Computer Architecture

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Computer Architecture

- A computer is essentially a large collection of **finite-state machines**.
- A common clock is used for all.
- The machines intercommunicate by the output of one machine being the input to another.
- Combinational logic can be interposed between output and input to affect data transformations.

Computer Architecture

- We will work with a simulated tutorial architecture:

  ISC: *Incredibly Simple Computer*

The ISC

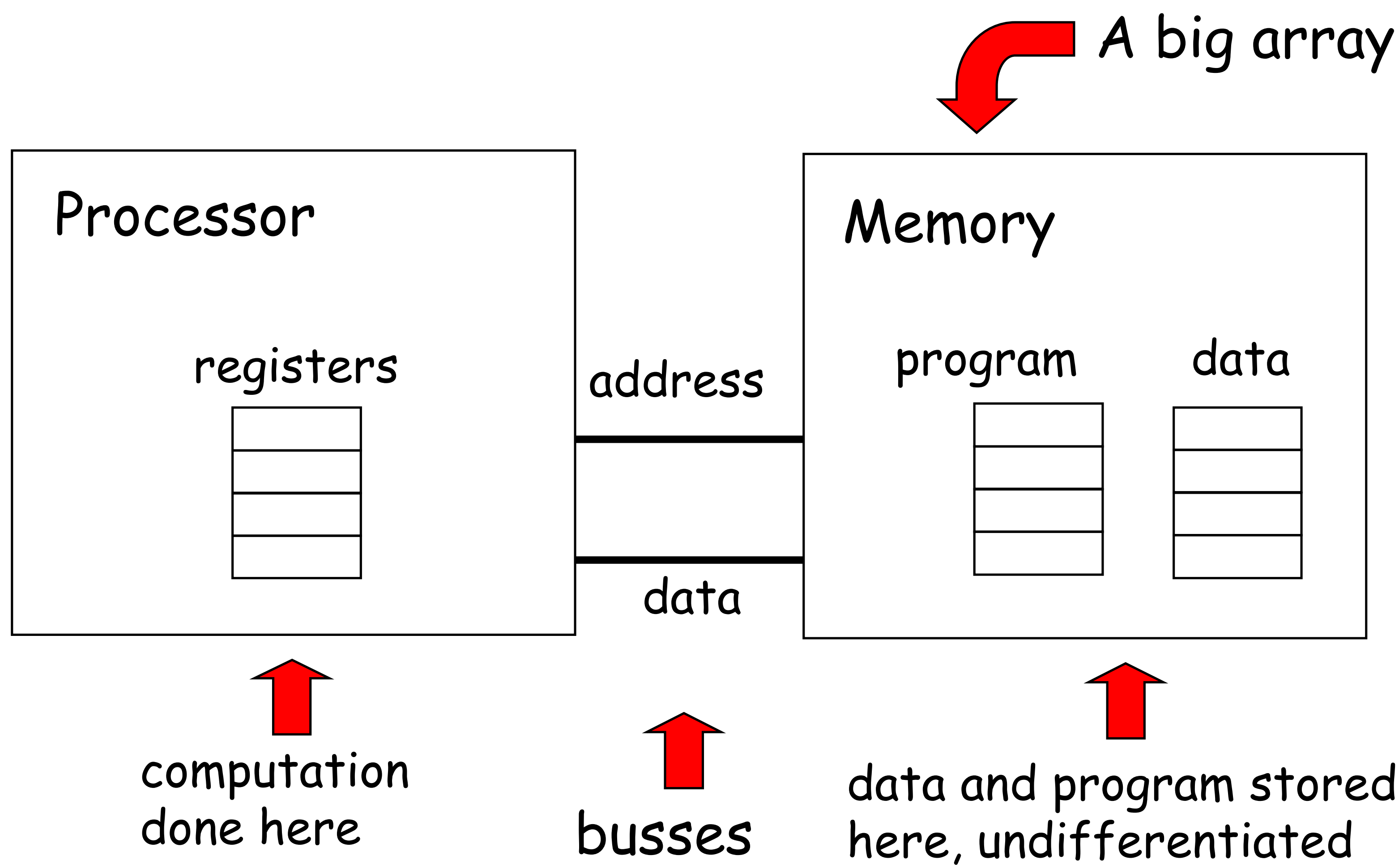
- ISC is an example of a

  RISC (Reduced Instruction Set Computer),

  as opposed to a

  CISC (Complex Instruction Set Computer)

ISC Design


A big array
Processor
registers
address
data
Memory
program
data
computation
done here
busses
data and program stored
here, undifferentiated

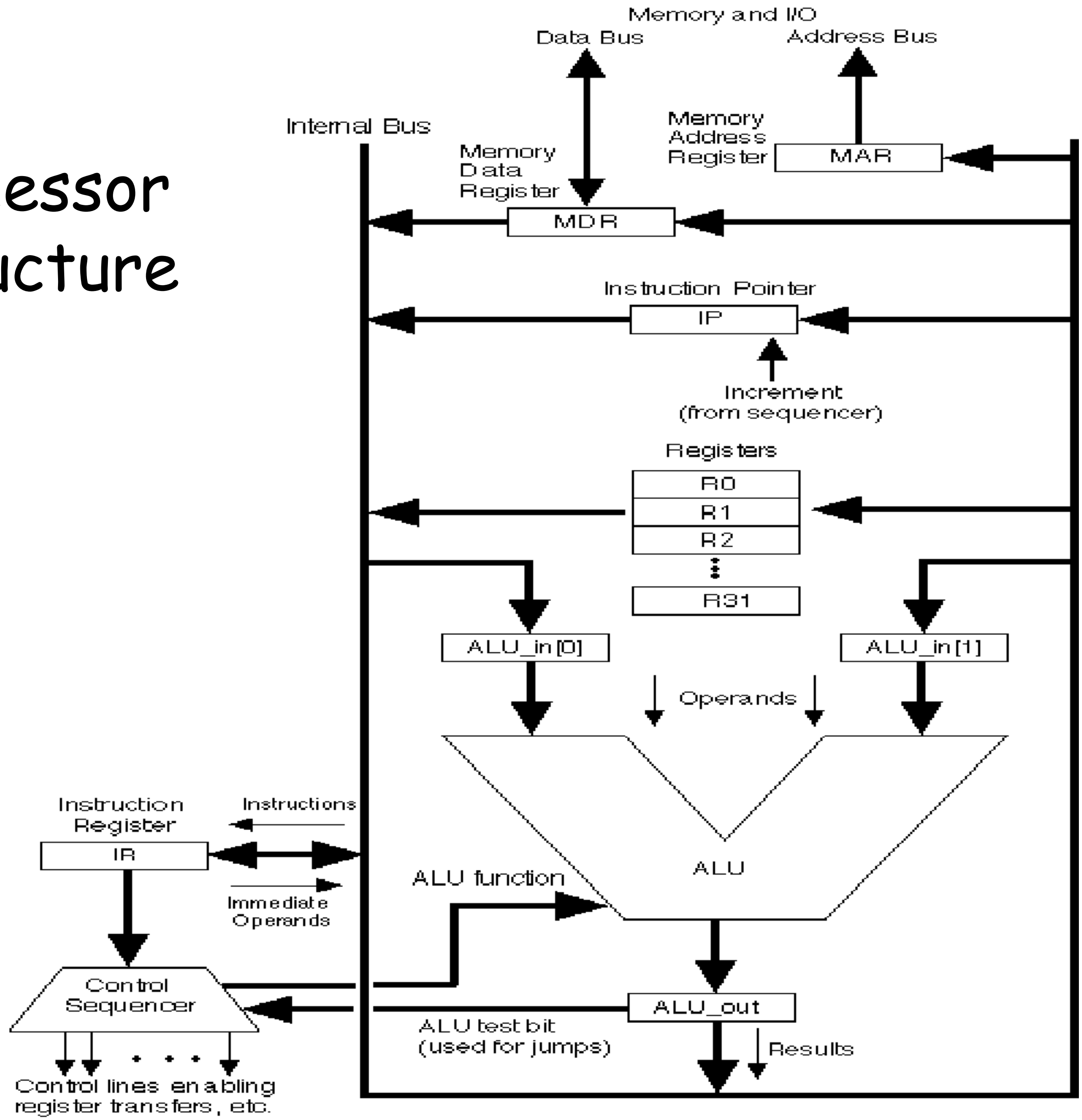
ISC Processor Components (1)

- **General Registers**: Hold operands and results, and addresses for jumps in program.
- **IR** (Instruction Register) holds currently executing instruction.
- **IP** (Instruction Pointer): Holds address of next instruction.
- **MDR** (Memory Data Register) holds data en-route to/from memory.
- **MAR** (Memory Address Register) holds address of memory location for data.

ISC Processor Components (2)

- **ALU** (Arithmetic-Logic Unit) Combinational unit performing addition, subtraction, logical operations, shifting, etc.
- **ALU registers**: Registers holding operands and results for ALU
- **Control sequencer**: Finite-state machine sequencing register and 3-state strobes, based upon the contents of the IR (Instruction Register)

ISC Processor Structure



Instruction Dichotomies

- Instructions that access memory ("memory access" instructions)
- Instructions that include an operand in the instruction itself ("immediate" instructions)
- Instructions that change instruction location ("jump" instructions)

Non-memory access instructions

add *Ra Rb Rc*

register indices (absolute or symbolic)

reg[Ra] = reg[Rb] + reg[Rc];

similarly for:

- sub
- mul
- div
- and
- or
- comp
- shr
- shl

"Immediate" instructions

C is a constant

It can be intended for arithmetic, logic, or as an address.

load immediate:

lim *Ra C*

→ Reg[Ra] = C;

add immediate:

aim *Ra C*

→ Reg[Ra] += C;'

Memory access instructions

load:

load *Ra Rb*

reg[Ra] = mem[reg[Rb]];

The address to be used is in one of the general registers.

store:

store *Ra Rb*

mem[reg[Ra]] = reg[Rb];

Jump instructions

jump-if-equal:

jeq *Ra Rb Rc*

Jump to address in Ra

if reg[Rb] == reg[Rc]

The address to be jumped to is in one of the general registers.

Similarly for:

jne jlt
jgt jlte
jgte

Jump instructions

The address to be jumped to is in one of the general registers.

jump-unconditionally

junc *Ra*

Jump to address in Ra.

Jump instructions

The address to be jumped to is in one of the general registers.

jump-to-subroutine

jsub *Ra Rb*

Jump to address in Ra.

The next location after the current one is put in Rb.

Control Sequencer FSM

- Inputs are bits from instruction being interpreted
- Outputs are strobes to various registers, 3-state devices, etc.

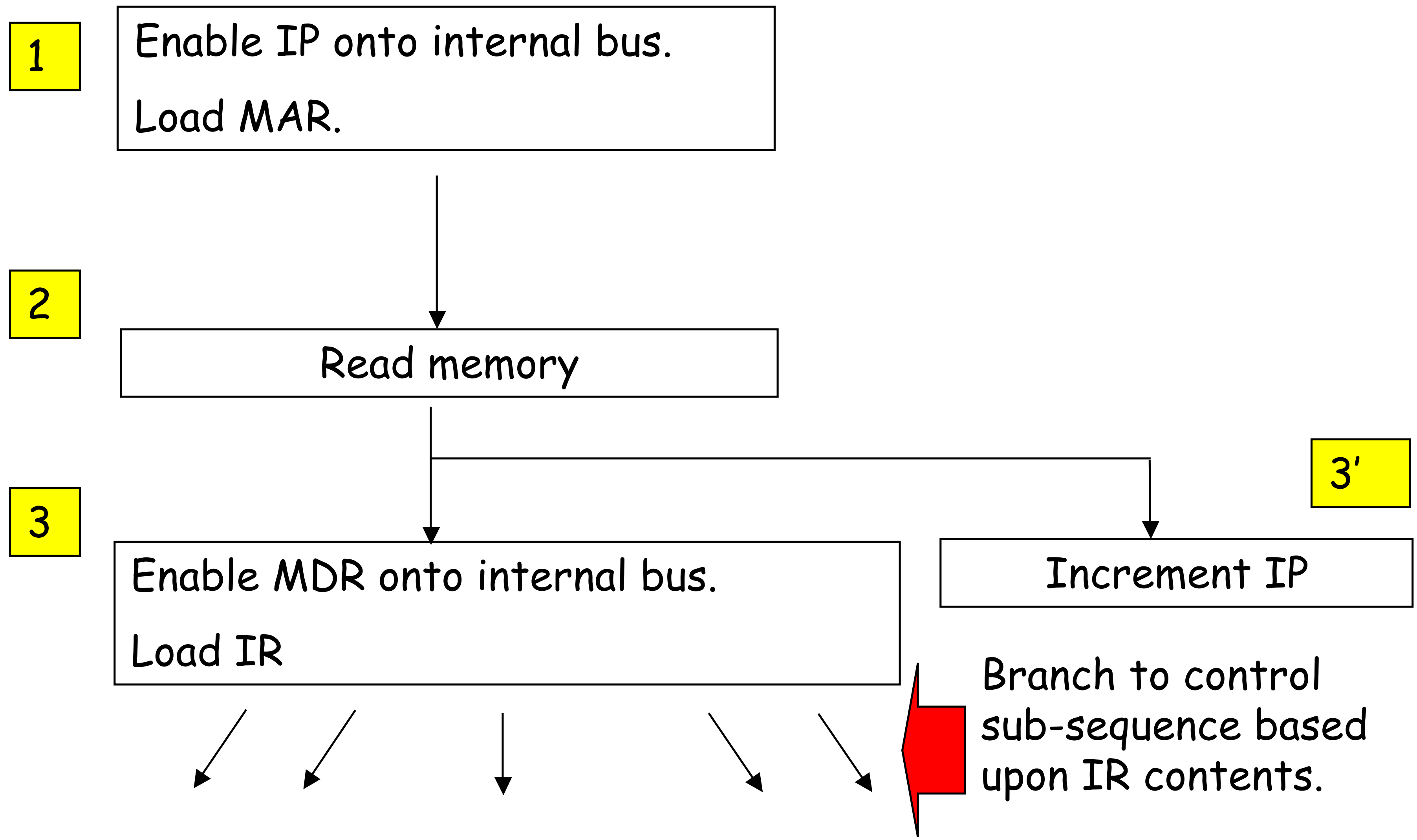
Control Sequence

- There is a sequence common to all instructions in which the instruction is fetched from memory,

  followed by

- A sequence particular to the type of instruction being executed.

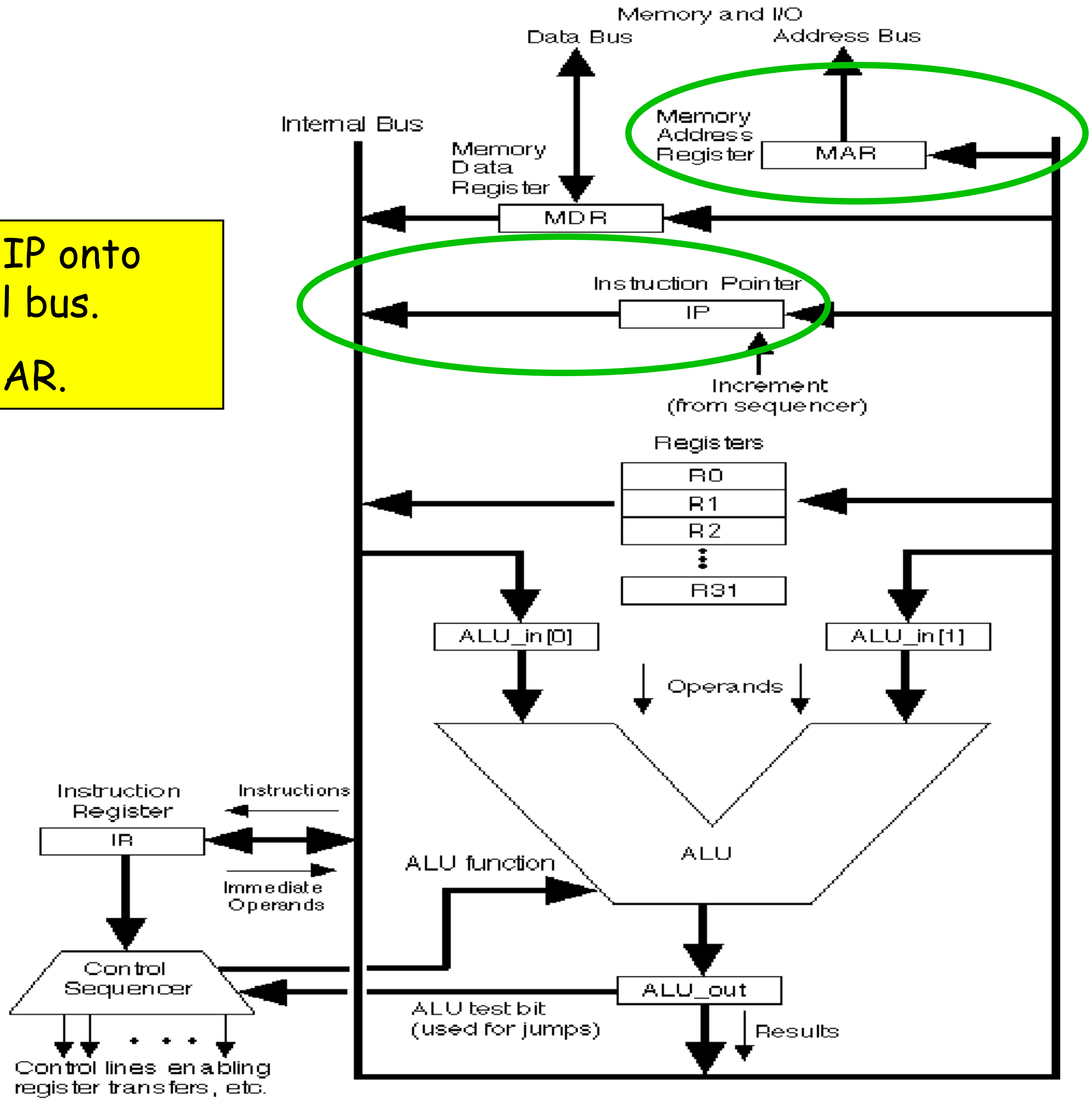
ISC Instruction Fetch



1

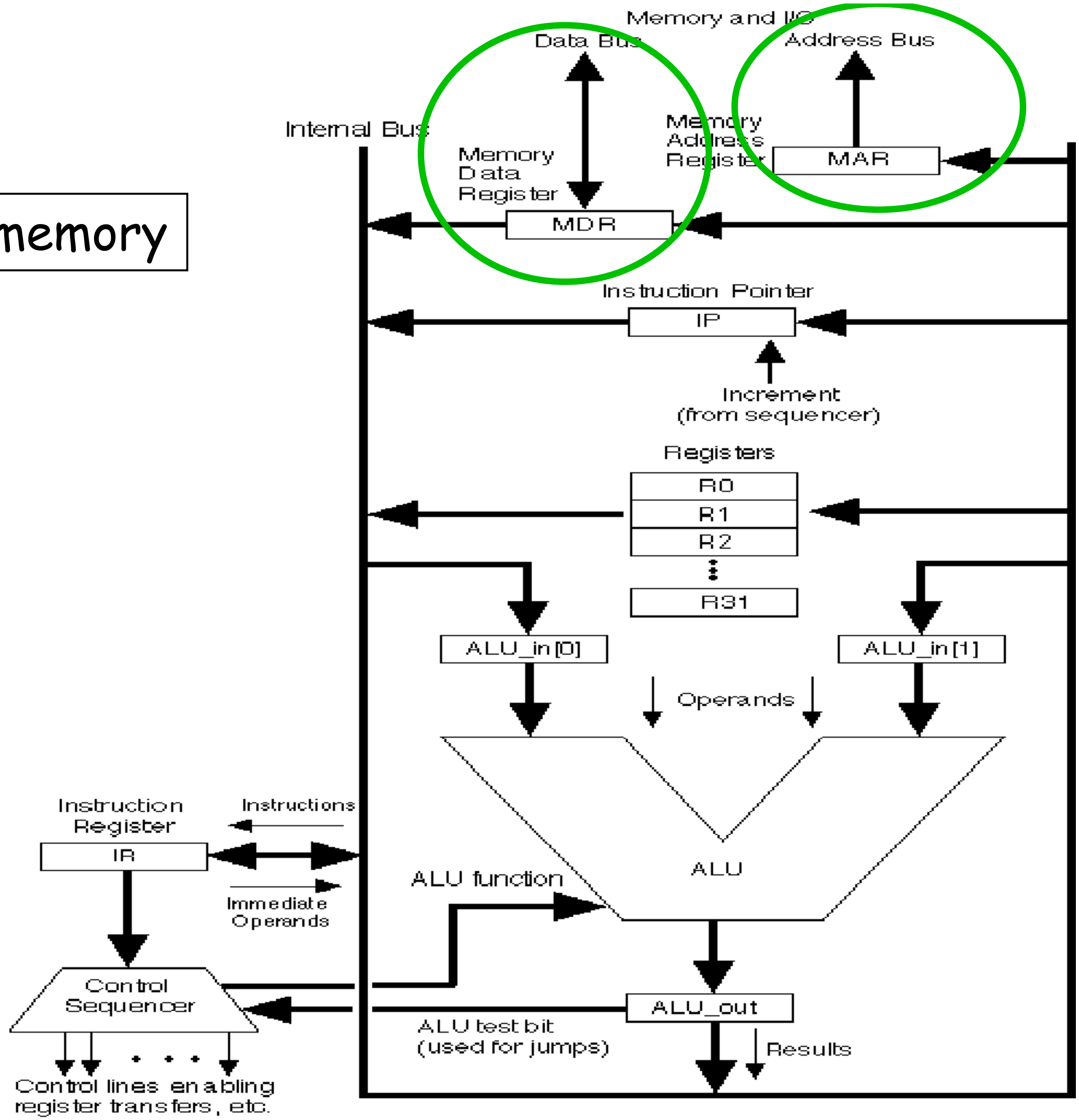
Enable IP onto internal bus.

Load MAR.



2

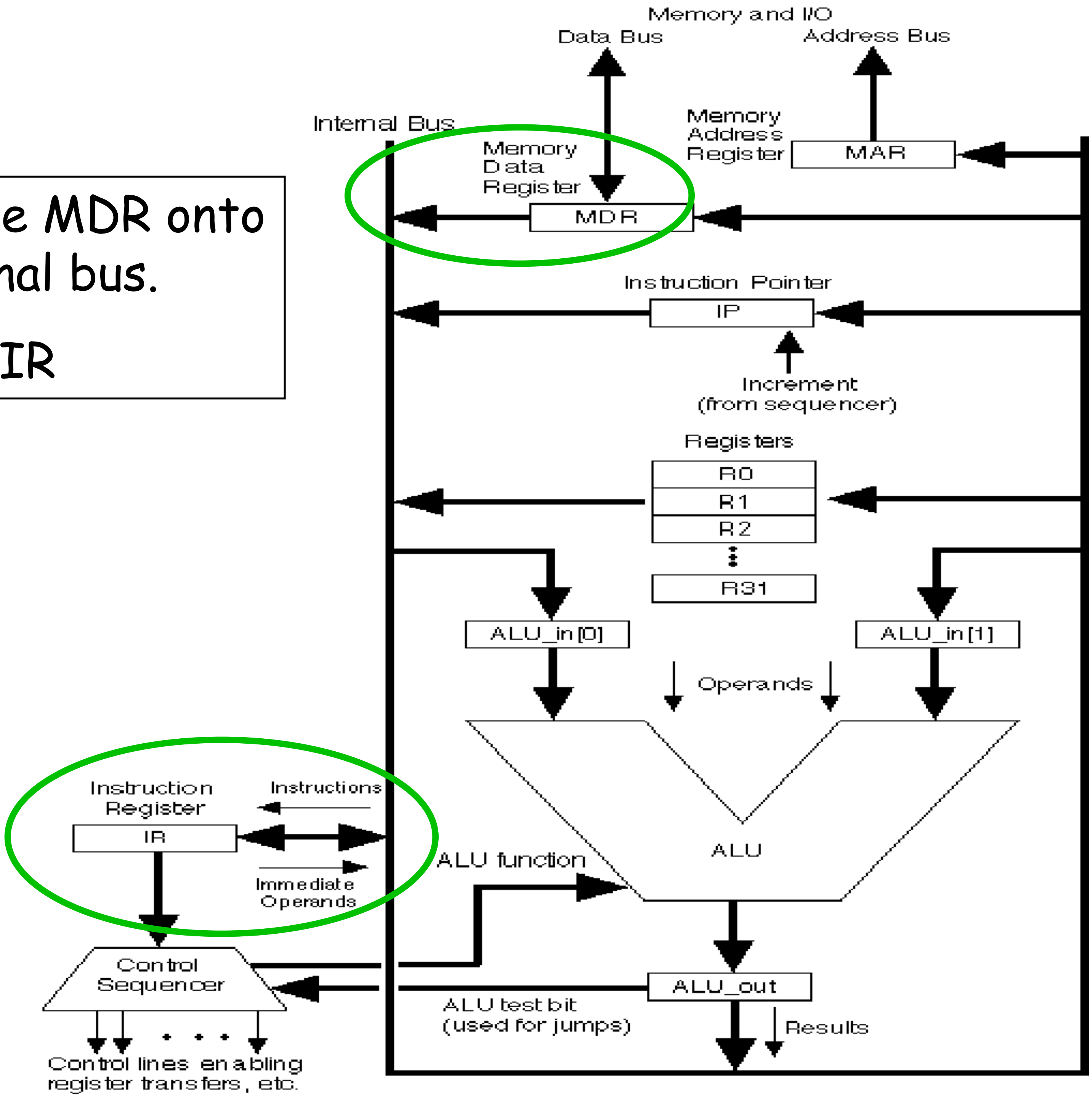
Read memory



3

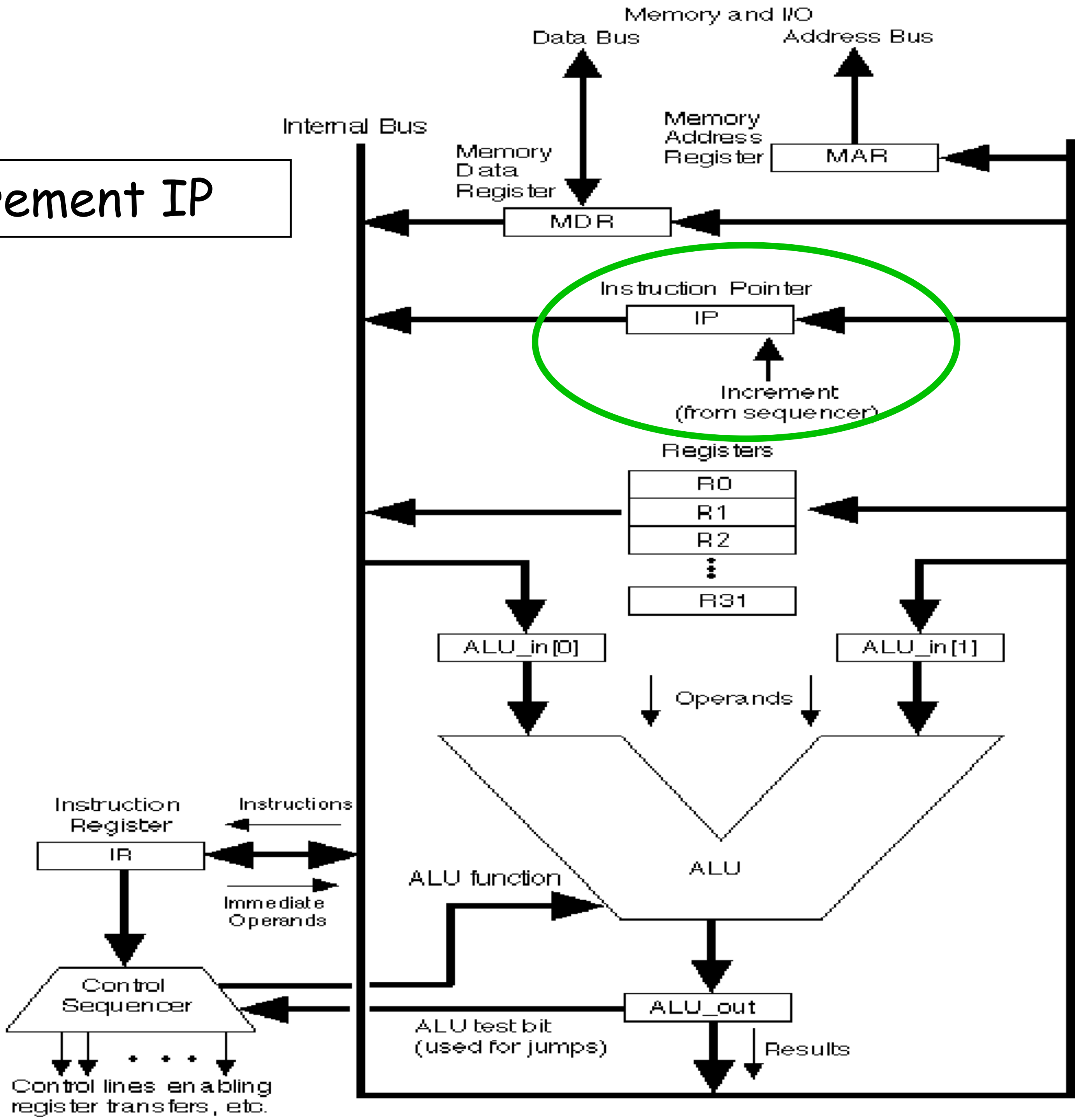
Enable MDR onto internal bus.

Load IR

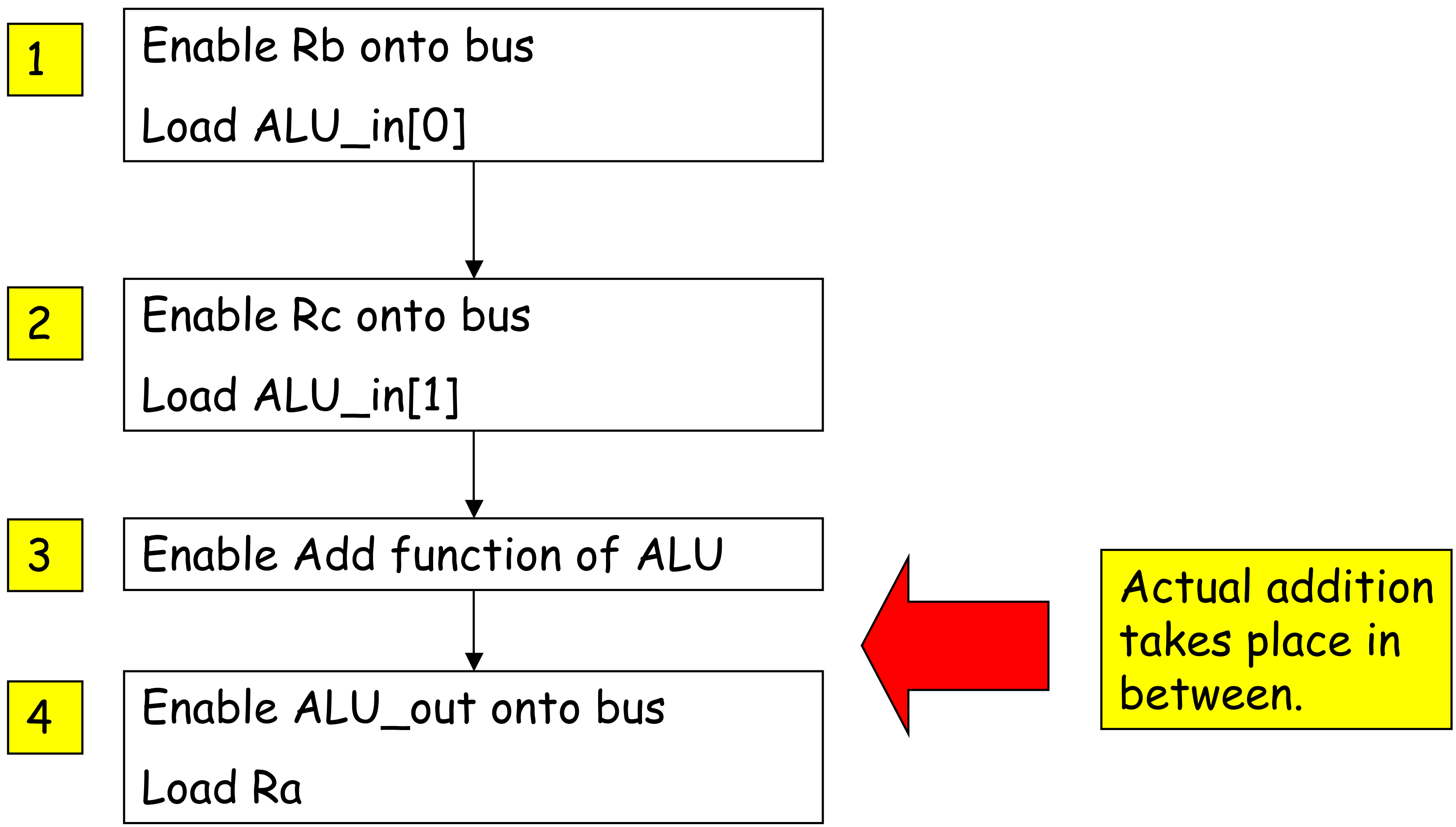


3'

Increment IP



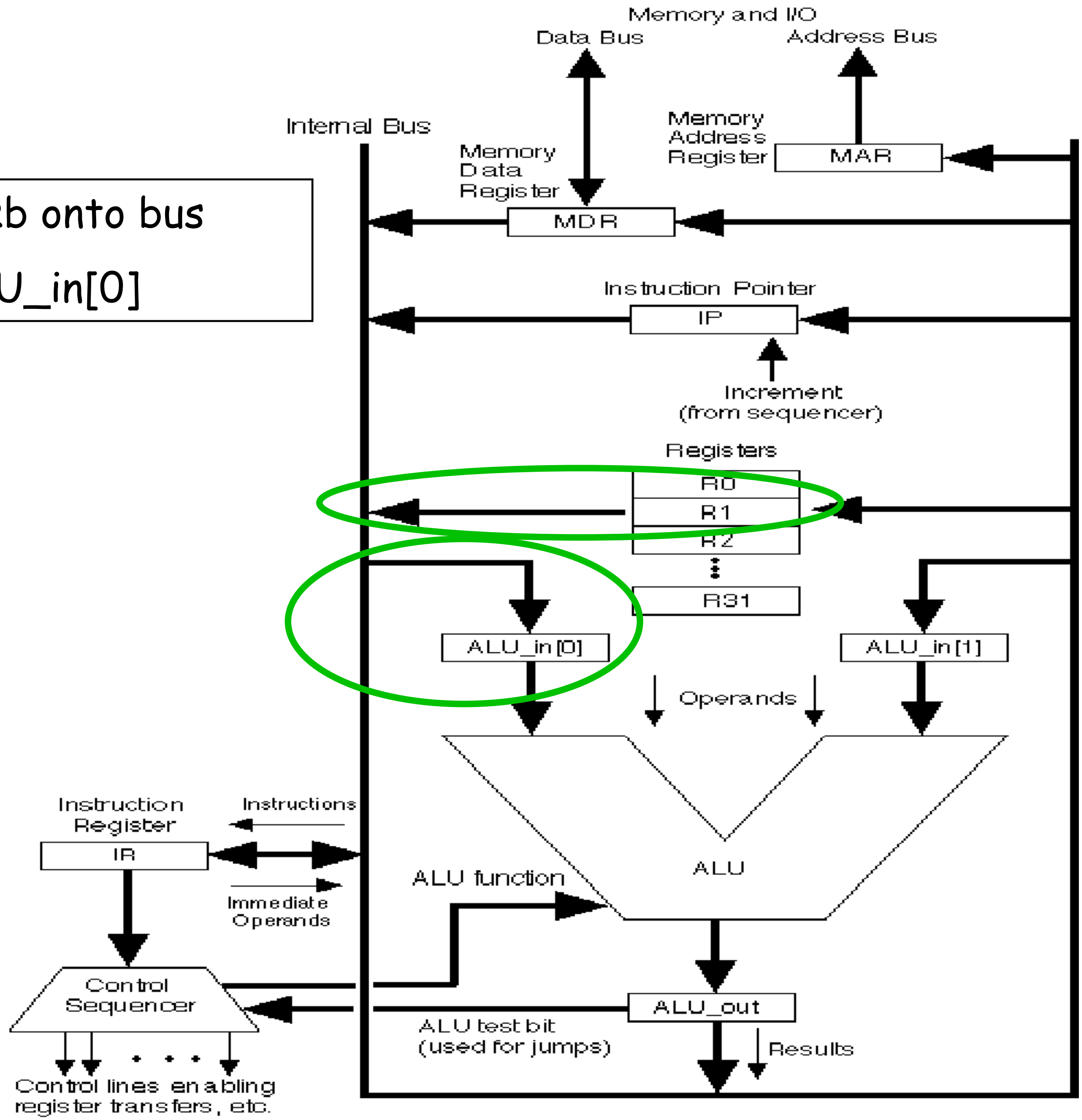
Control Subsequence Example: Add Ra Rb Rc



1

Enable Rb onto bus

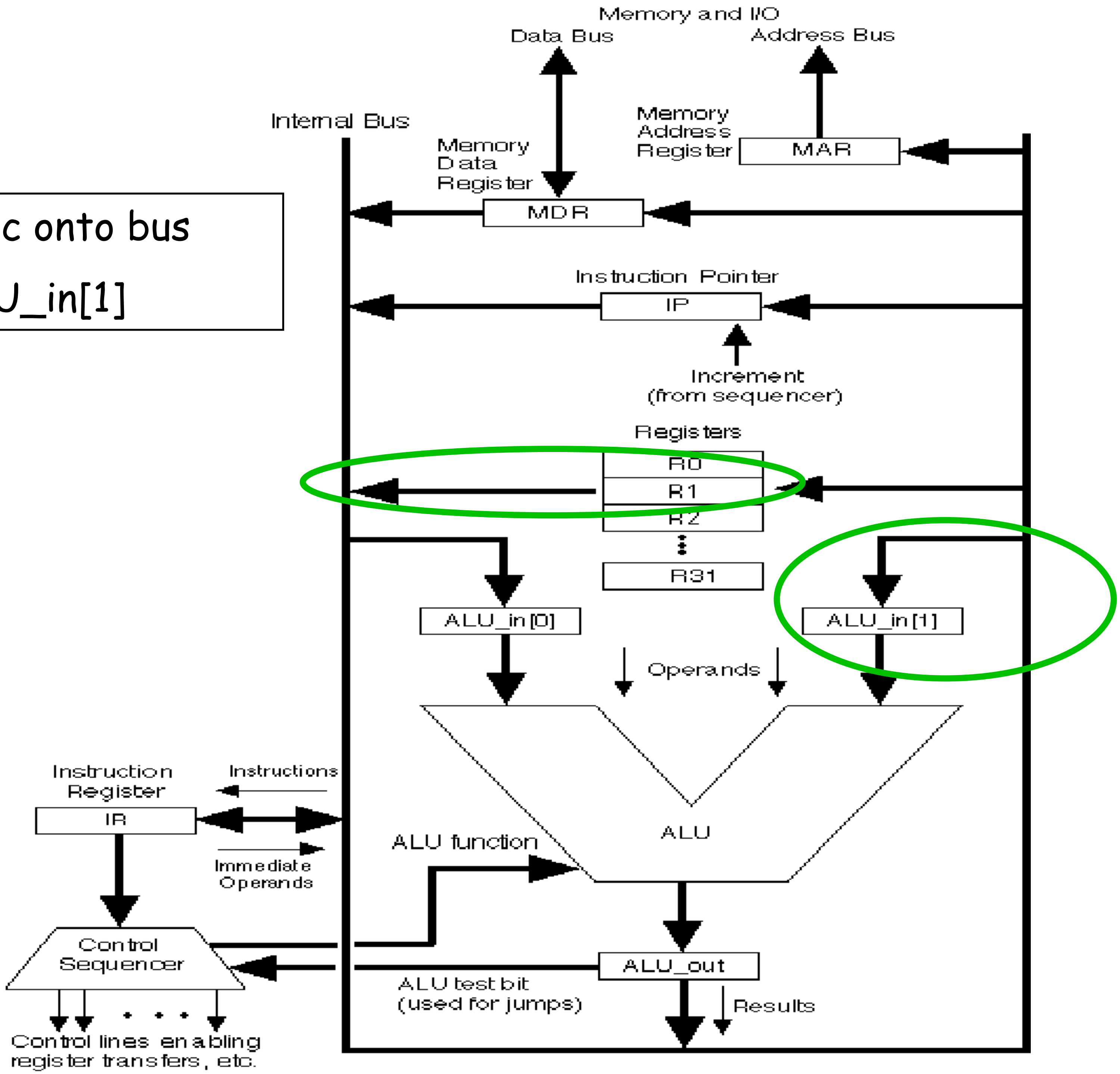
Load ALU_in[0]



2

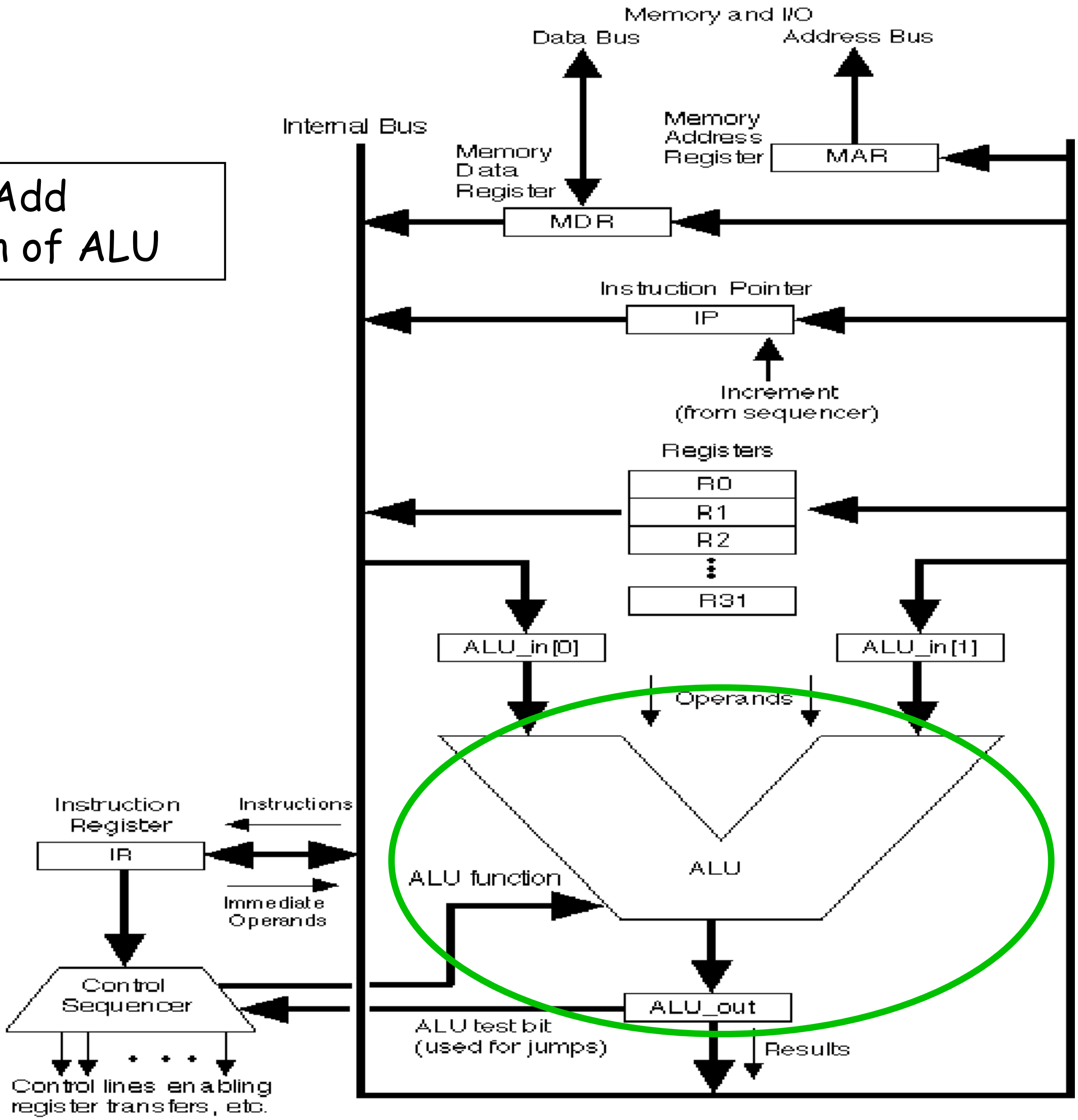
Enable Rc onto bus

Load ALU_in[1]



3

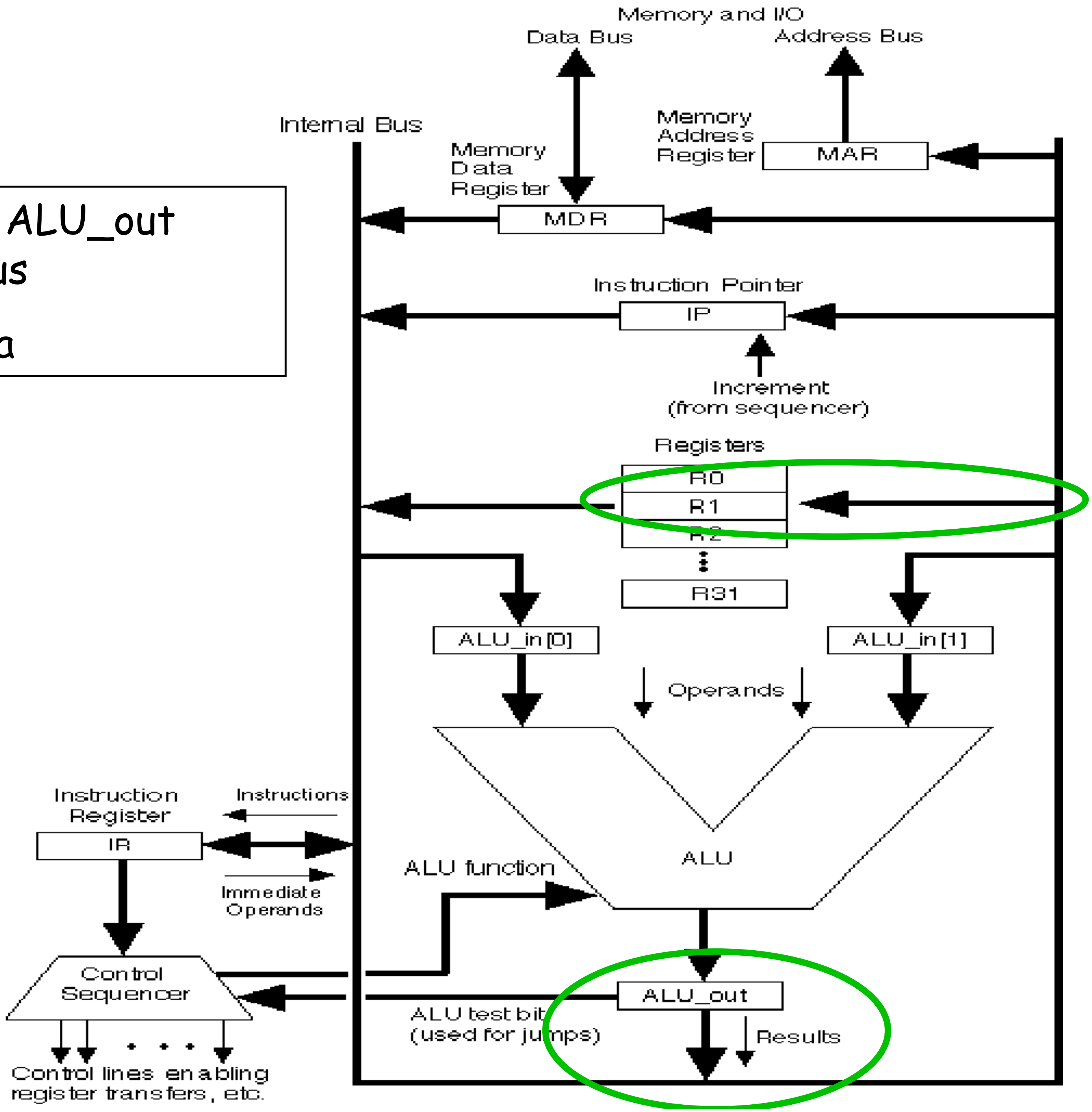
Enable Add function of ALU



4

Enable ALU_out
onto bus

Load Ra



Exercise

- What would the instruction subsequences be for:
  - aim (add immediate)
  - load
  - store
  - jeq (jump-if-equal)

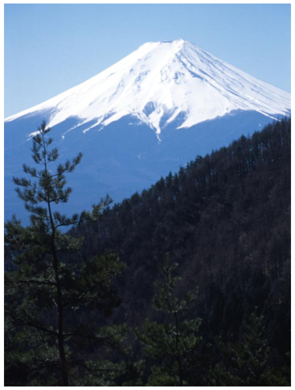
Machine-Level Programming

- Programming of the bare machine is typically done in "assembly language"
- One line of assembly language is roughly equal to one machine instruction
- A program, the "assembler", allows use of symbolic identifiers for addresses.

Programming in Assembly Language

- Programming in assembly language reminds me of the Japanese saying about climbing Mt. Fuji:

  "To never have climbed Mt. Fuji is to be a fool. Only a (bigger) fool would climb Mt. Fuji more than once."



ISCAL
ISC Assembly Language

- See http://www.cs.hmc.edu/~keller/isc/
- Free-form input, but generally format line-by-line
- Regular instructions
  - *Ra*, *Rb*, *Rc* are register names
  - *C* is a constant
    - **lim** *Ra C*
    - **add** *Ra Rb Rc*
    - **copy** *Ra Rb*
    - **shl** *Ra Rb*
    - **load** *Ra Rb*
    - etc.

ISCAL

- Assembler directives: not instructions to computer, but rather tell assembler what to do:
  - **define** *Identifier Value* — Defines *Identifier* to have *Value.*
  - **use** *Identifier* — Defines *Identifier* to name an unused register.
  - **origin** *Value* — Begin loading instructions at specified memory location. The location counter is incremented as loading progresses.
  - **label** *Identifier* — Associates current instruction location with *Identifier.*

ISCAL code for summing an array

```
   use array  use count             // array base and count
   use sum    use zero   use value  // local registers
   use loop   use done              // address registers
```

… insert code to load array and count values …

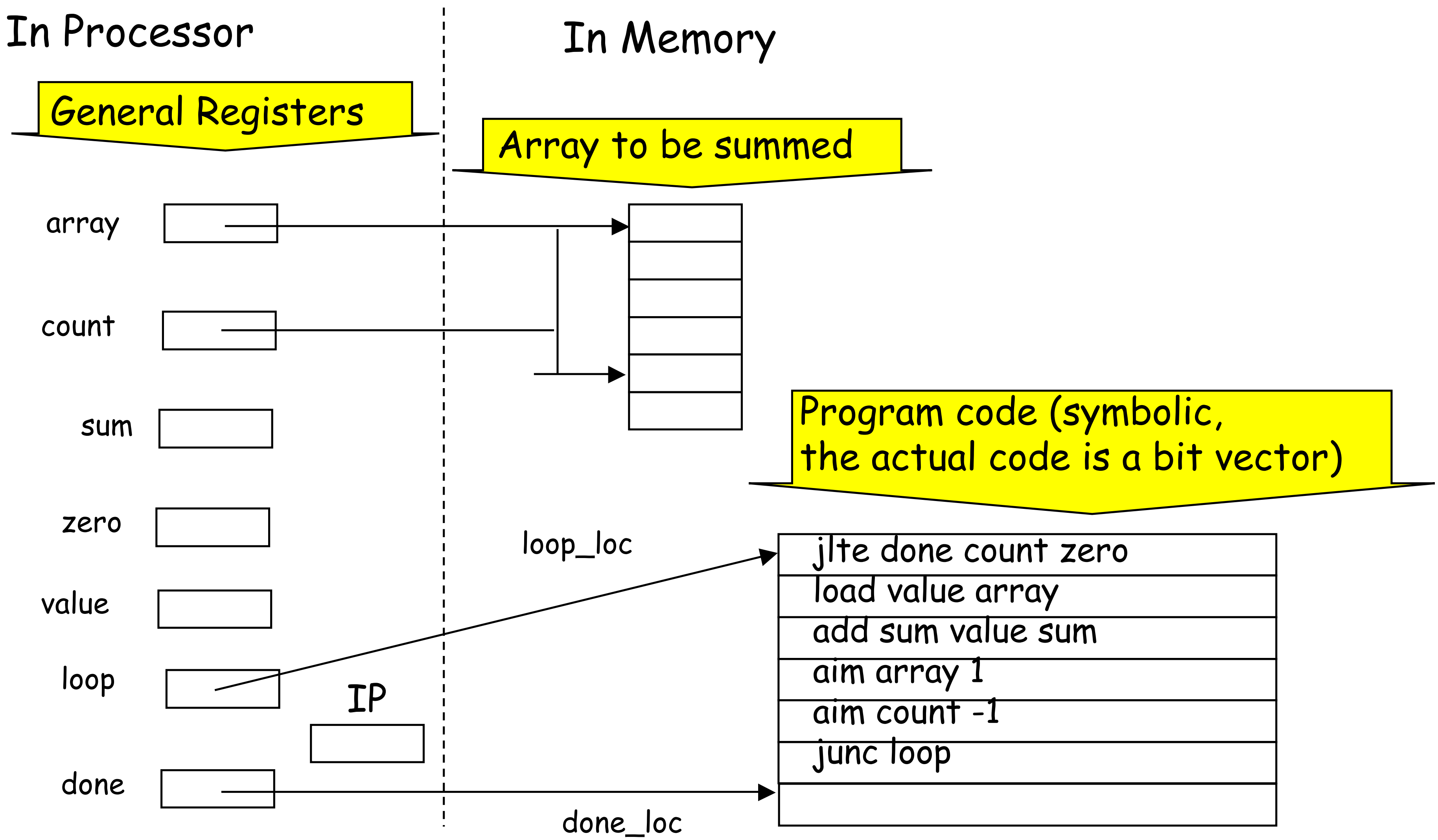
```
    lim sum  0          // initialize sum
    lim zero  0         // comparison value
    lim done done_loc   // address of instruction following
    lim loop loop_loc   // address of next instruction

label loop_loc

    jlte done count zero // jump if <= 0
    load value array     // load register next array value
    add sum value sum    // add the next number to the sum
    aim array 1          // add 1 to the array address
    aim count -1         // add -1 to the count
    junc loop            // go back and compare

label done_loc
```

Array Summation



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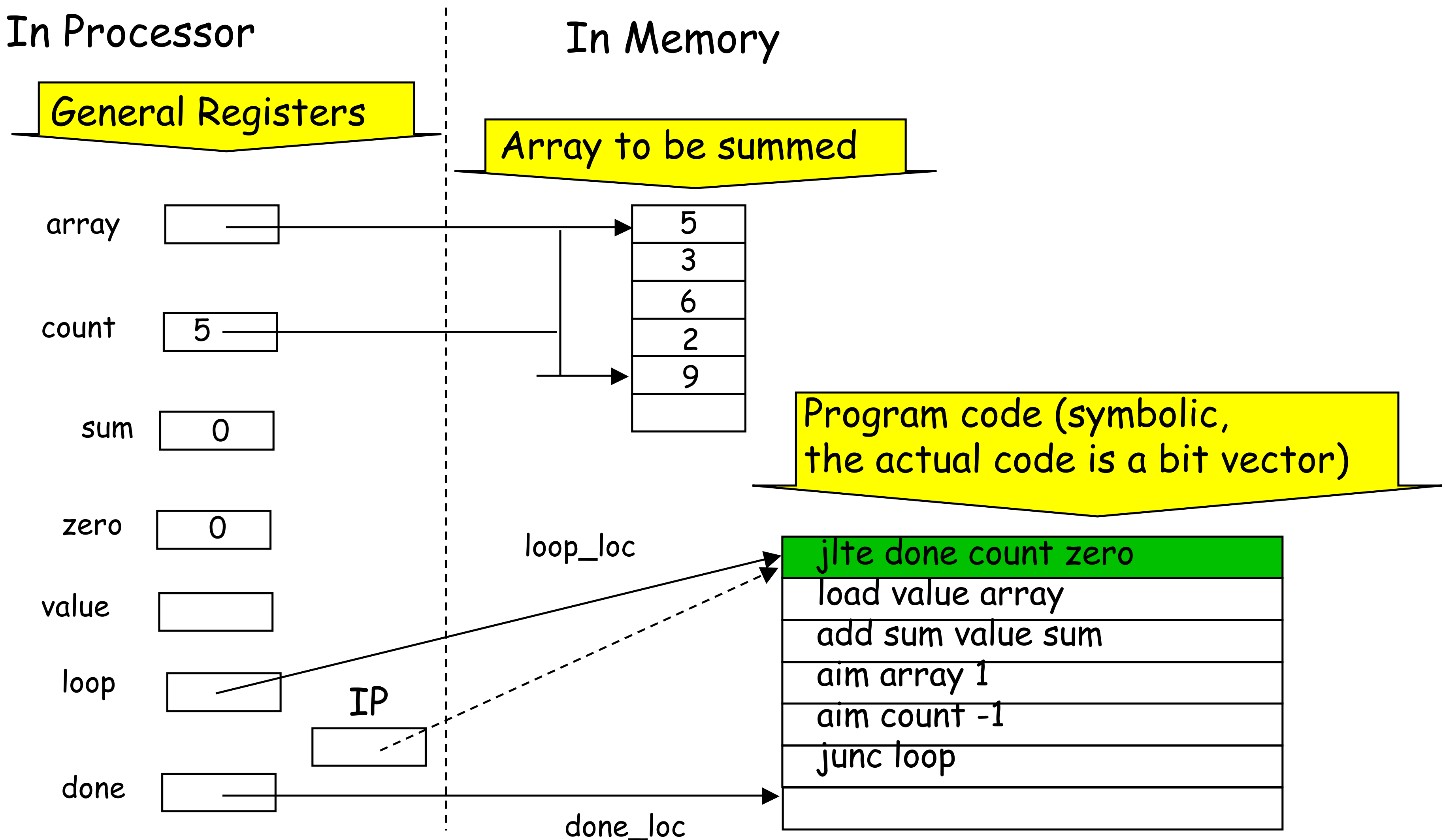

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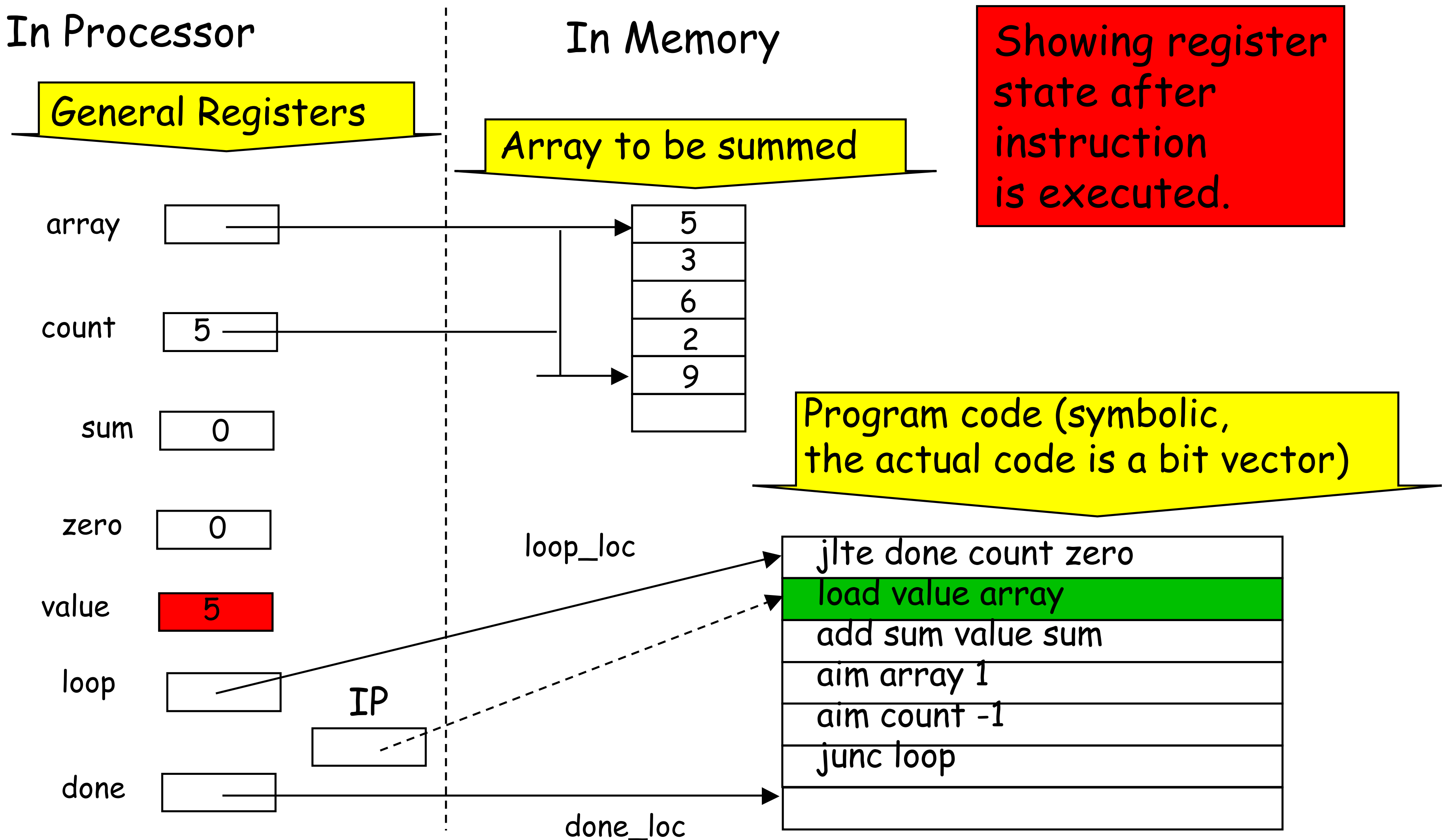

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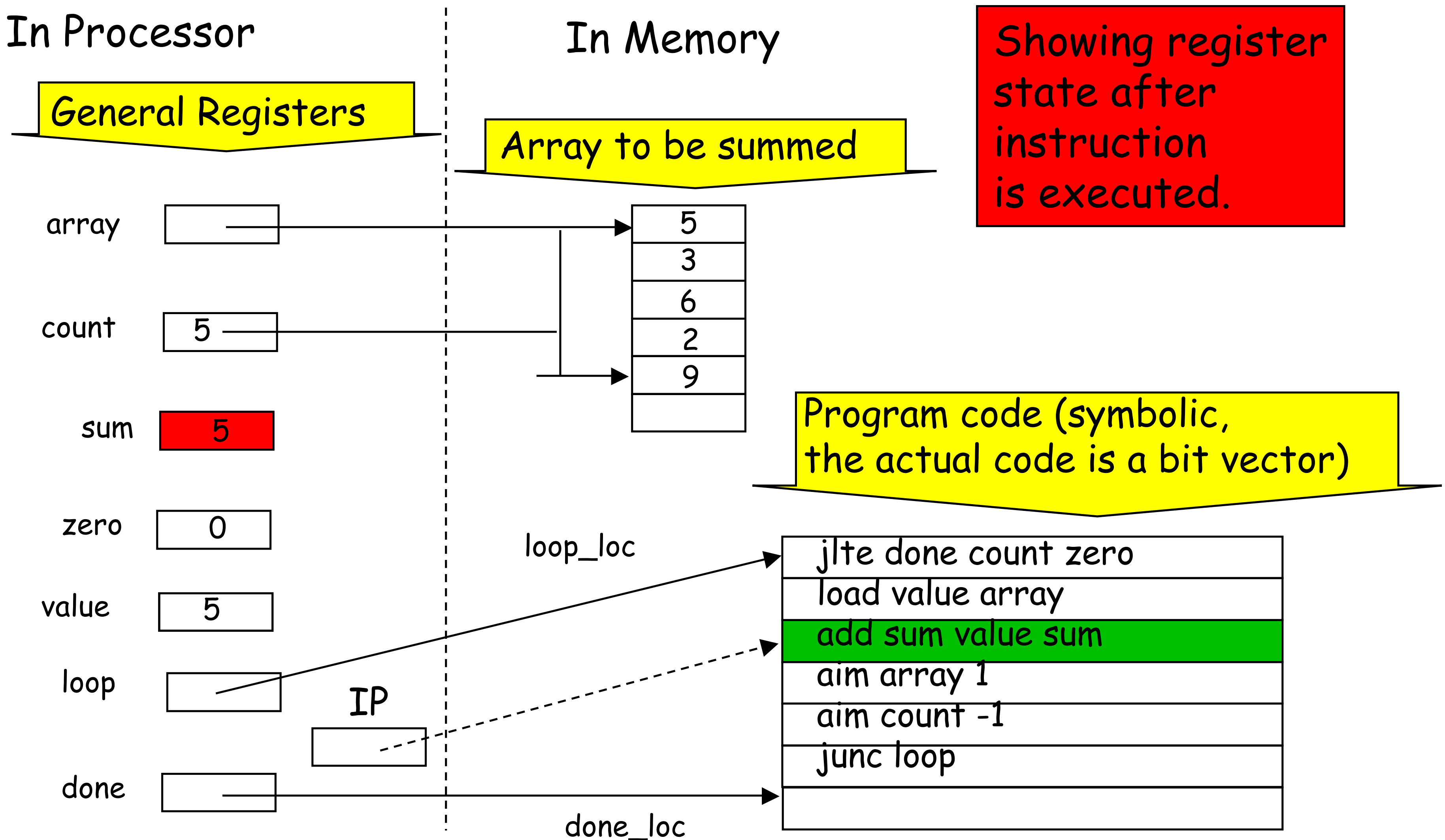

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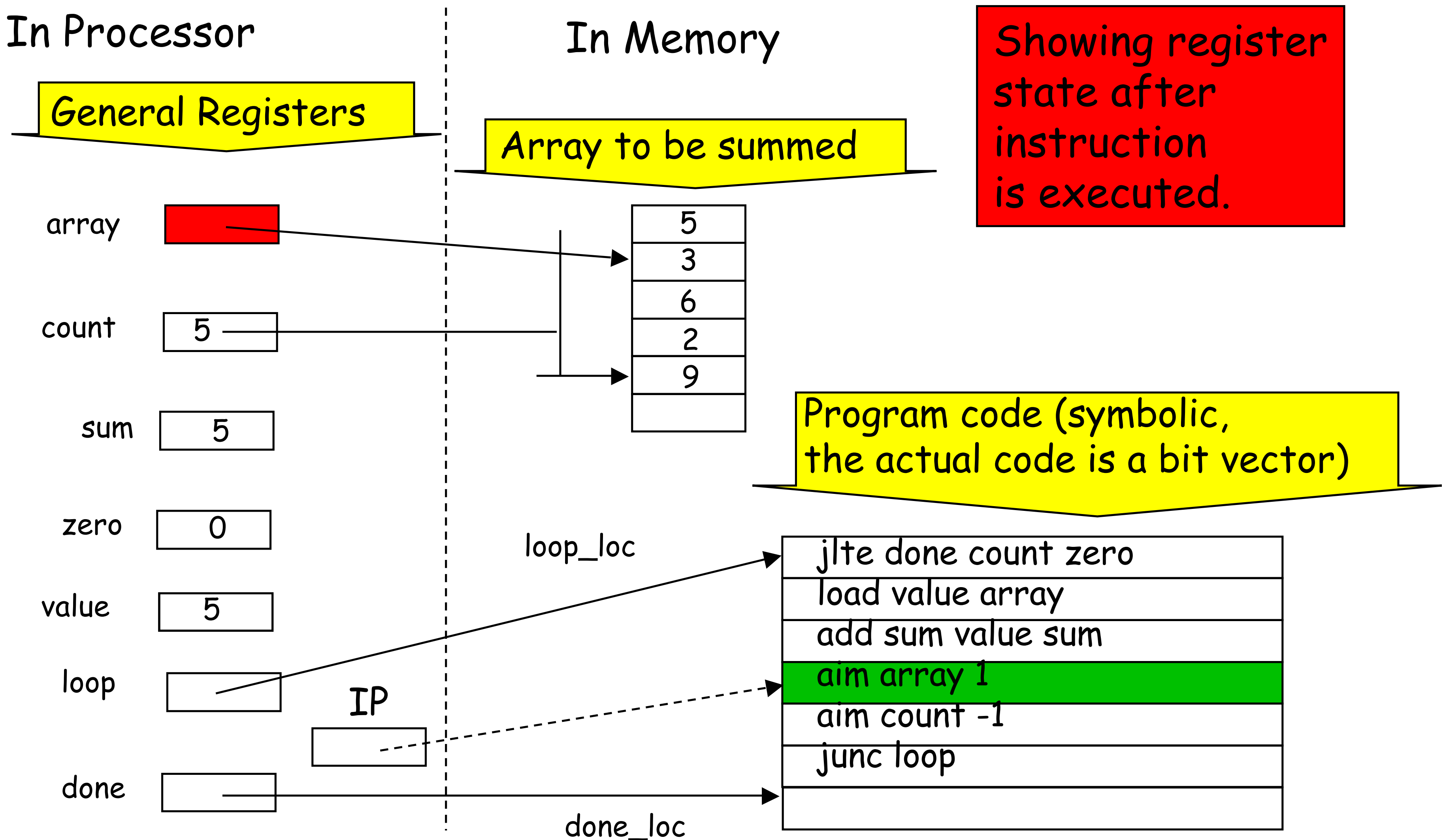

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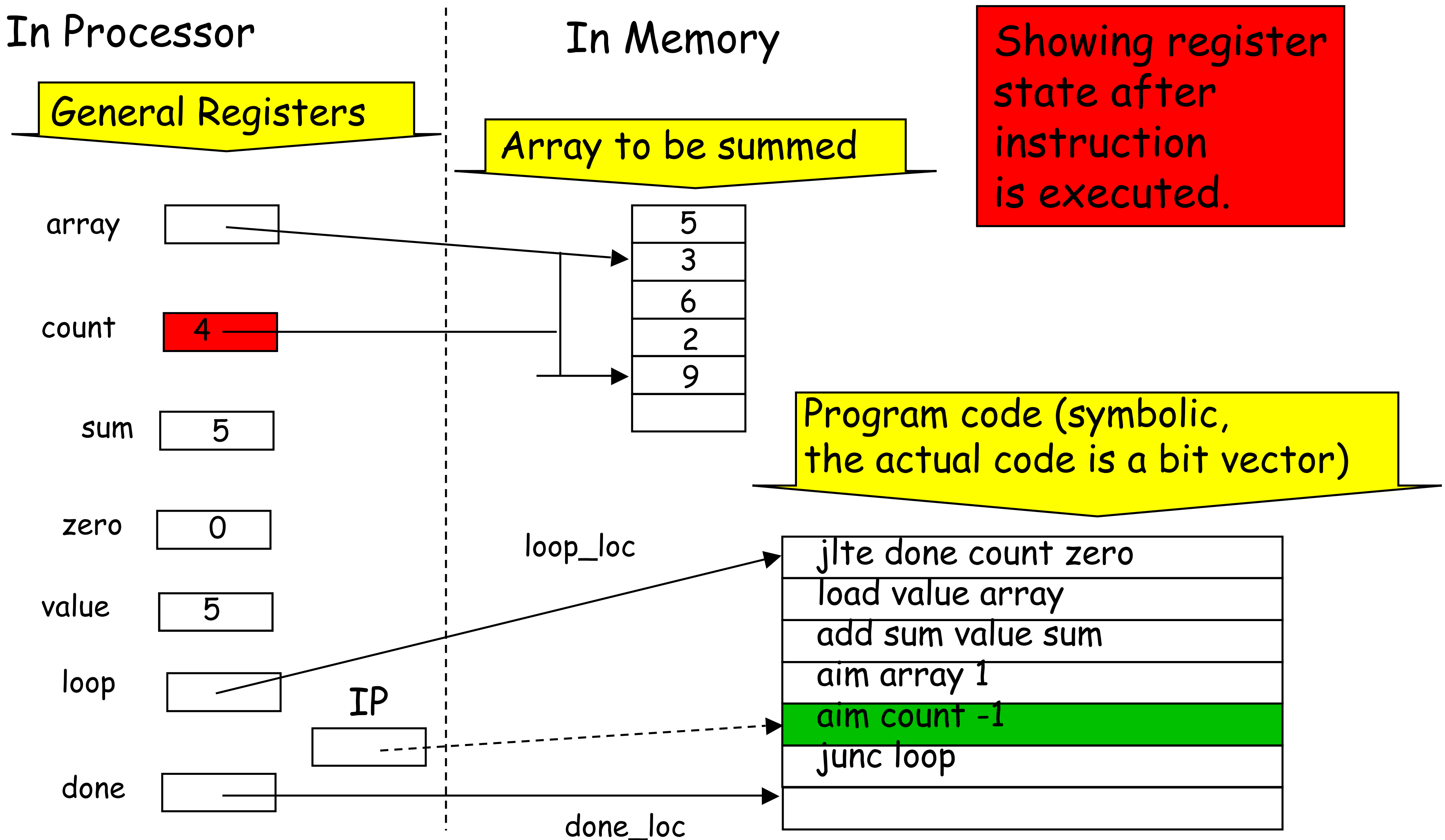

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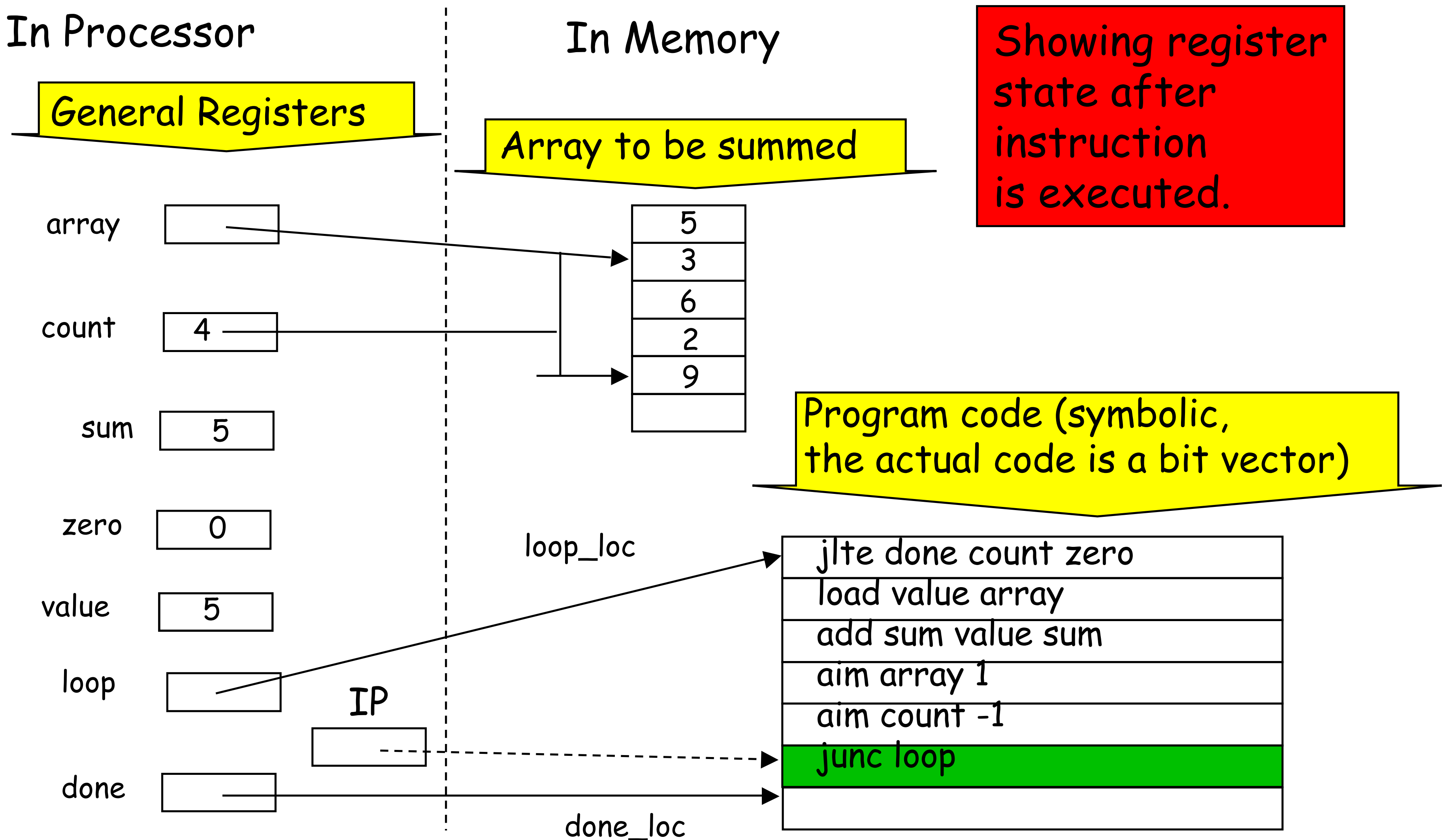

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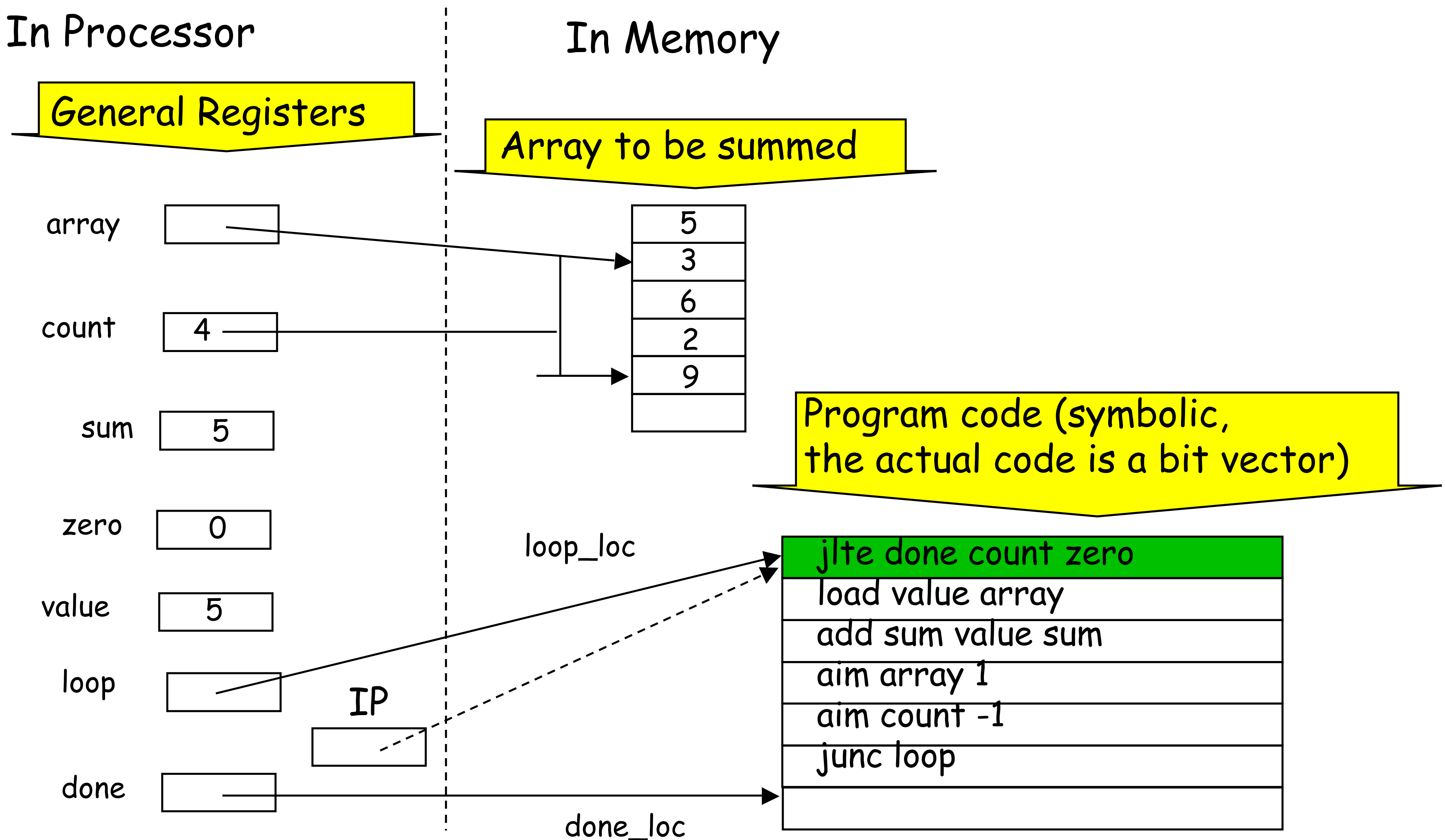

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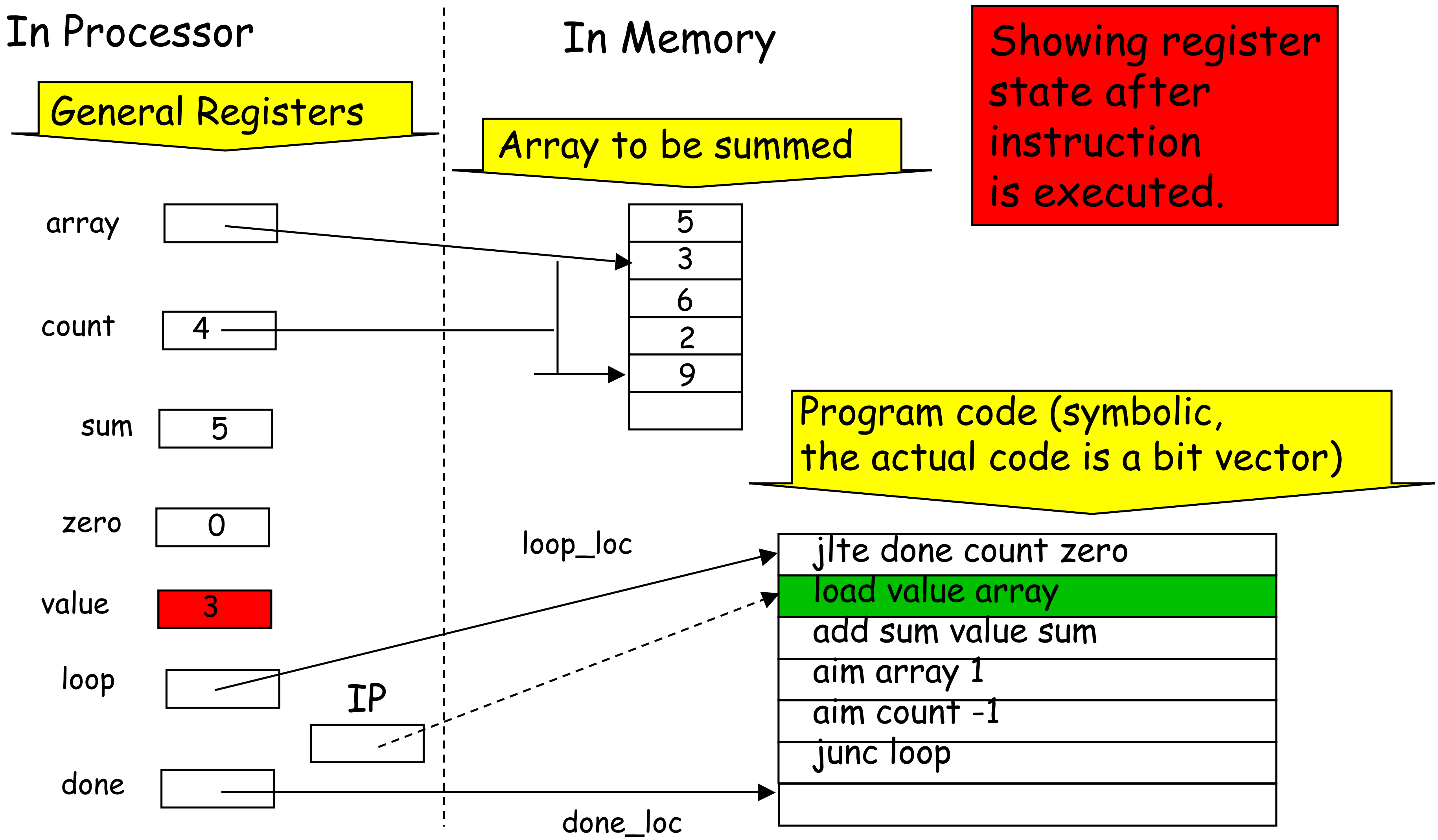

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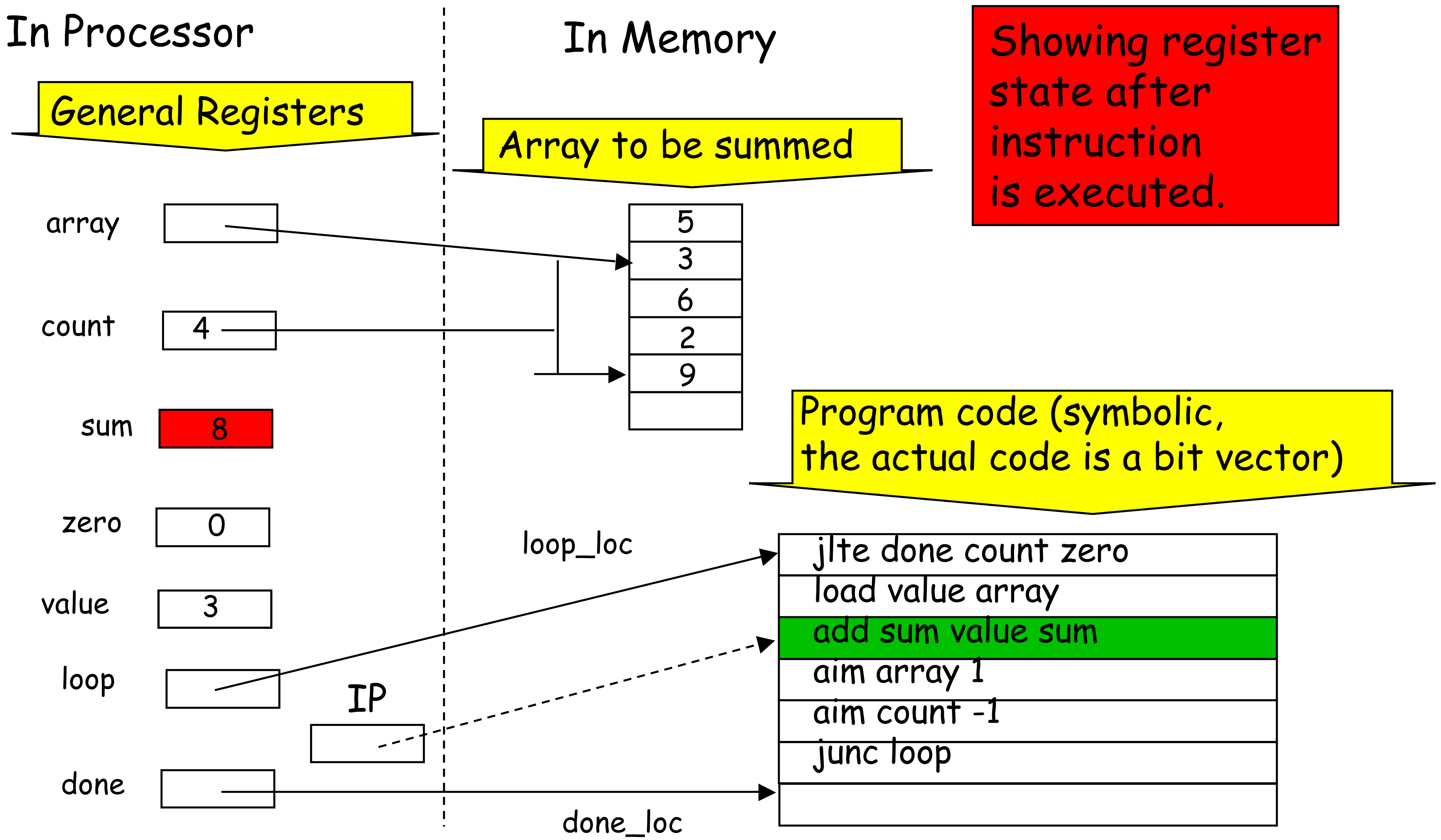

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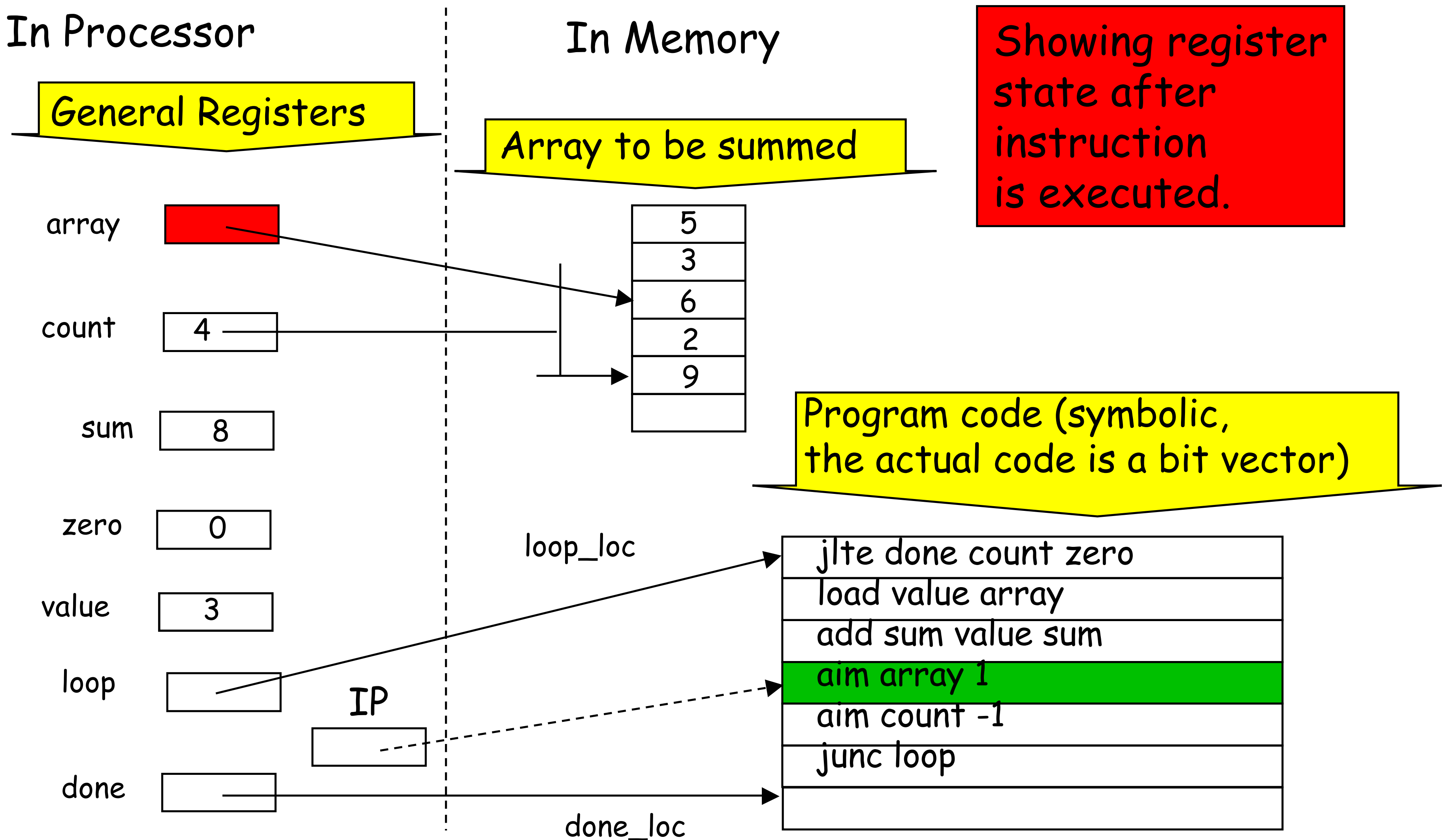

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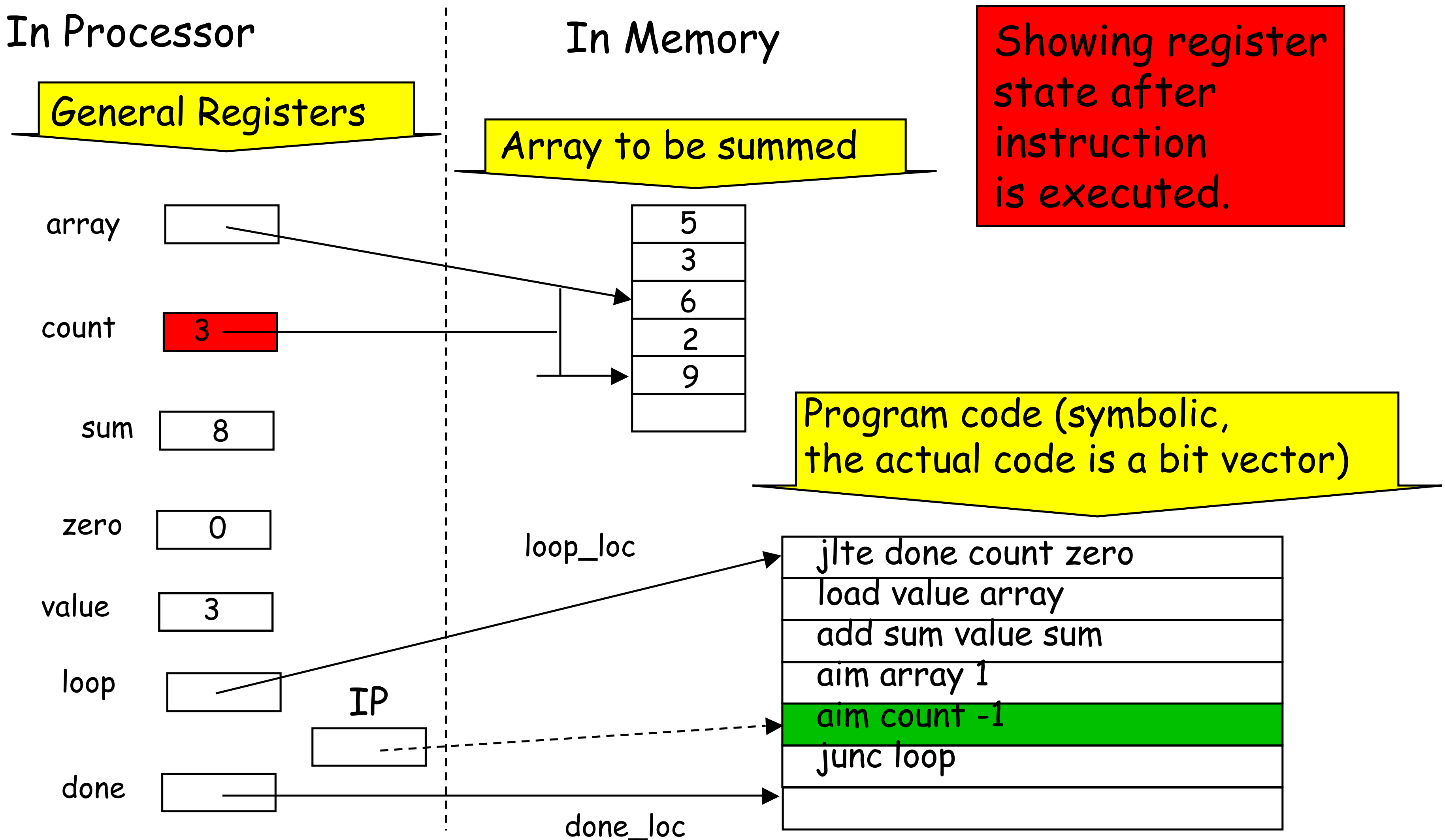

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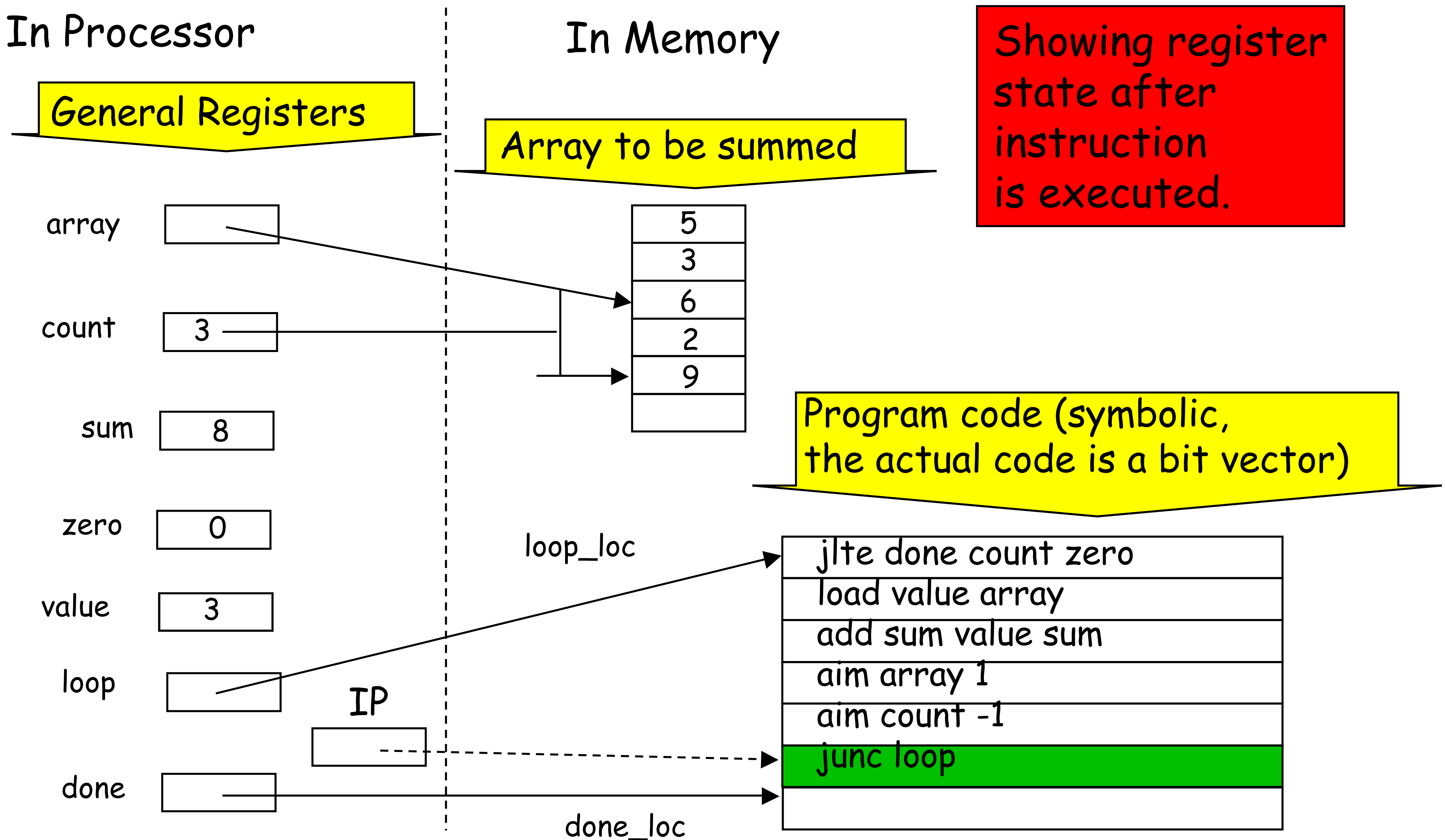

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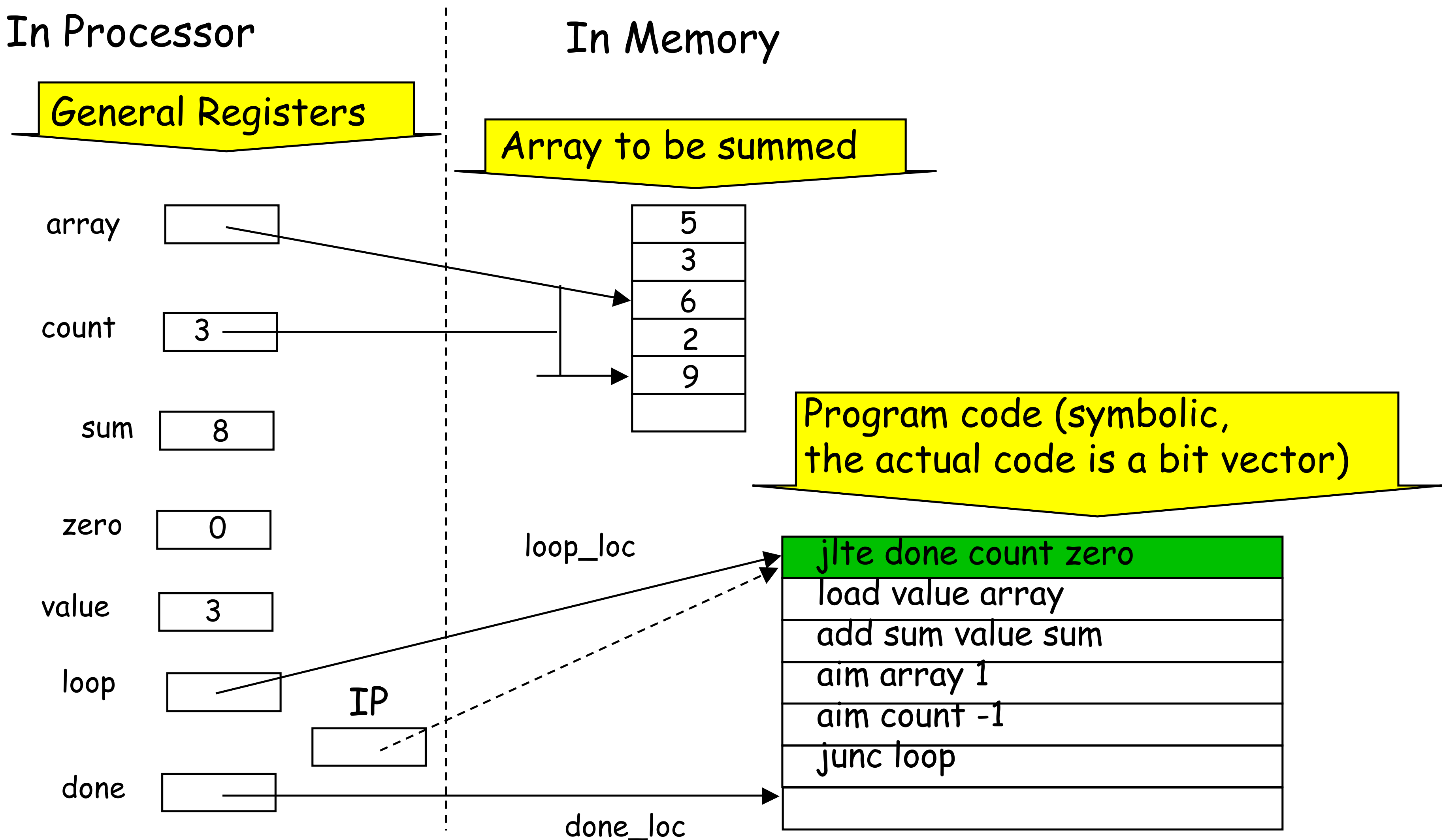

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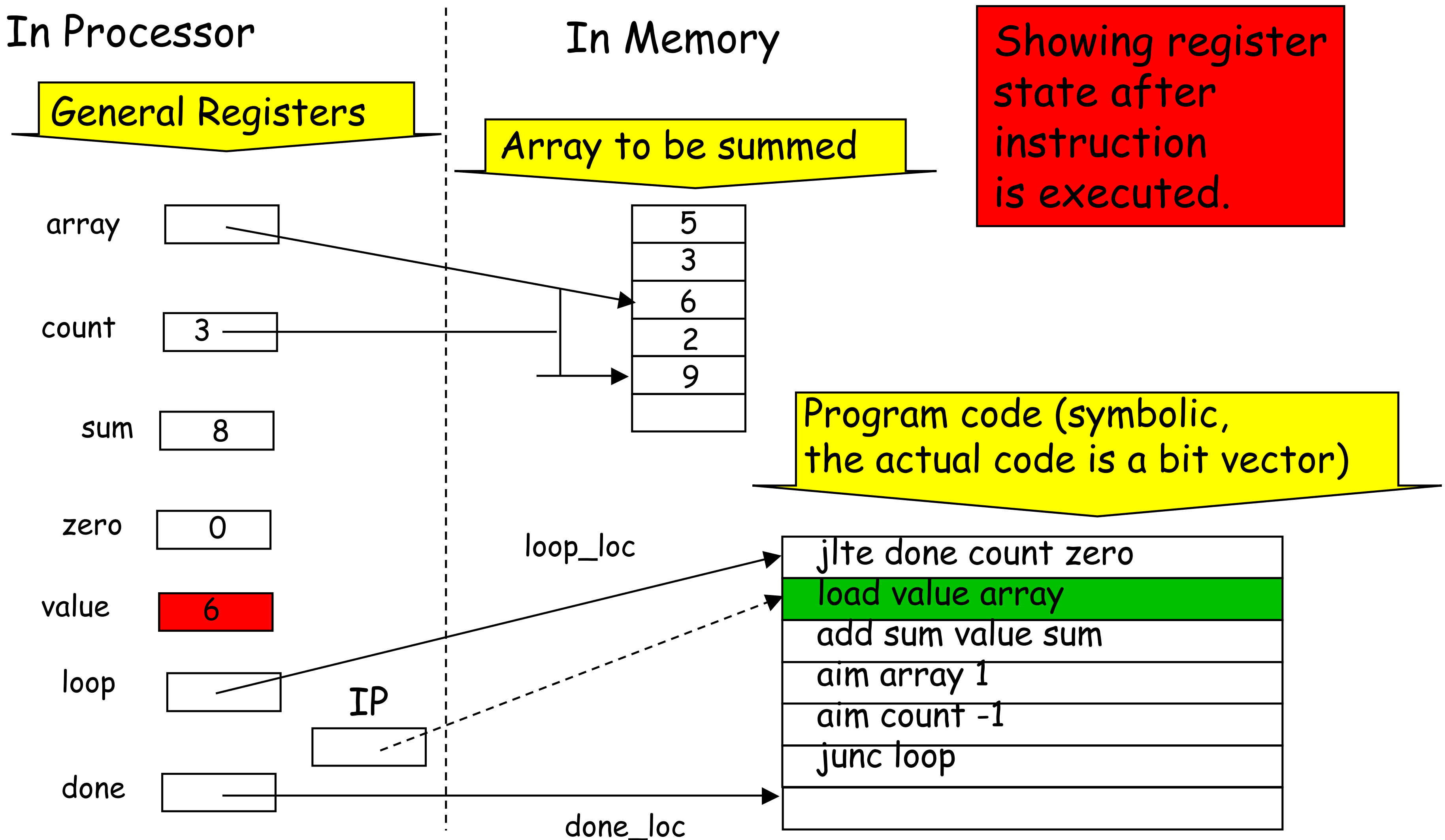

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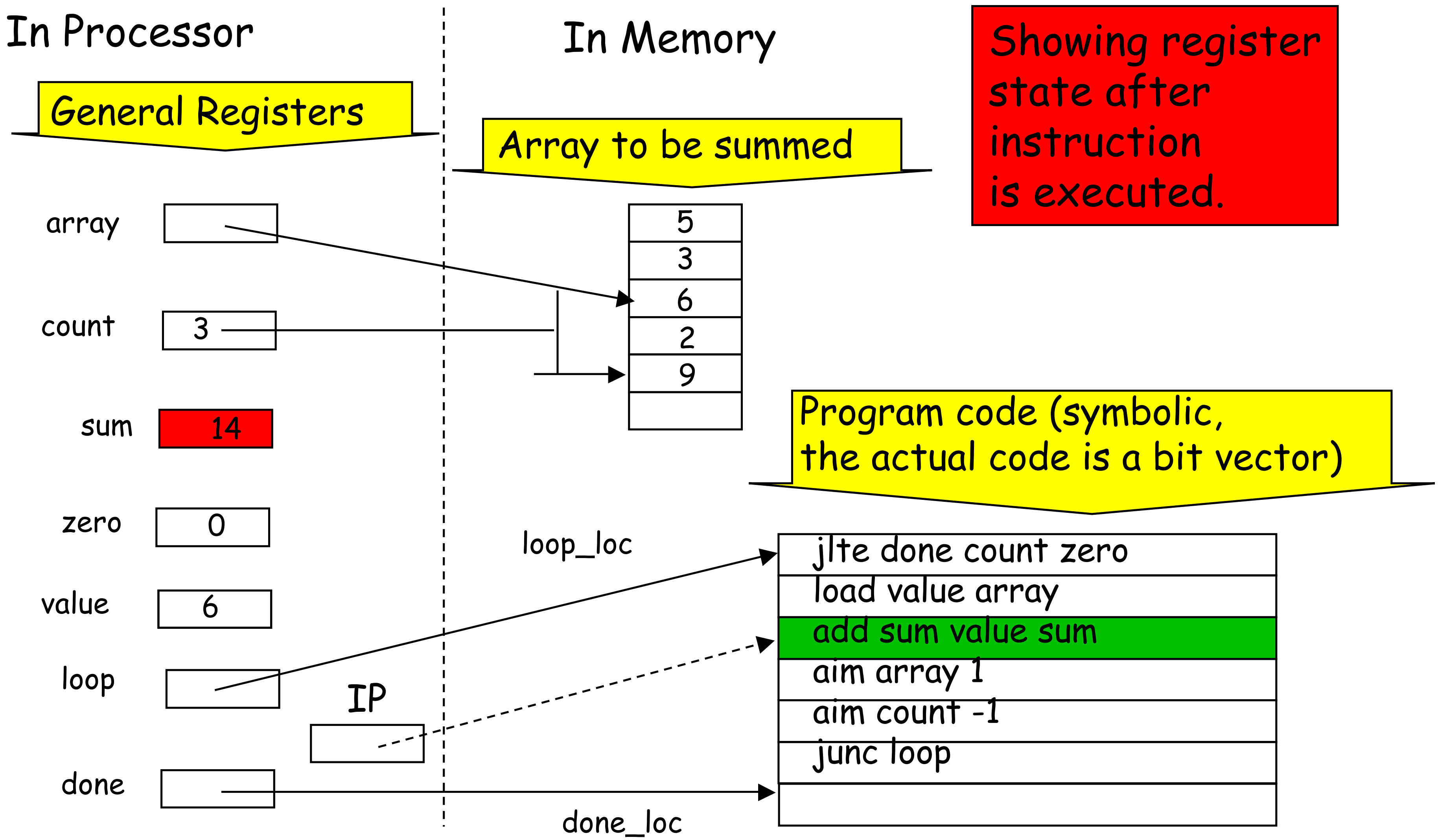

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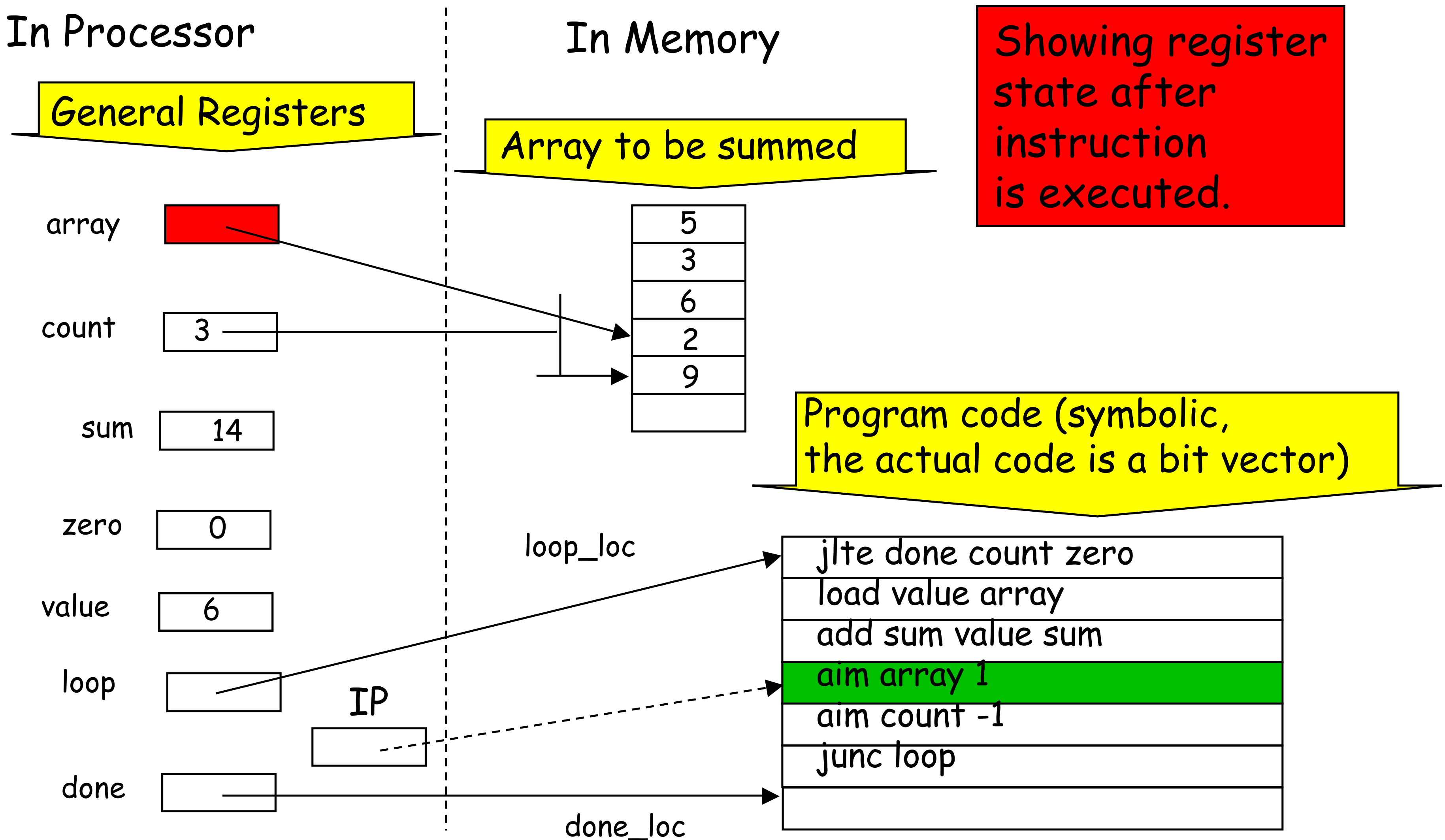

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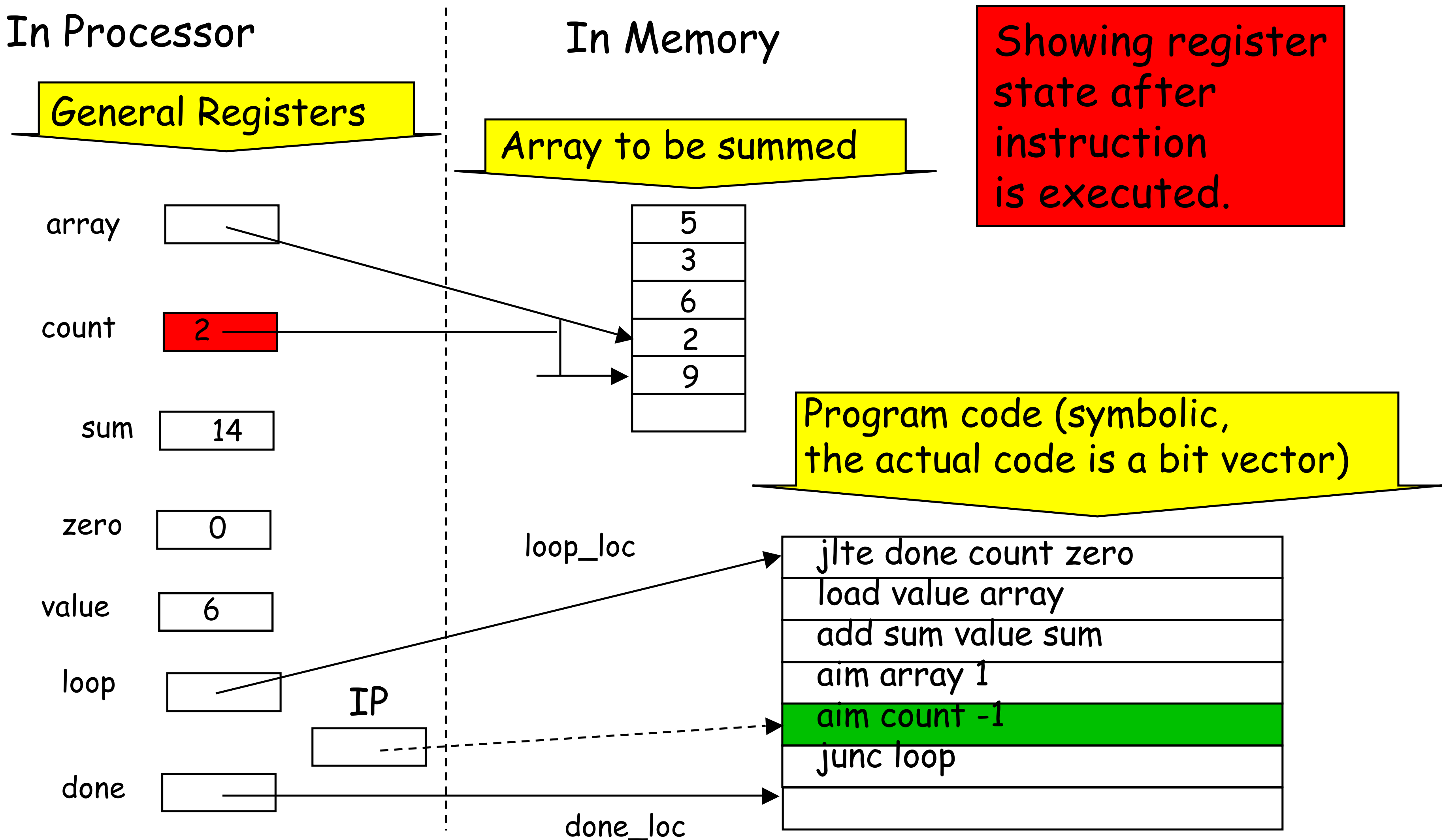

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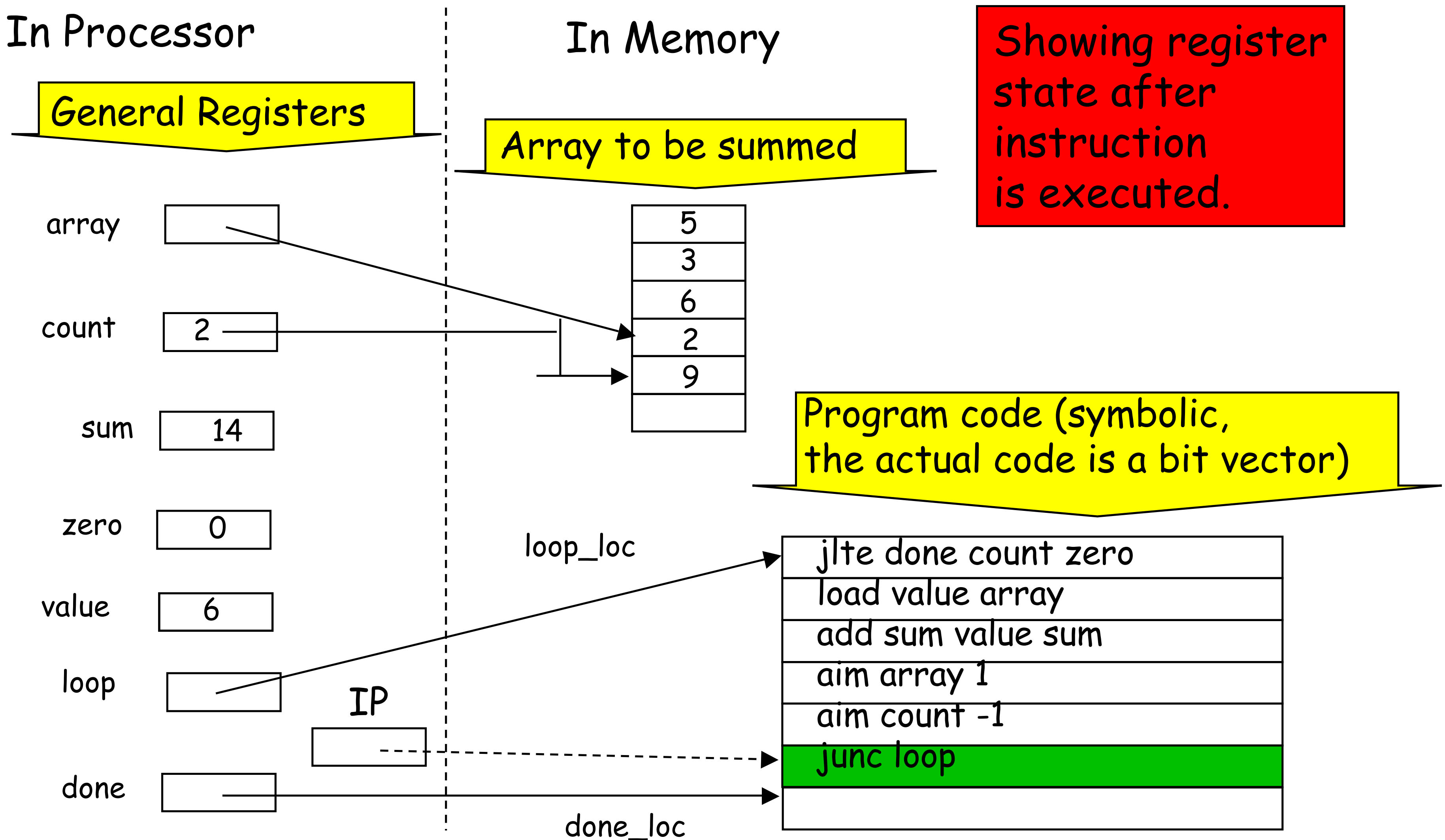

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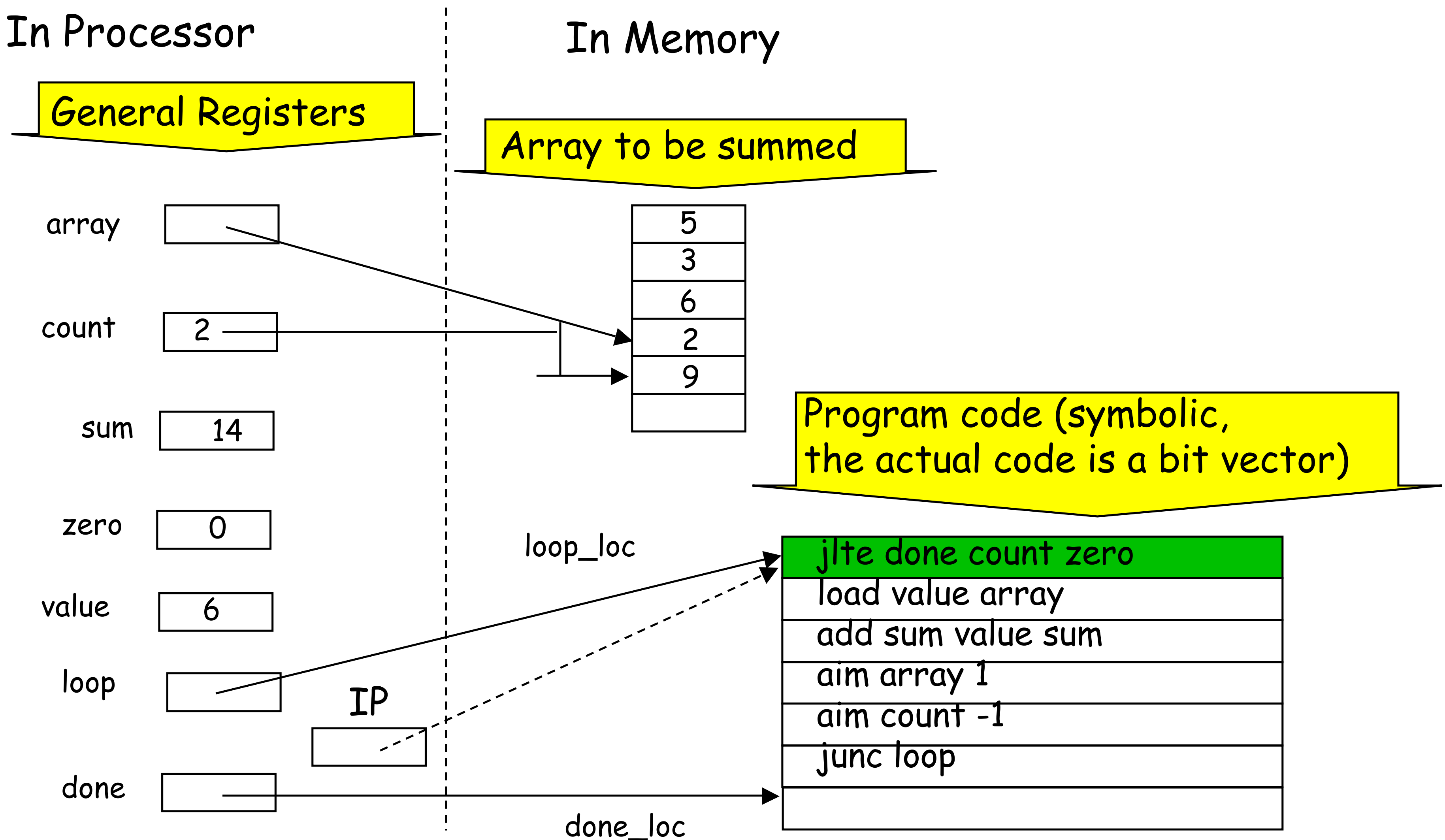

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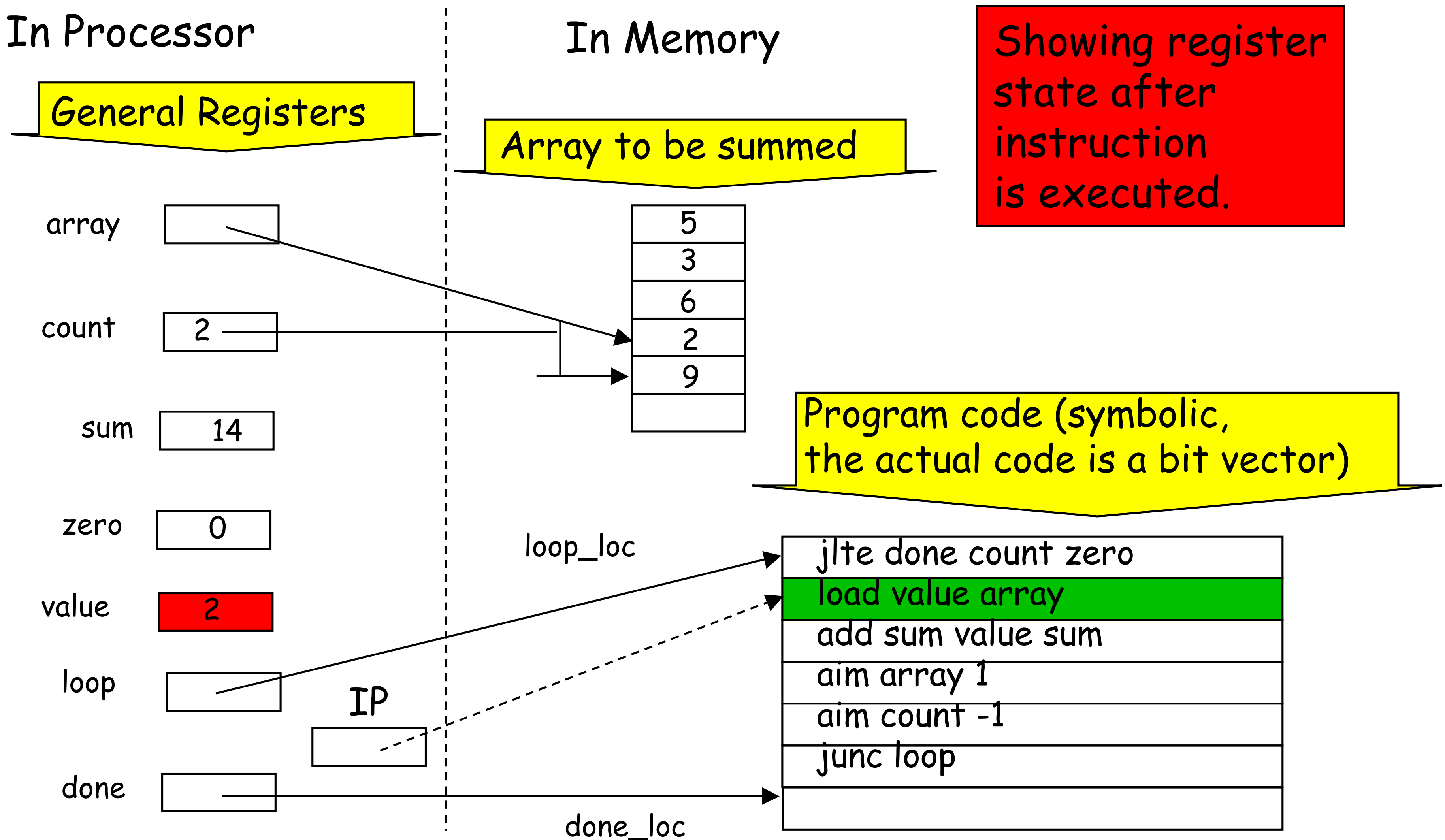

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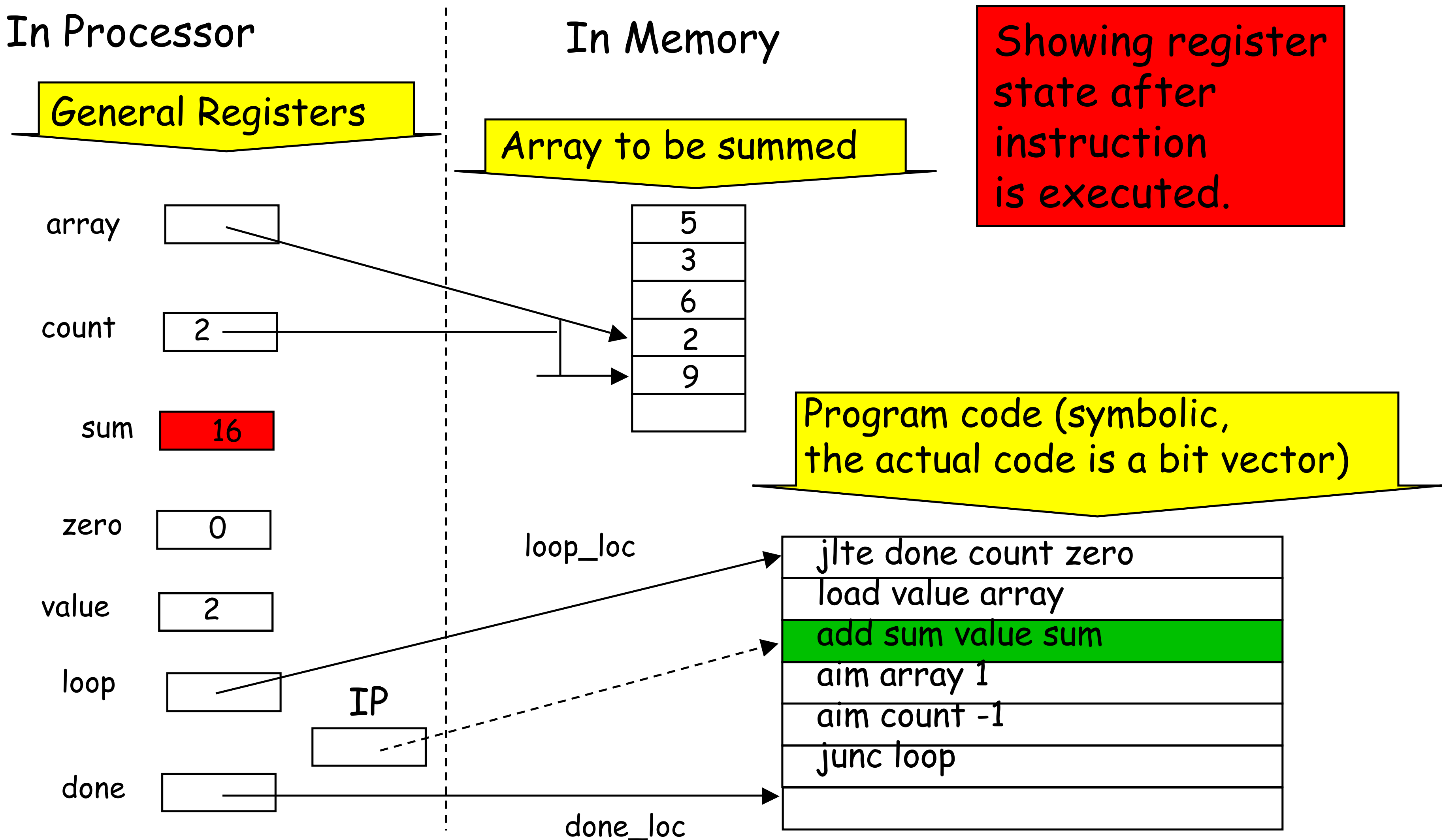

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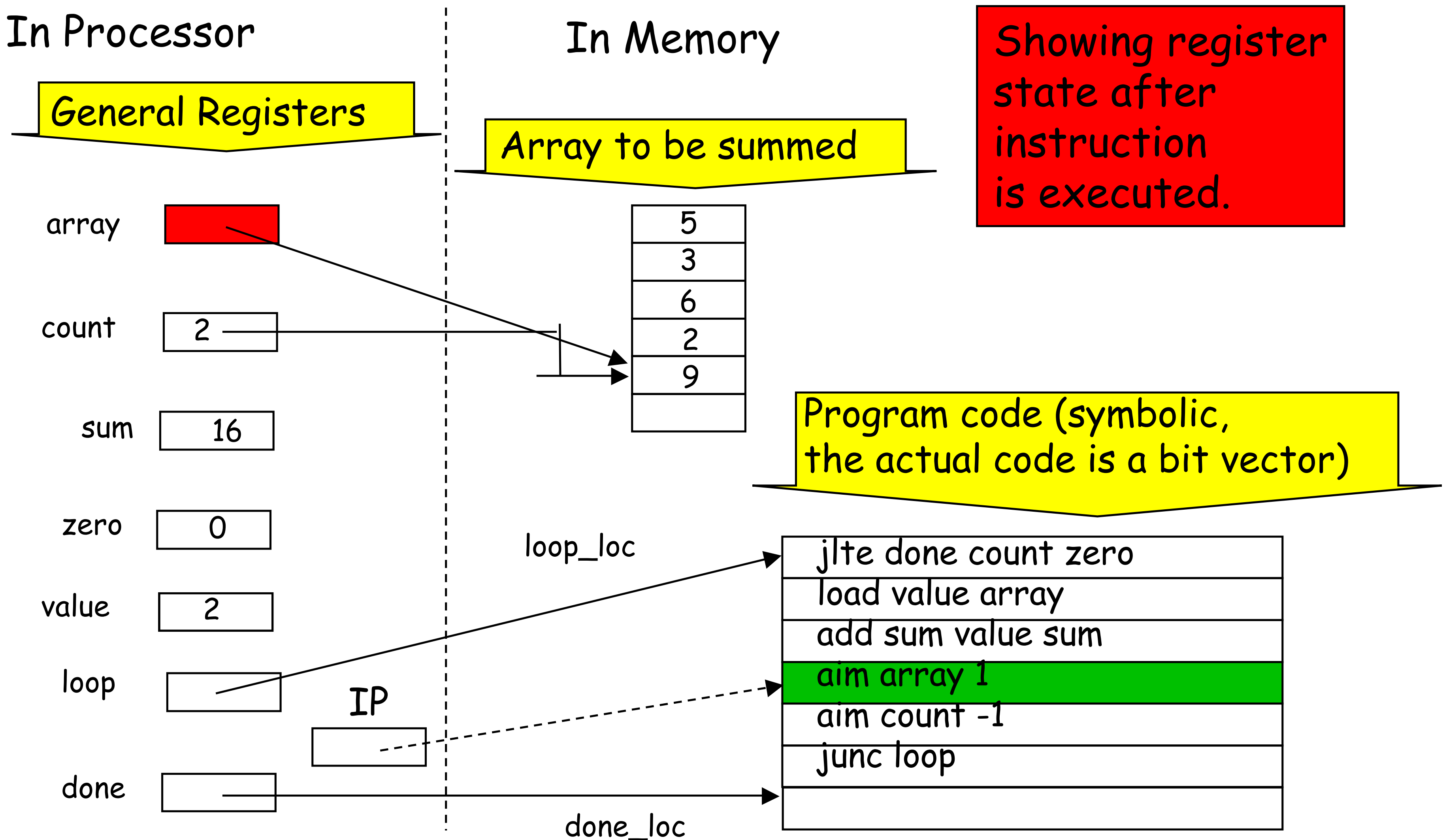

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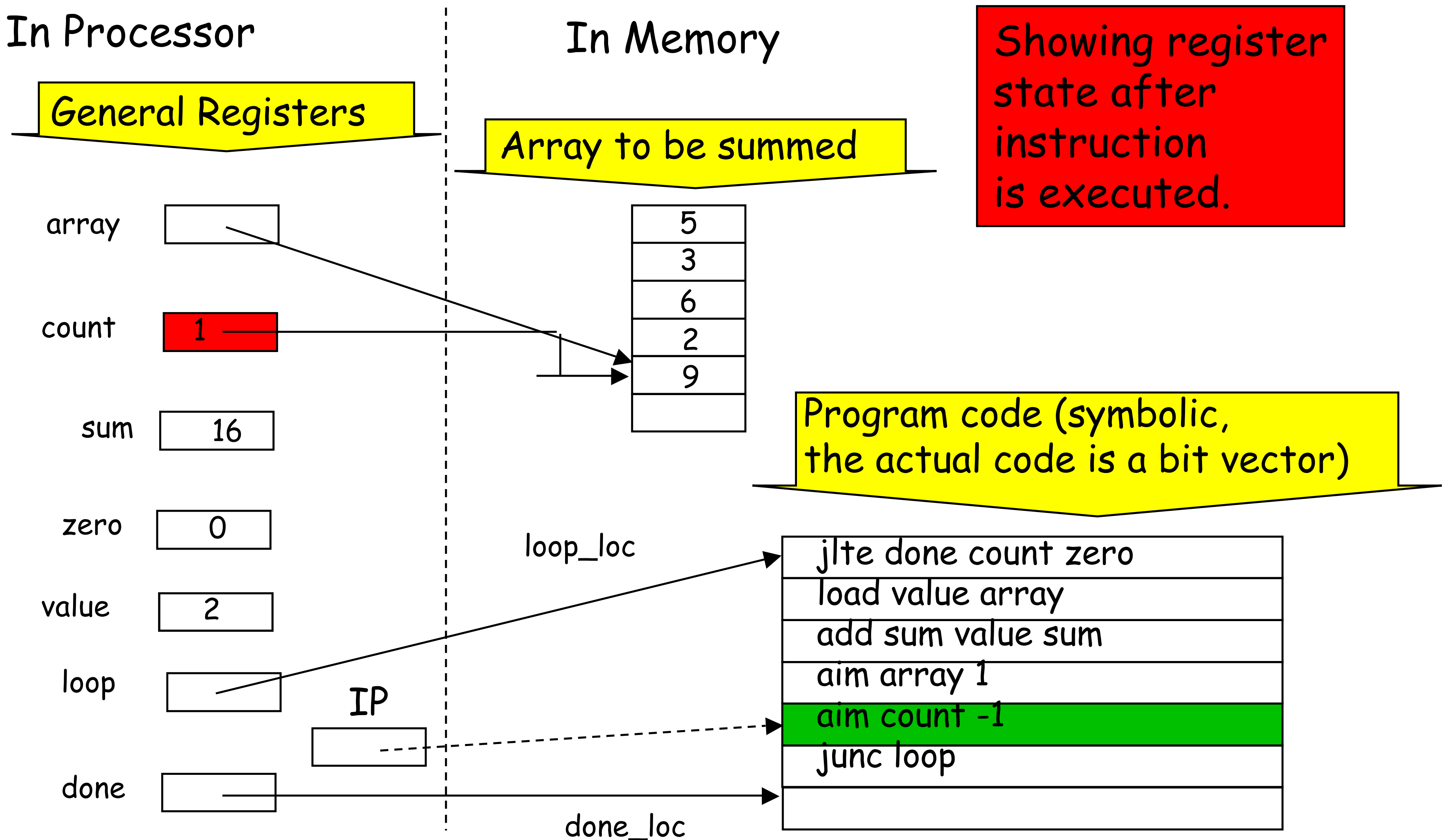

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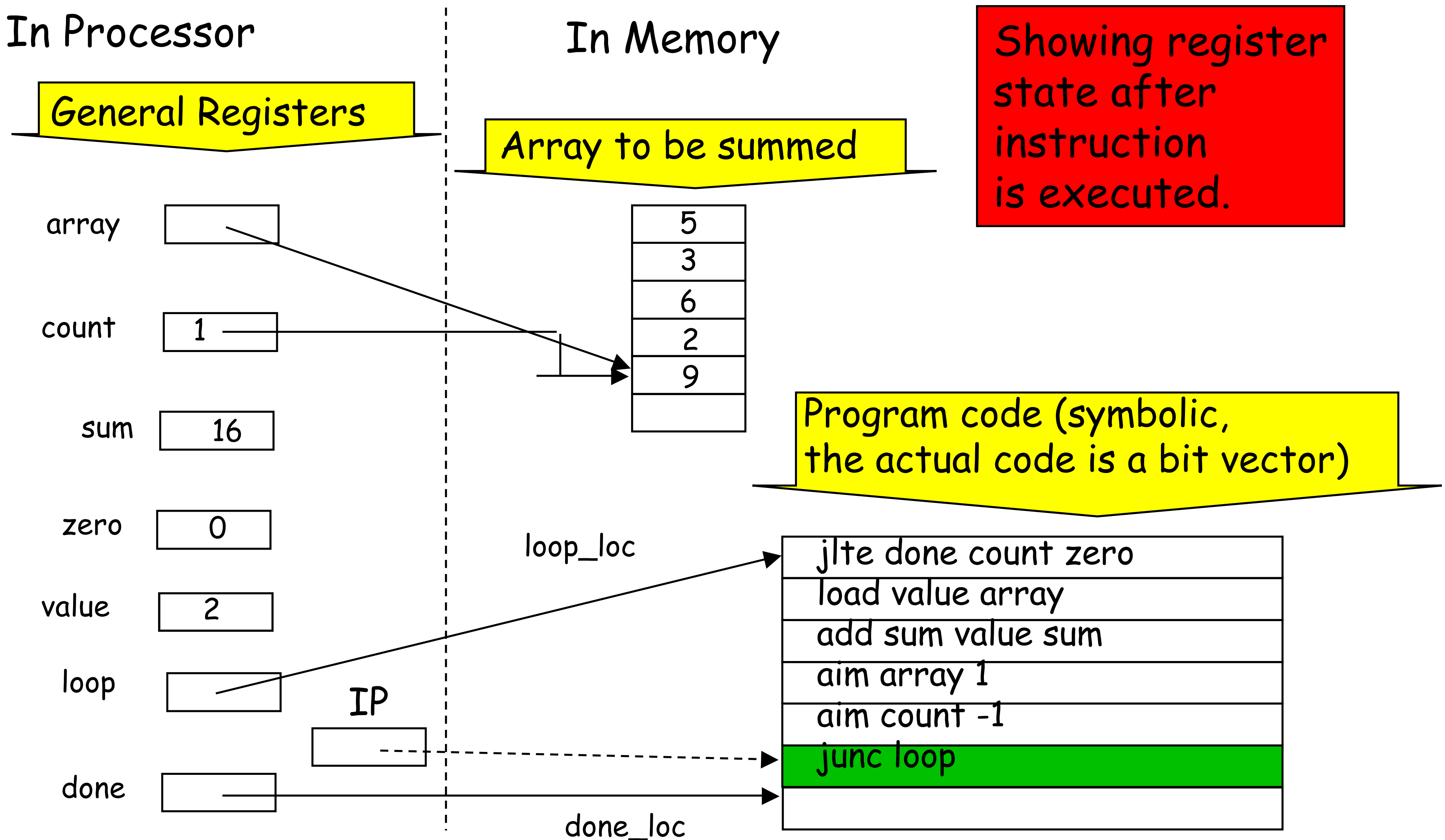

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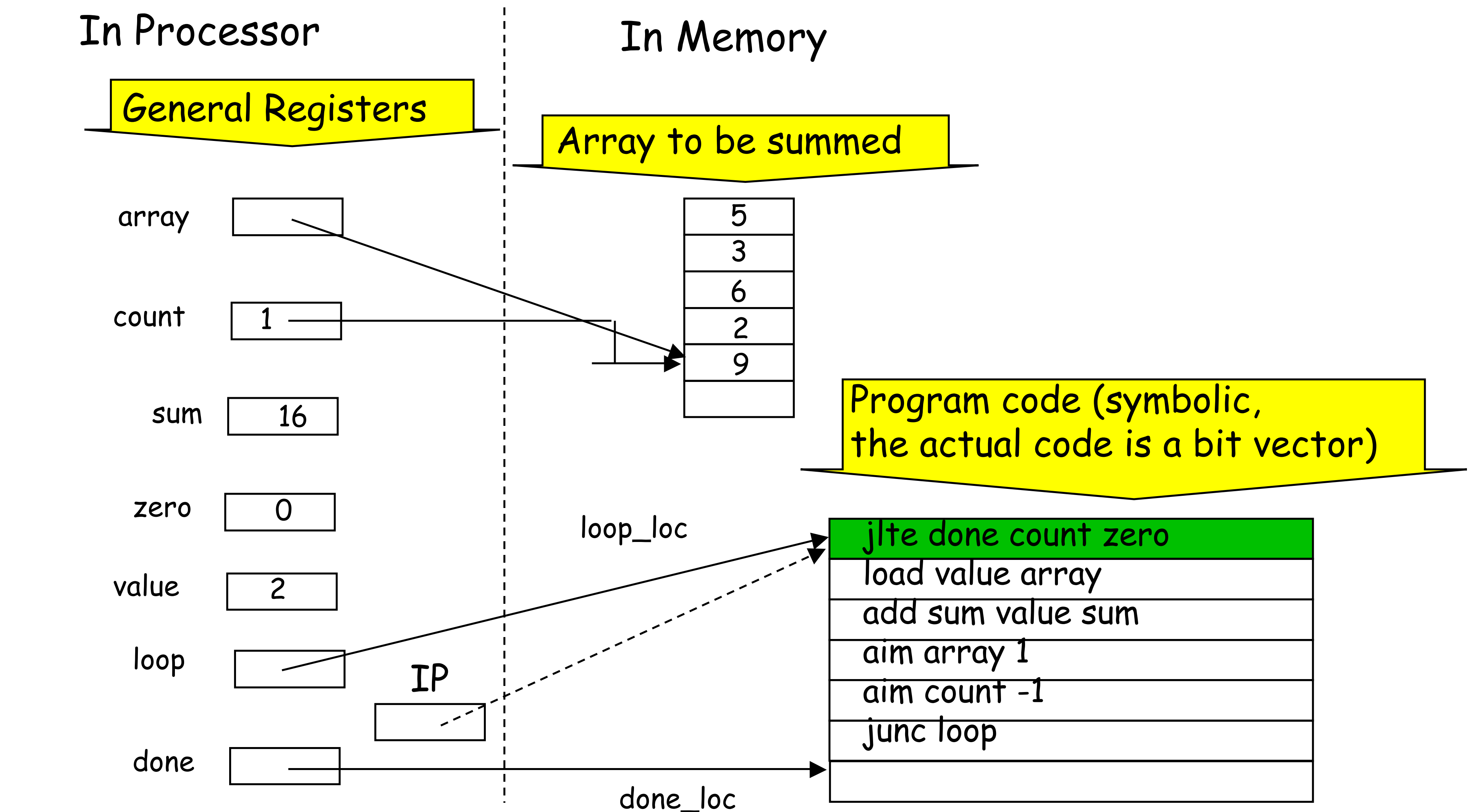

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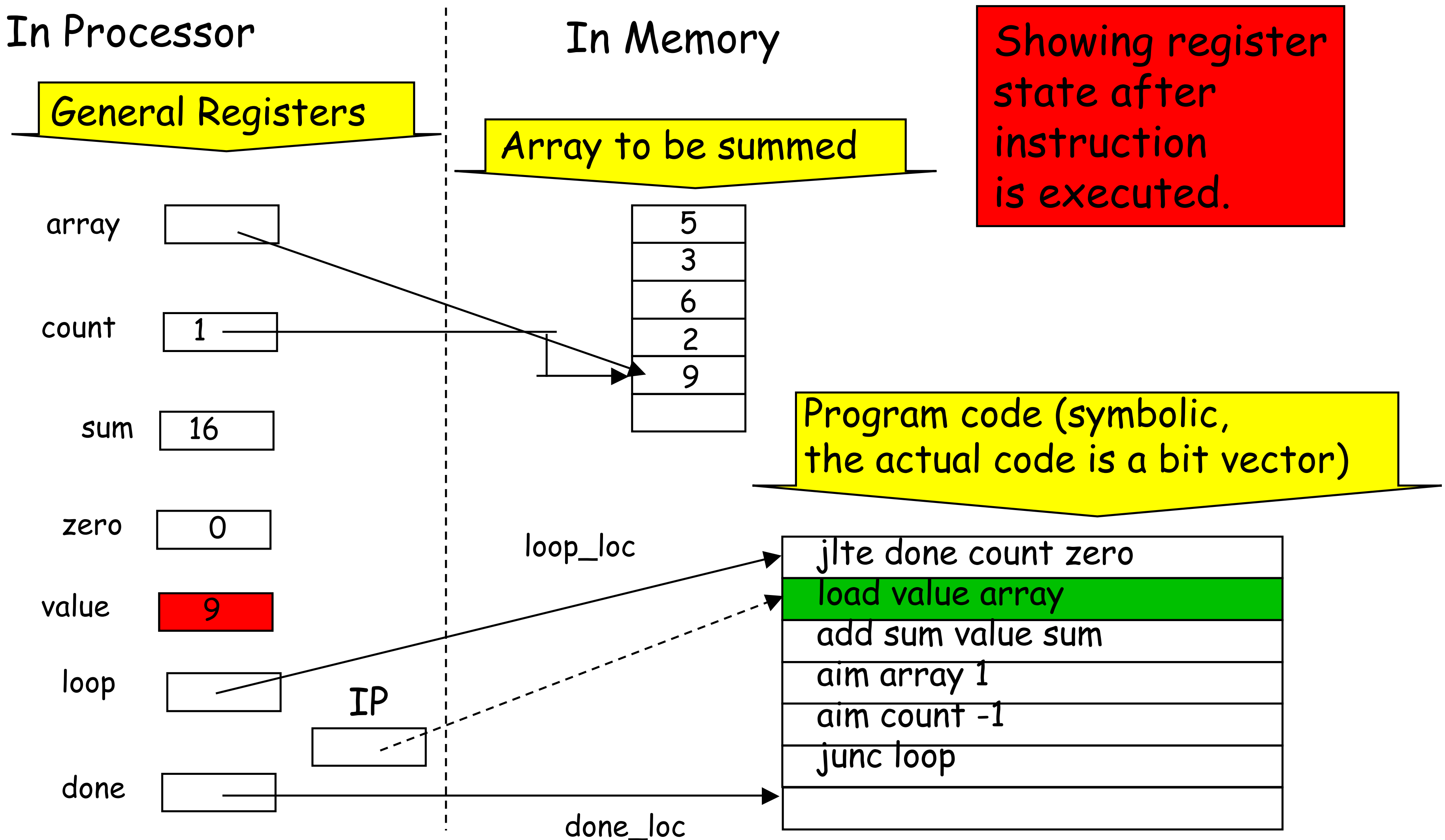

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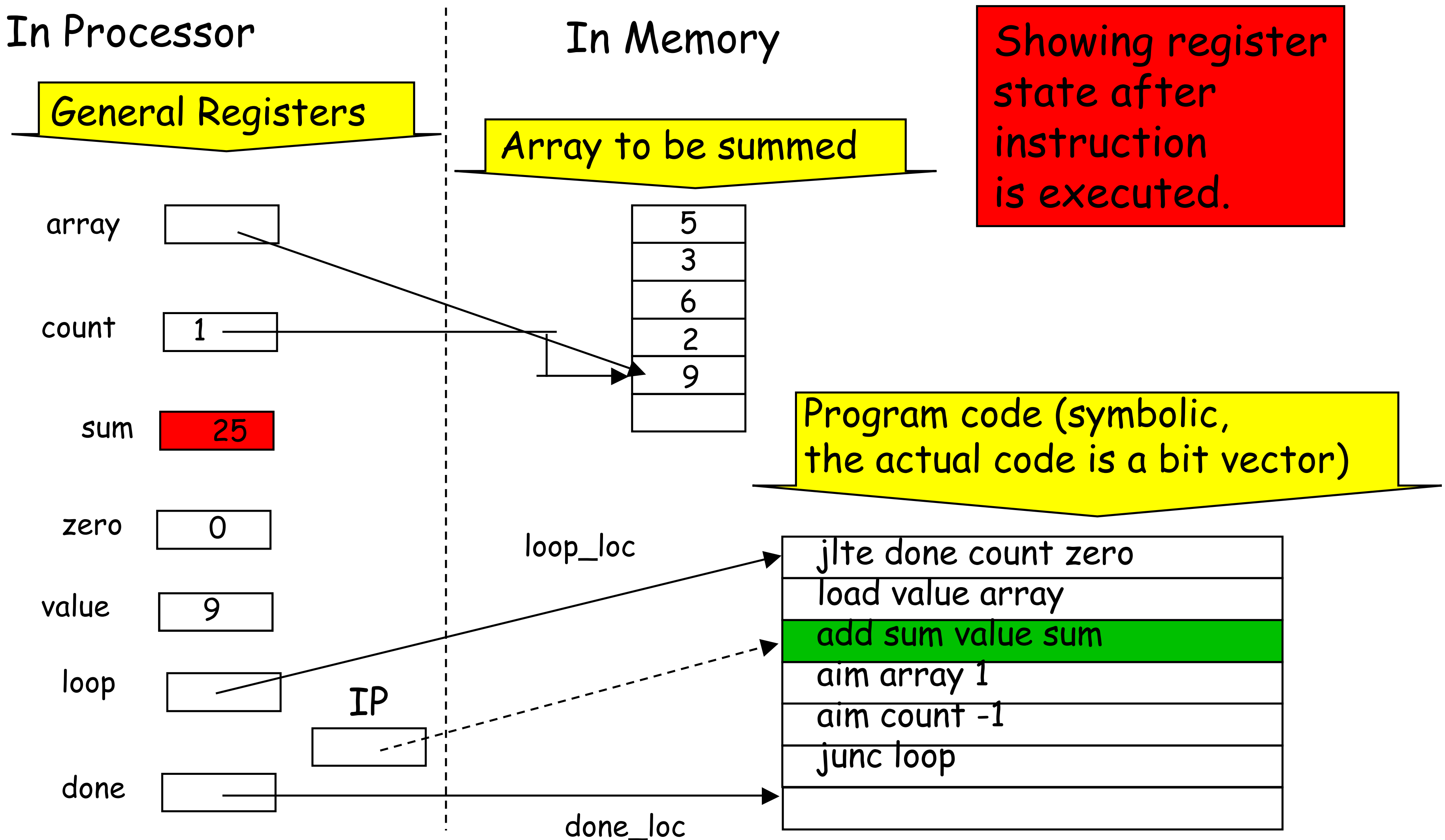
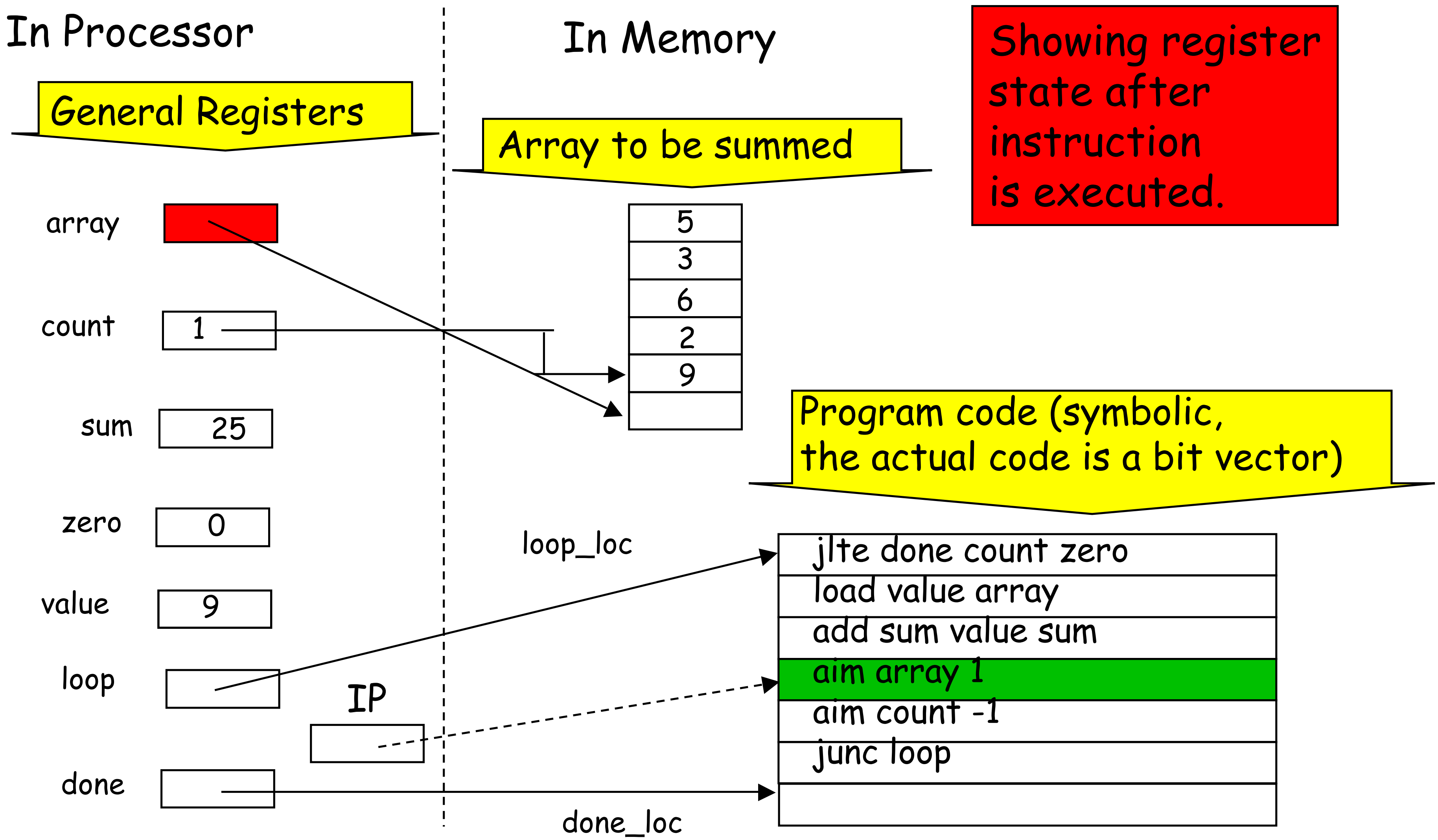


Showing register state after instruction is executed.

Array Summation



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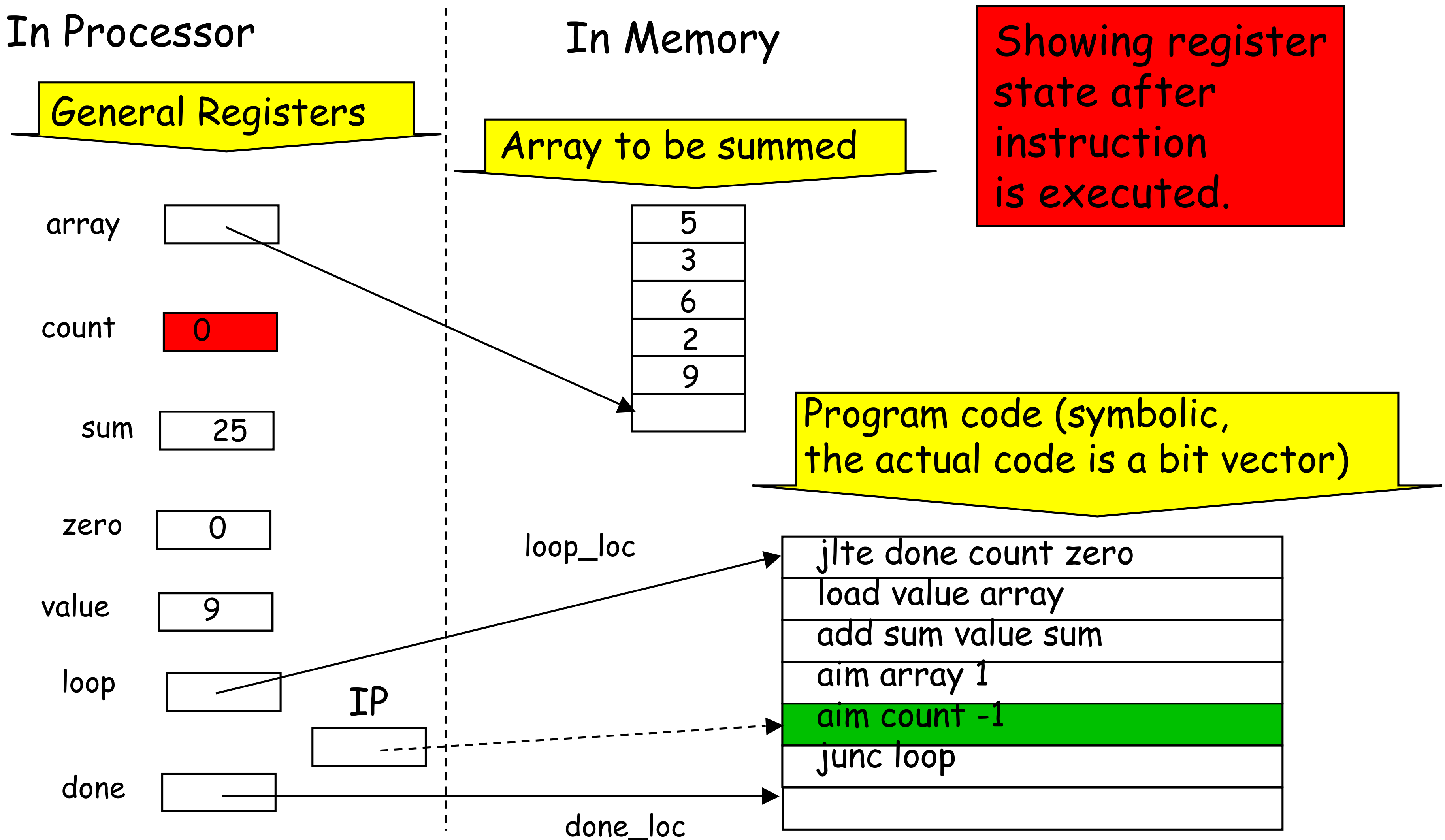

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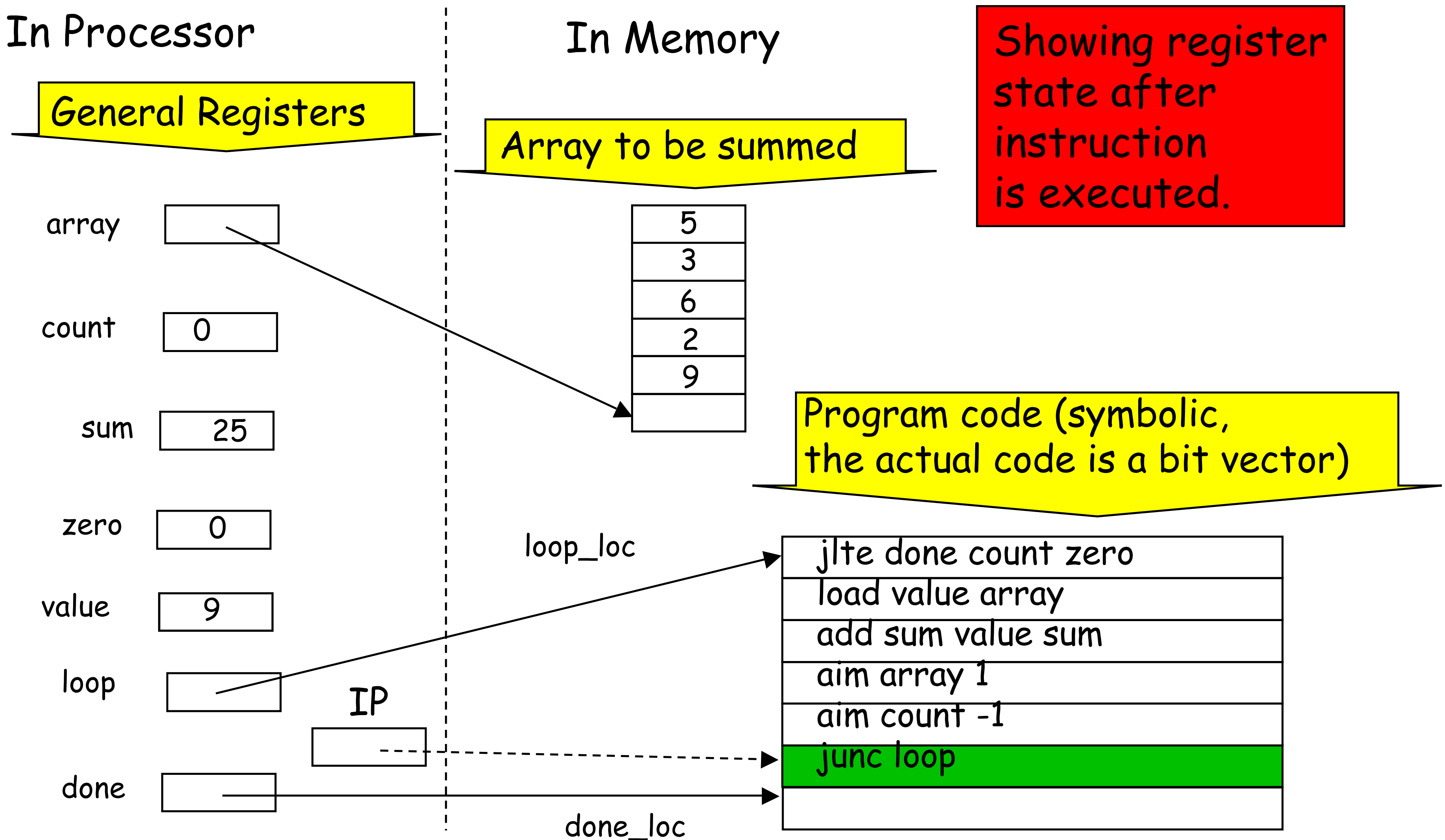

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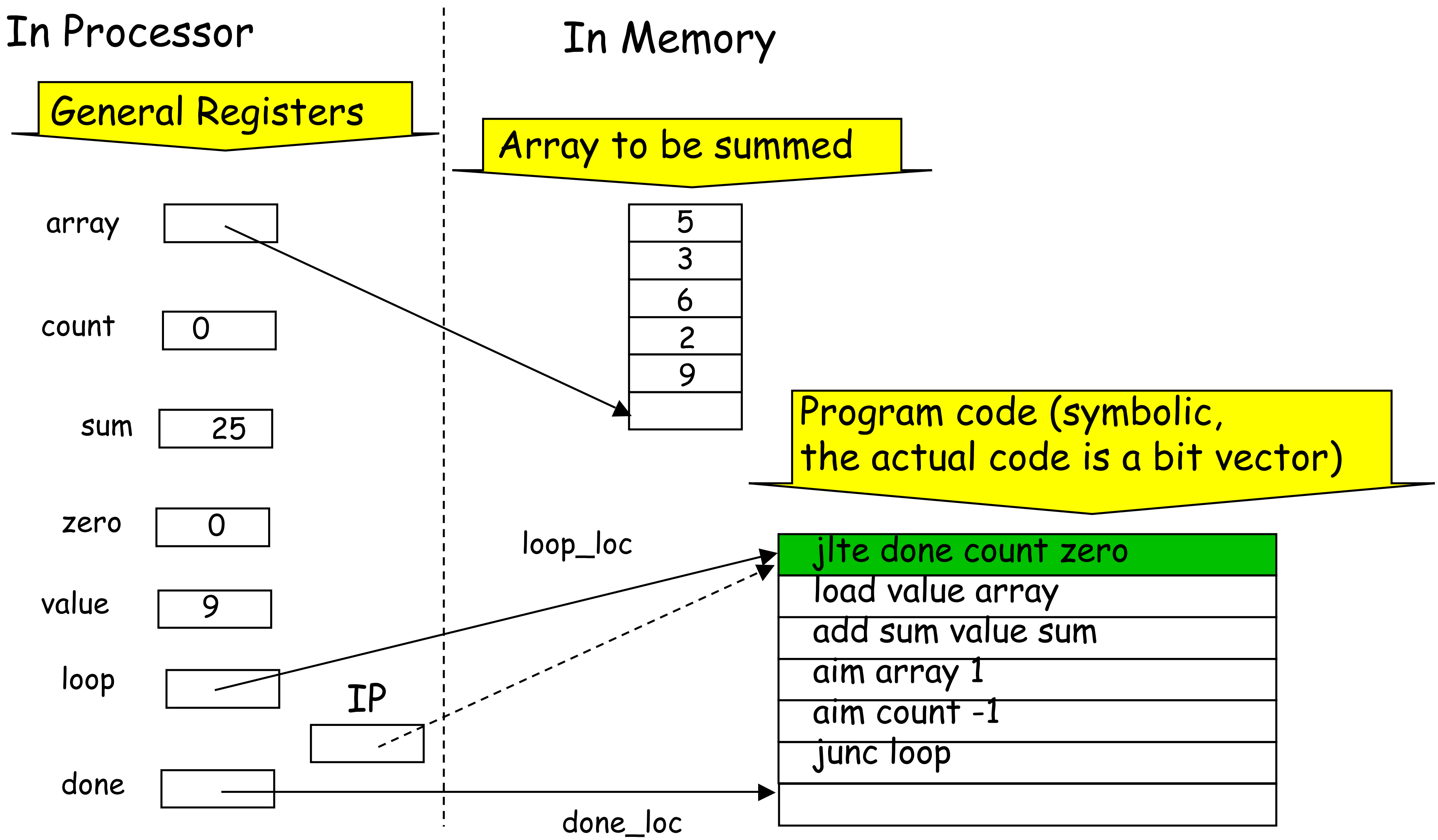

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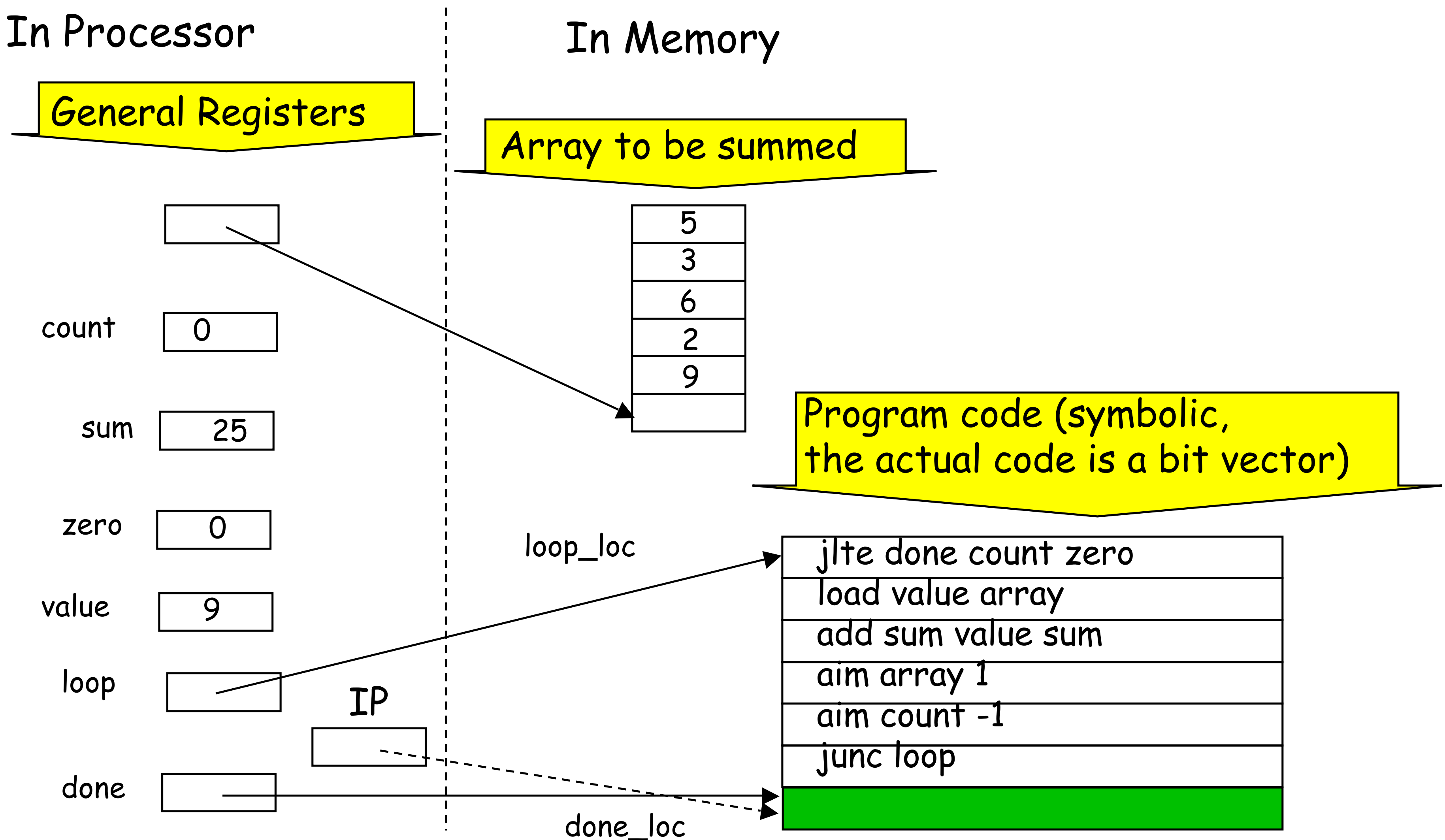

The ISC Assembler

- The ISC assembler is actually a combined assembler, loader, and tracer (for debugging).
- The executable is: /cs/cs60/bin/isc
- Sample programs are in /cs/cs60/isc/

The ISC Assembler

- The array summation program is in /cs/cs60/isc/array.isc. It includes additional code to create the array and output the result.

isc output

```
turing isc:1> isc array.isc
25

turing isc:2> isc -t array.isc
            Begin trace
line:   36 loc:    0 contents: lim     r9  (0)            0
    reg[9] = 0

. . . lots of trace output . . .
------- output ------
25
--------------------
line:   88 loc:   32 contents: junc    r9  (0)
    jumping unconditionally to 0
```

trace flag

Implementing Procedures

- A **procedure** is just some fixed code we jump to to perform some computation.
- We put the **arguments** to the procedure into pre-agreed **standard registers**, and get the result from another register.
- The **jsub** instruction can be used to get the **return address**.

Implementing Recursion

- Recursion presents a problem: The fixed code would tend to clobber (an inelegant way of saying “over-write”) the return address when the procedure calls itself.
- Also, the arguments in registered would get clobbered.

Stacks to the Rescue

- To deal with the clobbering problem, we can **save** the return address and any arguments on a **stack** allocated at a standard place in memory.
- The stack is typically an array, with a pointer to the top element.

```
lim stack_pointer save_area_loc  // initialize stack pointer

aim stack_pointer    -1          // always point to top of stack
```

Example: Recursive Factorial

```
    label fac                          // recursive factorial routine
        lim result 1                   // basis is 1
        jlte return arg zero           // return if count is 0 or less

push    aim  stack_pointer +1          // increment stack pointer
        store stack_pointer return     // save return address on stack

push    aim  stack_pointer +1          // increment stack pointer
        store stack_pointer arg        // save argument on stack

        aim arg -1                     // subtract 1 from argument
        jsub jump_target return        // call recursively

pop     load arg stack_pointer         // restore original argument
        aim  stack_pointer -1

pop     load return stack_pointer      // restore original return address
        aim  stack_pointer -1

        mul  result result arg         // multiply by original arg
        junc return                    // return to caller
```

Stack trace of factorial(4)

Stack trace of factorial(4)