

# **CS425**

# **Computer Systems Architecture**

**Fall 2025**

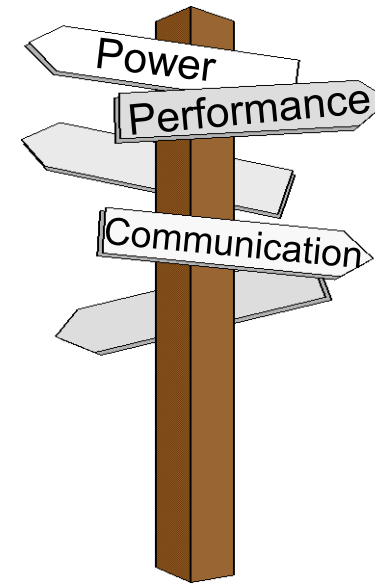
**Metrics**

# Outline

- Measurements and metrics:
  - Performance, Cost, Dependability, Power
- Guidelines and principles in the design of computers
- CPU Performance

# Major Design Challenges

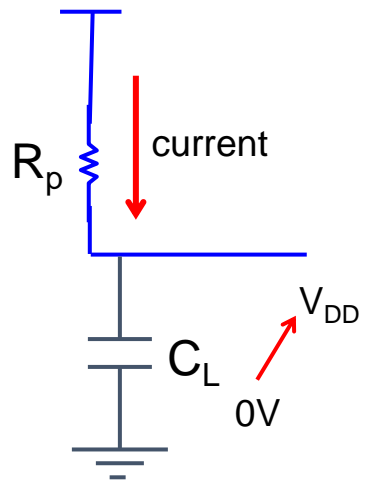
- Power
- CPU time
- Memory latency/bandwidth
- Storage latency/bandwidth
- Transactions per second
- Intercommunication
- Dependability



**Everything Looks a Little Different**

# Power Consumption

## Charge external capacitance



$$Q = C_L V_{DD}$$

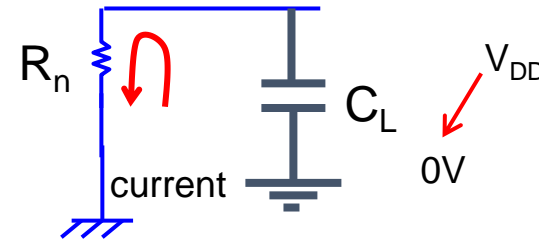
$$E_{\text{dynamic}} = Q V_{DD} = C_L V_{DD}^2$$

$\frac{1}{2} E_d$  thermal energy on  $R_p$

$\frac{1}{2} E_d$  stored on  $C_L$

(since  $E_{CL} = \frac{1}{2} C_L V_{DD}^2$ )

## Discharge external capacitance



$\frac{1}{2} E_{\text{dynamic}}$  stored on  $C_L$   
becomes thermal energy on  $R_N$

$$P_{\text{dynamic}} = \frac{1}{2} C_L V_{DD}^2 \text{ frequency}$$

# Power Equations

$$\textbf{Power}_{dynamic} = \frac{1}{2} \times \textbf{Capacitive load} \times \textbf{Voltage}^2 \times \textbf{Frequency}$$

$$\textbf{Energy}_{dynamic} = \textbf{Capacitive load} \times \textbf{Voltage}^2$$

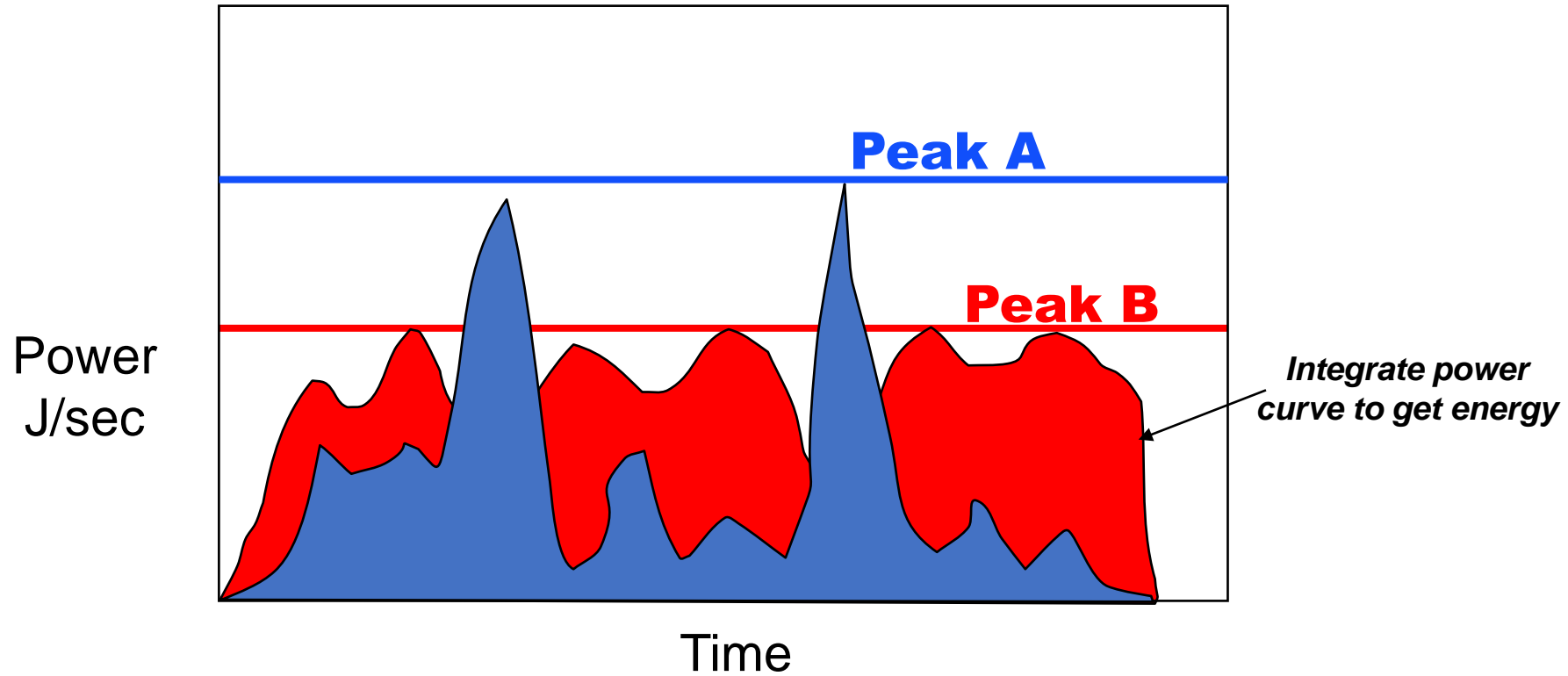
$$\textbf{Power}_{static} = \textbf{Current}_{static} \times \textbf{Voltage}$$

- Power due to switching more transistors increases
- Static power due to leakage current increasing

# Power and Energy

- Energy to complete operation (Joules)
  - Corresponds approximately to battery life
  - (Battery energy capacity actually depends on rate of discharge)
- Peak power dissipation (Watts = Joules/second)
  - Affects packaging (power and ground pins, thermal design)
- $d_i/d_t$ , peak change in supply current (Amps/second)
  - Affects power supply noise (power and ground pins, decoupling capacitors)

# Peak Power versus Lower Energy



- System **A** has higher peak power, but lower total energy
- System **B** has lower peak power, but higher total energy

# Measuring Reliability (Dependability)

## Reliability equations

*MTTF = Mean Time To Failure*

$$FIT = \text{Failures In Time (per billion hours)} = \frac{10^9}{MTTF}$$

*MTTR = Mean Time to Repair (MTBF = MTTF + MTTR)*

$$\text{Module availability} = \frac{MTTF}{MTTF + MTTR}$$

$$FIT_{\text{system}} = \sum_{i=1}^{\text{\#components}} FIT_i$$

**MTTF = 1,000,000 hours → FIT = ?**

Interesting Read: <https://spectrum.ieee.org/how-to-kill-a-supercomputer-dirty-power-cosmic-rays-and-bad-solder>



# Comparing Design Alternatives

**Design X is n times faster than design Y**

$$n = \frac{\text{Execution time}_Y}{\text{Execution time}_X} = \frac{\frac{1}{\text{Performance}_Y}}{\frac{1}{\text{Performance}_X}} = \frac{\text{Performance}_X}{\text{Performance}_Y}$$

- ▶ **Wall-clock time:** time to complete a task
- ▶ **CPU time:** time CPU is busy
- ▶ **Workload:** Mixture of programs (including OS) on a system
- ▶ **Kernels:** Common, important functions in applications
- ▶ **Microbenchmarks:** Synthetic programs trying to:
  - ▶ Isolate components and measure performance
  - ▶ Imitate workloads of real world in a controlled setting

# Benchmark Suites

**Desktop** (SPEC = Standard Performance Evaluation Corporation, 12 INT, 17 FP, 1980)

- ▶ SPECCPU (revised every few years)
- ▶ Real programs measuring processor-memory activity

## Multi-core desktop/server

- ▶ SPECOMP, SPECMPI (scientific), SPECapc (graphics)
- ▶ Focus on parallelism, synchronization, communication

## Client/Server

- ▶ SPECjbb, SPECjms, SPECjvm, SPECsfs, SPECmail SPECrate, SPECWeb ...
- ▶ Measuring throughput (how many tasks per unit of time)
- ▶ Measuring latency (how quickly does client get response)

## Embedded systems

- ▶ EEMBC, MiBench
- ▶ Measuring performance, throughput, latency

*The weakness of one benchmark is covered by the other benchmarks*

# Summarizing performance

## Arithmetic mean of wall-clock time

- ▶ Biased by long-running programs
- ▶ May rank designs in non-intuitive ways:
  - ▶ Machine A: Program  $P_1 \rightarrow 1000$  secs.,  $P_2 \rightarrow 1$  secs.
  - ▶ Machine B: Program  $P_1 \rightarrow 800$  secs.,  $P_2 \rightarrow 100$  secs.
  - ▶ What if machine runs  $P_2$  most of the time?

## Means

- ▶ Total time ignores program contribution to total workload
- ▶ Arithmetic mean biased by long programs
- ▶ Weighted arithmetic mean a better choice?
- ▶ How do we calculate weights?

# Summarizing performance (cont.)

## Weighted arithmetic mean

$$\sum_{i=1}^n Weight_i \times Time_i$$

**Example,  $W(1) = W(2) = 0.50$**

	Computer A	Computer B	Computer C
Program P1 (secs)	1	10	20
Program P2 (secs)	1000	100	20
Total time (secs)	1001	110	40
Weighted mean	500.50	55.00	20.00

# Summarizing performance (cont.)

## Weighted arithmetic mean

$$\sum_{i=1}^n Weight_i \times Time_i$$

**Example,  $W(1) = 0.909$   $W(2) = 0.091$**

	Computer A	Computer B	Computer C
Program P1 (secs)	1	10	20
Program P2 (secs)	1000	100	20
Total time (secs)	1001	110	40
Weighted mean	91.91	18.19	20.00

# Summarizing performance (cont.)

## Weighted arithmetic mean

$$\sum_{i=1}^n \text{Weight}_i \times \text{Time}_i$$

**Example,  $W(1) = 0.999$   $W(2) = 0.001$**

	Computer A	Computer B	Computer C
Program P1 (secs)	1	10	20
Program P2 (secs)	1000	100	20
Total time (secs)	1001	110	40
Weighted mean	2.00	10.09	20.00

# Summarizing performance (cont.)

## Measuring against a reference computer

$$SPEC_{ratio_A} = \frac{Execution\ time_{reference}}{Execution\ time_A} = Performance_A / Performance_{reference}$$

$$n = \frac{SPEC_{ratio_A}}{SPEC_{ratio_B}} = \frac{\frac{Execution\ time_{reference}}{Execution\ time_A}}{\frac{Execution\ time_{reference}}{Execution\ time_B}} = \frac{Execution\ time_B}{Execution\ time_A} = \frac{Performance_A}{Performance_B}$$

## Using ratios

- ▶ Ratios against reference machine are independent of running time of programs

# Summarizing performance (cont.)

## Geometric mean

$$\sqrt[n]{\prod_{i=1}^n \text{SPEC}_{\text{ratio}}(i)}$$

$$\frac{\text{Geometric mean}_A}{\text{Geometric mean}_B} = \text{Geometric mean}\left(\frac{A}{B}\right)$$

Used by SPEC98, SPEC92, SPEC95, ..., SPEC2006, SPEC2017



# Pros and cons of geometric means

## Pros

- ▶ Consistent rankings, independent of program frequencies
- ▶ Not influenced by peculiarities of any single machine

## Cons

- ▶ Geometric mean does not predict execution time
  - ▶ Sensitivity to benchmark vs. machine remains
  - ▶ Encourages machine tuning for specific benchmarks
  - ▶ Benchmarks can not be touched, but compilers can!
- ▶ Any “averaging” metric loses information

# Qualitative principles of design

## Taking advantage of parallelism

- ▶ Use pipelining to overlap instructions
- ▶ Use multiple execution units
- ▶ Use multiple cores
- ▶ Use multiple processors to increase throughput (system level: scalability)

## Locality (spatial and temporal locality)

- ▶ Programs reuse instructions and data
- ▶ 90-10 rule
  - ▶ 90% of execution time spent running 10% of instructions
- ▶ Programs access data in nearby addresses (spatial)

# Qualitative principles of design (cont.)

## Make the common case fast

- ▶ Trade-off's in design (e.g. performance vs. power/area)
- ▶ Provide efficient design for the common case
- ▶ Amdahl's Law

### Example:

First optimize **instruction fetch and decode unit** instead of **multiplier**

# Amdahl's Law

$$\text{Speedup} = \frac{\text{Execution time for entire task without using the enhancement}}{\text{Execution time for entire task using the enhancement when possible}}$$

$$\text{execution time}_{\text{new}} = \text{execution time}_{\text{old}} \times \left( (1 - \text{fraction}_{\text{enhanced}}) + \frac{\text{fraction}_{\text{enhanced}}}{\text{speedup}_{\text{enhanced}}} \right)$$

$$\text{speedup}_{\text{overall}} = \frac{\text{execution time}_{\text{old}}}{\text{execution time}_{\text{new}}} = \frac{1}{(1 - \text{fraction}_{\text{enhanced}}) + \frac{\text{fraction}_{\text{enhanced}}}{\text{speedup}_{\text{enhanced}}}} \Rightarrow$$

Upper Limit:  $\text{speedup}_{\text{overall}} \rightarrow \frac{1}{1 - \text{fraction}_{\text{enhanced}}}$



# Amdahl's Law example

- New CPU 10X faster
- I/O bound server, so 60% time waiting for I/O

$$\begin{aligned}\text{Speedup}_{\text{overall}} &= \frac{1}{(1 - \text{Fraction}_{\text{enhanced}}) + \frac{\text{Fraction}_{\text{enhanced}}}{\text{Speedup}_{\text{enhanced}}}} \\ &= \frac{1}{(1 - 0.4) + \frac{0.4}{10}} = \frac{1}{0.64} = 1.56\end{aligned}$$

- Apparently, its human nature to be attracted by 10X faster, vs. keeping in perspective its just 1.6X faster

# Processor Performance

## CPU time

$$\text{CPU time} = \text{CPU clock cycles} \times \text{Clock cycle time}$$

$$CPI = \frac{\text{CPU clock cycles}}{\text{instruction count}} \Rightarrow$$

$$\text{CPU time} = \text{instruction count} \times CPI \times \text{cycle time} \Rightarrow$$

$$\text{CPU time} = \frac{\text{instructions}}{\text{program}} \times \frac{\text{clock cycles}}{\text{instructions}} \times \frac{\text{seconds}}{\text{clock cycles}}$$

# Cycles Per Instruction (CPI)

“Average Cycles per Instruction”

$$\begin{aligned}\text{CPI} &= (\text{CPU Time} * \text{Clock Rate}) / \text{Instruction Count} \\ &= \text{Cycles} / \text{Instruction Count}\end{aligned}$$

$$\text{CPU time} = \text{Cycle Time} \times \sum_{j=1}^n \text{CPI}_j \times \text{IC}_j$$

$$\text{CPI} = \sum_{j=1}^n \text{CPI}_j \times F_j \quad \text{where } F_j = \frac{\text{IC}_j}{\text{Instruction Count}}$$

“Instruction Frequency”

# Example: Calculating CPI bottom up

Run benchmark and collect workload characterization  
(simulate, machine counters, or sampling)

Base Machine (Reg / Reg)

Op	Freq	CPI <sub>i</sub>	F*CPI <sub>i</sub>	(% Time)
ALU	50%	1	0.5	(33%)
Load	20%	2	0.4	(27%)
Store	10%	2	0.2	(13%)
Branch	20%	2	0.4	(27%)
			<hr/> 1.5	

Typical Mix of  
instruction types  
in program

Design guideline: Make the common case fast

MIPS 1% rule: only consider adding an instruction if it is shown to add 1% performance improvement on reasonable benchmarks.



# Processor Performance

*CPU time = instruction count  $\times$  CPI  $\times$  cycle time*

## How can CA help?

- ▶ Technology has been providing faster clock speeds
  - ▶ Main performance factor for almost 20 years
  - ▶ Trend seems to reverse
  - ▶ Limitations due to power consumption, reliability
- ▶ Architecture can pack more computing power in same area
- ▶ Architecture can improve CPI
- ▶ Algorithms and compilers can reduce instruction count

# Price / Performance

benchmark for online transaction processing (OLTP) is TPC-C

