

Intelligent RAM (IRAM):

Chips that remember and compute

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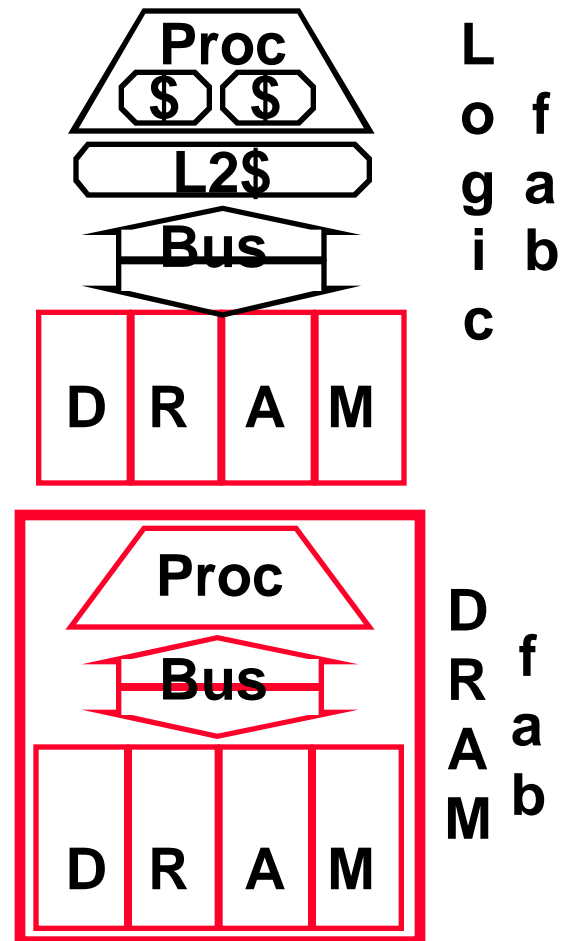
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IRAM Vision Statement

Microprocessor & DRAM on a single chip:

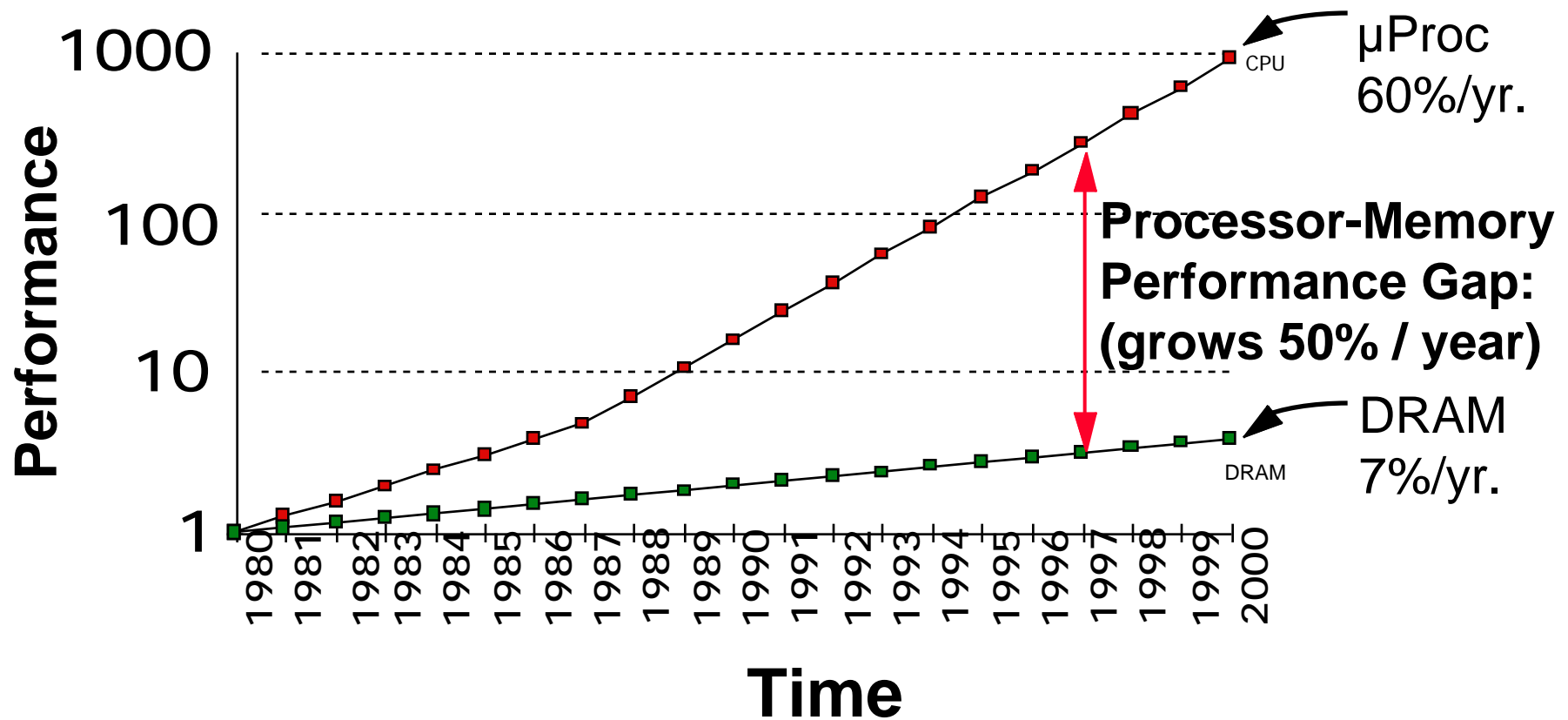
- bridge processor-memory performance gap via on-chip latency 5-10X, bandwidth 100X
- improve energy efficiency 2X-4X (no DRAM bus)
- adjustable memory size/width (designer picks any amount)
- smaller board area/volume



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 (<i>≈cost</i>)	%Transistors (<i>≈power</i>)
■ 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): $340 \text{ ns} / 5.0 \text{ ns} = 68 \text{ clks} \times 2$ or 136
 - 2nd Alpha (8400): $266 \text{ ns} / 3.3 \text{ ns} = 80 \text{ clks} \times 4$ or 320
 - 3rd Alpha (t.b.d.): $180 \text{ ns} / 1.7 \text{ ns} = 108 \text{ clks} \times 6$ or 648
 - $1/2X$ latency \times $3X$ clock rate \times $3X$ 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
 - ⇒ 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)

		DRAM Generation					
		'86	'89	'92	'96	'99	'02
		1 Mb	4 Mb	16 Mb	64 Mb	256 Mb	1 Gb
Minimum Memory Size	4 MB	32	8				
	8 MB		16	4			
	16 MB			8	2		
	32 MB				4	1	
	64 MB				8	2	
	128 MB					4	1
	256 MB					8	2

Memory per DRAM growth → @ 60% / year

Memory per System growth @ 25% / year ↓

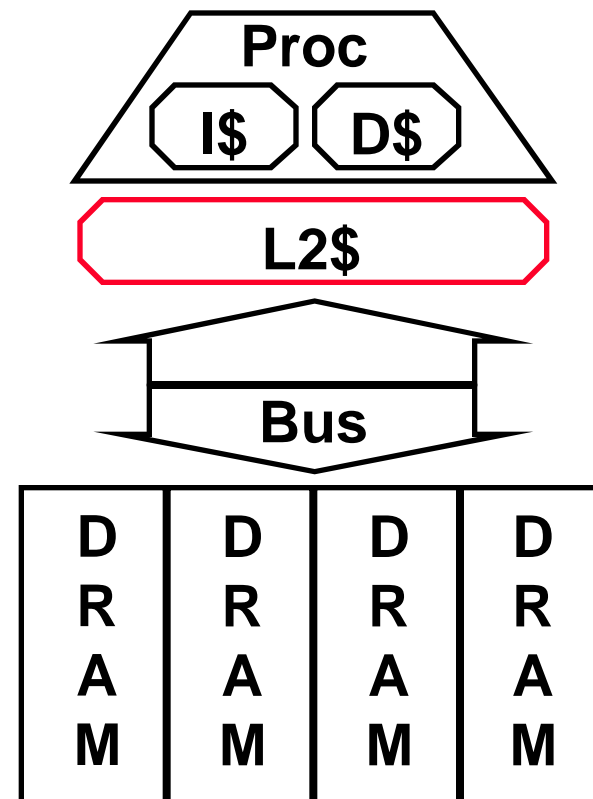
Reluctance for New DRAMs:

Proc. v. DRAM BW, Min. Mem. size

- Processor DRAM bus BW = width x clock rate
 - Pentium Pro = 64b x 66 MHz \approx 500 MB/sec
 - RISC = 256b x 66 MHz \approx 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 \Rightarrow 64-128 MB min. memory; 256Mb/Gb?
 - Wider DRAMs more expensive: bigger die, test time

Reluctance for New DRAMs: DRAM BW \neq 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?
- \ll 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
 - ⇒ 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 \Rightarrow much larger cache
 - \Rightarrow fewer off-chip references
 - \Rightarrow 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 \Rightarrow 1.2 to 1.8 times slower
 - Database \Rightarrow 1.1 times slower to 1.1 times faster
 - Sparse matrix \Rightarrow 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?
@ \approx 20% higher cost per wafer?
 - As die cost \approx $f(\text{die area}^4)$, 4% die shrink \Rightarrow 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 \Rightarrow 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

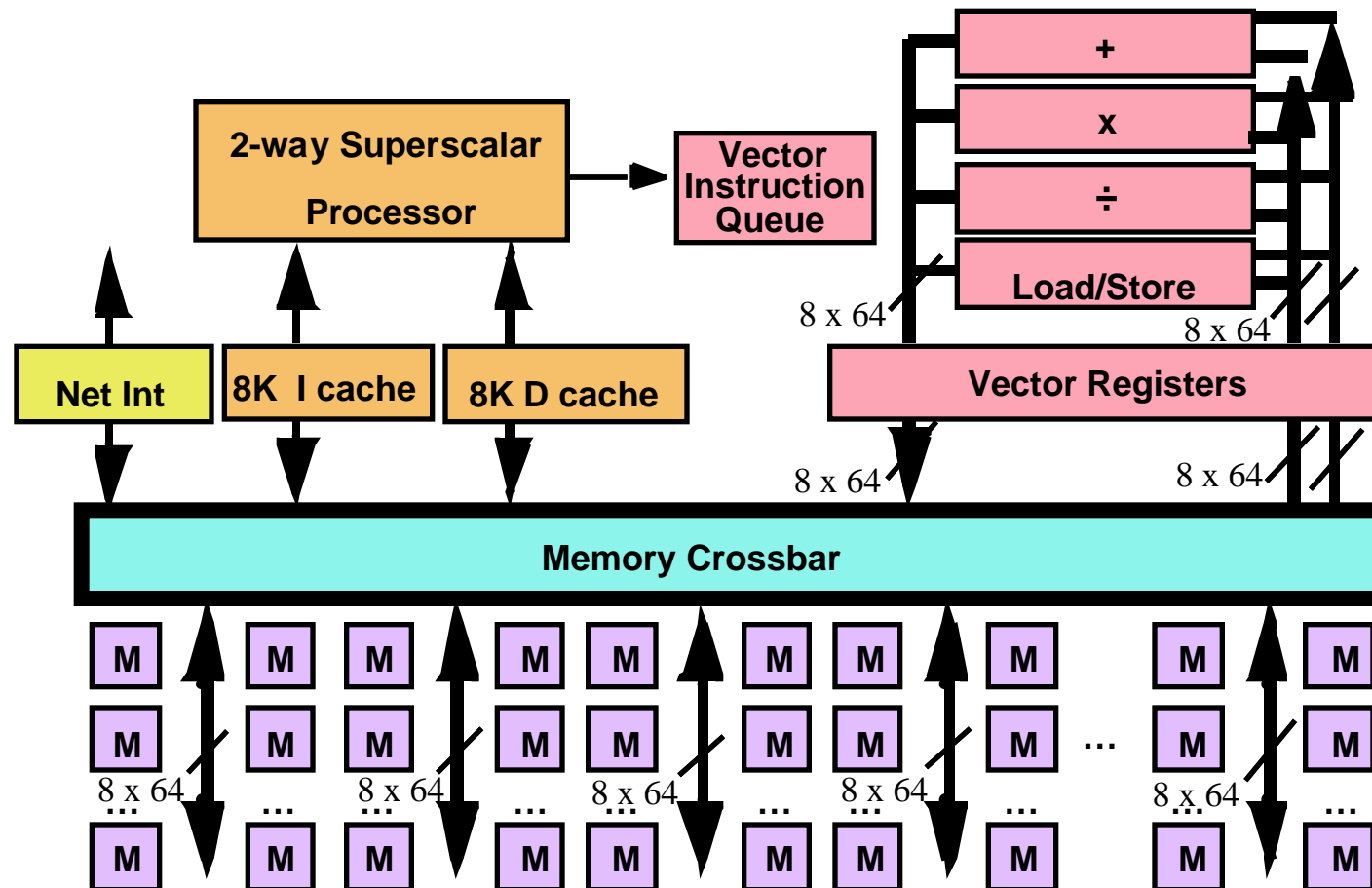
Why Vector? Isn't it dead?

- High cost:
 - \approx \$1M / processor?
- \approx 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 \Rightarrow scalar performs OK-good
- Multimedia apps (MMX) are vectorizable too

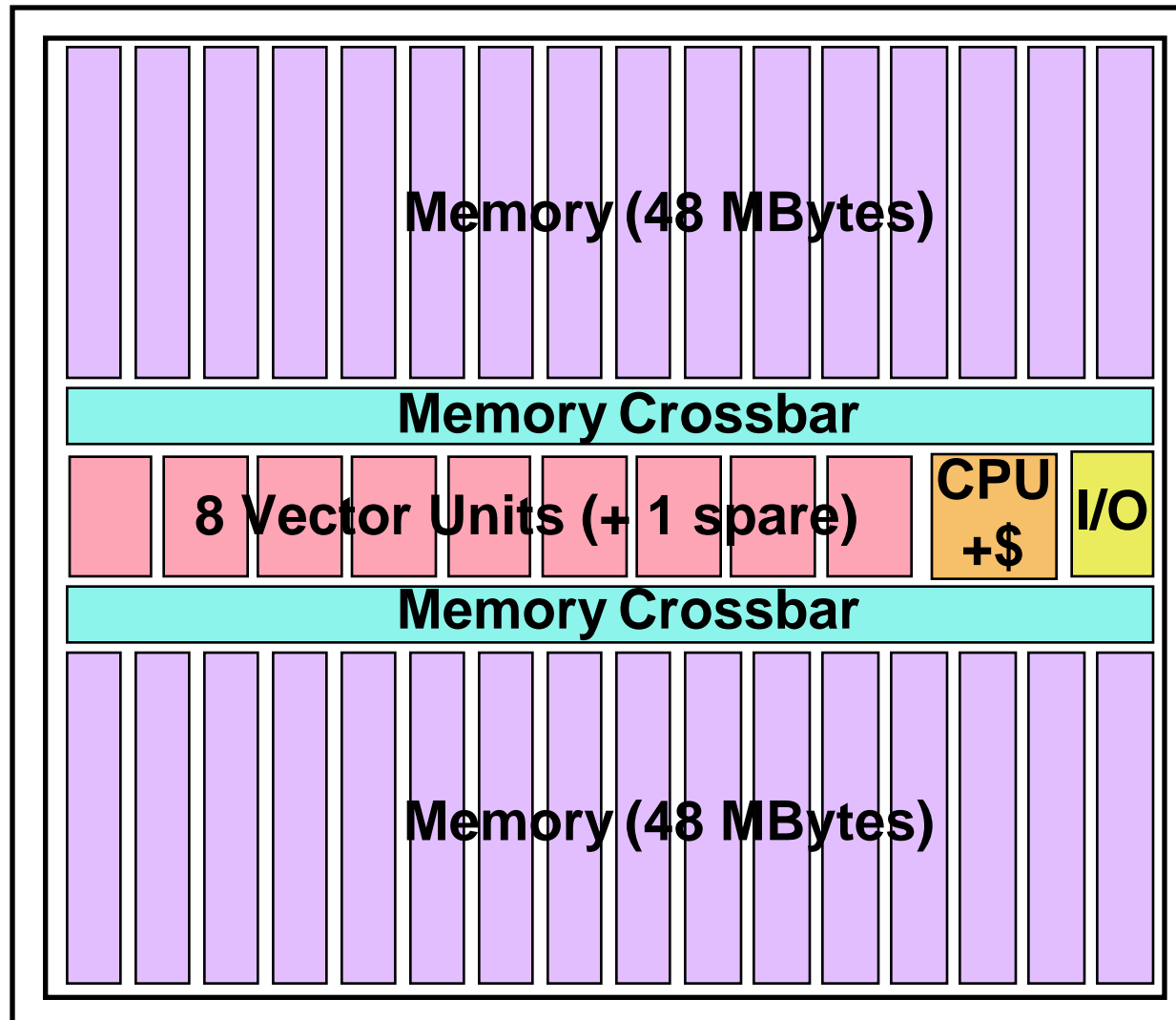
Software Technology Trends Affecting V-IRAM?

- 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 \Rightarrow
regular design
- Spare VU &
Memory \Rightarrow
 \approx 80% die
repairable

Vector IRAM Generations

- V-IRAM-1 (\approx 1999)
 - 256 Mbit generation (0.25)
 - Die size = DRAM (290 mm²)
 - 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 (\approx 2002)
 - 1 Gbit generation (0.18)
 - Die size = DRAM (420 mm²)
 - 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
 - Gbit Ethernet/FC-AL

Characterizing IRAM Performance

- Small memory on-chip (25 - 100 MB)
- Low latency main memory (20 - 30ns)
- High BW main memory (100 - 200 GB/sec)
- High BW I/O (0.5 - 2 GB/sec via N serial lines)
 - I/O must interact with processor (signal/interrupt), cache (consistency), main memory (repository)
 - Integrated CPU/cache/memory ideal for fast serial I/O; otherwise connect everywhere or use I/O bus

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: $\approx N$ 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: $\approx 2-4$ GIPS + 2 2-4Gb/s I/O + 2 2-4Gb/s Net
- ISIMM: 8 IRAMs + net switch + 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 \Rightarrow multiple chips
 - \Rightarrow **1st** solve the unsolved (parallel processing)
 - Gigabit DRAM \Rightarrow \approx 100 MB; OK for many apps?
- Fast Logic + DRAM available now/soon?
- Embedded apps leverage energy efficiency, adjustable mem. capacity, smaller board area
 - \Rightarrow 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 (μ P) industry in 5-7 years?
 - μ P-oriented vs. DRAM-oriented manufacturers:
 - Who ships the most memory?
 - Who ships the most microprocessors?

Interested in Participating?

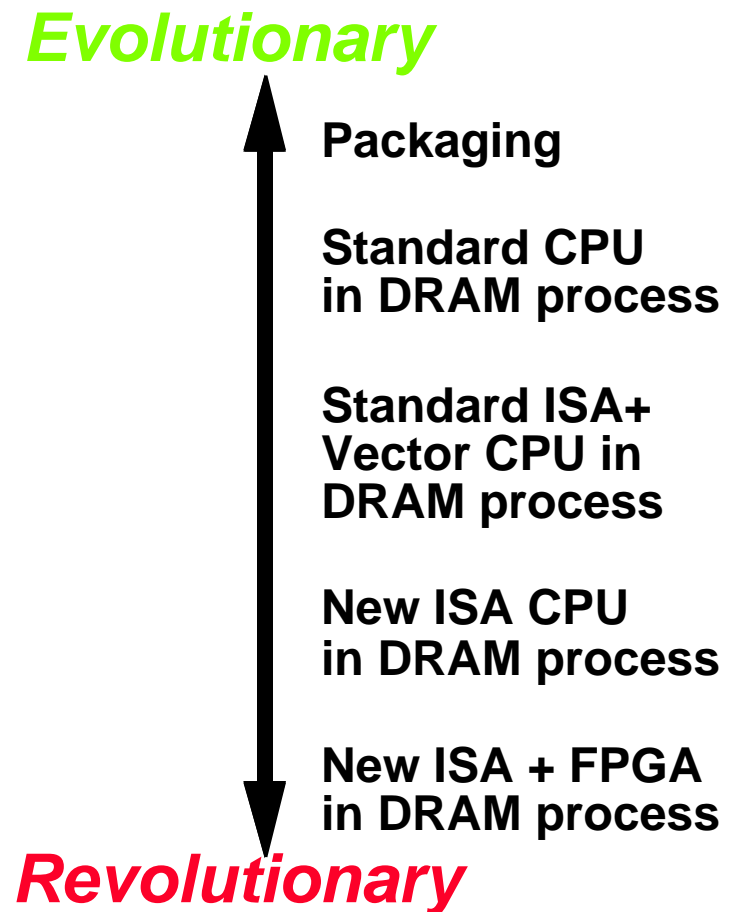
- Looking for industrial partners to help fab, (design?) test chips and prototype of V-IRAM-1
 - Fast, modern DRAM process
 - Existing RISC CPU core?
- Looking for partners with memory intensive apps
- Contact us if you're interested:
`http://iram.cs.berkeley.edu/`
`email: patterson@cs.berkeley.edu`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

Backup Slides

(The following slides are used to help answer questions)

IRAM Conclusion

- Research challenge is quantifying the evolutionary-revolutionary spectrum



Why a company should try IRAM

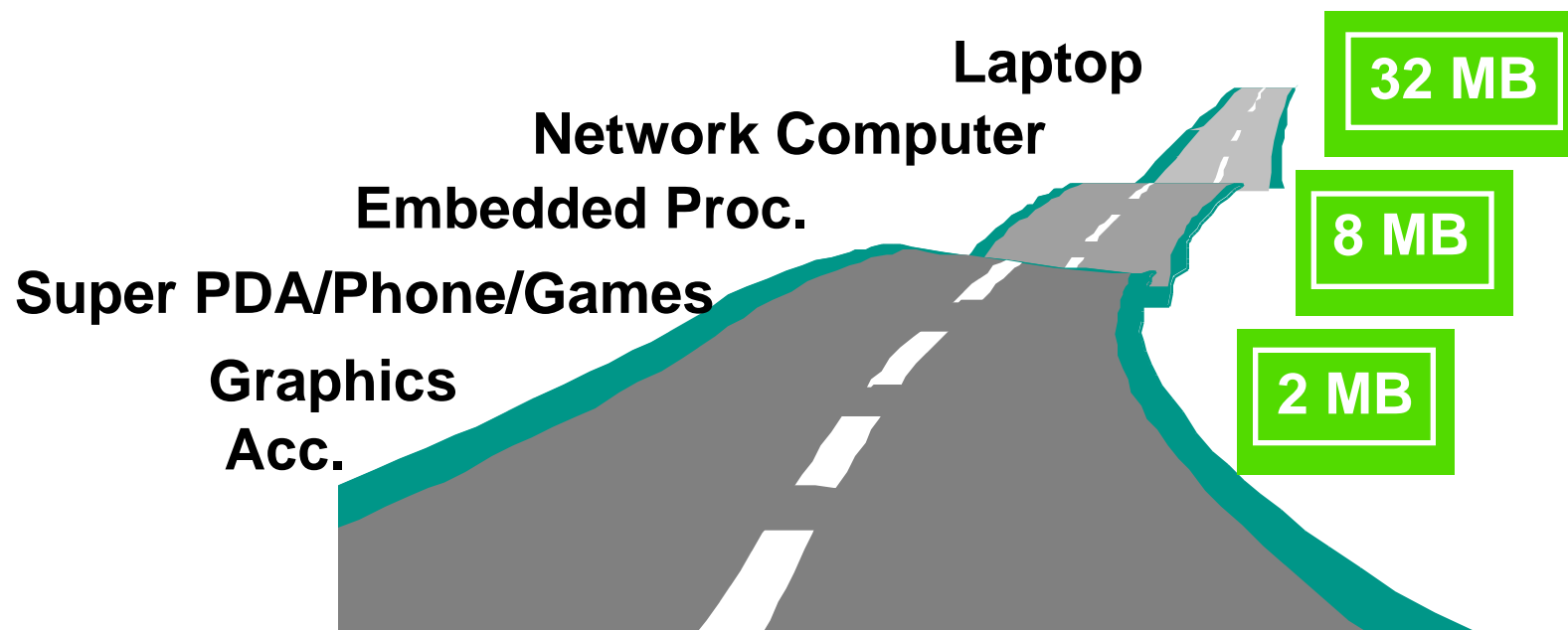
- If IRAM doesn't happen, then someday:
 - \$10B fab for 16B Xtor MPU (too many Xtors per die)??
 - \$10B fab for 16 Gbit DRAM (too many bits per die)??
- This is not rocket science. In 1997:
 - 25-50X improvement in memory density;
⇒ more memory per die or smaller die
 - 10X -100X improvement in memory 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 fab₃₃

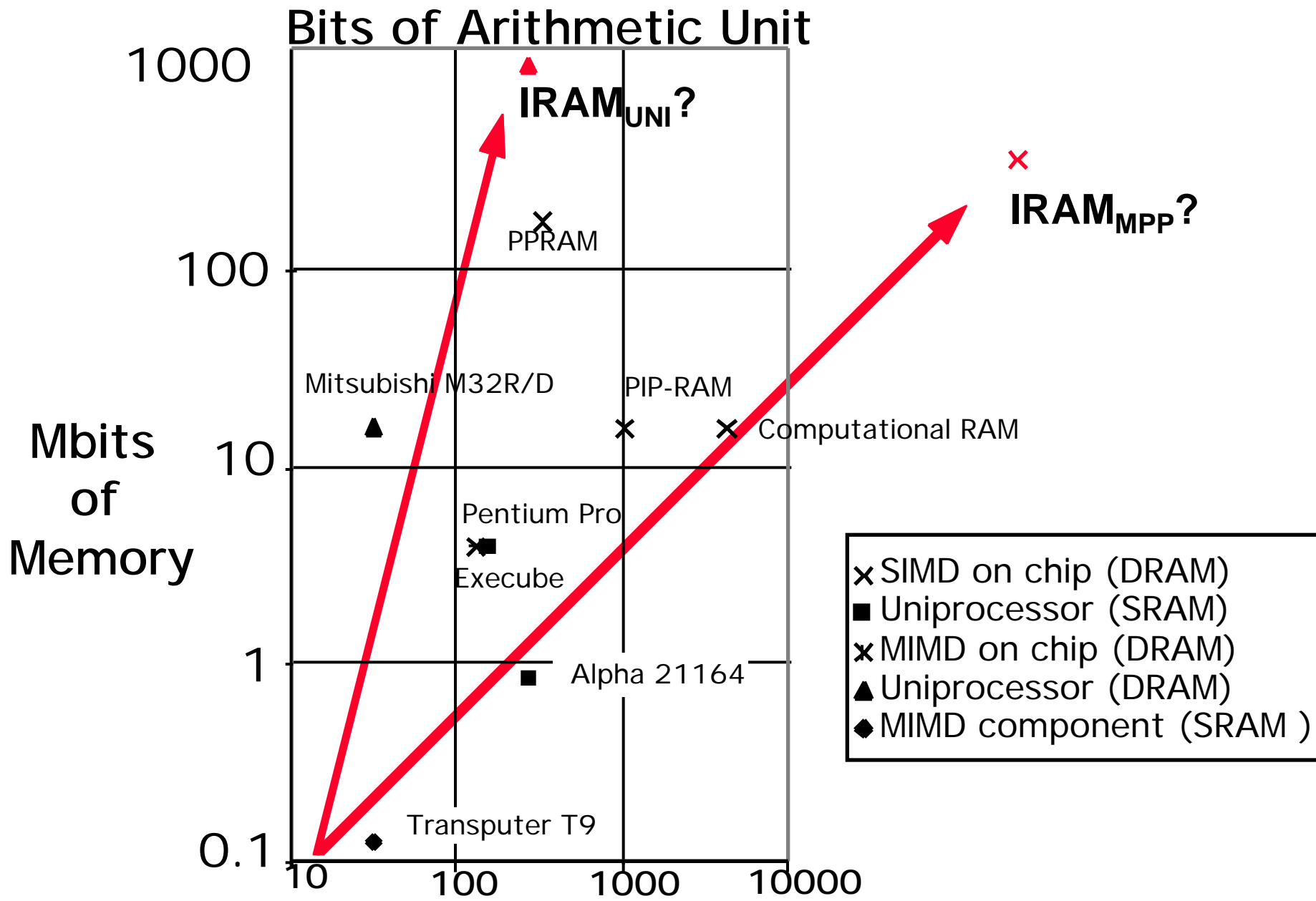
Words to Remember

“...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	<i>(n.a.)</i>

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

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?,

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, I/O, and Compilers/OS (1996-200?)