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
  - $0.8\mu, 0.5, 0.35, 0.25, 0.18, 0.15, 0.13, 0.09$
  - 10-20% reduction p.a.
  - switching delay reduces with line size
    → increases in clock speed
      - Pentium 66Mhz @ 0.8$\mu$, 150Mhz @ 0.6$\mu$, 233MHz @ 0.35$\mu$
  - density increases at square of 1/line size

- Die size increases at 10-29% p.a.

⇒ 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
→ May run out of physical address bits
  
  – banked (windowed) memory

• DRAM performance
  
  – just 35% latency improvement in 10 years!
  
  – new bus interfaces make more \textit{sequential} \textit{b/w} available
    
    * SDRAM, RAMBUS, DDR, DDR2
μprocessor Development Cycle

- Fabrication technology has huge influence on power and performance

→ 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
  – \( P = CV^2 f \)
  – may allow lower voltage
    * potential for cubic scaling
    * better than periodic HALTing
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.

```verilog
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, 20mm², 2.1M[1M])
  - $500: Pentium IV Celeron
    (1.2GHz, 0.13μm, 131mm², 28M[4M])
  - $150: Pentium IV
    (3.2GHz, 0.09μm, 180mm², 42M[7M])
  - $2200: Itanium2
    (1Ghz, 0.18μm, 421mm², 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 \times 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

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

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Benchmark # and Name</th>
<th>Reference Time</th>
<th>Base Run Time</th>
<th>Base SPEC Ratio</th>
<th>Run Time</th>
<th>SPEC Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Name: Alder</td>
<td>099.go</td>
<td>4600</td>
<td>567</td>
<td>8.11</td>
<td>567</td>
<td>8.11</td>
</tr>
<tr>
<td>CPU: 200MHz Pentium Pro Processor</td>
<td>124.m88ksim</td>
<td>1900</td>
<td>243</td>
<td>7.81</td>
<td>243</td>
<td>7.81</td>
</tr>
<tr>
<td>FPU: Integrated</td>
<td>126.m88ksim</td>
<td>1700</td>
<td>222</td>
<td>7.65</td>
<td>222</td>
<td>7.65</td>
</tr>
<tr>
<td>Number of CPU(s): 1</td>
<td>129.compress</td>
<td>1800</td>
<td>258</td>
<td>6.99</td>
<td>258</td>
<td>6.99</td>
</tr>
<tr>
<td>Primary Cache: 8KB+8KBD</td>
<td>130.li</td>
<td>1900</td>
<td>220</td>
<td>8.62</td>
<td>220</td>
<td>8.62</td>
</tr>
<tr>
<td>Secondary Cache: 256KB(I+D)</td>
<td>132.ijpeg</td>
<td>2400</td>
<td>285</td>
<td>8.43</td>
<td>285</td>
<td>8.43</td>
</tr>
<tr>
<td>Other Cache: None</td>
<td>134.perl</td>
<td>1900</td>
<td>232</td>
<td>8.21</td>
<td>232</td>
<td>8.21</td>
</tr>
<tr>
<td>Memory: 128MB (60ns fast page)</td>
<td>147.vortex</td>
<td>2700</td>
<td>295</td>
<td>9.14</td>
<td>295</td>
<td>9.14</td>
</tr>
<tr>
<td>Disk Subsystem: 2GB ST32550W</td>
<td>SPECint_base95 (G. Mean) 8.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Hardware: AHA-2940W Controller</td>
<td>SPECint95 (G. Mean) 8.09</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Software

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

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
Memory subsystem is four-way interleaved.
Pentium Pro 200

SPECint_base95 = 6.37

Hardware/Software Configuration for:
Pentium Pro 200

<table>
<thead>
<tr>
<th>Benchmark # and Name</th>
<th>Reference Time</th>
<th>Base Run Time</th>
<th>Base SPEC Ratio</th>
<th>Run Time</th>
<th>SPEC Ratio</th>
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<tbody>
<tr>
<td>099.go</td>
<td>4600</td>
<td>595</td>
<td>7.73</td>
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<tr>
<td>124.m88ksim</td>
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<td>--</td>
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<tr>
<td>126.gcc</td>
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<td>276</td>
<td>6.16</td>
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<td>--</td>
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<td>129.compress</td>
<td>1800</td>
<td>357</td>
<td>5.04</td>
<td>--</td>
<td>--</td>
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<tr>
<td>130.li</td>
<td>1900</td>
<td>277</td>
<td>6.85</td>
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</tr>
<tr>
<td>132.ijpeg</td>
<td>2400</td>
<td>384</td>
<td>6.26</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>134.perl</td>
<td>1900</td>
<td>279</td>
<td>6.81</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>147.vortex</td>
<td>2700</td>
<td>427</td>
<td>6.32</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

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**

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Reference Time</th>
<th>Base Time</th>
<th>Base Ratio</th>
<th>Runtime</th>
<th>Ratio</th>
<th>SPECint2000</th>
<th>SPECint_base2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>164.gzip</td>
<td>1400</td>
<td>358</td>
<td>392</td>
<td>357</td>
<td>393</td>
<td>544518</td>
<td>544518</td>
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<tr>
<td>175.vpr</td>
<td>1400</td>
<td>399</td>
<td>452</td>
<td>307</td>
<td>456</td>
<td>544518</td>
<td>544518</td>
</tr>
<tr>
<td>176.gcc</td>
<td>1100</td>
<td>178</td>
<td>617</td>
<td>160</td>
<td>687</td>
<td>544518</td>
<td>544518</td>
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<tr>
<td>181.mcf</td>
<td>1800</td>
<td>408</td>
<td>441</td>
<td>340</td>
<td>529</td>
<td>544518</td>
<td>5444518</td>
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<tr>
<td>186.crafty</td>
<td>1000</td>
<td>144</td>
<td>694</td>
<td>157</td>
<td>637</td>
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<td>544518</td>
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<tr>
<td>197.parser</td>
<td>1800</td>
<td>500</td>
<td>360</td>
<td>409</td>
<td>440</td>
<td>544518</td>
<td>544518</td>
</tr>
<tr>
<td>252.eon</td>
<td>1300</td>
<td>202</td>
<td>645</td>
<td>202</td>
<td>644</td>
<td>544518</td>
<td>544518</td>
</tr>
<tr>
<td>253.perlbmk</td>
<td>1800</td>
<td>342</td>
<td>526</td>
<td>332</td>
<td>543</td>
<td>544518</td>
<td>544518</td>
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<tr>
<td>254.gap</td>
<td>1100</td>
<td>301</td>
<td>365</td>
<td>303</td>
<td>363</td>
<td>544518</td>
<td>544518</td>
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<td>255.vortex</td>
<td>1900</td>
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<td>673</td>
<td>249</td>
<td>763</td>
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<td>544518</td>
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<td>256.bzip2</td>
<td>1500</td>
<td>268</td>
<td>560</td>
<td>264</td>
<td>568</td>
<td>544518</td>
<td>544518</td>
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<tr>
<td>300.twolf</td>
<td>3000</td>
<td>456</td>
<td>658</td>
<td>451</td>
<td>666</td>
<td>544518</td>
<td>544518</td>
</tr>
</tbody>
</table>

### 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 V6.3-129-44AH
- **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
- **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 -xtaso_short +GEMFB
  - 176.gcc: -g3 -fast -O4 -xtaso_short +GEMFB
  - 181.mcf: -g3 -fast -xtaso_short +GEMFB
  - 186.crafty: -g3 -fast -O4 -xtaso_short +GEMFB
  - 197.parser: -g3 -fast -O4 -xtaso_short +GEMFB
  - 252.eon: -O2
  - 253.perlbmk: -g3 -fast +GEMFB +SPIKEFB
  - 254.gap: -g3 -fast -O4 +GEMFB

Standard Performance Evaluation Corporation
info@spec.org
http://www.spec.org
spec
SPEC CINT95rate Results
ã
Copyright 1995, Standard Performance Evaluation Corporation
Volume: 7   Issue: 4
94

Digital Equipment Corp. AlphaServer 8400 5/300
SPEC license #2
Tested By: Digital PKO
Test Date: Oct-95
Hardware Avail: Apr-95
Software Avail: Aug-95
Contact: Information
For More
Manassas, VA 22110
10754 Ambassador Drive, Suite 201
SPEC
http://www.specbench.org
info@specbench.org
(703) 331-0180

SPECrate

099.go
124.m88ksim
126.gcc
129.compress
130.li
132.ijpeg
134.perl
147.vortex

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: 8KB I+8KB D 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

SPECint_rate_base95 = 642

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        |

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 invocation: cc -migrate -std1 (DEC C with -std1 for strict ANSI)
## Top SPEC2000 Results for each ISA

<table>
<thead>
<tr>
<th>machine</th>
<th>processor</th>
<th>cpu MHz</th>
<th>cache sizes</th>
<th>int</th>
<th>fp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel D925</td>
<td>Pentium IV-X</td>
<td>3466</td>
<td>12*/8+512+2M</td>
<td>1772</td>
<td>1724</td>
</tr>
<tr>
<td>AMD/ASUS</td>
<td>Opteron150</td>
<td>2400</td>
<td>64/64+1M</td>
<td>1663</td>
<td>1849</td>
</tr>
<tr>
<td>Intel D925</td>
<td>Pentium IV</td>
<td>3600</td>
<td>12*/8+1M</td>
<td>1575</td>
<td>1630</td>
</tr>
<tr>
<td>HP rx4640</td>
<td>Itanium2</td>
<td>1600</td>
<td>16/16+256+6M</td>
<td>1590</td>
<td>2612</td>
</tr>
<tr>
<td>IBM p570</td>
<td>Power5+</td>
<td>1900</td>
<td>64/32+2M+(36M)</td>
<td>1453</td>
<td>2733</td>
</tr>
<tr>
<td>HP Alpha GS1280</td>
<td>SPARC64-V</td>
<td>1350</td>
<td>128+128/2M</td>
<td>905</td>
<td>1340</td>
</tr>
<tr>
<td>Fujitsu</td>
<td>PPC970 (G5)</td>
<td>2000</td>
<td>64/32+512</td>
<td>800</td>
<td>840</td>
</tr>
<tr>
<td>Apple</td>
<td>Pentium-M</td>
<td>1000</td>
<td>32/32+1024</td>
<td>687</td>
<td>552</td>
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<td>HP</td>
<td>PA-8700</td>
<td>875</td>
<td>768/1.5M</td>
<td>678</td>
<td>674</td>
</tr>
<tr>
<td>HP c3750</td>
<td>R14000</td>
<td>600</td>
<td>32/32+(8M)</td>
<td>500</td>
<td>529</td>
</tr>
<tr>
<td>SGI Orgin 3200</td>
<td>Itanium</td>
<td>800</td>
<td>16/16+96+(4M)</td>
<td>379</td>
<td>701</td>
</tr>
</tbody>
</table>
## Selected SPEC95 Results

<table>
<thead>
<tr>
<th>machine</th>
<th>processor</th>
<th>cpu MHz</th>
<th>cache sizes</th>
<th>int_base</th>
<th>fp_base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun SS10/40</td>
<td>SuprSP</td>
<td>40</td>
<td>20/16</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Intel 440BX</td>
<td>Pentium II</td>
<td>300</td>
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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