Evicting the best page

- The goal of the page replacement algorithm:
  - reduce fault rate by selecting best victim page to remove
  - the best page to evict is one that will never be touched again
    - as process will never again fault on it
  - “never” is a long time
    - Belady’s proof: evicting the page that won’t be used for the longest period of time minimizes page fault rate
- Rest of this lecture:
  - survey a bunch of replacement algorithms

#1: Belady's Algorithm

- Pick the page that won't be used for longest time in future
  - Provably optimal lowest fault rate (remember SJF?)
    - Why?
  - Problem: impossible to predict future
- Why is Belady's algorithm useful?
  - as a yardstick to compare other algorithms to optimal
    - if Belady's isn't much better than yours, yours is pretty good
- Is there a lower bound?
  - unfortunately, lower bound depends on workload
    - but, random replacement is pretty bad

#2: FIFO

- FIFO is obvious, and simple to implement
  - when you page in something, put in on tail of list
  - on eviction, throw away page on head of list
- Why might this be good?
  - maybe the one brought in longest ago is not being used
- Why might this be bad?
  - then again, maybe it is being used
  - have absolutely no information either way
- FIFO suffers from Belady's Anomaly
  - fault rate might increase when algorithm is given more physical memory
    - a very bad property

Example of Belady's Anomaly

3 pages

Page Requests	**3**	**2**	**1**	**0**	**3**	**2**	**4**	**3**	**2**	**1**	**0**	**4**
Newest Page	*3*	*2*	*1*	*0*	*3*	*2*	*4*	4	4	*1*	*0*	0
		3	2	1	0	3	2	2	2	4	1	1
Oldest Page			3	2	1	0	3	3	3	2	4	4

4 pages

Page Requests	**3**	**2**	**1**	**0**	**3**	**2**	**4**	**3**	**2**	**1**	**0**	**4**
Newest Page	*3*	*2*	*1*	*0*	0	0	*4*	*3*	*2*	*1*	*0*	*4*
		3	2	1	1	1	0	4	3	2	1	0
			3	2	2	2	1	0	4	3	2	1
Oldest Page				3	3	3	2	1	0	4	3	2

(red *italics* indicates page fault)

#3: Least Recently Used (LRU)

- LRU uses reference information to make a more informed replacement decision
  - idea: past experience gives us a guess of future behavior
  - on replacement, evict the page that hasn't been used for the longest amount of time
    - LRU looks at the past, Belady's wants to look at future
  - when does LRU do well?
    - when does it suck?
- Implementation
  - to be perfect, must grab a timestamp on every memory reference and put it in the PTE (way too $$)
  - so, we need an approximation…

Approximating LRU

- Many approximations, all use the PTE reference bit
  - keep a counter for each page
  - at some regular interval, for each page, do:
    - if ref bit = 0, increment the counter (hasn't been used)
    - if ref bit = 1, zero the counter (has been used)
    - regardless, zero ref bit
  - the counter will contain the # of intervals since the last reference to the page
    - page with largest counter is least recently used
- Some architectures don't have PTE reference bits
  - can simulate reference bit using the valid bit to induce faults
    - hack, hack, hack

#4: LRU Clock

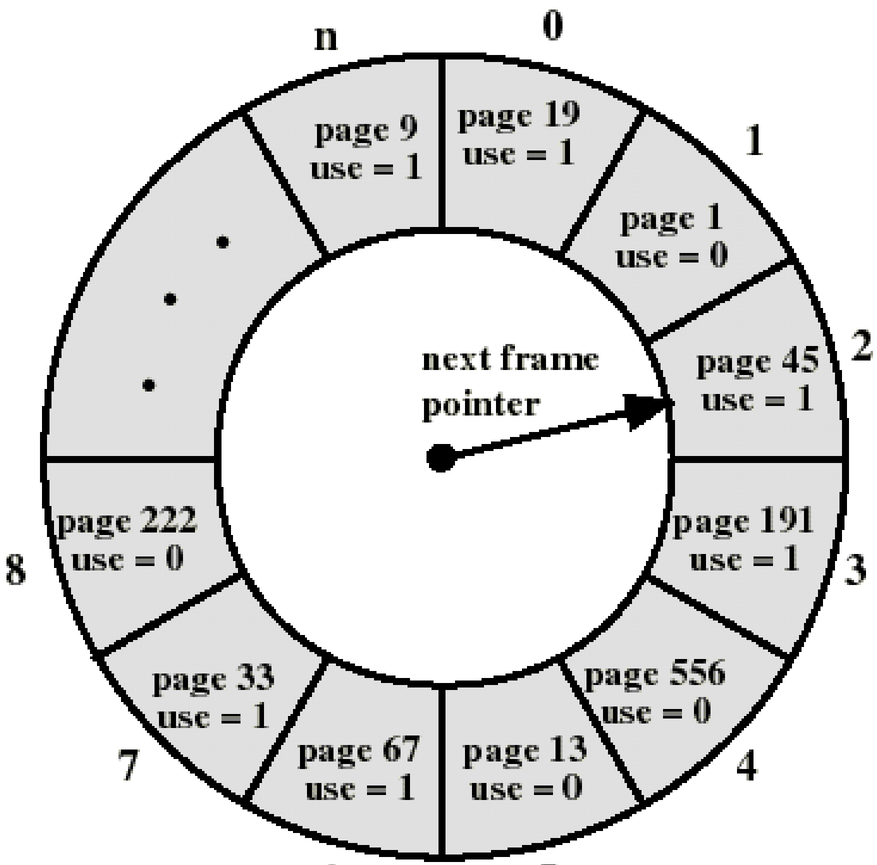
- AKA Not Recently Used (NRU) or Second Chance
  - replace page that is "old enough"
- Arrange all physical page frames in a big circle (clock)
    - just a circular linked list
  - a "clock hand" is used to select a good LRU candidate
    - sweep through the pages in circular order like a clock
    - if ref bit is off, it hasn't been used recently, we have a victim
      - so, what is minimum "age" if ref bit is off?
    - if the ref bit is on, turn it off and go to next page
  - arm moves quickly when pages are needed
  - low overhead if have plenty of memory
- if memory is large, "accuracy" of information degrades
  - add more hands to fix
- SHOW EXAMPLE!

Clock page replacement

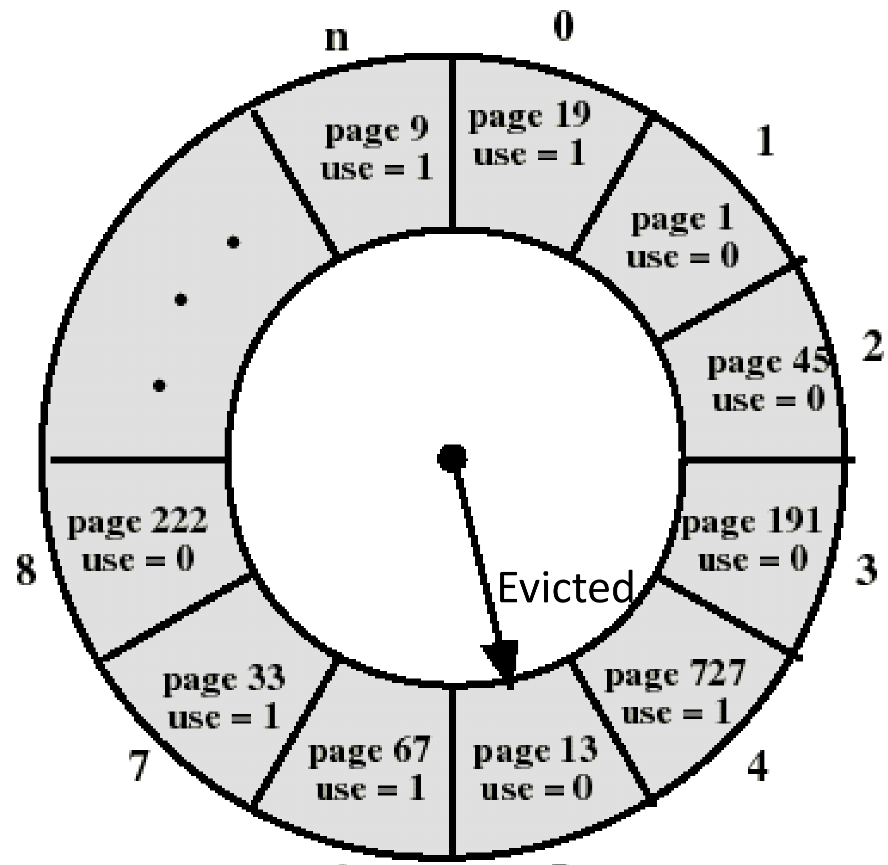
- Circular list instead of queue
- Clock hand points to oldest page
- If (Referenced==0) then
  - Page is unused so replace it
- Else
  - Clear Referenced
  - Advance clock hand

- (very similar to second chance – queue instead of list)

The Clock Policy: an example



(a) State of buffer just prior to a page replacement



(b) State of buffer just after the next page replacement

Another Problem: allocation of frames

- In a multiprogramming system, we need a way to allocate physical memory to competing processes
  - what if a victim page belongs to another process?
  - family of replacement algorithms that takes this into account
- Fixed space algorithms
  - each process is given a limit of pages it can use
  - when it reaches its limit, it replaces from its own pages
  - local replacement: some process may do well, others suffer
- Variable space algorithms
  - processes' set of pages grows and shrinks dynamically
  - global replacement: one process can ruin it for the rest
    - linux uses global replacement

#5: 2^{nd} Chance FIFO

- LRU Clock is a **global** algorithm
  - It looks at all physical pages, from all processes
  - Every process gets its memory taken away gradually
- Local algorithms: run page replacement separately for each process
- 2^{nd} Chance FIFO:
  - Maintain 2 FIFO queues per process
  - On first access, pages go at end of queue 1
  - When the drop off queue 1, page are invalidated and move to queue 2
  - When they drop off queue 2, they are replaced
  - If they are accessed in queue 2, they are put back on queue 1
- Options:
  - Move to queue 1 immediately when referenced: mark "invalid" when on queue 2
  - Move to queue 2 when about to be evicted: looks like clock
- Comparison to LRU clock:
  - Per-process, not whole machine
  - No scanning
  - Replacement order is FIFO, not PFN
  - Used in Windows NT, VMS

Second chance page replacement

- Inspect R bit of oldest page
  - Recall: R bits are set when page is referenced (read or write); periodically (after k clock interrupts), R bits are cleared.
  - If R==0 then
    - page is old & unused so replace it
  - Else
    - Clear R bit
    - Move page from head to tail of FIFO
      - (treating it as a newly loaded page)
    - Try a different page

Second chance page replacement

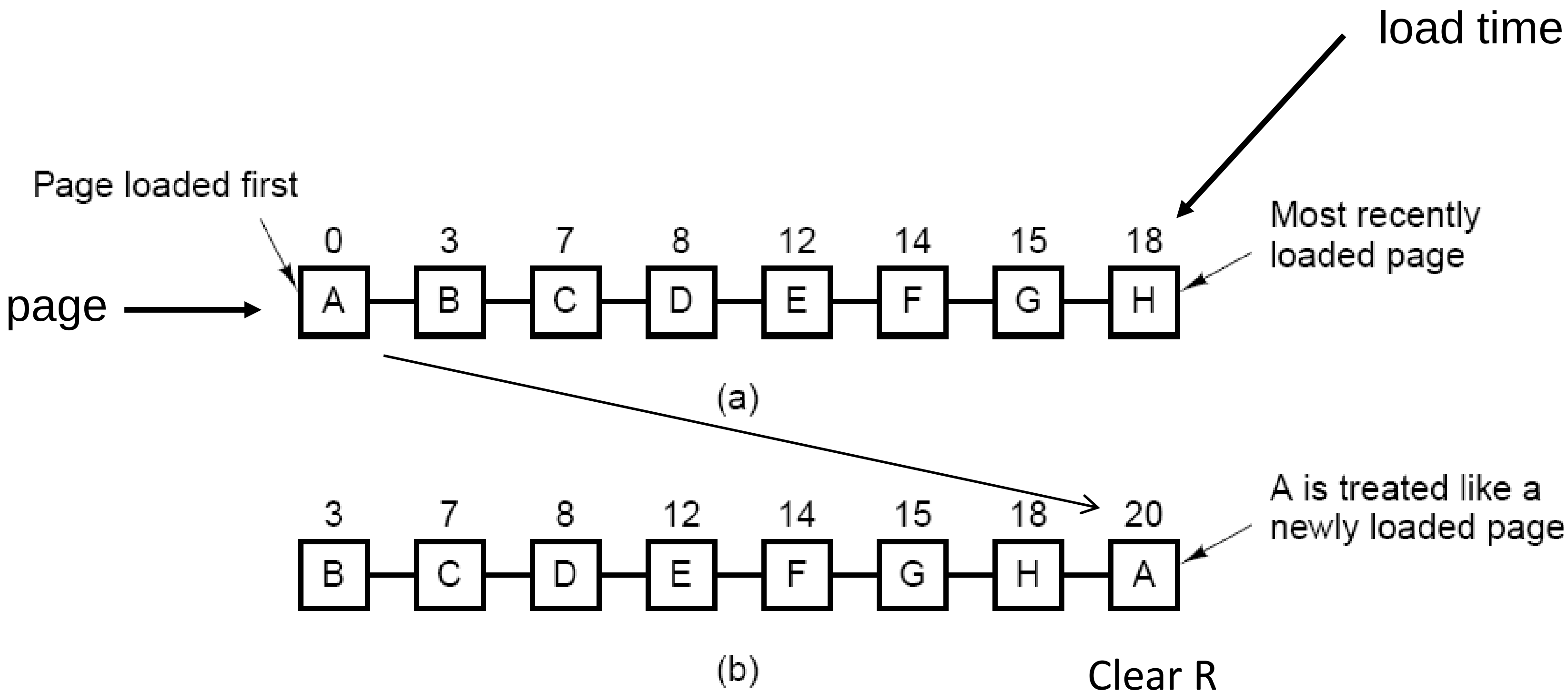


Fig. 4-16. Operation of second chance. (a) Pages sorted in FIFO order. (b) Page list if a page fault occurs at time 20 and *A* has its *R* bit set. The numbers above the pages are their loading times.

The Working Set Strategy

- Is a variable-allocation method with local scope based on the assumption of locality of references
- The working set for a process at time t, W(D,t), is the set of pages that have been referenced in the last D virtual time units
  - virtual time = time elapsed while the process was in execution (eg: number of instructions executed)
  - D is a window of time
  - at any t, |W(D,t)| is non decreasing with D
  - W(D,t) is an approximation of the program's locality

The Working Set Strategy

- The working set of a process first grows when it starts executing
- then stabilizes by the principle of locality
- it grows again when the process enters a new locality (transition period)
  - up to a point where the working set contains pages from two localities
- then decreases after a sufficient long time spent in the new locality

#6: Working Set Size

- The working set size changes with program locality
  - during periods of poor locality, more pages are referenced
  - within that period of time, the working set size is larger
- Intuitively, working set must be in memory, otherwise you'll experience heavy faulting (thrashing)
  - when people ask "How much memory does Firefox need?", really they are asking "what is Firefoxaverage (or worst case) working set size?"
- Hypothetical algorithm:
  - associate parameter "w" with each process = # of unique pages referenced in the last "t" ms that it executed
  - only allow a process to start if it's "w", when added to all other processes, still fits in memory
    - use a local replacement algorithm within each process (e.g. clock, 2nd chance FIFO)

The Working Set Strategy

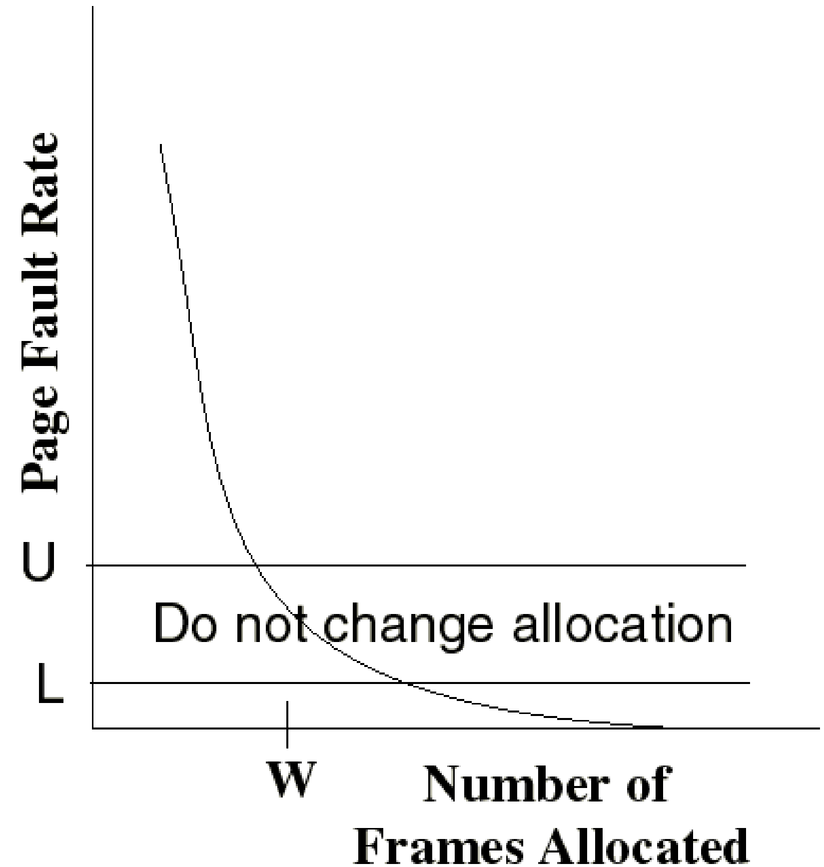
- the working set concept suggest the following strategy to determine the resident set size
  - Monitor the working set for each process
  - Periodically remove from the resident set of a process those pages that are not in the working set
  - When the resident set of a process is smaller than its working set, allocate more frames to it
    - If not enough free frames are available, suspend the process (until more frames are available)
      - ie: a process may execute only if its working set is in main memory

The Working Set Strategy

- Practical problems with this working set strategy
  - measurement of the working set for each process is impractical
    - necessary to time stamp the referenced page at every memory reference
    - necessary to maintain a time-ordered queue of referenced pages for each process
  - the optimal value for D is unknown and time varying
- Solution: rather than monitor the working set, monitor the page fault rate!

The Page-Fault Frequency Strategy

- Define an upper bound U and lower bound L for page fault rates
- Allocate more frames to a process if fault rate is higher than U
- Allocate less frames if fault rate is < L
- The resident set size should be close to the working set size W
- We suspend the process if the PFF > U and no more free frames are available



Summary

- demand paging
  - start with no physical pages mapped, load them in on demand
- page replacement algorithms
  - #1: Belady's – optimal, but unrealizable
  - #2: Fifo – replace page loaded furthest in past
  - #3: LRU – replace page referenced furthest in past
    - approximate using PTE reference bit
  - #4: LRU Clock – replace page that is "old enough"
  - #5: 2nd Chance FIFO – replace local page that is "old enough"
  - #6: working set – keep set of pages in memory that induces the minimal fault rate
- local vs. global replacement
  - should processes be allowed to evict each other's pages?

Thrashing

- What the OS does if page replacement algo's fail
  - happens if most of the time is spent by an OS paging data back and forth from disk
    - no time is spent doing useful work
    - the system is overcommitted
    - no idea which pages should be in memory to reduced faults
    - could be that there just isn't enough physical memory for all processes
  - solutions?
- Yields some insight into systems research[ers]
  - if system has too much memory
    - page replacement algorithm doesn't matter (overprovisioning)
  - if system has too little memory
    - page replacement algorithm doesn't matter (overcommitted)
  - problem is only interesting on the border between overprovisioned and overcommitted
    - many research papers live here, but not many real systems do…