CS660: Intro to Database Systems

Class 6: The Storage Layer

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https://bu-disc.github.io/CS660/

The Storage Layer

DBMS layers and storage hierarchy

Readings: Chapter 9.1

Disks

Flash disks

Buffer Management

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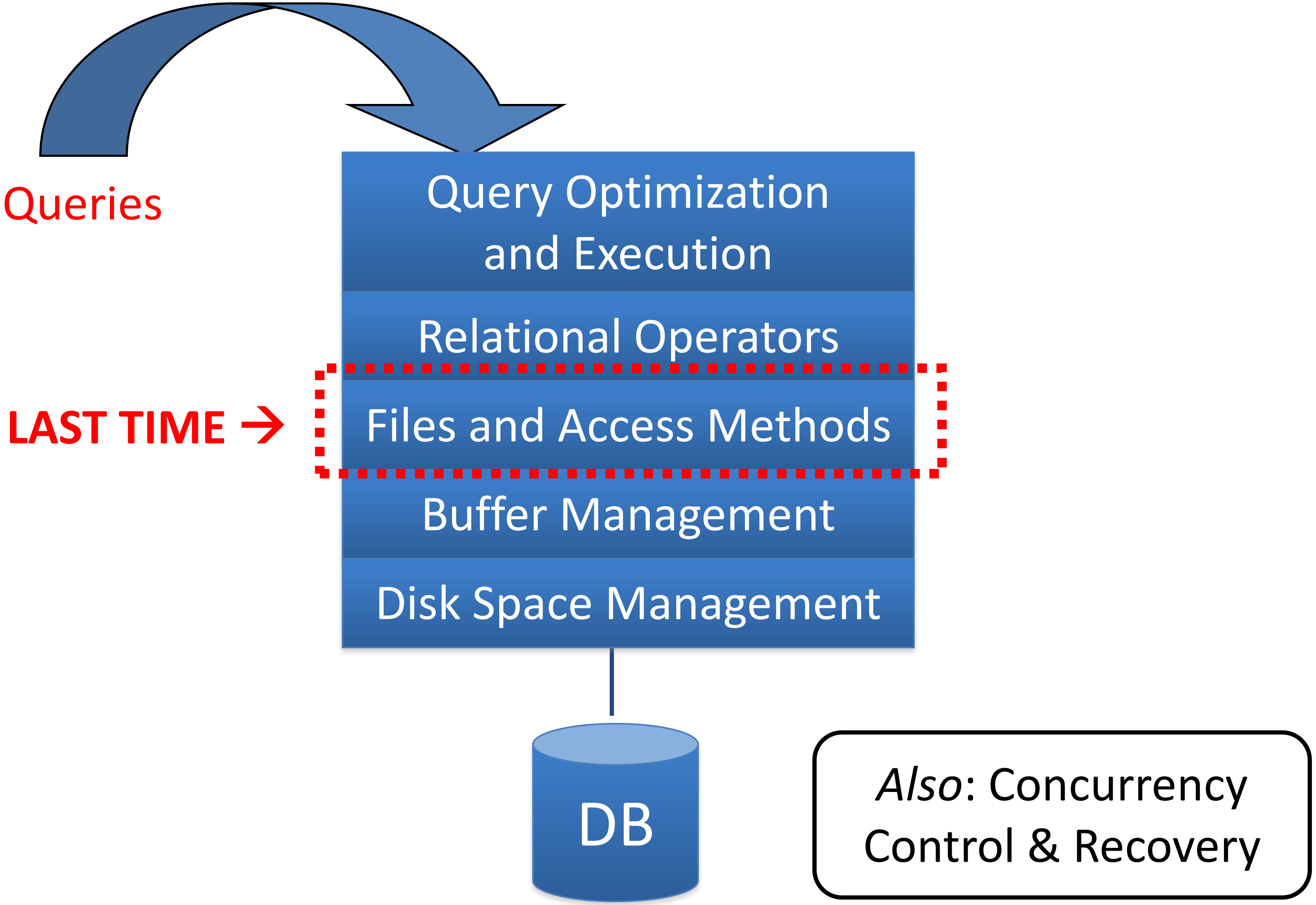
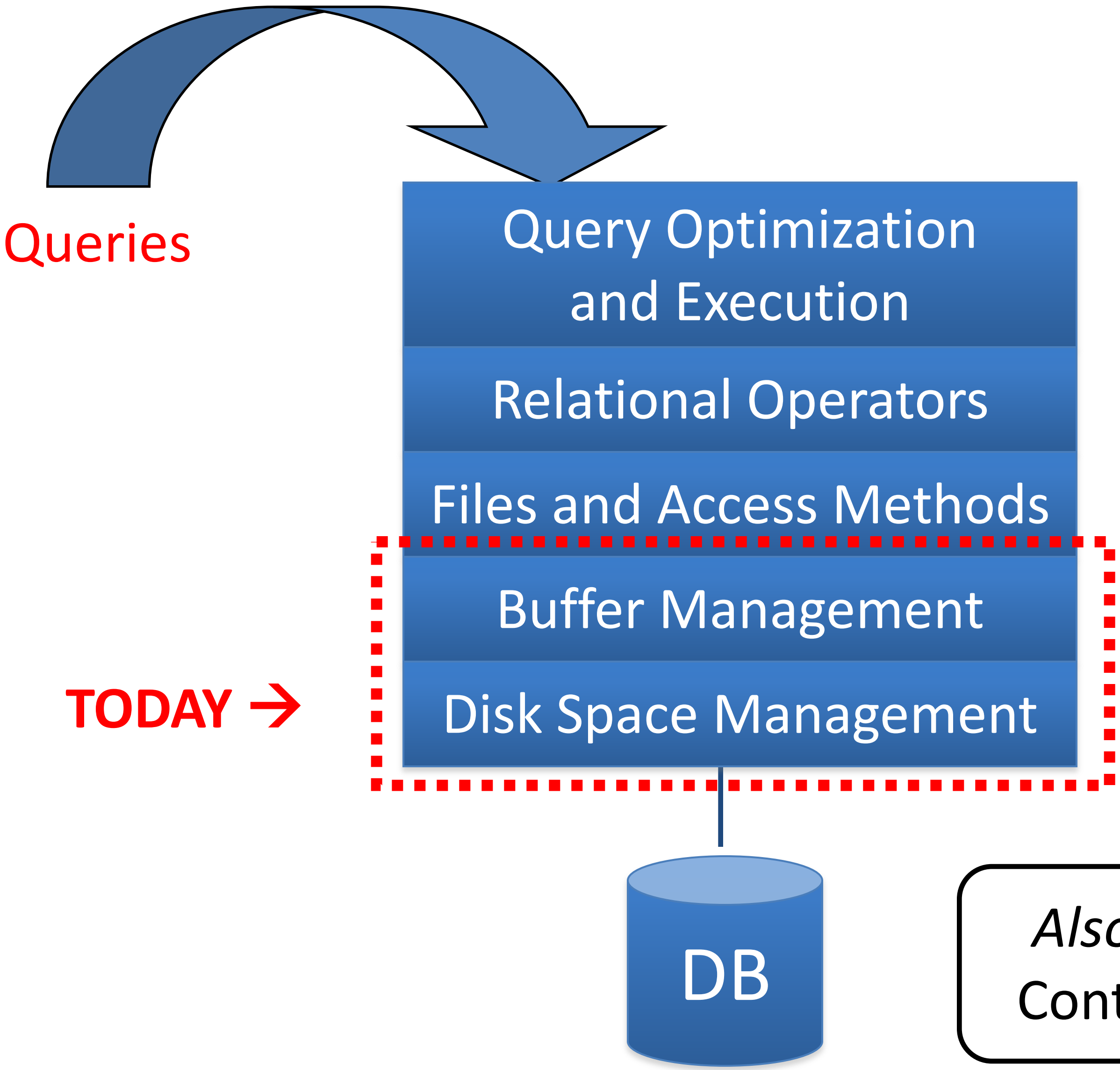
DBMS Layer-Cake

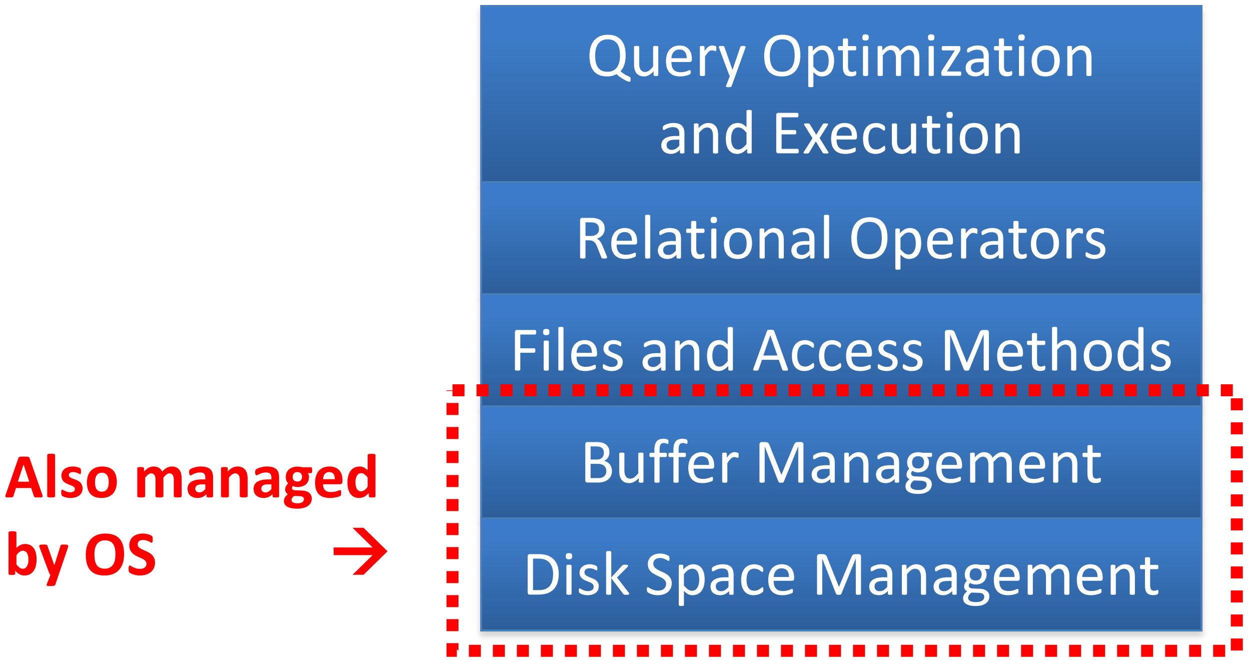


DBMS Layer-Cake



Also: Concurrency Control & Recovery

DBMS Layer-Cake



Why not OS?

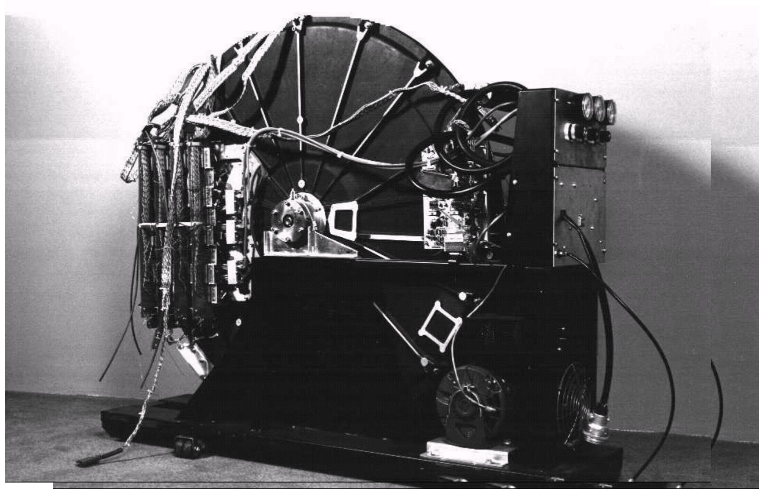
Layers of abstraction are good … but:

- Unfortunately, OS often gets in the way of DBMS

DBMS needs to do things “its own way”

- Specialized prefetching
- Control over buffer replacement policy
  - LRU not always best (sometimes worst!!)
- Control over thread/process scheduling
  - “Convoy problem” arises when OS scheduling conflicts with DBMS locking
- Control over flushing data to disk
  - WAL protocol requires flushing log entries to disk

Disks and Files

DBMS stores information  on disks.

In an electronic world, disks
are a mechanical anachronism!

This has major implications for DBMS design!

READ: transfer data from disk to main memory (RAM).

WRITE: transfer data from RAM to disk.

Both are high-cost operations, relative to
in-memory operations, so must be planned carefully!

Why Not Store It All in Main Memory?

Costs too high

High-end Databases today in the Petabyte range.

~ 60% of the cost of a production system is in the disks.

Main memory is volatile

We want data to be saved between runs. (Obviously!)

But, main-memory database systems do exist!

Smaller size, performance optimized

Volatility is ok for some applications

What about Flash?

Flash chips used for >20 years

Flash evolved

- USB keys
- Storage in mobile devices
- Consumer and enterprise flash disks (SSD)

Flash in a DBMS

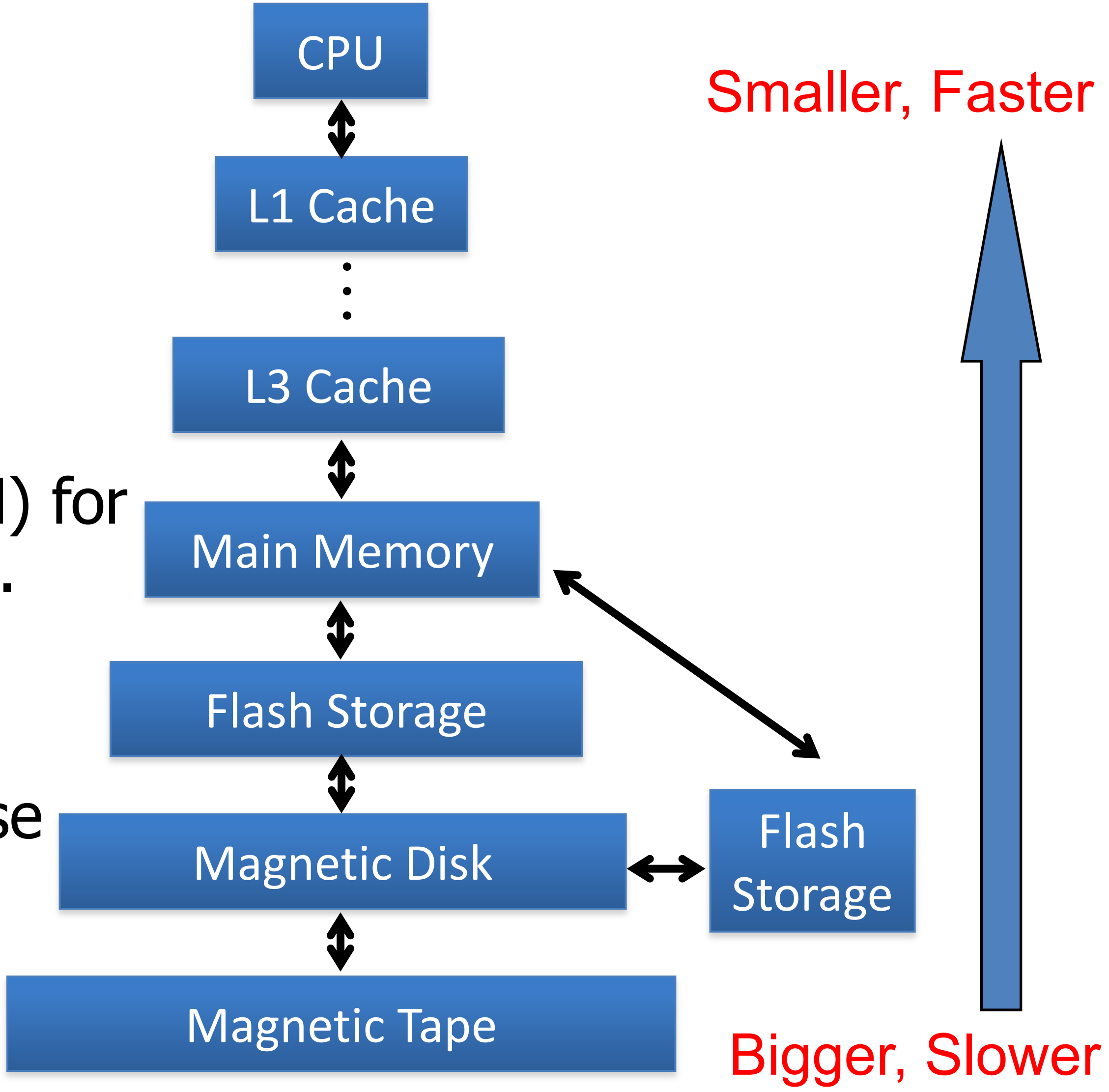
- Main storage
- Accelerator/enabler (Specialized cache, logging device)

The Storage Hierarchy

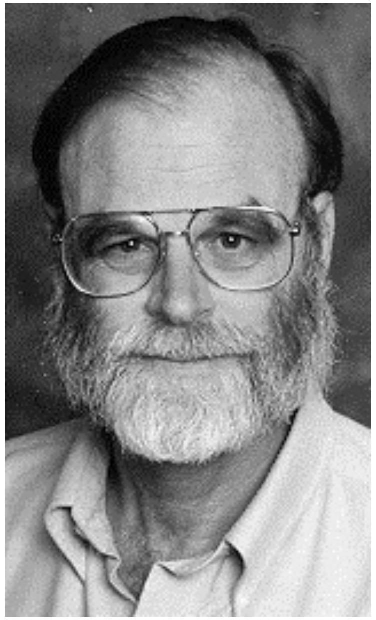
Main memory (RAM) for currently used data.

Disk for the main database (secondary storage).

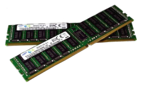
Tapes for archival storage (tertiary storage).



memory hierarchy (by Jim Gray)

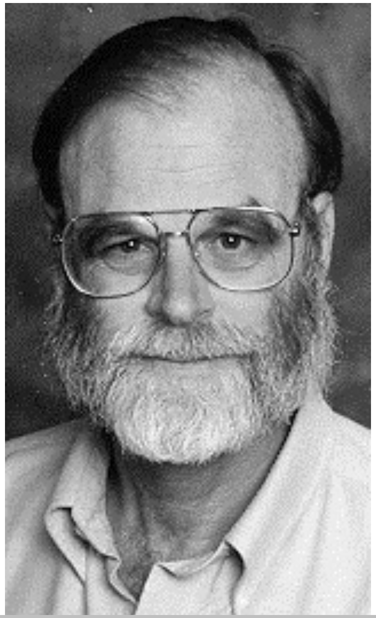


	registers/CPU	my head ~0
2x	**on chip cache**	this room 1min
10x	**on board cache**	this building 10min
100x	**memory**	Washington, DC 5 hours
10^6x	**disk**	Pluto 2 years
10^9x	**tape**	Andromeda 2000 years



Jim Gray, IBM, Tandem, Microsoft, DEC
“The Fourth Paradigm” is based on his vision
ACM Turing Award 1998
ACM SIGMOD Edgar F. Codd Innovations award 1993

memory hierarchy (by Jim Gray)



	registers/CPU	my head ~0
2x	**on chip cache**	this room 1min
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tape?

sequential-only magnetic storage

still a multi-billion industry

The Storage Layer

DBMS layers and storage hierarchy

Disks

Readings: Chapter 9.1, 9.2, HDD paper

Flash disks

Buffer Management

Disks

Secondary storage device of choice.

Main advantage over tapes: *random access* vs. *sequential*.

Data is stored and retrieved in units called *disk blocks* or *pages.*

Unlike RAM, time to retrieve a disk page varies depending upon location on disk.

- Therefore, relative placement of pages on disk has major impact on DBMS performance!

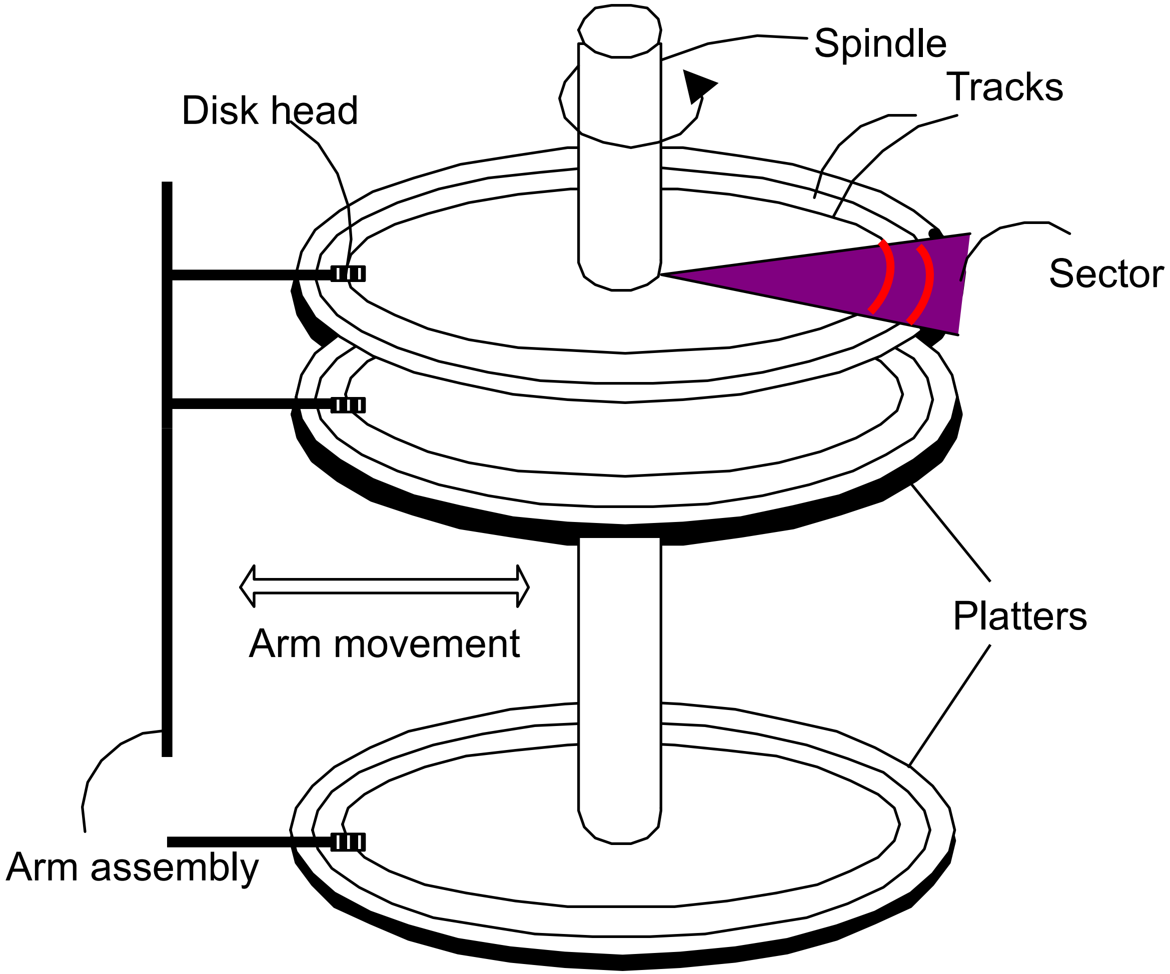
Anatomy of a Disk

The platters spin (5-15 kRPM).

The arm assembly is moved in or out to position a head on a desired track. Tracks under heads make a *cylinder* (imaginary!).

Only one head reads/writes at any one time.

- *Block size* is a multiple of *sector size* (which is fixed).
- Newer disks have several "zones", with more data on outer tracks.



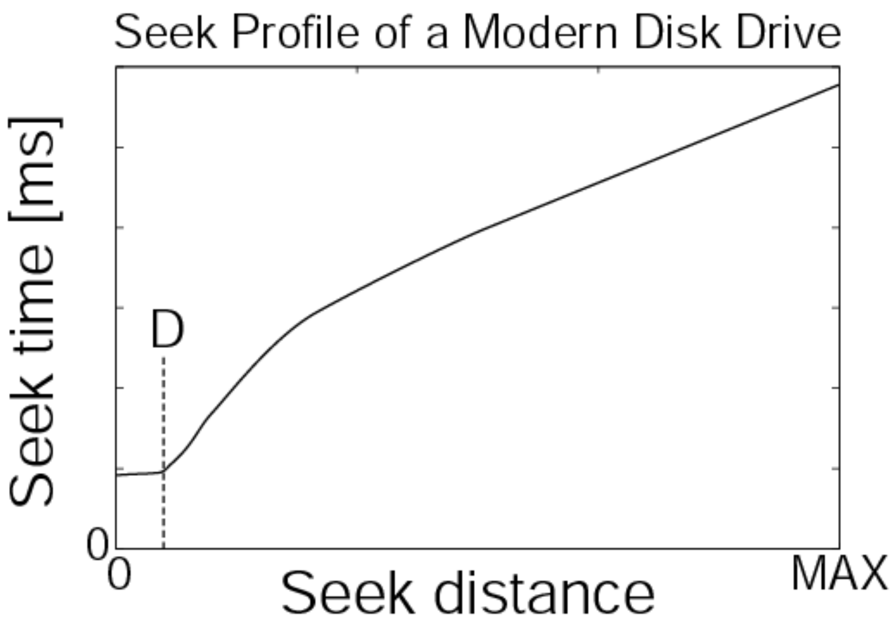
Accessing a Disk Page

Time to access (read/write) a disk block:

- *seek time* (moving arms to position disk head on track)
- *rotational delay* (waiting for block to rotate under head)
- *transfer time* (actually moving data to/from disk surface)

Seeking in modern disks

Seek time discontinuity

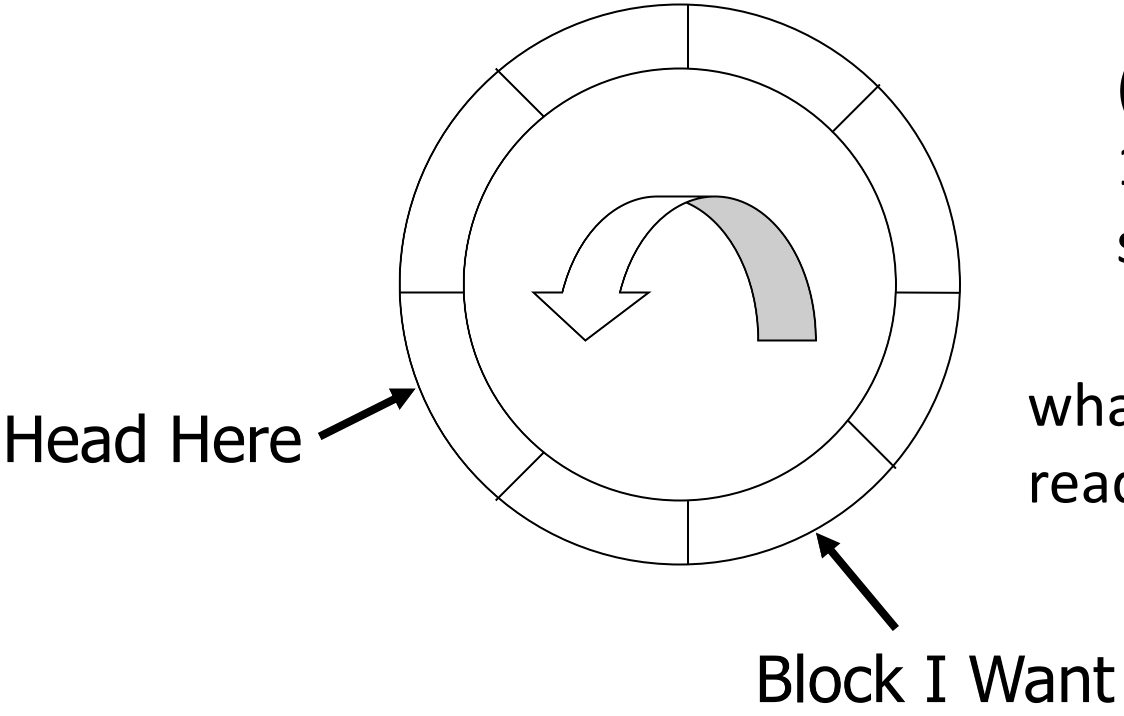


Short seeks are dominated by “settle time”

- Move to one of many nearby tracks within settle time
- D is on the order of tens to hundreds
- D gets larger with increase of disk track density

Rotational Delay

if the disk rotates with 10 KRPM, and I want to read
2/3 of the track away what is the rotational delay?



$(1/10000)*60sec =$
$10^{-4} * 60 = 6 *10^{-3} = 6ms$
so, $2/3 * 6ms = 4ms$

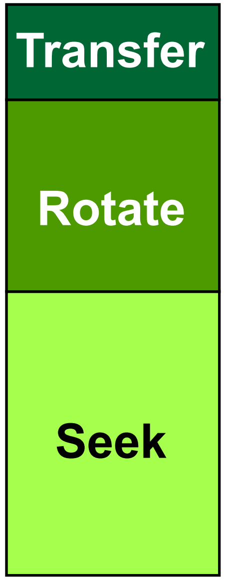
what if I am randomly
reading 4KB pages with this delay?

4KB/4ms = 1MB/s

Seek time & rotational delay dominate

- Seek time varies from about 1 to 20 ms
- Rotational delay varies from 0 to 10 ms
- Transfer rate is < 1ms per 4KB page

Key to lower I/O cost:
reduce seek/rotation delays!



Also note: For shared disks most time spent waiting in queue for access to arm/controller

Arranging Pages on Disk

"Next" block concept:

- blocks on same track, followed by
- blocks on same cylinder, followed by
- blocks on adjacent cylinder

Blocks in a file should be arranged sequentially on disk (by "next"), to minimize seek and rotational delay.

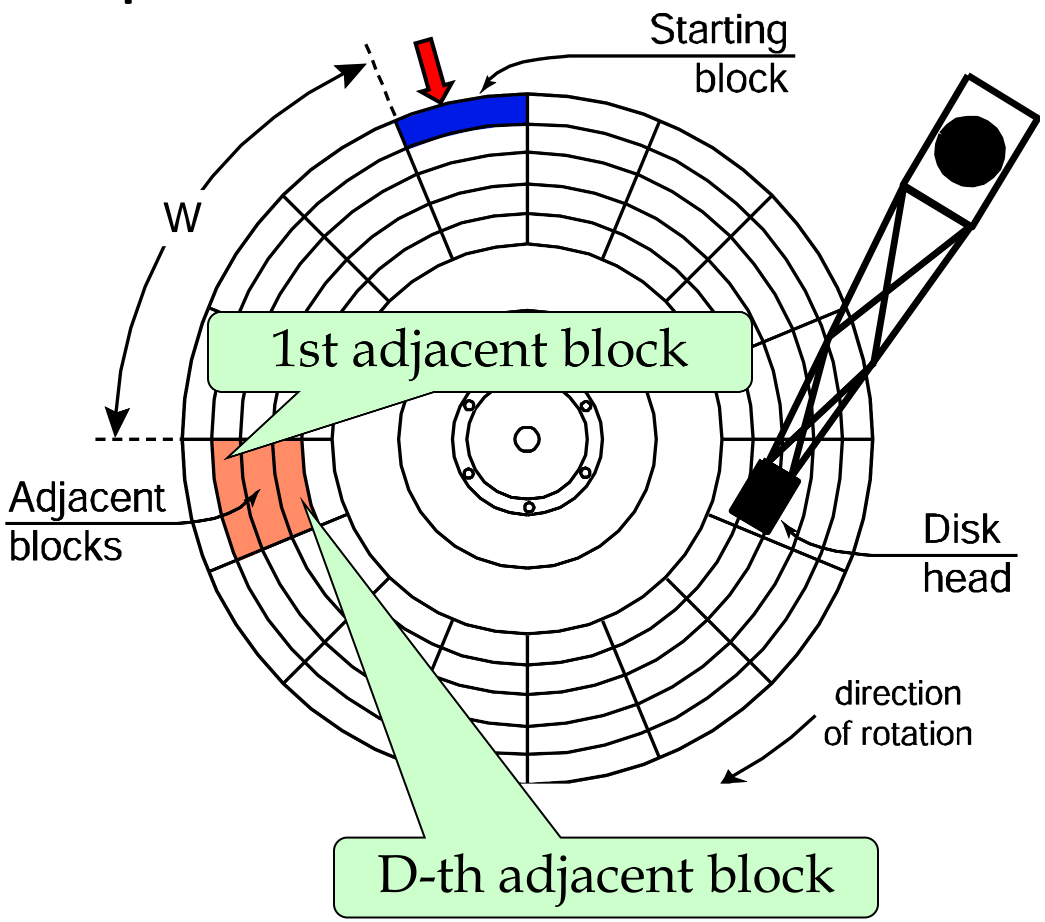
An important optimization: <u>pre-fetching</u>

- See R&G page 323

Define adjacent blocks

Access incurs settle time only

Equidistant wrt access time from starting block



D: # of adjacent blocks

W: degree disk will rotate during settle time

Disk block has more than one neighbor

Rules of thumb…

1. Memory access much faster than disk I/O (~ 1000x)

2. "Sequential" I/O faster than "random" I/O (~ 10x)

Disk Space Management

Lowest layer of DBMS software manages space on disk

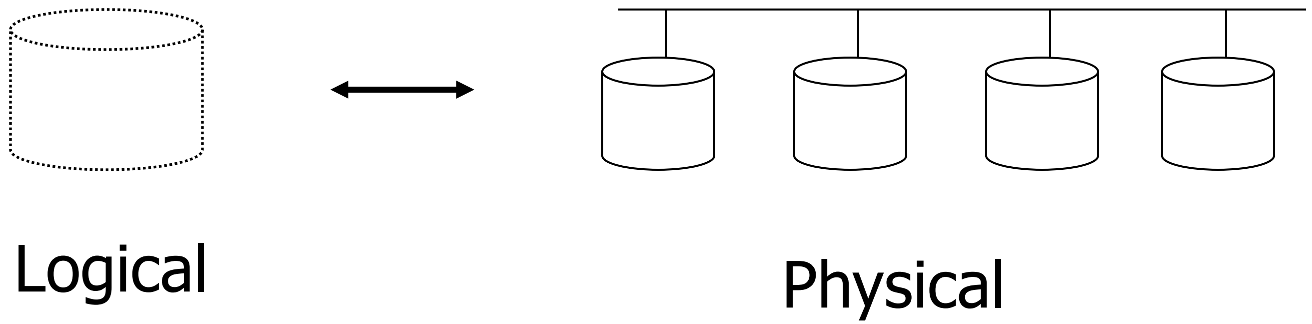
Higher levels call upon this layer to:

- allocate/de-allocate a page
- read/write a page

Best if a **request for a *sequence* of pages** is satisfied by **pages stored sequentially on disk**!

Higher levels **don't need to know** if/how this is done, or how free space is managed.

Disk Arrays: RAID



Benefits:

- Higher throughput (via data "striping")
- Longer MTTF (via redundancy)

The Storage Layer

DBMS layers and storage hierarchy

Disks

Flash disks

SSD paper

Buffer Management

Flash disks

Secondary storage *or* caching layer.

Main advantage over disks:

random reads as fast as *sequential* reads

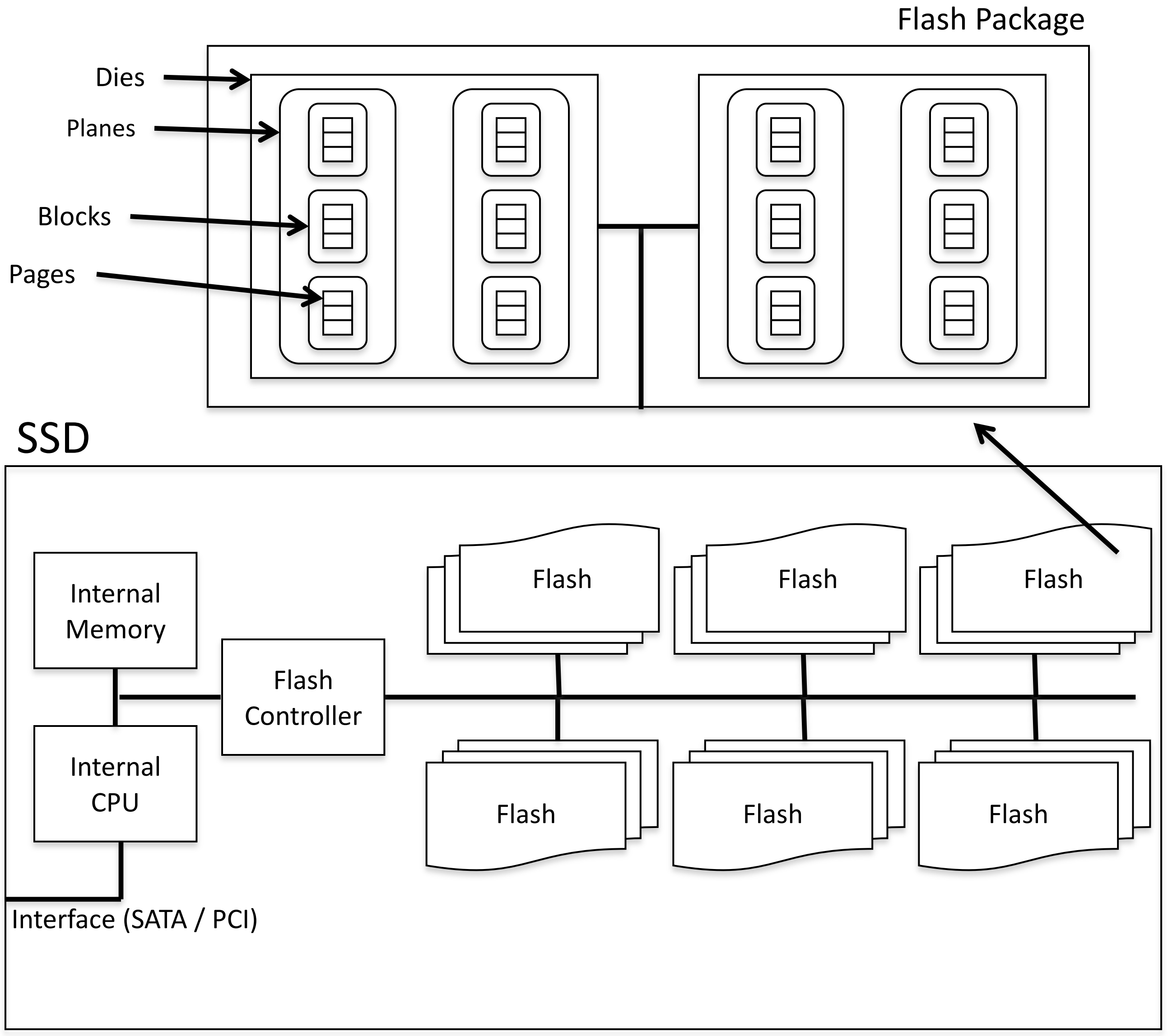
BUT: slow random writes (slower than reads)

pages (like disks) and pages organized in *flash blocks*

unlike HDD, like RAM:

time to retrieve a page is not related to location on flash disk.

The internals of flash disks



Interconnected flash chips

No mechanical limitations

Maintain the block API – compatible with disks layout

Internal parallelism in read/write

Complex software driver

Accessing a flash page

Access time depends on

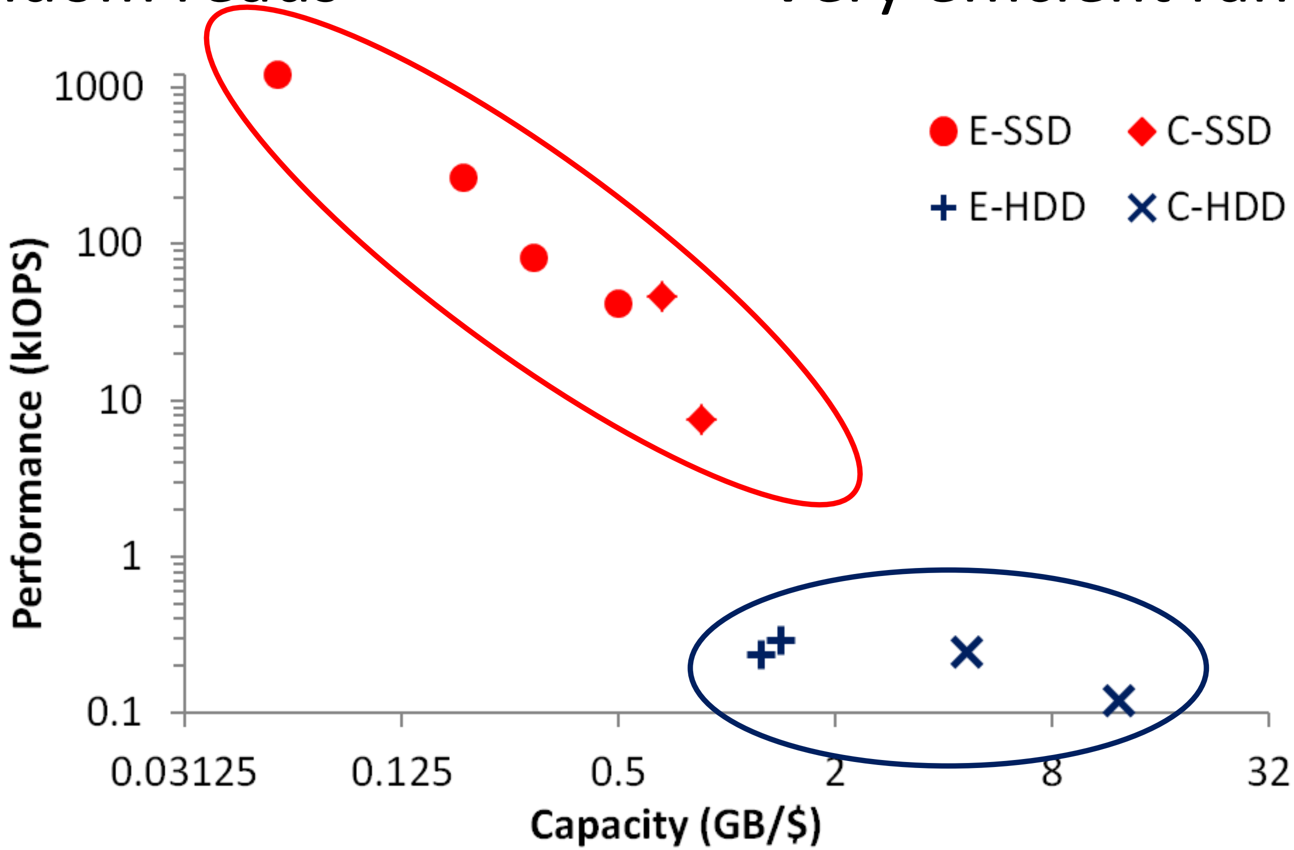
- Device organization (internal parallelism)
- Software efficiency (driver)
- Bandwidth of flash packages (bus speed)

Flash Translation Layer (FTL)

- Complex device driver (firmware)
- Tunes performance and device lifetime

Flash disks vs HDD

HDD	Flash disks
✓ Large – inexpensive capacity	x Small – expensive capacity
x Inefficient random reads	✓ Very efficient random reads



The Storage Layer

DBMS layers and storage hierarchy

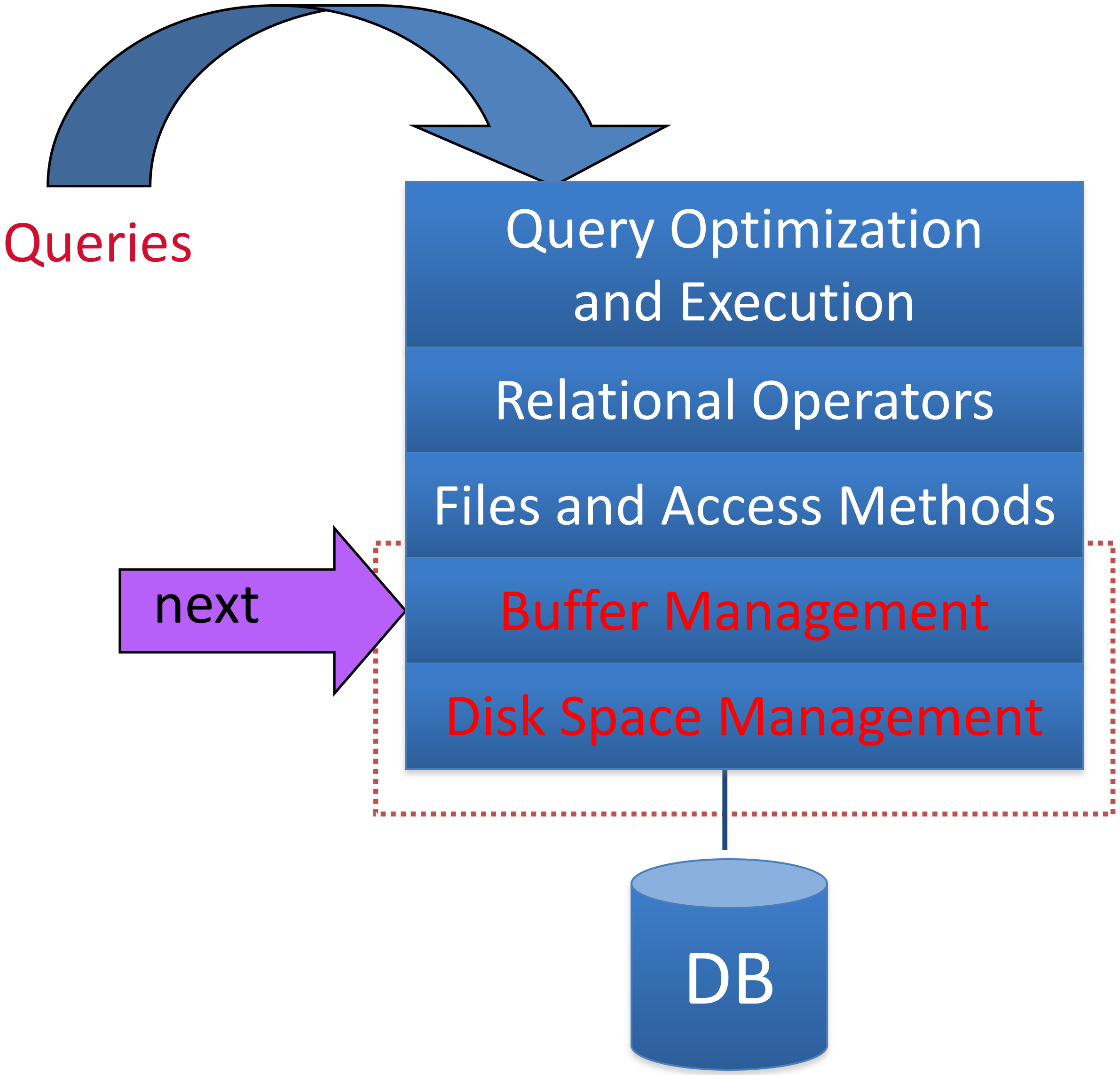
Disks

Flash disks

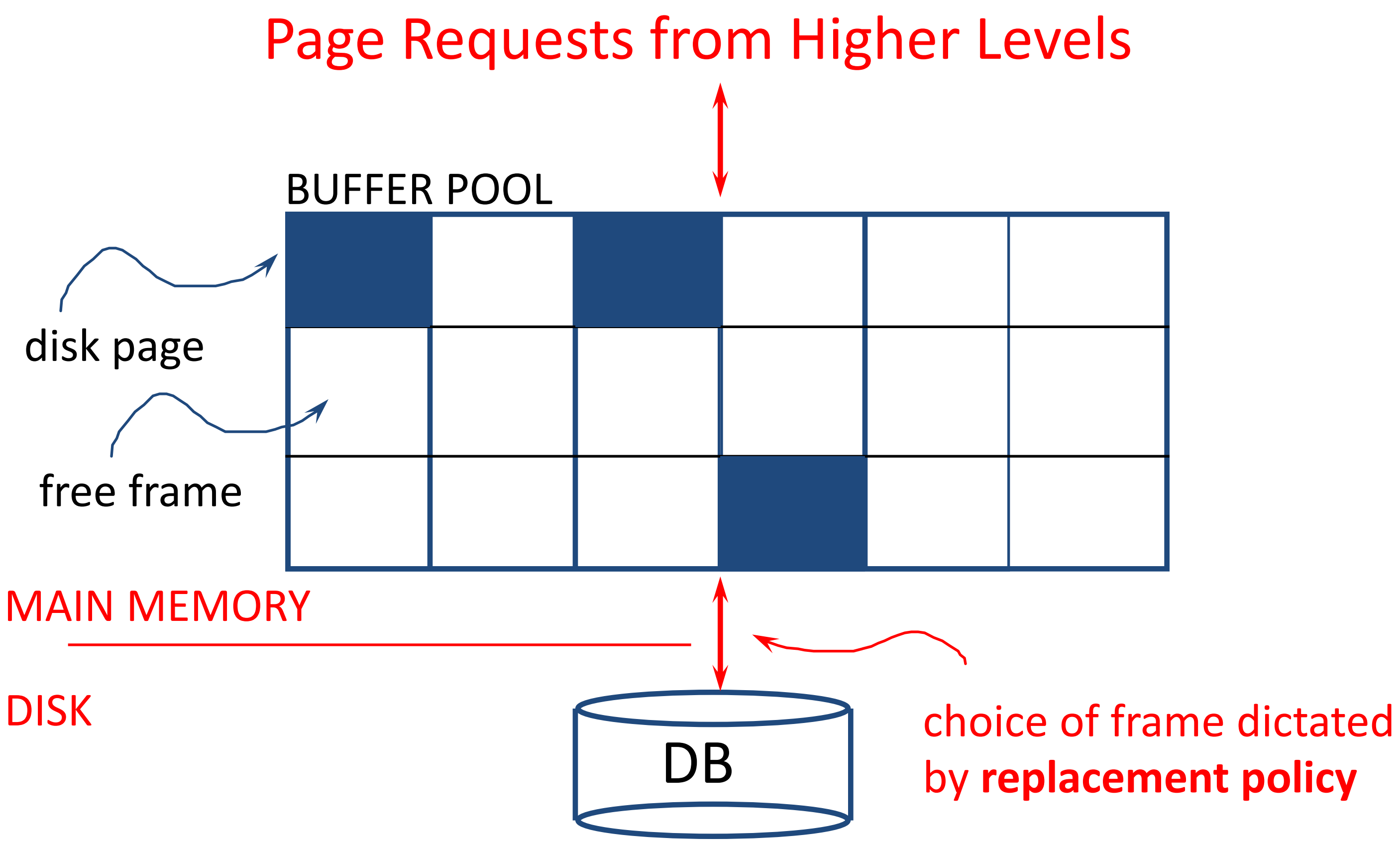
Buffer Management

Readings: Chapter 9.3, 9.4

Recall the BIG Picture



Buffer Management in a DBMS



Data must be in RAM for DBMS to operate on it!

Buffer Manager hides the fact that not all data is in RAM

(just like hardware cache policies hide the fact that not all data is in the caches)

When a Page is Requested ...

Buffer pool information table contains:

<frame#, pageid, pin_count, dirty>

has the page been updated

how many queries *still* need the page

If requested page is not in pool & buffer pool is full:

- Choose a frame for *replacement (only un-pinned pages are candidates)*
- If frame is "dirty", write it to disk
- Read requested page into chosen frame

Pin the page and return its address.

☛ *If requests can be predicted (e.g., sequential scans)*

pages can be pre-fetched several pages at a time!

More on Buffer Management

The page **requestor** (e.g., query, transaction) must **unpin** it, and indicate whether page has been **modified**:

- *dirty* bit is used for this.

Page in pool may be requested **many** times,

- a *pin count* is used. A page is a candidate for replacement iff *pin count* = 0 ("unpinned")

Note: CC & recovery may entail additional I/O when a frame is chosen for replacement. (*Write-Ahead Log* protocol; more later.)

Buffer Replacement Policy

Frame is chosen for replacement by a *replacement policy:*

- Least-recently-used (LRU), MRU, Clock, etc.

Policy can have big impact on # of I/O's;

depends on the *access pattern*.

LRU Replacement Policy

Least Recently Used (LRU)

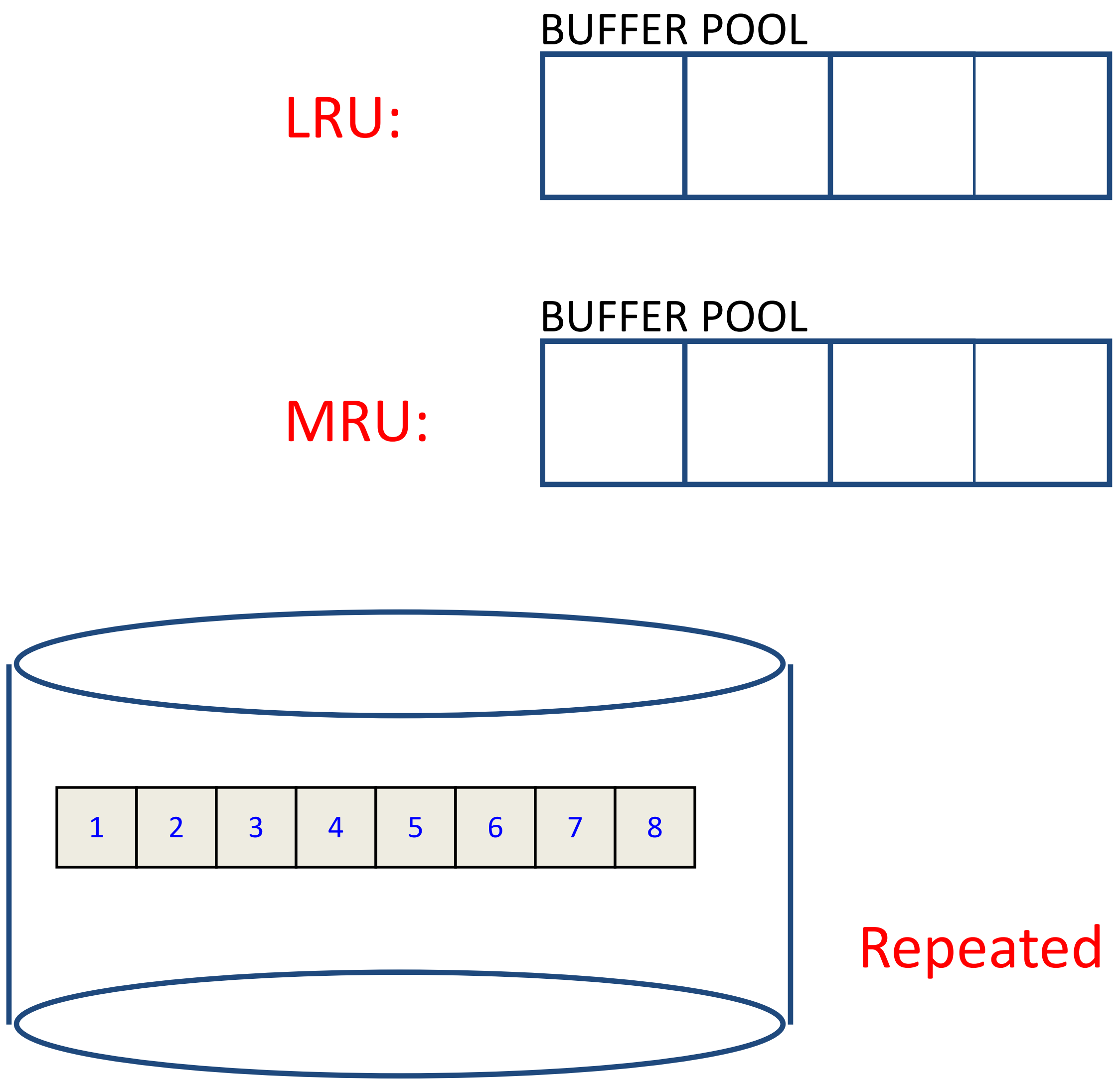
- for each page in buffer pool, keep track of time last *unpinned*
- replace the frame which has the oldest (earliest) time
- very common policy: intuitive and simple

Problems?

Problem: Sequential flooding

- LRU + repeated sequential scans.
- # buffer frames < # pages in file means each page request causes an I/O. *MRU* much better in this situation (but not in all situations, of course).

Sequential Flooding – Illustration



Repeated scan of file …

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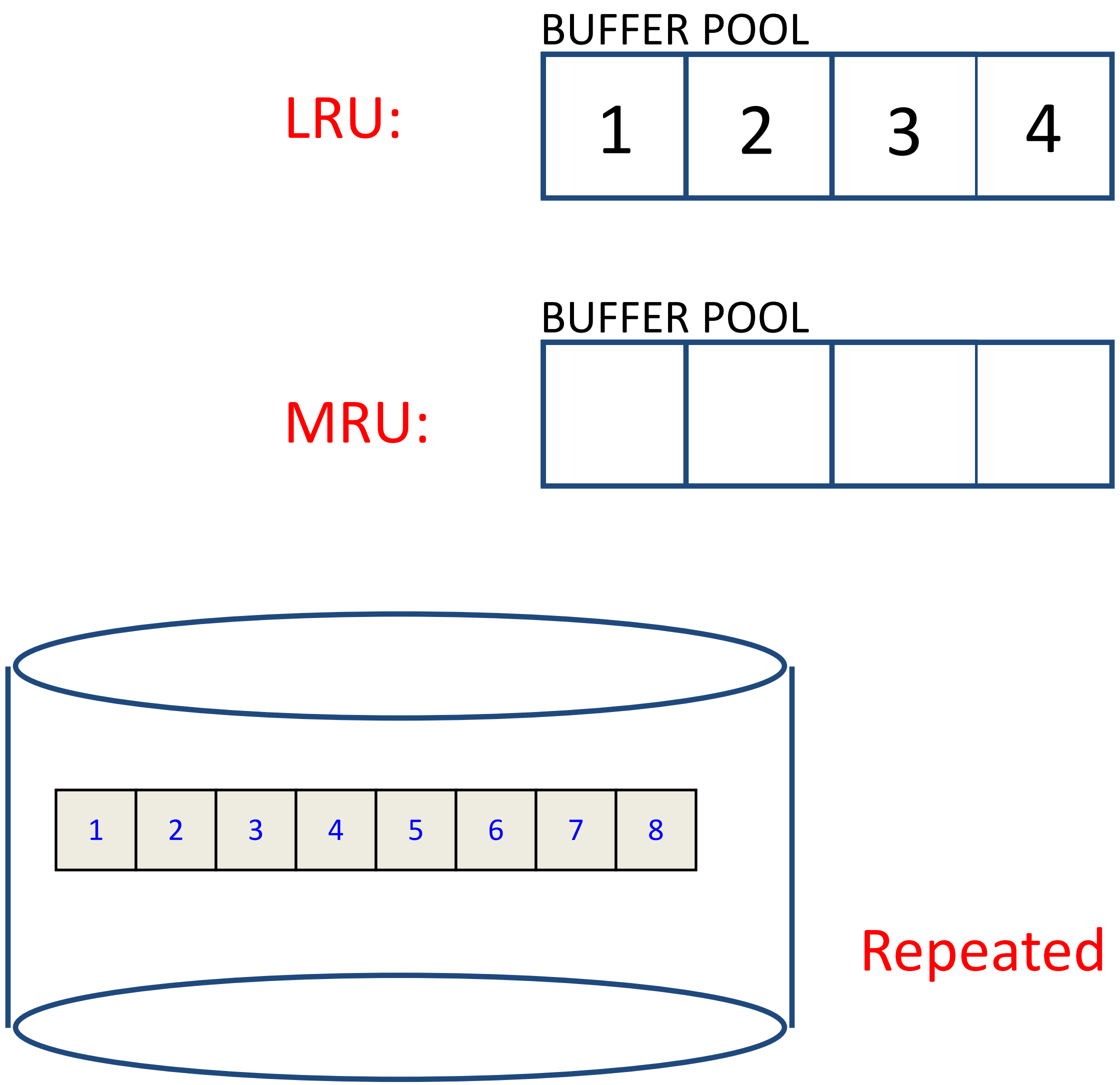

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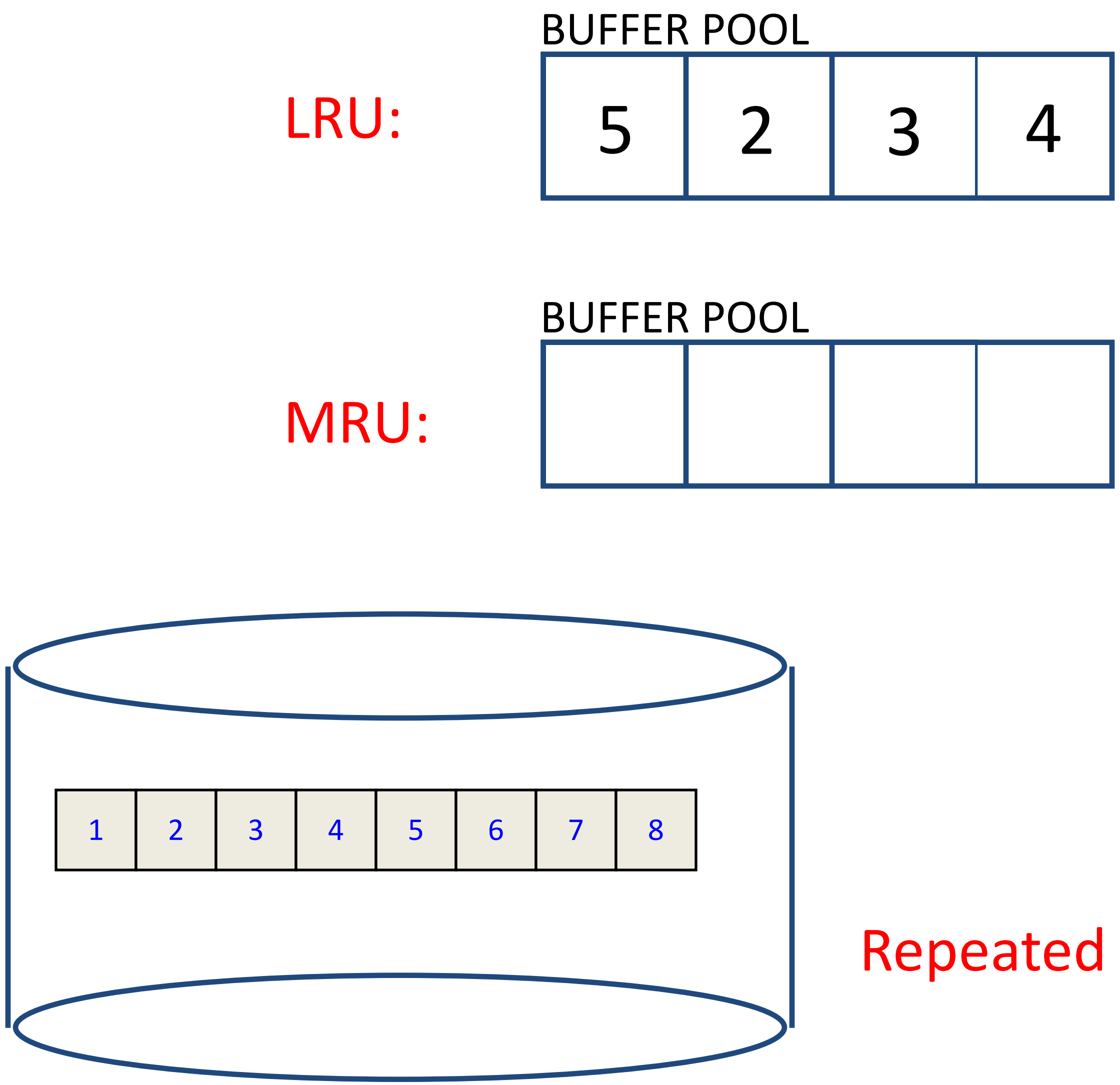

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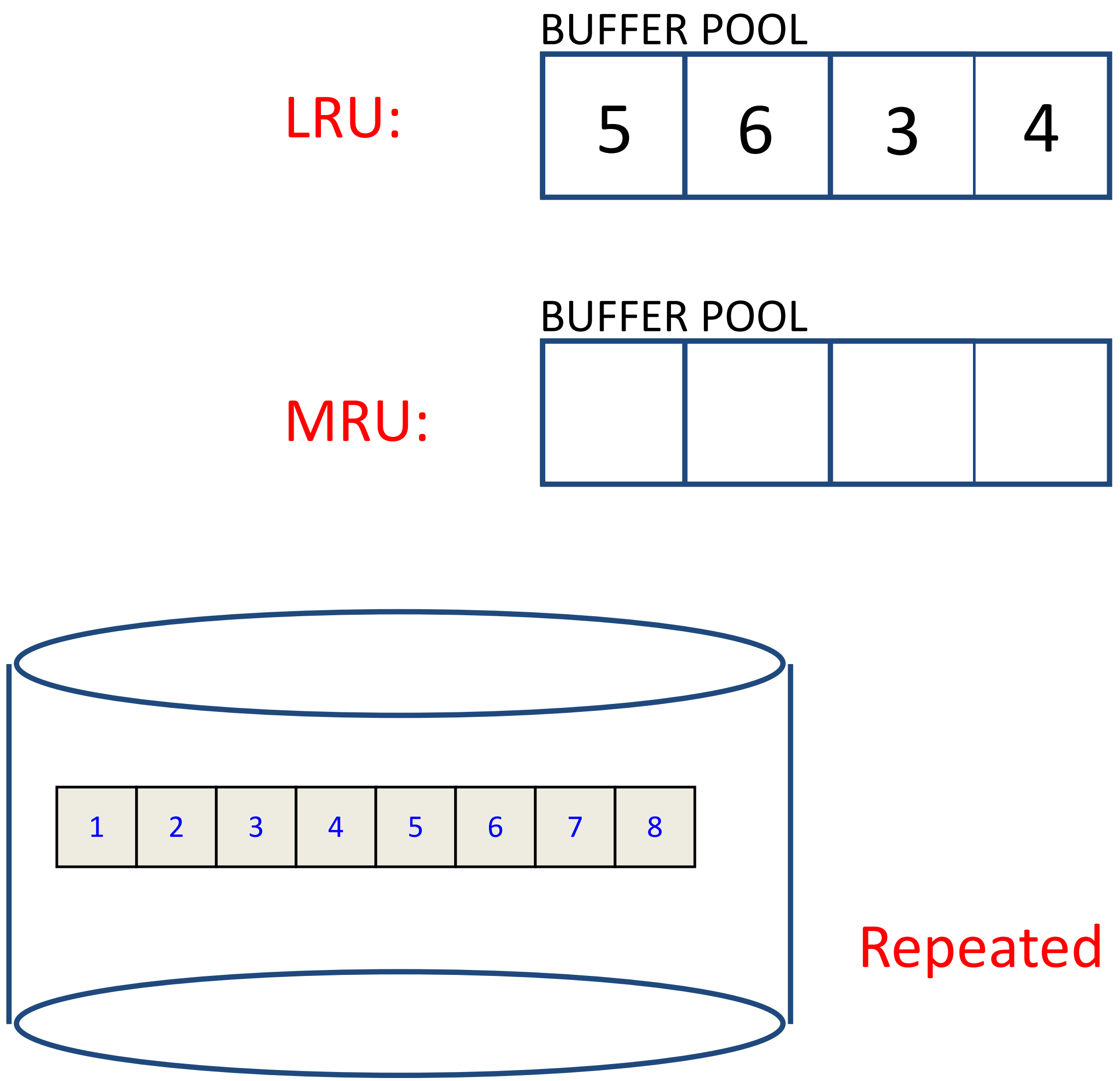

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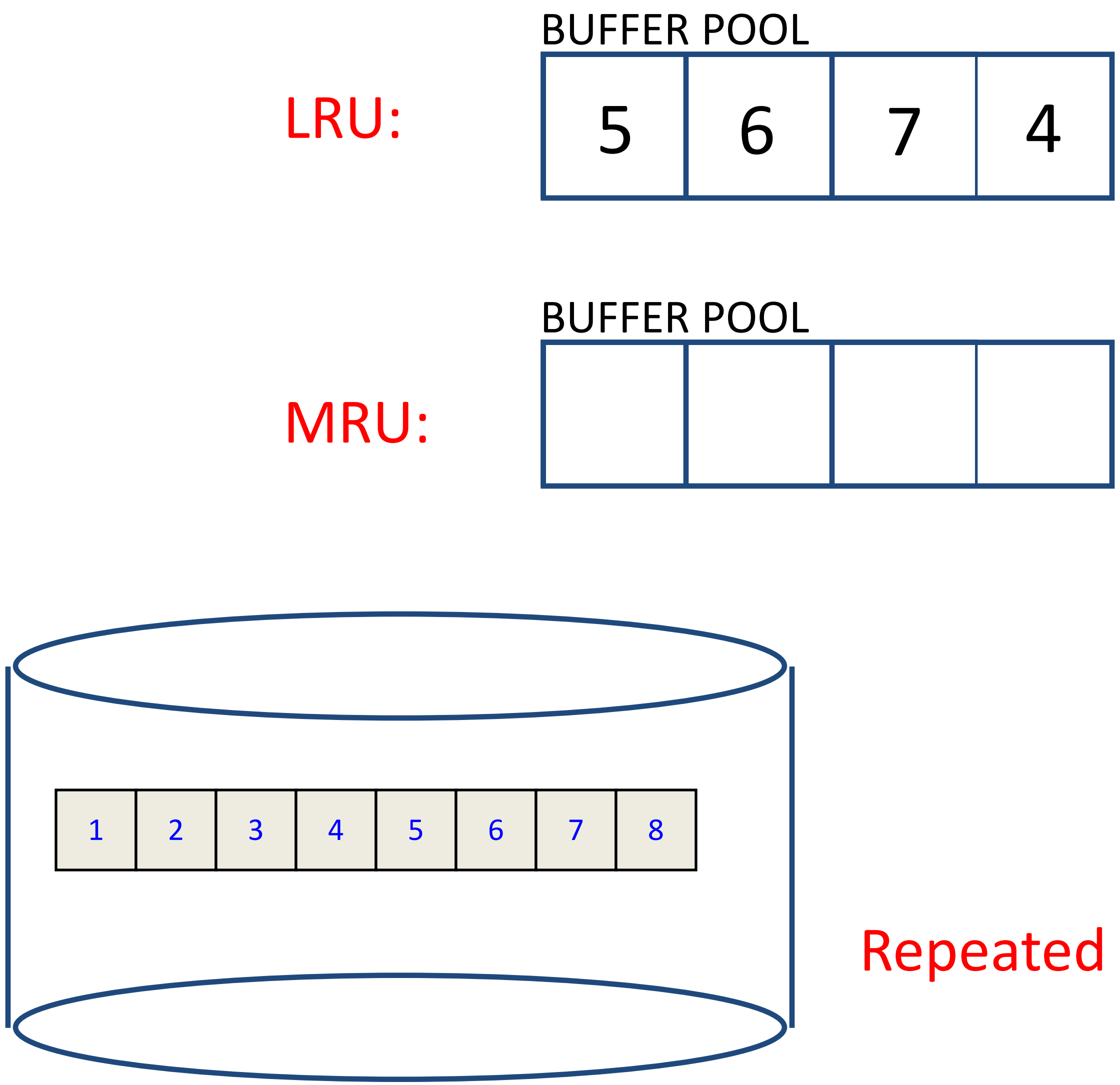

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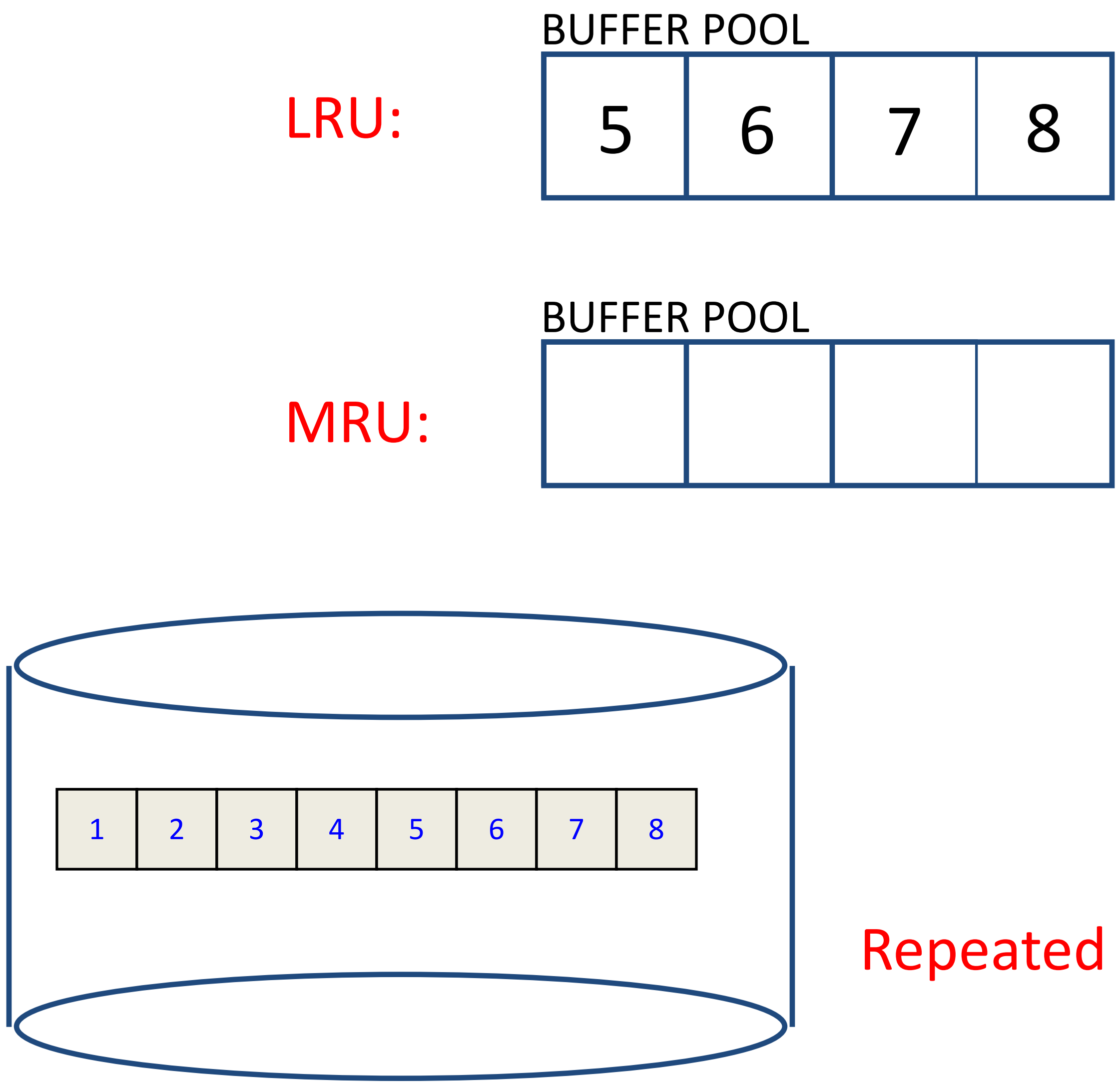

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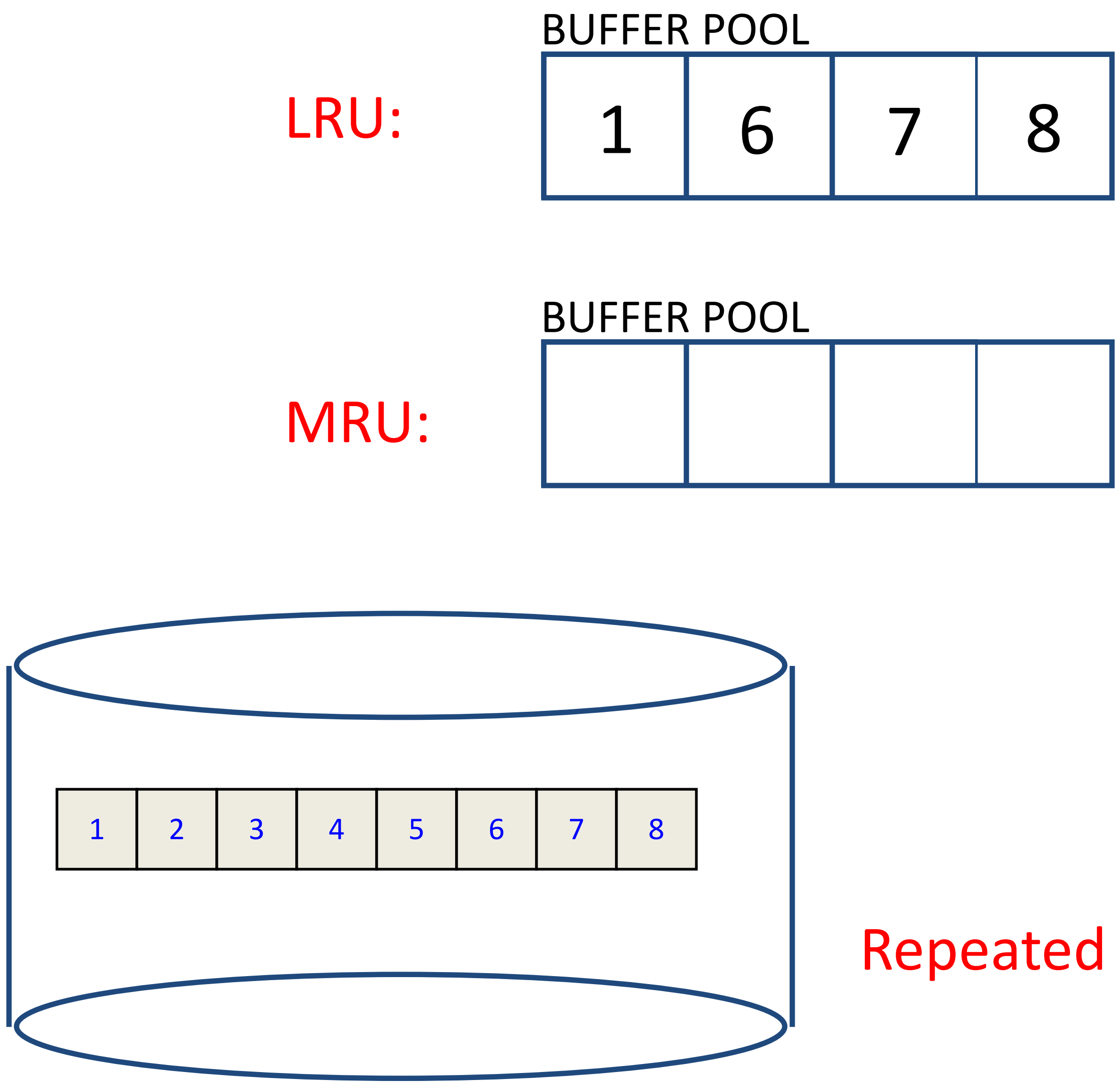

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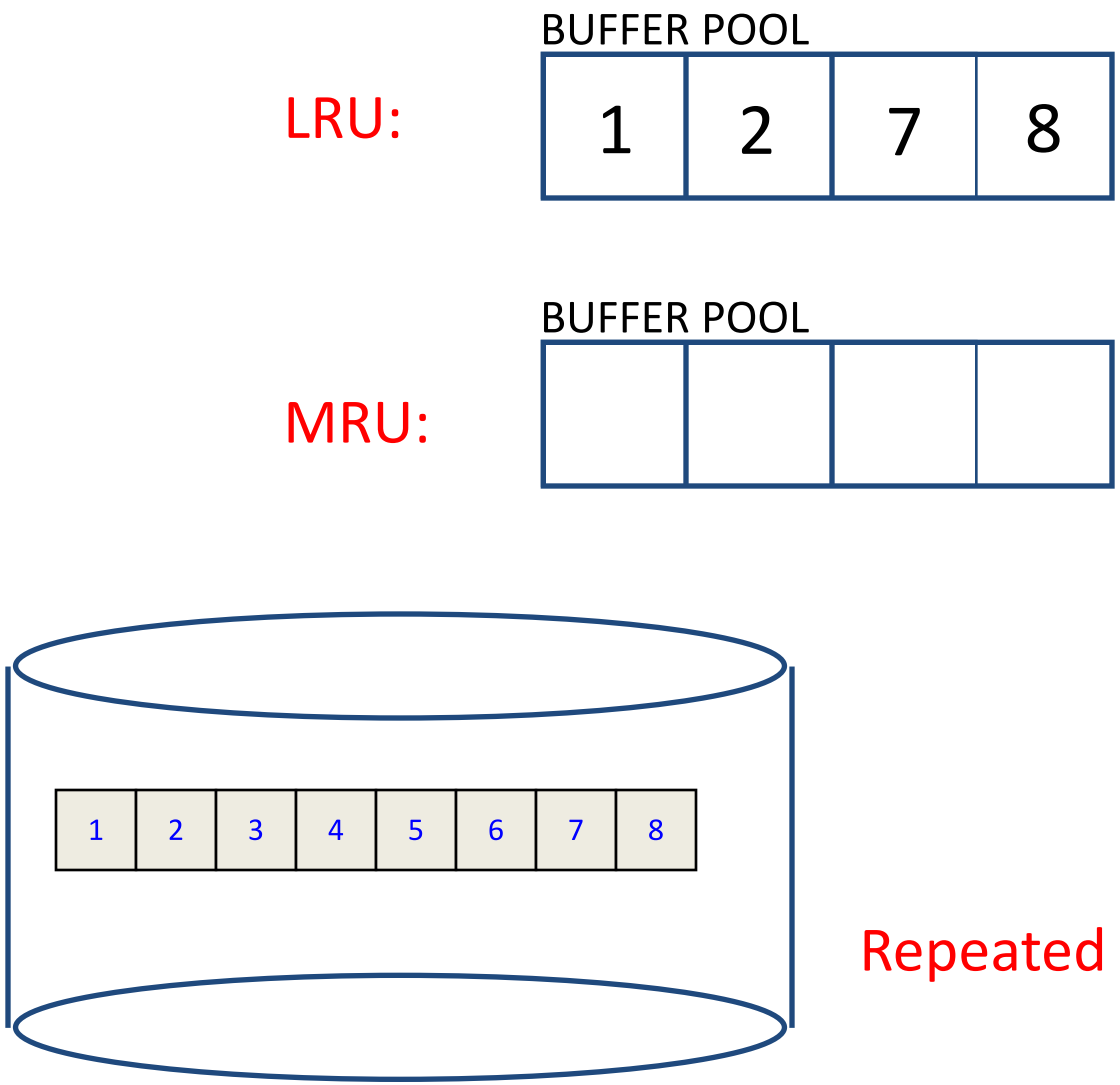

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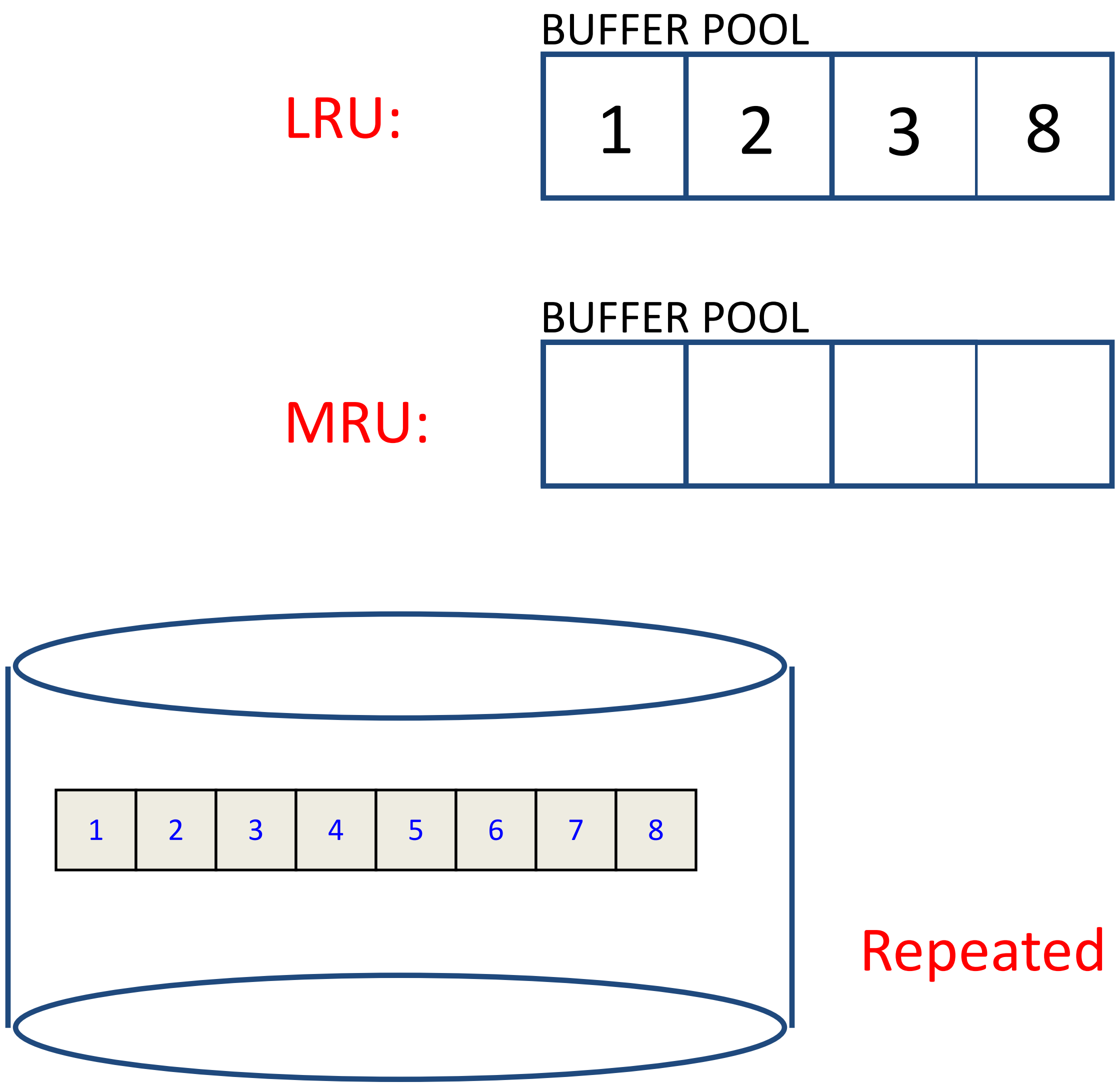

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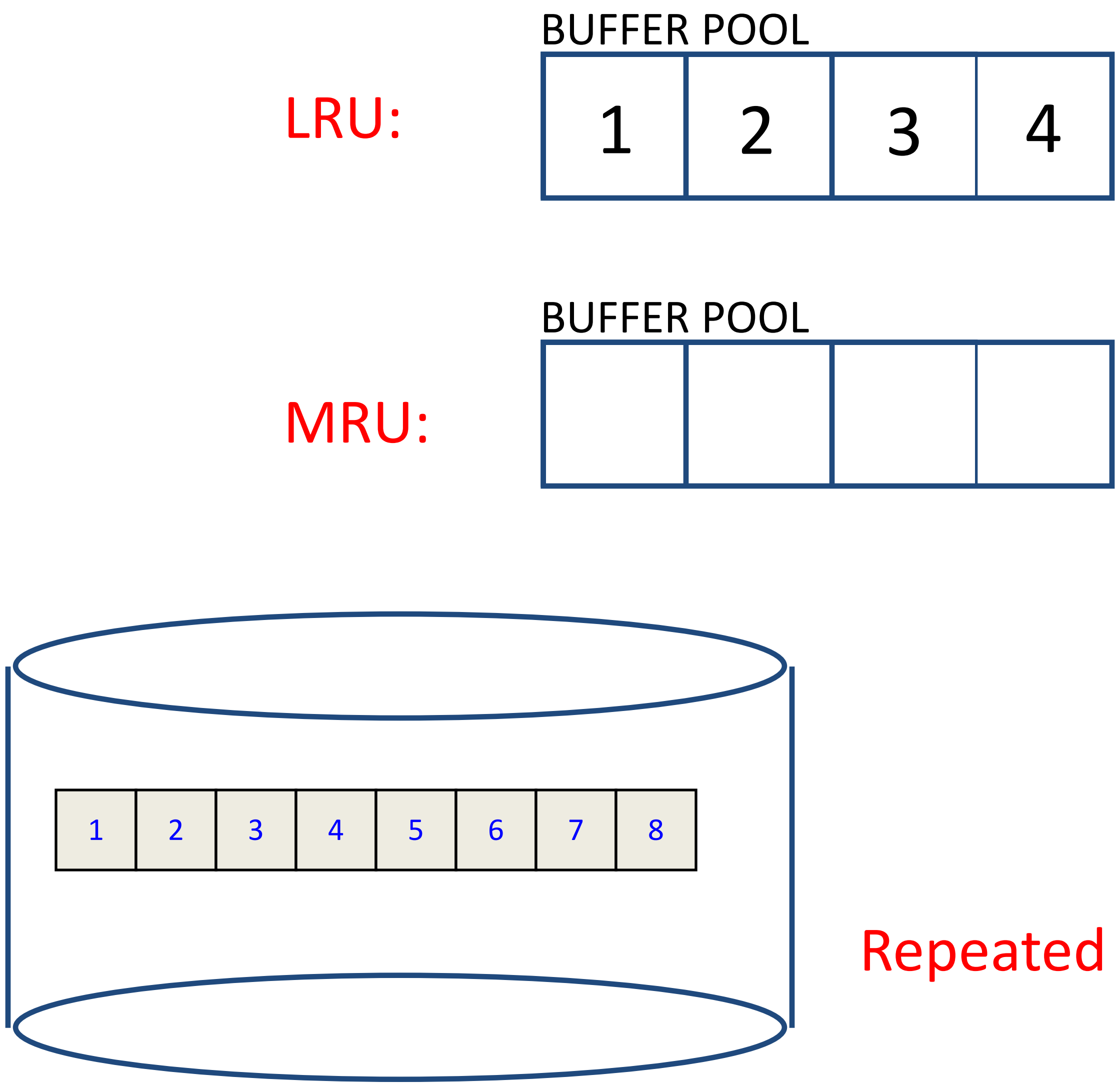

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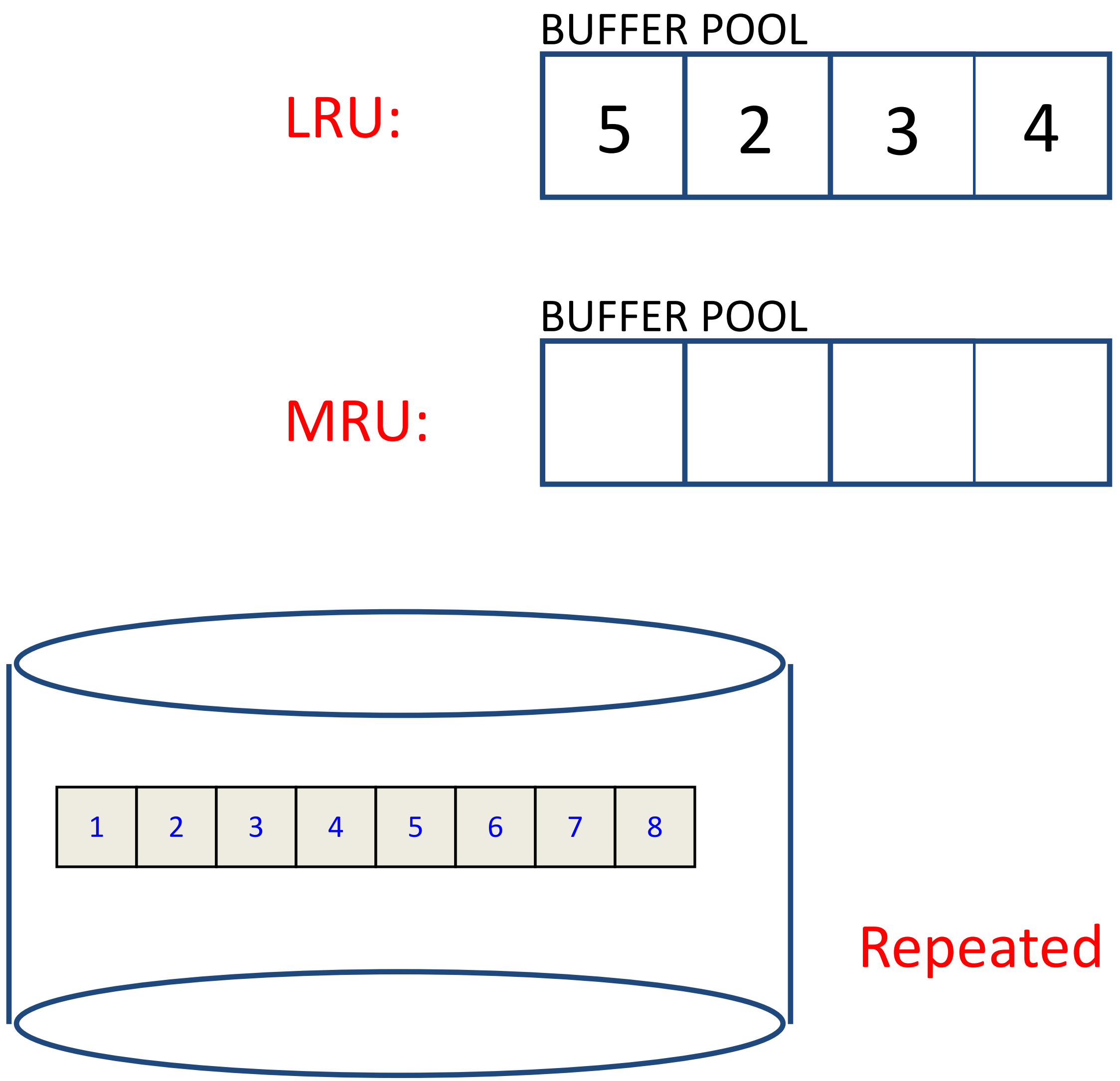

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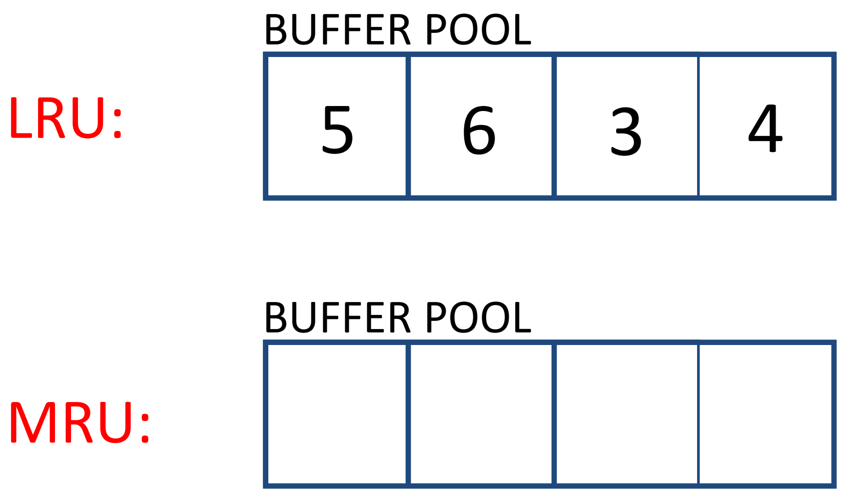

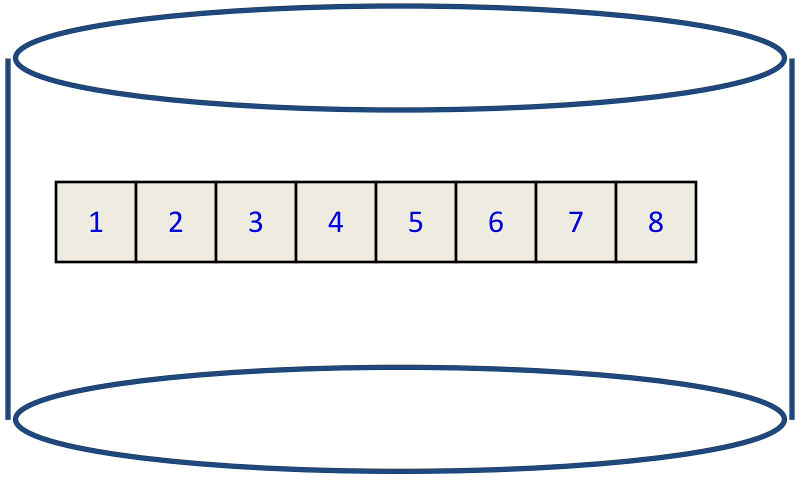

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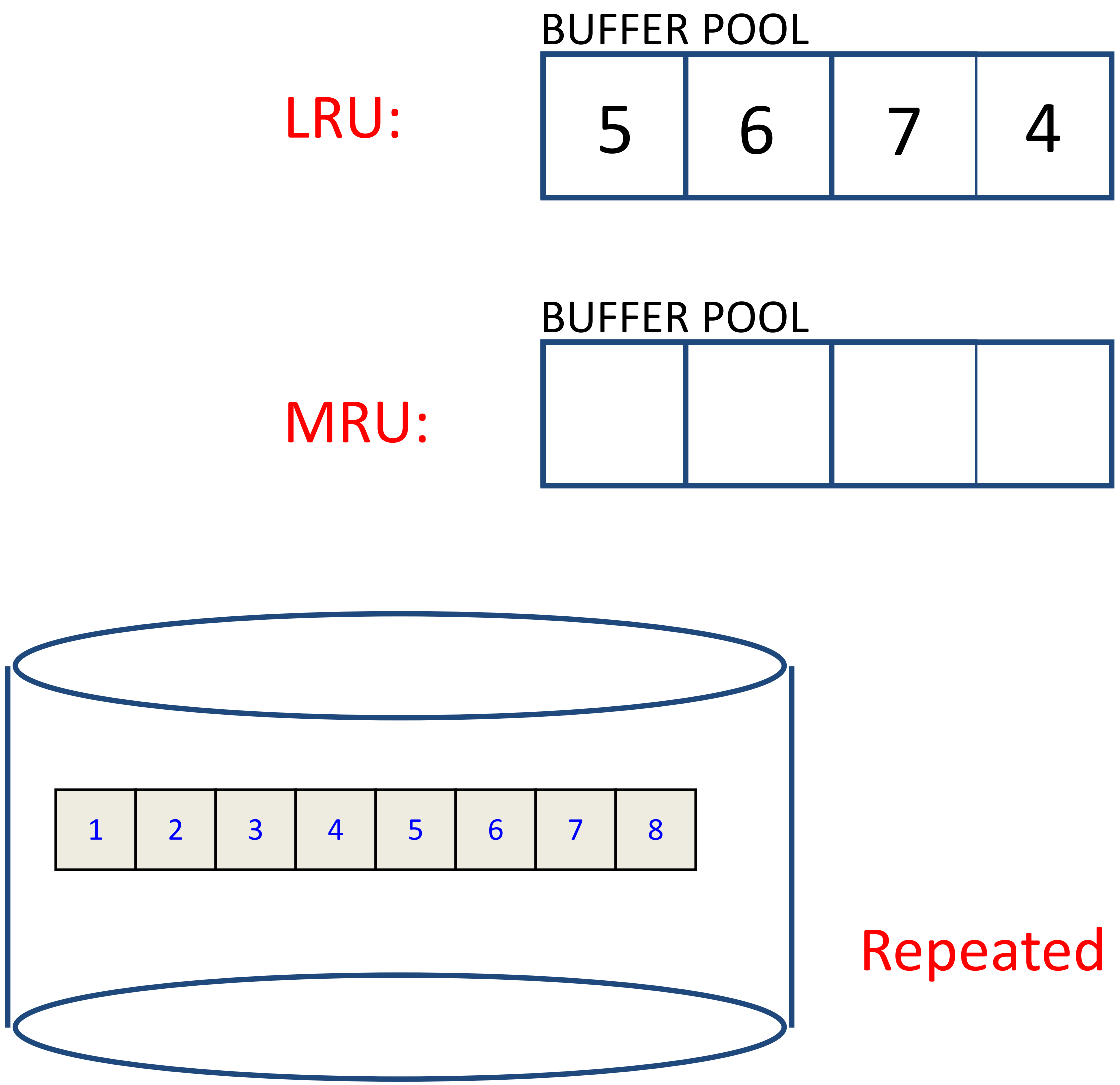


Repeated scan of file …

Sequential Flooding – Illustration

LRU:

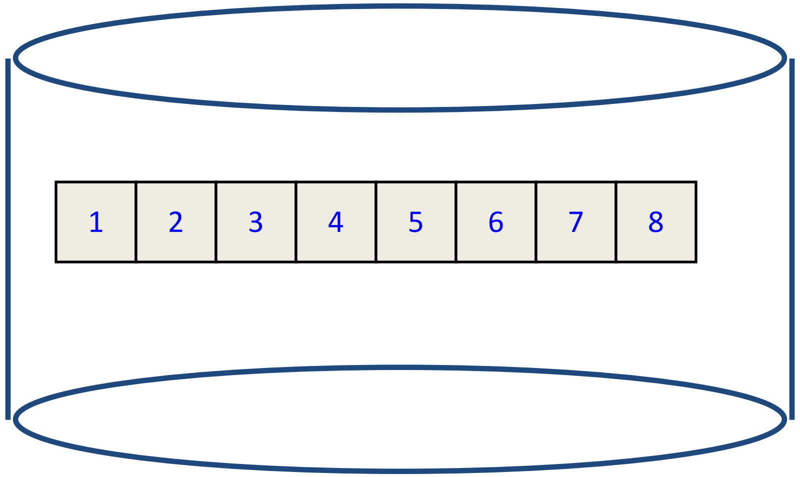
BUFFER POOL

5	6	7	8

for 2 scans every page access was a miss (had to go to disk)
2*8=16 disk accesses

MRU:

BUFFER POOL



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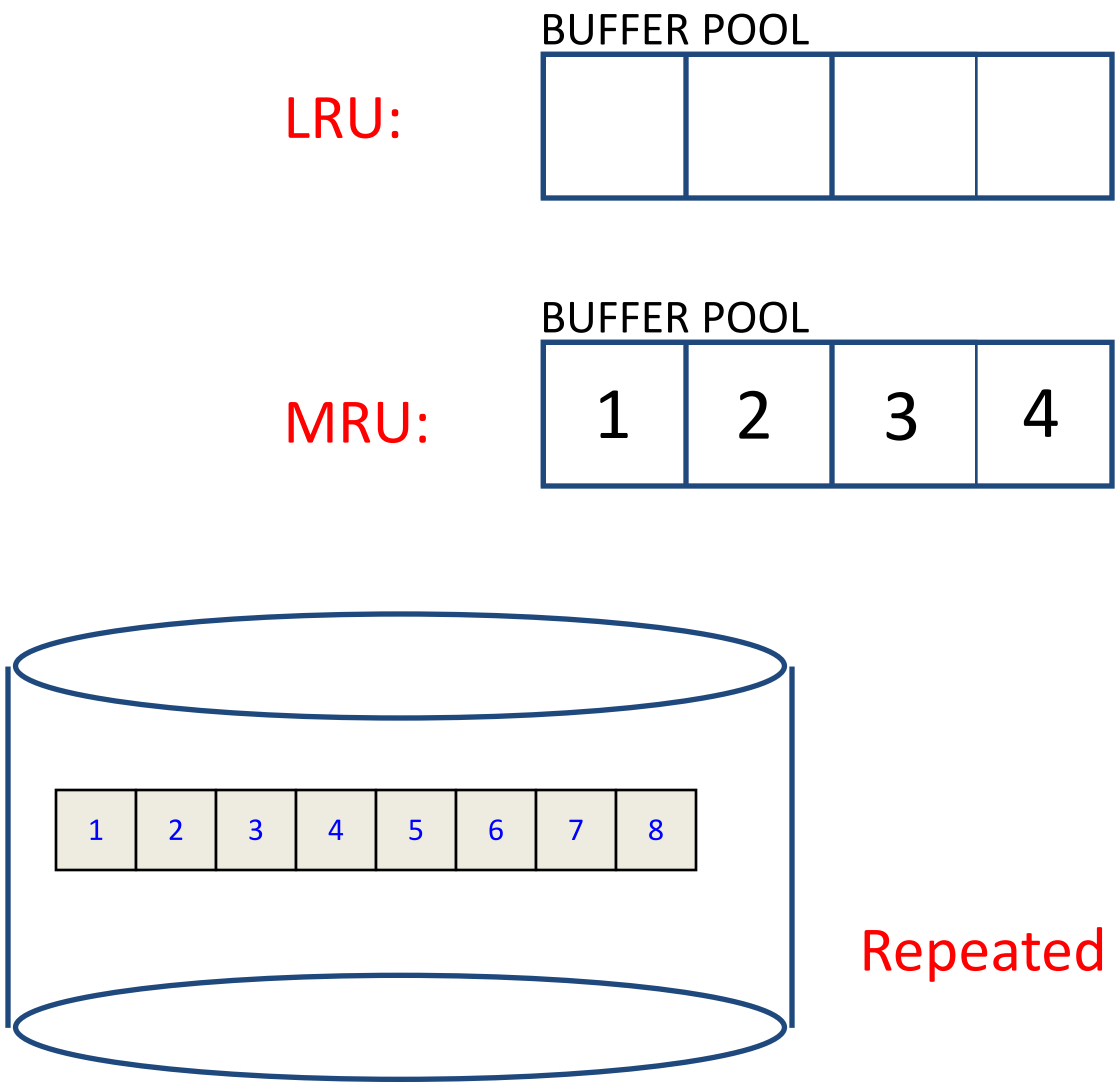

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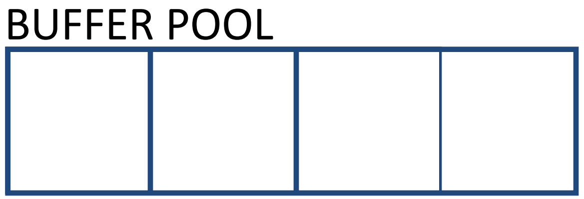
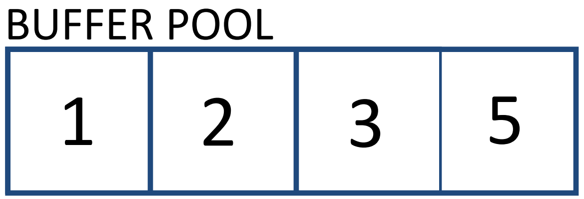
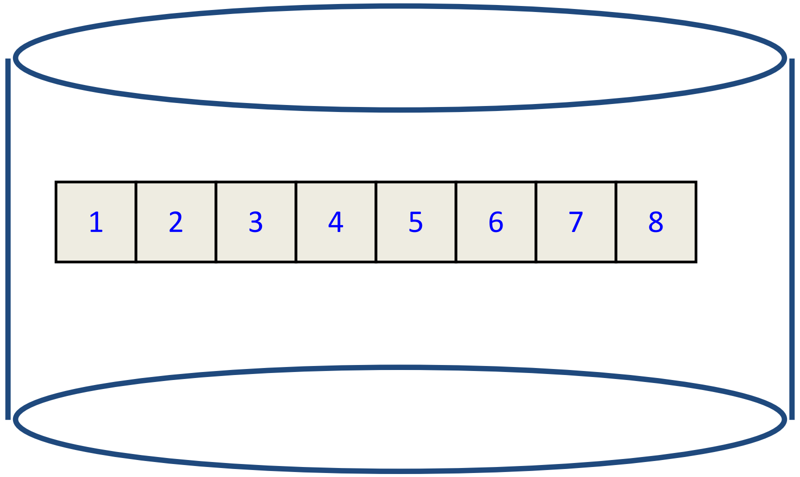


MRU:





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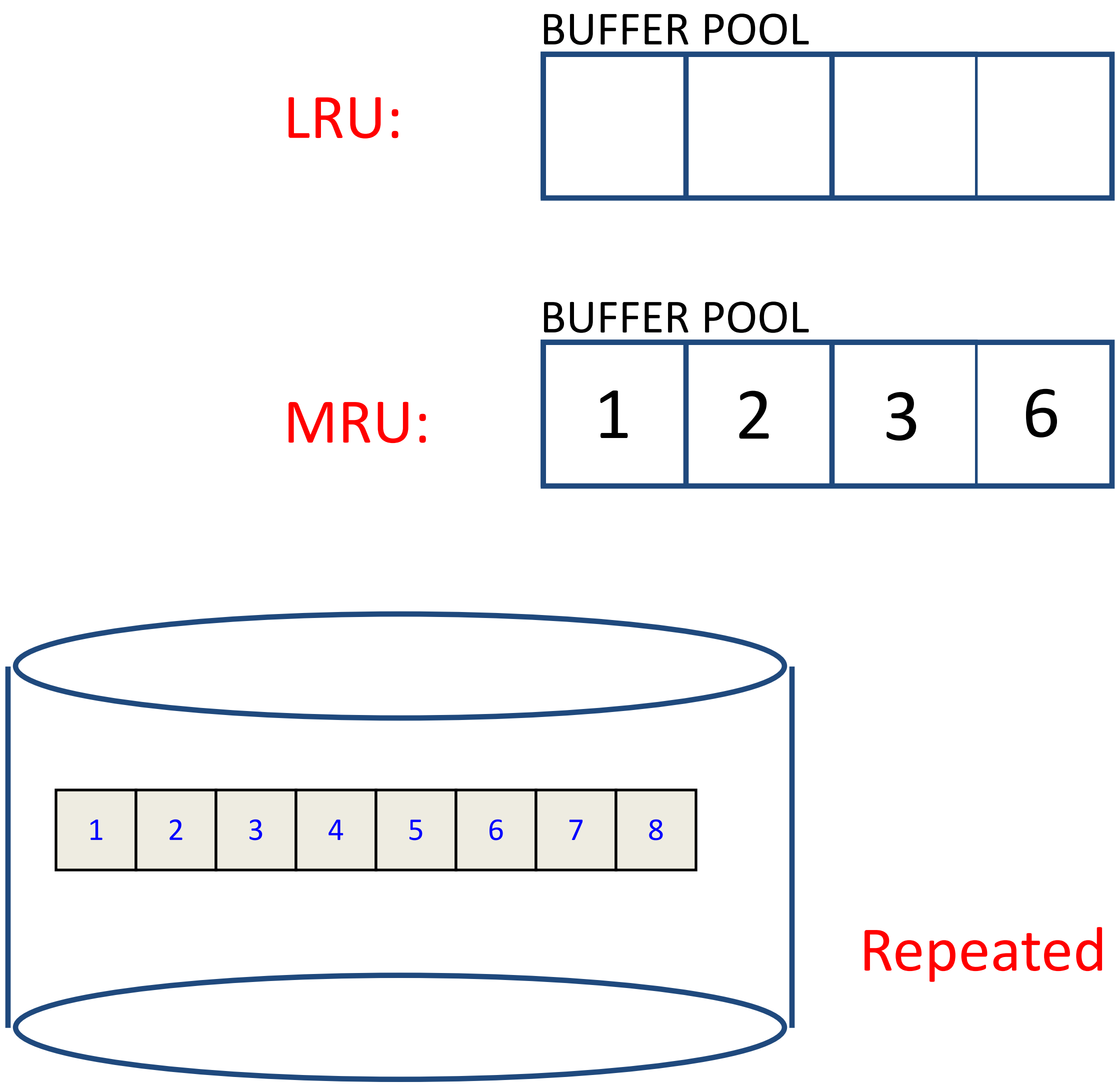

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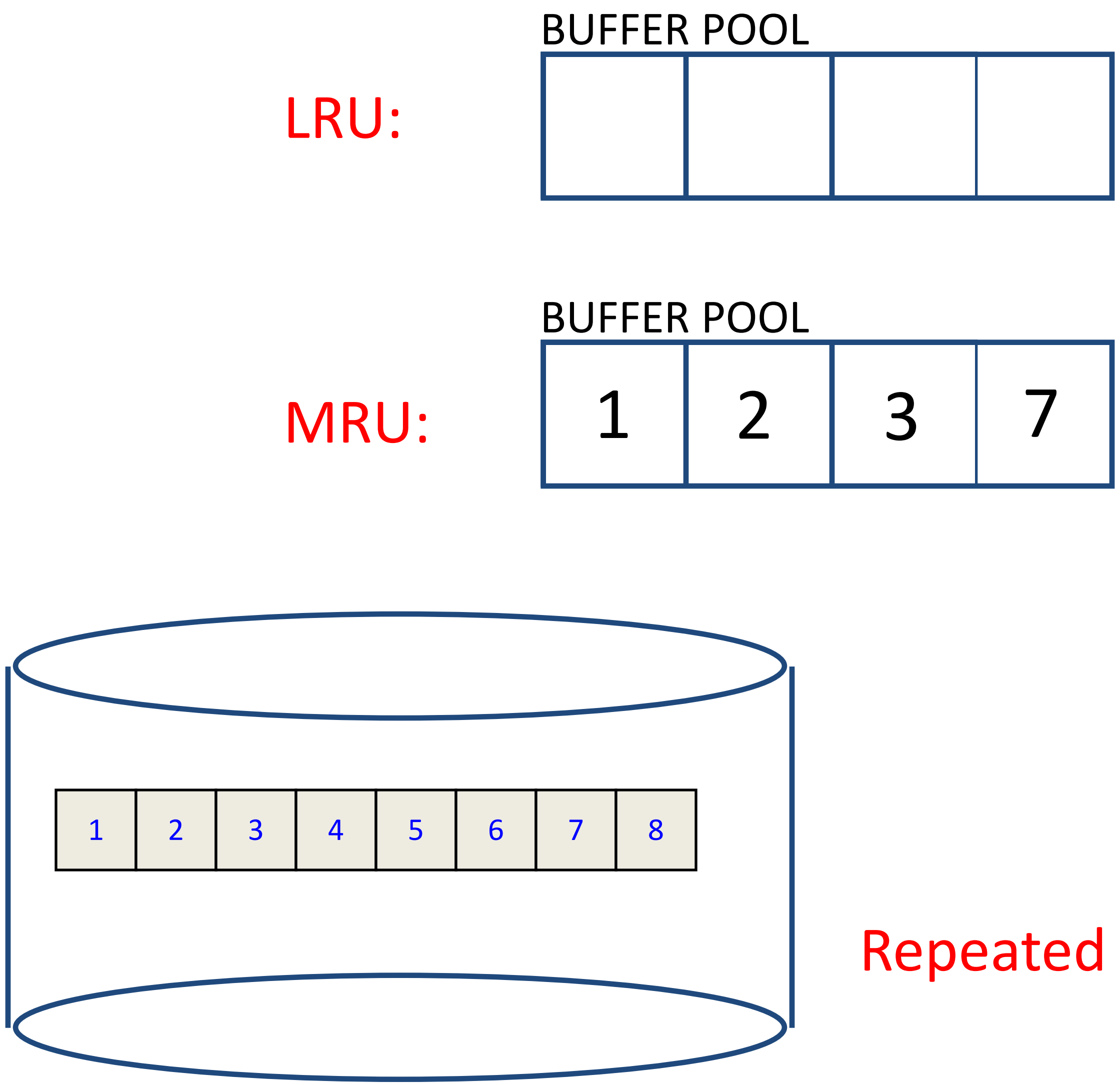

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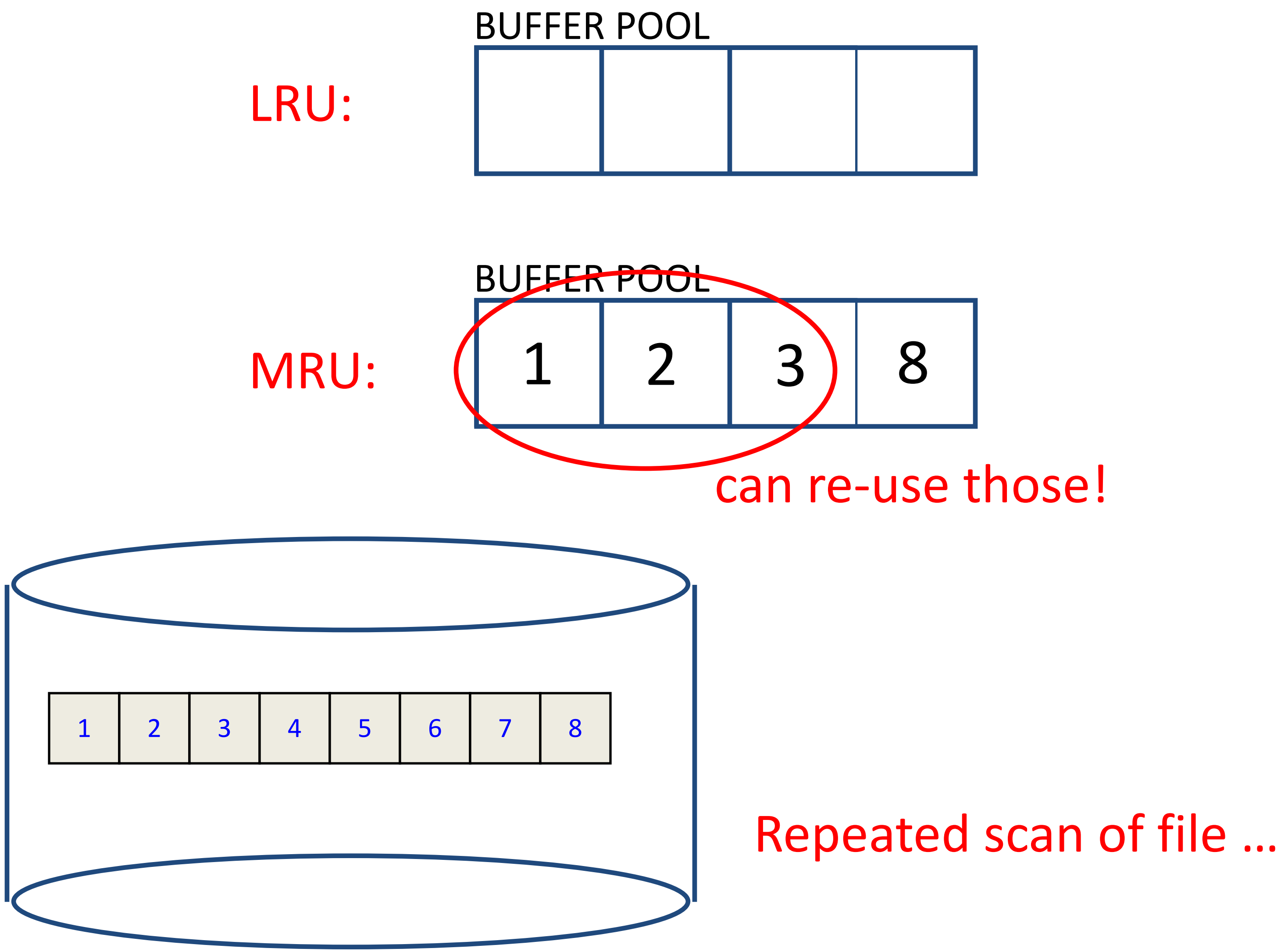

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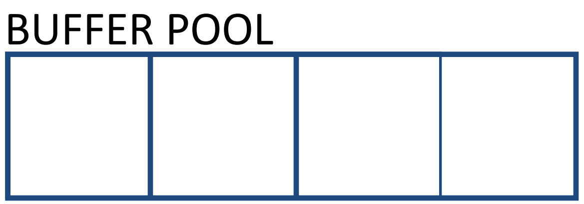
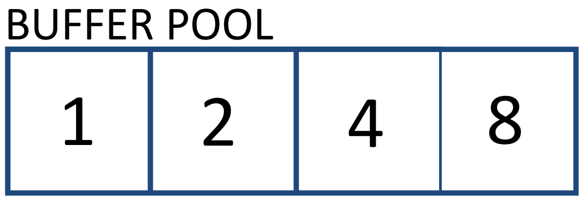
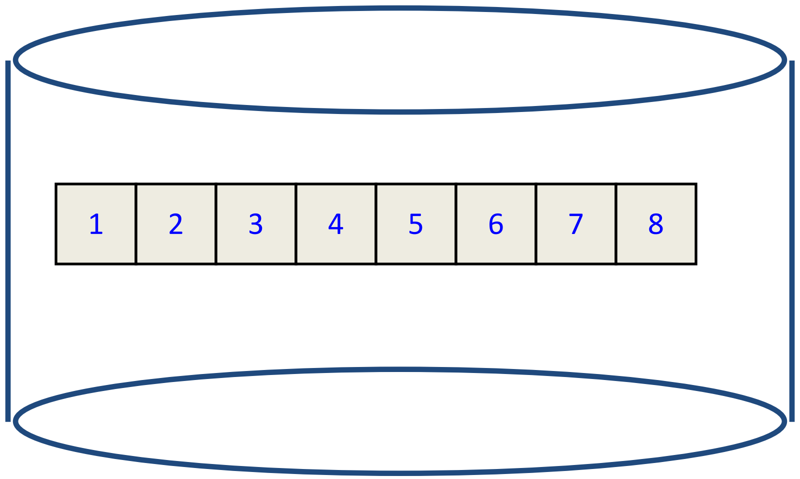


MRU:





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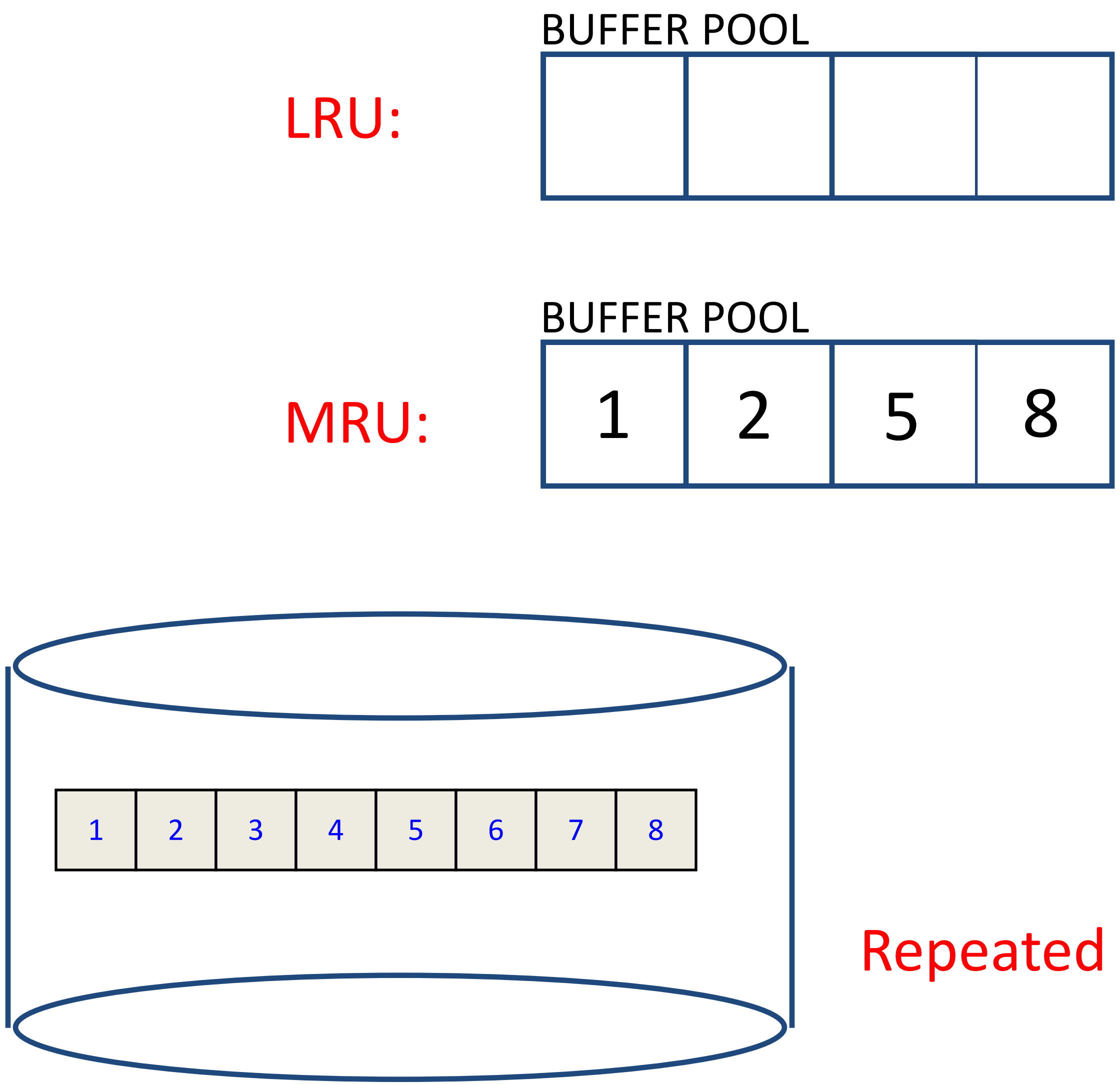

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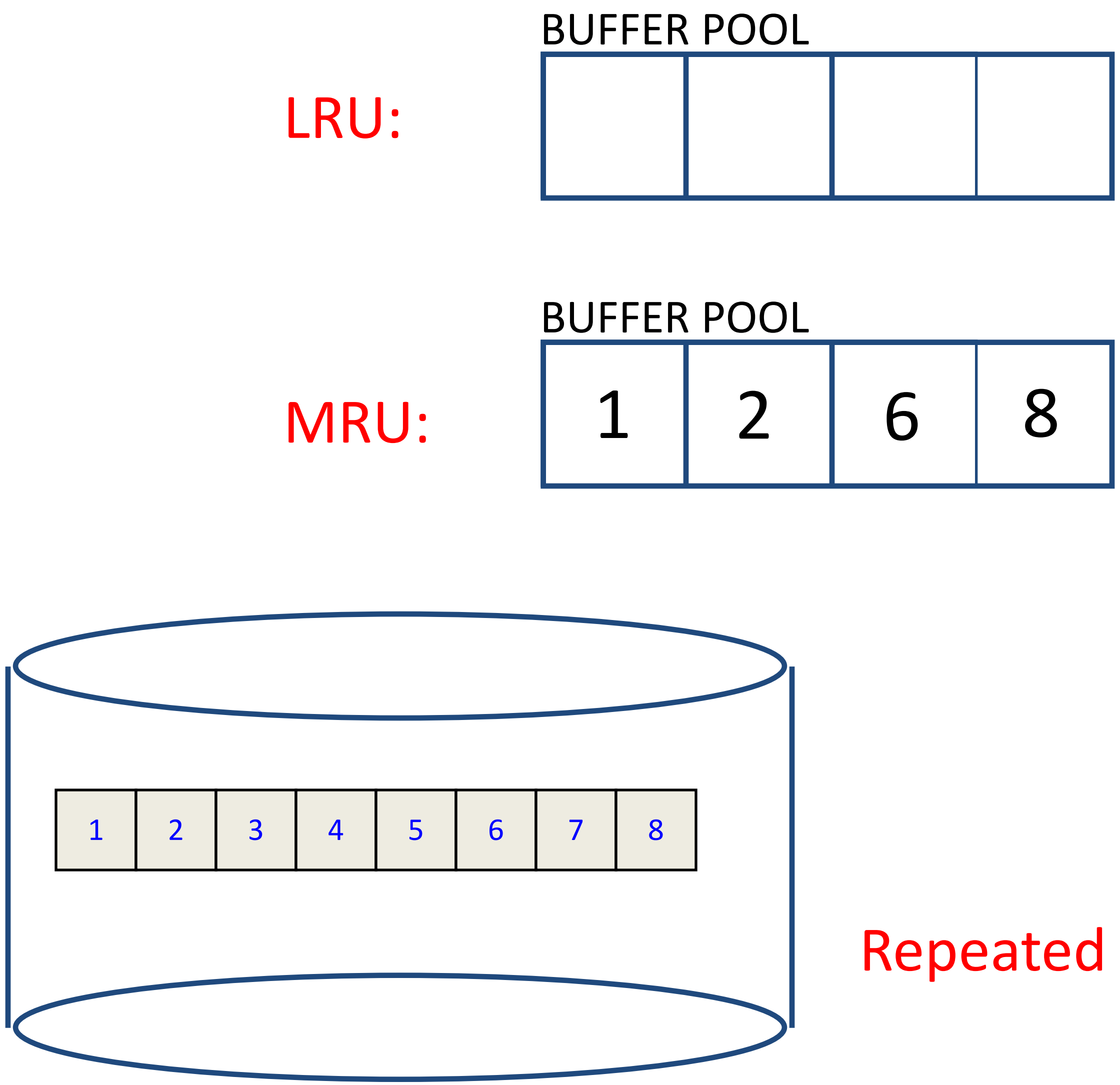

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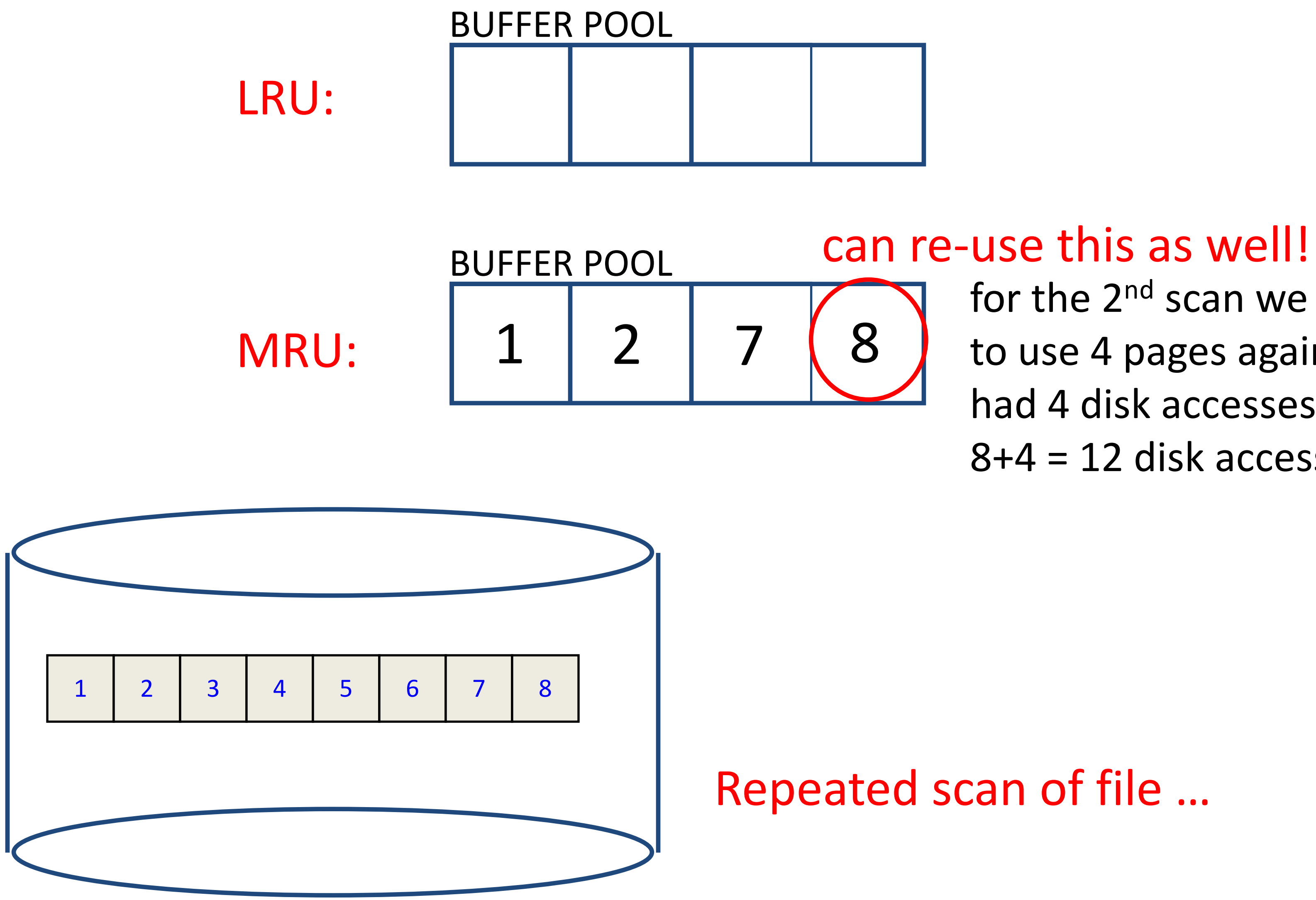


for the 2nd scan we were able to use 4 pages again, so we had 4 disk accesses:
8+4 = 12 disk accesses

Repeated scan of file …

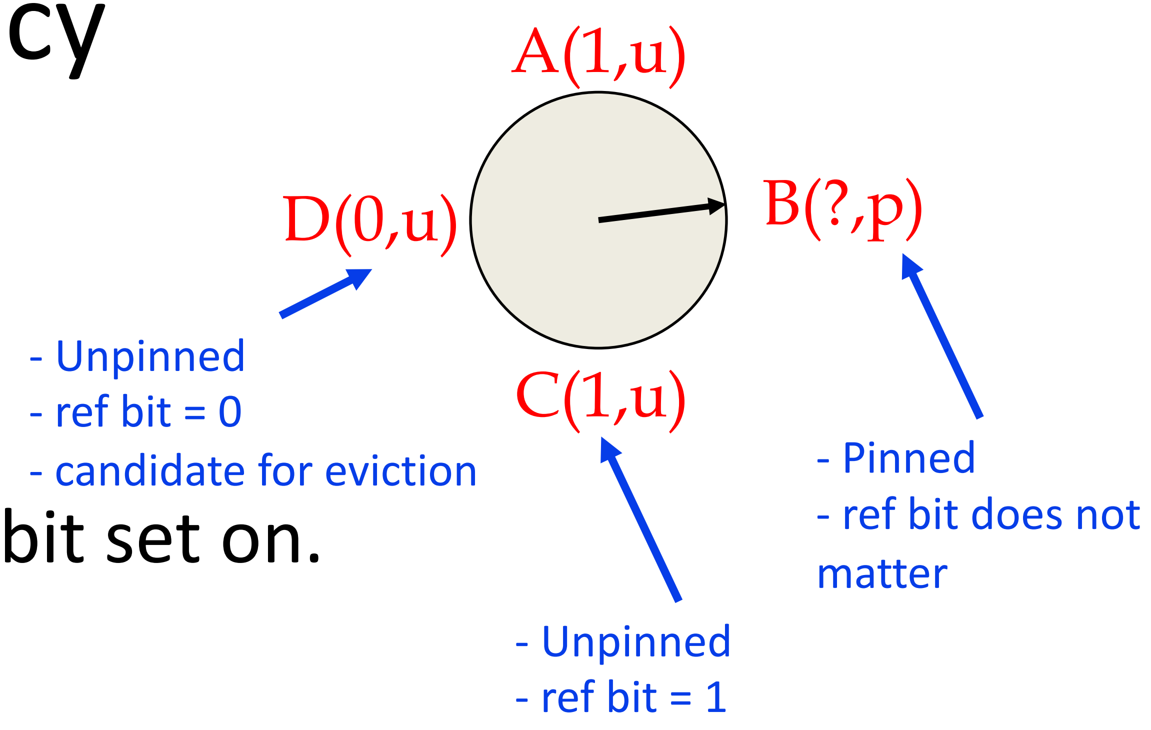
Implementing LRU

We need to both:

- support quick access to a page ID
  - a hash map for O(1) lookups
- maintain order of pages inserted
  - a double linked list (with pointers to the head and the tail)

```
IF page IN hashmap
    Move the accessed page to the tail of the linked list
ELSE
    IF bufferpool is full (i.e., eviction is needed)
        Remove the head from the list (LRU page)
        Delete its hashmap entry
    END IF
    Add the new page at the tail of the list and in hashmap
END IF
RETURN page
```

"Clock" Replacement Policy



An approximation of LRU.

Arrange frames into a cycle, store one "reference bit" per frame

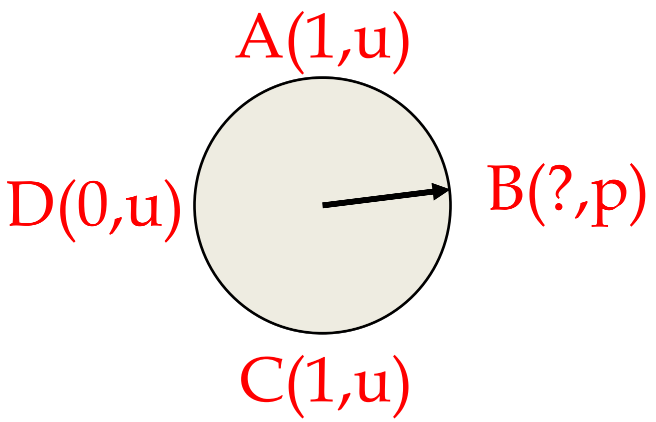
When pin count goes to 0, reference bit set on.

When replacement necessary:

```
do {
        if (pincount == 0 && ref bit is off)
                choose current page for replacement;
        else if (pincount == 0 && ref bit is on)
                turn off ref bit;
        advance current frame;
} until a page is chosen for replacement;
```

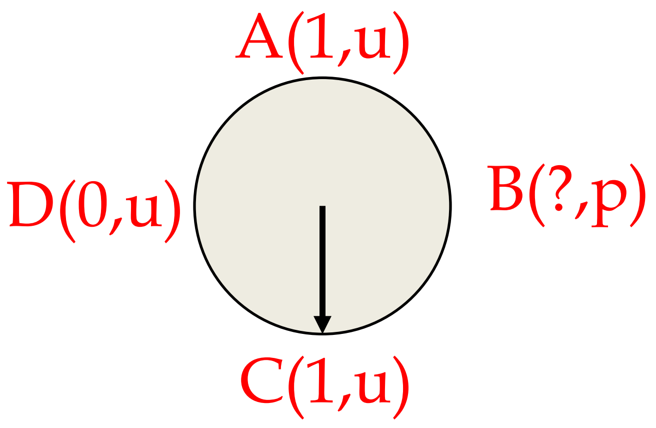
"Clock" Replacement Policy

```
do {
  if (pincount == 0 && ref bit is off)
          choose current page for replacement;
  else if (pincount == 0 && ref bit is on)
          turn off ref bit;
  advance current frame;
} until a page is chosen for replacement;
```



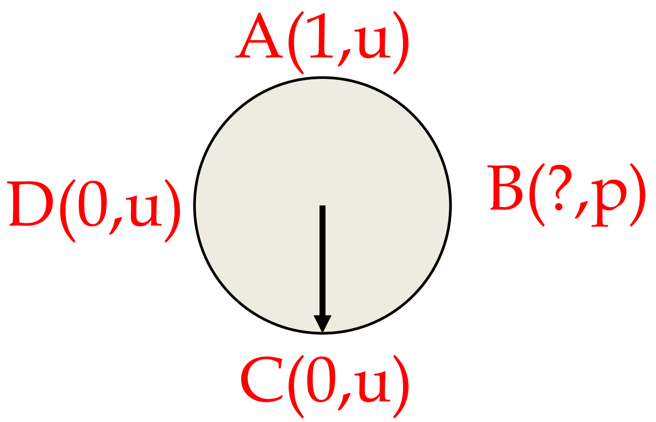
"Clock" Replacement Policy

```
do {
  if (pincount == 0 && ref bit is off)
          choose current page for replacement;
  else if (pincount == 0 && ref bit is on)
          turn off ref bit;
  advance current frame;
} until a page is chosen for replacement;
```



"Clock" Replacement Policy

```
do {
  if (pincount == 0 && ref bit is off)
        choose current page for replacement;
  else if (pincount == 0 && ref bit is on)
        turn off ref bit;
  advance current frame;
} until a page is chosen for replacement;
```



"Clock" Replacement Policy

```
do {
  if (pincount == 0 && ref bit is off)
        choose current page for replacement;
  else if (pincount == 0 && ref bit is on)
        turn off ref bit;
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} until a page is chosen for replacement;
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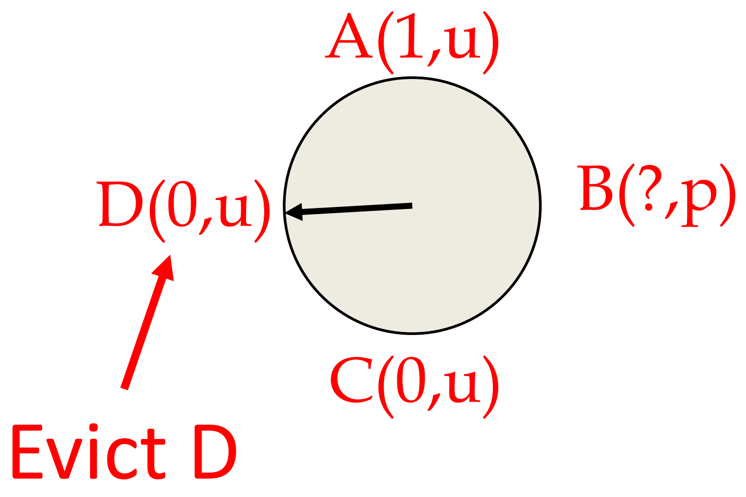

"Clock" Replacement Policy

```
do {
  if (pincount == 0 && ref bit is off)
        choose current page for replacement;
  else if (pincount == 0 && ref bit is on)
        turn off ref bit;
  advance current frame;
} until a page is chosen for replacement;
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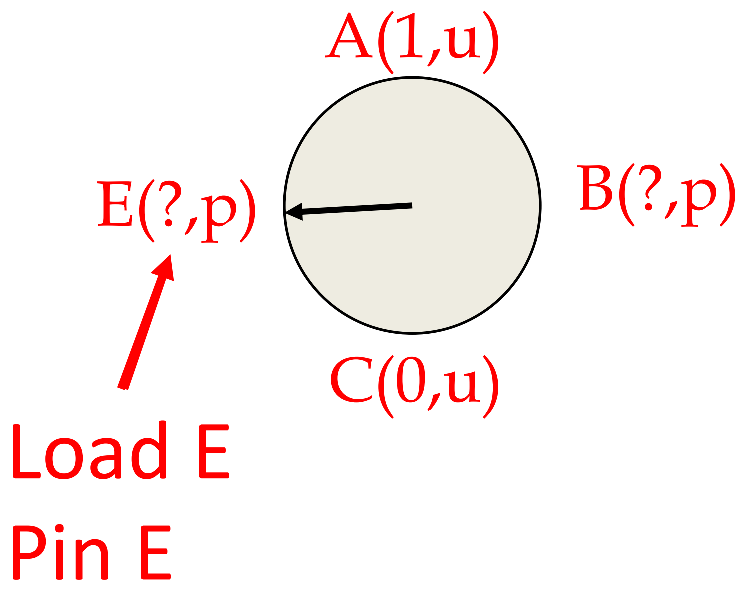

Summary

Disks provide cheap, non-volatile storage.

- Random access, but cost depends on location of page on disk; important to arrange data sequentially to minimize *seek* and *rotation* delays.

Buffer manager brings pages into RAM.

- Page stays in RAM until released by requestor.
- Written to disk when frame chosen for replacement (which is sometime after requestor releases the page).
- Choice of frame to replace based on *replacement policy.*
- Good to *pre-fetch* several pages at a time.