Performance & Wrap-Up

Lecture 20
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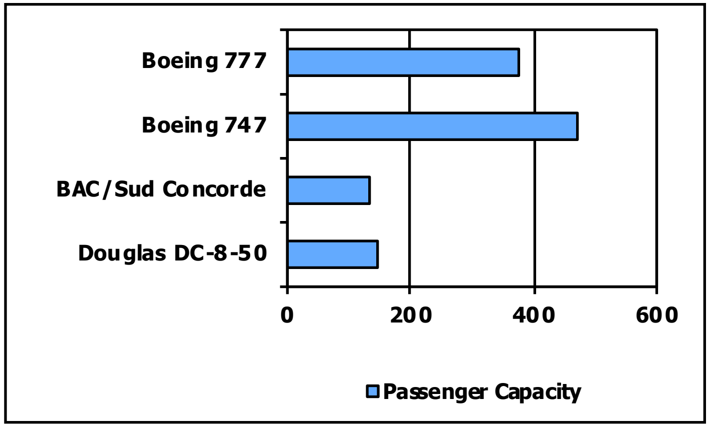
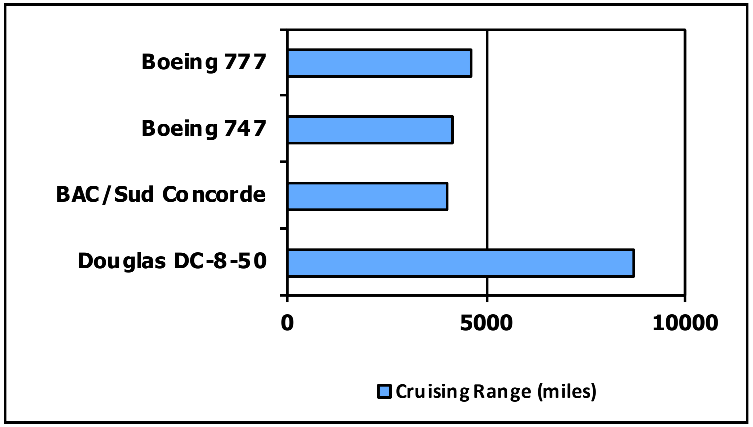
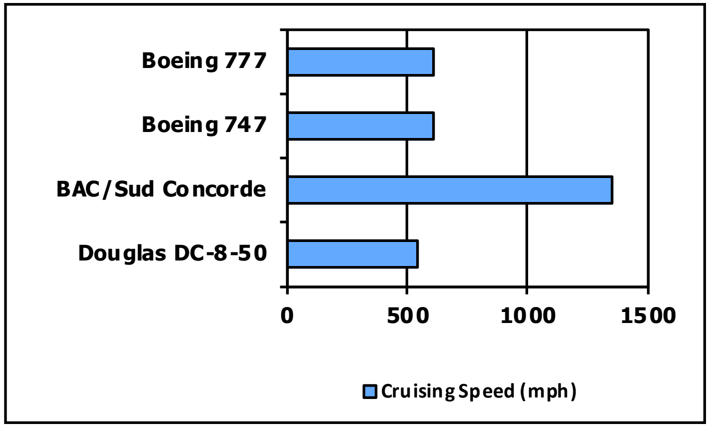
***Slide credits**: [CS:APP3e] slides from CMU; [COD5e] slides from Elsevier Inc.*

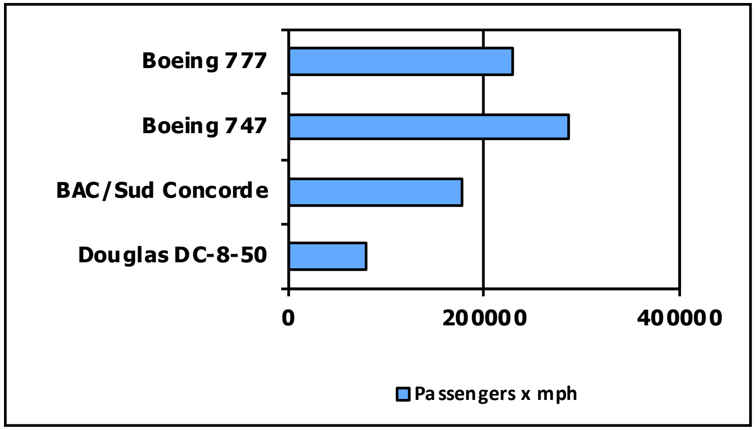
Performance Example

- Question: Which aircraft performs the best??









Today

Textbook: [P&H] 1.6

- Performance Metrics: Time and Rate
- Summarizing Performance
- Now What?

Performance Metrics #1: Time

- **Wall-clock time, response time, or elapsed time**
  - Actual time from start to completion
  - Includes everything: CPU time for other programs as well as for itself, I/O, operating system overheads, etc

- **CPU (execution) time**
  - CPU time spent for a given program
  - user CPU time + system CPU time
  - e.g., results of UNIX `time` command

```
90.7u  12.9s  2:39  65%
```

Performance Metrics #1: Time

- **Decomposition of CPU (Execution) Time**

$$\text{CPU time} = \frac{\text{Seconds}}{\text{Program}}$$

$$= \frac{\text{Cycles}}{\text{Program}} \times \frac{\text{Seconds}}{\text{Cycle}}$$

$$= \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Cycle}}$$

This equation is called "Iron Law of CPU Performance."

Performance Metrics #1: Time

- **More on CPI (Clocks or Cycles Per Instruction)**
  - $$\text{CPI} = \frac{\sum_{i=1}^{n} (\text{CPI}_i \times I_i)}{\text{Instruction Count}}$$
  - CPI Example

Instruction Class	Frequency	CPI_i
ALU operations	43%	1
Loads	21%	2
Stores	12%	2
Branches	24%	2

$$\boxed{\text{CPI} = 0.43 \times 1 + 0.21 \times 2 + 0.12 \times 2 + 0.24 \times 2}$$

Performance Metrics #1: Time

- **Comparing CPIs of two CPUs**
  - Example question: What is the CPI of CPU_S and CPU_Q?

Instruction Type	Instr. count (millions)	Cycles per Instr. (CPI)	
		CPU_S	CPU_Q
Arithmetic & Logic	10	1	1
Load & Store	5	4	2
Branch	4	2	3
Miscellaneous (기타)	1	4	4

$\mathbf{CPI_S} = (10 \times 1 + 5 \times 4 + 4 \times 2 + 1 \times 4) / (10 + 5 + 4 + 1) = 2.1$

$\mathbf{CPI_Q} = (10 \times 1 + 5 \times 2 + 4 \times 3 + 1 \times 4) / (10 + 5 + 4 + 1) = 1.8$

Question: So, CPU_Q always performs better?

Performance Metrics #1: Time

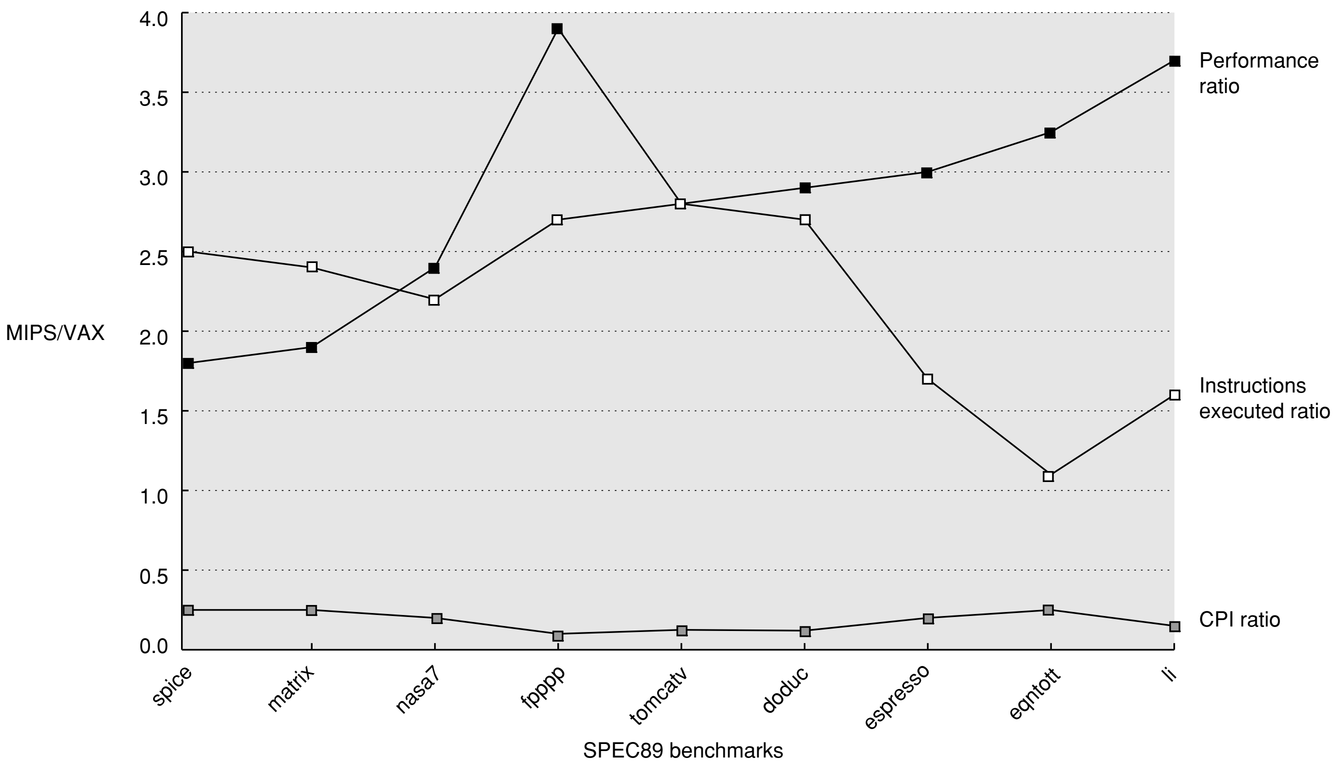
- Factors involved in the CPU Time

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

	Instructions / Program	Cycles / Instruction	Seconds / Cycle
Program	V		
Compiler	V		
ISA	V	V	
Organization		V	V
Technology			V

Performance Metrics #1: Time

- **RISC vs. CISC arguments**
  - **MIPS (typical RISC) vs. VAX8700 (typical CISC)**



Source : Hennessy & Patterson *Computer Architecture: A Quantitative Approach, 5th Ed.(Appencix L)*, Morgan Kaufmann, 2012

Performance Metrics #2: Rate

- **MIPS (million instructions per second)**
  - $\text{MIPS} = \dfrac{\text{Instruction count}}{\text{Execution time} \times 10^6}$
  - Specifies performance (roughly) inversely to execution time
  - Easy to understand; faster machines means bigger MIPS
  - Problems
    - It does not take into account the capabilities of the instructions.
    - It varies between programs on the same computer.
    - It can even vary inversely with performance!!

- **MFLOPS (million floating-point operations per second)**

Performance Metrics: Ratio

- "X is n times faster than Y" means:

$$\frac{\text{Execution Time}_Y}{\text{Execution Time}_X} = n$$

- "X is n% faster than Y" means:

$$\frac{\text{Execution Time}_Y}{\text{Execution Time}_X} = 1 + \frac{n}{100}$$

- "X is n order of magnitude faster than Y" means:

$$\frac{\text{Execution Time}_Y}{\text{Execution Time}_X} = 10^n$$

Summarizing Performance

- **Arithmetic mean** (Time) $$\frac{1}{n}\sum_{i=1}^{n} T_i$$
- **Harmonic mean** (Rate) $$\frac{n}{\sum_{i=1}^{n} \frac{1}{R_i}}$$
- **Geometric mean** (Ratio) $$\sqrt[n]{\prod_{i=1}^{n} Ratio_i}$$

Summarizing Performance: Arithmetic Mean

- **Used to summarize performance given in times**
  - Average Execution Time= $\left(\sum_{i=1}^{n} \text{Execution Times} \right) / n$
  - Assumes each benchmark is run an equal no. of times

- **Weighted Arithmetic Mean**
  - Weighted Average Execution Time = $\sum_{i=1}^{n} \left(W_i \times \text{Execution Times} \right) / \sum_{i=1}^{n} W_i$
  - One possible weight assignment: equal execution time on some machine

Summarizing Performance: Harmonic Mean

- **Used to summarize performance in rates (e.g., MIPS, FLOPS):**
  - Harmonic Mean = $n \;/\; \sum_{i=1}^{n} (1 / R_i)$
  - Example
    - Four programs execute at 10, 100, 50 and 20 MFLOPS, respectively
    - Harmonic mean is 4 / (1/10 + 1/100 + 1/50 + 1/20) = 22.2 MFLOPS

- **Weighted Harmonic Mean**
  - Weighted Harmonic Mean = $\sum_{i=1}^{n} W_i \;/\; \sum_{i=1}^{n} (W_i \;/\; R_i)$

Summary: Performance

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

- **"Execution time is the only and unimpeachable measure of performance"**
  - CPU time equation can predict performance by estimating the effects of changing features.
- **Measuring performance requires good care**
  - Good ways to summarize performance
  - Good workloads (benchmarks)

Today

Textbook: [P&H] 1.6

- Performance Metrics: Time and Rate
- Summarizing Performance
- **Now What?**

In Lecture 1…

- Do you remember this one?

Seoul National University

Why you should take this course?

- Because….You won't graduate if you don't take this course.
- Because….You want to design the next great instruction set.
  - Instruction set architecture has largely converged, especially in the desktop/server/laptop space.
  - Dictated by powerful market forces (Intel/ARM).
- Because….You want to become a computer architect and design the next great computer systems.
- **Because….The design, analysis, implementation concepts that you will learn are vital to all aspects of computer science and engineering – operating systems, computer networks, compiler, programming languages**
- **Because….The course will equip you with an intellectual toolbox for dealing with a host of systems design challenges**
- **And much more !!!**

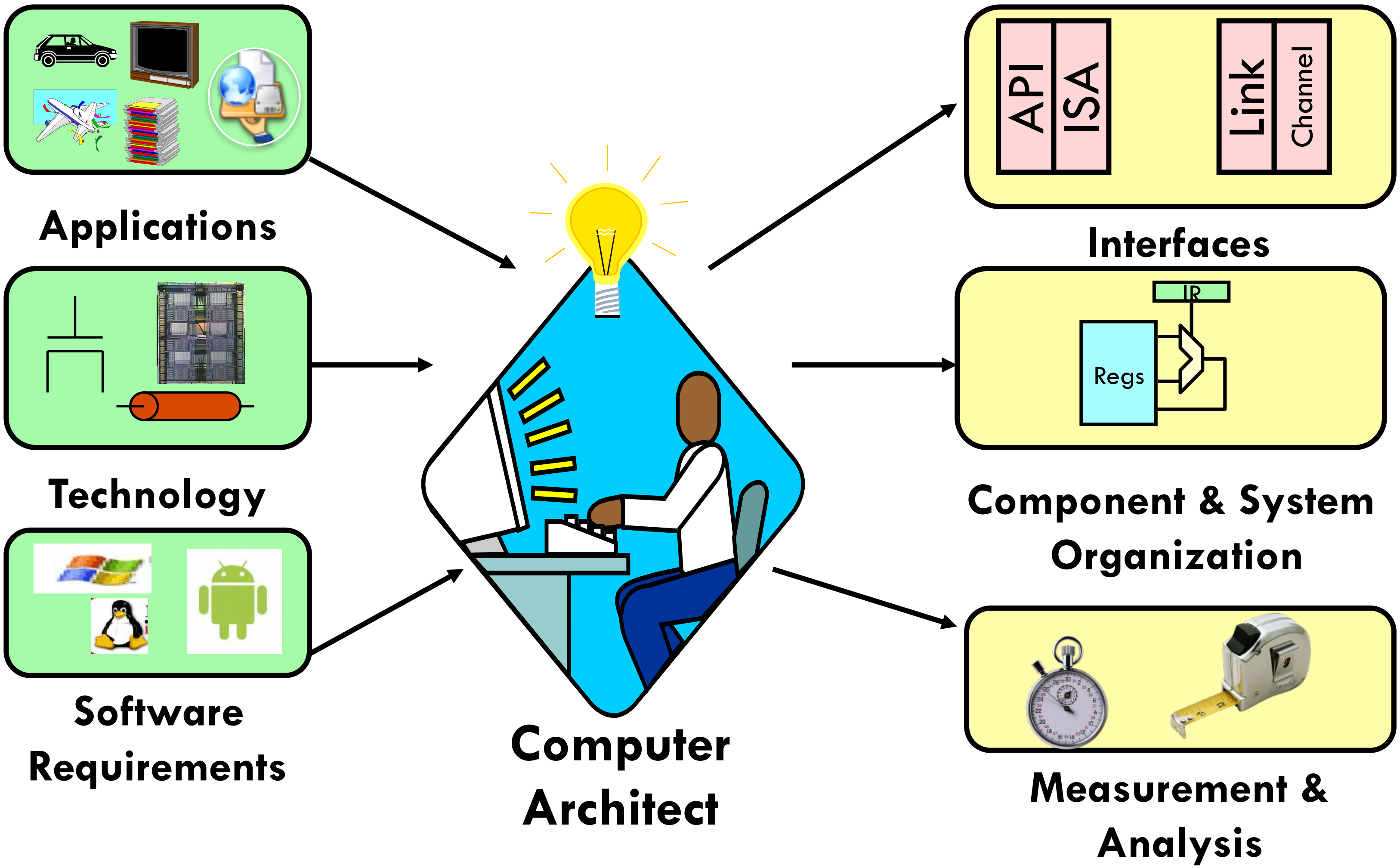
Source: Prof. Fernando C. Colon Osorio's lecture notes

SNU 4190.308-002: Computer Architecture (Fall 2016) 14

Where Are We Now?

- **Here is what we learned:**
  - Instruction Set Architecture (i.e., abstraction of hardware)
  - Representing numbers: integer and floating-point
  - x86-64 assembly and how to translate a C program into it
  - Basic processor organization
  - Branch prediction
  - Pipelining
  - Locality and memory hierarchy
  - Caches
  - Program optimization for caches
  - Virtual memory
  - Performance evaluation
- **I hope those tools provide a solid foundation for your CSE-related careers (as they did for mine).**

What Computer Architects Do?



Source: Stanford EE282 (Prof. C. Kozyrakis)

겨울방학 인턴/UROP 모집 공고

- **아키텍처 및 코드 최적화 연구실: 약간명 (1-2명)**
  - 빅데이터 프로세싱 (Apache Spark) 아키텍처 가속 기술 연구
  - JavaScript 기반 IoT 응용을 위한 CPU 아키텍처 연구
  - RISC-V CPU+Deep Learning Accelerator의 FPGA 프로토타이핑

- **학부행정실 UROP 공고 참고 (또는 contact professor)**

One More Thing

- **Final Exam**
  - Date: 12/18 (Tue) 10 AM – noon (2 hours)
  - Place: This classroom (#302-208)
  - Scope: Everything not in the scope of the midterm
  - Sample finals (with solutions) provided to help your study.
- **Please fill in course evaluation.**
  - I would appreciate your constructive feedback for the course.
  - I promise to LISTEN and IMPROVE the course based on it.
- **It was a great pleasure to teach you and I wish best of luck for all of your future endeavors! ☺**