Caching and Virtual Memory

Last Time

- Cache concept
  - Hardware vs. software caches
- When caches work and when they don't
  - Spatial/temporal locality vs. Zipf workloads

Main Points

- Cache Replacement Policies
  - FIFO, MIN, LRU, LFU, Clock
- Memory-mapped files
- Demand-paged virtual memory
- Other applications of virtual addressing

Cache Replacement Policy

- On a cache miss, how do we choose which entry to replace?
  - Assuming the new entry is more likely to be used in the near future
  - In direct mapped caches, not an issue!
- Policy goal: reduce cache misses
  - Improve expected case performance
  - Also: reduce likelihood of very poor performance

A Simple Policy

- Random?
  - Replace a random entry
- FIFO?
  - Replace the entry that has been in the cache the longest time
  - What could go wrong?

FIFO in Action

Reference	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
1	A				E				D				C		
2		B				A				E				D	
3			C				B				A				E
4				D				C				B			

Worst case for FIFO is if program strides through memory that is larger than the cache

MIN, LRU, LFU

- MIN
  - Replace the cache entry that will not be used for the longest time into the future
  - Optimality proof based on exchange: if evict an entry used sooner, that will trigger an earlier cache miss
- Least Recently Used (LRU)
  - Replace the cache entry that has not been used for the longest time in the past
  - Approximation of MIN
- Least Frequently Used (LFU)
  - Replace the cache entry used the least often (in the recent past)

LRU/MIN for Sequential Scan

								LRU							
Reference	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
1	A				E				D				C		
2		B				A				E				D	
3			C				B				A				E
4				D				C				B			
								MIN							
1	A					+					+			+	
2		B					+					+	C		
3			C					+	D					+	
4				D	E					+					+

LRU															
Reference	A	B	A	C	B	D	A	D	E	D	A	E	B	A	C
1	A		+				+				+			+	
2		B			+								+		
3				C					E			+			
4						D		+		+					C
FIFO															
1	A		+				+		E						
2		B			+						A			+	
3				C								+	B		
4						D		+		+					C
MIN															
1	A		+				+				+			+	
2		B			+								+		C
3				C					E			+			
4						D		+		+					

Belady's Anomaly

FIFO (3 slots)												
Reference	A	B	C	D	A	B	E	A	B	C	D	E
1	A			D			E					+
2		B			A			+		C		
3			C			B			+		D	
FIFO (4 slots)												
1	A				+		E				D	
2		B				+		A				E
3			C						B			
4				D						C		

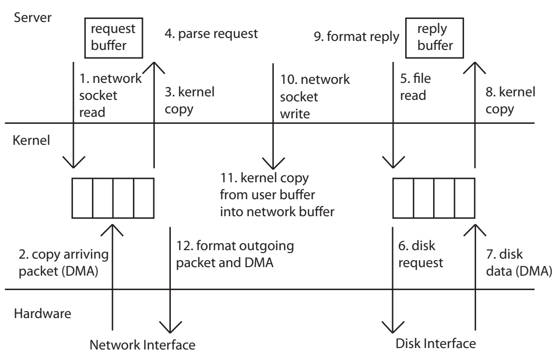
Models for Application File I/O

- Explicit read/write system calls
  - Data copied to user process using system call
  - Application operates on data
  - Data copied back to kernel using system call
- Memory-mapped files
  - Open file as a memory segment
  - Program uses load/store instructions on segment memory, implicitly operating on the file
  - Page fault if portion of file is not yet in memory
  - Kernel brings missing blocks into memory, restarts process

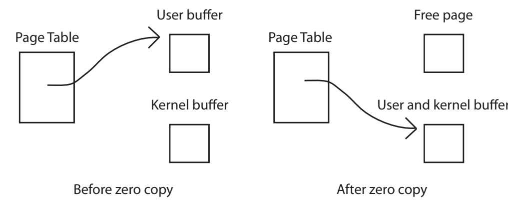
Advantages to Memory-mapped Files

- Programming simplicity, esp for large file
  - Operate directly on file, instead of copy in/copy out
- Zero-copy I/O
  - Data brought from disk directly into page frame
- Pipelining
  - Process can start working before all the pages are populated
- Interprocess communication
  - Shared memory segment vs. temporary file

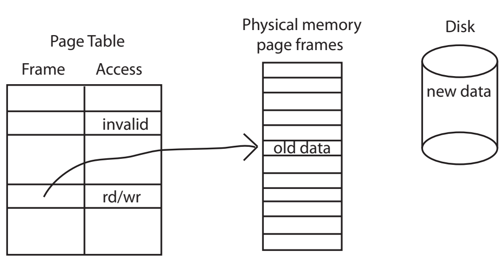
Web Server



Zero Copy I/O
Block Aligned Read/Write System Calls



Demand Paging



Demand Paging

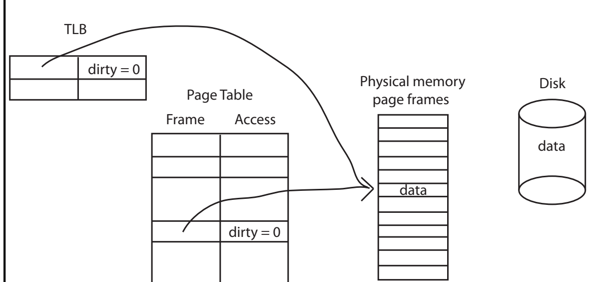
1. TLB miss
2. Page table walk
3. Page fault (page invalid in page table)
4. Trap to kernel
5. Convert address to file + offset
6. Allocate page frame
   – Evict page if needed
7. Initiate disk block read into page frame
8. Disk interrupt when DMA complete
9. Mark page as valid
10. Resume process at faulting instruction
11. TLB miss
12. Page table walk to fetch translation
13. Execute instruction

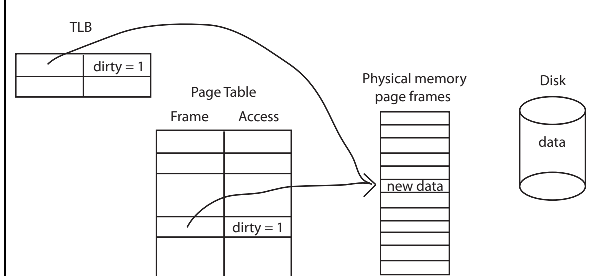
Allocating a Page Frame

- Select old page to evict
- Find all page table entries that refer to old page
  - If page frame is shared
- Set each page table entry to invalid
- Remove any TLB entries
  - Copies of now invalid page table entry
- Write changes to page to disk, if necessary

How do we know if page has been modified?

- Every page table entry has some bookkeeping
  - Has page been modified?
    - Set by hardware on store instruction to page
    - In both TLB and page table entry
  - Has page been used?
    - Set by hardware on load or store instruction to page
    - In page table entry on a TLB miss
- Can be reset by the OS kernel
  - When changes to page are flushed to disk
  - To track whether page is recently used





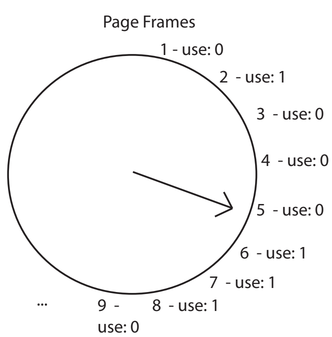
Emulating a Modified Bit

- Some processor architectures do not keep a modified bit in the page table entry
  - Extra bookkeeping and complexity
- OS can emulate a modified bit:
  - Set all clean pages as read-only
  - On first write, take page fault to kernel
  - Kernel sets modified bit, marks page as read-write

Emulating a Use Bit

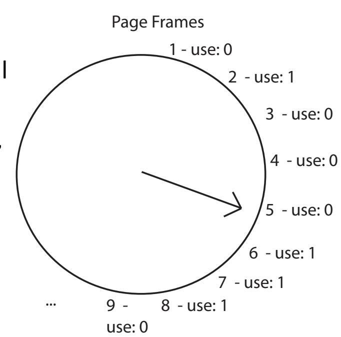
- Some processor architectures do not keep a use bit in the page table entry
  - Extra bookkeeping and complexity
- OS can emulate a use bit:
  - Set all unused pages as invalid
  - On first read/write, take page fault to kernel
  - Kernel sets use bit, marks page as read or read/write

Clock Algorithm: Estimating LRU



Clock Algorithm: Estimating LRU

- Periodically, sweep through all pages
- If page is unused, reclaim
- If page is used, mark as unused



Nth Chance: Not Recently Used

- Periodically, sweep through all page frames
- If page hasn't been used in any of the past N sweeps, reclaim
- If page is used, mark as unused and set as active in current sweep

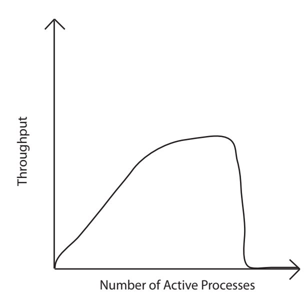
From Memory-Mapped Files to Demand-Paged Virtual Memory

- Every process segment backed by a file on disk
  - Code segment -> code portion of executable
  - Data, heap, stack segments -> temp files
  - Shared libraries -> code file and temp data file
  - Memory-mapped files -> memory-mapped files
  - When process ends, delete temp files
- Provides the illusion of an infinite amount of memory to programs
  - Unified LRU across file buffer and process memory

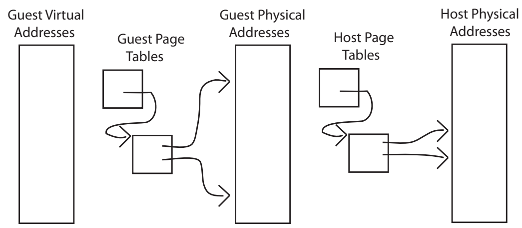
Question

- What happens to system performance as we increase the number of processes?
  - If the sum of the working sets > physical memory?

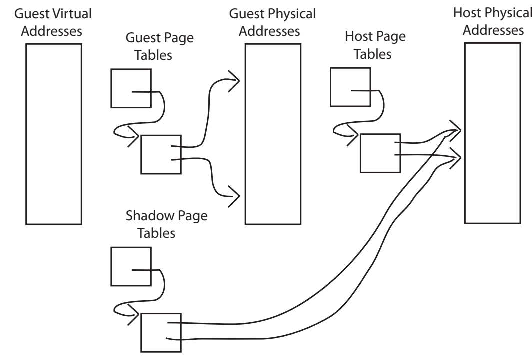
Thrashing



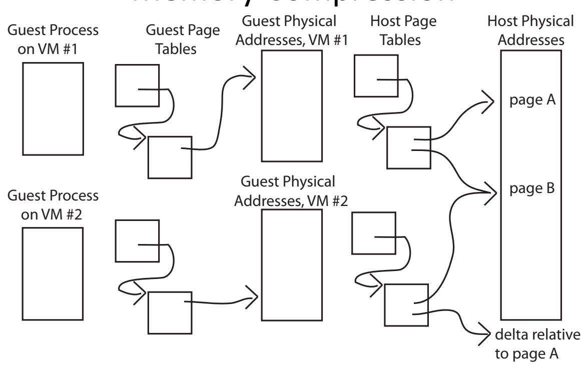
Virtual Machines and Virtual Memory



Shadow Page Tables



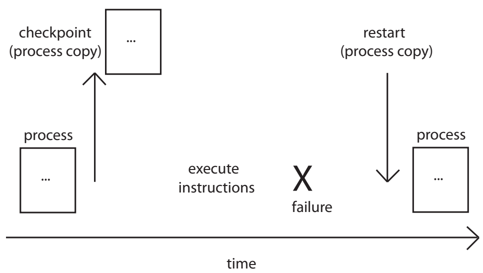
Memory Compression



Definitions

- Checkpoint
- Restart

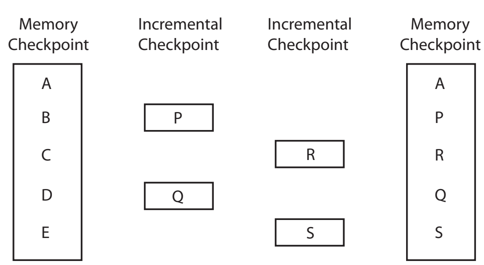
Transparent Checkpoint



Question

- How long do we need to wait between starting the checkpoint and resuming the execution of the program?

Incremental Checkpoint



Question

- What if we restart the process on a different machine?
  – Process migration!
- What if we checkpoint only key data structures?
  – Recoverable virtual memory