COS 318: Operating Systems

Virtual Memory Design Issues

Jaswinder Pal Singh
Computer Science Department
Princeton University

(http://www.cs.princeton.edu/courses/cos318/)

Design Issues

- Thrashing and working set
- Backing store
- Multiple page sizes and PT entries
- Pinning/locking pages
- Zero pages
- Shared pages
- Copy-on-write
- Distributed shared memory
- Virtual memory in Unix and Linux
- Virtual memory in Windows 2000

Virtual Memory Design Implications

- Revisit Design goals
  - Protection
    - Isolate faults among processes
  - Virtualization
    - Use disk to extend physical memory
    - Make virtualized memory user friendly (from 0 to high address)
- Implications
  - TLB and page table overhead and management
  - Paging between DRAM and disk
- VM access time

  Access time = h · memory access time + (1 - h) · disk access time

  - E.g. Suppose memory access time = 100ns, disk access time = 10ms
    - If h = 90%, VM access time is 1ms!

Thrashing

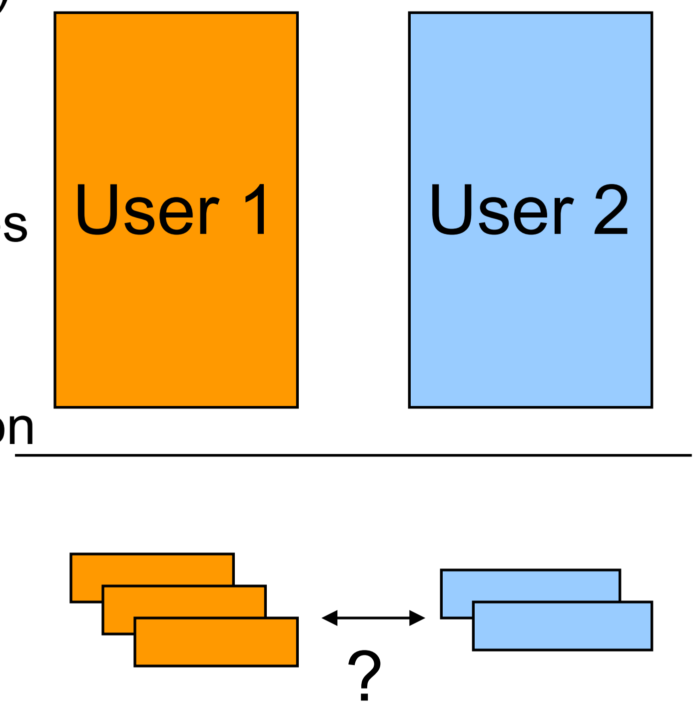
- Thrashing
  - Paging in and paging out all the time, I/O devices fully utilized
  - Processes block, waiting for pages to be fetched from disk
- Reasons
  - Process requires more physical memory than it has
  - Process does not reuse memory well
  - Process reuses memory, but what it needs does not fit
  - Too many processes, even though they individually fit
- Solution: **working set** (last lecture)
  - Pages referenced by a process in the last T seconds
  - Two design questions
    - Which working set should be in memory?
    - How to allocate pages?

Working Set: Fit in Memory

- Maintain two groups of processes
  - Active: working set loaded
  - Inactive: working set intentionally not loaded
- Two schedulers
  - A short-term scheduler schedules active processes
  - A long-term scheduler decides which arenactive and which inactive, such that active working sets fit in memory
- A key design point
  - How to decide which processes should be inactive
  - Typical method is to use a threshold on waiting time

Working Set: Global vs. Local Page Allocation

- The simplest is global allocation only
  - Pros: Pool sizes are adaptable
  - Cons: Too adaptable, little isolation (example?)
- A balanced allocation strategy
  - Each process has its own pool of pages
  - Paging allocates from its own pool and replaces from its own working set
  - Use a “slow” mechanism to change the allocations to each pool while providing isolation
- Design questions:
  - What is “slow?”
  - How big is each pool?
  - When to migrate?

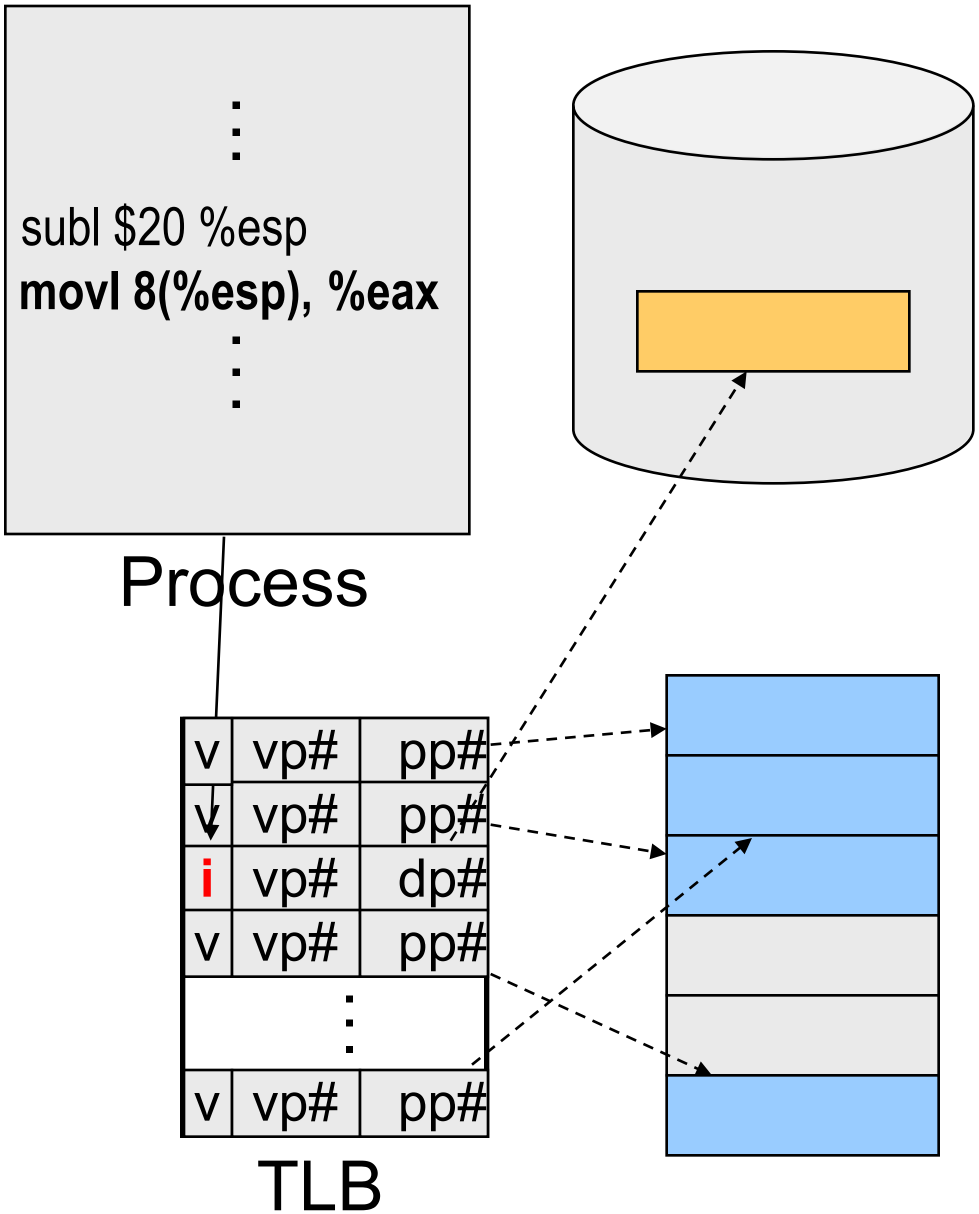


Backing Store

- Swap space
  - When process is created, allocate a swap space for it
  - Need to load or copy executables to the swap space
  - Need to consider process space growth
- Page creation
  - Allocate a disk address?
  - What if the page never swaps out?
  - What if the page never gets modified?
- Swap out
  - Use the same disk address?
  - Allocate a new disk address?
  - Swap out one or multiple pages?
- Text pages
  - They are read only in most cases. Treat them differently?

Revisit Address Translation

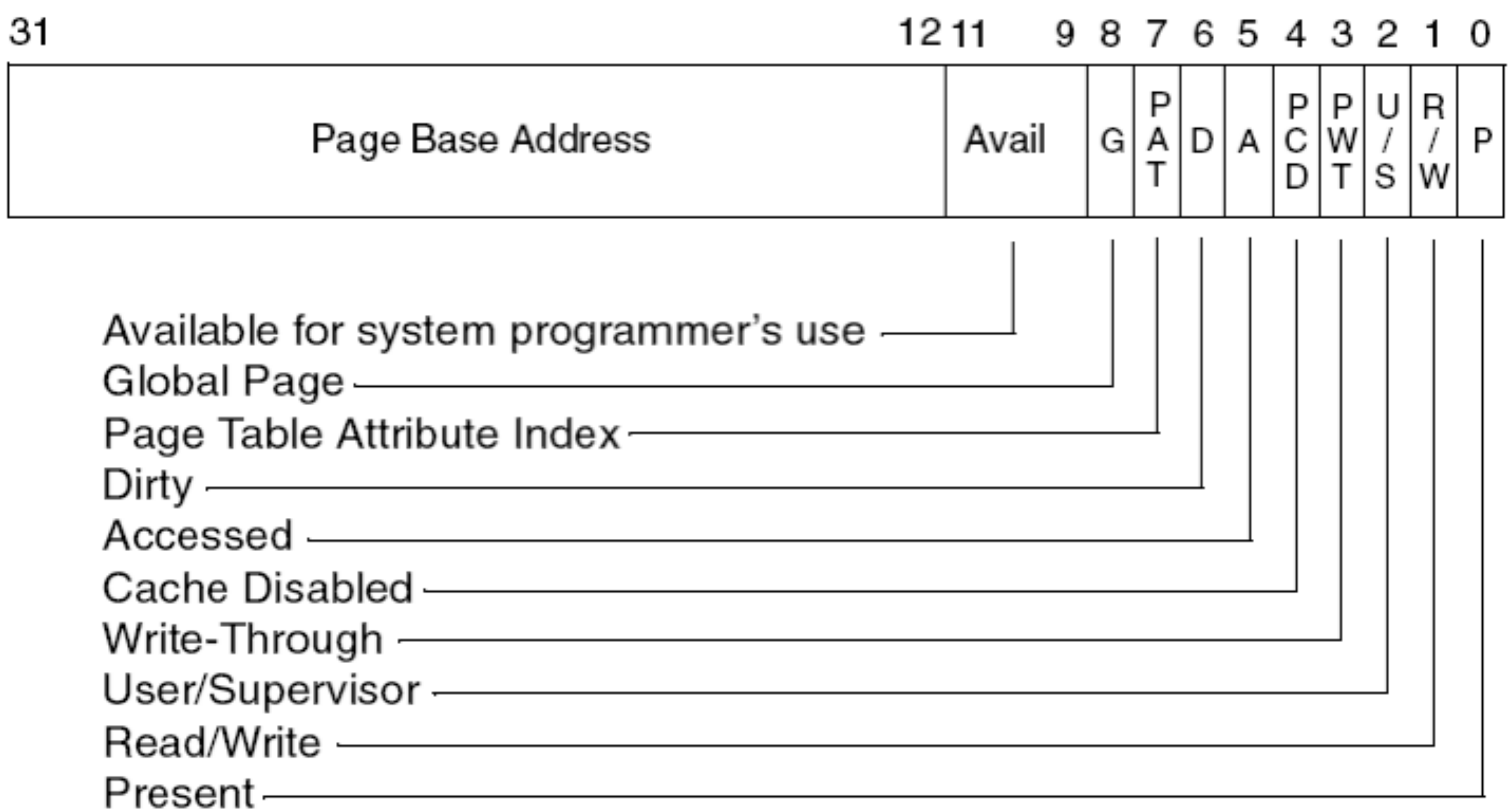
- Map to page frame and disk
  - If valid bit = 1, map to pp# physical page number
  - If valid bit = 0, map to dp# disk page number
- Page out
  - Invalidate page table entry and TLB entry
  - Copy page to disk
  - Set disk page number in PTE
- Page in
  - Find an empty page frame (may trigger replacement)
  - Copy page from disk
  - Set page number in PTE and TLB entry and make them valid



Example: x86 Paging Options

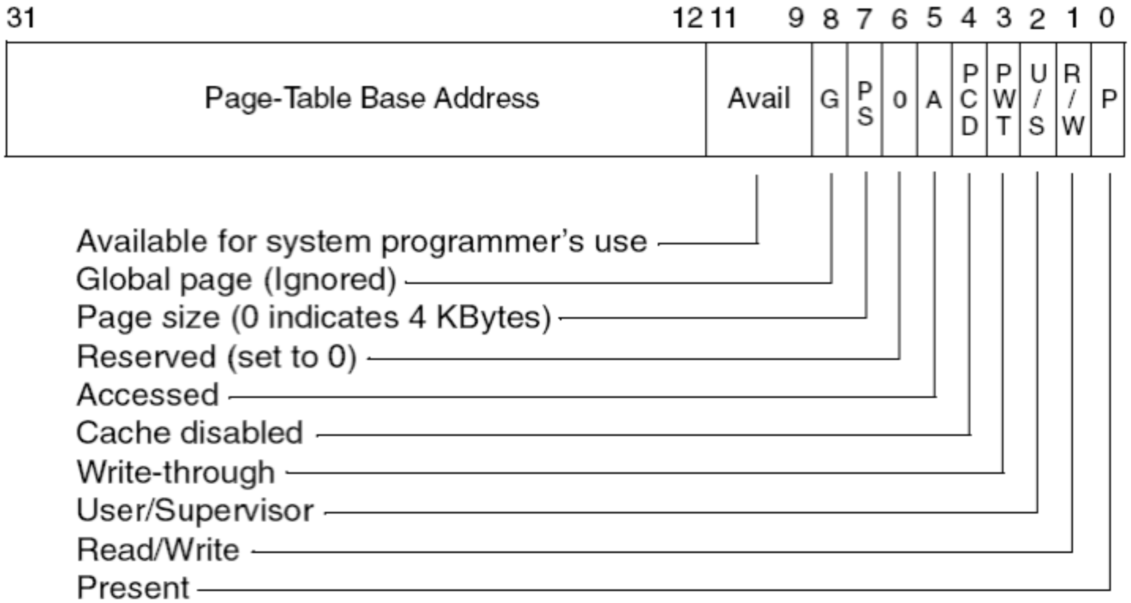
- Flags
  - PG flag (Bit 31 of CR0): enable page translation
  - PSE flag (Bit 4 of CR4): 0 for 4KB page size and 1 for large page size
  - PAE flag (Bit 5 of CR4): 0 for 2MB pages when PSE = 1 and 1 for 4MB pages when PSE = 1 extending physical address space to 36 bit
- 2MB and 4MB pages are mapped directly from directory entries
- 4KB and 4MB pages can be mixed

Page-Table Entry (4-KByte Page)

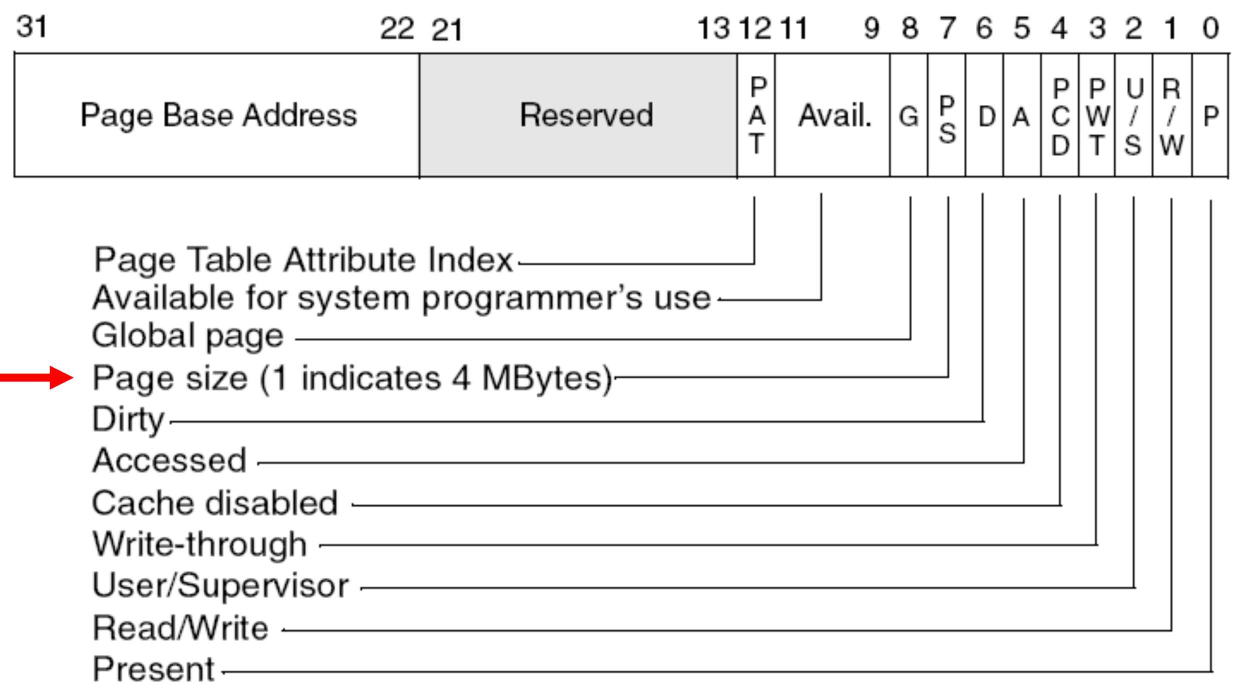


Example: x86 Directory Entry

Page-Directory Entry (4-KByte Page Table)



Page-Directory Entry (4-MByte Page)



Pin (or Lock) Page Frames

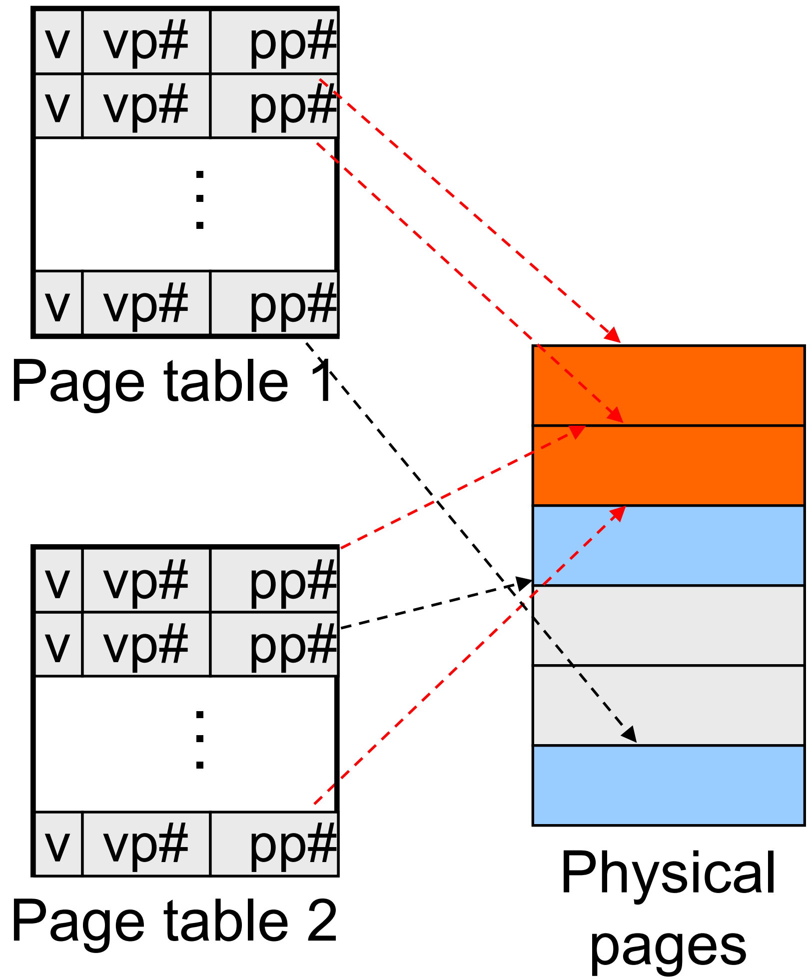
- When do you need it?
  - When DMA is in progress, you don't want to page the pages out to avoid CPU from overwriting the pages
- How to design the mechanism?
  - A data structure to remember all pinned pages
  - Paging algorithm checks the data structure to decide on page replacement
  - Special calls to pin and unpin certain pages

Zero Pages

- Zeroing pages
  - Initialize pages with 0’s
  - Heap and static data are initialized
- How to implement?
  - On the first page fault on a data page or stack page, zero it
  - Have a special thread zeroing pages

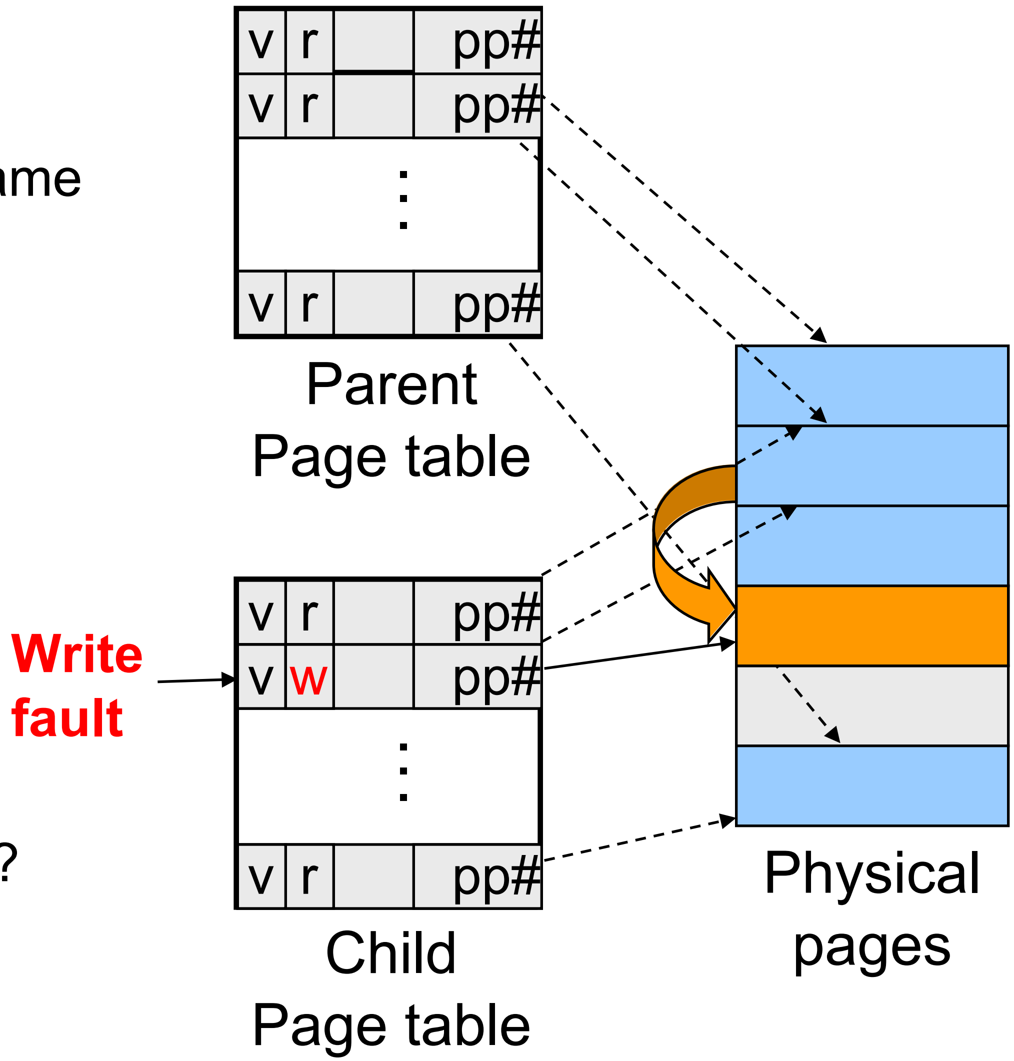
Shared Pages

- PTEs from two processes share the same physical pages
  - What use cases?
- Implementation issues
  - What if you terminate a process with shared pages
  - Paging in/out shared pages
  - Pinning, unpinning shared pages
  - Deriving the working set for a process with shared pages



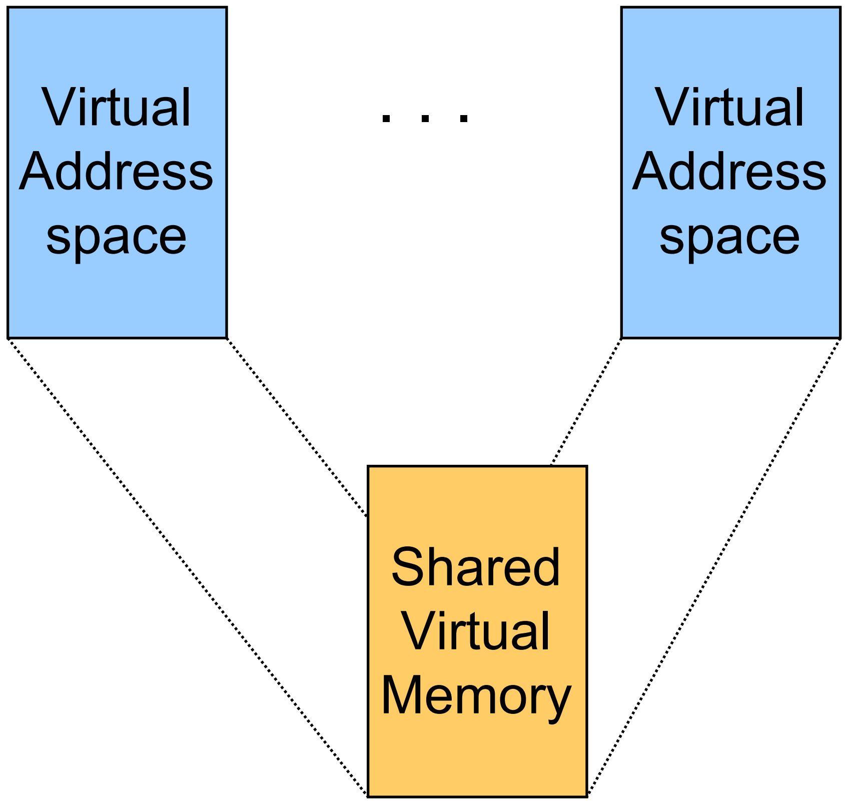
Copy-On-Write

- A technique to avoid preparing all pages to run a large process
- Method
  - Child's address space uses the same mapping as parent's
  - Make all pages read-only
  - Make child process ready
  - On a read, nothing happens
  - On a write, generates a fault
    - map to a new page frame
    - copy the page over
    - restart the instruction
- Issues
  - How to destroy an address space?
  - How to page in and page out?
  - How to pin and unpin?



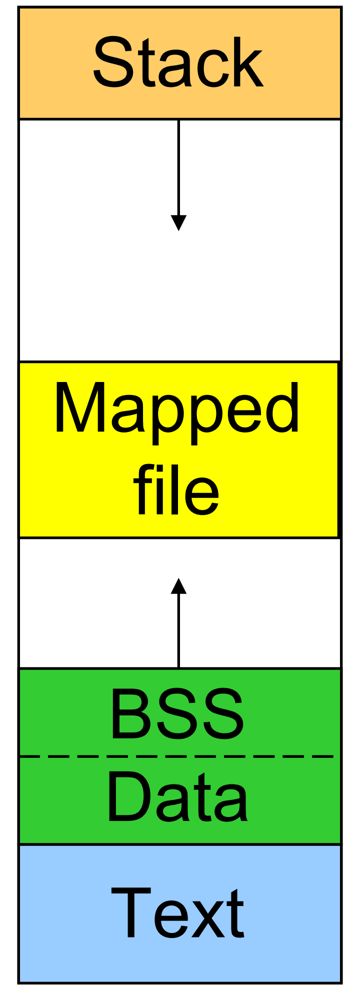
Distributed Shared Memory

- Run shared memory program on a cluster of computers
- Method
  - Multiple address space mapped to "shared virtual memory"
  - Page access bits are set according to coherence rules
    - Exclusive writer
    - N readers
  - A read fault will invalidate the writer, make read only and copy the page
  - A write fault will invalidate another writer or all readers and copy page
- Issues
  - Thrashing
  - Copy page overhead
  - Sychronizations



Address Space in Unix

- Stack
- Data
  - Un-initialized: BSS (Block Started by Symbol)
  - Initialized
  - brk(addr) to grow or shrink
- Text: read-only
- Mapped files
  - Map a file in memory
  - mmap(addr, len, prot, flags, fd, offset)
  - unmap(addr, len)



Address space

Virtual Memory in BSD4

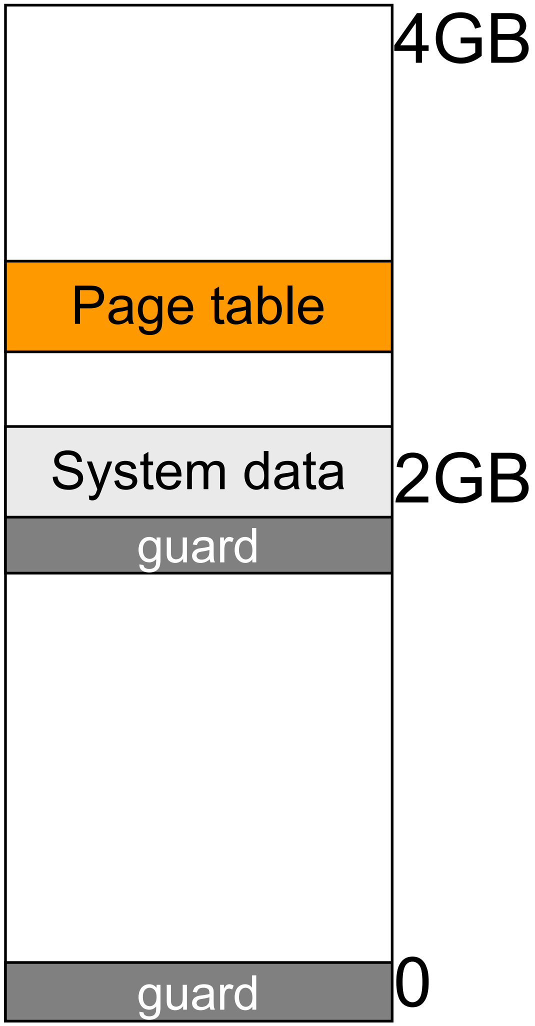
- Physical memory partition
  - Core map (pinned): everything about page frames
  - Kernel (pinned): the rest of the kernel memory
  - Frames: for user processes
- Page replacement
  - Run page daemon until there are enough free pages
  - Early BSD used the basic Clock (FIFO with 2nd chance)
  - Later BSD used Two-handed Clock algorithm
  - Swapper runs if page daemon can’t get enough free pages
    - Looks for processes idling for 20 seconds or more
    - 4 largest processes
    - Check when a process should be swapped in

Virtual Memory in Linux

- Linux address space for 32-bit machines
  - 3GB user space
  - 1GB kernel (invisible at user level)
- Backing store
  - Text segment uses executable binary file as backing storage
  - Other segments get backing storage on demand
- Copy-on-write for forking processes
- Multi-level paging
  - Directory, middle (nil for Pentium), page, offset
  - Kernel is pinned
  - Buddy algorithm with carving slabs for page frame allocation
- Replacement
  - Keep certain number of pages free
  - Clock algorithm on paging cache and file buffer cache
  - Clock algorithm on unused shared pages
  - Modified Clock on memory of user processes (most physical pages first)

Address Space in Windows 2K/XP

- Win2k user address space
  - Upper 2GB for kernel (shared)
  - Lower 2GB – 256MB are for user code and data (Advanced server uses 3GB instead)
  - The 256MB contains for system data (counters and stats) for user to read
  - 64KB guard at both ends
- Virtual pages
  - Page size
    - 4KB for x86
    - 8 or 16KB for IA64
  - States
    - Free: not in use and cause a fault
    - Committed: mapped and in use
    - Reserved: not mapped but allocated



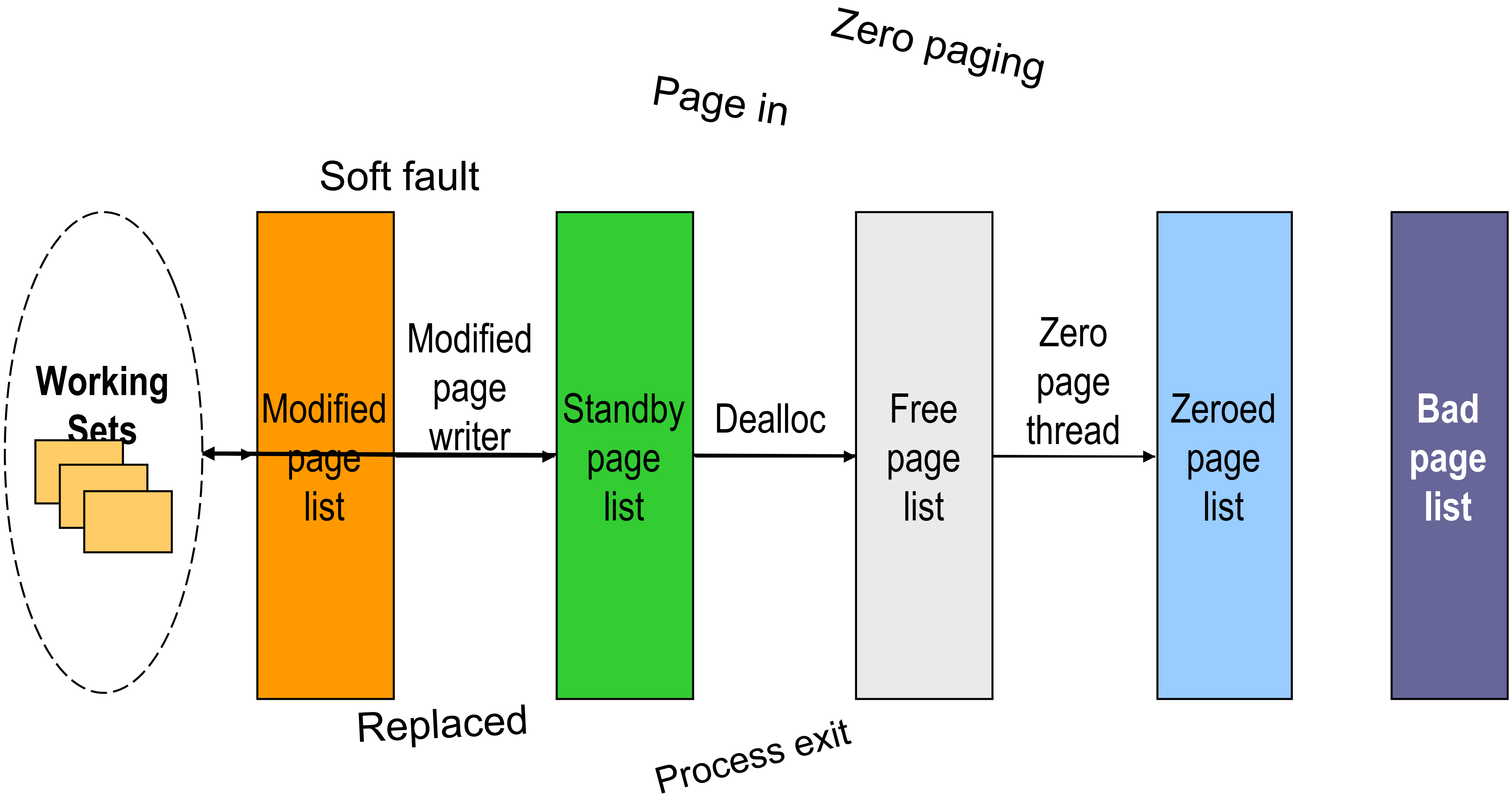
Backing Store in Windows 2K/XP

- Backing store allocation
  - Win2k delays backing store page assignments until paging out
  - There are up to 16 paging files, each with an initial and max sizes
- Memory mapped files
  - Delayed write back
  - Multiple processes can share mapped files w/ different accesses
  - Implement copy-on-write

Paging in Windows 2K/XP

- Each process has a working set with
  - Min size with initial value of 20-50 pages
  - Max size with initial value of 45-345 pages
- On a page fault
  - If working set < min, add a page to the working set
  - If working set > max, replace a page from the working set
- If a process has a lot of paging activities, increase its max
- Working set manager maintains a large number of free pages
  - In the order of process size and idle time
  - If working set < min, do nothing
  - Otherwise, page out the pages with highest "non-reference" counters in a working set for uniprocessors
  - Page out the oldest pages in a working set for multiprocessors
- The last 512 pages are never taken for paging

More Paging in Windows 2K/XP



Summary

- Must consider many issues
  - Global and local replacement strategies
  - Management of backing store
  - Primitive operations
    - Pin/lock pages
    - Zero pages
    - Shared pages
    - Copy-on-write
- Shared virtual memory can be implemented using access bits
- Real system designs are complex