COS 318: Operating Systems

Virtual Memory Design Issues: Paging and Caching

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Virtual Memory: Paging and Caching

- Need mechanisms for paging between memory and disk
- Need algorithms for managing physical memory as a cache

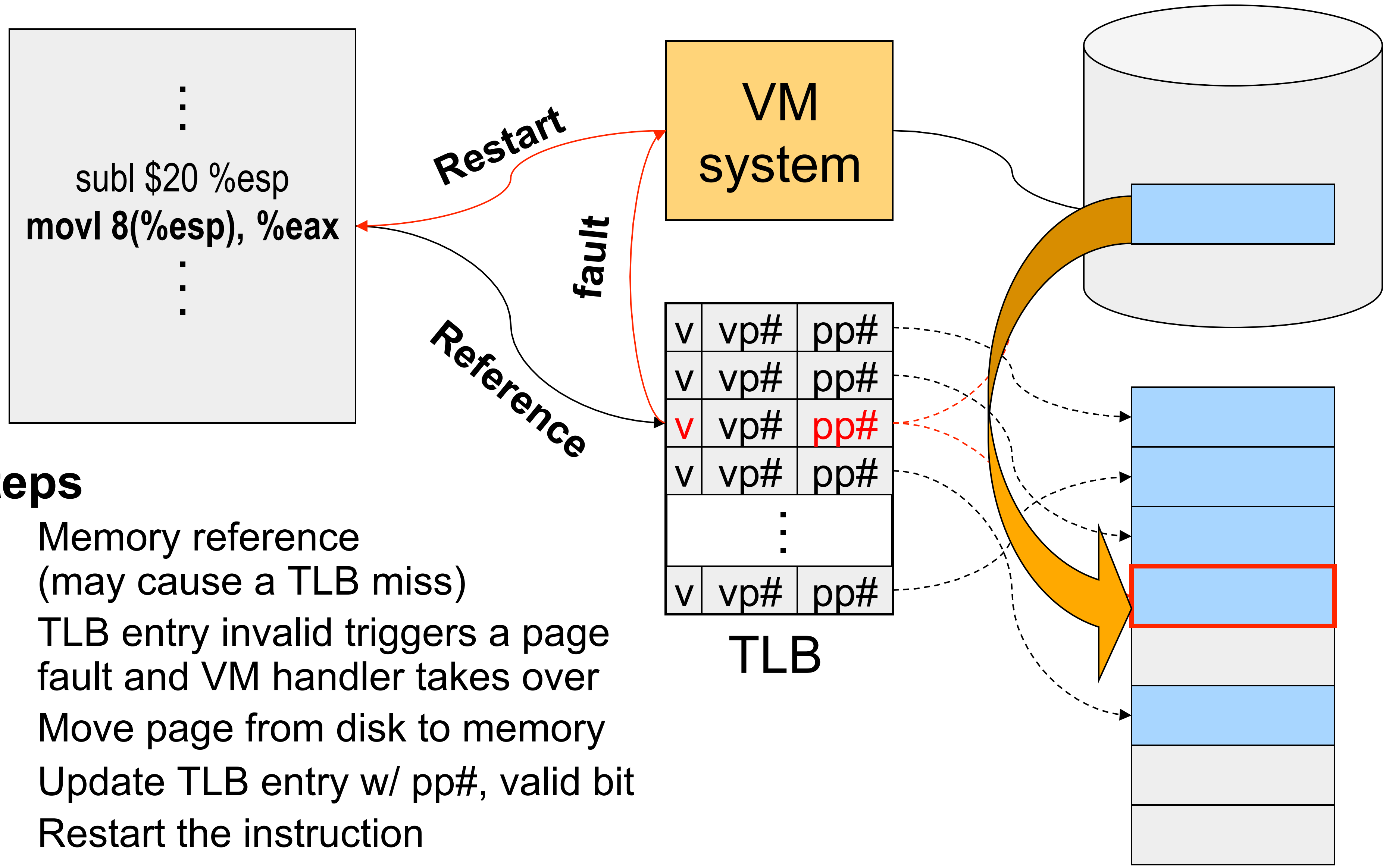
Today’s Topics

- Paging mechanism
- Page replacement algorithms
- When the cache doesn’t work

Virtual Memory Paging

- Simple world
  - Load entire process into memory. Run it. Exit.
- Problems
  - Slow (especially with big processes)
  - Wasteful of space (doesn't use all of its memory all the time)
- Solution
  - Demand paging: only bring in pages actually used
  - Paging: goal is only keep frequently used pages in memory
- Mechanism:
  - Virtual memory maps some to physical pages, some to disk

VM Paging Steps



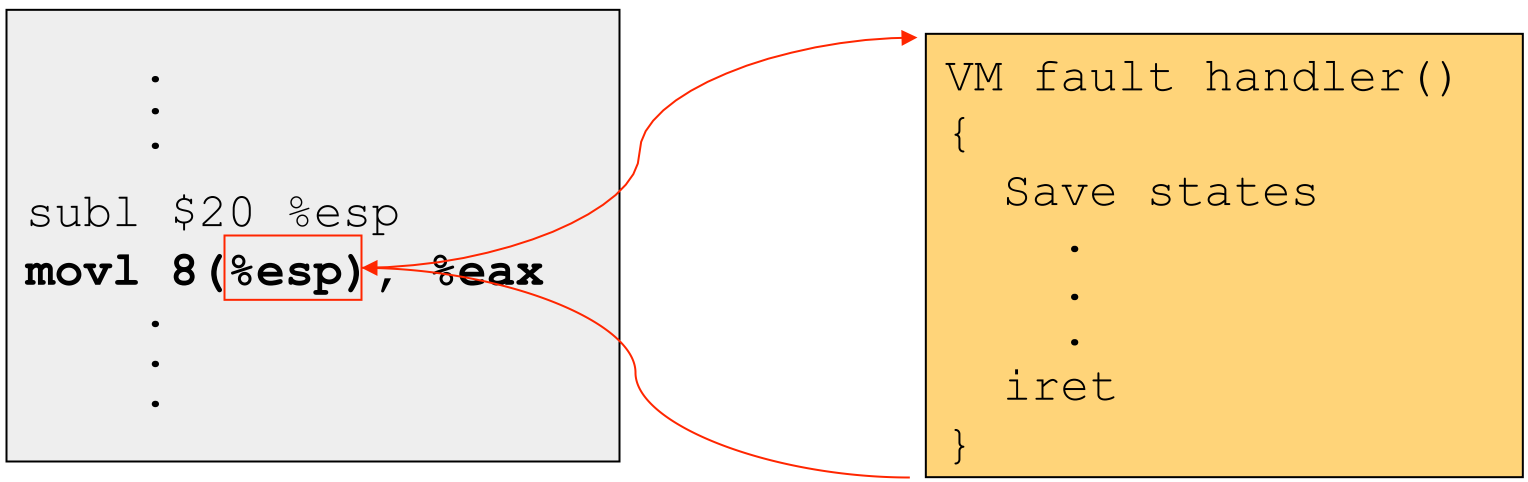
Steps

- Memory reference (may cause a TLB miss)
- TLB entry invalid triggers a page fault and VM handler takes over
- Move page from disk to memory
- Update TLB entry w/ pp#, valid bit
- Restart the instruction
- Memory reference again

Virtual Memory Issues

- What to page in?
  - Just the faulting page or more?
  - Want to know the future…
- What to replace?
  - Cache (main memory) too small. Which page to replace?
  - Want to know the future...

How Does Page Fault Work?



- User program should not be aware of the page fault
- Fault may have happened in the middle of the instruction!
- Can we skip the faulting instruction?
- Is a faulting instruction always restartable?

What to Page In?

- Page in the faulting page
  - Simplest, but each "page in" has substantial overhead
- Page in more pages each time (prefetch)
  - May reduce page faults if the additional pages are used
  - Waste space and time if they are not used
  - Real systems do some kind of prefetching
- Applications control what to page in
  - Some systems support for user-controlled prefetching
  - But, applications do not always know

VM Page Replacement

- Things are not always available when you want them
  - It is possible that no unused page frame is available
  - VM needs to do page replacement
- On a page fault
  - If there is an unused frame, get it
  - **If no unused page frame available,**
    - **Choose a used page frame**
    - **If it has been modified, write it to disk***
    - **Invalidate its current PTE and TLB entry**
  - Load the new page from disk
  - Update the faulting PTE and remove its TLB entry
  - Restart the faulting instruction

Page Replacement

* If page to be replaced is shared, find all page table entries that refer to it

Backing Store

- Swap space
  - When process is created, allocate swap space for it on disk
  - Need to load or copy executables to swap space
  - Need to consider swap space growth
- Can youh use the executable file as swap space?
  - For text and static data?
  - But what if the file is moved? Better to copy to swap space

Bookkeeping Bits Used by VM Methods

- Has page been modified?
  - "Dirty" or "Modified" bit set by hardware on store instruction
  - In both TLB and page table entry
- Has page been recently used?
  - "Referenced" bit set by hardware in PTE on every TLB miss
  - Can be cleared every now and then, e.g. on timer interrupt
- Bookkeeping bits can be reset by the OS kernel
  - When changes to page are flushed to disk
  - To track whether page is recently used

Virtual or physical dirty/use bits

- Most machines keep dirty/use bits in the page table entry
- Physical page is
  - modified if *any* PTE that points to it is modified
  - recently used if *any* PTE that points to it is recently used
- With software-controlled TLBs, can be simpler to keep dirty/use bits in the core map
  - Core map: map of physical page frames

Emulating a modified bit (Hardware Loaded TLB)

- Some processor architectures do not keep a modified bit per page
  - Extra bookkeeping and complexity
- Kernel can emulate a modified bit:
  - Set all clean pages as read-only
  - On first write to page, trap into kernel
  - Kernel sets modified bit, marks page as read-write
  - Resume execution
- Kernel needs to keep track of both
  - Current page table permission (e.g., read-only)
  - True page table permission (e.g., writeable, clean)

Emulating a recently used bit (Hardware Loaded TLB)

- Some processor architectures do not keep a recently used bit per page
  - Extra bookkeeping and complexity
- Kernel can emulate a recently used bit:
  - Set all recently unused pages as invalid
  - On first read/write, trap into kernel
  - Kernel sets recently used bit
  - Marks page as read or read/write
- Kernel needs to keep track of both
  - Current page table permission (e.g., invalid)
  - True page table permission (e.g., read-only, writeable)

Emulating modified/use bits w/ MIPS software-loaded TLB

- MIPS TLB entries have an extra bit: modified/unmodified
  - Trap to kernel if no entry in TLB, or if write to an unmodified page
- On a TLB read miss:
  - If page is clean, load TLB entry as read-only; if dirty, load as rd/wr
  - Mark page as recently used
- On a TLB write to an unmodified page:
  - Kernel marks page as modified in its page table
  - Reset TLB entry to be read-write
  - Mark page as recently used
- On TLB write miss:
  - Kernel marks page as modified in its page table
  - Load TLB entry as read-write
  - Mark page as recently used

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

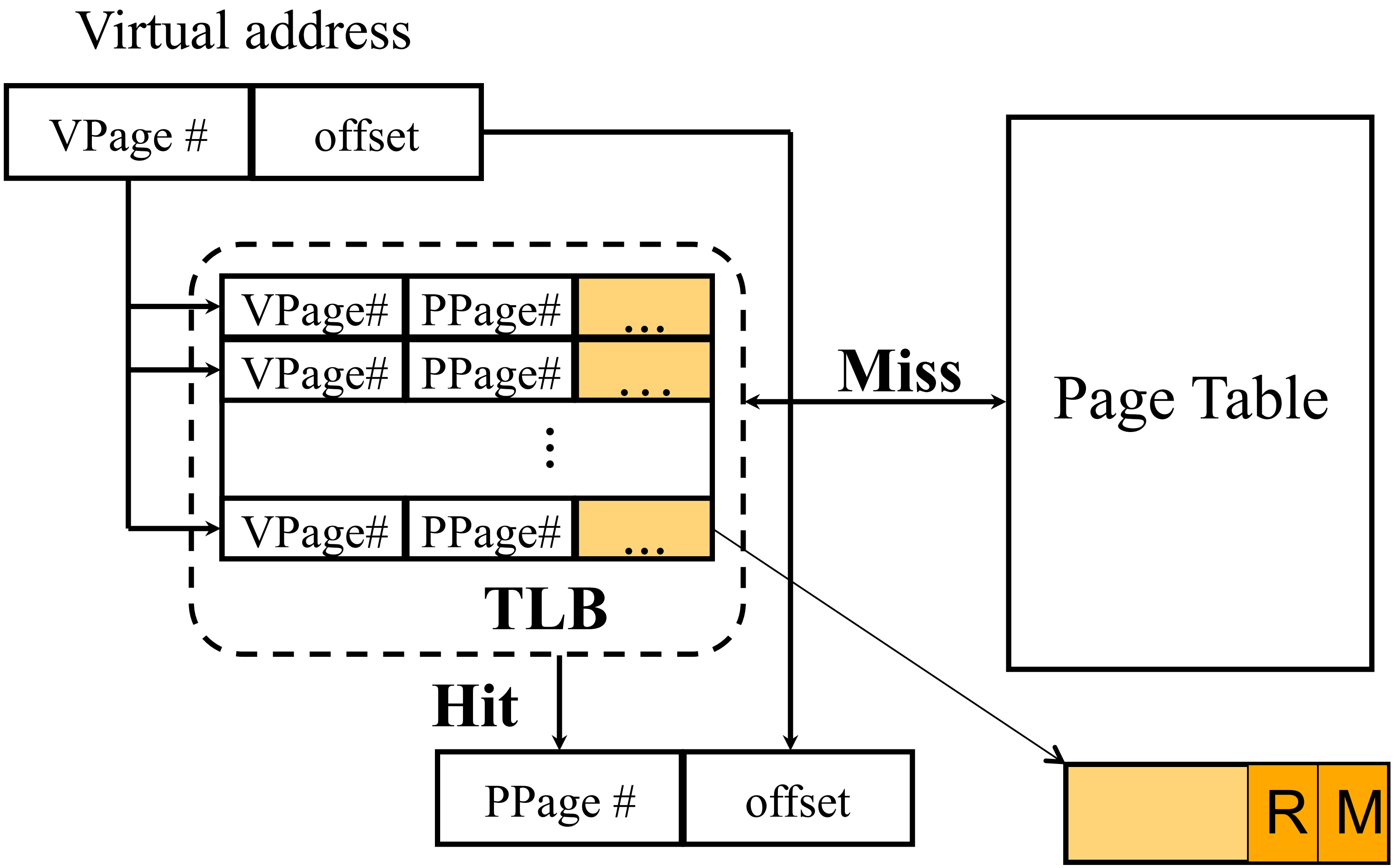
Which “Used” Page Frame To Replace?

- Random
- Optimal or MIN algorithm
- NRU (Not Recently Used)
- FIFO (First-In-First-Out)
- FIFO with second chance
- Clock (with second chance)
- Not Recently Used
- LRU (Least Recently Used)
- NFU (Not Frequently Used)
- Aging (approximate LRU)
- Working Set
- WSClock

Optimal or MIN

- Algorithm:
  - Replace the page that won't be used for the longest time (Know all references in the future)
- Example
  - Reference string: 1 2 3 4 1 2 5 1 2 3 4 5
  - 4 page frames
  - 6 faults
- Pros
  - Optimal solution and can be used as an off-line analysis method
- Cons
  - No on-line implementation

Revisit TLB and Page Table



- Important bits for paging
  - **Reference**: Set when referencing a location in the page (can clear every so often, e.g. on clock interrupt)
  - **Modify**: Set when writing to a location in the page

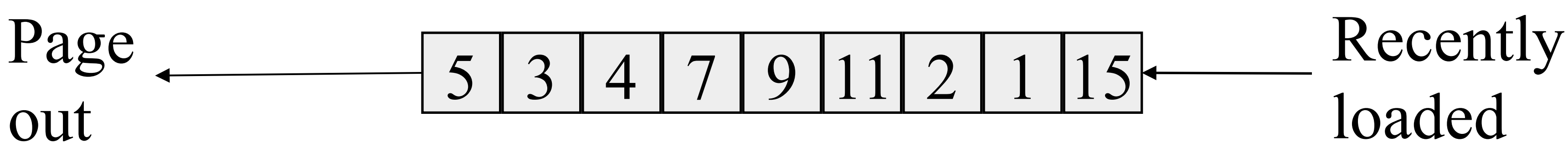
Not Recently Used (NRU)

- Algorithm
  - Randomly pick a page from one of the following sets (in this order)
    - Not referenced and not modified
    - Not referenced and modified
    - Referenced and not modified
    - Referenced and modified
  - Clear reference bits
- Example
  - 4 page frames
  - Reference string
  - 8 page faults

[1] [2] [3] [4] 1 2 [5] 1 2 [3] [4] [5]

- Pros
  - Implementable
- Cons
  - Require scanning through reference bits and modified bits

First-In-First-Out (FIFO)



- Algorithm
  - Throw out the oldest page
- Example
  - 4 page frames
  - Reference string
  - 10 page faults

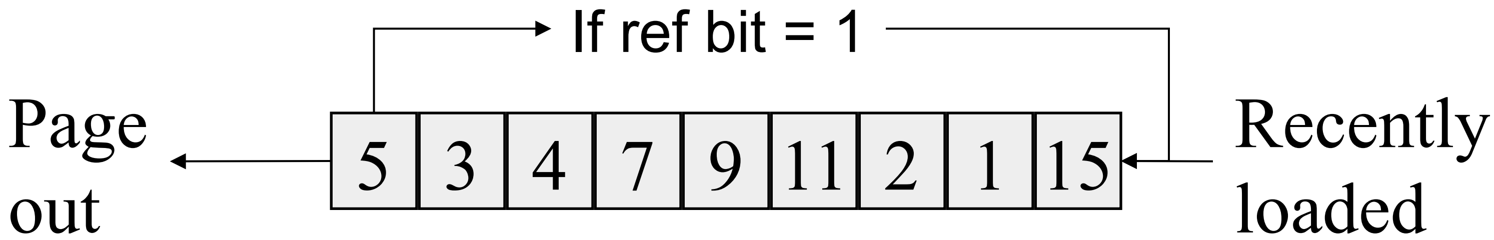
  [1] [2] [3] [4] 1 2 [5] [1] [2] [3] [4] [5]

- Pros
  - Low-overhead implementation
- Cons
  - May replace the heavily used pages (time a page first came in to memory may not be that indicative of its usage)
  - Worst case is program striding through data larger than memory

More Frames → Fewer Page Faults?

- Consider the following with 4 page frames
  - Algorithm: FIFO replacement
  - Reference string: [1] [2] [3] [4] 1 2 [5] [1] [2] [3] [4] [5]
  - 10 page faults
- Same string with 3 page frames
  - Algorithm: FIFO replacement
  - Reference string: [1] [2] [3] [4] [1] [2] [5] 1 2 [3] [4] 5
  - **9 page faults!**
- This is so called "Belady's anomaly" (Belady, Nelson, Shedler 1969)

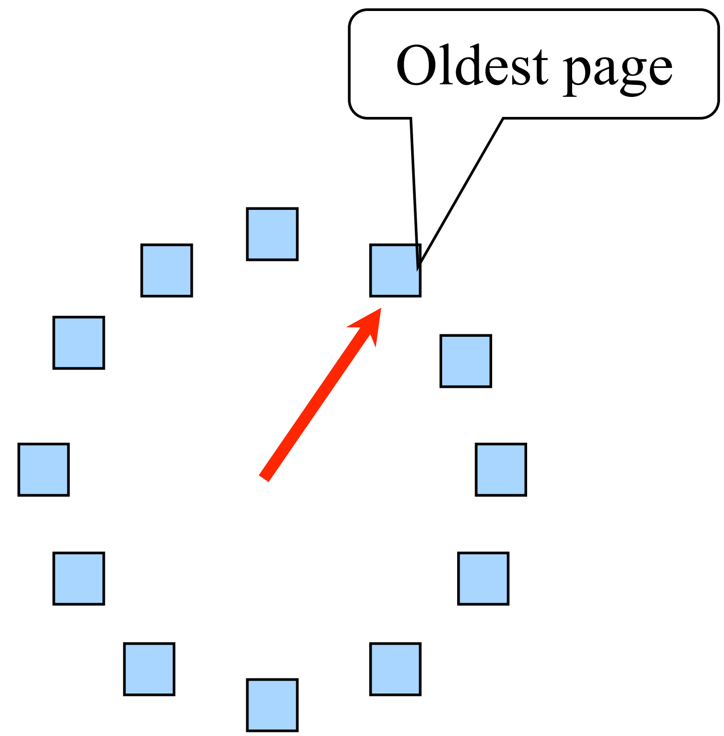
FIFO with 2nd Chance



- Address the problem with FIFO
  - Check the reference-bit of the oldest page
  - If it is 0, then replace it
  - If it is 1, clear the reference bit, put the page to the end of the list, update its “load time” to the current time, and continue searching
  - Looking for an old page not referenced in current clock interval
  - If don’t find one (all pages referenced in current interval) come back to first-checked page again (its R bit is now 0). Degenerates to pure FIFO.
- Example
  - 4 page frames
  - Reference string: 1 2 3 4 1 2 5 1 2 3 4 5
  - 8 page faults
- Pros
  - Simple to implement
- Cons
  - The worst case may take a long time

Clock

- FIFO Clock algorithm
  - Arrange physical pages in circle
  - Clock hand points to the oldest page
  - On a page fault, follow the hand to inspect pages
- Clock with Second Chance
  - If the reference bit is 1, set it to 0 and advance the hand
  - If the reference bit is 0, use it for replacement
- Compare with FIFO w/2nd chance
  - What's the difference?
- What if memory is very large
  - Take a long time to go around?



Nth chance: Not Recently Used

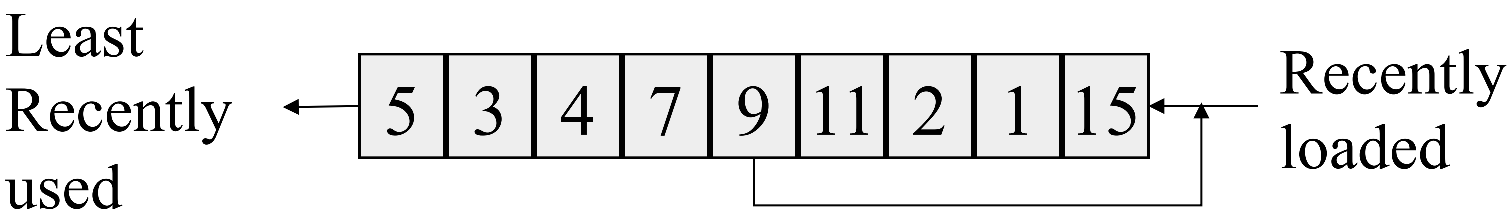
- Instead of one referenced bit per page, keep an integer
  - notInUseSince: number of sweeps since last use
- Periodically sweep through all page frames

```
if (page is used) {
    notInUseSince = 0;
} else if (notInUseSince < N) {
    notInUseSince++;
} else {
     replace page;
}
```

Implementation note

- Clock and Nth Chance can run synchronously
  - In page fault handler, run algorithm to find next page to evict
  - Might require writing changes back to disk first
- Or asynchronously
  - A thread maintains a pool of recently unused, clean pages
  - Find recently unused dirty pages, write mods back to disk
  - Find recently unused clean pages, mark invalid and move to pool
  - On page fault, check if requested page is in pool
  - If not, evict that page

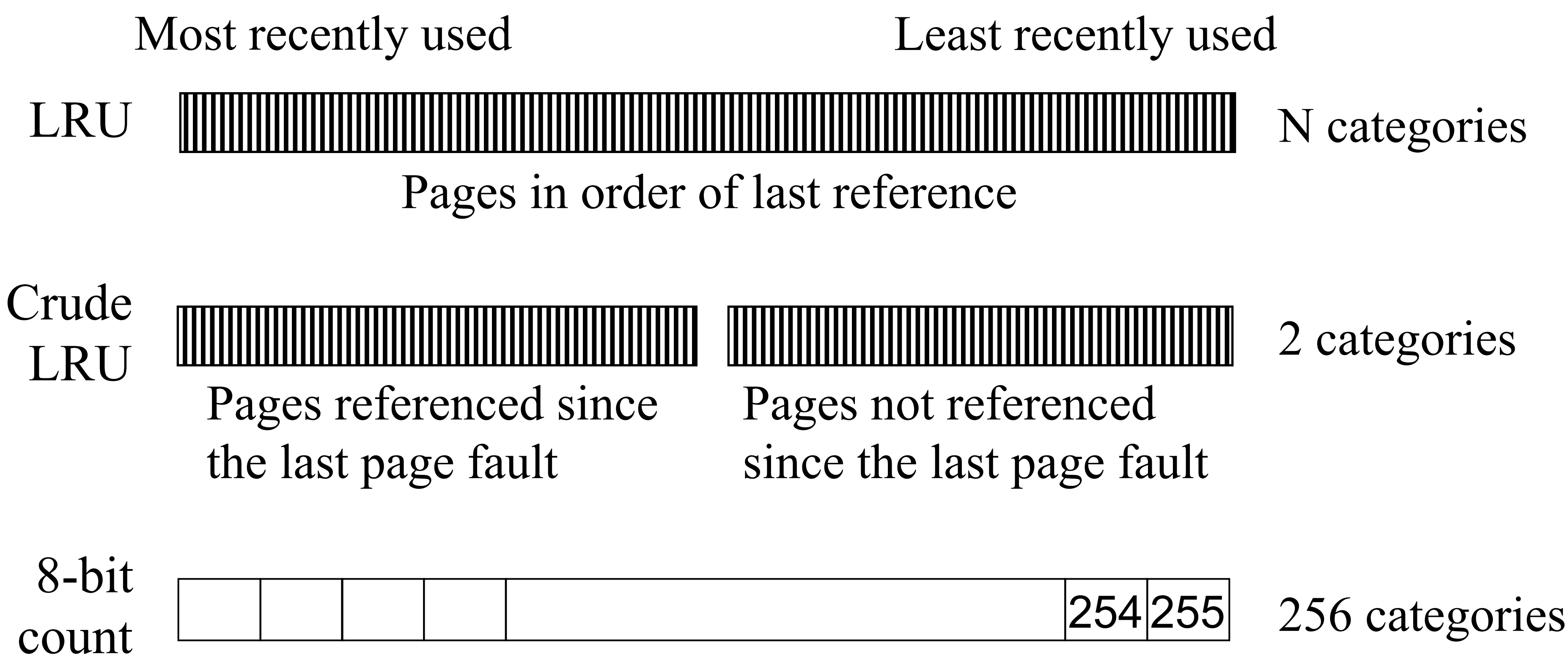
Least Recently Used



- Algorithm
  - Replace page that hasn't been used for the longest time
    - Order the pages by time of reference
    - Needs a timestamp for every referenced page
- Example
  - 4 page frames
  - Reference string: 1 2 3 4 1 2 5 1 2 3 4 5
  - 8 page faults
- Pros
  - Good to approximate MIN
- Cons
  - Difficult to implement

Approximation of LRU

- Use CPU ticks
  - For each memory reference, store the ticks in its PTE
  - Find the page with minimal ticks value to replace
- Use a smaller counter



Not Frequently Used (NFU)

- Software counter associated with every page
- Algorithm
  - At every clock interrupt, scan all pages, and for each page add the R bit value to its counter
  - At page fault, pick the page with the smallest counter to replace
- Problem
  - Never forgets anything: pages used a lot in the past will have higher counter values than pages used recently

Not Frequently Used (NFU) with Aging

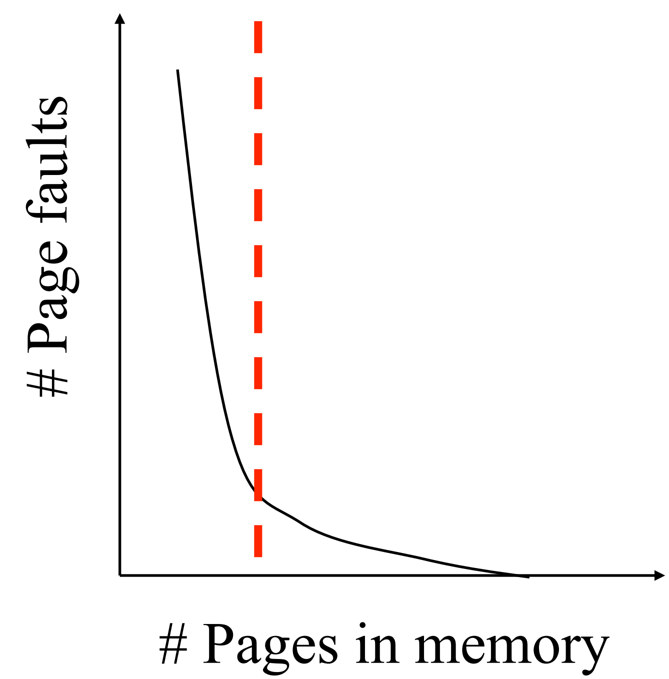
- Algorithm
  - At every clock interrupt, shift (right) reference bits into counters
  - At page fault, pick the page with the smallest counter to replace

00000000	00000000	10000000	01000000	10100000
00000000	10000000	01000000	10100000	01010000
10000000	11000000	11100000	01110000	00111000
00000000	00000000	00000000	10000000	01000000

- Old example
  - 4 page frames
  - Reference string: 1 2 3 4 1 2 5 1 2 3 4 5
  - 8 page faults
- Main difference between NFU and LRU?
  - NFU has a short history (counter length)
  - NFU cannot distinguish reference times within a clock interval
- How many bits are enough?
  - In practice 8 bits are quite good (8*20ms is a lot of history)

Program Behavior (Denning 1968)

- 80/20 rule
  - > 80% memory references are within <20% of memory space
  - > 80% memory references are made by < 20% of code
- Spatial locality
  - Neighbors are likely to be accessed
- Temporal locality
  - The same page is likely to be accessed again in the near future



Working Set

- Main idea (Denning 1968, 1970)
  - Define a working set as the set of pages in the most recent K page references
  - Keep the working set in memory will reduce page faults significantly
- Approximate working set
  - The set of pages of a process used in the last T seconds
- An algorithm
  - On a page fault, scan through all pages of the process
  - If the reference bit is 1, record the current time for the page
  - If the reference bit is 0, check the "time of last use,"
    - If the page has not been used within T, replace the page
    - Otherwise, go to the next
  - Add the faulting page to the working set

WSClock

- Follow the clock hand
- If the reference bit is 1
  - Set reference bit to 0
  - Set the current time for the page
  - Advance the clock hand
- If the reference bit is 0, check "time of last use"
  - If the page has been used within δ, go to the next
  - If the page has not been used within δ and modify bit is 1
    - Schedule the page for page out and go to the next
  - If the page has not been used within δ and modify bit is 0
    - Replace this page

Replacement Algorithms

- The algorithms
  - Random
  - Optimal or MIN algorithm
  - NRU (Not Recently Used)
  - FIFO (First-In-First-Out)
  - FIFO with second chance
  - Clock (with second chance)
  - Not Recently Used
  - LRU (Least Recently Used)
  - NFU (Not Frequently Used)
  - Aging (approximate LRU)
  - Working Set
  - WSClock
- Which are your top two?

Thrashing

- Thrashing
  - Paging in and 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
  - Pages referenced (by a process, or by all) in last T seconds
  - Really, the pages that need to cached to get good hit rate

Making the Best of a Bad Situation

- Single process thrashing?
  - If process does not fit or does not reuse memory, OS can do nothing except contain damage.

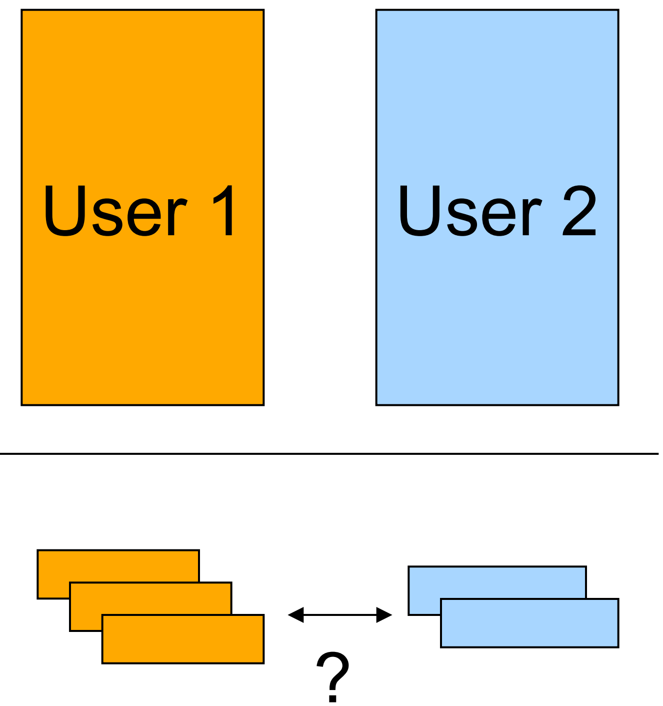
- System thrashing?
  - If thrashing because of the sum of several processes, adapt:
    - Figure out how much memory each process needs
    - Change scheduling priorities to run processes in groups whose memory needs can be satisfied (shedding load)
    - If new processes try to start, can refuse (admission control)

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

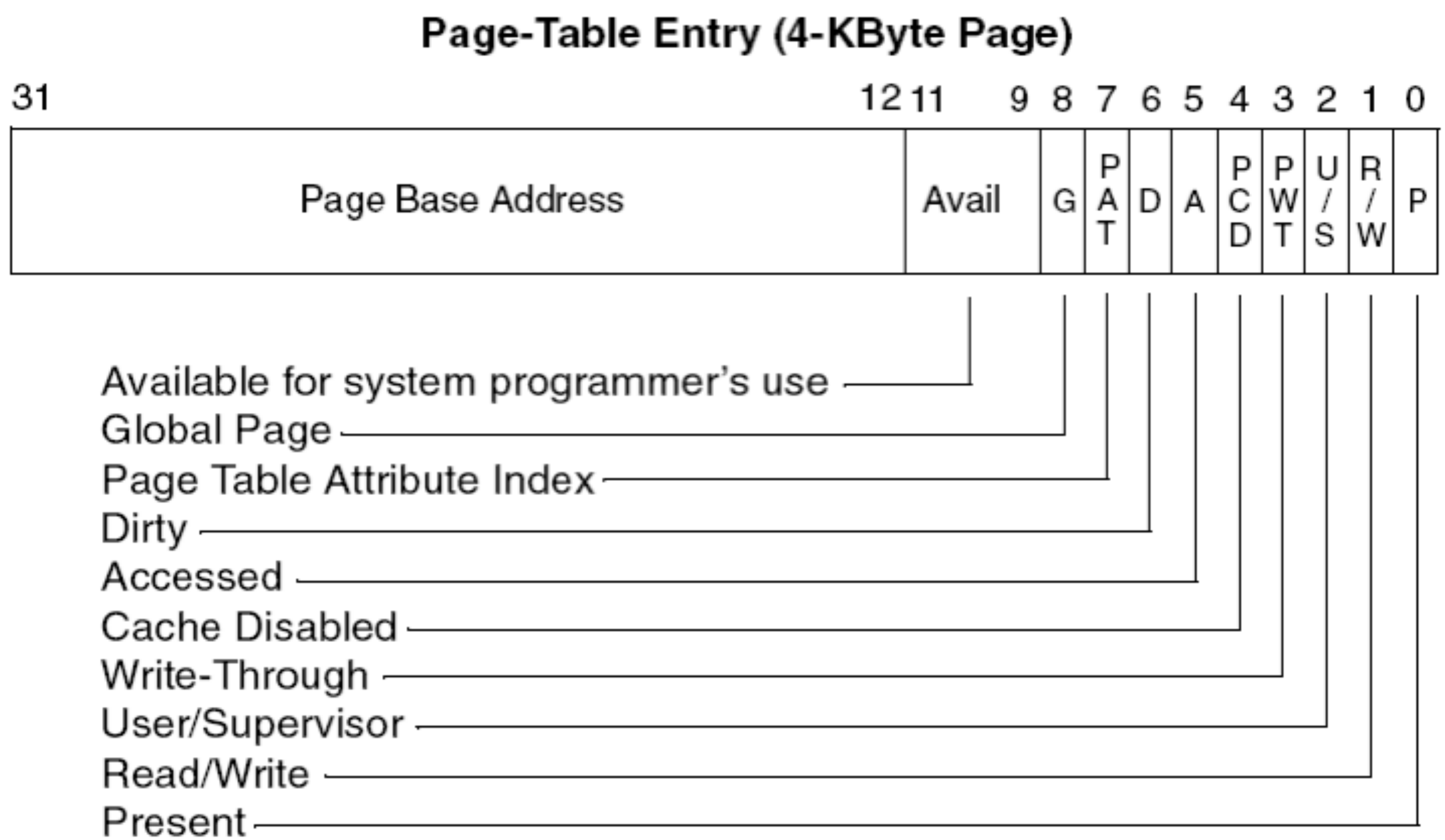
Working Set: Global vs. Local Page Allocation

- 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?

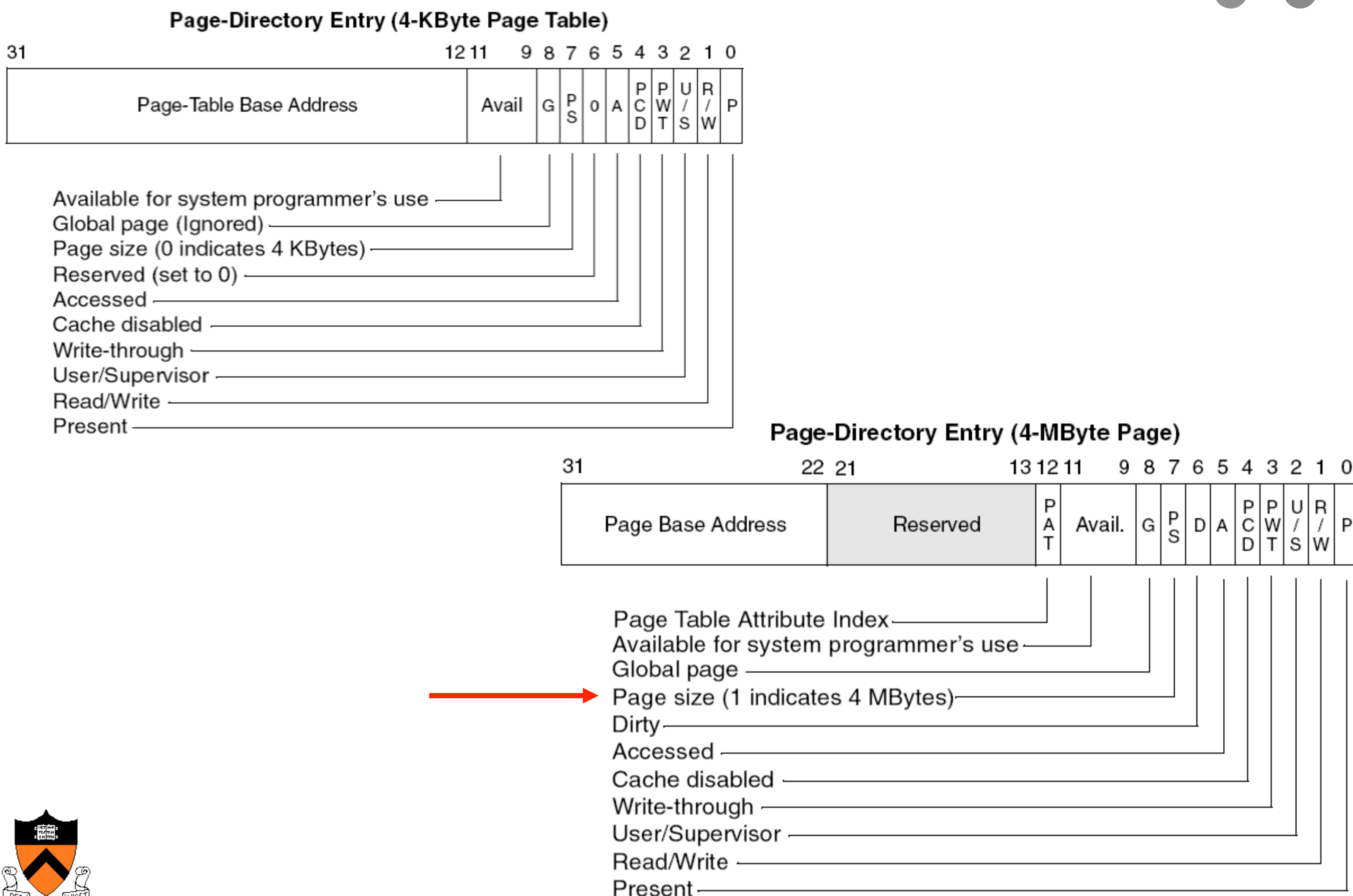


Example: x86 Paging Options

- 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



Example: x86 Directory Entry



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

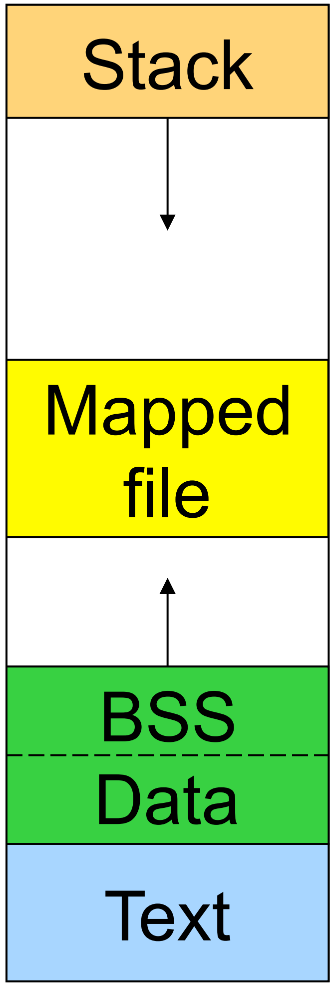
- Programming simplicity, esp for large files
  - Operate directly on file, instead of copy in/copy out
- Zero-copy I/O
  - Data brought from disk directly into page frame
- Pipelining
  - Process can start working before all the pages are populated
- Interprocess communication
  - Shared memory segment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

Memory-mapped Files to Demand-Paged VM

- 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
- Unified memory management across file buffer and process memory

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

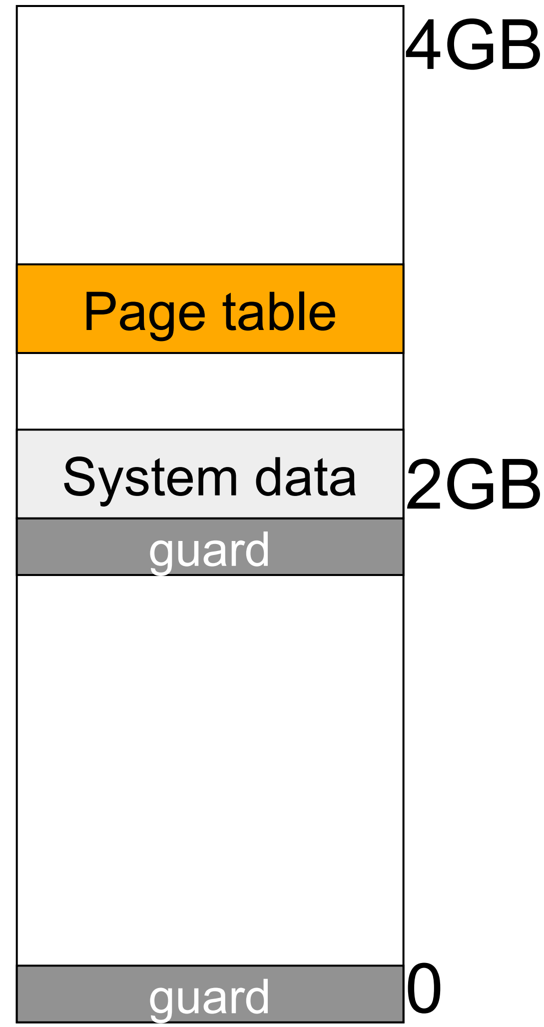
- Physical memory partition
  - Core map (pinned): everything about page frames
  - Kernel (pinned): the rest of the kernel memory
  - Frames: for user processes
- Page replacement
  - Run page daemon until there are enough free pages
  - Early BSD used the basic Clock (FIFO with 2nd chance)
  - Later 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



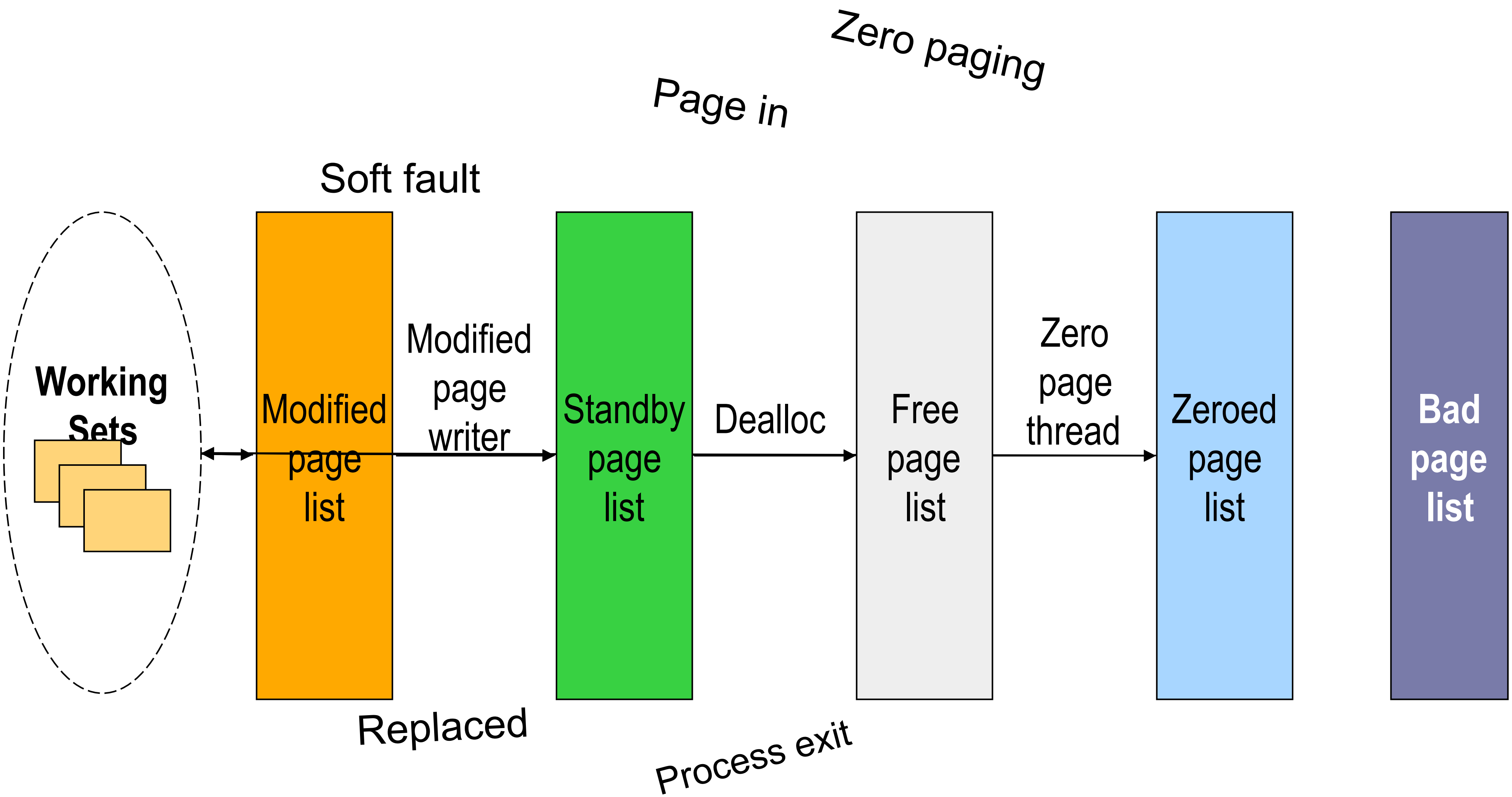
Backing Store in Windows 2K/XP

- 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

More Paging in Windows 2K/XP



Summary

- VM paging
  - Page fault handler
  - What to page in
  - What to page out
- LRU is good but difficult to implement
- Clock (FIFO with 2^{nd} hand) is considered a good practical solution
- Working set concept is important