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UC Berkeley CS61C : Machine Structures

Lecture 25
CPU Design: Designing a Single-cycle CPU

2007-03-16

UC Regents approve 7% student fee increase!

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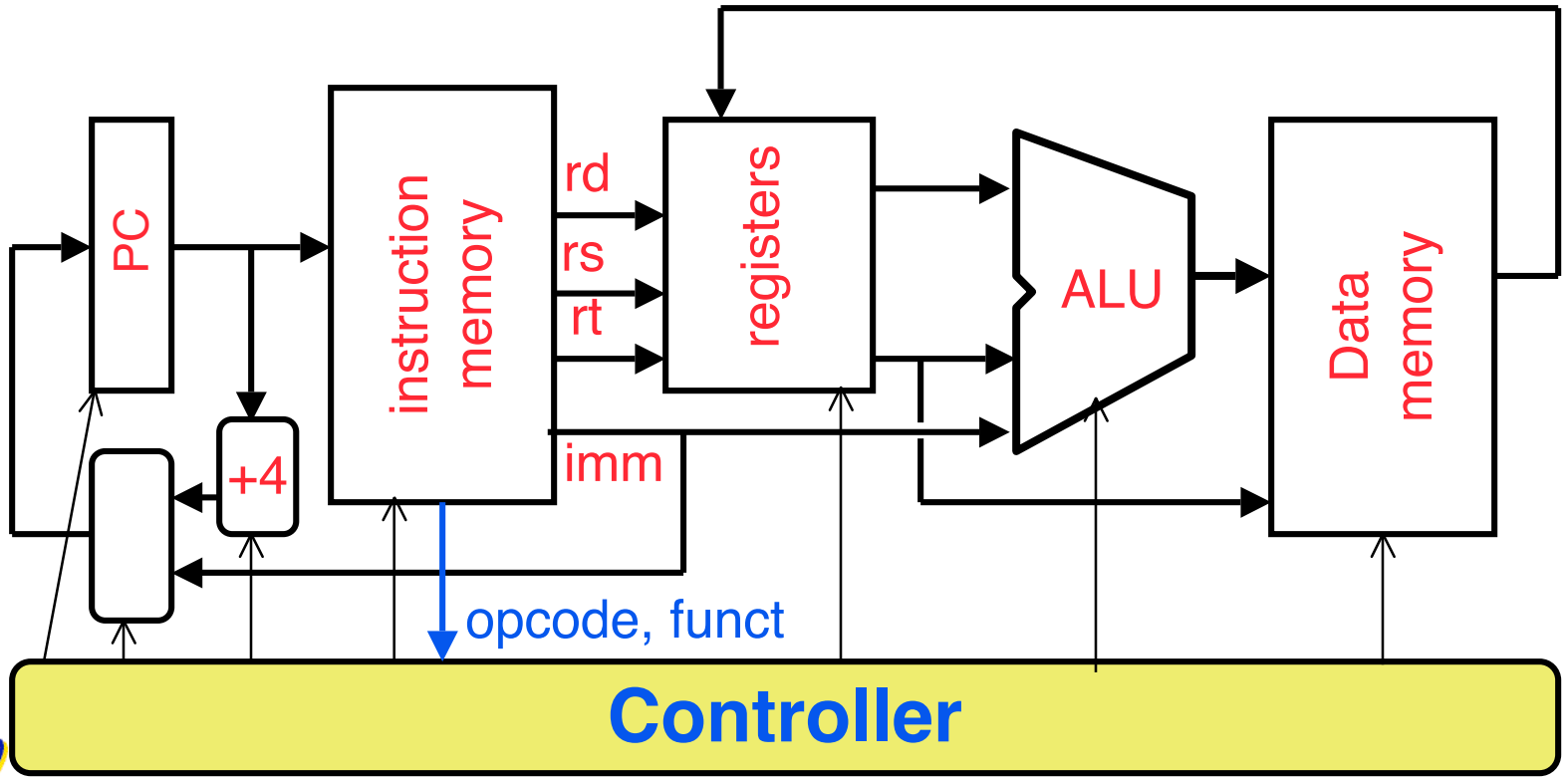
Review

- N-bit adder-subtractor done using N 1-bit adders with XOR gates on input
  - XOR serves as conditional inverter
- CPU design involves Datapath,Control
  - Datapath in MIPS involves 5 CPU stages

1) Instruction Fetch
2) Instruction Decode & Register Read
3) ALU (Execute)
4) Memory
5) Register Write

Datapath Summary

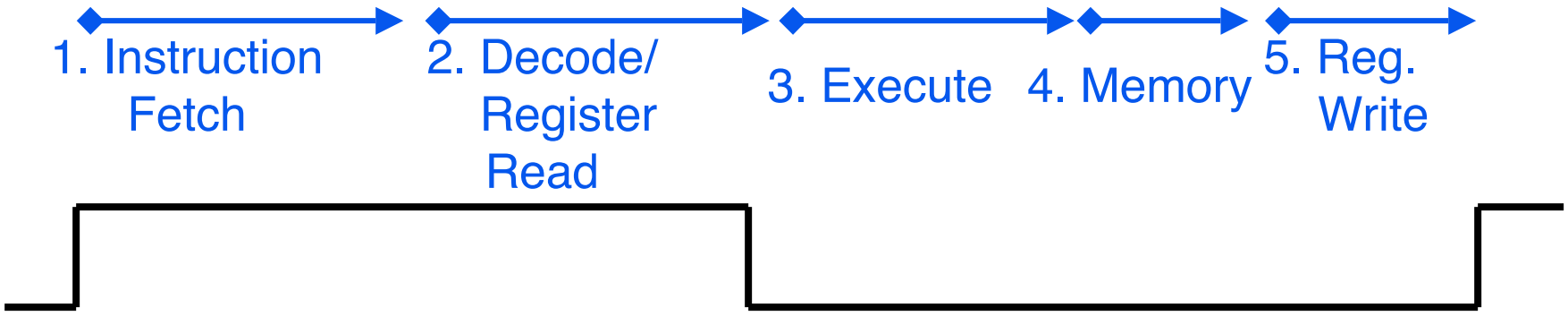
- The datapath based on data transfers required to perform instructions
- A *controller* causes the right transfers to happen



CPU clocking (1/2)

For each instruction, how do we control the flow of information though the datapath?

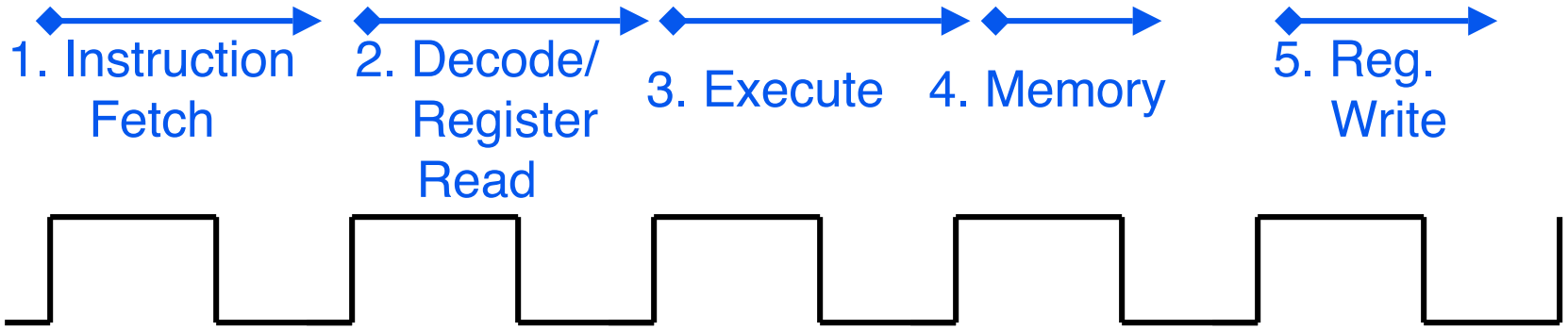
- **Single Cycle CPU: All stages of an instruction are completed within one *long* clock cycle.**
  - **The clock cycle is made sufficient long to allow each instruction to complete all stages without interruption and within one cycle.**



CPU clocking (2/2)

For each instruction, how do we control the flow of information though the datapath?

- **Multiple-cycle CPU: Only one stage of instruction per clock cycle.**
  - **The clock is made as long as the slowest stage.**



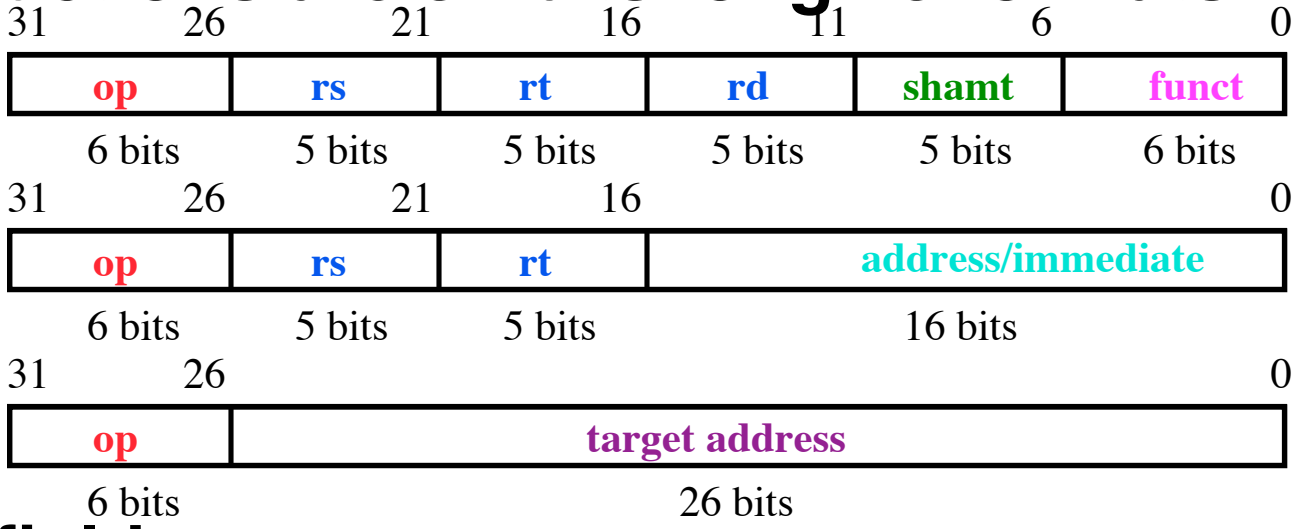
Several significant advantages over single cycle execution: Unused stages in a particular instruction can be skipped OR instructions can be pipelined (overlapped).

How to Design a Processor: step-by-step

1. Analyze instruction set architecture (ISA) ⇒ datapath requirements
   - meaning of each instruction is given by the *register transfers*
   - datapath must include storage element for ISA registers
   - datapath must support each register transfer
2. Select set of datapath components and establish clocking methodology
3. Assemble datapath meeting requirements
4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.
5. Assemble the control logic

Review: The MIPS Instruction Formats

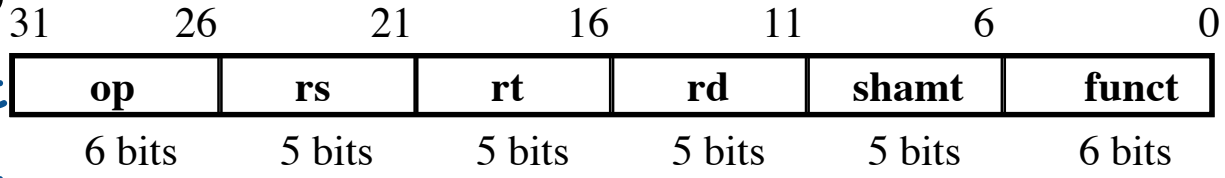
- All MIPS instructions are 32 bits long. 3 formats:
  - R-type
  - I-type
  - J-type



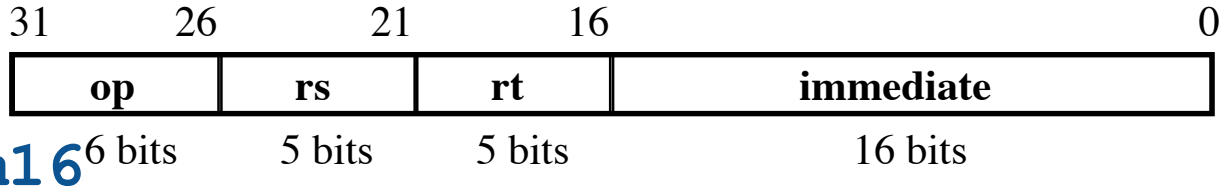
- The different fields are:
  - op: operation ("opcode") of the instruction
  - rs, rt, rd: the source and destination register specifiers
  - shamt: shift amount
  - funct: selects the variant of the operation in the "op" field
  - address / immediate: address offset or immediate value
  - target address: target address of jump instruction

Step 1a: The MIPS-lite Subset for today

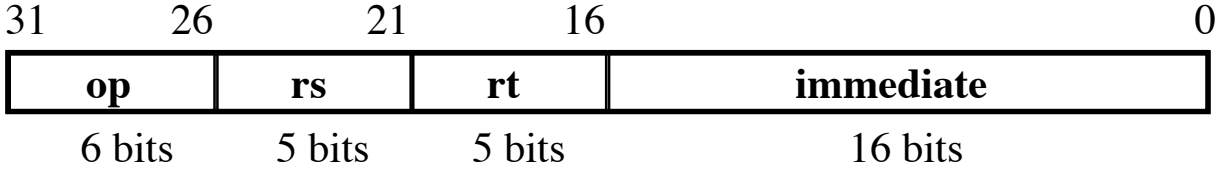
- **ADDU and SUBU**
  - `addu rd,rs,rt`
  - `subu rd,rs,rt`



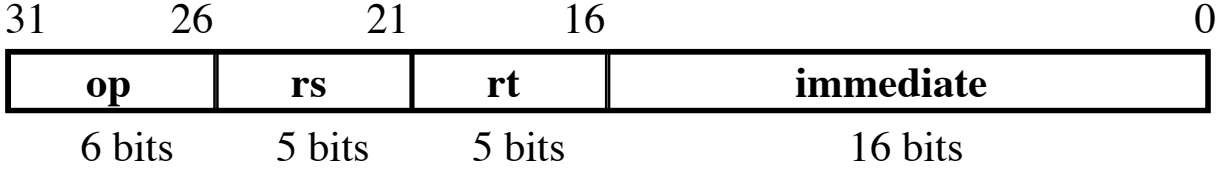
- **OR Immediate:**
  - `ori rt,rs,imm16`



- **LOAD and STORE Word**
  - `lw rt,rs,imm16`
  - `sw rt,rs,imm16`



- **BRANCH:**
  - `beq rs,rt,imm16`



Register Transfer Language

- RTL gives the meaning of the instructions

{op , rs , rt , rd , shamt , funct} ← MEM[PC]

{op , rs , rt , Imm16} ← MEM[PC]

- All start by fetching the instruction

inst	Register Transfers	
ADDU	R[rd] ← R[rs] + R[rt];	PC ← PC + 4
SUBU	R[rd] ← R[rs] – R[rt];	PC ← PC + 4
ORI	R[rt] ← R[rs] | zero_ext(Imm16);	PC ← PC + 4
LOAD	R[rt] ← MEM[R[rs] + sign_ext(Imm16)];	PC ← PC + 4
STORE	MEM[R[rs] + sign_ext(Imm16)] ← R[rt];	PC ← PC + 4
BEQ	if (R[rs] == R[rt]) then PC ← PC + 4 + (sign_ext(Imm16) || 00) else PC ← PC + 4	

Step 1: Requirements of the Instruction Set

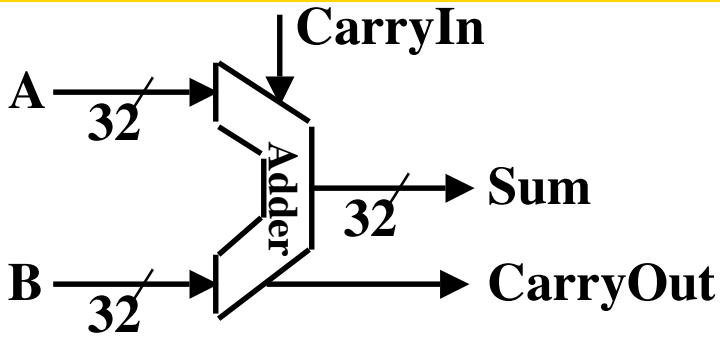
- Memory (MEM)
  - instructions & data (will use one for each)
- Registers (R: 32 x 32)
  - read RS
  - read RT
  - Write RT or RD
- PC
- Extender (sign/zero extend)
- Add/Sub/OR unit for operation on register(s) or extended immediate
- Add 4 or extended immediate to PC
- Compare registers?

Step 2: Components of the Datapath

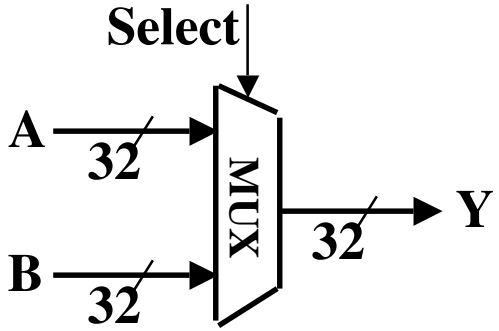
- Combinational Elements
- Storage Elements
  - Clocking methodology

Combinational Logic Elements (Building Blocks)

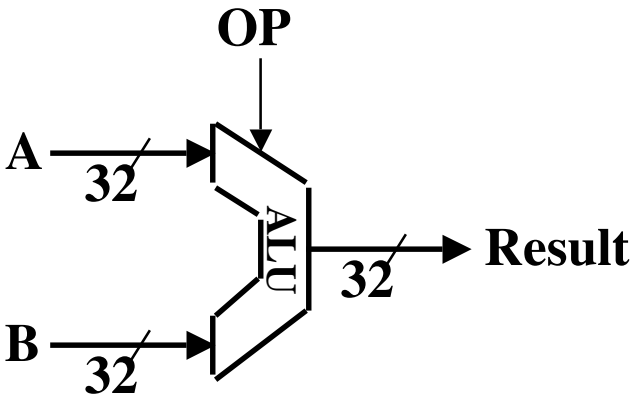
- **Adder**



- **MUX**



- **ALU**



ALU Needs for MIPS-lite + Rest of MIPS

- **Addition, subtraction, logical OR, ==:**

```
ADDU  R[rd] = R[rs] + R[rt]; ...

SUBU  R[rd] = R[rs] - R[rt]; ...

ORI  R[rt] = R[rs] | zero_ext(Imm16)...

BEQ   if ( R[rs] == R[rt] )...
```

- **Test to see if output == 0 for any ALU operation gives == test. How?**
- **P&H also adds AND, Set Less Than (1 if A < B, 0 otherwise)**
- **ALU follows chap 5**

Administrivia

- **Read the book! Important to understand lecture and for project.**
  - **P&H 5.1-5.4**

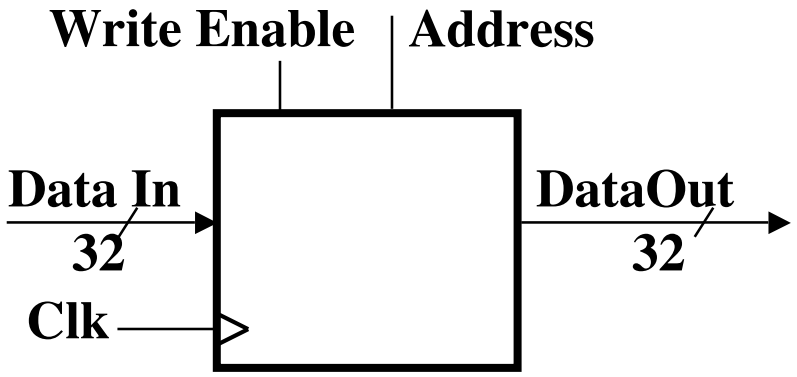
What Hardware Is Needed? (1/2)

- PC: a register which keeps track of memory addr of the next instruction
- General Purpose Registers
  - used in Stages 2 (Read) and 5 (Write)
  - MIPS has 32 of these
- Memory
  - used in Stages 1 (Fetch) and 4 (R/W)
  - cache system makes these two stages as fast as the others, on average

What Hardware Is Needed? (2/2)

- **ALU**
  - used in Stage 3
  - something that performs all necessary functions: arithmetic, logicals, etc.
  - we'll design details later
- **Miscellaneous Registers**
  - In implementations with only one stage per clock cycle, registers are inserted between stages to hold intermediate data and control signals as they travels from stage to stage.
  - Note: Register is a general purpose term meaning something that stores bits. Not all registers are in the "register file".

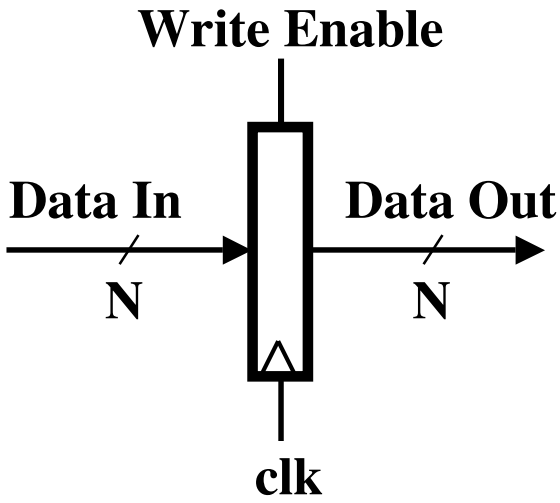
Storage Element: Idealized Memory



- Memory (idealized)
  - One input bus: Data In
  - One output bus: Data Out
- Memory word is selected by:
  - Address selects the word to put on Data Out
  - Write Enable = 1: address selects the memory word to be written via the Data In bus
- Clock input (CLK)
  - The CLK input is a factor ONLY during write operation
  - During read operation, behaves as a combinational logic block:
    - Address valid ⇒ Data Out valid after "access time."

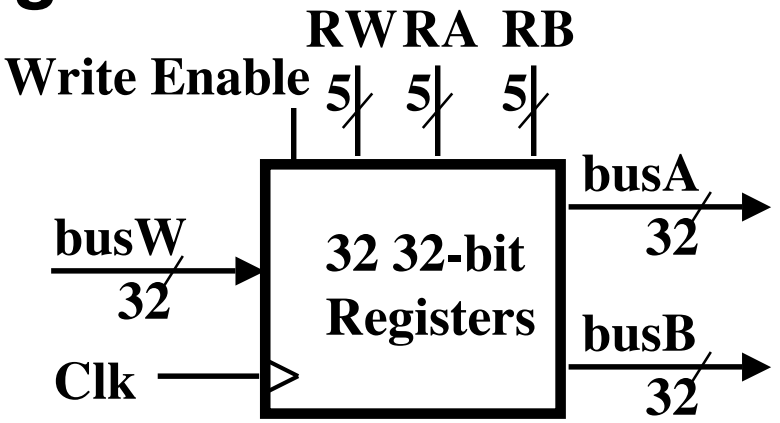
Storage Element: Register (Building Block)

- Similar to D Flip Flop except
  - N-bit input and output
  - Write Enable input
- Write Enable:
  - negated (or deasserted) (0): Data Out will not change
  - asserted (1): Data Out will become Data In on positive edge of clock



Storage Element: Register File

- Register File consists of 32 registers:
  - Two 32-bit output busses: busA and busB
  - One 32-bit input bus: busW



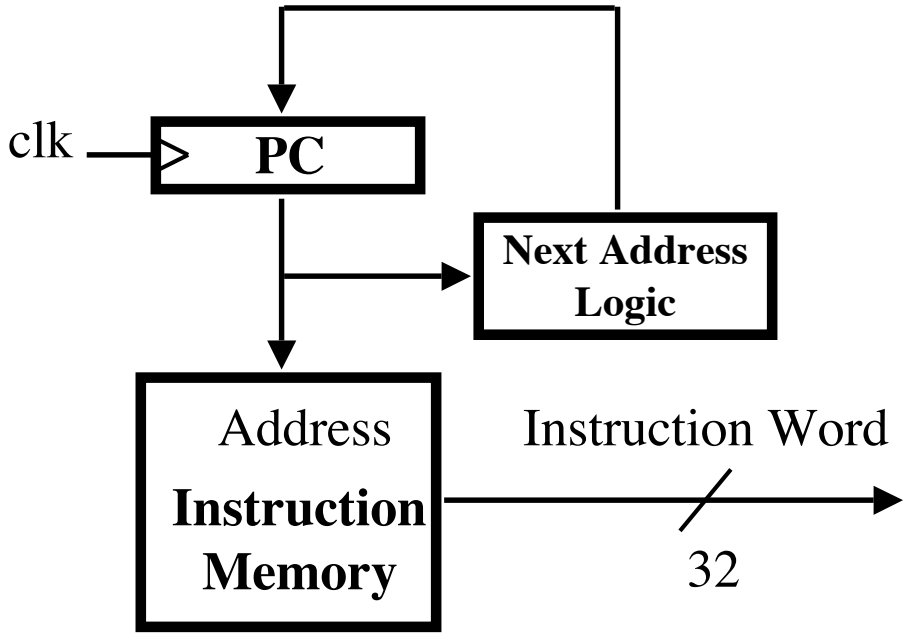
- Register is selected by:
  - RA (number) selects the register to put on busA (data)
  - RB (number) selects the register to put on busB (data)
  - RW (number) selects the register to be written via busW (data) when Write Enable is 1
- Clock input (clk)
  - The clk input is a factor ONLY during write operation
  - During read operation, behaves as a combinational logic block:
    - RA or RB valid ⇒ busA or busB valid after "access time."

Step 3: Assemble DataPath meeting requirements

- Register Transfer Requirements
  ⇒ Datapath Assembly
- Instruction Fetch
- Read Operands and Execute Operation

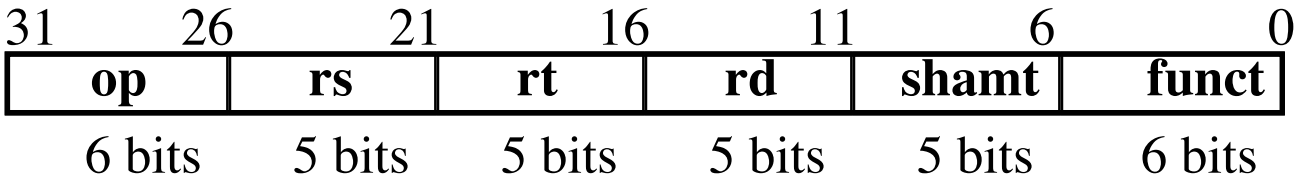
3a: Overview of the Instruction Fetch Unit

- The common RTL operations
  - Fetch the Instruction: mem[PC]
  - Update the program counter:
    - Sequential Code: PC ← PC + 4
    - Branch and Jump: PC ← "something else"

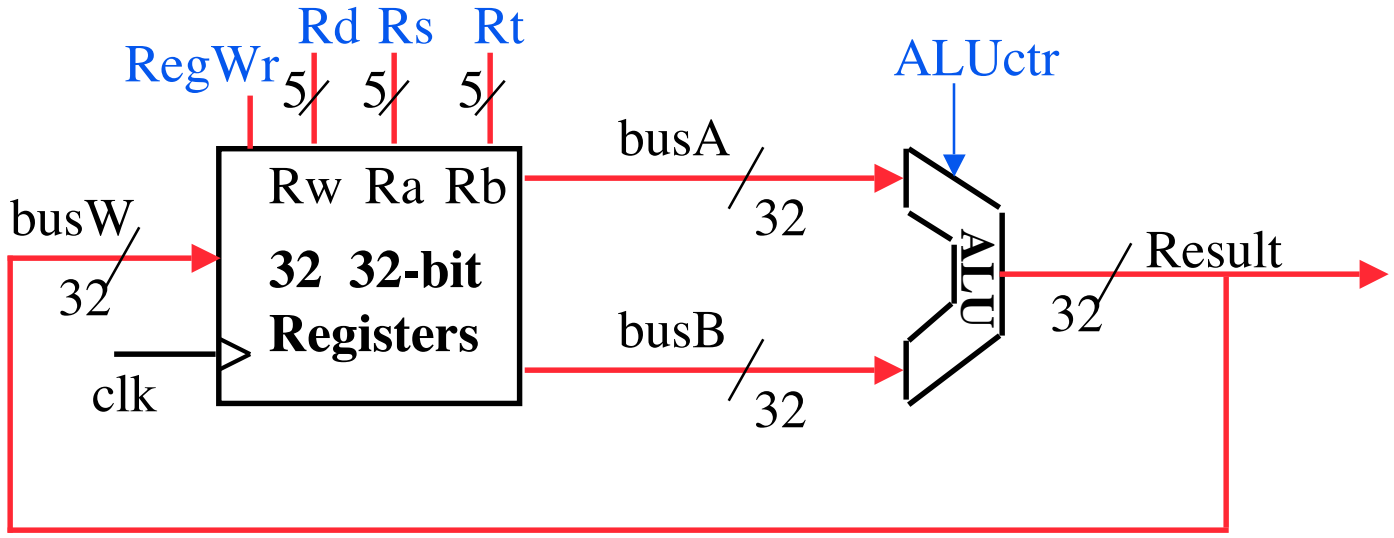


3b: Add & Subtract

- R[rd] = R[rs] op R[rt] Ex.: `addU rd,rs,rt`
  - Ra, Rb, and Rw come from instruction's Rs, Rt, and Rd fields



  - ALUctr and RegWr: control logic after decoding the instruction



Already defined the register file & ALU

Peer Instruction

A. Our ALU is a synchronous device

B. We should use the main ALU to compute PC=PC+4

C. The ALU is inactive for memory reads or writes.

	ABC
1:	FFF
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

Peer Instruction

A. If the destination reg is the same as the source reg, we could compute the incorrect value!

B. We're going to be able to read 2 registers and write a 3rd in 1 cycle

C. Datapath is hard, Control is easy

	ABC
0:	FFF
1:	FFT
2:	FTF
3:	FTT
4:	TFF
5:	TFT
6:	TTF
7:	TTT

Peer Instruction

A. Truth table for mux with 4-bits of signals has 2^4 rows

B. We could cascade N 1-bit shifters to make 1 N-bit shifter for sll, srl

C. If 1-bit adder delay is T, the N-bit adder delay would also be T

	ABC
1:	FFF
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

Peer Instruction Answer

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- 3. Assemble datapath meeting requirements
- 4. Analyze implementation of each instruction to determine setting of control points that effects the register transfer.
- 5. Assemble the control logic (hard part!)