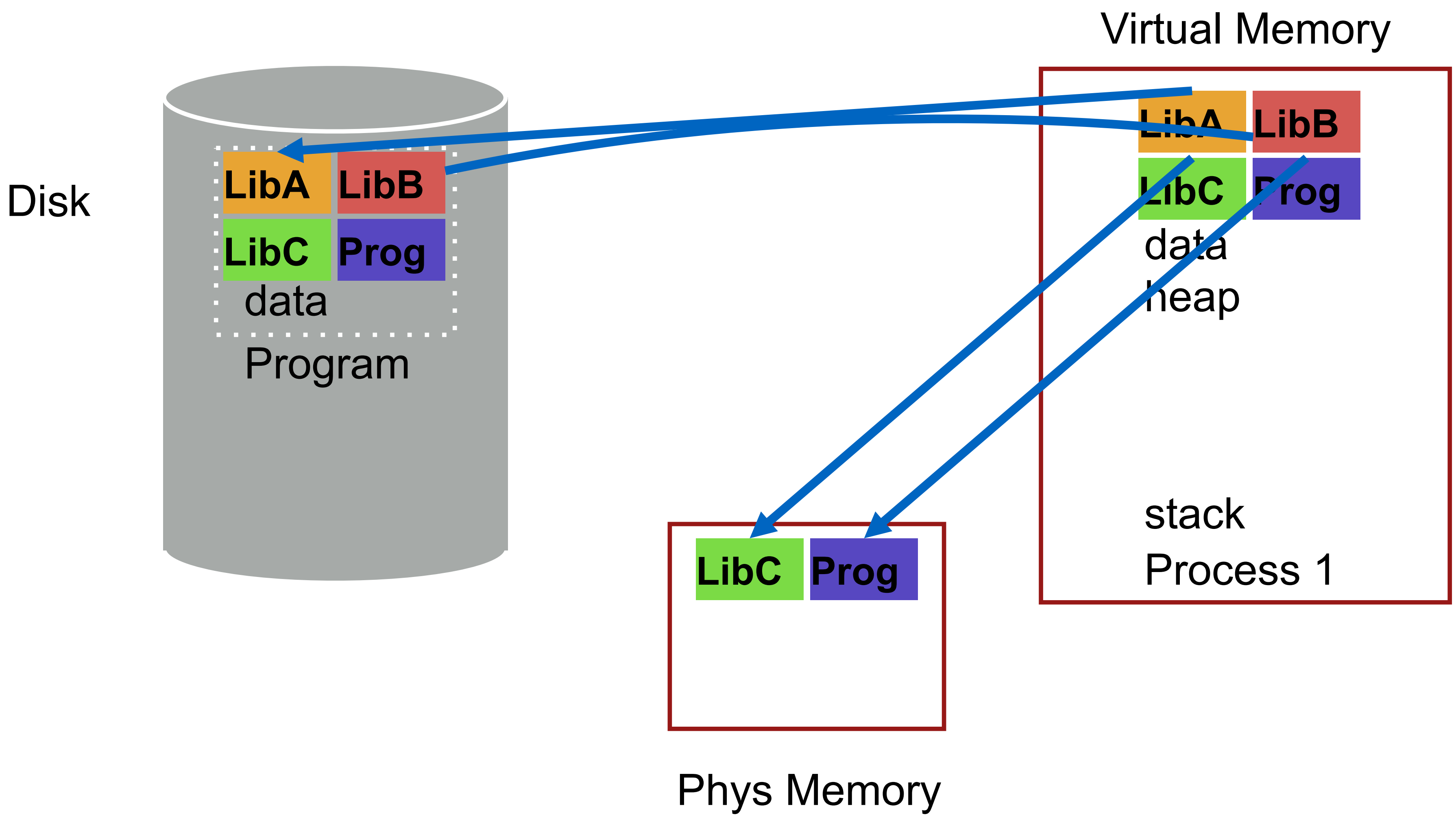
Virtual Memory



Virtual Memory
Disk
LibA
LibB
LibC
Prog
data
Program
LibA
LibB
LibC
Prog
data
heap
stack
Process 1
LibC
Prog
Phys Memory

Virtual Memory Mechanisms

If page fault (i.e., `present` bit is cleared)

- Trap into OS (not handled by hardware. Why?)
- OS selects victim page in memory to replace
- Write victim page out to disk if modified. Add `modified` (`“dirty”`) bit to PTE
- OS reads referenced page from disk into memory
- Page table is updated, `present` bit is set
- Process continues execution

What should scheduler do?

Mechanism for Continuing a Process

Continuing a process after a page fault is tricky

- Want page fault to be transparent to user
- Page fault may have occurred in middle of instruction
  - When instruction is being fetched
  - When data is being loaded or stored
- Requires hardware support
  - precise interrupts: stop CPU pipeline such that instructions before faulting instruction have completed, and those after can be restarted

Complexity depends upon instruction set

- Can faulting instruction be restarted from beginning?
  - Example: `move +(SP), R2`
  - Must track side effects so hardware can roll them back if needed

Virtual Memory Policies

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

OS has two decisions

- Page selection
  - **When** should a page (or pages) on disk be **brought into** memory?
- Page replacement
  - **Which** resident page (or pages) in memory should be **thrown out** to disk?

Average Memory Access Time (AMAT)

Hit% = portion of accesses that go straight to RAM

Miss% = portion of accesses that go to disk first

Tm = time for memory access

Td = time for disk access

AMAT = (Tm) + (Miss% * Td)

Page Selection

When should a page be brought from disk into memory?

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
- Problems: Pay the cost of a page fault for every newly accessed page

Page Selection

When should a page be brought from disk into memory?

Pre-paging (anticipatory, prefetching): Load page before referenced

- OS predicts future accesses (oracle) and brings pages into memory early
- Works well for some access patterns (e.g., sequential)
- Problems?

Page Selection

When should a page be brought from disk into memory?

Hints: Combine above 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

Page Replacement

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

OPT: Replace page not used for longest time in future

- Advantages: Guaranteed to minimize number of page faults
- Disadvantages: Requires that OS predict the future; Not practical, but good for comparison

OPT Replacement Example

Page reference string: 1,2,3,1,2,4,1,4,2,3, 2

Three pages
of physical memory

OPT

Miss: 1,2,3

Metric:
Miss
count

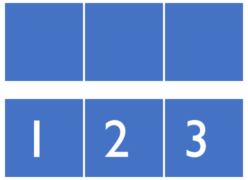
OPT Replacement Example

Page reference string: **1,2,3**,1,2,4,1,4,2,3, 2

Three pages
of physical memory

OPT

Miss: 1,2,3



Metric:
Miss count : 3

OPT Replacement Example

Page reference string: 1,2,3,**1,2**,4,1,4,2,3, 2

Three pages
of physical memory

OPT

Miss: 1,2,3			
	1	2	3
Hit 1	1	2	3
Hit 2	1	2	3

Metric:
Miss count : 3

Compulsory
misses

OPT Replacement Example

Page reference string: 1,2,3,1,2,**4,1**,4,2,3, 2

Three pages
of physical memory

OPT

Miss: 1,2,3			
	1	2	3
Hit 1	1	2	3
Hit 2	1	2	3
Miss:4, Replace: 3	1	2	4
Hit 1	1	2	4

Metric:
Miss count: 4

capacity
miss

OPT Replacement Example

Page reference string: 1,2,3,1,2,4,**1**,**4,2,**3, 2

Three pages
of physical memory

OPT

Miss: 1,2,3			
	1	2	3
Hit 1	1	2	3
Hit 2	1	2	3
Miss:4, Replace: 3	1	2	4
Hit 1	1	2	4
Hit: 4	1	2	4
Hit: 2	1	2	4

Metric:
Miss count: 4

OPT Replacement Example

Page reference string: 1,2,3,1,2,4,**1**,4,2,**3, 2**

Three pages of physical memory

OPT

Miss: 1,2,3			
	1	2	3
Hit 1	1	2	3
Hit 2	1	2	3
Miss:4, Replace: 3	1	2	4
Hit 1	1	2	4
Hit: 4	1	2	4
Hit: 2	1	2	4
Miss:3, Replace: 1	2	3	4
Hit: 2	2	3	4

Metric:
AMAT?
Miss count : 5

5 misses, 4 compulsory misses

AMAT = (Tm) + (Miss% * Td)

Assume Tm = 100ns
Assume Td = 1000000 ns (1millisec)

AMAT = ?

FIFO

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

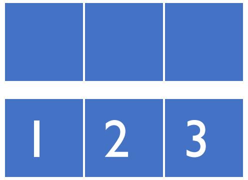
FIFO Example

Page reference string: **1,2,3**,1,2,4,1,4,2,3,2

Three pages
of physical memory

OPT

Miss: 1,2,3



Metric:
Miss count: 3

FIFO Example

Page reference string: 1,2,3,**1,2,4**,1,4,2,3,2

Three pages
of physical memory

	OPT		
Miss: 1,2,3			
	1	2	3
Hit: 1	1	2	3
Hit: 2	1	2	3
Miss:4, Replace:1	2	3	4

Metric:
Miss count: 4

FIFO Example

Page reference string: 1,2,3,1,2,4,**1,4**,2,3,2

Three pages
of physical memory

OPT

Miss: 1,2,3			
	1	2	3
Hit: 1	1	2	3
Hit: 2	1	2	3
Miss:4, Replace:1	2	3	4
Miss:1, Replace:2	3	4	1
Hit: 4	3	4	1

Metric:
Miss count: 5

FIFO Example

Page reference string: 1,2,3,1,2,4,1,4,**2,3**,2

Three pages
of physical memory

OPT

Miss: 1,2,3			
	1	2	3
Hit: 1	1	2	3
Hit: 2	1	2	3
Miss:4, Replace:1	2	3	4
Miss:1, Replace:2	3	4	1
Hit: 4	3	4	1
Miss:2, Replace:3	4	1	2
Miss:3, Replace:4	1	2	3

Metric:
Miss count : 7

FIFO Example

Page reference string: 1,2,3,1,2,4,1,4,2,3,**2**

Three pages
of physical memory

OPT

Miss: 1,2,3			
	1	2	3
Hit: 1	1	2	3
Hit: 2	1	2	3
Miss:4, Replace:1	2	3	4
Miss:1, Replace:2	3	4	1
Hit: 4	3	4	1
Miss:2, Replace:3	4	1	2
Miss:3, Replace:4	1	2	3
Hit: 2	1	2	3

Metric:
Miss count : 7

FIFO Example

Page reference string: 1,2,3,1,2,4,**1**,4,2,3,2

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Miss: 1,2,3			
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Hit: 1	1	2	3
Hit: 2	1	2	3
Miss:4, Replace:1	2	3	4
Miss:1, Replace:2	3	4	1
Hit: 4	3	4	1
Miss:2, Replace:3	4	1	2
Miss:3, Replace:4	1	2	3
Hit: 2	1	2	3

7 total misses, 4 compulsory misses

AMAT = (Tm) + (Miss% * Td)

Assume Tm = 100ns
Assume Td = 1000000 ns (1millisec)

AMAT = ?

LRU Example – Replace
Least Recently Used

Page reference string: 1,2,3,1,2,4,1,4,2,3,2

Three pages
of physical memory

OPT

Miss: 1,2,3			
	1	2	3
Hit: 1	1	2	3
Hit: 2	1	2	3
Miss:4, Replace:3	1	2	4
Hit: 1	1	2	4
Hit: 4	1	2	4
Hit: 2	1	2	4
Miss:3, Replace:1	2	4	3
Hit: 2	2	4	3

Metric: Miss count

5 total misses
4 compulsory misses

In this example, same as OPT!

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
  - Stack property: smaller cache a subset of bigger cache

- FIFO: Add more memory, usually have fewer page faults
  - Belady's anomaly: but there are cases where we have more page faults!

Consider access stream: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

Consider physical memory size: 3 pages vs. 4 pages

How many misses with FIFO?

3 pages: 9 misses
4 pages: 10 misses

Problems with LRU-based Replacement

LRU does not consider frequency of accesses

- Is a page accessed **once** in the past equal to one accessed **N** times?
- Common workload problem:
  - Scan (sequential read, never used again) one large data region flushes memory

Solution: Track frequency of accesses to page

Pure LFU (Least-frequently-used) replacement

- Problem: LFU can never forget pages from the far past

Implementing LRU

Perfect LRU on Software

- OS maintains ordered list of physical pages by reference time
- When page is referenced: Move page to front of list
- When need victim: Pick page at back of list
- Trade-off: Slow on memory reference, fast on replacement

Perfect LRU on Hardware

- Associate timestamp with each page (e.g., PTE)
- When page is referenced: Associate current system timestamp with page
- When need victim: Scan through PTEs to find oldest timestamp
- Trade-off: Fast on memory reference, slow on replacement (especially as size of memory grows)

In practice, do not implement Perfect LRU

- LRU is an approximation anyway, so approximate more
- Goal: Find an old page, but not necessarily the oldest

Clock Algorithm

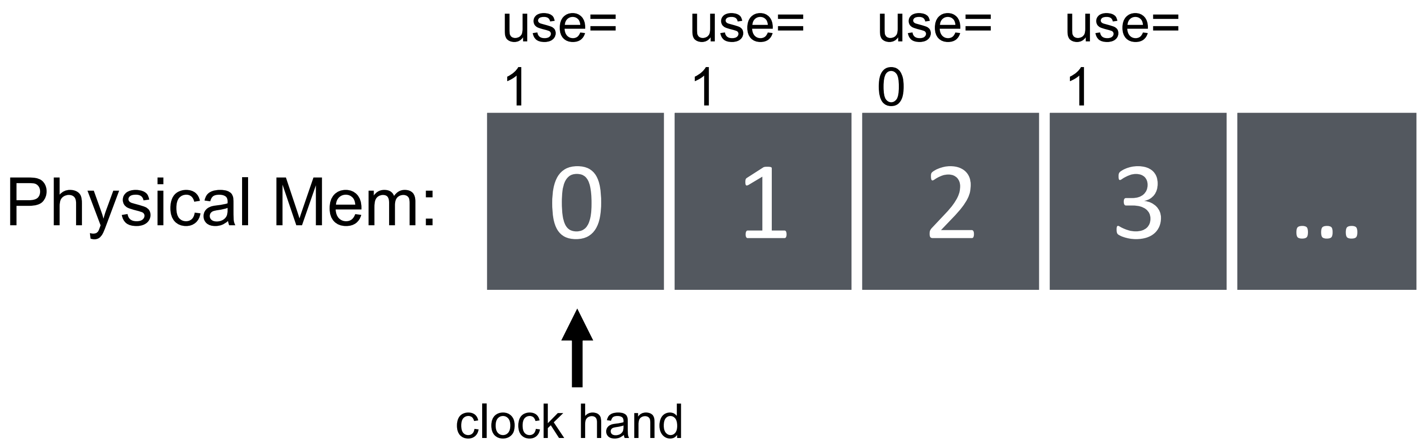
Hardware

- Keep `use` (or `reference`) bit for each page frame
- When page is referenced: set `use` bit

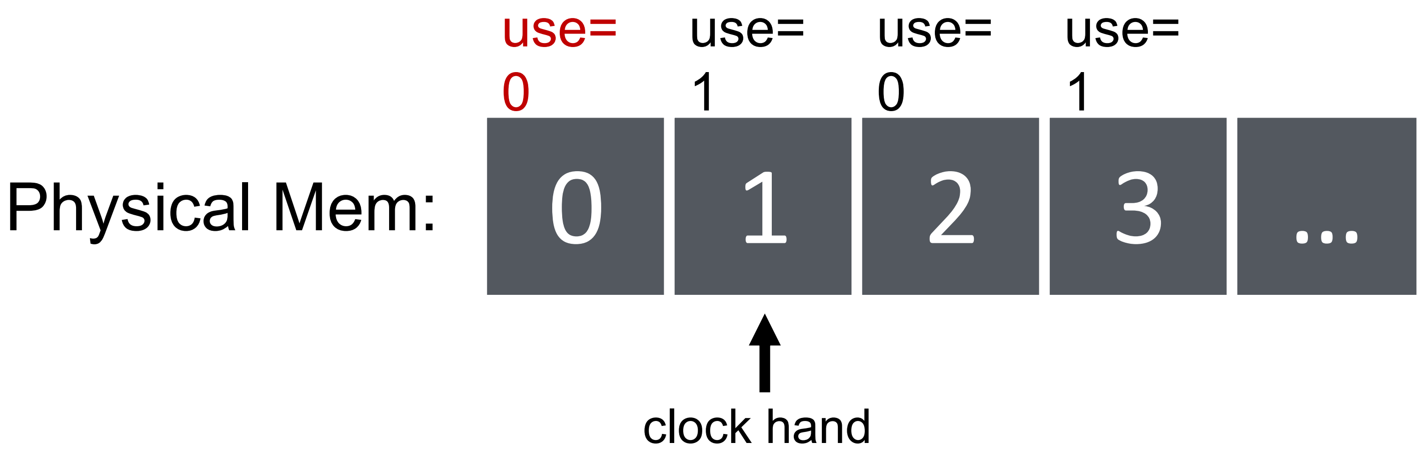
Operating System

- Page replacement: Look for page with `use` bit cleared (has not been referenced for a while)
- Implementation:
  - Keep pointer to last examined page frame (“clock hand”)
  - Traverse pages in circular fashion (like a clock)
  - Clear `use` bits as you search
  - Stop when find page with already cleared `use` bit, replace this page

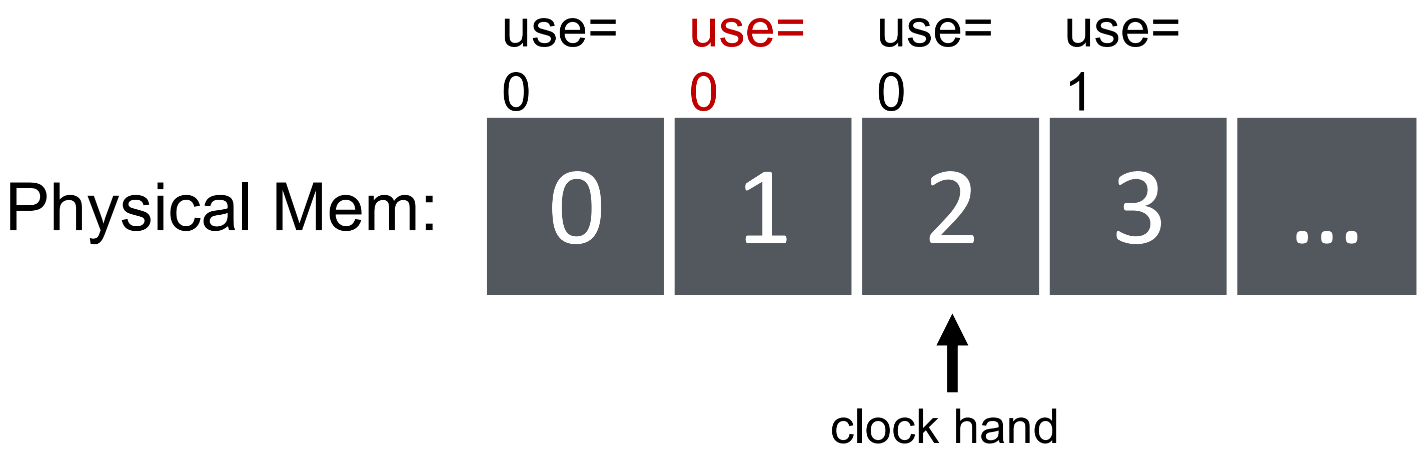
Clock: Look For a Page



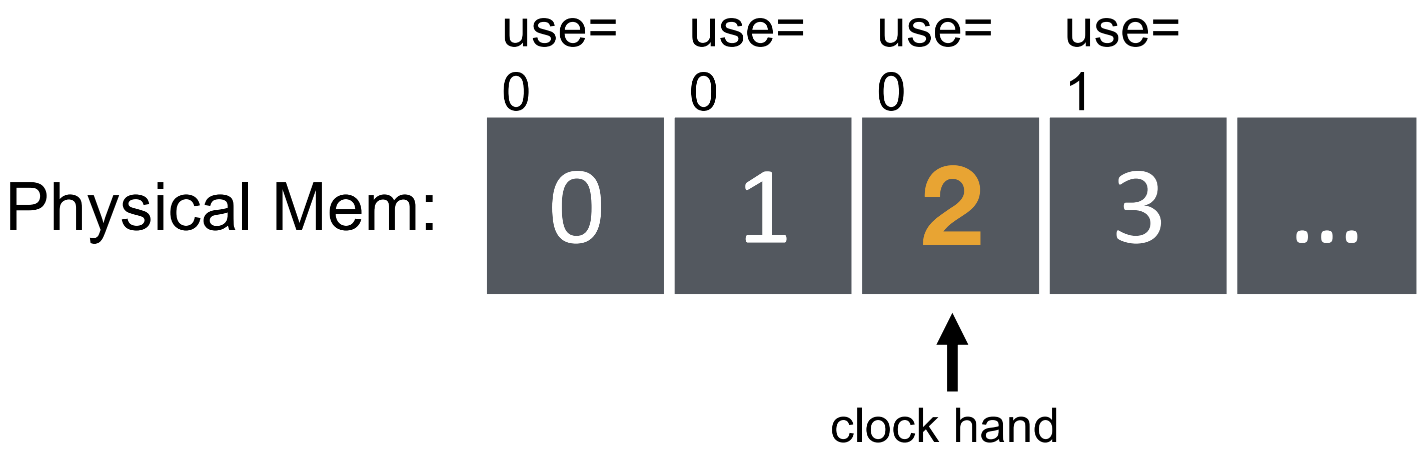
Clock:
Look For a Page



Clock: Look For a Page

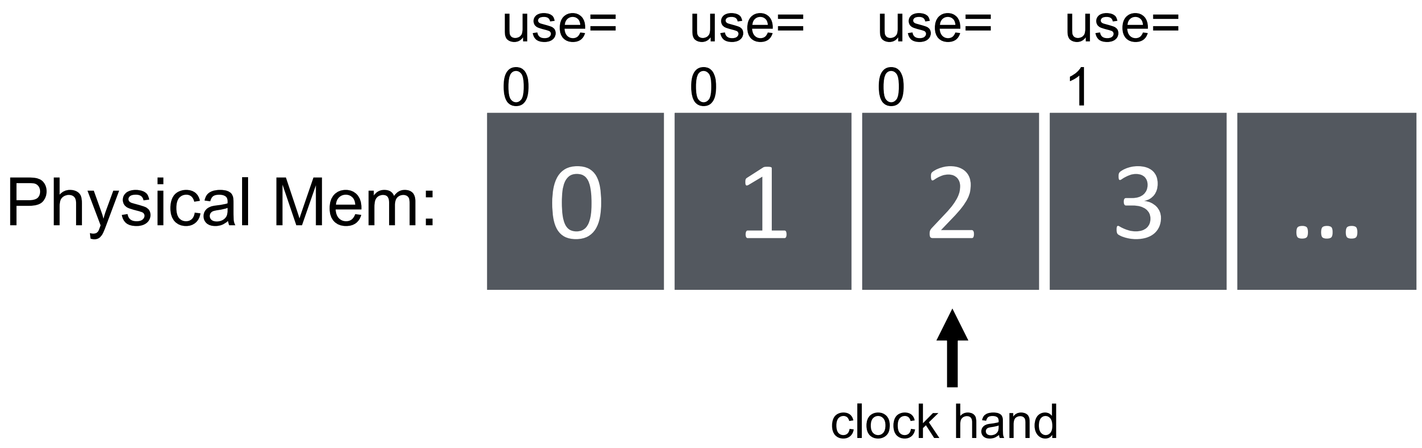


Clock:
Look For a Page



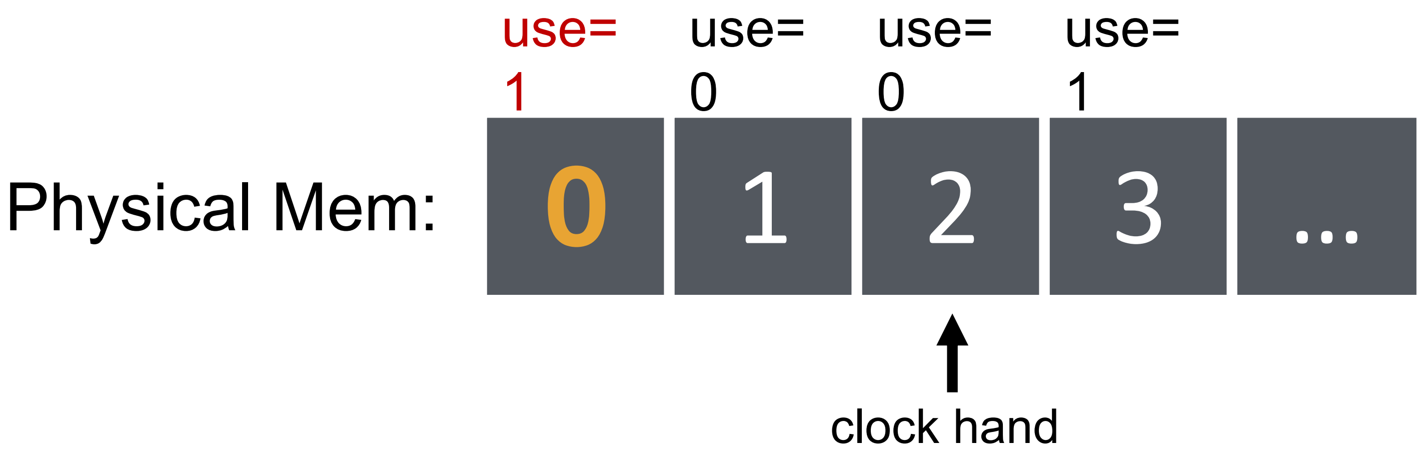
evict **page 2** because it has not been recently used

Clock: Look For a Page

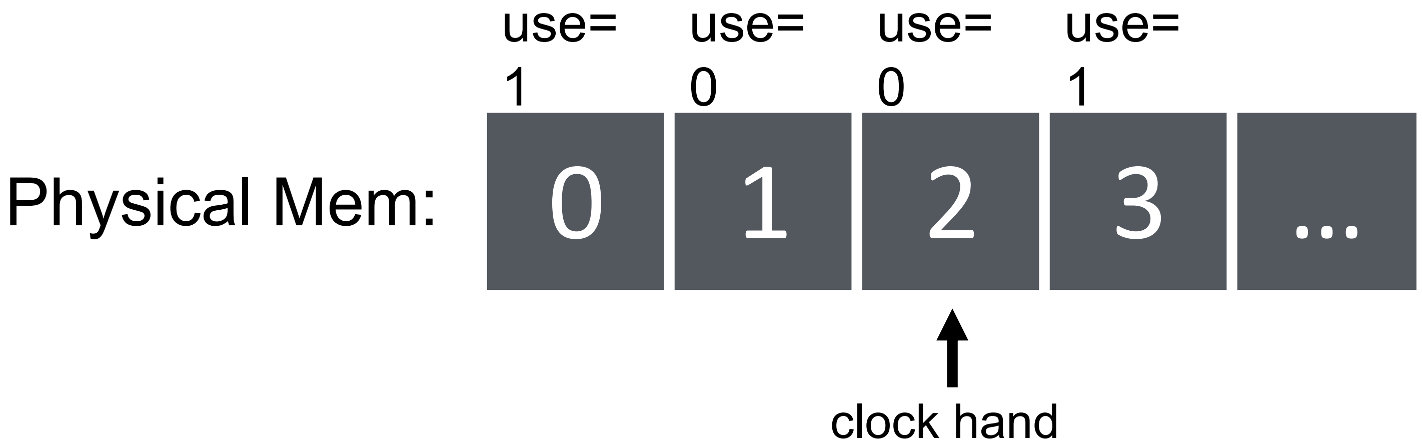


page 0 is accessed…

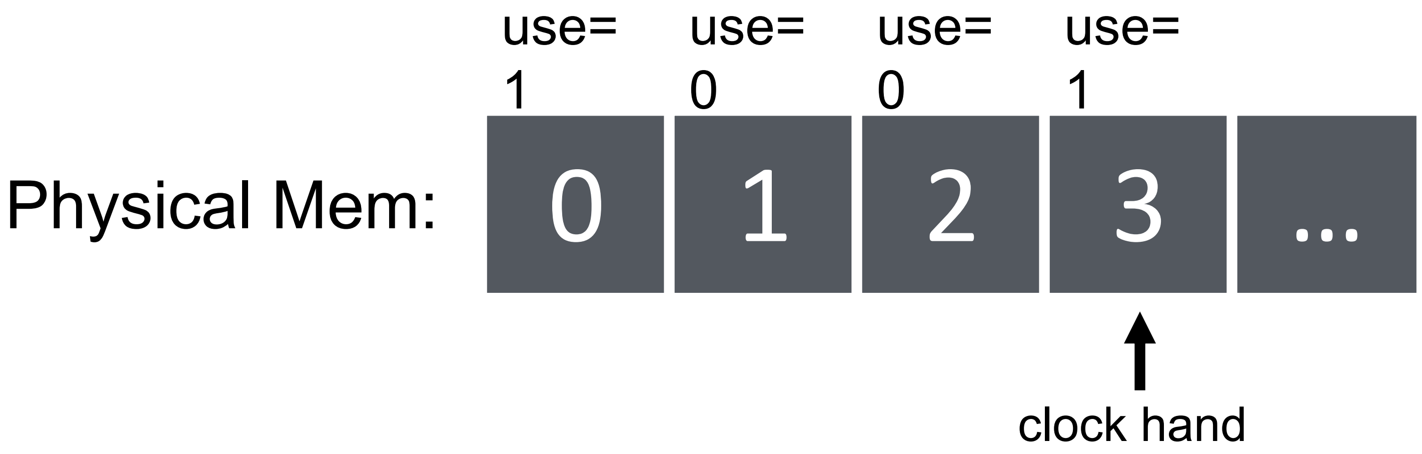
Clock:
Look For a Page



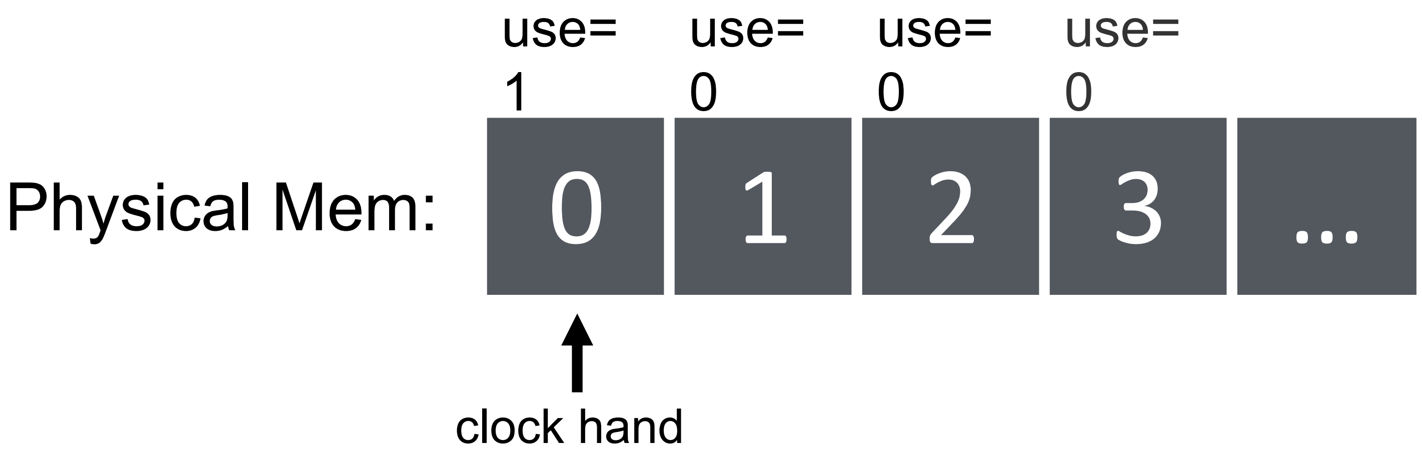
Clock:
Look For a Page



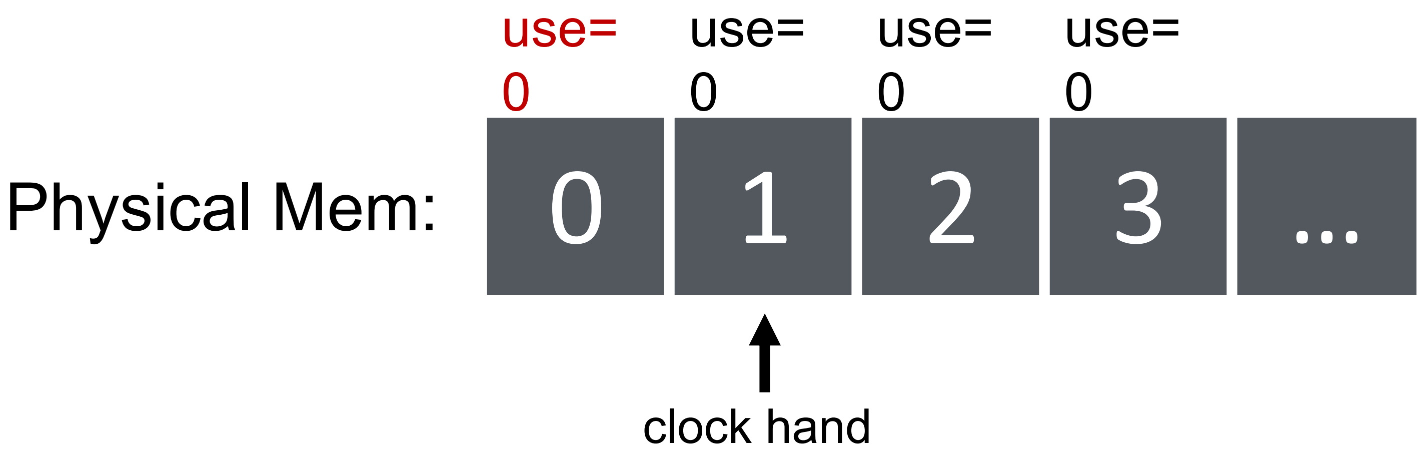
Clock:
Look For a Page



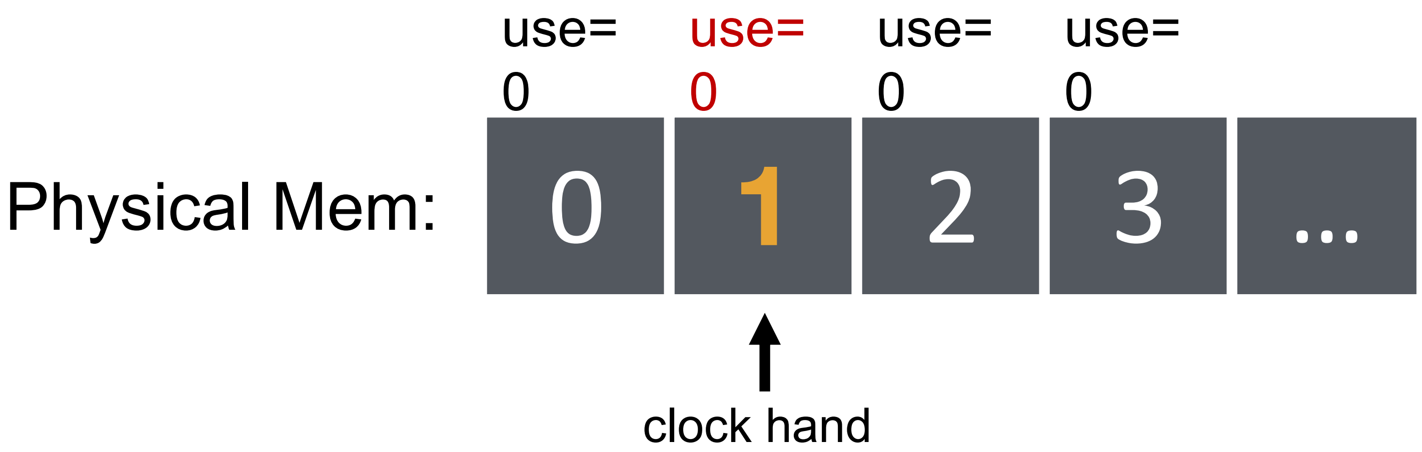
Clock:
Look For a Page



Clock:
Look For a Page



Clock: Look For a Page



evict **page 1** because it has not been recently used

Clock Extensions

Use modified ("dirty") bit to prefer to retain modified pages in memory

- Intuition: More expensive to replace dirty pages
  - Modified pages must be written to disk, clean pages do not have to be
- First replace pages that have `use` bit and `modified` bit cleared

Replace multiple pages at once

- Intuition: Expensive to run replacement algorithm and to write single block to disk
- Find multiple victims each time and track free list

Add software counter ("chance") to track use frequency

- Intuition: Want to differentiate pages by how much they are accessed
- Increment software counter if `use` bit is 0
- Replace when chance exceeds some specified limit

What if no hardware support?

What can the OS do if hardware does not have `use` bit (or `dirty` bit)?

- Can the OS “emulate” these bits?

Think about this question:

- Can the OS get control (i.e., generate a trap) every time `use` bit should be set? (i.e., when a page is accessed?)

Conclusion

Illusion of virtual memory: Processes can run when the sum of virtual address spaces is larger than physical memory

Mechanism:

- Extend page table entry with “present” bit
- OS handles page faults (or page misses) by reading in the desired page from disk

Policy:

- Page selection – demand paging, prefetching, hints
- Page replacement – OPT, FIFO, LRU, others

Implementations (clock) approximate LRU