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)

Performance vs. Time

- CPU: 60%/yr.
- DRAM: 7%/yr.

Processor-Memory Performance Gap: (grows 50% / year)
# Processor-Memory Performance Gap “Tax”

<table>
<thead>
<tr>
<th>Processor</th>
<th>% Area</th>
<th>% Transistors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha 21164</td>
<td>37%</td>
<td>77%</td>
</tr>
<tr>
<td>StrongArm SA110</td>
<td>61%</td>
<td>94%</td>
</tr>
<tr>
<td>Pentium Pro</td>
<td>64%</td>
<td>88%</td>
</tr>
</tbody>
</table>

- 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): $340 \text{ ns} / 5.0 \text{ ns} = 68 \text{ clks} \times 2 \text{ or } 136$
    2nd Alpha (8400): $266 \text{ ns} / 3.3 \text{ ns} = 80 \text{ clks} \times 4 \text{ or } 320$
    3rd Alpha (t.b.d.): $180 \text{ ns} / 1.7 \text{ ns} = 108 \text{ clks} \times 6 \text{ or } 648$
  - $1/2X$ 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)

<table>
<thead>
<tr>
<th>Minimum Memory Size</th>
<th>‘86</th>
<th>‘89</th>
<th>‘92</th>
<th>‘96</th>
<th>‘99</th>
<th>‘02</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Mb</td>
<td>4 Mb</td>
<td>16 Mb</td>
<td>64 Mb</td>
<td>256 Mb</td>
<td>1 Gb</td>
</tr>
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### DRAM Generation

<table>
<thead>
<tr>
<th>Memory per DRAM growth @ 60% / year</th>
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<tbody>
<tr>
<td>4 MB</td>
</tr>
<tr>
<td>8 MB</td>
</tr>
<tr>
<td>16 MB</td>
</tr>
<tr>
<td>32 MB</td>
</tr>
<tr>
<td>64 MB</td>
</tr>
<tr>
<td>128 MB</td>
</tr>
<tr>
<td>256 MB</td>
</tr>
</tbody>
</table>

### Memory per System growth @ 25% / year

| 8 MB | 2 |
| 16 MB| 4 |
| 32 MB| 8 |
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 ≠ 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
  ⇒ 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 \(\Rightarrow\) 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? @ ≈ 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: 
  $\approx 1\text{M} / \text{processor}$?
- $\approx 5\text{-}10\text{M}$ 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 (∼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 (∼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 ⇒ 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: \( \approx N \ \text{MIPS} \)
  - Large memory: \( N \ \text{Mbit/s disk I/O} \) & \( 2N \ \text{Mb/s Network} \)
  - Small memory: \( 2N \ \text{Mbit/s disk I/O} \) & \( 2N \ \text{Mb/s Network} \)
- Serial I/O at 2-4 Ghz today
- IRAM: \( \approx 2-4 \ \text{GIPS} + 2 \ 2-4Gb/s \ I/O + 2 \ 2-4Gb/s \ \text{Net} \)
- 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 ⇒ 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, ...)

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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)
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;
    \[ \Rightarrow \text{more memory per die or smaller die} \]
  - 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

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>IRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>on-chip L1$(SRAM)$</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>on-chip L2$(SRAM v. DRAM)$</td>
<td>2.4</td>
<td>1.6</td>
</tr>
<tr>
<td>L1 to Memory (off- v. on-chip)</td>
<td>98.5</td>
<td>4.6</td>
</tr>
<tr>
<td>L2 to Memory (off-chip)</td>
<td>316.0</td>
<td>(n.a.)</td>
</tr>
</tbody>
</table>

» Based on Digital StrongARM, 0.35 µm technology
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?)