Performance Metrics

Why study performance metrics?

- determine the benefit/lack of benefit of designs
- computer design is too complex to intuit performance & performance bottlenecks
- have to be careful about what you mean to measure & how you measure it

What you should get out of this discussion

- good metrics for measuring computer performance
- what they should be used for
- what metrics you shouldn't use & how metrics are misused

Performance of Computer Systems

Many different factors to take into account when determining performance:

- Technology
  - circuit speed (clock, MHz)
  - processor technology (how many transistors on a chip)
- Architecture & microarchitecture
  - type of processor (RISC or CISC)
  - configuration of the memory hierarchy
  - type of I/O devices
  - number of processors in the system
- Software
  - quality of the compilers
  - organization & quality of OS, databases, etc.

“Principles” of Experimentation

Meaningful metrics

execution time & component metrics that explain it

Reproducibility

machine configuration, compiler & optimization level, OS, input

Real programs

no toys, kernels, synthetic programs

SPEC is the norm (integer, floating point, graphics, webserver)

TPC-B, TPC-C & TPC-D for database transactions

Simulation

long executions, **warm start** to mimic **steady-state** behavior

usually applications only; some OS simulation

simulator “validation” & internal checks for accuracy

Metrics that Measure Performance

Raw speed: peak performance (never attained)

Execution time: time to execute one program from beginning to end

- the “performance bottom line”
- wall clock time, response time
- Unix time function: 13.7u 23.6s 18:27 3%

Throughput: total amount of work completed in a given time

  - instructions / cycle
  - transactions (database) or packets (web servers) / second
- an indication of how well hardware resources are being used
- good metrics for chip designers or managers of computer systems

(Often improving execution time will improve throughput & vice versa.)

Component metrics: subsystem performance, e.g., memory behavior

- help explain how execution time was obtained
- pinpoints performance bottlenecks

Execution Time

$$\text{Performance}_A = \frac{1}{\text{ExecutionTime}_A}$$

Processor A is faster than processor B, i.e.,

$$\text{ExecutionTime}_A < \text{ExecutionTime}_B$$

$$\text{Performance}_A > \text{Performance}_B$$

Relative Performance

$$\frac{\text{Performance}_A}{\text{Performance}_B} = \frac{\text{ExecutionTime}_B}{\text{ExecutionTime}_A} = n$$

performance of A is *n* times greater than B

execution time of B is *n* times longer than A

CPU Execution Time

The time the CPU spends executing an application

- no memory effects
- no I/O
- no effects of multiprogramming

$$\text{CPUExecutionTime} = \text{CPUClockCycles} \times \text{clockCycleTime}$$

Cycle time (clock period) is measured in time or rate

- clock cycle time = 1/clock cycle rate

$$\text{CPUExecutionTime} = \frac{\text{CPUClockCycles}}{\text{clockCycleRate}}$$

- clock cycle rate of 1 MHz $\Rightarrow$ cycle time of 1 μs
- clock cycle rate of 1 GHz $\Rightarrow$ cycle time of 1 ns

CPI

$$\mathbf{CPUClockCycles} = \mathbf{NumberOfInstructions} \times \mathbf{CPI}$$

Average number of clock cycles per instruction

- throughput metric
- component metric, not a measure of performance
- used for processor organization studies, given a fixed compiler & ISA

Can have different CPIs for classes of instructions

e.g., floating point instructions take longer than integer instructions

$$\mathbf{CPUClockCycles} = \sum_{1}^{n} (\mathbf{CPI_i} \times \mathbf{C_i})$$

where CPI_i = CPI for a particular class of instructions

where C_i = the number of instructions of the i^{th} class that have been executed

Improving part of the architecture can improve a CPI_i

- Talk about the contribution to CPI of a class of instructions

CPU Execution Time

$$\mathbf{CPUExecutionTime} = \mathbf{numberOfInstructions} \times \mathbf{CPI} \times \mathbf{clockCycleTime}$$

To measure:

- execution time: depends on all 3 factors
  - time the program
- number of instructions: determined by the ISA
  - programmable hardware counters
  - profiling
    - count number of times each basic block is executed & multiply by the number of instructions in each basic block
    - instruction sampling
- CPI: determined by the ISA & implementation
  - simulator: interpret (in software) every instruction & calculate the number of cycles it takes to simulate it
- clock cycle time: determined by the implementation & process technology

Factors are interdependent:

- RISC: increases instructions/program, but decreases CPI & clock cycle time because the instructions are simple
- CISC: decreases instructions/program, but increases CPI & clock cycle time because many instructions are more complex

Metrics Not to Use

MIPS (millions of instructions per second)

$$\frac{\text{instruction count}}{\text{execution time} \times 10^6} = \frac{\text{clock rate}}{\text{CPI} \times 10^6}$$

- instruction set-dependent (even true for similar architectures)
- implementation-dependent
- compiler technology-dependent
- program- & input-dependent
+ intuitive: the higher, the better

MFLOPS (millions of floating point operations per second)

$$\frac{\text{floating point operations}}{\text{execution time} \times 10^6}$$

+ FP operations are independent of FP instruction implementation
- different machines implement different FP operations
- different FP operations take different amounts of time
- only measures FP code

static metrics (code size)

Means

Measuring the performance of a workload

- **arithmetic**: used for averaging execution times

$$\left(\sum_{i=1}^{n} \text{time}_i\right) \times \frac{1}{n}$$

- **harmonic**: used for averaging rates

$$\frac{n}{\sum_{i=1}^{n} \frac{1}{\text{rate}_i}} = \frac{1}{\text{arithmeticMean}}$$

- weighted means: the programs are executed with different frequencies, for example:

$$\left(\sum_{i=1}^{n} \text{time}_i \times \text{weight}_i\right) \times \frac{1}{n}$$

Means

	FP Ops	Time (secs)		
		Computer A	Computer B	Computer C
program 1	100	1	10	20
program 2	100	1000	100	20
total		1001	110	40
arith mean		500.5	55	20

	FP Ops	Rate (FLOPS)		
		Computer A	Computer B	Computer C
program 1	100	100	10	5
program 2	100	.1	1	5
harm mean		.2	1.5	5
arith mean		50.1	5.5	5

Computer C is ~25 times faster than A when measuring execution time

Still true when measuring MFLOPS (a rate) with the harmonic mean

Speedup

$$\text{speedup} = \frac{\textbf{execution time}_{\text{beforeImprovement}}}{\textbf{execution time}_{\text{afterImprovement}}}$$

Amdahl's Law:

Performance improvement from speeding up a part of a computer system is limited by the proportion of time the enhancement is used.