The Microprocessor Revolution

- Mainframe / Scalar Supercomputer
  - CPU consists of multiple components
  - performance improving at 20-35% p.a.
  - often ECL or other exotic technology
  - huge I/O and memory bandwidth

- Microprocessors
  - usually a single CMOS part
  - performance improving at 35-50% p.a.
  - enabled through improvements in fabrication technology

– huge investment

– physical advantages of smaller size

– General Purpose Processors

  * desktop / server

  * SMP / Parallel supercomputers

– Embedded controllers / SoCs

– DSPs / Graphics Processors

Developments in CMOS

- Fabrication line size reduction
  - 0.8μ, 0.5, 0.35, 0.25, 0.18, 0.15, *0.13*, *0.09*
  - 10-20% reduction p.a.
  - switching delay reduces with line size

    $\rightarrow$ increases in clock speed

    - $*$ Pentium 66Mhz @ 0.8μ, 150Mhz @ 0.6μ, 233MHz @ 0.35μ
  - density increases at square of 1/line size
- Die size increases at 10-29% p.a.

$\Rightarrow$ Transistor count increase at 55% p.a.

- enables architectural jumps
- 8, 16, 32, 64, *128* bit ALUs
- large caches
  * PA-8500: 1.5MB on-chip
- new functional units (e.g. multiplier)
- duplicated functional units (multi-issue)
- whole System On a Chip (SoC)

Developments in DRAM Technology

- DRAM density
  - increases at 40-60% p.a.
  - equivalent to 0.5-1 address bits p.a.
  - cost dropping at same rate
    - 16M, 64M, *256M*, *1G*

- Consequences for processor architectures:

→ May not be able to address whole of memory from a single pointer

  - segmentation

$\rightarrow$ May run out of physical address bits

- banked (windowed) memory

- DRAM performance
  - just 35% latency improvement in 10 years!
  - new bus interfaces make more *sequential b/w* available
    - SDRAM, RAMBUS, DDR, DDR2

μprocessor Development Cycle

- Fabrication technology has huge influence on power and performance

$\rightarrow$ must use the latest fabrication process

- Full custom design *vs.* semi custom

- Keep development cycle short (3-4 years)
  - Non CMOS technology leads to complications

- Advance teams to research:
  - process characteristics

  - key circuit elements

  - packaging

  - floor plan

  - required performance

  - microarchitecture

  - investigate key problems

- Hope ISA features don't prove to be a handicap

- Keep up or die!

- Alpha architects planned for 1000x performance improvement over 25 years

Power Consumption

- Important for laptops, PDAs, mobile phones, set-top boxes, etc.
- 155W for Digital Alpha 21364 @ 1150MHz
- 130W for Itanium-2 @ 1500MHz
- 90W for AMD Opteron 148 @ 2GHz
- 81W for Pentium-IV @ 3GHz
- 12W for Intel Mobile Pentium M @ 1100Hz
- 420mW for Digital StrongArm @ 233MHz, 2.0V

- 130mW for Digital StrongArm @ 100MHz, 1.65V

- Smaller line size results in lower power
  - lower core voltage, reduced capacitance
  - greater integration avoids inter-chip signalling

- Reduce clock speed to scale power
  - $P = CV^2f$
  - may allow lower voltage
    - potential for cubic scaling
    - better than periodic HALTing

Performance per Watt

Dynamic Clock Gating

- Divide chip into a hundred or more clock zones,
- Only clock a zone when a clock cycle will change a registered value,
- Can save a factor of four power, even under heavy CPU load.

```
always @(posedge gated_clk) begin
        r1 <= a + b;
        r2 <= ...
        end

wire clock_needed = r1 != (a+b) || ... || ... ...;

CLOCKGATECELL g1(gated_clk, clk, clock_needed);
```

Cost and Price

- E.g.:
  - \$0.50: 8bit micro controller
  - \$3: XScale (ARM) (400MHz, 0.18μm, 20mm^2, 2.1M[1M])
  - \$500: Pentium IV Celeron (1.2GHz, 0.13μm, 131mm^2, 28M[4M])
  - \$150: Pentium IV (3.2GHz, 0.09μm, 180mm^2, 42M[7M])
  - \$2200: Itanium2 (1Ghz, 0.18μm, 421mm^2, 221M[15M])
- Costs influenced by die size, packaging, testing

- Large influence by manufacturing volume

- Costs reduce over product life (e.g. 40% p.a.)
  - Yield improves
  - Speed grade binning
  - Fab ‘shrinks’ and ‘steppings’

Compatibility

- 'Pin' Compatibility (second sourcing)

- Backwards Binary Compatibility
  - 8086, 80286, 80386, 80486, Pentium, Pentium Pro, Pentium II/III/IV, *Itanium*
  - NexGen, Cyrix, AMD, Transmeta
  - typically need to re-optimize

- Typically hard to change architecture
  - Users have huge investment in s/w
  - Binary translators e.g. FX!32, WABI

    * typically interface to native OS
  - Need co-operation from s/w vendors
    * multi-platform support costs $'s
  - Most computer sales are upgrades

- Platform independence initiatives
  - Source, p-Code, JAVA bytecode, .NET

Compatibility is very important

Performance Measurement

- Try before you buy! (often not possible)
- System may not even exist yet
  - use cycle-level simulation
- Real workloads often hard to characterize and measure improvements
  - especially interactive
- Marketing hype
  - MHz, MIPS, MFLOPS

- Algorithm kernels
  - Livermore Loops, Linpack
- Synthetic benchmarks
  - Dhrystones, Whetstones, iCOMP
- Benchmark suites
  - SPEC-INT, SPEC-FP, SPEC-HPC, NAS
- Application Benchmarks
  - TPC-C/H/R, SPECNFS, SPECWeb, Quake

Performance is application dependent

Standard Performance Evaluation Corporation

- SPEC is most widely used benchmark
  - processor manufactures
  - workstation vendors
- CPU INT / FP 89, 92, 95, 2000, (2004)
- Suite updated to reflect current workloads
- CINT95/2K: 8/12 integer C programs
- CFP95/2K: 10/14 floating point in C&Fortran

- measures:
  - processor
  - memory system
  - compiler
  - NOT OS, libc, disk, graphics, network

Choosing programs for SPEC2000

- More programs than SPEC95
- Bigger programs than SPEC95
  - Don't fit in on-chip caches
- Reflect some real workloads
- Run for several minutes
  - Amortize startup overhead & timing inaccuracies
- Not susceptible to trick transformations
  - Vendors invest huge s/w effort

- Fit in 256MB (95 was 64MB)
- Moving target...
- SPEC92, 95, 2K results not translatable

CINT95 suite (C)

099.go	An AI go-playing program
124.m88ksim	A chip simulator for the Motorola 88100
126.gcc	Based on the GNU C compiler version 2.5.3
129.compress	An in-memory version of the utility
130.li	Xlisp interpreter
132.ijpeg	De/compression on in-memory images
134.perl	An interpreter for the Perl language
147.vortex	An object oriented database

CFP95 suite (Fortran)

101.tomcatv	Vectorized mesh generation
102.swim	Shallow water equations
103.su2cor	Monte-Carlo method
104.hydro2d	Navier Stokes equations
107.mgrid	3d potential field
110.applu	Partial differential equations
125.turb3d	Turbulence modelling
141.apsi	Weather prediction
145.fpppp	Quantum chemistry
146.wave5	Maxwell's equations

SPEC reporting

- Time each program to run
- Reproduceability is paramount
  - Take mean of $\geq$ 3 runs
  - Full disclosure
- Baseline measurements
  - SPECint_base95
  - Same compiler optimizations for whole suite
- Peak measurements

- SPECint95
- Each benchmark individually tweaked
- Unsafe optimizations can be enabled!

- Rate measurements for multiprocessors
  - SPECint_rate95, SPECfp_rate95
  - time for N copies to complete x N

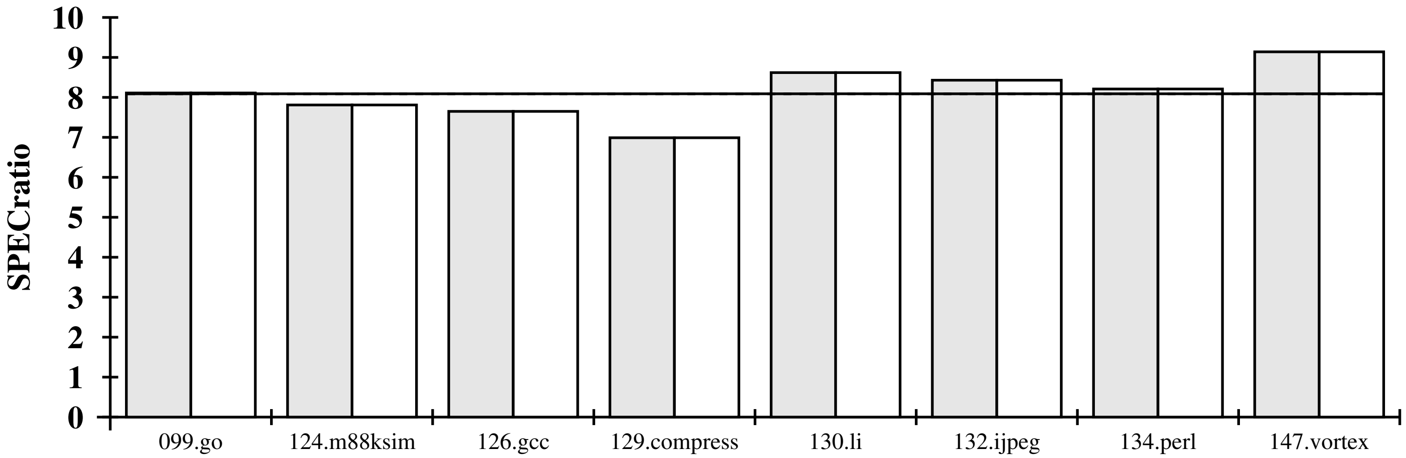
Totalling Results

- How to present results?
  - Present individual results?
  - Arithmetic mean?
  - Weighted harmonic mean?
  - SPEC uses Geometric mean, normalised against a reference platform
    - allows normalization before or after mean
    - performance ratio can be predicted by dividing means
- SPEC95 uses Sun SS10/40 as reference platform

Intel Corporation
Alder System (200MHz, 256KB L2)

SPECint_base95 = 8.09

SPEC license # 14	Tested By: Intel	Test Date: Oct-95	Hardware Avail: May-96	Software Avail: Feb-96



Hardware/Software Configuration for:
Alder System (200MHz, 256KB L2)

Hardware

Model Name:	Alder
CPU:	200MHz Pentium Pro Processor
FPU:	Integrated
Number of CPU(s):	1
Primary Cache:	8KBI+8KBD
Secondary Cache:	256KB(I+D)
Other Cache:	None
Memory:	128MB (60ns fast page)
Disk Subsystem:	2GB ST32550W
Other Hardware:	AHA-2940W Controller

Software

Operating System:	UnixWare 2.0, SDK
Compiler:	Intel C Reference Compiler 2.2 Beta
File System:	ufs, vxfs (/tmp as 8MB /tmpfs)
System State:	Single user (root + killall)

Benchmark # and Name	Reference Time	Base Run Time	Base SPEC Ratio	Run Time	SPEC Ratio
099.go	4600	567	8.11	567	8.11
124.m88ksim	1900	243	7.81	243	7.81
126.gcc	1700	222	7.65	222	7.65
129.compress	1800	258	6.99	258	6.99
130.li	1900	220	8.62	220	8.62
132.ijpeg	2400	285	8.43	285	8.43
134.perl	1900	232	8.21	232	8.21
147.vortex	2700	295	9.14	295	9.14
SPECint_base95 (G. Mean)			8.09		
		SPECint95 (G. Mean)			8.09

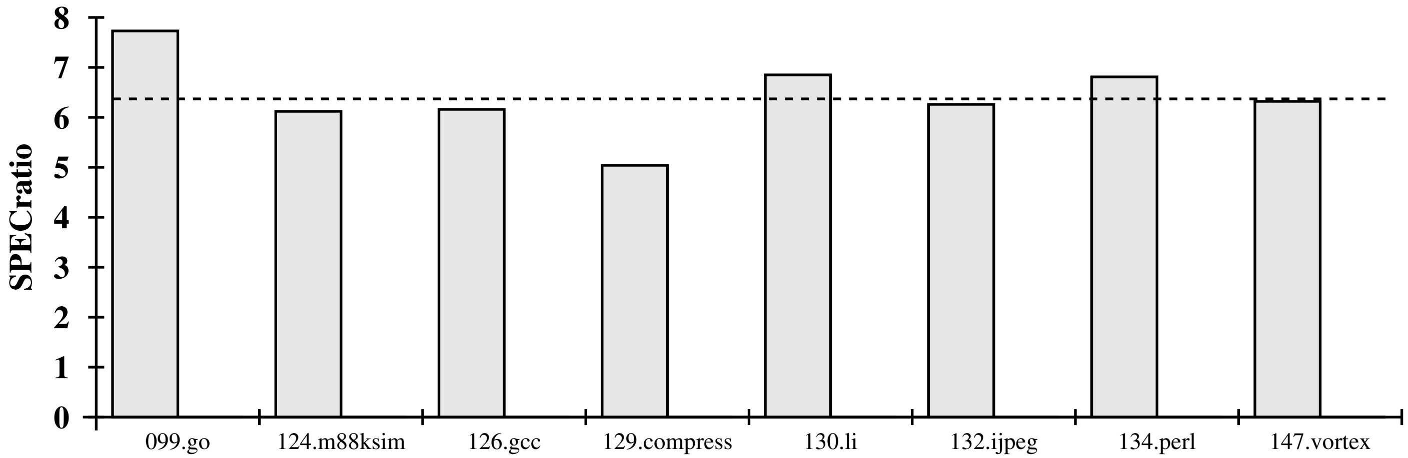
Notes/Tuning Information

```
Base and non-base flags are the same and use Feedback Directed Optimization
Pass1: -tp p6 -ipo -xi -prof_gen -ircdb_dir /tmp/IRCDB
Pass2: -tp p6 -ipo -xi -prof_use -ircdb_dir /tmp/IRCDB
-ircdb_dir is a location flag and not an optimization flag
Portability: 124: -DSYSV -DLEHOST 130, 134, 147: -lm  132: -DSYSV  126: -lm -lc -L/usr/ucblib -lucb -lmalloc
Memory subsystem is four-way interleaved.
```

Pentium Pro 200

SPECint_base95 = 6.37

SPEC license # 1178	Tested By: Ian Pratt, CUCL	Test Date: Date	Hardware Avail: Date	Software Avail: Date



Hardware/Software Configuration for:
Pentium Pro 200

Hardware

Model Name: Intel 440LX
CPU: Pentium Pro 200
FPU:
Number of CPU(s): 1
Primary Cache: 8KB+8KB
Secondary Cache: 256KB
Other Cache:
Memory: 128MB
Disk Subsystem: 4GB
Other Hardware:

Software

Operating System: Linux 20.0.30
Compiler: gcc 2.7.2p
File System: ext2
System State: multiuser

Benchmark # and Name	Reference Time	Base Run Time	Base SPEC Ratio	Run Time	SPEC Ratio
099.go	4600	595	7.73	--	--
124.m88ksim	1900	310	6.12	--	--
126.gcc	1700	276	6.16	--	--
129.compress	1800	357	5.04	--	--
130.li	1900	277	6.85	--	--
132.ijpeg	2400	384	6.26	--	--
134.perl	1900	279	6.81	--	--
147.vortex	2700	427	6.32	--	--
SPECint_base95 (G. Mean)			6.37		
		SPECint95 (G. Mean)			--

Notes/Tuning Information

```
Portability flags were:
Baseline flags were: -O2 -fomit-frame-pointer
Nonbase flags were:
```

CINT2000 Result

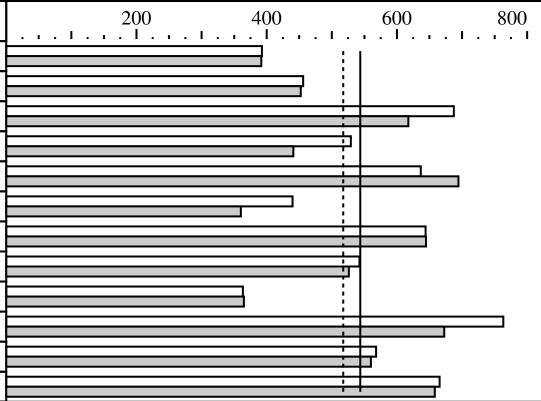
Compaq Computer Corporation
AlphaServer ES40 Model 6/833

SPECint2000 = 544

SPECint_base2000 = 518

SPEC license #: 2	Tested by: Compaq NH	Test date: Oct-2000	Hardware Avail: Jan-2001	Software Avail: Nov-2000

Benchmark	Reference Time	Base Runtime	Base Ratio	Runtime	Ratio
164.gzip	1400	358	392	357	393
175.vpr	1400	309	452	307	456
176.gcc	1100	178	617	160	687
181.mcf	1800	408	441	340	529
186.crafty	1000	144	694	157	637
197.parser	1800	500	360	409	440
252.eon	1300	202	645	202	644
253.perlbmk	1800	342	526	332	543
254.gap	1100	301	365	303	363
255.vortex	1900	282	673	249	763
256.bzip2	1500	268	560	264	568
300.twolf	3000	456	658	451	666



Hardware

CPU:	Alpha 21264B
CPU MHz:	833
FPU:	Integrated
CPU(s) enabled:	1
CPU(s) orderable:	1 to 4
Parallel:	No
Primary Cache:	64KB(I)+64KB(D) on chip
Secondary Cache:	8MB off chip
L3 Cache:	None
Other Cache:	None
Memory:	16GB
Disk Subsystem:	1x8GB BD0096349A
Other Hardware:	Ethernet

Software

Operating System:	Tru64 UNIX V5.1 + Patch Kit 1 libc
Compiler:	Compaq C V6.3-129-44A8I Compaq C++ V6.2-033-4298H
File System:	AdvFS
System State:	Multi-user

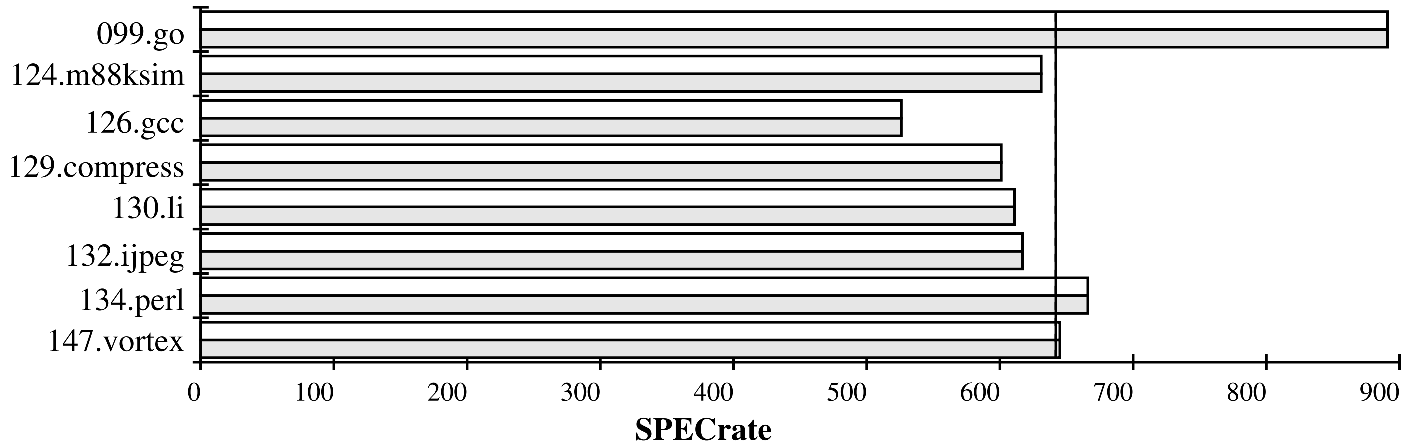
Notes/Tuning Information

```
Baseline C  : cc  -arch ev6 -fast GEMFB ONESTEP
         C++: cxx -arch ev6 -O2 ONESTEP

GEMFB: fdo_pre0     = mkdir /tmp/pb; rm -f /tmp/pb/${baseexe}*
       PASS1_CFLAGS = -prof_gen_noopt    -prof_dir /tmp/pb
       PASS2_CFLAGS = -prof_use_feedback -prof_dir /tmp/pb
       (base uses directory /tmp/pb; peak uses /tmp/pp)

SPIKEFB: fdo_post2  = spike -feedback ${baseexe} -o tmp ${baseexe};
                      mv tmp ${baseexe}
Peak: cc [except eon: cxx] -arch ev6 ONESTEP plus:
     164.gzip: -g3 -fast -O4 +GEMFB
      175.vpr: -g3 -fast -O4 +GEMFB
      176.gcc: -g3 -fast -O4 -xtaso_short +GEMFB
      181.mcf: -g3 -fast -xtaso_short +GEMFB
   186.crafty: -g3 -fast -O4 -inline speed
   197.parser: -g3 -fast -O4 -xtaso_short +GEMFB
      252.eon: -O2
  253.perlbmk: -g3 -fast +GEMFB +SPIKEFB
      254.gap: -g3 -fast -O4 +GEMFB
```

AlphaServer 8400 5/300

SPECint_rate_base95 = 642

SPEC license # 2	Tested By: Digital PKO	Test Date: Oct-95	Hardware Avail: Apr-95	Software Avail: Aug-95



Hardware/Software Configuration for:
AlphaServer 8400 5/300

Hardware

Model Name:	AlphaServer 8400 5/300
CPU:	300 MHz 21164
FPU:	Integrated
Number of CPU(s):	10
Primary Cache:	8KBI+8KBD on chip
Secondary Cache:	4MB
Other Cache:	none
Memory:	1GB
Disk Subsystem:	1 x 2GB 1 x 2GB
Other Hardware:	Ethernet

Software

Operating System:	Digital UNIX V3.2C (Rev 148)
Compiler:	DEC C V5.0-106
File System:	UFS
System State:	Multi User

Benchmark # and Name	Base Copies	Base Run Time	Base SPEC Ratio	Copies	Run Time	SPEC Ratio
099.go	10	464	891	10	464	891
124.m88ksim	10	271	631	10	271	631
126.gcc	10	291	526	10	291	526
129.compress	10	270	601	10	270	601
130.li	10	280	611	10	280	611
132.ijpeg	10	350	617	10	350	617
134.perl	10	257	666	10	257	666
147.vortex	10	377	645	10	377	645
SPECint_rate_base95 (G. Mean)			642			
		SPECint_rate95 (G. Mean)				642

Notes/Tuning Information

```
Baseline Optimizations: -O5 -ifo -non_shared -om
Portibility Flags: 124.m88ksim: -DLEHOST  134.perl: -DI_TIME
147.vortex: -D__RISC_64__

Compiler invokation: cc -migrate -std1 (DEC C with -std1 for strict ANSI)
```

Top SPEC2000 Results for each ISA

machine	processor	cpu MHz	cache sizes	int	fp
Intel D925	Pentium IV-X	3466	12*/8+512+2M	1772	1724
AMD/ASUS	Opteron150	2400	64/64+1M	1663	1849
Intel D925	Pentium IV	3600	12*/8+1M	1575	1630
HP rx4640	Itanium2	1600	16/16+256+6M	1590	2612
IBM p570	Power5+	1900	64/32+2M+(36M)	1453	2733
HP Alpha GS1280	21364	1300	64/64+(2M)	994	1684
Fujitsu	SPARC64-V	1350	128+128/2M	905	1340
Apple	PPC970 (G5)	2000	64/32+512	800	840
HP	Pentium-M	1000	32/32+1024	687	552
HP c3750	PA-8700	875	768/1.5M	678	674
SGI Orgin 3200	R14000	600	32/32+(8M)	500	529
HP rx4610	Itanium	800	16/16+96+(4M)	379	701

Selected SPEC95 Results

machine	processor	cpu MHz	cache sizes	int_base	fp_base
Sun SS10/40	SuprSP	40	20/16	1.00	1.00
Intel 440BX	Pentium II	300	16/16+(512)	12.2	8.4
Intel 440EX	Celeron A	300	16/16+128	11.3	8.3
Intel 440EX	Celeron	300	16/16	8.3	5.8
Compaq PC164LX	21164	533	8/8+96+(4M)	16.8	20.7
Compaq PC164SX	21164PC	533	16/16+(1M)	12.2	14.1
Intel 440BX	Pentium II	450	16/16+(512)	17.2	11.8
Intel 440BX	Pentium II	400	16/16+(512)	15.8	11.4
Intel 440BX	Pentium II	350	16/16+(512)	13.9	10.2
Intel 440BX	Pentium II	330	16/16+(512)	13.0	8.8
Intel 440BX	Pentium II	300	16/16+(512)	11.9	8.1
Intel 440BX	Pentium II	266	16/16+(512)	10.7	7.5
Intel 440BX	Pentium II	233	16/16+(512)	9.4	6.7
DEC 4100/5/400	A21164	400/75	8/8+96+4M	10.1	16.0
DEC 4100/5/400	2xA21164	400/75	8/8+96+4M	10.1	20.7
DEC 4100/5/400	4xA21164	400/75	8/8+96+4M	10.1	26.6
Intel XXpress	Pentium	200	8/8+1M	5.47	2.92
Intel Alder	PentPro	200	8/8+256	8.09	5.99

Comparing Implementations Summary

- Fabrication technology has a huge influence
- Exponential improvement in technology
- Processor for a product chosen on:
  - Instruction Set Compatibility
  - Power Consumption
  - Price
  - Performance
- Performance is application dependent

- Avoid MIPS, MHz
- Benchmark suites