EEL 5764: Graduate Computer Architecture

Appendix C – Memory Hierarchy Review

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These slides are provided by:
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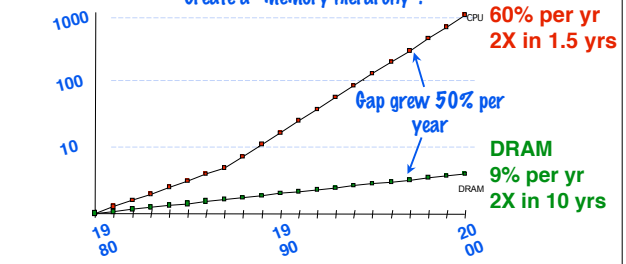
Modifications/additions have been made from the originals

Since 1980, CPU has outpaced DRAM ...

Q. How do architects address this gap?
A. Put smaller, faster "cache" memories between CPU and DRAM. Create a "memory hierarchy".



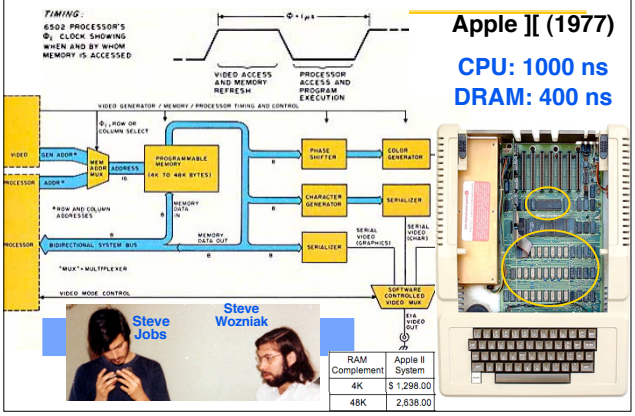
CPU 60% per yr 2X in 1.5 yrs

DRAM 9% per yr 2X in 10 yrs

1977: DRAM faster than microprocessors

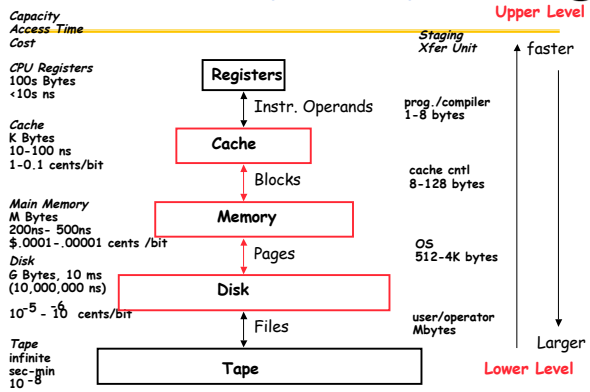
Apple][(1977)

CPU: 1000 ns
DRAM: 400 ns



RAM Complement	Apple II System
4K	$ 1,298.00
48K	2,638.00

Levels of the Memory Hierarchy



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Memory Hierarchy: Apple iMac G5

Managed by compiler | Managed by hardware | Managed by OS, hardware, application

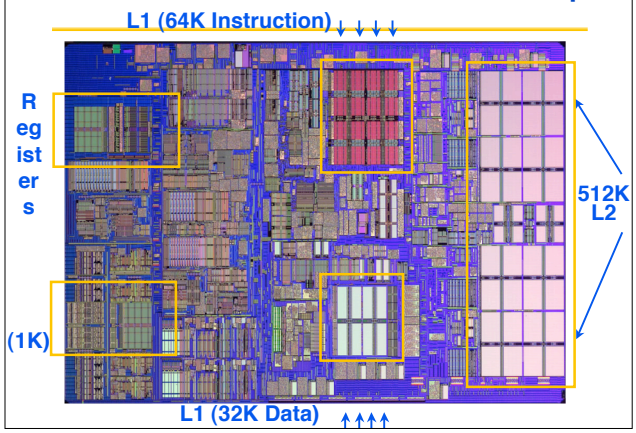
07	Reg	L1 Inst	L1 Data	L2	DRAM	Disk
Size	1K	64K	32K	512K	256M	80G
Latency Cycles, Time	1, 0.6 ns	3, 1.9 ns	3, 1.9 ns	11, 6.9 ns	88, 55 ns	10^7, 12 ms

iMac G5 1.6 GHz

Goal: Illusion of large, fast, cheap memory

Let programs address a memory space that scales to the disk size, at a speed that is usually as fast as register access

iMac's PowerPC 970: All caches on-chip



The Principle of Locality

- The Principle of Locality:
  - Program access a relatively small portion of the address space at any instant of time.
- Two Different Types of Locality:
  - Temporal Locality (Locality in Time): If an item is referenced, it will tend to be referenced again soon (e.g., loops, reuse)
  - Spatial Locality (Locality in Space): If an item is referenced, items whose addresses are close by tend to be referenced soon (e.g., straightline code, array access)
- Last 15 years, HW relied on locality for speed

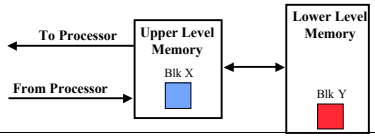
It is a property of programs which is exploited in machine design.

Programs with locality cache well ...

Donald J. Hatfield, Jeanette Gerald: Program Restructuring for Virtual Memory. IBM Systems Journal 10(3): 168-192 (1971)

Memory Hierarchy: Terminology

- Hit: data appears in some block in the upper level (example: Block X)
  - Hit Rate: the fraction of memory access found in the upper level
  - Hit Time: Time to access the upper level which consists of RAM access time + Time to determine hit/miss
- Miss: data needs to be retrieve from a block in the lower level (Block Y)
  - Miss Rate = 1 - (Hit Rate)
  - Miss Penalty: Time to replace a block in the upper level + Time to deliver the block the processor
- Hit Time << Miss Penalty (500 instructions)
  - May be better to recalculate results instead of refetching



Cache Measures

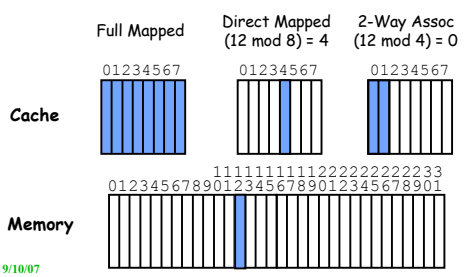
- *Hit rate*: fraction found in that level
  - So high that usually talk about *Miss rate*
  - Miss rate fallacy: as MIPS to CPU performance, miss rate to average memory access time in memory
- Average memory-access time
  = Hit time + Miss rate x Miss penalty
  (ns or clocks)
- *Miss penalty*: time to replace a block from lower level, including time to replace in CPU
  - *access time*: time to lower level
    = f(latency to lower level)
  - *transfer time*: time to transfer block
    =f(BW between upper & lower levels)

4 Questions for Memory Hierarchy

- Q1: Where can a block be placed in the upper level? *(Block placement)*
- Q2: How is a block found if it is in the upper level? *(Block identification)*
- Q3: Which block should be replaced on a miss? *(Block replacement)*
- Q4: What happens on a write? *(Write strategy)*

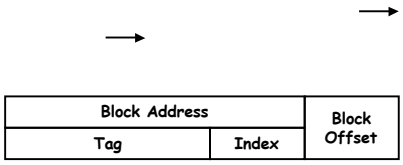
Q1: Where can a block be placed in the upper level?

- Block 12 placed in 8 block cache:
  - Fully associative, direct mapped, 2-way set associative
  - S.A. Mapping = Block Number Modulo Number Sets



Q2: How is a block found if it is in the upper level?

- Tag on each block
  - No need to check index or block offset
- Increasing associativity shrinks index, expands tag



Q3: Which block should be replaced on a miss?

- Easy for Direct Mapped
- Set Associative or Fully Associative:
  - Random
  - LRU (Least Recently Used)

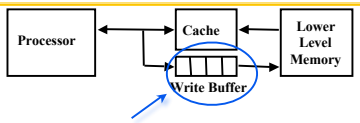
Assoc:	2-way		4-way		8-way	
Size	LRU	Ran	LRU	Ran	LRU	Ran
16 KB	5.2%	5.7%	4.7%	5.3%	4.4%	5.0%
64 KB	1.9%	2.0%	1.5%	1.7%	1.4%	1.5%
256 KB	1.15%	1.17%	1.13%	1.13%	1.12%	1.12%

Q4: What happens on a write?

	Write-Through	Write-Back
Policy	Data written to cache block also written to lower-level memory	Write data only to the cache Update lower level when a block falls out of the cache
Debug	Easy	Hard
Do read misses produce writes?	No	Yes
Do repeated writes make it to lower level?	Yes	No

Additional option -- let writes to an un-cached address allocate a new cache line ("write-allocate").

Write Buffers for Write-Through Caches



Holds data awaiting write-through to lower level memory

Q. Why a write buffer ?
A. So CPU doesn't stall

Q. Why a buffer, why not just one register ?
A. Bursts of writes are common.

Q. Are Read After Write (RAW) hazards an issue for write buffer?
A. Yes! Drain buffer before next read, or send read 1st after check write buffers.

5 Basic Cache Optimizations

- Reducing Miss Rate

1. Larger Block size (compulsory misses)
2. Larger Cache size (capacity misses)
3. Higher Associativity (conflict misses)

- Reducing Miss Penalty

4. Multilevel Caches

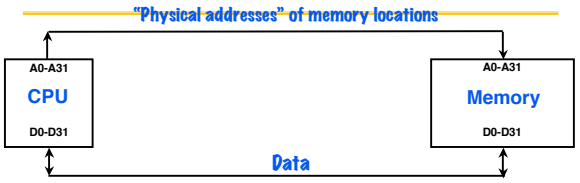
- Reducing hit time

5. Giving Reads Priority over Writes
   - E.g., Read complete before earlier writes in write buffer

Outline

- Memory hierarchy
- Locality
- Cache design
- Virtual address spaces
- Page table layout
- TLB design options

The Limits of Physical Addressing

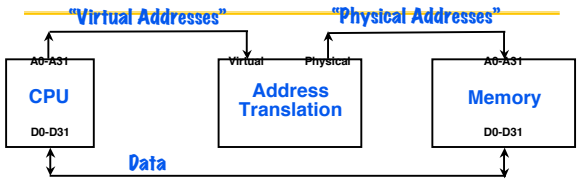


All programs share one address space:
The physical address space

Machine language programs must be aware of the machine organization

No way to prevent a program from accessing any machine resource

Solution: Add a Layer of Indirection



User programs run in an standardized virtual address space

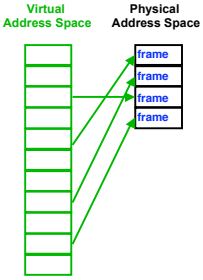
Address Translation hardware managed by the operating system (OS) maps virtual address to physical memory

Hardware supports "modern" OS features: Protection, Translation, Sharing

Three Advantages of Virtual Memory

- Translation:
  - Program can be given consistent view of memory, even though physical memory is scrambled
  - Makes multithreading reasonable (now used a lot!)
  - Only the most important part of program ("Working Set") must be in physical memory.
  - Contiguous structures (like stacks) use only as much physical memory as necessary yet still grow later.
- Protection:
  - Different processes protected from each other.
  - Different pages can be given special behavior
    - » (Read Only, Invisible to user programs, etc).
  - Kernel data protected from User programs
  - Very important for protection from malicious programs
- Sharing:
  - Can map same physical page to multiple users ("Shared memory")

Page tables encode virtual address spaces



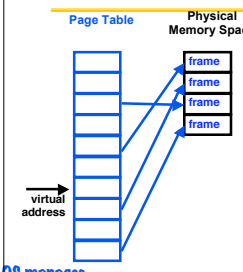
A virtual address space is divided into blocks of memory called pages

A machine usually supports pages of a few sizes (MIPS R4000):

Page Size
4 Kbytes
16 Kbytes
64 Kbytes
256 Kbytes
1 Mbyte
4 Mbytes
16 Mbytes

A valid page table entry codes physical memory "frame" address for the page

Page tables encode virtual address spaces



OS manages the page table for each ASID

A virtual address space is divided into blocks of memory called pages

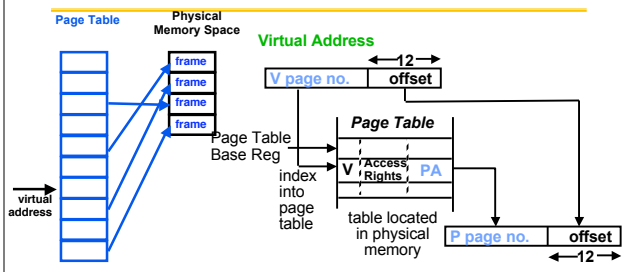
A machine usually supports pages of a few sizes (MIPS R4000):

Page Size
4 Kbytes
16 Kbytes
64 Kbytes
256 Kbytes
1 Mbyte
4 Mbytes
16 Mbytes

A page table is indexed by a virtual address

A valid page table entry codes physical memory "frame" address for the page

Details of Page Table



- Page table maps virtual page numbers to physical frames ("PTE" = Page Table Entry)
- Virtual memory => treat memory ≈ cache for disk

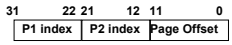
Page tables may not fit in memory!

A table for 4KB pages for a 32-bit address space has 1M entries

Each process needs its own address space!

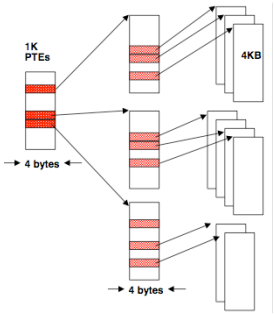
Two-level Page Tables

32 bit virtual address



Top-level table wired in main memory

Subset of 1024 second-level tables in main memory; rest are on disk or unallocated



VM and Disk: Page replacement policy

Page Table

dirty	used	
1	0	...
1	0	
0	1	
1	1	
0	0	

Dirty bit: page written.

Used bit: set to 1 on any reference

Set of all pages in Memory

Tail pointer: Clear the used bit in the page table

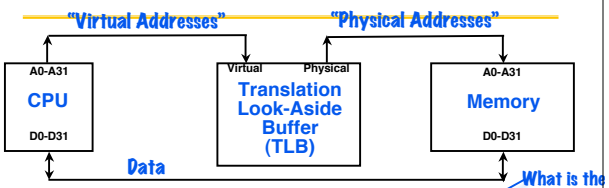
Head pointer: Place pages on free list if used bit is still clear. Schedule pages with dirty bit set to be written to disk.

Freelist

Free Pages

Architect's role: support setting dirty and used bits

MIPS Address Translation: How does it work?



What is the table of mappings that it caches?

Translation Look-Aside Buffer (TLB)

A small fully-associative cache of mappings from virtual to physical addresses

TLB also contains protection bits for virtual address

Fast common case: Virtual address is in TLB, process has permission to read/write it.