Computer Performance

He said, to speed things up we need to squeeze the clock
Why Study Performance?

Helps us make intelligent design choices
See through the marketing hype
Key to understanding underlying computer organization

• Why is some hardware faster than others for different programs?
• What factors of system performance are hardware related? (e.g., Do we need a new machine, or a new operating system?)
• How does a machine’s instruction set affect its performance?
Which Airplane has the Best Performance?

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How much faster is the Concorde than the 747?

How much larger is the 747’s capacity than the Concorde?

It is roughly 4000 miles from Raleigh to Paris. What is the throughput of the 747 in passengers/hr? The Concorde?

What is the latency of the 747? The Concorde?
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It is roughly 4000 miles from Raleigh to Paris. What is the throughput of the 747 in passengers/hr? The Concorde?

\[
470 \times \frac{610}{4000} = 71.675 \text{ passengers/hr}
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$$470 \times \frac{610}{4000} = 71.675 \text{ passengers/hr}$$

$$101 \times \frac{1350}{4000} = 34.0875 \frac{\text{pass}}{\text{hr}}$$

What is the latency of the 747? The Concorde?
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What is the latency of the 747? The Concorde? 6.56 hours, 2.96 hours
Performance Metrics

**Latency:** Clocks from input to corresponding output
   - How long does it take for my program to run?
   - How long must I wait after typing return for the result?

**Throughput:** How many results per clock
   - How many results can be processed per second?
   - What is the average execution rate of my program?
   - How much work is getting done?

*If we upgrade a machine with a new faster processor what do we improve?*

*If we add a new machine to the lab what do we increase?*
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Throughput
Maximum Performance: measured by the numbers of instructions executed per second
Design Tradeoffs

**Maximum Performance**: measured by the numbers of instructions executed per second

**Minimum Cost**: measured by the size of the circuit.
Design Tradeoffs

**Maximum Performance**: measured by the numbers of instructions executed per second

**Minimum Cost**: measured by the size of the circuit.

**Best Performance/Price**: measured by the ratio of MIPS to size. In power-sensitive applications MIPS/Watt is important too.
Execution Time

Elapsed Time/Wall Clock Time
counts everything (disk and memory accesses, I/O, etc.)
a useful number, but often not good for comparison purposes

CPU time
Doesn’t include I/O or time spent running other programs
can be broken up into system time, and user time

Our focus: user CPU time
Time spent executing actual instructions of “our” program
Book's Definition of Performance

For some program running on machine X,

\[ \text{Performance}_X = \frac{\text{Program Executions}}{\text{Time}_X} \text{ (executions/sec)} \]

"X is n times faster than Y"

\[ \frac{\text{Performance}_X}{\text{Performance}_Y} = n \]

Problem:

Machine A runs a program in 20 seconds
Machine B runs the same program in 25 seconds
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$$\text{Performance}_A = 1/20$$
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\[ \text{Performance}_A = 1/20 \quad \text{Performance}_B = 1/25 \]
For some program running on machine $X$, 

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"$X$ is $n$ times faster than $Y$"

$$\frac{\text{Performance}_X}{\text{Performance}_Y} = n$$

**Problem:**

Machine A runs a program in 20 seconds  
Machine B runs the same program in 25 seconds

$$\text{Performance}_A = \frac{1}{20} \quad \text{Performance}_B = \frac{1}{25}$$

Machine A is $\frac{(1/20)/(1/25)} = 1.25$ times faster than Machine B
Program Clock Cycles

Instead of reporting execution time in seconds, we often use cycle counts:

\[
\frac{\text{seconds}}{\text{program}} = \frac{\text{cycles}}{\text{program}} \times \frac{\text{seconds}}{\text{cycle}}
\]

Clock “ticks” indicate when machine state changes (one abstraction):

\[
\begin{array}{c}
\ldots \\
\text{time} \\
\ldots \\
\end{array}
\]

cycle time = time between ticks = seconds per cycle
clock rate (frequency) = cycles per second (1 Hz. = 1 cycle/sec)

A 2 GHz. clock has a cycle time of:

\[
\frac{1}{2 \times 10^9} = 0.5 \times 10^{-9} = 0.5 \text{ ns}
\]
Computer Performance Measure

\[ \text{MIPS} = \frac{\text{clocks/sec}}{\text{AVE}(\text{clocks/instruction})} \]

- Millions of Instructions per Second
- Frequency in MHz

Historically:
- PDP-11, VAX, Intel 8086: CPI > 1
- Load/Store RISC machines
- MIPS, SPARC, PowerPC, miniMIPS: CPI = 1
- Modern CPUs, Pentium, Athlon: CPI < 1
How to Improve Performance?

\[
\text{seconds per program} = \frac{\text{cycles per program}}{\text{cycles per cycle}} \times \frac{\text{seconds per program}}{\text{cycle}}
\]

\[
\text{MIPS} = \frac{\text{Freq}}{\text{CPI}}
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So, to improve performance (everything else being equal) you can either

- ________ the # of required cycles for a program, or
- ________ the clock cycle time or, said another way,
- ________ the clock rate.
- ________ the CPI (average clocks per instruction)
How to Improve Performance?

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**Decrease** the # of required cycles for a program, or (improve ISA/Compiler)

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- **Increase** the clock rate. *(reduce propagation delays or use pipelining)*
- **Decrease** the CPI *(average clocks per instruction)*
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- **Decrease** the # of required cycles for a program, or **(improve ISA/Compiler)**

- Decrease the clock cycle time or, said another way,

- **Increase** the clock rate. **(reduce propagation delays or use pipelining)**

- **Decrease** the CPI (average clocks per instruction) **(new hardware)**
How Many Cycles in a Program?

Could assume that # of cycles = # of instructions

This assumption can be incorrect,

Different instructions take different amounts of time on different machines.
Memory accesses might require more cycles than other instructions.
Floating-Point instructions might require multiple clock cycles to execute.
Branches might stall execution rate
Example

Our favorite program runs in 10 seconds on computer A, which has a 400 Mhz clock. We are trying to help a computer designer build a new machine B, to run this program in 6 seconds. The designer can use new (or perhaps more expensive) technology to substantially increase the clock rate, but has informed us that this increase will affect the rest of the CPU design, causing machine B to require 1.2 times as many clock cycles as machine A for the same program. What clock rate should we tell the designer to target?

Don’t panic, can easily work this out from basic principles
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\[
\frac{\text{cycles}}{\text{program}} = \left( \frac{\text{seconds}}{\text{program}} \right)_A \times \frac{\text{cycles}}{\text{second}} = 10 \times 400 \times 10^6 = 4 \times 10^9
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\[
\frac{\text{cycles}}{\text{second}} = \frac{\text{cycles / program}}{\left( \frac{\text{seconds / program}}{6} \right)_B} = \frac{1.2 \times 4 \times 10^9}{6} = 800 \times 10^6
\]

Don’t panic, can easily work this out from basic principles
Now that We Understand Cycles

A given program will require

- some number of instructions (machine instructions)
- some number of cycles
- some number of seconds

We have a vocabulary that relates these quantities:

- cycle time (seconds per cycle)
- clock rate (cycles per second)
- CPI (average clocks per instruction)

A floating point intensive application might have a higher CPI

- MIPS (millions of instructions per second)

This would be higher for a program using simple instructions
Performance Traps

Performance is determined by the execution time of a program that you care about.

Do any of the other variables equal performance?
- # of cycles to execute program?
- # of instructions in program?
- # of cycles per second?
- average # of cycles per instruction?
- average # of instructions per second?

Common pitfall:
Thinking only one of the variables is indicative of performance when it really isn’t.
Suppose we have two implementations of the same instruction set architecture (ISA).

For some program,

Machine A has a clock cycle time of 10 ns. and a CPI of 0.5
Machine B has a clock cycle time of 3 ns. and a CPI of 1.5

What machine is faster for this program, and by how much?

If two machines have the same ISA which quantity (e.g., clock rate, CPI, execution time, # of instructions, MIPS) will always be identical?
CPI Example

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\[
MIPS_A = \frac{freq}{CPI} = \frac{10^{-6}}{(10 \times 10^{-9})} = 200
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MIPS_A = \frac{freq}{CPI} = \frac{10^{-6}/(10 \times 10^{-9})}{0.5} = 200 \quad \quad MIPS_B = \frac{freq}{CPI} = \frac{10^{-6}/(3 \times 10^{-9})}{1.5} = 222.2
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\text{MIPS}_B = \frac{\text{freq}}{\text{CPI}} = \frac{10^{-6}/(3\times10^{-9})}{1.5} = 222.2
\]

\[
\text{Relative Performance} e = \frac{\text{MIPS}_A}{\text{MIPS}_B} = \frac{200}{222.2} = 0.9
\]

If two machines have the same ISA which quantity (e.g., clock rate, CPI, execution time, # of instructions, MIPS) will always be identical?
Two different compilers are being tested for a 500 MHz machine with three different classes of instructions: Class A, Class B, and Class C, which require one, two, and three cycles (respectively). Both compilers are used to produce code for a large piece of software. The first compiler's code uses 5 million Class A instructions, 1 million Class B instructions, and 2 million Class C instructions. The second compiler's code uses 7 million Class A instructions, 1 million Class B instructions, and 1 million Class C instructions.

Which program uses the fewest instructions?

Which sequence uses the fewest clock cycles?
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\text{Instructions}_1 = (5+1+2) \times 10^6 = 8 \times 10^6 \\
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Which sequence uses the fewest clock cycles?

\[
\text{Cycles}_1 = (5(1)+1(2)+2(3)) \times 10^6 = 13 \times 10^6 \\
\text{Cycles}_2 = (7(1)+1(2)+1(3)) \times 10^6 = 12 \times 10^6
\]
Benchmarks

Performance best determined by running a real application

Use programs typical of expected workload
Or, typical of expected class of applications
e.g., compilers/editors, scientific applications, graphics, etc.

Small benchmarks

nice for architects and designers
easy to standardize
can be abused

SPEC (System Performance Evaluation Cooperative)
companies have agreed on a set of real program and inputs
can still be abused
valuable indicator of performance (and compiler technology)
SPEC '89

Compiler “enhancements” and performance

![Chart showing SPEC performance ratio for various benchmarks with enhanced and original compiler performance compared.](chart.png)
# SPEC '95

## Benchmark Description

<table>
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<th>Description</th>
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<td>go</td>
<td>Artificial intelligence; plays the game of Go</td>
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<td>m88ksim</td>
<td>Motorola 88k chip simulator; runs test program</td>
</tr>
<tr>
<td>gcc</td>
<td>The Gnu C compiler generating SPARC code</td>
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<tr>
<td>compress</td>
<td>Compresses and decompresses file in memory</td>
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<tr>
<td>li</td>
<td>Lisp interpreter</td>
</tr>
<tr>
<td>jpeg</td>
<td>Image compression and decompression</td>
</tr>
<tr>
<td>perl</td>
<td>Manipulates strings and prime numbers in the special-purpose programming language Perl</td>
</tr>
<tr>
<td>vortex</td>
<td>A database program</td>
</tr>
<tr>
<td>tomatv</td>
<td>A mesh generation program</td>
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<tr>
<td>swim</td>
<td>Shallow water model with 513 x 513 grid</td>
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<td>su2cor</td>
<td>Quantum physics; Monte Carlo simulation</td>
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<td>hydro2d</td>
<td>Astrophysics; Hydrodynamic Naiver Stokes equations</td>
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<tr>
<td>mgrid</td>
<td>Multigrid solver in 3-D potential field</td>
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<tr>
<td>applu</td>
<td>Parabolic/elliptic partial differential equations</td>
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<tr>
<td>trub3d</td>
<td>Simulates isotropic, homogeneous turbulence in a cube</td>
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<td>apsi</td>
<td>Solves problems regarding temperature, wind velocity, and distribution of pollutant</td>
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<td>fpppp</td>
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**SPEC '95**

*Does doubling the clock rate double the performance?*

*Can a machine with a slower clock rate have better performance?*

![Graphs showing SPECint and SPECfp performance over clock rate for Pentium and Pentium Pro processors.](image)
Amdahl's Law

\[ t_{\text{improved}} = \frac{t_{\text{affected}}}{r_{\text{speedup}}} + t_{\text{unaffected}} \]

Example:

"Suppose a program runs in 100 seconds on a machine, where multiplies are executed 80% of the time. How much do we need to improve the speed of multiplication if we want the program to run 4 times faster?"

How about making it 5 times faster?

Principle: Make the common case fast
Amdahl's Law

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\[ 25 = \frac{80}{r} + 20 \]

\[ r = 16 \]

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"Suppose a program runs in 100 seconds on a machine, where multiplies are executed 80% of the time. How much do we need to improve the speed of multiplication if we want the program to run 4 times faster?"

\[ 25 = \frac{80}{r} + 20 \quad r = 16x \]

How about making it 5 times faster?

\[ 20 = \frac{80}{r} + 20 \quad r = ? \]

Principle: Make the common case fast
Example

Suppose we enhance a machine making all floating-point instructions run \textit{FIVE} times faster. If the execution time of some benchmark before the floating-point enhancement is 10 seconds, what will the speedup be if only half of the 10 seconds is spent executing floating-point instructions?

We are looking for a benchmark to show off the new floating-point unit described above, and want the overall benchmark to show at least a speedup of 3. What percentage of the execution time would floating-point instructions have to account for in this program in order to yield our desired speedup on this benchmark?
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\[ \frac{100}{3} = \frac{f}{5} + (100 - f) = 100 - \frac{4f}{5} \quad f = 83.33 \]
Remember

- Performance is specific to a particular program
  - Total execution time is a consistent summary of performance

- For a given architecture performance comes from:
  1) increases in clock rate (without adverse CPI affects)
  2) improvements in processor organization that lower CPI
  3) compiler enhancements that lower CPI and/or instruction count

- Pitfall: Expecting improvements in one aspect of a machine’s performance to affect the total performance

- You should not always believe everything you read!
Read carefully!