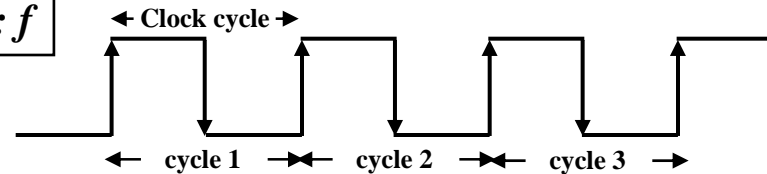


CPU Performance Evaluation: Cycles Per Instruction (CPI)

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

where: Clock rate = $1 / \text{clock cycle}$

$$f = 1/C$$



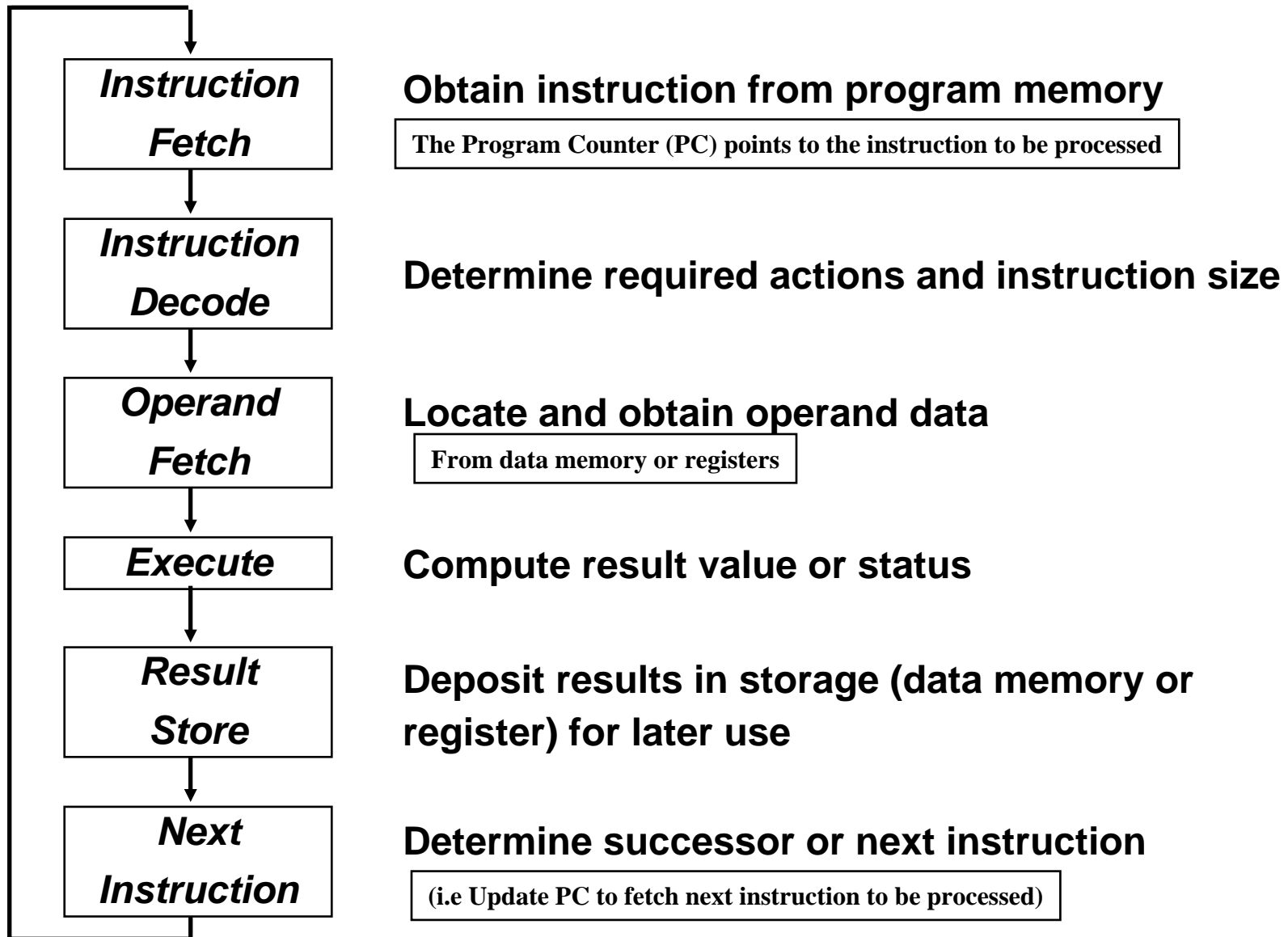
- The CPU clock rate depends on the specific CPU organization (design) and hardware implementation technology (VLSI) used.
- A computer machine (ISA) instruction is comprised of a number of elementary or micro operations which vary in number and complexity depending on the the instruction and the exact 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.
- Thus: A single machine instruction may take one or more CPU cycles to complete termed as the Cycles Per Instruction (CPI). Instructions Per Cycle = IPC = $1/\text{CPI}$
- Average (or effective) CPI of a program: The average CPI of all instructions executed in the program on a given CPU design.

4th Edition: Chapter 1 (1.4, 1.7, 1.8)
3rd Edition: Chapter 4

Cycles/sec = Hertz = Hz
MHz = 10^6 Hz GHz = 10^9 Hz

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Generic CPU Machine Instruction Processing Steps



CPI = Cycles per instruction

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Computer Performance Measures: Program Execution Time

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

- The total executed instruction count of the program. I
- The average number of cycles per instruction (average CPI). CPI
- Clock cycle of machine “A” C Or effective CPI

- How can one measure the performance of this machine (CPU) running this program?

- Intuitively the machine (or CPU) 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:

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

Programs/second ———— Seconds/program

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

$$\begin{aligned} \text{Speedup} &= \text{Performance}_A / \text{Performance}_B = \text{Execution Time}_B / \text{Execution Time}_A \\ &= 10 / 1 = 10 \end{aligned}$$

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.

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
- The average instruction executed takes a number of *cycles per instruction (CPI)* to be completed.
 - Measured in: cycles/instruction, **CPI**
- CPU has a fixed clock cycle time $C = 1/\text{clock rate}$
 - Measured in: seconds/cycle
- CPU execution time is the product of the above three parameters as follows:

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

$$C = 1/f$$

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

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

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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CPU Average CPI/Execution Time

For a given program executed on a given machine (CPU):

$$\text{CPI} = \frac{\text{Total program execution cycles}}{\text{Instructions count Executed}}$$

(i.e average or effective CPI)

$$\rightarrow \text{CPU clock cycles} = \text{Instruction count} \times \text{CPI}$$

$$\begin{aligned} \text{CPU execution time} &= \text{Instruction count} \times \text{CPI} \times \text{Clock cycle} \\ &= \text{CPU clock cycles} \times \text{Clock cycle} \\ &= \text{Instruction count} \times \text{CPI} \times \text{Clock cycle} \\ \mathbf{T} &= \mathbf{I} \times \mathbf{CPI} \times \mathbf{C} \end{aligned}$$

execution Time
per program in seconds

Number of
instructions executed

Average
or effective
CPI for
program

CPU Clock Cycle

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

CPI = Cycles Per Instruction

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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 = $C = 5 \times 10^{-9}$ seconds)
i.e 5 nanoseconds
- What is the execution time for this program:

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

$$\begin{aligned} \text{CPU time} &= \text{Instruction count} \times \text{CPI} \times \text{Clock cycle} \\ &= 10,000,000 \times 2.5 \times 1 / \text{clock rate} \\ &= 10,000,000 \times 2.5 \times 5 \times 10^{-9} \\ &= 0.125 \text{ seconds} \end{aligned}$$

Nanosecond = nsec = ns = 10^{-9} second
MHz = 10^6 Hz

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

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Factors Affecting CPU Performance

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

T	=	I	x	CPI	x	C
		Instruction Count		Cycles per Instruction		Clock Rate (1/C)
Program						
Compiler						
Instruction Set Architecture (ISA)						
Organization (CPU Design)						
Technology (VLSI)						

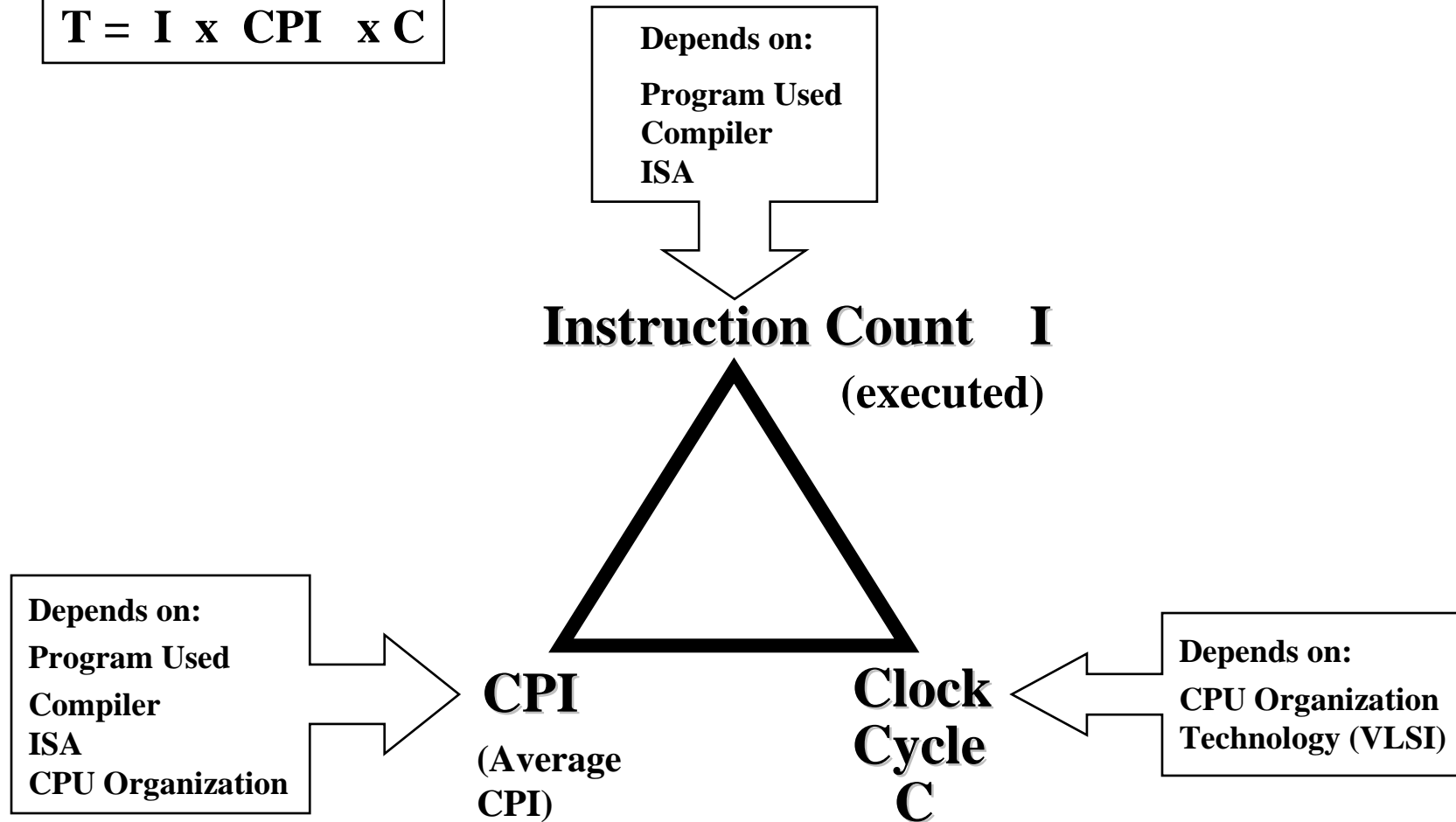
$$T = I \times \text{CPI} \times C$$

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Aspects of CPU Execution Time

CPU Time = Instruction count executed x CPI x Clock cycle

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



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Performance Comparison: Example

- From the previous example: A Program is running on a specific machine (CPU) 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. Thus: $C = 1/(200 \times 10^6) = 5 \times 10^{-9}$ seconds
- Using the same program with these changes:
 - A new compiler used: New executed instruction count, I: 9,500,000
New CPI: 3.0
 - Faster CPU implementation: New clock rate = 300 MHz Thus: $C = 1/(300 \times 10^6) = 3.33 \times 10^{-9}$ seconds
- What is the speedup with the changes?

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

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

$$\text{Clock Cycle} = C = 1/ \text{Clock Rate}$$

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

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Instruction Types & 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 $_i$ executed

CPI_i = Cycles per instruction for type $_i$

e.g ALU, Branch etc.

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

Depends on CPU Design

Then:

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

i.e average or effective CPI

Executed

Where:

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

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

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

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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

e.g ALU, Branch etc. ———

For a specific CPU design

- Two code sequences have the following instruction counts:

Program	Instruction counts for instruction class		
Code Sequence	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

i.e average or effective CPI

$$= 10 / 5 = 2$$

- CPU cycles for sequence 2 = $4 \times 1 + 1 \times 2 + 1 \times 3 = 9$ cycles

CPI for sequence 2 = $9 / 6 = 1.5$

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

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

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Instruction Frequency & CPI

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

C_i = Count of instructions of type $_i$ executed

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

CPI_i = Average cycles per instruction of type $_i$

F_i = Frequency or fraction of instruction type $_i$ 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 $i = \frac{CPI_i \times F_i}{CPI}$

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

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Instruction Type Frequency & CPI: A RISC Example

Program Profile or Executed Instructions Mix

Base Machine (Reg / Reg)

Depends on CPU Design

Op	Freq, F_i	CPI_i	$CPI_i \times F_i$	% Time
ALU	50%	1	.5	23% = $.5/2.2$
Load	20%	5	1.0	45% = $1/2.2$
Store	10%	3	.3	14% = $.3/2.2$
Branch	20%	2	.4	18% = $.4/2.2$

Given

Typical Mix

Sum = 2.2

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

i.e average or effective CPI

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

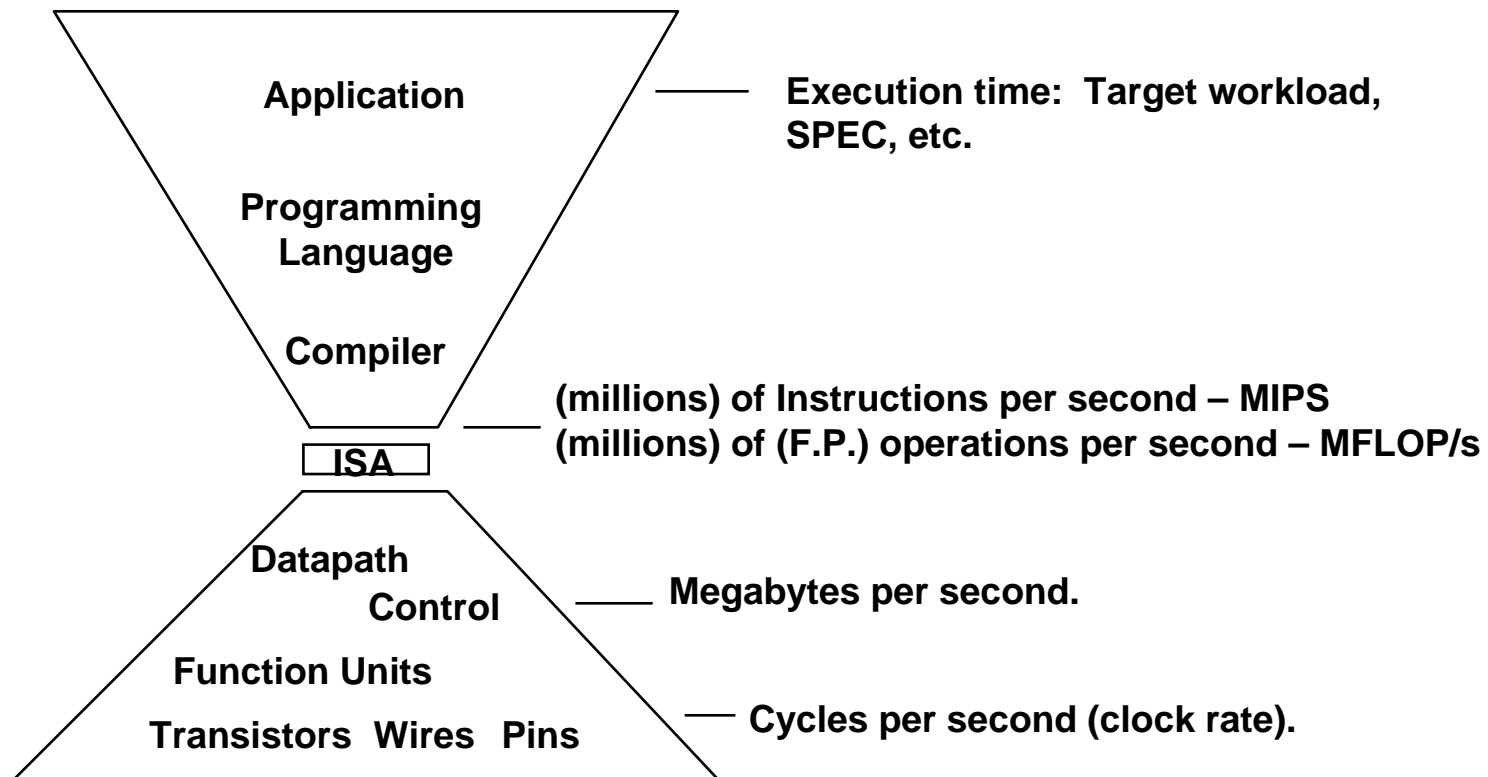
$$= .5 + 1 + .3 + .4$$

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

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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.

Types of Benchmarks

Pros

Cons

- Representative

Actual Target Workload

- Very specific.
- Non-portable.
- Complex: Difficult to run, or measure.

- Portable.
- Widely used.
- Measurements useful in reality.

Full Application Benchmarks

- Less representative than actual workload.

- Easy to run, early in the design cycle.

Small "Kernel"
Benchmarks

- Easy to "fool" by designing hardware to run them well.

- Identify peak performance and potential bottlenecks.

Microbenchmarks

- Peak performance results may be a long way from real application performance

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SPEC: System Performance Evaluation Corporation

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

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, ijpeg, 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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SPEC95 Programs

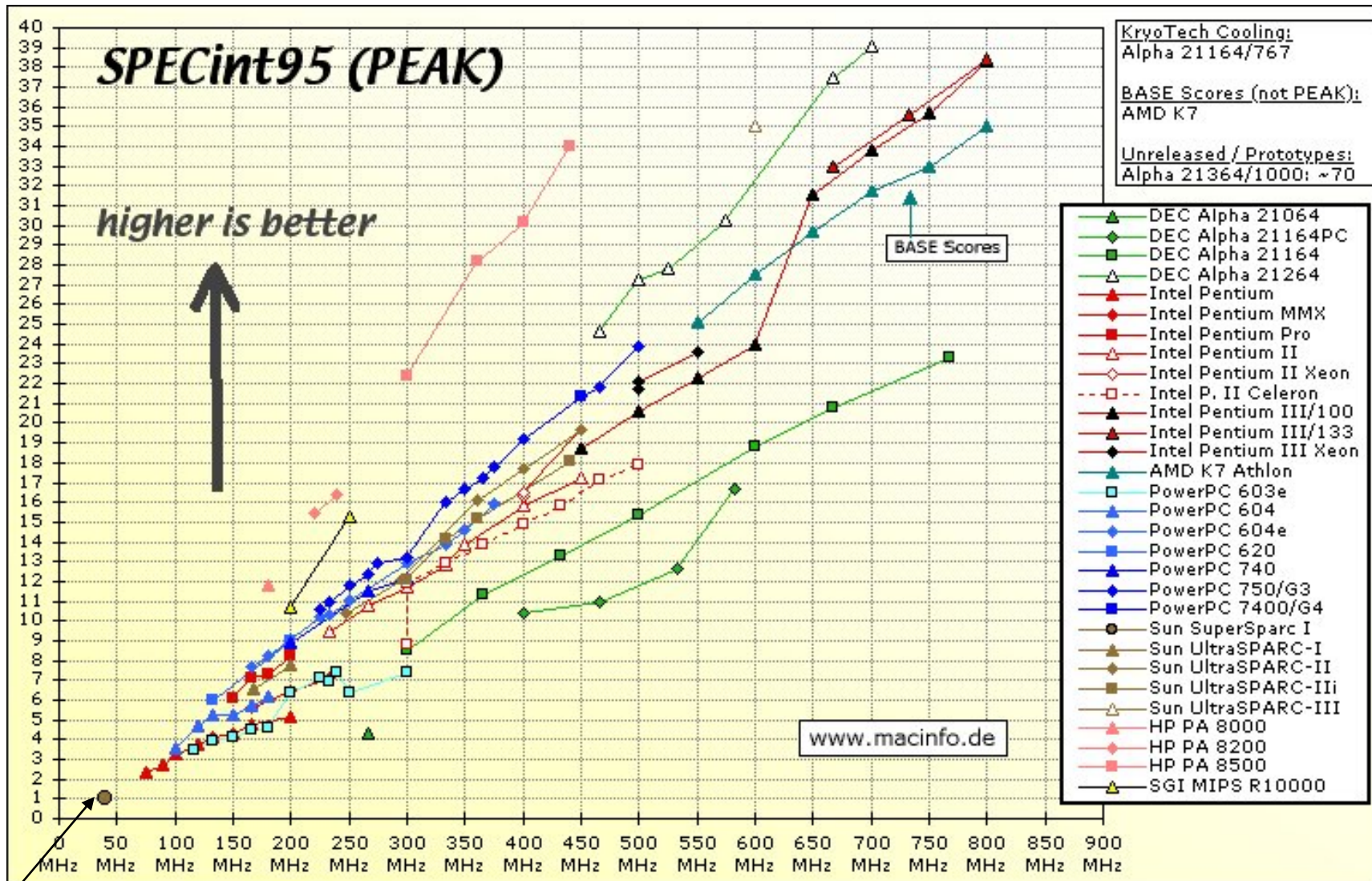
Programs application domain: Engineering and scientific computation

	Benchmark	Description
Integer	go	Artificial intelligence; plays the game of Go
	m88ksim	Motorola 88k chip simulator; runs test program
	gcc	The Gnu C compiler generating SPARC code
	compress	Compresses and decompresses file in memory
	li	Lisp interpreter
	jpeg	Graphic compression and decompression
	perl	Manipulates strings and prime numbers in the special-purpose programming language Perl
	vortex	A database program
Floating Point	tomcatv	A mesh generation program
	swim	Shallow water model with 513 x 513 grid
	su2cor	quantum physics; Monte Carlo simulation
	hydro2d	Astrophysics; Hydrodynamic Navier Stokes equations
	mgrid	Multigrid solver in 3-D potential field
	applu	Parabolic/elliptic partial differential equations
	trub3d	Simulates isotropic, homogeneous turbulence in a cube
	apsi	Solves problems regarding temperature, wind velocity, and distribution of pollutant
	fpppp	Quantum chemistry
	wave5	Plasma physics; electromagnetic particle simulation

Resulting Performance relative to a Sun SuperSpark I (50 MHz) which is given a score of SPECint95 = SPECfp95 = 1

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Sample SPECint95 (Integer) Results



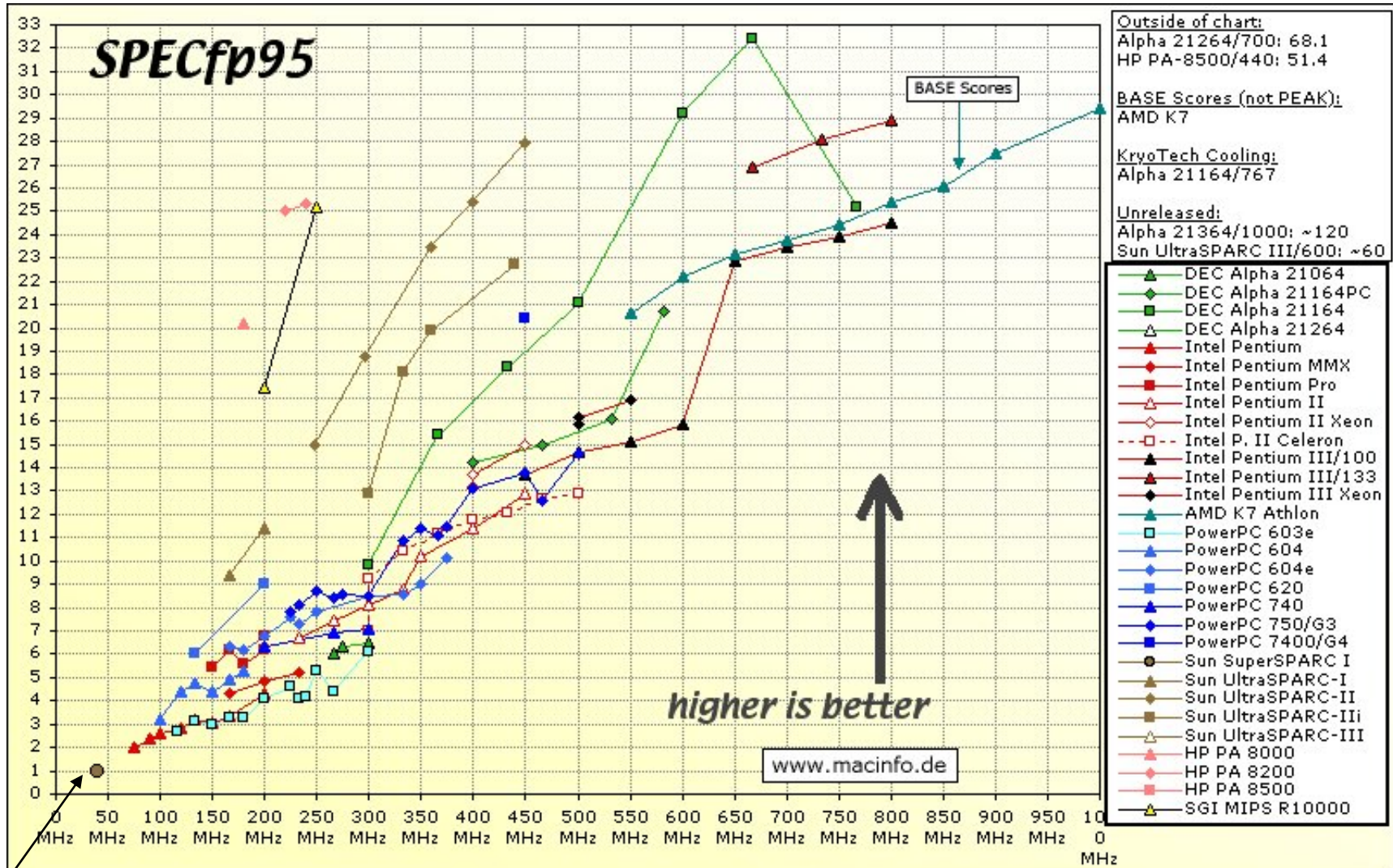
Source URL: <http://www.macinfo.de/bench/specmark.html>

Sun SuperSparc I (50 MHz) score = 1

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

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Sample SPECfp95 (Floating Point) Results



Source URL: <http://www.macinfo.de/bench/specmark.html>

Sun SuperSpark I (50 MHz) score = 1

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

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SPEC CPU2000 Programs

	Benchmark	Language	Descriptions
CINT2000 (Integer) 11 programs	164.zip	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
CFP2000 (Floating Point) 14 programs	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

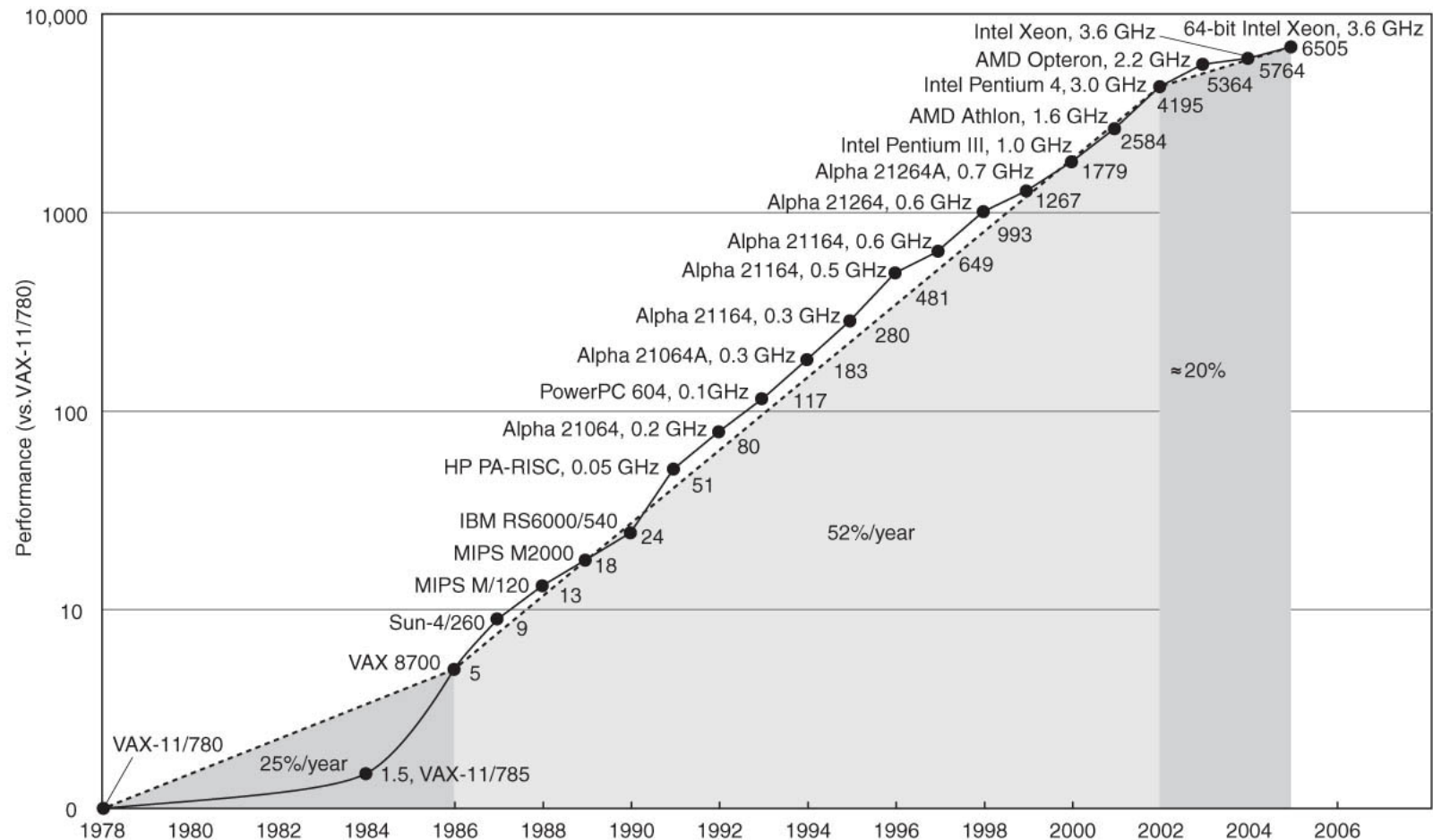
Programs application domain: Engineering and scientific computation

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

Integer SPEC CPU2000 Microprocessor Performance 1978-2006

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



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Top 20 SPEC CPU2000 Results (As of March 2002)

Top 20 SPECint2000

Top 20 SPECfp2000

#	MHz	Processor	int peak	int base	MHz	Processor	fp peak	fp base
1	1300	POWER4	814	790	1300	POWER4	1169	1098
2	2200	Pentium 4	811	790	1000	Alpha 21264C	960	776
3	2200	Pentium 4 Xeon	810	788	1050	UltraSPARC-III Cu	827	701
4	1667	Athlon XP	724	697	2200	Pentium 4 Xeon	802	779
5	1000	Alpha 21264C	679	621	2200	Pentium 4	801	779
6	1400	Pentium III	664	648	833	Alpha 21264B	784	643
7	1050	UltraSPARC-III Cu	610	537	800	Itanium	701	701
8	1533	Athlon MP	609	587	833	Alpha 21264A	644	571
9	750	PA-RISC 8700	604	568	1667	Athlon XP	642	596
10	833	Alpha 21264B	571	497	750	PA-RISC 8700	581	526
11	1400	Athlon	554	495	1533	Athlon MP	547	504
12	833	Alpha 21264A	533	511	600	MIPS R14000	529	499
13	600	MIPS R14000	500	483	675	SPARC64 GP	509	371
14	675	SPARC64 GP	478	449	900	UltraSPARC-III	482	427
15	900	UltraSPARC-III	467	438	1400	Athlon	458	426
16	552	PA-RISC 8600	441	417	1400	Pentium III	456	437
17	750	POWER RS64-IV	439	409	500	PA-RISC 8600	440	397
18	700	Pentium III Xeon	438	431	450	POWER3-II	433	426
19	800	Itanium	365	358	500	Alpha 21264	422	383
20	400	MIPS R12000	353	328	400	MIPS R12000	407	382

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>

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.hmmer	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

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)

Description	Name	I	CPI	C	T	Reference Time (seconds)	Score (speedup)
		Instruction Count × 10 ⁹	CPI	Clock cycle time (seconds × 10 ⁹)	Execution Time (seconds)		
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 Base Processor a 296-MHz UltraSPARC II which is given a score of SPECint2006 = SPECfp2006 = 1

T on base processor

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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.

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

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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)

Compiler Variations, MIPS & Performance: An Example

- For a machine (CPU) with instruction classes:

Instruction class	CPI
A	1
B	2
C	3

e.g ALU, Branch etc. ———

————— For a specific CPU design

- For a given high-level language program, two compilers produced the following executed 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.

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

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

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MIPS (The ISA not the metric) Loop Performance Example

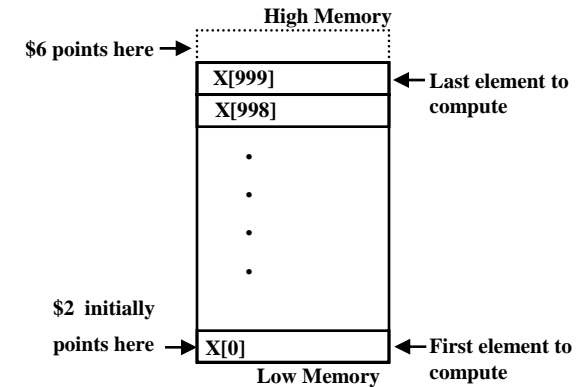
For the loop:

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

MIPS assembly code is given by:

```

        lw     $3, 0($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 (C = clock cycle = 2ns = 2x10⁻⁹ seconds) with following instruction type CPIs :

Instruction type	CPI
ALU	4
Load	5
Store	7
Branch	3

For this MIPS code running on this CPU find:

- 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

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MIPS (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 $CPI_{Branch} = 3$ $Fraction_{Branch} = F_{Branch} = 1000/5002 = 0.2 = 20\%$

$$2 \text{ CPU clock cycles} = \sum_{i=1}^n (CPI_i \times C_i)$$

$$= 2001 \times 4 + 1001 \times 5 + 1000 \times 7 + 1000 \times 3 = 23009 \text{ cycles}$$

$$3 \text{ Average CPI} = \text{CPU clock cycles} / I = 23009/5002 = 4.6$$

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

$$5 \text{ Execution time} = I \times CPI \times C = \text{CPU cycles} \times C = 23009 \times 2 \times 10^{-9} =$$

$$= 4.6 \times 10^{-5} \text{ seconds} = 0.046 \text{ msec} = 46 \text{ usec}$$

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

- 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 = $\text{Clock rate} / (CPI_{Branch} \times 10^6) = 500/3 = 166.67 \text{ MIPS}$

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.

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:

i.e using some enhancement

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

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

Before Enhancement

After Enhancement

Here: Task = Program

Recall: Performance = 1 / Execution Time

Performance Enhancement Calculations: Amdahl's Law

- The 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 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:

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

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:

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

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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%	CPI = 2.2
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 = $1 - F = 100\% - 45\% = 55\%$ or $.55$

Factor of enhancement = $S = 5/2 = 2.5$

Using Amdahl's Law:

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

An Alternative Solution Using CPU Equation

Op	Freq	Cycles	CPI(i)	% Time	
ALU	50%	1	.5	23%	CPI = 2.2
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 of load is now 2 instead of 5

New CPI = $.5 \times 1 + .2 \times 2 + .1 \times 3 + .2 \times 2 = 1.6$

$$\text{Speedup}(E) = \frac{\text{Original Execution Time}}{\text{New Execution Time}} = \frac{\cancel{\text{Instruction count}} \times \text{old CPI} \times \cancel{\text{clock cycle}}}{\cancel{\text{Instruction count}} \times \text{new CPI} \times \cancel{\text{clock cycle}}}$$

$$= \frac{\text{old CPI}}{\text{new CPI}} = \frac{2.2}{1.6} = 1.37$$

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

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

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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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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?

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

$$\rightarrow \text{Execution time with enhancement} = 100/5 = 20 \text{ seconds}$$

$$20 \text{ seconds} = (100 - 80 \text{ seconds}) + 80 \text{ seconds} / s$$

$$20 \text{ seconds} = 20 \text{ seconds} + 80 \text{ seconds} / s$$

$$\rightarrow 0 = 80 \text{ seconds} / s$$

No amount of multiplication speed improvement can achieve this.

Extending Amdahl's Law To Multiple Enhancements

n enhancements each affecting a different portion of execution time

- 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:

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

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

Unaffected fraction \nearrow

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

What if the fractions given are after the enhancements were applied? How would you solve the problem? (i.e find expression for speedup)

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

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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:

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

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

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

$$\text{Percentage}_2 = F_2 = 15\%$$

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

$$\text{Percentage}_3 = F_3 = 10\%$$

- 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?

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

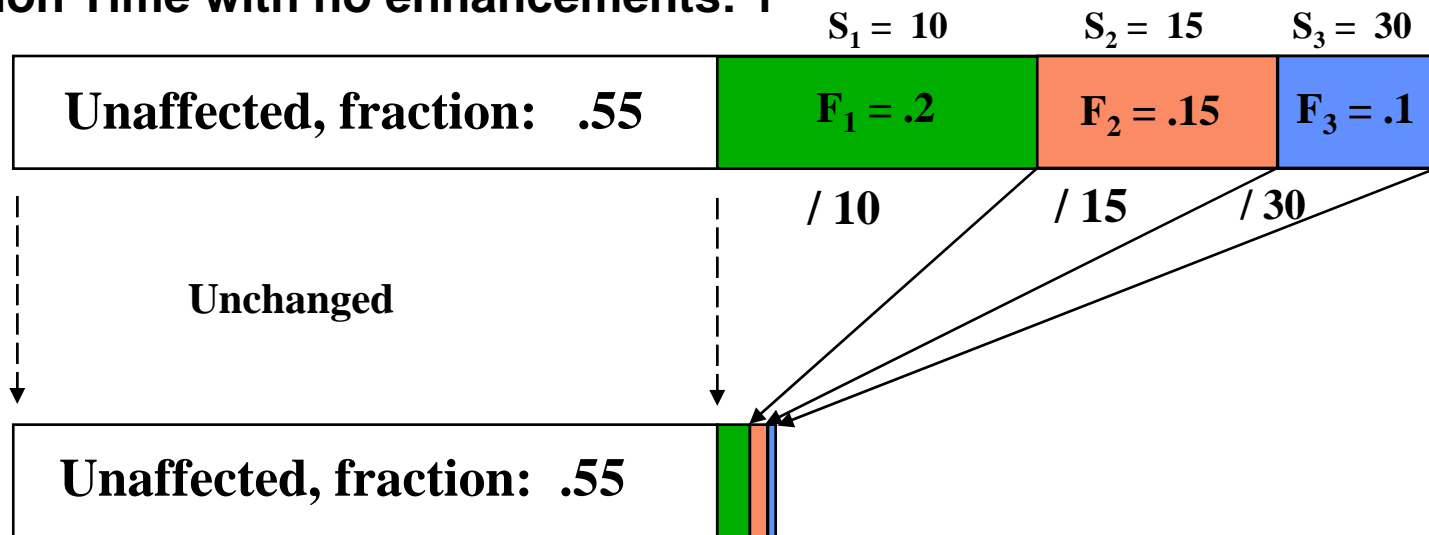
- $$\begin{aligned} \text{Speedup} &= 1 / [(1 - .2 - .15 - .1) + .2/10 + .15/15 + .1/30] \\ &= 1 / [.55 + .0333] \\ &= 1 / .5833 = 1.71 \end{aligned}$$

Pictorial Depiction of Example

Before:

Execution Time with no enhancements: 1

i.e normalized to 1



After:

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

Speedup = $1 / .5833 = 1.71$

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.

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“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

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

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:

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

Find original fractions?

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