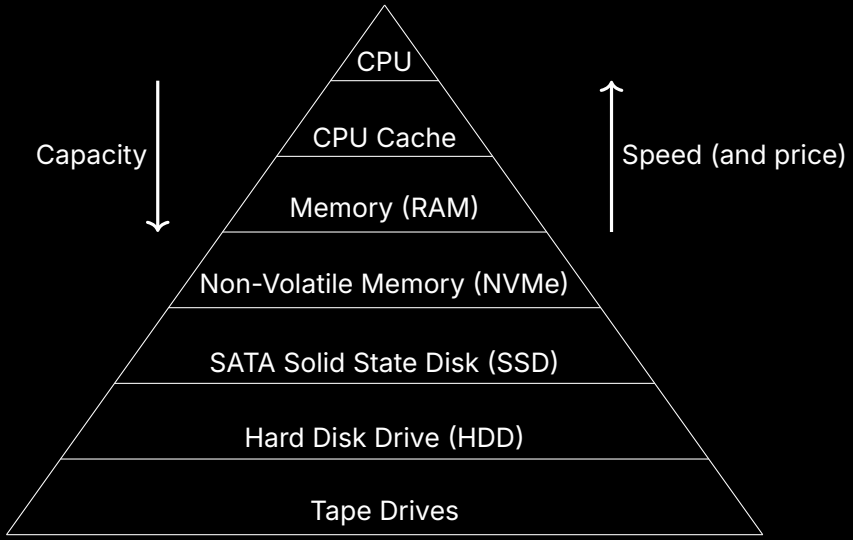
Page Replacement

2025 Winter ECE353: Systems Software
Jon Eyolfson

Lecture 19
2.0.1

Computer Memory Hierarchy is a Trade-off of Capacity and Speed



We Want to Hide the Hierarchy from the User

Each level wants to pretend it has the speed of the layer above it
and the capacity of the layer below it

The memory used by all the processes my exceed the amount of physical memory
Not all of them may be in use at the same time

Only keep referenced pages in memory, put others on disk
Swap pages back to memory when they're needed

Demand Paging

We use memory as a cache for the file system

Map memory pages to file system blocks
  Only load them into memory when they're used through the page fault handler

If the page doesn't represent a file, we can map it to swap space
  Move it to disk if we need to use more physical memory

A Processes' Working Set Should Fit in Physical Memory

Given an amount of time, the number of pages your process uses is called its *working set*

If you cannot fit your working set into physical memory your process will *thrash*

- It's constantly moving entries in and out of cache

Page Replacement Algorithms

Optimal
  Replace the page that won't be used for the longest

Random
  Replace a random page

First-in First-out (FIFO)
  Replace the oldest page first

Least Recently Used (LRU)
  Replace the page that hasn't been used in the longest time

Page Replacement Evaluation

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)

We'll use this for a bunch of examples during this lecture

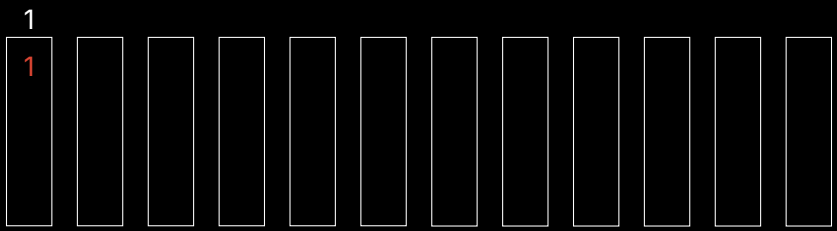
We want the fewest number of page faults

For every example we'll find the number of page faults

Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

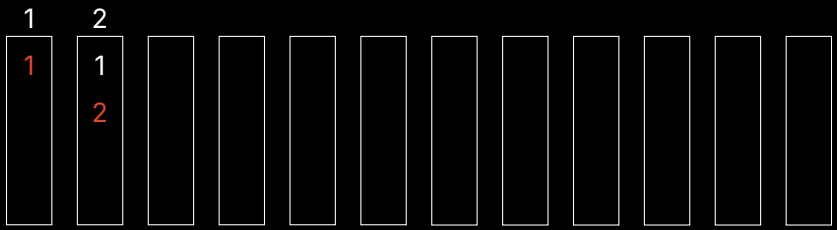
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

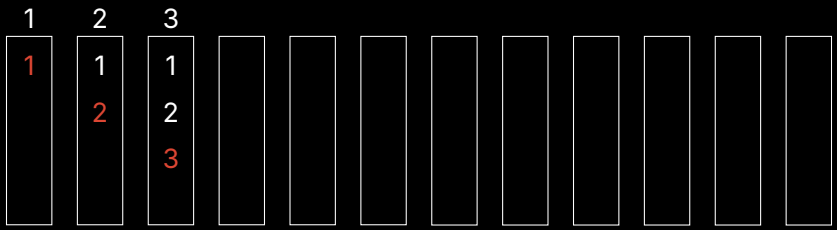
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

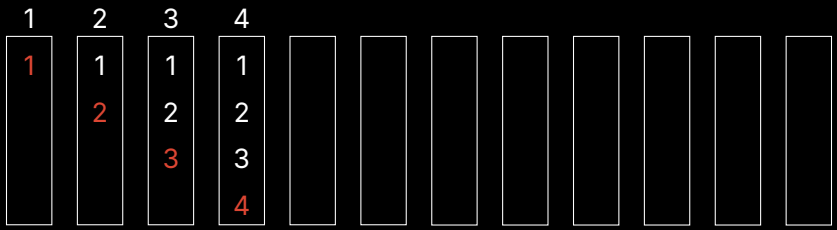
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

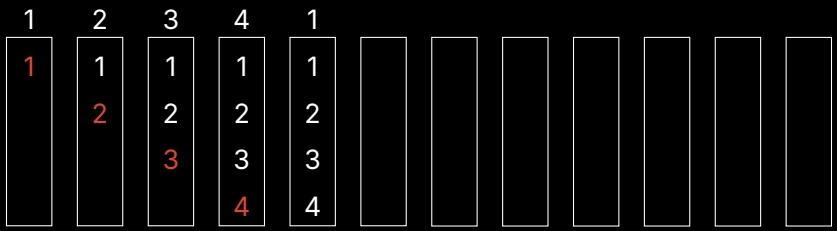
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

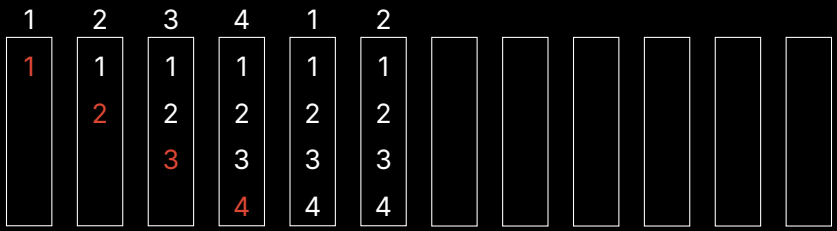
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

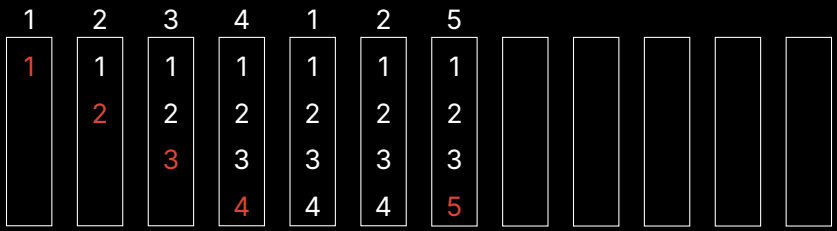
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

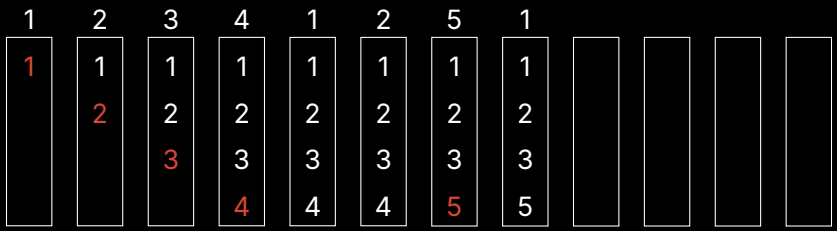
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

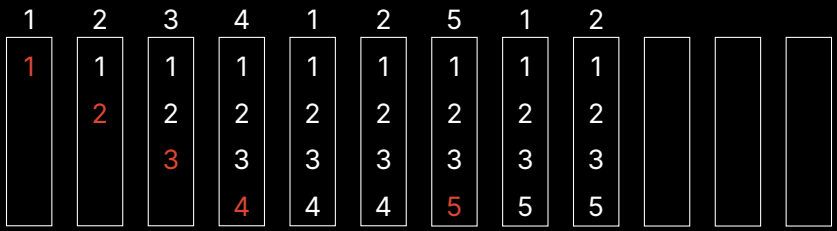
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

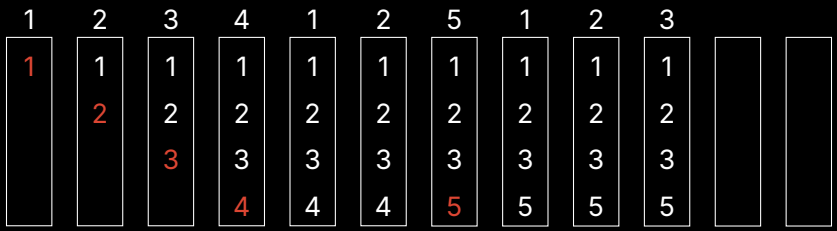
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

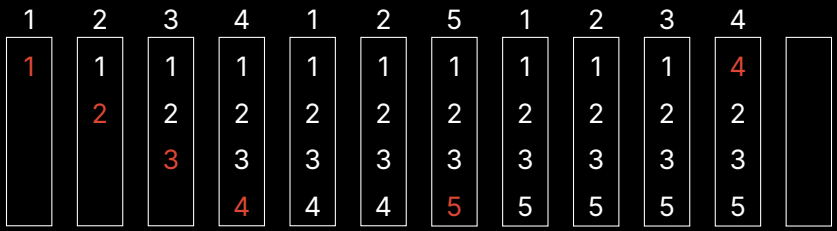
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

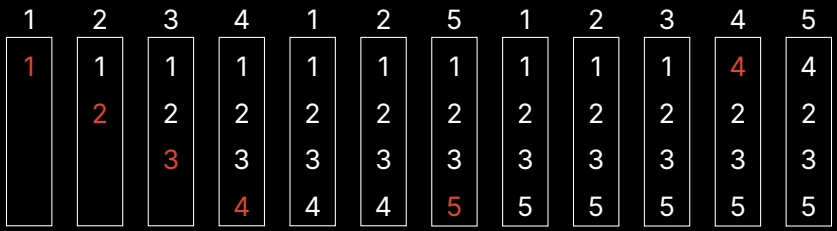
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

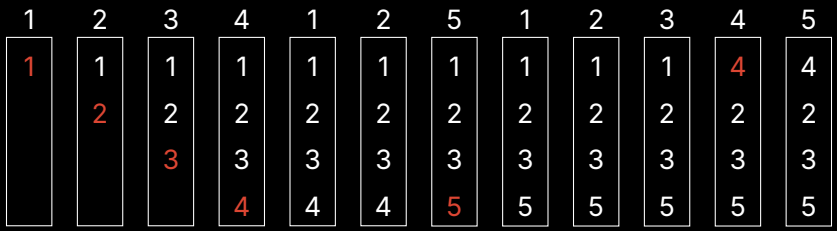
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



Optimal Example

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)

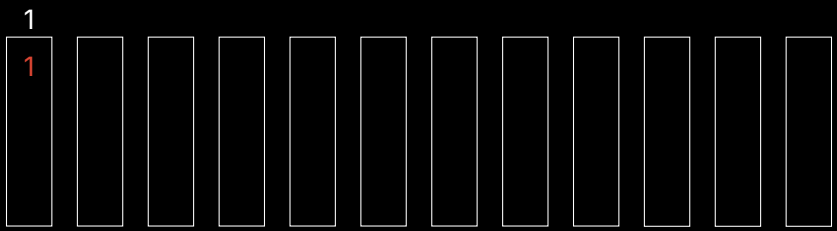


6 page faults

FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

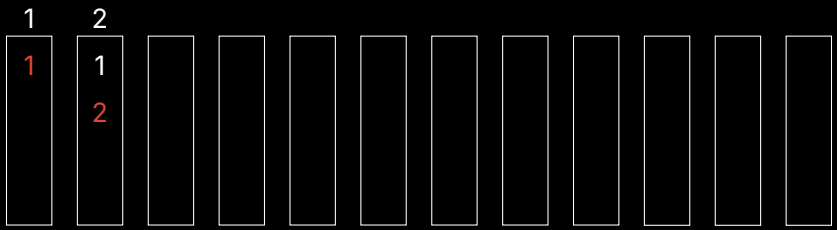
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

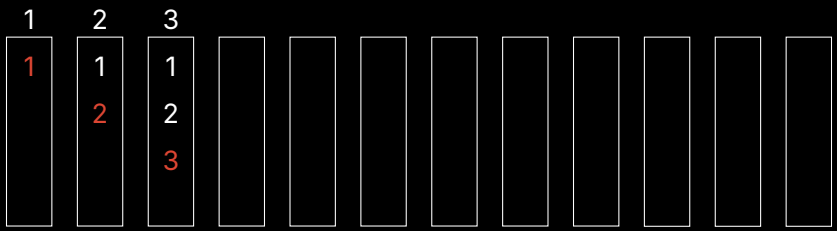
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

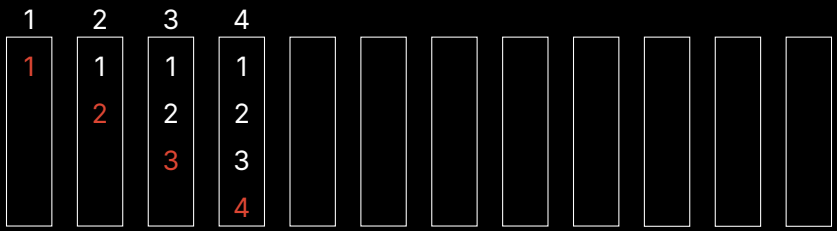
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

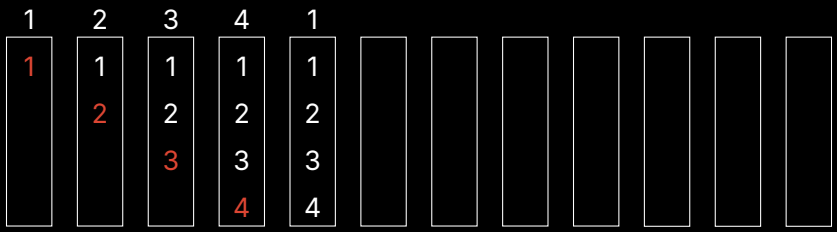
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

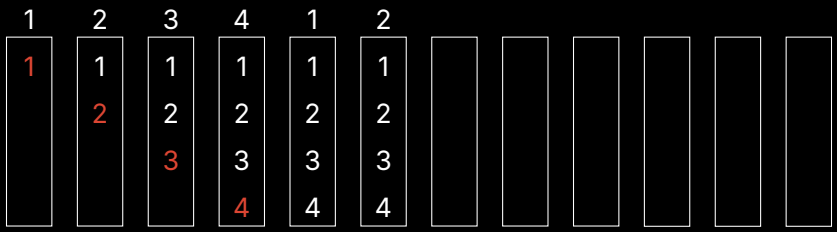
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

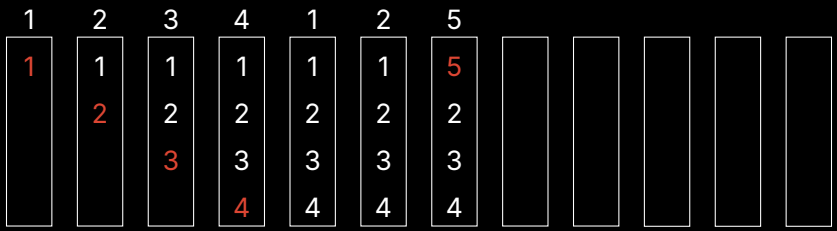
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

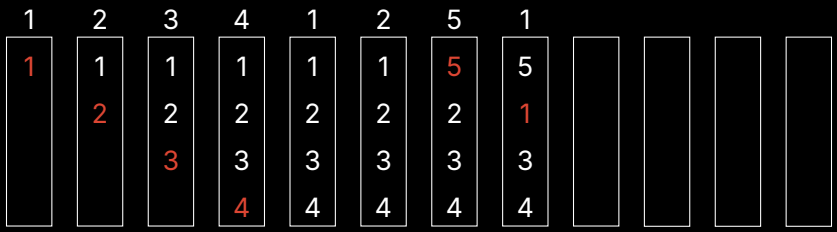
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

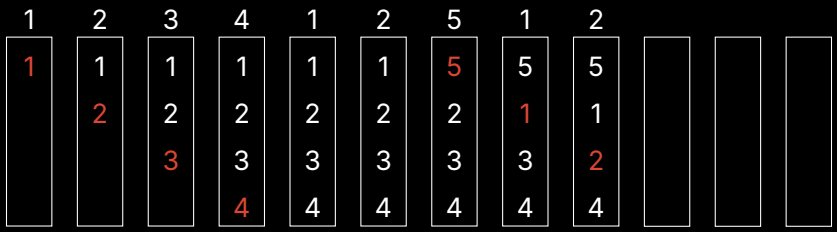
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

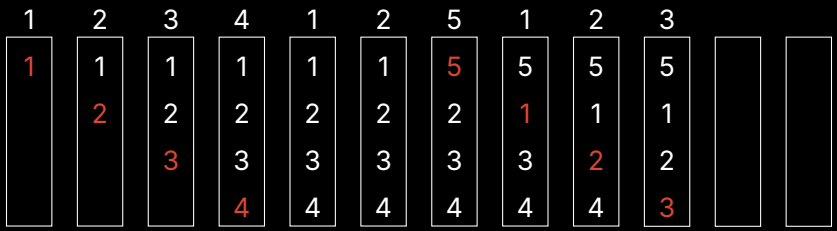
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

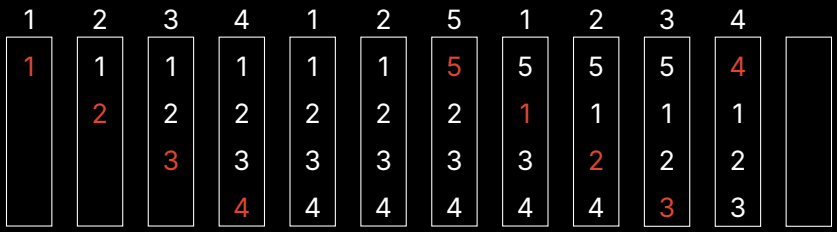
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

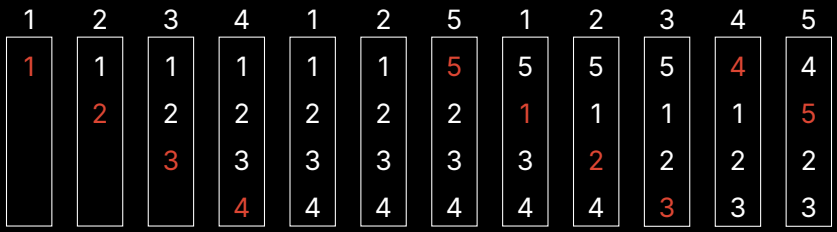
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

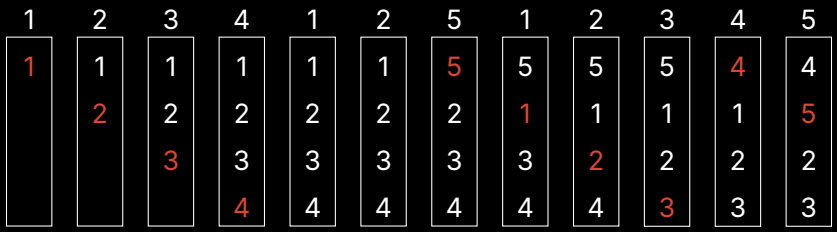
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)

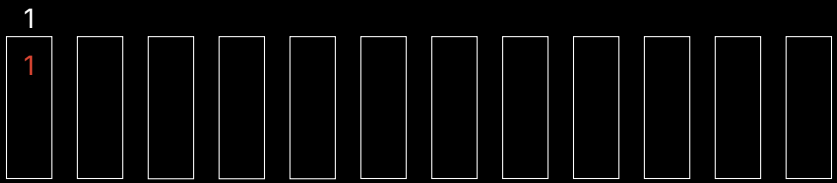


10 page faults

FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

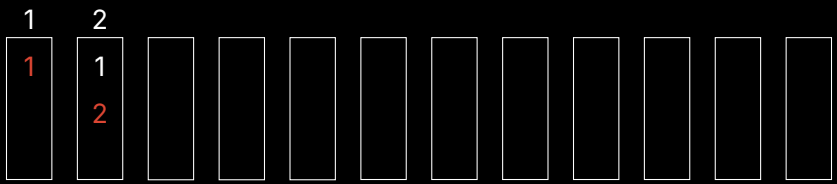
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

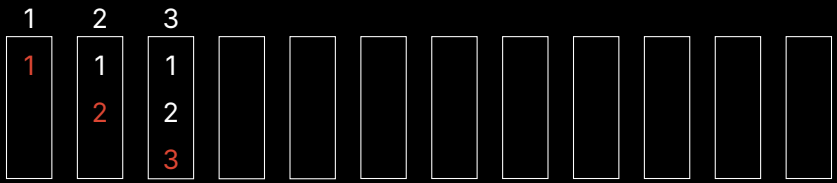
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

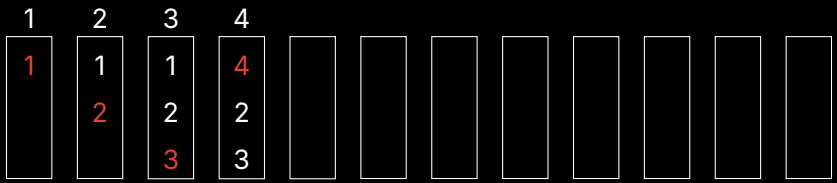
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

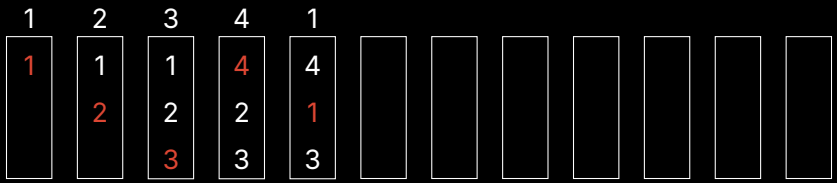
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

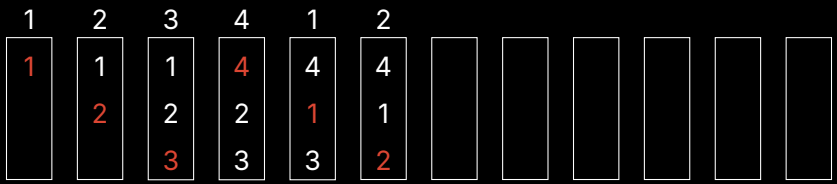
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

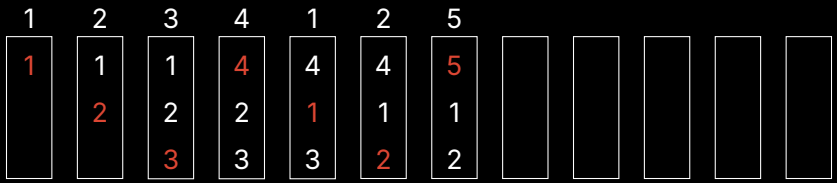
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

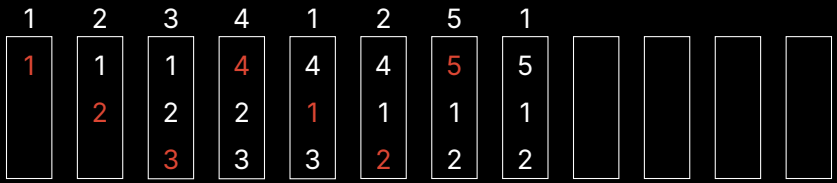
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

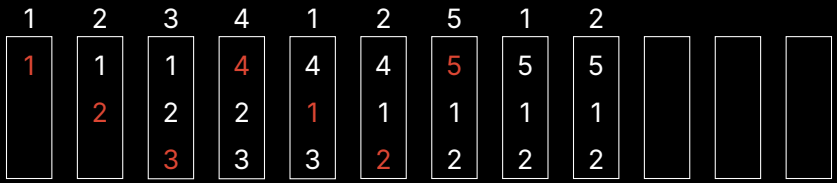
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

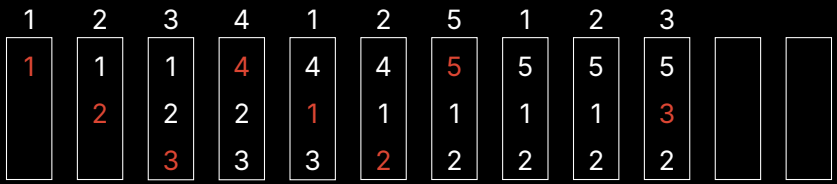
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

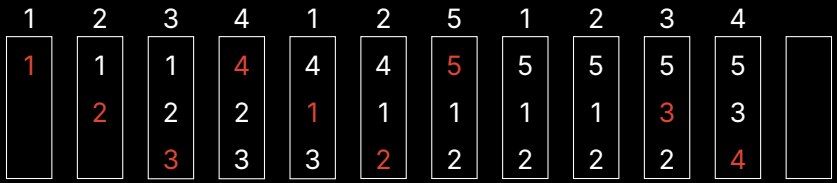
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

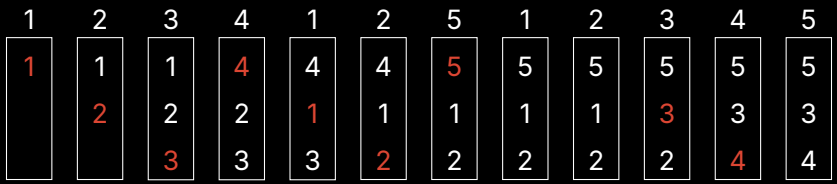
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)

1	2	3	4	1	2	5	1	2	3	4	5
1	1	1	4	4	4	5	5	5	5	5	5
	2	2	2	1	1	1	1	1	3	3	3
		3	3	3	2	2	2	2	2	4	4

FIFO Example (3 Page Frames)

Assume our physical memory can only hold **3** pages, and we access the following:

1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



9 page faults

Bélády's Anomaly Says More Page Frames Causes More Faults

This is a problem with FIFO algorithms
  Does not exist with LRU or "stack-based algorithms"

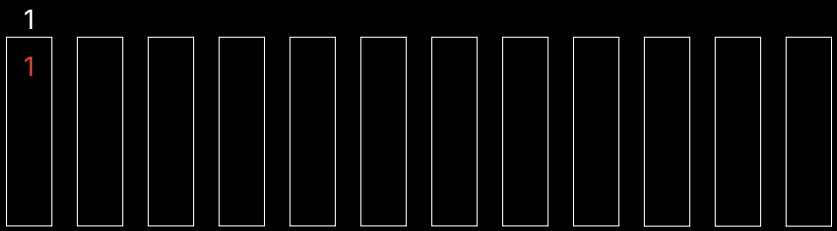
Paper in 2010 found that this FIFO anomaly is unbounded
(https://arxiv.org/abs/1003.1336)
  You could construct a sequence to get any arbitrary page fault ratio

For other algorithms:
  increasing the number of page frames decreases the number of page faults

LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

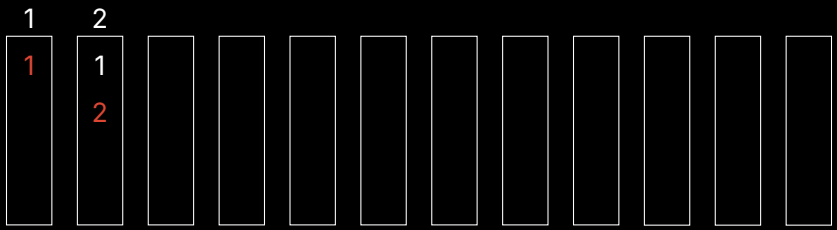
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

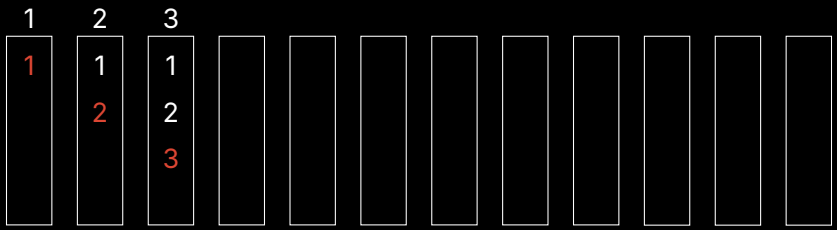
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

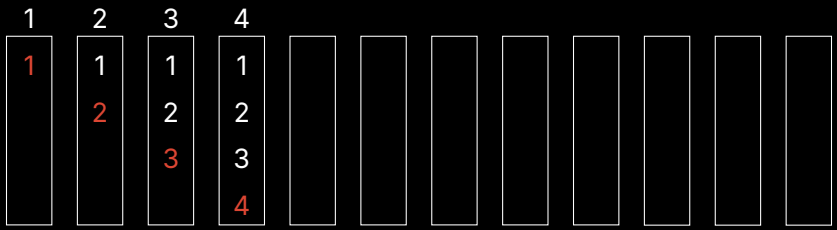
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

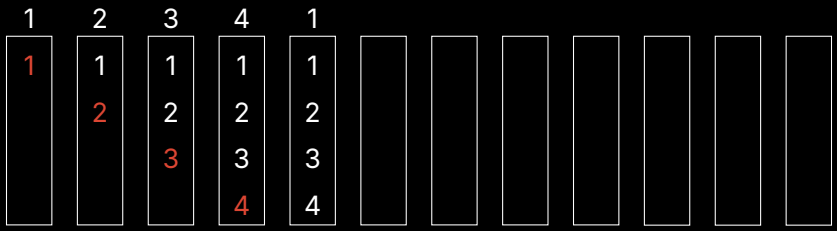
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

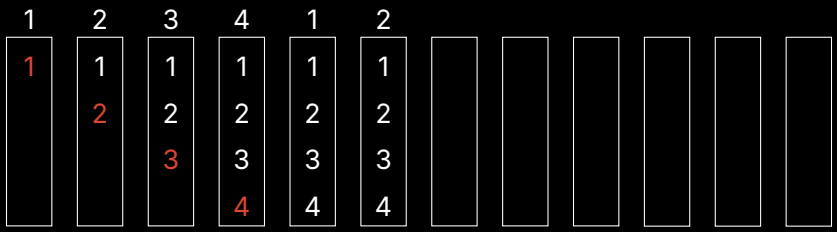
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

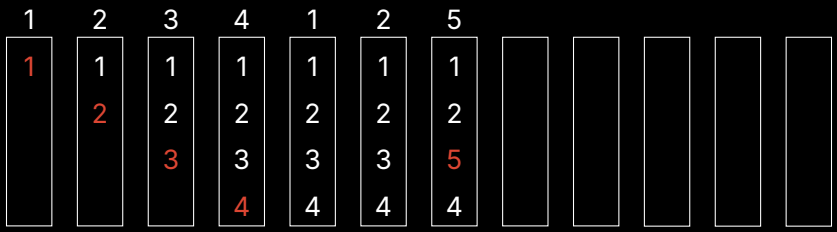
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

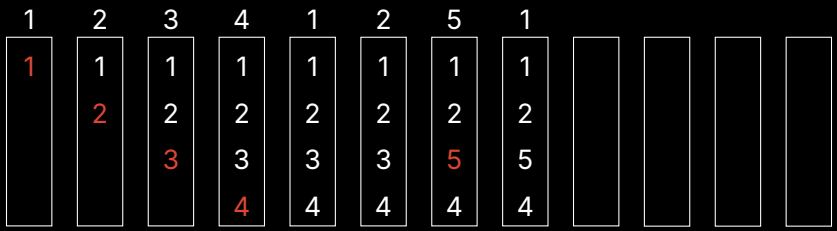
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

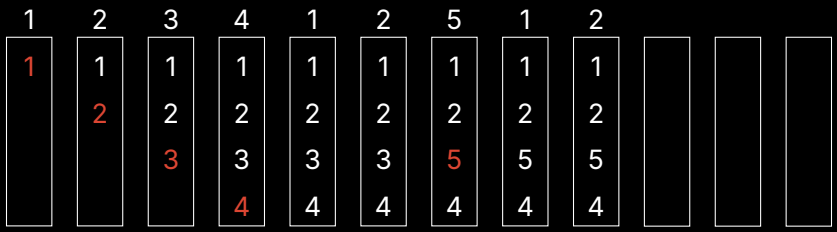
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

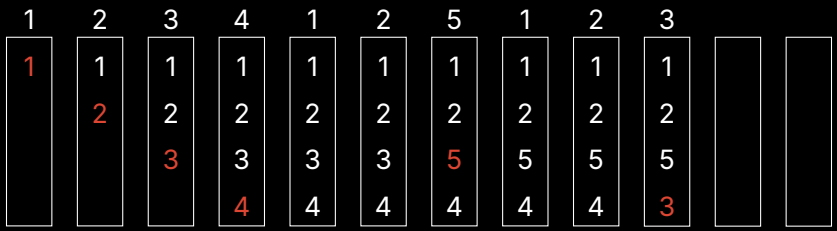
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

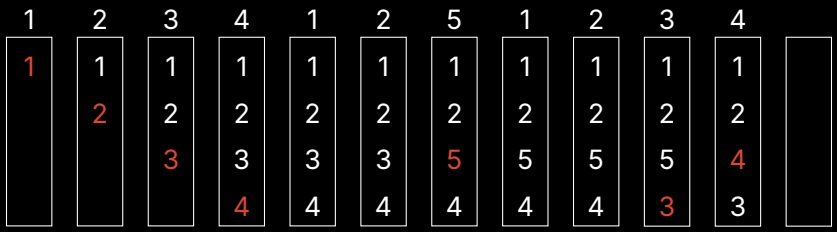
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

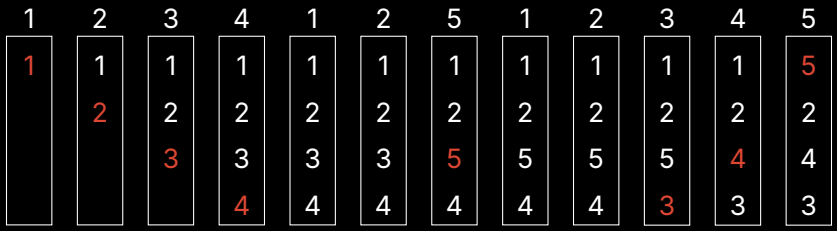
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

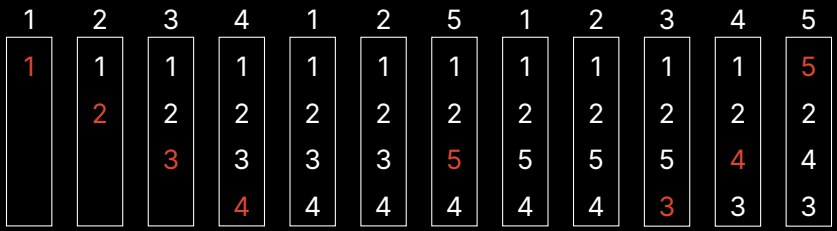
1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



LRU Example (Use FIFO to Break Ties)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 1 2 5 1 2 3 4 5 (all of the pages are initially on disk)



8 page faults

Implementing LRU in Hardware Has to Search All Pages

You could implement it by keeping a counter for each page

For each page reference, save the system clock into the counter

For replacement, scan through the pages and find the one with the oldest clock

Implementing LRU in Software is Too Expensive

Create a doubly linked list of pages

For each page reference, move it to the front of the list

For replacement, remove from the back of the list

It requires 6 pointer updates for each page reference, and also creates a high contention bottleneck for multiple processors

Implementing LRU in Practice Isn't Going to Work

We settle for approximate LRU
  LRU is an approximation of the optimal case anyways

There's lots of different tweaks you can do to implement it more efficiently

We'll be looking at the clock algorithm, but there's also:
  Least Frequently Used (LFU), 2Q, Adaptive Replacement Cache (ARC)

Page Replacement Algorithms Aim to Reduce Page Faults

We saw the following:

- Optimal (good for comparison but not realistic)
- Random (actually works surprisingly well, avoids the worst case)
- FIFO (easy to implement but Bélády's anomaly)
- LRU (gets close to optimal but expensive to implement)

Clock Algorithm

Data structures:

- Keeps a circular list of pages in memory
- Uses a reference bit for each page in memory (light grey in next slides)
- Has a “hand” (iterator) pointing to the last element examined

Algorithm, to insert a new page:

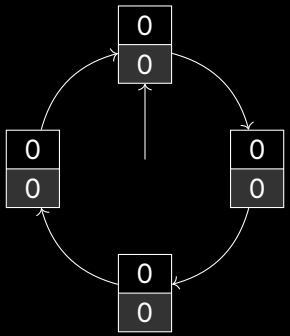
- Check the hand’s reference bit, if it’s 0 then place the page and advance hand
- If the reference bit is 1, set it to 0, advance the hand, and repeat

For page accesses, set the reference bit to 1

Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

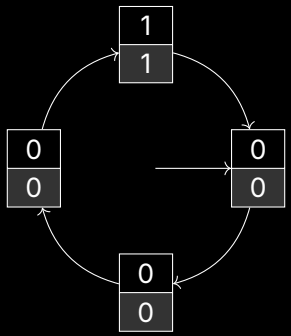


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1

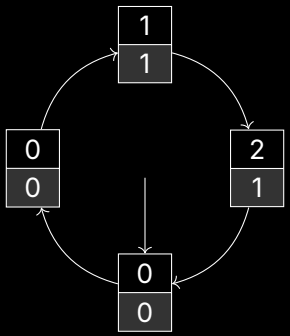


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2

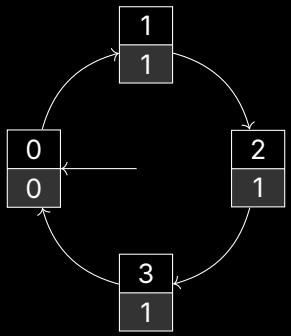


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3

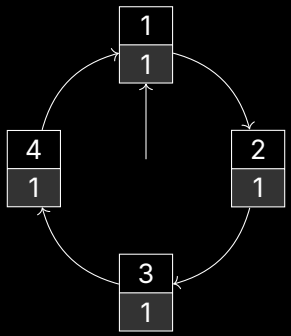


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4

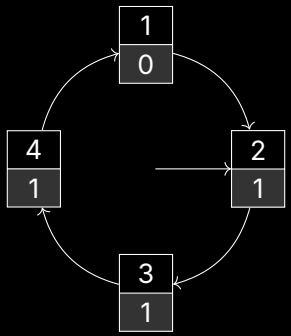


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5

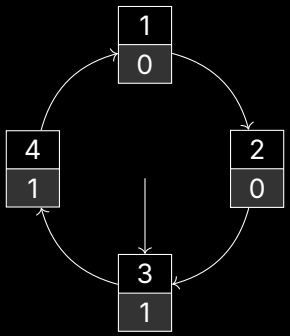


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5

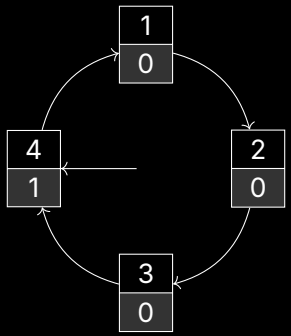


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5

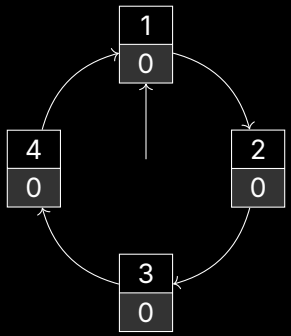


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5

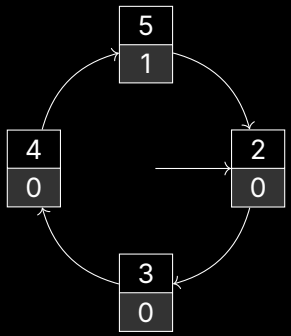


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5

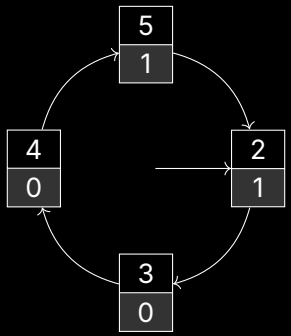


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5 2

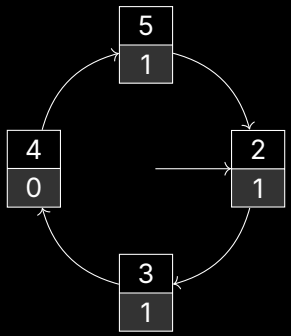


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5 2 3

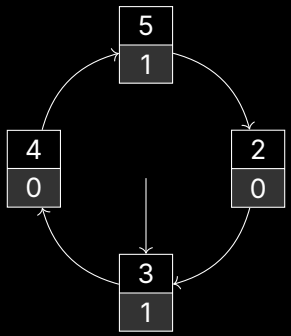


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5 2 3 1

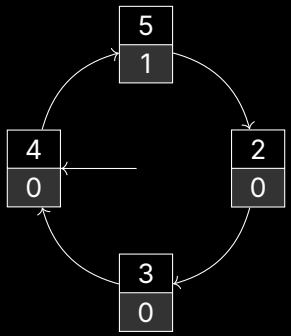


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5 2 3 1

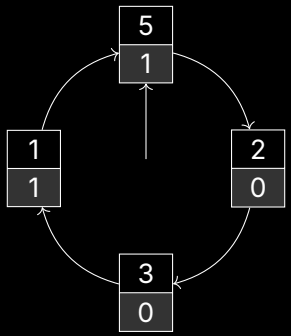


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5 2 3 1

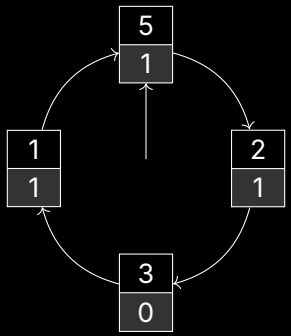


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

1 2 3 4 5 2 3 1 2

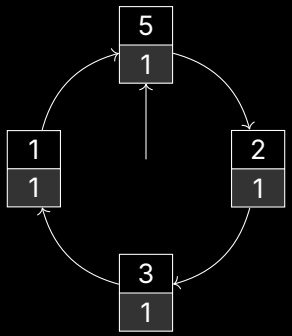


Clock Example (with Diagram)

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)

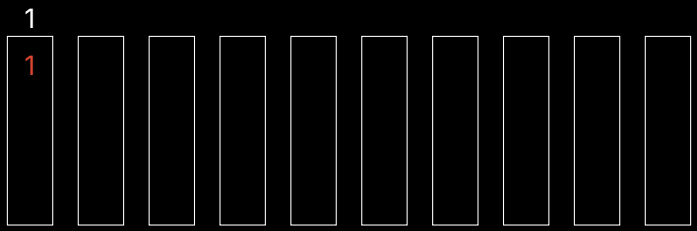
1 2 3 4 5 2 3 1 2 3



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

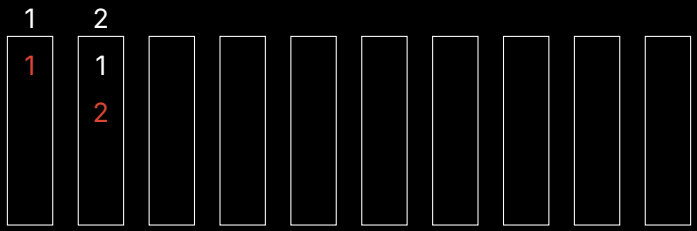
1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

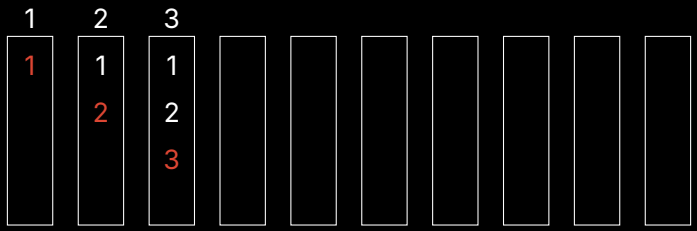
1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

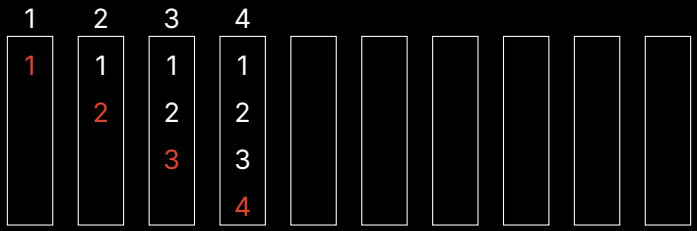
1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

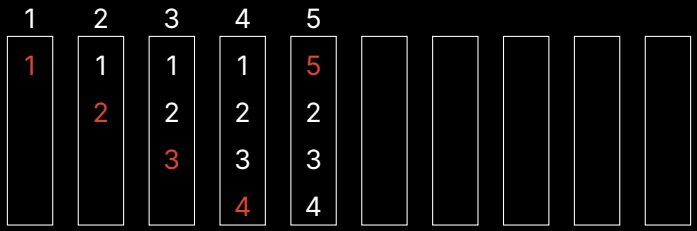
1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

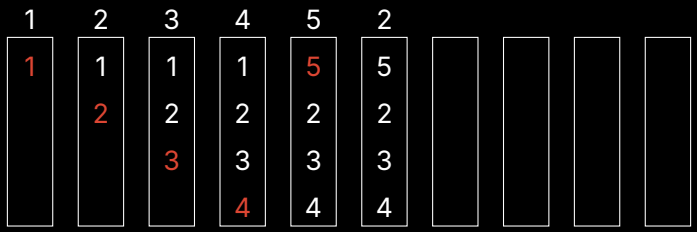
1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

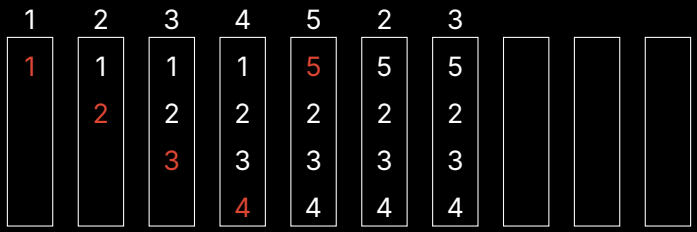
1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

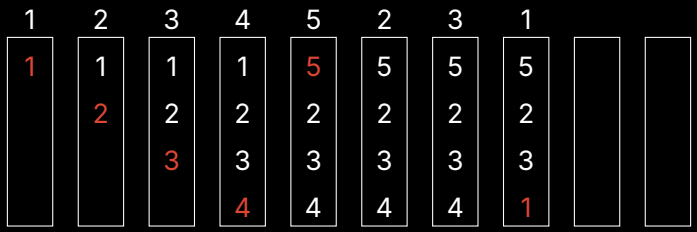
1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

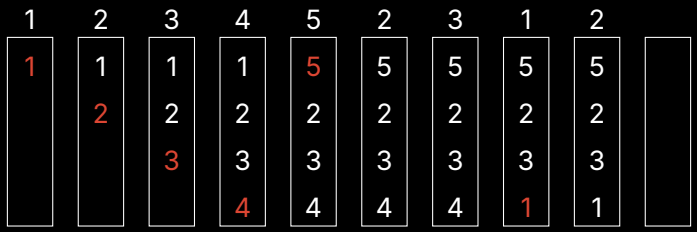
1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

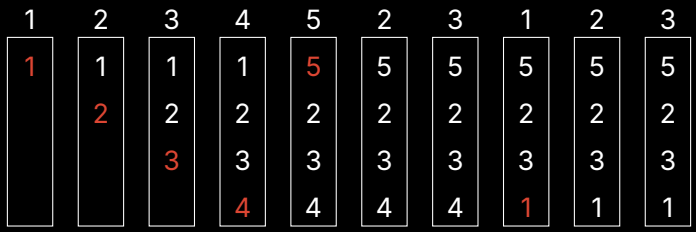
1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

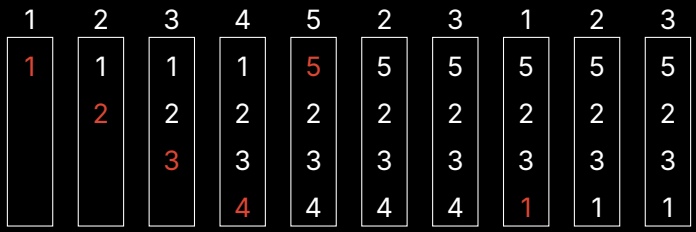
1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



Clock Example

Assume our physical memory can only hold 4 pages, and we access the following:

1 2 3 4 5 2 3 1 2 3 (all of the pages are initially on disk)



6 page faults

For Performance You May Choose to Disable Swapping

Memory is cheap, and has quite high capacity
- You'd rather know you need more memory than run slowly
  - Linux runs an OOM (out of memory) killer, that SIGKILLs the memory hog

Larger page sizes allow for speedups (2 MiB or 1 GiB page size)
- Trade more fragmentation for more TLB coverage

The Clock Algorithm is an Approximation of LRU

Data structures:

- Keeps a circular list of pages in memory
- Uses a reference bit for each page in memory (light grey in next slides)
- Has a “hand” (iterator) pointing to the last element examined

Algorithm, to insert a new page:

- Check the hand’s reference bit, if it’s 0 then place the page and advance hand
- If the reference bit is 1, set it to 0, advance the hand, and repeat

For page accesses, set the reference bit to 1