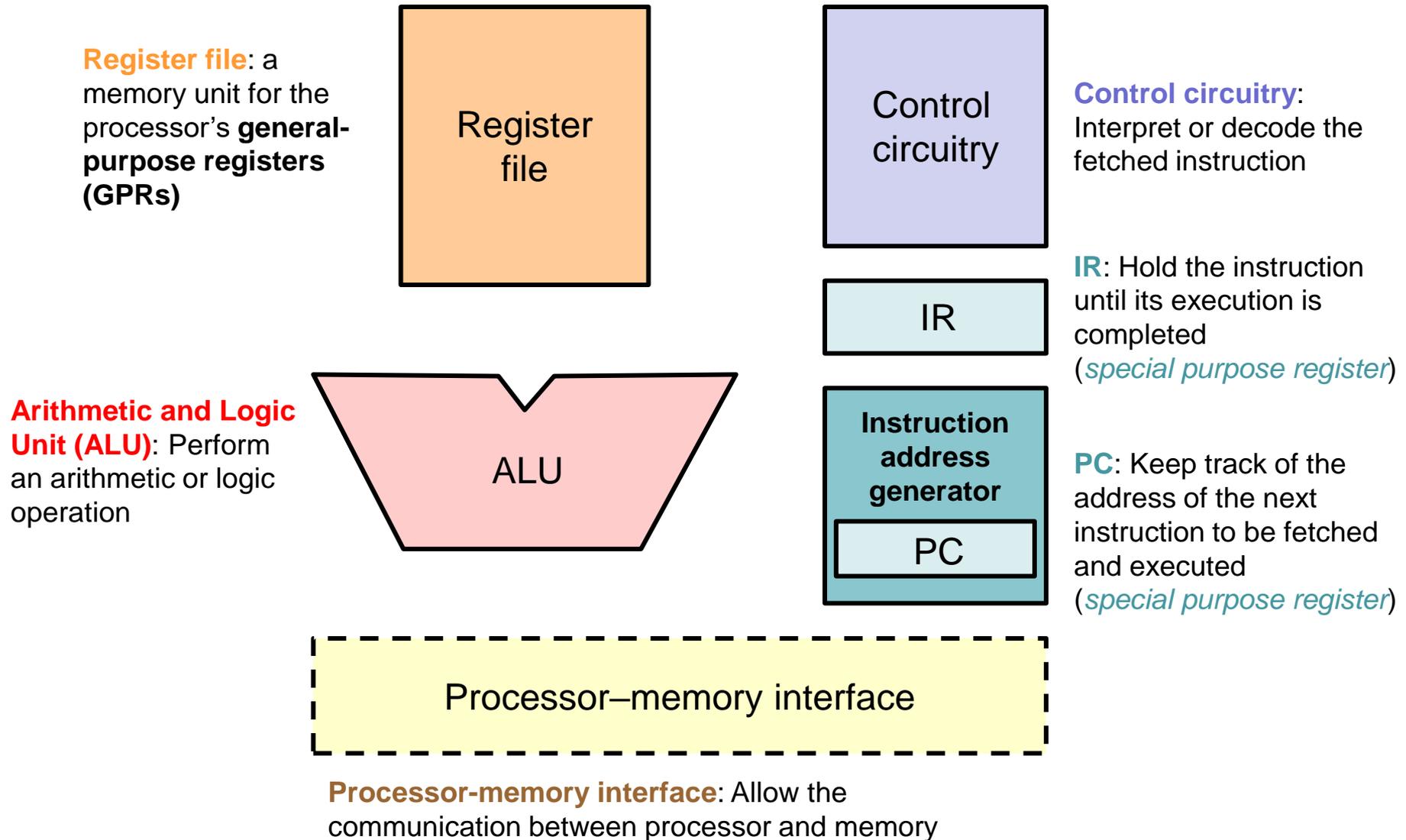
- Multiple-Bus Organization

Basic Processing Unit: Processor

- **Executes** machine-language instructions.
- **Coordinates** other units in a computer system.
- Often be called the central processing unit (CPU).
  - The term "central" is no longer appropriate today.
  - Today's computers often include several processing units.
    - E.g., multi-core processor, graphic processing unit (GPU), etc.

Main Components of a Processor

Register file: a memory unit for the processor's **general-purpose registers (GPRs)**

Register file

Arithmetic and Logic Unit (ALU): Perform an arithmetic or logic operation

ALU

Control circuitry

Control circuitry: Interpret or decode the fetched instruction

IR

IR: Hold the instruction until its execution is completed (*special purpose register*)

Instruction address generator

PC

PC: Keep track of the address of the next instruction to be fetched and executed (*special purpose register*)

Processor–memory interface

Processor-memory interface: Allow the communication between processor and memory
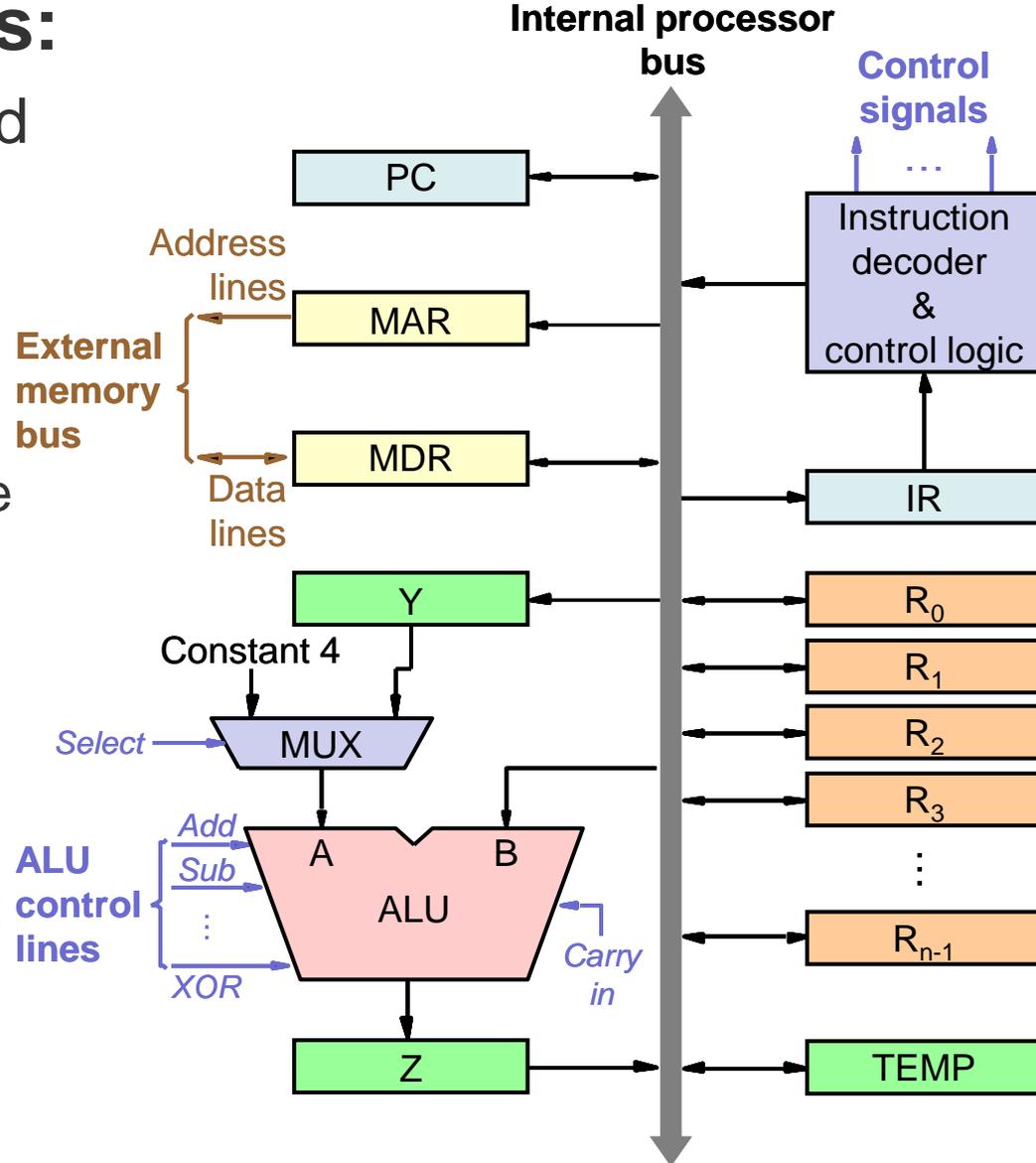
- **Internal Processor Bus:**
  - ALU, control circuitry, and all the registers are interconnected via a **single common bus**.
    - The bus is <u>internal</u> to the processor (i.e., only visible to the processor).
  - **Black** parts: <u>data (and control) path</u>
  - **Blue** parts: <u>control path</u>
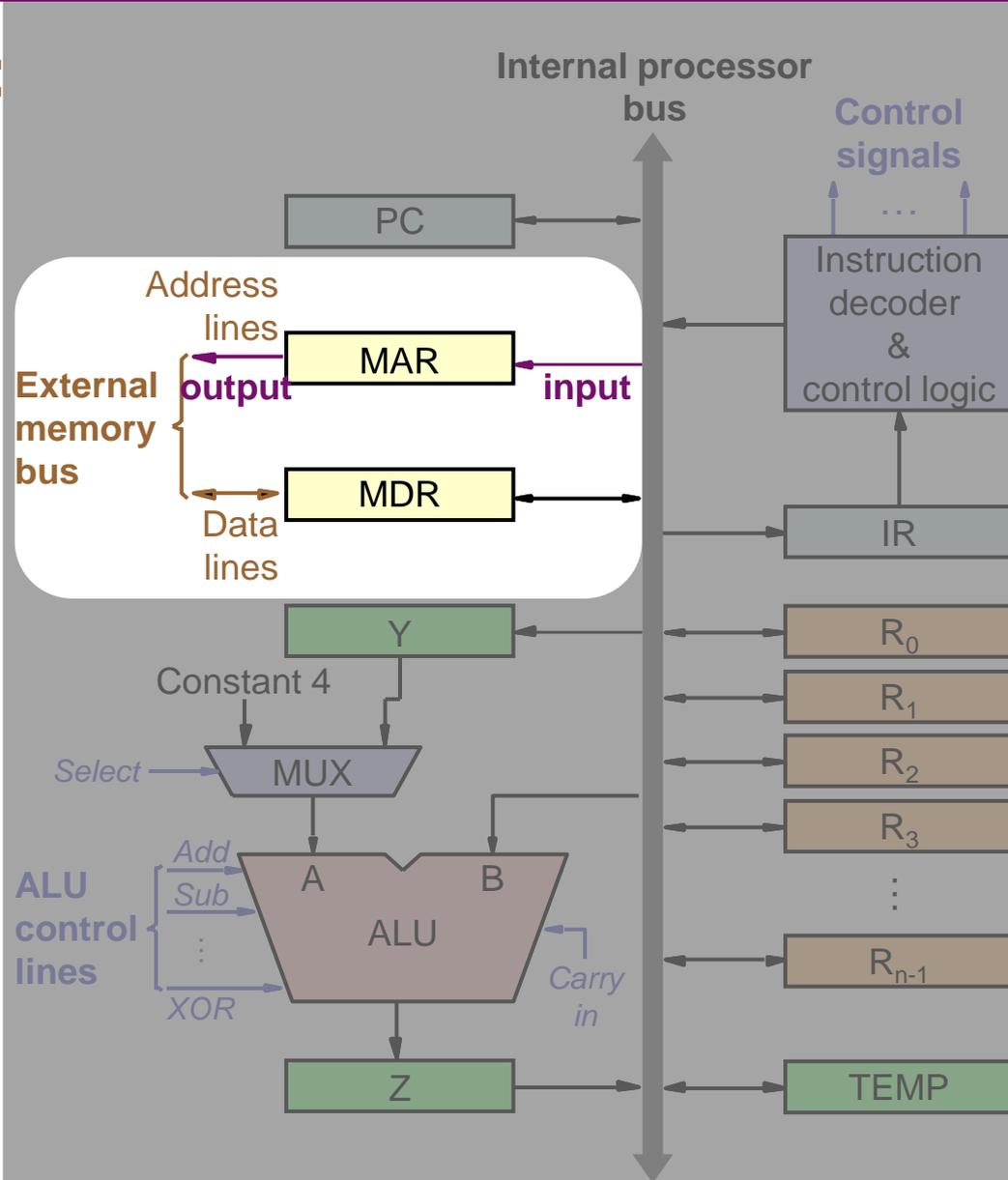- **External Memory Bus:**
  - **Brown** part: <u>external memory path</u>

- **External Memory Bus:**

  - **Processor-memory interface**: External memory bus are controlled through <u>MAR</u> and <u>MDR</u>.

  - **MAR**: Specify the requested memory address
    - **Input**: Address is specified by processor via <u>internal processor bus</u>.
    - **Output**: Address is send to the memory via <u>external memory bus</u>.

- **External Memory Bus:**
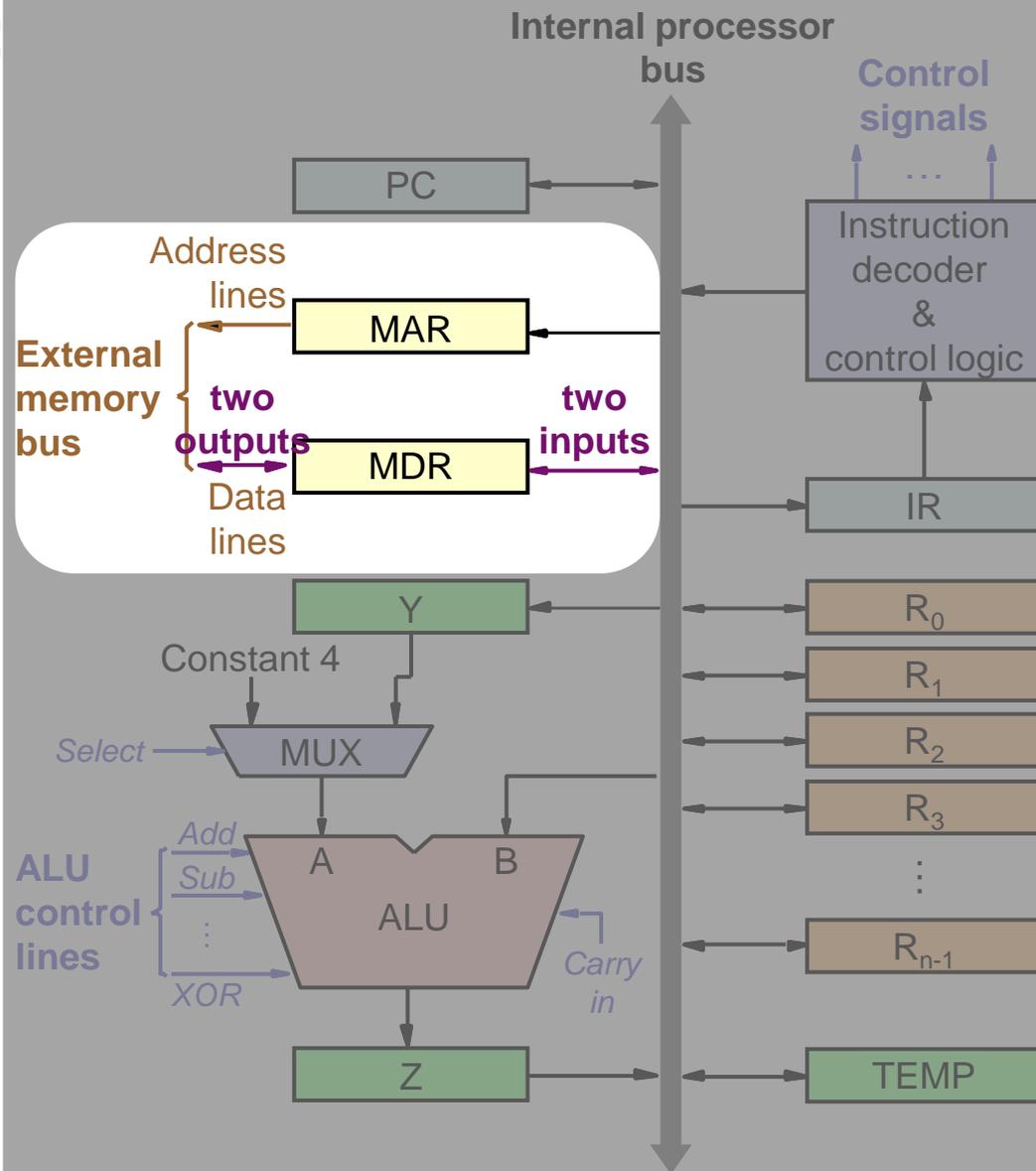
  – **MDR**: Keep the content of the requested memory address

    • There are two inputs and two outputs for MDR.

    • **Inputs**: Data may be placed into MDR either
      – From the internal processor bus or
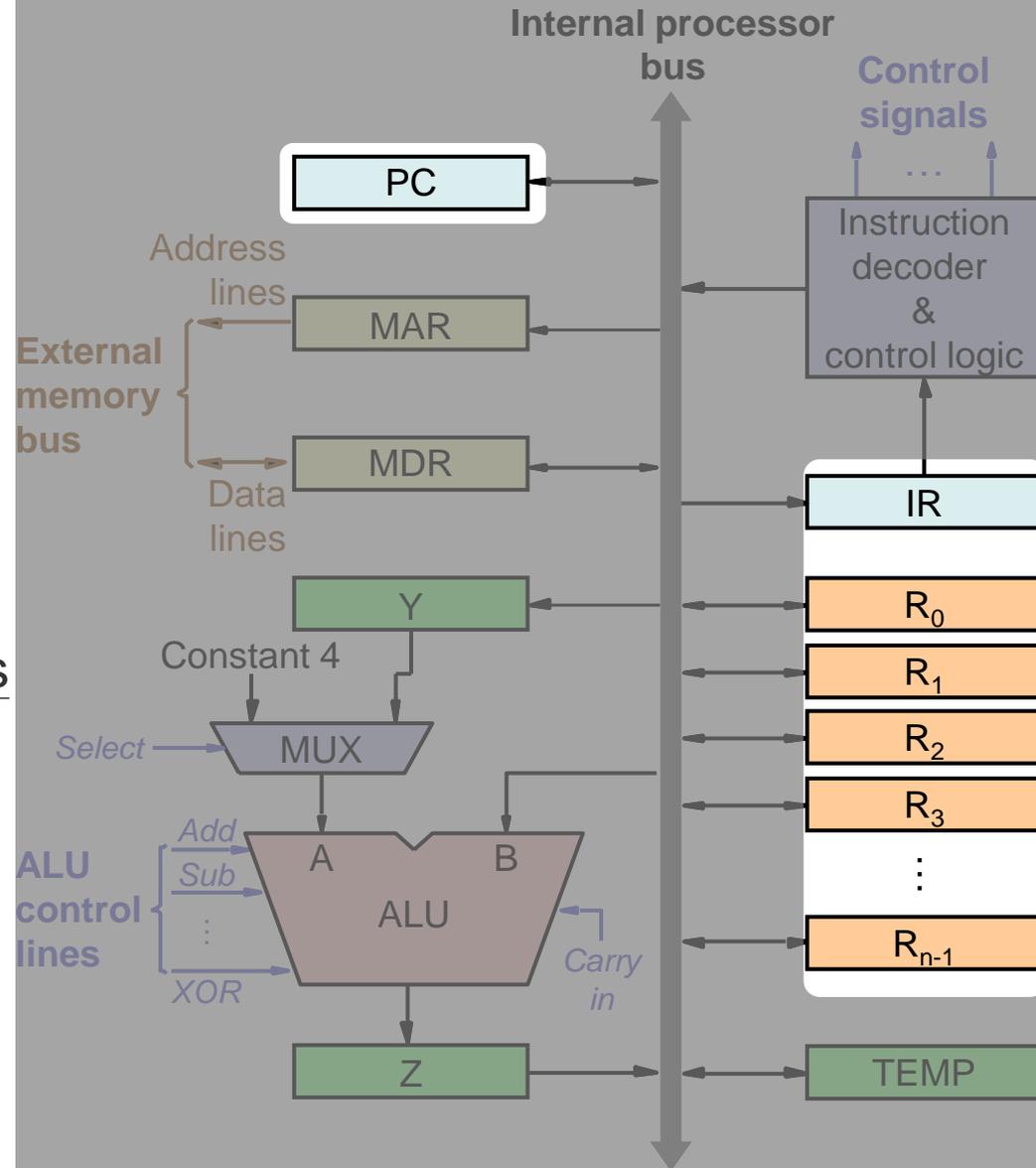   – From the external memory bus.

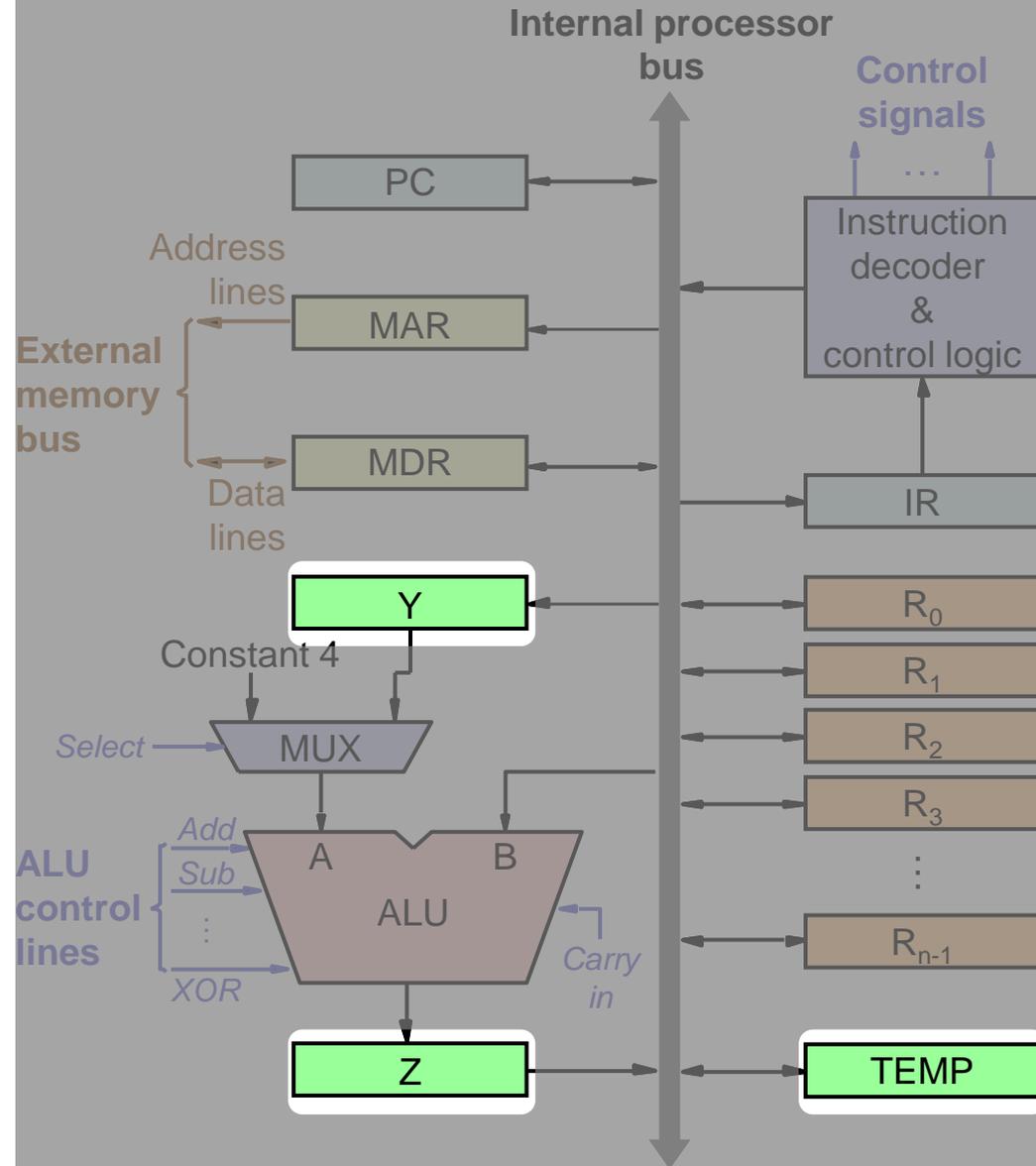   • **Outputs**: Data stored in MDR may be loaded from either bus.

- **General-Purpose Registers:**
  - R_0 through R_{n-1}
    - *n* varies from one processor to another.

- **Special Registers:**
  - **Program Counter**
    - Keep track of the address of the next instruction to be fetched and executed.
  - **Instruction Register**
    - Hold the instruction until the current execution is completed.

Internal processor bus

Control signals

…

PC

Address lines

MAR

External memory bus

MDR

Data lines

Instruction decoder & control logic

IR

Y

Constant 4

Select — MUX

Add
Sub
…
XOR

ALU control lines

A   B

ALU

Carry in

R_0

R_1

R_2

R_3

⋮

R_{n-1}

Z

TEMP

- **Special Registers: Y, Z, & TEMP**
  - <u>Transparent</u> to the programmer.
  - **Used** by the processor for <u>temporary storage</u> during execution of some instructions.
  - **Never used** for storing data generated by one instruction <u>for later use</u> by another instruction.
  - We will discuss their functionalities later.

Internal processor bus

Control signals

…

PC

Address lines

MAR

External memory bus

MDR

Data lines

Instruction decoder & control logic

IR

Y

Constant 4

Select → MUX

ALU control lines
- Add
- Sub
- …
- XOR

A   B

ALU

Carry in

Z

R_0

R_1

R_2

R_3

…

R_{n-1}

TEMP

- **Arithmetic and Logic Unit (ALU):**
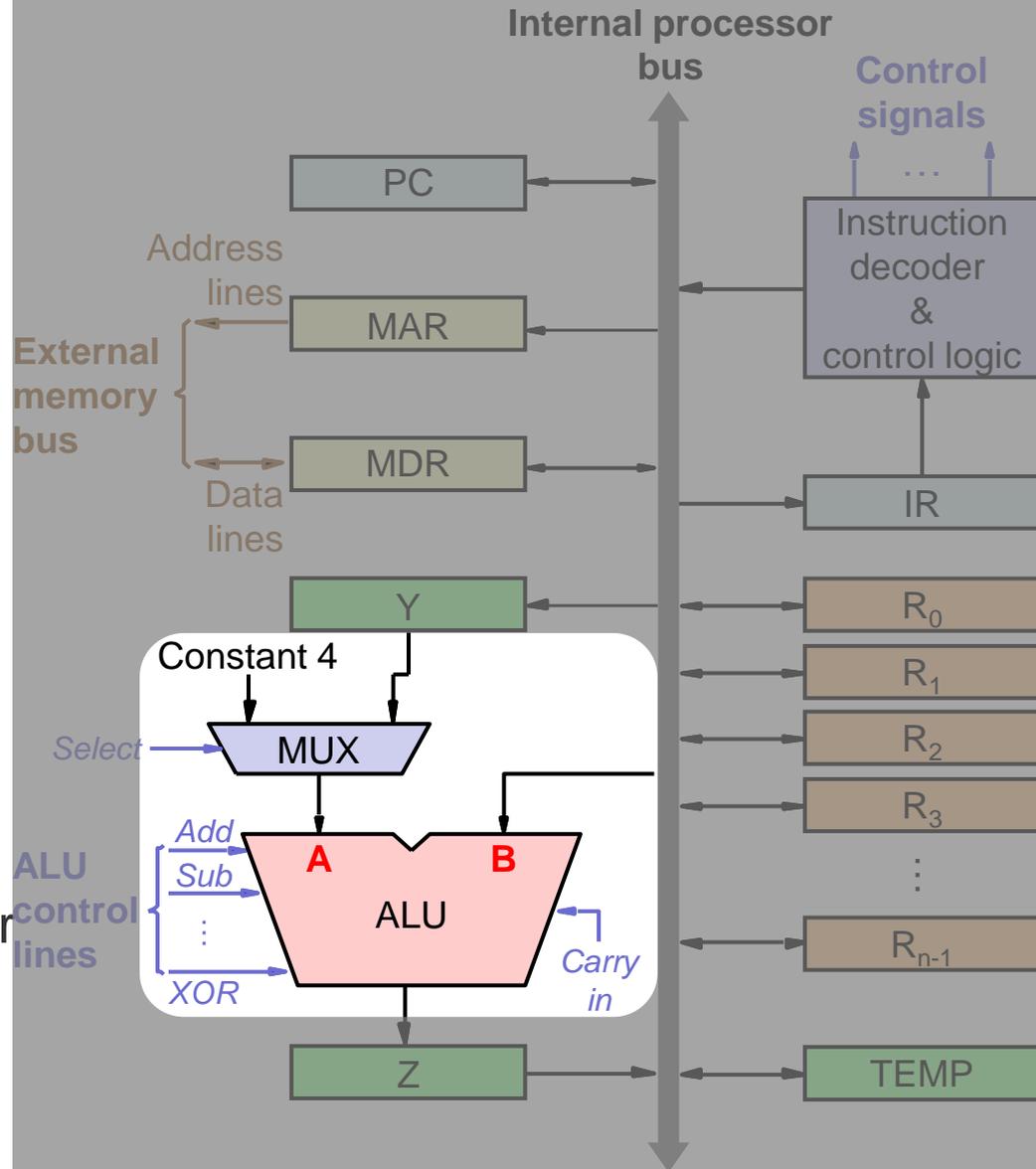 - Perform arithmetic or logic operation

    $Z = A$ operator B
    - Two inputs A and B
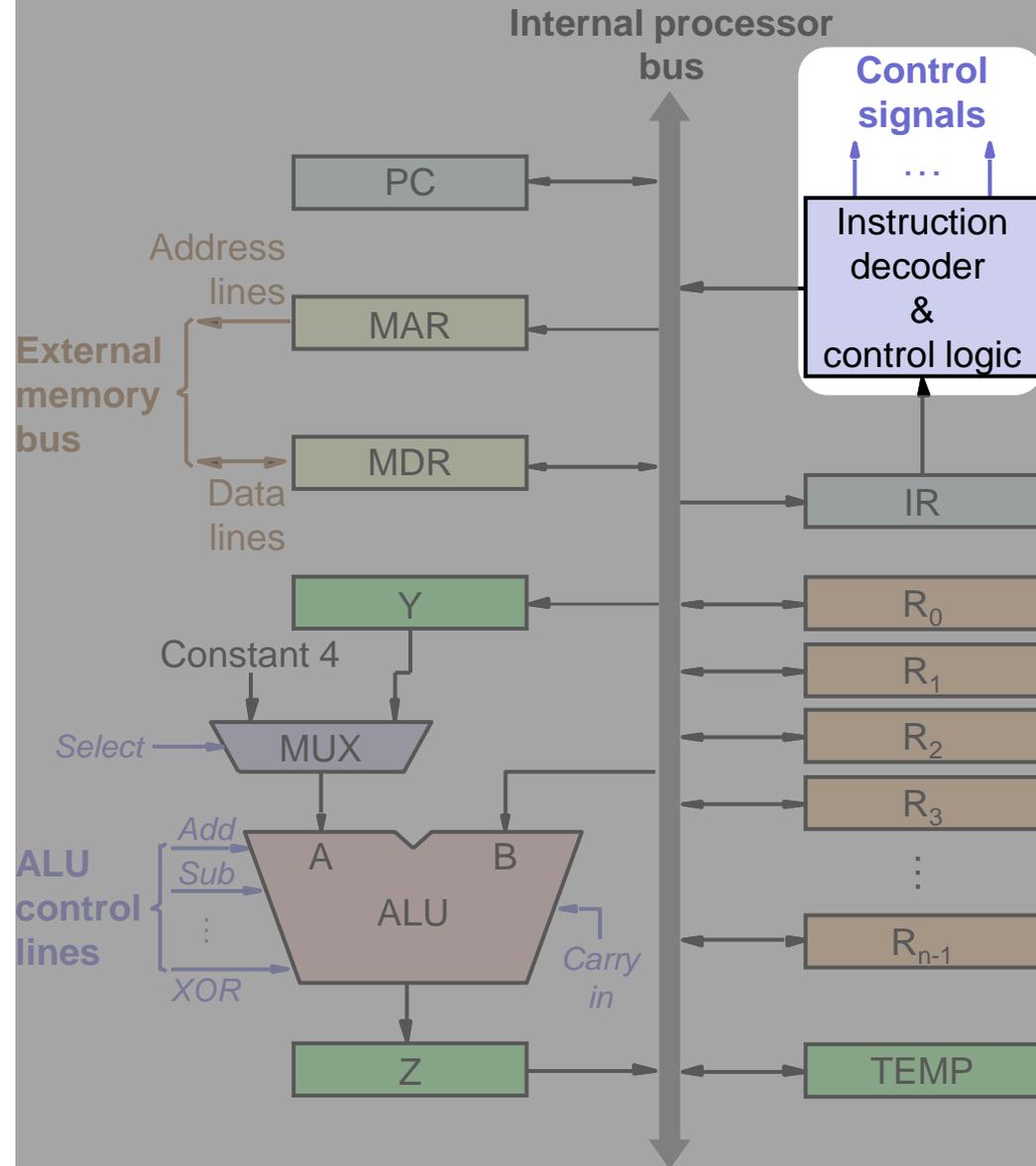   - One output to register Z

- **Multiplexer (MUX):**
  - The **input A** of ALU: Select (*ctrl line*) either
    - The output of register Y or
    - A constant value 4 (for incrementing PC).

Internal processor bus

Control signals

...

| PC |

Address lines

| MAR |

External memory bus

| MDR |

Data lines

Instruction decoder & control logic

| IR |

| Y |

Constant 4

Select → MUX

Add
Sub
...
XOR

ALU control lines

A   B

ALU

Carry in

| Z |

| R_0 |
| R_1 |
| R_2 |
| R_3 |
...
| R_{n-1} |

| TEMP |

Processor Internal: Control Circuitry

- **Instruction decoder:**
  - Interpret the fetched instruction stored in the IR register.

- **Control logic:**
  - Issue control signals to control the all the units inside the processor.
    - E.g., ALU control lines, select-signal for MUX, carry-in for ALU, etc.
  - Interact with the external memory bus.

Internal processor bus

Control signals
…

Instruction decoder & control logic

PC

Address lines

MAR

External memory bus

MDR

Data lines

IR

Y

Constant 4

Select — MUX

R_0

R_1

R_2

R_3

Add
Sub
…
XOR

ALU control lines

A   B

ALU

Carry in

R_{n-1}

Z

TEMP

Outline

- Processor Internal Structure

- Instruction Execution
  - Fetch Phase
  - Execute Phase

- Execution of A Complete Instruction

- Multiple-Bus Organization

Recall: Register Transfer Notation

- Register Transfer Notation (RTN) describes the *data transfer* from one *location* in computer to another.
  - Possible locations: memory locations, processor registers.
    - Locations can be identified symbolically with names (e.g. LOC).

Ex.

$$R2 \leftarrow [LOC]$$

  - *Transferring the contents of memory LOC into register R2.*

① **Contents of any location**: denoted by placing square brackets **[ ]** around its location name (e.g. **[LOC]**).

② **Right-hand side** of RTN: always denotes a value

③ **Left-hand side** of RTN: the name of a location where the value is to be placed (by overwriting the old contents)
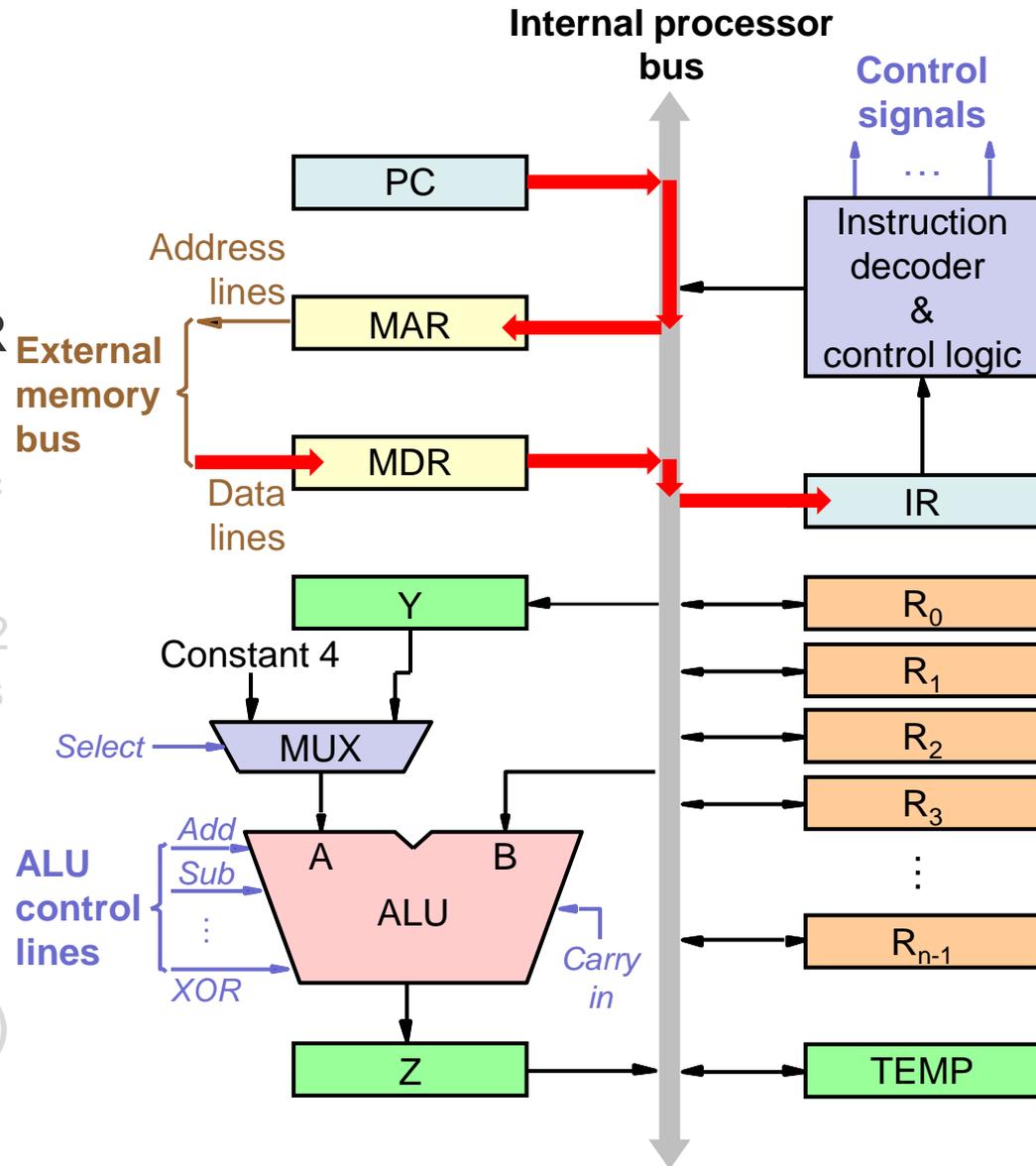
1) **Fetch Phase**

– **IR ← [[PC]]**

• Fetch the contents of the memory location pointed to by PC, and load into IR

– **PC ← [PC]+4**

• Increment the contents of PC by 4.

– Why 4? Instruction is 32 bits (4B) and memory is byte addressable.

2) Execute Phase

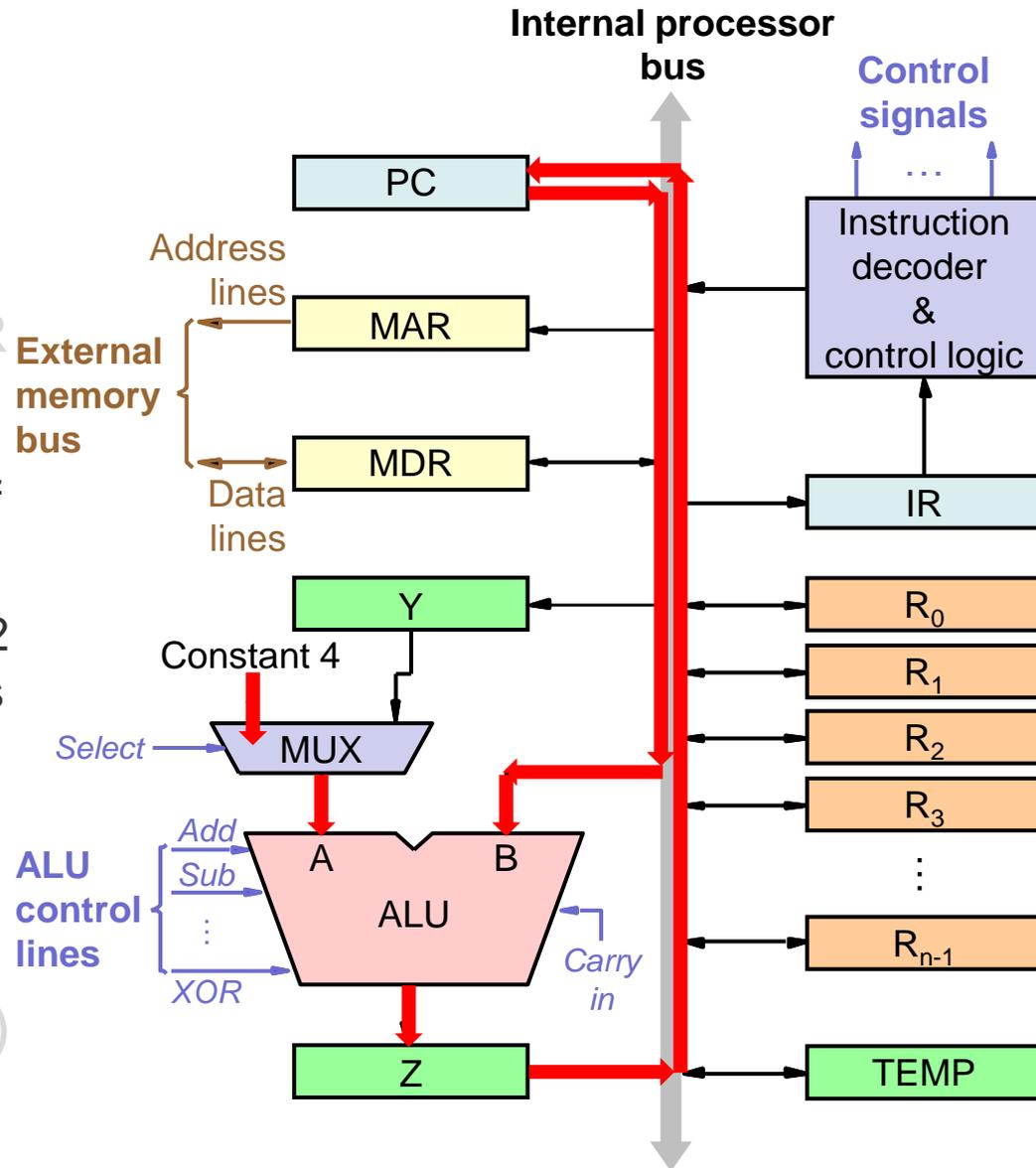– Decode instruction in IR

– Perform the operation(s)

1) Fetch Phase

- IR ← [[PC]]
  - Fetch the contents of the memory location pointed to by PC, and load into IR

- **PC ← [PC]+4**
  - Increment the contents of PC by 4.
    - Why 4? Instruction is 32 bits (4B) and memory is byte addressable.

2) Execute Phase

- Decode instruction in IR
- Perform the operation(s)

Internal processor bus

Control signals

…

PC

Address lines

MAR

External memory bus

MDR

Data lines

Instruction decoder & control logic

IR

Y

Constant 4

MUX

Select

Add
Sub
…
XOR

ALU control lines

A   B

ALU

Carry in

Z

R_0

R_1

R_2

R_3

⋮

R_{n-1}

TEMP

1) **Fetch Phase**

– **IR ← [[PC]]**

  • Fetch the contents of the memory location pointed to by PC, and load into IR

– **PC ← [PC]+4**

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    – Why 4? Instruction is 32 bits (4B) and memory is byte addressable.

2) **Execute Phase**

– Decode instruction in IR

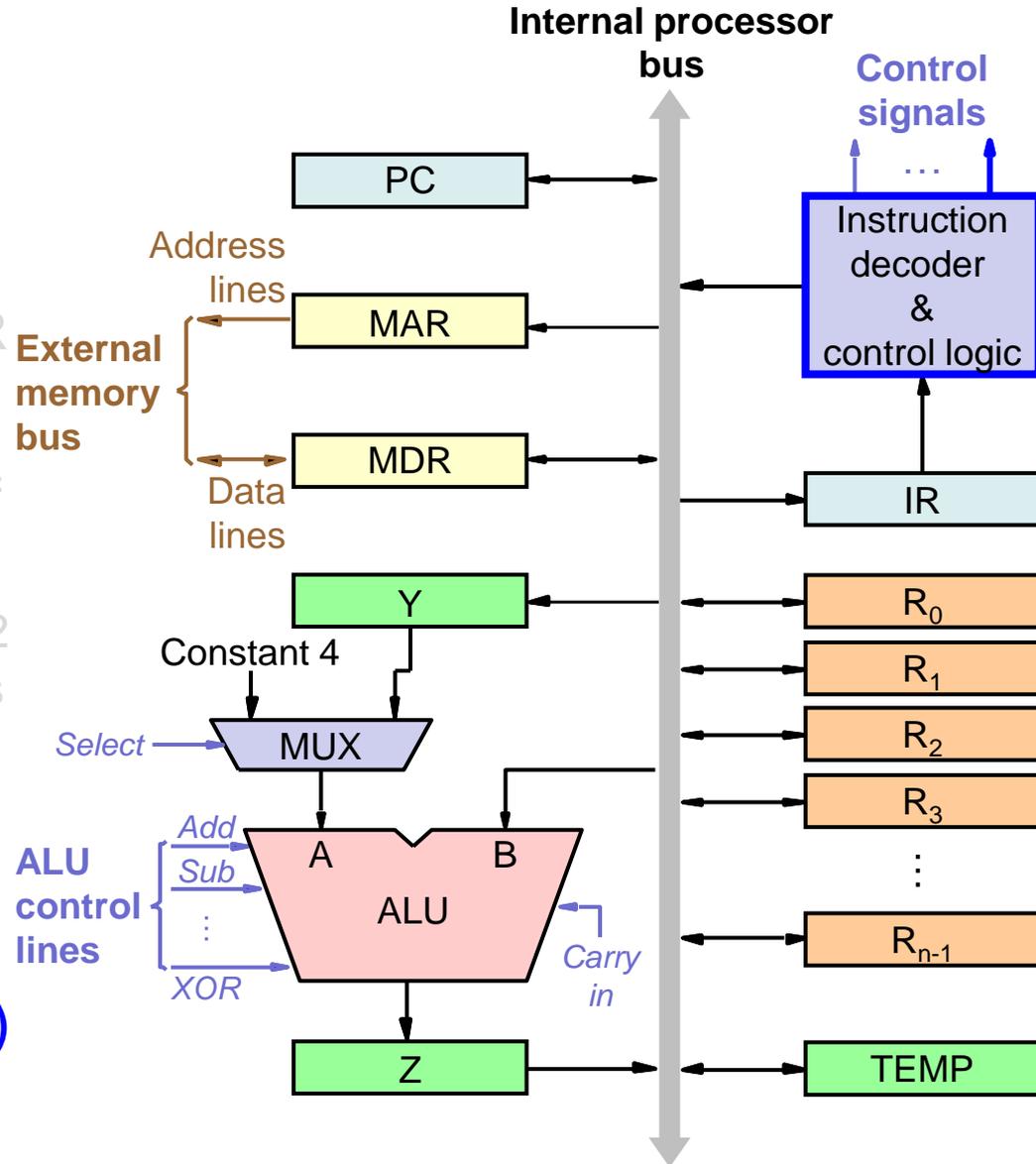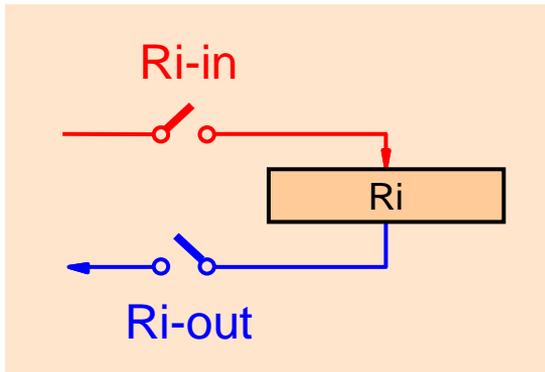– Perform the operation(s)

Instruction Execution: Execute Phase

- An instruction can be executed by performing one or more of the following operation(s):

  1) **Transfer data** from a register to another register or to the ALU

  2) **Perform arithmetic** (or logic) **operations** and store the result into the special register Z

  3) **Load content** of a memory location to a register

  4) **Store content** of a register to a memory location

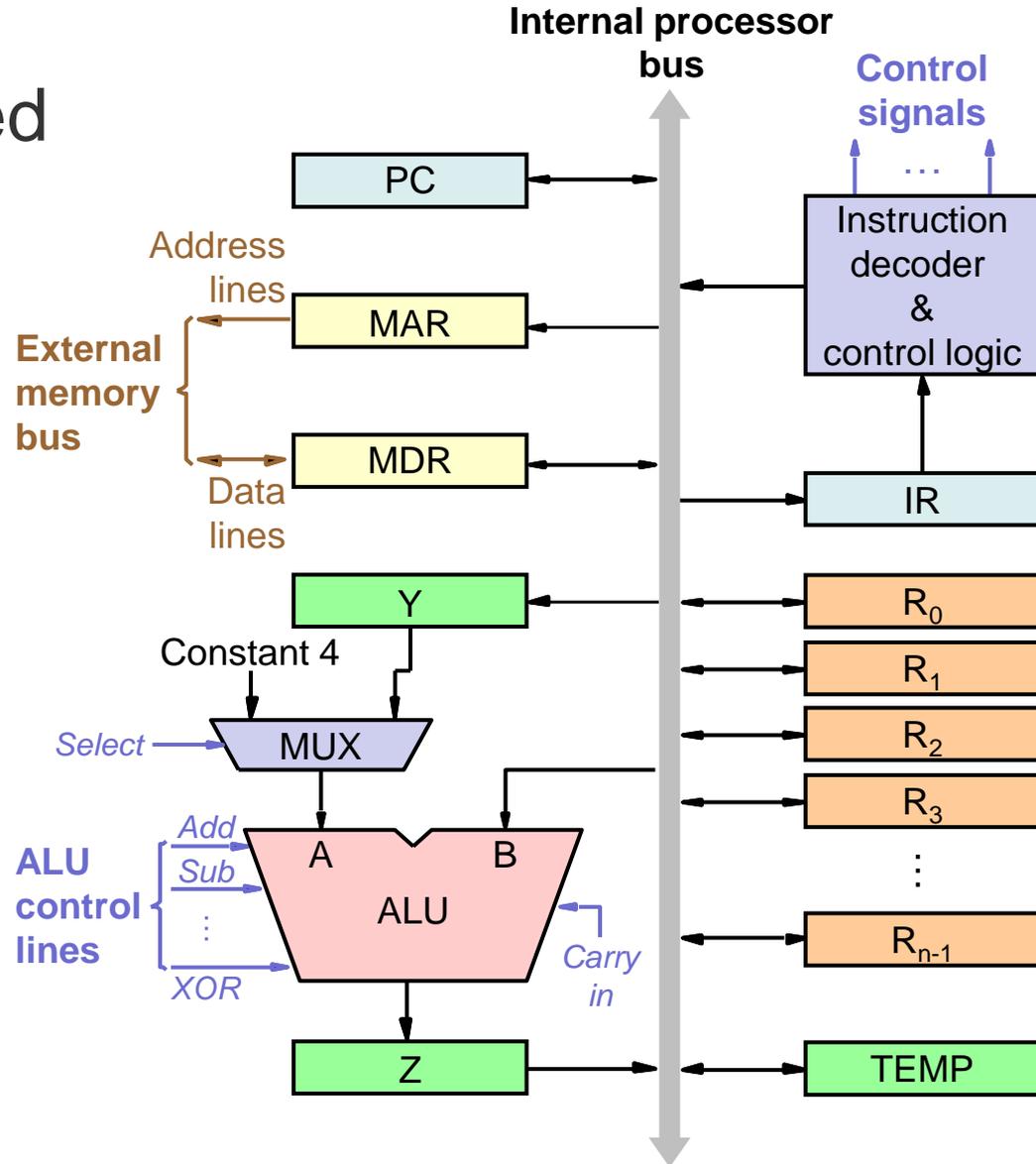- **Sequence of Control Steps**: Describes how these operations are performed in processor step by step.

- Input and output of register Ri are controlled by switches (⎯ᕁ⎯):
  - Ri-in: Allow data to be <u>transferred into</u> Ri

  Ri-in

  Ri

  Ri-out

  - Ri-out: Allow data to be <u>transferred out from</u> Ri

Internal processor bus

Control signals

...

PC

Address lines

Instruction decoder & control logic

MAR

External memory bus

MDR

Data lines

IR

Y

Constant 4

R_0

R_1

Select

MUX

R_2

R_3

Add

ALU control lines

Sub

A   B

...

...

ALU

R_{n-1}

XOR

Carry in

Z

TEMP
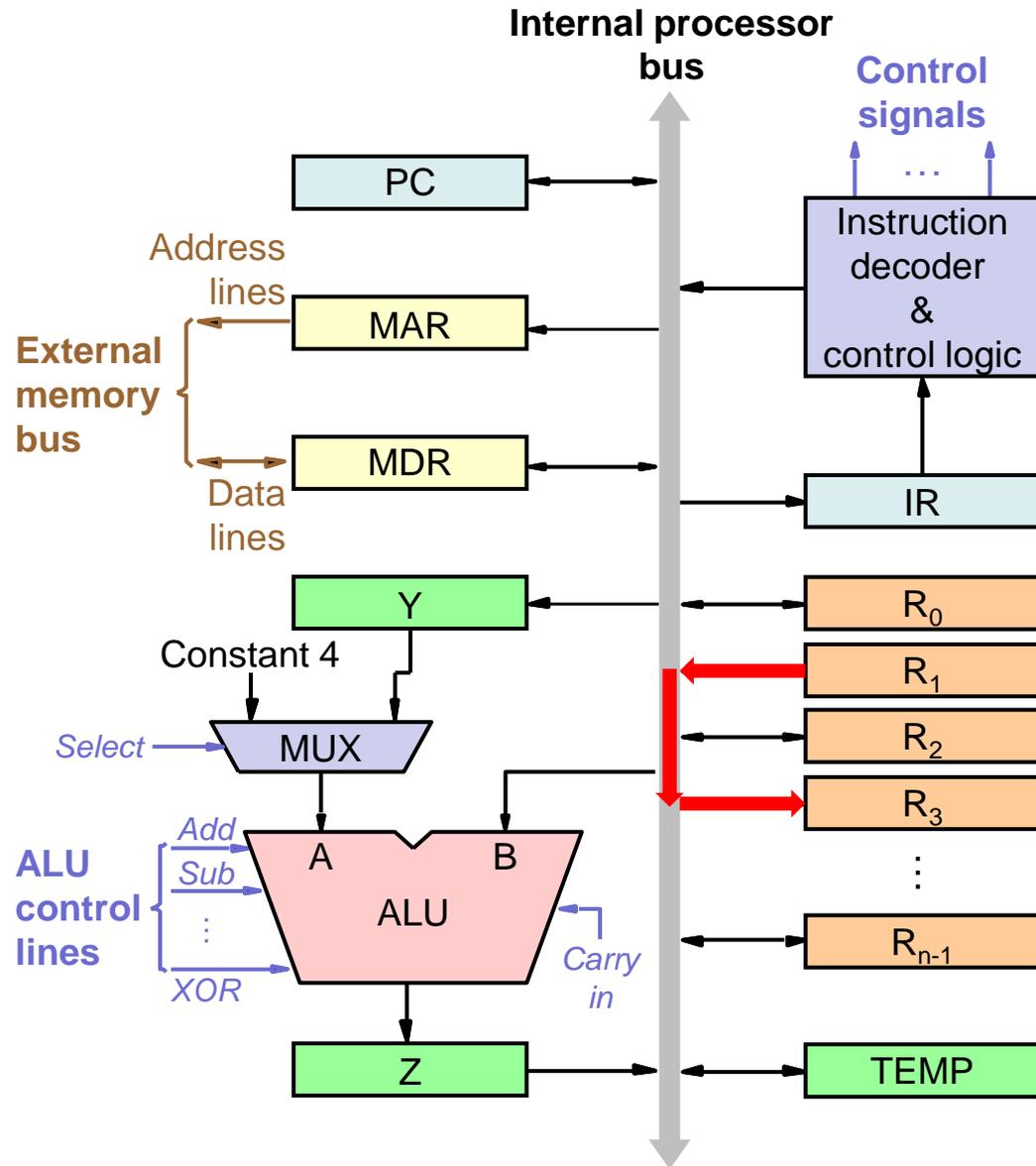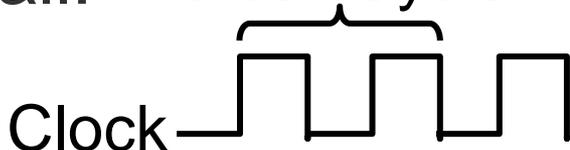
- Ex: **R3 ← [R1]**
  - ① Clock 1: R1-out, R3-in
    - Set R1-out to 1
    - Set R3-in to 1
    - Set all others to 0
  - ② Clock 2:
    - Reset R1-out to 0
    - Reset R3-in to 0

Sequence of Steps:
① R1-out, R3-in

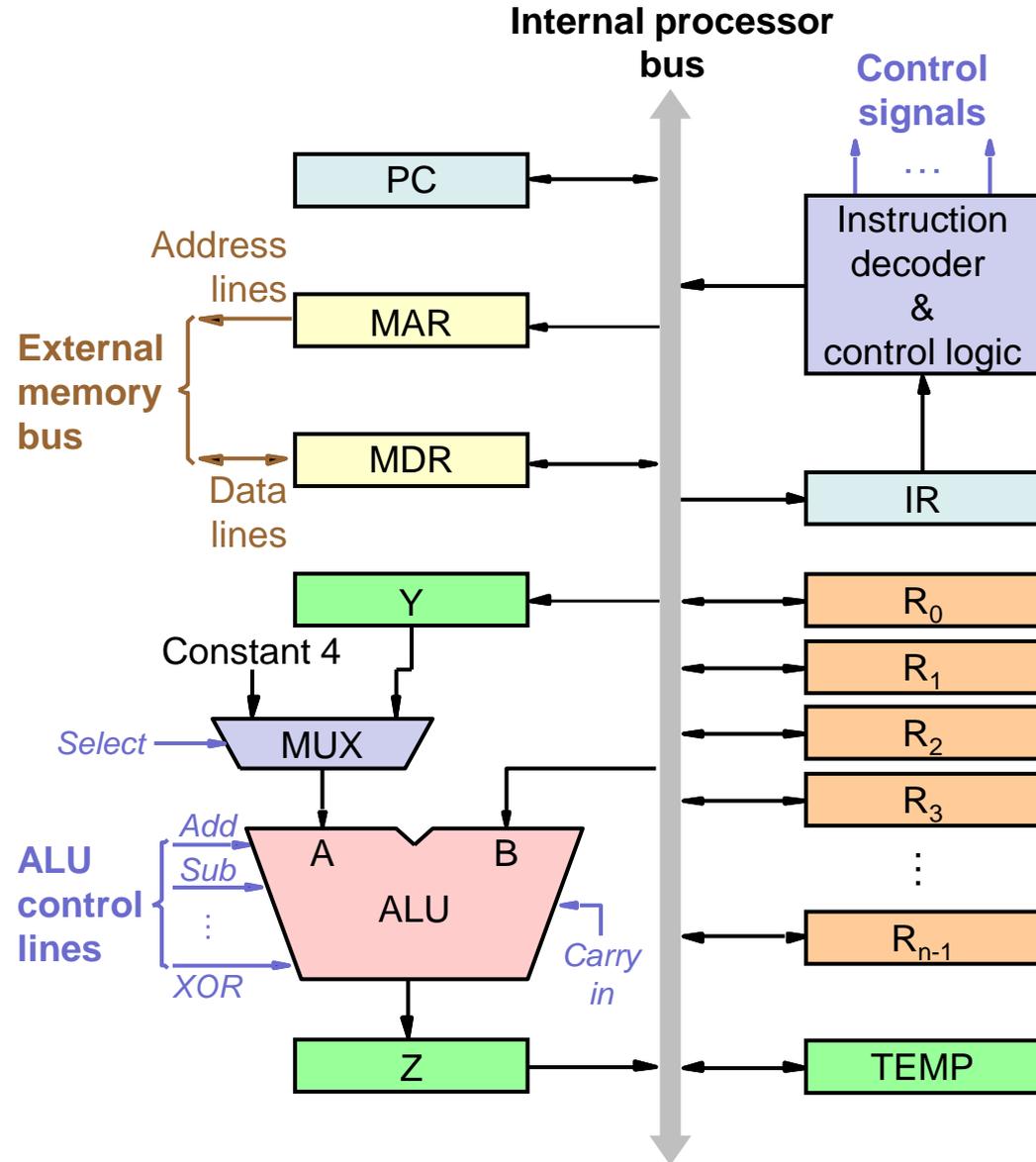*Note: Only state "**set**" for short.*

- Recall: Clock Cycle

Class Exercise 9.1

- What is the sequence of steps for the following operation?

   R1 ← [R3]

Internal processor bus

Control signals

PC

Instruction decoder & control logic

Address lines

MAR

External memory bus

MDR

Data lines

IR

Y

Constant 4

Select — MUX

ALU control lines

Add
Sub
XOR

A   B

ALU

Carry in

R_0

R_1

R_2

R_3
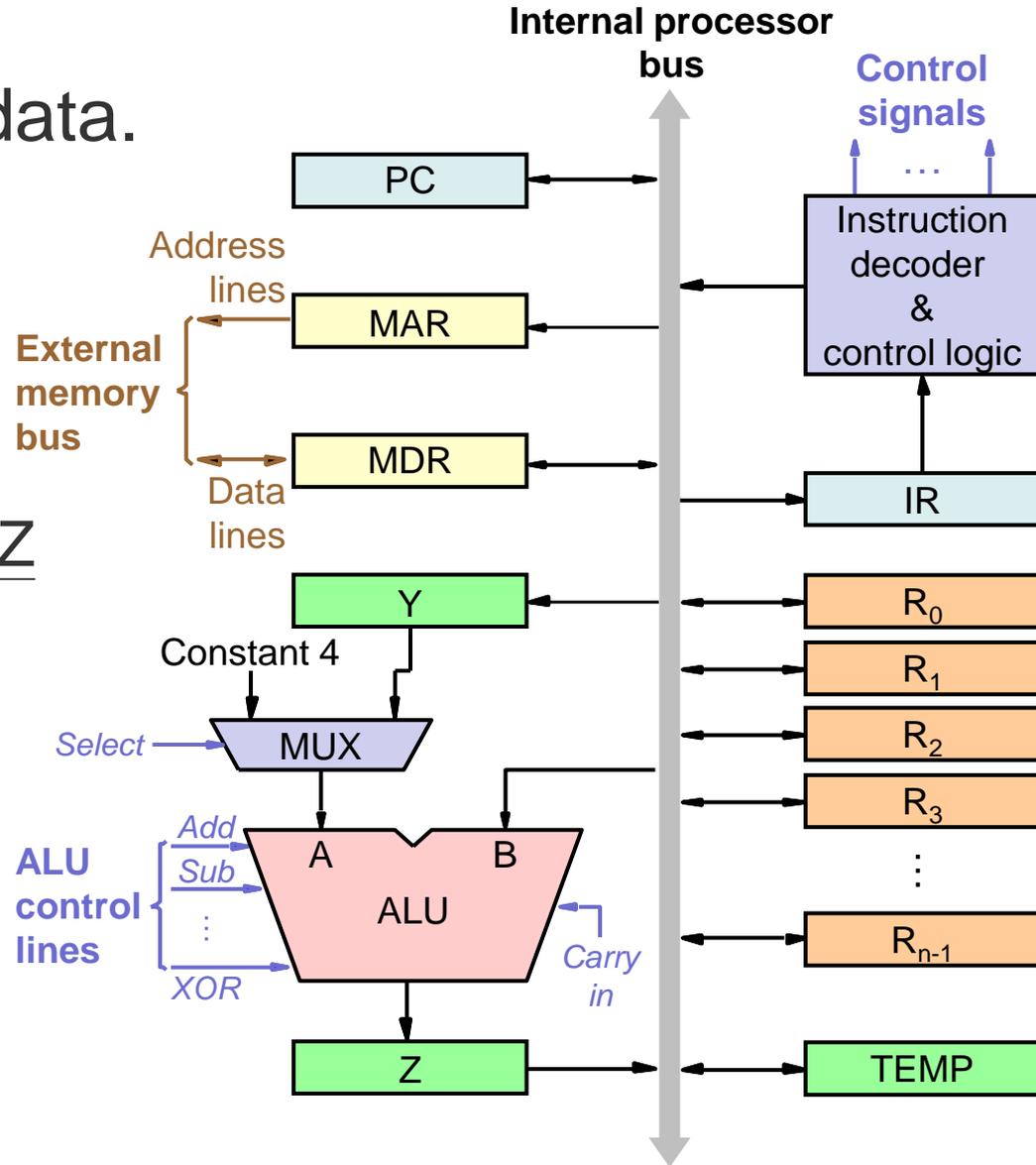
R_{n-1}

Z

TEMP

- **ALU**: A circuit <u>without</u> storage to manipulate data.
  - **Two inputs**: from A & B
    - **A**: #4 or <u>register Y</u>
    - **B**: Any other <u>register</u>
  - **ALU**: Perform operation
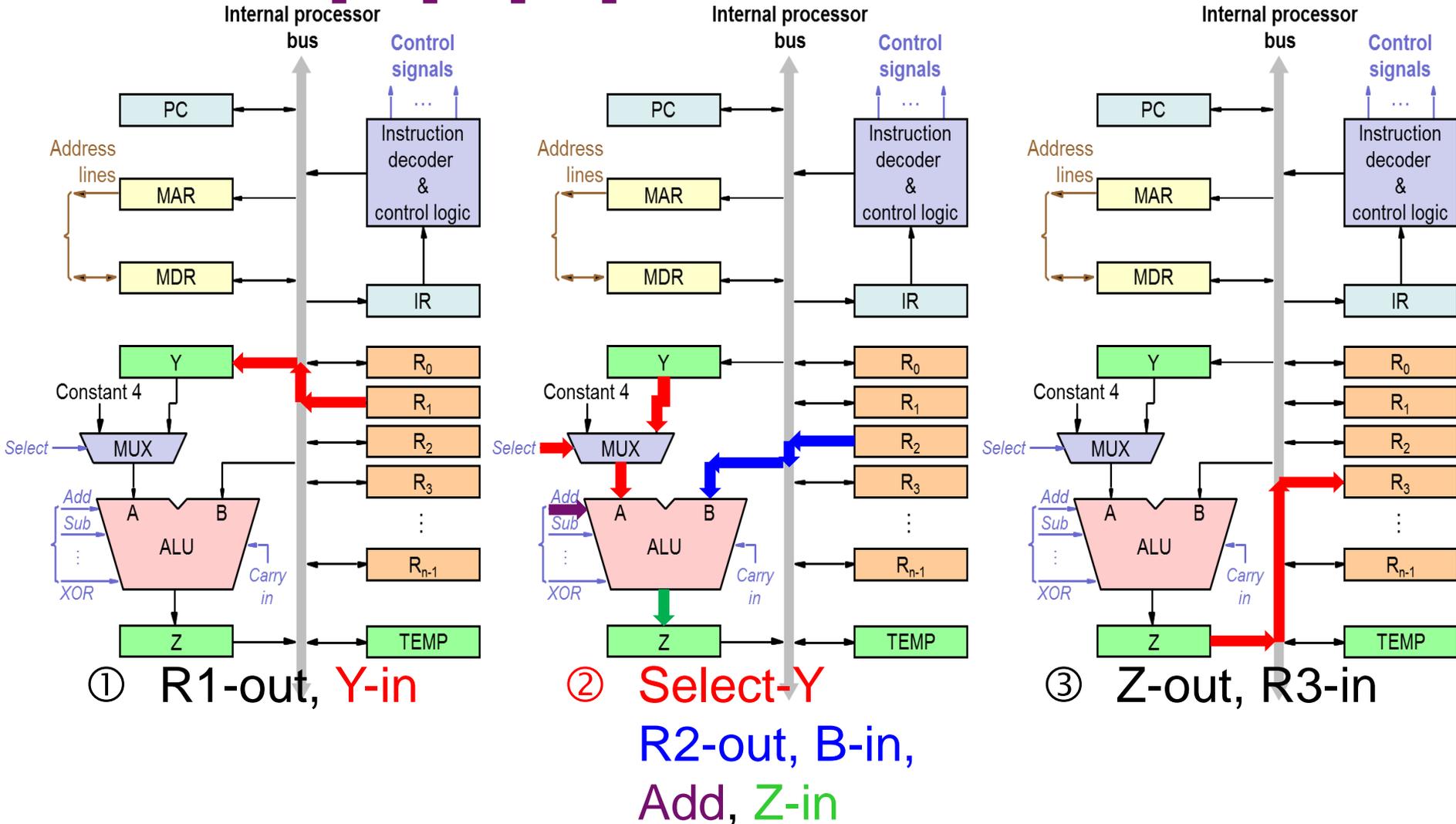 - **One output**: to <u>register Z</u>
- Ex: **R3 ← [R1] + [R2]**

Sequence of Steps:

① R1-out, Y-in

② Select-Y, R2-out, B-in, Add, Z-in

③ Z-out, R3-in

23

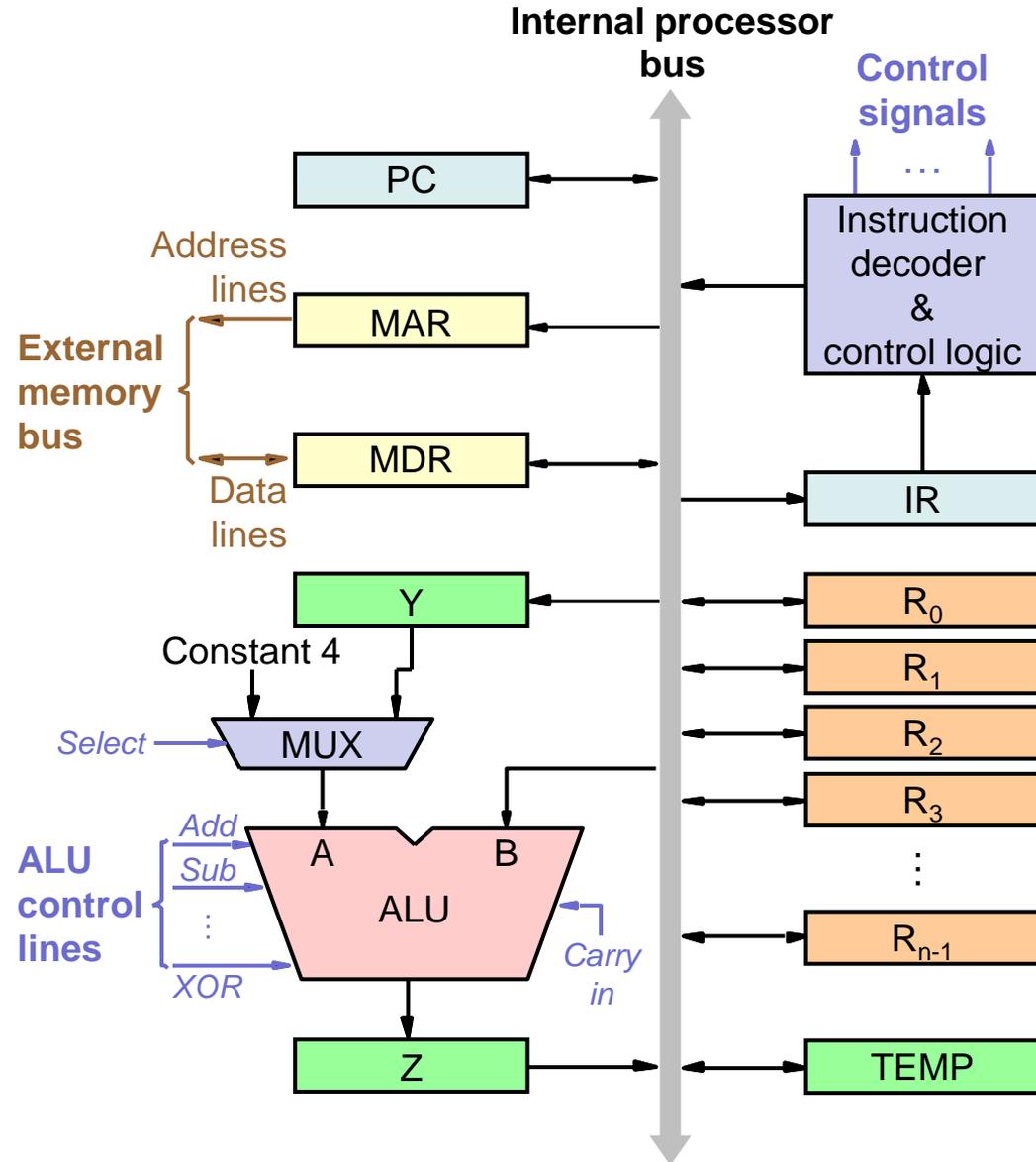# 2) Arithmetic or Logic Operation (Cont'd)

- Ex: **R3 ← [R1] + [R2]**

① R1-out, Y-in

② Select-Y
R2-out, B-in,
Add, Z-in

③ Z-out, R3-in

Question: Why to first transfer R1 to the special register Y?

- What is the sequence of steps for the following operation?

  R6 ← [R4] − [R5]

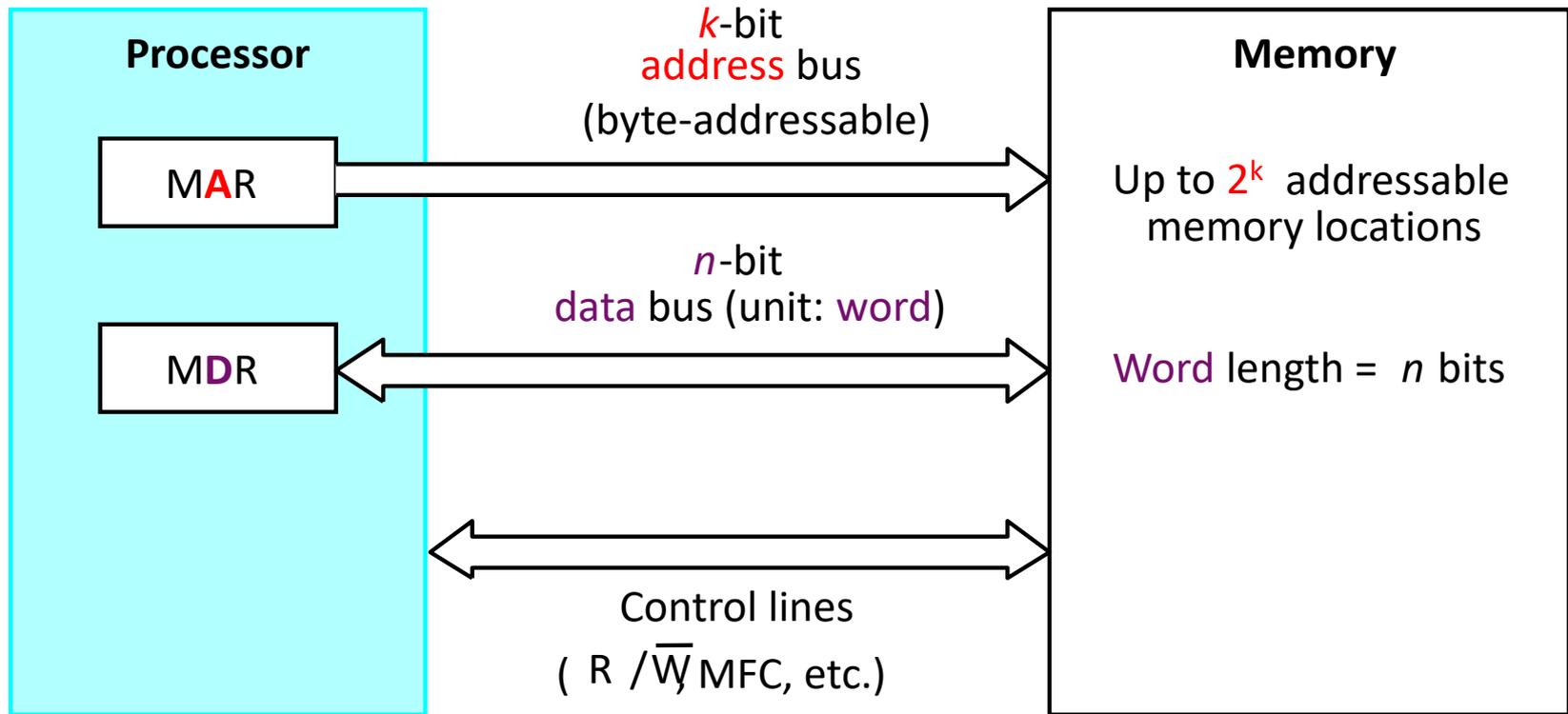- Data transferring takes place through MAR and MDR.
  - **MAR**: Memory Address Register
  - **MDR**: Memory Data Register

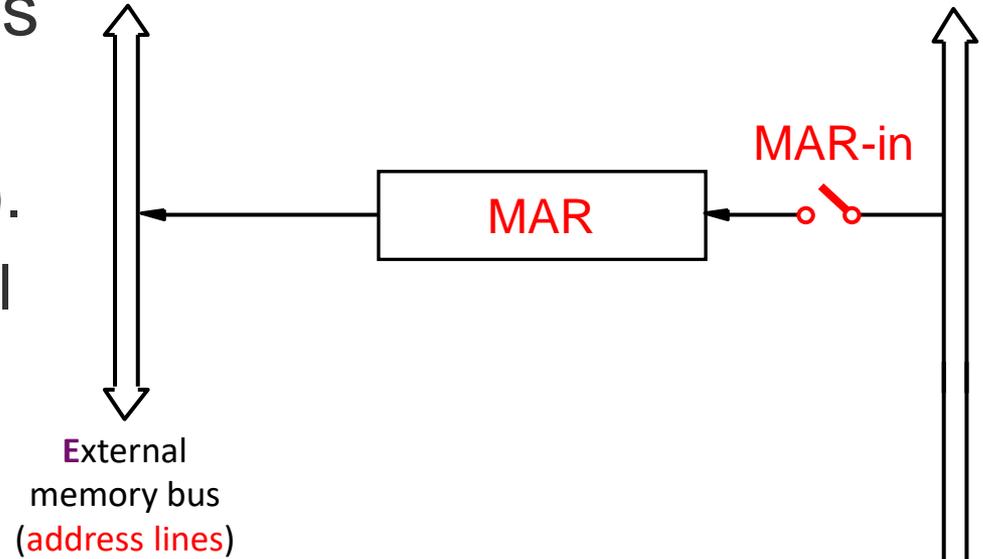*MFC (Memory Function Completed): Indicating the requested operation has been completed.*

- **MAR**: Memory Address Register
  - Uni-directional bus (←).
  - Connect to the external address lines directly.

- **MDR**: Memory Data Register
  - Bi-directional bus (←→).
  - MDR connections to both internal and external buses are all controlled by switches (⎯∘ᵒ⎯).

MAR-in

MAR

External memory bus (address lines)

MDR-outE   MDR-out

MDR

MDR-inE   MDR-in

External memory bus (data lines)

Internal processor bus
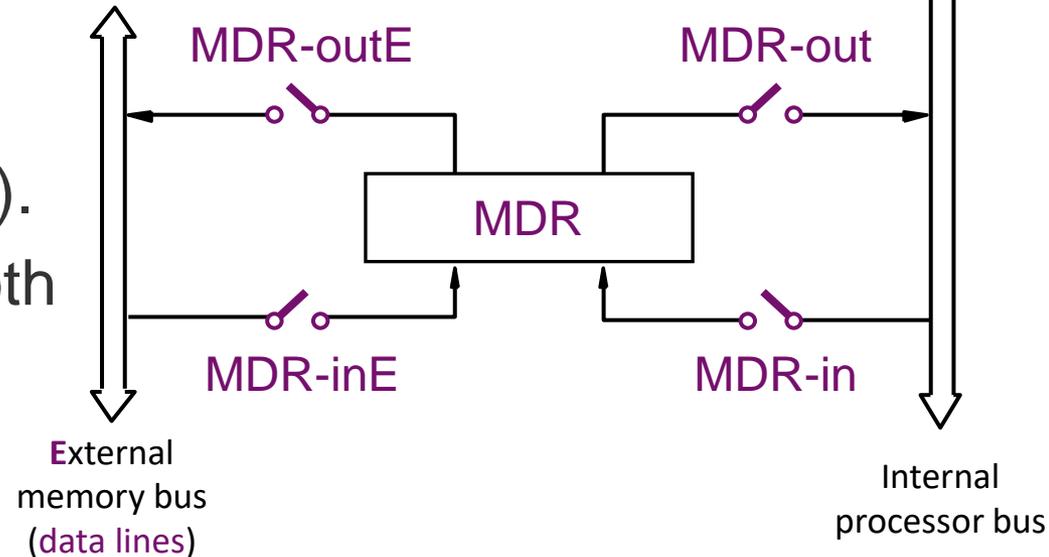
- Ex: **Mov R2, (R1)**

Sequence of Steps:

① ➡ R1-out,
MAR-in,
Read *(start to load a word from memory)*

② ➡ MDR-inE,
WaitMFC *(wait until the loading is completed)*
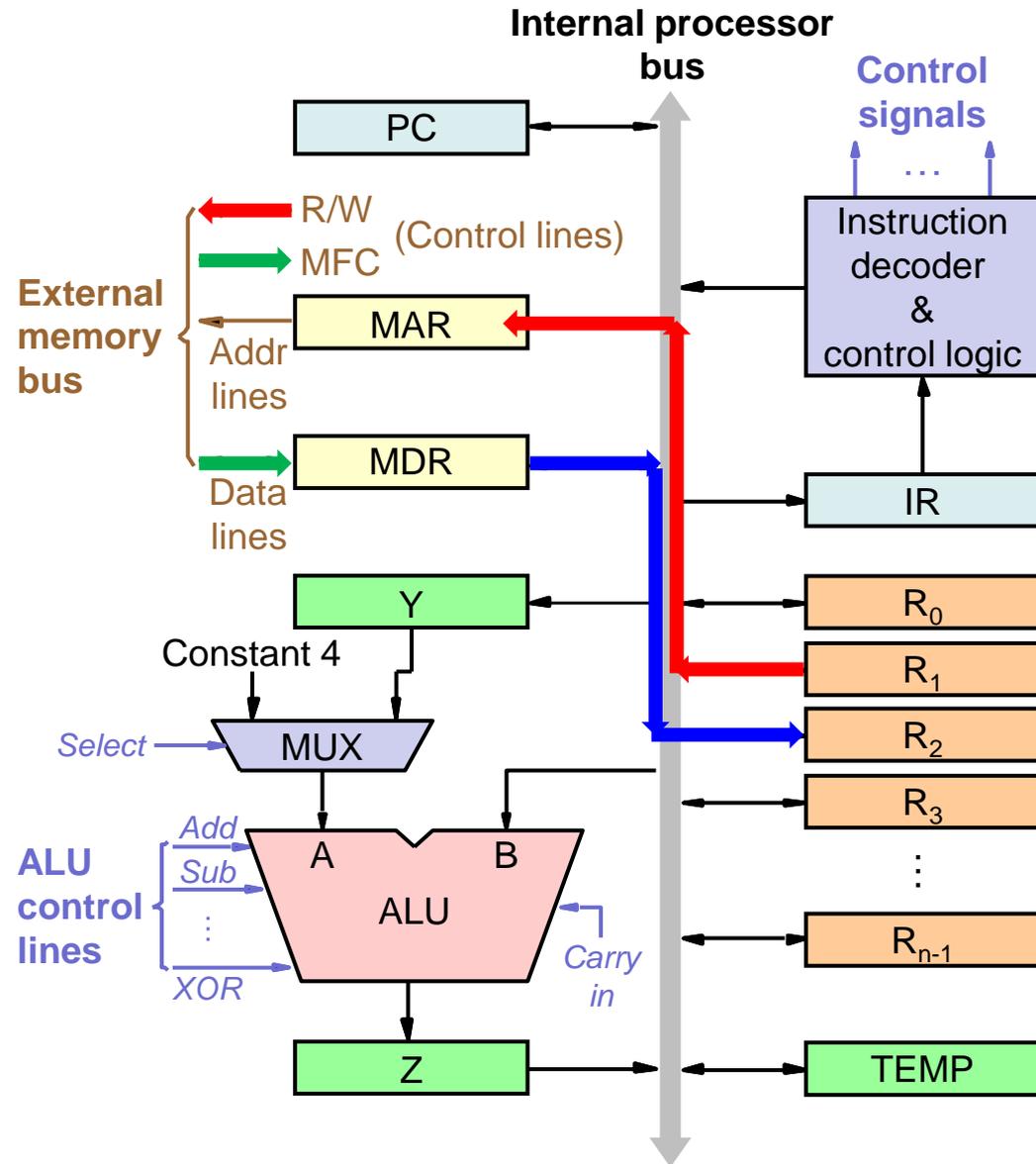
③ ➡ MDR-out,
R2-in

- **Timing Sequence:**

① ➡️R1-out *(not shown)*, MAR-in, Read *(start to read a word from memory)*

=== *assume memory read takes 3 cycles* ===

② ➡️MDR-inE, WaitMFC *(wait until the loading is completed)*

③ ➡️MDR-out, R2-in *(not shown)*

- What is the sequence of steps for the following operation?

  Mov R4, (R3)
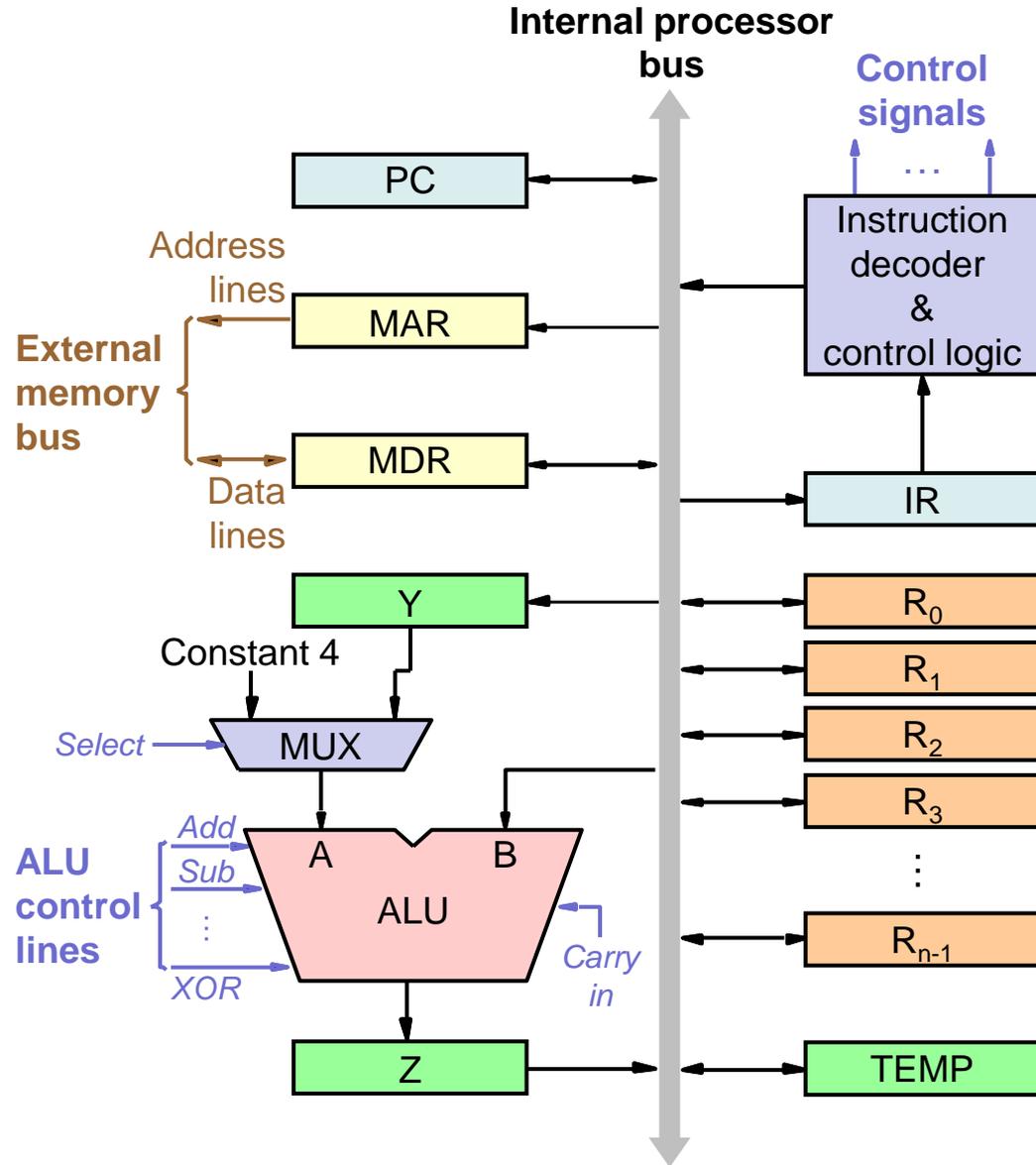
- This operation is similar to the previous one.

- Ex: **Mov (R1), R2**

Sequence of Steps:

① ➡ R1-out, MAR-in

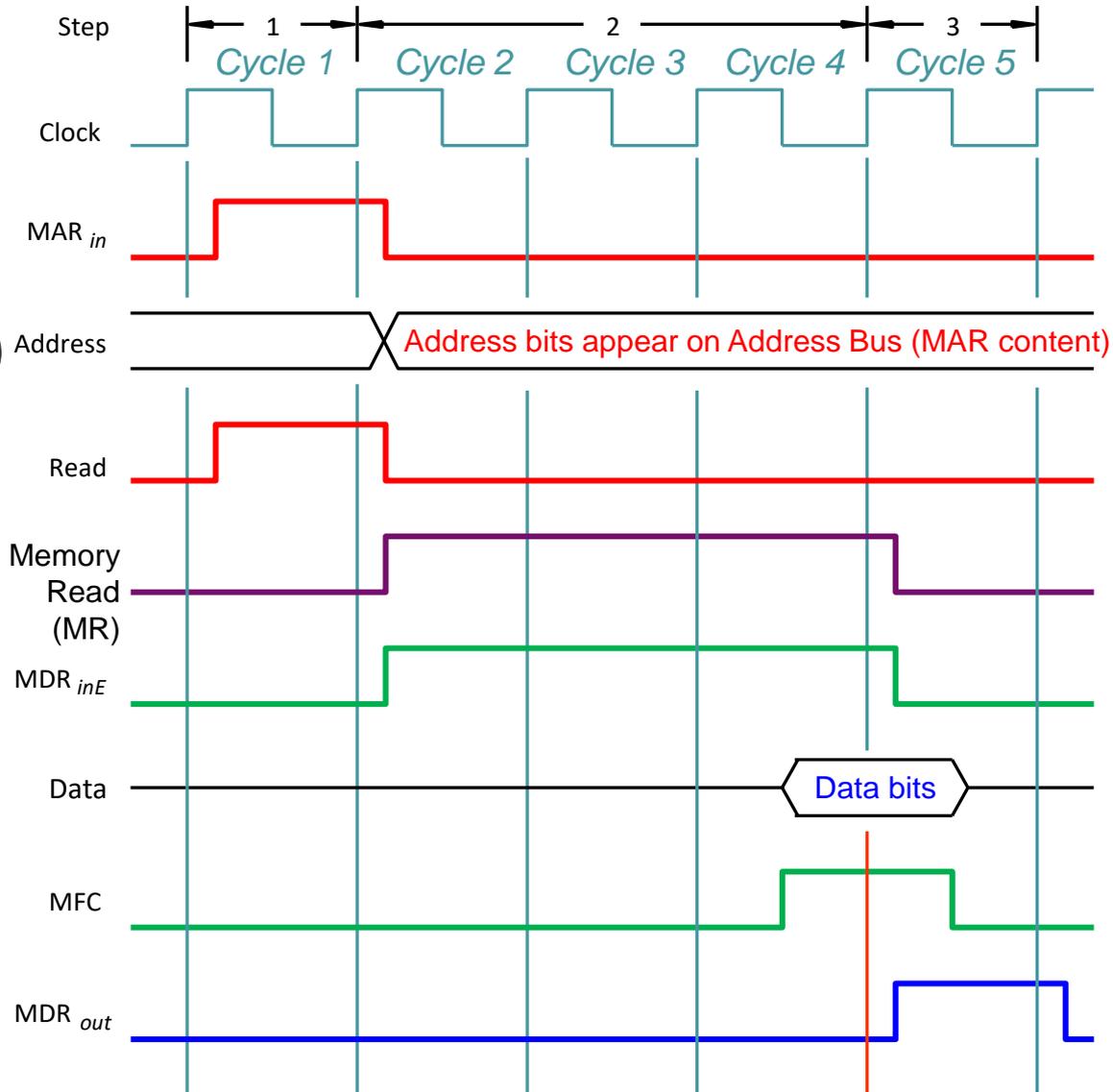② ➡ R2-out, MDR-in, Write *(start to store a word into memory)*

③ ➡ MDR-outE, WaitMFC *(wait until the storing is completed)*

Internal processor bus

Control signals

PC

R/W (Control lines)
MFC

External memory bus

MAR

Addr lines

Instruction decoder & control logic

MDR

Data lines

IR

Y

Constant 4

R_0

R_1

Select — MUX

R_2

Add
Sub
...
XOR

ALU control lines

A   B

ALU

Carry in

R_3

...

R_{n-1}

Z

TEMP
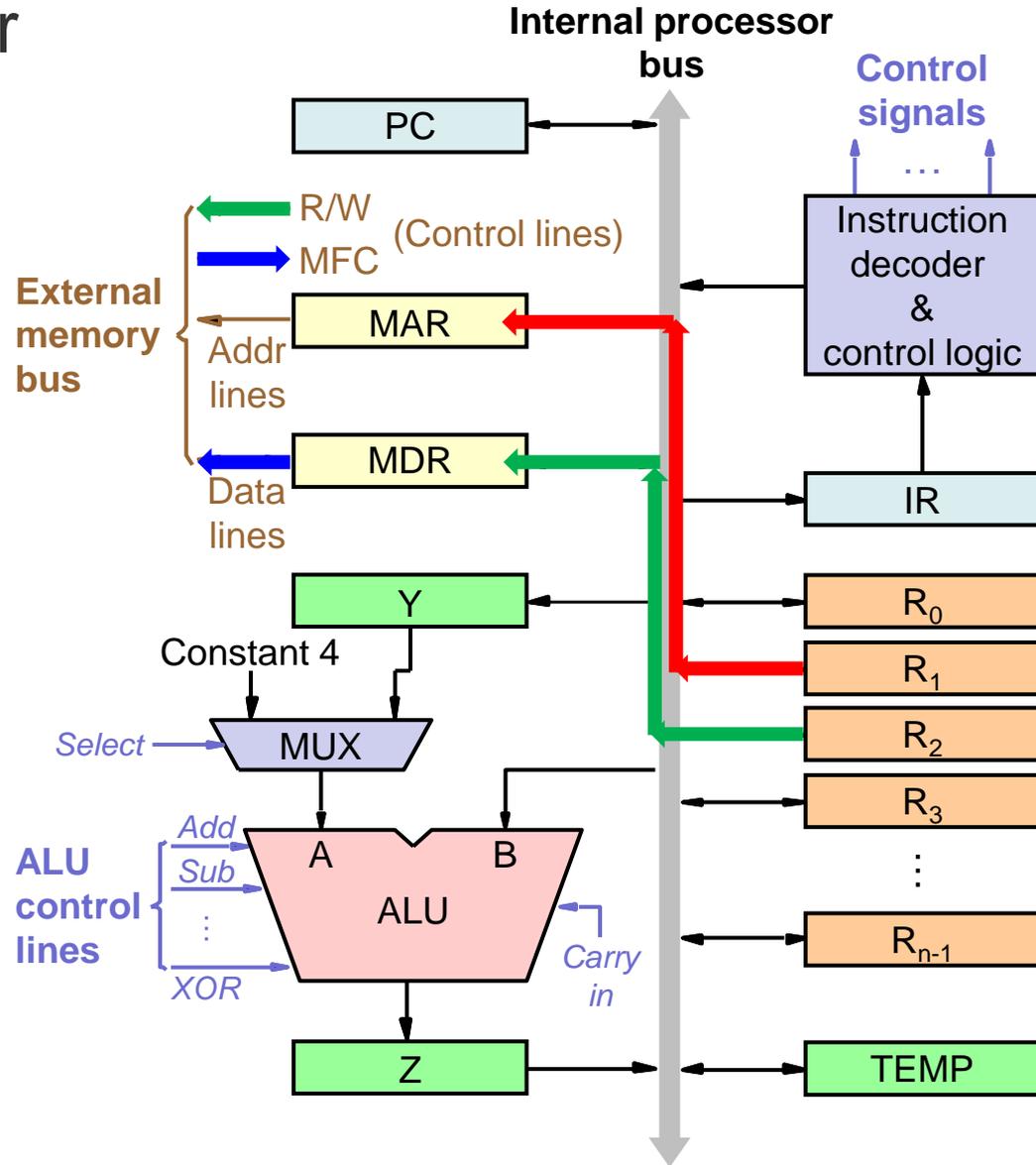
- What is the sequence of steps for the following operation?

  Mov (R3), R4
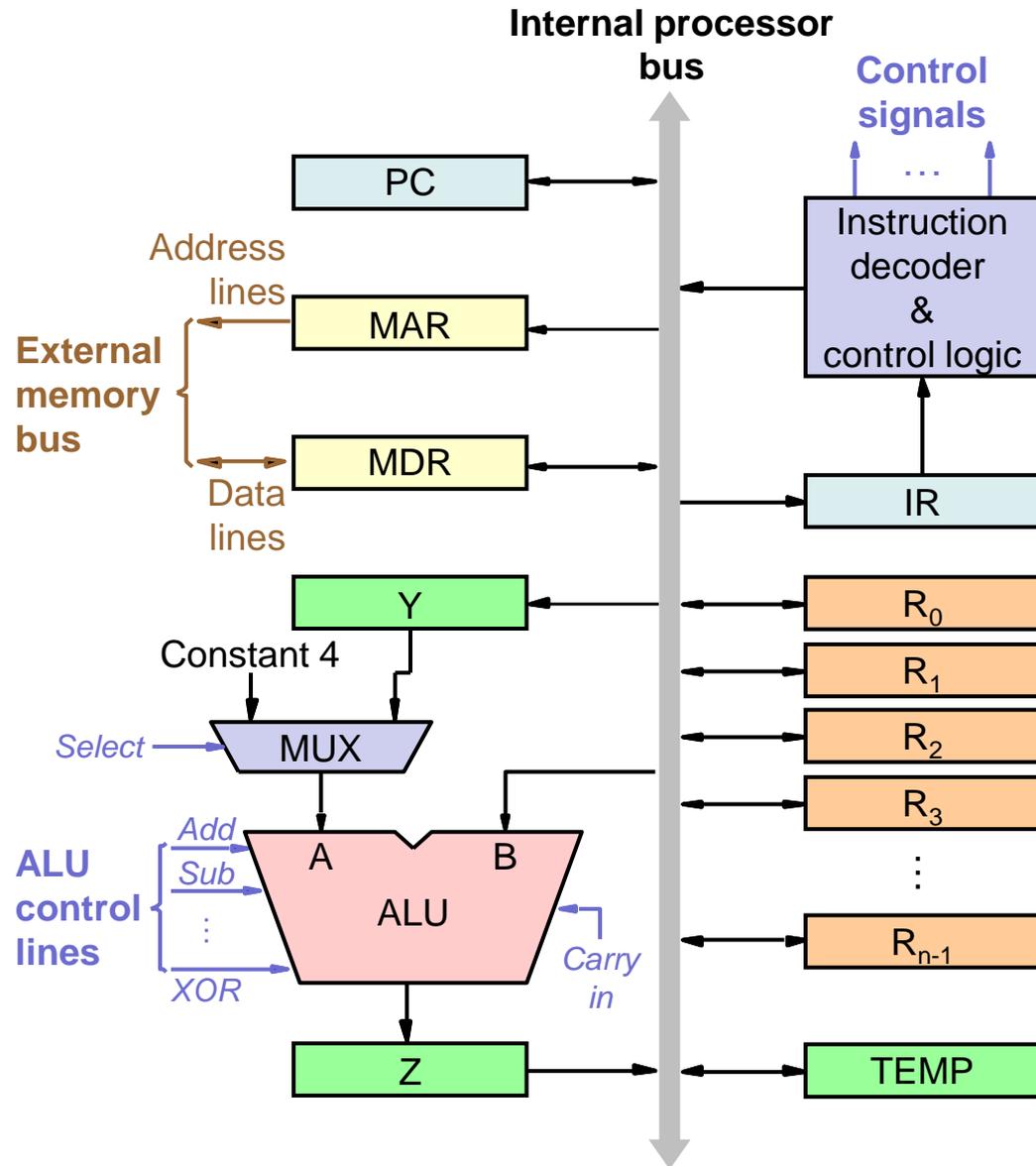
Loading Word vs Storing Word

- **Loading Word**
- Ex: **Mov R2, (R1)**

① R1-out,
MAR-in,
Read

② **MDR-inE**,
WaitMFC

③ **MDR-out**,
R2-in

- **Storing Word**
- Ex: **Mov (R1), R2**

① R1-out,
MAR-in

② R2-out,
MDR-in,
Write

③ **MDR-outE**,
WaitMFC

- **Fetch Phase**: The first phase of machine instruction execution
  - **IR ← [[PC]]**
    - Fetch the instruction from the memory location pointed to by PC, and load it into IR
  - **PC ← [PC]+4**
    - Increment the contents of PC by 4
- What is the <u>sequences of steps</u> for the fetch phase with <u>the highest parallelism</u>?

Internal processor bus

Control signals

...

PC

Address lines

MAR

External memory bus

Data lines

MDR

Instruction decoder & control logic

IR

Y

Constant 4

Select → MUX

ALU control lines
- *Add*
- *Sub*
- ...
- *XOR*

A   B

ALU

Carry in

Z

R_0

R_1

R_2

R_3

...

R_{n-1}

TEMP

- Ex: **Fetch Phase**

Sequence of Steps:

① **PC-out, MAR-in, Read**
  Select-4, B-in,
  Z-in, Add
  - ➡ **Fetch the instruction**
  - ➡ **Increment PC in parallel**

② MDR-inE, WaitMFC
  Z-out, PC-in, Y-in
  - – Y-in is for branch
    (discuss later).

③ MDR-out, IR-in

Internal processor bus

Control signals
...

PC

R/W
MFC   (Control lines)

External memory bus

MAR

Addr lines

MDR

Instruction decoder & control logic

IR

Y

Constant 4

Select → MUX

ALU control lines
  Add
  Sub
  ...
  XOR

A   B
ALU
Carry in

Z

R_0
R_1
R_2
R_3
...
R_{n-1}

TEMP

- Ex: **Fetch Phase**

Sequence of Steps:

① PC-out, MAR-in, Read Select-4, B-in, Z-in, Add
  - Fetch the instruction
  - Increment PC in parallel.

② ➡ MDR-inE, WaitMFC Z-out, PC-in, Y-in
  - ➡ Y-in is for branch (discuss later).

③ MDR-out, IR-in

Internal processor bus

Control signals
...

PC

(Control lines)
R/W
MFC

External memory bus
Addr lines

MAR

MDR

Instruction decoder & control logic

IR

Y

Constant 4

Select → MUX

ALU control lines
Add
Sub
...
XOR

A   B

ALU
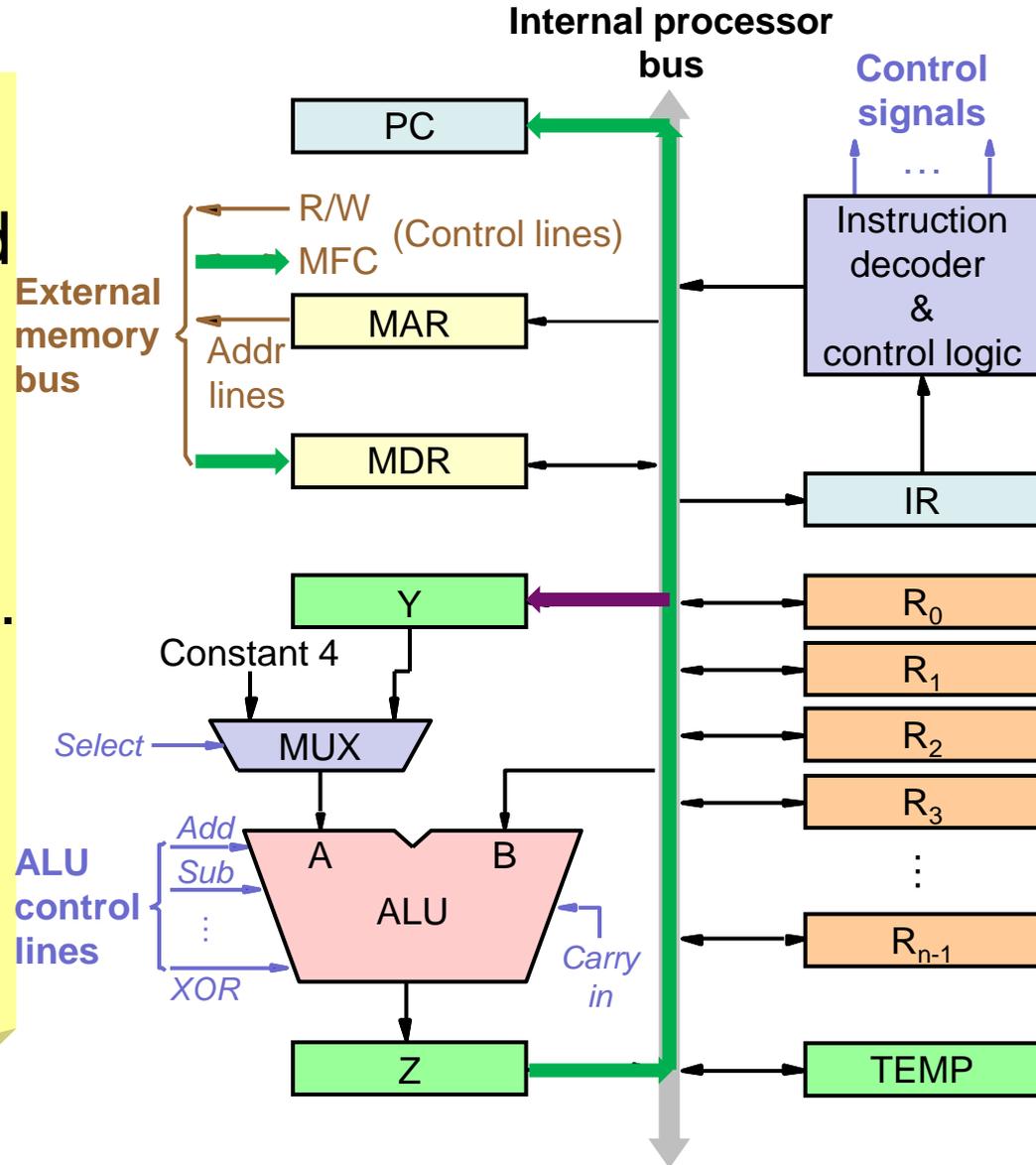
Carry in

Z

R_0

R_1

R_2

R_3

...

R_{n-1}

TEMP

- Ex: **Fetch Phase**

Sequence of Steps:

① **PC-out, MAR-in, Read Select-4, B-in, Z-in, Add**
  - Fetch the instruction
  - Increment PC in parallel.

② **MDR-inE, WaitMFC Z-out, PC-in, Y-in**
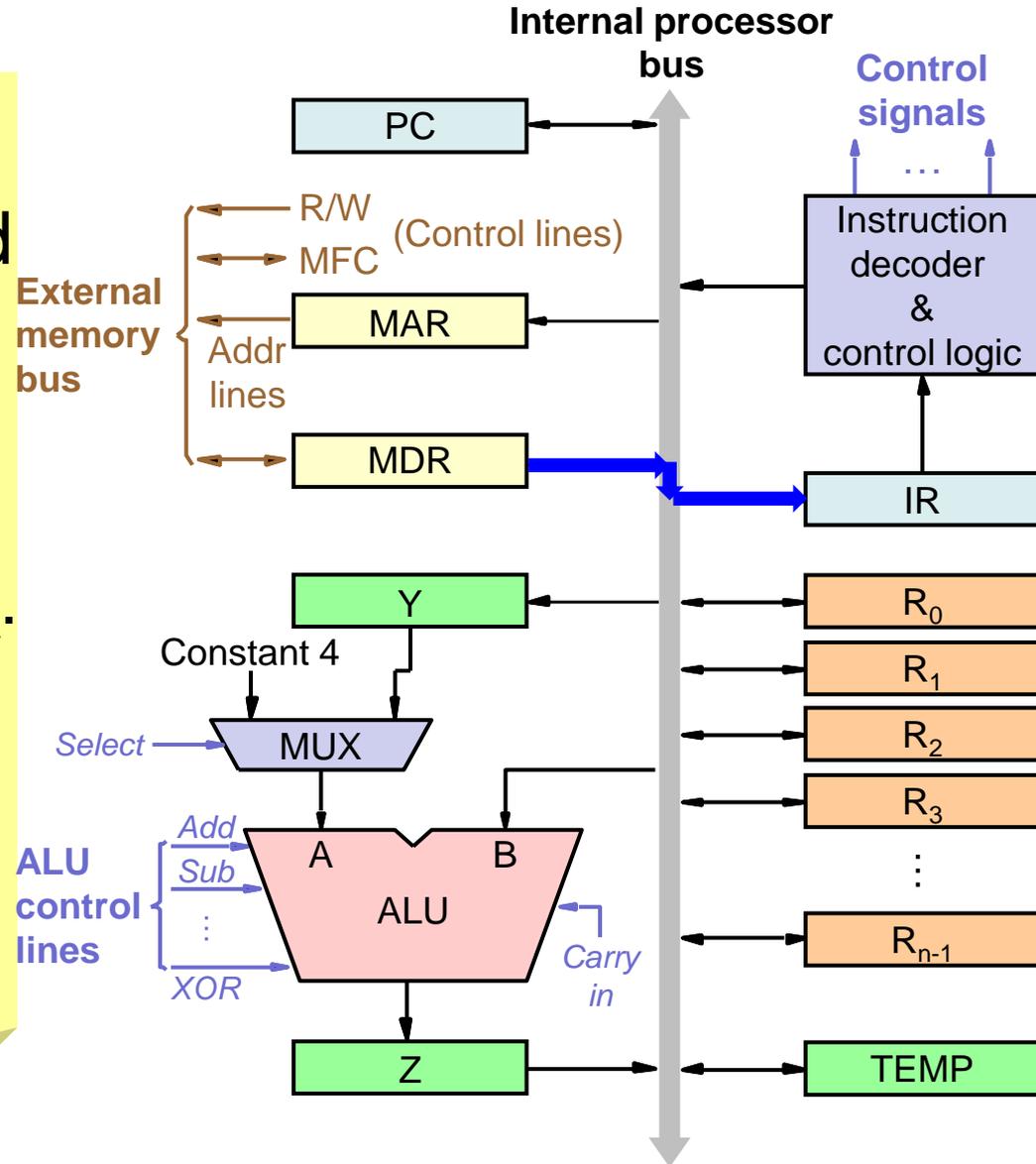 - Y-in is for branch (discuss later).

③ ➡ **MDR-out, IR-in**

Internal processor bus

Control signals
...

Instruction decoder & control logic

PC

R/W   (Control lines)
MFC

External memory bus

MAR

Addr lines

MDR

IR

Y

Constant 4

Select → MUX

ALU control lines
Add
Sub
...
XOR

A   B

ALU

Carry in

R₀
R₁
R₂
R₃
...
Rₙ₋₁

Z   TEMP

Observations and Insights

- The internal processor bus and the external memory bus can be operated independently (concurrently).
  - Since the separation provided by MAR and MDR.

- Independent operations imply the possibility of performing some steps in parallel.
  - E.g., memory access and PC increment, instruction decoding and reading source register

- During memory access, processor waits for MFC.
  - There is NOTHING TO DO BUT WAIT for few cycles.

Question: Is there any way to make the waiting shorter?

- Processor Internal Structure

- Instruction Execution

  – Fetch Phase

  – Execute Phase

- **Execution of A Complete Instruction**

- Multiple-Bus Organization

Example 1) ADD R1, (R3) (1/3)

- Instruction Execution: Fetch Phase & Execute Phase

Sequence of Steps:

1) Fetch the instruction

① PC-out, MAR-in, Read
   Select-4, B-in, Z-in, Add

② MDR-inE, WaitMFC
   Z-out, PC-in, Y-in

③ MDR-out, IR-in

2) Decode the instruction

④ **DecodeInstruction**

3) Load the operand [R3] from memory

⑤ R3-out, MAR-in, Read

⑥ R1-out, Y-in, MDR-inE, WaitMFC

4) Perform the addition

⑦ MDR-out, SelectY, Add, Z-in, B-in
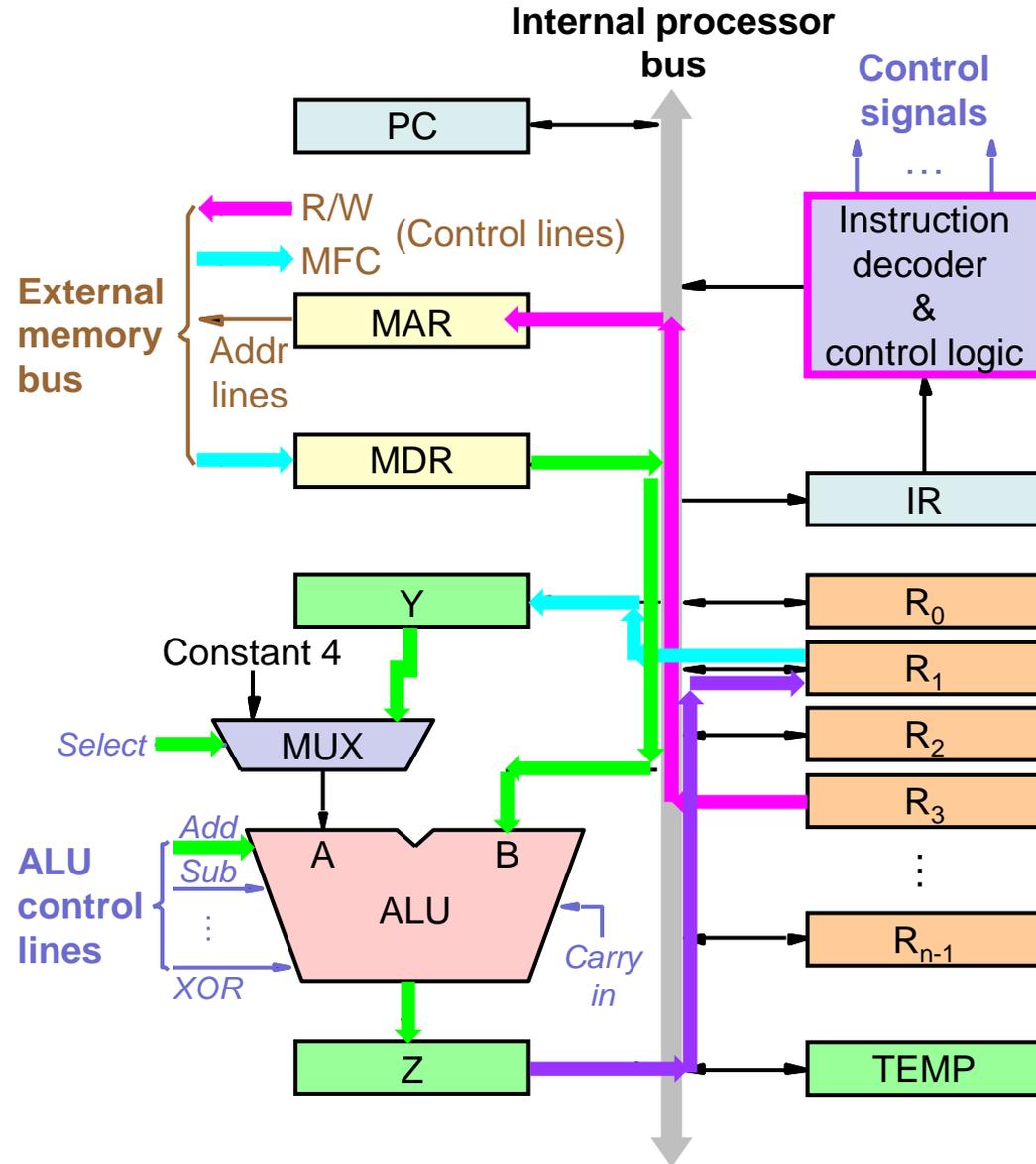
5) Store result to R1

⑧ Z-out, R1-in

Example 1) ADD R1, (R3) (2/3)

Sequence of Steps:

① PC-out, MAR-in, Read
   Select-4, B-in, Z-in, Add

② MDR-inE, WaitMFC
   Z-out, PC-in, Y-in

③ MDR-out, IR-in

④ **DecodeInstruction**

⑤ R3-out, MAR-in, Read

⑥ R1-out, Y-in, MDR-inE,
   WaitMFC

⑦ MDR-out, SelectY, Add,
   Z-in, B-in

⑧ Z-out, R1-in

Example 1) ADD R1, (R3) (3/3)

- Detailed Explanation for Sequence of Steps:
  - ① PC loaded into MAR, read request to memory, MUX selects 4, added to PC (B-in) in ALU, store sum in Z
  - ② Z moved to PC (and Y) while waiting for memory
  - ③ Word fetched from memory and loaded into IR
  - ④ **Instruction Decoding**: Figure out what the instruction should do and set control circuitry for steps 4 – 7
  - ⑤ R3 transferred to MAR, read request to memory
  - ⑥ Content of R1 moved to Y while waiting for memory
  - ⑦ Read operation completed, the loaded word is already in MDR and copied to B-in of ALU, SelectY as second input of ALU, add performed
  - ⑧ Result is transferred to R1

Example 2) Branch Instruction (1/2)

- Instruction Execution: Fetch Phase & Execute Phase

Sequence of Steps:

1) Fetch the instruction

① PC-out, MAR-in, Read
Select-4, B-in, Z-in, Add

② MDR-inE, WaitMFC
Z-out, PC-in, **Y-in**

③ MDR-out, IR-in

2) Decode the instruction

④ **DecodeInstruction**

3) Add the offset specified in the instruction (**Offset-field-of-IR**) to the PC

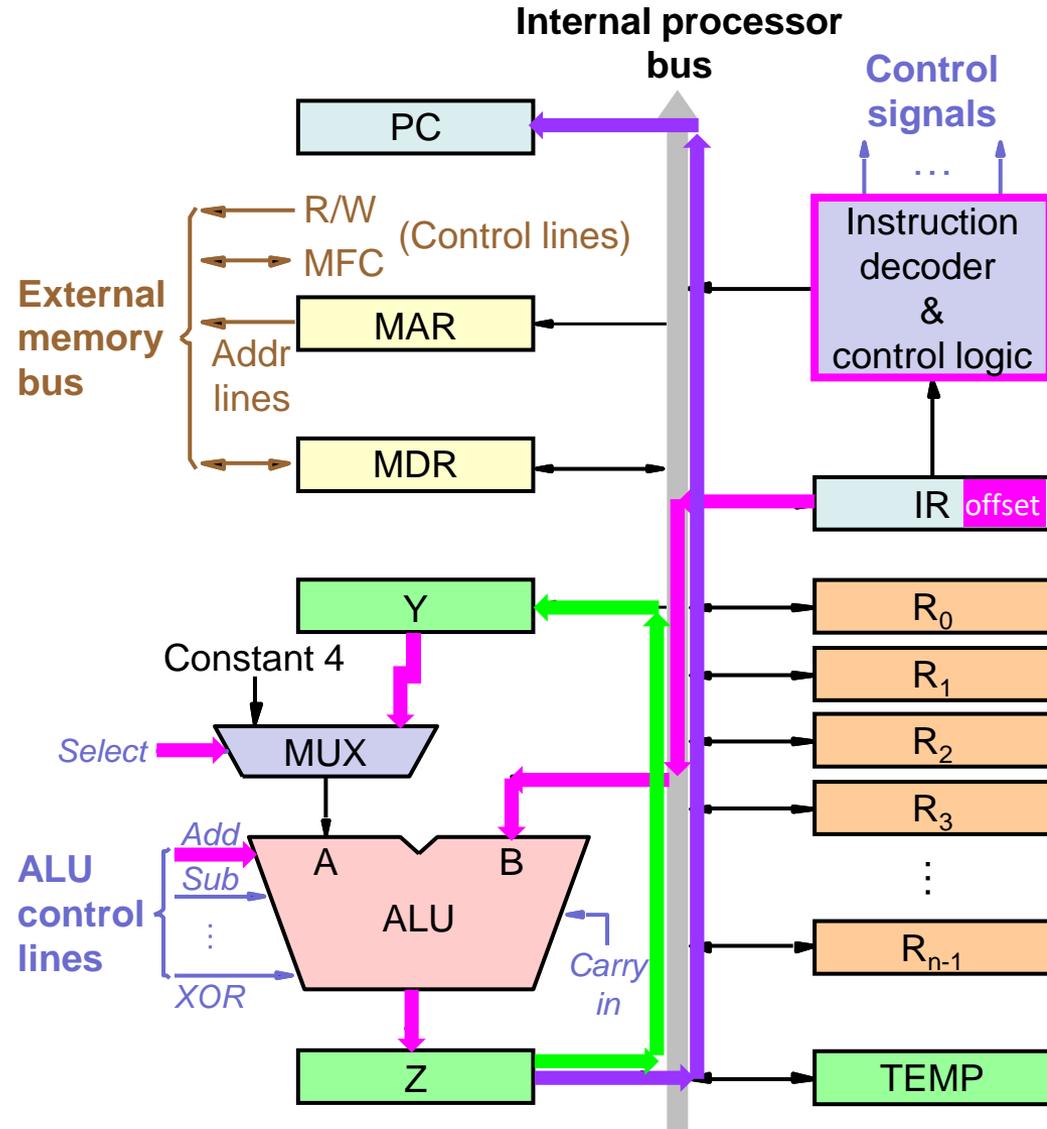⑤ **Offset-field-of-IR-out**, SelectY, Add, Z-in, B-in

4) Update the PC

⑥ Z-out, PC-in

Example 2) Branch Instruction (2/2)

Sequence of Steps:

① PC-out, MAR-in, Read Select-4, B-in, Z-in, Add

② ➡ MDR-inE, WaitMFC Z-out, PC-in, **Y-in**

③ MDR-out, IR-in

④ **DecodeInstruction**

⑤ ➡ **Offset-field-of-IR-out**, SelectY, Add, Z-in, B-in

⑥ ➡ Z-out, PC-in

Internal processor bus

Control signals

...

PC

R/W

MFC

(Control lines)

External memory bus

MAR

Addr lines

MDR

Instruction decoder & control logic

IR offset

Y

Constant 4

Select → MUX

ALU control lines

Add
Sub
⋮
XOR

A   B

ALU

Carry in

Z

R₀
R₁
R₂
R₃
⋮
Rₙ₋₁
TEMP

Question: What if we don't active Y-in at the second step?
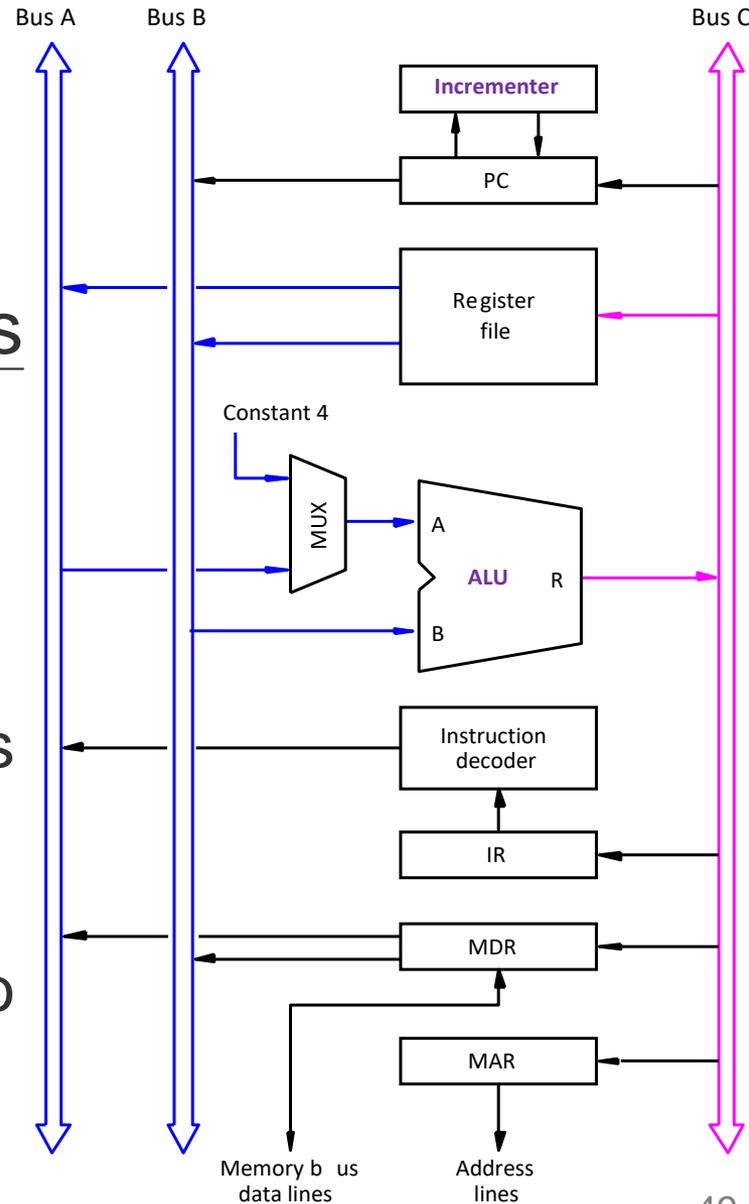
- Processor Internal Structure

- Instruction Execution

  – Fetch Phase
  – Execute Phase

- Execution of A Complete Instruction

- **Multiple-Bus Organization**

- **Disadvantage** of <u>single internal bus</u>: **Only one data item** can be transferred internally **at a time**.

- **Solution**: <u>Multiple Internal Buses</u>
  - All registers combined into a register file with **three** ports
    - TWO out-ports and ONE in-port.
    - Why 3? Typical instruction format!
  - **Buses A and B** allow simultaneous transfer of the two operands from registers to the ALU.
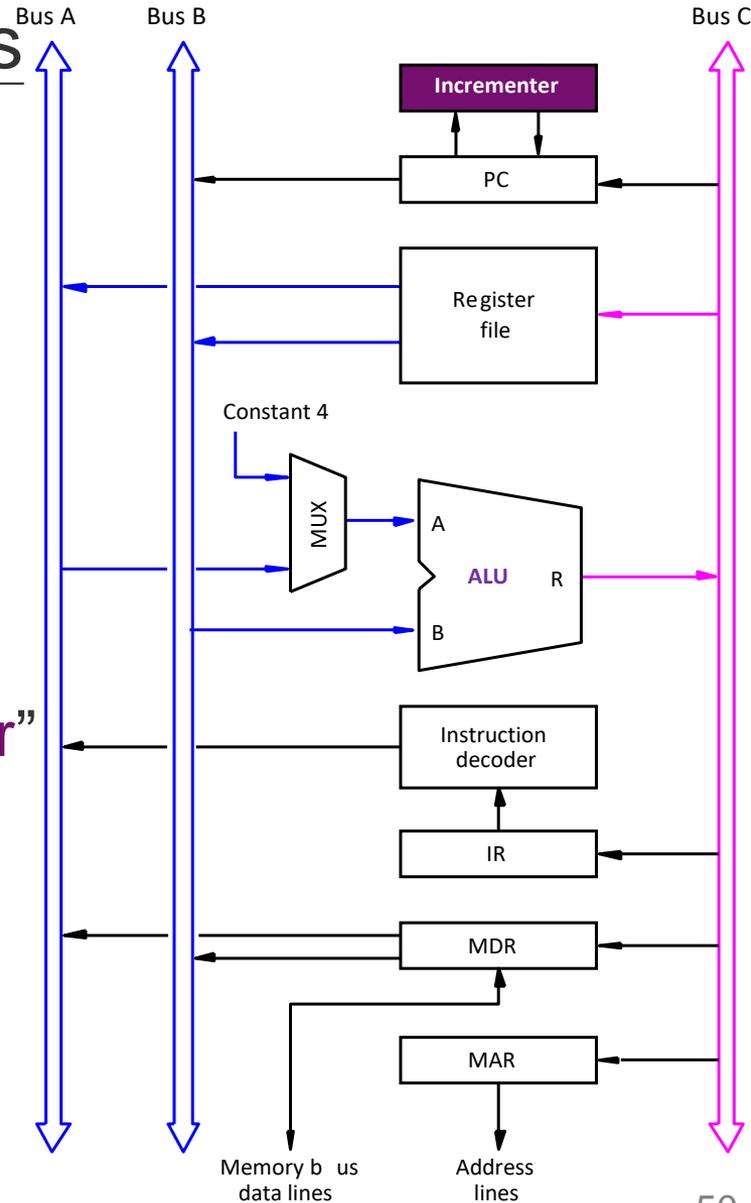 - **Bus C** allows transferring data into a third register during the same clock cycle.

Bus A   Bus B   Bus C

Incrementer

PC

Register file

Constant 4

MUX

ALU   A   B   R

Instruction decoder

IR

MDR

MAR

Memory b us data lines

Address lines

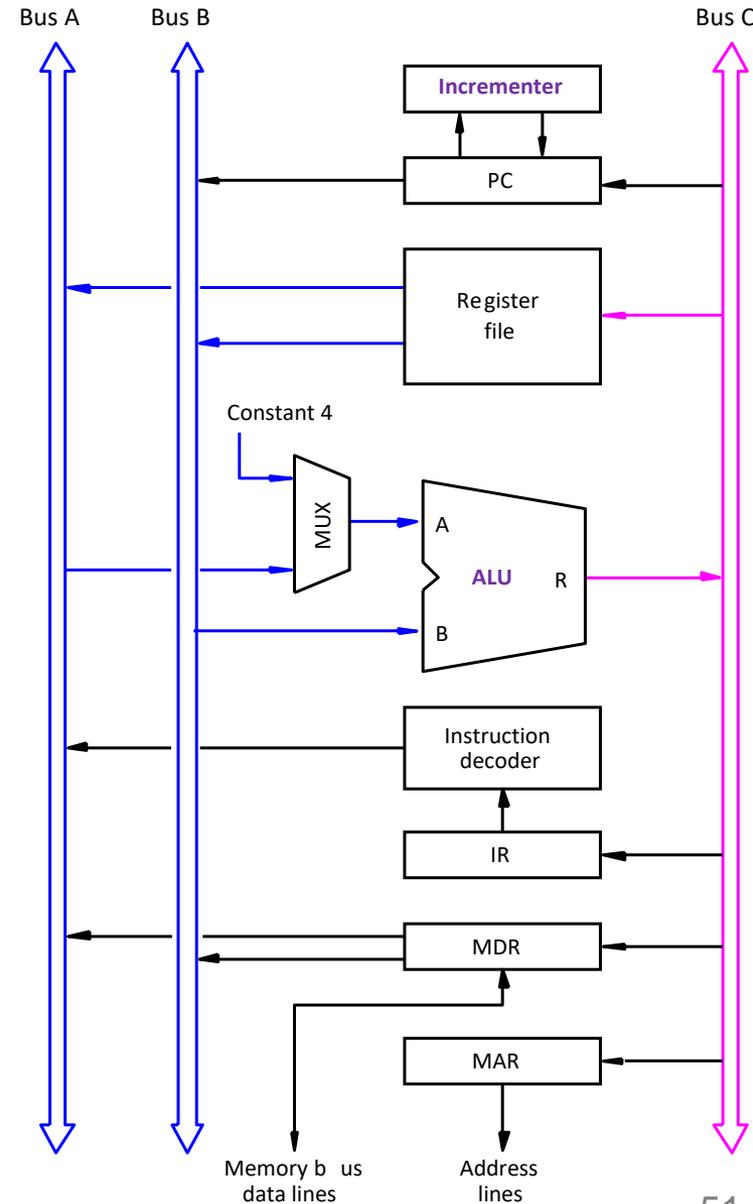- Solution: <u>Multiple Internal Buses</u>
  - How to do register transfer?
  - ALU can pass one of its operands to output R.
    - E.g. **R=A** or **R=B**

  - How to further reduce the internal bus contention?
  - Employ an additional "Incrementer" unit to compute [PC]+4 (**IncPC**).
    - ALU is not used for incrementing PC.
    - ALU still has a Constant 4 input for other instructions (e.g., post-increment: [SP]++ for stack push).

Bus A   Bus B   Bus C

Incrementer

PC

Register file

Constant 4

MUX

A

ALU   R

B

Instruction decoder

IR

MDR

MAR

Memory bus data lines   Address lines

- Can you tell what does the following execution do?

① PC-out, MAR-in, Read, **R=B**

② MDR-inE, WaitMFC, **IncPC**

③ MDR-out, IR-in, **R=B**

④ DecodeInstruction

⑤ **R4-outA, R5-outB, SelectA, Add, R6-in**

Summary

- Processor Internal Structure

- Instruction Execution

  - Fetch Phase

  - Execute Phase

- Execution of A Complete Instruction

- Multiple-Bus Organization