Computer Architecture
Processor implementation

http://d3s.mff.cuni.cz/teaching/nswi143

Lubomír Bulej

bulej@d3s.mff.cuni.cz

CHARLES UNIVERSITY IN PRAGUE

faculty of mathematics and physics

Implementing simplified MIPS ISA

- **Basic characteristics**
  - Simplified to demonstrate key concepts
- **Registers**
  - 32 general-purpose 32-bit registers: R0 – R31
  - PC register with address of instruction to execute
  - Special control registers
    - Exception address, etc.

Implementing simplified MIPS ISA (2)

- **Memory**
  - Access to 4-byte aligned addresses only
    - Corresponds to 32-bit word length of the processor
  - Indirect addressing with immediate displacement
    - **Load:** R2 := mem[R1 + immediate]
    - **Store:** mem[R1 + immediate] := R2

Implementing simplified MIPS ISA (3)

- **Operations**
  - Arithmetic and logic
    - Fully orthogonal, three-operand instructions
    - Source operands: register/register, register/immediate
    - Target operand: register
    - Includes data movement between registers
  - Load/store operations
    - Move data between registers and memory (load/store architecture)
  - Conditional branch
    - Tests equality/inequality of two registers
  - Unconditional jumps
    - Including jumps to subroutine and indirect jumps (return from a subroutine)
  - Special instructions

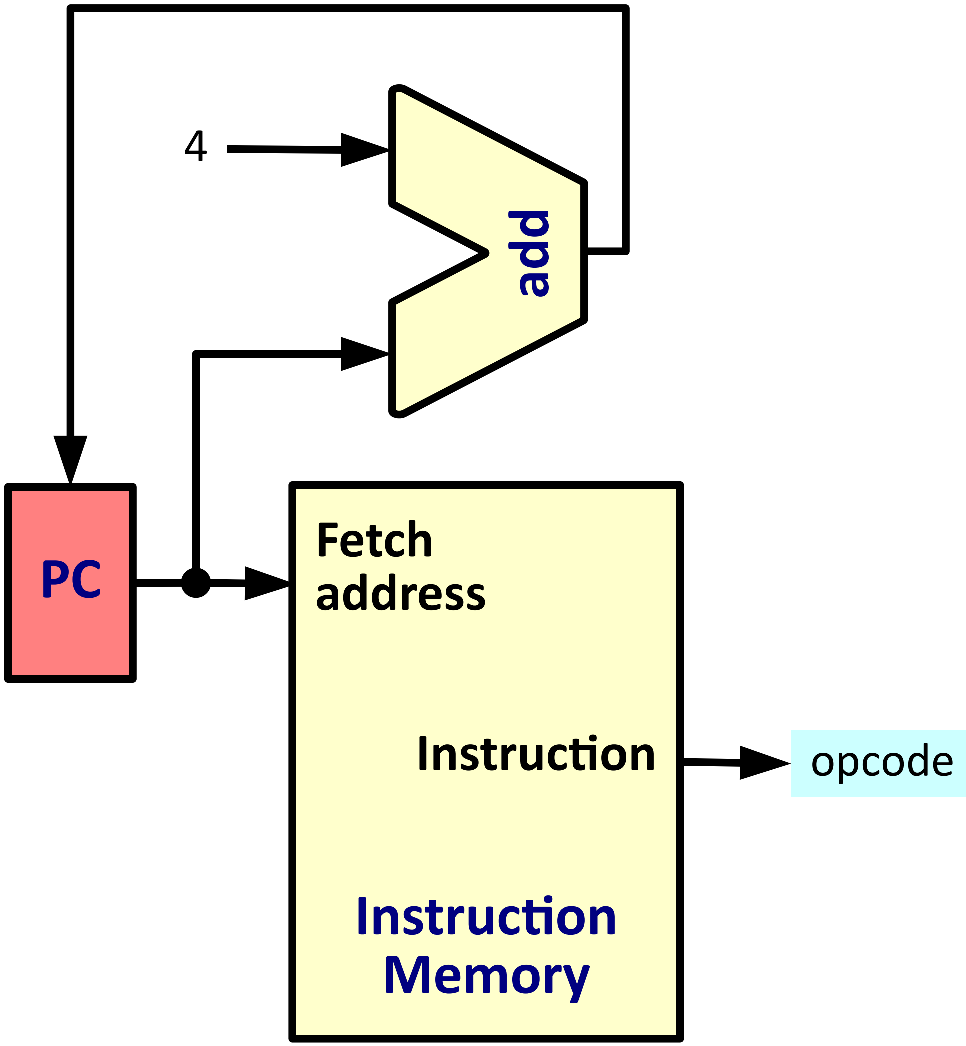
Implementing simplified MIPS ISA (4)

- **Single-cycle datapath**
  - Basic organization of data path elements
    - Combinational and sequential blocks
  - Operations executed in one long cycle
    - Suitable for operations of similar complexity
    - Writes to memory elements synchronized by clock
      - Clock signal is implicit, will not be shown
  - **Simplification:** separate instruction memory (Harvard architecture)

Implementing simplified MIPS ISA (5)

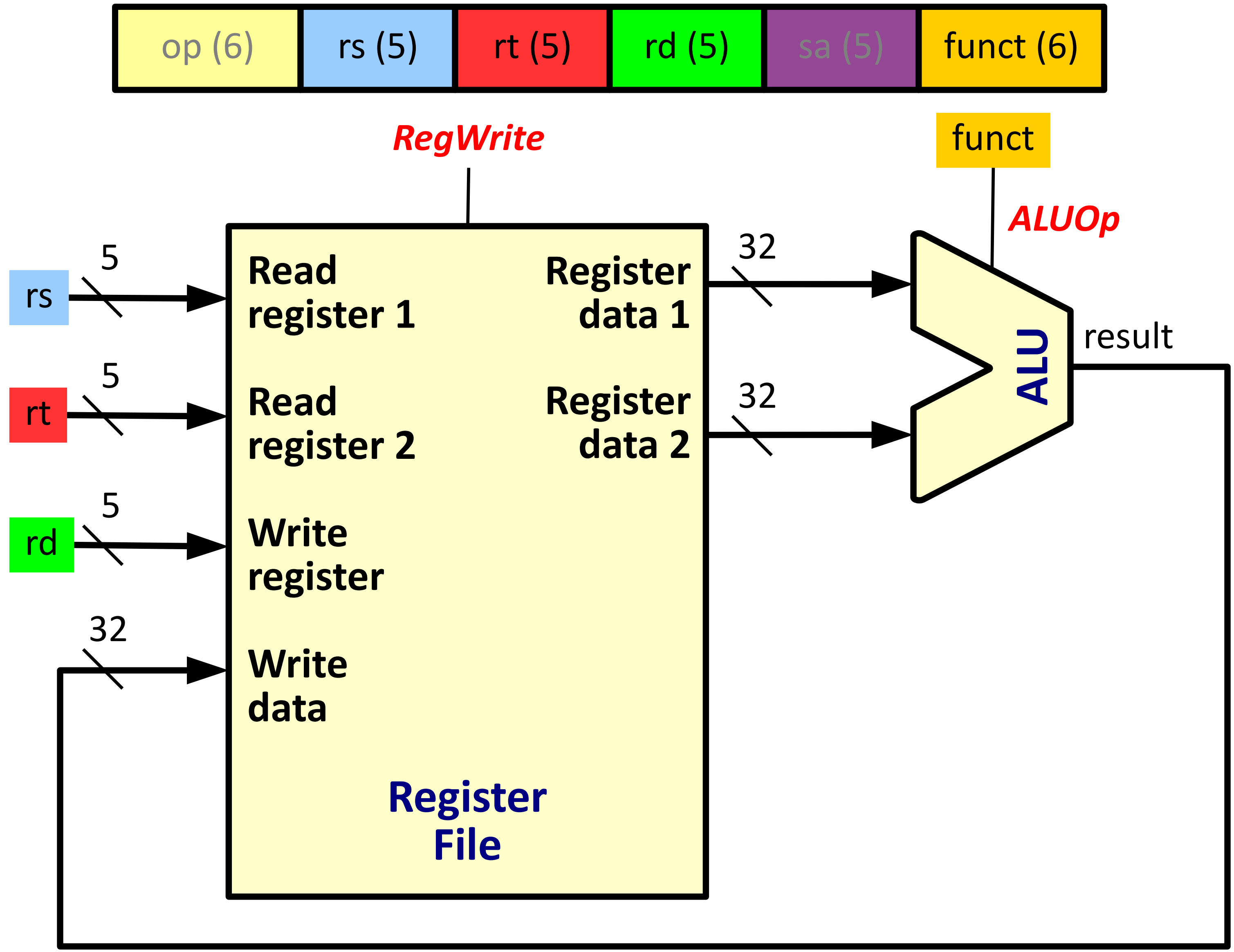
- **Steps to execute an instruction**
  1. Fetch instruction from memory
     - Read from an address supplied by the PC register
  2. Decode instruction and fetch instruction operands
  3. Execute operation corresponding to the opcode
     - Register operations, computing address for accessing memory, comparing operands for conditional branch.
  4. Store the result of the operation
     - Write data to register or memory
  5. Adjust PC to point at next instruction
     - One that immediately follows the current
     - One that is a target of a jump or branch

Reading an instruction (fetch)

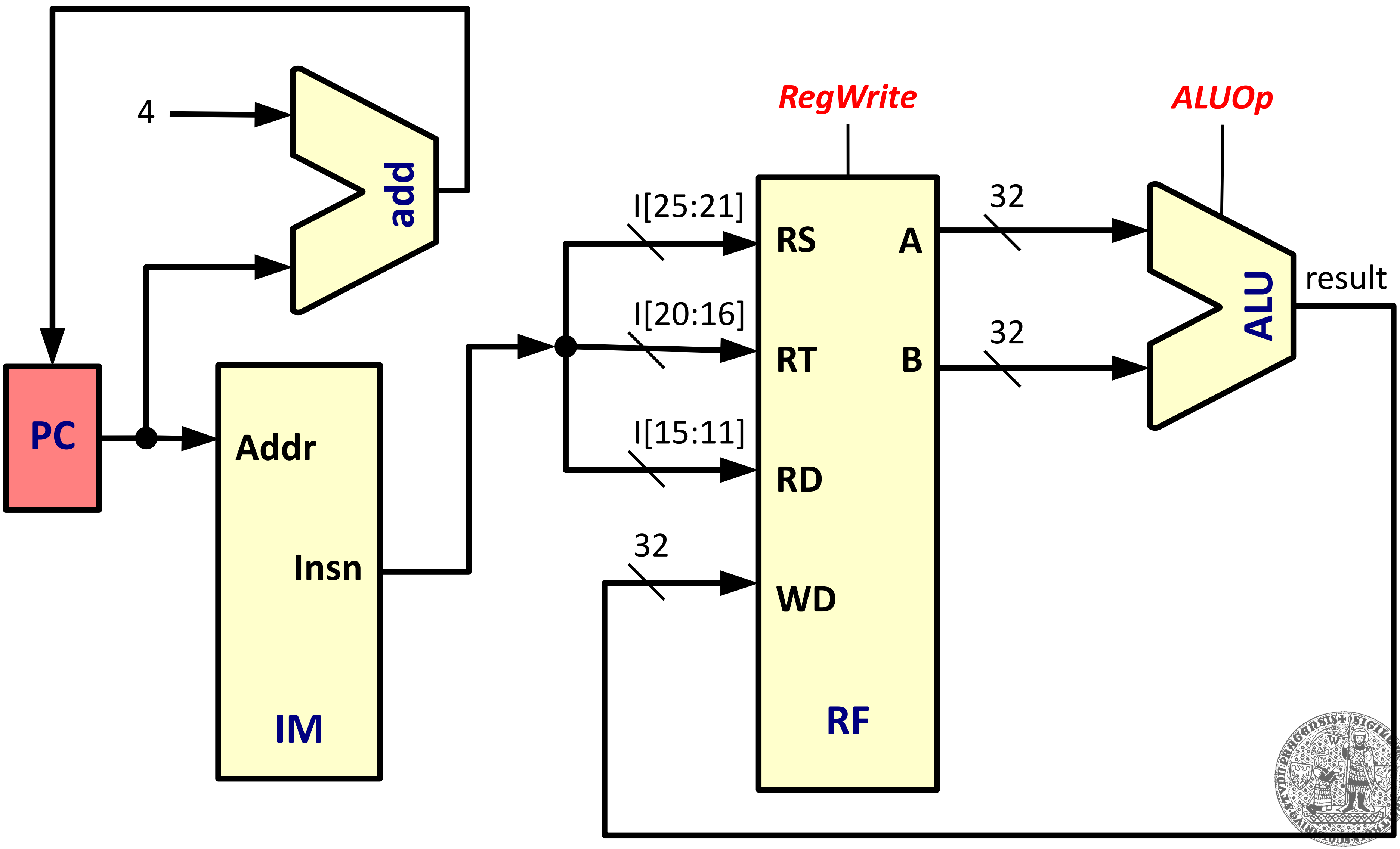


- **PC register**
  - Address of instruction in memory
  - Not directly accessible to a programmer
- **Adder**
  - Increment PC by 4
  - Advance to next instruction by default

Register operations (add, sub, ...)

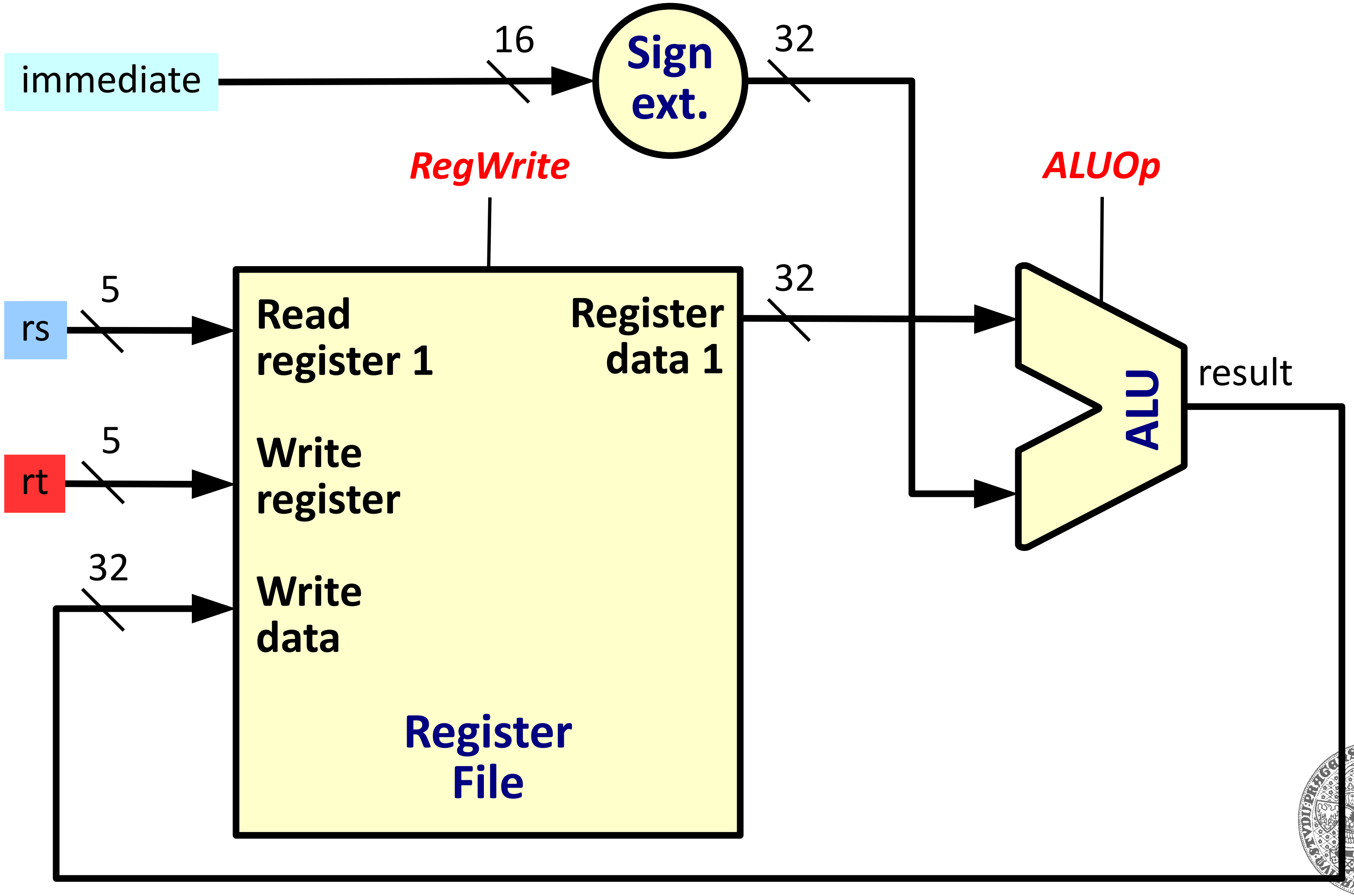


Support for register operations

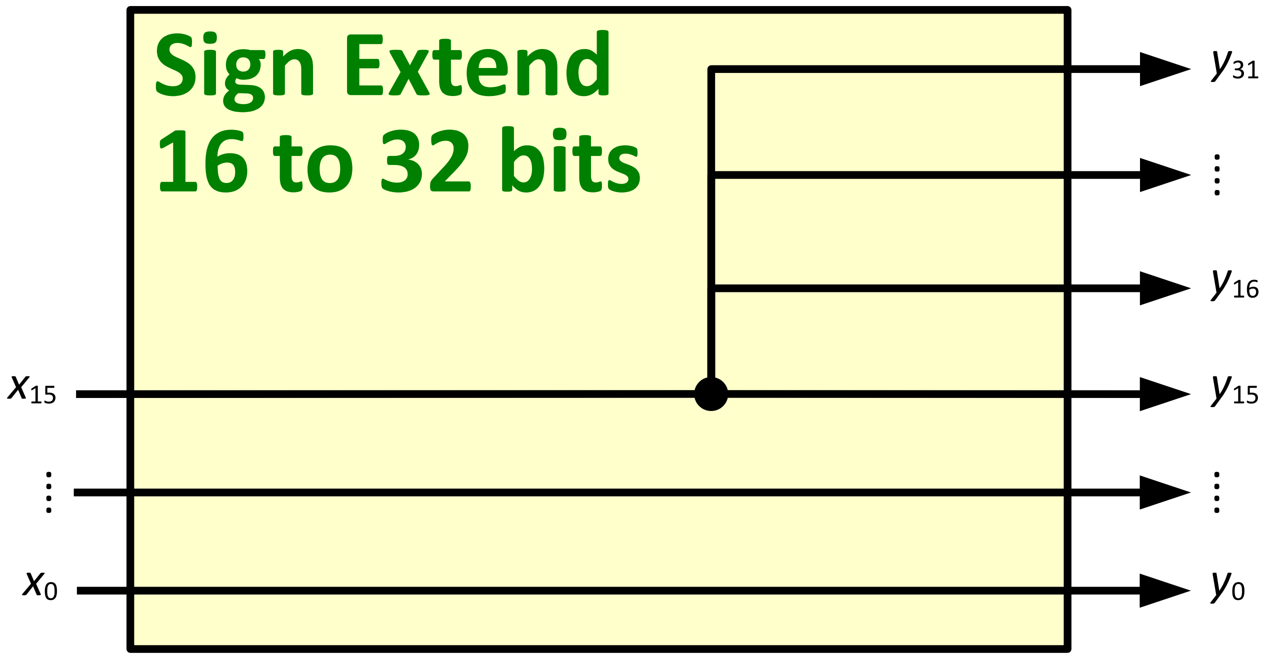


Immediate operand operations (addi, …)

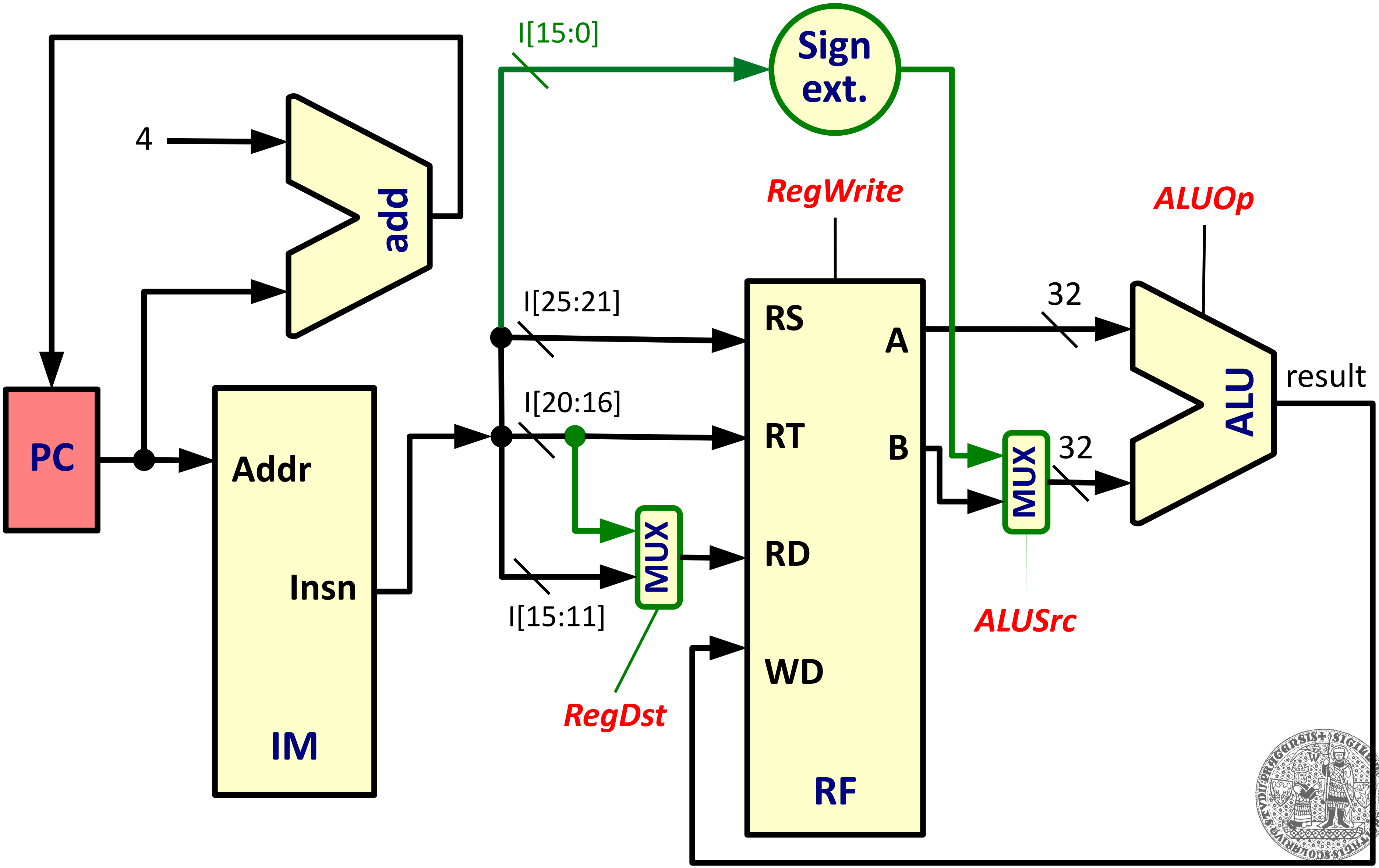
op (6)	rs (5)	rt (5)	immediate (16)



Implementing sign extension

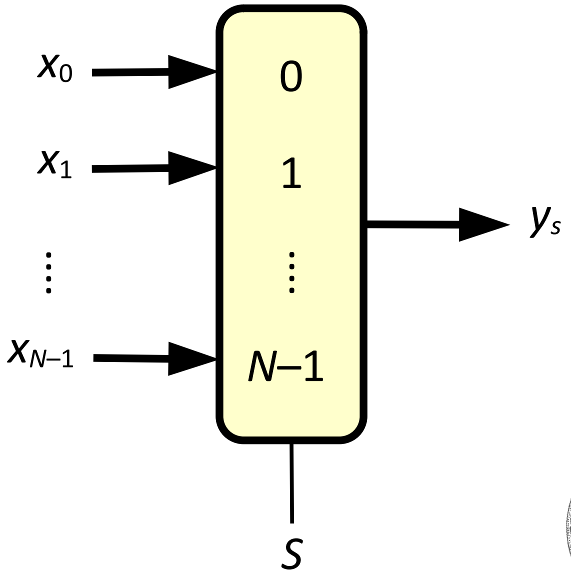


Support for immediate operands



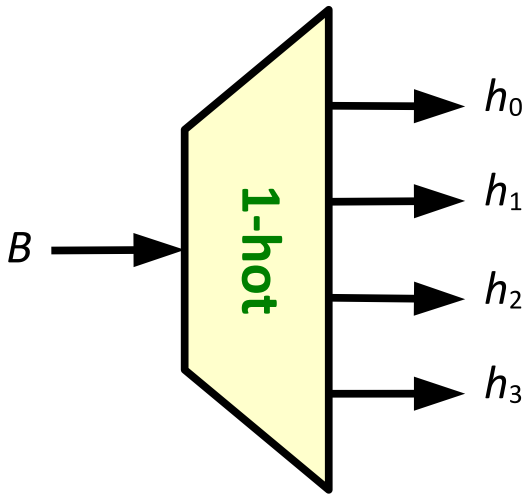
Multiplexer (mux)

- **Selects one of several inputs**
  - **Selector:** n-bit number $S \in \{0, ..., 2^{n-1}\}$
  - **Data input:** $N=2^n$ m-bit values $x_0, x_1, ..., x_{N-1}$
  - **Data output:** m-bit value $y=x_S$



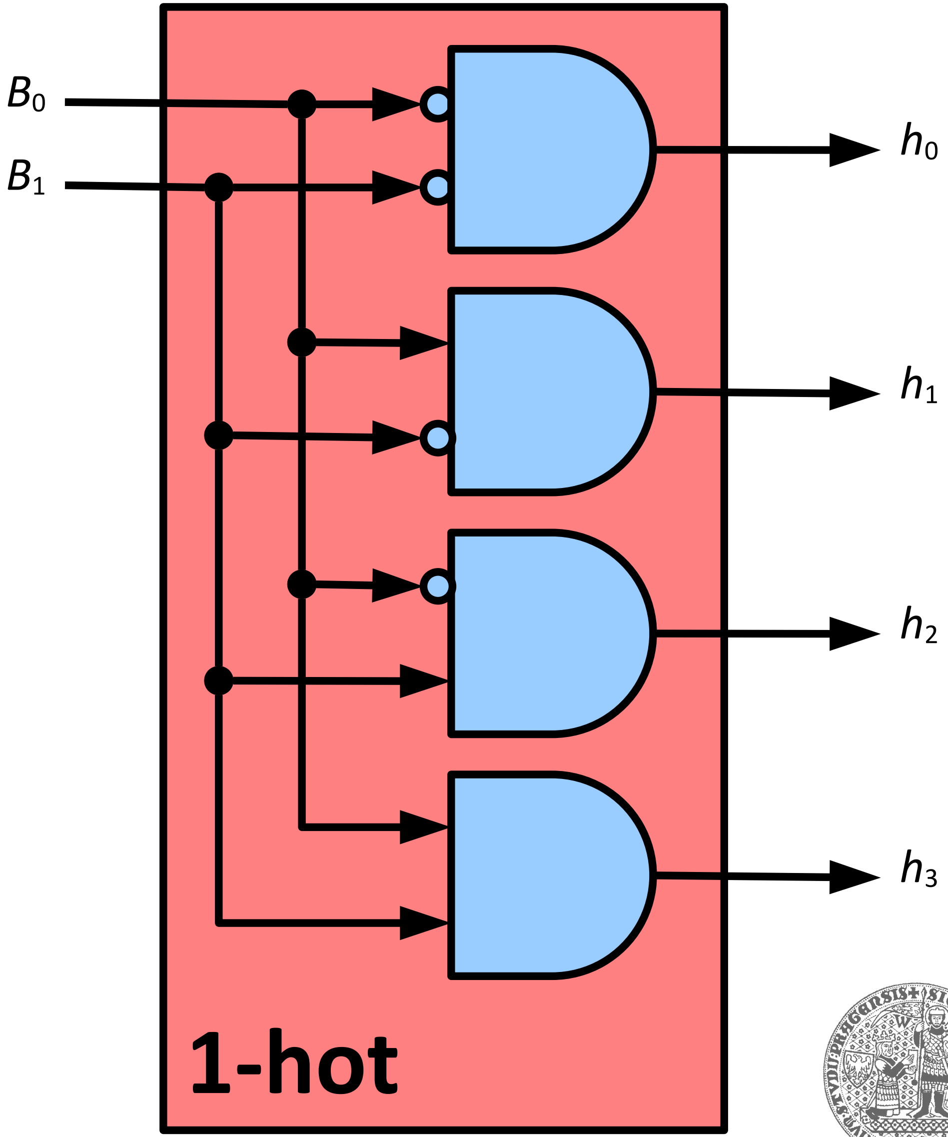
Implementing a multiplexer

- **Binary to "1-hot" decoder**
  - Activates 1 (selected output) of N outputs
  - **Input:** n-bit number $B \in \{0, ..., 2^{n-1}\}$
  - ***N*=2^n outputs:** B-th output logical 1 (hot), other outputs logical 0

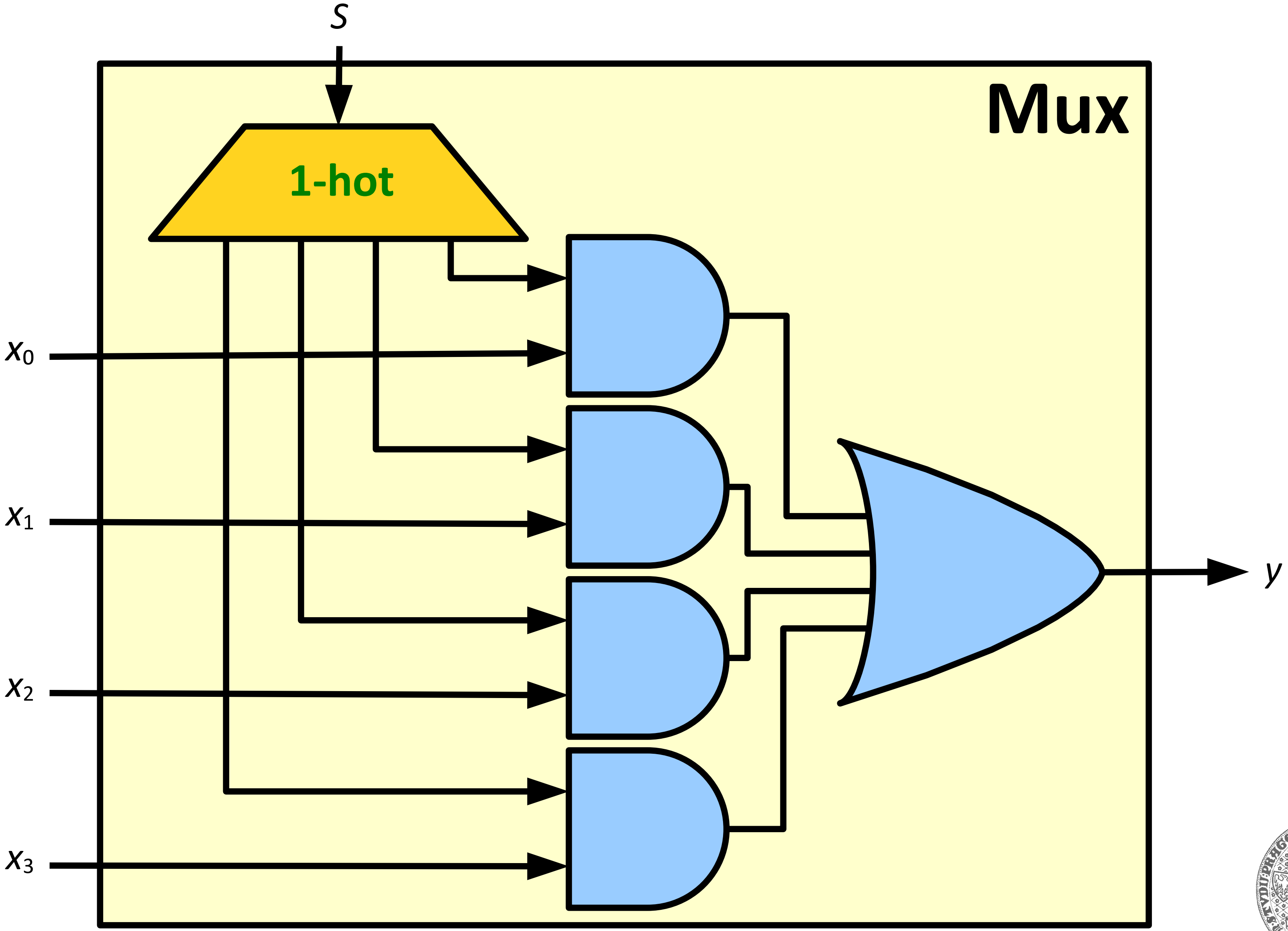


Binary to 1-hot for N=4 outputs

Inputs		Outputs			
B_1	B_0	h_3	h_2	h_1	h_0
0	0	0	0	0	1
0	1	0	0	1	0
1	0	0	1	0	0
1	1	1	0	0	0

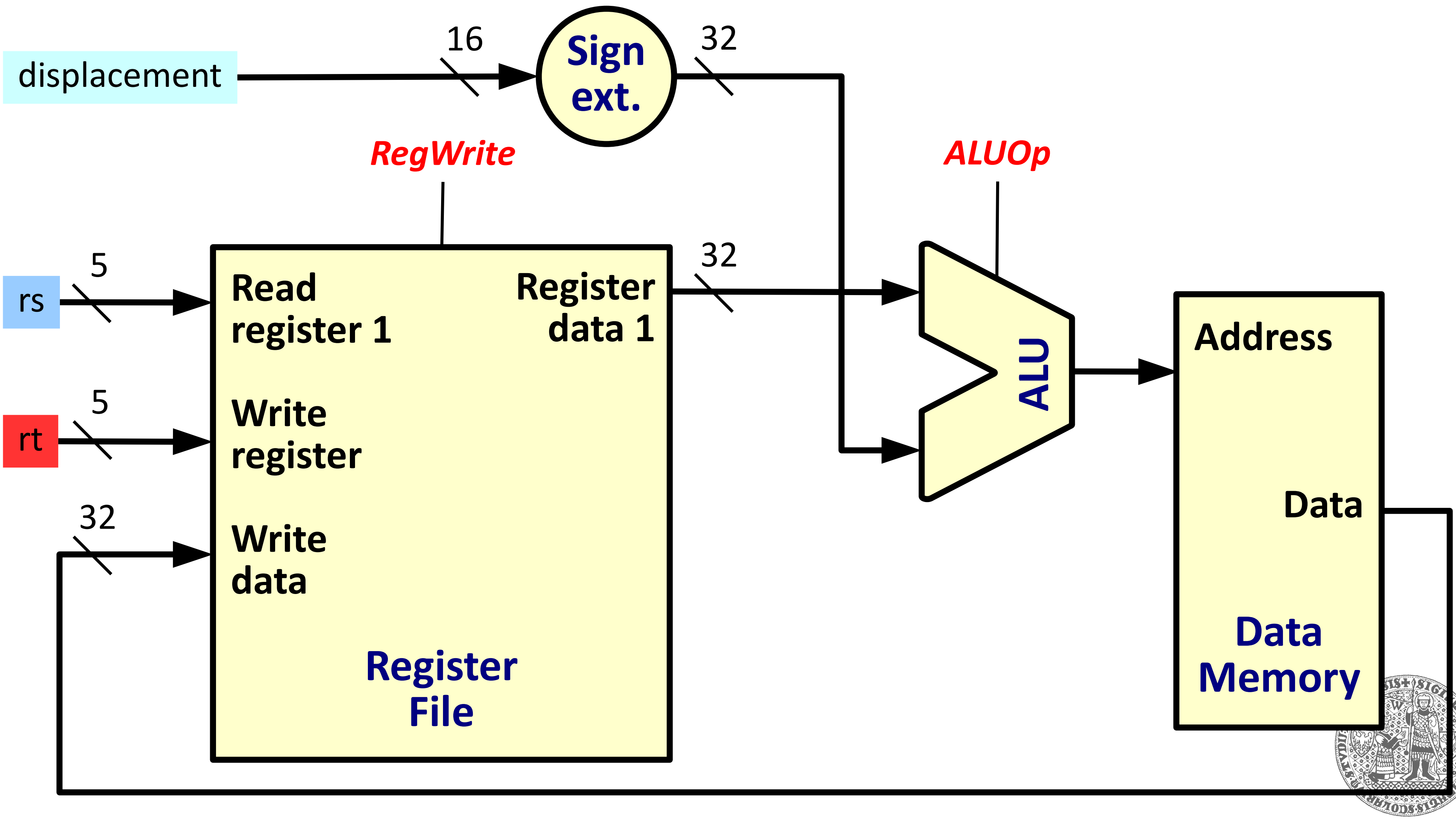


Implementing a multiplexer (4x 1-bit)



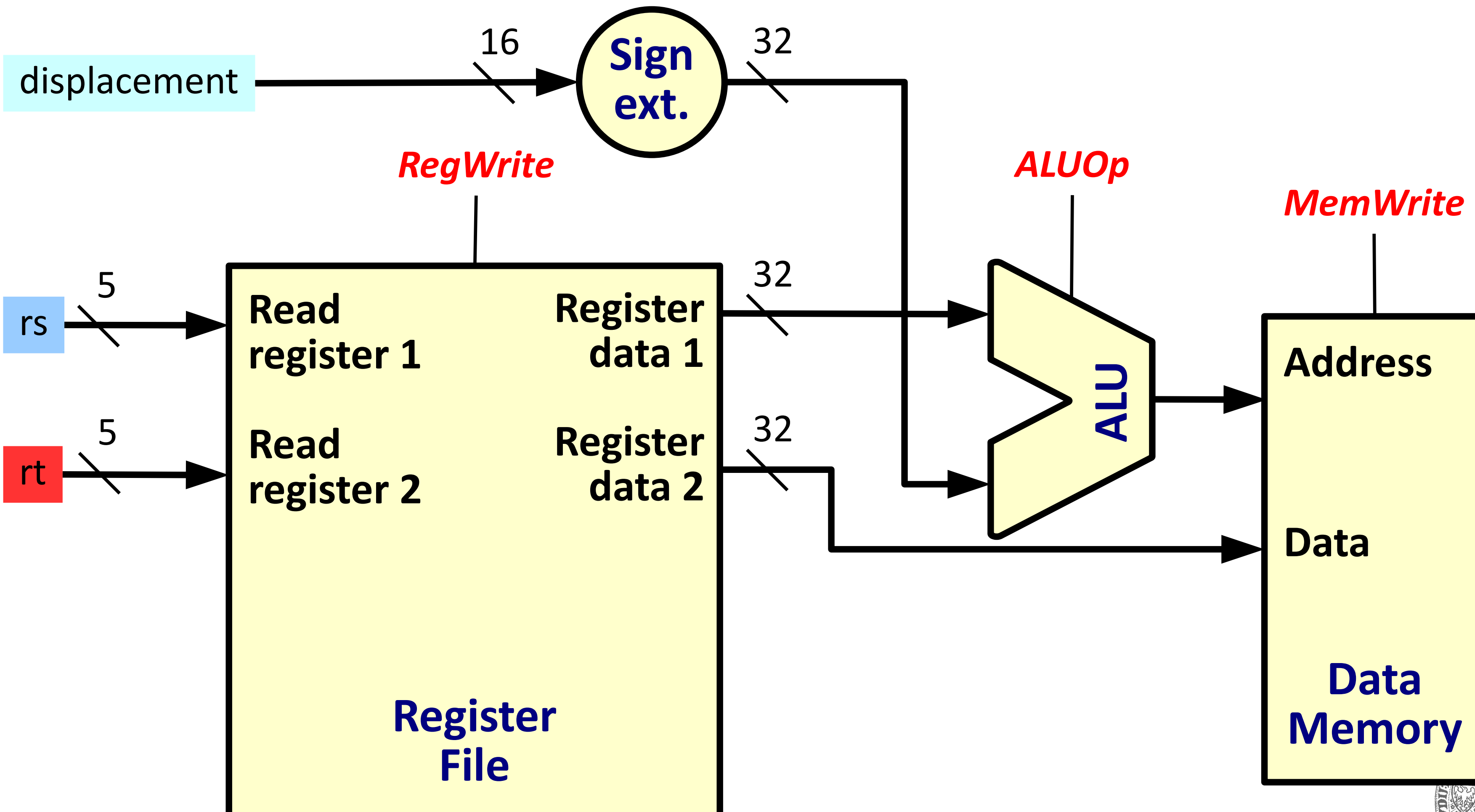
Loading words from memory (lw)

op (6)	rs (5)	rt (5)	displacement (16)

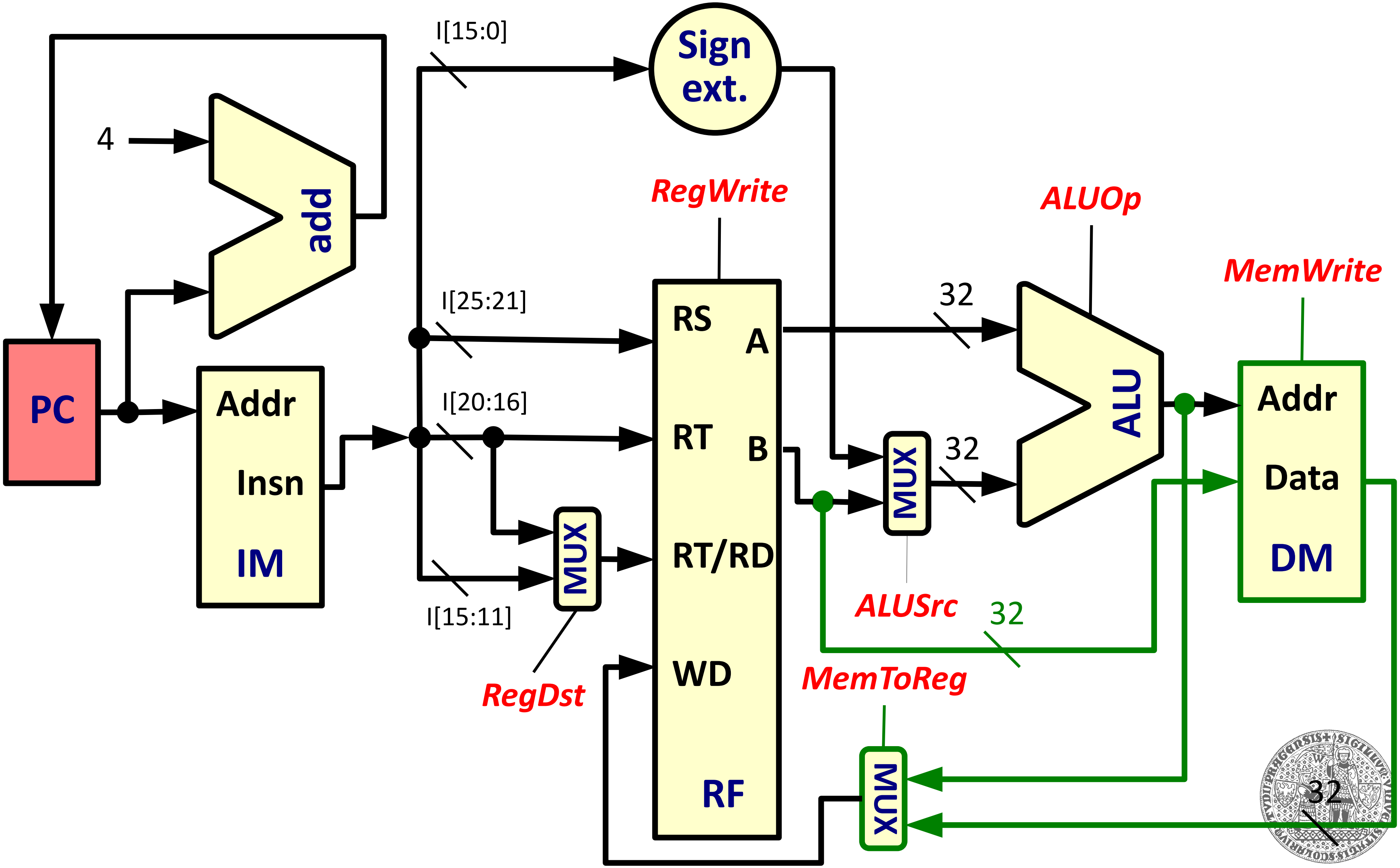


Storing words to memory (sw)

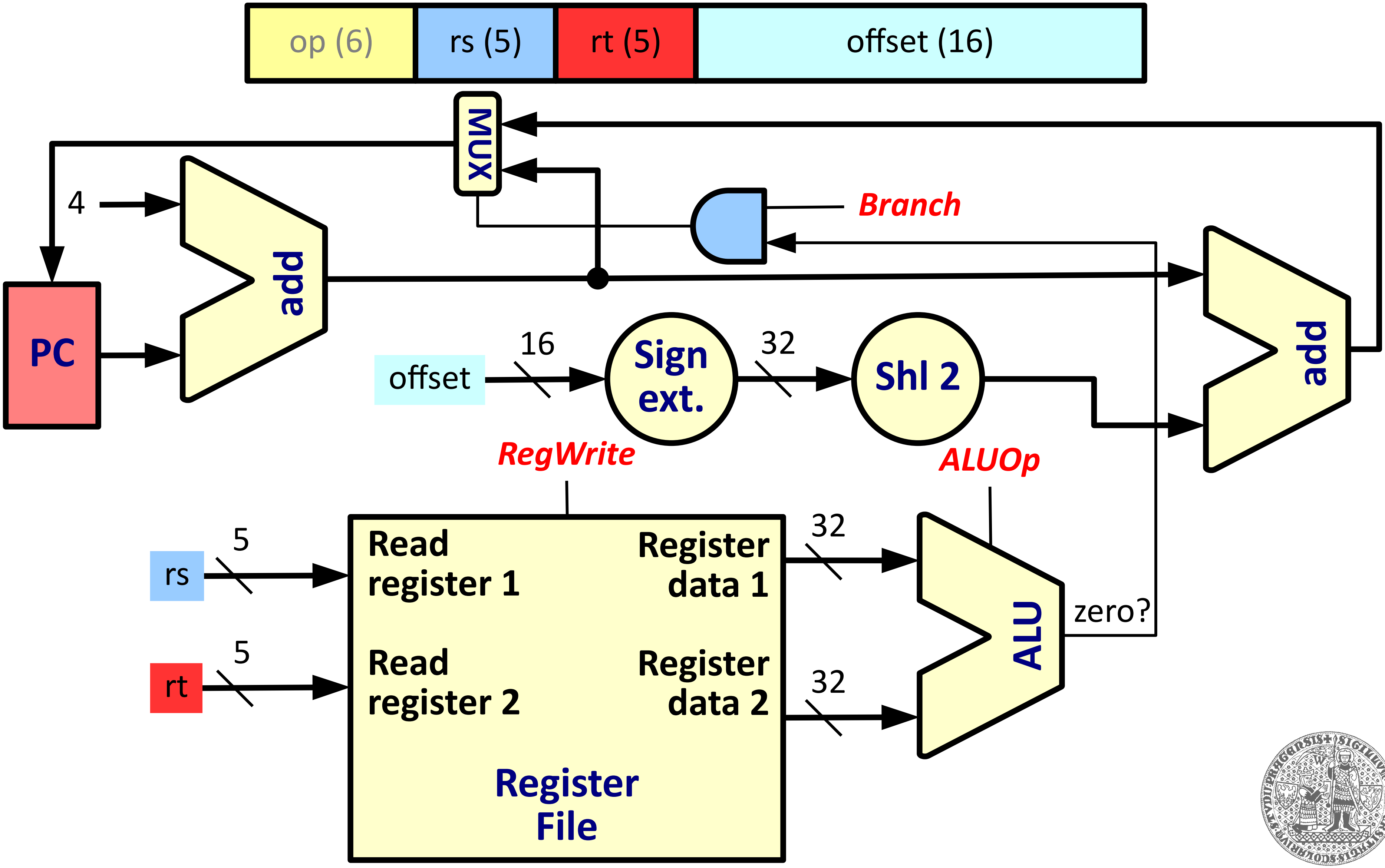
op (6)	rs (5)	rt (5)	displacement (16)



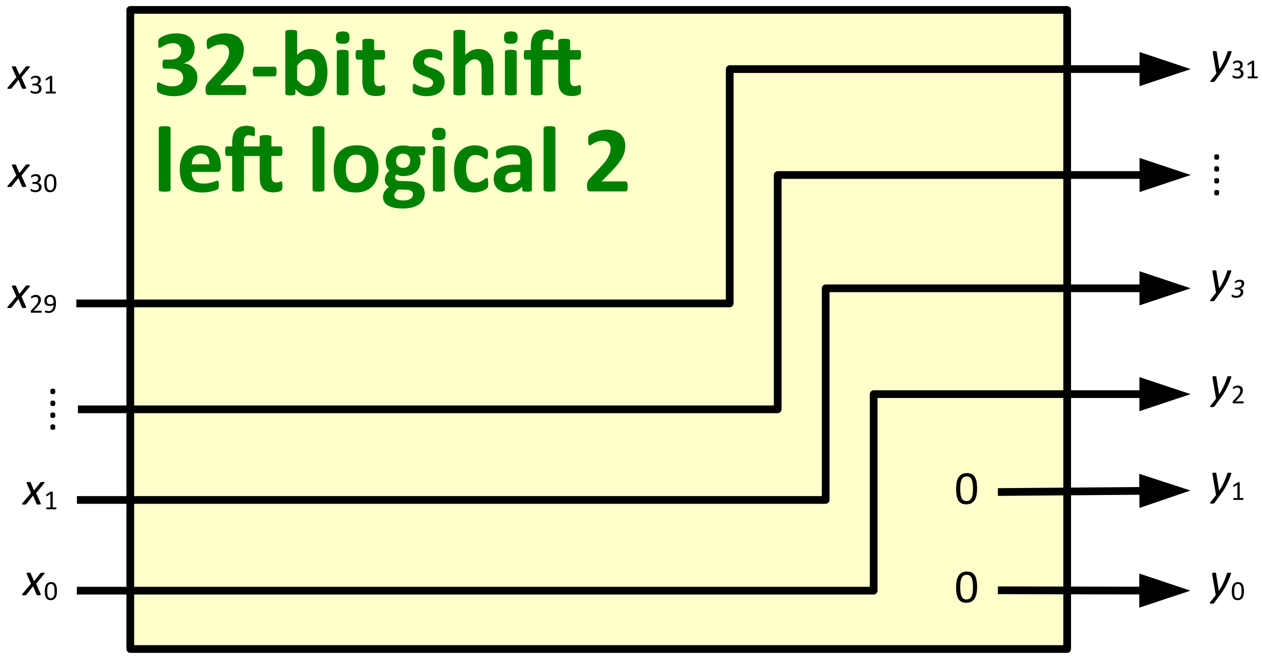
Support for memory access (load/store)



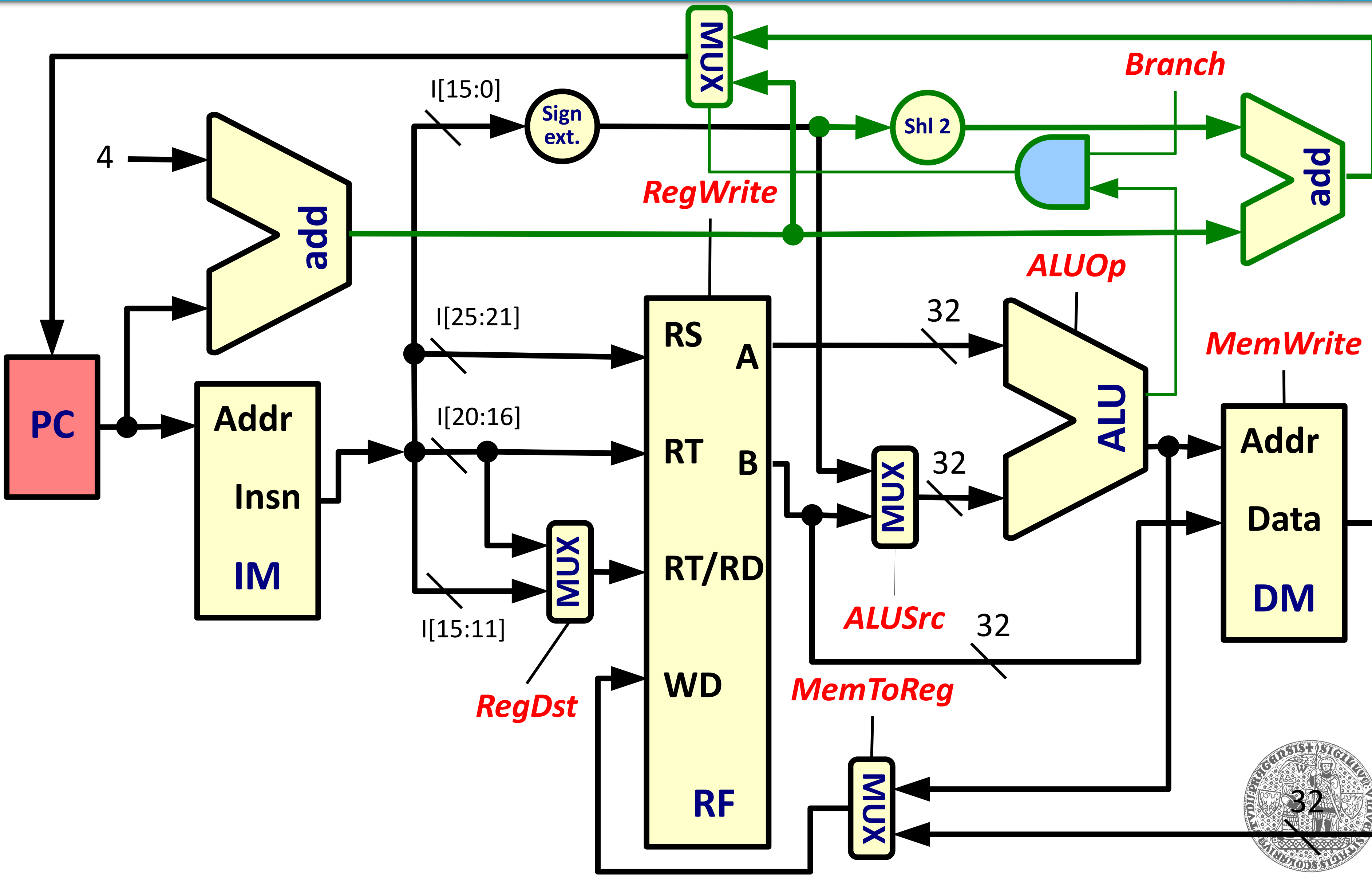
Conditional branch relative to PC (beq)



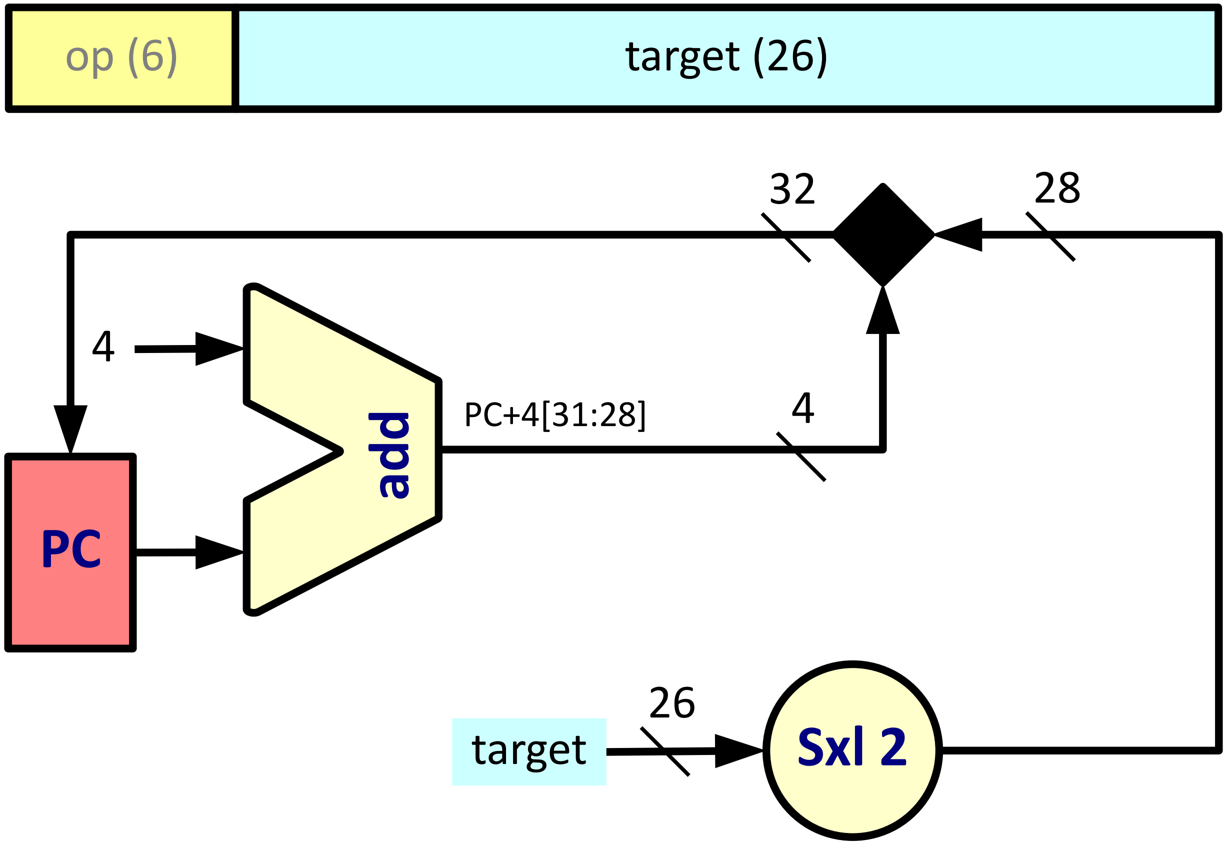
Implementing logical shift



Support for conditional branch

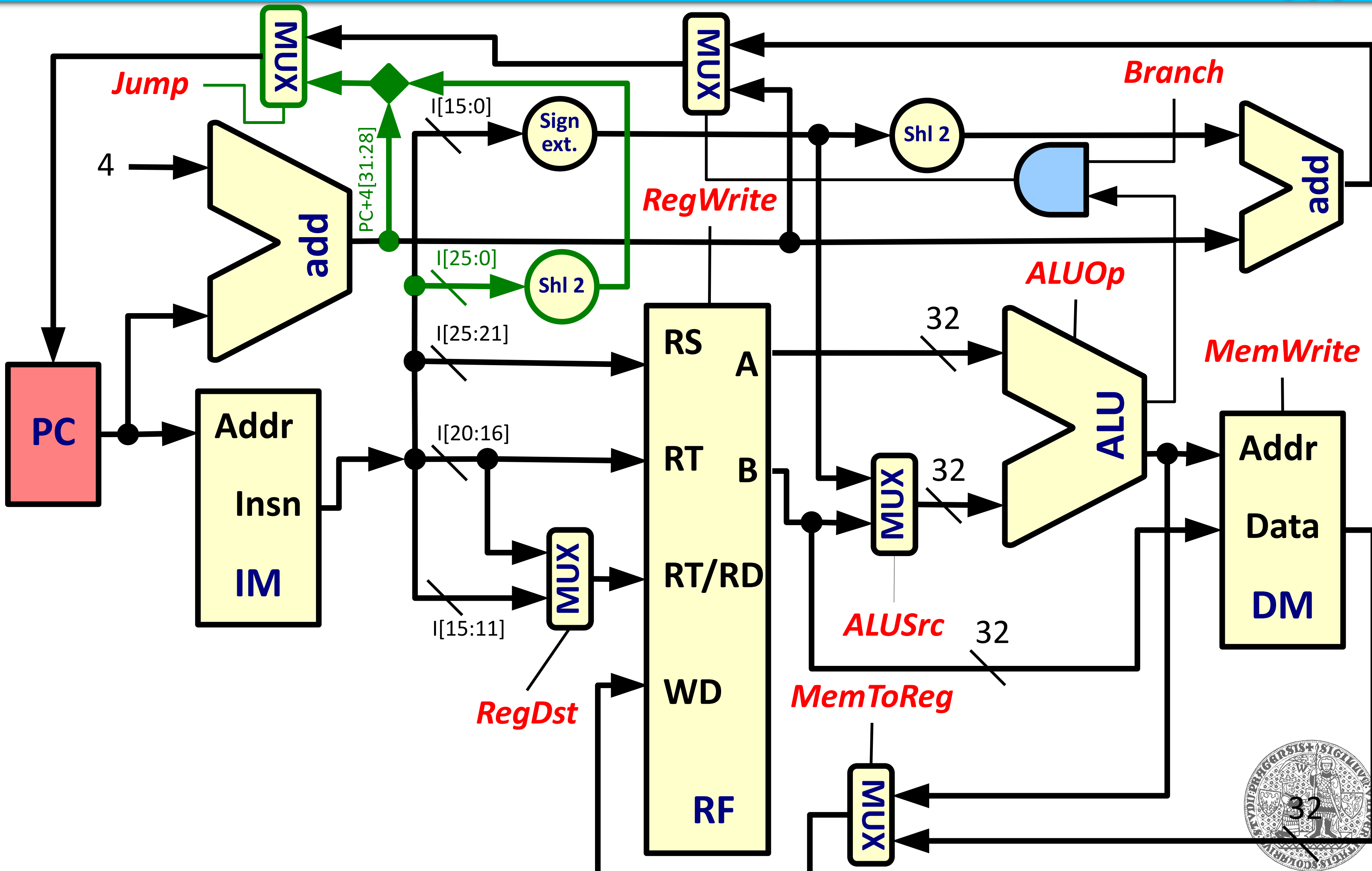


Unconditional jump (j)

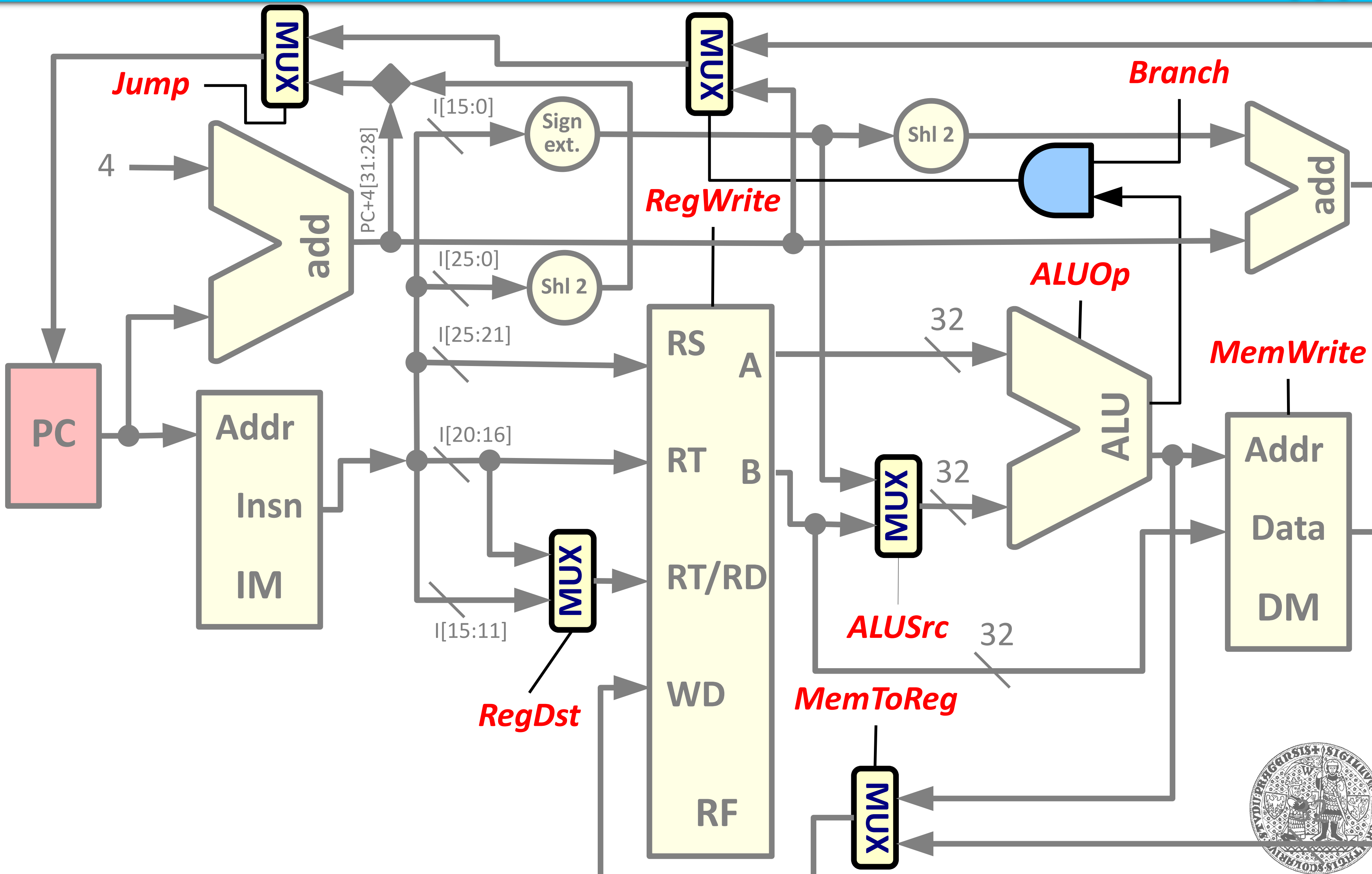


Shift (and extend) left by 2

Support for unconditional jump



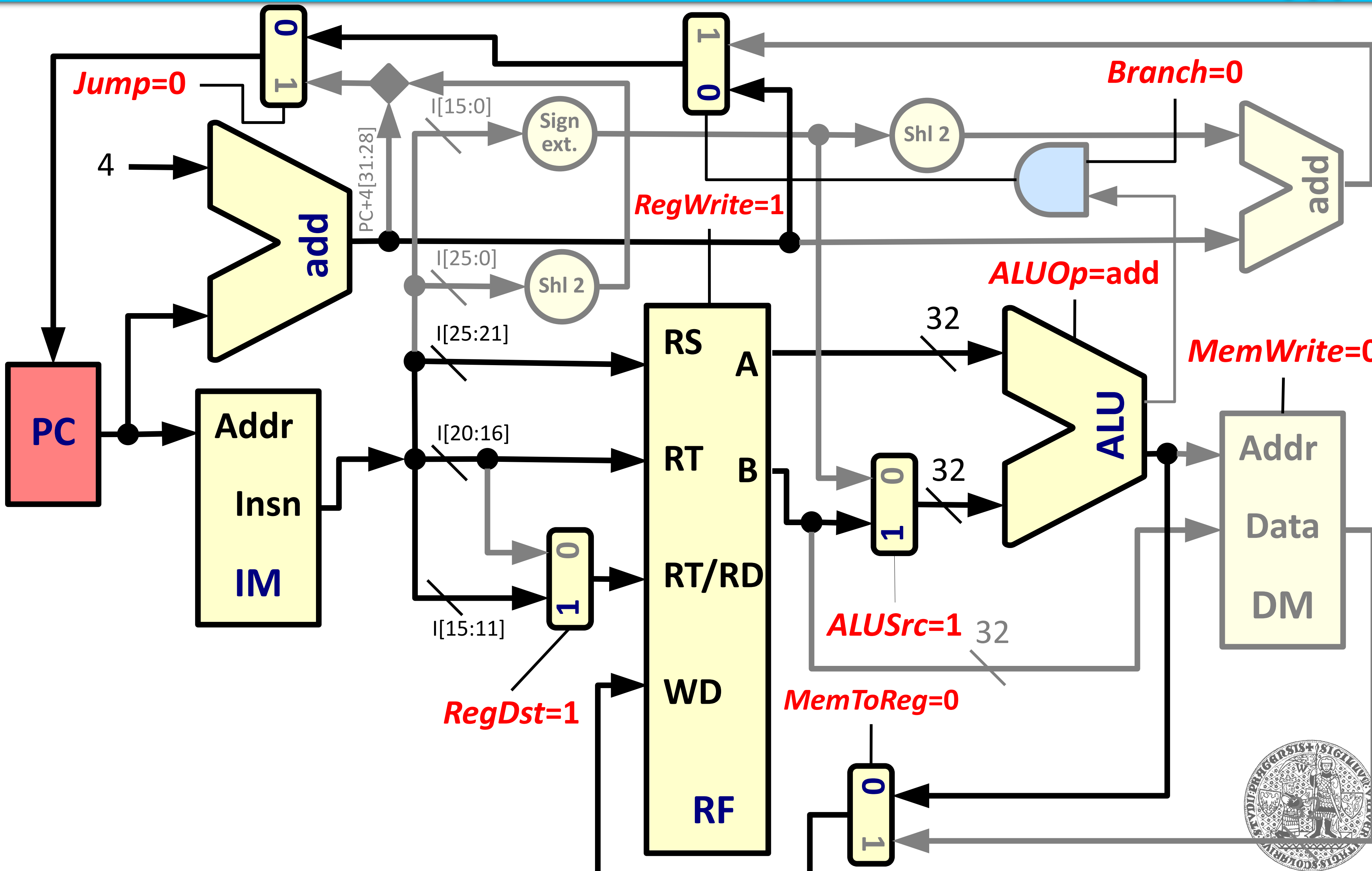
Single-cycle datapath control



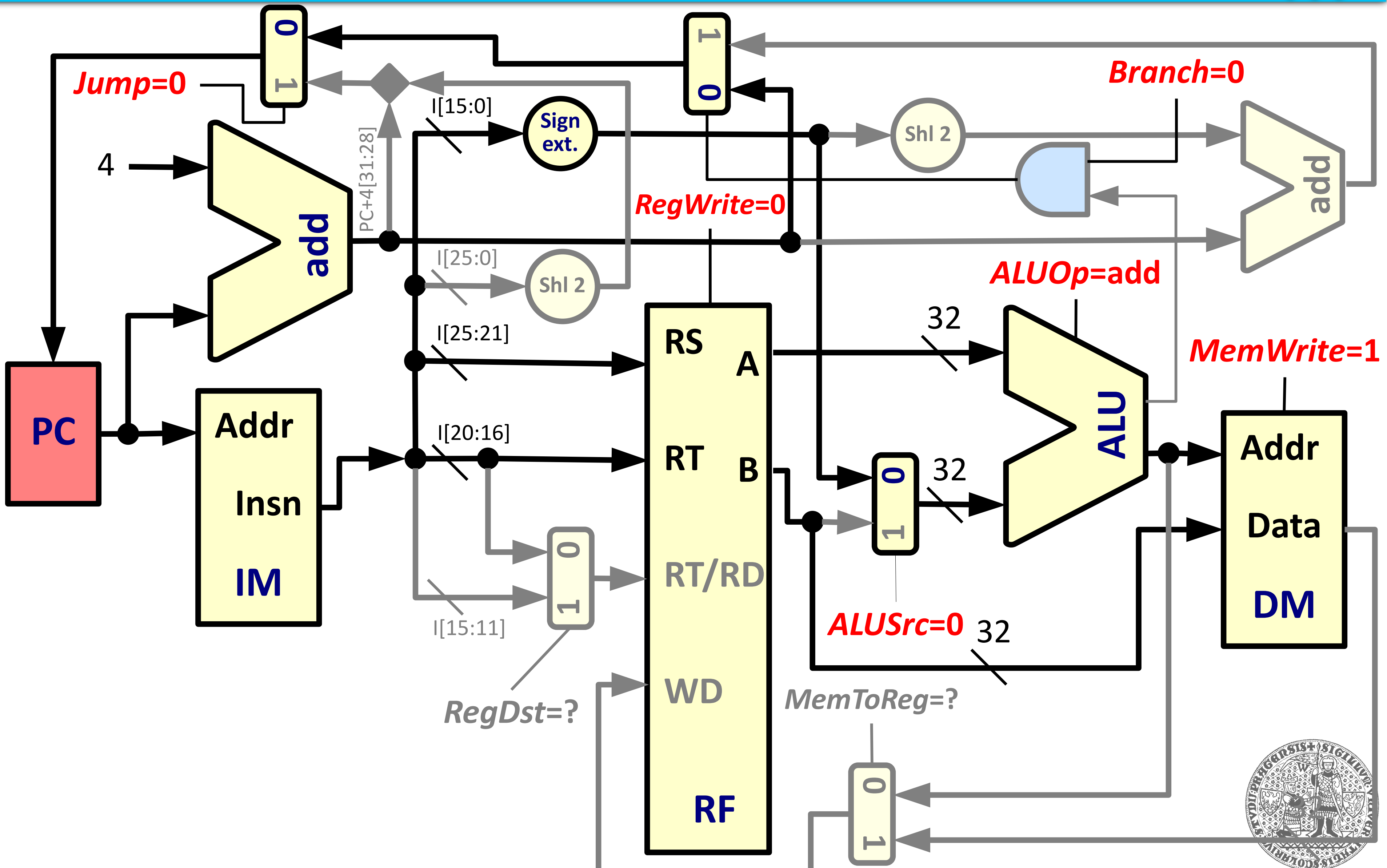
Single-cycle datapath control (2)

- **Controls the flow of data**
  - Depending on the type of operation
  - Responsible for control signals
    - Source of the next value of PC
    - Write to registers
    - Write to memory
    - ALU operations
    - Mux configuration

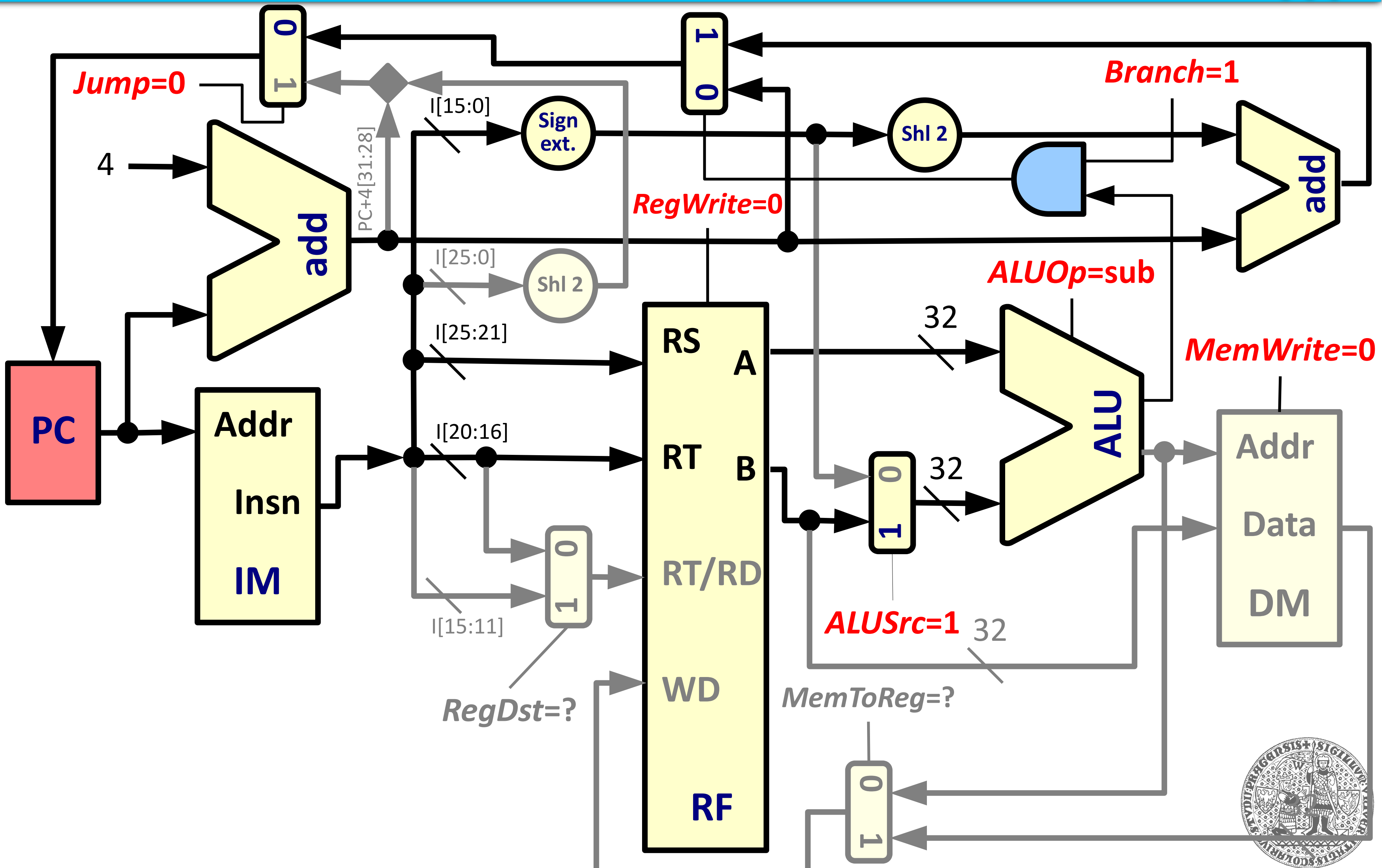
Example: datapath control for *add*



Example: datapath control for *sw*



Example: datapath control for *beq*



Datapath controller

- **Responsible for generating control signals**
  - Signal values determined by instruction opcode
  - Some control signals can be directly embedded in the instruction word
    - **MIPS:** *ALUOp* signals correspond to the bits in the `funct` field of the R-type instruction format
    - Simplifies controller implementation

ROM-based controller

- **Signal values stored in read-only memory**
  - Each word contains the values of all control signals
  - Words addressed by the opcode

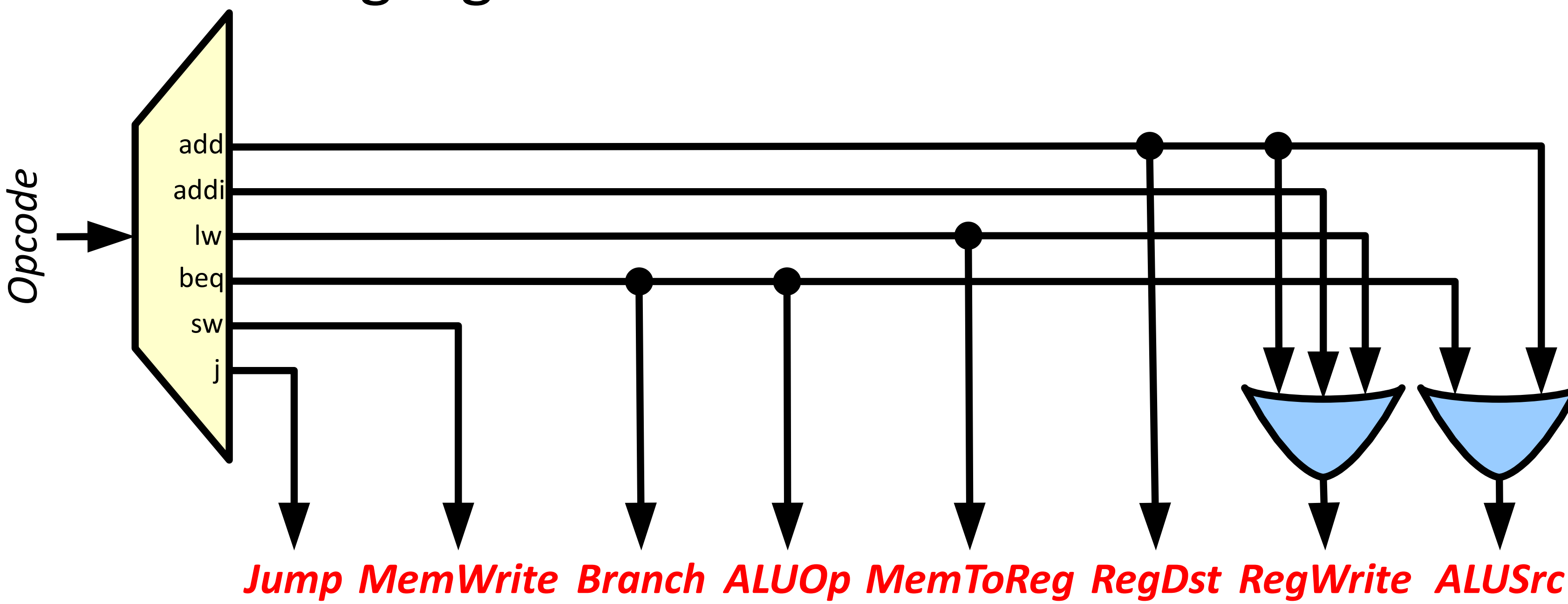
opcode	*Jump*	*Branch*	*RegDst*	*RegWrite*	*MemWrite*	*MemToReg*	*ALUOp*	*ALUSrc*
add	0	0	1	1	0	0	func	1
addi	0	0	0	1	0	0	add	0
lw	0	0	0	1	0	1	add	0
sw	0	0	?	0	1	?	add	0
beq	0	1	?	0	0	?	sub	1

ROM-based controller (2)

- **Real MIPS implementation**
  - Approx. 100 instructions and 300 control signals
    - Control ROM capacity needed: 30000 bits (~ 4 KB)
  - Implementation issues
    - Making ROM faster than the datapath

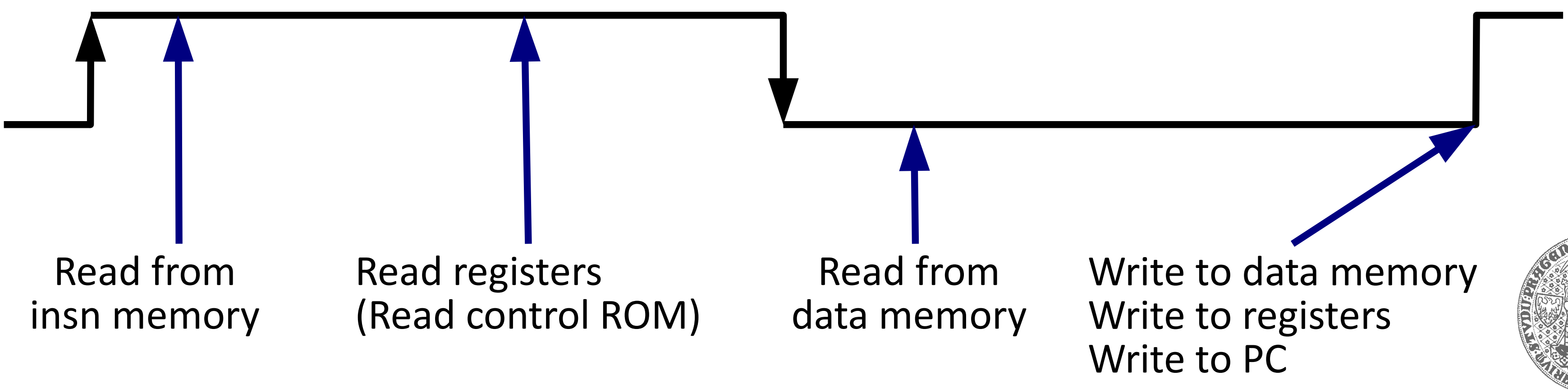
Logic-based controller (combinational)

- **Faster alternative to ROM**
  - Observation: only a few control signals need to be set to one (zero) at the same time
  - Contents of ROM can be efficiently expressed using logic functions



Instruction cycle

- **Datapath with continuous read**
  - No problem in our design
    - Writes (PC, RF, DM) are independent
    - No read follows write in the instruction cycle
    - Instruction fetch does not need control
      - After instruction is read, the controller decodes instruction opcode into control signals for the rest of the datapath
      - When PC changes, datapath starts processing another instruction



Single-cycle processor performance

- **Each instruction executed in 1 cycle (CPI=1)**
  - Single-cycle controller (control ROM or a combinational logic block)
  - Generally lower clock frequency
  - Clock period respects the “longest” instruction
    - Load Word (lw) in our case
    - Usually multiplication, division, or floating point ops
  - Datapath contains duplicate elements
    - Instruction and data memory, two extra adders

Multi-cycle datapath

- **Basic idea**
  - Simple instructions should not take as much time to execute as the complex ones
- **Variable instruction execution time**
  - Clock period is constant (cannot be changed dynamically), we need a „digital“ solution
  - We can make clock faster (shorter period) and split instruction execution into multiple stages
    - Clock period corresponds to **one execution stage**
    - Fixed **machine cycle** (clock period)
    - Variable **instruction cycle**

Example: multi-cycle CPU performance

- **Rough estimate, assuming the following**
  - Simple instructions take 10 ns to execute
  - Multiplication takes 40 ns
  - Instruction mix with 10% of multiplications
- **Single-cycle datapath**
  - Clock period 40 ns, CPI=1 → **25 MIPS**
- **Multi-cycle datapath**
  - Clock period 10 ns, 13 ns per instruction (average)
  - CPI=1.3 → **77 MIPS** (3x improvement)

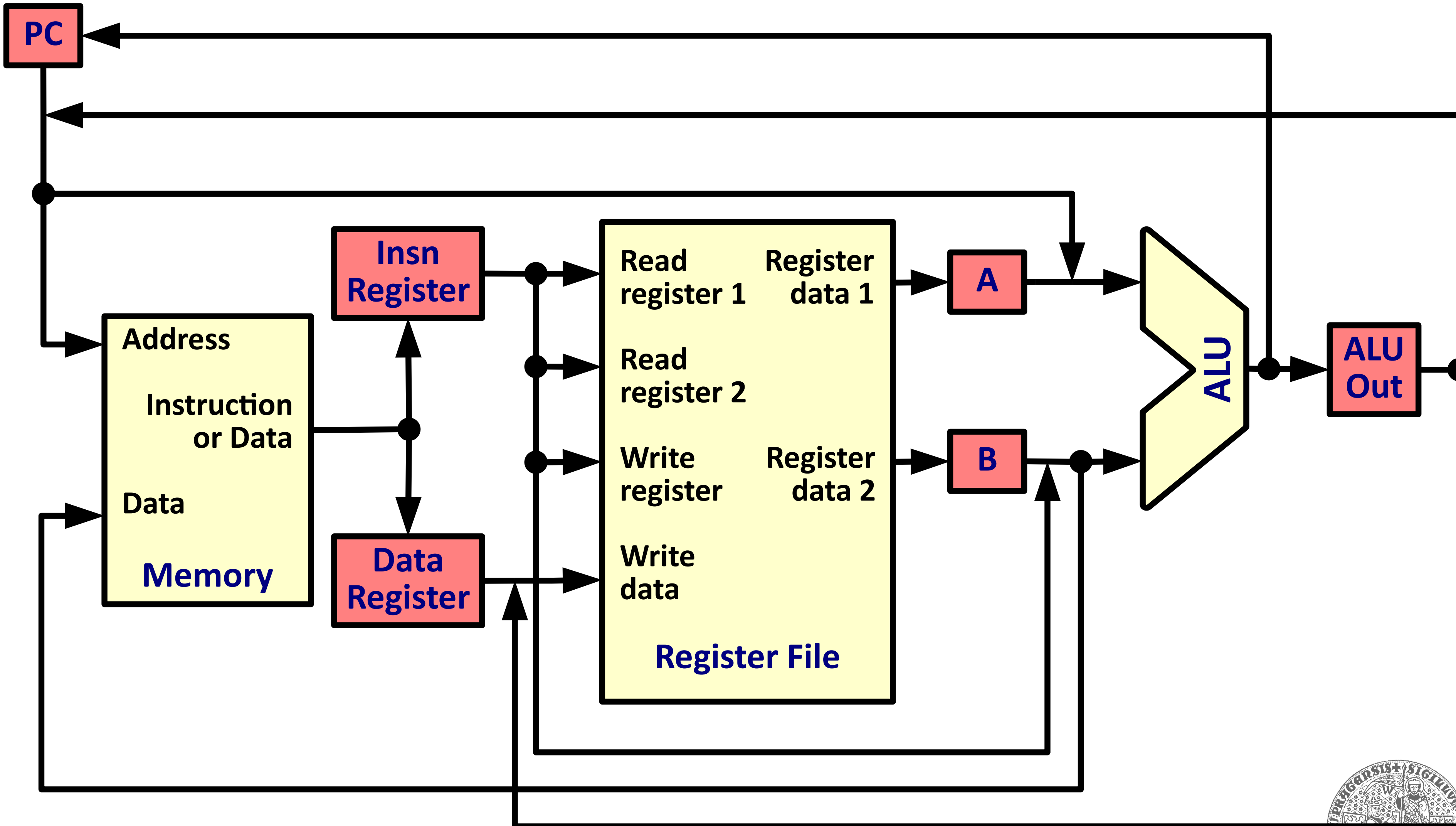
Multi-cycle datapath (2)

- **Instruction cycle**
  1. Read instruction from memory
  2. Decode instruction, read registers, compute branch target address
  3. Execute register operation / compute address for memory access / finish branch or jump
  4. Write register operation results / access memory
  5. Finish load from memory

Multi-cycle datapath (3)

- **Implementation issues**
  - Instruction execution split to stages
    - Need to isolate stages using latch registers to "remember" results from previous stage
  - Need to keep track of stages
    - Different sequences for different instruction types
    - Some instructions may skip stages and finish early
    - Controller needs to remember state → sequential logic

Multi-cycle datapath (4)



Stage 1: Instruction Read

- **Common for all instructions**
  - IR ← Memory[PC]
    - Read instruction into Instruction Register
    - Memory is used for both instruction and data access
    - Need to "remember" the instruction being executed
  - PC ← PC + 4
    - Advance PC to point at next instruction in sequence
    - Changing the PC will not change the instruction being executed: it was stored in the Instruction Register

Stage 2: Instruction Decode, Read Regs.

- **Common for all instructions**
  - A ← Reg[IR.rs]
    - Read contents of source register 1
    - Store value into latch A for next stage
  - B ← Reg[IR.rt]
    - Read contents of source register 2
    - Store value into latch B for next stage
  - ALUOut ← PC + (SignExtend(IR.addr) << 2)
    - Calculate branch target
    - Relative to (already updated) PC
    - Remains unused if not a branch

Stage 3: Execute / address calc.

- **Branch instruction *(finish)***
  - (A == B) ⇒ PC ← ALUOut
    - Branch target in ALUOut from previous stage
- **Jump instruction *(finish)***
  - PC ← PC[31:28] + (IR[25:0] << 2)
- **Register operation**
  - ALUOut ← A ***funct*** B, or alternatively
  - ALUOut ← A ***funct*** SignExtend(IR[15:0])
- **Memory access**
  - ALUOut ← A **+** SignExtend(IR[15:0])
    - Calculate address for memory access

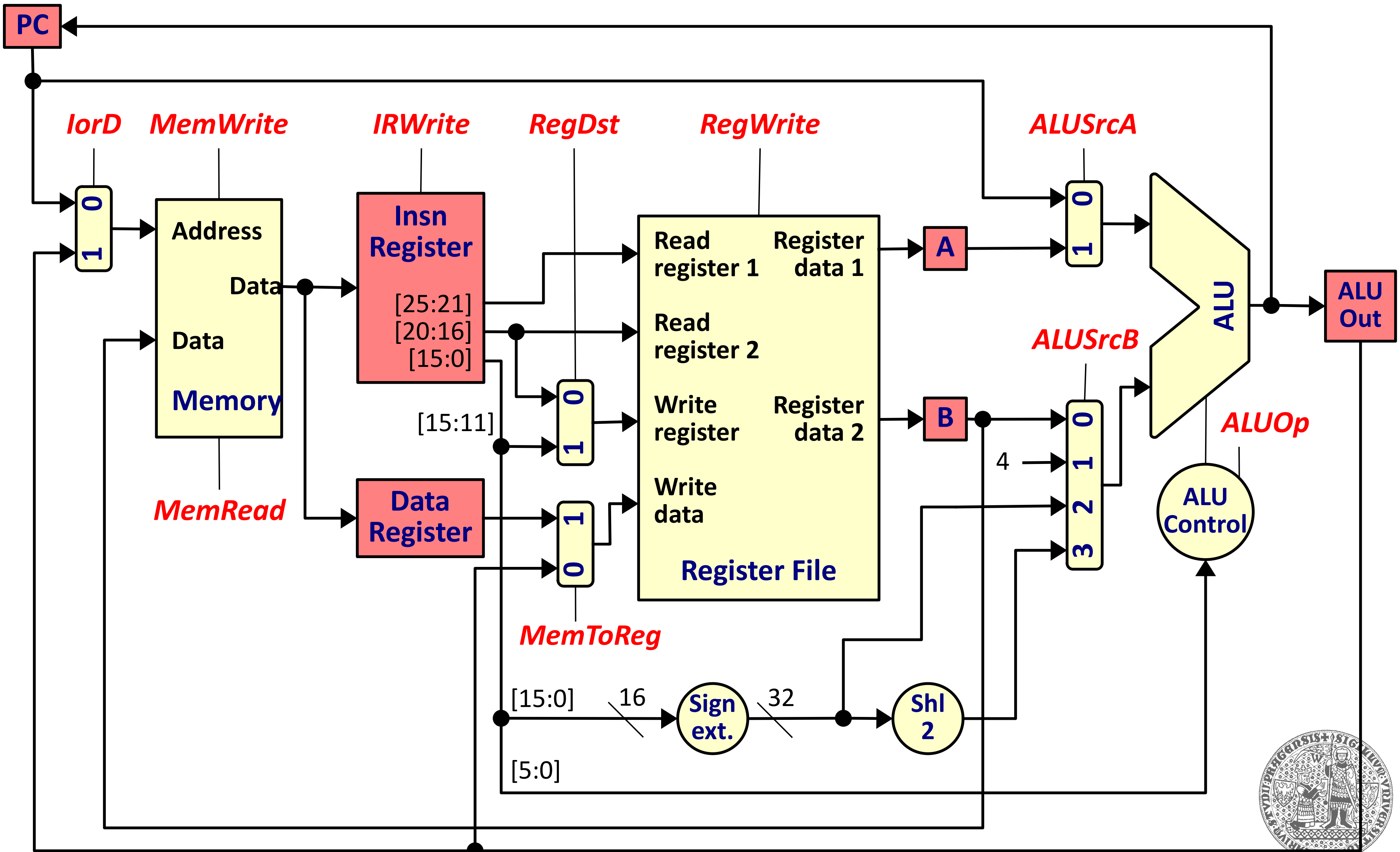
Stage 4: Write Results / memory access

- **Register operation *(finish)***
  - Reg[IR.rd] ← ALUOut
    - Result in ALUOut (from previous stage)
- **Write to memory *(finish)***
  - Memory[ALUOut] ← B
    - Address in ALUOut (from previous stage)
- **Read from memory**
  - DR ← Memory[ALUOut]
    - Address in ALUOut (from previous stage)
    - Store data into latch DR for next stage

Stage 5: Finish reading from memory

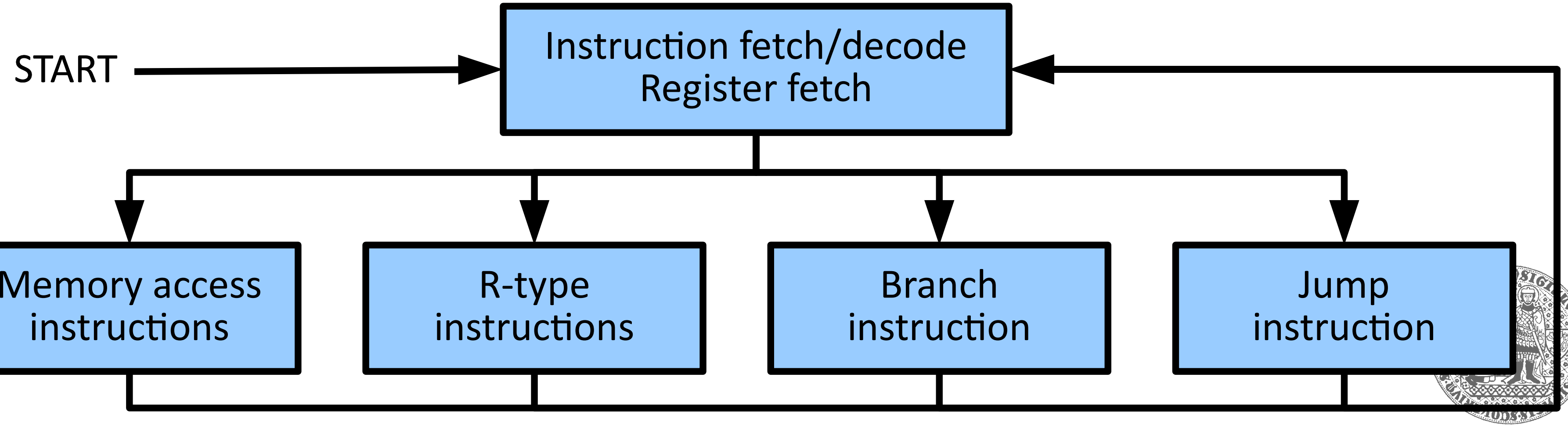
- **Read from memory *(finish)***
  - Reg[IR.rt] ← DR
    - Value stored in DR (from previous stage)

Multi-cycle datapath implementation

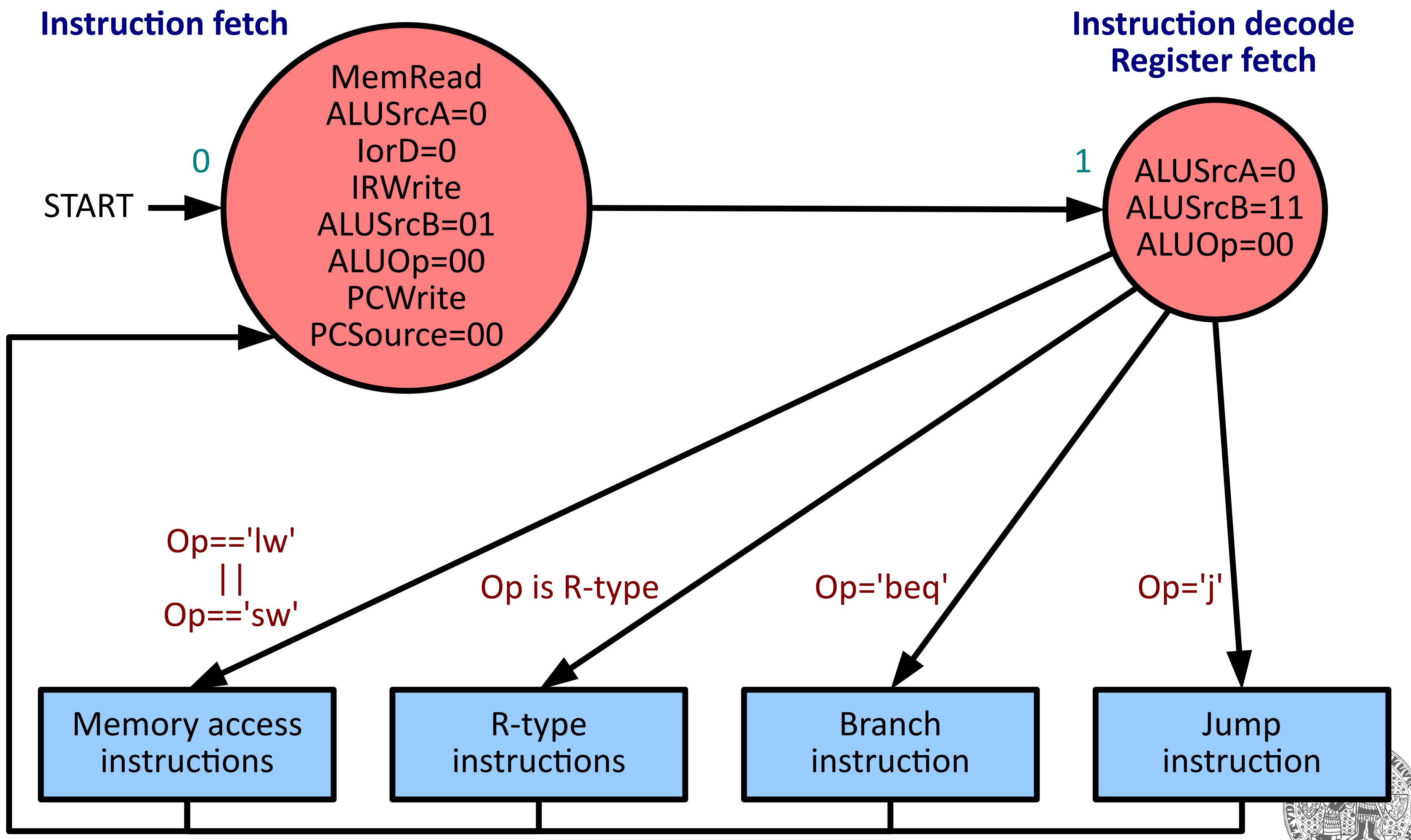


Multi-cycle datapath control

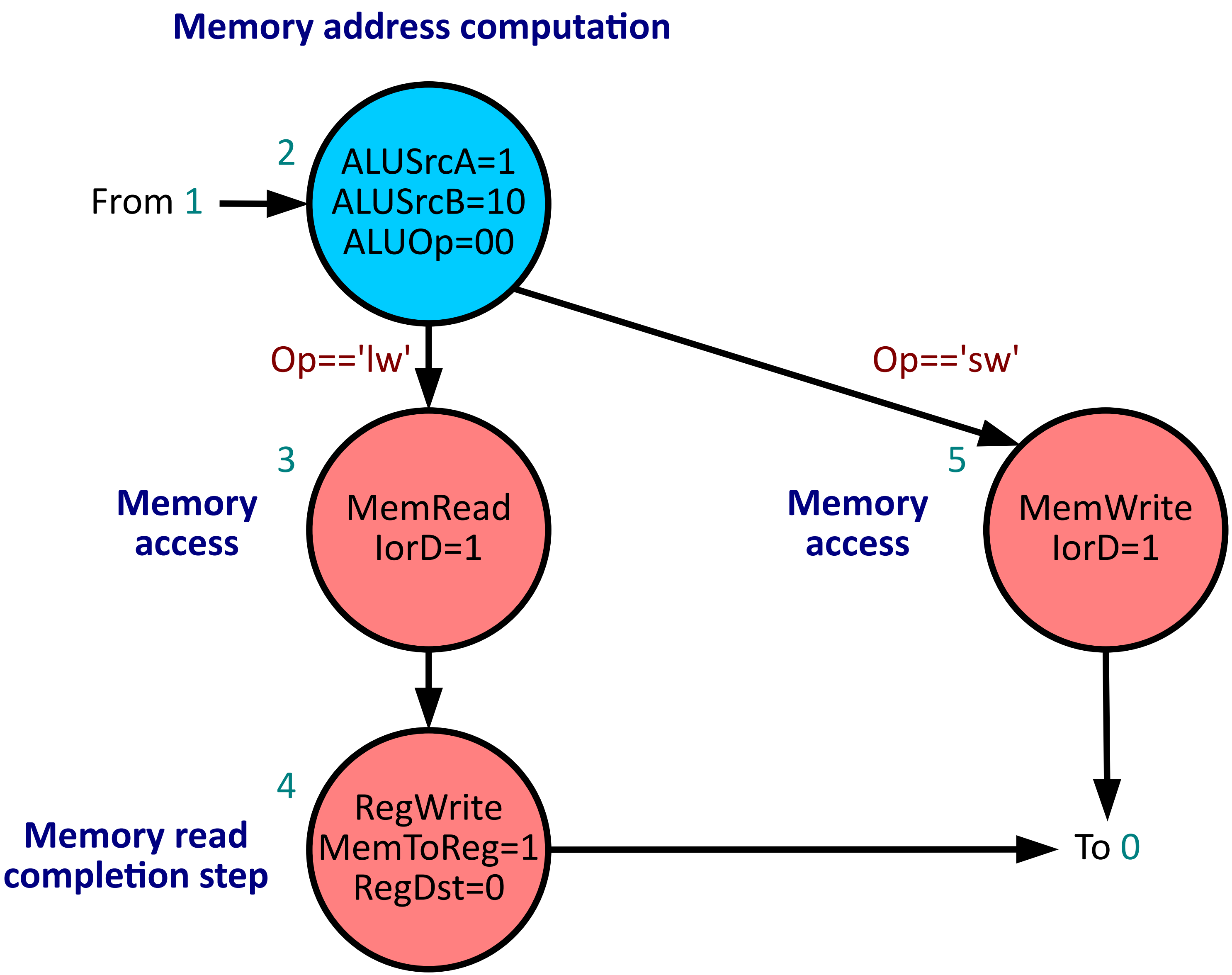
- **Sequential process**
  - Instructions executed in multiple cycles
  - Controller is a sequential circuit (automaton)
    - Current state stored in a state register
    - Combinational block determines next state
      - Depends on current state and instruction being executed
      - Updated on rising edge of the clock signal



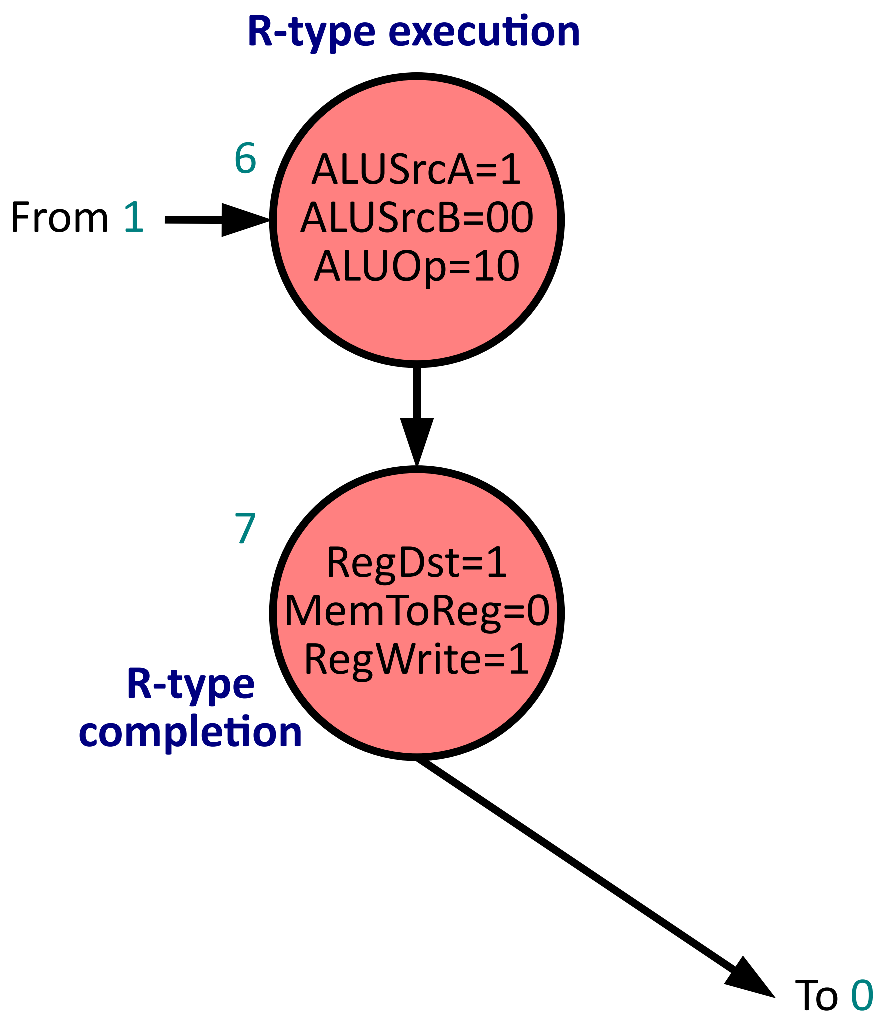
Instruction fetch/decode, Register fetch



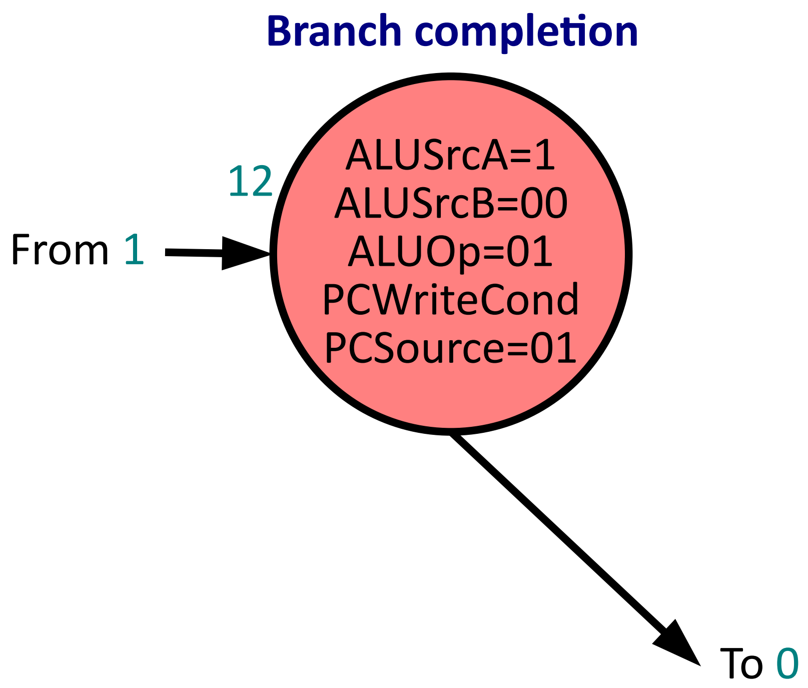
Memory access instructions



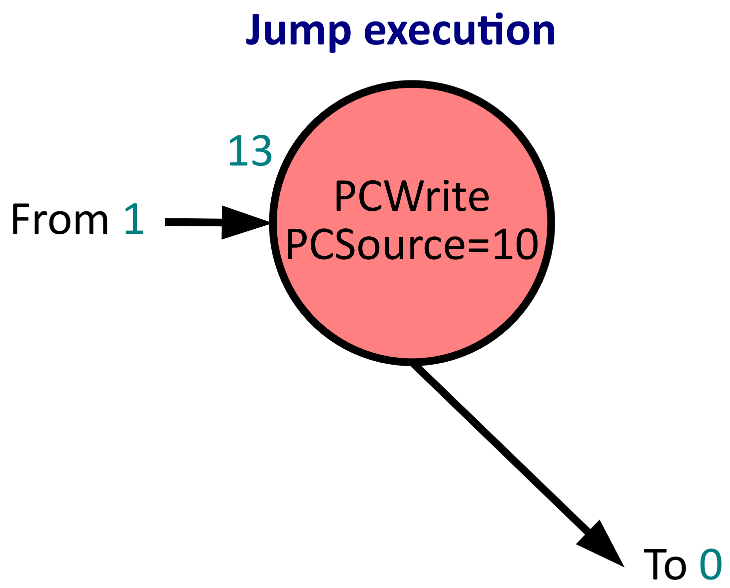
R-type instructions



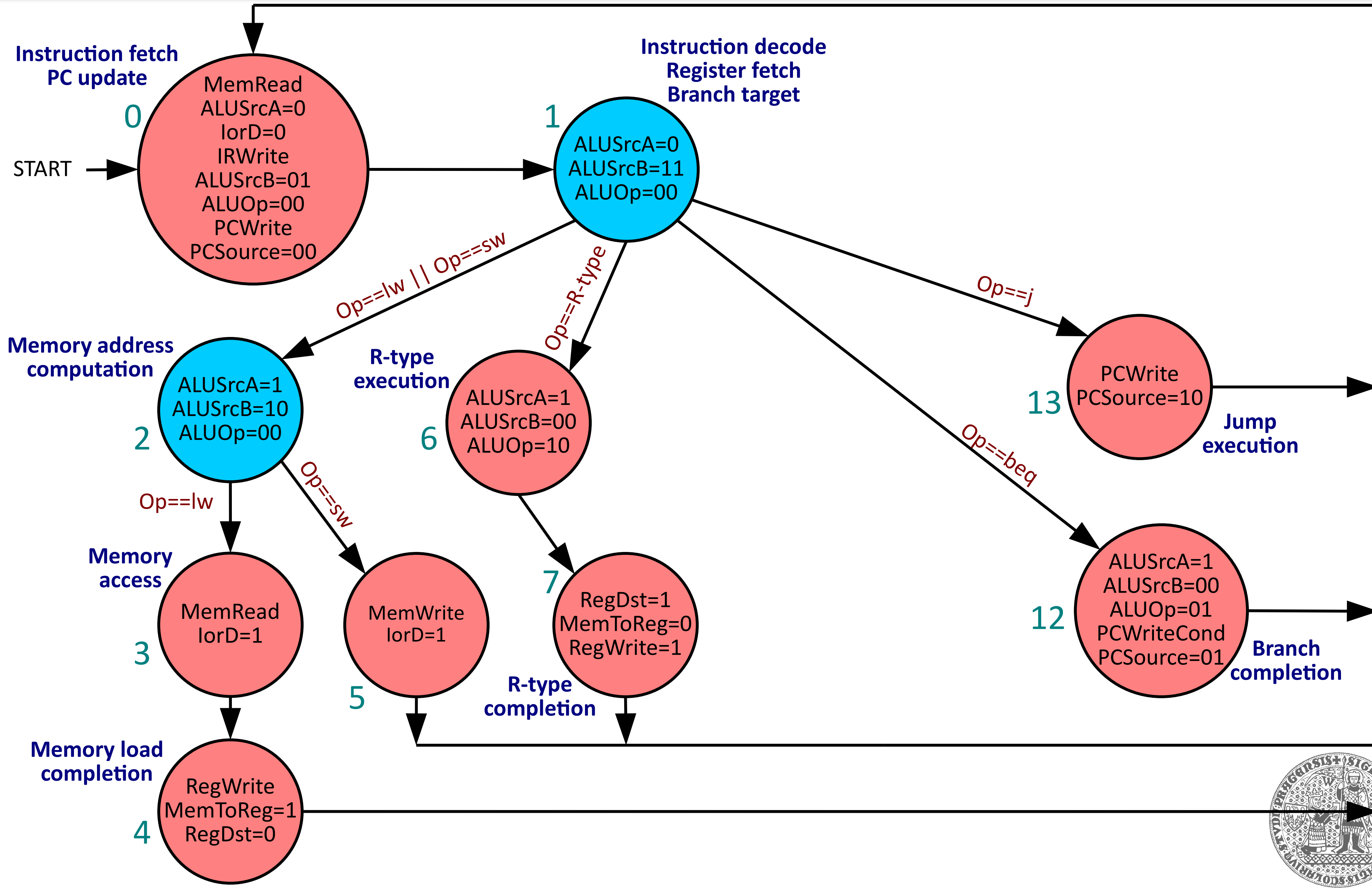
Branch instruction



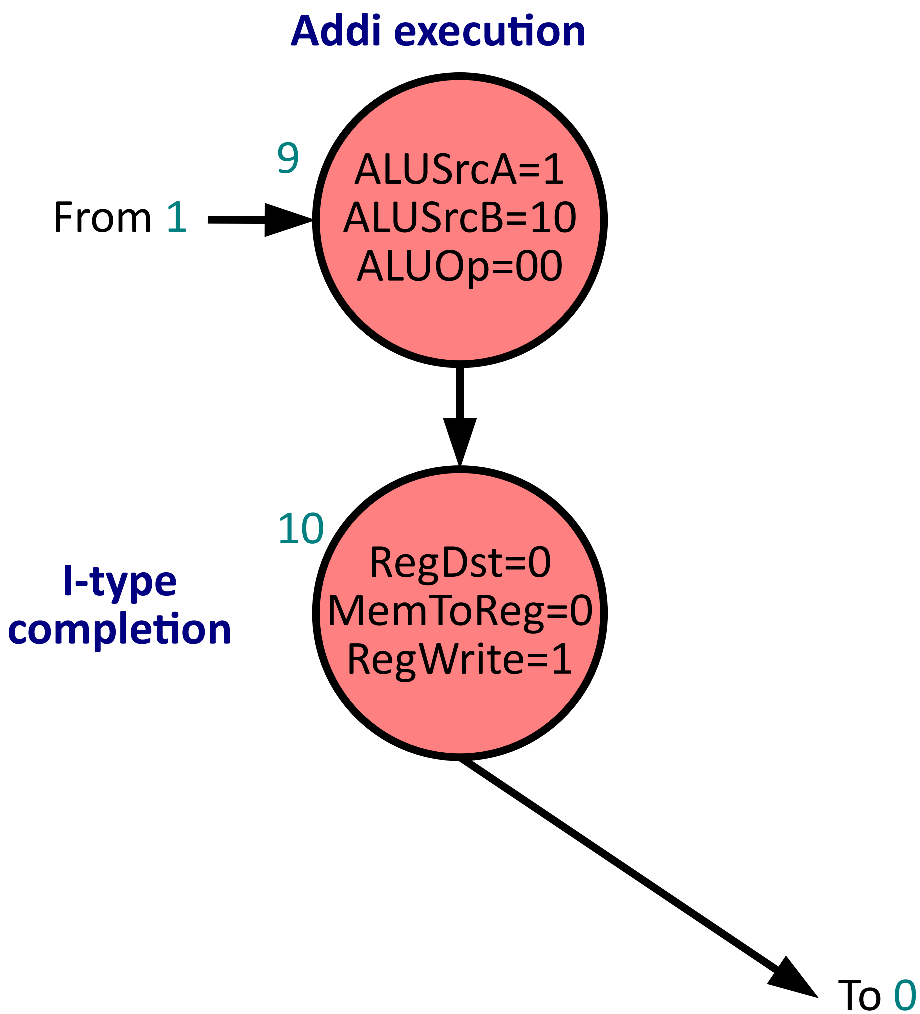
Jump instruction



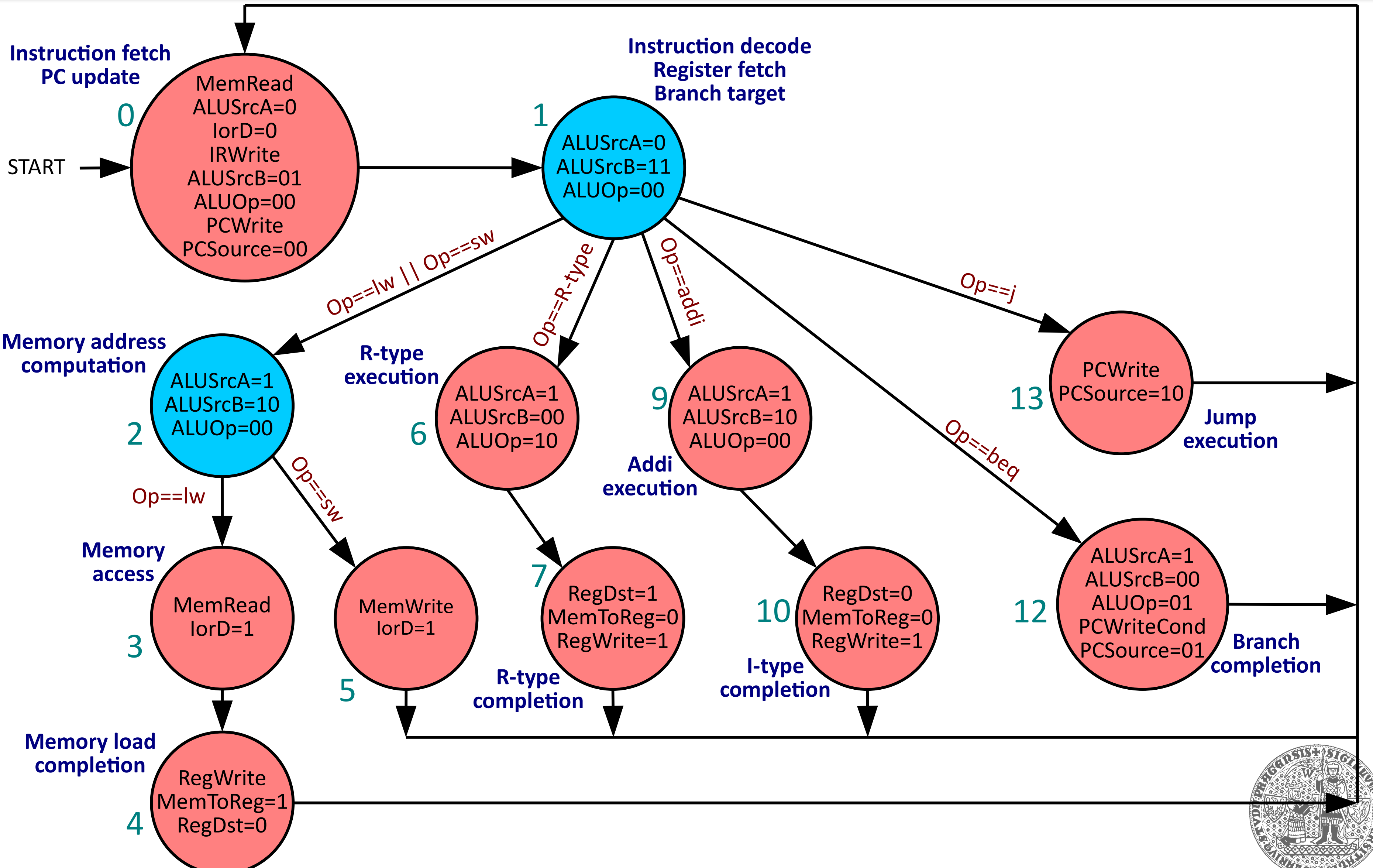
Multi-cycle datapath control (2)



Addi instruction



Multi-cycle datapath control (3)



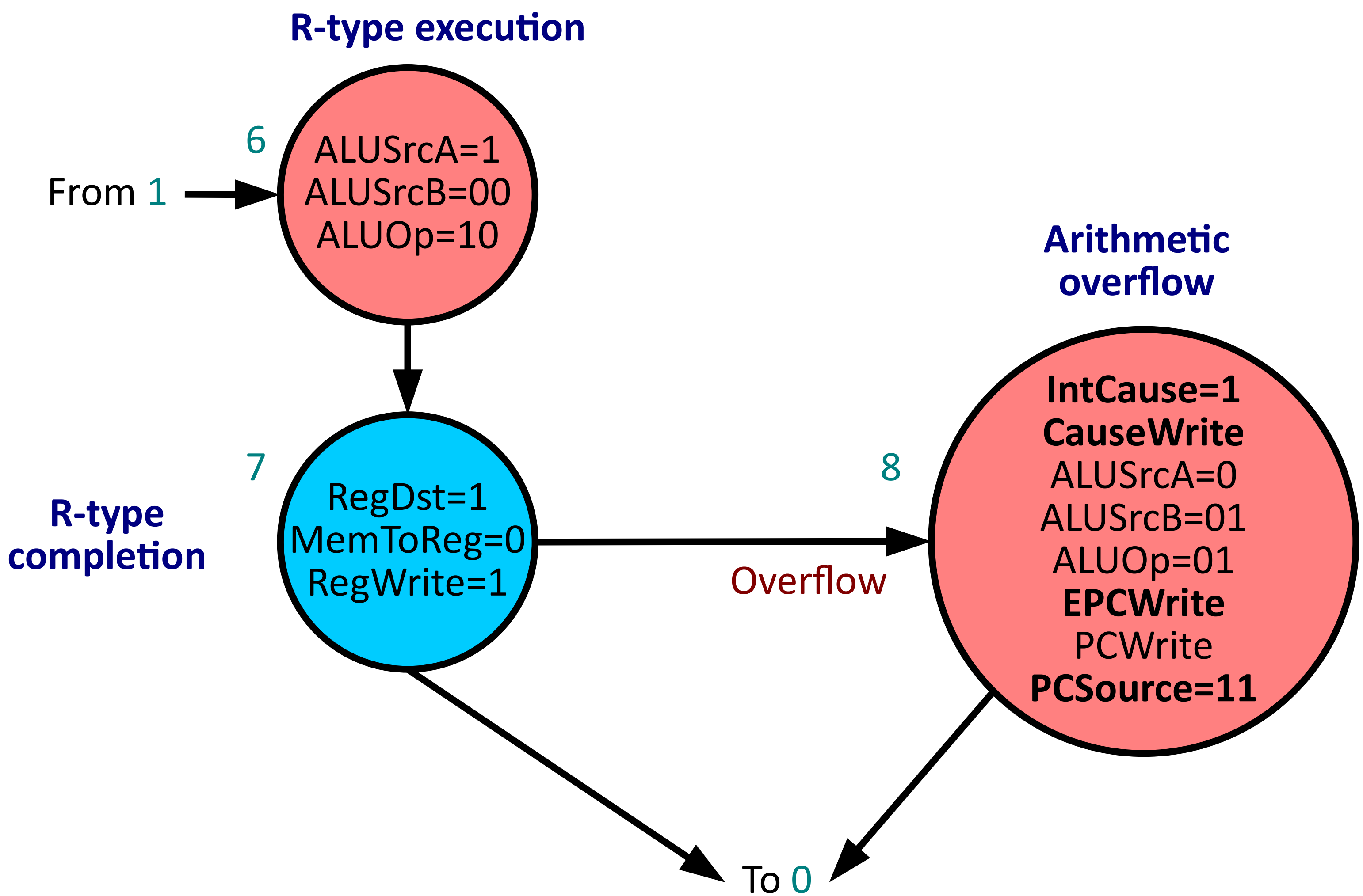
Flow of instructions

- **Normal/expected flow**
  - Sequential: common code operating on data
  - Non-sequential: branches and jumps
- **Unexpected flow**
  - Internal (*Exception/Trap*)
    - **Arithmetic overflow**
    - **Undefined instruction**
    - Unauthorized access to memory
    - Requesting service from operating system (system call)
    - Hardware failure
  - External (*Interrupt*)
    - Request for “attention” from an I/O device
    - Hardware failure

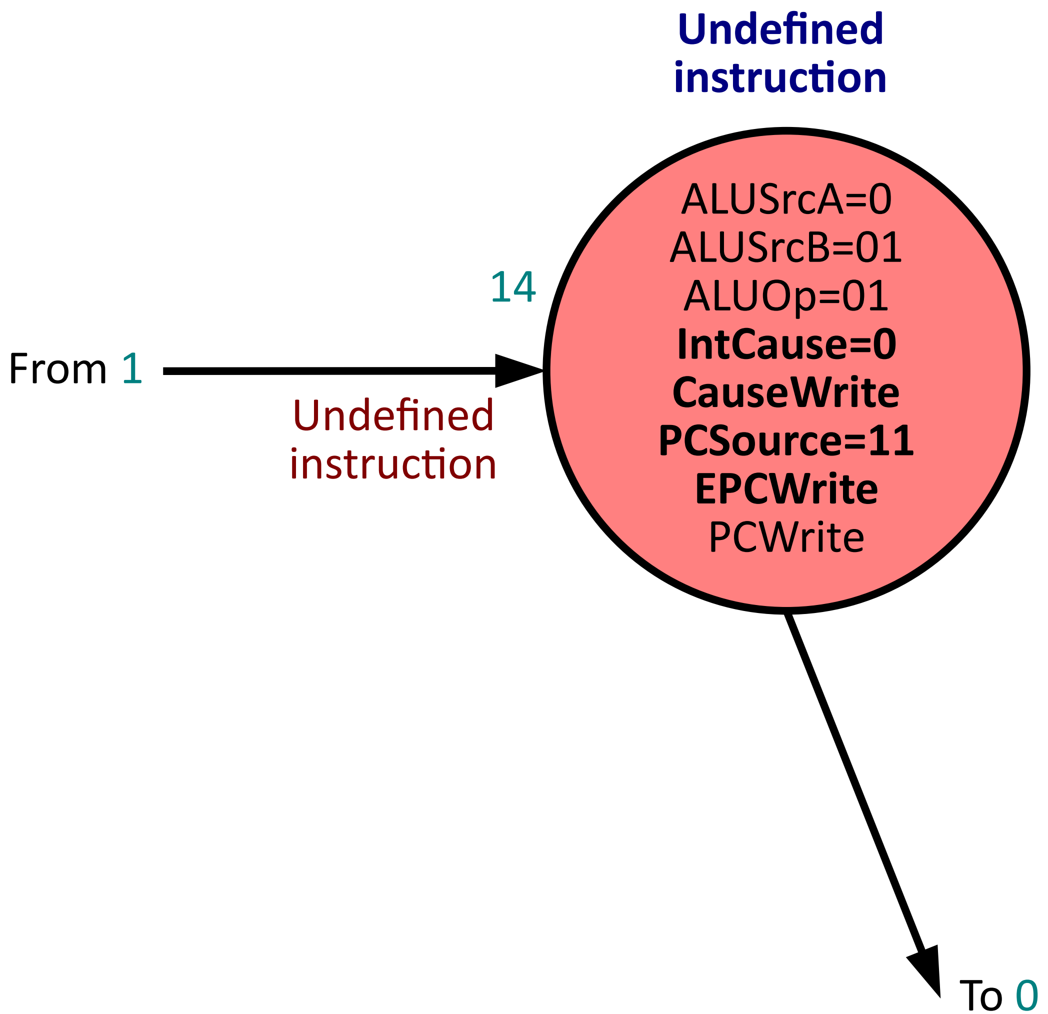
Supporting exceptions and interrupts

- **Hardware support (minimum necessary)**
  - Stop executing an instruction
    - Maintain valid processor and computation state
  - Allow to identify cause
    - Flag bits in a special register
    - Identifier of exception type
  - Store address of instruction that caused exception
    - Allows re-executing or skipping an instruction on resume
  - Jump to exception/interrupt handler
    - Single address for all exceptions/interrupts
    - Multiple addresses corresponding to exception type

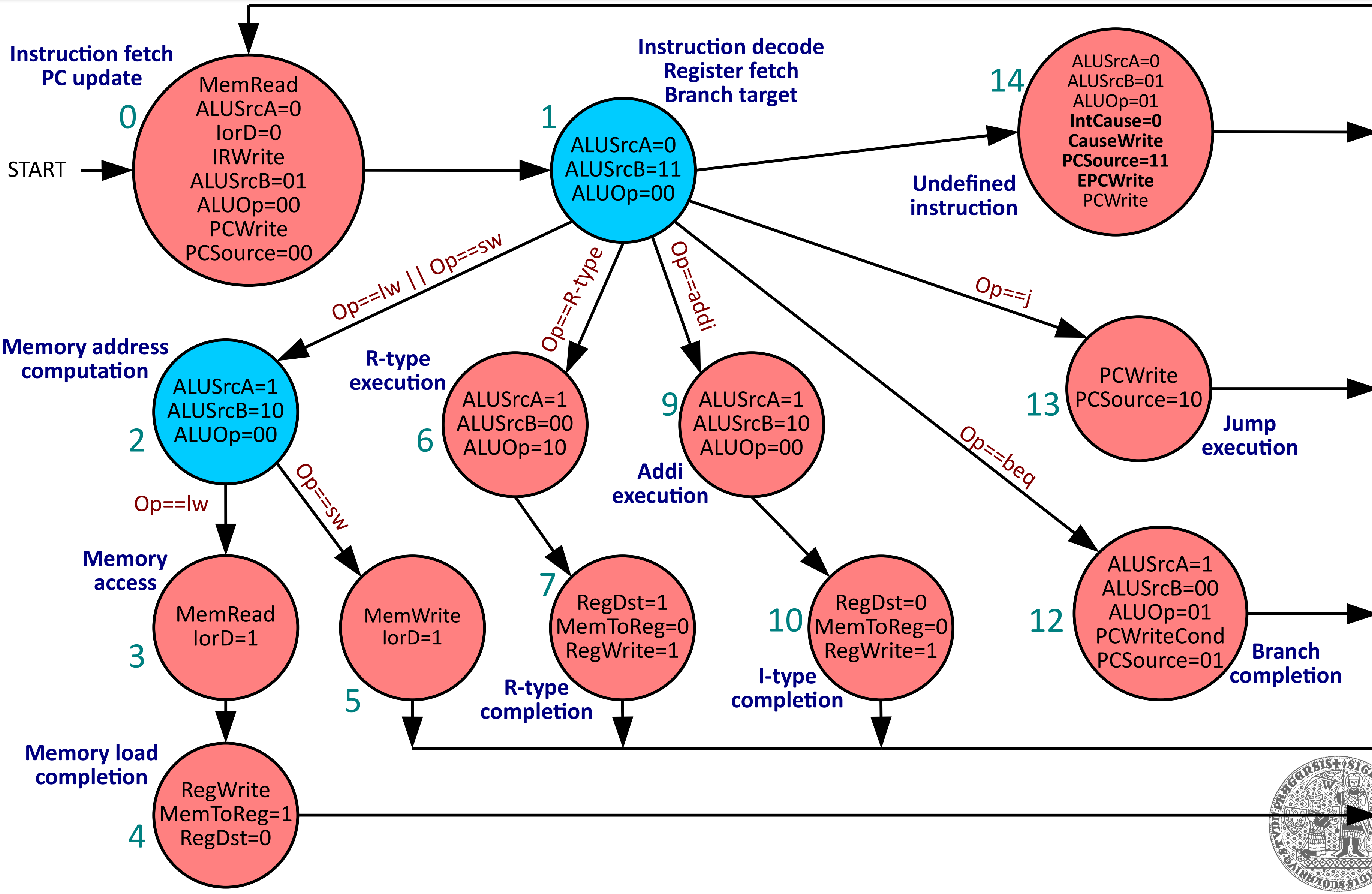
Arithmetic overflow exception



Undefined instruction exception



Multi-cycle datapath control (4)



Supporting exceptions and interrupts (2)

- **Software handler**
  - Store the current state of computation
    - Save contents of CPU registers to memory
  - Determine the cause of exception/interrupt and execute the corresponding handler routine
    - Deal with I/O device
    - Deal with memory management
    - Continue/terminate current process
    - Switch to another process
  - Restore state of current (next) process
  - Resume execution (jump into) of current (next) process
    - Restart instruction that caused an exception
    - Continue from next instruction

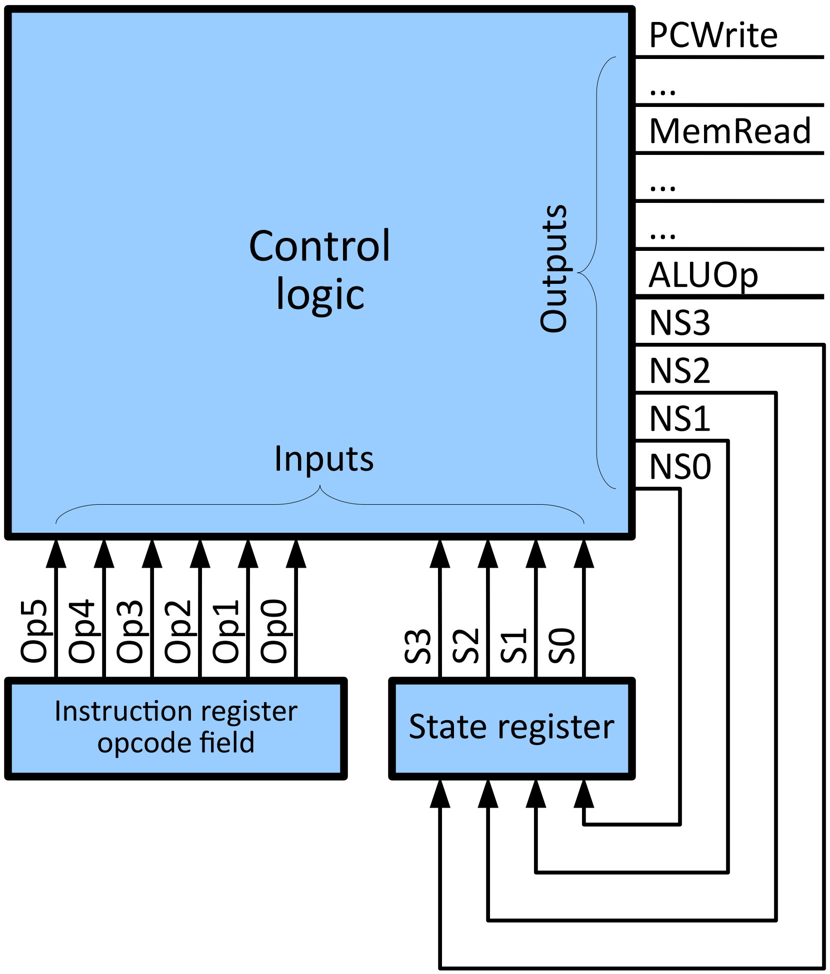
Multi-cycle datapath performance

- **Instruction mix**
  - 30% load (5ns), 10% store (5ns)
  - 50% add (4ns), 10% mul (20ns)
- **Single-cycle datapath (clock period 20ns, CPI = 1)**
  - ***20ns*** per instruction → ***50 MIPS***
- **Coarse-grained multi-cycle datapath (clock period 5ns)**
  - $CPI \approx (90\% \times 1) + (10\% \times 4) = 1.3$
  - ***6.5ns*** per instruction → ***153 MIPS***
- **Fine-grained multi-cycle datapath (clock period 1ns)**
  - $CPI \approx (30\% \times 5) + (10\% \times 5) + (50\% \times 4) + (10\% \times 20) = 6$
  - ***6ns*** per instruction → ***166 MIPS***

Implementing a sequential controller

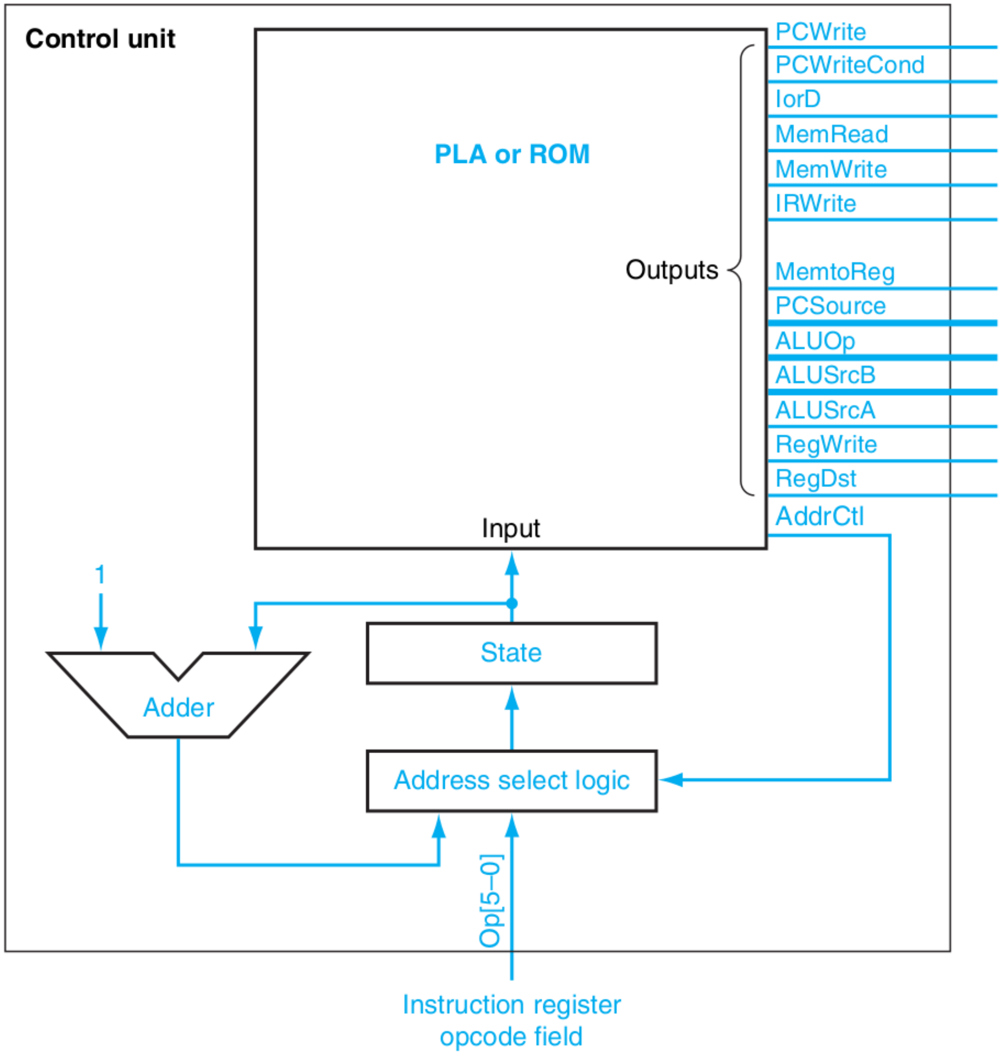
- **Implementing a finite-state automaton**
  - State + transition conditions = memory + combinational logic → sequential logic
    - Implementation depends on internal state representation
  - Sequential circuitry
    - 1 flip-flop per state (only one active at a time), active state shifted through enabling gates between flip-flops
    - State register + combinational logic
  - Simple sequencer + control memory
    - Micro- and nano- programming

Implementing a sequential controller

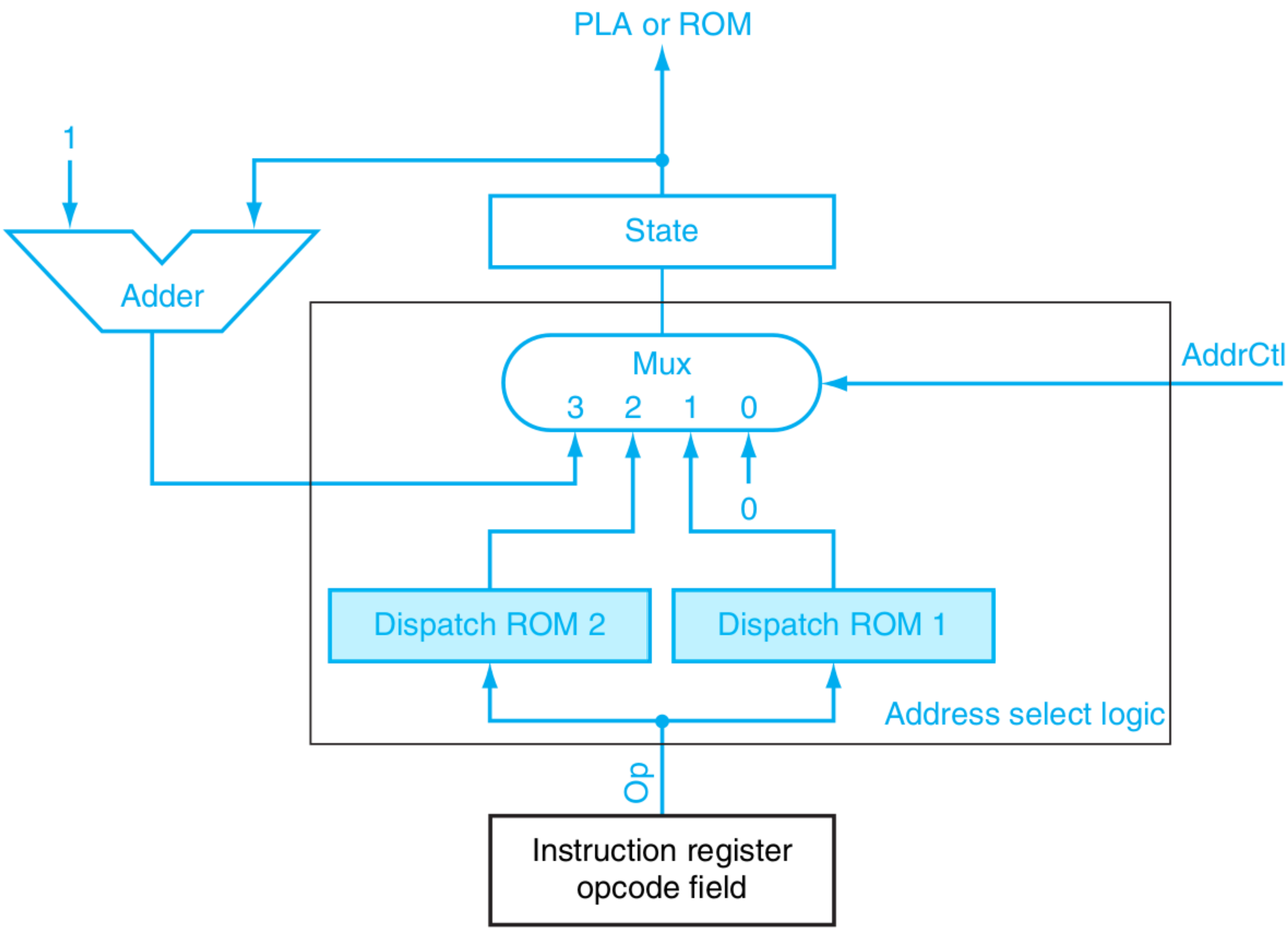


- **State register**
- **Control logic**
  - Combinational logic
  - ROM, FPGA

Next state is next control ROM address

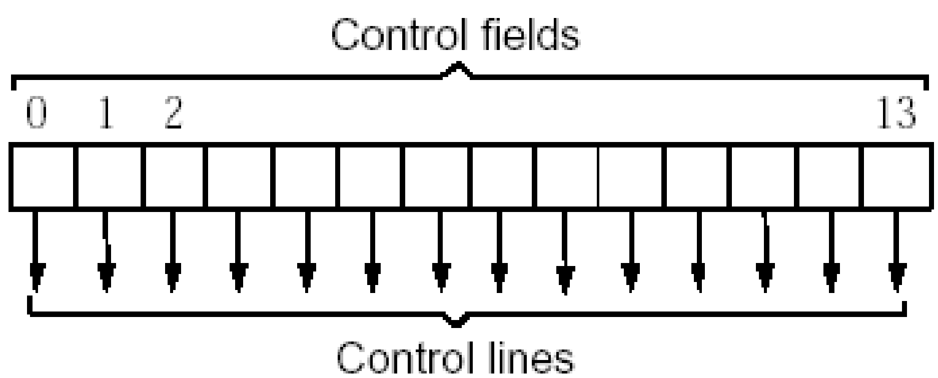


Control memory address select logic



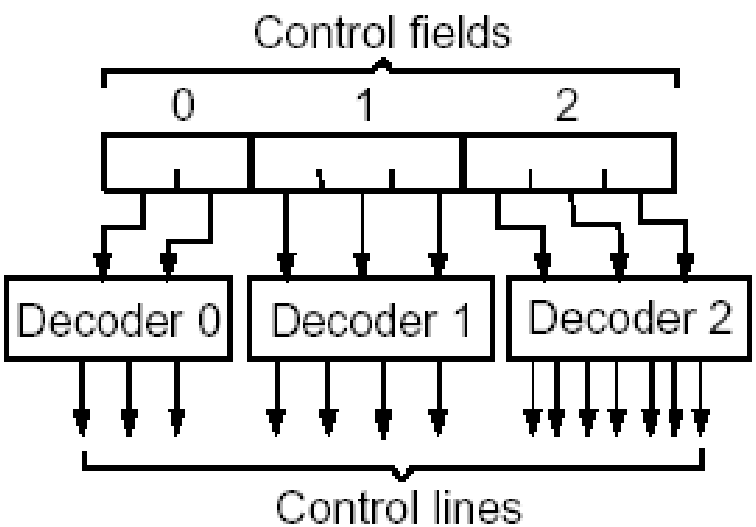
Horizontal micro-instructions

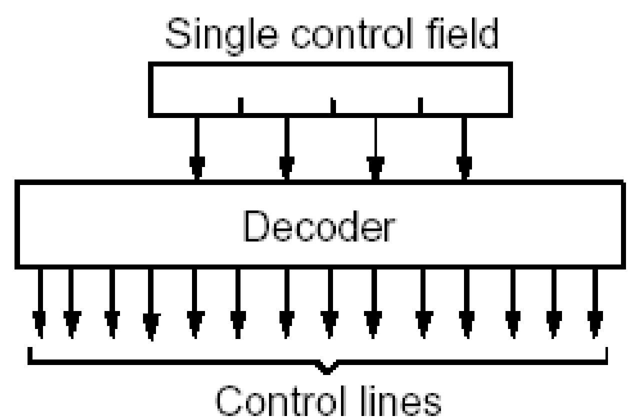
- **Direct representation of control signals**
  - Control memory contains raw control signals
  - Micro-instruction = set of control signal values
    - No need to decode (fast)
    - Any combination is possible (flexible)
    - Requires a lot of space



Vertical micro-instructions

- **Encoded representation of control signals**
  - Microinstructions identify valid combinations of control signals
    - Decoded intro actual control signals using a decoder
    - Reduces space at the cost of flexibility and latency

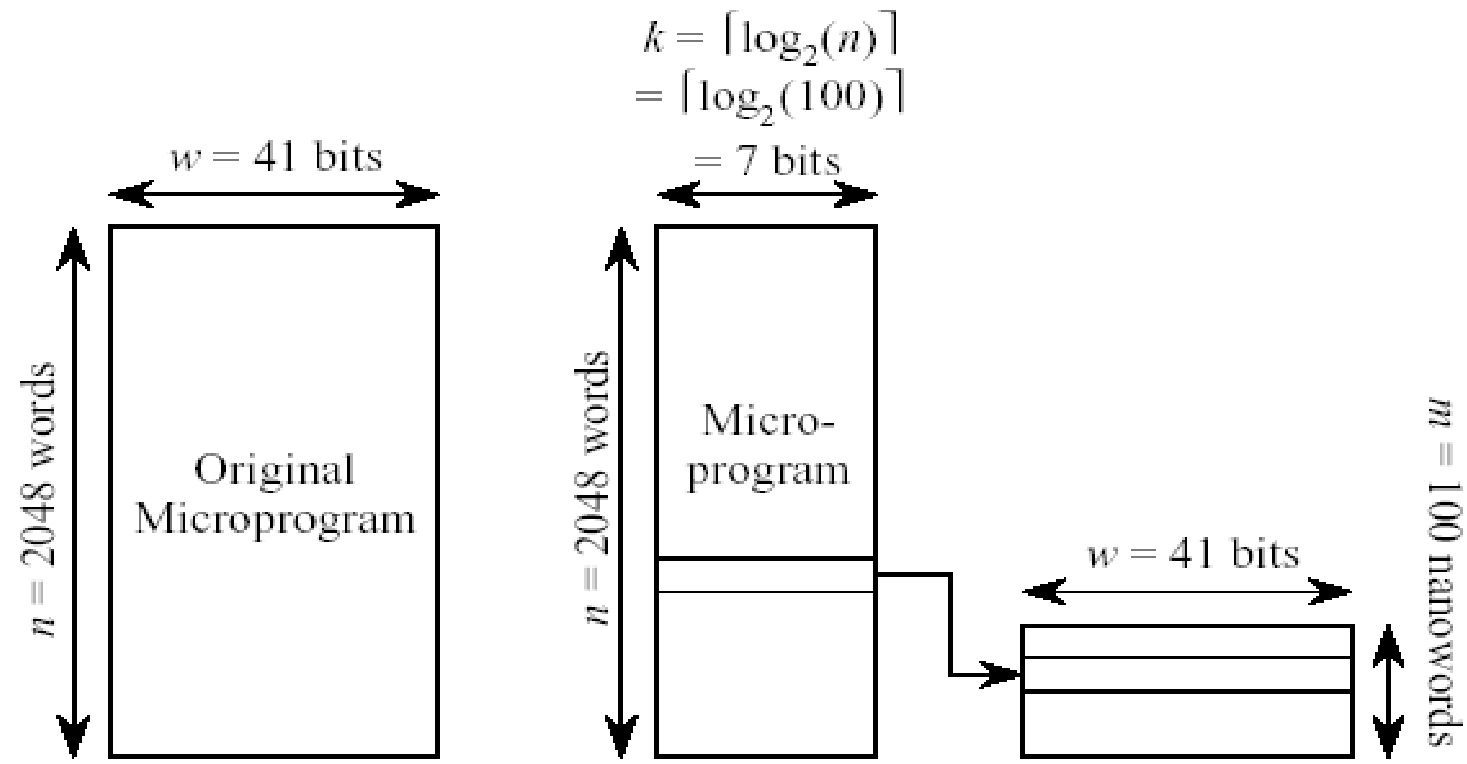




Nano-programming

- **Combines horizontal & vertical encoding**
  - Microprogram memory only contains numbers representing valid combinations of control signals (vertical format)
  - Decoding to horizontal format is realized using another memory (instead of a combinational circuit) which contains the control signal combination corresponding to microprogram code
  - Significantly reduces the amount of space required to store the microprogram, but increases decoding latency

Micro- vs nano-programming



Total Area $= n \times w =$
$2048 \times 41 = 83{,}968$ bits

Microprogram Area $= n \times k = 2048 \times 7$
$= 14{,}336$ bits
Nanoprogram Area $= m \times w = 100 \times 41$
$= 4100$ bits
Total Area $= 14{,}336 + 4100 = 18{,}436$ bits