CS61C
Review of Cache/VM/TLB

Lecture 26

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Outline

- Review Pipelining
- Review Cache/VM/TLB Review slides
- Administrivia, "What's this Stuff Good for?"
- 4 Questions on Memory Hierarchy
- Detailed Example
- 3Cs of Caches (if time permits)
- Cache Impact on Algorithms (if time permits)
- Conclusion

Review 1/3: Pipelining Introduction

- Pipelining is a fundamental concept
  - Multiple steps using distinct resources
  - Exploiting parallelism in instructions
- What makes it easy? (MIPS vs. 80x86)
  - All instructions are the same length
    ⇒ simple instruction fetch
  - Just a few instruction formats
    ⇒ read registers before decode instruction
  - Memory operands only in loads and stores
    ⇒ fewer pipeline stages
  - Data aligned ⇒ 1 memory access / load, store

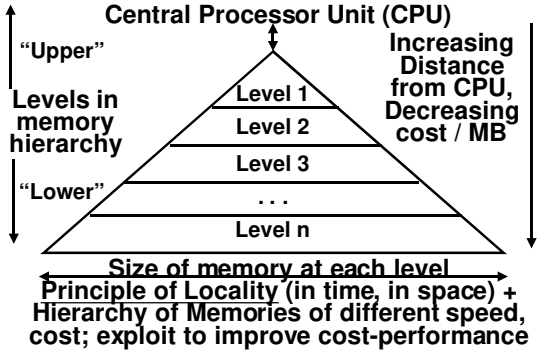
Review 2/3: Pipelining Introduction

- What makes it hard?
- Structural hazards: suppose we had only one cache?
  ⇒ Need more HW resources
- Control hazards: need to worry about branch instructions?
  ⇒ Branch prediction, delayed branch
- Data hazards: an instruction depends on a previous instruction?
  ⇒ need forwarding, compiler scheduling

Review 3/3: Advanced Concepts

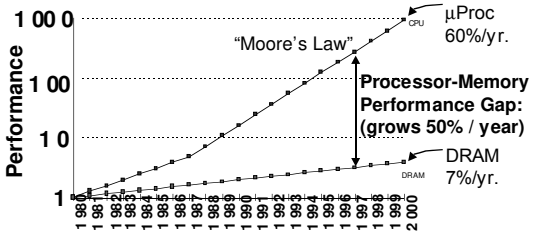
- Superscalar Issue, Execution, Retire:
  - Start several instructions each clock cycle (1999: 3-4 instructions)
  - Execute on multiple units in parallel
  - Retire in parallel; HW guarantees appearance of simple single instruction execution
- Out-of-order Execution:
  - Instructions issue in-order, but execute out-of-order when hazards occur (load-use, cache miss, multiplier busy, ...)
  - Instructions retire in-order; HW guarantees appearance of simple in-order execution

Memory Hierarchy Pyramid



Principle of Locality (in time, in space) +
Hierarchy of Memories of different speed, cost; exploit to improve cost-performance

Why Caches?



1989 first Intel CPU with cache on chip; Today 37% area of Alpha 21164, 61% StrongArm SA110, 64% Pentium Pro

Why virtual memory? (1/2)

- Protection
  - regions of the address space can be read only, execute only, . . .
- Flexibility
  - portions of a program can be placed anywhere, without relocation
- Expandability
  - can leave room in virtual address space for objects to grow
- Storage management
  - allocation/deallocation of variable sized blocks is costly and leads to (external) fragmentation

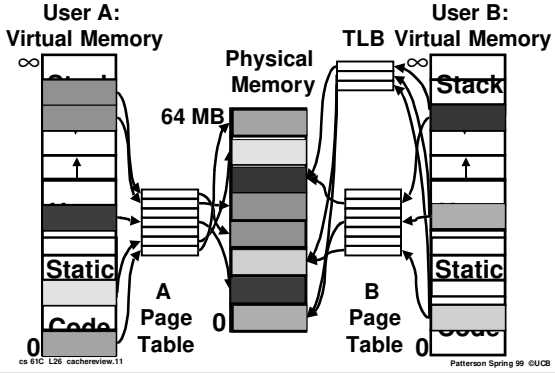
Why virtual memory? (2/2)

- Generality
  - ability to run programs larger than size of physical memory
- Storage efficiency
  - retain only most important portions of the program in memory
- Concurrent I/O
  - execute other processes while loading/dumping page

Why Translation Lookaside Buffer (TLB)?

- Paging is most popular implementation of virtual memory (vs. base/bounds)
- Every paged virtual memory access must be checked against Entry of Page Table in memory
- Cache of Page Table Entries makes address translation possible without memory access in common case

Paging/Virtual Memory Review



Three Advantages of Virtual Memory

1) Translation:
- Program can be given consistent view of memory, even though physical memory is scrambled
- Makes multiple processes reasonable
- 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.

Three Advantages of Virtual Memory

2) 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 ⇒ Far more "viruses" under Microsoft Windows

3) Sharing:
- Can map same physical page to multiple users ("Shared memory")

Virtual Memory Summary

° Virtual Memory allows protected sharing of memory between processes with less swapping to disk, less fragmentation than always swap or base/bound

° 3 Problems:

1) Not enough memory: Spatial Locality means small Working Set of pages OK

2) TLB to reduce performance cost of VM

3) Need more compact representation to reduce memory size cost of simple 1-level page table, especially for 64-bit address (See CS 162)

Administrivia

° 11th homework (last): Due Today

° Next Readings: A.7

M 5/3 Deadline to correct your grade record (up to 11th lab, 10th homework, 5th project)

W 5/5 Review: Interrupts / Polling; A.7
F 5/7 61C Summary / Your Cal heritage / HKN Course Evaluation
(Due: Final 61C Survey in lab)

Sun 5/9 Final Review starting 2PM (1 Pimintel)

W5/12 Final (5-8PM 1 Pimintel)
- Need Early Final? Contact mds@cory

"What's This Stuff (Potentially) Good For?"

Allow civilians to find mines, mass graves, plan disaster relief?

Private Spy in Space to Rival Military's Ikonos 1 spacecraft is just 0.8 tons, 15 feet long with its solar panels extended, it runs on just 1,200 watts of power -- a bit more than a toaster. It sees objects as small as one meter, and covers Earth every 3 days. The company plans to sell the imagery for $25 to $300 per square mile via www.spaceimaging.com. "We believe it will fundamentally change the approach to many forms of information that we use in business and our private lives." **N.Y. Times, 4/27/99**

4 Questions for Memory Hierarchy

° Q1: Where can a block be placed in the upper level? *(Block placement)*

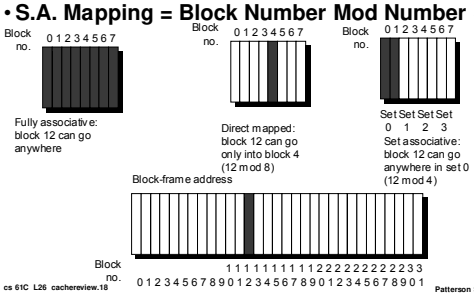
° Q2: How is a block found if it is in the upper level? *(Block identification)*

° Q3: Which block should be replaced on a miss? *(Block replacement)*

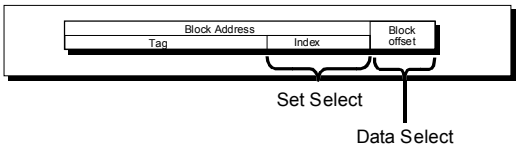
° Q4: What happens on a write? *(Write strategy)*

Q1: Where block placed in upper level?

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



Q2: How is a block found in upper level?



- Direct indexing (using index and block offset), tag compares, or combination
- Increasing associativity shrinks index, expands tag

Q3: Which block replaced on a miss?

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

Miss Rates

Associativity:	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—The information is written to both the block in the cache and to the block in the lower-level memory.
- Write back—The information is written only to the block in the cache. The modified cache block is written to main memory only when it is replaced.
  - is block clean or dirty?
- Pros and Cons of each?
  - WT: read misses cannot result in writes
  - WB: no writes of repeated writes
- WT always combined with write buffers

Comparing the 2 levels of hierarchy

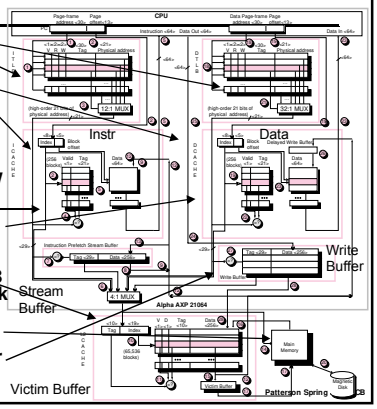
Cache Version	Virtual Memory vers.
Block or Line	Page
Miss	Page Fault
Block Size: 32-64B	Page Size: 4K-8KB
Placement: Direct Mapped, N-way Set Associative	Fully Associative
Replacement: LRU or Random	Least Recently Used (LRU)
Write Thru or Back	Write Back

Picking Optimal Page Size

- Minimize wasted storage
  - small page minimizes internal fragmentation
  - small page increase size of page table
- Minimize transfer time
  - large pages (multiple disk sectors) amortize access cost
  - sometimes transfer unnecessary info
  - sometimes prefetch useful data
  - sometimes discards useless data early
- General trend toward larger pages because
  - big cheap RAM
  - increasing mem / disk performance gap
  - larger address spaces

Alpha 21064

- Separate Instr & Data TLB
- Separate Instr & Data Caches
- TLBs fully associative
- TLB updates in SW
- Caches 8KB direct mapped, write thru
- 2 MB L2 cache, direct mapped, WB (off-chip) 32B block
- 256-bit to memory
- 4 entry write buffer between D$ & L2$



Starting an Alpha 21064: 1/6

- Starts in kernel mode where memory is not translated
- Since software managed TLB, 1st load TLB with 12 valid mappings for process in Instruction TLB
- Sets the PC to appropriate address for user program and goes into user mode
- Page frame portion of 1st instruction access is sent to Instruction TLB: checks for valid PTE and access rights match (otherwise an exception for page fault or access violation)

Starting an Alpha 21064: 2/6

- Since 256 32-byte blocks in instruction cache, 8-bit index selects the I cache block
- Translated address is compared to cache block tag (assuming tag entry is valid)
- If hit, proper 4 bytes of block sent to CPU
- If miss, address sent to L2 cache; its 2MB cache has 64K 32-byte blocks, so 16-bit index selects the L2 cache block; address tag compared (assuming its valid)
- If L2 cache hit, 32-bytes in 10 clock cycles

Starting an Alpha 21064: 3/6

- If L2 cache miss, 32-bytes in 36 clocks
- Since L2 cache is write back, any miss can result in a write to main memory; old block placed into buffer and new block fetched first; after new block loaded, and old block is written to memory if old block is dirty

Starting an Alpha 21064: 4/6

- Suppose 1st instruction is a load; 1st sends page frame to data TLB
- If TLB miss, software loads with PTE
- If data page fault, OS will switch to another process (since disk access = time to execute millions of instructions)
- If TLB hit and access check OK, send translated page frame address to Data Cache
- 8-bit portion of address selects data cache block; tags compared to see if a hit (if valid)
- If miss, send to L2 cache as before

Starting an Alpha 21064: 5/6

- Suppose instead 1st instruction is a store
- TLB still checked (no protection violations and valid PTE), send translated address to data cache
- Access to data cache as before for hit, except write new data into block
- Since Data Cache is write through, also write data to Write Buffer
- If Data Cache access on store is a miss, also write to write buffer since policy is no allocate on write miss

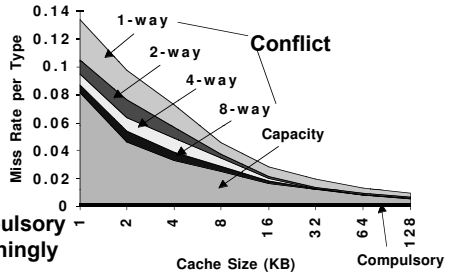
Starting an Alpha 21064: 5/6

- Write buffer checks to see if write is already to address within entry, and if so updates the block
- If 4-entry write buffer is full, stall until entry is written to L2 cache block
- All writes eventually passed to L2 cache
- If miss, put old block in buffer, and since L2 allocates on write miss, load missing data from cache;Write to portion of block,and mark new L2 cache block as dirty;
- If old block in buffer is dirty, then write it to memory

Classifying Misses: 3 Cs

- ***Compulsory***—The first access to a block is not in the cache, so the block must be brought into the cache. *(Misses in even an Infinite Cache)*
- ***Capacity***—If the cache cannot contain all the blocks needed during execution of a program, capacity misses will occur due to blocks being discarded and later retrieved. *(Misses in Fully Associative Size X Cache)*
- ***Conflict***—If block-placement strategy is set associative or direct mapped, conflict misses (in addition to compulsory & capacity misses) will occur because a block can be discarded and later retrieved if too many blocks map to its set. *(Misses in N-way Associative, Size X Cache)*

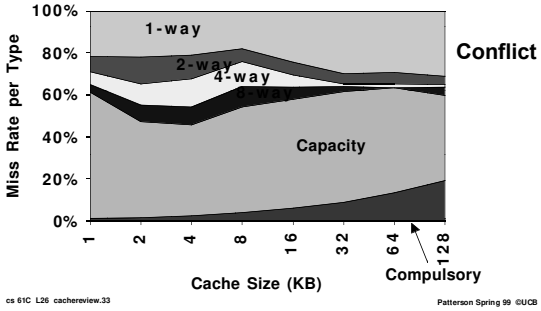
3Cs Absolute Miss Rate (SPEC92)



Compulsory vanishingly small

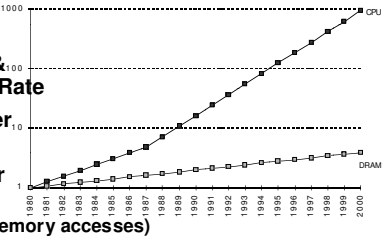
3Cs Relative Miss Rate

3Cs Flaws: for fixed block size
3Cs Pros: insight ⇒ invention

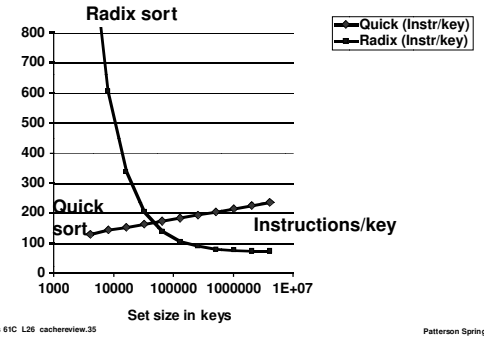


Impact of What Learned About Caches?

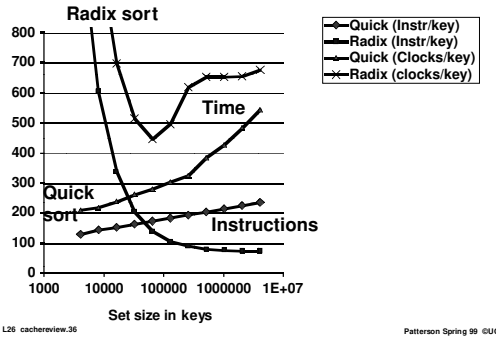
- 1960-1985: Speed = *f*(no. operations)
- 1990s
  - Pipelined Execution & Fast Clock Rate
  - Out-of-Order execution
  - Superscalar
- 1999: Speed = *f*(non-cached memory accesses)
- Superscalar, Out-of-Order machines hide L1 data cache miss (5 clocks) but not L2 cache miss (50 clocks)?



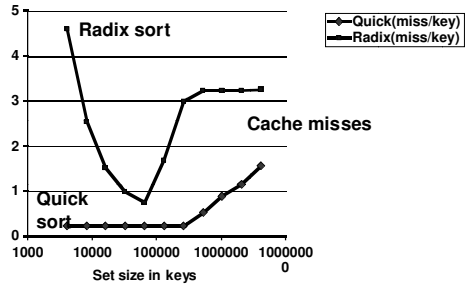
Quicksort vs. Radix as vary number keys: Instructions



Quicksort vs. Radix as vary number keys: Instructions and Time



Quicksort vs. Radix as vary number keys: Cache misses



What is proper approach to fast algorithms?

Cache/VM/TLB Summary: #1/3

- The Principle of Locality:
  - Program access a relatively small portion of the address space at any instant of time.
    - Temporal Locality: Locality in Time
    - Spatial Locality: Locality in Space
- 3 Major Categories of Cache Misses:
  - Compulsory Misses: sad facts of life. Example: cold start misses.
  - Capacity Misses: increase cache size
  - Conflict Misses: increase cache size and/or associativity.

Cache/VM/TLB Summary: #2/3

- Caches, TLBs, Virtual Memory all understood by examining how they deal with 4 questions: 1) Where can block be placed? 2) How is block found? 3) What block is replaced on miss? 4) How are writes handled?
- Page tables map virtual address to physical address
- TLBs are important for fast translation
- TLB misses are significant in processor performance

Cache/VM/TLB Summary: #3/3

- Virtual memory was controversial at the time: can SW automatically manage 64KB across many programs?
  - 1000X DRAM growth removed controversy
- Today VM allows many processes to share single memory without having to swap all processes to disk; VM protection is more important than memory hierarchy
- Today CPU time is a function of (ops, cache misses) vs. just f(ops): What does this mean to Compilers, Data structures, Algorithms?