CPU Structure and Function

Ch 12 [Sta10]

- Registers
- Instruction cycle
- Pipeline
- Dependences
- Dealing with Branches
General structure of CPU

- **ALU**
  - Calculations, comparisons
- **Registers**
  - Fast work area
- **Processor bus**
  - Moving bits
- **Control Unit (Ohjausyksikkö)**
  - What? Where? When?
  - Clock pulse
  - Generate control signals
    - What happens at the next pulse?
- **MMU?**
- **Cache?**
Registers

- Top of memory hierarchy
- User visible registers
  - Programmer / Compiler decides how to use these
  - How many? Names?
- Control and status registers
  - Some of these used indirectly by the program
    - PC, PSW, flags, …
  - Some used only by CPU internally
    - MAR, MBR, …
- Internal latches (apurekisteri) for temporal storage during instruction execution
  - Example: Instruction register (IR) instruction interpretation; operand first to latch and only then to ALU
  - ALU output before result moved to some register

```
ADD   R1,R2,R3
BNEQ   Loop
```
User visible registers

- Different processor families ⇒
  - different number of registers
  - different naming conventions (*nimeämistavat*)
  - different purposes

- General-purpose registers (*yleisrekisterit*)

- Data registers (*datarekisterit*) – not for addresses!

- Address registers (*osoiterekisterit*)
  - Segment registers (*segmenttirekisterit*)
  - Index registers (*indeksirekisterit*)
  - Stack pointer (*pino-osoitin*)
  - Frame pointer (*ympäristöosoitin*)

- Condition code registers (*tilarekisterit*)
Example

Number of registers:
8, 16, or 32 ok in 1980
RISC: several hundreds
PSW - Program Status Word

- Name varies in different architectures
- State of the CPU
  - Privileged mode vs user mode
- Result of comparison (*vertailu*)
  - Greater, Equal, Less, Zero, ...
- Exceptions (*poikkeus*) during execution?
  - Divide-by-zero, overflow
  - Page fault, “memory violation”
- Interrupt enable/ disable
  - Each ‘class’ has its own bit
- Bit for interrupt request?
  - I/O device requesting guidance

Design issues:
- OS support
- memory and registers in
- control data storing
- paging
- subroutines and stacks
- etc
Instruction cycle (*käskysyklī*)

1. Instruction fetch
2. Instruction address calculation
3. Instruction operation decoding
4. Operand fetch
5. Operand address calculation
6. Data Operation
7. Operand address calculation
8. Operand store
9. Indirection
10. Multiple operands
11. Return for string or vector data
12. No interrupt
13. Interrupt check
14. Interrupt complete, fetch next instruction

(Sa10 Fig 12.5)
Instruction fetch (käskyn nouto)

- MAR ← PC
- MAR ← MMU(MAR)
- Control Bus ← Reserve
- Control Bus ← Read
- PC ← ALU(PC+1)
- MBR ← MEM[MAR]
- Control Bus ← Release
- IR ← MBR

Cache (välimuisti)!
Prefetch (ennaltanouto)!

(Sta10 Fig 12.6)
Operand fetch, Indirect addressing (Operandin nouto, epäsuoora osoitus)

- MAR ← Address
- MAR ← MMU(MAR)
- Control Bus ← Reserve
- Control Bus ← Read
- MBR ← MEM[MAR]
- MAR ← MBR
- MAR ← MMU(MAR)
- Control Bus ← Read
- MBR ← MEM[MAR]
- Control Bus ← Release
- Cache!
- ALU? Regs? ← MBR

(Sta10 Fig 12.7)
Data flow, interrupt cycle

- MAR ← SP
- MAR ← MMU(MAR)
- Control Bus ← Reserve
- MBR ← PC
- Control Bus ← Write
- MAR ← SP ← ALU(SP+1)
- MAR ← MMU(MAR)
- MBR ← PSW
- Control Bus ← Write
- SP ← ALU(SP+1)
- PSW ← privileged & disable
- MAR ← Interrupt number
- Control Bus ← Read
- PC ← MBR ← MEM[MAR]
- Control Bus ← Release

No address translation!

SP = Stack Pointer (Sta10 Fig 12.8)
Instruction pipelining

(liukuhihna)
Laundry example (by David A. Patterson)

- Ann, Brian, Cathy, Dave: each have one load of clothes to wash, dry and fold
- Washer takes 30 min
- Dryer takes 40 min
- “Folder” takes 20 min
Sequential Laundry

- Takes 6 hours for 4 loads:

- If they learned pipelining, how long would laundry take?
Pipelined Laundry

- Takes 3.5 hours for 4 loads

At best case, one load is completed every 40 minutes! (0.67 h / finished load)
Lessons

- Pipelining does not help latency of single task, but it helps throughput of the entire workload
- Pipelining can delay single task compared with situation where it is alone in the system
  - Next stage occupied, must wait
- Multiple tasks operating simultaneously, but different phases
- Pipeline rate limited by slowest pipeline stage
  - Can proceed when all stages done
  - Not very efficient, if different stages have different durations, unbalanced lengths
- Potential speedup
  - \[ \text{maximum possible speedup} \]
  - number of pipe stages
Lessons

- Complex implementation,
- May need more resources
  - Enough electrical current and sockets to use both washer and dryer simultaneously
  - Two (or three) people present all the time in the laundry
  - 3 laundry baskets
- Time to “fill” pipeline and time to “drain” it reduce speedup
  - Resources are not fully utilized
- “Hiccups” (hikka)
  - Variation in task arrivals, works best with constant flow of tasks
2-stage instruction execution pipeline (2-vaiheinen liukuhihna)

- Instruction prefetch (ennaltanouto) at the same time as execution of previous instruction
- Principle of locality: assume ‘sequential’ execution
- Problems
  - Execution phase longer → fetch stage sometimes idle
  - Execution modifies PC (jump, branch) → fetched wrong instr.
    - Prediction of the next instruction’s location was incorrect!
- Not enough parallelism → more stages?

Discussion?
6-Stage (6-Phase) Pipeline

<table>
<thead>
<tr>
<th>Time</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<th>11</th>
<th>12</th>
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</thead>
<tbody>
<tr>
<td>FI - Fetch instruction</td>
<td>DI - Decode instruction</td>
<td>CO - Calculate operand addresses</td>
<td>FO - Fetch operands</td>
<td>EI - Execute instruction</td>
<td>WO - Write operand</td>
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(Sta10 Fig 12.10)
Pipeline speedup (*nopeutus*)?

- Lets calculate (based on Fig 12.10):
  - 6-stage pipeline, 9 instr. $\rightarrow$ 14 time units total
  - Same without pipeline $\rightarrow$ 9*6 = 54 time units
  - Speedup = $\frac{\text{time}_{\text{orig}}}{\text{time}_{\text{pipeline}}} = \frac{54}{14} = 3.86 < 6$
  - Maximum speed at times 6-14
    - one instruction per time unit finishes
    - 8 time units $\rightarrow$ 8 instruction completions
    - Maximum speedup = $\frac{\text{time}_{\text{orig}}}{\text{time}_{\text{pipeline}}} = \frac{48}{8} = 6$

- Not every instruction uses every stage
  - Will not affect the pipeline speed – some stages unused
  - Speedup may be small (some stages idle, waiting for slow)
  - Unused stage $\rightarrow$ CPU idle (execution “bubble”)
  - Serial execution could be faster (no wait for other stages)
Pipeline performance: one cycle time

\[ \tau = \max_{i=1..k} [\tau_i] + d = \tau_m + d \gg d \]

- Cycle time is the same for all stages
  - Time (in clock pulses) to execute the stage
- Each stage (phase) takes one cycle time to execute
- Slowest stage determines the pace (*tahti, etenemisvauhti*)
  - The longest duration becomes bottleneck

Stage i time
Latch delay, move data from one stage to next ~ one clock pulse

Max time (duration) of the slowest stage (*Hitaimman vaiheen (max) kesto*)

Cycle time (*jakson kesto*)
Pipeline Speedup

n instructions, k stages, \( \tau = \) cycle time

No pipeline: \[ T_1 = nk\tau \]

Pipeline: \[ T_k = [k + (n - 1)]\tau \]

Speedup: \[ S_k = \frac{T_1}{T_k} = \frac{nk\tau}{[k + (n - 1)]\tau} = \frac{nk}{[k + (n - 1)]} \]

Pessimistic: assumes the same duration for all stages

next (n-1) tasks (instructions) will finish each during one cycle, one after another

See Sta10 Fig 12.10 and check yourself!
more gains from multiple stages when more instructions without jumps

(Sta10 Fig 12.14)
Pipeline Features

- Extra issues
  - CPU must store ‘midresults’ somewhere between stages and move data from buffer to buffer
  - From one instruction's viewpoint the pipeline takes longer time than single execution

- But still
  - Executing large set of instructions is faster
  - Better throughput (instructions/sec)

- The parallel (concurrent) execution of instructions in the pipeline makes them proceed faster as whole, but slows down execution of single instruction
Pipeline Problems and Design Issues

- **Structural dependency** (*rakenteellinen riippuvuus*)
  - Several stages may need the same HW
  - Memory used by FI, FO, WO?
  - ALU used by CO, EI?

- **Control dependency** (*kontrolliriippuvuus*)
  - No knowledge on next instruction
  - E.g., (conditional) branch destination may be known only after EI-stage
  - Prefetched and executed wrong instructions?

- **Data dependency** (*datariippuvuus*)
  - E.g., instruction needs the result of the previous non-finished instruction

---

```
STORE    R1,VarX
ADD      R2,R3,VarY
MUL      R3,R4,R5

ADD      R1,R7, R9
Jump     There
ADD      R2,R3,R4
MUL      R1,R4,R5

MUL      R1,R2,R3
LOAD     R6, Arr(R1)
```
Pipeline Dependency Problem Solutions

- In advance: prevent (some) dependency problems completely
  - Structural dependency
    - More hardware, e.g., separate ALUs for CO and EI stages
    - Lots of registers, less operands from memory
  - Control dependency
    - Clear pipeline, fetch new instructions
    - Branch prediction, prefetch and execute these, those, or both?
  - Data dependency
    - Change execution order of instructions
    - By-pass (oikopolku) in hardware between stages: earlier instruction’s result can be accessed already before its WO-stage is done

- At run time: Hardware must notice and wait until all possible dependencies are cleared
  - Add extra waits, “bubbles”, to the pipeline; Commonly used
  - Bubble (kupla) delayes everything behind it in all stages
Data dependency

- **Read after Write (RAW)** (a.k.a true or flow dependency)
  - Occurs if succeeding read takes place before the preceding write operation is complete

- **Write after Read (WAR)** (a.k.a antidependency)
  - Occurs if the succeeding write operation completes before the preceding read operation takes place

- **Write after Write (WAW)** (a.k.a output dependency)
  - Occurs when the two write operations take place in the reversed order of the intended sequence

- The WAR and WAW are possible only in architectures where the instructions can finish in different order

Discussion?
**Example: Data Dependency - RAW**

<table>
<thead>
<tr>
<th></th>
<th>MUL R1, R2, R3</th>
<th>ADD R4, R5, R6</th>
<th>SUB R7, R1, R8</th>
<th>ADD R1, R1, R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FI</td>
<td>DI</td>
<td>FO</td>
<td>EI</td>
</tr>
<tr>
<td>2</td>
<td>DI</td>
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<tr>
<td>6</td>
<td>WO</td>
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</tr>
</tbody>
</table>

Dependancy: wait

Dependancy: no wait

**Discussion?**

"too far, no effect"
### Example: Change instruction execution order

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Registers</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUL</td>
<td>R1, R2, R3</td>
</tr>
<tr>
<td>ADD</td>
<td>R4, R5, R6</td>
</tr>
<tr>
<td>SUB</td>
<td>R7, R1, R8</td>
</tr>
<tr>
<td>ADD</td>
<td>R9, R0, R8</td>
</tr>
</tbody>
</table>

**Original Order:**

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Instruction</th>
<th>Register</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MUL</td>
<td>R1, R2, R3</td>
</tr>
<tr>
<td>2</td>
<td>ADD</td>
<td>R4, R5, R6</td>
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<td>SUB</td>
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<tr>
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<td>ADD</td>
<td>R9, R0, R8</td>
</tr>
<tr>
<td>5</td>
<td>MUL</td>
<td>R1, R2, R3</td>
</tr>
<tr>
<td>6</td>
<td>ADD</td>
<td>R4, R5, R6</td>
</tr>
</tbody>
</table>

**Switched Order:**

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Instruction</th>
<th>Register</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MUL</td>
<td>R1, R2, R3</td>
</tr>
<tr>
<td>2</td>
<td>ADD</td>
<td>R4, R5, R6</td>
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<tr>
<td>5</td>
<td>ADD</td>
<td>R4, R5, R6</td>
</tr>
<tr>
<td>6</td>
<td>MUL</td>
<td>R1, R2, R3</td>
</tr>
</tbody>
</table>

**Note:** Switching the order of instructions can affect the pipeline if there are dependencies. In this example, the original order has no effective dependencies, but the switched order needs a bubble due to the change in instruction execution order.
Example: By-pass (oikopolut)

- New wires (and temp registers, latches) in pipeline
- E.g., instr. result available to FO phase directly from phase EI

<table>
<thead>
<tr>
<th>MUL</th>
<th>ADD</th>
<th>SUB</th>
</tr>
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<td>R1, R2, R3</td>
<td>R4, R5, R1</td>
<td>R7, R4, R1</td>
</tr>
</tbody>
</table>

![Diagram with by-pass and no by-pass]

With by-pass:

No by-pass:
Pipelining and Jump Optimization

Multiple streams (Monta suorituspolkua)
Delayed branch (Viivästetty hyppy)
Prefetch branch target (Kohteen ennaltanouto)
Loop buffer (Silmukkapuskuri)
Branch prediction (Ennustuslogiikka)
Effect of Conditional Branch on Pipeline

Many phases, large Branch Penalty

(Sta10 Fig 12.11)

(Sta10 Fig 12.12)
Delayed Branch (viivästetty haarauminen)

- Compiler places some useful instructions (1 or more) after branch instructions (to delay slots)
  - Instructions in delay slots are always fully executed!
  - No roll-back of instructions needed due incorrect prediction
    - Rollback is difficult to do
  - If no useful instruction available, compiler uses NOP

- Less actual work lost if branch occurs
  - Next instruction almost done, when branch decision known

- This is easier than emptying the pipeline during branch

- Worst case: NOP-instructions waist some cycles
- Can be difficult to do (for the compiler)
Multiple instruction streams (*monta suorituspolku*)

- Execute speculatively to both directions
  - Prefetch instructions that follow the branch to the pipeline
  - Prefetch instructions from branch target to (another) pipeline
  - After branch decision: reject the incorrect pipeline (its results, changes)

Problems
- Branch target address known only after some calculations
- Second split on one of the pipelines
  - Continue any way? Only one speculation at a time?
- More hardware!
  - More pipelines, speculative results (registers!), control
- Speculative instructions may delay real work
  - Bus and register contention? More ALUs?

- Capability to *cancel* not-taken instruction stream from pipeline
  - easier, if all changes done in WB phase

IBM 370/168, IBM 3033, Intel IA-64
Prefetch branch target (kohteen ennaltanouto)

- Prefetch just branch target instruction, but do not execute it yet
  - Do only FI-stage
  - If branch taken, no need to wait for memory
- Must be able to clear the pipeline
- Prefetching branch target may cause page-fault

IBM 360/91 (1967)
Loop buffer (*silmukkapuskuri*)

- Keep $n$ most recently fetched instructions in high speed buffer inside the CPU
  - Use prefetch also
    - With good luck the branch target is in the buffer
    - F.ex. IF-THEN and IF-THEN-ELSE structures

- Works for small loops (at most $n$ instructions)
  - Fetch from memory just once

- Gives better spacial locality than just cache
Static Branch Prediction

- Make an (educated?) guess on which direction is more probable:
  - Branch or no?

- Static prediction \((staattinen\ ennustus)\)
  - Fixed: Always taken \((aina\ hypätään)\)
  - Fixed: Never taken \((ei\ koskaan\ hypätä)\)
    - ~ 50\% correct
  - Predict by opcode \((operaatiokoodin\ perusteella)\)
    - In advance decided which codes are more likely to branch
      - Compilers know this, and use it for better performance
    - For example, BLE instruction is commonly used at the end of stepping loop, guess a branch
    - ~ 75\% correct \([LILJ88]\)
### Dynamic Branch Prediction

#### Dynamic prediction
- Make a guess based on earlier history for (this) branch
- **Logic:** What has happened in the recent history with this instruction
  - Improves the accuracy of the prediction
- **Implementation:** extra internal memory = branch history table
  - Instruction address (for this branch)
  - Branch target (instruction or address) – need this for quick action
  - Decision: taken / not taken

#### Simple prediction based on just the previous execution
- 1 bit memory is enough
- Loops will always have one or two incorrect predictions
2-Bit Branch Prediction Logic for One Instruction

- Improved simple model
  - Don’t change the prediction with one misprediction
  - Based on two previous executions of this instruction
  - 2 bits enough

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PowerPC 620
(Sta10 Fig 12.19)
Branch Prediction History Table

- Branch instruction address
- Target address
- State

**State and prediction:**
- taken/not taken

**Where to jump, if branch taken:**

**Associative memory, Like cache**

**IPFAR = instruction prefix address register**

**Add new entry**
- **Update state**
- **Row:** "tag"

*(Sta10 Fig 12.20b)*
Summary

Pipeline basics
- Stage length, pipeline fill-up and drain times
- Response time, throughput, speedup

Hazards, dependencies
- Structural, control, data (RAW, WAR, WAW)
- How to avoid before time?
- How to handle at run time?

How to minimize branch costs?
- Delayed branch, multiple pipeline streams, prefetch branch target, loop buffer, branch prediction
Review Questions

- What information PSW needs to contain?
- Why 2-stage pipeline is not very beneficial?
- What elements effect the pipeline?
- What mechanisms can be used to handle branching?
- How does CPU move to interrupt handling?