

EE488
Computer Architecture
Lecture 2 - performance

2024 Summer

Today's Lecture

Performance Concepts

- Response Time
- Throughput

Performance Evaluation

- Benchmarks

Announcements

Processor Design Metrics

- Cycle Time
- Cycles per Instruction

Amdahl's Law

- Speedup what is important

Critical Path

Performance Concepts

Performance Perspectives

Purchasing perspective

- Given a collection of machines, which has the
 - Best performance ?
 - Least cost ?
 - Best performance / cost ?

Design perspective

- Faced with design options, which has the
 - Best performance improvement ?
 - Least cost ?
 - Best performance / cost ?

Both require

- basis for comparison
- metric for evaluation

Our goal: understand cost & performance implications of architectural choices

Two Notions of “Performance”

Plane	DC to Paris	Speed	Passengers	Throughput (pmph)
Boeing 747	6.5 hours	610 mph	470	286,700
Concorde	3 hours	1350 mph	132	178,200

Which has higher performance?

Execution time (response time, latency, ...)

- Time to do a task

Throughput (bandwidth, ...)

- Tasks per unit of time

Response time and throughput often are in opposition

Definitions

Performance is typically in units-per-second

- bigger is better

If we are primarily concerned with response time

- performance = $\frac{1}{\text{execution_time}}$

"X is n times faster than Y" means

$$\frac{\text{ExecutionTime}_y}{\text{ExecutionTime}_x} = \frac{\text{Performance}_x}{\text{Performance}_y} = n$$

Example

- Time of Concorde vs. Boeing 747?
 - Concord is 1350 mph / 610 mph = 2.2 **times faster**
= 6.5 hours / 3 hours
- Throughput of Concorde vs. Boeing 747 ?
 - Concord is 178,200 pmph / 286,700 pmph = 0.62 "times faster"
 - Boeing is 286,700 pmph / 178,200 pmph = 1.60 "times faster"
- Boeing is 1.6 times ("60%") faster in terms of throughput
- Concord is 2.2 times ("120%") faster in terms of flying time

We will focus primarily on execution time for a single job

Lots of instructions in a program => Instruction throughput important!

Benchmarks

Evaluation Tools

Benchmarks, traces and mixes

- Macrobenchmarks and suites
- Microbenchmarks
- Traces

LD 5EA3
ST 31FF
....
LD 1EA2
....

MOVE	39%
BR	20%
LOAD	20%
STORE	10%
ALU	11%

Workloads

Simulation at many levels

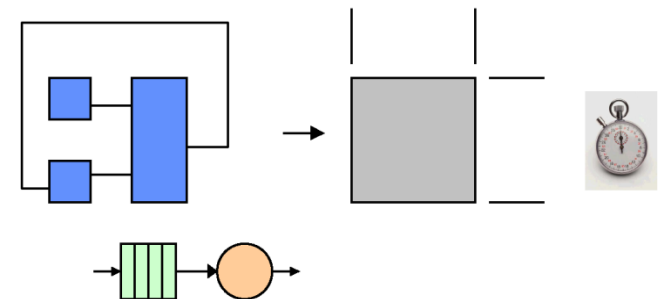
- ISA, microarchitecture, RTL, gate circuit
- Trade fidelity for simulation rate (Levels of abstraction)

Other metrics

- Area, clock frequency, power, cost, ...

Analysis

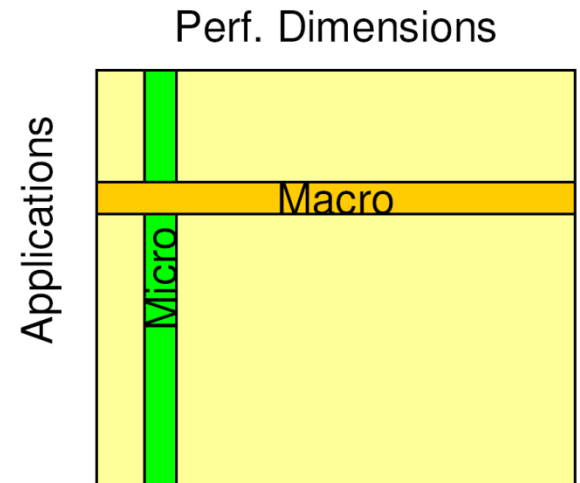
- Queuing theory, back-of-the-envelope
- Rules of thumb, basic laws and principles



Benchmarks

Microbenchmarks

- Measure one performance dimension
 - Cache bandwidth
 - Memory bandwidth
 - Procedure call overhead
 - FP(Floating Point) performance
- Insight into the underlying performance factors
- Not a good predictor of application performance



Macrobenchmarks

- Application execution time
 - Measures overall performance, but on just one application
 - Need application suite

Why Do Benchmarks?

How we evaluate differences

- Different systems
- Changes to a single system

Provide a target

- Benchmarks should represent large class of important programs
- Improving benchmark performance should help many programs

For better or worse, benchmarks shape a field

Good ones accelerate progress

- good target for development

Bad benchmarks hurt progress

- help real programs v. sell machines/papers?
- Inventions that help real programs don't help benchmark

Popular Benchmark Suites

Desktop

- SPEC CPU2000 - CPU intensive, integer & floating-point applications
- SPECviewperf, SPECapc - Graphics benchmarks
- SysMark, Winstone, Winbench

Embedded

- EEMBC - Collection of kernels from 6 application areas
- Dhrystone - Old synthetic benchmark

Servers

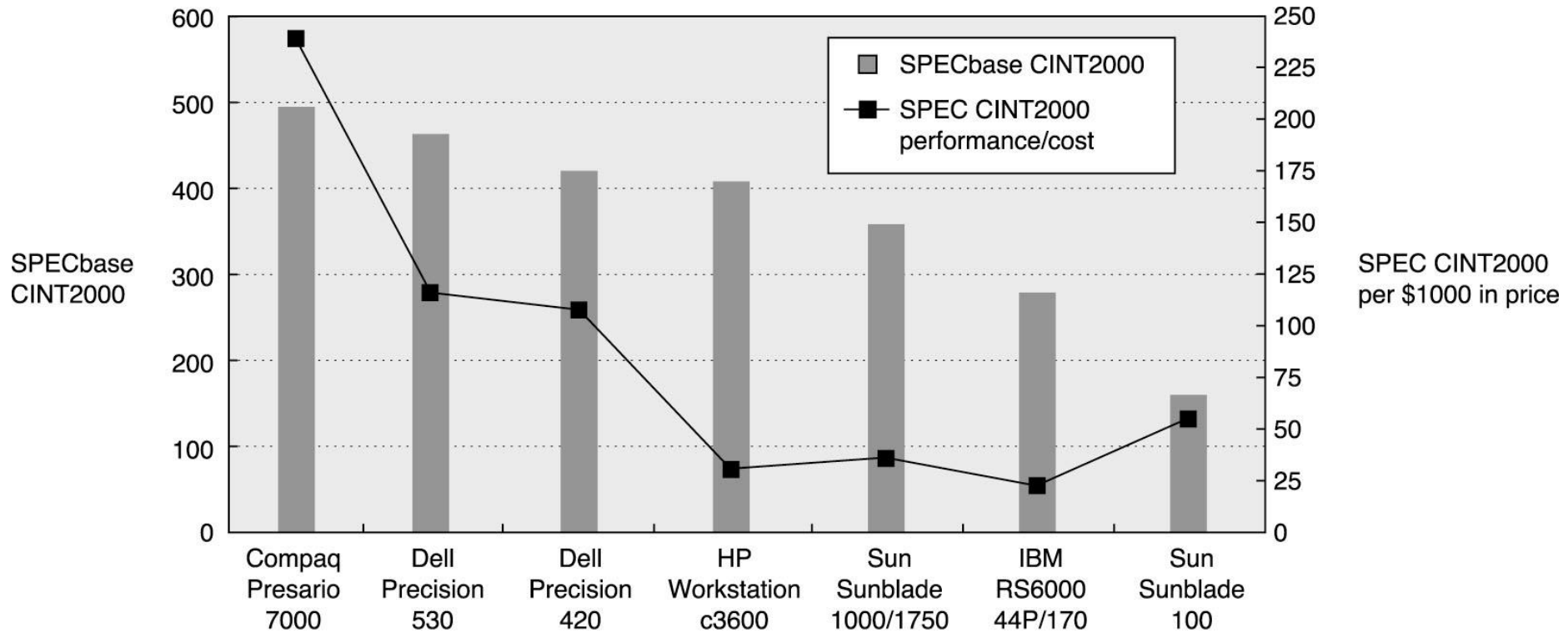
- SPECweb, SPECfs
- TPC-C - Transaction processing system
- TPC-H, TPC-R - Decision support system
- TPC-W - Transactional web benchmark

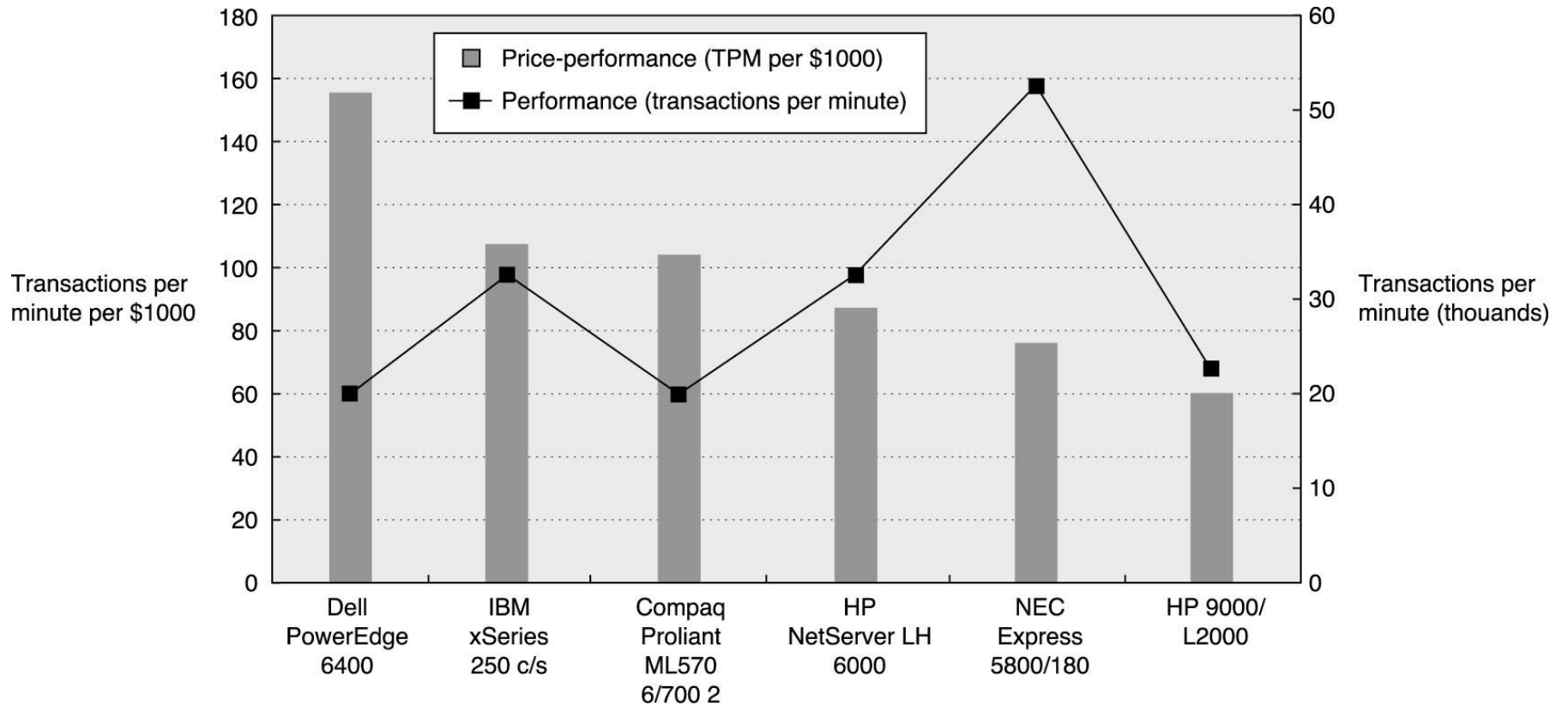
Parallel Computers

- SPLASH - Scientific applications & kernels

Most markets have specific benchmarks for design and marketing.

SPEC CINT2000





Basis of Evaluation

Pros

- representative
- portable
- widely used
- improvements useful in reality
- easy to run, early in design cycle
- identify peak capability and potential bottlenecks

Actual Target Workload

Full Application Benchmarks

Small "Kernel"
Benchmarks

Microbenchmarks

Cons

- very specific
- non-portable
- difficult to run, or measure
- hard to identify cause
- less representative
- easy to "fool"
- "peak" may be a long way from application performance

Programs to Evaluate Processor Performance

(Toy) Benchmarks

- 10-100 line
- e.g.,: sieve, puzzle, quicksort

Synthetic Benchmarks

- attempt to match average frequencies of real workloads
- e.g., Whetstone, dhrystone

Kernels

- Time critical excerpts

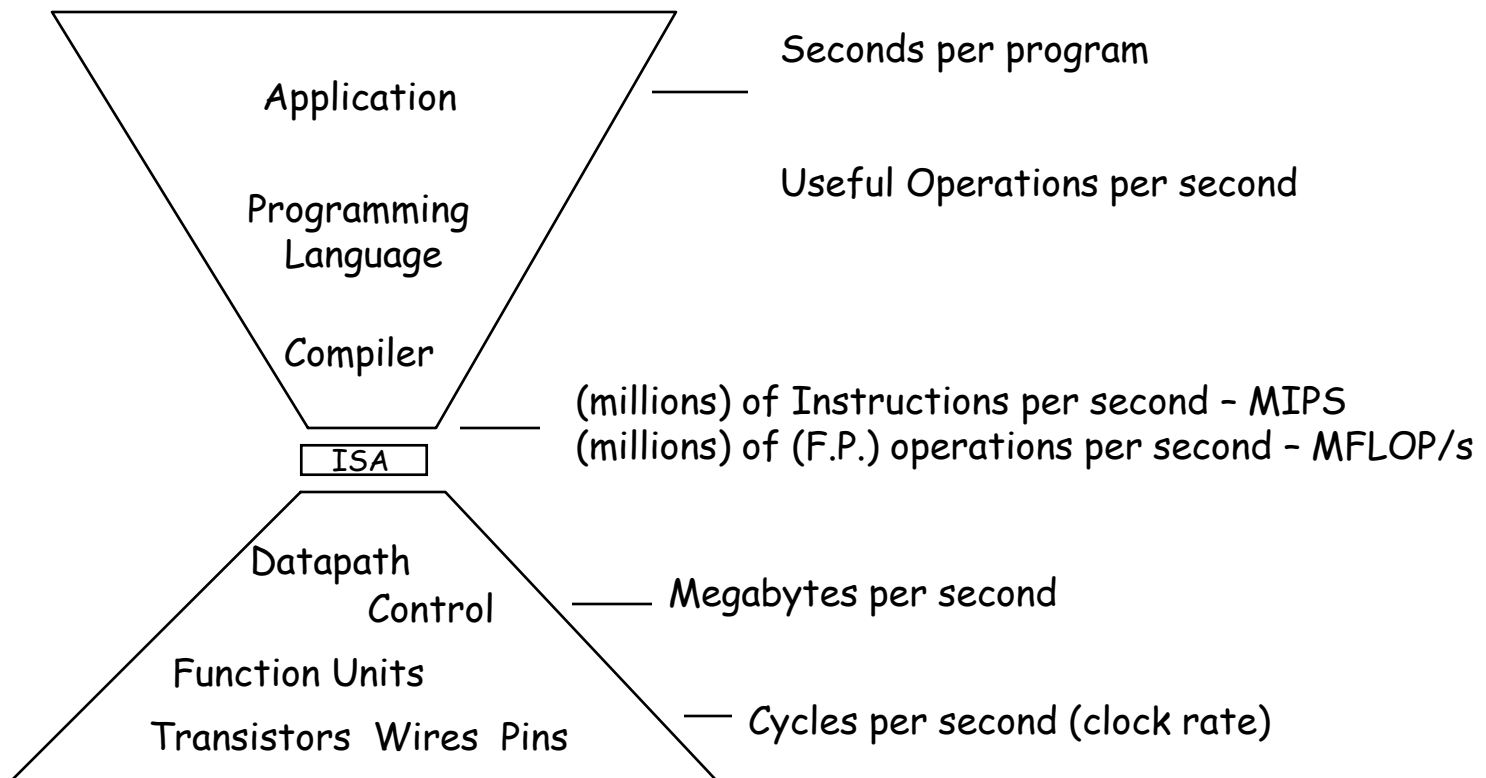
Announcements

Next lecture

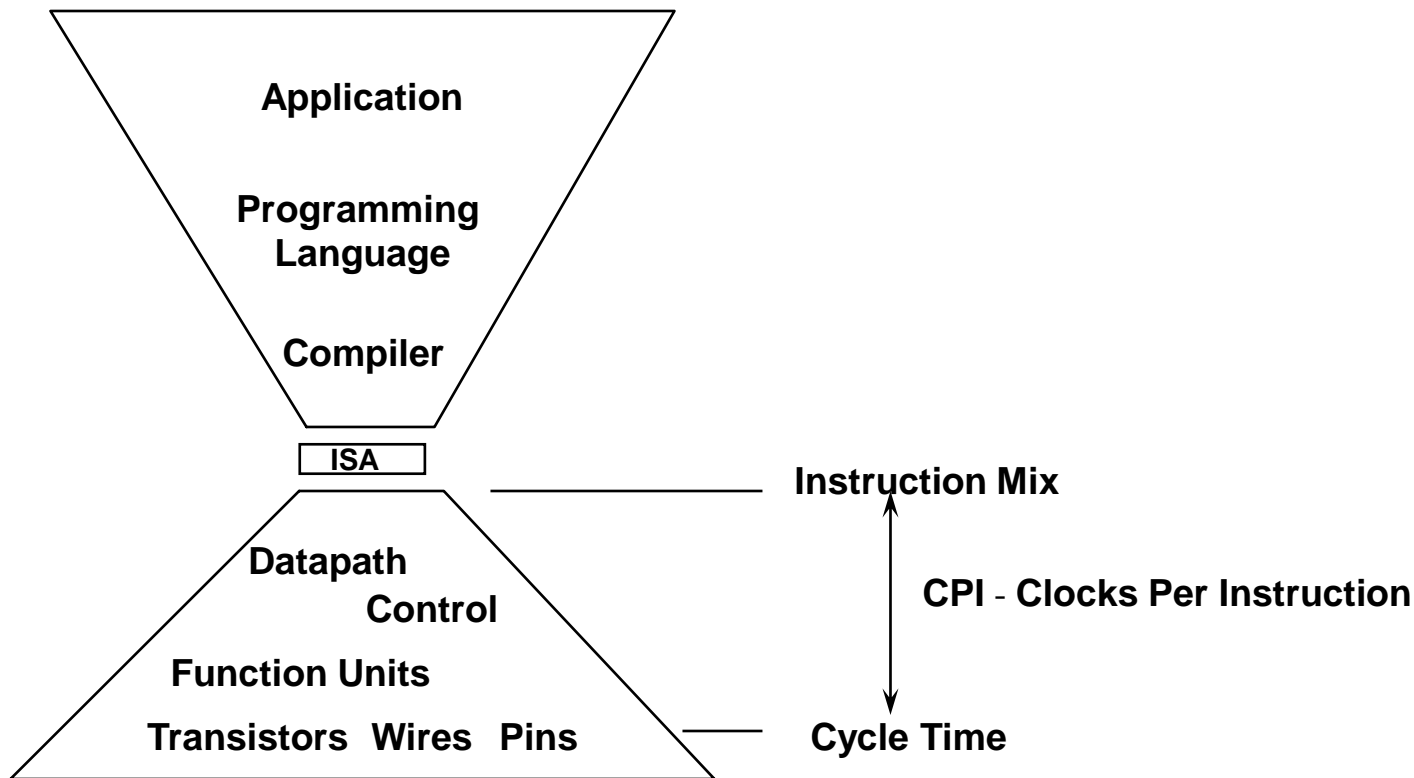
- Instruction Set Architecture

Processor Design Metrics

Metrics of Performance

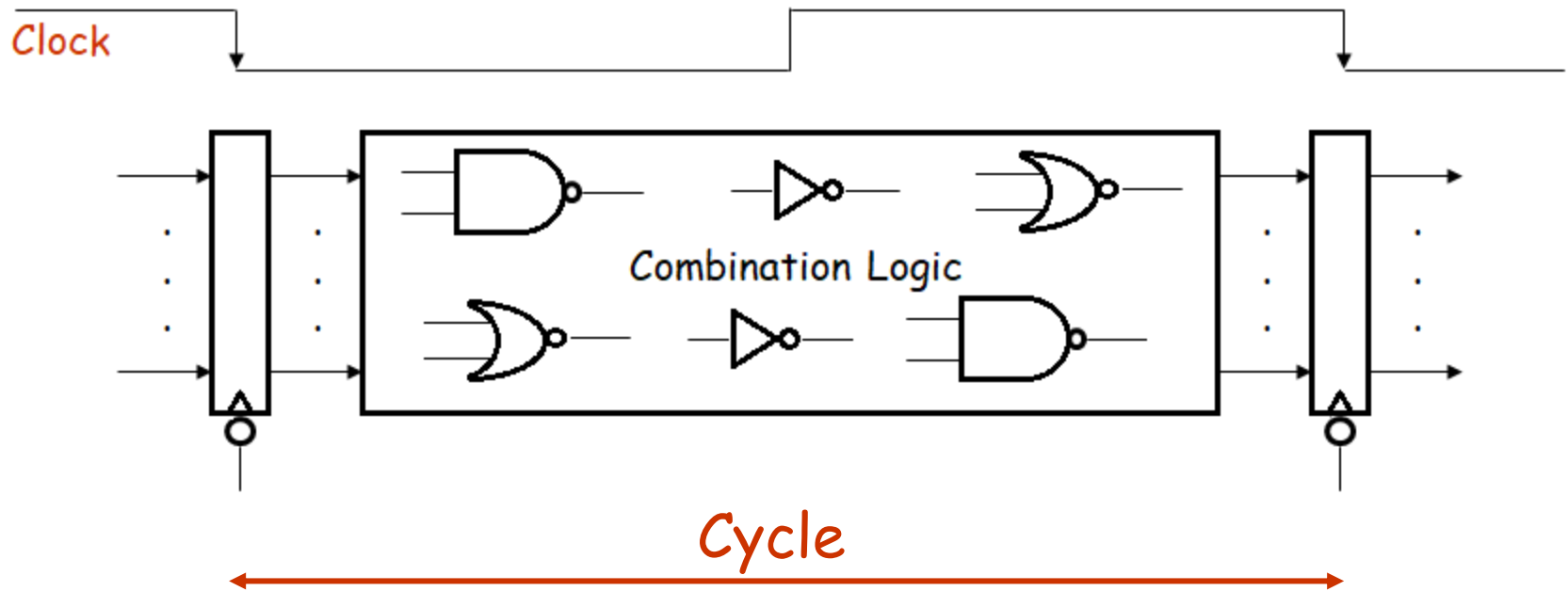


Organizational Trade-offs



CPI is a useful design measure relating the Instruction Set Architecture with the Implementation of that architecture, and the program measured

Processor Cycles



Most contemporary computers have fixed, repeating clock cycles

CPU Performance

$$\begin{aligned} CPUtime &= \frac{Seconds}{Program} = \frac{Cycles}{Program} \cdot \frac{Seconds}{Cycle} \\ &= \frac{Instructions}{Program} \cdot \frac{Cycles}{Instruction} \cdot \frac{Seconds}{Cycle} \end{aligned}$$

	IC	CPI	Clock Cycle
Program	✓		
Compiler	✓	(✓)	
Instruction Set	✓	✓	
Organization		✓	✓
Technology			✓

*IC – Instruction count of a program

Cycles Per Instruction (Throughput)

“Cycles per Instruction”

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

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

“Instruction Frequency”

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

Principal Design Metrics: CPI and Cycle Time

$$Performance = \frac{1}{ExecutionTime}$$

$$Performance = \frac{1}{CPI \times CycleTime}$$

$$Performance = \frac{1}{\frac{Cycles}{Instruction} \times \frac{Seconds}{Cycle}} = \frac{Instructions}{Seconds}$$

Example

Op	Freq	Cycles	CPI
ALU	50%	1	.5
Load	20%	5	1.0
Store	10%	3	.3
Branch	20%	2	.4
			<hr/> 2.2

Typical Mix



How much faster would the machine be if a better data cache reduced the average load time to 2 cycles?

- Load $\rightarrow 20\% \times 2 \text{ cycles} = .4$
- Total CPI 2.2 $\rightarrow 1.6$
- Relative performance is $2.2 / 1.6 = 1.38$

How does this compare with reducing the branch instruction to 1 cycle?

- Branch $\rightarrow 20\% \times 1 \text{ cycle} = .2$
- Total CPI 2.2 $\rightarrow 2.0$
- Relative performance is $2.2 / 2.0 = 1.1$

Summary: Evaluating Instruction Sets and Implementation

Design-time metrics:

- Can it be implemented, in how long, at what cost?
- Can it be programmed? Ease of compilation?

Static Metrics:

- How many bytes does the program occupy in memory?

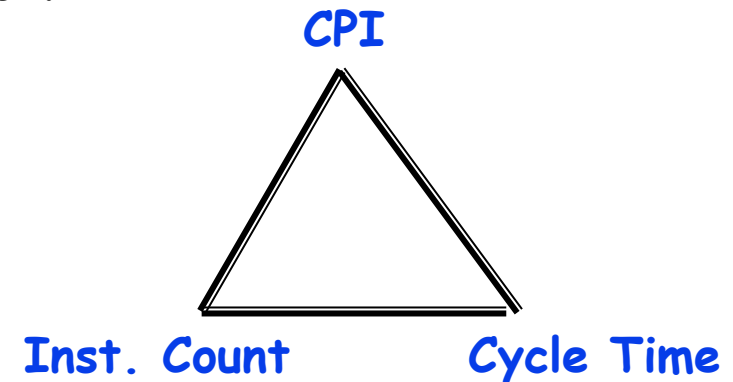
Dynamic Metrics:

- How many instructions are executed?
- How many bytes does the processor fetch to execute the program?
- How many clocks are required per instruction?
- How "lean" a clock is practical?

Best Metric:

Time to execute the program!

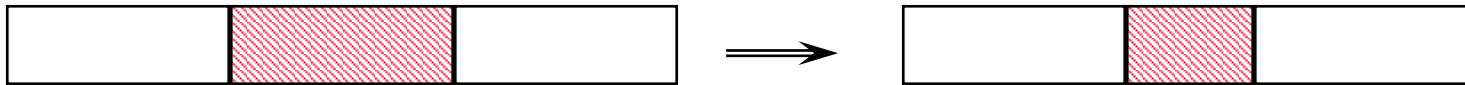
NOTE: Depends on instructions set, processor organization, and compilation techniques.



Amdahl's “Law”: Make the Common Case Fast

Speedup due to enhancement E:

$$\text{Speedup}(E) = \frac{\text{ExTime w/o } E}{\text{ExTime w/ } E} = \frac{\text{Performance w/ } E}{\text{Performance w/o } E}$$



Suppose that enhancement E accelerates a fraction F of the task by a factor S and the remainder of the task is unaffected then,

$$\text{ExTime}(\text{with } E) = ((1-F) + F/S) \times \text{ExTime}(\text{without } E)$$

Performance improvement is limited by how much the improved feature is used → Invest resources where time is spent.

$$\text{Speedup}_{\text{overall}} = \frac{\text{ExecTime}_{\text{old}}}{\text{ExecTime}_{\text{new}}} = \frac{1}{\frac{\text{Fraction}_{\text{enhanced}}}{\text{Speedup}_{\text{enhanced}}} + (1 - \text{Fraction}_{\text{enhanced}})}$$

Marketing Metrics

MIPS = Instruction Count / Time * 10^6
= Clock Rate / CPI * 10^6

- machines with different instruction sets ?
- programs with different instruction mixes ?
- dynamic frequency of instructions
- uncorrelated with performance

MFLOP/s = FP Operations / Time * 10^6

- machine dependent
- often not where time is spent

Summary

$$\text{CPU time} = \frac{\text{Seconds}}{\text{Program}} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Cycle}}$$

Time is the measure of computer performance!

Good products created when have:

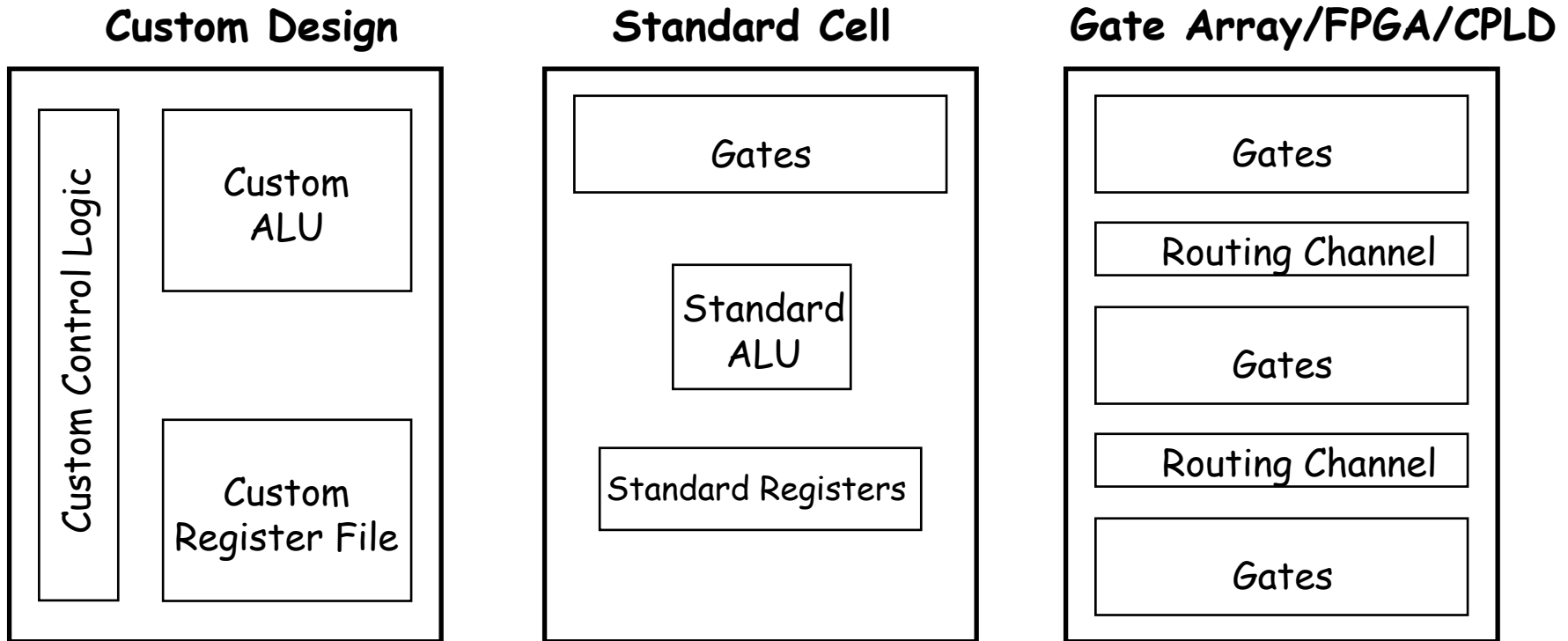
- Good benchmarks
- Good ways to summarize performance

If not good benchmarks and summary, then choice between improving product for real programs vs. improving product to get more sales → sales almost always wins

Remember Amdahl's Law: Speedup is limited by unimproved part of program

Critical Path

Range of Design Styles



←

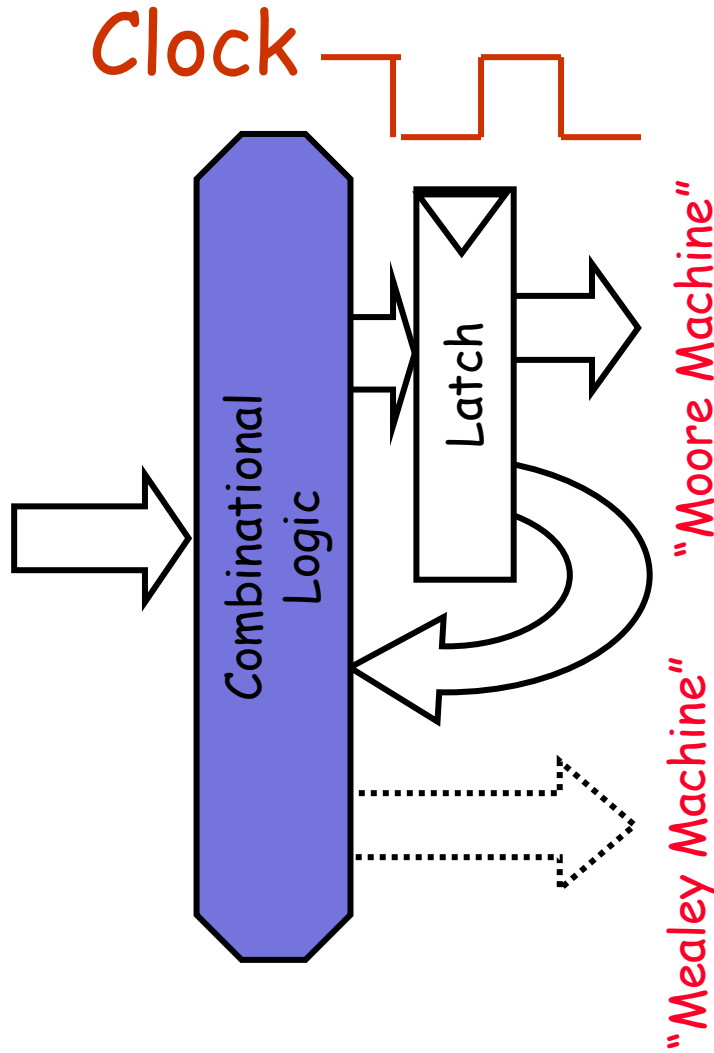
Performance

Design Complexity (Design Time)

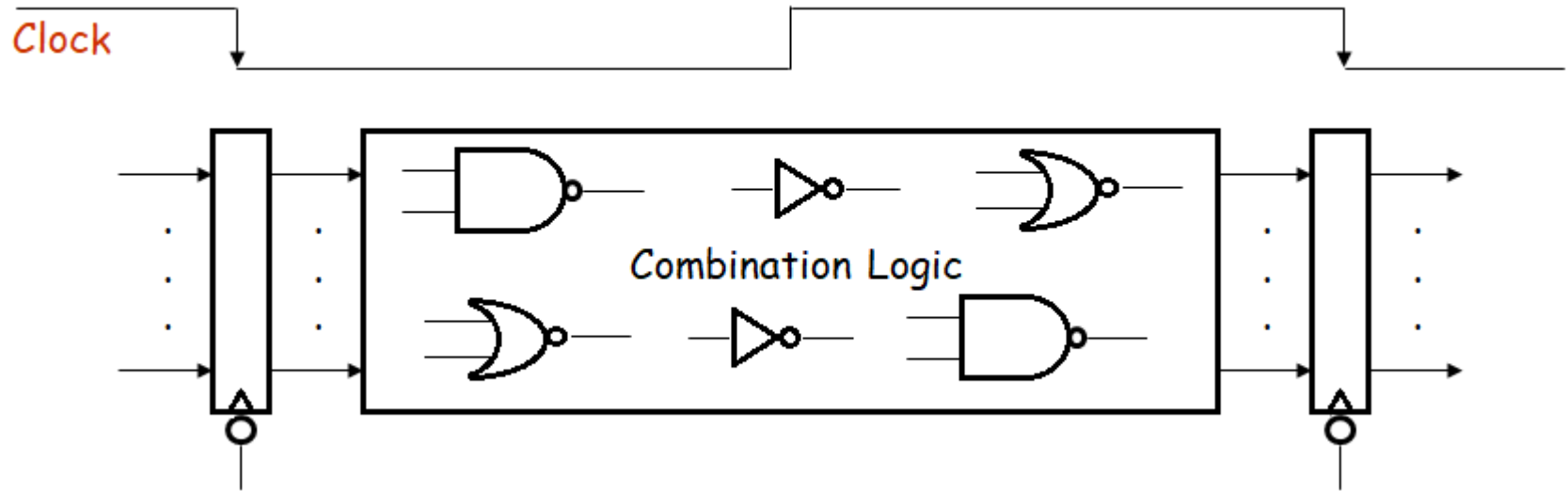
Compact

Longer wires

Implementation as Combinational Logic + Latch



Clocking Methodology

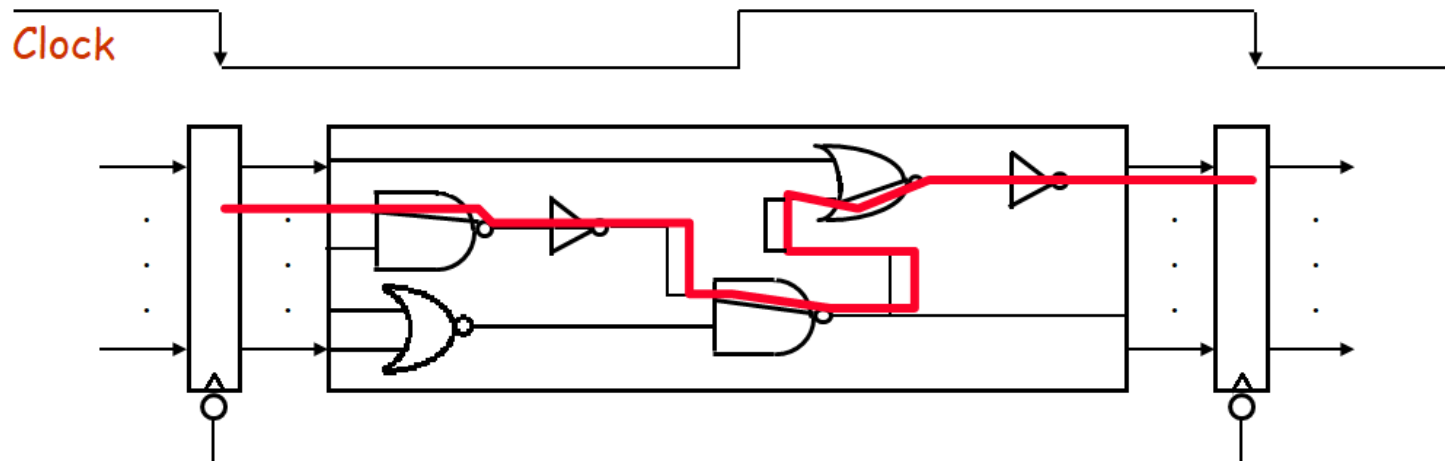


All storage elements are clocked by the same clock edge (but there may be clock skews)

The combination logic block's:

- Inputs are updated at each clock tick
- All outputs **MUST** be stable before the next clock tick

Critical Path & Cycle Time

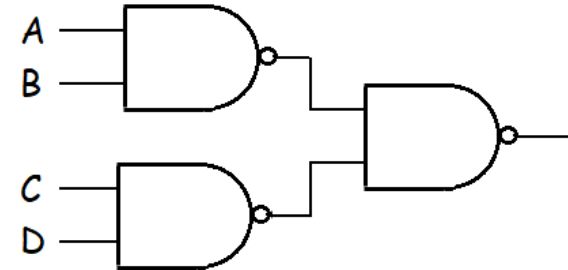
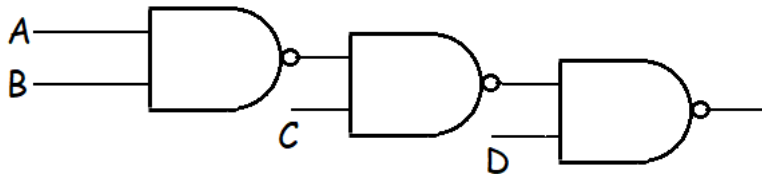


Critical path: the slowest path between any two storage devices

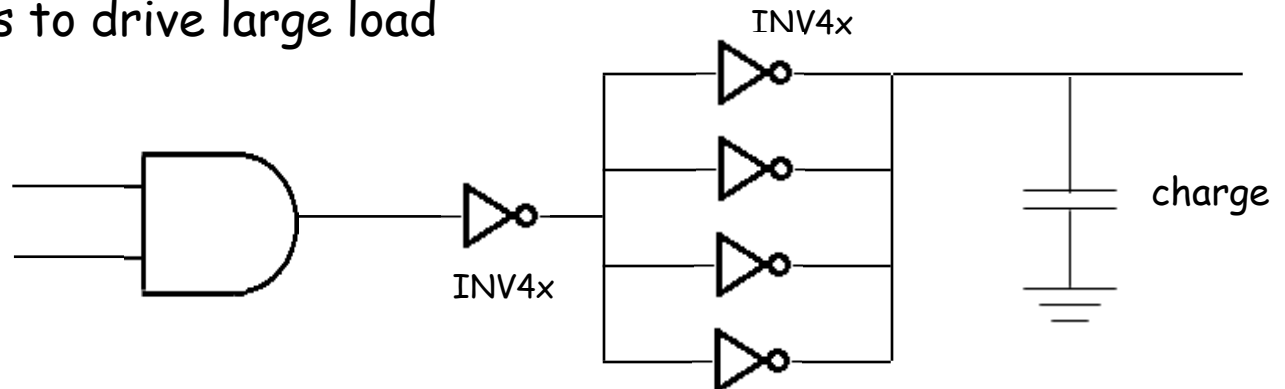
Cycle time is a function of the critical path

Tricks to Reduce Cycle Time

Reduce the number of gate levels



- Pay attention to loading
 - One gate driving many gates is a bad idea
 - Avoid using a small gate to drive a long wire
- Use multiple stages to drive large load
- Revise design



Summary

Performance Concepts

- Response Time
- Throughput

Performance Evaluation

- Benchmarks

Processor Design Metrics

- Cycle Time
- Cycles per Instruction

Amdahl's Law

- Speedup what is important

Critical Path