Introduction and review of Pipelines, Performance, Caches, and Virtual Memory

January 2007
Paul H J Kelly

These lecture notes are partly based on the course text, Hennessy and Patterson’s Computer Architecture, a quantitative approach (4th ed), and on the lecture slides of David Patterson’s Berkeley course (CS252)

Course materials online at http://www.doc.ic.ac.uk/~phjk/AdvancedCompArchitecture.html
Pre-requisites

◆ This a third-level computer architecture course

◆ The usual path would be to take this course after following a course based on a textbook like “Computer Organization and Design” (Patterson and Hennessy, Morgan Kaufmann)

◆ This course is based on the more advanced book by the same authors (see next slide)

◆ You can take this course provided you’re prepared to catch up if necessary
  - Read chapters 1 to 8 of “Computer Organization and Design” (COD) if this material is new to you
  - If you have studied computer architecture before, make sure COD Chapters 2, 6, 7 are familiar
  - See also “Appendix A Pipelining: Basic and Intermediate Concepts” of course textbook

◆ FAST review today of Pipelining, Performance, Caches, and Virtual Memory
This is a textbook-based course

  - John L. Hennessy, David A. Patterson
  - ~580 pages. Morgan Kaufmann (2007); ISBN: 978-0-12-370490-0
  - with substantial additional material on CD
  - Price: £ 36.99 (Amazon.co.uk, Jan 2006)
  - Publisher’s companion web site: [http://textbooks.elsevier.com/0123704901/](http://textbooks.elsevier.com/0123704901/)
  - Textbook includes some vital introductory material as appendices:
    - Appendix A: tutorial on pipelining (read it NOW)
    - Appendix C: tutorial on caching (read it NOW)
  - Further appendices (some in book, some in CD) cover more advanced material (some very relevant to parts of the course), eg
    - Networks
    - Parallel applications
    - Implementing Coherence Protocols
    - Embedded systems
    - VLIW
    - Computer arithmetic (esp floating point)
    - Historical perspectives
Who are these guys anyway and why should I read their book?

**John Hennessy:**
- Founder, MIPS Computer Systems
- President, Stanford University
  (previous president: Condoleezza Rice)

**David Patterson**
- Leader, Berkeley RISC project (led to Sun’s SPARC)
- RAID (redundant arrays of inexpensive disks)
- Professor, University of California, Berkeley
- Current president of the ACM
- Served on Information Technology Advisory Committee to the US President

**RAID-I** (1989) consisted of a Sun 4/280 workstation with 128 MB of DRAM, four dual-string SCSI controllers, 28 5.25-inch SCSI disks and specialized disk striping software.

**RISC-I** (1982) Contains 44,420 transistors, fabbed in 5 micron NMOS, with a die area of 77 mm², ran at 1 MHz. This chip is probably the first VLSI RISC.

http://www.cs.berkeley.edu/~pa/trees/Arch/prototypes2.html
Course web site:

http://www.doc.ic.ac.uk/~phjk/AdvancedCompArchitecture.htm

Course mailing list (see web page for link):

332-advancedcomputerarchitecture-2006@doc.ic.ac.uk

Mailing list archive:

http://mailman.doc.ic.ac.uk/pipermail/332-advancedcomputerarchitecture-2006/

Course textbook: H&P 4th ed

Read Appendix A right away
Course organisation

Lecturer:
- Paul Kelly

Tutorial helper:
- Ashley Brown – PhD student working on heterogenous multicore architectures and design-space exploration

3 hours per week
- Nominally two hours of lectures, one hour of classroom tutorials
- We will use the time more flexibly

Assessment:
- Exam
  - For CS M.Eng. Class, exam will take place in last week of term
  - For everyone else, exam will take place early in the summer term
  - The goal of the course is to teach you how to think about computer architecture
  - The exam usually includes some architectural ideas not presented in the lectures
- Coursework
  - You will be assigned a substantial, laboratory-based exercise
  - You will learn about performance tuning for computationally-intensive kernels
  - You will learn about using simulators, and experimentally evaluating hypotheses to understand system performance
  - You are encouraged to bring laptops to class to get started and get help during tutorials

Please do not use the computers for anything else during classes
Course overview (plan)

**Ch1**
- Review of pipelined, in-order processor architecture and simple cache structures

**Ch2**
- Virtual memory
- Benchmarking
- Fab

**Ch3**
- Caches in more depth
- Software techniques to improve cache performance

**Ch4**
- Instruction-level parallelism
- Dynamic scheduling, out-of-order
- Register renaming
- Speculative execution
- Branch prediction
- Limits to ILP

**Ch5**
- Compiler techniques – loop nest transformations
- Loop parallelisation, interchange, tiling/blocking, skewing
- Uniform frameworks

**Ch6**
- Multithreading, hyperthreading, SMT
- Static instruction scheduling
- Software pipelining
- EPIC/IA-64; instruction-set support for speculation and register renaming

**Ch7**
- Shared-memory multiprocessors
- Cache coherency
- Large-scale cache-coherency; ccNUMA, COMA

**Lab-based coursework exercise:**
- Simulation study
- “challenge”
- Using performance analysis tools

**Exam:**
- Answer 3 questions out of 4
- Partially based on recent processor architecture article, which we will study in advance (see past papers)
A "Typical" RISC

- 32-bit fixed format instruction (3 formats, see next slide)
- 32 32-bit general-purpose registers
  - (R0 contains zero, double-precision/long operands occupy a pair)
- Memory access only via load/store instructions
  - No instruction both accesses memory and does arithmetic
  - All arithmetic is done on registers
- 3-address, reg-reg arithmetic instruction
  - Subw r1,r2,r3 means r1 := r2-r3
  - Registers identifiers always occupy same bits of instruction encoding
- Single addressing mode for load/store:
  - Base + displacement
    - ie register contents are added to constant from instruction word, and
      used as address, eg “lw R2,100(r1)” means “r2 := Mem[100+r1]”
    - No indirection
- Simple branch conditions
- Delayed branch

see: SPARC, MIPS, ARM, HP PA-Risc,
DEC Alpha, IBM PowerPC,
CDC 6600, CDC 7600, Cray-1,
Cray-2, Cray-3

Not: Intel IA-32, IA-64 (?),
Motorola 68000,
DEC VAX, PDP-11, IBM
360/370

Eg: VAX matchc instruction!
### Example: MIPS (Note register location)

<table>
<thead>
<tr>
<th>Register-Register</th>
</tr>
</thead>
<tbody>
<tr>
<td>31 26 25 2120 16 15 1110 6 5 0</td>
</tr>
<tr>
<td>Op</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Register-Immediate</th>
</tr>
</thead>
<tbody>
<tr>
<td>31 26 25 2120 16 15 0</td>
</tr>
<tr>
<td>Op</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Branch</th>
</tr>
</thead>
<tbody>
<tr>
<td>31 26 25 2120 16 15 0</td>
</tr>
<tr>
<td>Op</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Jump / Call</th>
</tr>
</thead>
<tbody>
<tr>
<td>31 26 25 0</td>
</tr>
<tr>
<td>Op</td>
</tr>
</tbody>
</table>

Q: What is the largest signed immediate operand for “subw r1,r2,X“?
Q: What range of addresses can a conditional branch jump to?
5 Steps of MIPS Datapath

Instruction Fetch

Next PC

Memory

Instr. Decode Reg. Fetch

Next SEQ PC

Instruction

Reg File

Execute Addr. Calc

Reg File

Memory Access

从中断

Write Back

Address

ALU

Mux

Data Memory

Next PC

Address

ALU

Zero?

RS1

RS2

RD

Imm

Sign Extend

WB Data

ALU

Data Memory

ALU

Figure 3.1, Page 130, CA:AQA 2e
We will see more complex pipeline structures later. For example, the Pentium 4 “Netburst” architecture has 31 stages.
5-stage MIPS pipeline with pipeline buffers

- Data stationary control
  - local decode for each instruction phase / pipeline stage

Figure 3.4, Page 134, CA:AQA 2e
Pipelining doesn’t help latency of single instruction
- it helps throughput of entire workload

- Pipeline rate limited by slowest pipeline stage
- Potential speedup = Number pipe stages
- Unbalanced lengths of pipe stages reduces speedup
- Time to “fill” pipeline and time to “drain” it reduces speedup
- Speedup comes from parallelism
- For free - no new hardware
It's Not That Easy for Computers

- **Limits to pipelining:** Hazards prevent next instruction from executing during its designated clock cycle
  - **Structural hazards:** HW cannot support this combination of instructions
  - **Data hazards:** Instruction depends on result of prior instruction still in the pipeline
  - **Control hazards:** Caused by delay between the fetching of instructions and decisions about changes in control flow (branches and jumps).
One Memory Port/Structural Hazards

Time (clock cycles)

Cycle 1 Cycle 2 Cycle 3 Cycle 4 Cycle 5 Cycle 6 Cycle 7

Load

Instr 1

Instr 2

Instr 3

Instr 4

- Eg if there is only one memory for both instructions and data
- Two different stages may need access at the same time
- Example: IBM/Sony/Toshiba Cell processor

Figure 3.6, Page 142, CA:AQA 2e
One Memory Port/Structural Hazards

- Instr 3 cannot be loaded in cycle 4
- ID stage has nothing to do in cycle 5
- EX stage has nothing to do in cycle 6, etc. "Bubble" propagates

Figure 3.7, Page 143, CA:AQA 2e
Data Hazard on R1

Time (clock cycles)

Instr. Order

add r1, r2, r3
sub r4, r1, r3
and r6, r1, r7
or r8, r1, r9
xor r10, r1, r11

Figure 3.9, page 147, CA:AQA 2e
Three Generic Data Hazards

Read After Write (RAW)
Instr\textsubscript{J} tries to read operand before Instr\textsubscript{I} writes it.

I: add r1,r2,r3
J: sub r4,r1,r3

Caused by a “Dependence” (in compiler nomenclature). This hazard results from an actual need for communication.
Three Generic Data Hazards

◆ Write After Read (WAR)
  Instr\textsubscript{J} writes operand \textit{before} Instr\textsubscript{I} reads it

  \[
  \text{I: sub r4, r1, r3} \quad \text{J: add r1, r2, r3} \quad \text{K: mul r6, r1, r7}
  \]

◆ Called an “anti-dependence” by compiler writers. This results from reuse of the name “r1”.

◆ Can’t happen in MIPS 5 stage pipeline because:
  - All instructions take 5 stages, and
  - Reads are always in stage 2, and
  - Writes are always in stage 5
Three Generic Data Hazards

- **Write After Write (WAW)**
  Instr$_J$ writes operand *before* Instr$_I$ writes it.

  \[
  \begin{align*}
  I: & \text{ sub } r1, r4, r3 \\
  J: & \text{ add } r1, r2, r3 \\
  K: & \text{ mul } r6, r1, r7
  \end{align*}
  \]

- Called an "output dependence" by compiler writers
  This also results from the reuse of name "r1".

- Can't happen in MIPS 5 stage pipeline because:
  - All instructions take 5 stages, and
  - Writes are always in stage 5

- Will see WAR and WAW in later more complicated pipes
Forwarding to Avoid Data Hazard

Figure 3.10, Page 149, CA:AQA 2e

Inst. Order

add r1, r2, r3

sub r4, r1, r3

and r6, r1, r7

or r8, r1, r9

xor r10, r1, r11
HW Change for Forwarding

Figure 3.20, Page 161, CA:AQA 2e
Data Hazard Even with Forwarding

Figure 3.12, Page 153, CA:AQA 2e

Time (clock cycles)

Instruction Order

lw r1, 0(r2)
sub r4, r1, r6
and r6, r1, r7
or r8, r1, r9
Data Hazard Even with Forwarding

Figure 3.13, Page 154, CA:AQA 2e

EX stage waits in cycle 4 for operand
Following instruction ("and") waits in ID stage
Missed instruction issue opportunity...

Instr. Order

lw r1, 0(r2)

sub r4, r1, r6

and r6, r1, r7

or r8, r1, r9
Software Scheduling to Avoid Load Hazards

Try producing fast code for

\[ a = b + c; \]
\[ d = e - f; \]

assuming \( a, b, c, d, e, \) and \( f \) in memory.

**Slow code:**

\[
\begin{align*}
\text{LW} & \quad Rb,b \\
\text{LW} & \quad Rc,c \\
\text{ADD} & \quad Ra,Rb,Rc \\
\text{SW} & \quad a,Ra \\
\text{SW} & \quad a,Ra \\
\text{LW} & \quad Re,e \\
\text{LW} & \quad Re,e \\
\text{ADD} & \quad Ra,Rb,Rc \\
\text{SW} & \quad a,Ra \\
\text{SW} & \quad a,Ra \\
\text{SW} & \quad d,Rd \\
\text{SW} & \quad d,Rd
\end{align*}
\]

**Fast code:**

\[
\begin{align*}
\text{LW} & \quad Rb,b \\
\text{LW} & \quad Rc,c \\
\text{ADD} & \quad Ra,Rb,Rc \\
\text{LW} & \quad Re,e \\
\text{ADD} & \quad Ra,Rb,Rc \\
\text{SW} & \quad a,Ra \\
\text{SW} & \quad d,Rd
\end{align*}
\]
Software Scheduling to Avoid Load Hazards

Try producing fast code for

\[ a = b + c; \]
\[ d = e - f; \]

assuming \( a, b, c, d, e, \) and \( f \) in memory.

Slow code:

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Result</th>
<th>Slow code</th>
<th>Fast code</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW</td>
<td>Rb,b</td>
<td>LW Rb,b</td>
<td>LW Rb,b</td>
</tr>
<tr>
<td>LW</td>
<td>Rc,c</td>
<td>LW Rc,c</td>
<td>LW Rc,c</td>
</tr>
<tr>
<td>STALL</td>
<td></td>
<td></td>
<td>LW Re,e</td>
</tr>
<tr>
<td>ADD</td>
<td>Ra,Rb,Rc</td>
<td>ADD Ra,Rb,Rb</td>
<td>LW Re,e</td>
</tr>
<tr>
<td>SW</td>
<td>a,Ra</td>
<td>SW a,Ra</td>
<td></td>
</tr>
<tr>
<td>LW</td>
<td>Re,e</td>
<td>LW Re,e</td>
<td>ADD Ra,Rb,Rb</td>
</tr>
<tr>
<td>LW</td>
<td>Rf,f</td>
<td>LW Rf,f</td>
<td>SW a,Ra</td>
</tr>
<tr>
<td>STALL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUB</td>
<td>Rd,Re,Rf</td>
<td>SUB Rd,Re,Rf</td>
<td>SW a,Ra</td>
</tr>
<tr>
<td>SW</td>
<td>d,Rd</td>
<td>SW d,Rd</td>
<td></td>
</tr>
</tbody>
</table>

10 cycles (2 stalls) 8 cycles (0 stalls)

Show the stalls explicitly
Control Hazard on Branches
Three Stage Stall

10: \texttt{beq r1,r3,36}
14: \texttt{and r2,r3,r5}
18: \texttt{or r6,r1,r7}
22: \texttt{add r8,r1,r9}
36: \texttt{xor r10,r1,r11}
Example: Branch Stall Impact

- Suppose 30% of instructions are branch
- If we really had a 3 cycle stall everytime it would be bad!
- Two part solution:
  - Determine whether branch is taken or not sooner, AND
  - Compute taken branch target address earlier

- In the MIPS instruction set, the branch instruction tests if specified register $= 0$ or $\neq 0$
- MIPS Solution:
  - Move Zero test to ID/RF stage
  - Introduce a new adder to calculate new PC in ID/RF stage
  - 1 clock cycle penalty for branch versus 3
Pipelined MIPS Datapath with early branch determination

Figure 3.22, page 163, CA:AQA 2/e
Four Branch Hazard Alternatives

#1: Stall until branch direction is clear

#2: Predict Branch Not Taken
- Execute successor instructions in sequence
- "Squash" instructions in pipeline if branch actually taken
- With MIPS we have advantage of late pipeline state update
- 47% MIPS branches are not taken on average
- PC+4 already calculated, so use it to get next instruction

#3: Predict Branch Taken
- 53% MIPS branches are taken on average
- But in MIPS instruction set we haven’t calculated branch target address yet (because branches are relative to the PC)
  - MIPS still incurs 1 cycle branch penalty
  - With some other machines, branch target is known before branch condition
Four Branch Hazard Alternatives

#4: Delayed Branch
- Define branch to take place **AFTER** a following instruction

branch instruction
  sequential successor$_1$
  sequential successor$_2$
  ........
  sequential successor$_n$
  branch target if taken

- 1 slot delay allows proper decision and branch target address in 5 stage pipeline
- **MIPS** uses this; eg in

```
LW R3, #100
LW R4, #200
BEQZ R1, L1
SW R3, X
SW R4, X
L1:
  LW R5, X
```

- “SW R3, X” instruction is executed regardless
- “SW R4, X” instruction is executed only if R1 is non-zero
Four Branch Hazard Alternatives

#4: Delayed Branch

- Define branch to take place **AFTER** a following instruction

```
branch instruction
  sequential successor₁
  sequential successor₂
  .......... 
  sequential successorₙ
branch target if taken
```

- 1 slot delay allows proper decision and branch target address in 5 stage pipeline

- **MIPS** uses this; eg in

```
LW R3, #100
LW R4, #200
BEQZ R1, L1
SW R3, X
SW R4, X
L1:
LW R5, X
```

- "SW R3, X" instruction is executed regardless
- "SW R4, X" instruction is executed only if R1 is non-zero

```
If (R1==0)
  X=100
Else
  X=200
R5 = X
```
Delayed Branch

Where to get instructions to fill branch delay slot?
- Before branch instruction
- From the target address: only valuable when branch taken
- From fall through: only valuable when branch not taken

Compiler effectiveness for single branch delay slot:
- Fills about 60% of branch delay slots
- About 80% of instructions executed in branch delay slots useful in computation
- About 50% (60% x 80%) of slots usefully filled

Delayed Branch downside: 7-8 stage pipelines, multiple instructions issued per clock (superscalar)

Canceling branches
- Branch delay slot instruction is executed but write-back is disabled if it is not supposed to be executed
- Two variants: branch “likely taken”, branch “likely not-taken”
- allows more slots to be filled
Now, Review of Memory Hierarchy
Recap: Who Cares About the Memory Hierarchy?

Processor-DRAM Memory Gap (latency)

“Moore’s Law”

Processor-Memory Performance Gap: (grows 50% / year)

DRAM 9%/yr. (2X/10 yrs)

μProc 60%/yr. (2X/1.5yr)
Levels of the Memory Hierarchy

- **CPU Registers**
  - 100s Bytes
  - <1ns

- **Cache**
  - 10s-100s K Bytes
  - 1-10 ns
  - $10/ MByte

- **Main Memory**
  - M Bytes
  - 100ns- 300ns
  - $1/ MByte

- **Disk**
  - 10s G Bytes, 10 ms (10,000,000 ns)
  - $0.0031/ MByte

- **Tape**
  - infinite sec-min
  - $0.0014/ MByte

- **Upper Level**
  - Staging Xfer Unit
    - prog./compiler
      - 1-8 bytes
    - cache cntl
      - 8-128 bytes
    - OS
      - 512-4K bytes
    - user/operator
      - Mbytes

- **Lower Level**
  - faster
  - Larger
The Principle of Locality:

Programs access a relatively small portion of the address space at any instant of time.

Two Different Types of Locality:

- **Temporal Locality** (Locality in Time): If an item is referenced, it will tend to be referenced again soon (e.g., loops, reuse)

- **Spatial Locality** (Locality in Space): If an item is referenced, items whose addresses are close by tend to be referenced soon (e.g., straightline code, array access)

In recent years, architectures have become increasingly reliant (totally reliant?) on locality for speed.
Interesting exception: Cray/Tera MTA, first delivered June 1999:
  - www.cray.com/products/systems/mta/

- Each CPU switches every cycle between 128 threads
- Each thread can have up to 8 outstanding memory accesses
- 3D toroidal mesh interconnect
- Memory accessed hashed to spread load across banks
- MTA-1 fabricated using Gallium Arsenide, not silicon
- “nearly un-manufacturable” (wikipedia)
**Memory Hierarchy: Terminology**

- **Hit**: data appears in some block in the upper level (example: Block X)
  - **Hit Rate**: the fraction of memory access found in the upper level
  - **Hit Time**: Time to access the upper level which consists of RAM access time + Time to determine hit/miss

- **Miss**: data needs to be retrieved from a block in the lower level (Block Y)
  - **Miss Rate** = 1 - (Hit Rate)
  - **Miss Penalty**: Time to replace a block in the upper level + Time to deliver the block the processor

- **Hit Time << Miss Penalty** (500 instructions on Alpha 21264!)

![Memory Hierarchy Diagram]
Cache Measures

- **Hit rate**: fraction found in that level
  - So high that usually talk about *Miss rate*
  - Miss rate fallacy: as MIPS to CPU performance, miss rate to average memory access time in memory

- **Average memory-access time**
  \[ = \text{Hit time} + \text{Miss rate} \times \text{Miss penalty} \]
  (ns or clocks)

- **Miss penalty**: time to replace a block from lower level, including time to replace in CPU
  - **access time**: time to lower level
    \[ = f(\text{latency to lower level}) \]
  - **transfer time**: time to transfer block
    \[ = f(\text{BW between upper & lower levels}) \]
1 KB Direct Mapped Cache, 32B blocks

For a $2^N$ byte cache:
- The uppermost $(32 - N)$ bits are always the Cache Tag
- The lowest $M$ bits are the Byte Select (Block Size = $2^M$)

<table>
<thead>
<tr>
<th>Cache Tag</th>
<th>Example: 0x50</th>
<th>Cache Index</th>
<th>Byte Select</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ex: 0x01</td>
<td>Ex: 0x00</td>
</tr>
</tbody>
</table>

Valid Bit Cache Tag

Cache Data

<table>
<thead>
<tr>
<th>Byte 31</th>
<th>**</th>
<th>Byte 1</th>
<th>Byte 0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byte 63</td>
<td>**</td>
<td>Byte 33</td>
<td>Byte 32</td>
<td>1</td>
</tr>
</tbody>
</table>

| Byte 1023 | ** | Byte 992 | 31 |

Direct-mapped cache - storage
1 KB Direct Mapped Cache, 32B blocks

For a $2^N$ byte cache:
- The uppermost $(32 - N)$ bits are always the Cache Tag
- The lowest $M$ bits are the Byte Select (Block Size = $2^M$)

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Ex: 0x01
Ex: 0x00

Valid Bit  Cache Tag

0x50

Compare

Hit

Cache Data

<table>
<thead>
<tr>
<th>Byte 31</th>
<th>**</th>
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</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Byte 1023</td>
<td>**</td>
<td>Byte 992</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Direct-mapped cache – read access
1 KB Direct Mapped Cache, 32B blocks

- Cache location 0 can be occupied by data from main memory location 0, 32, 64, ... etc.
- Cache location 1 can be occupied by data from main memory location 1, 33, 65, ... etc.
  - In general, all locations with same Address<9:4> bits map to the same location in the cache. Which one should we place in the cache?
- How can we tell which one is in the cache?

### Cache Data

<table>
<thead>
<tr>
<th>Byte</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byte 31</td>
<td>**</td>
</tr>
<tr>
<td>Byte 63</td>
<td>**</td>
</tr>
<tr>
<td>Byte 33</td>
<td></td>
</tr>
<tr>
<td>Byte 992</td>
<td>**</td>
</tr>
</tbody>
</table>

Advanced Computer Architecture Chapter 1. p43
Direct-mapped Cache - structure

- **Capacity**: $C$ bytes (eg 1KB)
- **Blocksize**: $B$ bytes (eg 32)
- **Byte select bits**: $0..\log(B)-1$ (eg $0..4$)
- **Number of blocks**: $C/B$ (eg 32)
- **Address size**: $A$ (eg 32 bits)
- **Cache index size**: $I=\log(C/B)$ (eg $\log(32)=5$)
- **Tag size**: $A-I-\log(B)$ (eg $32-5-5=22$)
Two-way Set Associative Cache

- **N-way set associative**: $N$ entries for each Cache Index
  - $N$ direct mapped caches operated in parallel ($N$ typically 2 to 4)
- **Example**: Two-way set associative cache
  - Cache Index selects a “set” from the cache
  - The two tags in the set are compared in parallel
  - Data is selected based on the tag result
Disadvantage of Set Associative Cache

- **N-way Set Associative Cache v. Direct Mapped Cache:**
  - N comparators vs. 1
  - Extra MUX delay for the data
  - Data comes AFTER Hit/Miss

- **In a direct mapped cache, Cache Block is available BEFORE Hit/Miss:**
  - Possible to assume a hit and continue. Recover later if miss.
Basic cache terminology

Example: Intel Pentium 4 Level-1 cache (pre-Prescott)
- **Capacity:** 8K bytes (total amount of data cache can store)
- **Block:** 64 bytes (so there are 8K/64=128 blocks in the cache)
- **Sets:** 4 (addresses with same index bits can be placed in one of 4 ways)
- **Ways:** 32 (=128/4, that is each RAM array holds 32 blocks)
- **Index:** 5 bits (since $2^5=32$ and we need index to select one of the 32 ways)
- **Tag:** 21 bits (=32 minus 5 for index, minus 6 to address byte within block)
- **Access time:** 2 cycles, (.6ns at 3GHz; pipelined, dual-ported [load+store])
4 Questions for Memory Hierarchy

◆ Q1: Where can a block be placed in the upper level?
   *(Block placement)*

◆ Q2: How is a block found if it is in the upper level?
   *(Block identification)*

◆ Q3: Which block should be replaced on a miss?
   *(Block replacement)*

◆ Q4: What happens on a write?
   *(Write strategy)*
Q1: Where can a block be placed in the upper level?

In a fully-associative cache, block 12 can be placed in any location in the cache.

In a direct-mapped cache, block 12 can only be placed in one cache location, determined by its low-order address bits -

\[(12 \mod 8) = 4\]

In a two-way set-associative cache, the set is determined by its low-order address bits -

\[(12 \mod 4) = 0\]

Block 12 can be placed in either of the two cache locations in set 0.
Q2: How is a block found if it is in the upper level?

- **Tag on each block**
  - No need to check index or block offset

- **Increasing associativity shrinks index, expands tag**

---

**Tag on each block**

- No need to check index or block offset

**Increasing associativity shrinks index, expands tag**
Q3: Which block should be replaced on a miss?

- Easy for Direct Mapped
- Set Associative or Fully Associative:
  - Random
  - LRU (Least Recently Used)

<table>
<thead>
<tr>
<th>Assoc:</th>
<th>2-way</th>
<th>4-way</th>
<th>8-way</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 KB</td>
<td>5.2%</td>
<td>4.7%</td>
<td>4.4%</td>
</tr>
<tr>
<td></td>
<td>5.7%</td>
<td>5.3%</td>
<td>5.0%</td>
</tr>
<tr>
<td>64 KB</td>
<td>1.9%</td>
<td>1.5%</td>
<td>1.4%</td>
</tr>
<tr>
<td></td>
<td>2.0%</td>
<td>1.7%</td>
<td>1.5%</td>
</tr>
<tr>
<td>256 KB</td>
<td>1.15%</td>
<td>1.13%</td>
<td>1.12%</td>
</tr>
<tr>
<td></td>
<td>1.17%</td>
<td>1.13%</td>
<td>1.12%</td>
</tr>
</tbody>
</table>
Q4: What happens on a write?

- **Write through**—The information is written to both the block in the cache and to the block in the lower-level memory.

- **Write back**—The information is written only to the block in the cache. The modified cache block is written to main memory only when it is replaced.
  
  - is block clean or dirty?

**Pros and Cons of each?**

- WT: read misses cannot result in writes
- WB: no repeated writes to same location

**WT always combined with write buffers so that don't wait for lower level memory**
Write Buffer for Write Through

A Write Buffer is needed between the Cache and Memory

- Processor: writes data into the cache and the write buffer
- Memory controller: write contents of the buffer to memory

Write buffer is just a FIFO:

- Typical number of entries: 4
- Works fine if: Store frequency (w.r.t. time) \(<\) 1 / DRAM write cycle

Memory system designer’s nightmare:

- Store frequency (w.r.t. time) \(\rightarrow\) 1 / DRAM write cycle
- Write buffer saturation
By taking advantage of the principle of locality:
- Present the user with as much memory as is available in the cheapest technology.
- Provide access at the speed offered by the fastest technology.
Large-scale storage

StorageTek STK 9310 ("Powderhorn")
- 2,000, 3,000, 4,000, 5,000, or 6,000 cartridge slots per library storage module (LSM)
- Up to 24 LSMs per library (144,000 cartridges) under ACSLS control
- Up to 16 LSMs per library (96,000 cartridges) under NCS control
- 120 TB (1 LSM) to 28,800 TB capacity (24 LSM)
- Up to 30 MB/sec native throughput per hour

- Up to 28.8 petabytes
- Ave 4s to load tape
Summary #1/4: Pipelining & Performance

- Just overlap tasks; easy if tasks are independent
- Speed Up $\leq$ Pipeline Depth; if ideal CPI is 1, then:
  \[ \text{Speedup} = \frac{\text{Pipeline depth}}{1 + \text{Pipeline stall CPI}} \times \frac{\text{Cycle Time}_{\text{unpipelined}}}{\text{Cycle Time}_{\text{pipelined}}} \]

- Hazards limit performance on computers:
  - Structural: need more HW resources
  - Data (RAW, WAR, WAW): need forwarding, compiler scheduling
  - Control: delayed branch, prediction

- Time is measure of performance: latency or throughput

- CPI Law:
  \[
  \text{CPU time} = \frac{\text{Seconds}}{\text{Program}} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Cycle}}
  \]
Summary #2/4: Caches

◆ The Principle of Locality:
  - Program access a relatively small portion of the address space at any instant of time.
    - Temporal Locality: Locality in Time
    - Spatial Locality: Locality in Space

◆ Three Major Categories of Cache Misses:
  - **Compulsory Misses**: sad facts of life. Example: cold start misses.
  - **Capacity Misses**: increase cache size
  - **Conflict Misses**: increase cache size and/or associativity.

◆ Write Policy:
  - **Write Through**: needs a write buffer.
  - **Write Back**: control can be complex

◆ Today CPU time is often dominated by memory access time, not just computational work. What does this mean to Compilers, Data structures, Algorithms?
Additional material
Pipelining: A very familiar idea...

- Laundry Example
- Ann, Brian, Cathy, Dave each have one load of clothes to wash, dry, and iron
- Washer takes 30 minutes
- Dryer takes 40 minutes
- Ironing takes 20 minutes
Sequential Laundry takes 6 hours for 4 loads.

If they learned pipelining, how long would laundry take?
Pipelined Laundry: Principle: everyone starts work ASAP

Pipelined laundry takes 3.5 hours for 4 loads
Pipelined Laundry: Lessons-

- Pipelining doesn't help latency of single task, it helps throughput of entire workload
- Pipeline rate limited by slowest pipeline stage
- Multiple tasks operating simultaneously
- Potential speedup = Number pipe stages
- Unbalanced lengths of pipe stages reduces speedup
- Time to "fill" pipeline and time to "drain" it reduces speedup
- Speedup comes from parallelism
  - For free – no new hardware

Pipelined laundry takes 3.5 hours for 4 loads
Now, review basic performance issues in processor design

Which is faster?

<table>
<thead>
<tr>
<th>Plane</th>
<th>Washington DC to Paris</th>
<th>Speed</th>
<th>Passengers</th>
<th>Throughput (pmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing 747</td>
<td>6.5 hours</td>
<td>610 mph</td>
<td>470</td>
<td>286,700</td>
</tr>
<tr>
<td>BAC/Sud Concorde</td>
<td>3 hours</td>
<td>1350 mph</td>
<td>132</td>
<td>178,200</td>
</tr>
</tbody>
</table>

- Time to run the task (ExTime)
  - Execution time, response time, latency
- Tasks per day, hour, week, sec, ns ... (Performance)
  - Throughput, bandwidth

(Background material not covered in lectures)
Definitions

Performance is in units of things per sec
   bigger is better

If we are primarily concerned with response time

performance(x) = \frac{1}{\text{execution\_time}(x)}

"X is n times faster than Y" means

\[
\frac{\text{Performance}(X)}{\text{Performance}(Y)} = \frac{\text{Execution\_time}(Y)}{\text{Execution\_time}(X)}
\]

Background material not covered in lectures)
## Aspects of CPU Performance (CPU Law)

The CPU time can be calculated using the formula:

\[
\text{CPU time} = \frac{\text{Seconds}}{\text{Program}} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Cycle}}
\]

<table>
<thead>
<tr>
<th></th>
<th>Inst Count</th>
<th>CPI</th>
<th>Clock Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compiler</td>
<td>X</td>
<td>(X)</td>
<td></td>
</tr>
<tr>
<td>Inst. Set.</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Organization</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Technology</td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

*Background material not covered in lectures*
Cycles Per Instruction (Throughput)

“Average Cycles per Instruction”

\[
CPI = \frac{(CPU \ Time \times Clock \ Rate)}{Instruction \ Count} = \frac{Cycles}{Instruction \ Count}
\]

\[
CPU \ time = Cycle \ Time \times \sum_{j=1}^{n} CPI_j \times I_j
\]

“Instruction Frequency”

\[
CPI = \sum_{j=1}^{n} CPI_j \times F_j \quad \text{where} \quad F_j = \frac{I_j}{\text{Instruction \ Count}}
\]

Background material not covered in lectures)
Example: Calculating CPI

<table>
<thead>
<tr>
<th>Op</th>
<th>Freq</th>
<th>Cycles</th>
<th>CPI(i)</th>
<th>(% Time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALU</td>
<td>50%</td>
<td>1</td>
<td>.5</td>
<td>(33%)</td>
</tr>
<tr>
<td>Load</td>
<td>20%</td>
<td>2</td>
<td>.4</td>
<td>(27%)</td>
</tr>
<tr>
<td>Store</td>
<td>10%</td>
<td>2</td>
<td>.2</td>
<td>(13%)</td>
</tr>
<tr>
<td>Branch</td>
<td>20%</td>
<td>2</td>
<td>.4</td>
<td>(27%)</td>
</tr>
</tbody>
</table>

**Typical Mix of instruction types in program**

- ALU: 50% of time, 1 cycle per instruction, CPI = 0.5, 33% of CPI
- Load: 20% of time, 2 cycles per instruction, CPI = 0.4, 27% of CPI
- Store: 10% of time, 2 cycles per instruction, CPI = 0.2, 13% of CPI
- Branch: 20% of time, 2 cycles per instruction, CPI = 0.4, 27% of CPI

**CPI Calculation:**

\[
CPI = \frac{0.5 \times 33\% + 0.4 \times 27\% + 0.2 \times 13\% + 0.4 \times 27\%}{100\%} = 1.5
\]
**Example: Branch Stall Impact**

- Assume CPI = 1.0 ignoring branches
- Assume solution was stalling for 3 cycles
- If 30% branch, Stall 3 cycles

<table>
<thead>
<tr>
<th>Op</th>
<th>Freq</th>
<th>Cycles</th>
<th>CPI(i)</th>
<th>(% Time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other</td>
<td>70%</td>
<td>1</td>
<td>.7</td>
<td>(37%)</td>
</tr>
<tr>
<td>Branch</td>
<td>30%</td>
<td>4</td>
<td>1.2</td>
<td>(63%)</td>
</tr>
</tbody>
</table>

=> new CPI = 1.9, or almost 2 times slower

Background material not covered in lectures)
Example 2: Speed Up Equation for Pipelining

\[
\text{CPI}_{\text{pipelined}} = \text{Ideal CPI} + \text{Average Stall cycles per Inst}
\]

\[
\text{Speedup} = \frac{\text{Ideal CPI} \times \text{Pipeline depth}}{\text{Ideal CPI} + \text{Pipeline stall CPI}} \times \frac{\text{Cycle Time}_{\text{unpipelined}}}{\text{Cycle Time}_{\text{pipelined}}}
\]

For simple RISC pipeline, Ideal CPI = 1:

\[
\text{Speedup} = \frac{\text{Pipeline depth}}{1 + \text{Pipeline stall CPI}} \times \frac{\text{Cycle Time}_{\text{unpipelined}}}{\text{Cycle Time}_{\text{pipelined}}}
\]

Background material not covered in lectures)
Example 3: Evaluating Branch Alternatives (for 1 program)

\[
\text{Pipeline speedup} = \frac{\text{Pipeline depth}}{1 + \text{Branch frequency} \times \text{Branch penalty}}
\]

<table>
<thead>
<tr>
<th>Scheduling scheme</th>
<th>Branch penalty</th>
<th>CPI</th>
<th>speedup v. stall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stall pipeline</td>
<td>3</td>
<td>1.42</td>
<td>1.0</td>
</tr>
<tr>
<td>Predict taken</td>
<td>1</td>
<td>1.14</td>
<td>1.26</td>
</tr>
<tr>
<td>Predict not taken</td>
<td>1</td>
<td>1.09</td>
<td>1.29</td>
</tr>
<tr>
<td>Delayed branch</td>
<td>0.5</td>
<td>1.07</td>
<td><strong>1.31</strong></td>
</tr>
</tbody>
</table>

Assuming Conditional & Unconditional branches make up 14% of the total instruction count, and 65% of them change the PC

Background material not covered in lectures)
Example 4: Dual-port vs. Single-port

- **Machine A**: Dual ported memory ("Harvard Architecture")
- **Machine B**: Single ported memory, but its pipelined implementation has a 1.05 times faster clock rate
- **Ideal CPI = 1** for both
- **Loads are 40% of instructions executed**

\[
\text{SpeedUp}_A = \frac{\text{Pipeline Depth}}{1 + 0} \times \left( \frac{\text{clock}_\text{unpipe}}{\text{clock}_\text{pipe}} \right) = \text{Pipeline Depth}
\]

\[
\text{SpeedUp}_B = \frac{\text{Pipeline Depth}}{1 + 0.4 \times 1} \times \left( \frac{\text{clock}_\text{unpipe}}{(\text{clock}_\text{unpipe} / 1.05)} \right) = \left( \frac{\text{Pipeline Depth}}{1.4} \right) \times 1.05 = 0.75 \times \text{Pipeline Depth}
\]

\[
\frac{\text{SpeedUp}_A}{\text{SpeedUp}_B} = \frac{\text{Pipeline Depth}}{(0.75 \times \text{Pipeline Depth})} = 1.33
\]

**Machine A is 1.33 times faster**

(Background material not covered in lectures)