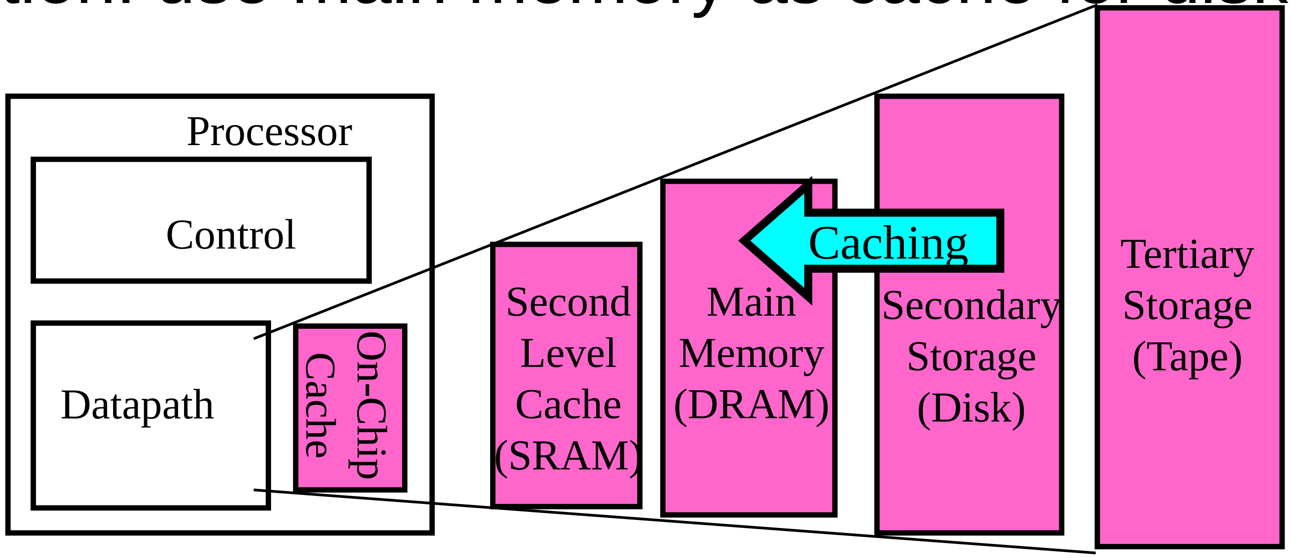
CMPT 300
Introduction to Operating Systems

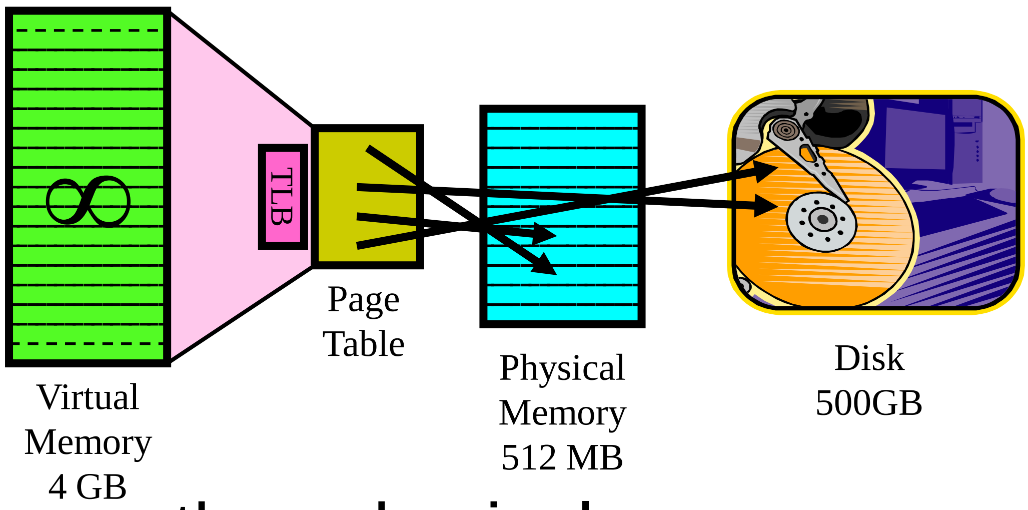
Page Replacement Algorithms

Demand Paging

- Modern programs require a lot of physical memory
  - Memory per system growing faster than 25%-30%/year
- But they don't use all their memory all of the time
  - 90-10 rule: programs spend 90% of their time in 10% of their code
  - Wasteful to require all of user's code to be in memory
- Solution: use main memory as cache for disk



Illusion of Infinite Memory



- Disk is larger than physical memory ⇒
  - In-use virtual memory can be bigger than physical memory
  - Combined memory of running processes much larger than physical memory
    - More programs fit into memory, allowing more concurrency
- Principle: Transparent Level of Indirection (page table)
  - Supports flexible placement of physical data
    - Data could be on disk or somewhere across network
  - Variable location of data transparent to user program
    - Performance issue, not correctness issue

Demand Paging is Caching

- Since Demand Paging is Caching, must ask:
  - What is block size?
    - 1 page
  - What is organization of this cache (i.e. direct-mapped, set-associative, fully-associative)?
    - Fully associative: arbitrary virtual→physical mapping
  - How do we find a page in the cache when look for it?
    - First check TLB, then page-table traversal
  - What is page replacement policy? (i.e. LRU, Random…)
    - This requires more explanation… (kinda LRU)
  - What happens on a miss?
    - Go to lower level to fill miss (i.e. disk)
  - What happens on a write? (write-through, write back)
    - Write-back. Need dirty bit!

Demand Paging Example

- Since Demand Paging like caching, can compute average access time! ("Effective Access Time")
  - EAT = Hit Rate x Hit Time + Miss Rate x Miss Time
- Example:
  - Memory access time = 200 nanoseconds
  - Average page-fault service time = 8 milliseconds
  - Suppose p = Probability of miss, 1-p = Probably of hit
  - Then, we can compute EAT as follows:

    EAT = (1 – p) x 200ns + p x 8 ms
    = (1 – p) x 200ns + p x 8,000,000ns
    = 200ns + p x 7,999,800ns
- If one access out of 1,000 causes a page fault, then EAT = 8.2 μs:
  - This is a slowdown by a factor of 40!
- What if want slowdown by less than 10%?
  - 200ns x 1.1 < EAT $\Rightarrow$ p < 2.5 x 10^{-6}
  - This is about 1 page fault in 400000!

What Factors Lead to Misses?

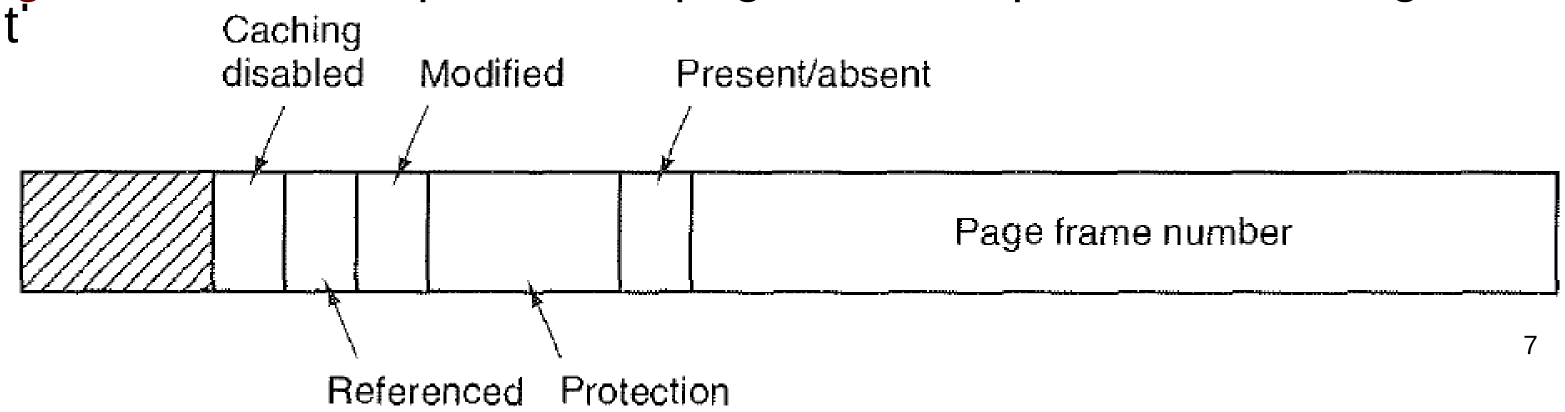
- Compulsory Misses:
  - Pages that have never been paged into memory before
  - How might we remove these misses?
    - Prefetching: loading them into memory before needed
    - Need to predict future somehow! More later.
- Capacity Misses:
  - Not enough memory. Must somehow increase size.
  - Can we do this?
    - One option: Increase amount of DRAM (not quick fix!)
    - Another option: If multiple processes in memory: adjust percentage of memory allocated to each one!
- Conflict Misses:
  - Technically, conflict misses don't exist in virtual memory, since it is a "fully-associative" cache
- Policy Misses:
  - Caused when pages were in memory, but kicked out prematurely because of the replacement policy
  - How to fix? Better replacement policy

Replacement policy

- Why do we care about Replacement Policy?
  - Replacement is an issue with any cache
  - Particularly important with pages
    - The cost of being wrong is high: must go to disk
    - Must keep important pages in memory, not toss them out
- The simplest algorithm:
  - Pick random page for every replacement
  - Typical solution for TLB. Simple hardware
  - Unpredictable – makes it hard to make real-time guarantees

Recall: What is in a Page Table Entry (PTE)?

- *Page frame number.* Physical memory address of this page
- *Present/absent bit,* also called *valid bit.* If this bit is 1, the page is in memory and can be used. If it is 0, the page is not currently in memory. Accessing a page table entry with this bit set to 0 causes a page fault to get page from disk.
- *Protection bits* tell what kinds of access are permitted on the page. 3 bits, one bit each for enabling read, write, and execute.
- *Modified (M) bit,* also called *dirty bit,* is set to 1 when a page is written to
- *Referenced (R) bit,* is set whenever a page is referenced, either for reading or writing.
  - M and R bits are very useful to page replacement algorithms
- *Caching disabled bit,* important for pages that map onto device registers rather t



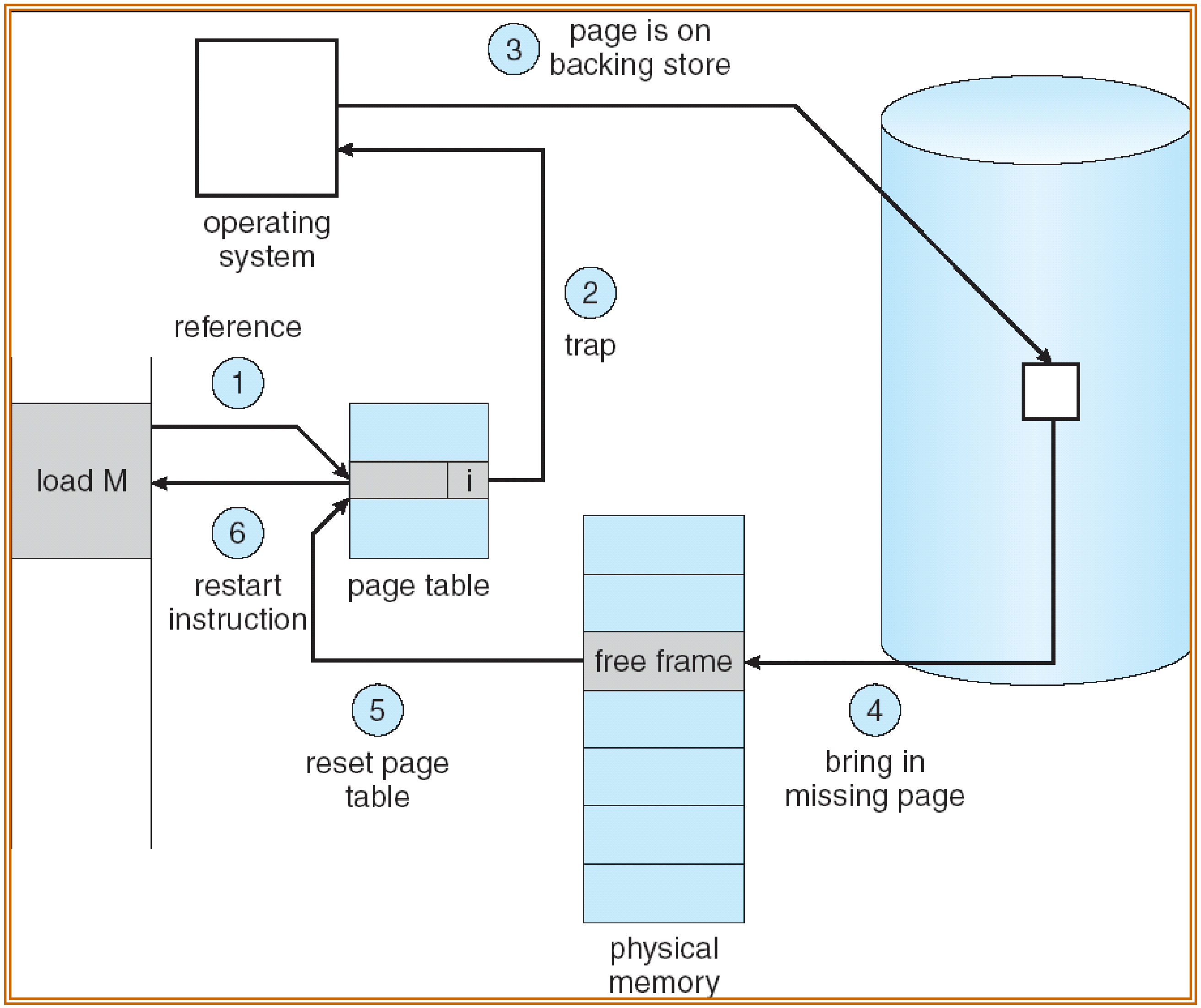
R & M bits

- Referenced (R) bit indicates if the page has been used recently.
  - Each time the page is referenced (read or written to), the R bit is set to 1.
  - OS defines a *clock period* for paging management. Every clock period, the R bit for each page is reset to 0.
    - R=0 → page is old (not used for some time)
    - R=1 → page is new (recently used)
- Modified (M) bit indicates if the page has been modified (written to) since it was last synced with disk.
  - The flag is reset when the page is saved to disk
  - When a page is removed from physical memory
    - M=1 → it will be saved to disk
    - M=0 → it will be abandoned and not saved to disk

Demand Paging Mechanisms

- PTE helps us implement demand paging
  - Present ⇒ Page in memory, PTE points at physical page
  - Absent ⇒ Page not in memory; use info in PTE to find it on disk when necessary
- Suppose user references page with Absent PTE?
  - Memory Management Unit (MMU) traps to OS
    - Resulting trap is a "Page Fault"
  - What does OS do on a Page Fault?:
    - Choose an old page to replace
    - If old page modified, write page contents back to disk
    - Change its PTE and any cached TLB to be invalid
    - Load new page into memory from disk
    - Update PTE, invalidate TLB for new entry
    - Continue thread from original faulting location
  - TLB for new page will be loaded when thread continues!
  - While pulling pages off disk for one process, OS runs another process from ready queue
    - Suspended process sits on wait queue

Steps in Handling a Page Fault



Page Replacement Algorithms

- Optimal (OPT)
- Not recently used (NRU)
- First-In, First-Out (FIFO)
- Second chance (SC)
- Least recently used (LRU)
- Not frequently used (NFU)
- Aging algorithm
- Clock algorithm
- Working set
- WSClock

OPT page replacement

- Replace page that won’t be used for the longest time
- Optimal, but infeasible in practice, since can’t really know future…
- Makes good comparison case, however

Not recently used (NRU)

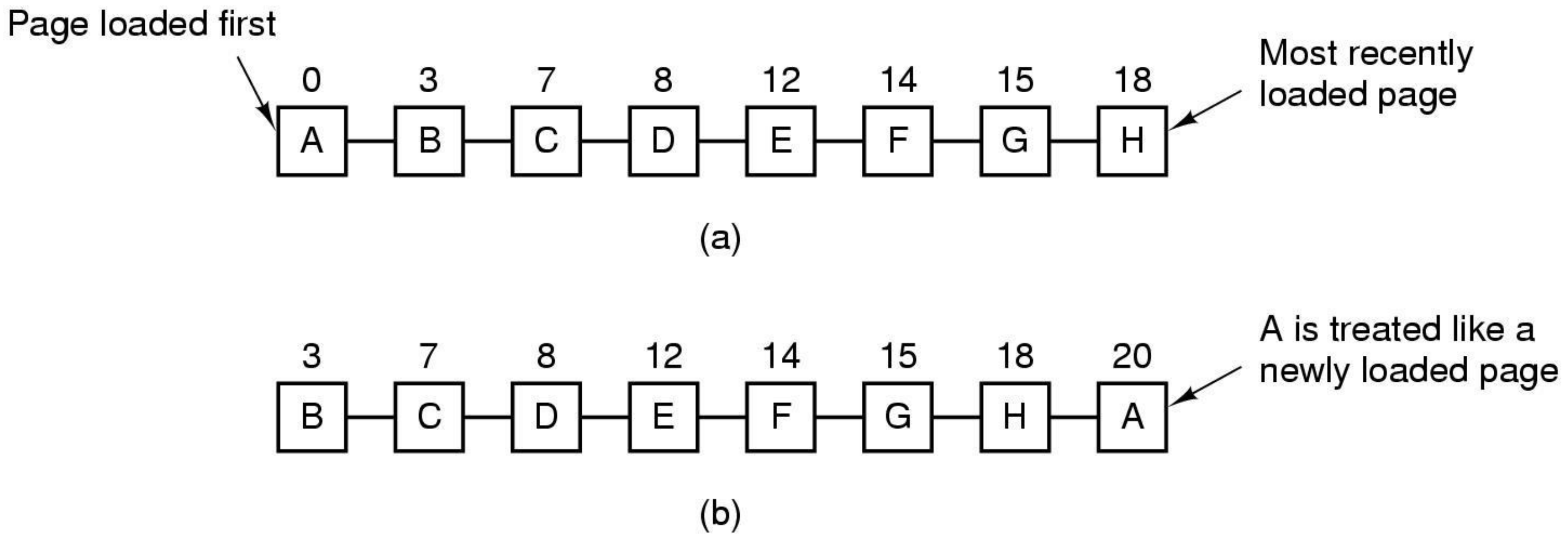
- Use the referenced and modified bits in the page table entries. 4 possibilities:
  1. Not referenced, not modified
  2. Not referenced, modified (reference cleared on clock interrupt)
  3. Referenced, not modified
  4. Referenced, modified
- When a page fault occurs, find any page in group 1, failing that any page in group 2, failing that any page in group 3, failing that any page in group 4. If there is more than one page in the lowest group, randomly choose one page from the group.
- Rationale: replace the page that has not been referenced or modified.

FIFO

- Throw out oldest page.
  - Be fair – let every page live in memory for same amount of time.
- Bad, because it tends to throw out heavily used pages instead of infrequently used pages
  - Second-chance algorithm avoids this problem by giving recently-used pages a second chance

Second-Chance Algorithm

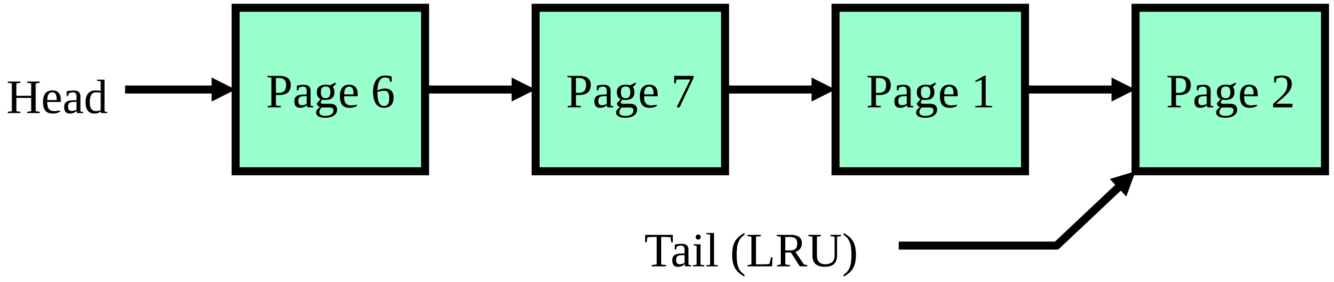
- Give recently-used pages a second chance
  - If the oldest page has R=0, then choose it for replacement; if R=1, then move it to the end, and update its load time as through it's a new arrival



- (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 load times.

Least Recently Used (LRU)

- Replace page that hasn't been used for the longest time
- Programs have locality, so if something not used for a while, unlikely to be used in the near future.
- Seems like LRU should be a good approximation to OPT.
- How to implement LRU? Use a list!



  - On each use, remove page from list and place at head
  - LRU page is at tail
- Problems with this scheme for paging?
  - List must be updated at every memory reference; List manipulation is expensive
- In practice, people approximate LRU (more later)

Example: FIFO

- Consider a cache size of 3 page frames, and following reference stream of virtual pages:
  - A B C A B D A D B C B
- Consider FIFO Page replacement:
  - FIFO: 7 faults.
  - When referencing D, replacing A is bad choice, since need A again right away

Ref: Page:	A	B	C	A	B	D	A	D	B	C	B
1	A					D				C	
2		B					A				
3			C						B		

Example: OPT

- Suppose we have the same reference stream:
  - A B C A B D A D B C B
- Consider OPT Page replacement:
  - 5 faults
  - Where will D be brought in? Look for page not referenced farthest in future (C).
- What will LRU do?
  - Same decisions as OPT here, but won't always be true!

Ref: / Page:	A	B	C	A	B	D	A	D	B	C	B
1	A									C	
2		B									
3			C			D					

When will LRU perform badly?

- Consider the following: A B C D A B C D A B C D
- LRU Performs as follows (same as FIFO here):
  - Every reference is a page fault!

Ref: / Page:	A	B	C	D	A	B	C	D	A	B	C	D
1	A			D			C			B		
2		B			A			D			C	
3			C			B			A			D

OPT Does much better

- But it's not implementable

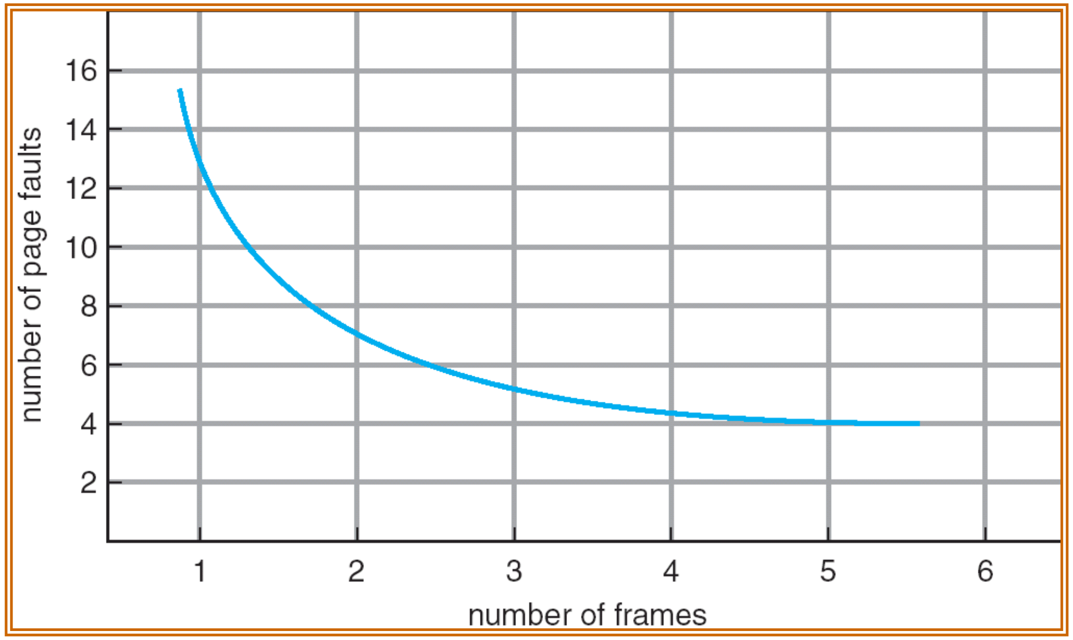
Ref: Page:	A	B	C	D	A	B	C	D	A	B	C	D
1	A									B		
2		B					C					
3			C	D								

Exercise

- Consider a cache size of 3 page frames, and following reference stream of virtual pages:
  - 7 0 1 2 0 3 0 4 2 3 0 3 2 1 2 0 1 7 0 1
  - Run FIFO, OPT and LRU on this example.
- Answer:
  - FIFO: http://cs.uttyler.edu/Faculty/Rainwater/COSC3355/Animations/fifopagereplacement.htm
  - OPT: http://cs.uttyler.edu/Faculty/Rainwater/COSC3355/Animations/optimalpagereplacement.htm
  - LRU: http://cs.uttyler.edu/Faculty/Rainwater/COSC3355/Animations/lrupagereplacement.htm

Graph of Page Faults Versus The Number of Page Frames

- One desirable property: When you add memory the miss rate goes down
  - Does this always happen?
  - Seems like it should, right?
- No: BeLady’s anomaly
  - Certain replacement algorithms (FIFO) don’t have this obvious property!



BeLady’s anomaly

- Does adding memory reduce number of page faults?
  - Yes for LRU and OPT
  - Not necessarily for FIFO! (Called Belady’s anomaly)
- After adding memory:
  - With FIFO, contents can be completely different
  - In contrast, with LRU or OPT, contents of memory with X pages are a subset of contents with X+1 Page

Ref: Page:	A	B	C	D	A	B	E	A	B	C	D	E
1	A			D			E					
2		B			A					C		
3			C			B					D	

9 page faults

Ref: Page:	A	B	C	D	A	B	E	A	B	C	D	E
1	A						E				D	
2		B						A				E
3			C						B			
4				D						C		

10 page faults

Implementing LRU

- Perfect:
  - Timestamp page on each reference
  - Keep list of pages ordered by time of reference
  - Too expensive to implement in reality
- Techniques for approximating LRU. Goal is to Replace an old page, not the oldest page
- Hardware techniques
  - 64-bit counter
  - n x n matrix
- Software techniques
  - Not recently used (NRU)
  - Aging Algorithm
  - Clock Algorithm

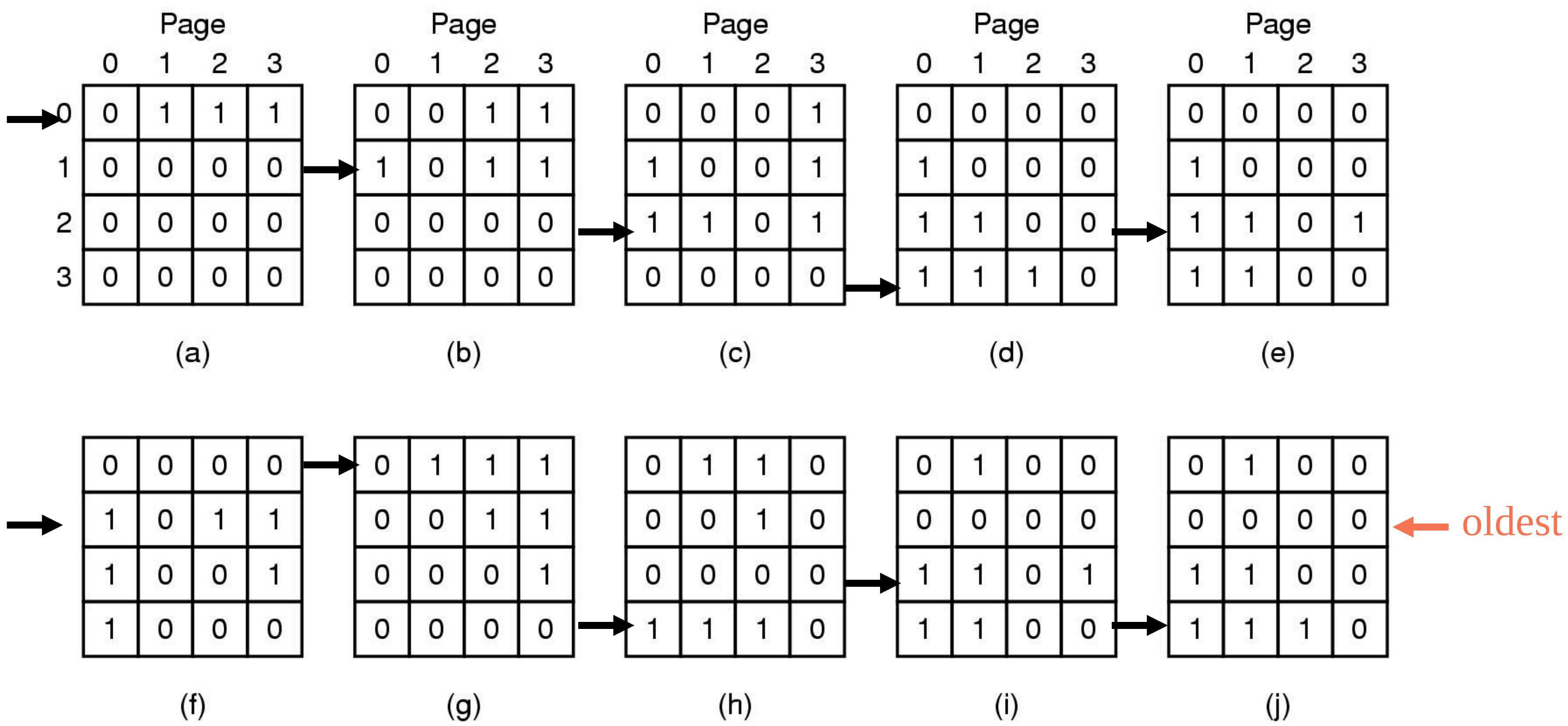
LRU in hardware

- Implementation #1:
  - 64 bit counter, C, incremented after every instruction
  - Each page also has a 64 bit counter
  - When a page is referenced, C is copied to its counter.
  - Page with lowest counter is oldest.

LRU in hardware

- Implementation #2:
  - Given n page frames, let M be a n x n matrix of bits initially all 0.
  - Reference to page frame k occurs.
  - Set all bits in row k of M to 1.
  - Set all bits in column k of M to 0.
  - Row with lowest binary value is least recently used.

LRU in hardware: implementation #2 example



(a)

Page	0	1	2	3
0	0	1	1	1
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0

(b)

Page	0	1	2	3
0	0	0	1	1
1	1	0	1	1
2	0	0	0	0
3	0	0	0	0

(c)

Page	0	1	2	3
0	0	0	0	1
1	1	0	0	1
2	1	1	0	1
3	0	0	0	0

(d)

Page	0	1	2	3
0	0	0	0	0
1	1	0	0	0
2	1	1	0	0
3	1	1	1	0

(e)

Page	0	1	2	3
0	0	0	0	0
1	1	0	0	0
2	1	1	0	1
3	1	1	0	0

(f)

0	0	0	0
1	0	1	1
1	0	0	1
1	0	0	0

(g)

0	1	1	1
0	0	1	1
0	0	0	1
0	0	0	0

(h)

0	1	1	0
0	0	1	0
0	0	0	0
1	1	1	0

(i)

0	1	0	0
0	0	0	0
1	1	0	1
1	1	0	0

(j)

0	1	0	0
0	0	0	0
1	1	0	0
1	1	1	0

Figure 3-17. LRU using a matrix when pages are referenced in the order 0, 1, 2, 3, 2, 1, 0, 3, 2, 3.

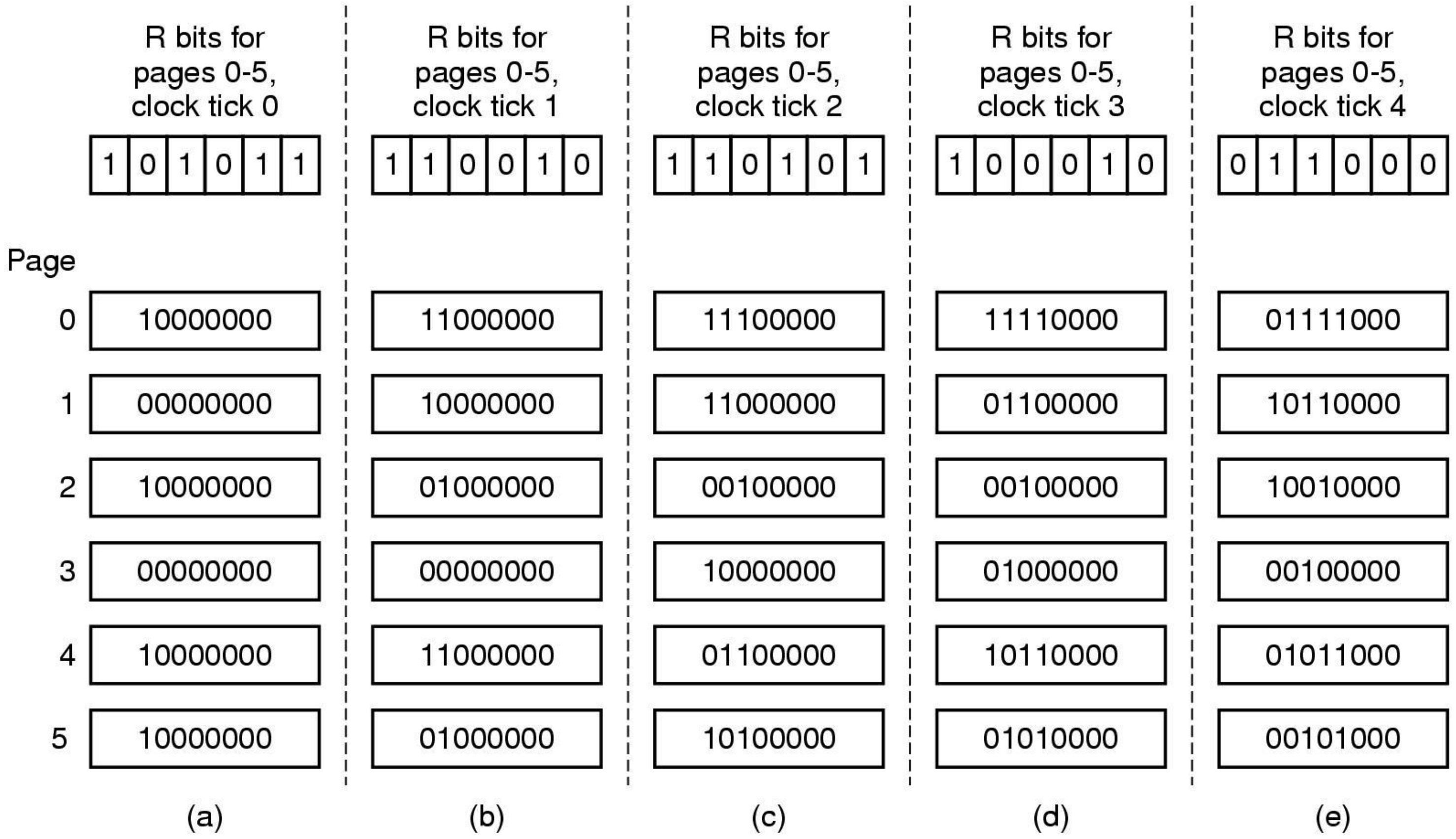
Not frequently used (NFU)

- A software counter associated with each page, initially zero. At end of each clock period, the operating system scans all the pages in memory.
- For each page, the *R bit* (0 or 1), is added to the counter (arithmetic addition), which roughly keeps track of how often each page has been referenced. When a page fault occurs, the page with the smallest counter is chosen for replacement.
- Problem: It never forgets!
  - So pages that were frequently referenced (during initialization for example) but are no longer needed appear to be FU.

Aging algorithm

- Idea: Gradually forget the past
  - A k-bit software counter is associated with each page, the counter is initialized to 0
  - Shift all counters to right 1 bit before R bit is added in.
  - Then R bit is added to MSb (Most Significant (leftmost) bit)
  - Page with lowest counter value is chosen for removal.

Aging algorithm example


R bits for pages 0-5, clock tick 0
1 0 1 0 1 1
R bits for pages 0-5, clock tick 1
1 1 0 0 1 0
R bits for pages 0-5, clock tick 2
1 1 0 1 0 1
R bits for pages 0-5, clock tick 3
1 0 0 0 1 0
R bits for pages 0-5, clock tick 4
0 1 1 0 0 0
Page
(a)
(b)
(c)
(d)
(e)

Page	(a)	(b)	(c)	(d)	(e)
0	10000000	11000000	11100000	11110000	01111000
1	00000000	10000000	11000000	01100000	10110000
2	10000000	01000000	00100000	00100000	10010000
3	00000000	00000000	10000000	01000000	00100000
4	10000000	11000000	01100000	10110000	01011000
5	10000000	01000000	10100000	01010000	00101000

- Shown are six pages for five clock periods. The five clock periods are represented by (a) to (e).

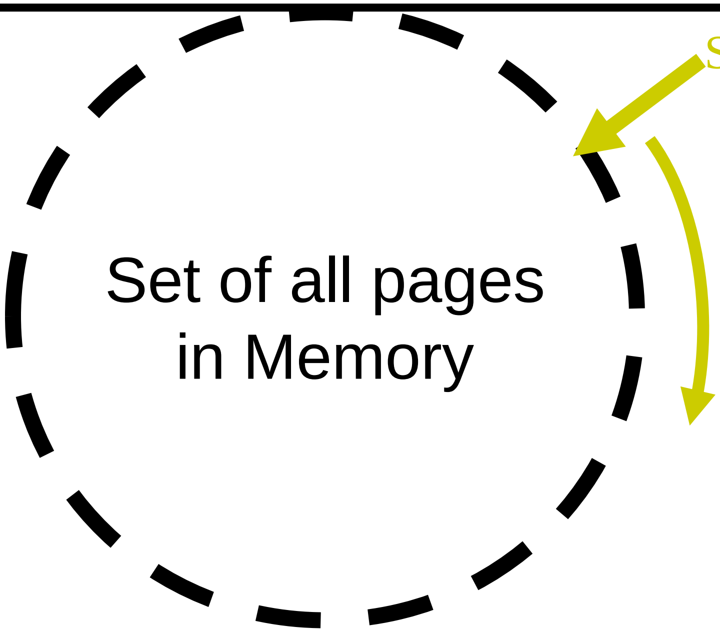
Aging vs. LRU

- Aging has a finite history of memory
    - Consider aging with an 8-bit counter with value 0. It cannot distinguish between a page referenced 9 clock periods ago, and another referenced 1000 block periods ago.
    - If the counter has infinitely many bits, then it implements LRU exactly.
- 8 bits generally enough
    - If clock period is 20ms, a history of 160ms is perhaps adequate

Clock Algorithm

- A variant of second-chance algorithm
- Recall "R" (reference) bit in PTE:
  - Hardware sets R bit on each reference
  - Instead of clearing R periodically (with "clock period" mentioned before) driven by OS timer, clear it at page-fault events
- Arrange physical page frames in a circle with single clock hand. On each page fault:
  - Advance clock hand (not real-time)
  - Check R bit:
    - R=1→used recently; clear and leave alone
    - R=0→selected candidate for replacement
- Will always find a page or loop forever?
  - Even if all R bits set, will eventually loop around ⇒ FIFO

Clock Algorithm


Set of all pages
in Memory
Single Clock Hand:
Advances only on page fault!
Check for pages not used recently
Mark pages as not used recently

- What if hand moving slowly?
  - Not many page faults and/or find page quickly
- What if hand is moving quickly?
  - Lots of page faults and/or lots of reference bits set
- One way to view clock algorithm: Partitioning of pages into two groups: young and old
- Animation: http://gaia.ecs.csus.edu/~zhangd/oscal/ClockFiles/Clock.htm (usrname/passwd: CSC139/csus.os.prin)
- (Uncheck "use modified bit" button. Note that it uses "U" instead of "R" for the reference bit.)

Nth Chance version of Clock Algorithm

- Nth chance algorithm: Give page N chances
  - OS keeps counter per page: # sweeps
  - On page fault, OS checks R bit:
    - R=1⇒clear R bit and also set counter to N (ref'ed in last sweep)
    - R=0⇒decrement count; if count=0, replace page
  - Means that clock hand has to sweep by N times without page being used before page is replaced
- How do we pick N?
  - Why pick large N? Better approx to LRU
    - If N ~ 1K, really good approximation
  - Why pick small N? More efficient
    - Otherwise might have to look a long way to find free page
- What about dirty pages?
  - Takes extra overhead to replace a dirty page, so give dirty pages an extra chance before replacing?
  - Common approach:
    - Clean pages, use N=1
    - Dirty pages, use N=2

Allocation of Page Frames

- How do we allocate memory (page frames) among different processes?
  - Does every process get the same fraction of memory? Different fractions?
  - Should we completely swap some processes out of memory?
- Each process needs *minimum* number of pages
  - Want to make sure that all processes that are loaded into memory can make forward progress
  - Example: IBM 370: 6 pages to handle SS MOVE instruction:
    - instruction is 6 bytes, might span 2 pages
    - 2 pages to handle *from*
    - 2 pages to handle *to*

Possible Replacement Scopes:

- Possible Replacement Scopes:
  - Global replacement – process selects replacement frame from set of all frames; one process can take a frame from another
    - Achieve effective utilization of memory through sharing
  - Local replacement – each process selects from only its own set of allocated frames
    - Achieve memory isolation among processes

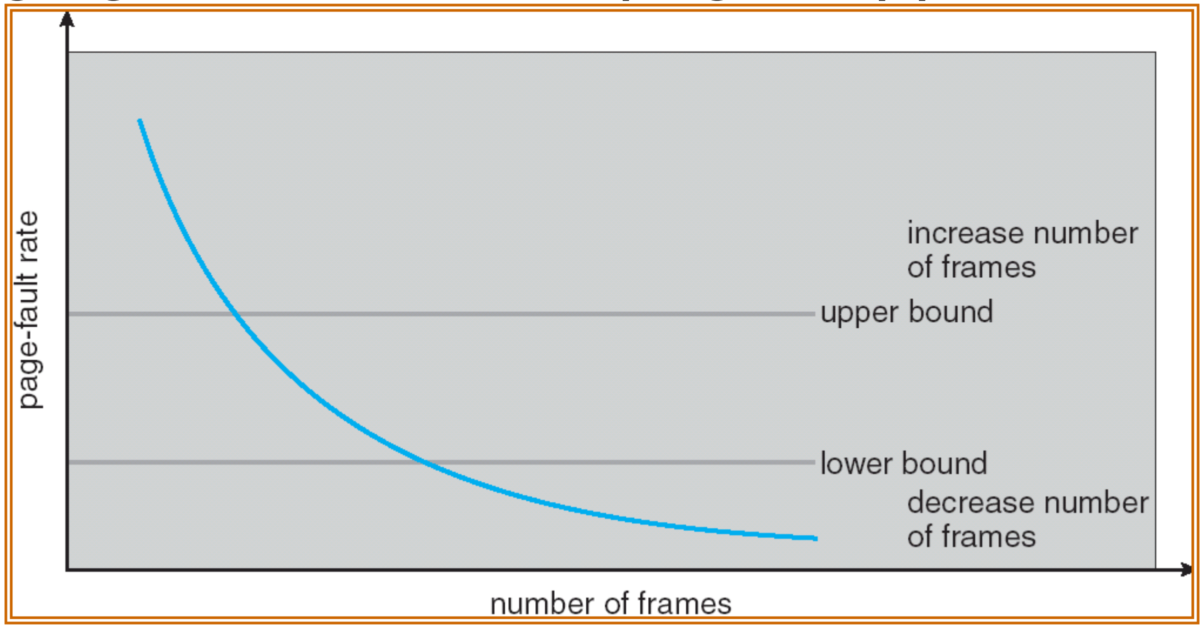
Fixed/Priority Allocation

- Equal allocation (Fixed Scheme):
  - Every process gets same amount of memory
  - Example: 100 frames, 5 processes$\Rightarrow$process gets 20 frames
- Proportional allocation (Fixed Scheme)
  - Allocate according to the size of process
  - Computation proceeds as follows:
    s_i = size of process p_i and $S = \Sigma s_i$
    m = total number of frames

    a_i = allocation for p_i = $\frac{s_i}{S} \times m$
- Priority Allocation:
  - Proportional scheme using priorities rather than size
    - Same type of computation as previous scheme
  - Possible behavior: If process p_i generates a page fault, select for replacement a frame from a process with lower priority number

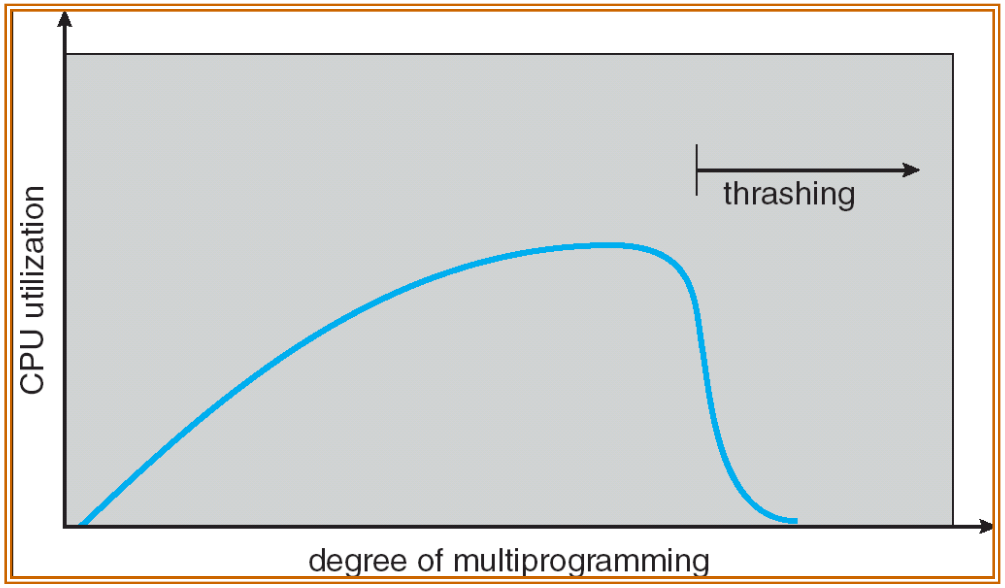
Page-Fault Frequency Allocation

- Can we reduce Capacity misses by dynamically changing the number of pages/application?



- Establish "acceptable" page-fault rate
  - If actual rate too low, process loses frame
  - If actual rate too high, process gains frame
- Question: What if we just don't have enough memory?

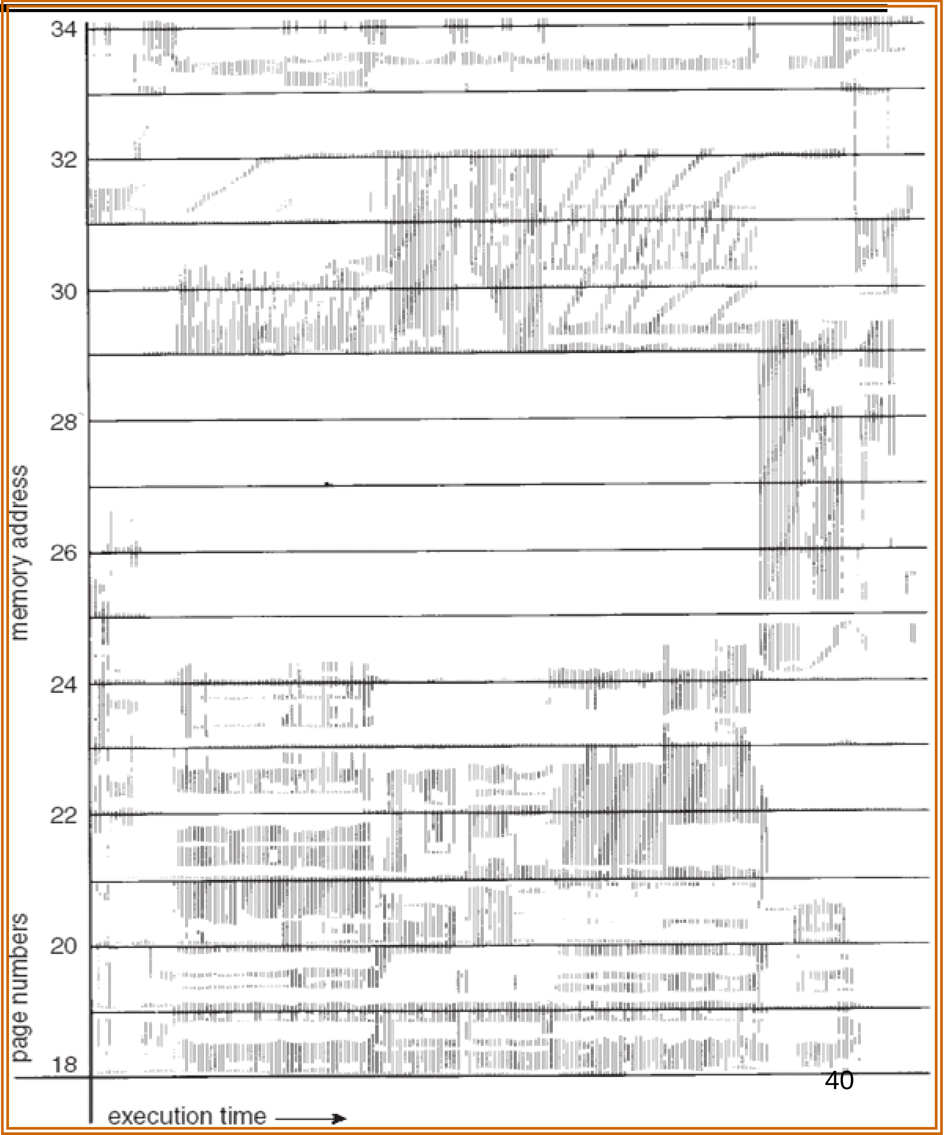
Thrashing



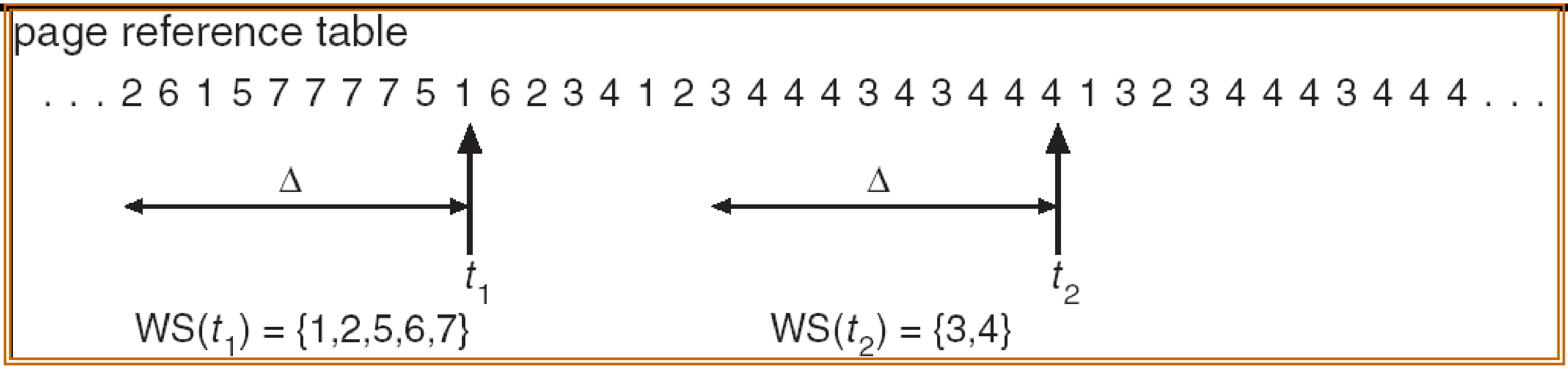
- If a process does not have "enough" pages, the page-fault rate is very high. This leads to:
  - low CPU utilization
  - operating system spends most of its time swapping to disk
- Thrashing ≡ a process is busy swapping pages in and out
- Questions:
  - How do we detect Thrashing?
  - What is best response to Thrashing?

Locality In A Memory-Reference Pattern

- Program Memory Access Patterns have temporal and spatial locality
  - Group of Pages accessed along a given time slice called the "Working Set"
  - Working Set defines minimum number of pages needed for process to behave well
- Not enough memory for Working Set⇒Thrashing
  - Better to swap out process?



Working-Set Model



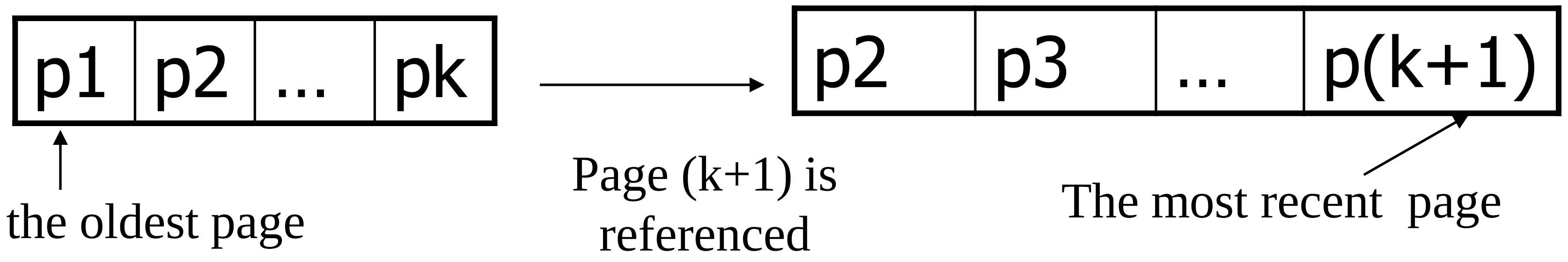
- $\Delta \equiv$ working-set window $\equiv$ fixed number of page references
  - Example: 10 million references
- WS_i (working set of Process P_i) = total set of pages referenced in the most recent Δ (varies in time)
  - if Δ too small will not encompass entire locality
  - if Δ too large will encompass several localities
  - if $\Delta = \infty \Rightarrow$ will encompass entire program
- $D = \Sigma|WS_i| \equiv$ total demand frames
- if $D > m \Rightarrow$ Thrashing
  - Policy: if D > m, then suspend one of the processes
  - This can improve overall system behavior by a lot!
- Animation: http://cs.uttyler.edu/Faculty/Rainwater/COSC3355/Animations/workingset.htm

What about Compulsory Misses?

- Recall that compulsory misses are misses that occur the first time that a page is seen
  - Pages that are touched for the first time
  - Pages that are touched after process is swapped out/swapped back in
- Clustering:
  - On a page-fault, bring in multiple pages “around” the faulting page
  - Since efficiency of disk reads increases with sequential reads, makes sense to read several sequential pages
- Working Set Tracking:
  - Use algorithm to try to track working set of application
  - When swapping process back in, swap in working set

Maintaining WS: A Simple Way

- Store page numbers in a shift register of length *k*, and with every memory reference, we do
  - Shift the register left one position, and
  - Insert the most recently referenced page number on the right
  - The set of *k* page numbers in the register is the working set.
- Too expensive to do this for each memory reference.



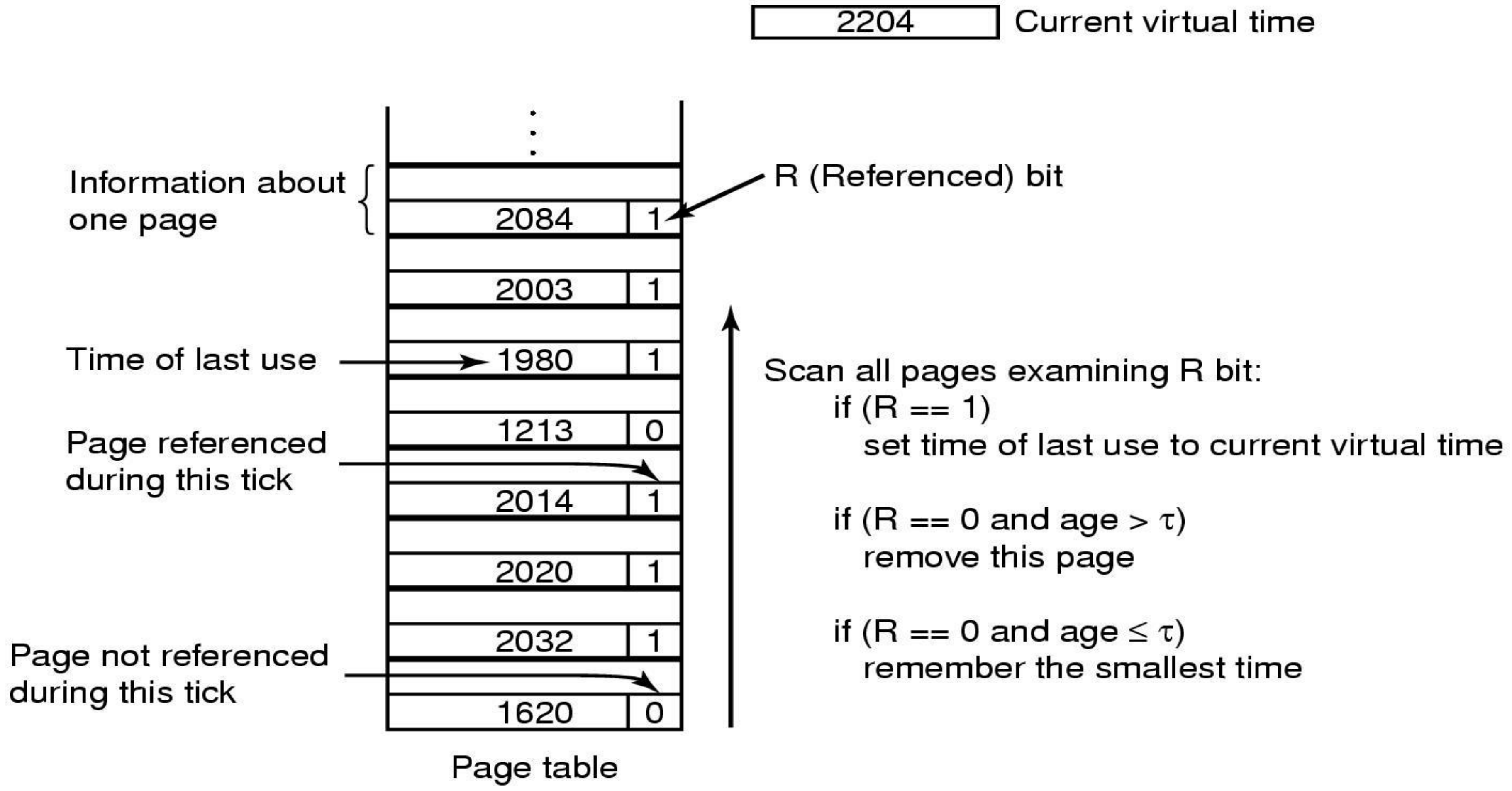
Implementation: Defining a working set

- Since not practical to keep history of past Δ memory references, use *working set window* of τ ms.
  - e.g., instead of defining working set as those pages used during previous 10 million references, define it as pages used during past working set window of 100ms
  - Note: not wall-clock time! If a process starts running at time T, and runs for 40ms at time T+100ms, it's execution time is 40ms. (the other 60ms is used for running other processes)
- We use the term *current virtual time* to denote execution time of a process since its start
  - Working set of a process is set of pages it referenced during the past τ ms of virtual time

Working set algorithm

- Recall: the R bit of a PTE is cleared every clock period. Assume the working set window τ ms spans multiple clock periods.
- *On every page* fault, the page table is scanned to look for a suitable page to evict. The *R bit* of each PTE is examined.
  - If R=1 the page has been accessed this clock period and is part of WS.
    - Its *Time of last use* is updated to the present time.
    - If R=1 for all pages in memory, a random page is evicted
  - If R=0 the age (difference between the present time and *Time of last use*) is determined.
    - If age > τ, then the page is no longer considered to be part of WS. It may be removed and replaced with the new page
    - If age ≤ τ, then the page is still in WS. If all pages in physical memory are still in WS, the oldest one is chosen for eviction

Working set algorithm example



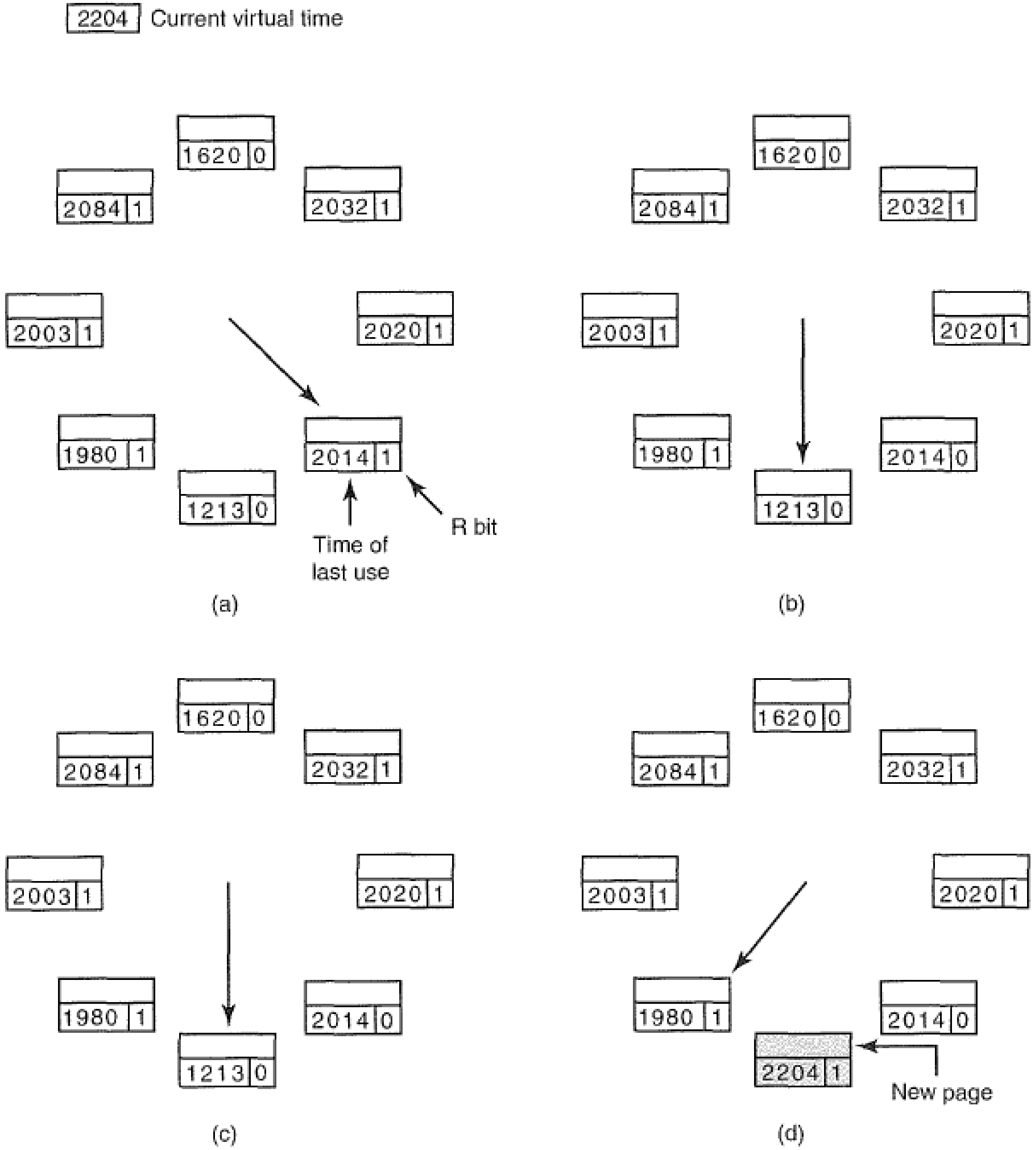
```
Scan all pages examining R bit:
    if (R == 1)
      set time of last use to current virtual time

    if (R == 0 and age > τ)
      remove this page

    if (R == 0 and age ≤ τ)
      remember the smallest time
```

WSClock algorithm

- Basic working set algorithm requires entire page table to be scanned at every page fault until a victim is located
- WSClock algorithm is a combination of Clock algorithm and working set algorithm:
  - Instead of clearing R periodically driven by OS timer, clear it at page-fault events
- Arrange physical page frames in a circle with single clock hand. On each page fault:
  - Advance clock hand (not real time)
  - Check R bit:
    - R=1→used recently; clear and leave alone
    - R=0→additional checking for page age:
      - If age > τ, not in WS; selected candidate for replacement
      - If age ≤ τ, in WS. If all pages in physical memory are still in WS, the oldest one is chosen for eviction
- Worst-case same as working set algorithm, but average case much better
- (Note: this is a simplified version of WSClock that does not consider the modified bit. The algorithm in textbook is more complex.)



Operations of the WSClock algorithm.

(a) and (b) give an example of what happens when R = 1. (c) and (d) give an example of R = 0 and age $> \tau$.

Summary

- Replacement algorithms
  - OPT: Replace page that will be used farthest in future
  - FIFO: Place pages on queue, replace page at end
  - Second-chance: giving recently-used pages a second chance
  - LRU: Replace page used farthest in past
  - Approximations to LRU
    - NFU & Aging:
      - Keep track of recent use history for each page
    - Clock Algorithm:
      - Arrange all pages in circular list
      - Sweep through them, marking as not “in use”
      - If page not “in use” for one pass, than can replace
    - Nth-chance clock algorithm
      - Give pages multiple passes of clock hand before replacing
- Working Set:
  - Set of pages touched by a process recently
- Working set algorithm:
  - Tries to keep each working set in memory
- Thrashing: a process is busy swapping pages in and out
  - Process will thrash if working set doesn’t fit in memory
  - Need to swap out a process

Summary

Algorithm	Comment
Optimal	Not implementable, good as benchmark
NRU	Very crude
FIFO	Might throw out important pages
Second chance	Big improvement over FIFO
Clock	Realistic
LRU	Excellent, but difficult to implement exactly
NFU	Fairly crude approximation to LRU
Aging	Efficient algorithm approximates LRU well
Working set	Somewhat expensive to implement
WSClock	Good efficient algorithm