

# Computing System Fundamentals/Trends + Review of Performance Evaluation and ISA Design

- **Computing Element Choices:**
  - Computing Element Programmability
  - Spatial vs. Temporal Computing
  - Main Processor Types/Applications
- **General Purpose Processor Generations**
- **The Von Neumann Computer Model**
- **CPU Organization (Design)**
- **Recent Trends in Computer Design/performance**
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- **Review of Performance Evaluation Review from 350:**
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  - CISC vs. RISC
- **A RISC Instruction Set Example: MIPS64**
- **The Role of Compilers in Performance Optimization**

**4<sup>th</sup> Edition: Chapter 1, Appendix B (ISA)**  
**3<sup>rd</sup> Edition: Chapters 1 and 2**

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# Computing Element Choices

- **General Purpose Processors (GPPs):** Intended for general purpose computing (desktops, servers, clusters..)
- **Application-Specific Processors (ASPs):** Processors with ISAs and architectural features tailored towards specific application domains
  - E.g Digital Signal Processors (DSPs), Network Processors (NPs), Media Processors, Graphics Processing Units (GPUs), Vector Processors???
- **Co-Processors:** A hardware (hardwired) implementation of specific algorithms with limited programming interface (augment GPPs or ASPs)
- **Configurable Hardware:**
  - Field Programmable Gate Arrays (FPGAs)
  - Configurable array of simple processing elements
- **Application Specific Integrated Circuits (ASICs):** A custom VLSI hardware solution for a specific computational task
- The choice of one or more depends on a number of factors including:
  - Type and complexity of computational algorithm (general purpose vs. Specialized)
  - Desired level of flexibility/programmability
  - Development cost/time
  - Power requirements
  - Performance requirements
  - System cost
  - Real-time constrains

The main goal of this course is to study recent architectural design techniques in high-performance GPPs

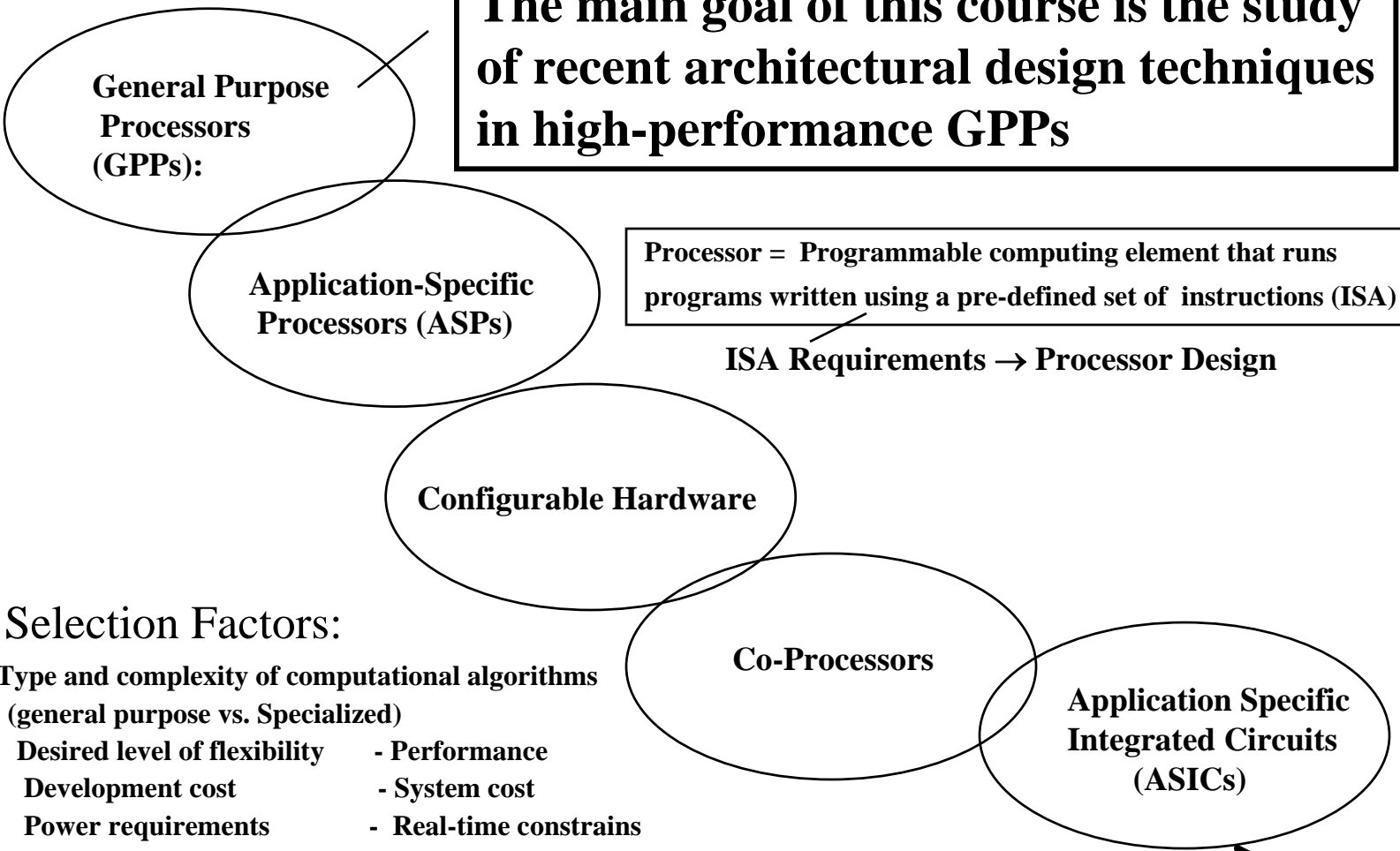
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# Computing Element Choices

The main goal of this course is the study of recent architectural design techniques in high-performance GPPs

Programmability / Flexibility ↑



Processor = Programmable computing element that runs programs written using a pre-defined set of instructions (ISA)

ISA Requirements → Processor Design

### Selection Factors:

- Type and complexity of computational algorithms (general purpose vs. Specialized)
- Desired level of flexibility
- Development cost
- Power requirements
- Performance
- System cost
- Real-time constraints

Specialization , Development cost/time  
Performance/Chip Area/Watt  
(Computational Efficiency)

Performance →

Software ← → Hardware

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## Computing Element Choices:

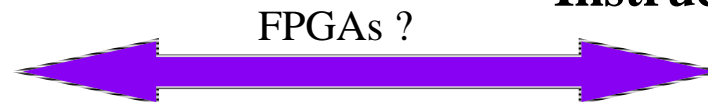
# Computing Element Programmability

(Hardware)  
Fixed Function:

- Computes one function (e.g. FP-multiply, divider, DCT)
- Function defined at fabrication time
- e.g hardware (ASICs)

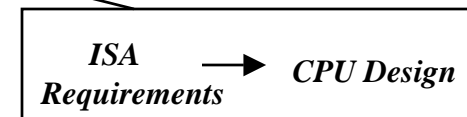
(Processor) Software  
Programmable: Program

- Computes “any” computable function (e.g. Processors)
- Function defined after fabrication
- Instruction Set (ISA)



Parameterizable Hardware:  
Performs limited “set” of functions

e.g. Co-Processors



Processor = Programmable computing element  
that runs programs written using pre-defined instructions (ISA)

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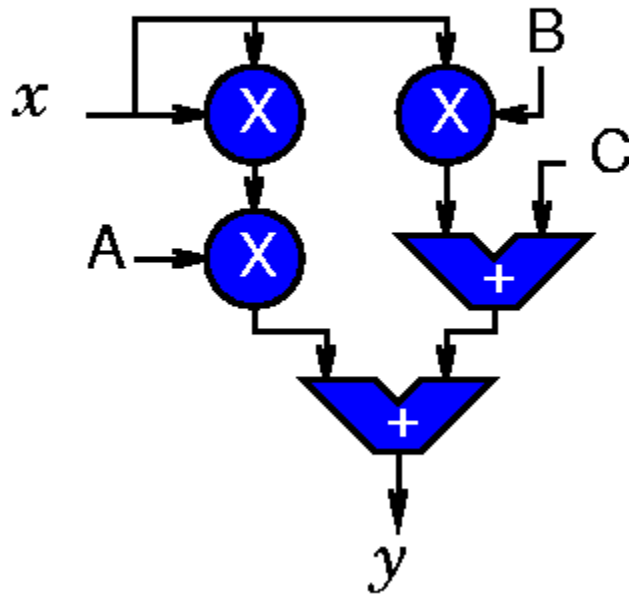
# Computing Element Choices:

Space vs. Time Tradeoff

# Spatial vs. Temporal Computing

## Spatial

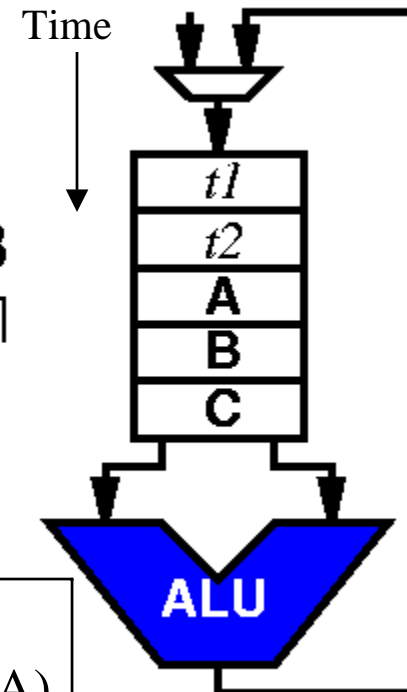
(using hardware)



## Temporal

(using software/program running on a processor)

```
t1 ← x
t2 ← A × t1
t2 ← t2 + B
t2 ← t2 × t1
y ← t2 + C
```



Processor Instructions (ISA)

ISA Requirements → Processor Design

Processor = Programmable computing element that runs programs written using a pre-defined set of instructions (ISA)

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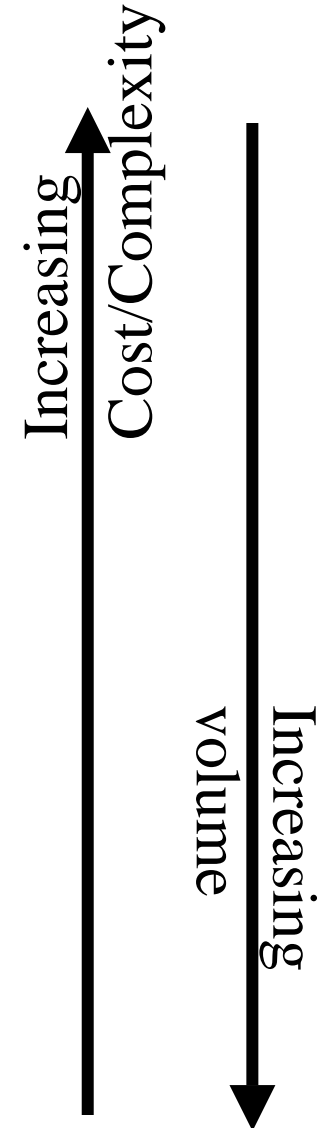
# Main Processor Types/Applications

- **General Purpose Processors (GPPs)** - high performance.
  - RISC or CISC: Intel P4, IBM Power4, SPARC, PowerPC, MIPS ...
  - Used for general purpose software
  - Heavy weight OS - Windows, UNIX
  - Workstations, Desktops (PC's), Clusters

64 bit
- **Embedded processors and processor cores**
  - e.g: Intel XScale, ARM, 486SX, Hitachi SH7000, NEC V800...
  - Often require Digital signal processing (DSP) support or other application-specific support (e.g network, media processing)
  - Single program
  - Lightweight, often realtime OS or no OS
  - Examples: Cellular phones, consumer electronics .. (e.g. CD players)

16-32 bit
- **Microcontrollers**
  - Extremely cost/power sensitive
  - Single program
  - Small word size - 8 bit common
  - Highest volume processors by far
  - Examples: Control systems, Automobiles, toasters, thermostats, ...

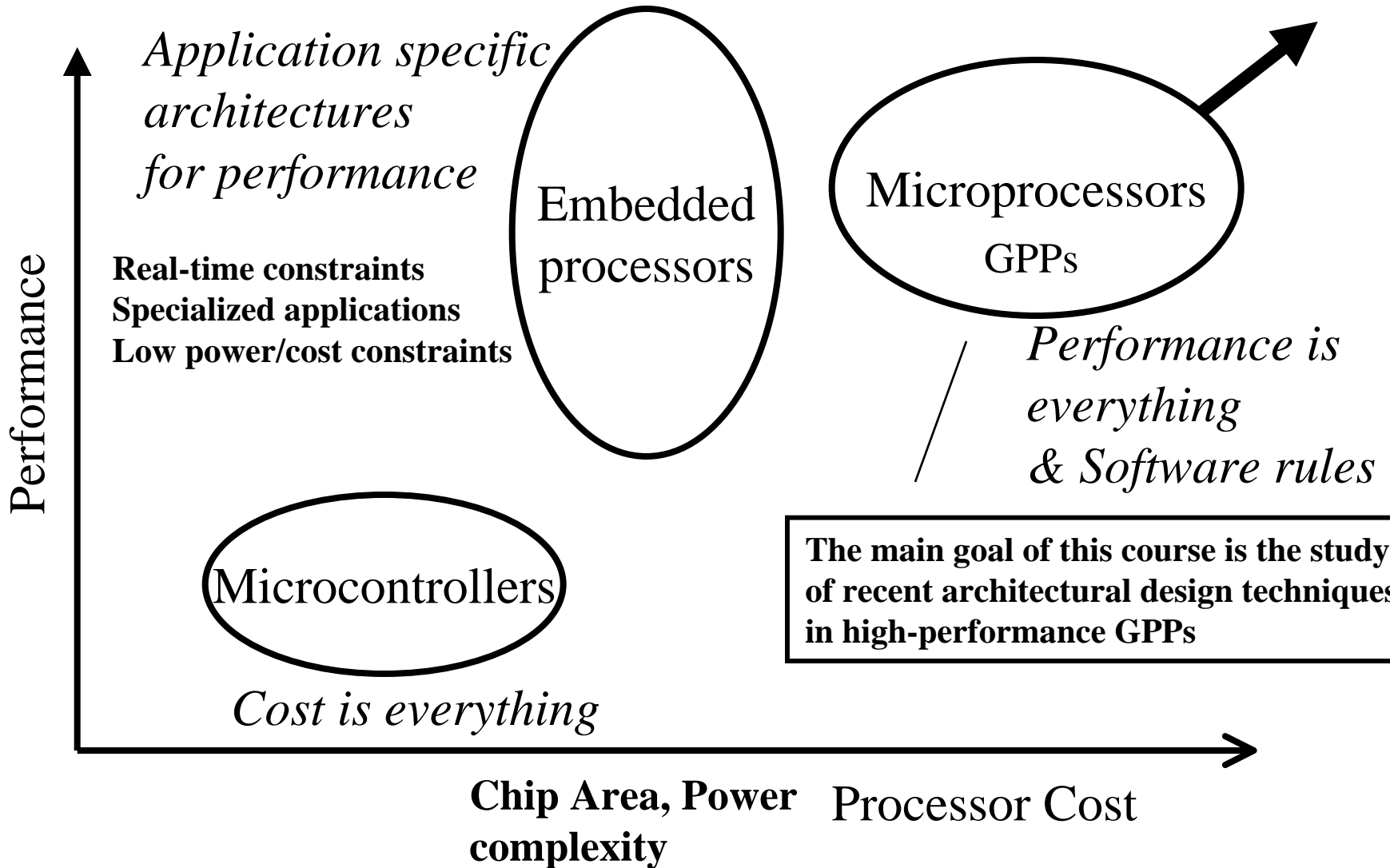
8-16 bit ?



Examples of Application-Specific Processors (ASPs)

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# The Processor Design Space



Processor = Programmable computing element that runs programs written using a pre-defined set of instructions (ISA)

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# General Purpose Processor Generations

Classified according to implementation technology of logic devices:

- **The First Generation, 1946-59: Vacuum Tubes, Relays, Mercury Delay Lines:**
  - ENIAC (Electronic Numerical Integrator and Computer): First electronic computer, 18000 vacuum tubes, 1500 relays, 5000 additions/sec (1944).
  - First stored program computer: EDSAC (Electronic Delay Storage Automatic Calculator), 1949.
- **The Second Generation, 1959-64: Discrete Transistors.**
  - e.g. IBM Main frames
- **The Third Generation, 1964-75: Small and Medium-Scale Integrated (MSI) Circuits.**
  - e.g Main frames (IBM 360) , mini computers (DEC PDP-8, PDP-11).
- **The Fourth Generation, 1975-Present: The Microcomputer. VLSI-based Microprocessors.** (Microprocessor = VLSI-based Single-chip processor)
  - First microprocessor: Intel's 4-bit 4004 (2300 transistors), 1970.
  - Personal Computer (PCs), laptops, PDAs, servers, clusters ...
  - Reduced Instruction Set Computer (RISC) 1984

**Common factor among all generations:**

All target the The Von Neumann Computer Model or paradigm

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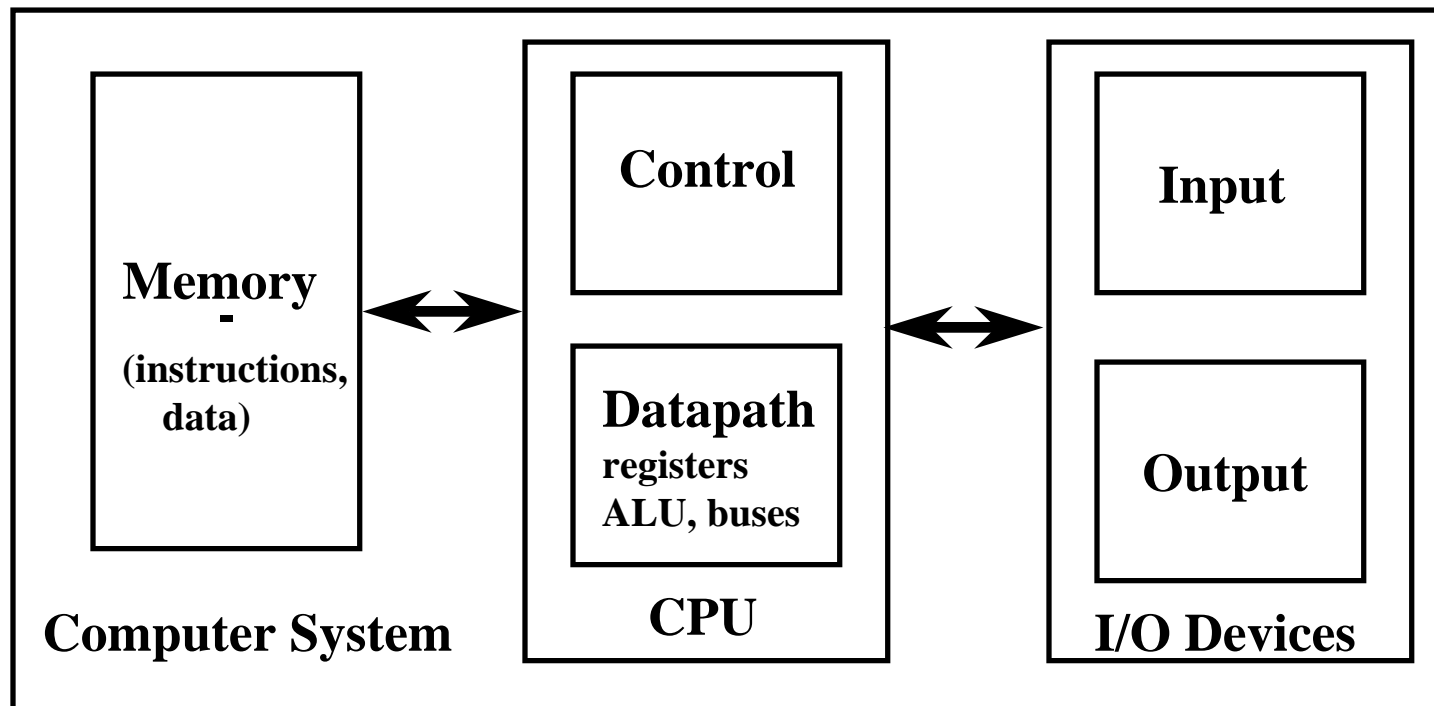
# The Von Neumann Computer Model

- Partitioning of the programmable computing engine into components:

- Central Processing Unit (CPU): Control Unit (instruction decode , sequencing of operations), Datapath (registers, arithmetic and logic unit, buses).
- Memory: Instruction and operand storage.
- Input/Output (I/O) sub-system: I/O bus, interfaces, devices.
- The stored program concept: Instructions from an instruction set are fetched from a common memory and executed one at a time

AKA Program Counter  
PC-Based Architecture

The Program Counter (PC) points to next instruction to be processed



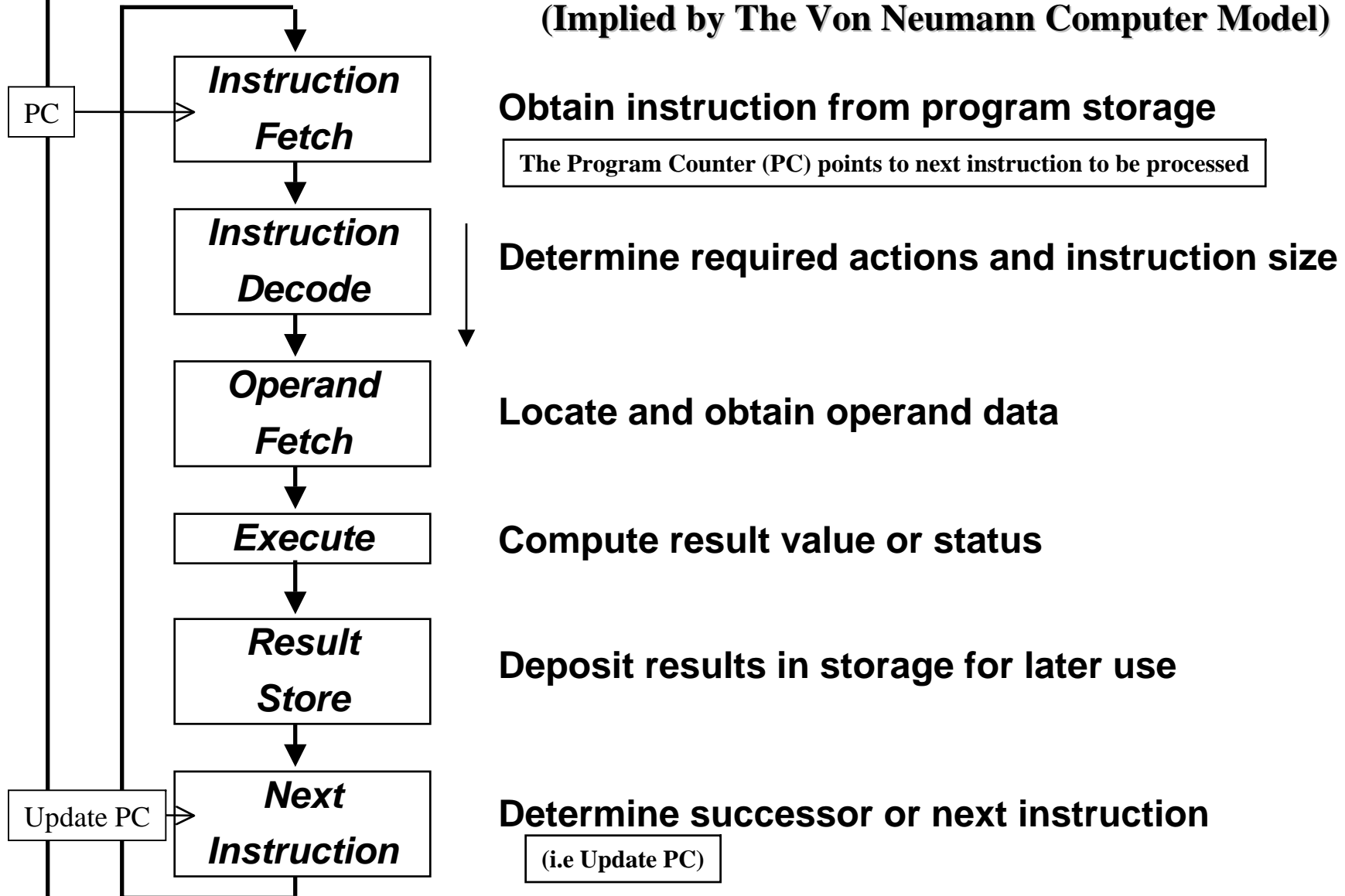
**Major CPU Performance Limitation:** The Von Neumann computing model implies sequential execution one instruction at a time

**Another Performance Limitation:** Separation of CPU and memory  
(The Von Neumann memory bottleneck)

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# Generic CPU Machine Instruction Processing Steps

(Implied by The Von Neumann Computer Model)



Major CPU Performance Limitation: The Von Neumann computing model implies sequential execution one instruction at a time

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# CPU Organization (Design)

- **Datapath Design:** **Components & their connections** needed by ISA instructions
  - Capabilities & performance characteristics of principal Functional Units (FUs):
    - (e.g., Registers, ALU, Shifters, Logic Units, ...)
  - Ways in which these components are interconnected (buses connections, multiplexors, etc.).
  - How information flows between components.
- **Control Unit Design:** **Control/sequencing of operations of datapath components to realize ISA instructions**
  - Logic and means by which such information flow is controlled.
  - Control and coordination of FUs operation to realize the targeted Instruction Set Architecture to be implemented (can either be implemented using a finite state machine or a microprogram).
- Description of hardware operations with a suitable language, possibly using Register Transfer Notation (RTN).

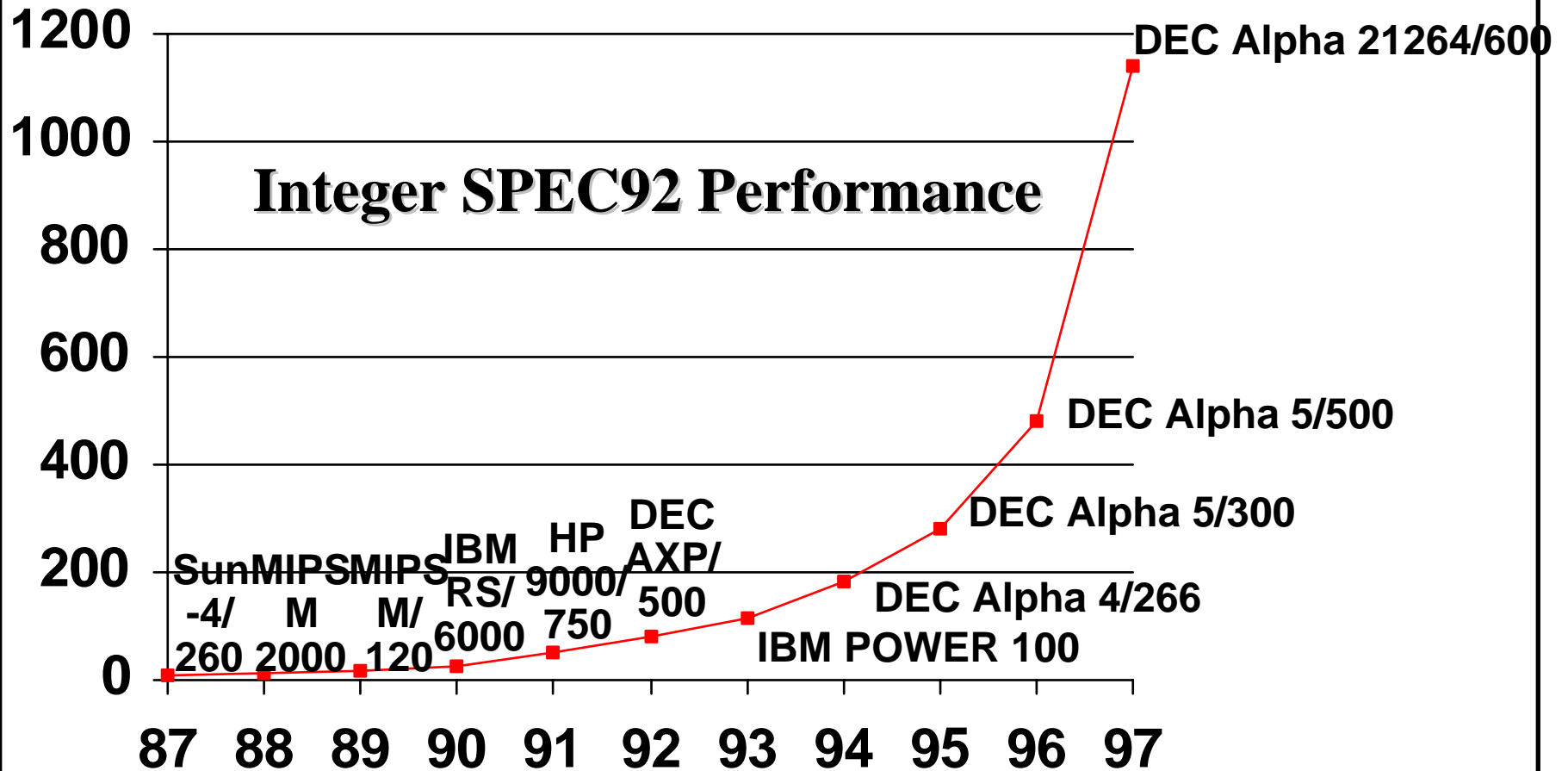
# Recent Trends in Computer Design

- The cost/performance ratio of computing systems have seen a steady decline due to advances in:
  - Integrated circuit technology: *decreasing feature size,  $\lambda$* 
    - Clock rate improves roughly proportional to improvement in  $\lambda$
    - Number of transistors improves proportional to  $\lambda^2$  (or faster).
  - Architectural improvements in CPU design.
- Microprocessor systems directly reflect IC and architectural improvement in terms of a yearly 35 to 55% improvement in performance.
- Assembly language has been mostly eliminated and replaced by other alternatives such as C or C++
- Standard operating Systems (UNIX, Windows) lowered the cost of introducing new architectures.
- Emergence of RISC architectures and RISC-core (x86) architectures.
- Adoption of quantitative approaches to computer design based on empirical performance observations.
- Increased importance of exploiting thread-level parallelism (TLP) in main-stream computing systems.

e.g Multiple (2 to 8) processor cores on a single chip (multi-core)

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# Microprocessor Performance 1987-97

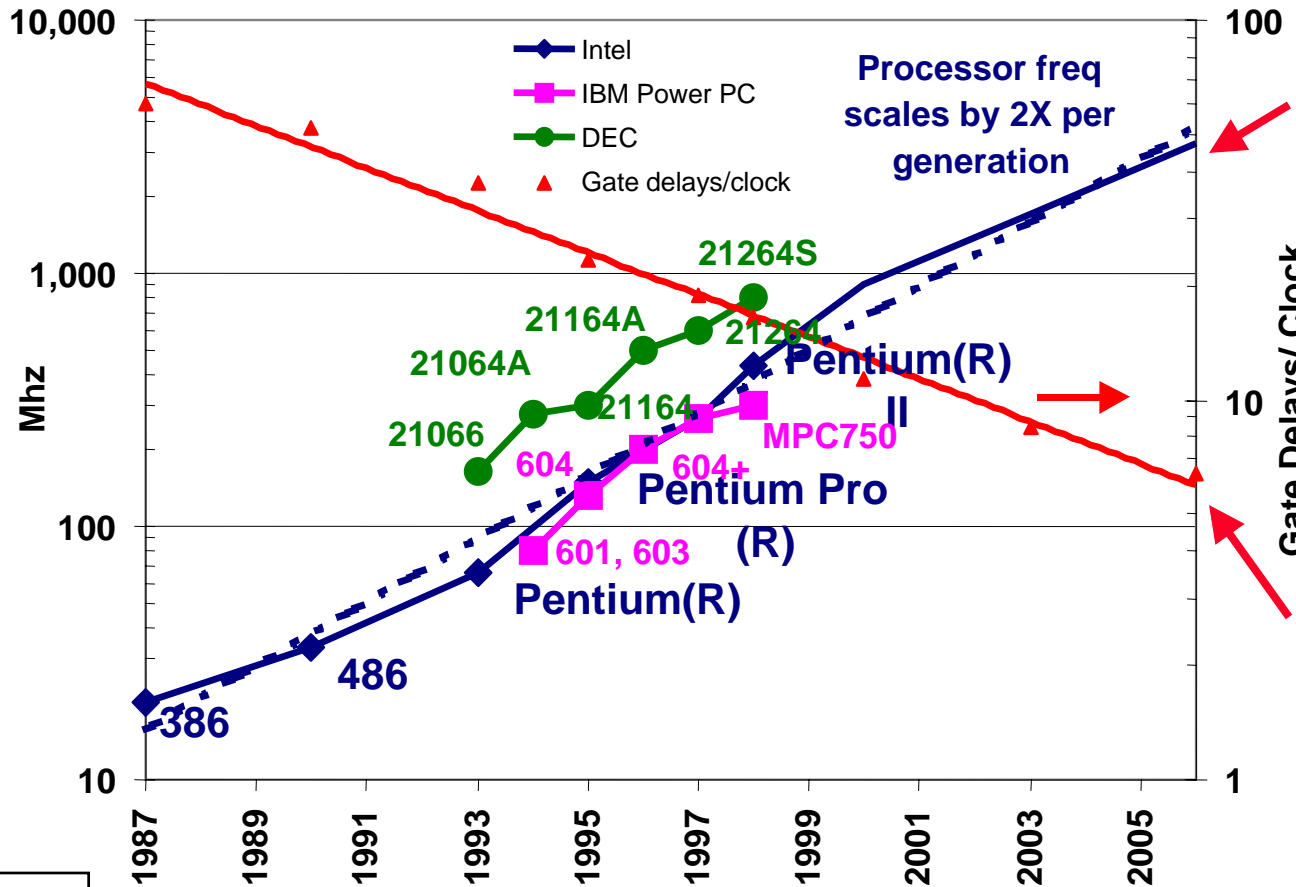


> 100x performance increase in the last decade

$$T = I \times \text{CPI} \times C$$

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# Microprocessor Frequency Trend



**Reality Check:**  
 Clock frequency scaling is slowing down!  
 (Did silicon finally hit the wall?)

**Why?**  
 1- Static power leakage  
 2- Clock distribution delays

**Result:**  
 Deeper Pipelines  
 Longer stalls  
 Higher CPI  
 (lowers effective performance per cycle)

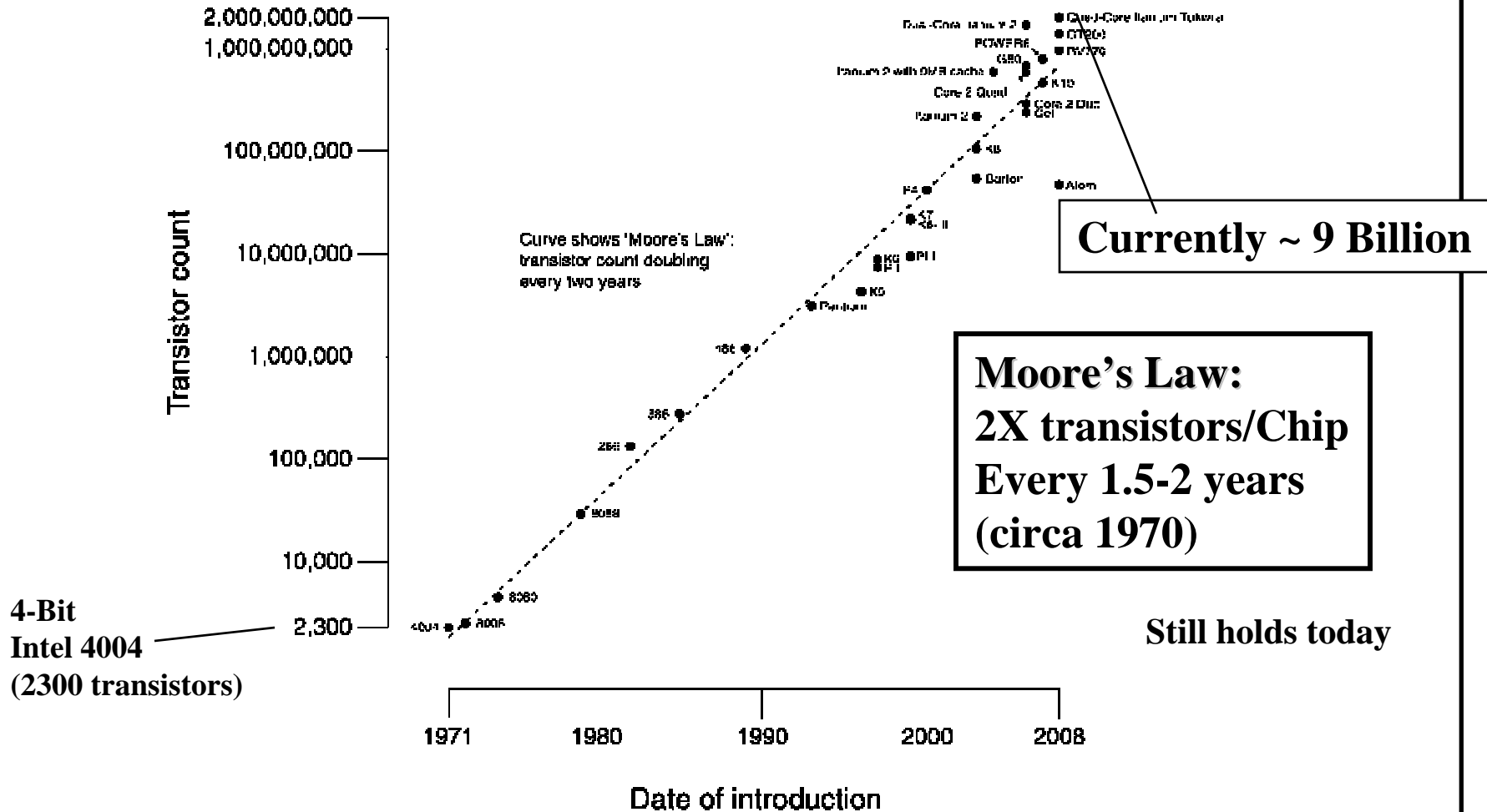
- No longer the case
1. Frequency doubles each generation ?
  2. Number of gates/clock reduce by 25%
  3. Leads to deeper pipelines with more stages  
 (e.g Intel Pentium 4E has 30+ pipeline stages)

$$T = I \times CPI \times C$$

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# Microprocessor Transistor Count Growth Rate

CPU Transistor Counts 1971-2008 & Moore's Law



~ 4,000,000x transistor density increase in the last 45 years

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# Computer Technology Trends: *Evolutionary but Rapid Change*

- **Processor:**

- 1.5-1.6 performance improvement every year; Over 100X performance in last decade.

- **Memory:**

- DRAM capacity: > 2x every 1.5 years; 1000X size in last decade.
- Cost per bit: Improves about 25% or more per year.
- Only 15-25% performance improvement per year.

- **Disk:**

- Capacity: > 2X in size every 1.5 years.
- Cost per bit: Improves about 60% per year.
- 200X size in last decade.
- Only 10% performance improvement per year, due to mechanical limitations.

Performance gap compared to CPU performance causes system performance bottlenecks

- **State-of-the-art PC First Quarter 2017 :**

- Processor clock speed: ~ 4000 MegaHertz (4 Giga Hertz)
- Memory capacity: ~ 16000 MegaByte (16 Giga Bytes)
- Disk capacity: ~ 8000 GigaBytes (8 Tera Bytes)

With 2-8 processor cores on a single chip

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# Computer Architecture Vs. Computer Organization

- The term **Computer architecture** is sometimes erroneously restricted to computer instruction set design, with other aspects of computer design called implementation

The ISA forms an abstraction layer that sets the requirements for both compiler and CPU designers

- More accurate definitions:

- **Instruction set architecture (ISA)**: The actual programmer-visible instruction set and serves as the boundary between the software and hardware.
- Implementation of a machine has two components:

CPU Micro-architecture  
(CPU design)

- **Organization**: includes the high-level aspects of a computer's design such as: The memory system, the bus structure, the internal CPU unit which includes implementations of arithmetic, logic, branching, and data transfer operations.
- **Hardware**: Refers to the specifics of the machine such as detailed logic design and packaging technology.

Hardware design and implementation

- In general, **Computer Architecture** refers to the above three aspects: Instruction set architecture, organization, and hardware.

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# The Task of A Computer Designer

- Determine what attributes that are important to the design of the new machine (CPU).
- Design a machine to maximize performance while staying within cost and other constraints and metrics.
- It involves more than instruction set design.
  - 1 – Instruction set architecture. (ISA)
  - 2 – CPU Micro-architecture (CPU design).
  - 3 – Implementation.
- Implementation of a machine has two components:
  - Organization.
  - Hardware.

e.g  
Power consumption  
Heat dissipation  
Real-time constraints

# Recent Architectural Improvements

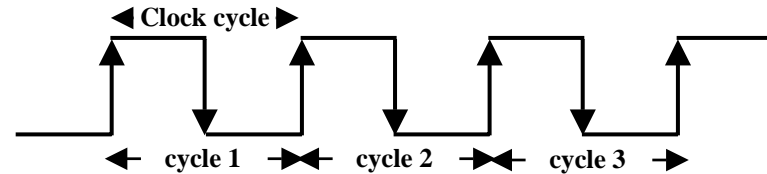
- **Long memory latency-hiding techniques, including:**
  - Increased optimization and utilization of multi-level cache systems.
- **Improved handling of pipeline hazards.**
- **Improved hardware branch prediction techniques.**
- **Optimization of pipelined instruction execution:**
  - **Dynamic hardware-based pipeline scheduling.** AKA Out-of-Order Execution
  - **Dynamic speculative execution.**
- **Exploiting Instruction-Level Parallelism (ILP) in terms of multiple-instruction issue and multiple hardware functional units.**
- **Inclusion of special instructions to handle multimedia applications (limited vector processing).**
- **High-speed bus designs to improve data transfer rates.**
  - Also, increased utilization of point-to-point interconnects instead of one system bus (e.g HyperTransport)

# CPU Performance Evaluation:

## Cycles Per Instruction (CPI)

- Most computers run synchronously utilizing a CPU clock running at a constant clock rate:

where:  $f = \frac{1}{C}$  Clock rate = 1 / clock cycle



- The CPU clock rate depends on the specific CPU organization (design) and hardware implementation technology (VLSI) used
- A computer machine (ISA) instruction is comprised of a number of elementary or micro operations which vary in number and complexity depending on the instruction and the exact CPU organization (Design)
  - A micro operation is an elementary hardware operation that can be performed during one CPU clock cycle.
  - This corresponds to one micro-instruction in microprogrammed CPUs.
  - Examples: register operations: shift, load, clear, increment, ALU operations: add , subtract, etc.

- CPI** • Thus a single machine instruction may take one or more CPU cycles to complete termed as the Cycles Per Instruction (CPI). CPI = 1/IPC
- Average CPI of a program: The average CPI of all instructions executed in the program on a given CPU design.

(From 350)

Instructions Per Cycle = IPC = 1/CPI

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# Computer Performance Measures: Program Execution Time

- For a specific program compiled to run on a specific machine (CPU) “A”, the following parameters are provided:

I = Dynamic instruction  
count executed

- The total instruction <sup>executed</sup> count of the program.  $I$
- The average number of cycles per instruction (average CPI).  $CPI$
- Clock cycle of machine “A”  $C$

- How can one measure the performance of this machine running this program?
  - Intuitively the machine is said to be faster or has better performance running this program if the total execution time is shorter.
  - Thus the inverse of the total measured program execution time is a possible performance measure or metric:

$$\text{Performance}_A = 1 / \text{Execution Time}_A$$

How to compare performance of different machines?

What factors affect performance? How to improve performance?

# Comparing Computer Performance Using Execution Time

- To compare the performance of two machines (or CPUs) “A”, “B” running a given specific program:

$$\text{Performance}_A = 1 / \text{Execution Time}_A$$

$$\text{Performance}_B = 1 / \text{Execution Time}_B$$

- Machine A is  $n$  times faster than machine B means (or slower? if  $n < 1$ ) :

$$\text{Speedup} = n = \frac{\text{Performance}_A}{\text{Performance}_B} = \frac{\text{Execution Time}_B}{\text{Execution Time}_A}$$

- **Example:** (i.e Speedup is ratio of performance, no units)

For a given program:

Execution time on machine A:  $\text{Execution}_A = 1$  second

Execution time on machine B:  $\text{Execution}_B = 10$  seconds

$$\text{Speedup} = \frac{\text{Performance}_A}{\text{Performance}_B} = \frac{\text{Execution Time}_B}{\text{Execution Time}_A}$$

$$\text{Performance}_B = 10 / 1 = 10$$

The performance of machine A is 10 times the performance of machine B when running this program, or: Machine A is said to be 10 times faster than machine B when running this program.

(From 350) The two CPUs may target different ISAs provided the program is written in a high level language (HLL)

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# CPU Execution Time: The CPU Equation

- A program is comprised of a number of instructions executed, **I**

– Measured in: instructions/program

I = Dynamic instruction count executed

- The average instruction executed takes a number of *cycles per instruction (CPI)* to be completed.

– Measured in: cycles/instruction, **CPI**

Or Instructions Per Cycle (IPC):  
IPC = 1/CPI

- CPU has a fixed clock cycle time C = 1/clock rate

– Measured in: seconds/cycle

C = 1/f

- CPU execution time is the product of the above three parameters as follows:

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

$$T = I \times \text{CPI} \times C$$

execution Time  
per program in seconds

Number of  
instructions executed

Average CPI for program

CPU Clock Cycle

(This equation is commonly known as the CPU performance equation)

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(From 350)



# CPU Execution Time: Example

- A Program is running on a specific machine (CPU) with the following parameters:
  - Total executed instruction count: 10,000,000 instructions
  - Average CPI for the program: 2.5 cycles/instruction.
  - CPU clock rate: 200 MHz. (clock cycle =  $5 \times 10^{-9}$  seconds)
- What is the execution time for this program:

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

$$\begin{aligned} \text{CPU time} &= \text{Instruction count} \times \text{CPI} \times \text{Clock cycle} \\ &= 10,000,000 \times 2.5 \times 1 / \text{clock rate} \\ &= 10,000,000 \times 2.5 \times 5 \times 10^{-9} \\ &= .125 \text{ seconds} \end{aligned}$$

(From 350)

$$T = I \times \text{CPI} \times C$$

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# Aspects of CPU Execution Time

$$\text{CPU Time} = \text{Instruction count} \times \text{CPI} \times \text{Clock cycle}$$

Depends on:  
Program Used  
Compiler  
ISA

$$T = I \times \text{CPI} \times C$$

**Instruction Count  $I$**   
(executed)

$I$  = Dynamic instruction  
count executed

Depends on:  
Program Used  
Compiler  
ISA  
CPU Organization

**CPI**  
(Average  
CPI)

**Clock  
Cycle**  
 $C = 1/f$

Depends on:  
CPU Organization  
Technology (VLSI)

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(From 350)

# Factors Affecting CPU Performance

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

	Instruction Count I	Average CPI	Clock Cycle C
Program	X	X	
Compiler	X	X	
Instruction Set Architecture (ISA)	X	X	
Organization (CPU Design)		X	X
Technology (VLSI)			X

(From 350)

$$T = I \times \text{CPI} \times C$$

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# Performance Comparison: Example

- From the previous example: A Program is running on a specific machine with the following parameters:
  - Total executed instruction count, I: 10,000,000 instructions
  - Average CPI for the program: 2.5 cycles/instruction.
  - CPU clock rate: 200 MHz.
- Using the same program with these changes:
  - A new compiler used: New instruction count executed 9,500,000  
New CPI: 3.0
  - Faster CPU implementation: New clock rate = 300 MHz
- What is the speedup with the changes?

$$\text{Speedup} = \frac{\text{Old Execution Time}}{\text{New Execution Time}} = \frac{I_{\text{old}} \times \text{CPI}_{\text{old}} \times \text{Clock cycle}_{\text{old}}}{I_{\text{new}} \times \text{CPI}_{\text{new}} \times \text{Clock Cycle}_{\text{new}}}$$

$$\begin{aligned}\text{Speedup} &= (10,000,000 \times 2.5 \times 5 \times 10^{-9}) / (9,500,000 \times 3 \times 3.33 \times 10^{-9}) \\ &= .125 / .095 = 1.32 \\ &\text{or } 32 \% \text{ faster after changes.}\end{aligned}$$

(From 350)

Clock Cycle = 1/ Clock Rate

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# Instruction Types & Average CPI

- Given a program with  $n$  types or classes of instructions executed on a given CPU with the following characteristics:

$C_i$  = Count of instructions of type <sub>$i$</sub>  Executed

$CPI_i$  = Cycles per instruction for type <sub>$i$</sub>   $i = 1, 2, \dots, n$

Then:

$$\text{CPI} = \text{CPU Clock Cycles} / \text{Instruction Count } I$$

Where:

$$\text{CPU clock cycles} = \sum_{i=1}^n (CPI_i \times C_i)$$

Executed

$$\text{Instruction Count } I = \sum C_i$$

i.e. Average or effective CPI

Executed

(From 350)

$$T = I \times CPI \times C$$

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# Instruction Types & CPI: An Example

- An instruction set has three instruction classes:

Instruction class	CPI
A	1
B	2
C	3

For a specific CPU design

- Two code sequences have the following instruction counts:

Code Sequence	Instruction counts for instruction class		
	A	B	C
1	2	1	2
2	4	1	1

- CPU cycles for sequence 1 =  $2 \times 1 + 1 \times 2 + 2 \times 3 = 10$  cycles  
 CPI for sequence 1 = clock cycles / instruction count  
 $= 10 / 5 = 2$
- CPU cycles for sequence 2 =  $4 \times 1 + 1 \times 2 + 1 \times 3 = 9$  cycles  
 CPI for sequence 2 =  $9 / 6 = 1.5$

$$CPU \text{ clock cycles} = \sum_{i=1}^n (CPI_i \times C_i)$$

$$CPI = CPU \text{ Cycles} / I$$

(From 350)

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# Instruction Frequency & Average CPI

- Given a program with  $n$  types or classes of instructions with the following characteristics:

$C_i$  = Count of instructions of type <sub>$i$</sub>

$i = 1, 2, \dots, n$

$CPI_i$  = Average cycles per instruction of type <sub>$i$</sub>

$F_i$  = Frequency or fraction of instruction type <sub>$i$</sub>  executed  
=  $C_i / \text{total executed instruction count} = C_i / I$

Then:

Where: Executed Instruction Count  $I = \sum C_i$

$$CPI = \sum_{i=1}^n (CPI_i \times F_i)$$

i.e average or effective CPI

Fraction of total execution time for instructions of type  $i = \frac{CPI_i \times F_i}{CPI}$

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(From 350)

# Instruction Type Frequency & CPI: A RISC Example

Program Profile or Executed Instructions Mix

Base Machine (Reg / Reg)

Given

Op	Freq, $F_i$	$CPI_i$
ALU	50%	1
Load	20%	5
Store	10%	3
Branch	20%	2

$CPI_i \times F_i$

% Time

23% =  $.5/2.2$

45% =  $1/2.2$

14% =  $.3/2.2$

18% =  $.4/2.2$

$$\frac{CPI_i \times F_i}{CPI}$$

Typical Mix

$$CPI = \text{Sum} = 2.2$$

Average

$$CPI = \sum_{i=1}^n (CPI_i \times F_i)$$

$$CPI = .5 \times 1 + .2 \times 5 + .1 \times 3 + .2 \times 2 = 2.2$$

$$= .5 + 1 + .3 + .4$$

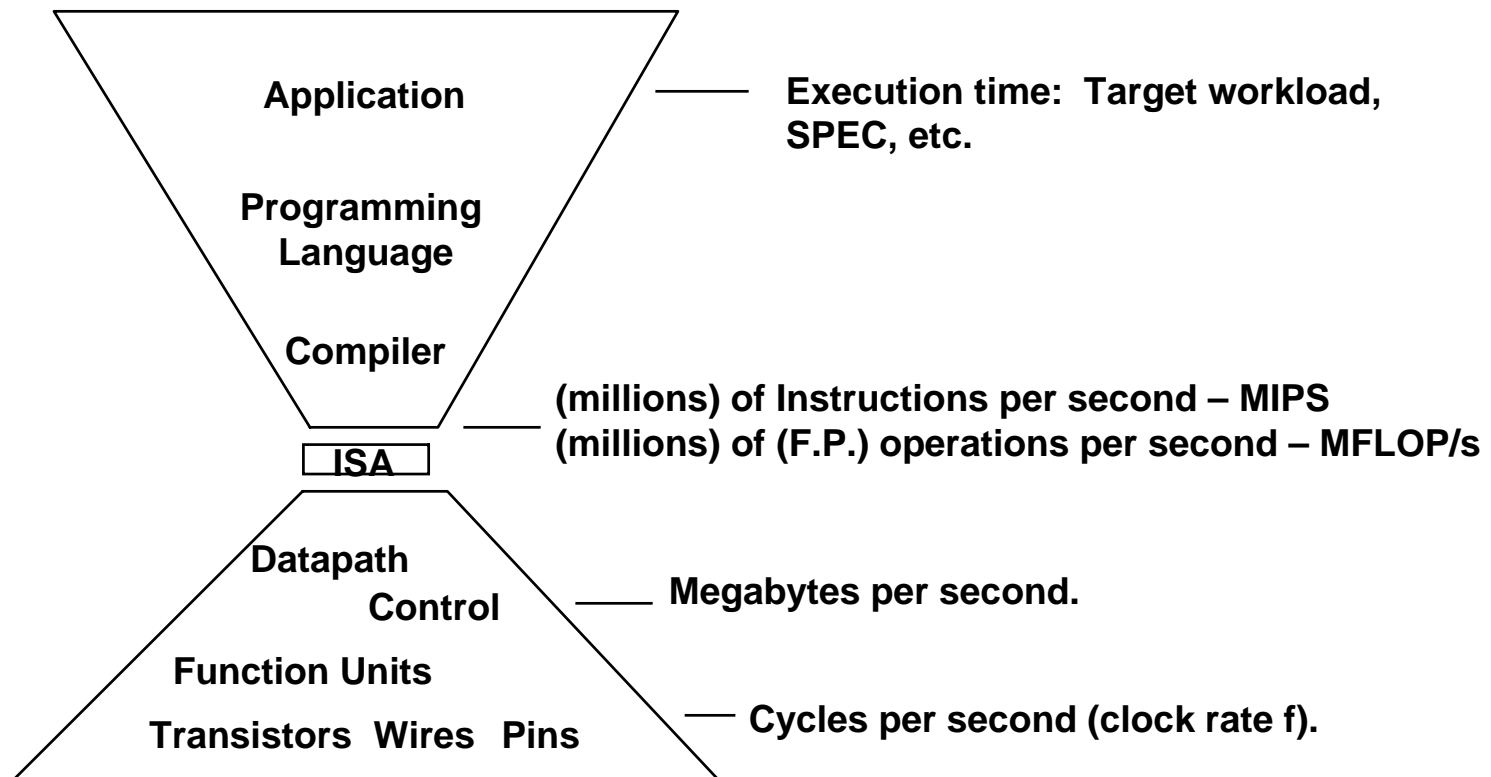
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(From 350)



# Metrics of Computer Performance

(Measures)



Each metric has a purpose, and each can be misused.

# Choosing Programs To Evaluate Performance

Levels of programs or benchmarks that could be used to evaluate performance:

- **Actual Target Workload:** Full applications that run on the target machine.
- **Real Full Program-based Benchmarks:**
  - Select a specific mix or suite of programs that are typical of targeted applications or workload (e.g SPEC95, SPEC CPU2000).
- **Small “Kernel” Benchmarks:** Also called synthetic benchmarks
  - Key computationally-intensive pieces extracted from real programs.
    - Examples: Matrix factorization, FFT, tree search, etc.
  - Best used to test specific aspects of the machine.
- **Microbenchmarks:**
  - Small, specially written programs to isolate a specific aspect of performance characteristics: Processing: integer, floating point, local memory, input/output, etc.

# SPEC: System Performance Evaluation Corporation

The most popular and industry-standard set of CPU benchmarks.

Target Programs application domain: Engineering and scientific computation

- **SPECmarks, 1989:**
  - 10 programs yielding a single number (“SPECmarks”).
- **SPEC92, 1992:**
  - SPECInt92 (6 integer programs) and SPECfp92 (14 floating point programs).
- **SPEC95, 1995:**
  - SPECint95 (8 integer programs):
    - go, m88ksim, gcc, compress, li, jpeg, perl, vortex
  - SPECfp95 (10 floating-point intensive programs):
    - tomcatv, swim, su2cor, hydro2d, mgrid, applu, turb3d, apsi, fppp, wave5
  - Performance relative to a Sun SuperSpark I (50 MHz) which is given a score of SPECint95 = SPECfp95 = 1
- **SPEC CPU2000, 1999:**
  - CINT2000 (11 integer programs). CFP2000 (14 floating-point intensive programs)
  - Performance relative to a Sun Ultra5\_10 (300 MHz) which is given a score of SPECint2000 = SPECfp2000 = 100
- **SPEC CPU2006, 2006:**
  - CINT2006 (12 integer programs). CFP2006 (17 floating-point intensive programs)
  - Performance relative to a Sun Ultra Enterprise 2 workstation with a 296-MHz UltraSPARC II processor which is given a score of SPECint2006 = SPECfp2006 = 1

All based on execution time and give speedup over a reference CPU

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# SPEC CPU2000 Programs

	Benchmark	Language	Descriptions
<b>CINT2000 (Integer)</b>	164.gzip	C	Compression
	175.vpr	C	FPGA Circuit Placement and Routing
	176.gcc	C	C Programming Language Compiler
	181.mcf	C	Combinatorial Optimization
	186.crafty	C	Game Playing: Chess
	197.parser	C	Word Processing
	252.eon	C++	Computer Visualization
	253.perlbnk	C	PERL Programming Language
	254.gap	C	Group Theory, Interpreter
	255.vortex	C	Object-oriented Database
	256.bzip2	C	Compression
	300.twolf	C	Place and Route Simulator
<b>CFP2000 (Floating Point)</b>	168.wupwise	Fortran 77	Physics / Quantum Chromodynamics
	171.swim	Fortran 77	Shallow Water Modeling
	172.mgrid	Fortran 77	Multi-grid Solver: 3D Potential Field
	173.applu	Fortran 77	Parabolic / Elliptic Partial Differential Equations
	177.mesa	C	3-D Graphics Library
	178.galgel	Fortran 90	Computational Fluid Dynamics
	179.art	C	Image Recognition / Neural Networks
	183.quake	C	Seismic Wave Propagation Simulation
	187.facerec	Fortran 90	Image Processing: Face Recognition
	188.amp	C	Computational Chemistry
	189.lucas	Fortran 90	Number Theory / Primality Testing
	191.fma3d	Fortran 90	Finite-element Crash Simulation
	200.sixtrack	Fortran 77	High Energy Nuclear Physics Accelerator Design
301.apsi	Fortran 77	Meteorology: Pollutant Distribution	

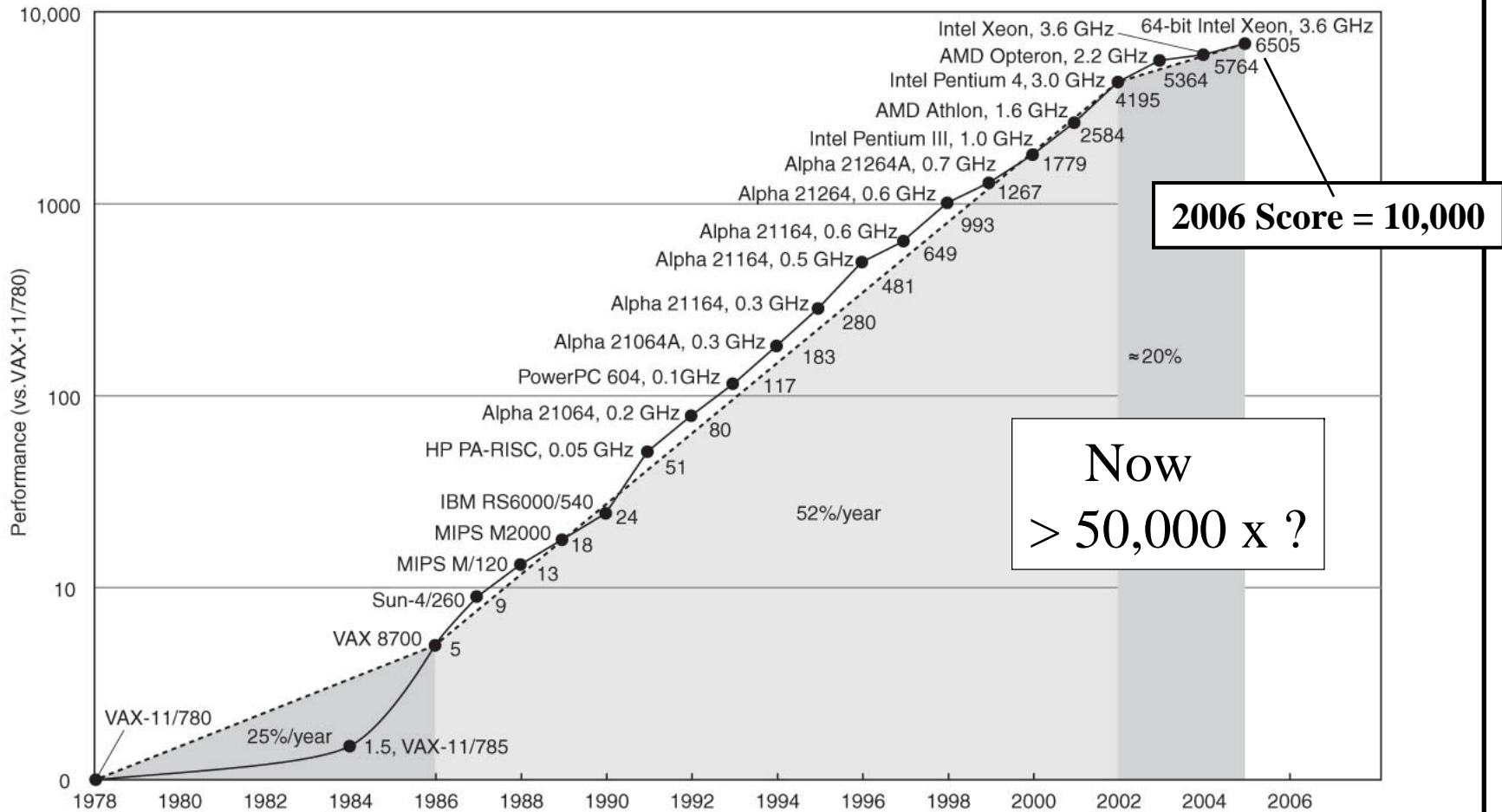
Programs application domain: Engineering and scientific computation

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Source: <http://www.spec.org/osg/cpu2000/>

# Integer SPEC CPU2000 Microprocessor Performance 1978-2006

Performance relative to VAX 11/780 (given a score = 1)



1978 Score = 1

$$T = I \times CPI \times C$$

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# Top 20 SPEC CPU2000 Results (As of October 2006)

## Top 20 SPECint2000

## Top 20 SPECfp2000

#	MHz	Processor	int peak	int base	MHz	Processor	fp peak	fp base
1	2933	Core 2 Duo EE	3119	3108	2300	POWER5+	3642	3369
2	3000	Xeon 51xx	3102	3089	1600	DC Itanium 2	3098	3098
3	2666	Core 2 Duo	2848	2844	3000	Xeon 51xx	3056	2811
4	2660	Xeon 30xx	2835	2826	2933	Core 2 Duo EE	3050	3048
5	3000	Opteron	2119	1942	2660	Xeon 30xx	3044	2763
6	2800	Athlon 64 FX	2061	1923	1600	Itanium 2	3017	3017
7	2800	Opteron AM2	1960	1749	2667	Core 2 Duo	2850	2847
8	2300	POWER5+	1900	1820	1900	POWER5	2796	2585
9	3733	Pentium 4 E	1872	1870	3000	Opteron	2497	2260
10	3800	Pentium 4 Xeon	1856	1854	2800	Opteron AM2	2462	2230
11	2260	Pentium M	1839	1812	3733	Pentium 4 E	2283	2280
12	3600	Pentium D	1814	1810	2800	Athlon 64 FX	2261	2086
13	2167	Core Duo	1804	1796	2700	PowerPC 970MP	2259	2060
14	3600	Pentium 4	1774	1772	2160	SPARC64 V	2236	2094
15	3466	Pentium 4 EE	1772	1701	3730	Pentium 4 Xeon	2150	2063
16	2700	PowerPC 970MP	1706	1623	3600	Pentium D	2077	2073
17	2600	Athlon 64	1706	1612	3600	Pentium 4	2015	2009
18	2000	Pentium 4 Xeon LV	1668	1663	2600	Athlon 64	1829	1700
19	2160	SPARC64 V	1620	1501	1700	POWER4+	1776	1642
20	1600	Itanium 2	1590	1590	3466	Pentium 4 EE	1724	1719

Performance relative to a Sun Ultra5\_10 (300 MHz) which is given a score of SPECint2000 = SPECfp2000 = 100

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Source: <http://www.aceshardware.com/SPECmine/top.jsp>

# SPEC CPU2006 Programs

## CINT2006 (Integer)

12 programs

Benchmark	Language	Descriptions
400.perlbench	C	PERL Programming Language
401.bzip2	C	Compression
403.gcc	C	C Compiler
429.mcf	C	Combinatorial Optimization
445.gobmk	C	Artificial Intelligence: go
456.hmmmer	C	Search Gene Sequence
458.sjeng	C	Artificial Intelligence: chess
462.libquantum	C	Physics: Quantum Computing
464.h264ref	C	Video Compression
471.omnetpp	C++	Discrete Event Simulation
473.astar	C++	Path-finding Algorithms
483.Xalancbmk	C++	XML Processing

## CFP2006 (Floating Point)

17 programs

410.bwaves	Fortran	Fluid Dynamics
416.gamess	Fortran	Quantum Chemistry
433.milc	C	Physics: Quantum Chromodynamics
434.zeusmp	Fortran	Physics/CFD
435.gromacs	C/Fortran	Biochemistry/Molecular Dynamics
436.cactusADM	C/Fortran	Physics/General Relativity
437.leslie3d	Fortran	Fluid Dynamics
444.namd	C++	Biology/Molecular Dynamics
447.dealII	C++	Finite Element Analysis
450.soplex	C++	Linear Programming, Optimization
453.povray	C++	Image Ray-tracing
454.calculix	C/Fortran	Structural Mechanics
459.GemsFDTD	Fortran	Computational Electromagnetics
465.tonto	Fortran	Quantum Chemistry
470.lbm	C	Fluid Dynamics
481.wrf	C/Fortran	Weather Prediction
482.sphinx3	C	Speech recognition

Target Programs application domain: Engineering and scientific computation

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Source: <http://www.spec.org/cpu2006/>

# Example Integer SPEC CPU2006 Performance Results

For 2.5 GHz AMD Opteron X4 model 2356 (Barcelona)

$$I \times CPI \times C = T \quad \text{Base Machine Time}$$

Description	Name	Instruction Count $\times 10^9$	CPI	Clock cycle time (seconds $\times 10^9$ )	Execution Time (seconds)	Reference Time (seconds)	Speedup SPECratio
Interpreted string processing	perl	2,118	0.75	0.4	637	9,770	15.3
Block-sorting compression	bzip2	2,389	0.85	0.4	817	9,650	11.8
GNU C compiler	gcc	1,050	1.72	0.4	724	8,050	11.1
Combinatorial optimization	mcf	336	10.00	0.4	1,345	9,120	6.8
Go game (AI)	go	1,658	1.09	0.4	721	10,490	14.6
Search gene sequence	hmmer	2,783	0.80	0.4	890	9,330	10.5
Chess game (AI)	sjeng	2,176	0.96	0.4	837	12,100	14.5
Quantum computer simulation	libquantum	1,623	1.61	0.4	1,047	20,720	19.8
Video compression	h264avc	3,102	0.80	0.4	993	22,130	22.3
Discrete event simulation library	omnetpp	587	2.94	0.4	690	6,250	9.1
Games/path finding	astar	1,082	1.79	0.4	773	7,020	9.1
XML parsing	xalancbmk	1,058	2.70	0.4	1,143	6,900	6.0
Geometric Mean							11.7

Performance relative to a Sun Ultra Enterprise 2 workstation with a 296-MHz UltraSPARC II processor which is given a score of SPECint2006 = SPECfp2006 = 1

$$T = I \times CPI \times C$$

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# Computer Performance Measures :

## MIPS (Million Instructions Per Second) Rating

- For a specific program running on a specific CPU the MIPS rating is a measure of how many millions of instructions are executed per second:

$$\text{MIPS Rating} = \text{Instruction count} / (\text{Execution Time} \times 10^6)$$

$$= \text{Instruction count} / (\text{CPU clocks} \times \text{Cycle time} \times 10^6)$$

$$= (\text{Instruction count} \times \text{Clock rate}) / (\text{Instruction count} \times \text{CPI} \times 10^6)$$

$$= \text{Clock rate} / (\text{CPI} \times 10^6)$$

- Major problem with MIPS rating: As shown above the MIPS rating does not account for the count of instructions executed (I).
  - A higher MIPS rating in many cases may not mean higher performance or better execution time. i.e. due to compiler design variations.
- In addition the MIPS rating:
  - Does not account for the instruction set architecture (ISA) used.
    - Thus it cannot be used to compare computers/CPU's with different instruction sets.
  - Easy to abuse: Program used to get the MIPS rating is often omitted.
    - Often the Peak MIPS rating is provided for a given CPU which is obtained using a program comprised entirely of instructions with the lowest CPI for the given CPU design which does not represent real programs.

(From 350)

$$T = I \times \text{CPI} \times C$$

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# Computer Performance Measures :

## MIPS (Million Instructions Per Second) Rating

- Under what conditions can the MIPS rating be used to compare performance of different CPUs?
- The MIPS rating is only valid to compare the performance of different CPUs provided that the following conditions are satisfied:
  - 1 The same program is used  
(actually this applies to all performance metrics)
  - 2 The same ISA is used
  - 3 The same compiler is used

⇒ (Thus the resulting programs used to run on the CPUs and obtain the MIPS rating are identical at the machine code level including the same instruction count) (binary)

~ I

(From 350)

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# Compiler Variations, MIPS, Performance: An Example

- For the machine (CPU) with instruction classes:

Instruction class	CPI
A	1
B	2
C	3

- For a given program two compilers produced the following instruction counts:

	Instruction counts (in millions) for each instruction class		
Code from:	A	B	C
Compiler 1	5	1	1
Compiler 2	10	1	1

- The machine is assumed to run at a clock rate of 100 MHz

(From 350)

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# Compiler Variations, MIPS, Performance: An Example (Continued)

$$\text{MIPS} = \text{Clock rate} / (\text{CPI} \times 10^6) = 100 \text{ MHz} / (\text{CPI} \times 10^6)$$

$$\text{CPI} = \text{CPU execution cycles} / \text{Instructions count}$$

$$\text{CPU clock cycles} = \sum_{i=1}^n (\text{CPI}_i \times C_i)$$

$$\text{CPU time} = \text{Instruction count} \times \text{CPI} / \text{Clock rate}$$

- For compiler 1:
  - $\text{CPI}_1 = (5 \times 1 + 1 \times 2 + 1 \times 3) / (5 + 1 + 1) = 10 / 7 = 1.43$
  - $\text{MIP Rating}_1 = 100 / (1.428 \times 10^6) = 70.0$
  - $\text{CPU time}_1 = ((5 + 1 + 1) \times 10^6 \times 1.43) / (100 \times 10^6) = 0.10 \text{ seconds}$
- For compiler 2:
  - $\text{CPI}_2 = (10 \times 1 + 1 \times 2 + 1 \times 3) / (10 + 1 + 1) = 15 / 12 = 1.25$
  - $\text{MIPS Rating}_2 = 100 / (1.25 \times 10^6) = 80.0$
  - $\text{CPU time}_2 = ((10 + 1 + 1) \times 10^6 \times 1.25) / (100 \times 10^6) = 0.15 \text{ seconds}$

MIPS rating indicates that compiler 2 is better  
while in reality the code produced by compiler 1 is faster

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# MIPS32 (The ISA not the metric) Loop Performance Example

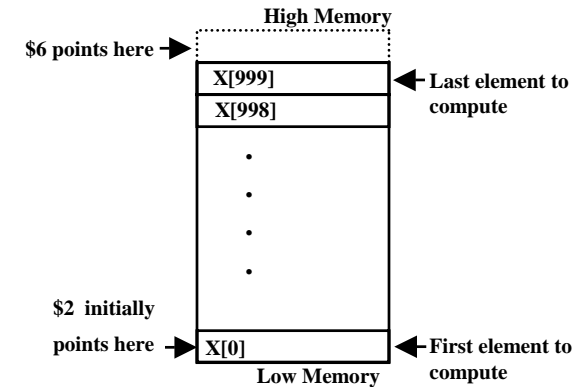
For the loop:

```
for (i=0; i<1000; i=i+1){
    x[i] = x[i] + s; }
```

MIPS32 assembly code is given by:

```

        lw      $3, 8($1)      ; load s in $3
        addi   $6, $2, 4000   ; $6 = address of last element + 4
loop:   lw      $4, 0($2)      ; load x[i] in $4
        add    $5, $4, $3     ; $5 has x[i] + s
        sw    $5, 0($2)      ; store computed x[i]
        addi   $2, $2, 4      ; increment $2 to point to next x[ ] element
        bne   $6, $2, loop    ; last loop iteration reached?
```



The MIPS code is executed on a specific CPU that runs at 500 MHz (clock cycle = 2ns = 2x10<sup>-9</sup> seconds) with following instruction type CPIs :

For this MIPS code running on this CPU find:

Instruction type	CPI
ALU	4
Load	5
Store	7
Branch	3

- 1- Fraction of total instructions executed for each instruction type
- 2- Total number of CPU cycles
- 3- Average CPI
- 4- Fraction of total execution time for each instructions type
- 5- Execution time
- 6- MIPS rating , peak MIPS rating for this CPU

X[ ] array of words in memory, base address in \$2,  
s a constant word value in memory, address in \$1

From 350

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## MIPS32 (The ISA) Loop Performance Example (continued)

- The code has 2 instructions before the loop and 5 instructions in the body of the loop which iterates 1000 times,
- Thus: Total instructions executed,  $I = 5 \times 1000 + 2 = 5002$  instructions

### 1 Number of instructions executed/fraction $F_i$ for each instruction type:

- ALU instructions =  $1 + 2 \times 1000 = 2001$      $CPI_{ALU} = 4$      $Fraction_{ALU} = F_{ALU} = 2001/5002 = 0.4 = 40\%$
- Load instructions =  $1 + 1 \times 1000 = 1001$      $CPI_{Load} = 5$      $Fraction_{Load} = F_{Load} = 1001/5002 = 0.2 = 20\%$
- Store instructions = 1000     $CPI_{Store} = 7$      $Fraction_{Store} = F_{Store} = 1000/5002 = 0.2 = 20\%$
- Branch instructions = 1000     $CPI_{Branch} = 3$      $Fraction_{Branch} = F_{Branch} = 1000/5002 = 0.2 = 20\%$

2  $CPU \text{ clock cycles} = \sum_{i=1}^n (CPI_i \times C_i)$   
 $= 2001 \times 4 + 1001 \times 5 + 1000 \times 7 + 1000 \times 3 = 23009 \text{ cycles}$

3 Average CPI = CPU clock cycles / I =  $23009/5002 = 4.6$

### 4 Fraction of execution time for each instruction type:

- Fraction of time for ALU instructions =  $CPI_{ALU} \times F_{ALU} / CPI = 4 \times 0.4 / 4.6 = 0.348 = 34.8\%$
- Fraction of time for load instructions =  $CPI_{load} \times F_{load} / CPI = 5 \times 0.2 / 4.6 = 0.217 = 21.7\%$
- Fraction of time for store instructions =  $CPI_{store} \times F_{store} / CPI = 7 \times 0.2 / 4.6 = 0.304 = 30.4\%$
- Fraction of time for branch instructions =  $CPI_{branch} \times F_{branch} / CPI = 3 \times 0.2 / 4.6 = 0.13 = 13\%$

Instruction type	CPI
ALU	4
Load	5
Store	7
Branch	3

5 Execution time = I x CPI x C = CPU cycles x C =  $23009 \times 2 \times 10^{-9} =$   
 $= 4.6 \times 10^{-5} \text{ seconds} = 0.046 \text{ msec} = 46 \text{ usec}$

6 MIPS rating = Clock rate / (CPI x  $10^6$ ) =  $500 / 4.6 = 108.7 \text{ MIPS}$

- The CPU achieves its peak MIPS rating when executing a program that only has instructions of the type with the lowest CPI. In this case branches with  $CPI_{Branch} = 3$
- Peak MIPS rating = Clock rate / ( $CPI_{Branch} \times 10^6$ ) =  $500/3 = 166.67 \text{ MIPS}$

# Computer Performance Measures :

## MFLOPS (Million FLOating-Point Operations Per Second)

- A floating-point operation is an addition, subtraction, multiplication, or division operation applied to numbers represented by a single or a double precision floating-point representation.
- MFLOPS, for a specific program running on a specific computer, is a measure of millions of floating point-operation (megaflops) per second:

$$\text{MFLOPS} = \text{Number of floating-point operations} / (\text{Execution time} \times 10^6)$$

- MFLOPS rating is a better comparison measure between different machines (applies even if ISAs are different) than the MIPS rating.
  - Applicable even if ISAs are different
- Program-dependent: Different programs have different percentages of floating-point operations present. i.e compilers have no floating-point operations and yield a MFLOPS rating of zero.
- Dependent on the type of floating-point operations present in the program.
  - Peak MFLOPS rating for a CPU: Obtained using a program comprised entirely of the simplest floating point instructions (with the lowest CPI) for the given CPU design which does not represent real floating point programs.

(From 350)

Current peak MFLOPS rating: 8,000-20,000  
MFLOPS (8-20 GFLOPS) per processor core

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# Quantitative Principles of Computer Design

- **Amdahl's Law:**

The performance gain from improving some portion of a computer is calculated by:

Or CPU

i.e using some enhancement

$$\text{Speedup} = \frac{\text{Performance for entire task using the enhancement}}{\text{Performance for the entire task without using the enhancement}}$$

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

(From 350)



# Performance Enhancement Calculations: Amdahl's Law

- The overall performance enhancement possible due to a given design improvement is limited by the amount that the improved feature is used
- Amdahl's Law:

Performance improvement or speedup due to enhancement E:

$$\text{Speedup}(E) = \frac{\text{Execution Time without E}}{\text{Execution Time with E}} = \frac{\text{Performance with E}}{\text{Performance without E}}$$

– Suppose that enhancement E accelerates a fraction F of the (original) execution time by a factor S and the remainder of the time is unaffected then:

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

Hence speedup is given by:

$$\text{Speedup}(E) = \frac{\cancel{\text{Execution Time without E}}}{((1 - F) + F/S) \times \cancel{\text{Execution Time without E}}} = \frac{1}{(1 - F) + F/S}$$

F (Fraction of execution time enhanced) refers to original execution time before the enhancement is applied

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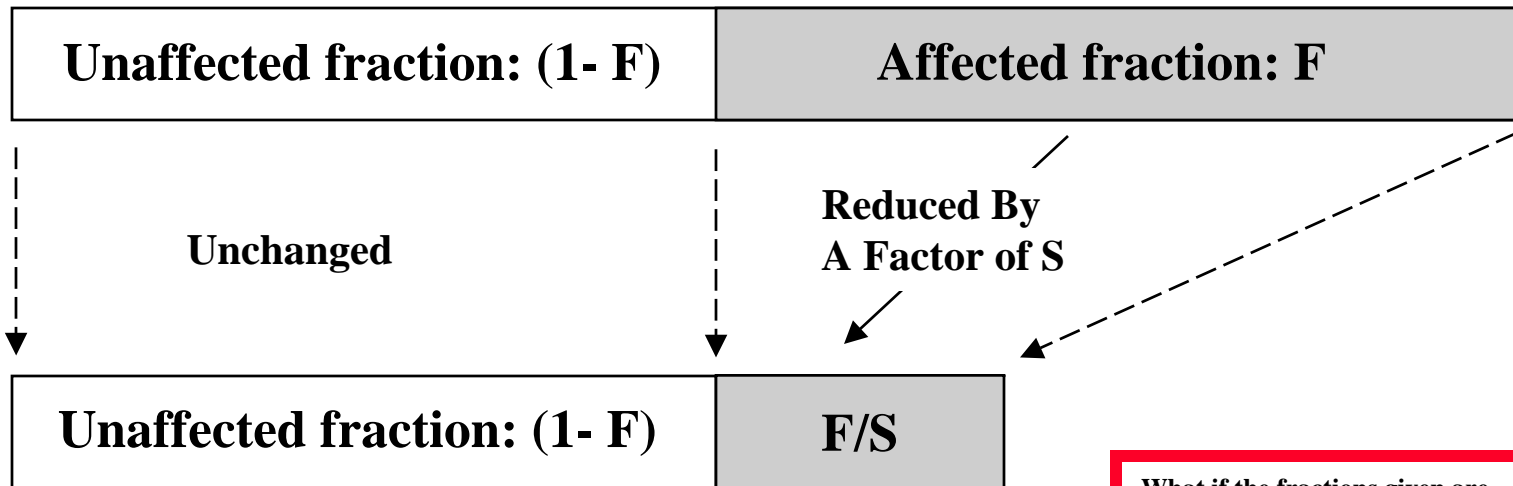
# Pictorial Depiction of Amdahl's Law

Enhancement E accelerates fraction F of original execution time by a factor of S

**Before:**

**Execution Time without enhancement E: (Before enhancement is applied)**

- shown normalized to  $1 = (1-F) + F = 1$



**After:**

**Execution Time with enhancement E:**

What if the fractions given are after the enhancements were applied? How would you solve the problem?

$$\text{Speedup}(E) = \frac{\text{Execution Time without enhancement E}}{\text{Execution Time with enhancement E}} = \frac{1}{(1 - F) + F/S}$$

# Performance Enhancement Example

- For the RISC machine with the following instruction mix given earlier:

Op	Freq	Cycles	CPI(i)	% Time	
ALU	50%	1	.5	23%	<b>CPI = 2.2</b>
Load	20%	5	1.0	45%	
Store	10%	3	.3	14%	
Branch	20%	2	.4	18%	

- If a CPU design enhancement improves the CPI of load instructions from 5 to 2, what is the resulting performance improvement from this enhancement:

Fraction enhanced =  $F = 45\%$  or  $.45$

Unaffected fraction =  $100\% - 45\% = 55\%$  or  $.55$

Factor of enhancement =  $5/2 = 2.5$

Using Amdahl's Law:

$$\text{Speedup}(E) = \frac{1}{(1 - F) + F/S} = \frac{1}{.55 + .45/2.5} = 1.37$$

(From 350)

# An Alternative Solution Using CPU Equation

Op	Freq	Cycles	CPI(i)	% Time	
ALU	50%	1	.5	23%	<b>CPI = 2.2</b>
Load	20%	5	1.0	45%	
Store	10%	3	.3	14%	
Branch	20%	2	.4	18%	

- If a CPU design enhancement improves the CPI of load instructions from 5 to 2, what is the resulting performance improvement from this enhancement:

**Old CPI = 2.2**

**New CPI = .5 x 1 + .2 x 2 + .1 x 3 + .2 x 2 = 1.6**

$$\begin{aligned}
 \text{Speedup}(E) &= \frac{\text{Original Execution Time}}{\text{New Execution Time}} = \frac{\cancel{\text{Instruction count}} \times \text{old CPI} \times \cancel{\text{clock cycle}}}{\cancel{\text{Instruction count}} \times \text{new CPI} \times \cancel{\text{clock cycle}}} \\
 &= \frac{\text{old CPI}}{\text{new CPI}} = \frac{2.2}{1.6} = 1.37
 \end{aligned}$$

Which is the same speedup obtained from Amdahl's Law in the first solution.

(From 350)

$$T = I \times \text{CPI} \times C$$

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# Performance Enhancement Example

- A program runs in 100 seconds on a machine with multiply operations responsible for 80 seconds of this time. By how much must the speed of multiplication be improved to make the program four times faster?

$$\text{Desired speedup} = 4 = \frac{100}{\text{Execution Time with enhancement}}$$

→ Execution time with enhancement =  $100/4 = 25$  seconds

$$25 \text{ seconds} = (100 - 80 \text{ seconds}) + 80 \text{ seconds} / S$$

$$25 \text{ seconds} = 20 \text{ seconds} + 80 \text{ seconds} / S$$

→  $5 = 80 \text{ seconds} / S$

→  $S = 80/5 = 16$

Alternatively, it can also be solved by finding enhanced fraction of execution time:

$$F = 80/100 = .8$$

and then solving Amdahl's speedup equation for desired enhancement factor S

$$\text{Speedup}(E) = \frac{1}{(1 - F) + F/S} = 4 = \frac{1}{(1 - .8) + .8/S} = \frac{1}{.2 + .8/S}$$

Hence multiplication should be 16 times

Solving for S gives S= 16

faster to get an overall speedup of 4.

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(From 350)

# Performance Enhancement Example

- For the previous example with a program running in 100 seconds on a machine with multiply operations responsible for 80 seconds of this time. By how much must the speed of multiplication be improved to make the program five times faster?

$$\text{Desired speedup} = 5 = \frac{100}{\text{Execution Time with enhancement}}$$

→ Execution time with enhancement = 20 seconds

$$\begin{aligned} 20 \text{ seconds} &= (100 - 80 \text{ seconds}) + 80 \text{ seconds} / n \\ 20 \text{ seconds} &= 20 \text{ seconds} + 80 \text{ seconds} / n \end{aligned}$$

→  $0 = 80 \text{ seconds} / n$

No amount of multiplication speed improvement can achieve this.

# Extending Amdahl's Law To Multiple Enhancements

- Suppose that enhancement  $E_i$  accelerates a fraction  $F_i$  of the original execution time by a factor  $S_i$  and the remainder of the time is unaffected then:

$$Speedup = \frac{\cancel{\text{Original Execution Time}}}{\left( (1 - \sum_i F_i) + \sum_i \frac{F_i}{S_i} \right) \times \cancel{\text{Original Execution Time}}}$$

Unaffected fraction  $\nearrow$

$$Speedup = \frac{1}{\left( (1 - \sum_i F_i) + \sum_i \frac{F_i}{S_i} \right)}$$

What if the fractions given are after the enhancements were applied? How would you solve the problem?

**Note:** All fractions  $F_i$  refer to original execution time before the enhancements are applied.

# Amdahl's Law With Multiple Enhancements: Example

- Three CPU performance enhancements are proposed with the following speedups and percentage of the code execution time affected:

$$\text{Speedup}_1 = S_1 = 10$$

$$\text{Percentage}_1 = F_1 = 20\%$$

$$\text{Speedup}_2 = S_2 = 15$$

$$\text{Percentage}_1 = F_2 = 15\%$$

$$\text{Speedup}_3 = S_3 = 30$$

$$\text{Percentage}_1 = F_3 = 10\%$$

These fractions are from before enhancements are applied

- While all three enhancements are in place in the new design, each enhancement affects a different portion of the code and only one enhancement can be used at a time.
- What is the resulting overall speedup?

$$\text{Speedup} = \frac{1}{\left( (1 - \sum_i F_i) + \sum_i \frac{F_i}{S_i} \right)}$$

$$\begin{aligned} \text{Speedup} &= 1 / [(1 - .2 - .15 - .1) + .2/10 + .15/15 + .1/30] \\ &= 1 / [ .55 + .0333 ] \\ &= 1 / .5833 = 1.71 \end{aligned}$$

(From 350)

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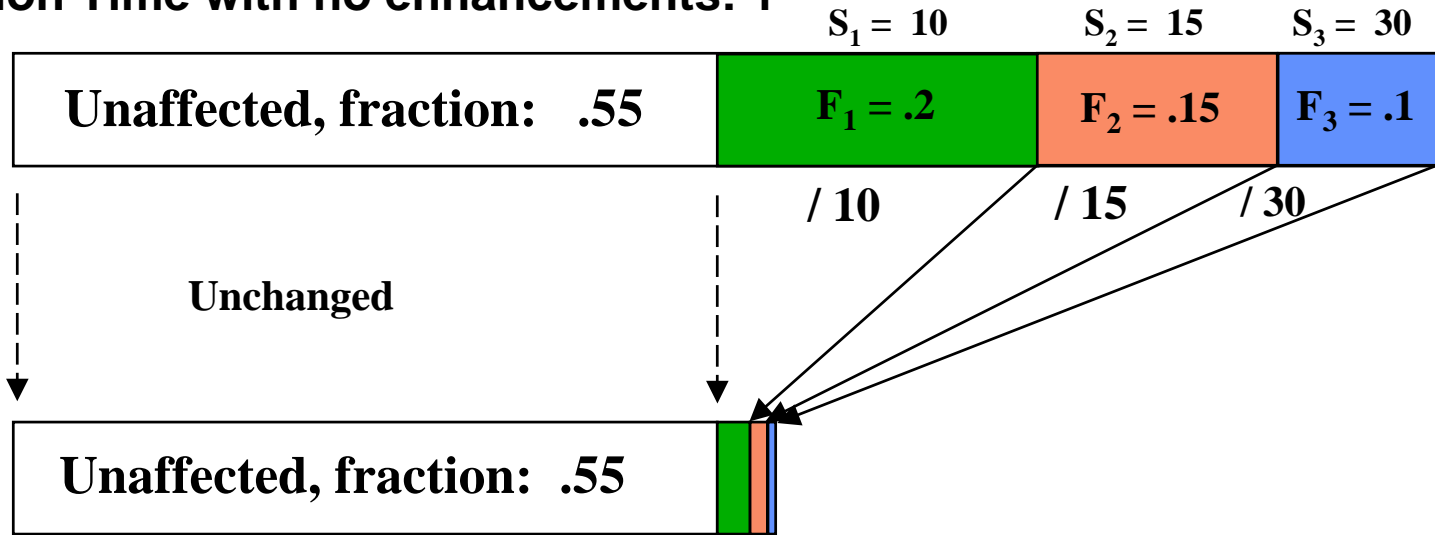
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# Pictorial Depiction of Example

Before:

Execution Time with no enhancements: 1



After:

Execution Time with enhancements:  $.55 + .02 + .01 + .00333 = .5833$

Speedup =  $1 / .5833 = 1.71$

Note: All fractions ( $F_i$ ,  $i = 1, 2, 3$ ) refer to original execution time.

What if the fractions given are after the enhancements were applied?  
How would you solve the problem?

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(From 350)

# “Reverse” Multiple Enhancements Amdahl's Law

- Multiple Enhancements Amdahl's Law assumes that the fractions given refer to original execution time.
- If for each enhancement  $S_i$  the fraction  $F_i$  it affects is given as a fraction of the resulting execution time after the enhancements were applied then:

$$Speedup = \frac{\left( (1 - \sum_i F_i) + \sum_i F_i \times S_i \right) \times \text{Resulting Execution Time}}{\text{Resulting Execution Time}}$$

Unaffected fraction

$$Speedup = \frac{(1 - \sum_i F_i) + \sum_i F_i \times S_i}{1} = (1 - \sum_i F_i) + \sum_i F_i \times S_i$$

1 i.e as if resulting execution time is normalized to 1

- For the previous example assuming fractions given refer to resulting execution time after the enhancements were applied (not the original execution time), then:

$$\begin{aligned} Speedup &= (1 - .2 - .15 - .1) + .2 \times 10 + .15 \times 15 + .1 \times 30 \\ &= .55 + 2 + 2.25 + 3 \\ &= 7.8 \end{aligned}$$

# Instruction Set Architecture (ISA)

“... the attributes of a [computing] system as seen by the programmer, *i.e.* the conceptual structure and functional behavior, as distinct from the organization of the data flows and controls the logic design, and the physical implementation.”

*i.e. CPU Design*

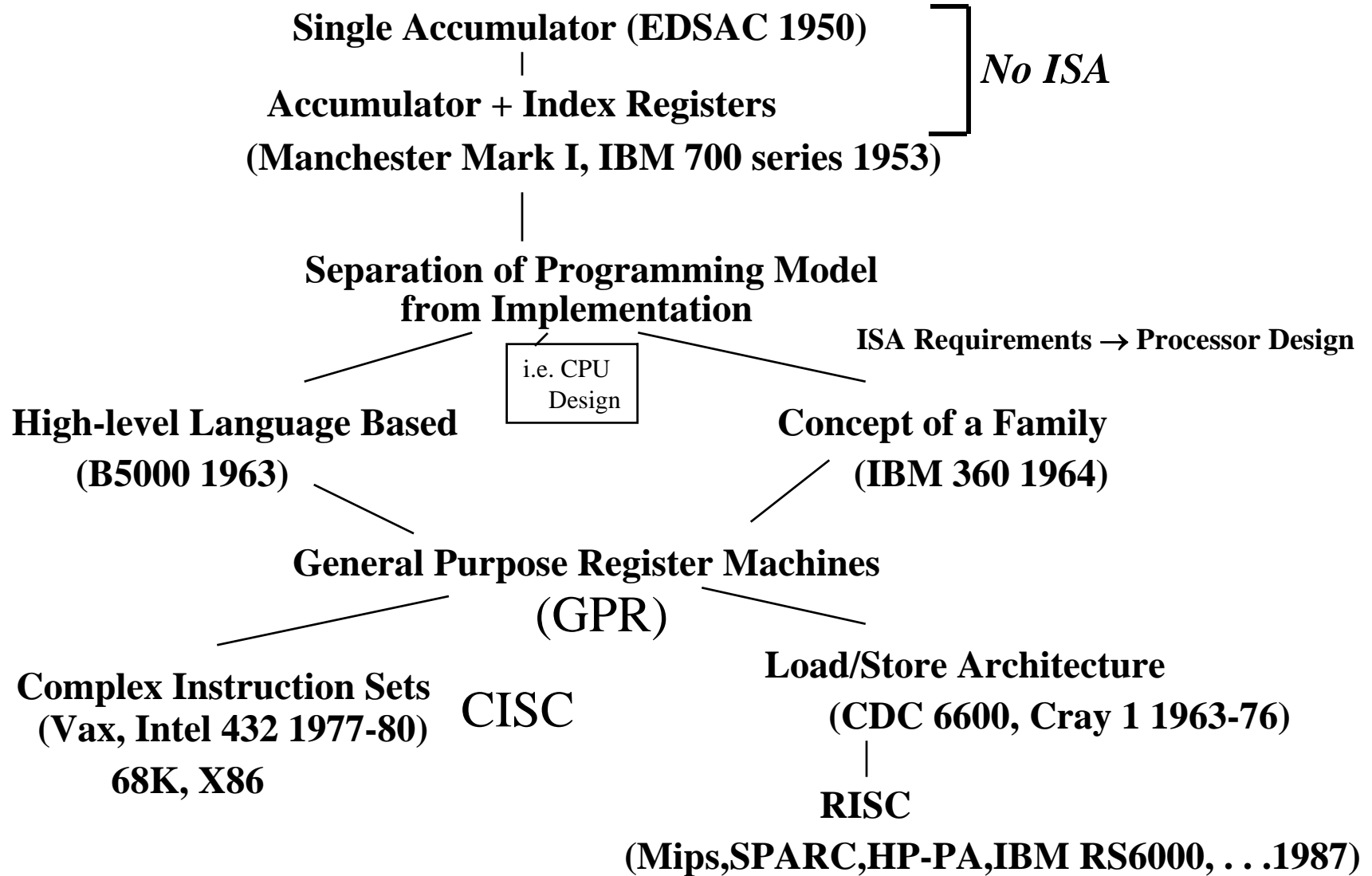
– Amdahl, Blaaw, and Brooks, 1964.

The ISA forms an abstraction layer that sets the requirements for both compiler and CPU designers

The instruction set architecture is concerned with:

- **Organization of programmable storage (memory & registers):** Includes the amount of addressable memory and number of available registers.
- **Data Types & Data Structures:** Encodings & representations.
- **Instruction Set:** What operations are specified.
- **Instruction formats and encoding.**
- **Modes of addressing and accessing data items and instructions**
- **Exceptional conditions.**

# Evolution of Instruction Sets



The ISA forms an abstraction layer that sets the requirements for both compiler and CPU designers

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# Complex Instruction Set Computer (CISC) ISAs

- **Emphasizes doing more with each instruction:**
  - Thus fewer instructions per program (more compact code).
- **Motivated by the high cost of memory and hard disk capacity when original CISC architectures were proposed**
  - When M6800 was introduced: 16K RAM = \$500, 40M hard disk = \$ 55, 000
  - When MC68000 was introduced: 64K RAM = \$200, 10M HD = \$5,000
- **Original CISC architectures evolved with faster more complex CPU designs but backward instruction set compatibility had to be maintained.**
- **Wide variety of addressing modes:**
  - 14 in MC68000, 25 in MC68020
- **A number instruction modes for the location and number of operands:**
  - The VAX has 0- through 3-address instructions.
- **Variable-length instruction encoding.**

Why?

Circa 1980

to reduce code size

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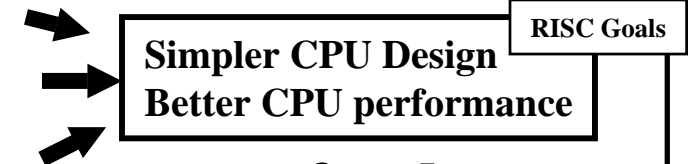
# Reduced Instruction Set Computer (RISC)

~1984 ISAs

RISC: Simplify ISA → Simplify CPU Design → Better CPU Performance

- Focuses on reducing the number and complexity of instructions of the machine.
- Reduced CPI. Goal: At least one instruction per clock cycle. (CPI = 1 or less)
- Designed with pipelining in mind.
- Fixed-length instruction encoding.
- Only load and store instructions access memory for data.
- Simplified addressing modes. (Thus more instructions executed than CISC)
  - Usually limited to immediate, register indirect, register displacement, indexed.
- Delayed loads and branches.
- Instruction pre-fetch and speculative execution.
- Examples: MIPS, ARM, POWER, PowerPC, Alpha ..

Machine = CPU or ISA



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# Types of Instruction Set Architectures According To Operand Addressing Fields

## Memory-To-Memory Machines:

- Operands obtained from memory and results stored back in memory by any instruction that requires operands.
- No local CPU registers are used in the CPU datapath.
- Include:
  - The 4 Address Machine.
  - The 3-address Machine.
  - The 2-address Machine.

## The 1-address (Accumulator) Machine:

- A single local CPU special-purpose register (accumulator) is used as the source of one operand and as the result destination.

## The 0-address or Stack Machine:

- A push-down stack is used in the CPU.

## General Purpose Register (GPR) Machines:

- The CPU datapath contains several local general-purpose registers which can be used as operand sources and as result destinations.
- A large number of possible addressing modes.
- Load-Store or Register-To-Register Machines: GPR machines where only data movement instructions (loads, stores) can obtain operands from memory and store results to memory.

GPR  
ISAs

CISC to RISC observation (load-store simplifies CPU design)

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# General-Purpose Register (GPR) ISAs/Machines

- Every ISA designed after 1980 uses a load-store GPR architecture (i.e RISC, to simplify CPU design).

## Why GPR?

- 1 • Registers, like any other storage form internal to the CPU, are faster than memory.
  - 2 • Registers are easier for a compiler to use.
  - 3 • Shorter instruction encoding.
- GPR architectures are divided into several types depending on two factors:
    - Whether an ALU instruction has two or three operands.
    - How many of the operands in ALU instructions may be memory addresses.



# ISA Examples

Machine	Number of General Purpose Registers	Architecture	year
EDSAC	1	accumulator	1949
IBM 701	1	accumulator	1953
CDC 6600	8	load-store	1963
IBM 360	16	register-memory	1964
DEC PDP-8	1	accumulator	1965
DEC PDP-11	8	register-memory	1970
Intel 8008 (8-bit)	1	accumulator	1972
Motorola 6800	1	accumulator	1974
DEC VAX	16	register-memory memory-memory	1977
Intel 8086 (16-bit)	1	extended accumulator	1978
Motorola 68000	16	register-memory	1980
Intel 80386 (32-bit)	8	register-memory	1985
MIPS	32	load-store	1985
HP PA-RISC	32	load-store	1986
SPARC	32	load-store	1987
PowerPC	32	load-store	1992
DEC Alpha	32	load-store	1992
HP/Intel IA-64	128	load-store	2001
AMD64 (EMT64) - 64-bit	16	register-memory	2003

# Typical Memory Addressing Modes

Addressing Mode	Sample Instruction	Meaning
Register	Add R4, R3	$\text{Regs}[\text{R4}] \leftarrow \text{Regs}[\text{R4}] + \text{Regs}[\text{R3}]$
Immediate	Add R4, #3	$\text{Regs}[\text{R4}] \leftarrow \text{Regs}[\text{R4}] + 3$
Displacement	Add R4, 10 (R1)	$\text{Regs}[\text{R4}] \leftarrow \text{Regs}[\text{R4}] + \text{Mem}[10 + \text{Regs}[\text{R1}]]$
Indirect	Add R4, (R1)	$\text{Regs}[\text{R4}] \leftarrow \text{Regs}[\text{R4}] + \text{Mem}[\text{Regs}[\text{R1}]]$
Indexed	Add R3, (R1 + R2)	$\text{Regs}[\text{R3}] \leftarrow \text{Regs}[\text{R3}] + \text{Mem}[\text{Regs}[\text{R1}] + \text{Regs}[\text{R2}]]$
Absolute	Add R1, (1001)	$\text{Regs}[\text{R1}] \leftarrow \text{Regs}[\text{R1}] + \text{Mem}[1001]$
Memory indirect	Add R1, @ (R3)	$\text{Regs}[\text{R1}] \leftarrow \text{Regs}[\text{R1}] + \text{Mem}[\text{Mem}[\text{Regs}[\text{R3}]]]$
Autoincrement	Add R1, (R2) +	$\text{Regs}[\text{R1}] \leftarrow \text{Regs}[\text{R1}] + \text{Mem}[\text{Regs}[\text{R2}]]$ $\text{Regs}[\text{R2}] \leftarrow \text{Regs}[\text{R2}] + d$
Autodecrement	Add R1, - (R2)	$\text{Regs}[\text{R2}] \leftarrow \text{Regs}[\text{R2}] - d$ $\text{Regs}[\text{R1}] \leftarrow \text{Regs}[\text{R1}] + \text{Mem}[\text{Regs}[\text{R2}]]$
Scaled	Add R1, 100 (R2) [R3]	$\text{Regs}[\text{R1}] \leftarrow \text{Regs}[\text{R1}] +$ $\text{Mem}[100 + \text{Regs}[\text{R2}] + \text{Regs}[\text{R3}] * d]$

For GPR ISAs

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# Addressing Modes Usage Example

For 3 programs running on VAX ignoring direct register mode:

<b>Displacement</b>	<b>42% avg, 32% to 55%</b>	<b>75%</b>	<b>88%</b>
<b>Immediate:</b>	<b>33% avg, 17% to 43%</b>		
<b>Register deferred (indirect):</b>	<b>13% avg, 3% to 24%</b>		
<b>Scaled:</b>	<b>7% avg, 0% to 16%</b>		
<b>Memory indirect:</b>	<b>3% avg, 1% to 6%</b>		
<b>Misc:</b>	<b>2% avg, 0% to 3%</b>		

**75% displacement & immediate**

**88% displacement, immediate & register indirect.**

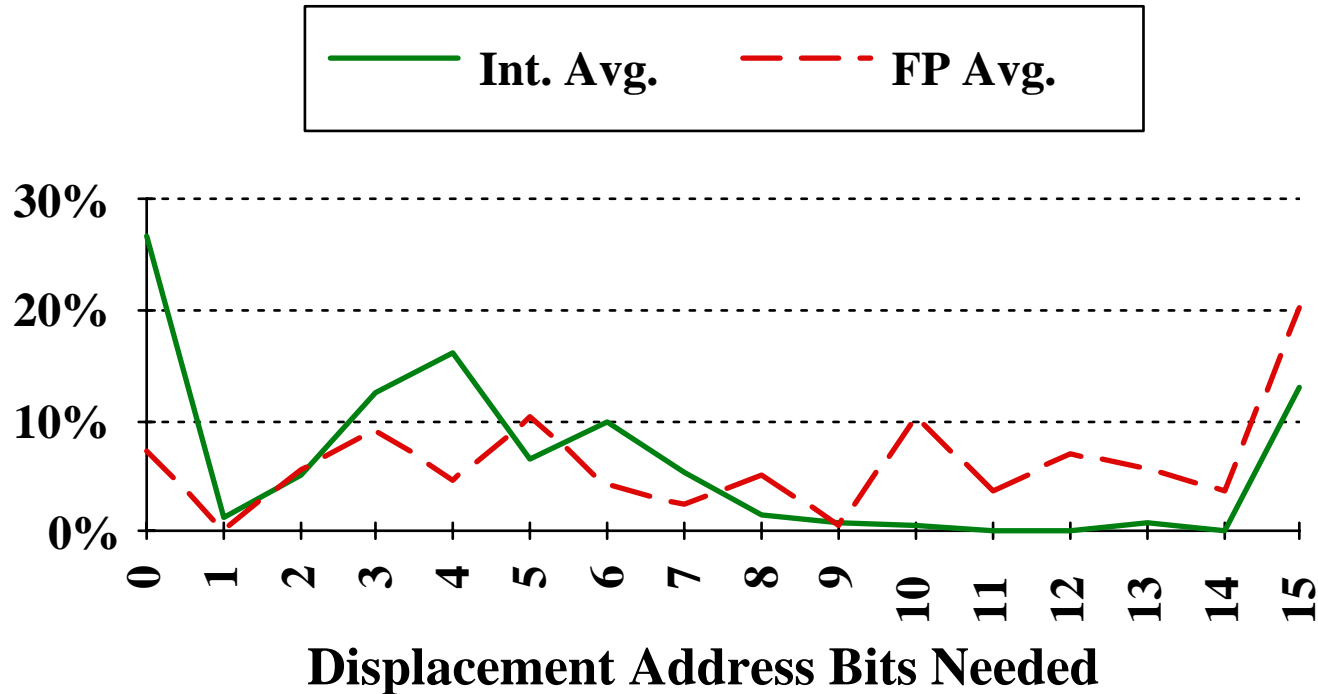
**Observation: In addition Register direct, Displacement, Immediate, Register Indirect addressing modes are important.**

CISC to RISC observation  
(fewer addressing modes simplify CPU design)

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# Displacement Address Size Example

Avg. of 5 SPECint92 programs v. avg. 5 SPECfp92 programs



1% of addresses > 16-bits

12 - 16 bits of displacement needed

CISC to RISC observation

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# Operation Types in The Instruction Set

## Operator Type

## Examples

Arithmetic and logical	Integer arithmetic and logical operations: add, or
Data transfer <span style="border: 1px solid black; padding: 0 5px;">2</span>	Loads-stores (move on machines with memory addressing)
Control <span style="border: 1px solid black; padding: 0 5px;">3</span>	Branch, jump, procedure call, and return, traps.
System	Operating system call, virtual memory management instructions
Floating point	Floating point operations: add, multiply.
Decimal	Decimal add, decimal multiply, decimal to character conversion
String	String move, string compare, string search
Media	The same operation performed on multiple data (e.g Intel MMX, SSE)

1

# Instruction Usage Example: Top 10 Intel X86 Instructions

Rank	instruction	Integer Average Percent total executed
1	load	22%
2	conditional branch	20%
3	compare	16%
4	store	12%
5	add	8%
6	and	6%
7	sub	5%
8	move register-register	4%
9	call	1%
10	return	1%
	<b>Total</b>	<b>96%</b>

**Observation: Simple instructions dominate instruction usage frequency.**

CISC to RISC observation

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# Instruction Set Encoding

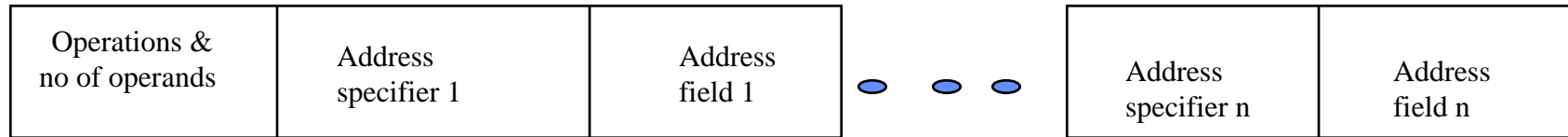
## Considerations affecting instruction set encoding:

- To have as many registers and addressing modes as possible.
- The Impact of of the size of the register and addressing mode fields on the average instruction size and on the average program.
- To encode instructions into lengths that will be easy to handle in the implementation. On a minimum to be a multiple of bytes.
  - Fixed length encoding: Faster and easiest to implement in hardware. e.g. Simplifies design of pipelined CPUs
  - Variable length encoding: Produces smaller instructions. to reduce code size
  - Hybrid encoding.

CISC to RISC observation

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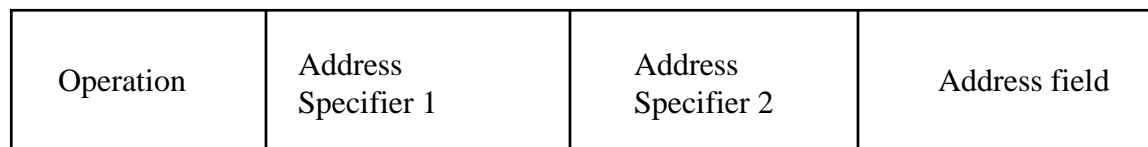
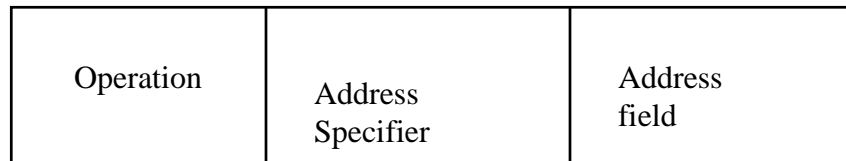
# Three Examples of Instruction Set Encoding



**Variable: VAX (1-53 bytes)**



**Fixed: MIPS, PowerPC, SPARC (Each instruction is 4 bytes, e.g RISC ISAs)**



**Hybrid : IBM 360/370, Intel 80x86**



# Example CISC ISA:

## Motorola 680X0

### 18 addressing modes:

- Data register direct.
- Address register direct.
- Immediate.
- Absolute short.
- Absolute long.
- Address register indirect.
- Address register indirect with postincrement.
- Address register indirect with predecrement.
- Address register indirect with displacement.
- Address register indirect with index (8-bit).
- Address register indirect with index (base).
- Memory indirect postindexed.
- Memory indirect preindexed.
- Program counter indirect with index (8-bit).
- Program counter indirect with index (base).
- Program counter indirect with displacement.
- Program counter memory indirect postindexed.
- Program counter memory indirect preindexed.

### GPR ISA (Register-Memory)

### Operand size:

- Range from 1 to 32 bits, 1, 2, 4, 8, 10, or 16 bytes.

### Instruction Encoding:

- Instructions are stored in 16-bit words.
- the smallest instruction is 2- bytes (one word).
- The longest instruction is 5 words (10 bytes) in length.

**2 Bytes → 10 Bytes**

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# Example CISC ISA:

## Intel IA-32, X86 (80386)

GPR ISA (Register-Memory)

### 12 addressing modes:

- Register.
- Immediate.
- Direct.
- Base.
- Base + Displacement.
- Index + Displacement.
- Scaled Index + Displacement.
- Based Index.
- Based Scaled Index.
- Based Index + Displacement.
- Based Scaled Index + Displacement.
- Relative.

### Operand sizes:

- Can be 8, 16, 32, 48, 64, or 80 bits long.
- Also supports string operations.

### Instruction Encoding:

- The smallest instruction is one byte.
- The longest instruction is 12 bytes long.
- The first bytes generally contain the opcode, mode specifiers, and register fields.
- The remainder bytes are for address displacement and immediate data.

One Byte → 12 Bytes

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# Example RISC ISA:

## HP Precision Architecture, HP PA-RISC

Load-Store GPR

### 7 addressing modes:

- Register
- Immediate
- Base with displacement
- Base with scaled index and displacement
- Predecrement
- Postincrement
- PC-relative

### Operand sizes:

- Five operand sizes ranging in powers of two from 1 to 16 bytes.

### Instruction Encoding:

- Instruction set has 12 different formats.
- All are 32 bits (4 bytes) in length.

# RISC ISA Example:

## **MIPS-I** MIPS R3000 (32-bits)

### Instruction Categories:

- Load/Store.
- Computational.
- Jump and Branch.
- Floating Point (using coprocessor).
- Memory Management.
- Special.

**Load-Store GPR**

### 5 Addressing Modes:

- Register direct (arithmetic).
- Immediate (arithmetic).
- Base register + immediate offset (loads and stores).
- PC relative (branches).
- Pseudodirect (jumps)

### Operand Sizes:

- Memory accesses in any multiple between 1 and 4 bytes.

### Registers

**R0 - R31**

**PC**

**HI**

**LO**

**Instruction Encoding: 3 Instruction Formats, all 32 bits wide (4 bytes).**

R	OP	rs	rt	rd	sa	funct
I	OP	rs	rt	immediate		
J	OP	jump target				

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(Used as target ISA for CPU design in 350)

# An Instruction Set Example: MIPS64

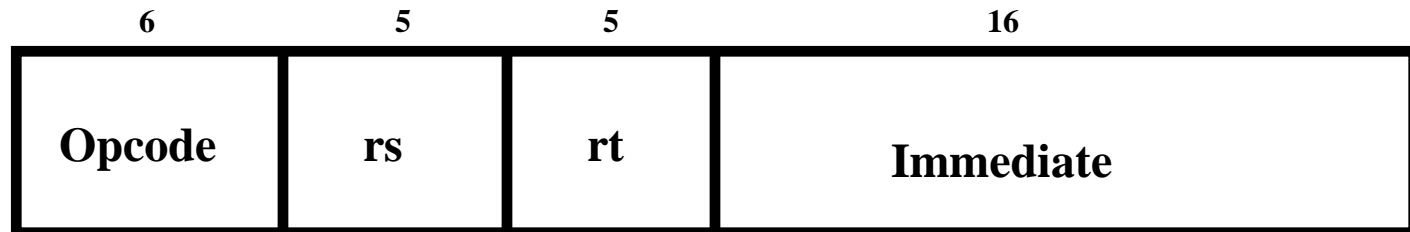
- A RISC-type 64-bit instruction set architecture based on instruction set design considerations of chapter 2:
  - Use general-purpose registers with a load/store architecture to access memory. Load/Store GPR similar to all RISC ISAs
  - Reduced number of addressing modes: displacement (offset size of 16 bits), immediate (16 bits).
  - Data sizes: 8 (byte), 16 (half word), 32 (word), 64 (double word) bit integers and 32-bit or 64-bit IEEE 754 floating-point numbers.  
4 Bytes      8 Bytes
  - Use fixed instruction encoding (32 bits) for performance.
  - 32, 64-bit general-purpose integer registers GPRs, R0, ..., R31. R0 always has a value of zero.
  - Separate 32, 64-bit floating point registers FPRs: F0, F1 ... F31  
When holding a 32-bit single-precision number the upper half of the FPR is not used.

64-bit version of 32-bit MIPS ISA used in 350  
4<sup>th</sup> Edition in Appendix B (3<sup>rd</sup> Edition: Chapter 2)

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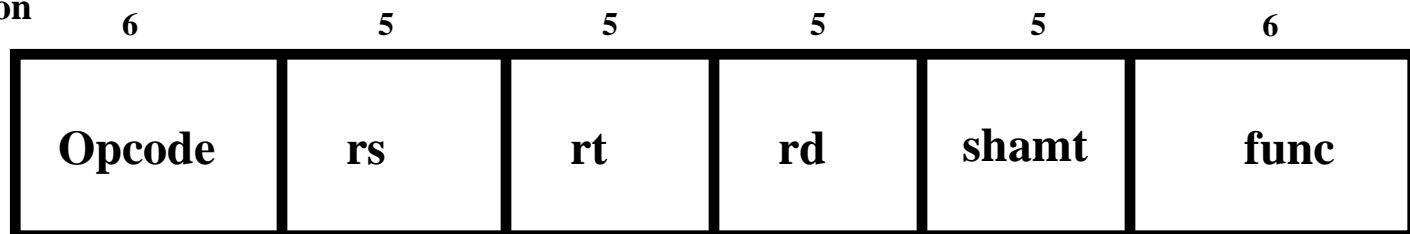
# MIPS64 Instruction Format

I - type instruction



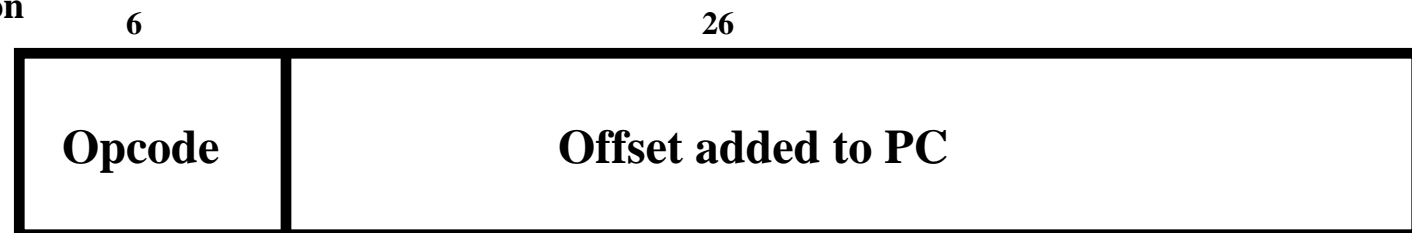
Encodes: Loads and stores of bytes, words, half words. All immediates ( $rt \leftarrow rs \text{ op immediate}$ )  
Conditional branch instructions  
Jump register, jump and link register ( $rs = \text{destination}$ ,  $\text{immediate} = 0$ )

R - type instruction



Register-register ALU operations:  $rd \leftarrow rs \text{ func } rt$  Function encodes the data path operation:  
Add, Sub .. Read/write special registers and moves.

J - Type instruction

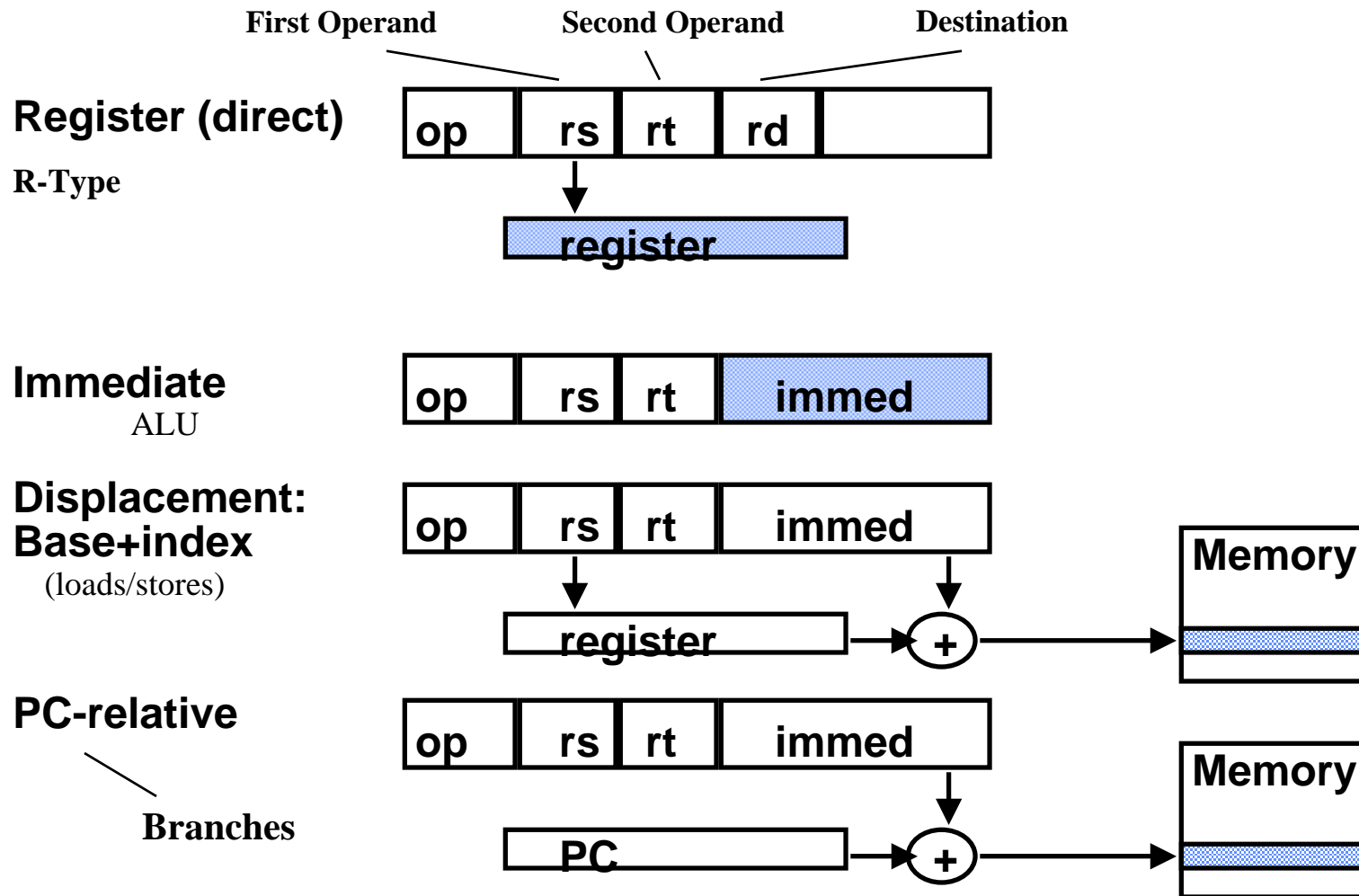


Jump and jump and link. Trap and return from exception

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# MIPS Addressing Modes/Instruction Formats

- All instructions 32 bits wide



Pseudodirect Addressing for jumps (J-Type) not shown here

# MIPS64 Instructions: Load and Store

<b>LD R1,30(R2)</b>	<b>Load double word</b>	$\text{Regs}[\text{R1}] \leftarrow_{64} \text{Mem}[30+\text{Regs}[\text{R2}]]$
<b>LW R1, 60(R2)</b>	<b>Load word</b>	$\text{Regs}[\text{R1}] \leftarrow_{64} (\text{Mem}[60+\text{Regs}[\text{R2}]]_0)^{32} \#\#$ $\text{Mem}[60+\text{Regs}[\text{R2}]]$
<b>LB R1, 40(R3)</b>	<b>Load byte</b>	$\text{Regs}[\text{R1}] \leftarrow_{64} (\text{Mem}[40+\text{Regs}[\text{R3}]]_0)^{56} \#\#$ $\text{Mem}[40+\text{Regs}[\text{R3}]]$
<b>LBU R1, 40(R3)</b>	<b>Load byte unsigned</b>	$\text{Regs}[\text{R1}] \leftarrow_{64} 0^{56} \#\# \text{Mem}[40+\text{Regs}[\text{R3}]]$
<b>LH R1, 40(R3)</b>	<b>Load half word</b>	$\text{Regs}[\text{R1}] \leftarrow_{64} (\text{Mem}[40+\text{Regs}[\text{R3}]]_0)^{48} \#\#$ $\text{Mem}[40 + \text{Regs}[\text{R3}]] \#\# \text{Mem}[41+\text{Regs}[\text{R3}]]$
<b>L.S F0, 50(R3)</b>	<b>Load FP single</b>	$\text{Regs}[\text{F0}] \leftarrow_{64} \text{Mem}[50+\text{Regs}[\text{R3}]] \#\# 0^{32}$
<b>L.D F0, 50(R2)</b>	<b>Load FP double</b>	$\text{Regs}[\text{F0}] \leftarrow_{64} \text{Mem}[50+\text{Regs}[\text{R2}]]$
<b>SD R3,500(R4)</b>	<b>Store double word</b>	$\text{Mem}[500+\text{Regs}[\text{R4}]] \leftarrow_{64} \text{Reg}[\text{R3}]$
<b>SW R3,500(R4)</b>	<b>Store word</b>	$\text{Mem}[500+\text{Regs}[\text{R4}]] \leftarrow_{32} \text{Reg}[\text{R3}]$
<b>S.S F0, 40(R3)</b>	<b>Store FP single</b>	$\text{Mem}[40, \text{Regs}[\text{R3}]] \leftarrow_{32} \text{Regs}[\text{F0}]_{0\dots31}$
<b>S.D F0,40(R3)</b>	<b>Store FP double</b>	$\text{Mem}[40+\text{Regs}[\text{R3}]] \leftarrow_{64} \text{Regs}[\text{F0}]$
<b>SH R3, 502(R2)</b>	<b>Store half</b>	$\text{Mem}[502+\text{Regs}[\text{R2}]] \leftarrow_{16} \text{Regs}[\text{R3}]_{48\dots63}$
<b>SB R2, 41(R3)</b>	<b>Store byte</b>	$\text{Mem}[41 + \text{Regs}[\text{R3}]] \leftarrow_8 \text{Regs}[\text{R2}]_{56\dots63}$

8 bytes = 64 bit = Double Word

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# MIPS64 Instructions:

## Integer Arithmetic/Logical

**DADDU R1, R2, R3**    Add unsigned     $\text{Regs}[R1] \leftarrow \text{Regs}[R2] + \text{Regs}[R3]$

**DADDI R1, R2, #3**    Add immediate     $\text{Regs}[R1] \leftarrow \text{Regs}[R2] + 3$

**LUI R1, #42**    Load upper immediate     $\text{Regs}[R1] \leftarrow 0^{32} \text{\#}\#42 \text{\#}\# 0^{16}$

**DSLL R1, R2, #5**    Shift left logical     $\text{Regs}[R1] \leftarrow \text{Regs}[R2] \ll 5$

**DSLT R1, R2, R3**    Set less than    if ( $\text{regs}[R2] < \text{Regs}[R3]$ )  
 $\text{Regs}[R1] \leftarrow 1$  else  $\text{Regs}[R1] \leftarrow 0$

# MIPS64 Instructions:

## Control-Flow

<b>J name</b>	<b>Jump</b>	$PC_{36..63} \leftarrow \text{name}$
<b>JAL name</b>	<b>Jump and link</b>	$\text{Regs}[31] \leftarrow PC+4; PC_{36..63} \leftarrow \text{name};$ $((PC+4) - 2^{27}) \leq \text{name} < ((PC + 4) + 2^{27})$
<b>JALR R2</b>	<b>Jump and link register</b>	$\text{Regs}[R31] \leftarrow PC+4; PC \leftarrow \text{Regs}[R2]$
<b>JR R3</b>	<b>Jump register</b>	$PC \leftarrow \text{Regs}[R3]$
<b>BEQZ R4, name</b>	<b>Branch equal zero</b>	<b>if (Regs[R4] == 0) PC ← name;</b> $((PC+4) - 2^{17}) \leq \text{name} < ((PC+4) + 2^{17})$
<b>+ BEQ , BNE</b>		
<b>BNEZ R4, Name</b>	<b>Branch not equal zero</b>	<b>if (Regs[R4] != 0) PC ← name</b> $((PC+4) - 2^{17}) \leq \text{name} < ((PC + 4) + 2^{17})$
<b>MOVZ R1,R2,R3</b>	<b>Conditional move if zero</b>	<b>if (Regs[R3] == 0) Regs[R1] ← Regs[R2]</b>
	Condition Register	

Conditional instruction example

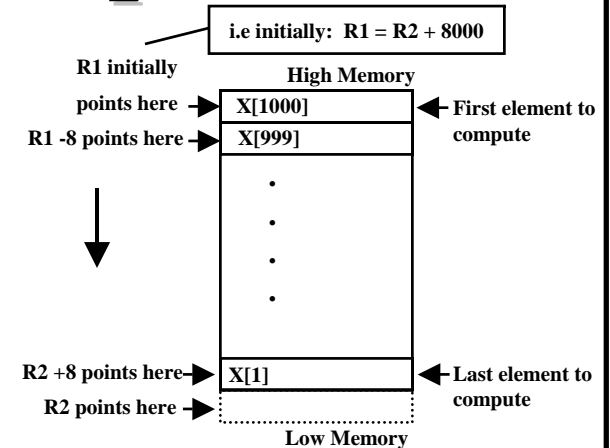
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# MIPS64 Loop Example

(with Floating Point Operations)

- For the loop:

```
for (i=1000; i>0; i=i-1)
    x[i] = x[i] + s;
```



The straightforward MIPS64 assembly code is given by:

Loop: L.D	F0, 0 (R1)	;F0=array element
ADD.D	F4, F0, F2	;add scalar in F2 (constant S)
S.D	F4, 0(R1)	;store result
DADDUI	R1, R1, # -8	;decrement pointer 8 bytes
BNE	R1, R2, Loop	;branch R1!=R2

i.e. initially:  $R1 = R2 + 8000$

R1 is initially the address of the element with highest address.  
 $8(R2)$  is the address of the last element to operate on.

Instructions before the loop to initialize R1, R2 not shown here

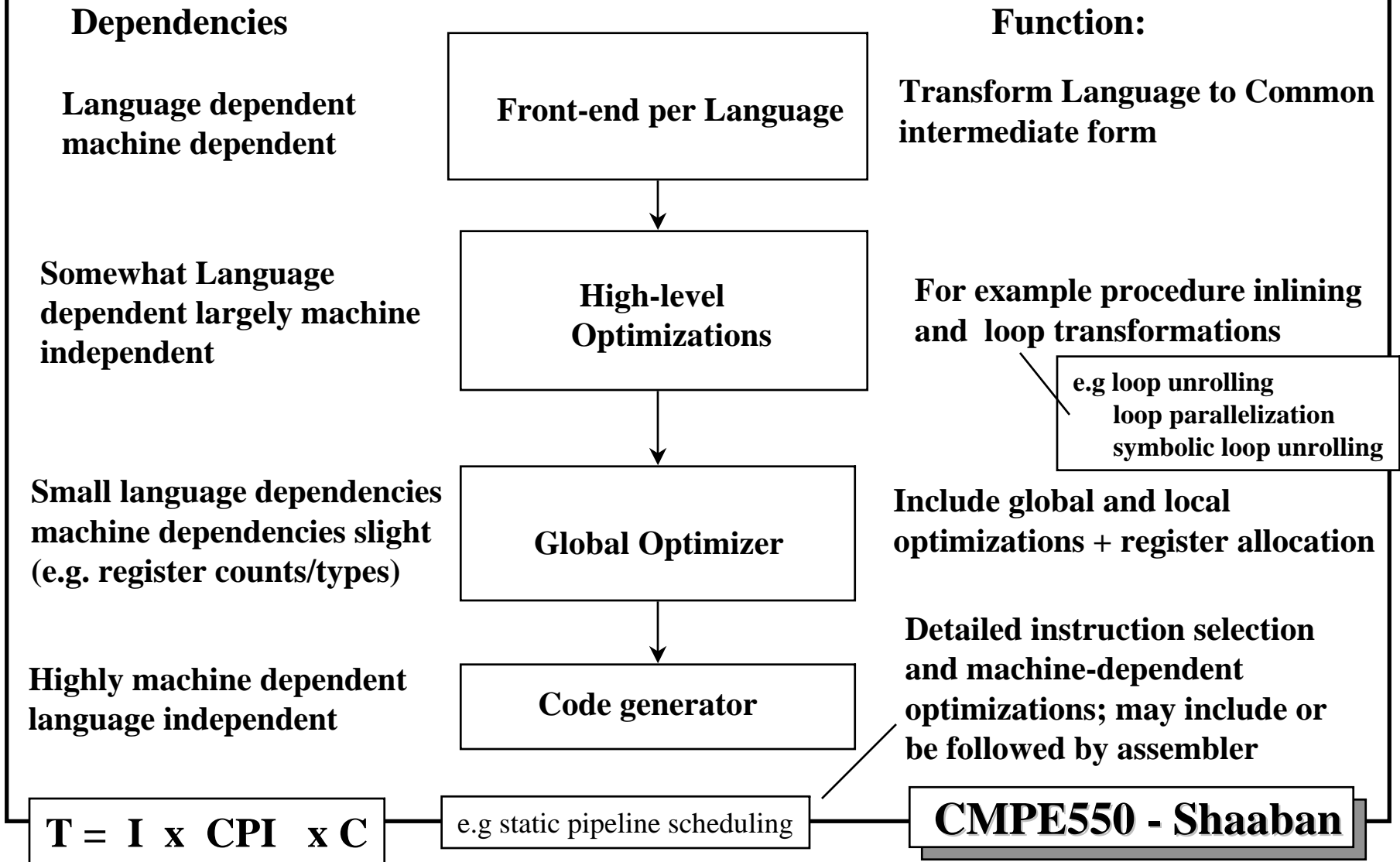
X[ ] array of double-precision floating-point numbers (8-bytes each)

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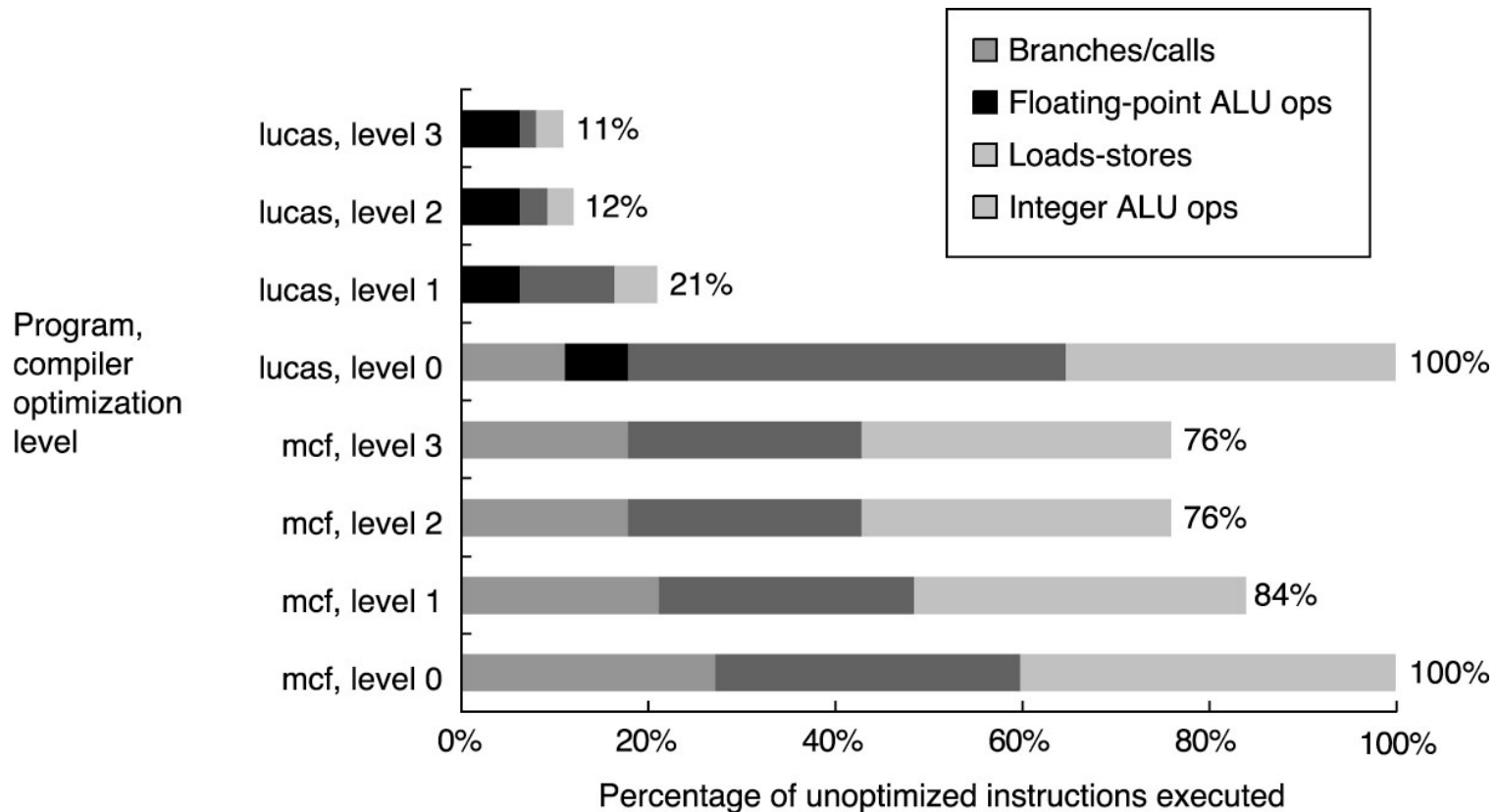
(Example from Chapter 2.2, will use later to illustrate loop unrolling)

# The Role of Compilers

## The Structure of Recent Compilers:



# Compiler Optimization and Executed Instruction Count



Change in instruction count executed (I) for the programs lucas and mcf from SPEC2000 as compiler optimizations vary.

$$T = I \times \text{CPI} \times C$$

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