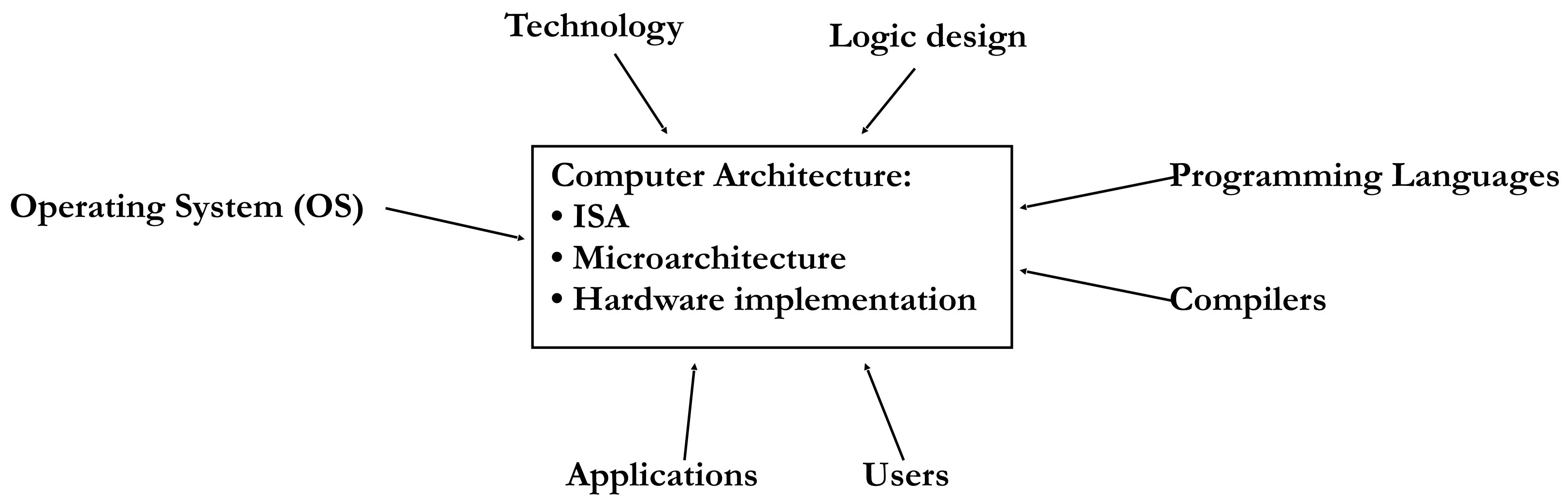
## Announcements

- Course web site: http://www.inf.ed.ac.uk/teaching/courses/car
  - Lecture slides
  - Tutorial problems
  - Courseworks
- Piazza discussion forum: http://piazza.com/ed.ac.uk/spring2018/car
- Tutorials start in week 3

## Summary: Computer Architecture

### What is Computer Architecture?



### Metrics of interest for computer architects

- Performance
- Cost
- Reliability
- Power
- Area

## Performance of Computer Architectures

- Metrics:
  - Execution time, response time: overall time for a given computation (e.g. full program execution, one transaction)
  - Latency: time to complete a given task (e.g. memory latency, I/O latency, instruction latency)
  - Bandwidth, throughput: rate of completion of tasks (e.g. memory bandwidth, transactions per second, MIPS, FLOPS)
- MIPS, FLOPS: must use with caution
- Benchmarking:
  - toy benchmarks, synthetic benchmarks, kernels, real programs,
  - Input sets
  - Standard benchmarking suites: SPEC INT/FP, EEMBC Coremark, CloudSuite

## CPU Performance Terminology

A is n times faster than B means

$$\frac{\text{Execution time of B}}{\text{Execution time of A}} = n$$

A is m% faster than B means

$$\frac{\text{Execution time of B} - \text{Execution time of A}}{\text{Execution time of A}} \times 100 = m$$

## Improving Performance: Principles of CA Design

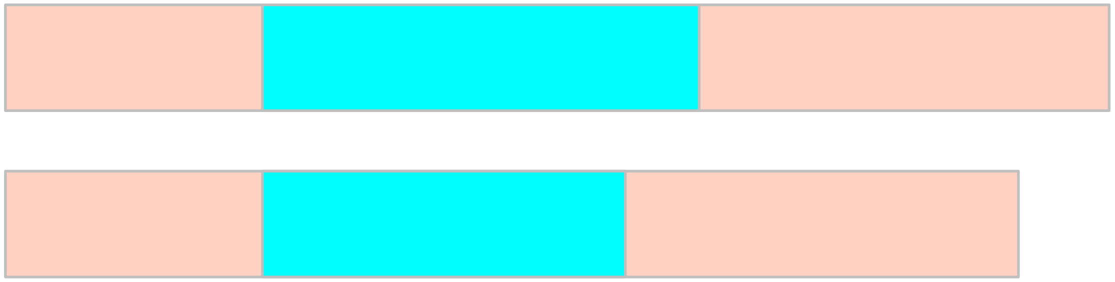
- Take advantage of parallelism
  - System level: multiple processors, multiple disks
  - Processor level: operate on multiple instructions at once (e.g., pipelining, superscalar issue)
  - Circuit level: operate on multiple bits at once (e.g., carry-lookahead ALU)
- Principle of locality
  - Spatial and Temporal Locality
  - 90% of program executing in 10% of code
  - E.g. Caches
- Focus on the common case
  - Amdahl's law, CPU Performance equation
  - E.g. RISC design principle

## Amdahl's Law

Speedup due to an enhancement E:

$\text{Time}_{\text{before}}$

$\text{Time}_{\text{after}}$



$$Speedup(S) = \frac{Execution\ time\ before\ E}{Execution\ time\ after\ E}$$

Suppose that enhancement E accelerates a fraction F of the task by a factor S, and the remainder of the task is unaffected. What is the Execution $\text{time}_{\text{after}}$ and Speedup(S)?

## Amdahl's Law

$$Execution\ time_{after} = ExecTime_{before} \times \left[(1-F) + \frac{F}{S}\right]$$

$$Speedup(S) = \frac{ExecTime_{before}}{ExecTime_{after}} = \frac{1}{\left[(1-F) + \frac{F}{S}\right]}$$

## Amdahl's Law - Example

Floating point instructions contribute 10% to the program execution time and are improved to run 2x faster.

Q: What is the execution time and speedup after improvement?

Answer:

$$F = 0.1, \qquad S = 2$$

$$ExTime_{after} = ExTime_{before} \times \left[(1 - 0.1) + \frac{0.1}{2}\right] = 0.95\ ExTime_{before}$$

$$Speedup(S) = \frac{ExTime_{before}}{ExTime_{after}} = \frac{1}{0.95} = 1.053$$

## Factors that affect CPU performance

Instruction count (IC)

- Compiler, ISA

Cycles per instruction (CPI)

- ISA, microarchitecture

Clock time (1/*f*)

- Microarchitecture, technology

**What determines these factors?**

## The CPU Performance Equation

**CPU time = IC x CPI x Clock time**

where: CPU time = execution time
IC = number of instructions executed (instruction count)
CPI = number of average clock cycles per instruction
Clock time = duration of processor clock

$$\textbf{CPU time} = \left( \sum_{i=1}^{n} IC_i \times CPI_i \right) \times \textbf{Clock time}$$

where: $IC_i$ = IC for instruction (instruction group) i
$CPI_i$ = CPI for instruction (instruction group) i

$$CPI = \frac{\left( \sum_{i=1}^{n} IC_i \times CPI_i \right)}{IC} = \sum_{i=1}^{n} \left( CPI_i \times \frac{IC_i}{IC} \right)$$

## Examples

**Example:**

- Branch instructions take 2 cycles, all other instructions take 1 cycle
- CPU A uses extra compare instruction per branch
- Clock frequency of CPU A is 1.25 times faster than CPU B
- On CPU A, 20% of instructions are branches (thus other 20% are compare instructions)

**Find the relative performance of CPUs A and B**

$$CPI_A = CPI_{branch} \times \frac{IC_{branch}}{IC} + CPI_{others} \times \frac{IC_{others}}{IC} = 2 \times 0.2 + 1 \times 0.8 = 1.2$$

$$CPI_B = CPI_{branch} \times \frac{IC_{branch}}{IC} + CPI_{others} \times \frac{IC_{others}}{IC} = 2 \times 0.25 + 1 \times 0.75 = 1.25$$

$$\text{CPU time}_B = IC_B \times CPI_B \times \text{Clock time}_B = 0.8 \times IC_A \times 1.25 \times (1.25 \times \text{Clock time}_A)$$

$$= 1.25 \times IC_A \times \text{Clock time}_A$$

$$\text{CPU time}_A = IC_A \times CPI_A \times \text{Clock time}_A = IC_A \times 1.2 \times \text{Clock time}_A$$

**CPU A is faster!**

## Improving CPU Performance

- IC:
  - Compiler optimizations (constant folding, constant propagation)
  - ISA (More complex instructions)
- CPI:
  - Microarchitecture (Pipelining, Out-of-order execution, branch prediction)
  - Compiler (Instruction scheduling)
  - ISA (Simpler instructions)
- Clock period:
  - Technology (Smaller transistors)
  - ISA (Simple instructions that can be easily decoded)
  - Microarchitecture (Simple architecture)