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

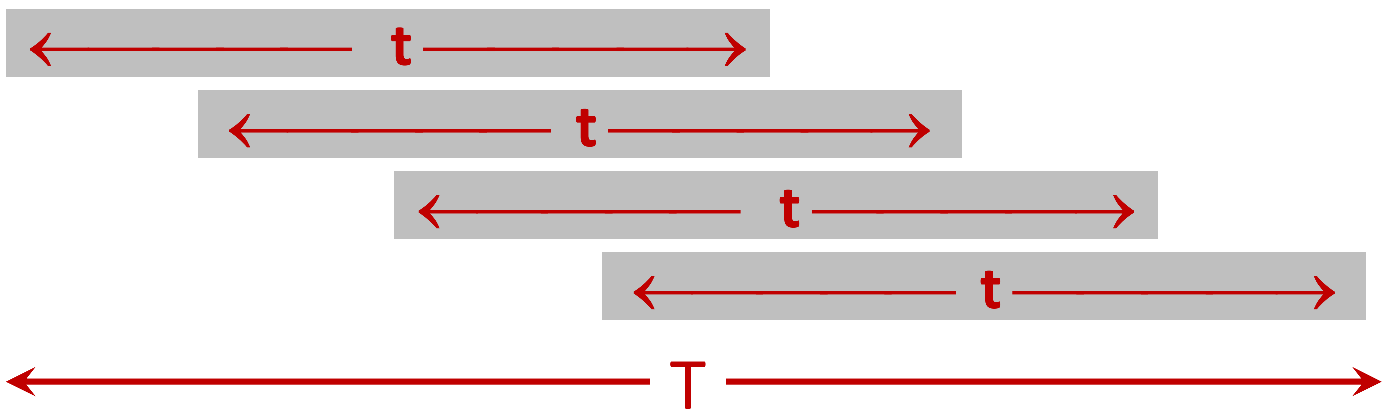
- To the first order, **performance $\propto$ 1 / time**

- 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/latency



- Optimizations can tradeoff one for the other

(think school bus vs F1 race car)

Throughput ≠ Throughput

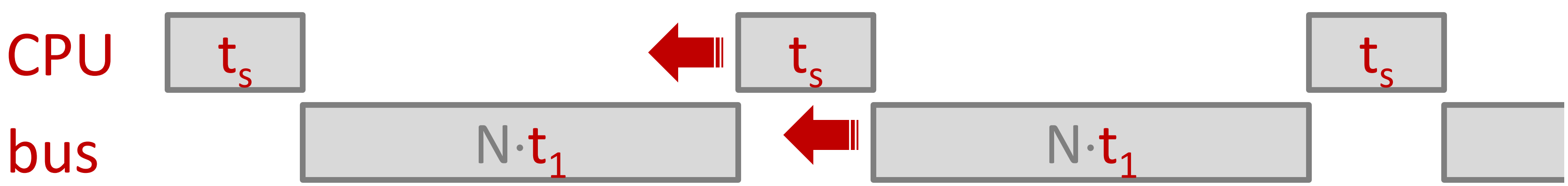
- Throughput becomes a function of N when there is a non-recurring start-up cost (aka overhead)
- For start-up-time=t_s and $throughput_{raw}=1/t_1$
  - $throughput_{effective} = N / (t_s + N \cdot t_1)$
  - if $t_s >> N \cdot t_1$, $throughput_{effective} \approx N/t_s$
  - if $t_s << N \cdot t_1$, $throughput_{effective} \approx 1/t_1$

  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
  - $throuhgput_{effective}$ 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 = (inst/program) (cyc/inst) (time/cyc)

1/IPC 1/MIPS 1/GHz

note workload dependence

- Contributing factors
  - time/cyc: architecture and implementation
  - cyc/inst: architecture, implementation, instruction mix
  - inst/program: architecture, nature and quality of prgm
- **Note**: cyc/inst is a workload average

potentially large instantaneous variations
due to instruction type and sequence

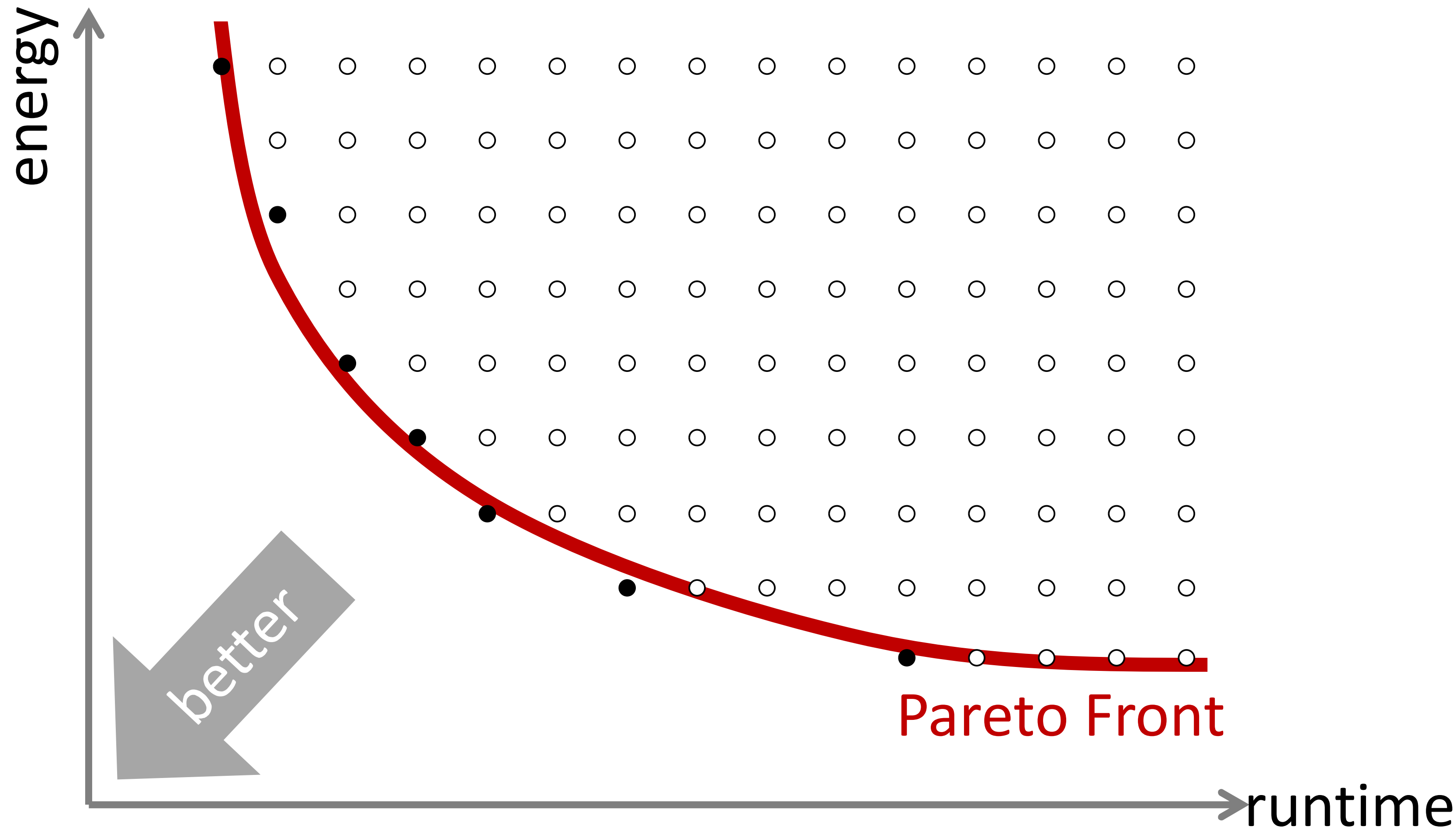
When it is about more than time

Tradeoff

- There are other important metric 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?

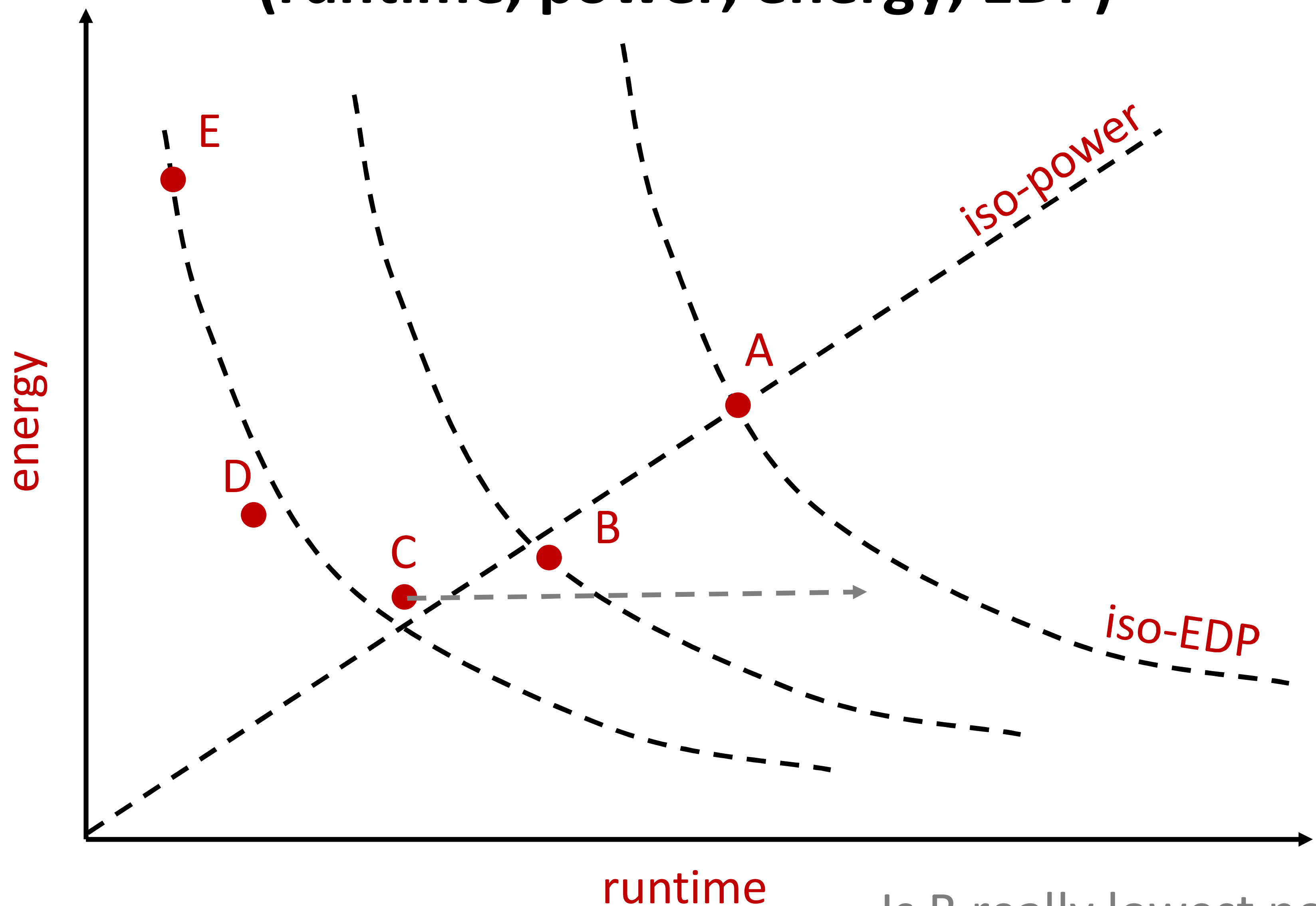
Composite Metrics

- 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 = 1 / Time
  - shorter latency ⇒ higher performance
  - higher throughput (job/time) ⇒ higher performance

- Pop Quiz

  if X is 50% slower than Y and $Time_X$=1.0s, what is $Time_Y$
  - Case 1: $Time_Y$ = 0.5s since $Time_Y/Time_X$=0.5
  - Case 2: $Time_Y$ = 0.66666s since $Time_X/Time_Y$=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

  $1 + m/100 = \text{Performance}_X / \text{Performance}_Y$

- 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"

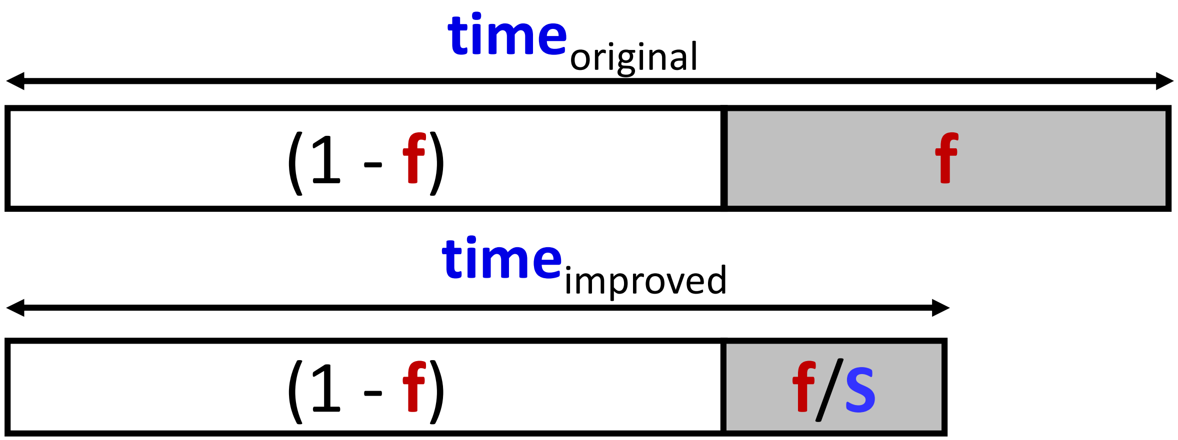
Speedup

- If X is an "enhanced" version of Y, the "speedup" of the enhancement is

$$S = Time_{without\ enhancement} / Time_{with\ enhancement}$$
$$= Time_Y / Time_X$$

Amdahl's Law on Speedup

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



$$\textbf{time}_{improved} = \textbf{time}_{original} \cdot ((1-\textbf{f}) + \textbf{f}/\textbf{S})$$

$$\textbf{S}_{\textbf{effective}} = 1 / ((1-\textbf{f}) + \textbf{f}/\textbf{S})$$

  - 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!=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 = number of A_i executions / 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"

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

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

	normalized to X			normalized to Y			normalized to Z		
	X	Y	Z	X	Y	Z	X	Y	Z
$Time_{A0}$	1	10	20	0.1	1	2	0.05	0.5	1
$Time_{A1}$	1	0.1	0.02	10	1	0.2	50	5	1

AM of ratio	1	5.05	10.01	5.05	1	1.1	25.03	2.75	1
GM of ratio	1	1.0	0.63	1.0	1	0.63	1.58	1.58	1

[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 (30mph + 90mph)/2
- To compute average rate
  - either, expand fully

    average speed = total distance / total time

    = 20 / (10/30 + 10/90) = 45mph
  - or, use harmonic mean formula

$$HM = n \Big/ \sum_{i=0}^{n-1} \frac{1}{Rate_i} \qquad WHM = 1 \Big/ \sum_{i=0}^{n-1} \frac{w_i}{Rate_i}$$

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), lbm (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

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