CSCI [4|6] 730 Operating Systems

Virtual Memory

Virtual Memory Questions?

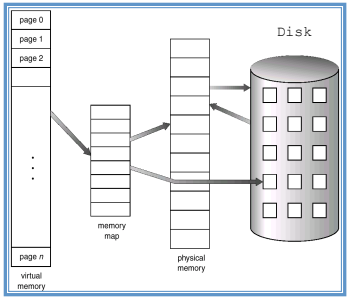
- What is virtual memory and when is it useful?
- What is demand paging?
- What pages should :
  - Persist in memory, and
  - and which should be **replaced**?
- What is trashing and how can it be prevented?
- What is the **working set model**?

Operating System's Goals

- Support processes when there is not enough physical memory
  - Single process with very large address space
  - Multiple processes with combined address spaces
- User code should be independent of amount of physical memory
  - Correctness, if not performance

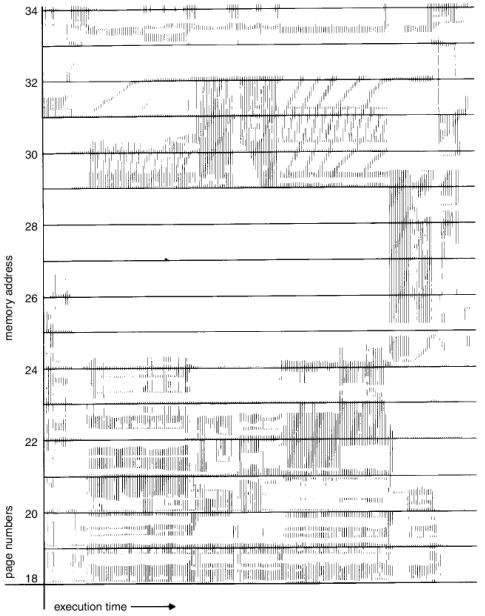
The Illusion: "*Virtual*" Memory

- OS provides an *illusion* of more memory than is physically available:
  - Large, *infinite*, logical space (fiction)
  - Small physical memory (reality)
- Why should this work (allowing the illusion)?
  - Typically: Only part of the program needs to be in memory (at a particular time) for execution
  - Efficiency: Relies on key properties of user processes
    - workload and
    - machine architecture (hardware)



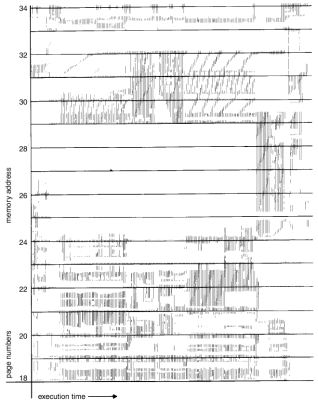
The Million Dollar Question?

- How do the OS decide what is in "main" memory and what is on disk?
- How can we decide?
  - We can:
    - Memory Access Patterns



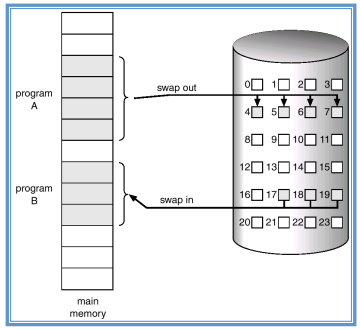
Observations: Memory Access Patterns

- Sequential memory accesses of a process are predictable and tend to have *locality of reference*:
  - Spatial: reference memory addresses *near* previously referenced addresses (in physical memory)
  - Temporal: reference memory addresses that have referenced in the past (or recent past).
- Processes spend majority of time in small portion of code
  - Estimate: 90% of time in it is 10% of code, doesn't jump around much.
- Implication:
  - Process only uses small amount of address space at any moment
  - Only small amount of address space must be resident in physical memory



Approach: Demand Paging

- (Old) Approach 1: Favor one process and bring (swap in) in its entire address space.
- (New) Approach 2: Demand Paging: Bring in pages into memory only when needed (lazy pager instead of a swapper).
  - Less memory
  - Faster response time?
- Process viewed as a sequence of page accesses rather than contiguous address space



Virtual Memory Approach: Intuition

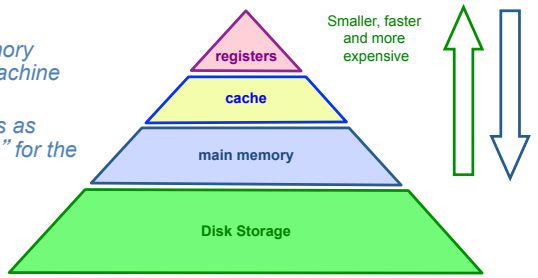
- Idea: OS keeps unreferenced pages on disk and referenced pages in physical memory
  - Slower, cheaper backing store than memory
- Process can run
  - Even when not all pages are loaded into main memory
- OS and hardware cooperate to provide illusion of large disk as fast as main memory
  - Same behavior as if all of address space in main memory
  - Hopefully have similar performance!
- Requirements:
  - OS must have mechanism to identify location of each page in address space in memory, or on disk
  - OS must have (allocation) policy for
    - determining which pages live in memory, and
    - which (remain) on disk
  - OS must have (replacement) policy which pages should be evicted.

Reflect: Virtual Address Space Mechanisms

- Each page in virtual address space maps to one of three locations:
  - Physical main memory: Small, fast, expensive
  - Disk (backing store): Large, slow, cheap
  - Nothing (error): Free

Leverage memory hierarchy of machine architecture

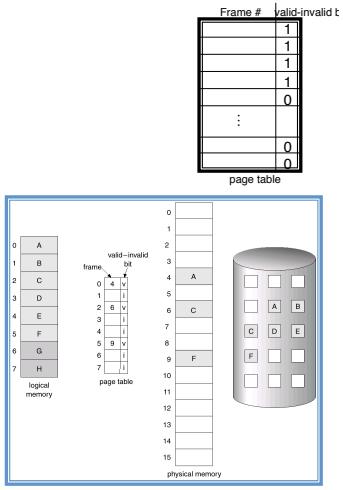
Each layer acts as "backing store" for the layer above



Virtual Address Space Mechanisms

Extend page tables with an extra bit to indicate whether it is in memory or on disk (a resident bit):

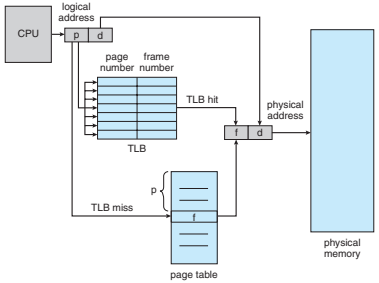
- `valid (or invalid)`
- Page in memory: valid bit set in page table entry (PTE)
- Page out to disk: `valid` bit cleared (`invalid`)
  - PTE points to block on disk
  - Causes trap into OS when page is referenced
  - Trap: page fault
- Page table ?
  - Main memory
  - Cache (the look-aside buffer) TLB



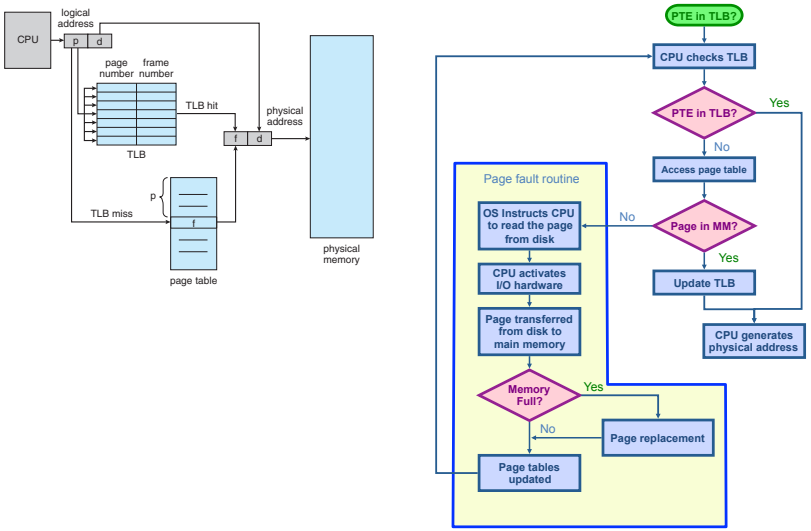
Virtual Memory Mechanisms (cont)

The TLB factor: Hardware and OS cooperate to translate addresses

- First, hardware checks TLB for virtual address
  - TLB hit: Address translation is done; page in physical memory
  - TLB miss:
    - Hardware or OS walk page tables
    - If PTE designates page is valid, then page in physical memory
- Main Memory Miss: Not in main memory: Page fault (i.e., `invalid`)
  - Trap into OS (not handled by hardware)
  - [if memory is full)] OS selects victim page in memory to replace
    - Write victim page out to disk if modified (add `dirty` bit to PTE)
  - OS reads referenced page from disk into memory
  - Page table is updated, `valid` bit is set
  - Process continues execution



Flow of "Paging" Operations



Virtual Memory Policies

- OS needs to decide on policies on page faults concerning:
  - Page selection (When to bring in)
    - When should a page (or pages) on disk be brought into memory?
    - Two cases
      - When process starts, code pages begin on disk
      - As process runs, code and data pages may be moved to disk
  - Page replacement (What to replace)
    - Which resident page (or pages) in memory should be thrown out to disk?
- Goal: Minimize number of page faults
  - Page faults require milliseconds to handle (reading from disk)
  - Implication: Plenty of time for OS to make good decision

The *When*: Page *Selection*

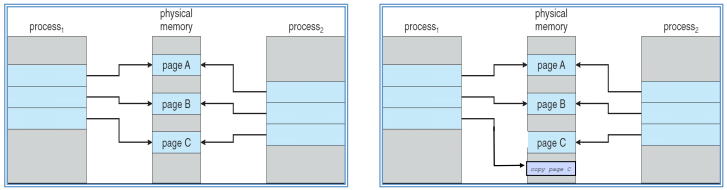
- When should a page be brought from disk into memory?
- Request paging: User specifies which pages are needed for process
  - Problems:
    - Manage memory by hand
    - Users do not always know future references
    - Users are not impartial (and infact they may be wrong)
- Demand paging: Load page only when page fault occurs
  - Intuition: Wait until page must absolutely be in memory
  - When process starts: No pages are loaded in memory
  - Advantage: Less work for user
  - Disadvantage: Pay cost of page fault for every newly accessed page

Page *Selection* Continued

- Pre-paging (anticipatory, prefetching): OS loads page into memory *before* page is referenced
  - OS predicts future accesses (the oracle) and brings pages into memory ahead of time (neighboring pages).
    - How?
    - Works well for some access patterns (e.g., sequential)
  - Advantages: May avoid page faults
  - Problems? :
- Hints: Combine *demand* or *pre-paging* with user- supplied hints about page references
  - User specifies: may need page in future, don't need this page anymore, or sequential access pattern, ...
  - Example: `madvise()` in Unix (1994 4.4 BSD UNIX)

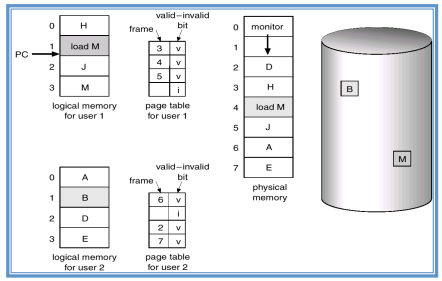
Virtual Page Optimizations

- Copy-on-Write: on process creation allow parent and child to share the same page in *memory until one modifies* the page.



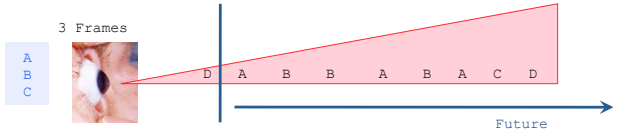
What happens if there is no free frame?

- Page replacement
  - find some page in memory, that is not really in use, and swap it out.
- Observation: Same page may be brought into memory several times (so try to keep that one in memory)
  - Frequently used.



Page *Replacement Strategies*

- Which page in main memory should selected as victim?
  - Write out victim page to disk if modified (dirty bit set)
  - If victim page is not modified (clean), just discard (cheaper to replace)



- OPT: Replace page *not used for longest time* in future
  - Advantage: Guaranteed to minimize number of page faults
  - Disadvantage: Requires that OS predict the future
    - Not practical, but is good to use comparison (best you can do)
- Random: Replace any page at random
  - Advantage: Easy to implement
  - Surprise?: Works okay when memory is not severely over-committed (recall lottery scheduling, random is not too shabby, in many areas)

Page Replacement Continued

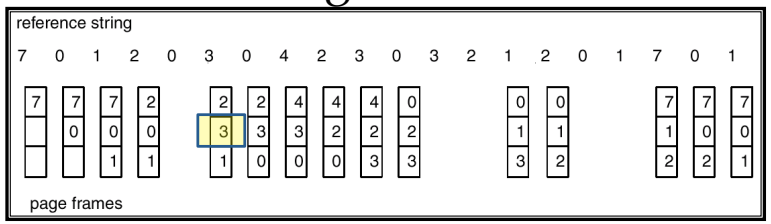
- FIFO: Replace page that has been in memory the longest
  - Intuition: First referenced long time ago, done with it now
  - Advantages:
    - Fair: All pages receive equal residency
    - Easy to implement (circular buffer)
  - Disadvantage: Some pages may always be needed
- L(east)RU: Replace page *not used* for longest time in past
  - Intuition: Use the past to predict the future
  - Advantages:
    - With locality, LRU approximates OPT (but look backwards)
  - Disadvantages:
    - Harder to implement, must track which pages have been accessed
    - Does not handle all workloads well

MFR, LFU

How to **Evaluate** Page Replacement Algorithms?

- Want: lowest page-fault rate (least #misses)
- Idea: Keep track of memory references – test with particular string of memory references and count page faults (based on real data or generated)
- Algorithm: Convert address to page location
  - Example: Assume 100 bytes per page and
    - Step 1: Assume the address sequence:
      - 0100, 0210, 0250, 0300, 0350, 0380, 0400, 0160, 0250, 0505, 0100, 0110, 0230, 0350, 0450, 0450, 0500, 0500
    - Step 2: Convert address to a page reference string:
      - 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5.
    - Step 3: Count page faults (hits don't count).

Example: Counting Faults of FIFO Page Replacement Algorithm

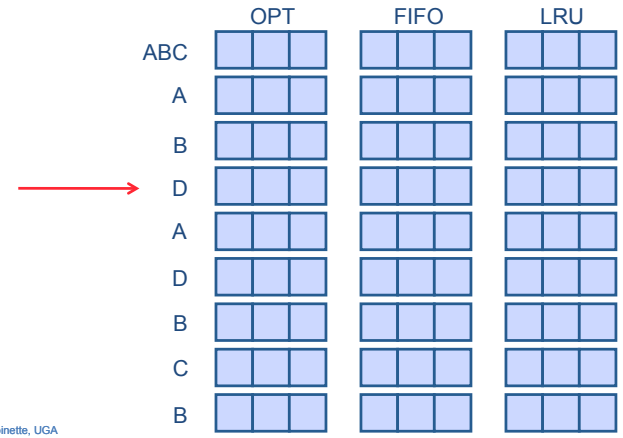


First IN is the one that is first OUT (not last accessed)

- **3 Frames are available**
- **FIFO: Replace page that has been in memory the longest**
- **Count page faults ? [15]**

Page Replacement Example (compare algorithms)

Page reference string: A B C A B D A D B C B
Three pages of physical memory



Page Replacement *Example*

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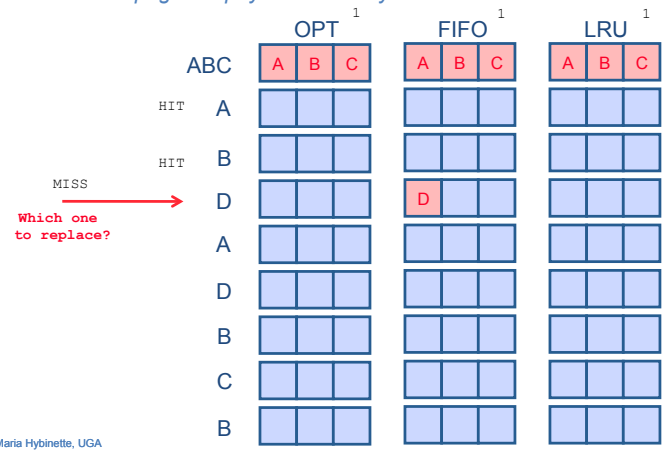

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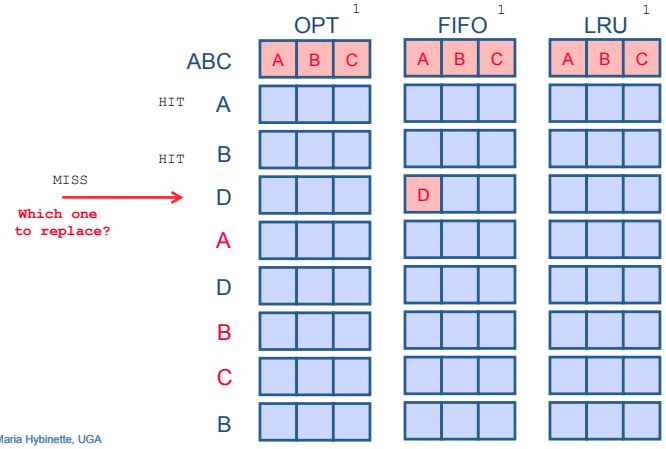

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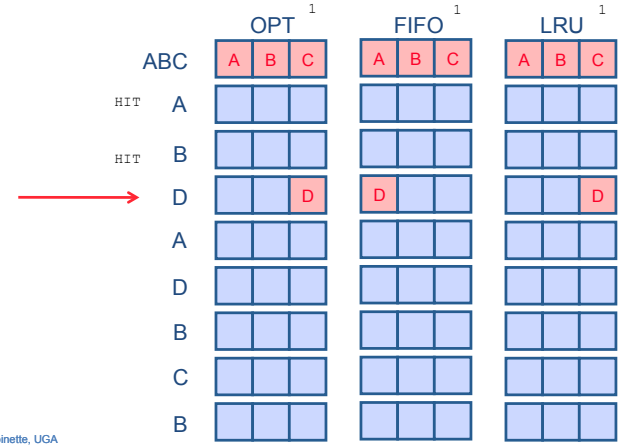

Page Replacement *Example*

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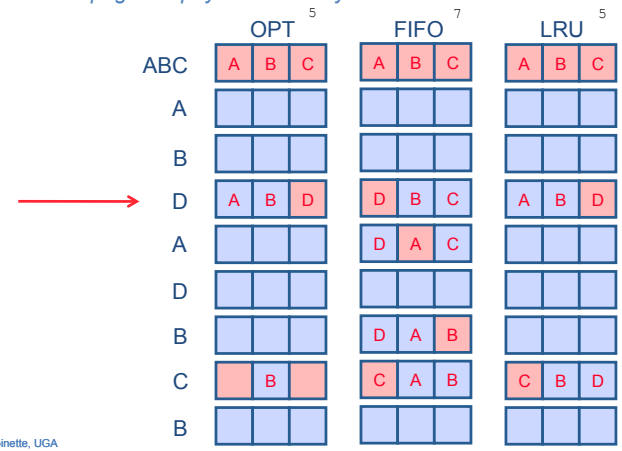


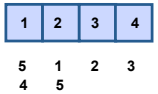
Page Replacement: Adding *More* Memory

- Add more physical memory, what happens to performance?
  - Ideally the numbers of page faults should should *decrease* as the number of available frames *increases*
  - 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5.
  - If 1 page frame (any strategy) : Number of page faults? (lots)
    - 12 page faults, one fault for every page
  - If 12 frames : Number of page faults? (fewer) more than we need
    - 5 page faults

First-In-First-Out (FIFO) Algorithm: Add Memory (3 Frames to 4 Frames)

- **Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5**
- **3 frames (3 pages can be in memory at a time per process)**

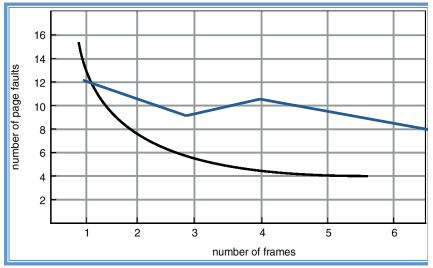
- 4 frames



- **FIFO Replacement – Belady's Anomaly**
  - » **Violates the Principle: More frames ⇒ less page faults**
  - » **9 PF -> 10 PF (more page faults as we increase memory)**
  - » **There is some string that have more page faults)**

Summary : Page Replacement: Add memory

- Add more physical memory, what happens to performance?
  - Ideally the numbers of page faults should should decrease as number of available frames increases
  - 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5.
  - If 1 page frame : 12 faults every access is fault
  - If 3 page frame: 9 faults
  - If 4 page frame: 10 faults
  - If 12 frames : 5 faults



Page Replacement Comparison

- Add more physical memory, what happens to performance?
  - LRU, OPT: Add more memory, guaranteed to have fewer (or same number of) page faults
    - Smaller memory sizes are guaranteed to contain a subset of larger memory sizes
  - FIFO: Add more memory, usually have fewer page faults
    - Belady's anomaly: But may actually have more page faults!

Implementing LRU

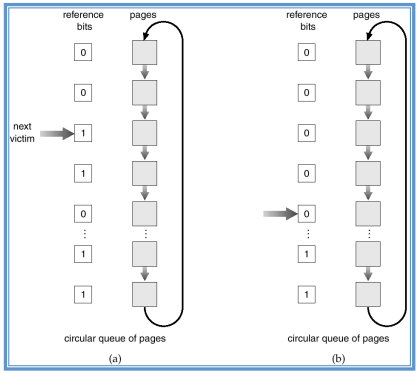
- Software Perfect LRU (Stack)
  - OS maintains ordered list of physical pages by reference time
  - When page is referenced: Move page to front of list (top)
    - slow, worst case search n pages to find oldest
  - When need victim: Pick page at back of list (bottom) fast (1)
  - Trade-off: Slow on memory reference (find it), fast on replacement
- Avoid reference Cost: Hardware Perfect LRU
  - Associate register with each page (fast access)
    - When page is referenced: Store system clock in register (fast)
  - When need victim: Scan through registers to find *oldest* clock (slow)
  - Trade-off: Fast on memory reference, slow on replacement (especially as size of memory grows). Expensive.
- In practice, do not implement Perfect LRU
  - LRU is an approximation anyway, so approximate it even more.
  - Goal: Find an old page, but just old enough
    - not necessarily the very oldest

Clock or *Second* Chance Algorithm

Select Victim for replacement

- Hardware (use a reference bit)
  - Keep `use` (or `reference`) bit for each page frame initialized to 0.
  - When page is referenced (increment)
    - set `use` bit (1), making it less likely to be replaced.
- Operating System
  - Page replacement: Look for page with where `use` bit is clear (0) (has not been referenced for a while),
    - Pages that are set to 1 are decremented and clock is reset as well and gets a second chance.
  - Implementation:
    - Keep pointer to last examined page frame
    - Traverse pages in circular buffer
    - Clear `use` bits while searching for replacement.
    - Stop when find page with an already cleared `use` bit, replace this page

Clock Algorithm Example



- Worst Case – behaves same as FIFO:
  - All bits are set -> FIFO (slow)

Clock Extensions

- Replace multiple pages at once
  - Intuition: Expensive to run replacement algorithm and to write single block to disk
  - Find multiple victims each time (multiple zeros)
- Use a Two-handed clock
  - Intuition (problem of the 1 handed clock)
    - If it takes long time for clock hand to sweep through pages, then all use bits might be set (all are 1s)
      - Traditional clock cannot differentiate between usage of different pages (only between 1s and 0s).
  - Allow smaller time between "clearing use bit" and testing (reading the bit).
    - First hand: Clears use bit
    - Second hand: Looks for victim page with use bit still cleared

More Clock Extensions

Provide a richer "past" history than just one bit.

- Add a software byte (to keep a bit mask)
  - Intuition: Keep track of history when last used
- Implementation: Reference bit
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1.
  - Keep a *history* of reference bit in an (8 bits) byte:
    - Shift reference bit for each page into high order bit, and other bits right one bit.
    - 11000100 (more recently used than below)
    - 01110111
    - 00000000 (not ben referenced at all.
  - →Lowest number is the LRU page

Other Issues (R/W)

- Use `dirty` bit to give preference to dirty pages (to stay)
  - Intuition: More expensive to replace dirty pages
    - Dirty pages must be written to disk, clean pages do not
  - Replace pages that have `use` bit and `dirty` bit cleared

0, 0	Not recently used, not modified	Best to replace
0, 1	Not recently used, but modified	Needs to be written out
1, 0	Recently used, not modified	Probably used again soon
1, 1	Recently used and modified	Probably used again soon and need to be written out

Problems with LRU-based Replacement

- Locality of reference:
  - Same pages referred frequently (warm pages)
  - Example: 2, 1, 3, 2, 4, 2, 4, 1, 5, 6, 2, …
- Leading question:
  - Is a page that has been accessed once in the past as likely to be accessed in the future as one that has been accessed N times?

Problems with LRU-based Replacement

- Example: 2, 1, 3, 2, 4, 2, 4, 1, 5, 6, 2, …
- Problem:
  - Dislodges warm pages if a long sequence of one time page references occur.
    - In the above ex, page 2 may get dislodged by the access pattern …, 4, 1, 5, 6,
  - LRU does not consider *frequency* of accesses
- Solution: Track frequency of accesses of a page
  - Pure LFU (Least-frequently-used) replacement
- Problem: but LFU can never forget pages from the far past… (so we need to add aging to the algorithm….)

Questions

- How to allocate memory *across* competing processes?
- What is thrashing? What is a working set?
- How to ensure working set of all processes fit?

Allocating Memory across Processes

- Problem:
  - 2 processes and 25 free frames how are these frames divided up between processes?
- Three General Approaches:
  - Global Replacement
  - Per-Process Replacement
  - Per-User Replacement (set of processes linked to a user)

Global Replacement

- Global replacement
  - Pages from all processes lumped into single replacement pool
  - Each process competes with other processes for frames
  - Advantages:
    - Flexibility of allocation
    - Minimize total number of page faults
  - Disadvantages:
    - One memory-intensive process can hog memory, hurt all other processes (not fair)
    - Paging behavior of one process depends on the behavior of other processes

Per-process replacement

- Per-process free pool of pages:
  - Equal, Fixed Allocation: Fixed number of pages per process
    - 100 frames and 5 processes, give each 20 pages.
    - Fixed fraction of physical memory
  - Proportional Allocation:
    - Proportional to size of address space of a process.
    - Adjust size allocated if a process have higher priority
- Page fault in one process only replaces frame of that process
- Advantage: Relieves interference from other processes
- Disadvantage: Potentially inefficient allocation of resources

Per-User Replacement

- Advantages: Users running more processes cannot hog memory
- Disadvantage: Inefficient allocation

Over Committing Memory

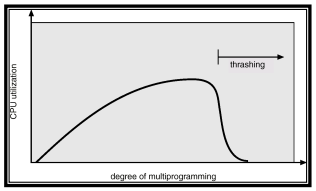
- When does the Virtual Memory illusion break?
- Example:
  - Set of processes *frequently* referencing 33 important pages - more than the memory available (then you are stuck with always replacing a page that is frequently referenced).
    - Physical memory can fit 32 pages
- What happens?
  - System Repeat Cycle:
    - Reference page not in memory
    - Replace a page in memory with newly referenced page
    - Replace another page right away again, since all its pages are in active use…

Thrashing

- Thrashing:
  - Definition: Spends more time paging than execution, i.e. system reading and writing pages instead of executing useful instructions
  - Observation – A global replacement algorithm aggravates the problem.
  - Symptom: Average memory access time equals to disk access time
    - Breaks the virtual memory illusion because memory appears as slow as disk rather than disk appearing fast as memory (system is reading/writing instead of executing)
    - Memory appears as slow as disk, instead of disk appearing as fast as memory
  - Processes execute less – system admits more processes -> thrashing gets worse

System does not know it is thrashing

- If a process does not have "enough" pages, the page-fault rate is very high.
  - low CPU utilization.
  - operating system thinks that it needs to increase the degree of multiprogramming.
  - another process added to the system
- Why the CPU utilization decreases:
  - Suppose a process need more frames, starts faulting, removing frames from others, in turn making the other processes fault
  - Processes queue up for the paging device, CPU decreases
  - OS add processes that immediately need new frames further taking away pages from running processes



Thrashing: Solutions

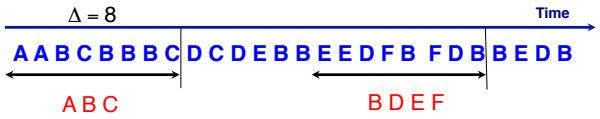
- Limit thrashing by using a local replacement
  - Process does not steal frames from other and cause others to thrash
  - Average service time for a page fault can still increase…
- Admission Control:
  - Determine of much memory each process needs
  - Long-term scheduling policy:
    - Run only processes whose memory requirement can be satisfied
- What if memory requirement of one process is too high?
  - Observation: a process moves through different ``localities'' through out is lifetime
    - Locality: Set of pages that are actively used together
  - Solution: Idea: Amortize page allocated so that a process get enough page for its current locality….

Motivation for Solution

- Thrashing cannot be fixed with better replacement policies
  - Page replacement policies do not indicate that a page must be kept in memory
  - Only show which pages are better than others to replace
- Student's analogy to thrashing: Too many courses
  - Solution: Drop a course (focus on other remaning courses)
- OS solution: Admission control
  - Determine how much memory each process needs
  - Long-term scheduling policy
    - Run only those processes whose memory requirements can be satisfied
  - What if memory needs of one process are too large?

Working Set

- Informal definition
  - Collection of pages the process is referencing frequently
  - Collection of pages that must be resident to avoid thrashing
- Formal definition
  - Assume locality; use recent past to predict future
  - Pages referenced by process in last T seconds of execution
  - Working set changes slowly over time
- Example (figure out number of frames needed by inspecting the past using a window based approach)



- Balance Set -

- Motivation: Process should not be scheduled unless current working set can be resident in main memory
- Divide runnable processes into two groups:
  - Active: Working set is loaded
  - Inactive: Working set is swapped to disk
- Balance set: Sum of working sets of all active processes
- Interaction with scheduler
  - If balance set exceeds size of memory, move some process to inactive set
    - Which process???
  - If balance set is less than size of memory, move some process to active set
    - Which process?
  - Any other considerations?

Working Set Implementation

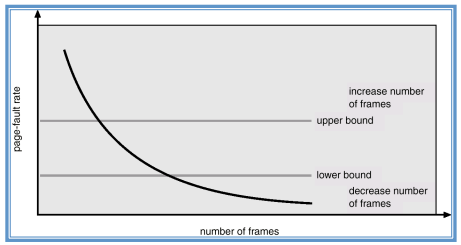
- Leverage `use` bits (as in the clock algorithm)
- OS maintains `idle time` for each page
  - Amount of CPU received by process since last access to page
  - Periodically scan all resident pages of a process
    - If `use` bit is set, clear pages' idle time
    - If `use` bit is clear, add process CPU time (since last scan) to idle time
  - If idle time < ΔT , page is in working set

Thought Questions

- How should value of ΔT be configured?
  - What if ΔT is too large?
- How should working set be defined when pages are shared?
  - Put jobs sharing pages in same balance set
- What processes should compose balance set?
- How much memory is needed for a "balanced system"?
  - Balanced system: Each resource (e.g., CPU, memory, disk) becomes bottleneck at nearly same time
  - How much memory is needed to keep the CPU busy?
  - With working set approach, CPU may be idle even with runnable processes

Page-Fault Frequency Scheme

- Observation: Thrashing has a high page-fault rate
- Idea: Control page fault-rate by controlling # frames that are allocated to a process
  - Too high page fault rate : process need more frames
  - Too low : process has too many frames
- Approach: Establish "acceptable" page-fault rate (upper and lower bound)
  - If actual rate falls below lower limit, process loses frame.
  - If actual rate exceeds upper limit, process gains frame.



Current Trend: Thoughts?

- VM code is not as critical
  - Reason #1: Personal vs. time-shared machine
    - Why does this matter? Clouds?
  - Reason #2: Memory is more affordable, more memory
- Less hardware support for replacement policies
  - Software emulation of use and dirty bits
- Larger page sizes
  - Better TLB coverage
  - Smaller page tables
  - Disadvantage: More internal fragmentation
    - Multiple page sizes