University of Pittsburgh

Introduction to Operating Systems
CS 1550

Spring 2023

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(Some slides are from **Silberschatz, Galvin and Gagne ©2013)**

Announcements

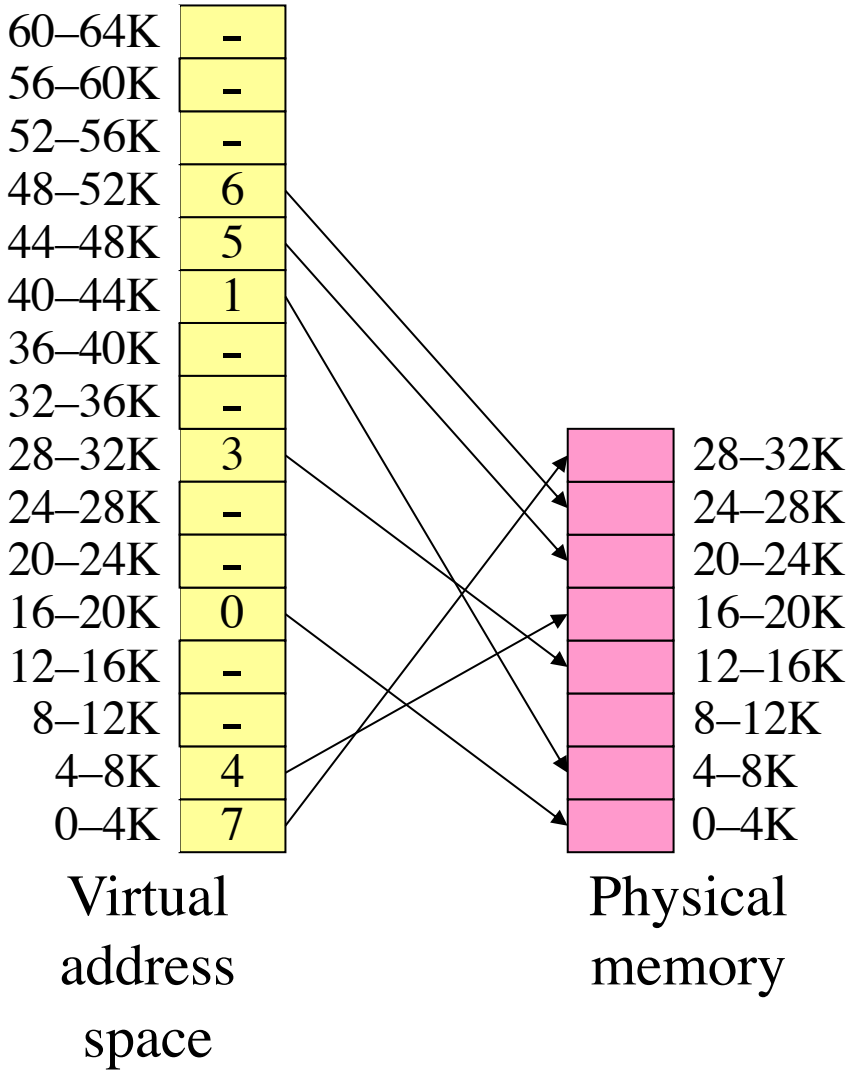
- Upcoming deadlines
  - Homework 8 is due this Friday: 2 extra attempts
  - Quiz 2 is this Friday at 11:59 pm
  - Lab 3 is due on Tuesday 3/28 at 11:59 pm
  - Project 3 is due Friday 4/7 at 11:59 pm

Previous Lecture …

- Memory allocation and protection
  - Take 1: Variable-size segments, base and limit registers
  - Take 2: Virtual memory
    - Fixed-size pages, on-demand, appear as if having more memory that physically in the system

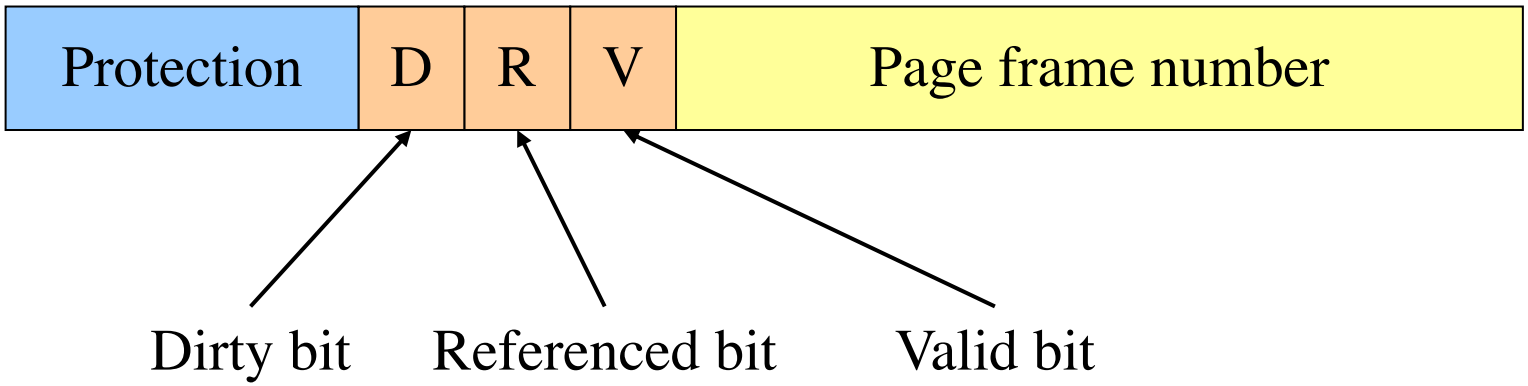
Paging and page tables

- Virtual addresses mapped to physical addresses
  - Unit of mapping is called a *page*
  - All addresses in the same virtual page are in the same physical page
  - *Page table entry* (PTE) contains translation for a single page
- Table translates virtual page number to physical page number
  - Not all virtual memory has a physical page
  - Not every physical page need be used
- Example:
  - 64 KB virtual memory
  - 32 KB physical memory



What's in a page table entry?

- Each entry in the page table contains
  - Valid bit: set if this logical page number has a corresponding physical frame in memory
    - If not valid, remainder of PTE is irrelevant
  - Page frame number: page in physical memory
  - Referenced bit: set if data on the page has been accessed
  - Dirty (modified) bit :set if data on the page has been modified
  - Protection information



Implementing page tables in hardware

- Page table resides in main (physical) memory
- CPU uses special registers for paging
  - Page table base register (PTBR) points to the page table
  - Page table length register (PTLR) contains length of page table: restricts maximum legal logical address
- Translating an address requires two memory accesses
  - First access reads page table entry (PTE)
  - Second access reads the data / instruction from memory
- Reduce number of memory accesses
  - Can't avoid second access (we need the value from memory)
  - Eliminate first access by keeping a hardware cache (called a *translation lookaside buffer* or TLB) of recently used page table entries

Problem of the Day

- Page fault forces a choice
  - No room for new page (steady state)
  - A page must be removed to make room for an incoming page.
  - Which page to select?
    - Victim page
    - Evicted/purged

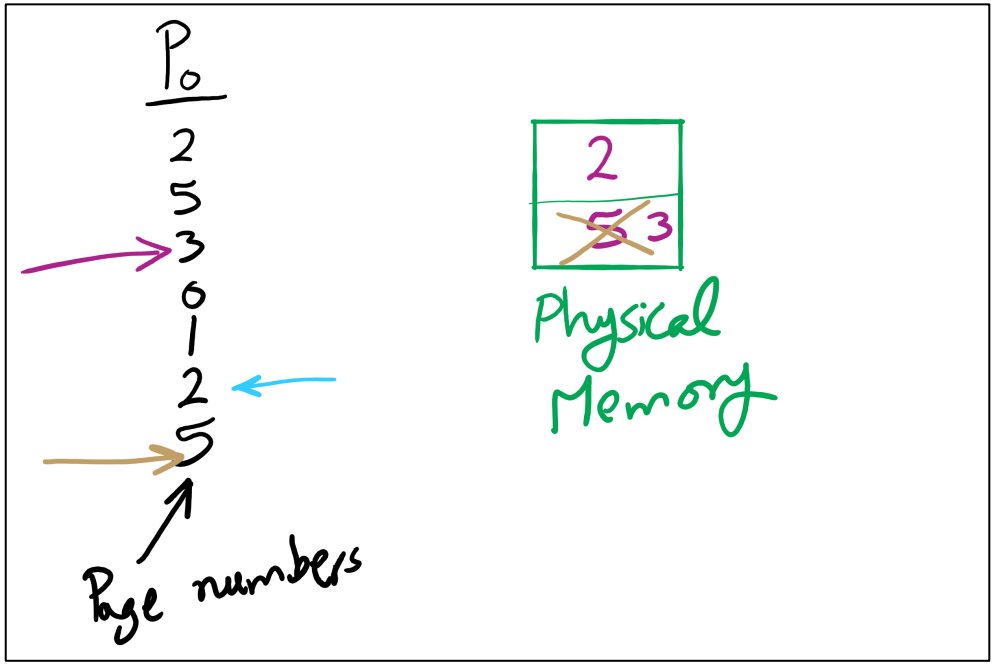
Page replacement algorithms

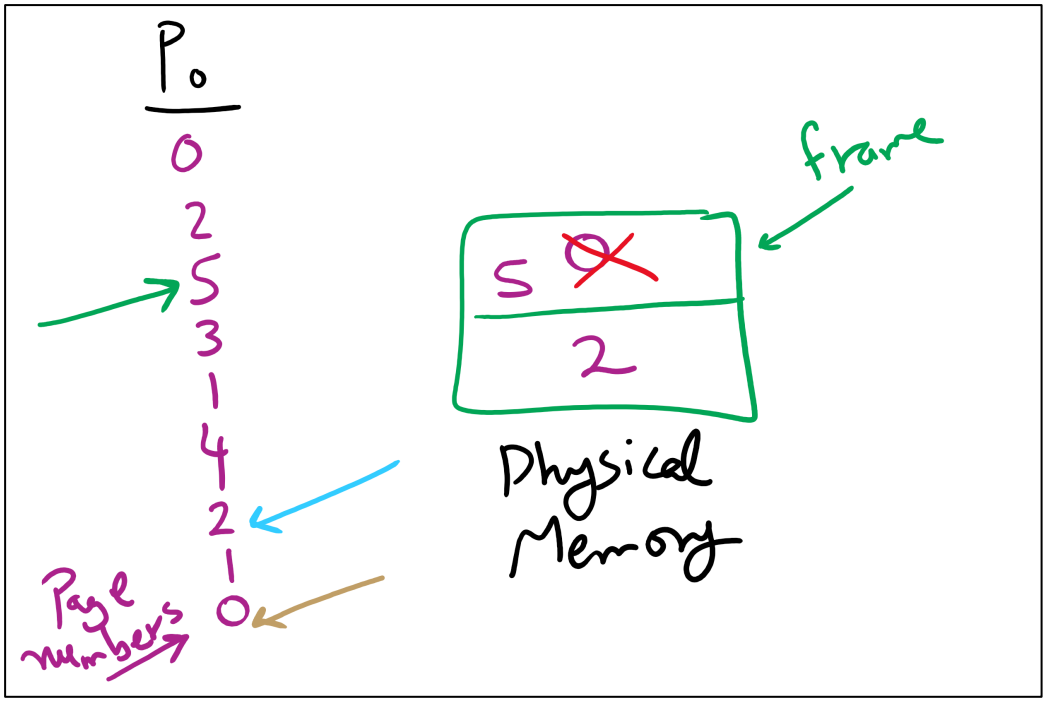
- How is a page removed from physical memory?
  - If the page is unmodified, simply overwrite it: a copy already exists on disk
  - If the page has been modified, it must be written back to disk: prefer unmodified pages?
- Better not to choose an often used page
  - It'll probably need to be brought back in soon

Optimal page replacement algorithm

- What's the best we can possibly do?
  - Assume perfect knowledge of the future
  - Not realizable in practice (usually)
  - Useful for comparison: if another algorithm is within 5% of optimal, not much more can be done…
- Algorithm: replace the page that will be used furthest in the future
  - Only works if we know the whole sequence!
  - Can be approximated by running the program twice
    - Once to generate the reference trace
    - Once (or more) to apply the optimal algorithm
- Nice, but not achievable in real systems!

OPT Examples

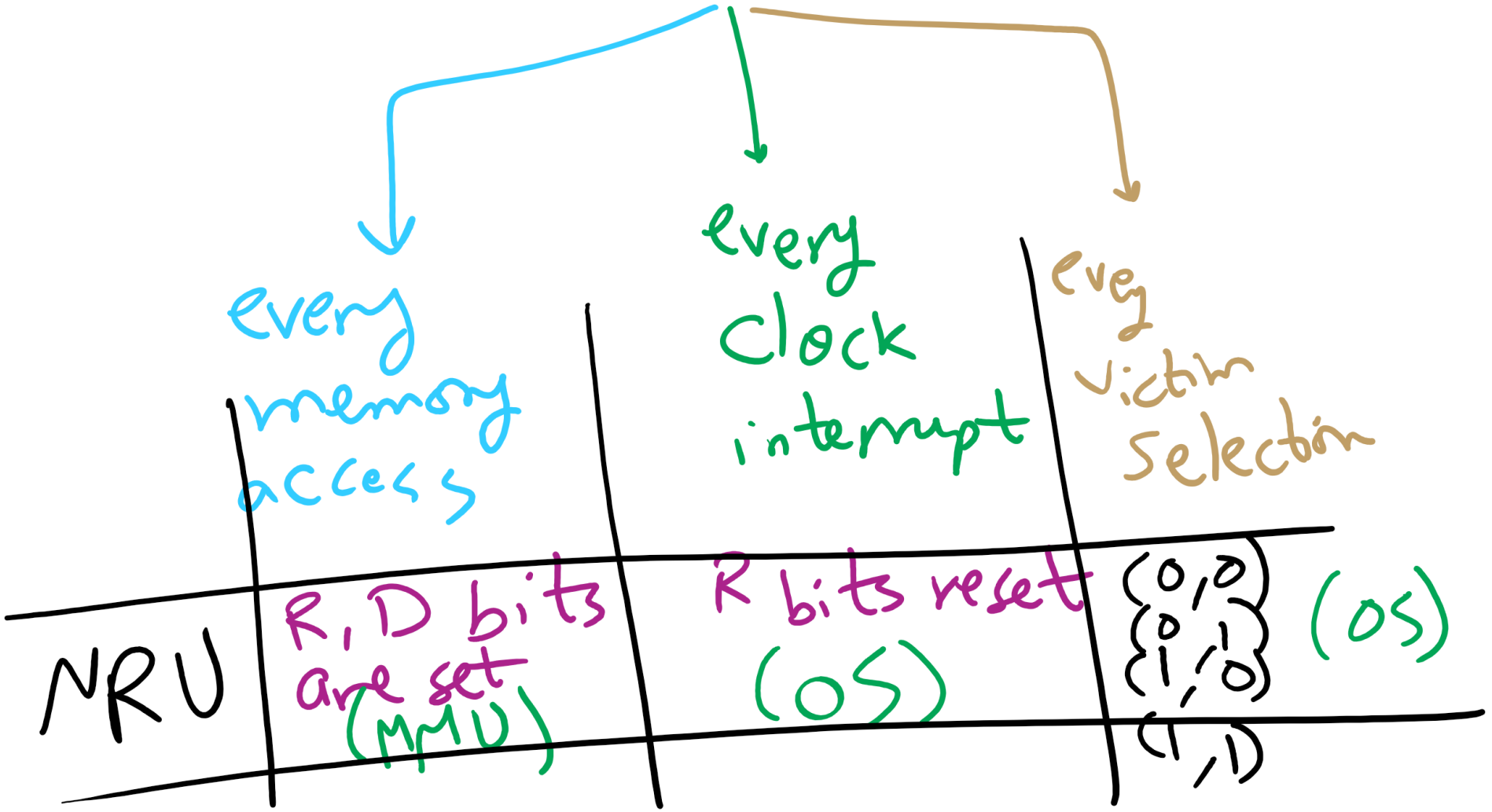




Not-recently-used (NRU) algorithm

- Each page has reference bit and dirty bit
  - Bits are set when page is referenced and/or modified
- Pages are classified into four classes
  - 0: not referenced, not dirty
  - 1: not referenced, dirty
  - 2: referenced, not dirty
  - 3: referenced, dirty
- Clear reference bit for all pages periodically
  - Can't clear dirty bit: needed to indicate which pages need to be flushed to disk
  - Class 1 contains dirty pages where reference bit has been cleared
- Algorithm: remove a page from the lowest non-empty class
  - Select a page at random from that class
- Easy to understand and implement
- Performance adequate (though not optimal)

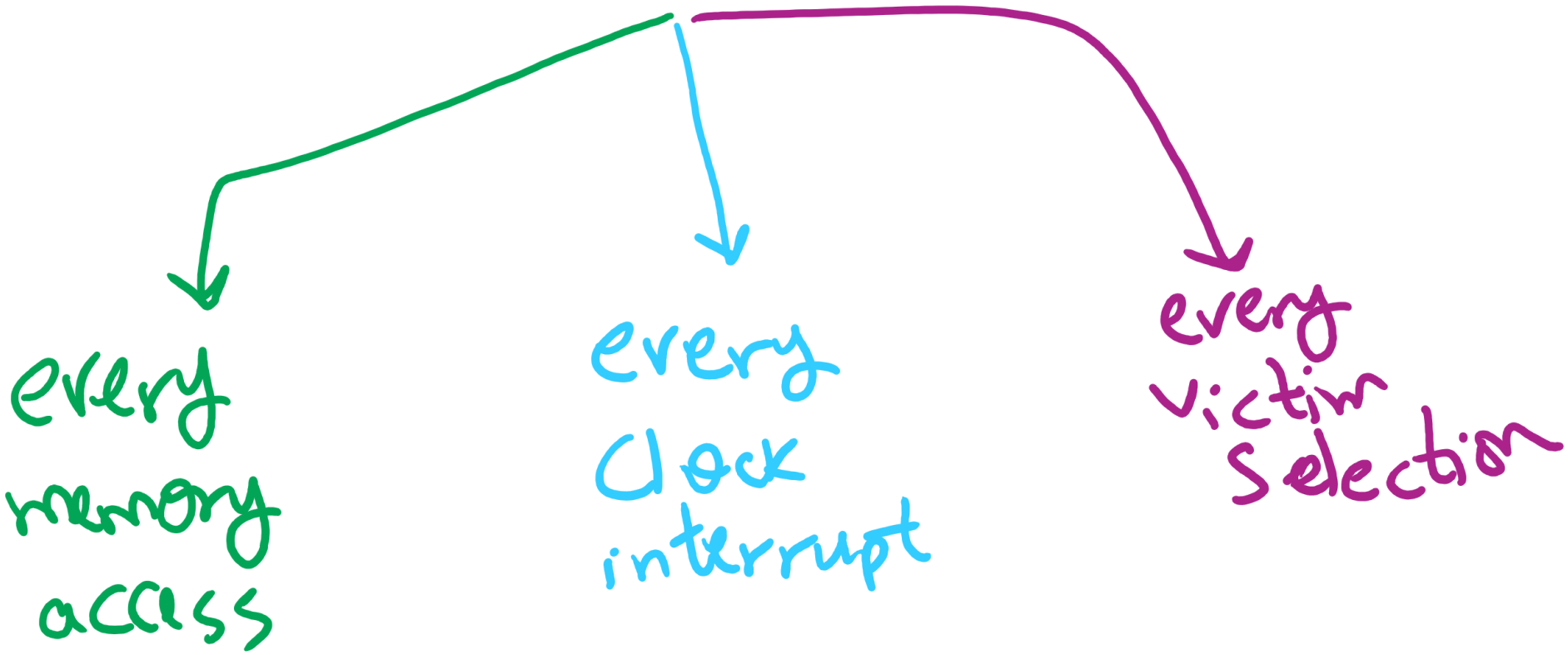
NRU Operation



First-In, First-Out (FIFO) algorithm

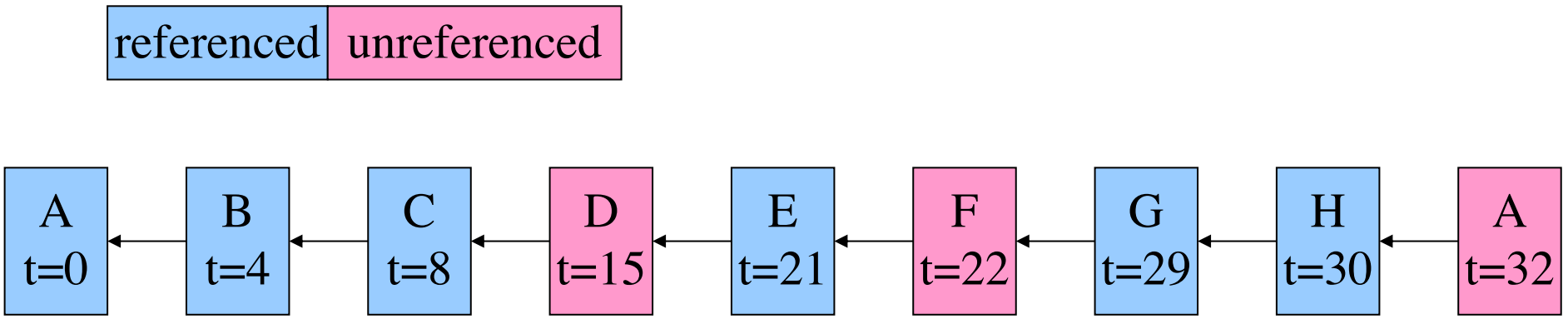
- Maintain a linked list of all pages
  - Maintain the order in which they entered memory
- Page at front of list replaced
- Advantage: (really) easy to implement
- Disadvantage: page in memory the longest may be often used
  - This algorithm forces pages out regardless of usage
  - Usage may be helpful in determining which pages to keep

Page Replacement Algorithms Components



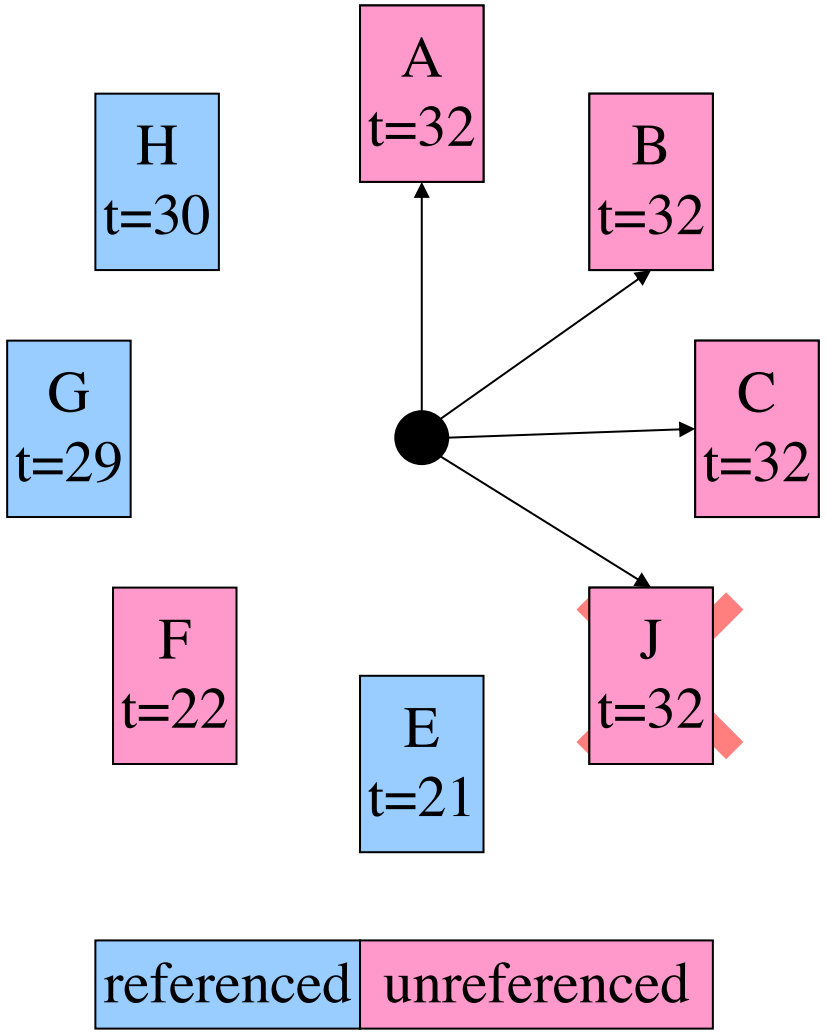
Second chance page replacement

- Modify FIFO to avoid throwing out heavily used pages
  - If reference bit is 0, throw the page out
  - If reference bit is 1
    - Reset the reference bit to 0
    - Move page to the tail of the list
    - Continue search for a free page
- Still easy to implement, and better than plain FIFO



Clock algorithm

- Same functionality as second chance
- Simpler implementation
  - “Clock” hand points to next page to replace
  - If R=0, replace page
  - If R=1, set R=0 and advance the clock hand
- Continue until page with R=0 is found
  - This may involve going all the way around the clock…



Least Recently Used (LRU)

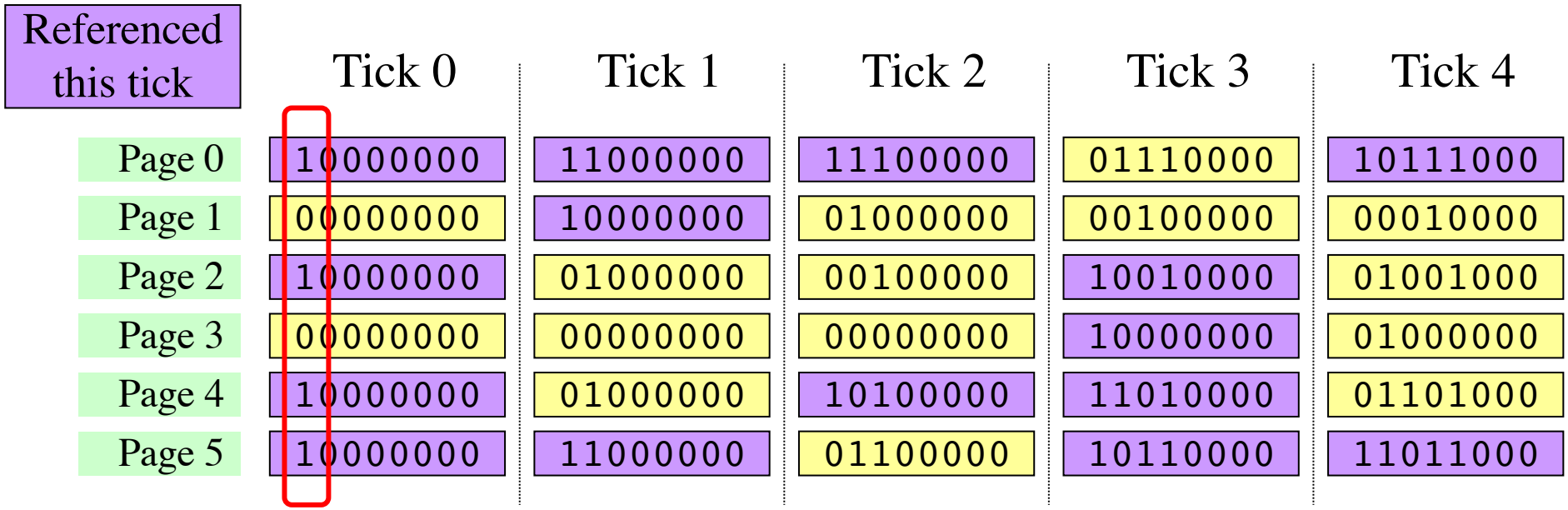
- Assume pages used recently will be used again soon
  - Throw out page that has been unused for longest time
- Must keep a linked list of pages
  - Most recently used at front, least at rear
  - Update this list every memory reference!
    - This can be somewhat slow: hardware has to update a linked list on every reference!
- Alternatively, keep counter in each page table entry
  - Global counter increments with each CPU cycle
  - Copy global counter to PTE counter on a reference to the page
  - For replacement, evict page with lowest counter value

Simulating LRU in software

- Few computers have the necessary hardware to implement full LRU
  - Linked-list method impractical in hardware
  - Counter-based method could be done, but it's slow to find the desired page
- Approximate LRU with Not Frequently Used (NFU) algorithm
  - At each clock interrupt, scan through page table
  - If R=1 for a page, add one to its counter value
  - On replacement, pick the page with the lowest counter value
- Problem: no notion of age—pages with high counter values will tend to keep them!

Aging replacement algorithm

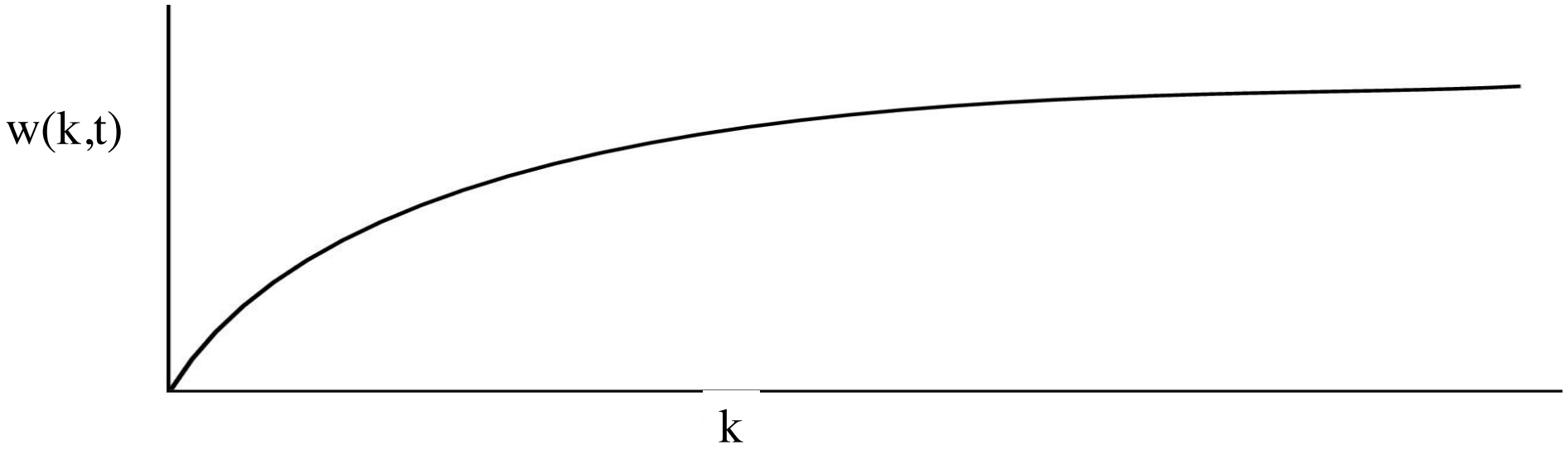
- Reduce counter values over time
  - Divide by two every clock cycle (use right shift)
  - More weight given to more recent references!
- Select page to be evicted by finding the lowest counter value
- Algorithm is:
  - Every clock tick, shift all counters right by 1 bit
  - On reference, set leftmost bit of a counter (can be done by copying the reference bit to the counter at the clock tick)



Working set

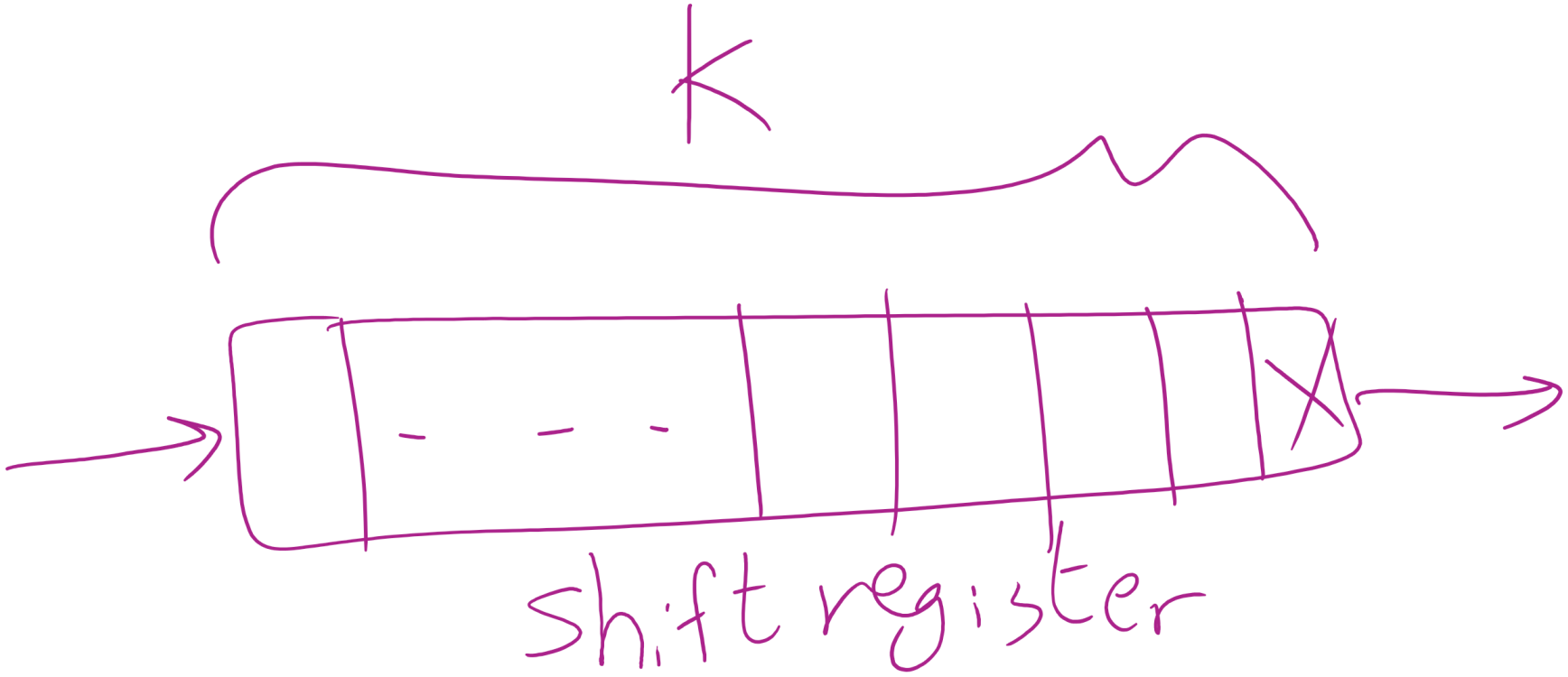
- *Demand paging*: bring a page into memory when it's requested by the process
- How many pages are needed?
  - Could be all of them, but not likely
  - Instead, processes reference a small set of pages at any given time—*locality of reference*
  - Set of pages can be different for different processes or even different times in the running of a single process
- Set of pages used by a process in a given interval of time is called the *working set*
  - If entire working set is in memory, no page faults!
  - If insufficient space for working set, thrashing may occur
  - Goal: keep most of working set in memory to minimize the number of page faults suffered by a process

How big is the working set?

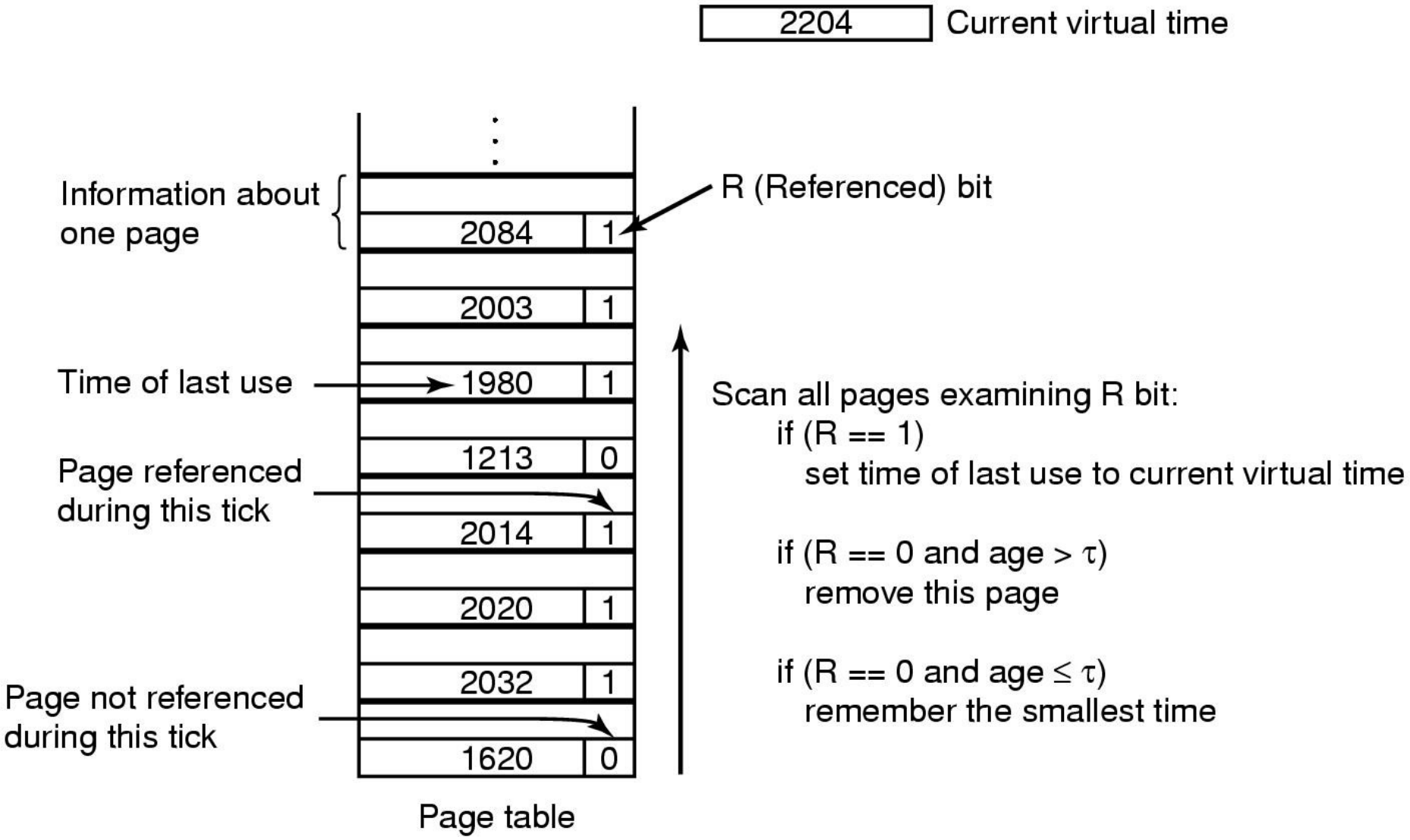


- Working set is the set of pages used by the *k* most recent memory references
- w(k,t) is the size of the working set at time *t*
- Working set may change over time
  - Size of working set can change over time as well…

Keeping track of the Working Set



Working set page replacement algorithm



Summary

- Page replacement algorithms

Algorithm	Comment
OPT (Optimal)	Not implementable, but useful as a benchmark
NRU (Not Recently Used)	Crude
FIFO (First-In, First Out)	Might throw out useful pages
Second chance	Big improvement over FIFO
Clock	Better implementation of second chance
LRU (Least Recently Used)	Excellent, but hard to implement exactly
NFU (Not Frequently Used)	Poor approximation to LRU
Aging	Good approximation to LRU, efficient to implement
Working Set	Somewhat expensive to implement
WSClock	Implementable version of Working Set

Algorithm Simulation

- How to simulate page replacement algorithms
  - FIFO/Clock
  - LRU, OPT

How is modeling done?

- Generate a list of references
  - Artificial (made up)
  - Trace a real workload (set of processes)
- Use an array (or other structure) to track the pages in physical memory at any given time
  - May keep other information per page to help simulate the algorithm (modification time, time when paged in, etc.)
- Run through references, applying the replacement algorithm
- Example: FIFO replacement on reference string 0 1 2 3 0 1 4 0 1 2 3 4
  - Page replacements highlighted in yellow

Page referenced	0	1	2	3	0	1	4	0	1	2	3	4
Youngest page	0	1	2	3	0	1	4	4	4	2	3	3
		0	1	2	3	0	1	1	1	4	2	2
Oldest page			0	1	2	3	0	0	0	1	4	4

Interactive Simulation Tool

- https://sim-50.github.io/cs-tools/

FIFO with 3 frames

FIFO Example 1

FIFO with 4 frames

Belady's anomaly

- Reduce the number of page faults by supplying more memory
  - Use previous reference string and FIFO algorithm
  - Add another page to physical memory (total 4 pages)
- More page faults (10 vs. 9), not fewer!
  - This is called *Belady's anomaly*
  - Adding more pages shouldn't result in worse performance!
- Motivated the study of paging algorithms

CLOCK Simulation

Modeling more replacement algorithms

- Paging system characterized by:
  - Reference string of executing process
  - Page replacement algorithm
  - Number of page frames available in physical memory (*m*)
- Model this by keeping track of all *n* pages referenced in array *M*
  - Top part of *M* has *m* pages in memory
  - Bottom part of *M* has *n-m* pages stored on disk
- Page replacement occurs when page moves from top to bottom
  - Top and bottom parts may be rearranged without causing movement between memory and disk

Example: LRU

- Model LRU replacement with
  - 8 unique references in the reference string
  - 4 pages of physical memory
- Array state over time shown below
- LRU treats list of pages like a stack

	0	2	1	3	5	4	6	3	7	4	7	3	3	5	5	3	1	1	1	7	1	3	4	1
	0	2	1	3	5	4	6	3	7	4	7	3	3	5	5	3	1	1	1	7	1	3	4	1
		0	2	1	3	5	4	6	3	7	4	7	7	3	3	5	3	3	3	1	7	1	3	4
			0	2	1	3	5	4	6	3	3	4	4	7	7	7	5	5	5	3	3	7	1	3
				0	2	1	3	5	4	6	6	6	6	4	4	4	7	7	7	5	5	5	7	7
					0	2	1	1	5	5	5	5	5	6	6	6	4	4	4	4	4	4	5	5
						0	2	2	1	1	1	1	1	1	1	1	6	6	6	6	6	6	6	6
							0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
									0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Stack algorithms

- LRU is an example of a stack algorithm
- For stack algorithms
  - Any page in memory with *m* physical pages is also in memory with *m*+1 physical pages
  - Increasing memory size is guaranteed to reduce (or at least not increase) the number of page faults
- Stack algorithms do not suffer from Belady's anomaly
- *Distance* of a reference == position of the page in the stack before the reference was made
  - Distance is ∞ if no reference had been made before
  - Distance depends on reference string and paging algorithm: might be different for LRU and optimal (both stack algorithms)

Predicting page fault rates using distance

- Distance can be used to predict page fault rates
- Make a single pass over the reference string to generate the distance string on-the-fly
- Keep an array of counts
  - Entry *j* counts the number of times distance *j* occurs in the distance string
- The number of page faults for a memory of size *m* is the sum of the counts for *j*>*m*
  - This can be done in a single pass!
  - Makes for fast simulations of page replacement algorithms
- This is why virtual memory theorists like stack algorithms!

LRU

OPT