`inst.eecs.berkeley.edu/~cs61c/su05`

CS61C : Machine Structures

Lecture #23: VM I

2005-08-1

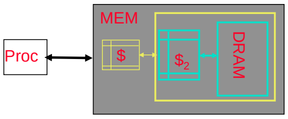
Andy Carle

Outline

- Cache Review
- Virtual Memory

Improving Miss Penalty

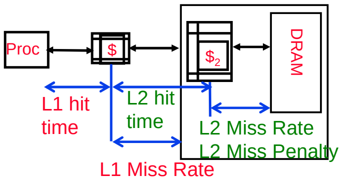
- When caches first became popular, Miss Penalty ~ 10 processor clock cycles
- Today 2400 MHz Processor (0.4 ns per clock cycle) and 80 ns to go to DRAM ⇒ 200 processor clock cycles!



Solution: another cache between memory and the processor cache: Second Level (L2) Cache

---

Analyzing Multi-level cache hierarchy



Avg Mem Access Time =

L1 Hit Time + L1 Miss Rate * L1 Miss Penalty

L1 Miss Penalty = AMAT$_{L2}$ =

L2 Hit Time + L2 Miss Rate * L2 Miss Penalty

Avg Mem Access Time =

L1 Hit Time + L1 Miss Rate *

(L2 Hit Time + L2 Miss Rate * L2 Miss Penalty)

Typical Scale

- L1
  - size: tens of KB
  - hit time: complete in one clock cycle
  - miss rates: 1 – 5%
- L2:
  - size: hundreds of KB
  - hit time: few clock cycles
  - miss rates: 10 – 20%
- L2 miss rate is fraction of L1 misses that also miss in L2
  - why so high?

Example: with L2 cache

- Assume
  - L1 Hit Time = 1 cycle
  - L1 Miss rate = 5%
  - L2 Hit Time = 5 cycles
  - L2 Miss rate = 15% (% L1 misses that miss)
  - L2 Miss Penalty = 200 cycles
- L1 miss penalty = 5 + 0.15 * 200 = 35
- Avg mem access time = 1 + 0.05 x 35
  = 2.75 cycles

Example: without L2 cache

- Assume
  - L1 Hit Time = 1 cycle
  - L1 Miss rate = 5%
  - L1 Miss Penalty = 200 cycles
- Avg mem access time = 1 + 0.05 x 200
  = 11 cycles
- 4x faster with L2 cache! (2.75 vs. 11)

Cache Summary

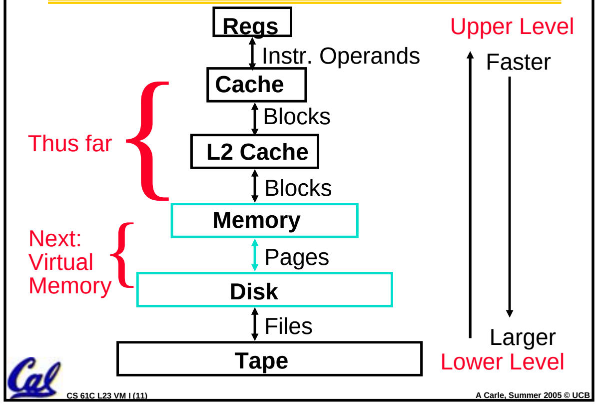
- Cache design choices:
  - size of cache: speed v. capacity
  - direct-mapped v. associative
  - for N-way set assoc: choice of N
  - block replacement policy
  - 2nd level cache?
  - Write through v. write back?
- Use performance model to pick between choices, depending on programs, technology, budget, ...

VM

Generalized Caching

- We've discussed memory caching in detail. Caching in general shows up over and over in computer systems
  - Filesystem cache
  - Web page cache
  - Game Theory databases / tablebases
  - Software memoization
  - Others?
- Big idea: if something is expensive but we want to do it repeatedly, do it once and cache the result.

Another View of the Memory Hierarchy



Memory Hierarchy Requirements

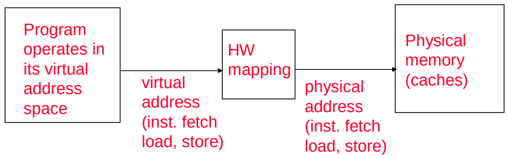
- What else might we want from our memory subsystem? …
  - Share memory between multiple processes but still provide protection – don't let one program read/write memory from another
    - Emacs on star
  - Address space – give each process the illusion that it has its own private memory
    - Implicit in our model of a linker
- Called Virtual Memory

Virtual Memory Big Ideas

- Each address that a program uses (pc, $sp, $gp, .data, etc) is fake (even after linking)!
- Processor inserts new step:
  - Every time we reference an address (in IF or MEM) …
  - Translate fake address to real one.

virtual physical

VM Ramifications



Program operates in its virtual address space

virtual address (inst. fetch load, store)

HW mapping

physical address (inst. fetch load, store)

Physical memory (caches)

- Immediate consequences:
  - Each program can operate in isolation!
  - OS can decide where and when each goes in memory!
  - HW/OS can grant different rights to different processes on same chunk of physical mem!
- Big question:
  - How do we manage the VA➔PA mappings?

(Weak) Analogy

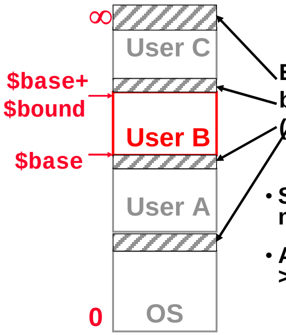
- Book title like virtual address
- Library of Congress call number like physical address
- Card catalogue like page table, mapping from book title to call number
- On card for book, in local library vs. in another branch like valid bit indicating in main memory vs. on disk
- On card, available for 2-hour in library use (vs. 2-week checkout) like access rights

---

VM

- Ok, now how do we implement it?
- Simple solution:
  - Linker assumes start addr at 0x0.
  - Each process has a $base and $bound:
    - $base: start of physical address space
    - $bound: size of physical address space
  - Algorithms:
    - VA➔PA Mapping: PA = VA + $base
    - Bounds check: VA < $bound

Simple Example: Base and Bound Reg



☹ so what's wrong?

Enough space for User D, but discontinuous ("fragmentation problem")

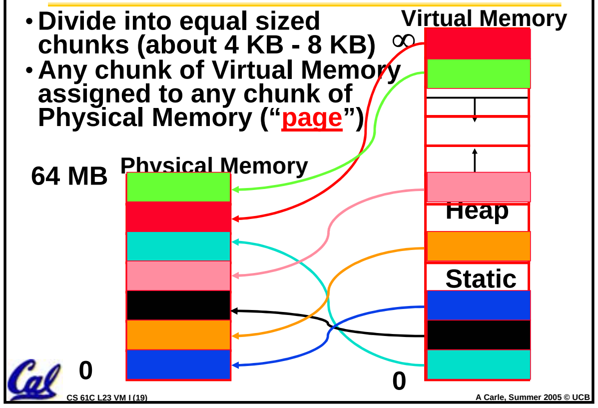
- Same flaws as freelist malloc!
- Also: what if process size > mem
- What to do??

VM Observations

- Working set of process is small, but distributed all over address space ➔
  - Arbitrary mapping function,
    - keep working set in memory
    - rest on disk or unallocated.
- Fragmentation comes from variable-sized physical address spaces
  - Allocate physical memory in fixed sized chunks (1 mapping per chunk)
  - FA placement of chunks
    - i.e. any V chunk of any process can map to any P chunk of memory.

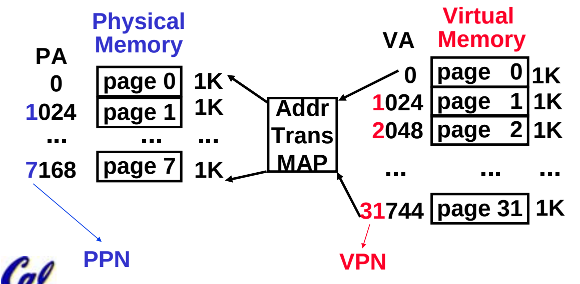
Mapping Virtual Memory to Physical Memory

- Divide into equal sized chunks (about 4 KB - 8 KB)
- Any chunk of Virtual Memory assigned to any chunk of Physical Memory ("page")



Paging Organization

1KB Pages	Page is unit of mapping	Page also unit of transfer from disk to physical memory



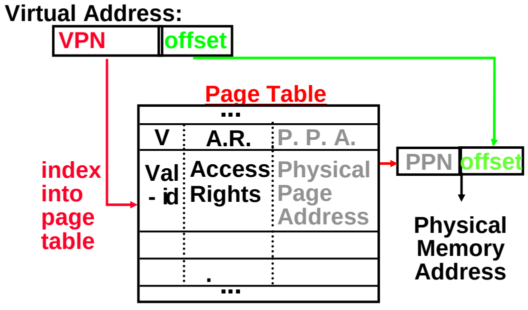
Virtual Memory Mapping Function

Page Number	Offset

- Use table lookup ("Page Table") for mappings: V Page number is index
- Mapping Function
  - Physical Offset = Virtual Offset
  - Physical Page Number = PageTable[Virtual Page Number]

FYI: P.P.N. also called "Page Frame" or "Frame #".

Address Mapping: Page Table



Page Table located in physical memory

Page Table

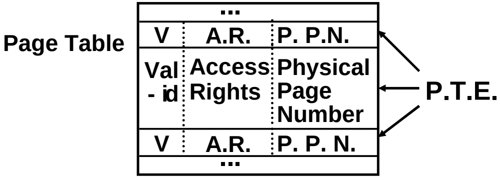
- A page table: mapping function
  - There are several different ways, all up to the operating system, to keep this data around.
  - Each process running in the operating system has its own page table
    - Historically, OS changes page tables by changing contents of Page Table Base Register
      - Not anymore! We'll explain soon.

Requirements revisited

- Remember the motivation for VM:
- Sharing memory with protection
  - Different physical pages can be allocated to different processes (sharing)
  - A process can only touch pages in its own page table (protection)
- Separate address spaces
  - Since programs work only with virtual addresses, different programs can have different data/code at the same address!

Page Table Entry (PTE) Format

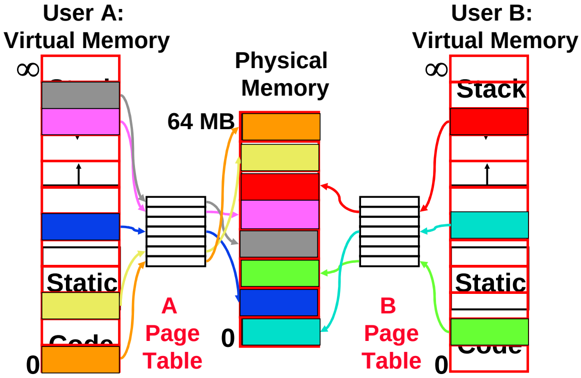
- Contains either Physical Page Number or indication not in Main Memory
- OS maps to disk if Not Valid (V = 0)



- If valid, also check if have permission to use page: **Access Rights** (A.R.) may be Read Only, Read/Write, Executable

---

Paging/Virtual Memory Multiple Processes



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

Notes on Page Table

- OS must reserve "**Swap Space**" on disk for each process
- To grow a process, ask Operating System
  - If unused pages, OS uses them first
  - If not, OS swaps some old pages to disk
  - (Least Recently Used to pick pages to swap)
- Will add details, but Page Table is essence of Virtual Memory

---

Peer Instruction

A. Locality is important yet different for cache and virtual memory (VM): temporal locality for caches but spatial locality for VM

B. Cache management is done by hardware (HW) and page table management is done by software

C. VM helps both with security and cost

And in conclusion…

- Manage memory to disk? Treat as cache
  - Included protection as bonus, now critical
  - Use Page Table of mappings for each user vs. tag/data in cache
- Virtual Memory allows protected sharing of memory between processes
- Spatial Locality means Working Set of Pages is all that must be in memory for process to run fairly well