Comp4611 Tutorial 1

Computer Processor History
Die Cost Calculation
Performance Measuring & Evaluation

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Advances Come from Design

4004 (1971)
• Intel's first microprocessor

8008 (1972)
• twice as powerful as the 4004

8080 (1974)
• brains of the first personal computer
• ~US$ 400

8086 – 8088 (1978)
• brains of IBM's new hit product -- the IBM PC
• The 8088's success propelled Intel into the ranks of the Fortune 500, and Fortune magazine named the company one of the "Business Triumphs of the Seventies."

Advances Come from Design

80286 (1982)
• first Intel processor that could run all the software written for its predecessor
• Within 6 years of its release, an estimated 15 million 286-based personal computers were installed around the world.

80386 (1985)
• 275,000 transistors--more than 100times as many as the original 4004
• 32-bit chip
• "multi tasking"

80486 (1989)
• 32 bit chip
• built-in math coprocessor
• packaged together with cache memory chip
• command-level computer → point-and-click computing
• color computer

Advances Come from Design

Pentium (1993)
• incorporate "real world" data such as speech, sound, handwriting and photographic images

Pentium Pro (1995)
• 5.5 million transistors
• packaged together with a second speed-enhancing cache memory chip,
• pipelining
• enabling fast computer-aided design, mechanical engineering and scientific computation

Pentium II (1997)
• 7.5 million-transistor
• MMX technology, designed specifically to process video, audio and graphics data efficiently
• high-speed cache memory chip

Celeron (1999)
• excellent performance in gaming

Advances Come from Design

Pentium III (1999)
• 9.5 million transistors, 0.25-micron technology
• 70 new SSE (Streaming SIMD Extension) instructions
• dramatically enhance the performance of advanced imaging, 3-D, streaming audio, video and speech recognition applications, Internet experiences

Pentium 4 (2000)
• 42 million transistors and circuit lines of 0.18 microns
• 1.5 gigahertz (4004 ran at 108 kilohertz)
• SSE2 instructions, more pipeline stages, higher successful prediction rate
• can create professional-quality movies; deliver TV-like video via the Internet; communicate with real-time video and voice; render 3D graphics in real time; quickly encode music for MP3 players; and simultaneously run several multimedia applications while connected to the Internet.

Advances Come from Design

Pentium D
• Dual-core processing technology
→ high-end entertainment: multimedia entertainment, digital photo editing, multiple users and multitasking

Pentium Dual-Core
• High-value performance for multitasking (CPU executes more instructions in less time)
• Smart Cache: smarter, more efficient cache and bus design
→ enhanced performance, responsiveness and power savings

Core 2 Duo
• A dual-core CPU
• A new microarchitecture to replace Netburst
• Memory Hierarchy System
• Low power consumption

Core™2 Quad
• Four execution cores
• More intensive entertainment and more media multitasking

Advances Come from Technology

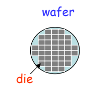
Processor	Intel® Pentium® D Processor	Intel® Pentium® Dual-Core Processor	Intel® Core™2 Duo Processor	Intel® Core™2 Quad Processor
Process Technology	65 nm - 90 nm	65 nm	65 nm	65 nm
L2 Cache	1MB - 2MB for each core	1MB	2M - 4M	8M
Clock Speed	2.80 - 3.60 GHz	1.6 - 2 GHz	1.86 - 3.0 GHz	2.4 - 2.66 GHz
Chipset	Intel® 945P, 945G, 955X, 975X chipsets	N/A	Intel® Q965, Q963, G965, P965, 975X	Intel® P965, 975X

Increase **in *processor performance* due to the *growth* in *CPU* Transistor Count**

Cost Formula Summary

$$\text{IC Cost} = \frac{\text{Die Cost} + \text{Testing Cost} + \text{Packaging Cost}}{\text{Final Test Yield}}$$

$$\text{Die Cost} = \frac{\text{Wafer Cost}}{(\text{Dies/Wafer}) \times \text{Die Yield}}$$



$$\text{Dies per Wafer} = \frac{\pi(\text{Wafer diameter}/2)^2}{\text{Die Area}} - \frac{\pi(\text{Wafer diameter})}{(2 \times \text{Die Area})^{1/2}}$$

$$\text{Dies Yield} = \text{Wafer Yield} \times \left(1 + \frac{\text{Defects per unit area} \times \text{Die Area}}{\alpha}\right)^{-\alpha}$$

Where α is a parameter inversely proportional to the number of mask Levels, which is a measure of the manufacturing complexity.
For today's CMOS process, good estimate is $\alpha = 3.0 - 4.0$

Yield: the percentage of manufactured devices that survives the testing procedure

Example: Die Cost

Given:

wafer 30cm, die 1cm, defect density 0.6 per cm^2, α=4.0
30-cm-diameter wafer with 3-4 metal layers : $3500
wafer yield is 100%

Calculate:

die cost

Step 1: dies per wafer

$$\text{Dies per Wafer} = \frac{\pi(\text{Wafer diameter}/2)^2}{\text{Die Area}} - \frac{\pi(\text{Wafer diameter})}{(2 \times \text{Die Area})^{1/2}}$$

$$= \frac{\pi(30/2)^2}{1 \times 1} - \frac{\pi \times 30}{\sqrt{2 \times 1 \times 1}} = 640$$

Example: Die Cost

Given:

wafer 30cm, die 1cm, defect density 0.6 per cm^2, α=4.0
30-cm-diameter wafer with 3-4 metal layers : $3500
wafer yield is 100%

Calculate:

die cost

Step 2: die yield

$$\text{Dies Yield} = \text{Wafer Yield} \times \left(1 + \frac{\text{Defects per unit area} \times \text{Die Area}}{\alpha}\right)^{-\alpha}$$

$$= 1 \times \left(1 + \frac{0.6 \times 1}{4.0}\right)^{-4} = 0.57$$

Example: Die Cost

Given:

wafer 30cm, die 1cm, defect density 0.6 per cm^2, α=4.0
30-cm-diameter wafer with 3-4 metal layers : $3500
wafer yield is 100%

Calculate:

die cost

Step 3: die cost

$$\text{Die Cost} = \frac{\text{Wafer Cost}}{(\text{Dies/Wafer}) \times \text{Die Yield}}$$

$$= \frac{3500}{640 \times 0.57} = 9.59$$

How to Measure Performance ?

- Performance Rating
  - CPU Time
  - Benchmark programs
    - Integer programs and floating point programs
      - Compression
      - Compiler
      - Artificial Intelligence
      - Physics / Quantum Computing
      - Video Compression
      - Path-finding Algorithms
  - Amdahl's Law

Measuring Performance

- Performance = 1 / Execution Time

$$\text{CPU time} = \frac{\text{Seconds}}{\text{Program}} = \underbrace{\frac{\text{Instructions}}{\text{Program}}}_{\text{Instruction count}} \times \underbrace{\frac{\text{Cycles}}{\text{Instruction}}}_{\text{CPI}} \times \underbrace{\frac{\text{Seconds}}{\text{Cycle}}}_{\text{Clock cycle} = 1\,/\,\text{Clock rate}}$$

Measuring Performance

CPU time = Instruction count x CPI x (1/clock rate)

Example 1:

A SPEC CPU2006 integer benchmark (464.h264ref, a video compression program written in C) is run on a Pentium D processor:

Total instruction count:	3731 billion
Average CPI for the program:	2.5 cycles/instruction.
CPU clock rate:	2.1 GHz

CPU time $= 3731 \times 10^9 \times 2.5 / (2.1 \times 10^9)$
$= 4442$ seconds

Source: Analysis of Redundancy and Application Balance in the SPEC CPU2006 Benchmark Suite

Measuring Performance

$$\text{Speedup} = \frac{\text{Old Execution Time}}{\text{New Execution Time}} = \frac{I_{old} \times CPI_{old} \times \text{Clock cycle}_{old}}{I_{new} \times CPI_{new} \times \text{Clock Cycle}_{new}}$$

Example 2:

Suppose SPEC CPU2006 integer benchmark (464.h264ref) is run on a faster processor, with a new compiler:

New total instruction count:	2000 billion
New average CPI for the program:	4 cycles/instruction.
New CPU clock rate:	3.6 GHz

New CPU time $= 2000 \times 10^9 \times 4 / (3.6 \times 10^9)$
$= 2222$ seconds

$$\text{Speedup} = \frac{\text{Old CPU time}}{\text{New CPU time}} = \frac{4442}{2222} = 1.999$$

Measuring Performance

$$\text{Speedup} = \frac{\text{Old Execution Time}}{\text{New Execution Time}} = \frac{I_{old} \times CPI_{old} \times \text{Clock cycle}_{old}}{I_{new} \times CPI_{new} \times \text{Clock Cycle}_{new}}$$

Example 3:

Should this be implemented?

Instruction Class	Frequency	Old CPI	New CPI
ALU	40%	3	2
Load	20%	1	2
Store	20%	1	2
Branch	20%	2	3

Shouldn't be implemented

Old CPI
$= 0.40 \times 3 + 0.2 \times 1 + 0.2 \times 1 + 0.2 \times 2$
$= 2$

New CPI
$= 0.4 \times 2 + 0.2 \times 2 + 0.2 \times 2 + 0.2 \times 3$
$= 2.2$

Speedup
$$= \frac{\cancel{I_{old}} \times 2 \times \cancel{\text{Clock cycle}_{old}}}{\cancel{I_{new}} \times 2.2 \times \cancel{\text{Clock cycle}_{new}}}$$
$= 0.91$

Metrics for Performance

CPU time: most accurate and fair measure

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

$$\text{CPU clock cycles} = \sum_{i=1}^{n} (CPI_i \times IC_i)$$

$$CPI = \sum_{i=1}^{n} (CPI_i \times F_i)$$

a priori frequency of the instruction set

Example 4: Performance

- Suppose we have made the following measurements:
  Frequency of FP operations (other than FPSQR) = 23%
  Average CPI of FP operations (other than FPSQR) = 4.0
  Frequency of FPSQR = 2%, CPI of FPSQR = 20
  Average CPI of other instructions = 1.33
- Assume that the two design alternatives
  - decrease the CPI of FPSQR to 3
  - decrease the average CPI of FP operations (other than FPSQR) to 2.
- Compare these two design alternatives using the CPU performance equation.

Solution

Step 1: Original CPI without enhancement:

CPI $_{original}$ = 4×23% + 20x2% +1.33×75% = 2.3175

Step 2: compute the CPI for the enhanced FPSQR by subtracting the cycles saved from the original CPI:

CPI $_{with\ new\ FPSQR}$ = CPI $_{original}$ - 2%×(CPI $_{old\ FPSQR}$ – CPI $_{new\ FPSQR\ only}$)
= 2.3175 - 0.02x(20-3) = 1.9775

Step 3: compute the CPI for the enhancement of all FP instructions:

CPI $_{with\ new\ FP}$ = CPI $_{original}$ - 23%×(CPI $_{old\ FP}$ – CPI $_{new\ FP}$)
= 2.3175 - 0.23x(4-2) = 1.8575

Step 4: the speedup for the FP enhancement over FPSQR enhancement is:

Speedup = CPU time $_{with\ new\ FPSQR}$ / CPU time $_{with\ new\ FP}$
= I × CPI $_{with\ new\ FPSQR}$ × C / I × CPI $_{with\ new\ FP}$ × C
= 1.9775 / 1.8575 = 1.065

Comparing Performance

- Total execution time

	Machine A	Machine B
Program 1	1	10
Program 2	1000	100
Total	1001	110

How much faster is Machine B than Machine A?

9.1 times?

Machine A is faster in running Program 1.
Machine B is faster in running Program 2.

UNCLEAR

Comparing Performance

Arithmetic Mean: $\frac{1}{n}\sum_{i=1}^{n}$ **Execution Time$_i$**

	Machine A	Machine B
Program 1	1	10
Program 2	1000	100
Total	1001	110
AM	500.5	55

	Machine A	Machine B
Program 1	200	400
Program 2	250	400
Program 3	450	100
AM	300	300

Can be misleading

Valid only if programs run equally

Comparing Performance

Weighted Arithmetic Mean: $\sum_{i=1}^{n}$ **Weight$_i$ x Execution Time$_i$**

	Machine A	Machine B	W (1)
Program 1	200	400	0.4
Program 2	250	500	0.4
Program 3	550	100	0.2
AM	300	300	
WAM (1)	200 x 0.4 + 250 x 0.4 + 550 x 0.2 = 290	400 x 0.4 + 500 x 0.4 + 100 x 0.2 = 380	

Machine A is better

Comparing Performance

Weighted Arithmetic Mean: $\sum_{i=1}^{n}$ **Weight$_i$ x Execution Time$_i$**

	Machine A	Machine B	W (2)
Program 1	200	400	0.2
Program 2	250	500	0.2
Program 3	550	100	0.6
AM	300	300	
WAM (2)	200 x 0.2 + 250 x 0.2 + 550 x 0.6 = 420	400 x 0.2 + 500 x 0.2 + 100 x 0.6 = 240	

Machine B is better

Depend very much on how to weigh each testing item

Comparing Performance

Geometric Mean: $\sqrt[n]{\prod_{i=1}^{n} \text{Execution time ratio}_i}$

	Machine A	Machine B
Program 1	1	10
Program 2	1000	100
Total	1001	110

Same GM ≠ same execution time or same performance

Normalized Execution Time *to a reference machine*

	Normalized to A	
	Machine A	Machine B
Program 1	1	10
Program 2	1	0.1
GM	1	1

$$\frac{GeometricMean_A}{GeometricMean_B} = \frac{\sqrt[n]{\prod_{i=1}^{n} SPECRatioA_i}}{\sqrt[n]{\prod_{i=1}^{n} SPECRatioB_i}} = \sqrt[n]{\prod_{i=1}^{n} \frac{SPECRatioA_i}{SPECRatioB_i}}$$

$$= \sqrt[n]{\prod_{i=1}^{n} \frac{ExecutionTimeB_i}{ExecutionTimeA_i}} = \sqrt[n]{\prod_{i=1}^{n} \frac{PerformanceA_i}{PerformanceB_i}}$$

Amdahl's Law

- Amdahl's Law – law of diminishing returns
- In general case, assume several enhancements has been taken for the system, the speedup for whole system is,

$$\text{Speedup}_{\text{overall}} = \frac{\text{Execution Time Without Enhancement}}{\text{Execution Time With Enhancement}}$$

$$= \frac{1}{(1-F1-F2...)+\frac{F1}{S1}+\frac{F2}{S2}+...}$$

where ***Fi*** is the fraction of enhancement ***i*** and ***Si*** is the speedup of the corresponding enhancement

- The new execution time is

$$\text{Execution time}_{\text{new}} = \text{Execution time}_{\text{old}} \times \left((1-\sum_i \text{Fraction}_{i\ \text{enhanced}}) + \sum_i \frac{\text{Fraction}_{i\ \text{enhanced}}}{\text{Speedup}_{i\ \text{enhanced}}} \right)$$

Example on Amdahl's Law

- Float instruction:
  - Fraction: 50%
  - Speedup: 2.0x
- Integer instruction:
  - Fraction: 30%
  - Speedup: 3.0x
- Others keep the same.

$$\text{Speedup} = \frac{1}{\left((1-\sum_i \text{Fraction}_{i\ \text{enhanced}}) + \sum_i \frac{\text{Fraction}_{i\ \text{enhanced}}}{\text{Speedup}_{i\ \text{enhanced}}} \right)}$$

= 1 / ((1-0.5-0.3)+(0.5/2+0.3/3))=1.818

Intuition – make the common case fast

- I have two processors, which can help accelerate one of the below parts by parallel processing. Two parts occupy the total time percentage of 95% and 5%.
- $\text{Fraction}_{\text{enhanced}}$ = 95%, $\text{Speedup}_{\text{enhanced}}$ = 2.0x
  $\text{Speedup}_{\text{overall}}$ = 1/((1-0.95)+0.95/2) = 1.905
- $\text{Fraction}_{\text{enhanced}}$ = 5%, $\text{Speedup}_{\text{enhanced}}$ = 2.0x
  $\text{Speedup}_{\text{overall}}$ = 1/((1-0.05)+0.05/2) = 1.026

1.905 vs. 1.026

Make the common case faster!!

- $\text{Fraction}_{\text{enhanced}}$ = 5%, $\text{Speedup}_{\text{enhanced}}$ -> infinity
  $\text{Speedup}_{\text{overall}}$ = 1/(1-0.05) = 1.052

1.052 is still much smaller than 1.905.

A Common Confusion: CPI vs. Amdahl's Law

- Assume a program consists of three classes of instructions A,B and C, as shown below.
- An enhancement is made by doubling the speed of instruction class A
- Assume instruction count for the program and CPU clock cycle is not influenced
- What is the overall speedup achieved for the program

Instruction Class	Frequency	Old CPI	New CPI
A	20%	2	1
B	20%	3	3
C	60%	4	4

Method 1: CPI

$$CPI_{old} = 0.2\times2+0.2\times3+0.6\times4 = 3.4$$
$$CPI_{new} = 0.2\times1+0.2\times3+0.6\times4 = 3.2$$
$$Speedup_{overall} = \frac{\text{Execution time}_{\text{old}}}{\text{Execution time}_{\text{new}}} = \frac{\text{CPI}_{\text{old}}\times\text{IC}\times\text{Clock Cycle}}{\text{CPI}_{\text{new}}\times\text{IC}\times\text{Clock Cycle}} = 1.0625$$

~~Method 2: Amdahl's Law~~

$$\cancel{Speedup_{overall} = \frac{1}{(1-20\%)+\frac{20\%}{2}} = 1.111}$$

The fraction in Amdahl's law is **time fraction**

Method 2: Amdahl's Law

$$\text{Time fraction of A} = \frac{2\times20\%}{2\times20\%+3\times20\%+4\times60\%} = 0.11764$$
$$Speedup_{overall} = \frac{1}{(1-0.11764)+\frac{0.11764}{2}} = 1.0625$$