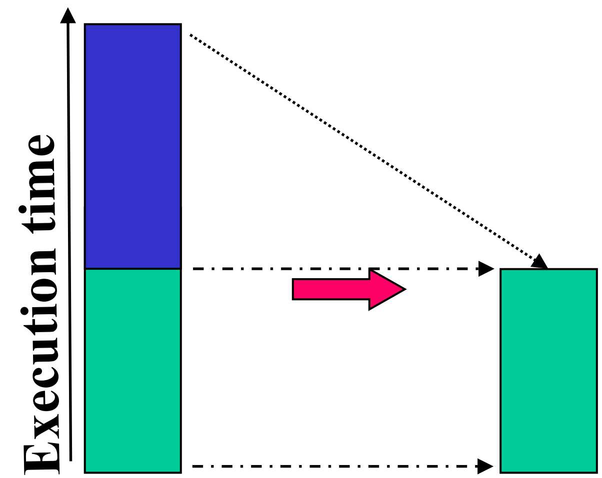
Lecture 4

14-01-2021

Amdahl's Law: Exercise 2

- A software engineer decides to rewrite a portion of a sequential program that accounts for 60% of execution time of the program:

  - **So that this portion can be run on multiple processors in parallel.**



- What is the maximum speedup that the software engineer can hope to achieve?

- $\boxed{100/40=2.5}$

Performance Measurements

- Performance measurement is important:
  - Helps us to determine if one processor (or computer) works faster than another.
  - **Intuitively, a computer has higher performance if it executes programs faster…**

How to Select A Computer System?

- Suppose you are working in a company.
- You have been asked by your manager to select a computer for some specific application:
  - **Lets say: to run a web service for your organization…**
- **How will you proceed?**

Purchasing Decision by a Novice…

- Computer A has a 2.5Ghz processor
- Computer B has a 3.2GHz processor
- Which one is faster?

B is naturally faster…

Simpleton

Obviously WRONG!

Where is the fallacy?

Comparing Computer Performance

- We say computer X is n times faster than Y, iff

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

Relative Performance

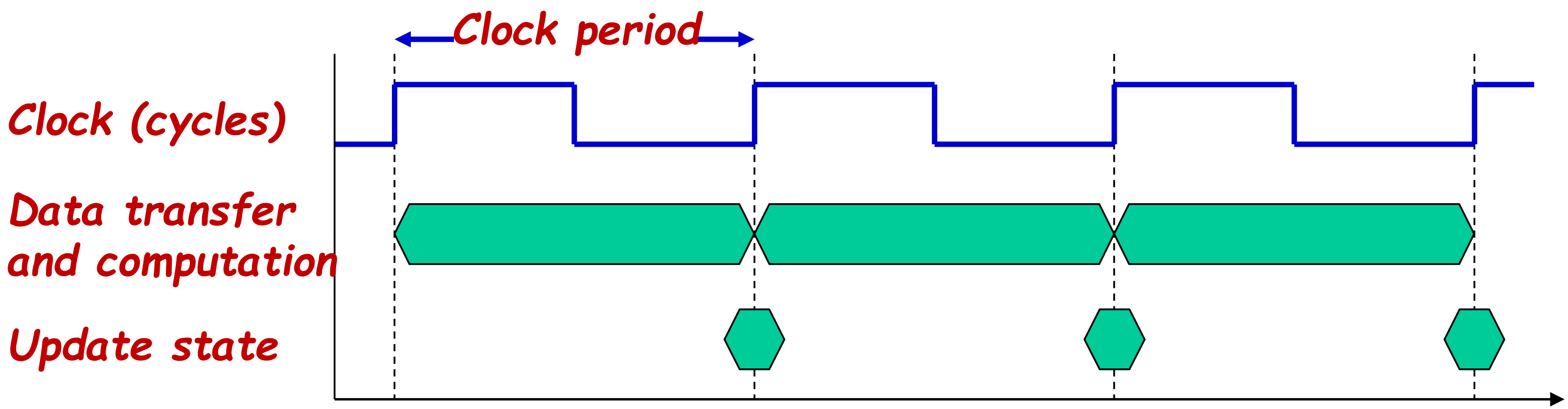
- Define Performance = 1/Execution Time
- "X is n time faster than Y"

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

- *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*

CPU Clocking

- All operation of computer are 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 can be improved by:
  - Reducing number of clock cycles
  - Increasing clock rate
  - Hardware designer must often trade off clock rate against cycle count

CPU Time Exercise

- Computer A: 2 GHz clock, takes 10s CPU time
- Computer B:
  - Completes the job in 6s CPU time
  - Has faster clock, but uses 1.2 × clock cycles
  - What is Computer B's clock rate?

$$\text{Clock Rate}_B = \frac{\text{Clock Cycles}_B}{\text{CPU Time}_B} = \frac{1.2 \times \text{Clock Cycles}_A}{6\text{s}}$$

$$\text{Clock Cycles}_A = \text{CPU Time}_A \times \text{Clock Rate}_A$$

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

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

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 (IC) 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**

Exercise

- 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?

$$\text{CPU Time}_A = \text{Instruction Count} \times \text{CPI}_A \times \text{Cycle Time}_A$$
$$= \text{I} \times 2.0 \times 250\text{ps} = \text{I} \times 500\text{ps}$$
$$\text{CPU Time}_B = \text{Instruction Count} \times \text{CPI}_B \times \text{Cycle Time}_B$$
$$= \text{I} \times 1.2 \times 500\text{ps} = \text{I} \times 600\text{ps}$$
$$\frac{\text{CPU Time}_B}{\text{CPU Time}_A} = \frac{\text{I} \times 600\text{ps}}{\text{I} \times 500\text{ps}} = 1.2$$

A is faster…

…by this much

Exercise

- A given application written in Java runs in 15 seconds on a desktop processor.
  - A new Java compiler is released that requires only 0.6 as many instructions as the old compiler.
  - Unfortunately, it increases the CPI by 1.1.
- How fast can we expect the application to run using this new compiler?

Ans: 15 sec × 0.66= 9.9 sec

Clock-Rate Based Performance Measurement

- Comparing performance based on clock rates alone, is obviously meaningless:
  - **Execution time=CPI × Clock cycle time × Number of instructions**
  - Caveat:
    - A processor with a higher clock rate may actually execute programs much slower!

Exercise: Which Machine is Faster and what is the speedup?

- **Machine A for prog X**
  - Clock cycle time = 10ns/cycle
  - CPI = 2.0

- **Machine B for prog X**
  - Clock cycle time = 30ns/cycle
  - CPI = 0.5

Assume same ISA.

Let I = number of instructions in the program.

CPU clock cycles (A) = I * 2.0
CPU time (A) = CPU clock cycles * clock cycle time
= I * 2.0 * 10
= I * 20 ns

CPU clock cycles (B) = I * 0.5
CPU time (B) = CPU clock cycles * clock cycle time
= I * 0.5 * 30
= I * 15 ns

$$\frac{Performance(A)}{Performance(B)} = \frac{Execution(B)}{Execution(A)} = 0.75$$

Exercise: Calculate Overall CPI (Cycles per Instruction)

Operation	Freq	CPI(i)
ALU	40%	1
Load	27%	2
Store	13%	2
Branch	20%	5

Typical Instruction Mix

Overall CPI= 1*0.4+ 2*0.27+ 2*0.13+5*0.2

= 2.2

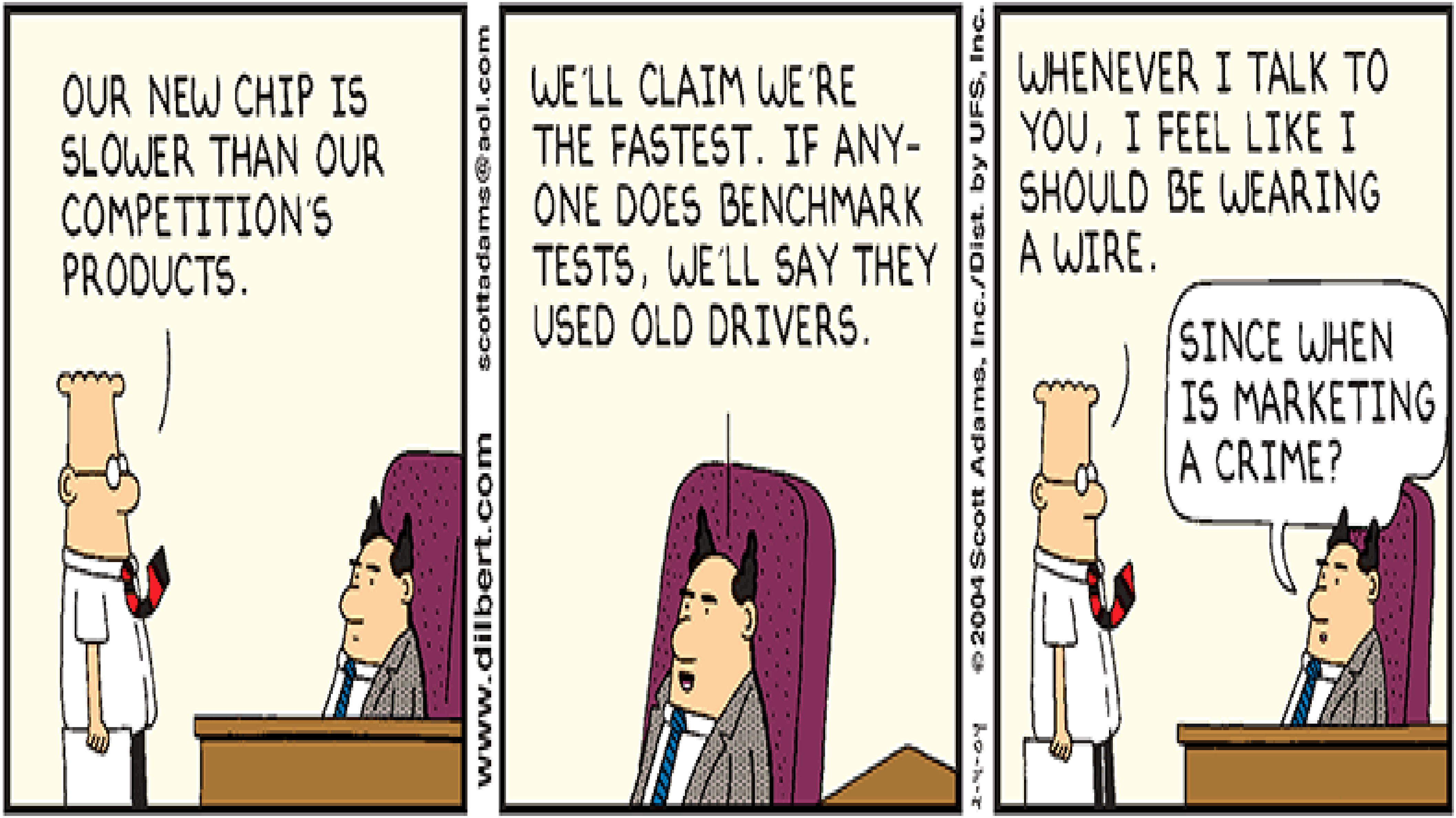
MIPS and MFLOPS

- Used extensively 30 years back.
- MIPS: millions of instructions processed per second.
- MFLOPS: Millions of FLoating point OPerations completed per Second

$$\text{MIPS} = \frac{\text{Instruction Count}}{\text{Exec. Time} \times 10^6} = \frac{\text{Clock Rate}}{\text{CPI} \times 10^6}$$

Problems with MIPS

- MIPS suffers from several severe shortcomings.
- So severe, made some one coin:
  - **"Meaningless Information about Processing Speed"**
- **A Major Problem:**
  - MIPS depends on the program being executed to measure MIPS.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WHENEVER I TALK TO YOU, I FEEL LIKE I SHOULD BE WEARING A WIRE.
SINCE WHEN IS MARKETING A CRIME?

Exercise 4

- A computer A-100 executes a certain benchmark program with an average CPI of 2.0.
- Another computer A-101 has the same instruction set but has an enhanced compiler.
- The compiler for A-101 generated 20% less instructions for the same benchmark program.
- The compiled code when run on A-101 achieved a CPI of 0.5 at 800MHz.
- In order for the two machines to have the same MIPS rating, what should be the clock rate of the computer A-100?

Exercise 4: Answer

- Let I be the number of instructions in the benchmark program
- A-101 executes 0.8*I instructions in 0.8*I*CPI(A-101)*C(A-101) seconds
- $= 0.8*I*0.5/(800*10^{6})$ seconds
- MIPS= 800/0.5= 1600
- MIPS of A-100=$I*10^{-6}/(I*2*C)=10^{-6}/(2*C)$
- Frequency of A-100=3200 MHz = 3.2GHz

Toy Benchmarks

- The performance of different computers can be compared by running some standard programs:
  - Quick sort, Merge sort, etc.
- But, the basic problem remains:
  - Even if a computer performs well for a toy benchmark, it may not perform well for the required applications.
  - **What can be a solution then?**

Synthetic Benchmarks

- Basic Principle: Analyze the distribution of instructions over a large number of practical programs.
- Synthesize a program that has the same instruction distribution as a typical program:
  - Need not compute something meaningful.
- Dhrystone, Khornerstone, Linpack are some of the older synthetic benchmarks:
  - More recent is **SPEC**…

Dhrystone

- Short synthetic benchmark program
  - Largely uses integer programming.
  - Based on published statistics on use of programming language features;
  - original publication in CACM 27,10 (Oct. 1984),
- **Problems:** Due to its small size (100 HLL statements, about 1.5 KB code), the memory system outside the cache is not tested;
  - **Compilers can easily optimize for Dhrystone.**

Linpack

- Developed from the "LINPACK" package of linear algebra routines.
  - Originally written in FORTRAN; a C version also exists.
- Almost all of the benchmark's time is spent in a subroutine executing the inner loop for frequent matrix operations:
  - Such as **y(i) = y(i) + a * x(i)**
- The standard version operates on 100x100 matrices;
  - There are also versions for sizes 300x300 and 1000x1000, with different optimization rules.
- **Problems:**
  - Code mostly concerns for matrix computation.
  - LINPACK is easily vectorizable on most systems.

Problems with Benchmarks

- Linpack consists of different types of operations on 300*300 matrices.
  - Optimization of this inner-loop resulted in performance improvement by a factor of 9.
- Optimizing compilers can discard 25% Dhrystone code
- Solution: **Benchmark suite**

SPEC Benchmarks

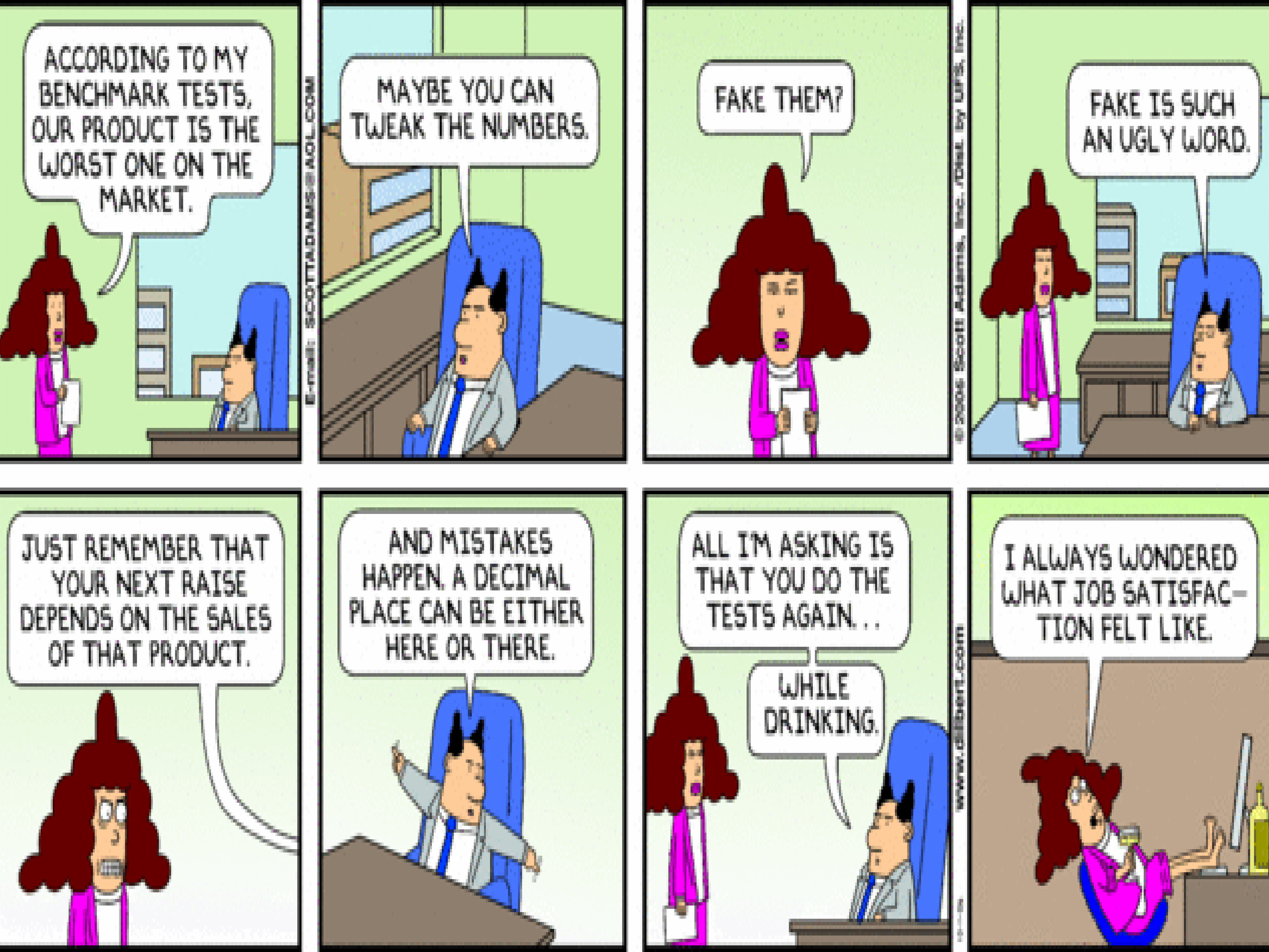
- SPEC: Standard Performance Evaluation Corporation:
  - A non-profit organization (www.spec.org)
  - **Uses a suite of programs**
- CPU-intensive benchmark for evaluating processor performance of workstation:
  - Generations: SPEC89, SPEC92, SPEC95, and SPEC2000 …
  - Emphasizes memory system performance in SPEC2000.

Other SPEC Benchmarks

- **SPECviewperf:** 3D graphics performance
  - For applications such as CAD/CAM, visualization, content creations, etc.
- **SPEC JVM98:** performance of client-side Java virtual machine.
- **SPEC JBB2000:** Server-side Java application
- **SPEC WEB2005:** evaluating WWW servers
  - Contains multiple workloads utilizing both http and https, dynamic content implemented in PHP and JSP.

Summary of SPEC Benchmarks

- CPU: CPU2006
- Graphics: SPECviewperf
- Java Client/Server: jAppServer2004
- Mail Servers: MAIL2001
- Network File System: SDS97_R1
- Power (under development)
- Web Servers: WEB2005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