Performance

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The slides are the product of many rounds of teaching CS 3410 by Professors Weatherspoon, Bala, Bracy, and Sirer.
Goals for today

Performance

- What is performance?
- How to get it?
Performance

Complex question

• How fast is the processor?
• How fast your application runs?
• How quickly does it respond to you?
• How fast can you process a big batch of jobs?
• How much power does your machine use?
Measures of Performance

Clock speed

- 1 KHz, $10^3$ Hz: cycle is 1 millisecond, ms, ($10^{-6}$)
- 1 MHz, $10^6$ Hz: cycle is 1 microsecond, us, ($10^{-6}$)
- 1 Ghz, $10^9$ Hz: cycle is 1 nanosecond, ns, ($10^{-9}$)
- 1 Thz, $10^{12}$ Hz: cycle is 1 picosecond, ps, ($10^{-12}$)

Instruction/application performance

- MIPs (Millions of instructions per second)
- FLOPs (Floating point instructions per second)
  - GPUs: GeForce GTX Titan (2,688 cores, 4.5 Tera flops, 7.1 billion transistors, 42 Gigapixel/sec fill rate, 288 GB/sec)
- Benchmarks (SPEC)
CPI: “Cycles per instruction” → Cycle/instruction for on average

- **IPC = 1/CPI**
  - Used more frequently than CPI
  - Favored because “bigger is better”, but harder to compute with
- Different instructions have different cycle costs
  - E.g., “add” typically takes 1 cycle, “divide” takes >10 cycles
- Depends on relative instruction frequencies

CPI example

- Program has equal ratio: integer, memory, floating point
- Cycles per insn type: integer = 1, memory = 2, FP = 3
- What is the CPI? \((33\% \times 1) + (33\% \times 2) + (33\% \times 3) = 2\)
- **Caveat**: calculation ignores many effects
  - Back-of-the-envelope arguments only
Measures of Performance

General public (mostly) ignores CPI
- Equates clock frequency with performance!

Which processor would you buy?
- Processor A: CPI = 2, clock = 5 GHz
- Processor B: CPI = 1, clock = 3 GHz
- Probably A, but B is faster (assuming same ISA/compiler)

Classic example
- 800 MHz PentiumIII faster than 1 GHz Pentium4!
- Example: Core i7 faster clock-per-clock than Core 2
- Same ISA and compiler!

Meta-point: danger of partial performance metrics!
Measures of Performance

Latency

• How long to finish my program
  – Response time, elapsed time, wall clock time
  – CPU time: user and system time

Throughput

• How much work finished per unit time

Ideal: Want high throughput, low latency

... also, low power, cheap ($$) etc.
How to make the computer faster?

Decrease latency

Critical Path

- Longest path determining the minimum time needed for an operation
- Determines minimum length of clock cycle i.e. determines maximum clock frequency

Optimize for latency on the critical path

- Parallelism (like carry look ahead adder)
- Pipelining
- Both
## Latency: Optimize Delay on Critical Path

E.g. Adder performance

<table>
<thead>
<tr>
<th>32 Bit Adder Design</th>
<th>Space</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ripple Carry</td>
<td>≈ 300 gates</td>
<td>≈ 64 gate delays</td>
</tr>
<tr>
<td>2-Way Carry-Skip</td>
<td>≈ 360 gates</td>
<td>≈ 35 gate delays</td>
</tr>
<tr>
<td>3-Way Carry-Skip</td>
<td>≈ 500 gates</td>
<td>≈ 22 gate delays</td>
</tr>
<tr>
<td>4-Way Carry-Skip</td>
<td>≈ 600 gates</td>
<td>≈ 18 gate delays</td>
</tr>
<tr>
<td>2-Way Look-Ahead</td>
<td>≈ 550 gates</td>
<td>≈ 16 gate delays</td>
</tr>
<tr>
<td>Split Look-Ahead</td>
<td>≈ 800 gates</td>
<td>≈ 10 gate delays</td>
</tr>
<tr>
<td>Full Look-Ahead</td>
<td>≈ 1200 gates</td>
<td>≈ 5 gate delays</td>
</tr>
</tbody>
</table>
Single-cycle datapath: true “atomic” F/EX loop
Fetch, decode, execute one instruction/cycle
+ Low CPI (later): 1 by definition
– Long clock period: accommodate slowest insn
(\text{PC} \rightarrow \text{I$} \rightarrow \text{RF} \rightarrow \text{ALU} \rightarrow \text{D$} \rightarrow \text{RF})
New: Multi-Cycle Datapath

Multi-cycle datapath: attacks slow clock
Fetch, decode, execute one insn over multiple cycles
Allows insns to take different number of cycles
±Opposite of single-cycle: short clock period, high CPI
Single- vs. Multi-cycle Performance

Single-cycle

- Clock period = 50ns, CPI = 1
- Performance = 50ns/insn

Multi-cycle: opposite performance split

- Shorter clock period
- Higher CPI

Example

- branch: 20% (3 cycles), ld: 20% (5 cycles), ALU: 60% (4 cycle)
- Clock period = 11ns, CPI = (20%*3) + (20%*5) + (60%*4) = 4
  - Why is clock period 11ns and not 10ns?
- Performance = 44ns/insn

Aside: CISC makes perfect sense in multi-cycle datapath
Multi-Cycle Instructions

But what to do when operations take diff. times?

E.g: Assume:

- load/store: 100 ns \( \leftarrow 10 \text{ MHz} \)
- arithmetic: 50 ns \( \leftarrow 20 \text{ MHz} \)
- branches: 33 ns \( \leftarrow 30 \text{ MHz} \)

Single-Cycle CPU

10 MHz (100 ns cycle) with
- 1 cycle per instruction
Multi-Cycle Instructions

Multiple cycles to complete a single instruction

E.g: Assume:

- load/store: 100 ns
- arithmetic: 50 ns
- branches: 33 ns

---

Multi-Cycle CPU

30 MHz (33 ns cycle) with
- 3 cycles per load/store
- 2 cycles per arithmetic
- 1 cycle per branch

---

Single-Cycle CPU

10 MHz (100 ns cycle) with
- 1 cycle per instruction

---

ms = 10^{-3} second
us = 10^{-6} seconds
ns = 10^{-9} seconds
ps = 10^{-12} seconds
Instruction mix for some program P, assume:

- 25% load/store (3 cycles/instruction)
- 60% arithmetic (2 cycles/instruction)
- 15% branches (1 cycle/instruction)

Multi-Cycle performance for program P:

Multi-Cycle @ 30 MHz

Single-Cycle @ 10 MHz
Total Time

CPU Time = \# Instructions \times CPI \times Clock Cycle Time

sec/prgrm = Instr/prgm \times cycles/instr \times seconds/cycle

**Instructions per program:** “dynamic instruction count”
- Runtime count of instructions executed by the program
- Determined by program, compiler, ISA

**Cycles per instruction:** “CPI” (typical range: 2 to 0.5)
- How many cycles does an instruction take to execute?
- Determined by program, compiler, ISA, micro-architecture

**Seconds per cycle:** clock period, length of each cycle
- Inverse metric: cycles/second (Hertz) or cycles/ns (Ghz)
- Determined by micro-architecture, technology parameters

For lower latency (=better performance) minimize all three
- Difficult: *often pull against one another*
Total Time

CPU Time = # Instructions x CPI x Clock Cycle Time

sec/prgrm = Instr/prgm x cycles/instr x seconds/cycle

E.g. Say for a program with 400k instructions, 30 MHz:

CPU [Execution] Time = ?
Example

**Goal:** Make Multi-Cycle @ 30 MHz CPU (15MIPS) run 2x faster by making arithmetic instructions faster

*Instruction mix* (for P):
- 25% load/store, CPI = 3
- 60% arithmetic, CPI = 2
- 15% branches, CPI = 1
Example

Goal: Make Multi-Cycle @ 30 MHz CPU (15MIPS) run 2x faster by making arithmetic instructions faster

Instruction mix (for P):
- 25% load/store, CPI = 3
- 60% arithmetic, CPI = 2
- 15% branches, CPI = 1

Goal: Make processor run 2x faster, i.e. 30 MIPS instead of 15 MIPS
Amdahl’s Law

Execution time after improvement = \[
\frac{\text{execution time affected by improvement}}{\text{amount of improvement}} + \text{execution time unaffected}
\]

Or: Speedup is limited by popularity of improved feature

Corollary: Make the common case fast
- Don’t optimize 1% to the detriment of other 99%
- Don’t over-engineer capabilities that cannot be utilized

Caveat: Law of diminishing returns
Performance Recap