ECE/CS 250
Computer Architecture

Summer 2017

Processor Design: Datapath and Control

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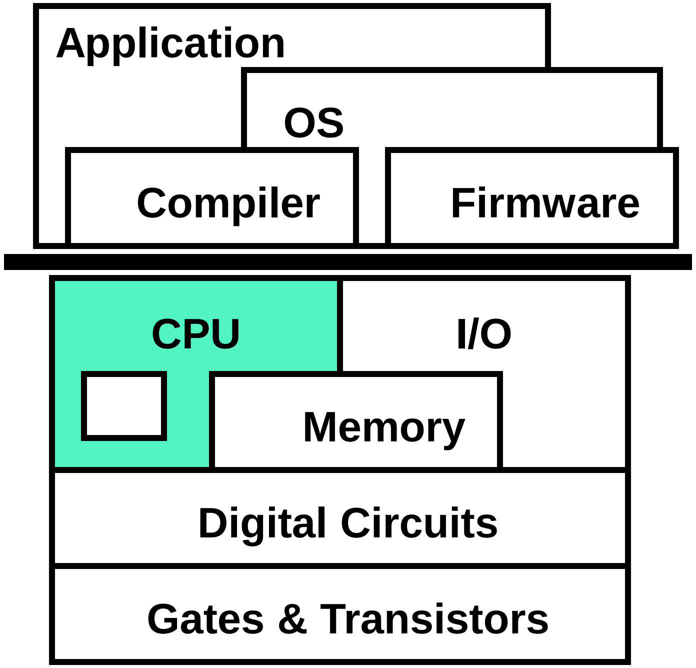
Slides are derived from work by
Daniel J. Sorin (Duke), Amir Roth (Penn)

Where We Are in This Course Right Now

- So far:
  - We know what a computer architecture is
  - We know what kinds of instructions it might execute
  - We know how to perform arithmetic and logic in an ALU
- Now:
  - We learn how to design a processor in which the ALU is just one component
  - Processor must be able to fetch instructions, decode them, and execute them
  - There are many ways to do this, even for a given ISA
- Next:
  - We learn how to design memory systems

This Unit: Processor Design



- Datapath components and timing
  - Registers and register files
  - Memories (RAMs)
- Mapping an ISA to a datapath
- Control
- Exceptions

Readings

- Patterson and Hennessy
    - Chapter 4: Sections 4.1-4.4
- Read this chapter carefully
    - It has many more examples than I can cover in class

So You Have an ALU…

- Important reminder: a processor is just a big finite state machine (FSM) that interprets some ISA

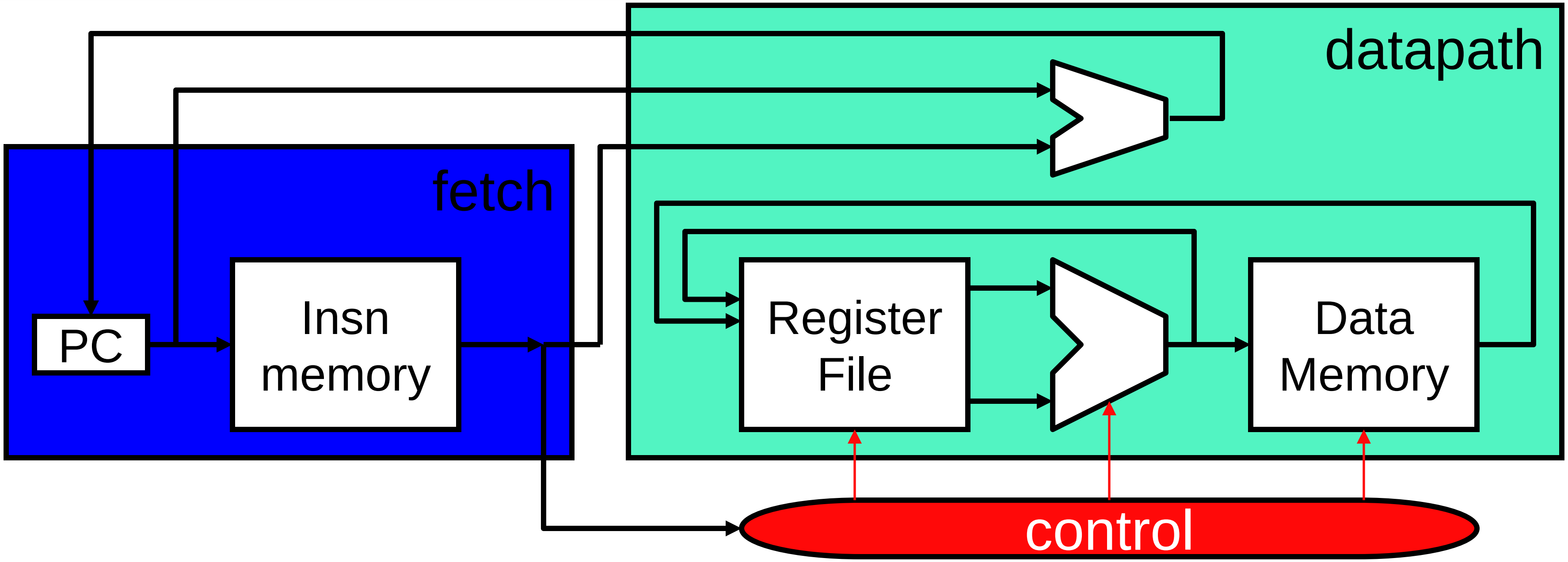
- Start with one instruction

  `add $3,$2,$4`

  - ALU performs just a small part of execution of instruction
  - You have to read and write registers
  - You have have to fetch the instruction to begin with

- What about loads and stores?
  - Need some sort of memory interface
- What about branches?
  - Need some hardware for that, too

Datapath and Control



- **Datapath**: registers, memories, ALUs (computation)
- **Control**: which registers read/write, which ALU operation
- **Fetch**: get instruction, translate into control
- Processor Cycle: **Fetch** → **Decode** → **Execute**

Building a Processor for an ISA

- Fetch is pretty straightforward
  - Just need a register (called the Program Counter or PC) to hold the next address to fetch from instruction memory
  - Provide address to instruction memory → instruction memory provides instruction at that address

- Let’s start with the datapath
  1. Look at ISA
  2. Make sure datapath can implement every instruction

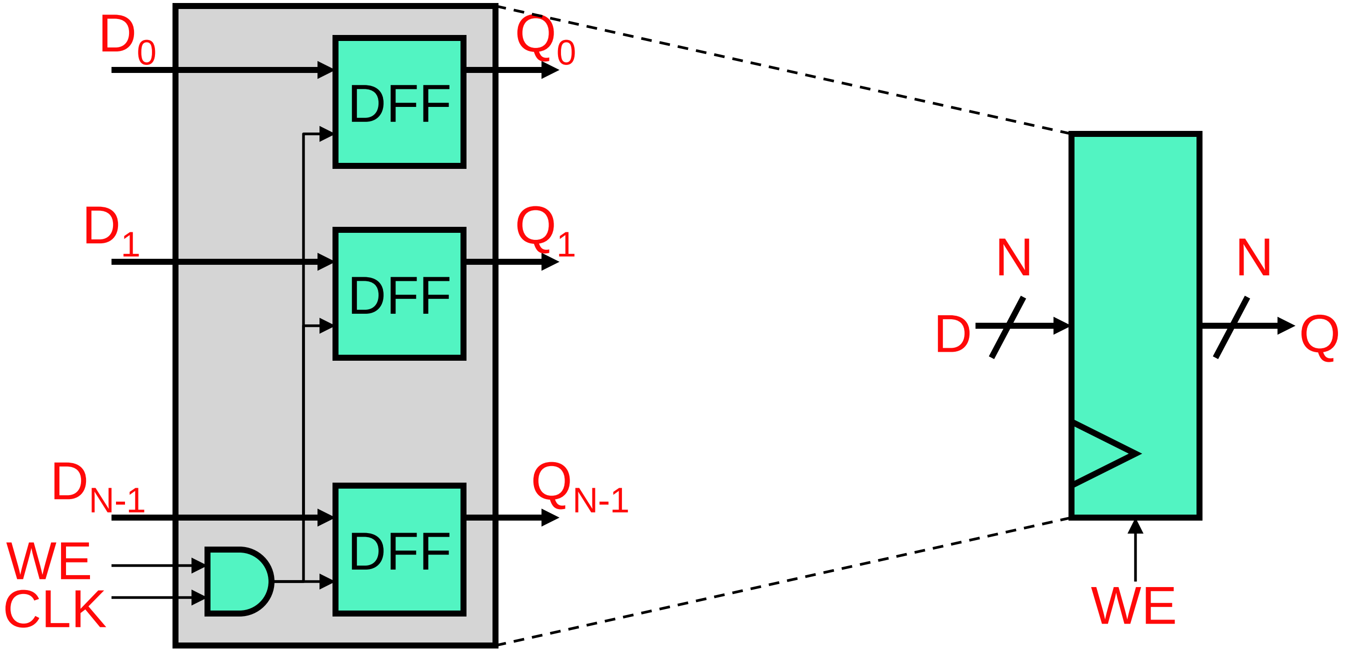
Datapath for MIPS ISA

- Consider only the following instructions

```
add $1,$2,$3
addi $1,$2,<value>
lw $1,4($3)
sw $1,4($3)
beq $1,$2,PC_relative_target
j Absolute_target
```

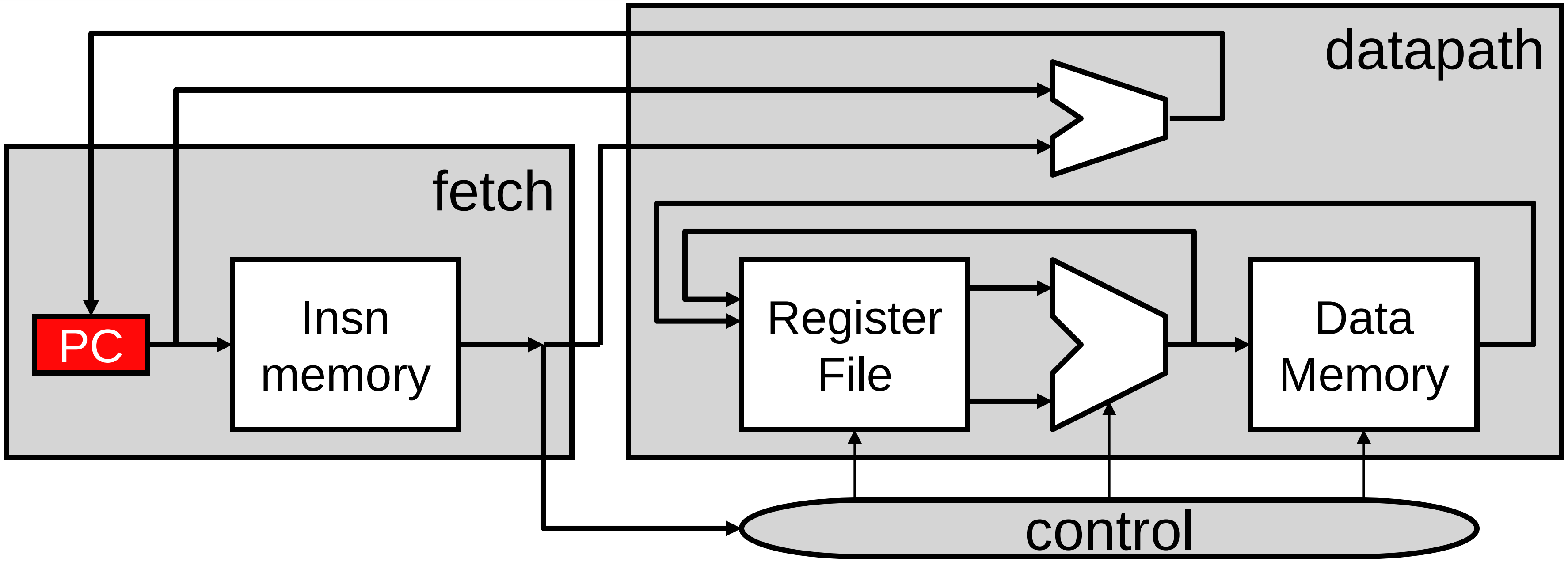
- Why only these?
  - Most other instructions are similar from datapath viewpoint
  - I leave the ones that aren't for you to figure out

Review: A Register



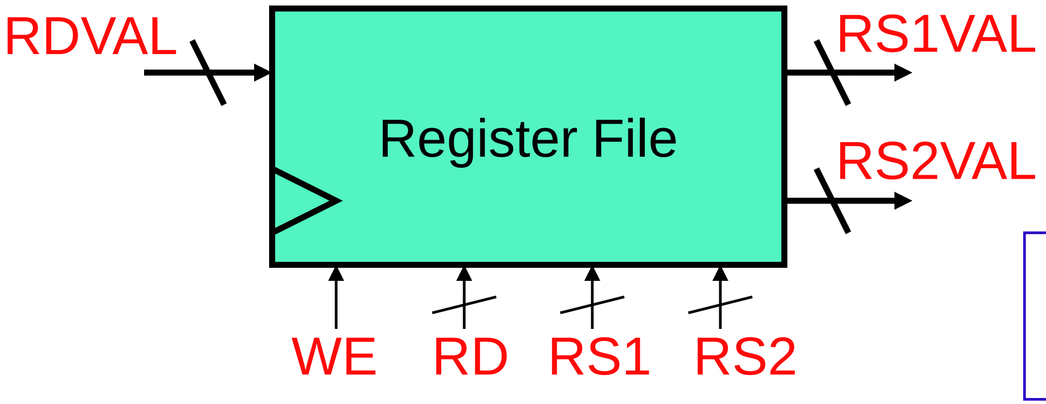
- **Register**: DFF array with shared clock, write-enable (WE)
  - Notice: both a clock and a WE (DFF_{WE} = clock & $register_{WE}$)
  - Convention I: clock represented by wedge
  - Convention II: if no WE, DFF is written on every clock

Uses of Registers



- A single register is good for some things
  - PC: program counter
  - Other things which aren’t the ISA registers (more later in semester)

What About the ISA Registers?

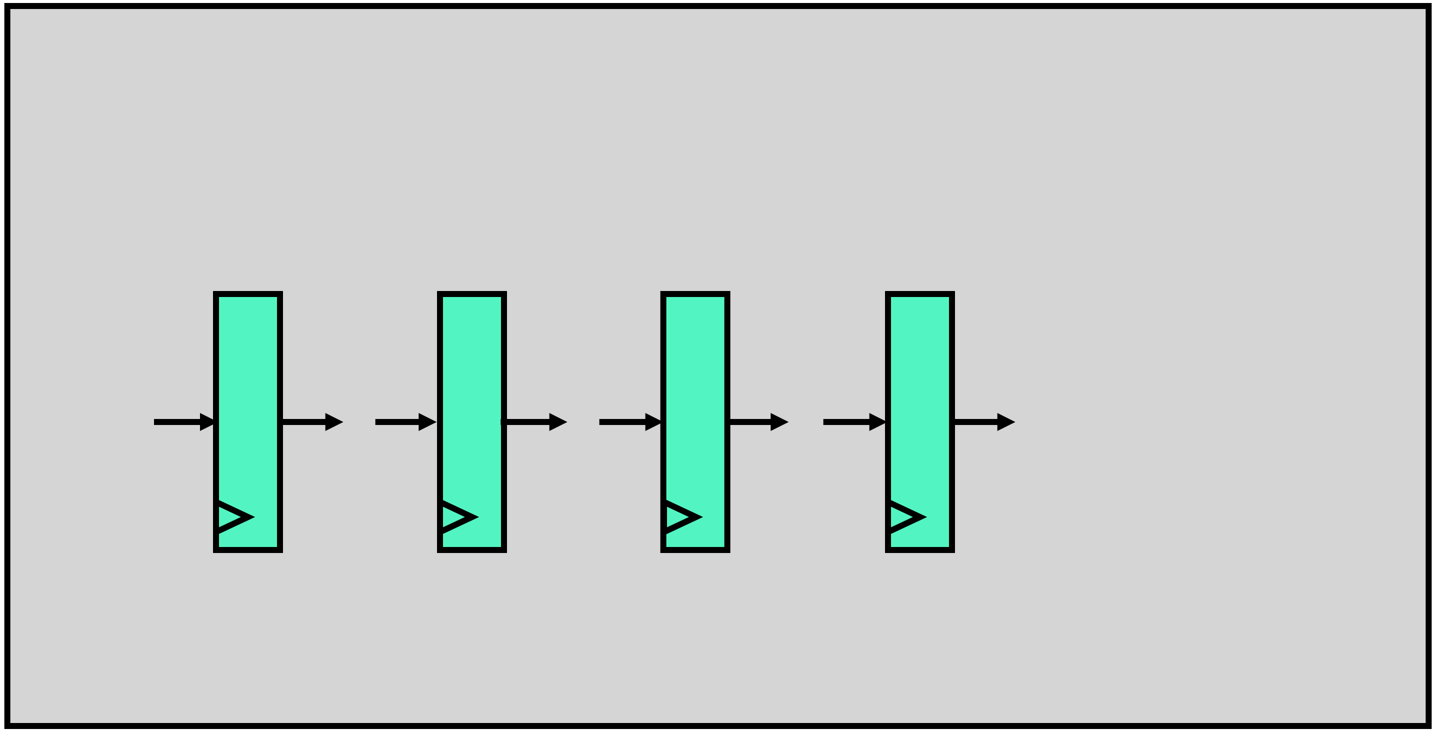


RD = dest reg

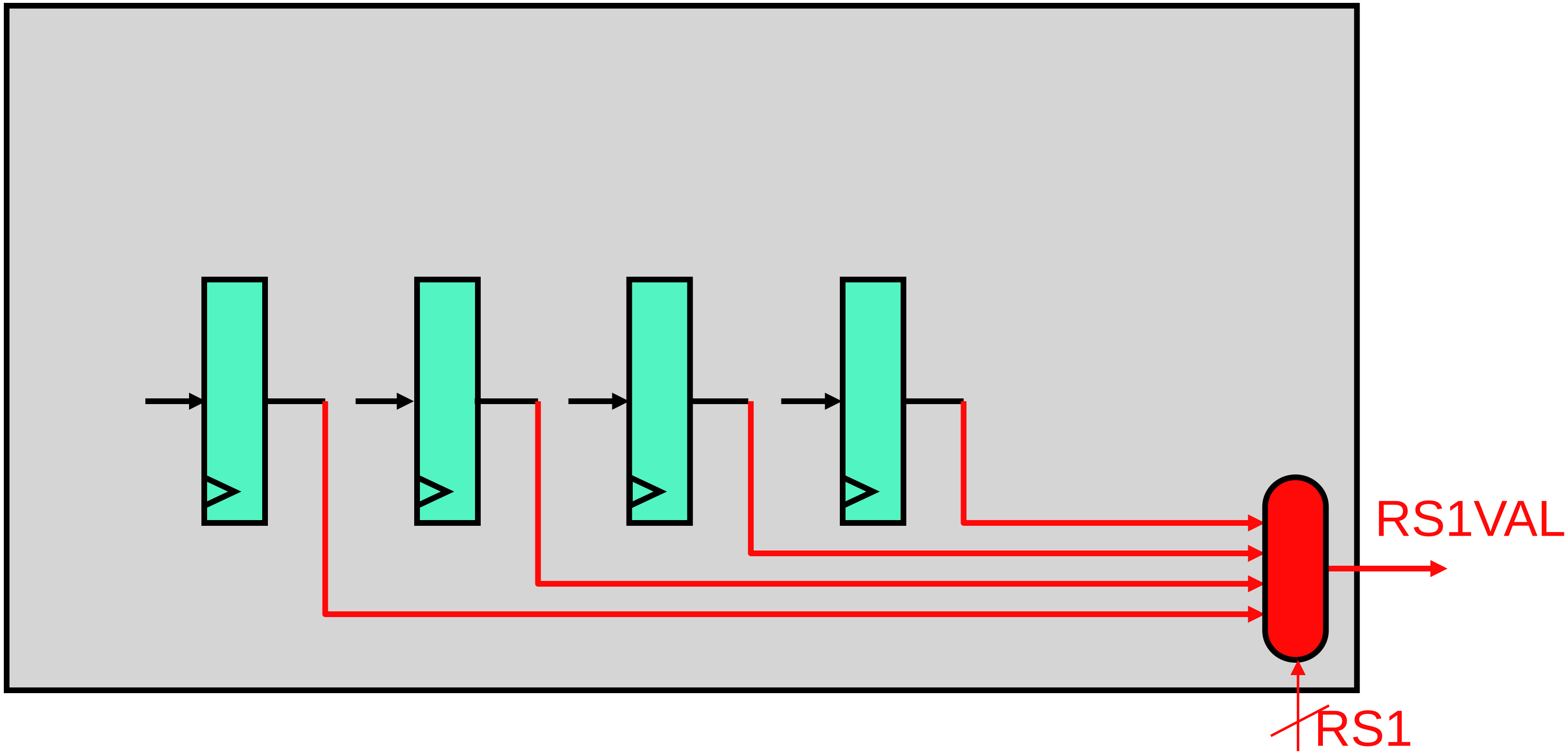
RS = source reg

- **Register file**: the ISA (“architectural”, ”visible”) registers
  - Two read “ports” + one write “port”
    - Maximum number of reads/writes in single instruction (R-type)
- **Port**: wires for accessing an array of data
  - Data bus: width of data element (MIPS: 32 bits)
  - Address bus: width of $\log_2$ number of elements (MIPS: 5 bits)
  - Write enable: if it’s a write port
  - M ports = M parallel and independent accesses

A Register File With Four Registers

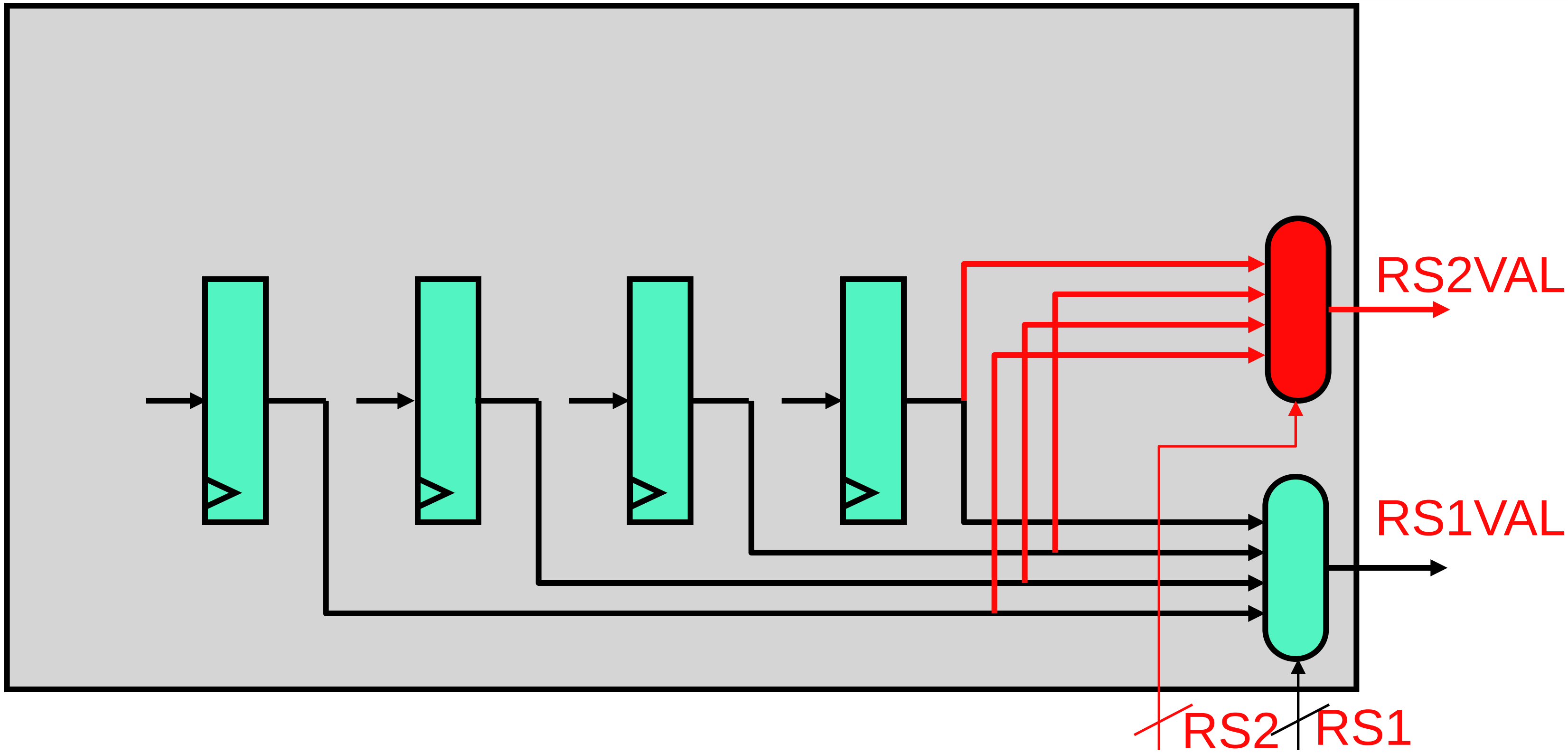


Add a Read Port for RS1



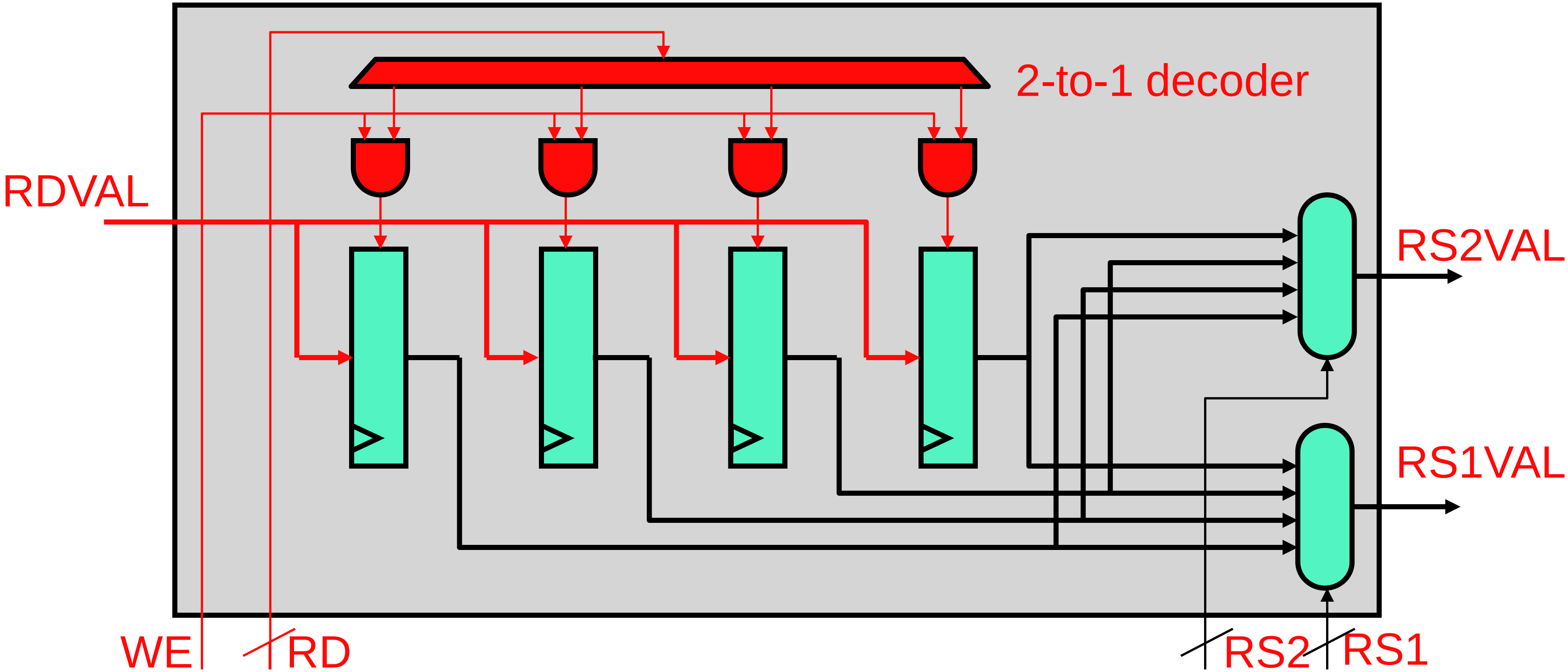
- Output of each register into 4to1 mux (RS1VAL)
  - RS1 is select input of RS1VAL mux

Add Another Read Port for RS2



- Output of each register into another 4to1 mux (RS2VAL)
    - RS2 is select input of RS2VAL mux

Add a Write Port for RD



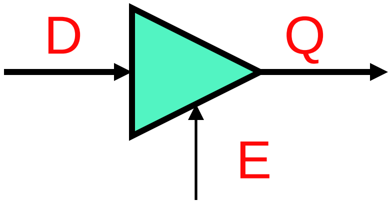
- Input RDVAL into each register
  - Enable only one register’s WE: (Decoded RD) & (WE)
- What if we needed two write ports?

Another Read Port Implementation

- A read port that uses muxes is fine for 4 registers
  - Not so good for 32 registers (32-to-1 mux is very slow)

- Alternative implementation uses **tri-state buffers**
  - Truth table (E = enable, D = input, Q = output)

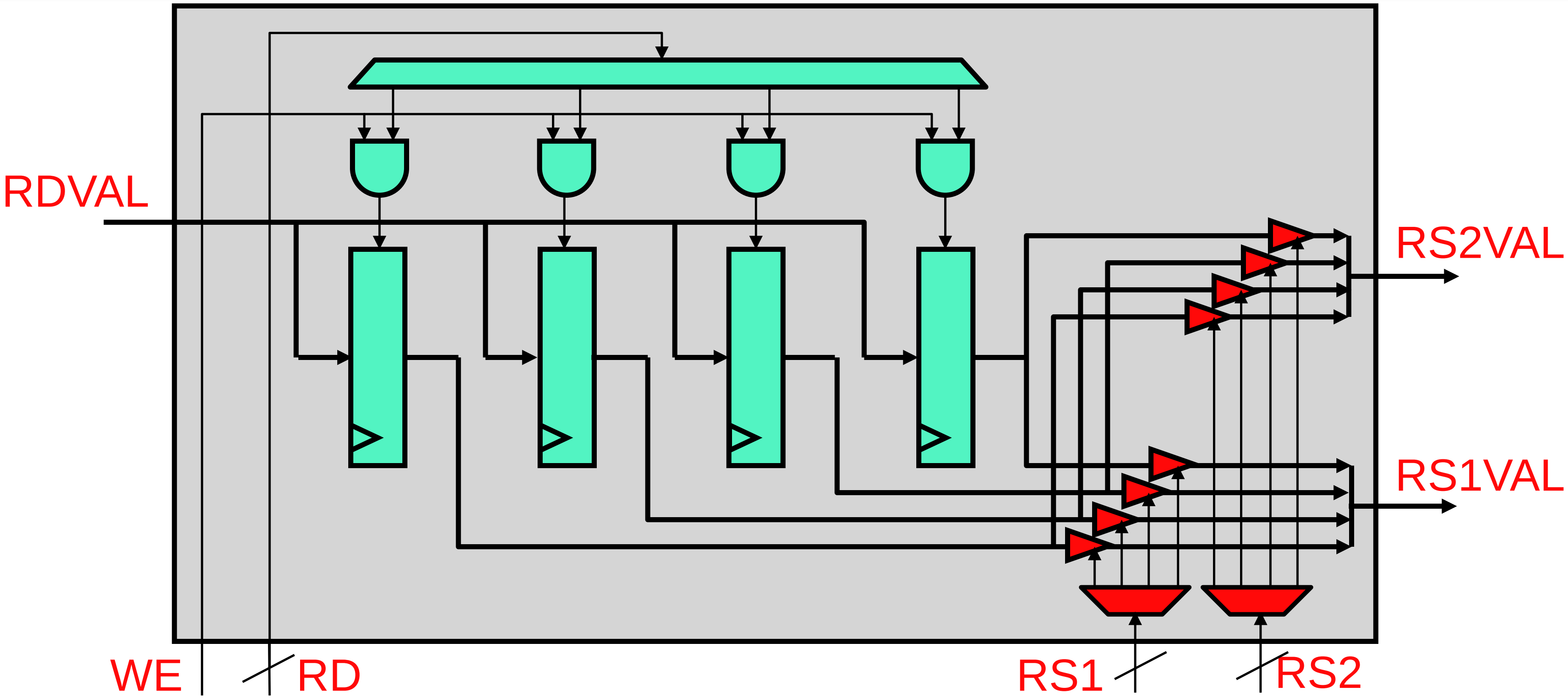
E	**D**	**→**	**Q**
1	D	→	D
0	D	→	**Z**



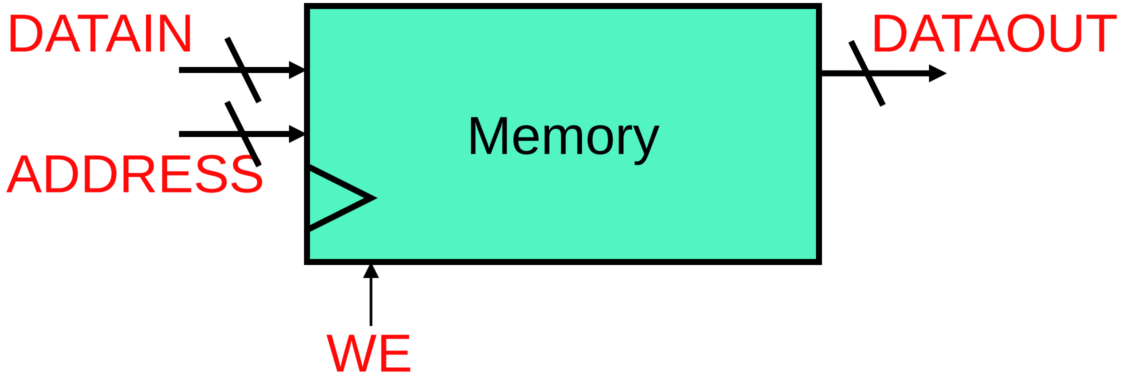
  - **Z**: "high impedance" state, no current flowing

  - Mux: connect multiple tri-stated buses to one output bus
  - Key: only one input "driving" at any time, all others must be in "Z"
    - Else, all hell breaks loose (electrically)

Register File With Tri-State Read Ports



Another Useful Component: Memory

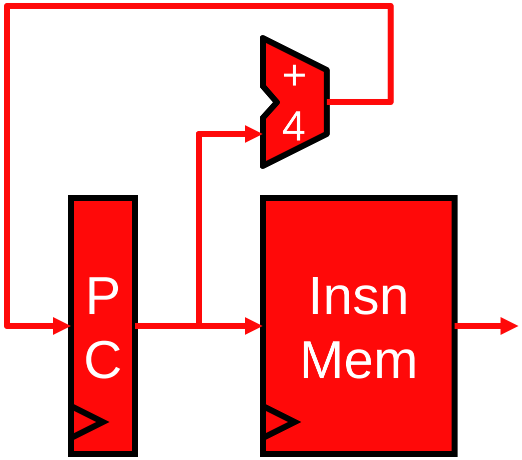


- **Memory**: where instructions and data reside
    - One read/write "port": one access per cycle, either read **or** write
        - One address bus
    - One input data bus for writes, one output data bus for reads

- Actually, a more traditional definition of memory is
    - One input/output data bus
    - No clock → asynchronous "strobe" instead

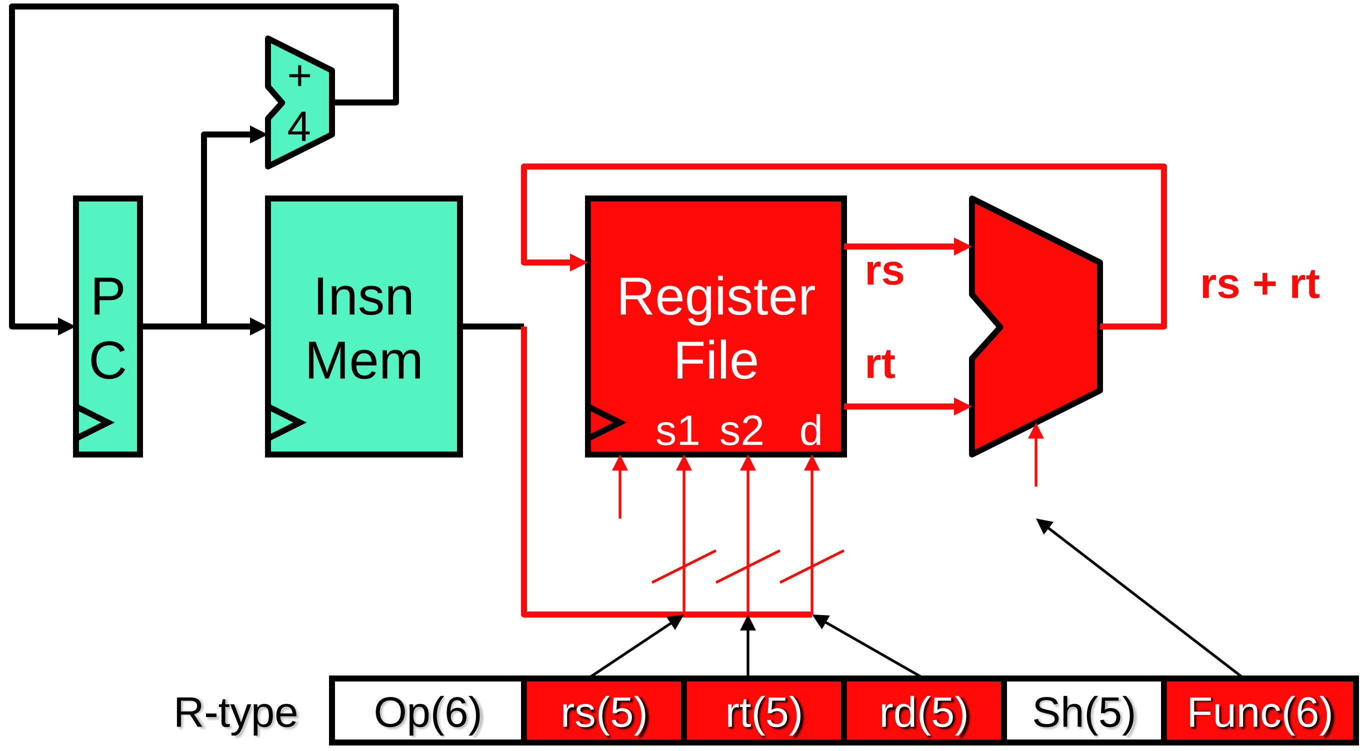
Let’s Build A MIPS-like Datapath

Start With Fetch



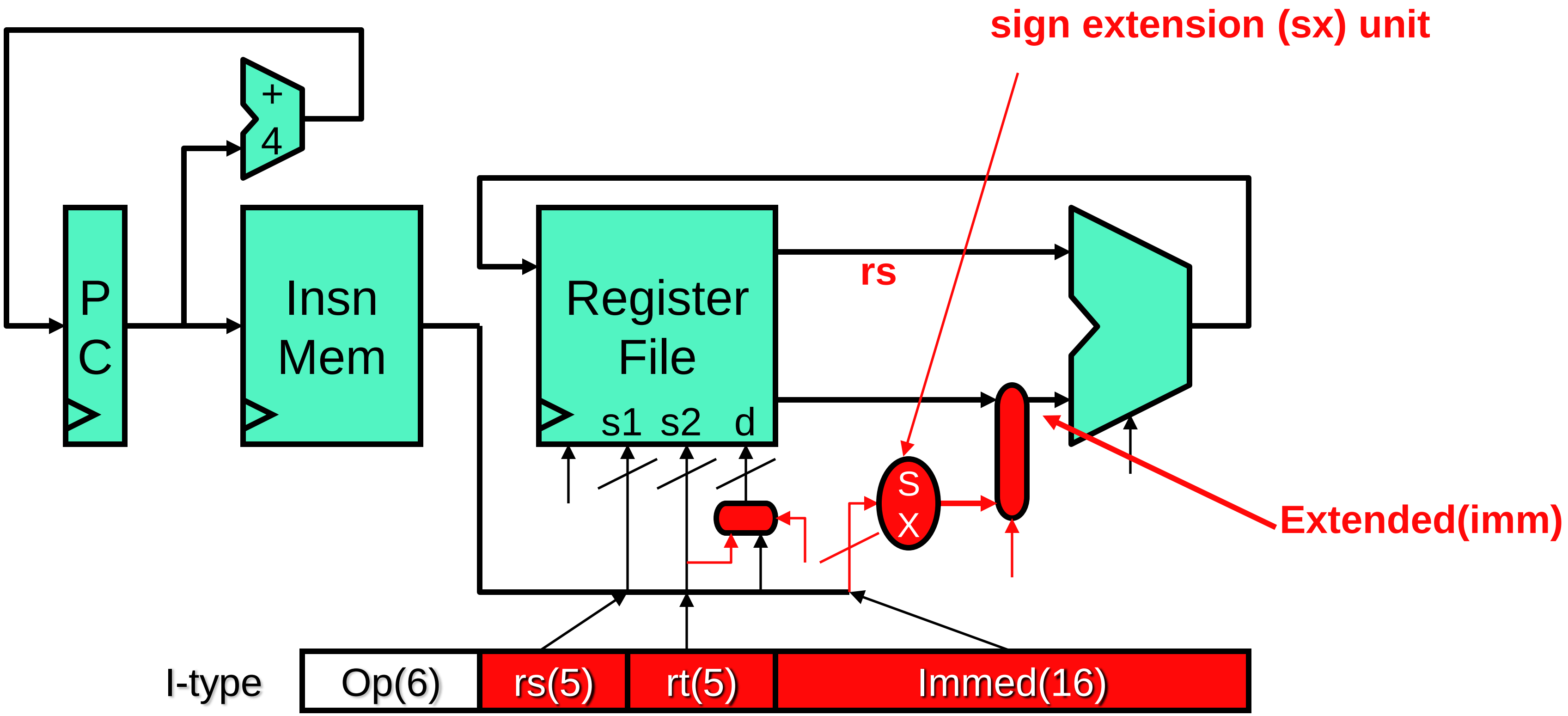
- PC and instruction memory
- A +4 incrementer computes default next instruction PC
    - Why +4 (and not +1)? What will it be for 16-bit Duke 250/16?

First Instruction: add $rd, $rs, $rt



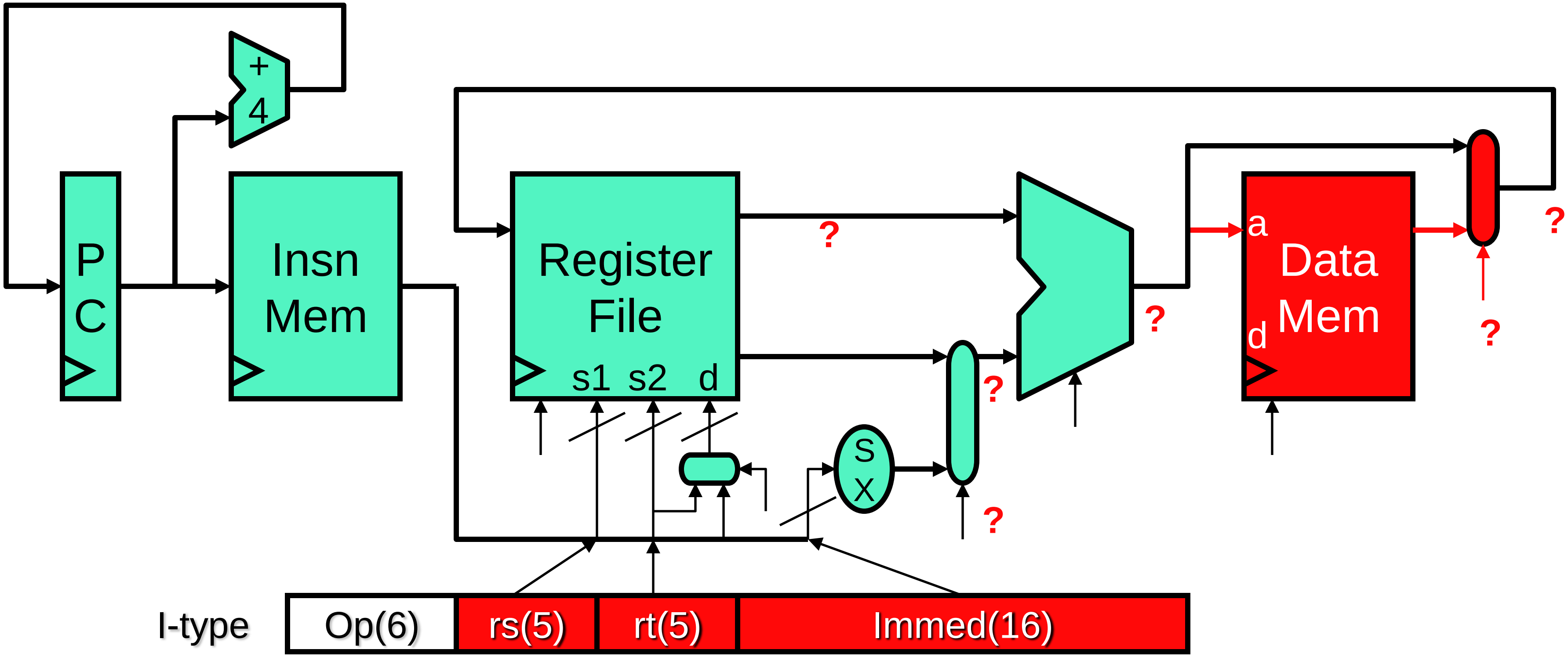
- Add register file and ALU

Second Instruction: addi $rt, $rs, imm



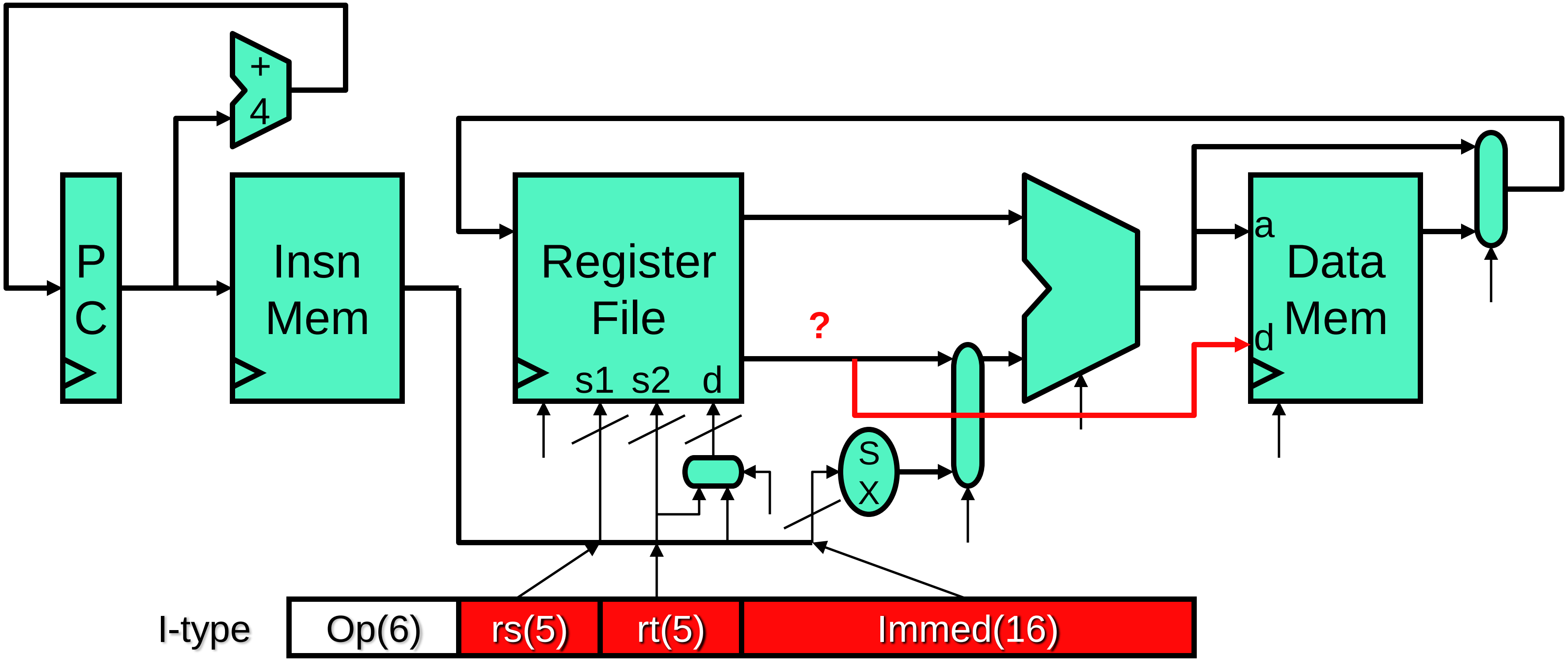
- Destination register can now be either rd or rt
- Add sign extension unit and mux into second ALU input

Third Instruction: lw $rt, imm($rs)



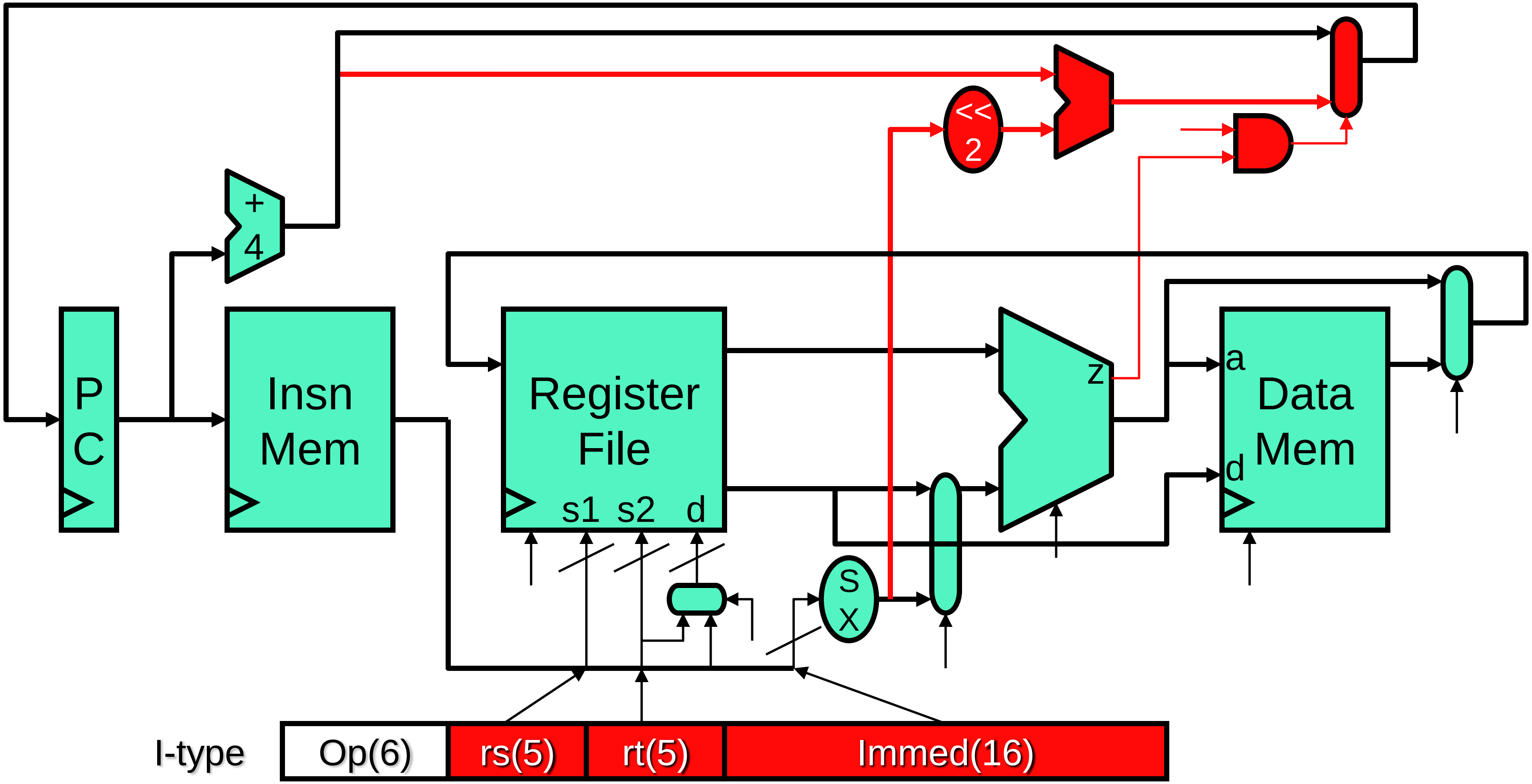
- Add data memory, address is ALU output (rs+imm)
- Add register write data mux to select memory output or ALU output

Fourth Instruction: sw $rt, imm($rs)



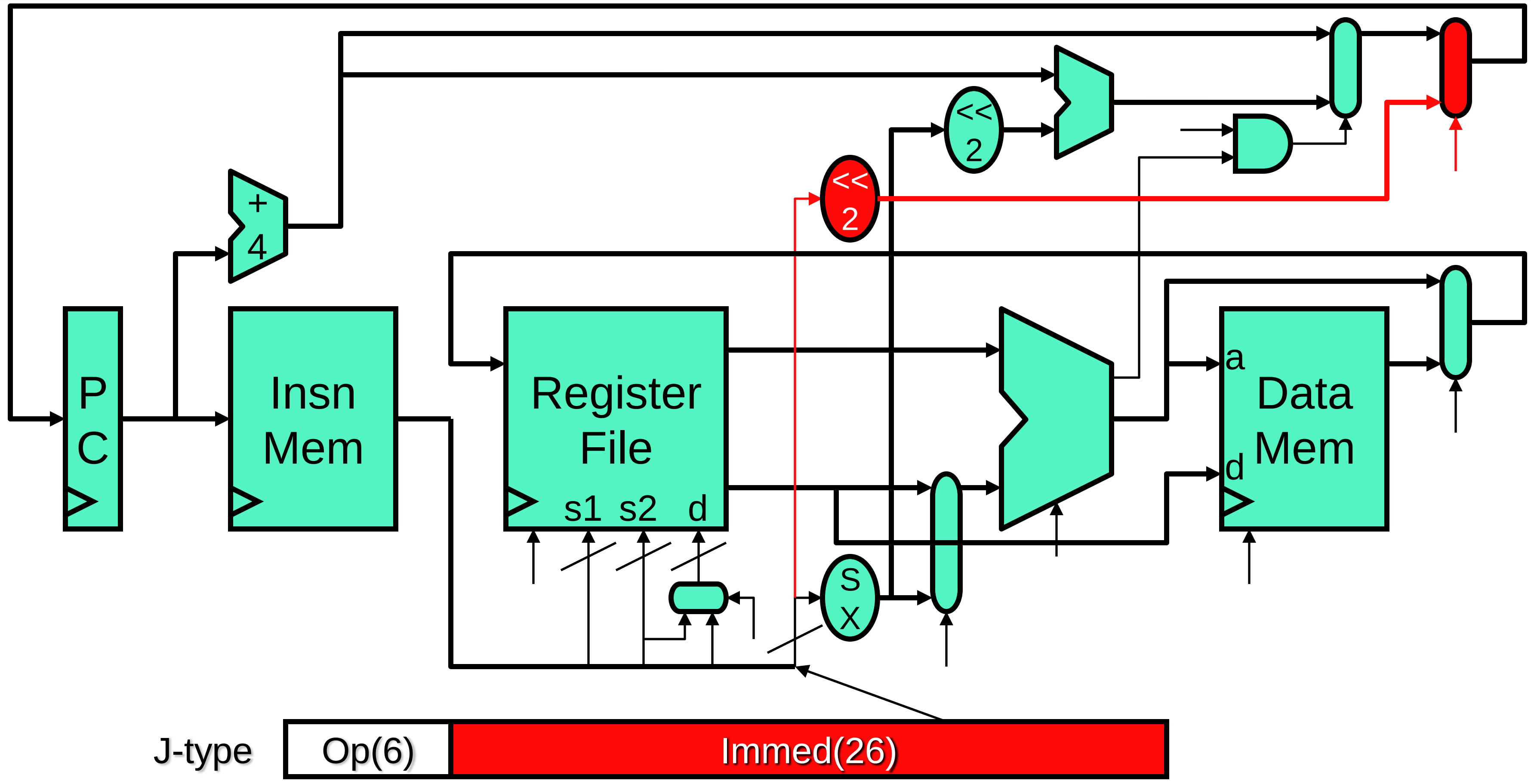
- Add path from second input register to data memory data input
- Disable RegFile’s WE signal

Fifth Instruction: beq `$1,$2,target`



- Add left shift unit (why?) and adder to compute PC-relative branch target
- Add mux to do what?

Sixth Instruction: j



- Add shifter to compute left shift of 26-bit immediate
- Add additional PC input mux for jump target

Seventh, Eight, Ninth Instructions

- Are these the paths we would need for all instructions?

  `sll $1,$2,4  // shift left logical`
  - Like an arithmetic operation, but need a shifter too

  `slt $1,$2,$3  // set less than (slt)`
  - Like subtract, but need to write the condition bits, not the result
    - Need zero extension unit for condition bits
    - Need additional input to register write data mux

  `jal absolute_target   // jump and link`
  - Like a jump, but also need to write PC+4 into $ra ($31)
    - Need path from PC+4 adder to register write data mux
    - Need to be able to specify $31 as an implicit destination

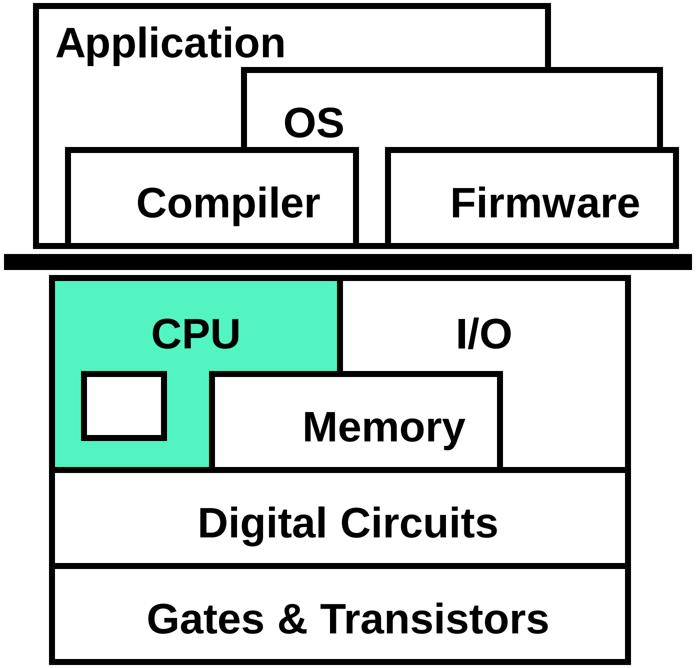
  `jr $31   // jump register`
  - Like a jump, but need path from register read to PC write mux

Clock Timing

- Must deliver clock(s) to avoid races
- Can’t write and read same value at same clock edge
  - Particularly a problem for RegFile and Memory
- May create multiple clock edges (from single input clock) by using buffers (to delay clock) and inverters

- For Homework 4 (the Duke 250/16 CPU):
  - Keep the clock SIMPLE and GLOBAL
  - You may need to do the PC on *rising* edge and everything else on *falling* edge
    - If the PC changes *while* the operation is occuring, the instruction bits will change before the answer is computed -> non-deterministic behavior*
    - Changing clock edges in this way will separate PC++ from logic
    - A cheap way to make something trigger on the other clock edge is to NOT the clock on the way in to that component

This Unit: Processor Design



- Datapath components and timing
  - Registers and register files
  - Memories (RAMs)
  - Clocking strategies
- Mapping an ISA to a datapath
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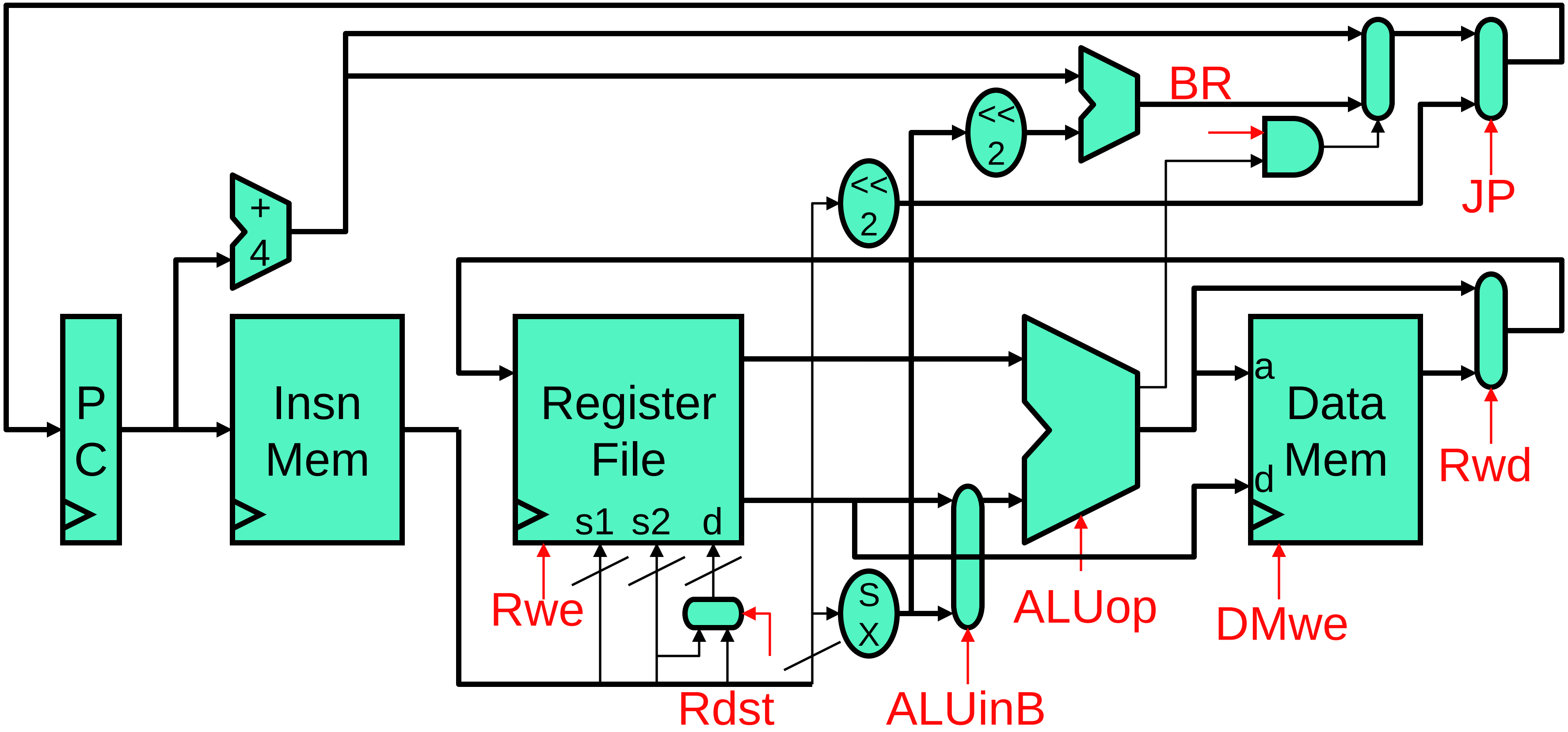
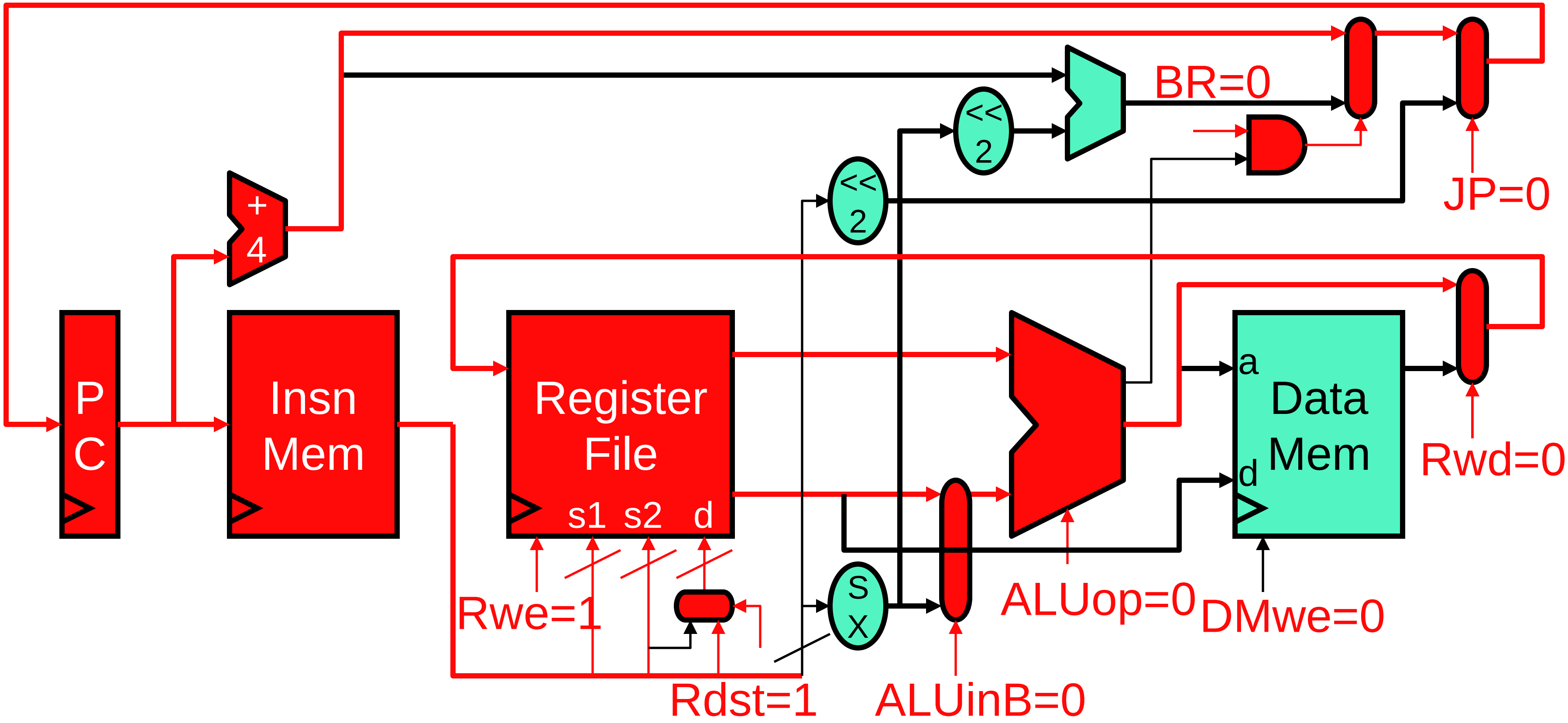
What Is Control?

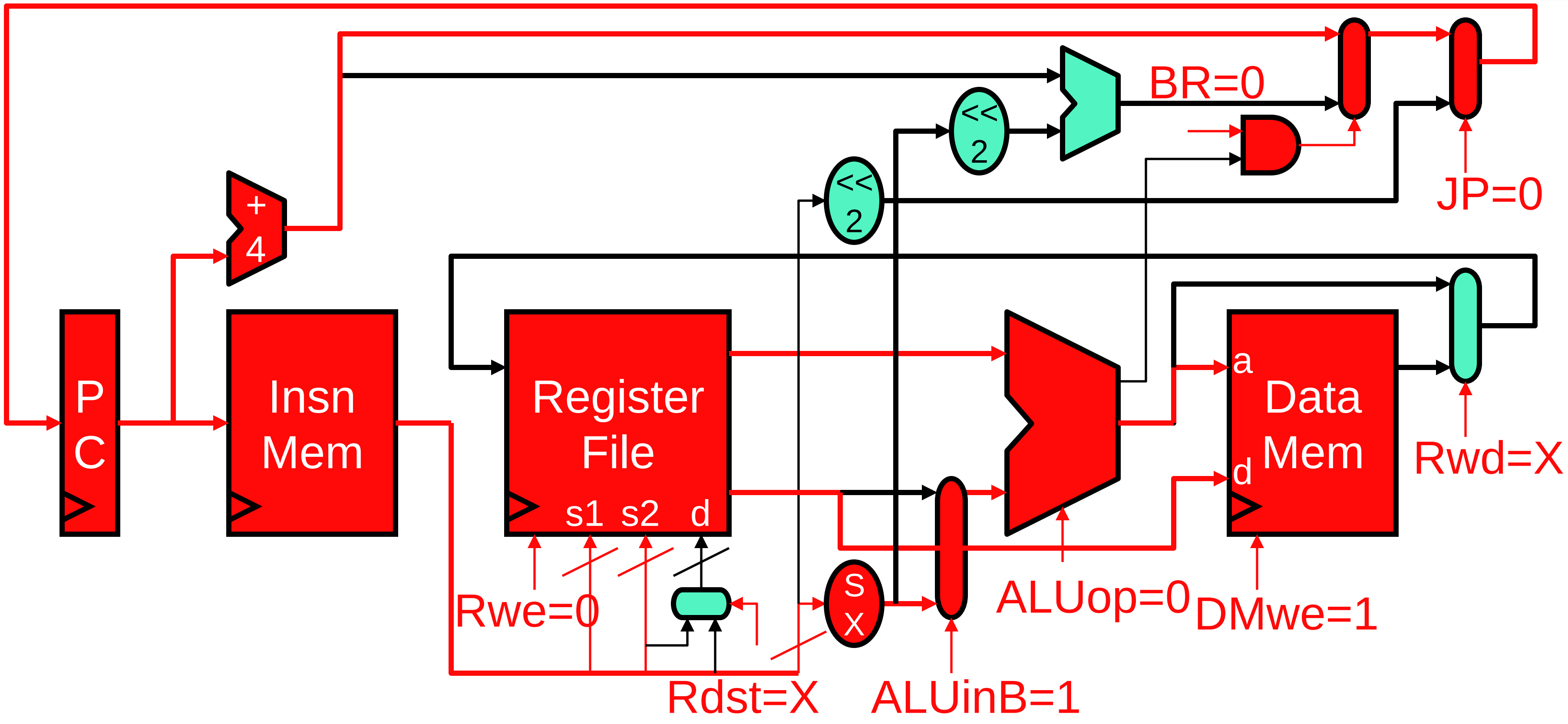


- 9 signals control flow of data through this datapath
  - MUX selectors, or register/memory write enable signals
  - Datapath of current microprocessor has 100s of control signals

Example: Control for add

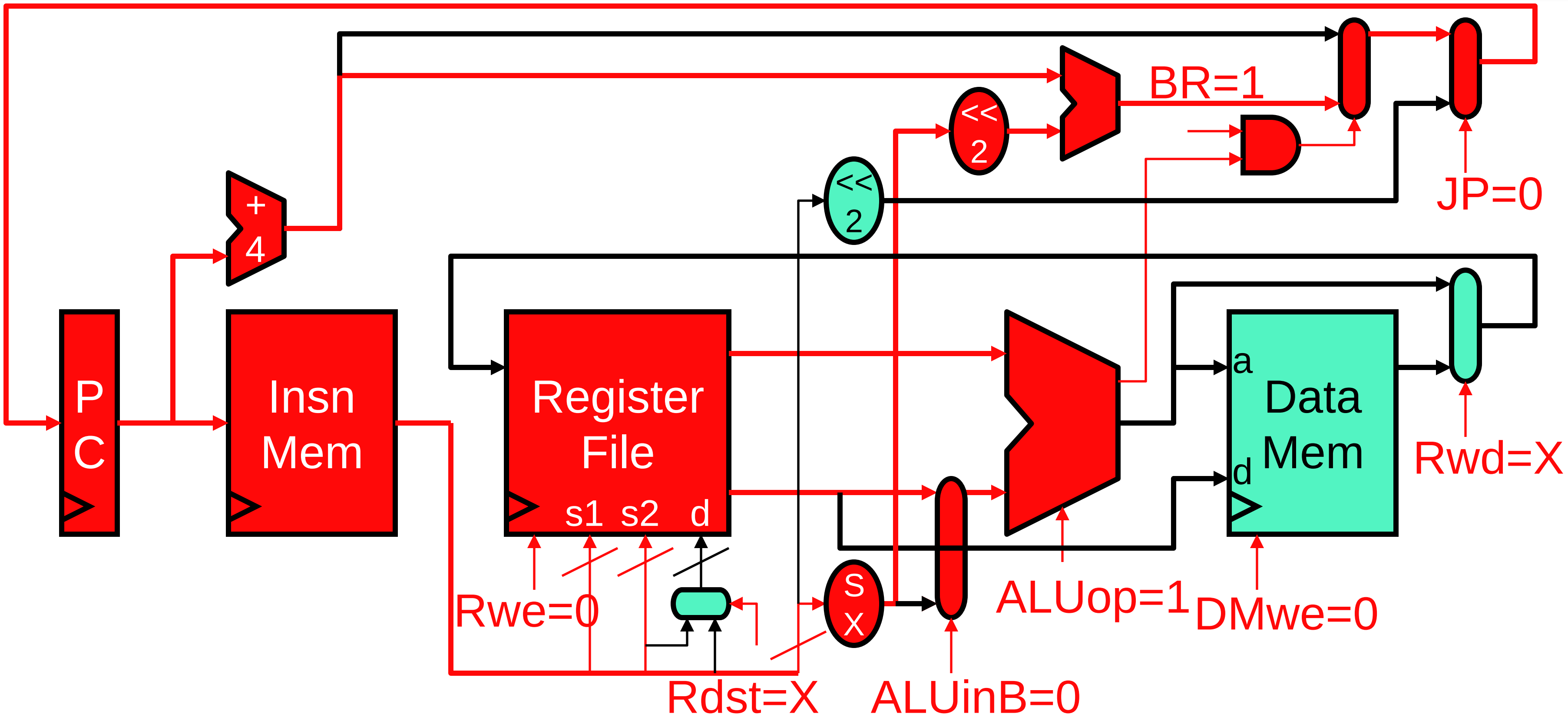


Example: Control for sw



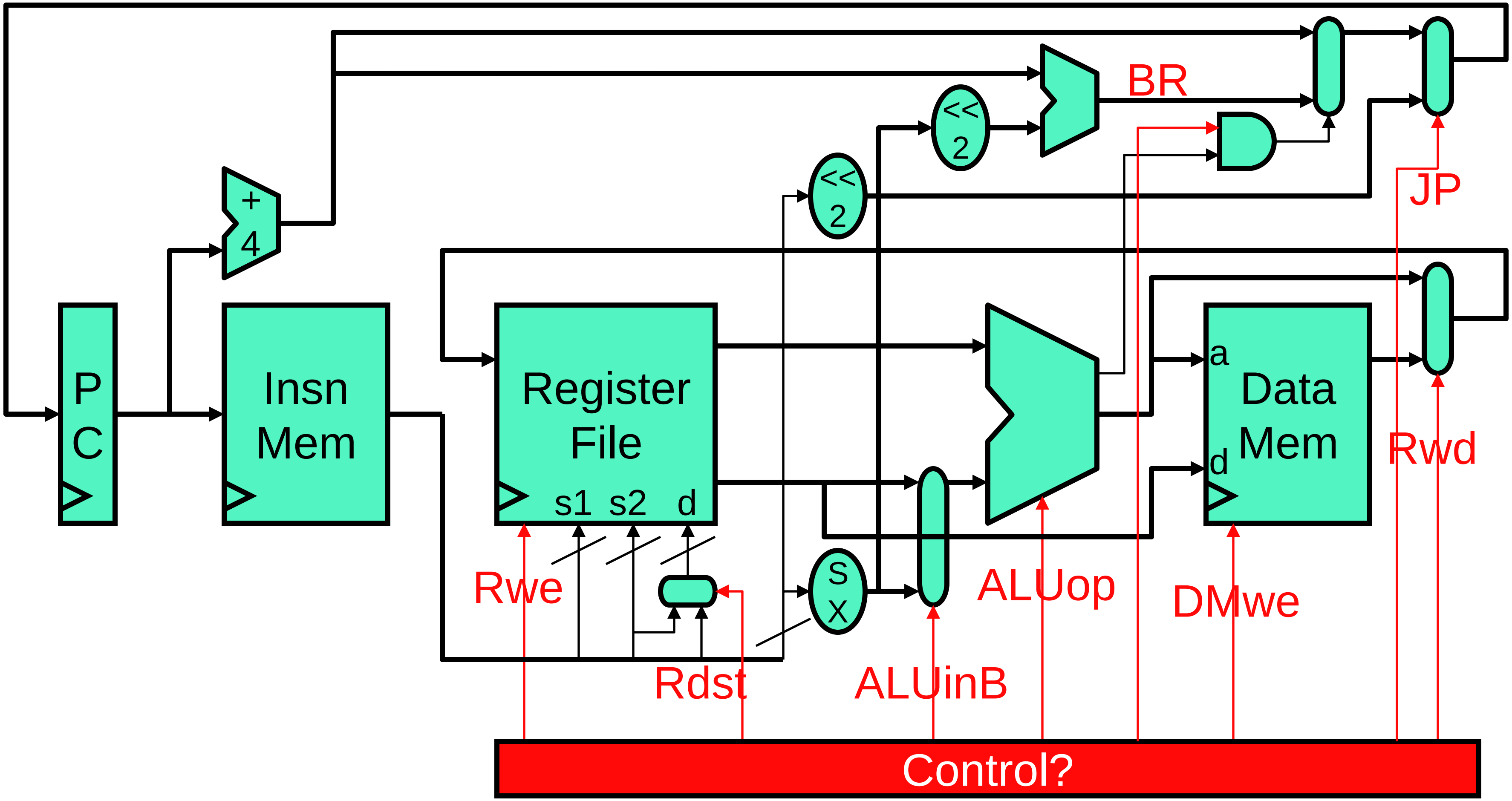
- Difference between a sw and an add is 5 signals
  - 3 if you don’t count the X (“don’t care”) signals

Example: Control for beq `$1,$2,target`



- Difference between a store and a branch is only 4 signals

How Is Control Implemented?



Implementing Control

- Each instruction has a unique set of control signals
  - Most signals are function of opcode
  - Some may be encoded in the instruction itself
    - E.g., the ALUop signal is some portion of the MIPS Func field
    - \+ Simplifies controller implementation
    - – Requires careful ISA design

- Options for implementing control
  1. Use instruction type to look up control signals in a table
  2. Design FSM whose outputs are control signals
  - Either way, goal is same: turn instruction into control signals

Control Implementation: ROM

- **ROM (read only memory)**: like a RAM but unwritable
  - Bits in data words are control signals
  - Lines indexed by opcode

- Example: ROM control for our simple datapath

opcode →

	BR	JP	ALUinB	ALUop	DMwe	Rwe	Rdst	Rwd
→ add	0	0	0	0	0	1	1	0
→ addi	0	0	1	0	0	1	1	0
→ lw	0	0	1	0	0	1	0	1
→ sw	0	0	1	0	1	0	0	0
→ beq	1	0	0	1	0	0	0	0
→ j	0	1	0	0	0	0	0	0

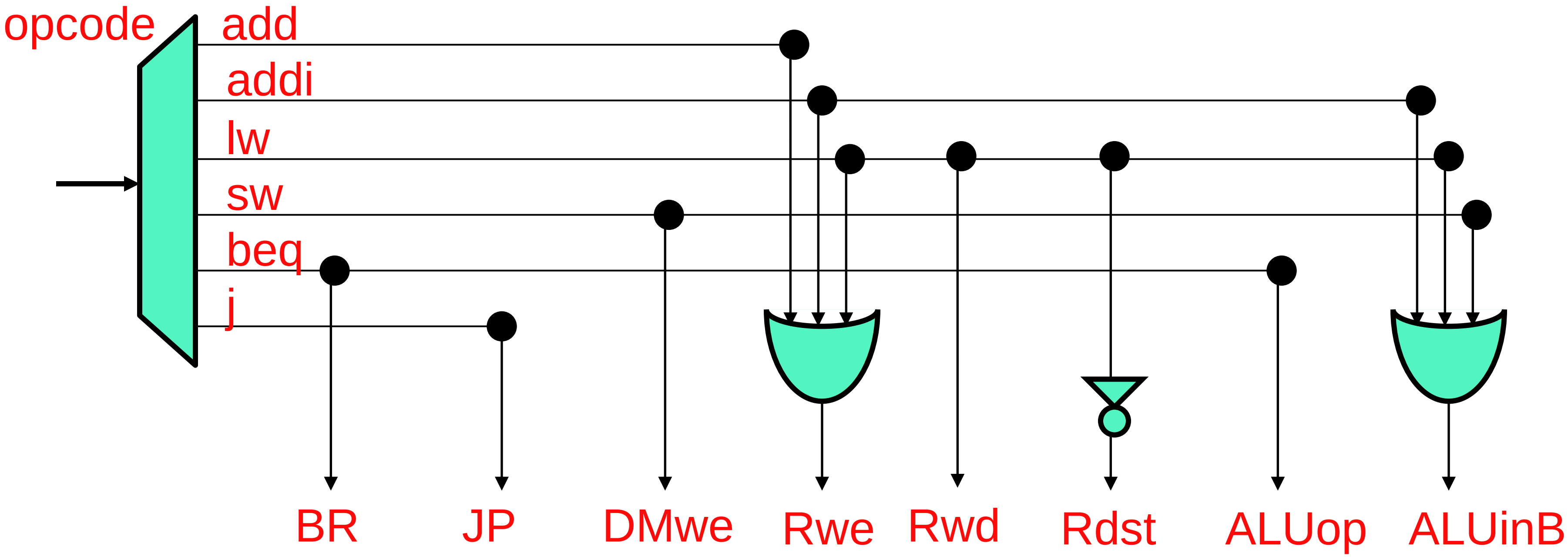
ROM vs. Combinational Logic

- A control ROM is fine for 6 insns and 9 control signals
- A real machine has 100+ insns and 300+ control signals
  - Even “RISC”s have lots of instructions
  - 30,000+ control bits (~4KB)
  - – Not huge, but hard to make fast
    - Control must be faster than datapath

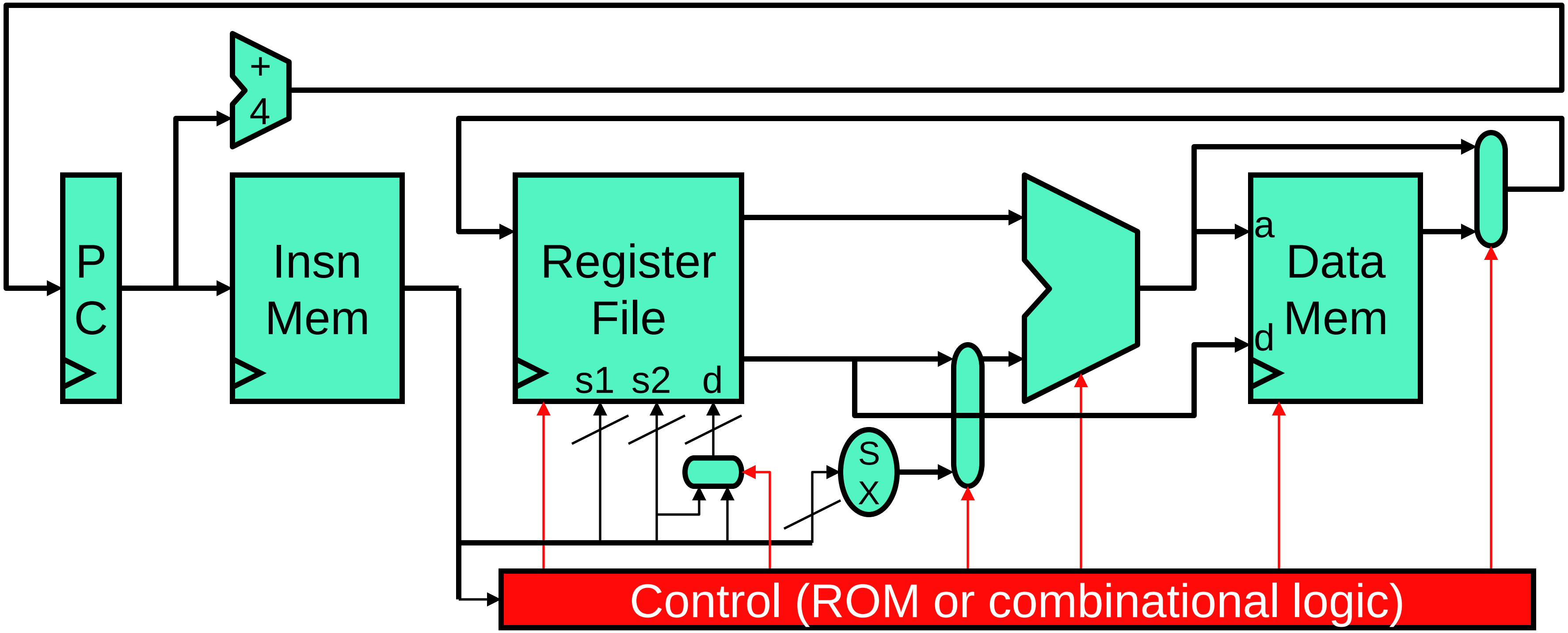
- Alternative: **combinational logic**
  - It’s that thing we know how to do! *Nice!*
  - Exploits observation: many signals have few 1s or few 0s

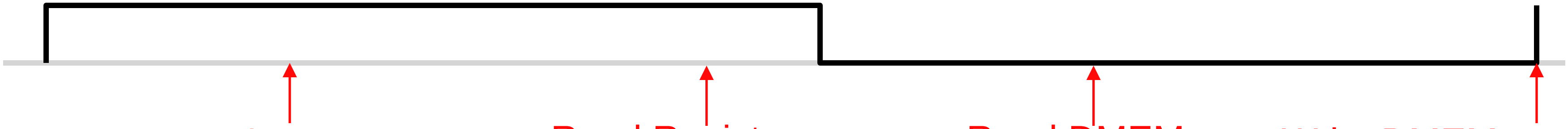
Control Implementation: Combinational Logic

- Example: combinational logic control for our simple datapath



Datapath and Control Timing





Read IMem

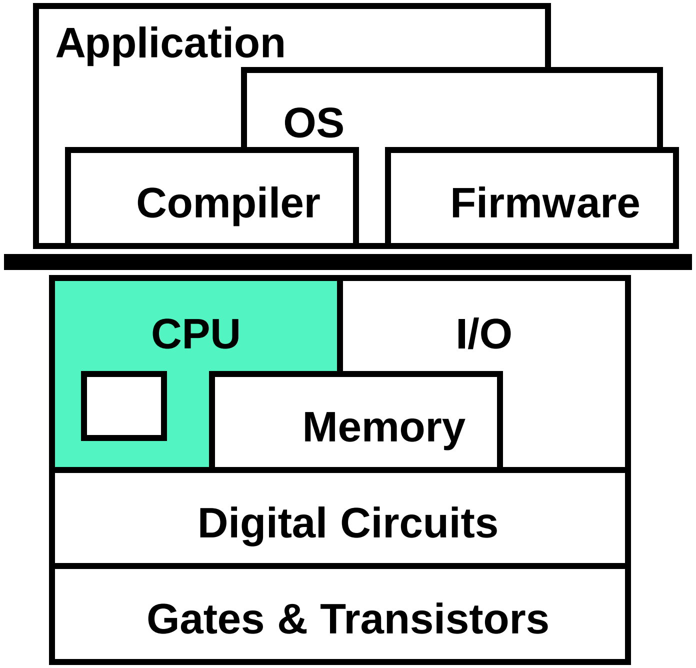
Read Registers
(Read Control ROM)

Read DMEM

Write DMEM
Write Registers
Write PC

How do we sub-divide timing like this? ***Pipelining!*** (Covered later)

This Unit: Processor Design



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Exceptions

- **Exceptions and interrupts**
  - Infrequent (exceptional!) events
    - I/O, divide-by-0, illegal instruction, page fault, protection fault, ctrl-C, ctrl-Z, timer
  - Handling requires intervention from operating system
    - End program: divide-by-0, protection fault, illegal insn, ^C
    - Fix and restart program: I/O, page fault, ^Z, timer
  - Handling should be transparent to application code
    - Don’t want to (can’t) constantly check for these using insns
    - Want “Fix and restart” equivalent to “never happened”

Exception Handling

- What does exception handling look like to software?
  - When exception happens…

  - Control transfers to OS at pre-specified exception handler address
  - OS has privileged access to registers user processes do not see
    - These registers hold information about exception
    - Cause of exception (e.g., page fault, arithmetic overflow)
    - Other exception info (e.g., address that caused page fault)
    - PC of application insn to return to after exception is fixed
  - OS uses privileged (and non-privileged) registers to do its "thing"
  - OS returns control to user application

- Same mechanism available programmatically via SYSCALL

MIPS Exception Handling

- MIPS uses registers to hold state during exception handling
  - These registers live on “coprocessor 0”
  - **`$14`**: EPC (holds PC of user program during exception handling)
  - **`$13`**: exception type (SYSCALL, overflow, etc.)
  - **`$8`**: virtual address (that produced page/protection fault)
  - **`$12`**: exception mask (which exceptions trigger OS)
- Exception registers accessed using two **privileged** instructions **`mfc0`**, **`mtc0`**
  - Privileged = user process can’t execute them
  - mfc0: move (register) from coprocessor 0 (to user reg)
  - mtc0: move (register) to coprocessor 0 (from user reg)
- Privileged instruction **`rfe`** restores user mode
  - Kernel executes this instruction to restore user program

MIPS Exception Handling

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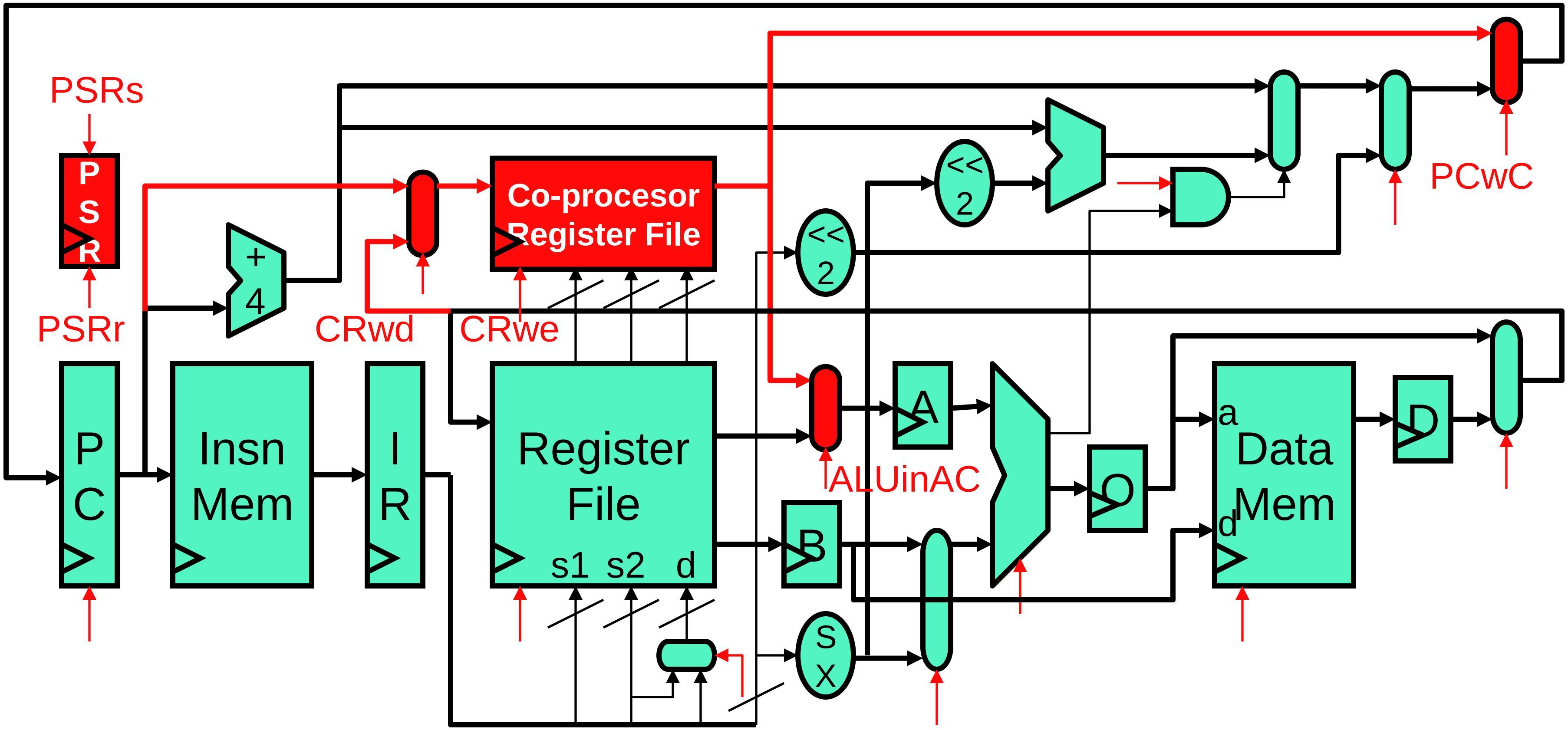
DON'T GET TOO OBSESSED ABOUT HOW EXACTLY MIPS DOES THIS – FOCUS ON THE BIG PICTURE AND WHAT MUST HAPPEN IN GENERAL

- Privileged instruction **`rfe`** restores user mode
  - Kernel executes this instruction to restore user program

Implementing Exceptions

- Why do architects care about exceptions?
  - Because we use datapath and control to implement them
  - More precisely… to implement aspects of exception handling
    - Recognition of exceptions
    - Transfer of control to OS
    - Privileged OS mode
- Later in semester, we’ll talk more about exceptions (b/c we need them for I/O)

Datapath with Support for Exceptions



- Co-processor register (CR) file needn't be implemented as RF
    - Independent registers connected directly to pertinent muxes
- PSR (processor status register): in privileged mode?

Summary

- We now know how to build a fully functional processor
- But …
  - We’re still treating memory as a black box (actually two green boxes, to be precise)
  - Our fully functional processor is slow. Really, really slow.

“Single-Cycle” Performance

- Useful metric: cycles per instruction (CPI)

\+ Easy to calculate for single-cycle processor: CPI = 1

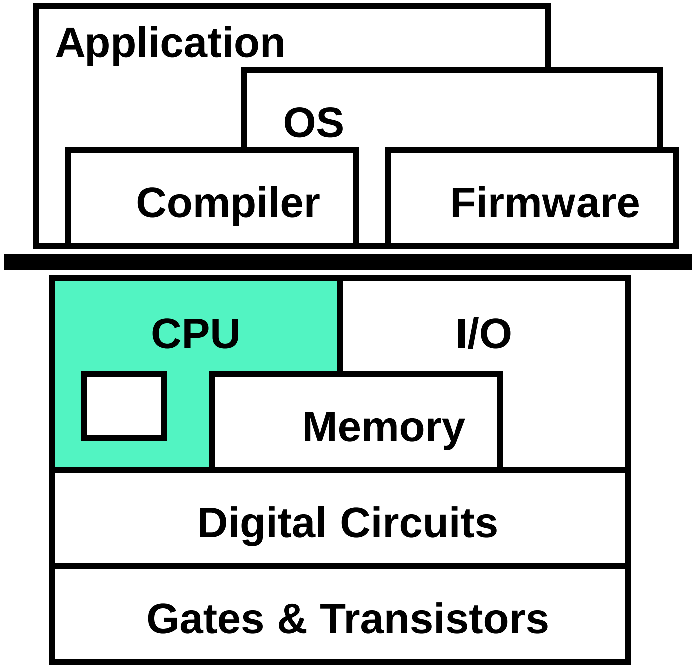
  - Seconds/program = (insns/program) * 1 CPI * (N seconds/cycle)
  - ICQ: How many cycles/second in 3.8 GHz processor?

– Slow!

  - Clock period must be elongated to accommodate longest operation
    - In our datapath: lw
    - Goes through five structures in series: insn mem, register file (read), ALU, data mem, register file again (write)
  - No one will buy a machine with a slow clock
    - Not even your grandparents!

- Later in semester: faster processor cores

This Unit: Processor Design



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Next up: Memory Systems