Intelligent RAM (IRAM): Chips that remember and compute

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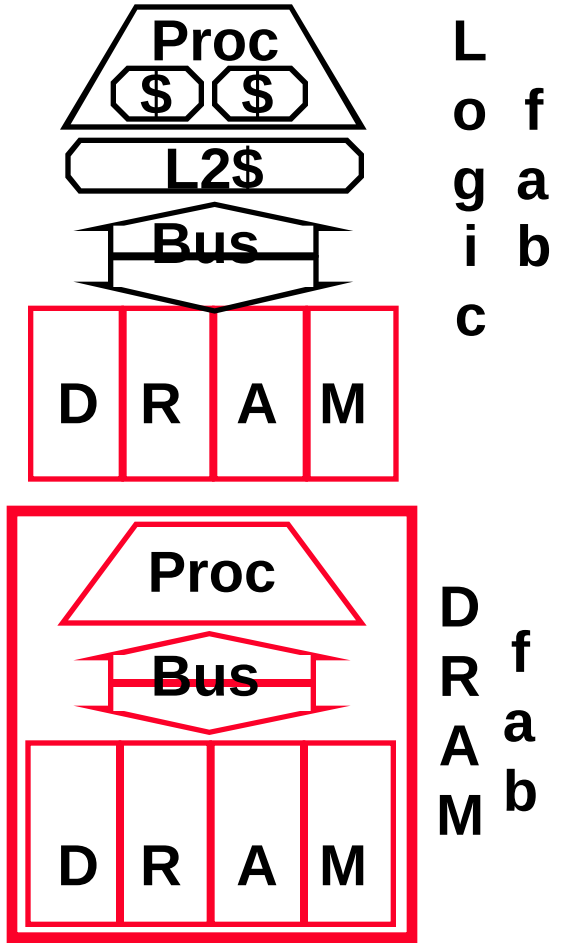
IRAM Vision Statement

Microprocessor & DRAM on a single chip:

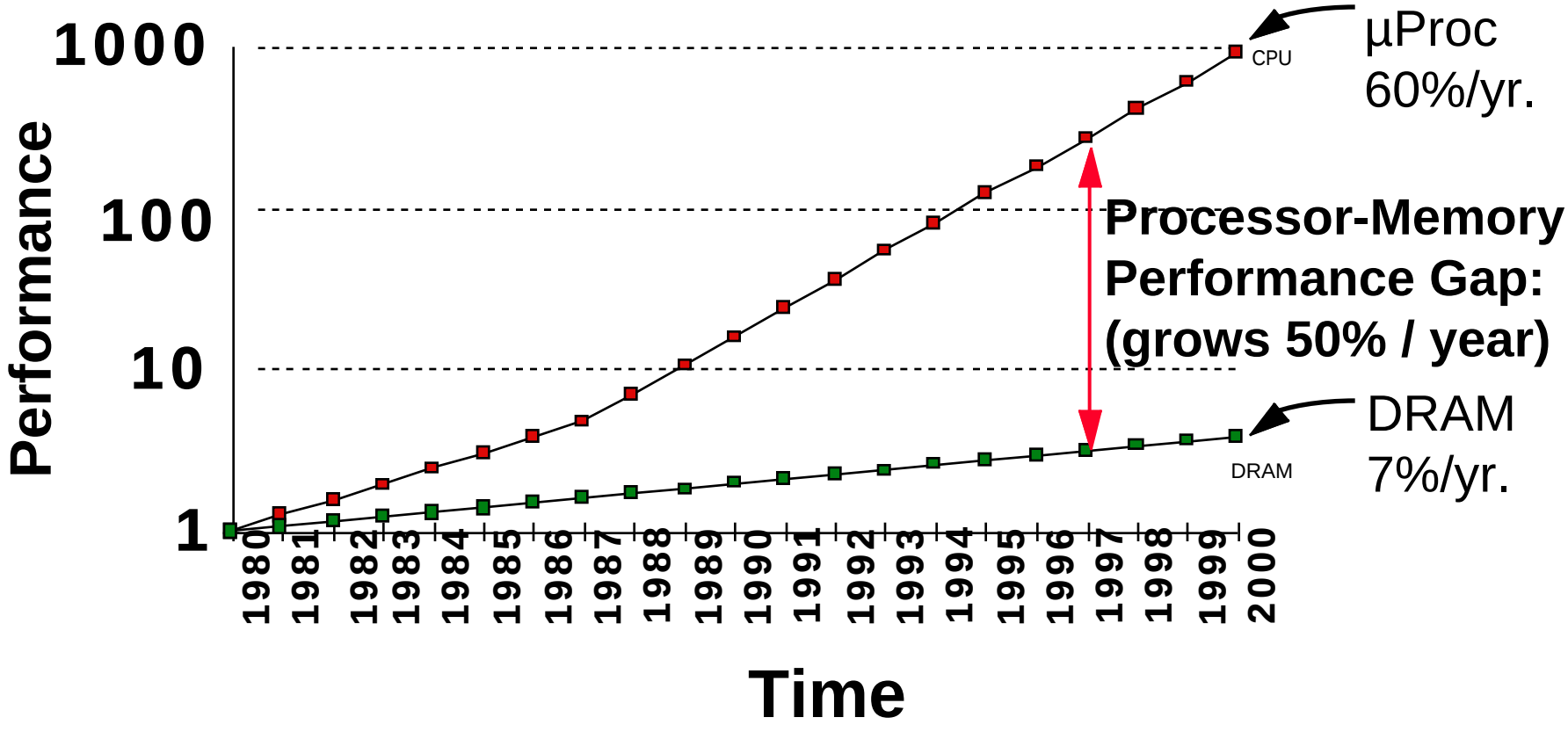
- bridge processor-memory performance gap via on-chip latency 5-10X,bandwidth 100X
- improve energy efficiency 2X-4X (no DRAM bus)
- adjustable memory size/width (designer picks any amount)
- smaller board area/volume



Outline

- Today's Situation: Microprocessor
- Today's Situation: DRAM
- IRAM Opportunities
- IRAM Architecture Options
- IRAM Challenges
- Potential Industrial Impact

Processor-DRAM Gap (latency)



Processor-Memory Performance Gap "Tax"

Processor	% Area *(≈cost)*	%Transistors *(≈power)*
Alpha 21164	37%	77%
StrongArm SA110	61%	94%
Pentium Pro	64%	88%

- 2 dies per package: Proc/I$/D$ + L2$
- Caches have no inherent value, only try to close performance gap

Today's Situation: Microprocessor

- Microprocessor-DRAM performance gap
  - time of a full cache miss in instructions executed

    1st Alpha (7000): 340 ns/5.0 ns = 68 clks x 2 or 136

    2nd Alpha (8400): 266 ns/3.3 ns = 80 clks x 4 or 320

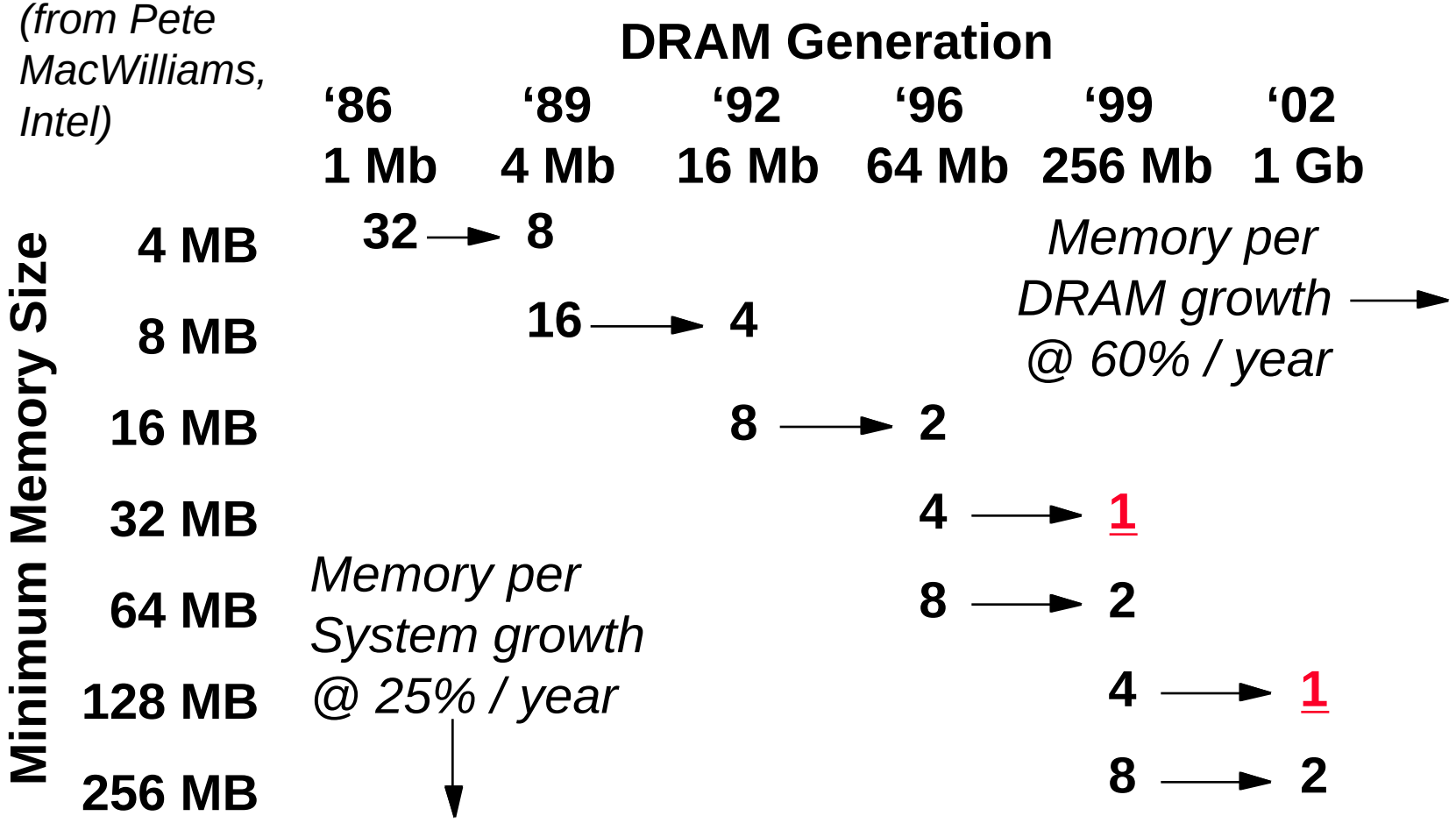
    3rd Alpha (t.b.d.): 180 ns/1.7 ns =108 clks x 6 or 648
  - 1/2X latency x 3X clock rate x 3X Instr/clock $\Rightarrow \approx$5X
- Power limits performance (battery, cooling)
- Rely on caches to bridge gap
  - Doesn't work well for a few apps: data bases, …

Today's Situation: DRAM

- Commodity, second source industry
  $\Rightarrow$ high volume, low profit, conservative
  - Little organization innovation (vs. processors) in 20 years: page mode, EDO, Synch DRAM
- DRAM industry at a crossroads:
  - Fewer DRAMs per computer over time
  - Starting to question buying larger DRAMs?

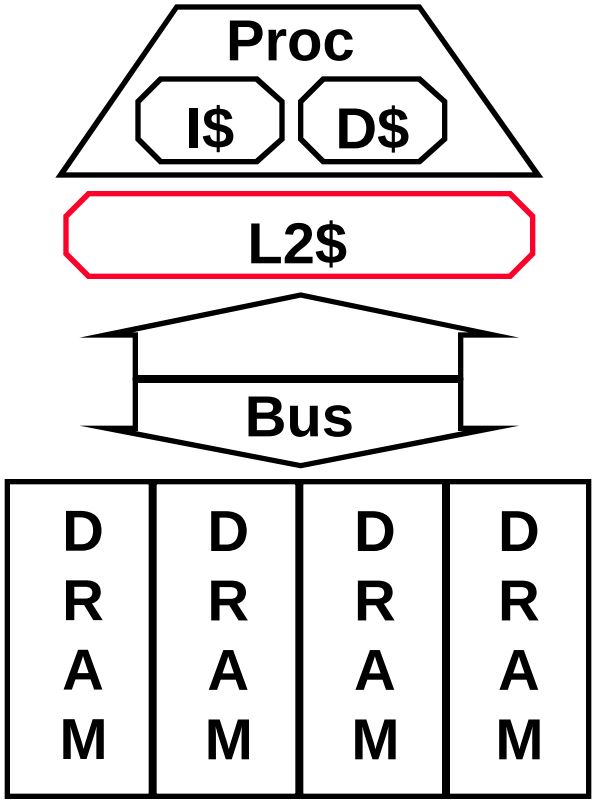
Fewer DRAMs / System over Time

(from Pete MacWilliams, Intel)



Reluctance for New DRAMs: DRAM BW ≠ App BW

- More App Bandwidth (BW)
  - ⇒ Cache misses
  - ⇒ DRAM RAS/CAS
- Application BW
  - ⇒ Lower DRAM latency
- RAMBUS, Synch DRAM increase BW but higher latency
- EDO DRAM, Synch DRAM < 5% performance in PCs



Multiple Motivations for IRAM

- Some apps: energy, board area, memory size
- Gap means performance limit is memory
- Dwindling interest in future DRAM: 256Mb/1Gb?
  - Too much memory per chip?
  - Industry supplies higher bandwidth at higher latency, but computers need lower latency
- Alternatives: packaging breakthrough, more out-of-order CPU, fix capacity but shrink DRAM die, ...

Potential IRAM Latency: 5 - 10X

- No parallel DRAMs, memory controller, bus to turn around, SIMM module, pins…
- New focus: Latency oriented DRAM?
  - Dominant delay = RC of the word lines
  - keep wire length short & block sizes small?
- << 30 ns for 1024b IRAM “RAS/CAS”?
- AlphaSta. 600: 180 ns=128b, 270 ns= 512b
  Next generation (21264): 180 ns for 512b?

Potential IRAM Bandwidth: 100X

- 1024 1Mbit modules, each 1Kb wide(1Gb)
  - 10% @ 40 ns RAS/CAS = 320 GBytes/sec
- If cross bar switch or multiple busses deliver 1/3 to 2/3 of total 10% of modules
  $\Rightarrow$ 100 - 200 GBytes/sec
- FYI: AlphaServer 8400 = 1.2 GBytes/sec
  - 75 MHz, 256-bit memory bus, 4 banks

Potential Energy Efficiency: 2X-4X

- Case study of StrongARM memory hierarchy vs. IRAM memory hierarchy
  - cell size advantages ⇒ much larger cache
    ⇒ fewer off-chip references
    ⇒ up to 2X-4X energy efficiency for memory
  - less energy per bit access for DRAM
- Memory cell area ratio /process:21164,SA 110

cache/logic	: SRAM/SRAM	: DRAM/DRAM
25-50	: 10	: 1

Potential Innovation in Standard DRAM Interfaces

- Optimizations when chip is a system vs. chip is a memory component
  - Lower power with more selective module activation?
  - Lower voltage if all signals on chip?
  - Improved yield with variable refresh rate?
- IRAM advantages even greater if innovate inside DRAM memory modules?

"Vanilla" Approach to IRAM

- Estimate performance IRAM version of Alpha (same caches, benchmarks, standard DRAM)
  - Used optimistic and pessimistic factors for logic (1.3-2.0 slower), SRAM (1.1-1.3 slower), DRAM speed (5X-10X faster) for standard DRAM
  - SPEC92 benchmark ⇒ 1.2 to 1.8 times slower
  - Database ⇒ 1.1 times slower to 1.1 times faster
  - Sparse matrix ⇒ 1.2 to 1.8 times faster
- Conventional architecture/benchmarks/DRAM not exciting performance; energy,board area only

A More Revolutionary Approach

- Faster logic in DRAM process
  - DRAM vendors offer same fast transistors + same number metal layers as good logic process? @ ≈ 20% higher cost per wafer?
  - As die cost ≈ f(die area^4), 4% die shrink ⇒ equal cost
- Find an architecture to exploit IRAM yet simple programming model so can deliver exciting cost/performance for many applications
  - Evolve software while changing underlying hardware
  - Simple ⇒ sequential (not parallel) program; large memory; uniform memory access time

Example IRAM Architecture Options

- (Massively) Parallel Processors (MPP) in IRAM
  - Hardware: best potential performance / transistor, but less memory per processor
  - Software: few successes in 30 years: databases, file servers, dense matrix computations, ... delivered MPP performance often disappoints
- Vector architecture in IRAM: More promising?
  - Simple model: seq. program, uniform mem. access
  - Multimedia apps (MMX) broaden vector relevance
  - Can tradeoff more hardware for slower clock rate
  - Cray on a chip:vector processor+interleaved memory

Why Vector? Isn't it dead?

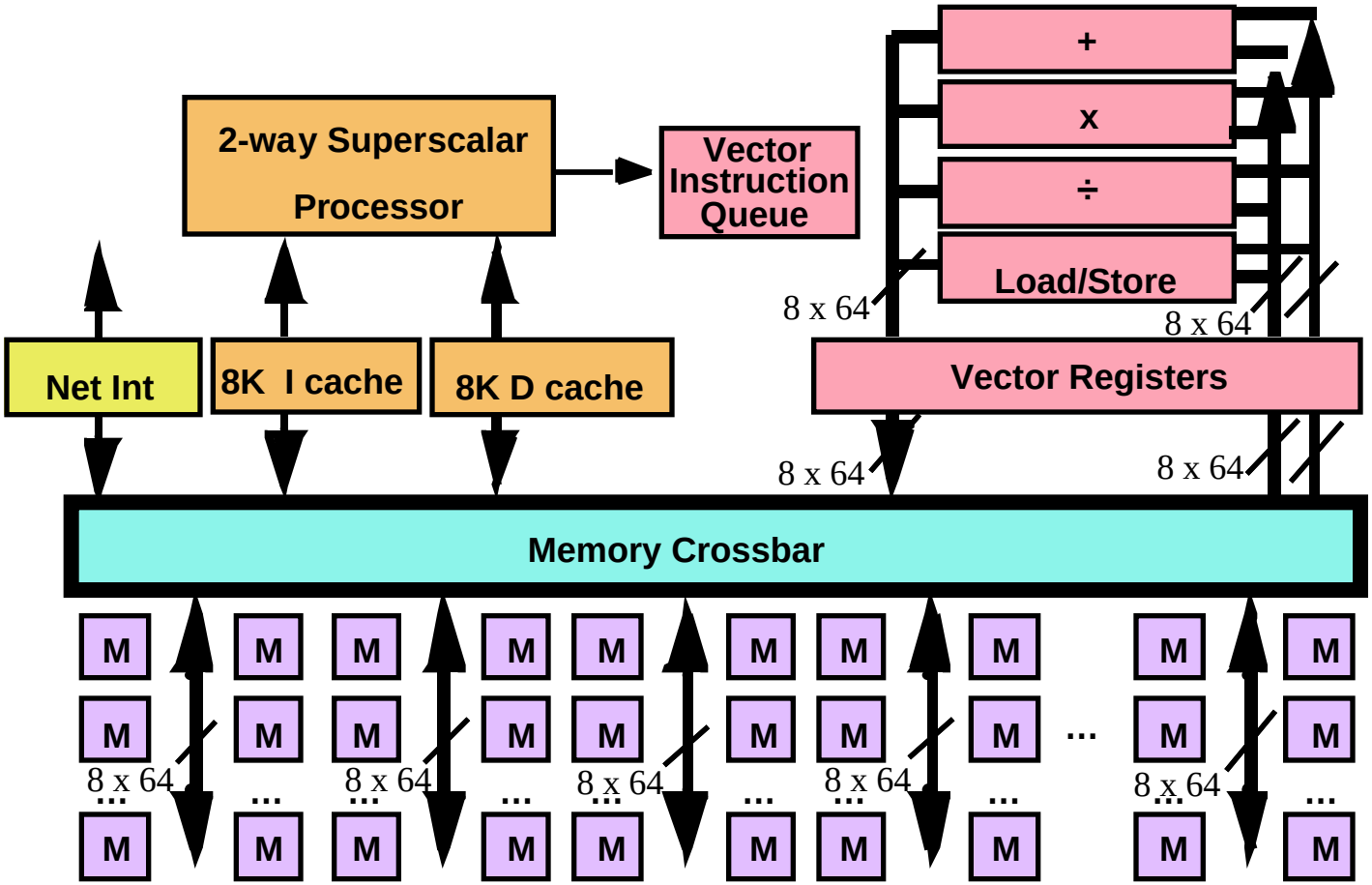
- High cost: ≈ $1M / processor?
- ≈5-10M transistors for vector processor?
- Low latency, high BW memory system?
- Energy?
- Poor scalar performance?
- Limited to scientific applications?

- Single-chip CMOS microprocessor/IRAM
- Small % in future + scales to 10B transistors
- IRAM = low latency, high bandwidth memory
- Fewer instructions v. VLIW/ speculative, superscalar CPU
- Include modern, modest CPU ⇒ scalar performs OK-good
- Multimedia apps (MMX) are vectorizable too

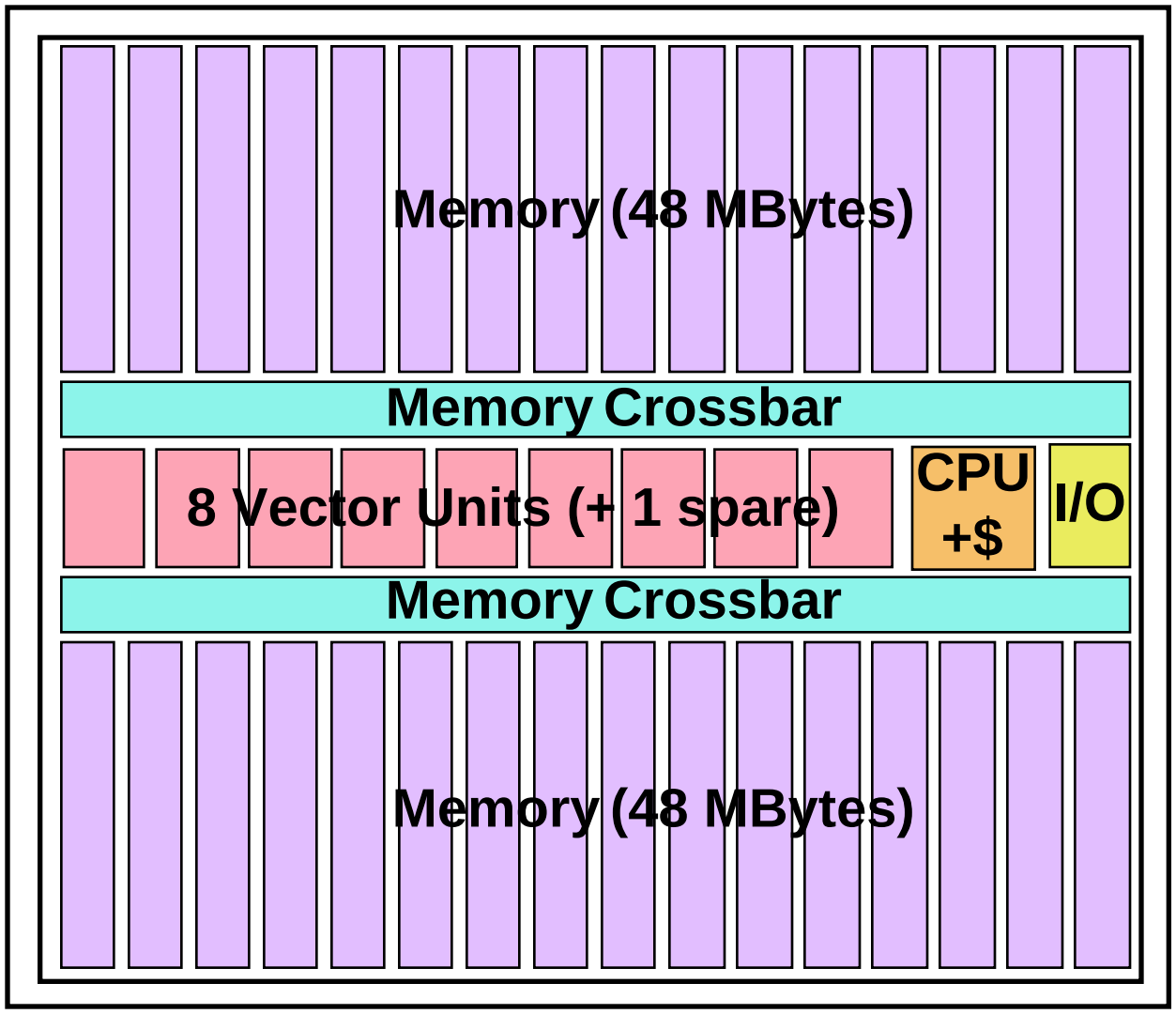
Software Technology Trends Affecting V-IRAM?

- V-IRAM: any CPU + V-IRAM co-processor on-chip
  - scalar/vector interactions are limited, simple
- Vectorizing compilers built for 25 years
  - can buy one for new machine from The Portland Group
- Library solutions; retarget packages (e.g., MMX)
- SW distribution model is evolving?
  - Old Model SW distribution: binary for processor on CD
  - New Model #1: Binary translation to new machine?
  - New Model #2: Java byte codes over network + Just-In-Time compiler to tailor program to machine?

V-IRAM-2: 0.18 µm, Fast Logic, 1GHz
16 GFLOPS(64b) / 128 GOPS(8b) / 96MB



V-IRAM-2 Floorplan



- 0.18 µm, 1 Gbit DRAM
- Die size = DRAM die
- 1B Xtors: 80% Memory, 4% Vector, 3% CPU ⇒ regular design
- Spare VU & Memory ⇒ ≈80% die repairable

Vector IRAM Generations

- V-IRAM-1 (≈1999)
- 256 Mbit generation (0.25)
- Die size = DRAM (290 mm^2)
- 1.5 - 2.0 volts (logic)
- 0.5 - 2.0 watts
- 300 - 500 MHz
- 4 64-bit pipes/lanes
- 4 GFLOPS(64b)/32GOPS(8b)
- 24 MB capacity + DRAM bus
- PCI bus/Fast serial lines

- V-IRAM-2 (≈2002)
- 1 Gbit generation (0.18)
- Die size = DRAM (420 mm^2)
- 1.0 - 1.5 volts (logic)
- 0.5 - 2.0 watts
- 500 - 1000 MHz
- 8 64-bit pipes/lanes
- 16 GFLOPS/128GOPS
- 96 MB cap. + DRAM bus
- Firewire/FC-AL serial lines

IRAM Applications

- "Supercomputer on a AA battery"
  - Super PDA/Smart Phone:
    speech I/O + "voice" email + pager + GPS +...
  - Super Gameboy/Portable Network Computer:
    3D graphics + 3D sound + speech I/O+ Gbit link + ...
- Intelligent SIMM ("ISIMM")
  - Put IRAMs + serial network + serial I/O into SIMM & put in standard memory system $\Rightarrow$ Cluster/Network of IRAMs
  - Read/compare/write all memory in 1 ms
  - Apps? Full text search? Fast sort? No index database?
- Intelligent Disk ("IDISK") 2.5" disk + IRAM + net.

ISIMM / IDISK Example: Sort

- Berkeley NOW cluster has world record sort: 6GB disk-to-disk using 64 processors in 1 minute
- Balanced system ratios for processor:memory:I/O
  - Processor: ≈ N MIPS
  - Large memory: N Mbit/s disk I/O & 2N Mb/s Network
  - Small memory: 2N Mbit/s disk I/O & 2N Mb/s Network
- Serial I/O at 2-4 Ghz today
- IRAM: ≈ 2-4 GIPS + 2 2-4Gb/s I/O + 2 2-4Gb/s Net
- ISIMM: 8 IRAMs + net swtich + FC-AL links + disks
- IDISK: Intelligent Disks + switch = cluster

Why IRAM now?
Lower risk than before

- DRAM manufacturers now facing challenges
  - Before not interested, so early IRAM = SRAM
- Past efforts memory limited ⇒ multiple chips
  ⇒ 1st solve the unsolved (parallel processing)
  - Gigabit DRAM ⇒ ≈100 MB; OK for many apps?
- Fast Logic + DRAM available now/soon?
- Embedded apps leverage energy efficiency, adjustable mem. capacity, smaller board area
  ⇒ OK market v. desktop (55M 32b RISC ‘96)

IRAM Challenges

- Chip
  - Speed, area, power, yield, cost in DRAM process?
  - Good performance and reasonable power?
  - BW/Latency oriented DRAM tradeoffs?
  - Testing time of IRAM vs DRAM vs microprocessor?
  - Reconfigurable logic to make IRAM more generic?
- Architecture
  - How to turn high memory bandwidth into performance for real applications?
  - Extensible IRAM: Large program/data solution? (e.g., external DRAM, clusters, CC-NUMA, ...)

IRAM Conclusion

- IRAM potential in bandwidth (memory and I/O), latency, energy, capacity, board area; challenges in yield, power, testing, memory size
- 10X-100X improvements based on technology shipping for 20 years (not photons, MEMS, ...)
- Potential shift in balance of power in DRAM/ microprocessor (µP) industry in 5-7 years?
  - µP-oriented vs. DRAM-oriented manufacturers:
  - Who ships the most memory?
  - Who ships the most microprocessors?

Interested in Participating?

- Looking for industrial partners to help fab, (design?) test chips and prototype of V-IRAM-1
  - Fast, modern DRAM process
  - Existing RISC CPU core?
- Looking for partners with memory intensive apps
- Contact us if you're interested:
  `http://iram.cs.berkeley.edu/`
  `email: patterson@cs.berkeley.edu`
- Thanks for advice/support: DARPA, Intel, Neomagic, Samsung, SGI/Cray, Sun

Backup Slides

(The following slides are used to help answer questions)

Why a company should try IRAM

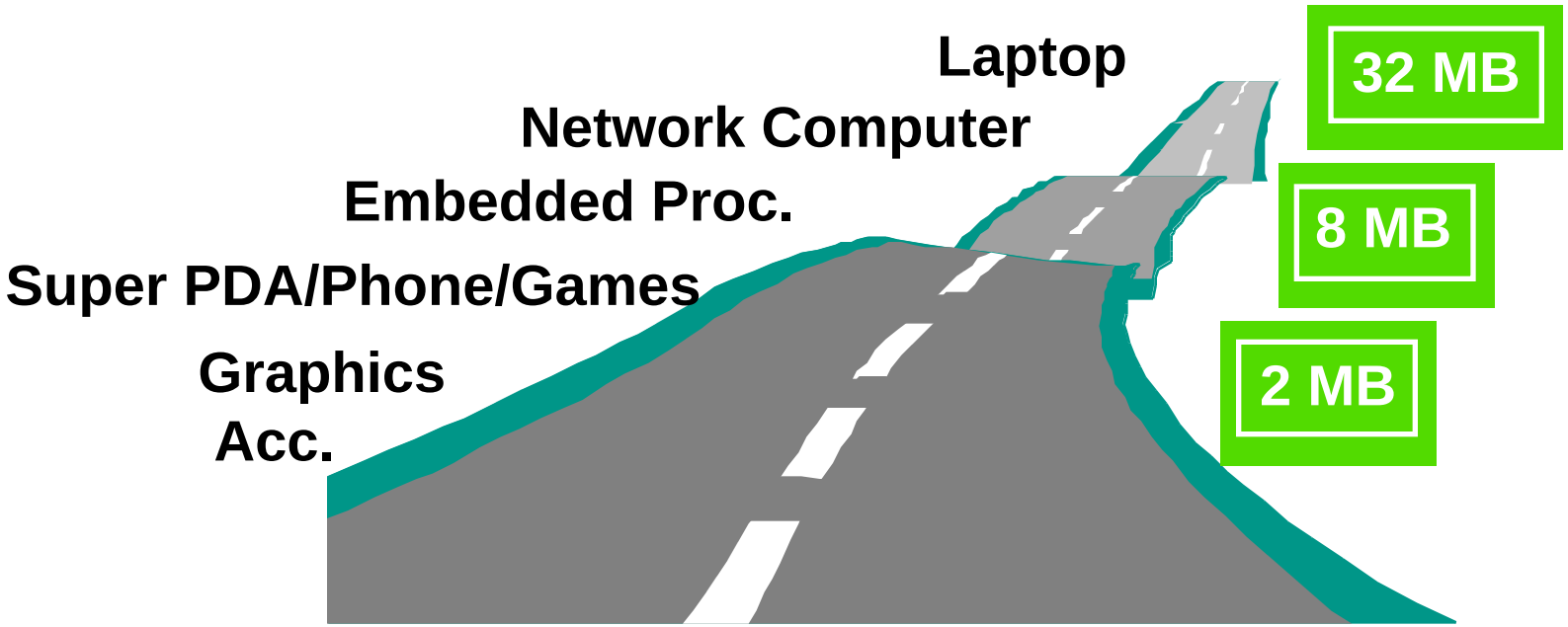
- If IRAM doesn't happen, then someday:
  - $10B fab for 16B Xtor MPU (too many Xtors per die)??
  - $10B fab for 16 Gbit DRAM (too many bits per die)??
- This is not rocket science. In 1997:
  - 25-50X improvement in memory density;
    $\Rightarrow$ more memory per die or smaller die
  - 10X -100X improvement in memory performance
  - Regularity simplifies design/CAD/validate: 1B Xtors "easy"
  - Logic same speed
  - $\approx$ 20% higher cost / wafer (but redundancy improves yield)
- IRAM success requires MPU expertise + DRAM fab

Words to Remember

"...a strategic inflection point is a time in the life of a business when its fundamentals are about to change. ... Let's not mince words: A strategic inflection point can be deadly when unattended to. Companies that begin a decline as a result of its changes rarely recover their previous greatness."

– *Only the Paranoid Survive*, Andrew S. Grove, 1996

Commercial IRAM highway is governed by memory per IRAM?



Energy to Access Memory by Level of Memory Hierarchy

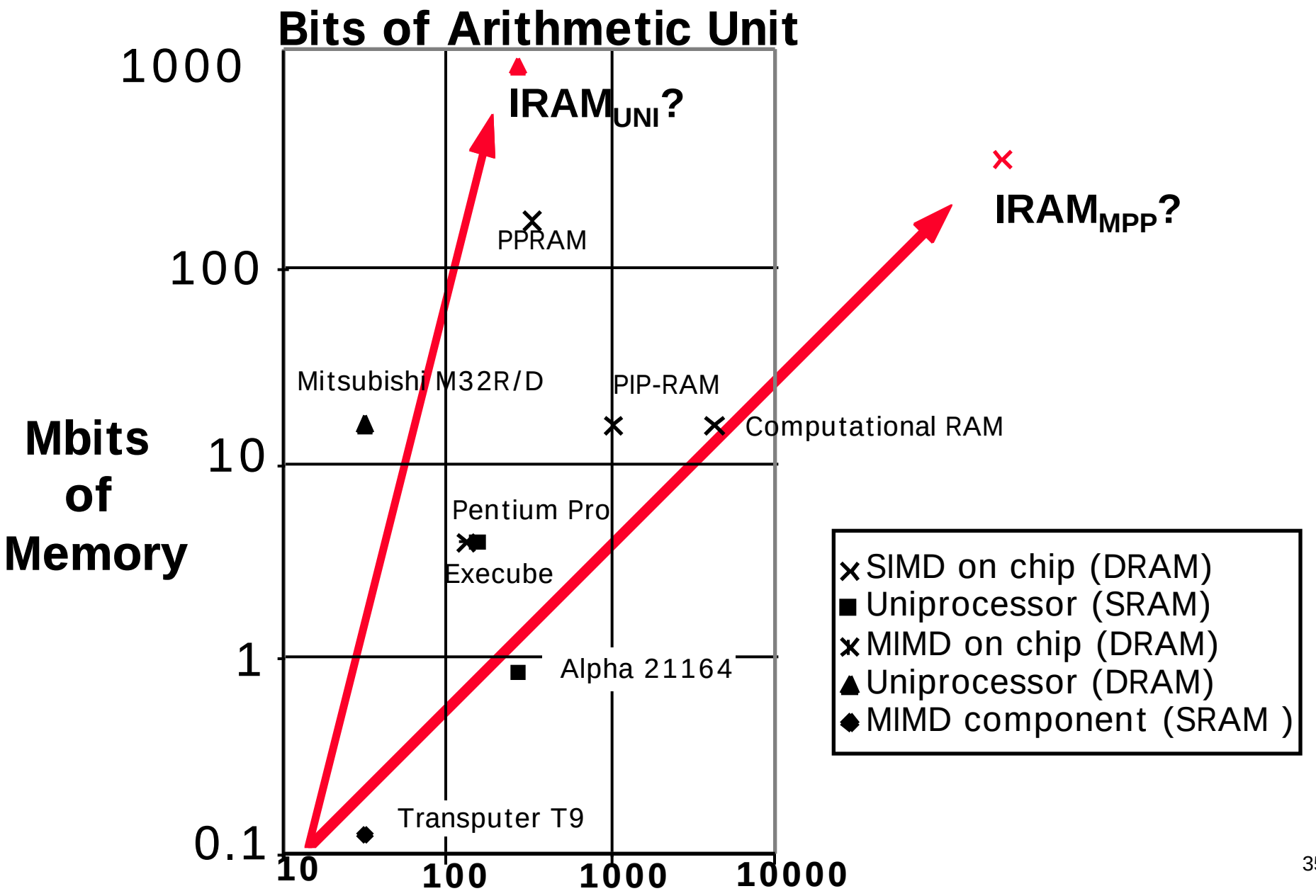
- For 1 access, measured in nJoules

	Conventional	IRAM
on-chip L1$(SRAM)	0.5	0.5
on-chip L2$(SRAM v. DRAM)	2.4	1.6
L1 to Memory (off- v. on-chip)	98.5	4.6
L2 to Memory (off-chip)	316.0	*(n.a.)*

  - » Based on Digital StrongARM, 0.35 µm technology
  - » See "The Energy Efficiency of IRAM Architectures," *24th Int'l Symp. on Computer Architecture*, June 1997

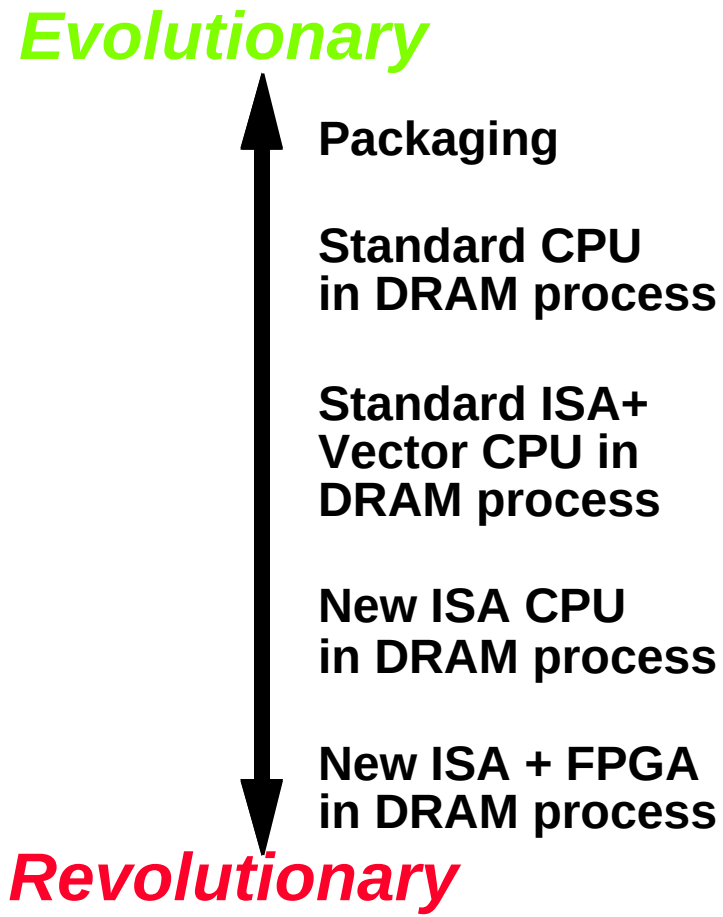
Reluctance for New DRAMs: Proc. v. DRAM BW, Min. Mem. size

- Processor DRAM bus BW = width x clock rate
  - Pentium Pro = 64b x 66 MHz ≈ 500 MB/sec
  - RISC = 256b x 66 MHz ≈ 2000 MB/sec
- DRAM bus BW = width x “clock rate”
  - EDO DRAM, 8b wide x 40 MHz = 40 MB/sec
  - Synch DRAM, 16b wide x 125 MHz = 250 MB/sec
- CPU BW / DRAM BW = 8 -16 chips minimum
  - 64Mb ⇒ 64-128 MB min. memory; 256Mb/Gb?
  - Wider DRAMs more expensive: bigger die, test time


Bits of Arithmetic Unit
1000
100
10
1
0.1
Mbits of Memory
10
100
1000
10000
IRAM$_{UNI}$?
IRAM$_{MPP}$?
PPRAM
Mitsubishi M32R/D
PIP-RAM
Computational RAM
Pentium Pro
Execube
Alpha 21164
Transputer T9
SIMD on chip (DRAM)
Uniprocessor (SRAM)
MIMD on chip (DRAM)
Uniprocessor (DRAM)
MIMD component (SRAM)

IRAM Conclusion

- Research challenge is quantifying the evolutionary-revolutionary spectrum



Justification#2: Berkeley has done one lap; ready for new architecture?

- RISC: Instruction set /Processor design + Compilers (1980-84)
- SOAR/SPUR: Obj. Oriented SW, Caches, & Shared Memory Multiprocessors + OS kernel (1983-89)
- RAID: Disk I/O + File systems (1988-93)
- NOW: Networks + Protocols (1993-98)
- IRAM: Instruction set /Processor design/Memory Hierarchy and Compilers/OS (1996-200?)

21st Century Benchmarks?

- Potential Applications (new model highlighted)
  - **Text**: spelling checker (ispell), Java compilers (Javac, Espresso), content-based searching (Digital Library)
  - **Image**: text interpreter(Ghostscript), mpeg-encode, ray tracer (povray), Synthetic Aperture Radar (2D FFT)
  - **Multimedia**: Speech (Noway), Handwriting (HSFSYS)
  - **Simulations**: Digital circuit (DigSim),Mandelbrot (MAJE)
- Others? suggestions requested!
  - Encryption (pgp), Games?, Object Relational Database?, Word Proc?, Reality Simulation/Holodeck?,