C335
Computer Structures

Introduction to CPU Design

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Adapted from Morgan Kaufmann, Dr. L. Zhang and others
Major Components of a Computer

Processor
- Control
- Datapath

Memory (passive)
(where programs, data live when running)

Devices
- Input
- Output

Computer

Keyboard, Mouse
Disk
(where programs, data live when not running)

Display, Printer
The CPU

- **Processor (CPU):** the active part of the computer, which does all the work (data manipulation and decision-making)

- **Datapath:** portion of the processor which contains hardware necessary to perform operations required by the processor (the brawn)

- **Control:** portion of the processor (also in hardware) which tells the datapath what needs to be done (the brain)
Stages of the Datapath: Overview

- **Problem**: a single, atomic block which “executes an instruction” (performs all necessary operations beginning with fetching the instruction) would be too bulky and inefficient.

- **Solution**: break up the process of “executing an instruction” into stages, and then connect the stages to create the whole datapath.
  - smaller stages are easier to design
  - easy to optimize (change) one stage without touching the others.
There is a wide variety of MIPS instructions: so what general steps do they have in common?

Stage 1: Instruction Fetch

- no matter what the instruction is, the 32-bit instruction word must first be fetched from memory (the cache-memory hierarchy)
- also, this is where we Increment PC (that is, \( PC = PC + 4 \), to point to the next instruction: byte addressing so + 4)
Stage 2: **Instruction Decode**

- upon fetching the instruction, we next gather data from the fields (*decode all necessary instruction data*)
- first, read the **Opcode** and **Funct** to determine instruction type and field lengths
- second, read in data from all necessary registers
  - for *add*, read
  - for *addi*, read
  - for *jal*, read
Stage 3: **ALU** (Arithmetic-Logic Unit)

- the real work of most instructions is done here: arithmetic (+, -, *, /), shifting, logic (&, |), comparisons (slt)

- what about loads and stores?
  - `lw $t0, 40($t1)`
  - the address we are accessing in memory = the value in $t1 PLUS the value 40
  - so we do this addition in this stage
Stage 4: Memory Access

- actually only the load and store instructions do anything during this stage; the others remain idle during this stage or skip it all together
- since these instructions have a unique step, we need this extra stage to account for them
- as a result of the cache system, this stage is expected to be *fast*
Stage 5: **Register Write**

- most instructions write the result of some computation into a register
- examples: arithmetic, logical, shifts, loads, slt
- what about stores, branches, jumps (j, jr)?
  - don’t write anything into a register at the end
  - these remain idle during this fifth stage or skip it all together
Generic Steps of Datapath

1. Instruction Fetch
2. Decode/Register Read
3. Execute
4. Memory
5. Reg. Write
Add $r3, $r1, $r2 # r3 = r1 + r2

- Stage 1: fetch this instruction, inc. PC
- Stage 2: decode to find it’s an add, then read registers $r1 and $r2
- Stage 3: add the two values retrieved in Stage 2
- Stage 4: idle (nothing to write to memory)
- Stage 5: write result of Stage 3 into register $r3
Example: add Instruction

```
add r3, r1, r2
```
Datapath Walkthroughs (2/3)

- `slti $r3,$r1,17`

  - Stage 1: fetch this instruction, inc. PC
  - Stage 2: decode to find it’s an `slti`, then read register $r1
  - Stage 3: compare value retrieved in Stage 2 with the integer 17
  - Stage 4: idle
  - Stage 5: write the result of Stage 3 in register $r3
Example: `slti` Instruction

```
slti r3, r1, 17
```

![Diagram of the `slti` instruction process](image)
Datapath Walkthroughs (3/3)

- **`sw  $r3, 16($r1)`**
  - Stage 1: fetch this instruction, inc. PC
  - Stage 2: decode to find it’s a `sw`, then read registers `$r1` and `$r3`
  - Stage 3: add 16 to value in register `$r1` (retrieved in Stage 2)
  - Stage 4: write value in register `$r3` (retrieved in Stage 2) into memory address computed in Stage 3
  - Stage 5: idle (nothing to write into a register)
Example: \texttt{sw} Instruction

```
sw r3, 16(r1)
```

- \texttt{SW} instruction
- \text{PC} + 4
- \text{instruction memory}
- \text{ALU}
- \text{Data memory}
- \text{MEM[r1+16] \text{\textless} r3}
- \text{reg[1]} + 16
- \text{reg[3]}
- \text{imm}
- \text{reg[1]}
- \text{16}
- \text{3}
- \text{1}

Diagram shows the flow of data and instructions through the computer's registers and memory.
Why Five Stages? (1/2)

- Could we have a different number of stages?
  - Yes, and other architectures do

- So why does MIPS have five if instructions tend to idle for at least one stage?
  - The five stages are the union of all the operations needed by all the instructions of MIPS.
  - There is one instruction that uses all five stages: the load
Why Five Stages? (2/2)

- \texttt{lw} \ $r3, 16($r1)
  - Stage 1: fetch this instruction, inc. PC
  - Stage 2: decode to find it’s a \texttt{lw}, then read register \$r1
  - Stage 3: add 16 to value in register \$r1 (retrieved in Stage 2)
  - Stage 4: read value from memory address compute in Stage 3
  - Stage 5: write value found in Stage 4 into register \$r3
Example: lw Instruction

```
lw r3, 16(r1)
reg[1]+16
MEM[r1+16]
```
Datapath Summary

- The datapath is based on data transfers required to perform instructions
- A *controller* causes the right transfers to happen
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 possible
What Hardware Is Needed? (2/2)

- ALU
  - used in Stage 3
  - something that performs all necessary functions: arithmetic, logicals, etc.

- 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”.
**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.

1. Instruction Fetch
2. Decode/Register Read
3. Execute
4. Memory
5. Reg. Write
Multiple-cycle CPU: Only one stage of instruction per clock cycle.

- The clock is made as long as the slowest stage.

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

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

- 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