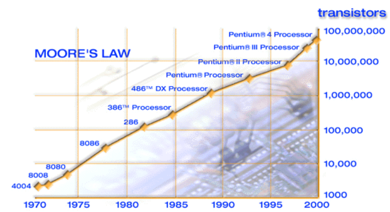
Performance of computer systems

- Many different factors among which:
  - Technology
    - Raw speed of the circuits (clock, switching time)
    - Process technology (how many transistors on a chip)
  - Organization
    - What type of processor (e.g., RISC vs. CISC)
    - What type of memory hierarchy
    - What types of I/O devices
  - How many processors in the system
  - Software
    - O.S., compilers, database drivers etc

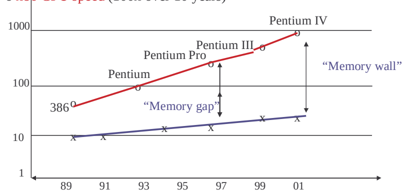
Moore's Law



Courtesy Intel Corp.

Processor-Memory Performance Gap

- x Memory latency decrease (10x over 8 years but densities have increased 100x over the same period)
- o x86 CPU speed (100x over 10 years)



What are some possible metrics

- Raw speed (peak performance = clock rate)
- ***Execution time*** (or response time): time to execute one (suite of) program from beginning to end.
  - Need benchmarks for integer dominated programs, scientific, graphical interfaces, multimedia tasks, desktop apps, utilities etc.
- ***Throughput*** (total amount of work in a given time)
  - measures utilization of resources (good metric when many users: e.g., large data base queries, Web servers)
- Quite often improving execution time will improve throughput and vice-versa

Execution time Metric

- Execution time: inverse of performance

  $Performance_A = 1 / (Execution\_time_A)$
- Processor A is faster than Processor B

  $Execution\_time_A < Execution\_time_B$

  $Performance_A > Performance_B$
- Relative performance

  $Performance_A / Performance_B = Execution\_time_B / Execution\_time_A$

Measuring execution time

- Wall clock, response time, elapsed time
- Some systems have a "time" function
  - Unix 13.7u 23.6s 18:37 3% 2069+1821k 13+24io 62pf+0w
- Difficult to make comparisons from one system to another because of too many factors
- Remainder of this lecture: *CPU execution time*
  - Of interest to microprocessors vendors and designers

Definition of CPU execution time

CPU execution_time = CPU clock_cycles*clock cycle_time

- *CPU clock_cycles* is program dependent thus
  CPU execution_time is program dependent
- *clock cycle_time (*nanoseconds, *ns)* depends on the particular processor
- *clock cycle_time = 1/ clock cycle_rate* (rate in *MHz*)
  - clock cycle_time = 1µs, clock cycle_rate = 1 MHz
  - clock cycle_time = 1ns, clock cycle_rate = 1 GHz
- Alternate definition
  CPU execution_time = CPU clock_cycles / clock cycle_rate

CPI -- Cycles per instruction

- Definition: CPI average number of clock cycles per instr.

*CPU clock_cycles = Number of instr. * CPI*

CPU exec_time = Number of instr. * CPI *clock cycle_time

- Computer architects try to minimize CPI
  - or maximize its inverse IPC : number of instructions per cycle
- CPI in isolation is not a measure of performance
  - program dependent, compiler dependent
  - but good for assessing architectural enhancements (experiments with same programs and compilers)
- In an ideal pipelined processor (to be seen soon) CPI =1
  - but… not ideal so CPI > 1
  - could have CPI <1 if several instructions execute in parallel (superscalar processors)

Classes of instructions

- Some classes of instr. take longer to execute than others
  - e.g., floating-point operations take longer than integer operations
- Assign CPI's per classes of inst., say CPI_i
  CPU exec_time = $\Sigma (CPI_i * C_i)$* *clock cycle_time*
  where C_i is the number of insts. of class *i* that have been executed
- Note that minimizing the number of instructions does not necessarily improve execution time
- Improving one part of the architecture can improve the CPI of one class of instructions
  - One often talks about the contribution to the CPI of a class of instructions

How to measure the average CPI

Elapsed time: wall clock

A given of the processor

*CPU exec_time = Number of instr. * CPI *clock cycle_time*

- Count instructions executed in each class
- Needs a simulator
  - interprets every instruction and counts their number
- or a profiler
  - discover the most often used parts of the program and instruments only those
  - or use sampling
- Use of programmable hardware counters
  - modern microprocessors have this feature but it's limited

Other popular performance measures: MIPS

- MIPS (Millions of instructions per second)
  MIPS = Instruction count / (Exec.time * 10^6)
  MIPS = (Instr. count * clock rate)/(Instr. count *CPI * 10^6)
  MIPS = clock rate /(CPI * 10^6)
- MIPS is a rate: the higher the better
- MIPS in isolation no better than CPI in isolation
  - Program and/or compiler dependent
  - Does not take the instruction set into account
  - can give "wrong" comparative results

Other metric: MFLOPS

- Similar to MIPS in spirit
- Used for scientific programs/machines
- MFLOPS: million of floating-point ops/second

Benchmarks

- Benchmark: workload representative of what a ***system*** will be used for
- Industry benchmarks
  - SPECint and SPECfp industry benchmarks updated every few years, Currently SPEC CPU2000
  - Linpack (Lapack), NASA kernel: scientific benchmarks
  - TPC-A, TPC-B, TPC-C and TPC-D used for databases and data mining
  - Other specialized benchmarks (Olden for list processing, Specweb, SPEC JVM98 etc…)
  - Benchmarks for desktop applications, web applications are not as standard
  - Beware! Compilers are super optimized for the benchmarks

How to report (benchmark) performance

- If you measure execution **times** use **arithmetic mean**
  - e.g., for n benchmarks

    $(\Sigma exec\_time_i) / n$
- If you measure **rates** use **harmonic mean**

    $n / (\Sigma 1/rate_i) = 1/(arithmetic\ mean)$

Computer design: Make the common case fast

- Amdahl's law (speedup)
- Speedup = (performance with enhancement)/(performance base case)

  Or equivalently,

  Speedup = (exec.time base case)/(exec.time with enhancement)
- For example, application to parallel processing
  - *s* fraction of program that is sequential
  - Speedup S is at most 1/*s*
  - That is if 20% of your program is sequential the maximum speedup with an infinite number of processors is at most 5