18-447 Lecture 5: Performance (Uniprocessor)

James C. Hoe
Department of ECE
Carnegie Mellon University
Housekeeping

• Your goal today
  – appreciate the subtleties of measuring/summarizing/comparing performance
  – focus is on sequential execution performance
    • L12: power&energy; L23: parallel performance

• Notices
  – Lab 1, Part A, due this week
  – Lab 2, Part B, due next week
  – HW1, due next Wed

• Readings
  – P&H Ch 1.6~1.9
  – P&H Appendix C for next time
It’s about time

• To the first order, performance $\propto 1 / \text{time}$

• Two very different kinds of performance!!
  – latency = time between start and finish of a task
  – throughput = number of tasks finished in a given unit of time (a rate measure)

• Either way, shorter the time, higher the performance, but not to be mixed up
Throughput ≠ 1/Latency

• If it takes $t$ sec to do 1 task, latency = $t$; does throughput = $1/t$?

• If it takes $T$ sec to do $N$ tasks, throughput = $N/T$; does latency = $T/N$?

• When there is concurrency, throughput ≠ $1/\text{latency}$

• Optimizations can tradeoff one for the other (think school bus vs F1 race car)
Throughput ≠ Throughput

• Throughput becomes a function of N when there is a non-recurring start-up cost (aka overhead)

• For start-up-time=$t_s$ and throughput$_{raw}$=$1/t_1$
  – throughput$_{effective}$ = $N / (t_s + N \cdot t_1)$
  – if $t_s \gg N \cdot t_1$, throughput$_{effective} \approx N/t_s$
  – if $t_s \ll N \cdot t_1$, throughput$_{effective} \approx 1/t_1$

  we say $t_s$ is “amortized” in the latter case

• E.g., programmed DMA transfer on a bus
  – bus throughput$_{raw}$ = 1GByte/sec = 1 Byte / (10⁻⁹ sec)
  – 10⁻⁶ sec to program a DMA engine
  – throughput$_{effective}$ for transferring 1B/1KB/1MB/1GB?

DMA=Direct Memory Access
Latency ≠ Latency

• What are you doing during the latency period?
• Latency = hands-on time + hands-off time
• In the DMA example
  – CPU is busy for the $t_s$ to program the DMA engine
  – CPU has to wait $N \cdot t_1$ for DMA to complete
  – CPU could be doing something else during $N \cdot t_1$ to “hide” that latency
Not all times are created equally

• You are not alone in a real system
• Program runtime according to UNIX
  – user CPU time: time spent running your process
  – system CPU time: time spent running code on behalf of your process
  – elapsed time: **wall-clock time**
• Takeaways:
  – elapsed time != user CPU time + system CPU time
  – real system measurements have variance

  measure wall-clock time of actual workload multiple times on unloaded system
Pseudo Performance

• The metrics you are most likely to see in marketing
  – GHz (billion cycles per second)
  – IPC (instruction per cycle)
  – MIPS (million instructions per second)

• “Sounds” like performance but incomplete and misleading
  – MIPS and IPC are averages (depend on inst mix)
  – GHz, MIPS or IPC can be improved at the expense of each other and actual performance

  e.g., 1.4GHz Intel P4 ≈ 1.0GHz Intel P3?
Iron Law of Processor Performance

• wall clock time = \( \frac{\text{inst/program}}{\text{cyc/inst}} \times \frac{\text{time/cyc}}{1/\text{IPC}} \times \frac{1}{1/\text{MIPS}} \times \frac{1}{1/\text{GHz}} \)

  
  note workload dependence

• Contributing factors
  – \text{time/cyc}: architecture and implementation
  – \text{cyc/inst}: architecture, implementation, instruction mix
  – \text{inst/program}: architecture, nature and quality of prgm

• **Note**: \text{cyc/inst} is a workload average

  potentially large instantaneous variations
  due to instruction type and sequence
When it is about more than time
Tradeoff

• There are other important metrics of goodness beside performance: power/energy, cost, risk, social factors . . . ethics . . .

• Cannot optimize individual metrics without considering tradeoff between them

• E.g. runtime vs. energy
  – may be willing to spend more energy per task to run faster
  – conversely, may be willing to run slower for less energy per task
  – but never use more energy to run slower

  "...$5.8 million the value of a statistical life..." FAA
Pareto Optimality

All points on front are optimal (can’t do better)
How to select between them?
Composite Metrics

• Define scalar function to reflect desiderata---incorporate dimensions and their relationships

• E.g., energy-delay product
  – can’t cheat by minimizing one ignoring other
  – but is smaller really better?
    be wary of relevance to application context

• Floors and ceilings
  – real-life designs more often about good enough than optimal
  – e.g., meet a perf floor under a power(cost)-ceiling
    Not all desires reducible to quantifiable terms!!
Which is Design Point is Best?
(runtime, power, energy, EDP)

Is B really lowest power?
Comparing and Summarizing Performance
Relative Performance

- Performance = \( \frac{1}{\text{Time}} \)
  - shorter latency ⇒ higher performance
  - higher throughput (job/time) ⇒ higher performance

- Pop Quiz
  if \( X \) is 50% slower than \( Y \) and \( \text{Time}_X = 1.0s \), what is \( \text{Time}_Y \)
  - Case 1: \( \text{Time}_Y = 0.5s \) since \( \text{Time}_Y / \text{Time}_X = 0.5 \)
  - Case 2: \( \text{Time}_Y = 0.66666s \) since \( \text{Time}_X / \text{Time}_Y = 1.5 \)
Relative Performance

• “X is n times faster than Y” means

\[ n = \text{Performance}_X / \text{Performance}_Y \]
\[ = \text{Throughput}_X / \text{Throughput}_Y \]
\[ = \text{Time}_Y / \text{Time}_X \]

• “X is m% faster than Y” means

\[ 1 + \frac{m}{100} = \text{Performance}_X / \text{Performance}_Y \]

• To avoid confusion, stick with definition of “faster”
  – for case 1 say “Y is 100% faster than X”
  – for case 2 say “Y is 50% faster than X”
Speedup

• If $X$ is an “enhanced” version of $Y$, the “speedup” of the enhancement is

\[
S = \frac{\text{Time}_{\text{without enhancement}}}{\text{Time}_{\text{with enhancement}}} = \frac{\text{Time}_Y}{\text{Time}_X}
\]
Amdahl’s Law on Speedup

- If only a fraction \( f \) (of time) is speedup by \( S \)

\[
\frac{\text{time}_{\text{original}}}{\text{time}_{\text{improved}}} = \frac{1 - f}{(1 - f) + f/S}
\]

\( S_{\text{effective}} = \frac{1}{(1 - f) + f/S} \)

- if \( f \) is small, \( S \) doesn’t matter
- even when \( f \) is large, diminishing return on \( S \);
  eventually “1-f” dominates
Summarizing Performance

• When comparing two computers \( X \) and \( Y \), the relative performance of \( X \) and \( Y \) depends on program executed
  – \( X \) can be \( m\% \) faster than \( Y \) on prog A
  – \( X \) can be \( n\% \) (where \( m\neq n \)) faster than \( Y \) on prog B
  – \( Y \) can be \( k\% \) faster than \( X \) on prog C
• Which computer is faster and by how much?
  – depends on which program(s) you care about
  – if multiple programs, also depends their relative importance (frequency or occupancy??)
• Many ways to summarize performance comparisons into a single numerical measure
  – know what the resulting “number” actually mean
  – know when to use which to be meaningful
Arithmetic Mean

• Suppose workload is applications $A_0, A_1, \ldots, A_{n-1}$
• Arithmetic mean of run time is

$$\frac{1}{n} \sum_{i=0}^{n-1} Time_{A_i}$$

– comparing AM same as comparing total run-time

  caveat: longer running apps have greater contribution than shorter running apps

• If $AM_X / AM_Y = n$ then $Y$ is $n$ times faster than $X$ . . .

True: $A_0, A_1, \ldots, A_{n-1}$ run equal number of times always

False: some apps run more frequently

Especially bad if most frequent apps also shortest
Weighted Arithmetic Mean

- Describe relative frequency of apps by weights $w_0, w_1, \ldots, w_{n-1}$
  - $w_i = \text{number of } A_i \text{ executions} / \text{total app executions}$
  - $\sum_{i=0}^{n-1} w_i = 1$

- Weighted AM of the run time $= \sum_{i=0}^{n-1} w_i \cdot Time_{A_i}$

- If $WAM_X/WAM_Y = n$ then $Y$ is $n$ times faster than $X$ on a workload characterized by $w_0, w_1, \ldots, w_{n-1}$

- But $w_i$ isn’t always known, so why not “normalize”

$$\frac{1}{n} \sum_{i=0}^{n-1} \frac{Time_{A_i \text{ on } X}}{Time_{A_i \text{ on } Y}} \quad \text{or} \quad \sqrt[n]{\prod_{i=0}^{n-1} \frac{Time_{A_i \text{ on } X}}{Time_{A_i \text{ on } Y}}}$$

What does it mean though?
Danger of Normalized Performance

- Suppose
  - $A_0$ takes 1s on $X$; 10s on $Y$; 20s on $Z$
  - $A_1$ takes 1000s on $X$; 100s on $Y$; 20s on $Z$
  - $A_0 + A_1 = 1001s$ on $X$; 110s on $Y$; 40s on $Z$

<table>
<thead>
<tr>
<th></th>
<th>normalized to $X$</th>
<th>normalized to $Y$</th>
<th>normalized to $Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X$</td>
<td>$Y$</td>
<td>$Z$</td>
</tr>
<tr>
<td>Time $A_0$</td>
<td>1</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Time $A_1$</td>
<td>1</td>
<td>0.1</td>
<td>0.02</td>
</tr>
<tr>
<td>AM of ratio</td>
<td>1</td>
<td>5.05</td>
<td>10.01</td>
</tr>
<tr>
<td>GM of ratio</td>
<td>1</td>
<td>1.0</td>
<td>0.63</td>
</tr>
</tbody>
</table>

[Computer Architecture: A quantitative approach. Hennessy and Patterson]
Harmonic Mean

• Don’t take AM of rates (e.g. throughput)
  – If you drive 30mph for 10 miles and 90mph for 10 miles, average speed is not \((30\text{mph} + 90\text{mph})/2\)

• To compute average rate
  – either, expand fully
    
    \[
    \text{average speed} = \frac{\text{total distance}}{\text{total time}}
    \]
    
    \[
    = \frac{20}{(10/30 + 10/90)} = 45\text{mph}
    \]

  – or, use harmonic mean formula
    
    \[
    HM = n\sqrt{n-1} \sum_{i=0}^{n-1} \frac{1}{Rate_i}
    \]
    
    \[
    WHM = \frac{1}{\sum_{i=0}^{n-1} \frac{w_i}{Rate_i}}
    \]

  HM is just formula for expanded calculation
Standard Benchmarks

• Why standard benchmarks?
  – everyone cares about different applications (different aspects of performance)
  – your application may not be available for the machine you want to study

• E.g. SPEC Benchmarks (www.spec.org)
  – a set of “realistic”, general-purpose, public-domain applications chosen by a multi-industry committee
  – updated every few year to reflect changes in usage and technology
  – a sense of objectivity and predictive power

Everyone knows it is not perfect, but at least everyone plays/cheats by the same rules
SPEC CPU Benchmark Suites

- **CINT2006** (C or C++)  
  perlbench (prog lang), bzip2 (compress), gcc (compile), mcf (optimize), gobmk (go), hmmer (gene seq. search), sjeng (chess), libquantum (physics sim.), h264ref (video compress), omnetpp (discrete event sim.), astar (path-finding), xalancbmk (XML)

- **CFP2006** (F77/F90 unless otherwise noted)  
  bwaves (CFD), gamess (quantum chem), milc (C, QCD), zeusmp (CFD), gromacs (C+Fortran, molecular dyn), cactusADM (C+Fortran, relativity), leslie3d (CFD), namd (C++, molecular dyn), dealII (C++, finite element), soplex (C++, Linear Programming), povray (C++, Ray-trace), calculix (C+Fortran, Finite element), GemsFDTD (E&M), tonto (quantum chem), ibm (C, CFD), wrf (C+Fortran, weather), sphinx3 (C, speech recog)

- Reports GM of performance normalized to a 1997-era 296MHz Sun UltraSparc II

(http://www.spec.org/cpu2006)
Performance Recap

• There is no one-size-fits-all methodology
  – be sure you understand what you want to measure
  – be sure you understand what you measured
  – be sure what you report is accurate and representative
  – be ready to come clean with raw data

• No one believes your numbers anyway
  – explain what effect you are trying to measure
  – explain what and how you actually measured
  – explain how performance is summarized and represented

When it matters, people will check for themselves
Most important is to be truthful

We, the members of the IEEE, in recognition of the importance of our technologies . . . do hereby commit ourselves to the highest ethical and professional conduct and agree:

7. to be honest and realistic in stating claims or estimates based on available data;

--- Paragraph 7.8 IEEE Code of Ethics, IEEE Policies