PERFORMANCE, POWER, ENERGY

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Recall: Processor Performance

- Clock cycle time (CT = 1/clock frequency)
  - Influenced by technology and pipeline
- Cycles per instruction (CPI)
  - Influenced by architecture
  - IPC may be used instead (IPC = 1/CPI)
- Instruction count (IC)
  - Influenced by ISA and compiler
- CPU time = IC x CPI x CT
Example: Clock Cycle Time

- I execute a scientific program with 1B instructions on my laptop. I observe an average cycle per instruction (CPI) of 4.5 for each run. Compute the CPU time if the clock frequency is 2GHz.
Example: Clock Cycle Time

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\[
\text{CPU time} = \text{IC} \times \text{CPI} \times \text{CT}
\]

\[
= 1 \times 10^9 \times 4.5 \times 0.5 \times 10^{-9}
\]

\[
= 2.25 \text{ seconds}
\]
I execute a scientific program with 1B instructions on my laptop. I observe an average cycle per instruction (CPI) of 4.5 for each run. Compute the CPU time after overclocking to 3.2GHz.
Example: Clock Cycle Time

- I execute a scientific program with 1B instructions on my laptop. I observe an average cycle per instruction (CPI) of 4.5 for each run. Compute the CPU time after overclocking to 3.2GHz.

\[
\text{CPU time} = IC \times CPI \times CT
\]

\[
= 1 \times 10^9 \times 4.5 \times 0.3125 \times 10^{-9}
\]

\[
= 1.40625 \text{ seconds}
\]
Example: Cycles Per Instruction

- Computer A: Cycle Time = 250ps, CPI = 2.0
- Computer B: Cycle Time = 500ps, CPI = 1.2
- Same ISA and same program
- Which is faster, and by how much?
Example: Cycles Per Instruction

- **Computer A**: Cycle Time = 250ps, CPI = 2.0
- **Computer B**: Cycle Time = 500ps, CPI = 1.2
- Same ISA and same program
- Which is faster, and by how much?

\[
\text{CPU Time}_A = \text{Instruction Count} \times \text{CPI}_A \times \text{Cycle Time}_A
\]
\[
= I \times 2.0 \times 250\text{ps} = I \times 500\text{ps}
\]

\[
\text{CPU Time}_B = \text{Instruction Count} \times \text{CPI}_B \times \text{Cycle Time}_B
\]
\[
= I \times 1.2 \times 500\text{ps} = I \times 600\text{ps}
\]

\[
\frac{\text{CPU Time}_B}{\text{CPU Time}_A} = \frac{I \times 600\text{ps}}{I \times 500\text{ps}} = 1.2
\]

A is faster…

...by this much
Example: Instruction Count

There exist two algorithms for a scientific problem. Program A implements Algorithm A using 10B instructions. But, Program B needs only 2B instructions for Algorithm B. Compute the CPU times for an average IPC of 0.25 on a 4GHz processor.
Example: Instruction Count

- There exist two algorithms for a scientific problem. Program A implements Algorithm A using 10B instructions. But, Program B needs only 2B instructions for Algorithm B. Compute the CPU times for an average IPC of 0.25 on a 4GHz processor.

- Program A: CPU time = \(10 \times 10^9 \times 4 \times 0.25 \times 10^{-9}\)
  
  \[= 10 \text{ seconds}\]

- Program B: CPU time = \(2 \times 10^9 \times 4 \times 0.25 \times 10^{-9}\)
  
  \[= 2 \text{ seconds}\]
Measuring Performance

- What program to use for measuring performance?
- Benchmarks Suites
  - A set of representative programs that are likely relevant to the user
  - Examples:
    - SPEC CPU 2006: CPU-oriented programs (for desktops)
    - SPECweb: throughput-oriented (for servers)
    - EEMBC: embedded processors/workloads
**SPEC CPU Benchmark**

- Programs used to measure performance
  - Supposedly typical of actual workload
- **Standard Performance Evaluation Corp (SPEC)**
  - Develops benchmarks for CPU, I/O, Web, ...
- **SPEC CPU2006**
  - Elapsed time to execute a selection of programs
    - Negligible I/O, so focuses on CPU performance
  - Normalize relative to reference machine
  - Summarize as geometric mean of performance ratios
    - CINT2006 (integer) and CFP2006 (floating-point)

\[
\sqrt[n]{\prod_{i=1}^{n} \text{Execution time ratio}_i}
\]
Consider an employee who is given a fix budget of $500 to enhance the performance their laptop. There exist two options for system upgrade: (a) make CPU 2x faster and (b) make memory 1.5x faster. Which one is upgrade option is better?
Amdahl’s Law

- The law of diminishing returns

\[
\text{Execution time after improvement} = \frac{\text{Execution time affected by improvement}}{\text{Amount of improvement}} + \text{Execution time unaffected}
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\text{Execution time}_{\text{new}} = \text{Execution time}_{\text{old}} \times \left( \left(1 - \text{Fraction}_{\text{enhanced}}\right) + \frac{\text{Fraction}_{\text{enhanced}}}{\text{Speedup}_{\text{enhanced}}} \right)
\]
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\[
\text{Speedup}_{\text{overall}} = \frac{\text{Execution time}_{\text{old}}}{\text{Execution time}_{\text{new}}} = \frac{1}{(1 - \text{Fraction}_{\text{enhanced}}) + \frac{\text{Fraction}_{\text{enhanced}}}{\text{Speedup}_{\text{enhanced}}}}
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Scenario 1: 20% CPU and 80% Memory

(a): speedup=$1.11^x$  (b): speedup=$1.36^x$
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- Scenario 1: 20% CPU and 80% Memory
  - (a): speedup=1.11x  (b): speedup=1.36x

- Scenario 2: 70% CPU and 30% Memory
  - (a): speedup=1.53x  (b): speedup=1.11x
Our new processor is 10x faster on computation than the original processor. Assuming that the original processor is busy with computation 40% of the time and is waiting for IO 60% of the time, what is the overall speedup?
Example Problem

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\[ f = 0.4 \quad s = 10 \]

\[ \text{Speedup} = \frac{1}{(0.6 + 0.4/10)} = \frac{1}{0.64} = 1.5625 \]
Power and Energy

- **Power = Voltage x Current (P = VI)**
  - Instantaneous rate of energy transfer (Watt)

- **Energy = Power x Time (E = PT)**
  - The cost of performing a task (Joule)
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  - The cost of performing a task \ (\text{Joule})

- Peak Power = 3W
- Average Power = 1.66W
- Total Energy = 5J
CPU Power and Energy

- All consumed energy is converted to heat
  - CPU power is the rate of heat generation
  - Excessive peak power may result in burning the chip
- Static and dynamic energy components
  - \( \text{Energy} = (\text{Power}_{\text{Static}} + \text{Power}_{\text{Dynamic}}) \times \text{Time} \)
Example: Power and Energy

- Consider using Zoom for a 50-minute IVC meeting on your laptop that dissipates 75W dynamic power. Assume that your laptop dissipates 15W static power. Compute the total energy consumed for the meeting?
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\[
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- Energy = $(\text{Power}_{\text{Static}} + \text{Power}_{\text{Dynamic}}) \times \text{Time}$
- $= (15 + 75) \times 3000 = 270 \text{kJ}$
- $1 \text{kWh} = 3,600 \text{kJ} \rightarrow \text{Cost} = 1.5¢$
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- Static and dynamic energy components
  - Energy = (Power_{Static} + Power_{Dynamic}) \times Time

- How to compute for CPU?
  - \text{Power}_{\text{Static}} = \text{Voltage} \times \text{Current}_{\text{Static}}
  - \text{Power}_{\text{Dynamic}} = \text{Capacitance} \times \text{Voltage}^2 \times (\text{Activity} \times \text{Frequency})
Power Reduction Techniques

- Reducing capacitance (C)
- Reducing voltage (V)
- Reducing frequency (F)
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- Reducing voltage (V)
  - Negative effect on frequency
  - Opportunistically power gating (wakeup time)
  - Dynamic voltage and frequency scaling
- Reducing frequency (F)

\[ F \times A \]
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- Reducing frequency (F)
  - Negative effect on CPU time
  - Clock gating in unused resources
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  - Negative effect on CPU time
  - Clock gating in unused resources

- Points to note
  - Utilization directly effects dynamic power
  - Lowering power does NOT mean lowering energy
Example: Frequency Scaling

- Consider a processor consuming 80W dynamic power. By only reducing the frequency from 4GHz to 2GHz, what will be the new dynamic power?
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\]

- @4GHz \hspace{2cm} \text{Power}_{\text{Dynamic}} = 80W
- @2GHz \hspace{2cm} \text{Power}_{\text{Dynamic}} = 40W