Operating Systems (Honor Track)

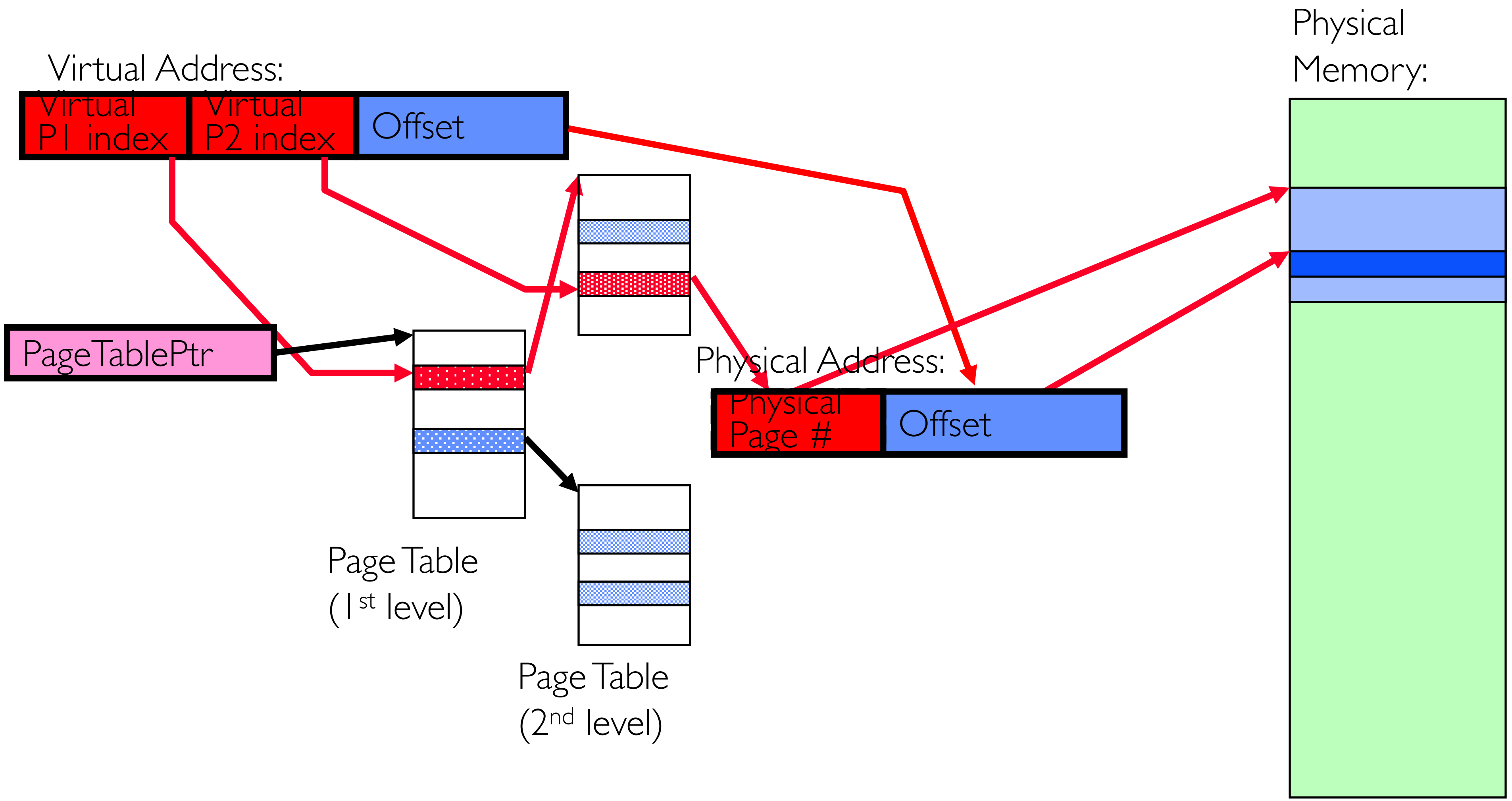
Memory 4: Demand Paging

Xin Jin

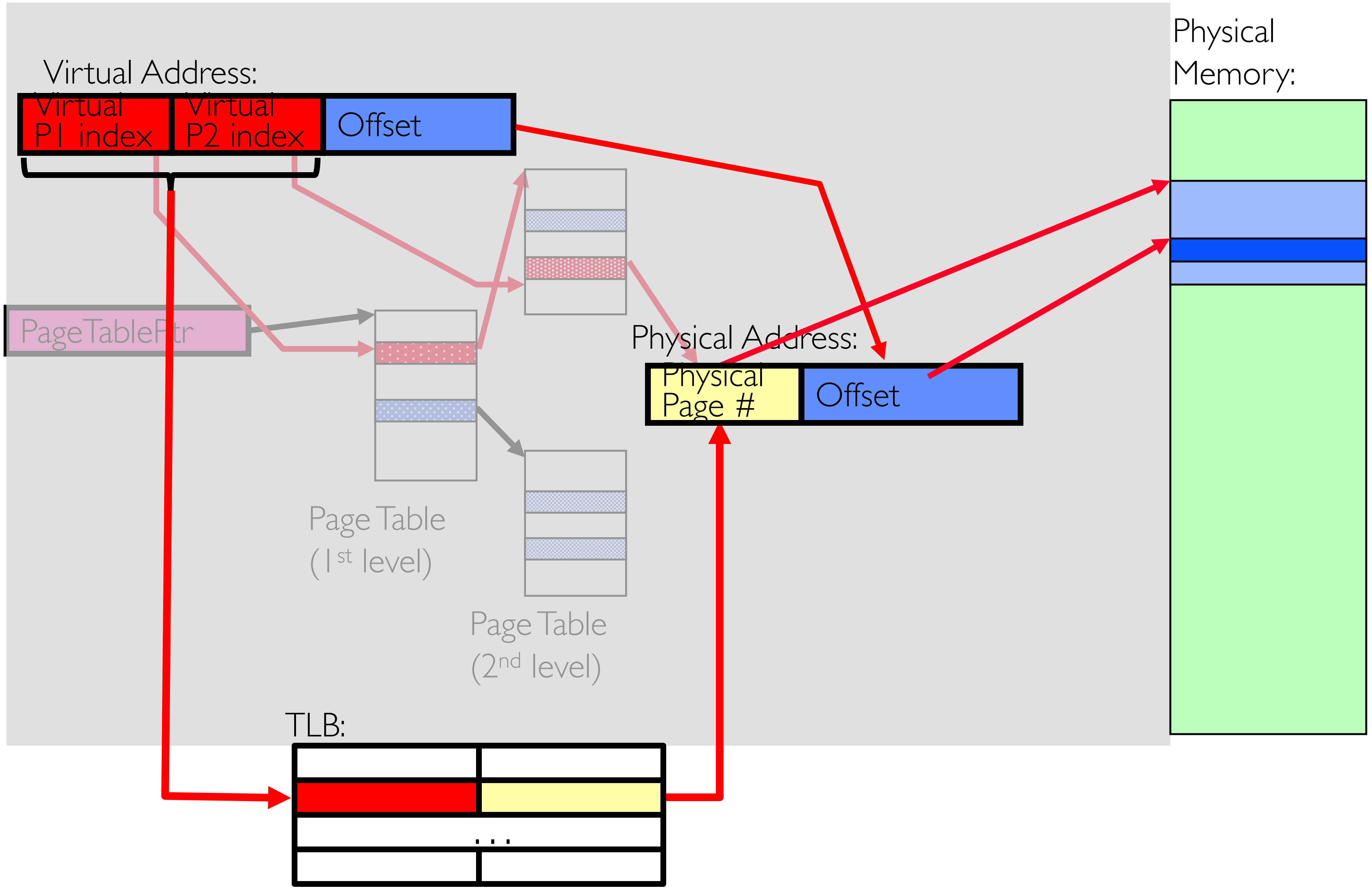
Spring 2023

Acknowledgments: Ion Stoica, Berkeley CS 162

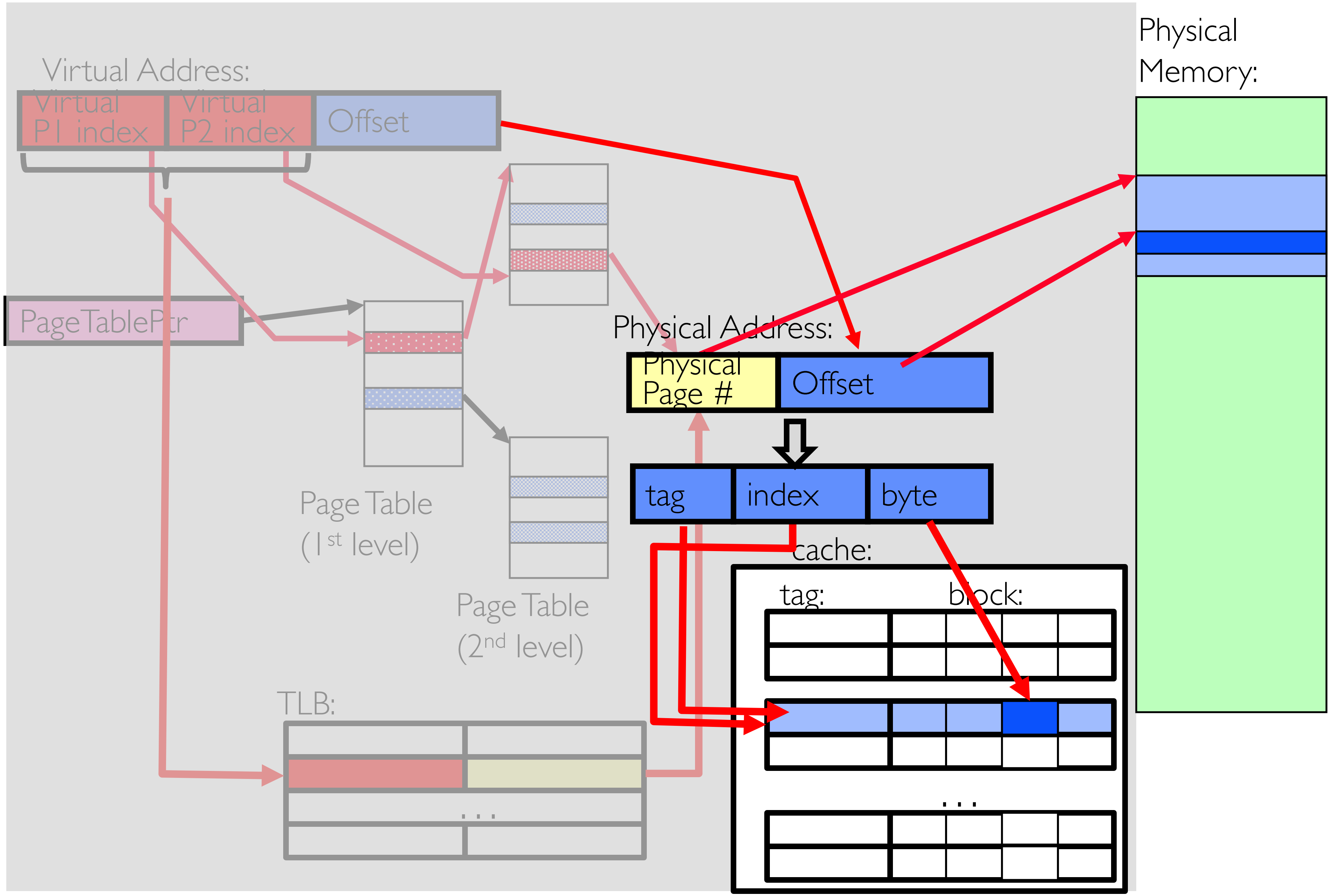
Recap: Putting Everything Together: Address Translation



Recap: Putting Everything Together: TLB



Recap: Putting Everything Together: Cache



Recap: Demand Paging as Caching, …

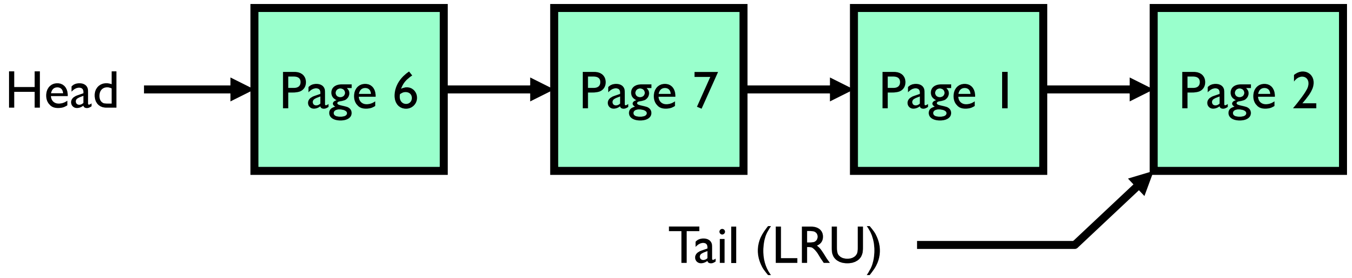
- What “block size”? - 1 page (e.g., 4 KB)
- What “organization” i.e., direct-mapped, set-associative, fully-associative?
  - Fully associative since arbitrary mapping
- How do we locate a page?
  - First check TLB, then page-table traversal
- What is page replacement policy? (i.e., LRU, Random…)
  - This requires more explanation… (more later)
- What happens on a miss?
  - Go to lower level to fill miss (i.e., disk)
- What happens on a write? (write-through, write back)
  - Definitely write-back – need dirty bit!

Recap: Page Replacement Policies

- 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
- FIFO (First In, First Out)
  - Throw out oldest page. Be fair – let every page live in memory for same amount of time.
  - Bad – throws out heavily used pages instead of infrequently used
- RANDOM:
  - Pick random page for every replacement
  - Typical solution for TLB's. Simple hardware
  - Pretty unpredictable – makes it hard to make real-time guarantees
- MIN (Minimum):
  - Replace page that won't be used for the longest time
  - Great (provably optimal), but can't really know future…
  - But past is a good predictor of the future …

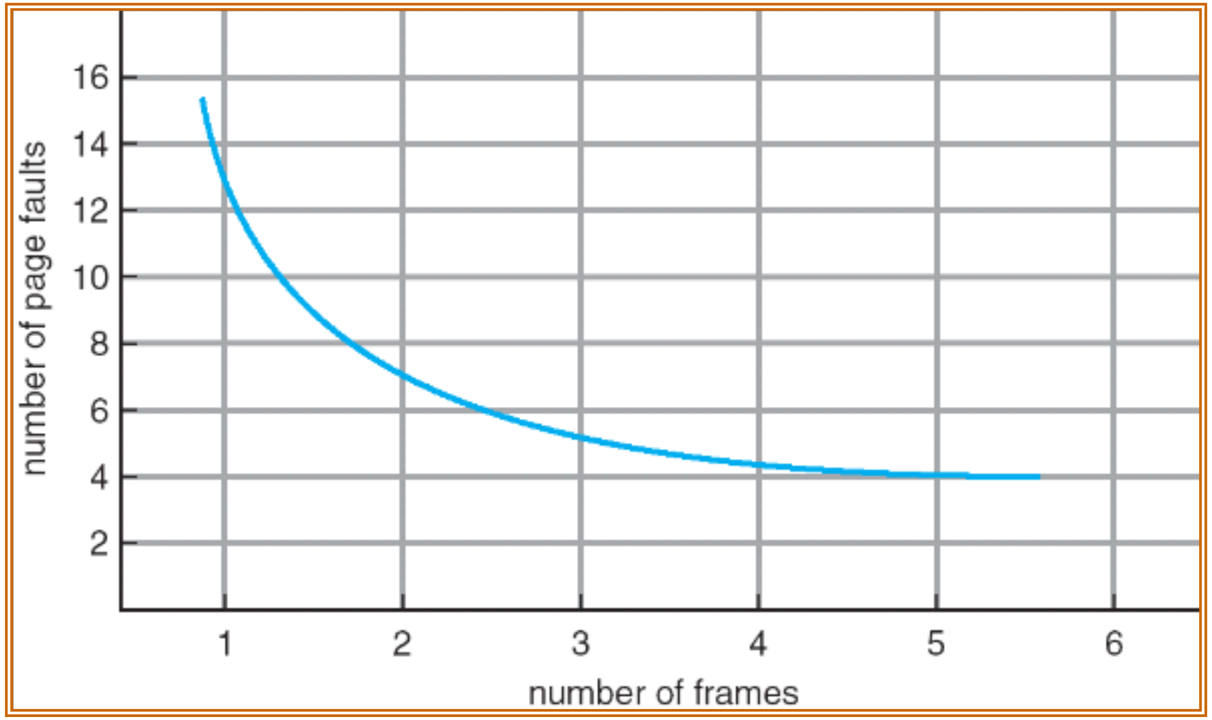
Recap: Replacement Policies (Con't)

- LRU (Least Recently Used):
  - 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 MIN.
- 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?
  - Need to know immediately when page used so that can change position in list…
  - Many instructions for each hardware access
- In practice, people approximate LRU (more later)

Graph of Page Faults Versus The Number of Frames



- One desirable property: When you add memory the miss rate drops (stack property)
  - Does this always happen?
  - Seems like it should, right?

Group Discussion

- One desirable property: When you add memory the miss rate drops (stack property)
  - Does this always happen?
  - Seems like it should, right?

- Topic: Bélády’s anomaly
  - Does LRU and MIN have this property?
    - If so, can you prove it?
    - If not, can you give an example?

- Discuss in groups of two to three students
  - Each group chooses a leader to summarize the discussion
  - In your group discussion, please do not dominate the discussion, and give everyone a chance to speak

- Answer: Yes for LRU and MIN
  - Contents of memory with X pages are a subset of contents with X+1 pages

Group Discussion

- One desirable property: When you add memory the miss rate drops (stack property)
  - Does this always happen?
  - Seems like it should, right?

- Topic: Bélády’s anomaly
  - Does FIFO have this property?
    - If so, can you prove it?
    - If not, can you give an example?

- Discuss in groups of two to three students
  - Each group chooses a leader to summarize the discussion
  - In your group discussion, please do not dominate the discussion, and give everyone a chance to speak

Adding Memory Doesn't Always Help Fault Rate

- Does adding memory reduce number of page faults?
  - Yes for LRU and MIN
  - Not necessarily for FIFO! (Called Bélády's anomaly)

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	

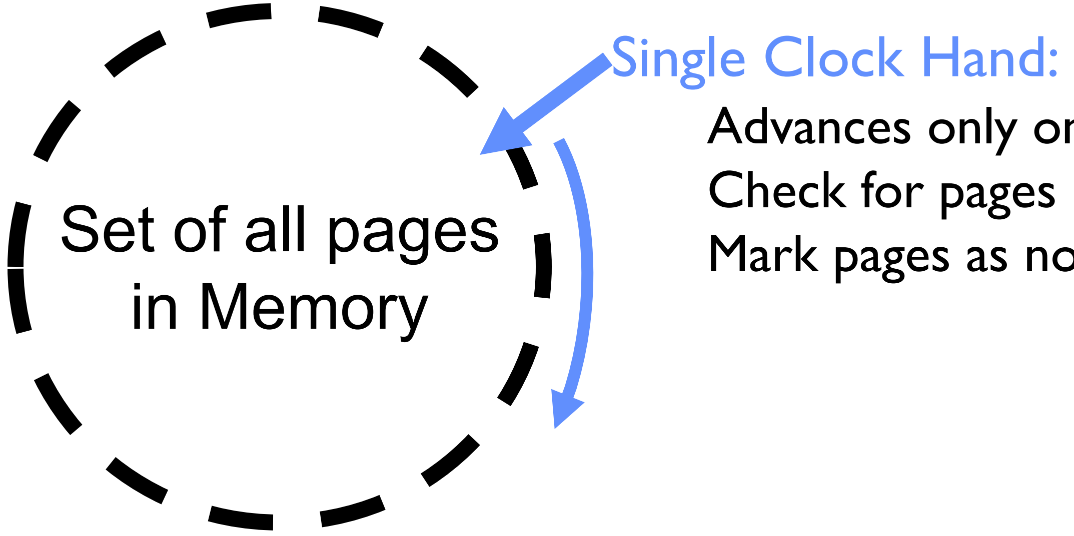
9 page faults

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!

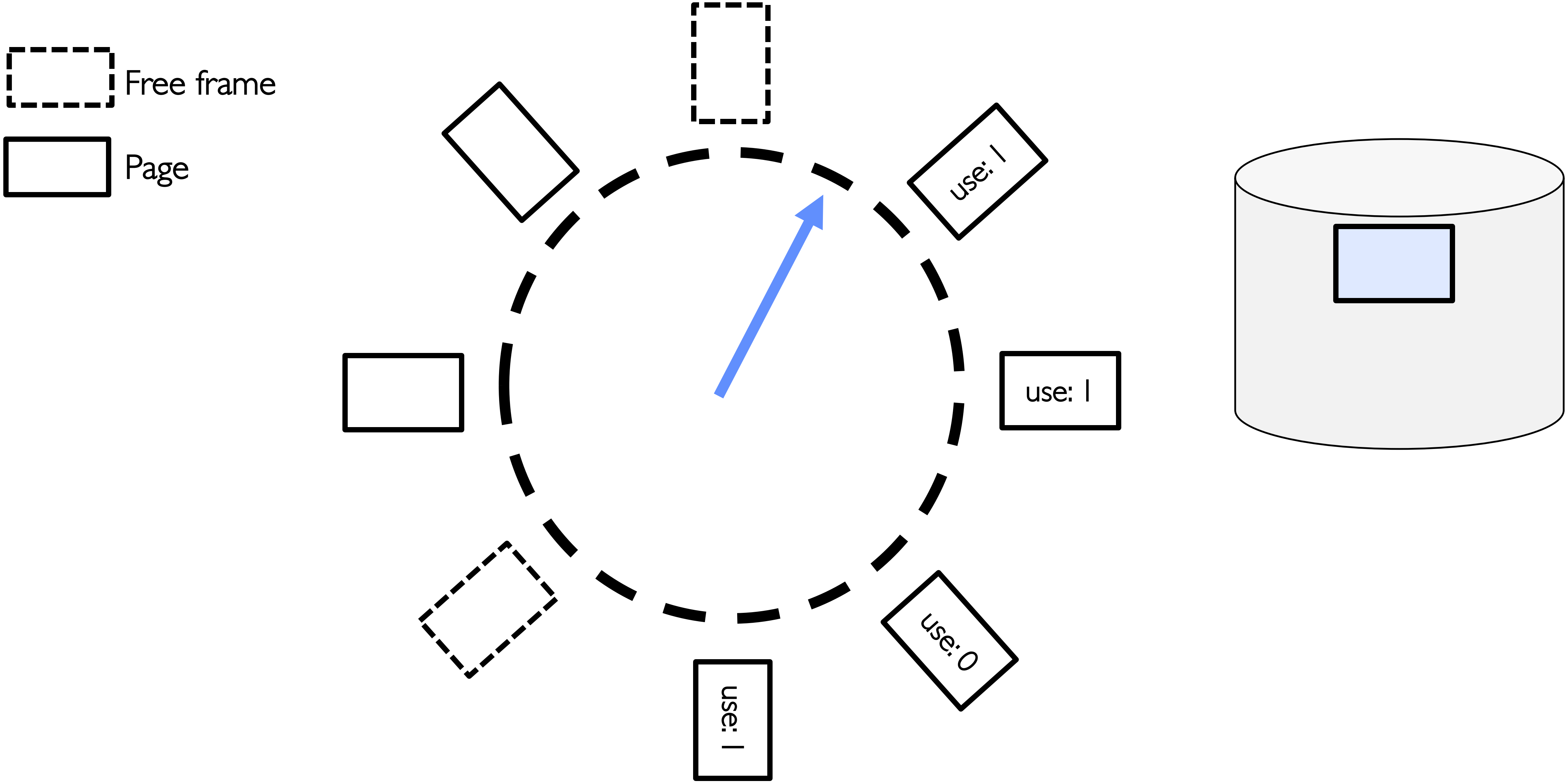
- After adding memory:
  - With FIFO, contents can be completely different
  - In contrast, with LRU or MIN, contents of memory with X pages are a subset of contents with X+1 Page

Approximating LRU: Clock Algorithm

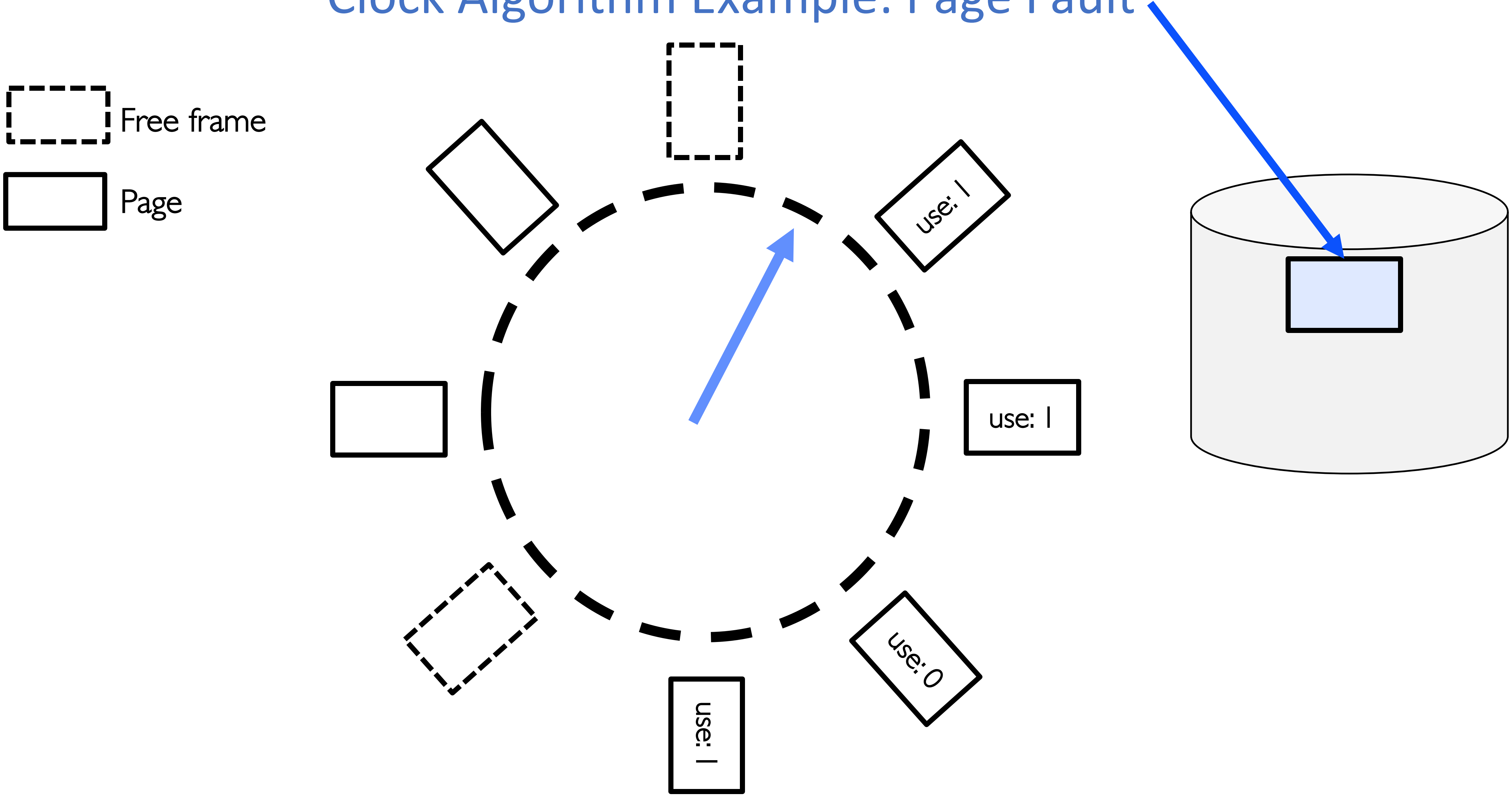


- Clock Algorithm: Arrange physical pages in circle with single clock hand
  - Approximate LRU (*approximation to approximation to MIN*)
  - Replace an old page, not the oldest page
- Details:
  - Hardware "use" bit per physical page (called "accessed" in Intel architecture):
    - » Hardware sets use bit on each reference
    - » If use bit isn't set, means not referenced in a long time
  - On page fault:
    - » Advance clock hand (not real time)
    - » Check use bit: 1→ used recently; clear and leave alone
      0→ selected candidate for replacement

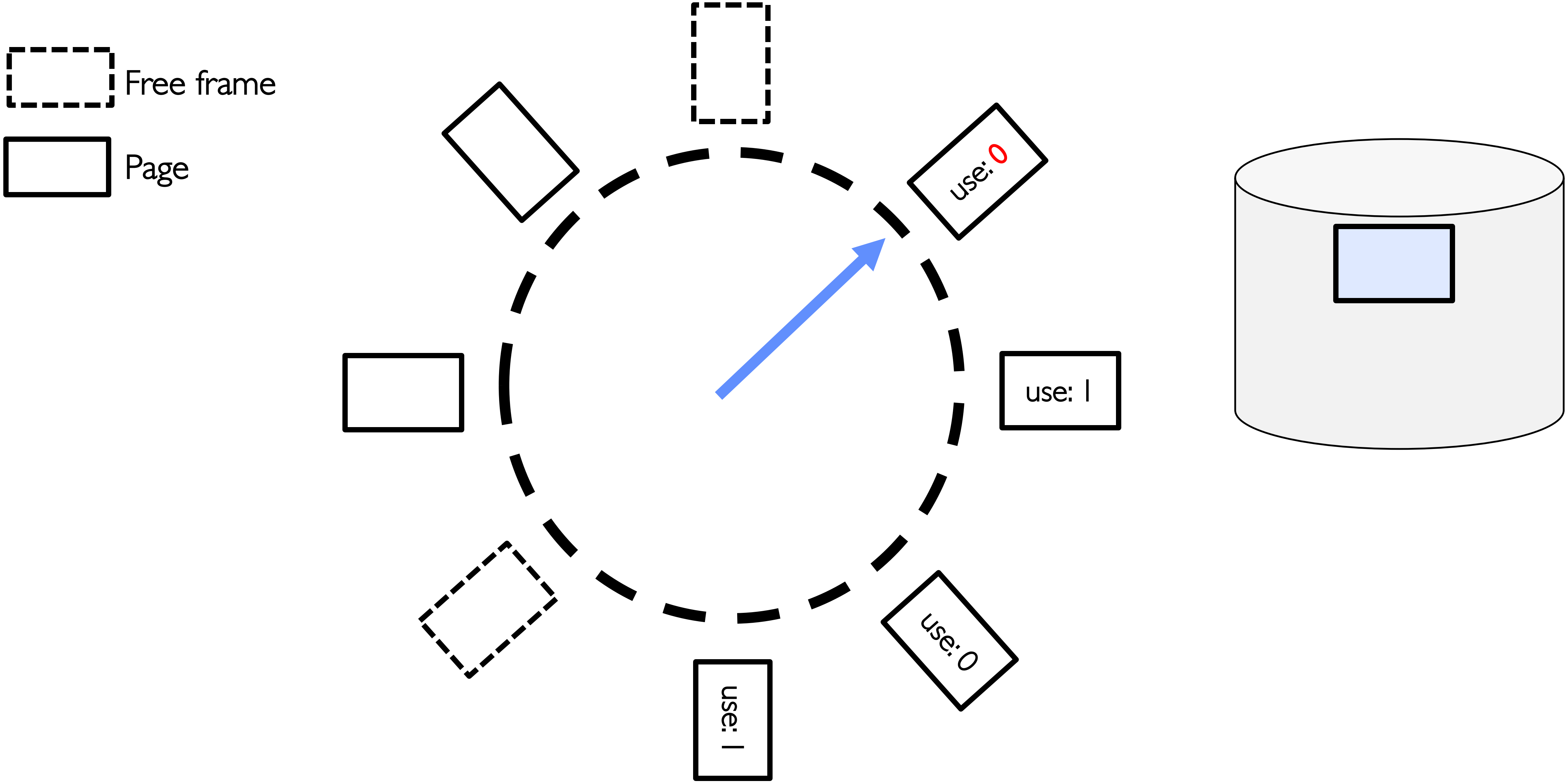
Clock Algorithm Example



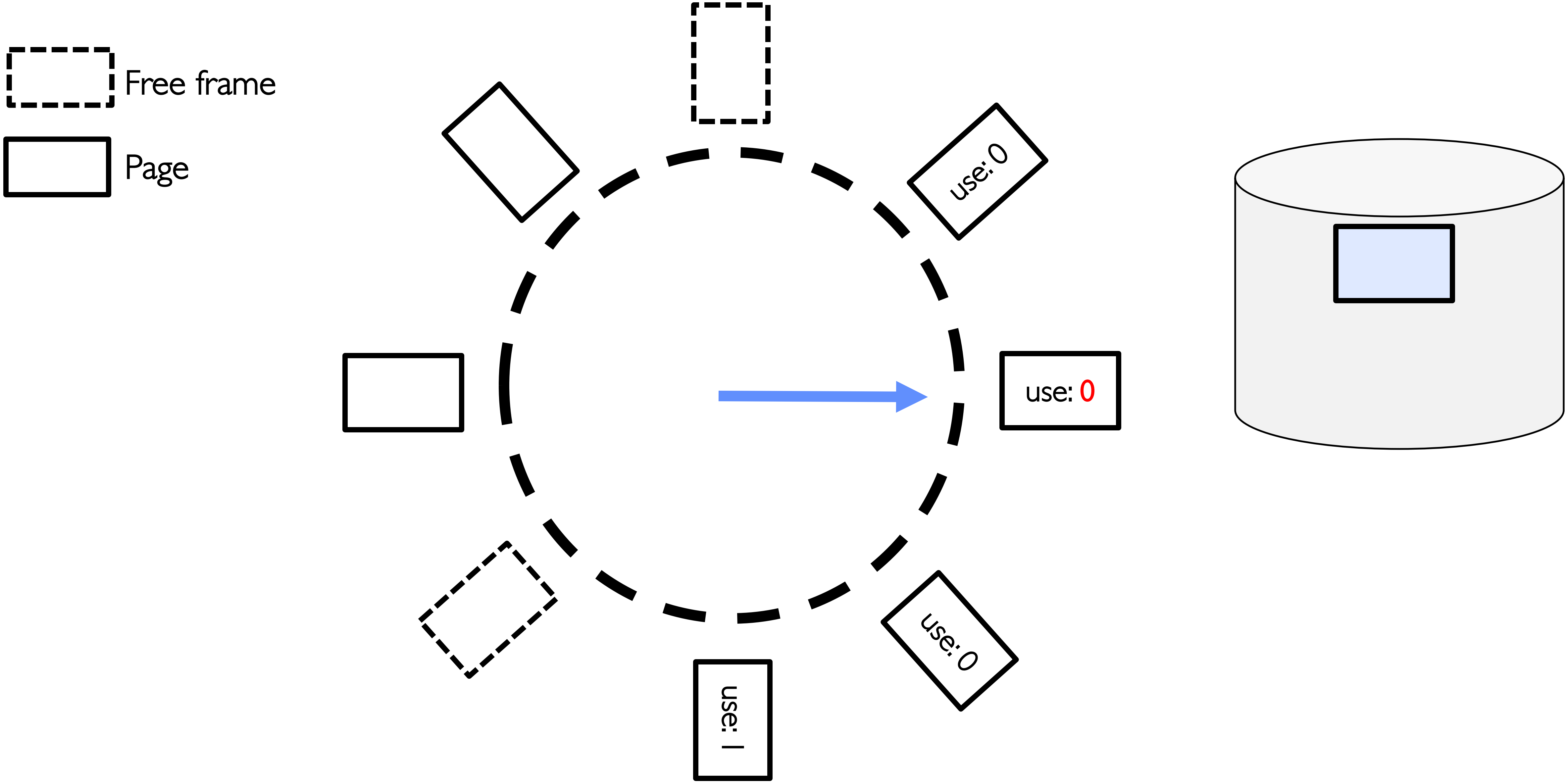
Clock Algorithm Example: Page Fault



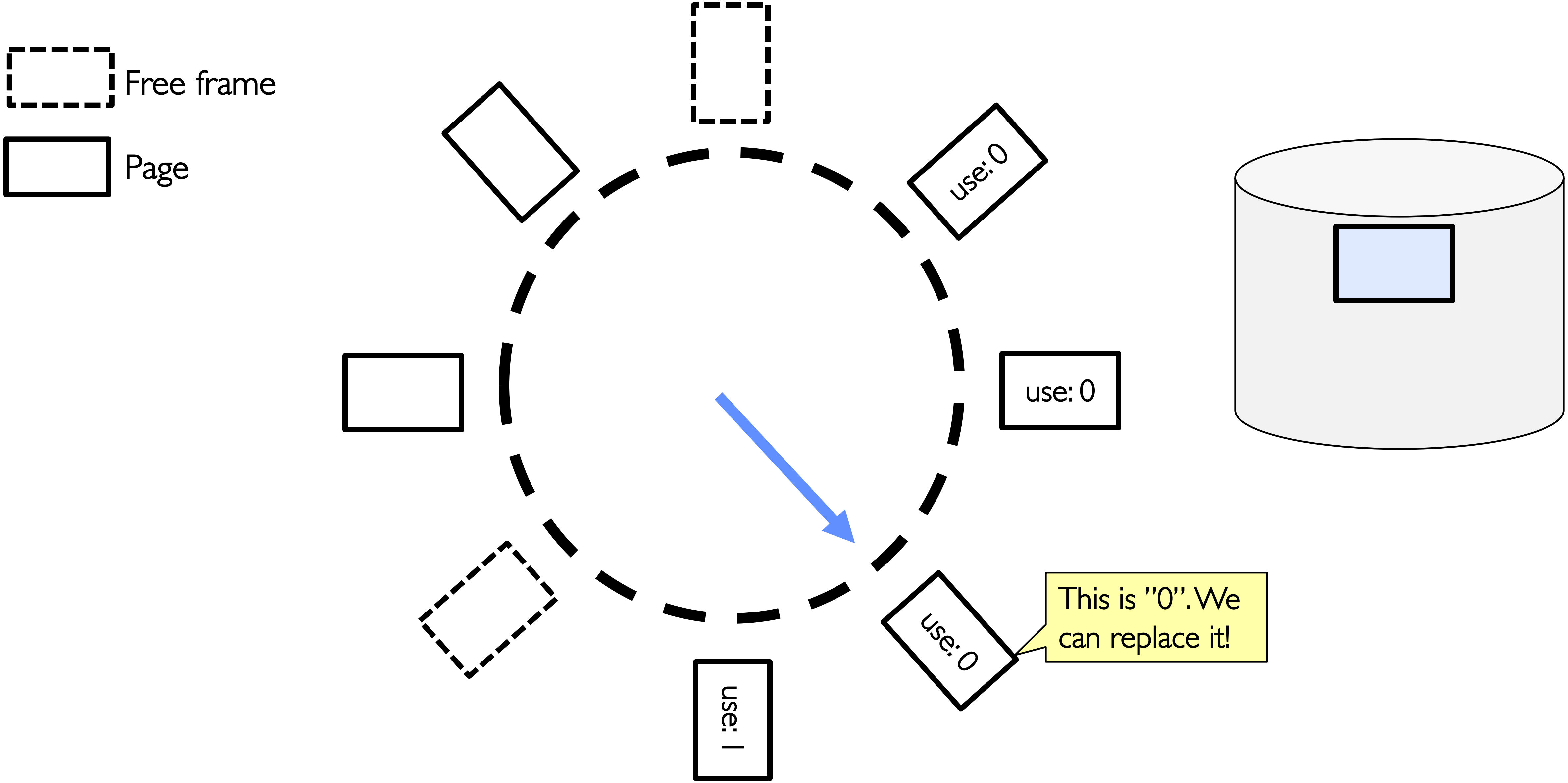
Clock Algorithm Example: Page Fault



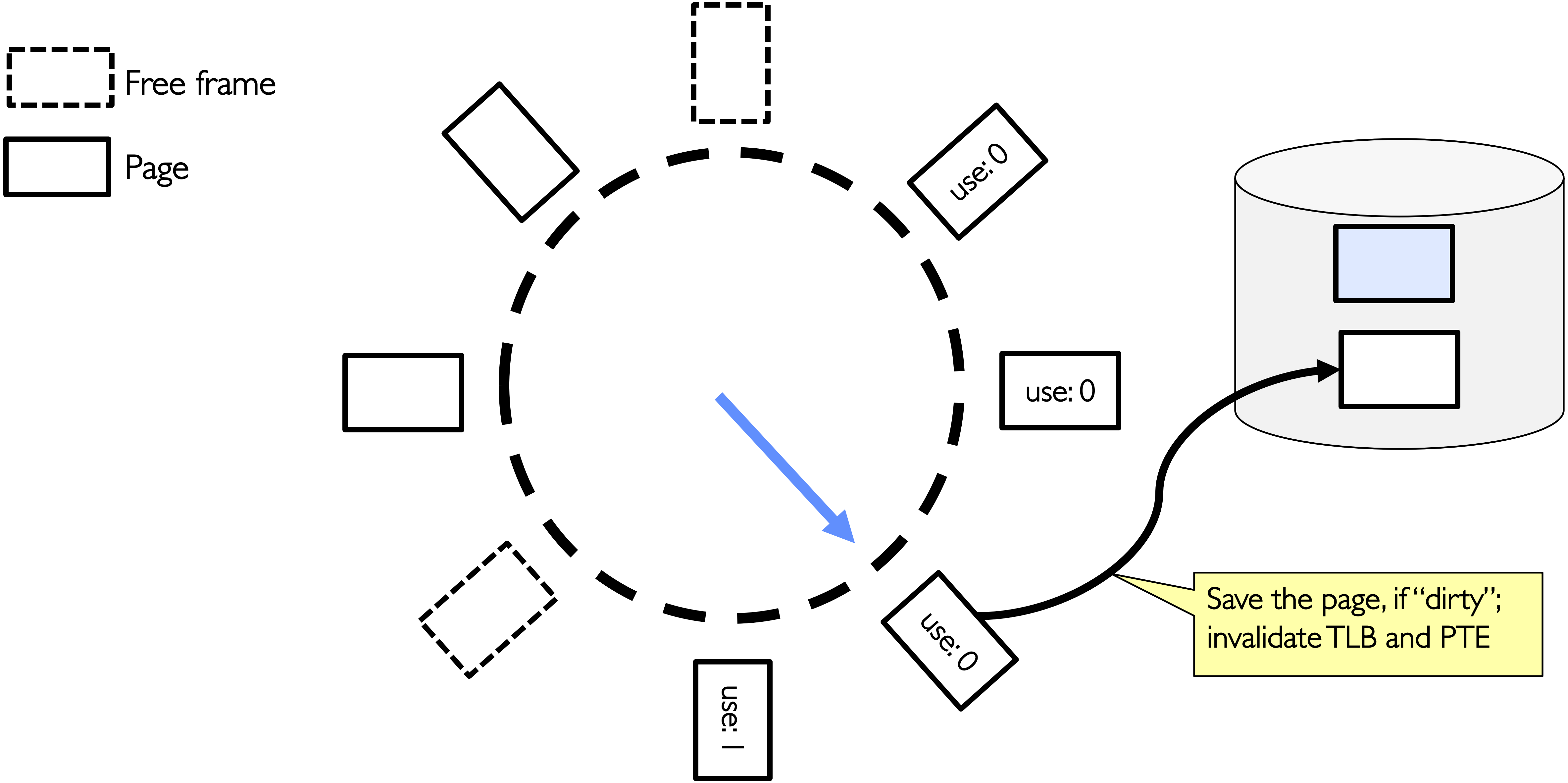
Clock Algorithm Example: Page Fault



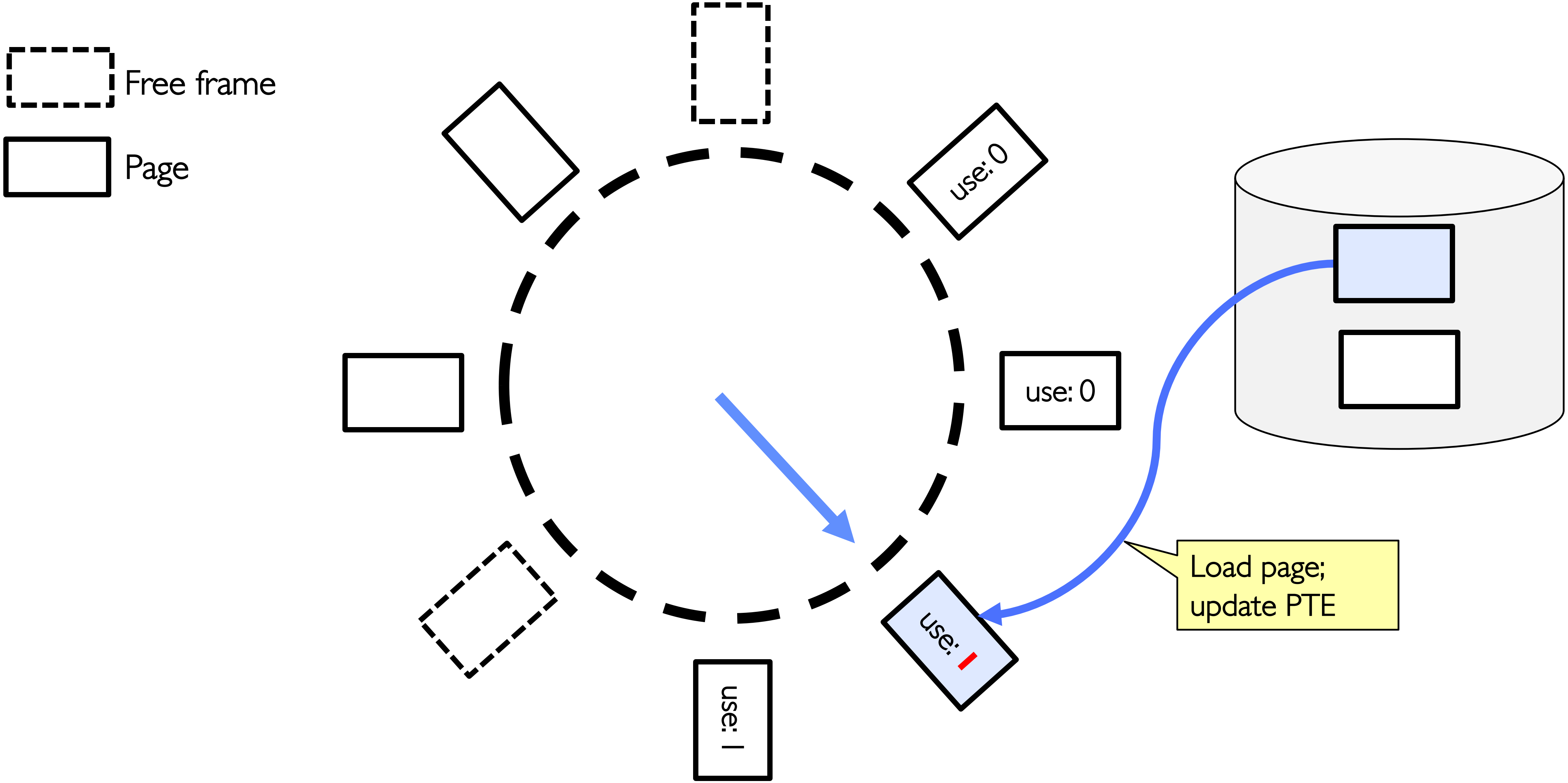
Clock Algorithm Example: Page Fault



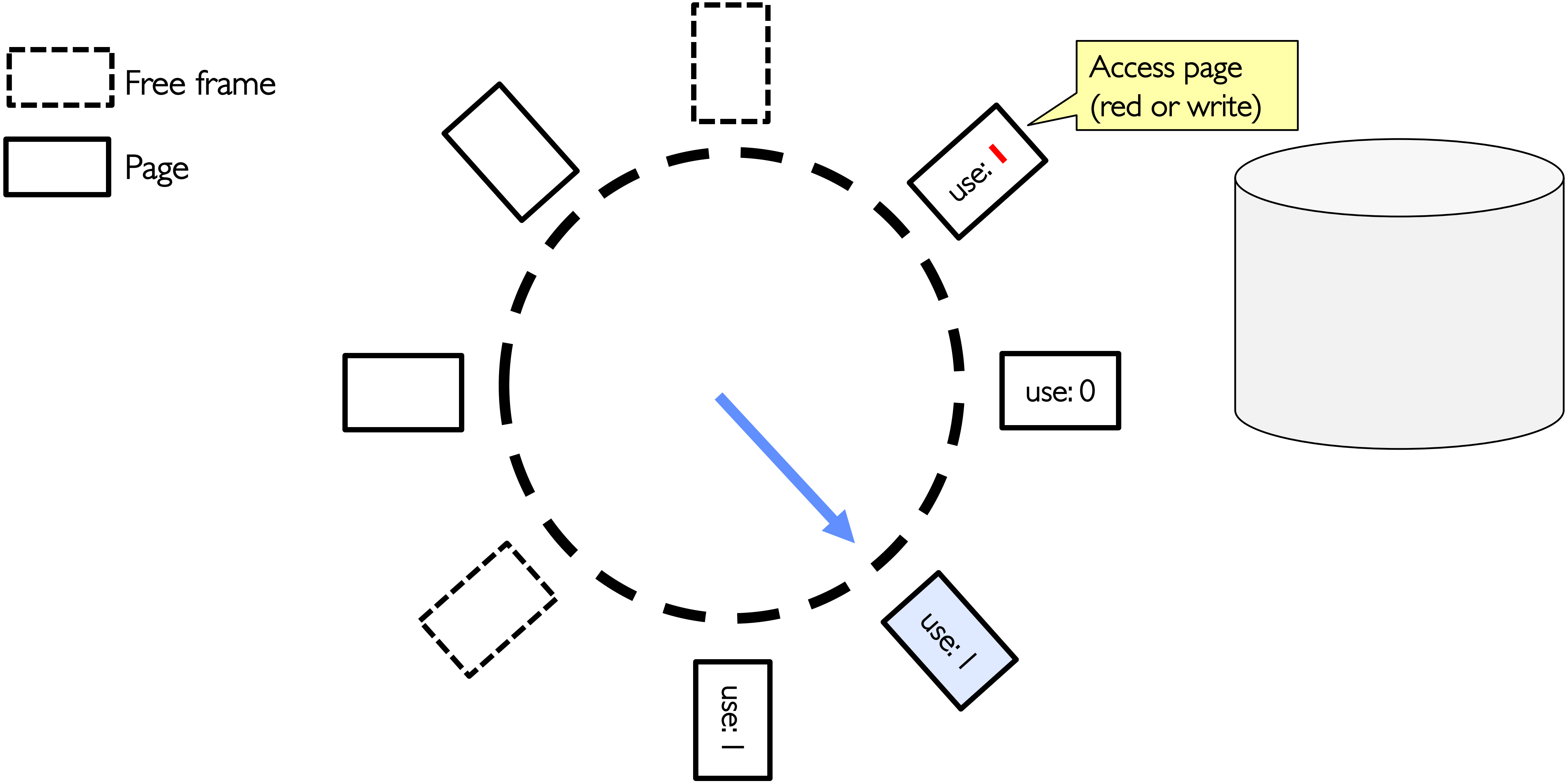
Clock Algorithm Example: Page Fault



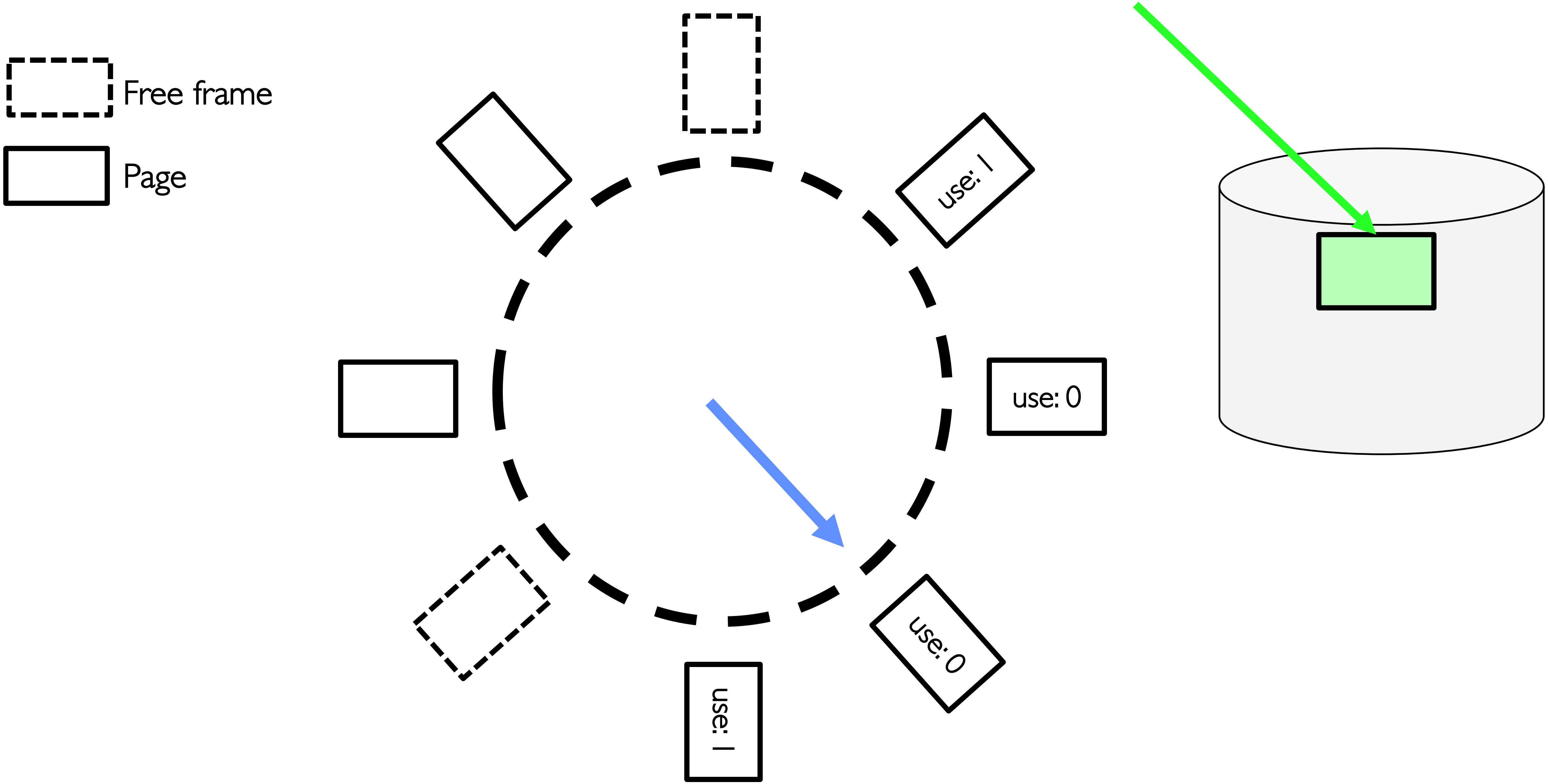
Clock Algorithm Example: Page Fault



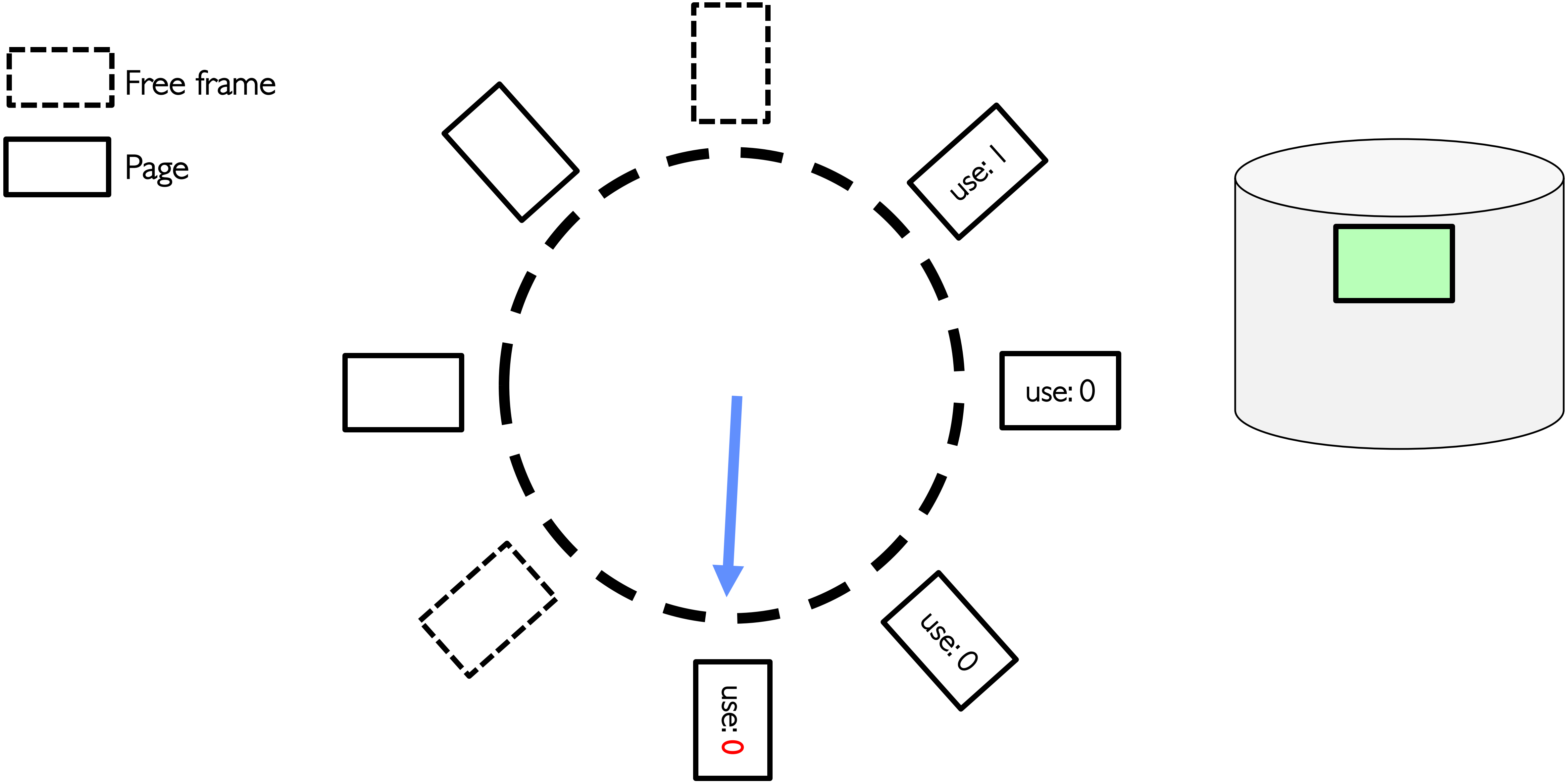
Clock Algorithm Example



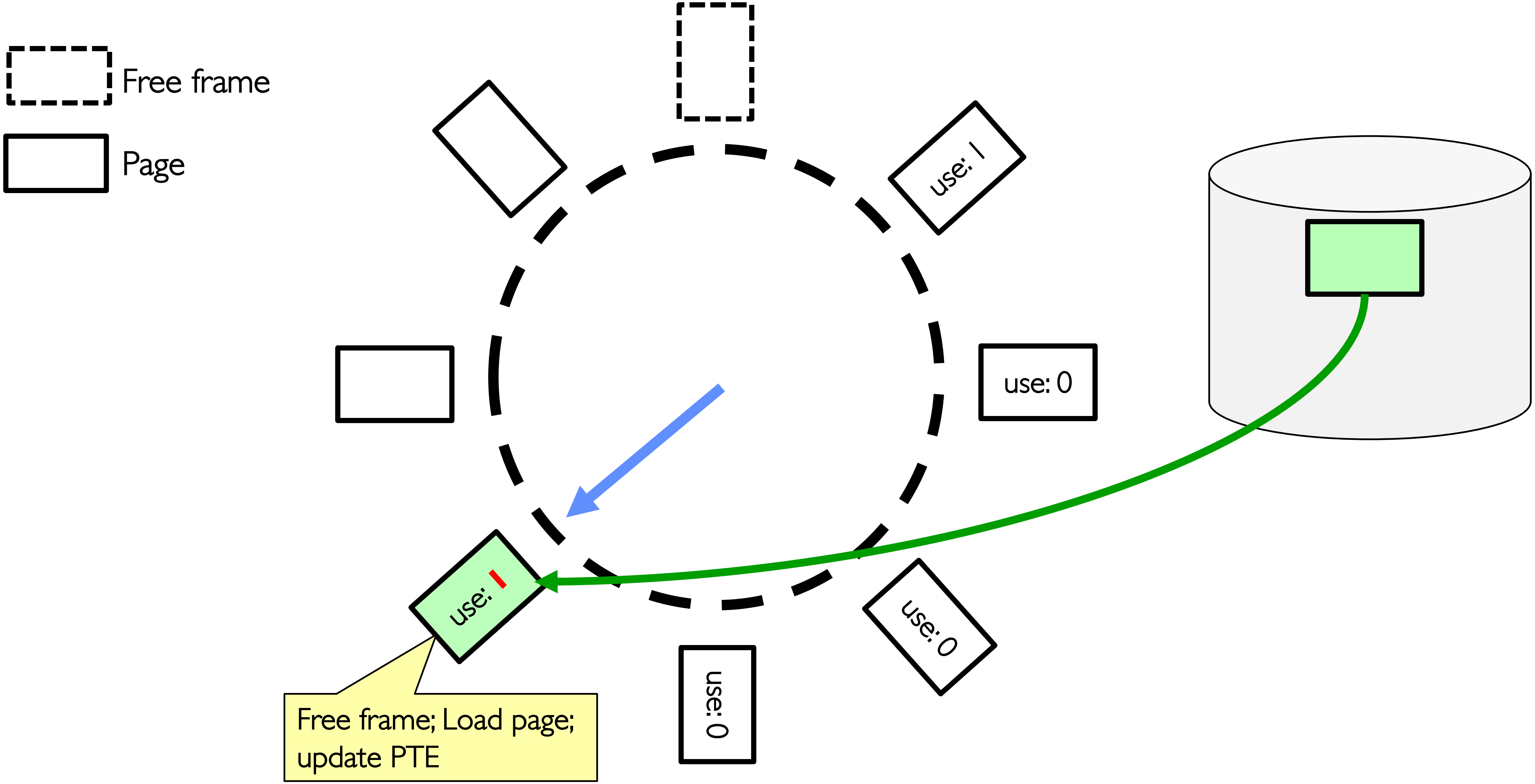
Clock Algorithm Example: Another Page Fault



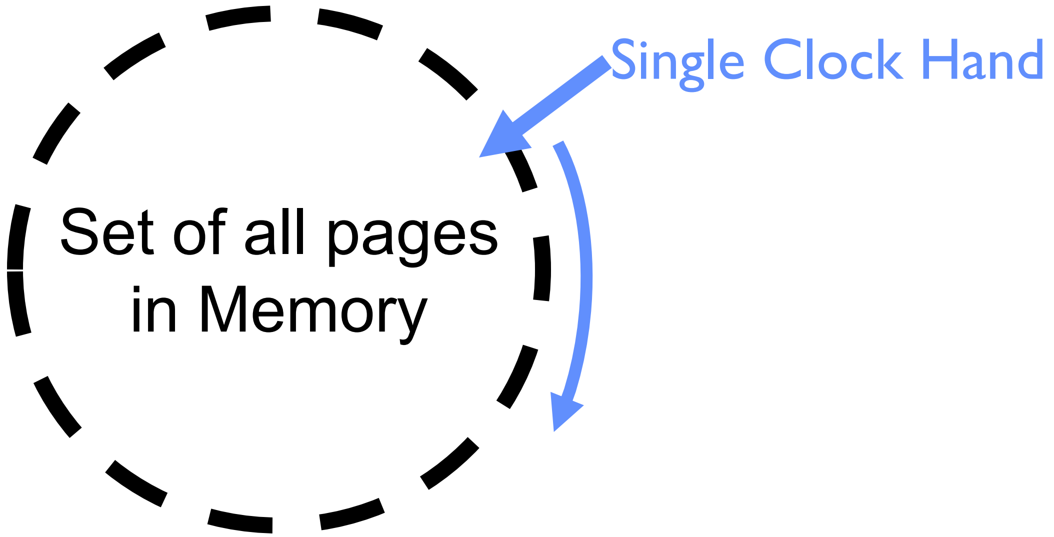
Clock Algorithm Example: Another Page Fault



Clock Algorithm Example: Another Page Fault

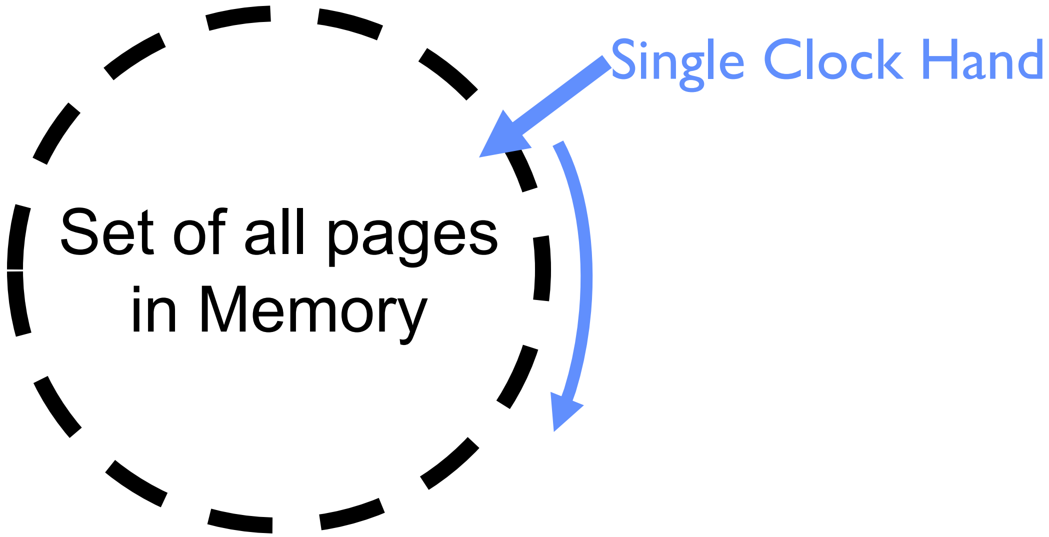


Group Discussion: Clock Algorithm



- Will always find a page or loop forever?
- What if hand is moving slowly?
  - Good sign or bad sign?
- What if hand is moving quickly?
  - Good sign or bad sign?

Clock Algorithm: More details



- Will always find a page or loop forever?
  - Even if all use bits set, will eventually loop all the way around
- What if hand is moving slowly?
  - Good sign or bad sign?
    - » Not many page faults or find page quickly
- What if hand is moving quickly?
  - Good sign or bad sign?
    - » Lots of page faults or lots of reference bits set
- One way to view clock algorithm:
  - Crude partitioning of pages into two groups: young and old
  - Why not partition into more than 2 groups?

N^{th} Chance version of Clock Algorithm

- N^{th} chance algorithm: Give page N chances
  - OS keeps counter per page: # sweeps
  - On page fault, OS checks use bit:
    - » 1 → clear use and also clear counter (used in last sweep)
    - » 0 → increment counter; if count=N, 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 approximation 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 "modified" (or "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 (and write back to disk when N=1)

Group Discussion

- Topic: Clock algorithm variations
  - Do we really need a hardware-supported "modified" bit?
  - Do we really need a hardware-supported "use" bit?

- Discuss in groups of two to three students
  - Each group chooses a leader to summarize the discussion
  - In your group discussion, please do not dominate the discussion, and give everyone a chance to speak

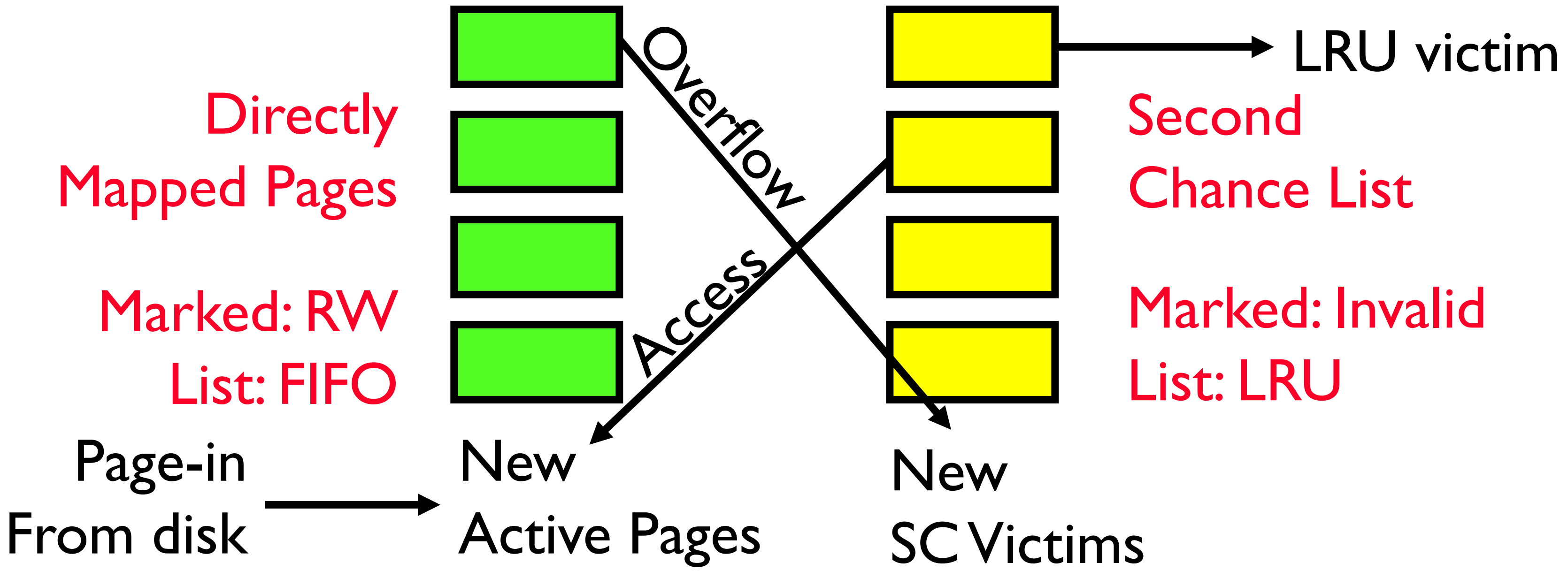
Clock Algorithms Variations

- Do we really need hardware-supported "modified" bit?
  - No. Can emulate it using read-only bit
    - » Need software DB of which pages are allowed to be written (needed this anyway)
    - » We will tell MMU that pages have more restricted permissions than they actually do to force page faults (and allow us notice when page is written)
  - Algorithm (Clock-Emulated-Modified):
    - » Initially, mark all pages as read-only (W→0), even writable data pages. Further, clear all software versions of the "modified" bit → 0 (page not dirty)
    - » Writes will cause a page fault. Assuming write is allowed, OS sets software "modified" bit → 1, and marks page as writable (W→1).
    - » Whenever page written back to disk, clear "modified" bit → 0, mark read-only

Clock Algorithms Variations (continued)

- Do we really need a hardware-supported "use" bit?
  - No. Can emulate it similar to above (e.g. for read operation)
    - » Kernel keeps a "use" bit and "modified" bit for each page
  - Algorithm (Clock-Emulated-Use-and-Modified):
    - » Mark all pages as invalid, even if in memory.
      Clear emulated "use" bits → 0 and "modified" bits → 0 for all pages (not used, not dirty)
    - » Read or write to invalid page traps to OS to tell use page has been used
    - » OS sets "use" bit → 1 in software to indicate that page has been "used".
      Further:
      1) If read, mark page as read-only, W→0 (will catch future writes)
      2) If write (and write allowed), set "modified" bit → 1, mark page as writable (W→1)
    - » When clock hand passes, reset emulated "use" bit → 0 and mark page as invalid again
    - » Note that "modified" bit left alone until page written back to disk
- Remember, however, clock is just an approximation of LRU!
  - Can we do a better approximation, given that we have to take page faults on some reads and writes to collect use information?
  - Need to identify an old page, not oldest page!
  - Answer: second chance list

Second-Chance List Algorithm (VAX/VMS)

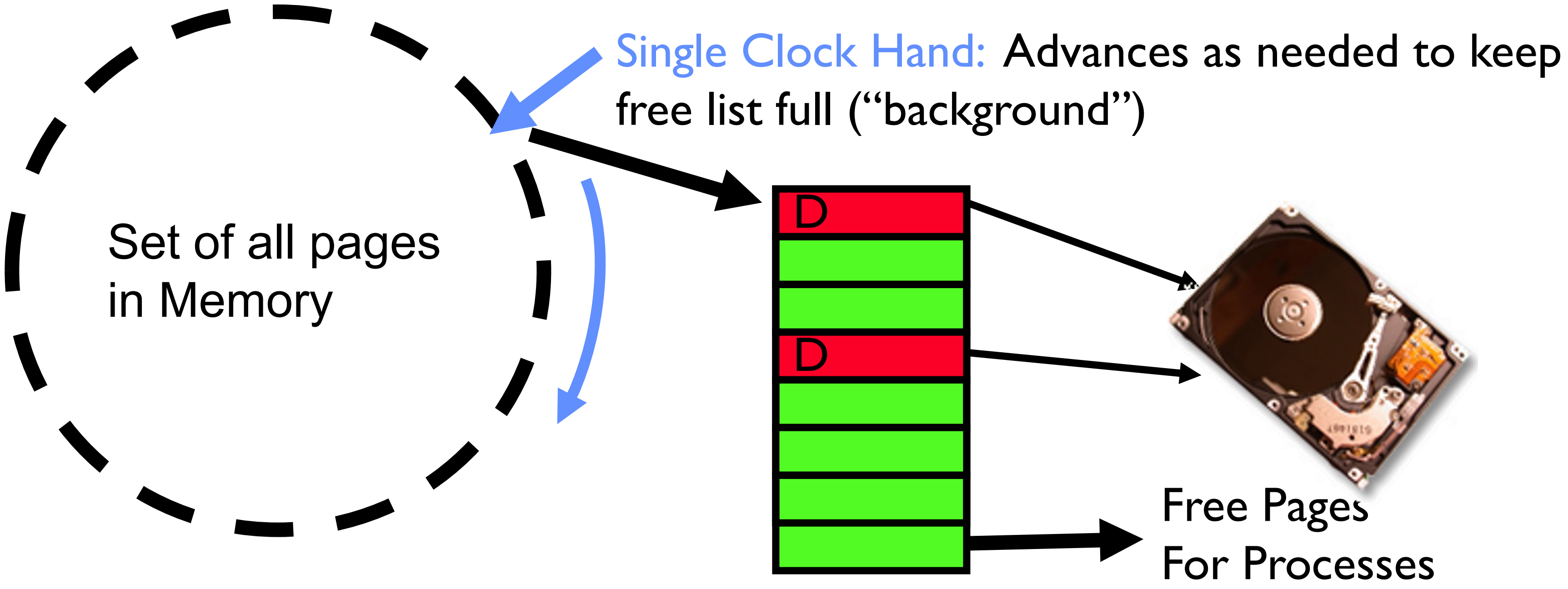


- Split memory in two: Active list (RW), SC list (Invalid)
- Access pages in Active list at full speed
- Otherwise, Page Fault
  - Always move overflow page from end of Active list to front of Second-chance list (SC) and mark invalid
  - Desired Page in SC List: move it to front of Active list, mark it RW
  - Not in SC list: page in to front of Active list, mark RW; page out LRU victim at end of SC list

Second-Chance List Algorithm (continued)

- How many pages for second chance list?
  - If 0 $\Rightarrow$ FIFO
  - If all $\Rightarrow$ LRU, but page fault on every page reference
- Pick intermediate value. Compared to FIFO:
  - Pro: Few disk accesses (page only goes to disk if unused for a long time)
  - Con: Increased overhead trapping to OS (software / hardware tradeoff)
- History: The VAX architecture did not include a “use” bit.
  Why did that omission happen???
  - Strecker (architect) asked OS people, they said they didn’t need it, so didn’t implement it
  - He later got blamed, but VAX did OK anyway

Free List



- Keep set of free pages ready for use in demand paging
  - Free list filled in background by Clock algorithm or other technique ("Pageout daemon")
  - Dirty pages start copying back to disk when enter list
- Like VAX second-chance list
  - If page needed before reused, just return to active set
- Advantage: faster for page fault
  - Can always use page (or pages) immediately on fault

Reverse Page Mapping (Sometimes called "Coremap")

- When evicting a page frame, how to know which PTEs to invalidate?
  - Hard in the presence of shared pages (forked processes, shared memory, …)
- Reverse mapping mechanism must be very fast
  - Must hunt down all page tables pointing at given page frame when freeing a page
  - Must hunt down all PTEs when seeing if pages "active"
- Implementation options:
  - For every page descriptor, keep linked list of page table entries that point to it
    - » Management nightmare – expensive
  - Linux: Object-based reverse mapping
    - » Link together memory region descriptors instead (much coarser granularity)
    - » E.g., program code and files mapped in with mmap()

Allocation of Page Frames (Memory Pages)

- How do we allocate memory 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:
  - Global replacement – process selects replacement frame from set of all frames; one process can take a frame from another
  - Local replacement – each process selects from only its own set of allocated frames

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 $S = \sum s_i$

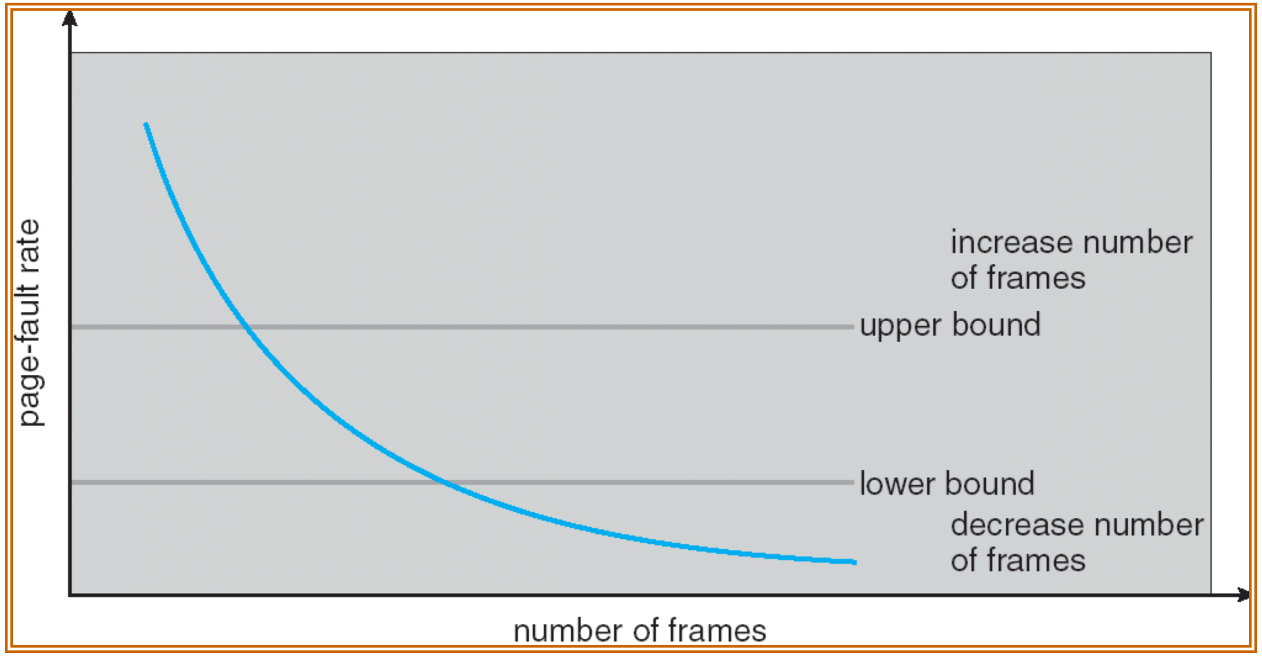
    m = total number of physical frames in the system

    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

- Perhaps we should use an adaptive scheme instead???
  - What if some application just needs more memory?

Page-Fault Frequency Allocation

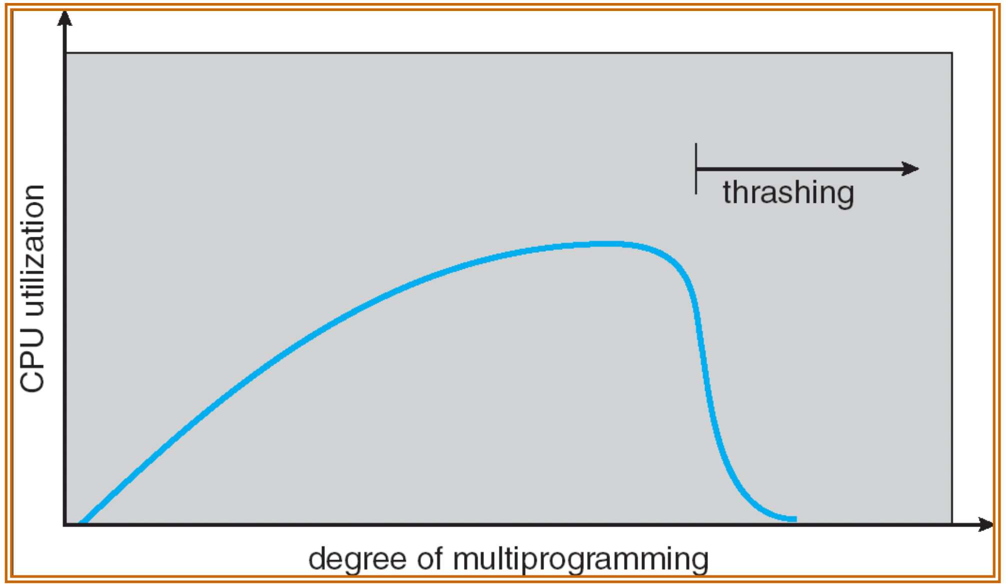
- Can we reduce capacity misses by dynamically changing the number of pages/application?



- 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?

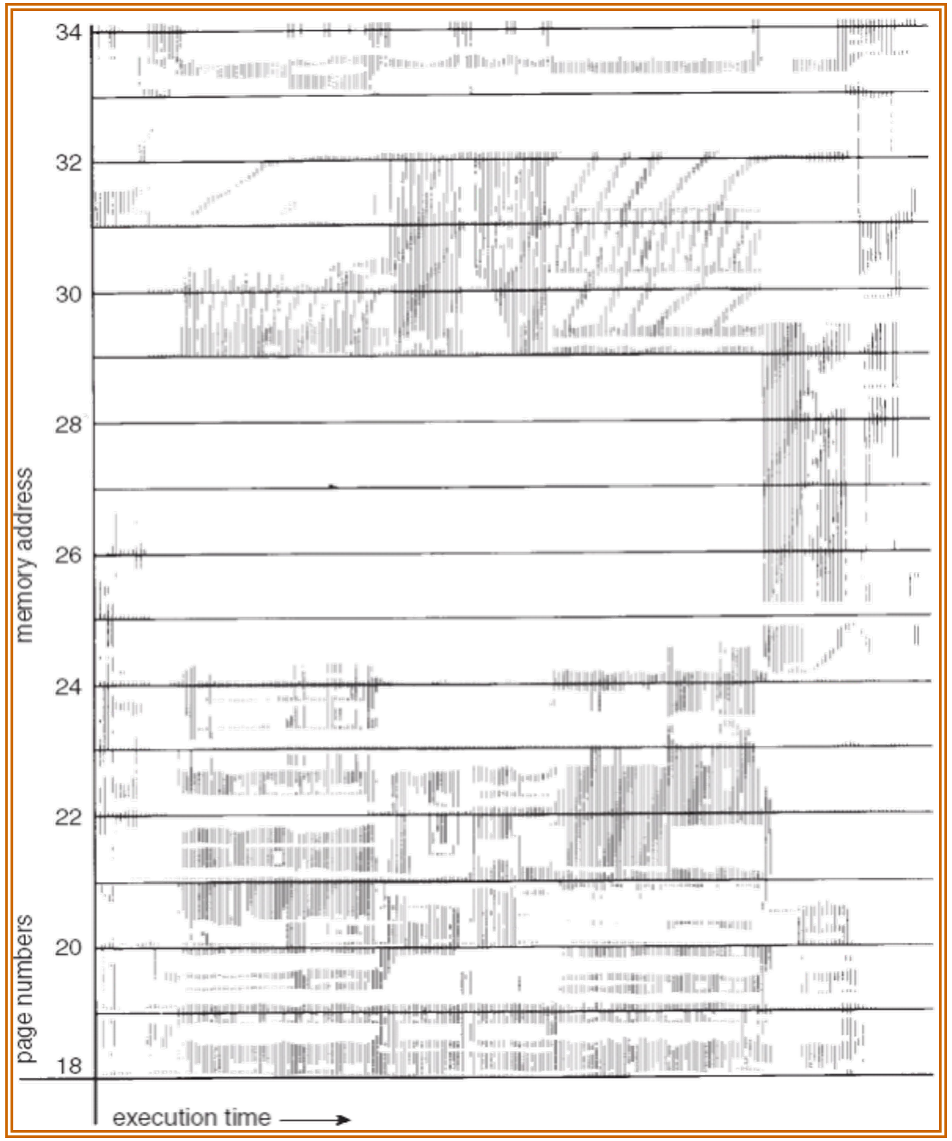
Thrashing

- 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 with little or no actual progress
- Questions:
  - How do we detect Thrashing?
  - What is best response to Thrashing?

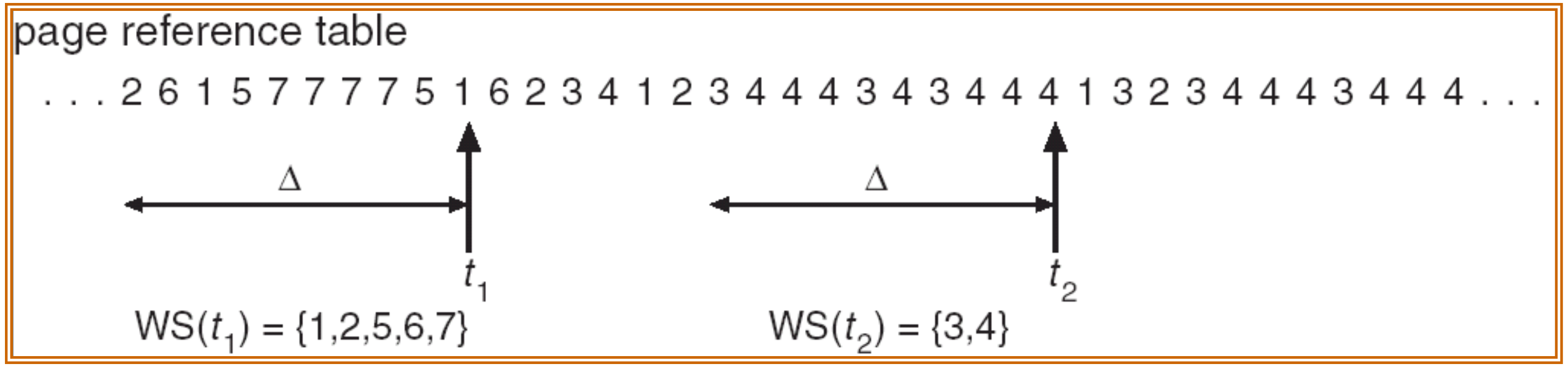


Locality In A Memory-Reference Pattern

- 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 for process to behave well
- Not enough memory for Working Set $\Rightarrow$ Thrashing
  - Better to swap out process?



Working-Set Model



- $\Delta \equiv$ working-set window $\equiv$ fixed number of page references
  - Example: 10,000 instructions
- WSi (working set of Process Pi) = 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
- $D = \Sigma|WSi| \equiv$ total demand frames
- if $D > m \Rightarrow$ Thrashing
  - Policy: if D > m, then suspend/swap out processes
  - This can improve overall system behavior by a lot!

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

Summary

- Clock Algorithm: Approximation to LRU
  - 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
- N^{th}-chance clock algorithm: Another approximate LRU
  - Give pages multiple passes of clock hand before replacing
- Second-Chance List algorithm: Yet another approximate LRU
  - Divide pages into two groups, one of which is truly LRU and managed on page faults.
- Working Set:
  - Set of pages touched by a process recently
- 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