UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

Dipartimento di Scienze Fisiche, Informatiche e Matematiche

3. Prestazioni dei Computer

Architettura dei calcolatori [MN1-1143]

Corso di Laurea in INFORMATICA
(D.M.270/04) [16-215]
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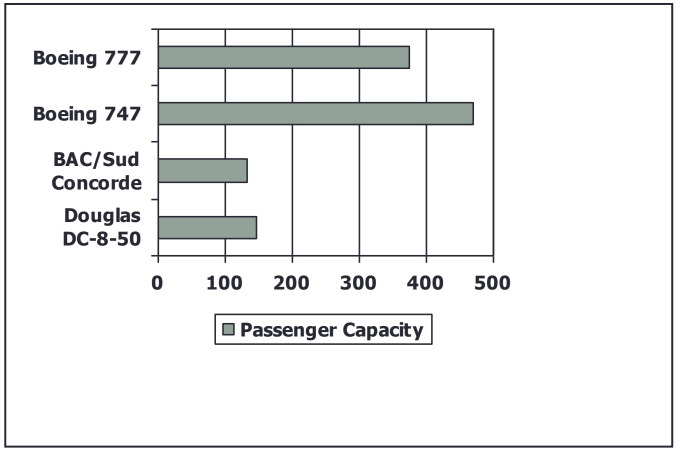
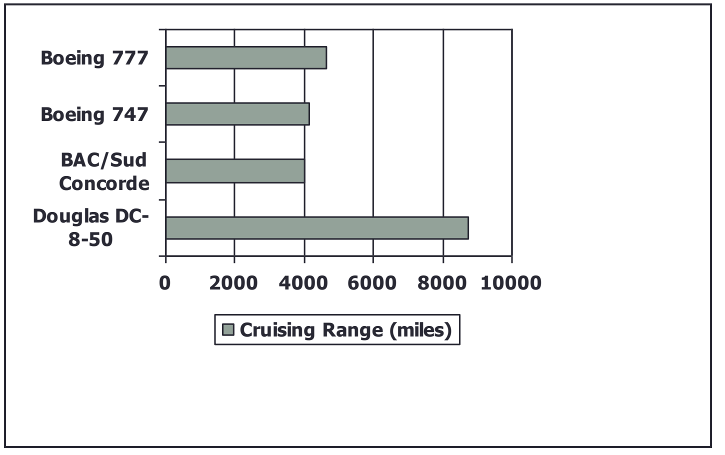
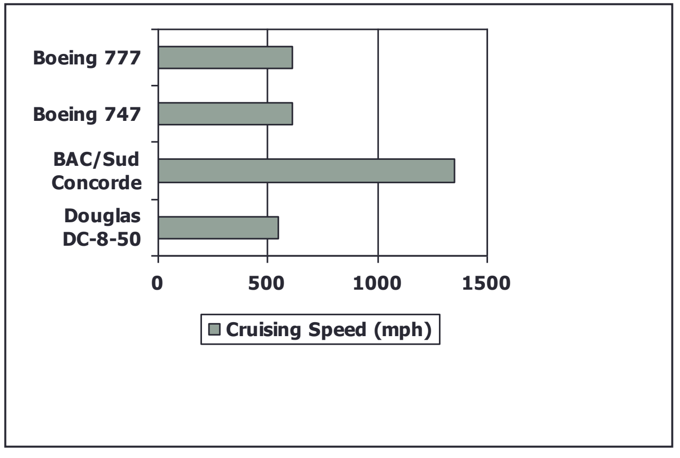
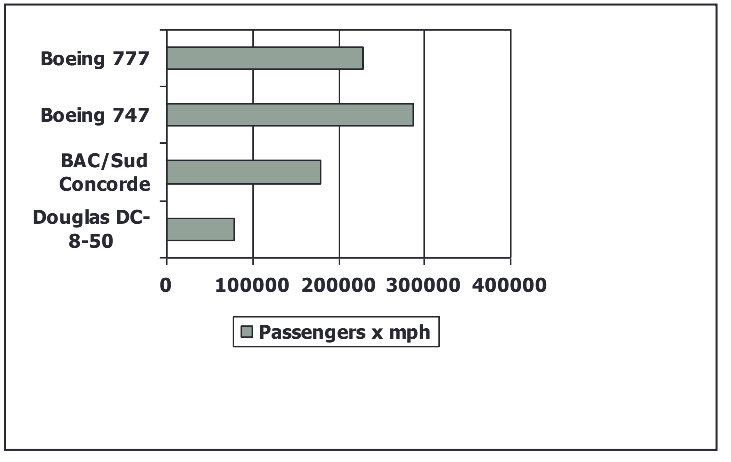
Defining Performance

- Which airplane has the best performance?









Response Time and Throughput

- **Response time (latency, execution time)**
  - How long it takes to do a task
- **Throughput**
  - Total work done per unit time
    - e.g., tasks/transactions/… per hour
- How are response time and throughput affected by
  - Replacing the processor with a faster version?
  - Adding more processors?
- We’ll focus on response time for now…

Understanding Computer Performance

What determines the performance of a program?

- Algorithm
  - Determines number of operations executed

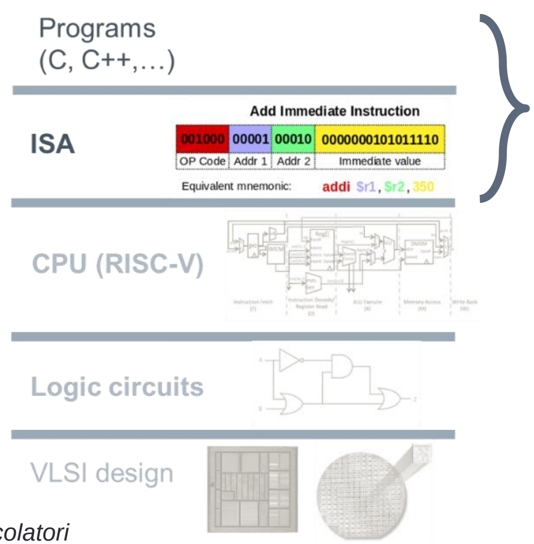
```
ALGORITHM 1

BEGIN:
      ISTR1
      ISTR2
      ISTR3
      ISTR4
      ...
      ISTR20
END
```

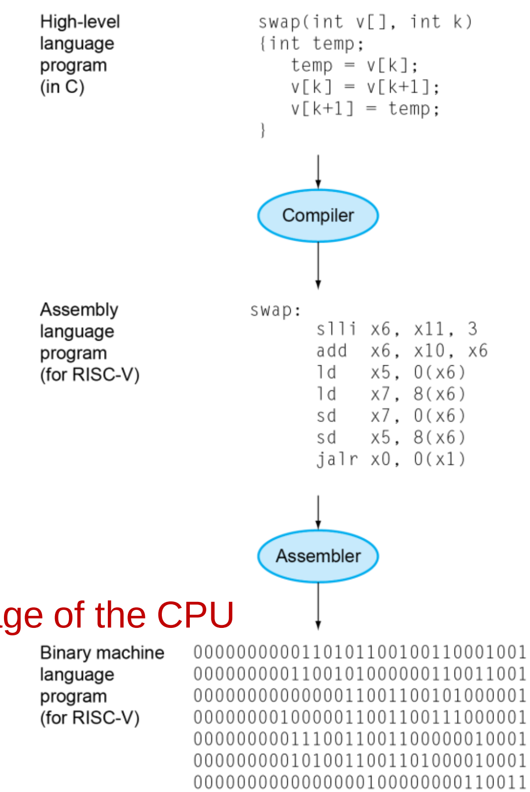
```
ALGORITHM 2

BEGIN:
      ISTR1
      ISTR2
      ISTR3
      ISTR4
      ...
      ISTR15
END
```

Understanding Computer Performance

What determines the performance of a program?

- Algorithm
  - Determines number of operations executed
- Programming language, compiler, architecture
  - Determine number of machine instructions executed per operation

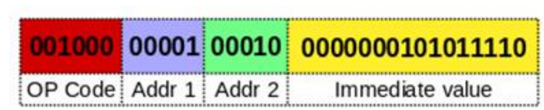




language of the CPU

The HW/SW interface

ISA



Understanding Computer Performance

What determines the performance of a program?

- Algorithm
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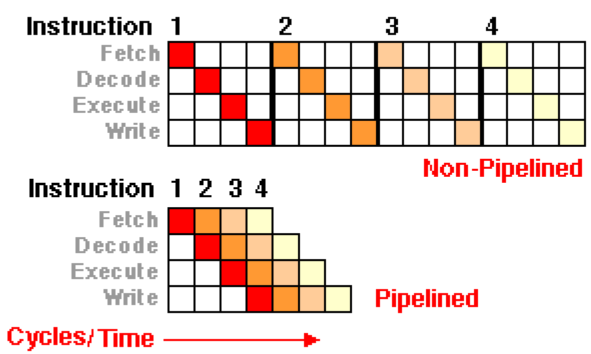
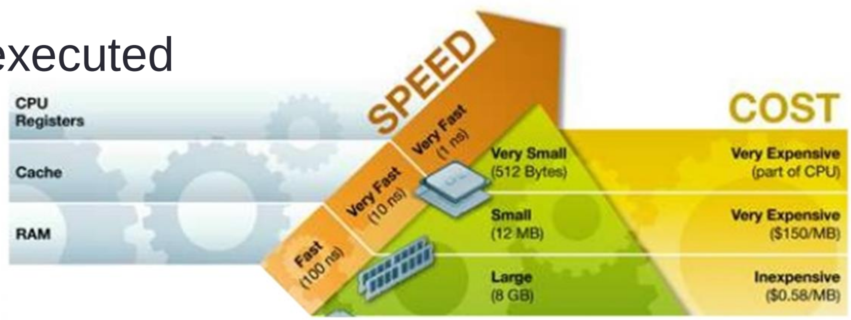
- Programming language, compiler, architecture
  - Determine number of **machine instructions** executed per operation

- Processor and memory system
  - Determine how **fast** instructions are executed





Understanding Computer Performance

What determines the performance of a program?

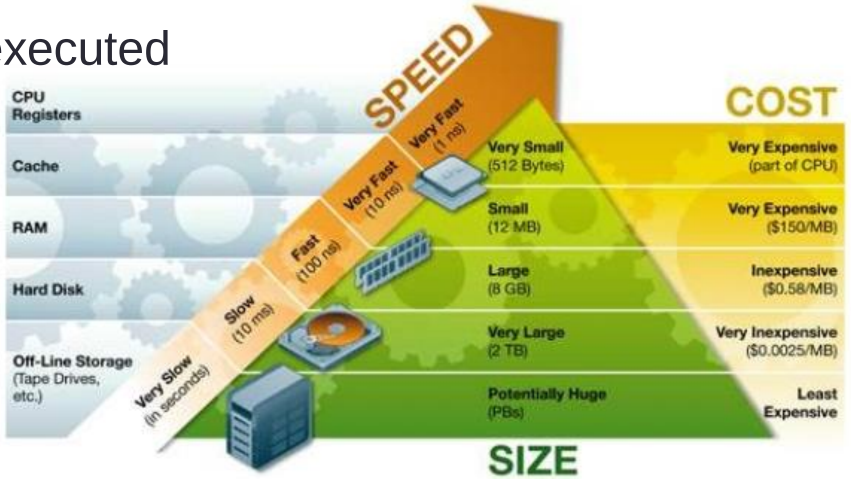
- Algorithm
  - Determines number of **operations** executed

- Programming language, compiler, architecture
  - Determine number of **machine instructions** executed per operation

The HW/SW interface

- Processor and memory system
  - Determine how **fast** instructions are executed

- I/O system (including OS)
  - Determines how fast I/O operations are executed



Relative Performance

- Define **Performance = 1/Execution Time**
- "X is n time faster than Y"

$$\text{Performance}_X / \text{Performance}_Y$$
$$= \text{Execution time}_Y / \text{Execution time}_X = n$$

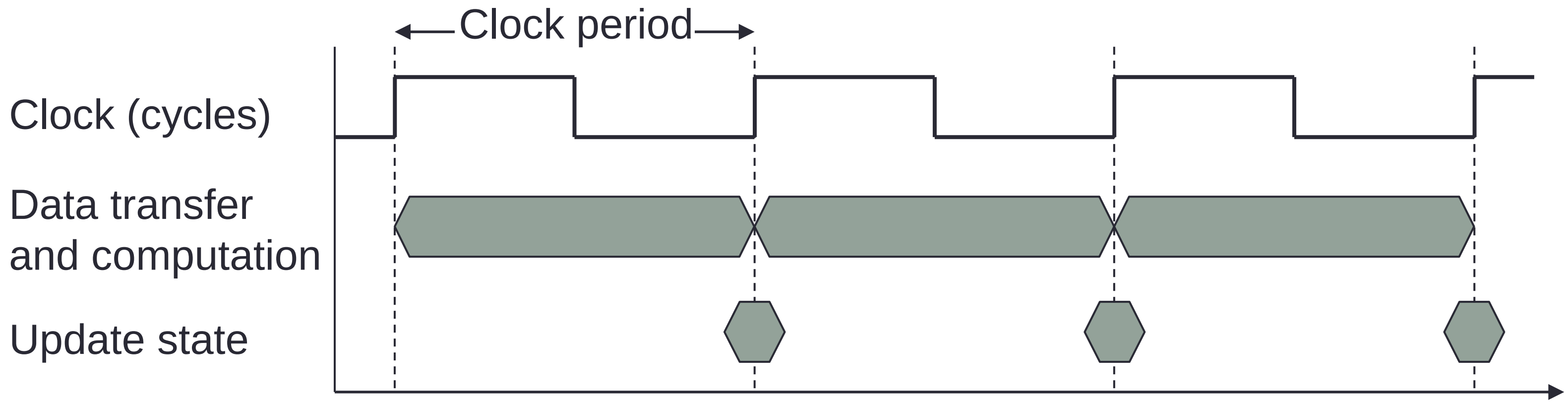
- **Example**: time taken to run a program
  - 10s on A, 15s on B
  - Execution Time_B / Execution Time_A
    = 15s / 10s = 1.5
  - So A is 1.5 times faster than B

Measuring Execution Time

- **Elapsed time**
  - Total response time, including all aspects
    - Processing, I/O, OS overhead, idle time
  - Determines system performance
- **CPU time**
  - Time spent processing a given job
    - Discounts I/O time, other jobs' shares
  - Comprises user CPU time and system CPU time
  - Different programs are affected differently by CPU and system performance

CPU Clocking

- Operation of digital hardware governed by a constant-rate clock



- **Clock period**: duration of a clock cycle
  - e.g., 250ps = 0.25ns = 250×10^{-12}s
- **Clock frequency (rate)**: cycles per second
  - e.g., 4.0GHz = 4000MHz = 4.0×10^{9}Hz

CPU Time

$$\text{CPU Time} = \text{CPU Clock Cycles} \times \text{Clock Cycle Time}$$

$$= \frac{\text{CPU Clock Cycles}}{\text{Clock Rate}}$$

- Performance improved by
  - Reducing number of clock cycles
  - Increasing clock rate
  - Hardware designer must often trade off clock rate against cycle count

CPU Time Example

- Computer A: 2GHz clock, 10s CPU time
- Designing Computer B
  - Aim for 6s CPU time
  - Can do faster clock, but causes 1.2 × clock cycles
- How fast must Computer B clock be?

$$\text{Clock Rate}_B$$

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$$= 10\text{s} \times 2\text{GHz} = 20 \times 10^9$$

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$$\text{Clock Rate}_B = \frac{1.2 \times 20 \times 10^9}{6\text{s}} = \frac{24 \times 10^9}{6\text{s}}$$

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$$\text{Clock Rate}_B = \frac{1.2 \times 20 \times 10^9}{6\text{s}} = \frac{24 \times 10^9}{6\text{s}} = 4\text{GHz}$$

Instruction Count and CPI

$$\text{Clock Cycles} = \text{Instruction Count} \times \text{Cycles per Instruction}$$

$$\text{CPU Time} = \text{Instruction Count} \times \text{CPI} \times \text{Clock Cycle Time}$$

$$= \frac{\text{Instruction Count} \times \text{CPI}}{\text{Clock Rate}}$$

- **Instruction Count** for a program
  - Determined by program, ISA and compiler

- Average **cycles per instruction (CPI)**
  - Determined by CPU hardware
  - If different instructions have different *CPI*
    - Average CPI affected by instruction mix

CPI Example

- Computer A: Cycle Time = 250ps, CPI = 2.0
- Computer B: Cycle Time = 500ps, CPI = 1.2
- Same ISA
- Which is faster, and by how much?

$$\text{CPU Time}_A$$

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$$

$$\text{CPU Time}_B$$

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$$= \text{I} \times 2.0 \times 250\text{ps} = \text{I} \times 500\text{ps}$$
$$\text{CPU Time}_B = \text{Instruction Count} \times \text{CPI}_B \times \text{Cycle Time}_B$$

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\text{CPU Time}_B &= \text{Instruction Count} \times \text{CPI}_B \times \text{Cycle Time}_B \\
&= I \times 1.2 \times 500\text{ps} = I \times 600\text{ps}
\end{aligned}$$

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A is faster…

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$$\frac{\text{CPU Time}_B}{\text{CPU Time}_A}$$

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$$\frac{\text{CPU Time}_B}{\text{CPU Time}_A} = \frac{I \times 600\text{ps}}{I \times 500\text{ps}} = 1.2$$

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\text{CPU Time}_B &= \text{Instruction Count} \times \text{CPI}_B \times \text{Cycle Time}_B \\
&= I \times 1.2 \times 500\text{ps} = I \times 600\text{ps}
\end{aligned}$$

$$\frac{\text{CPU Time}_B}{\text{CPU Time}_A} = \frac{I \times 600\text{ps}}{I \times 500\text{ps}} = 1.2 \quad \leftarrow \text{…by this much}$$

CPI in More Detail

- If different instruction classes take different numbers of cycles

$$\text{Clock Cycles} = \sum_{i=1}^{n} (\text{CPI}_i \times \text{Instruction Count}_i)$$

- Weighted average CPI

$$\text{CPI} = \frac{\text{Clock Cycles}}{\text{Instruction Count}} = \sum_{i=1}^{n} \left(\text{CPI}_i \times \underbrace{\frac{\text{Instruction Count}_i}{\text{Instruction Count}}}_{\text{Relative frequency}} \right)$$

CPI Example

- Alternative compiled code sequences using instructions in classes A, B, C

Class	A	B	C
CPI for class	1	2	3
IC in sequence 1	2	1	2
IC in sequence 2	4	1	1

- Sequence 1: IC = 5
  - Clock Cycles
    $= 2\times1 + 1\times2 + 2\times3$
    $= 10$
  - Avg. CPI = 10/5 = 2.0
- Sequence 2: IC = 6
  - Clock Cycles
    $= 4\times1 + 1\times2 + 1\times3$
    $= 9$
  - Avg. CPI = 9/6 = 1.5

Performance Summary

$$\text{CPU Time} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock cycle}}$$

- Performance depends on
  - **Algorithm**: affects IC, possibly CPI
  - **Programming language**: affects IC, CPI
  - **Compiler**: affects IC, CPI
  - **Instruction set architecture (ISA)**: affects IC, CPI, T_c