CS150: Database & Datamining
Lecture 8: The IO Model

ShanghaiTech-SIST

Spring 2019

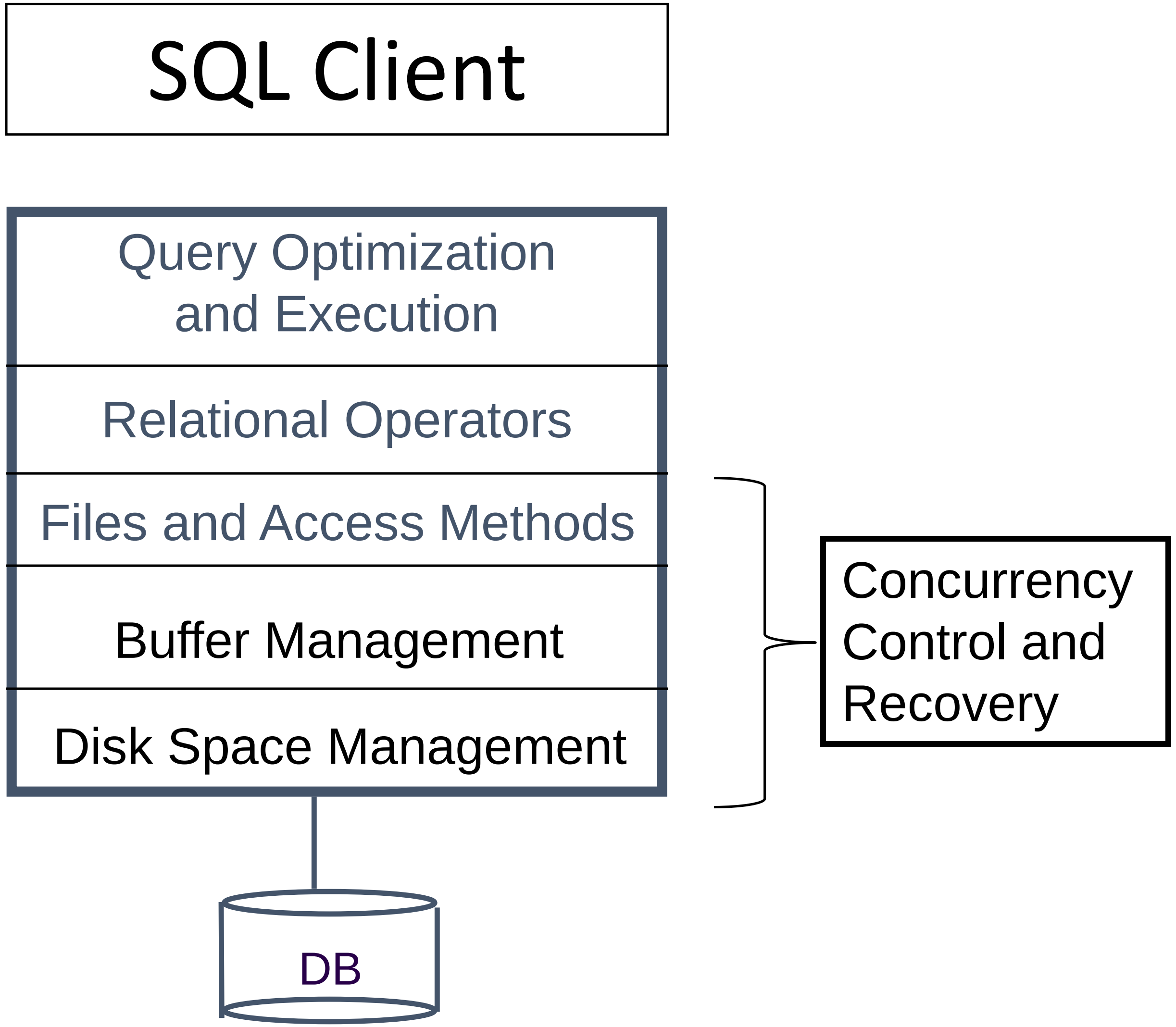
Acknowledgement: Slides are adopted from the Berkeley course CS186 by Joey Gonzalez and Joe Hellerstein, Stanford CS145 by Peter Bailis.

Transition to **Mechanisms**

1. So you can **understand** what the database is doing!
    1. Understand the CS challenges of a database and how to use it.
    2. Understand how to optimize a query

2. Many **mechanisms** have become **stand-alone systems**
    - **Indexing** to Key-value stores
    - Embedded join processing
    - SQL-like languages take some aspect of what we discuss (PIG, Hive)

Block diagram of a DBMS



Today’s Lecture

1. The Disk and Files

2. The Buffer

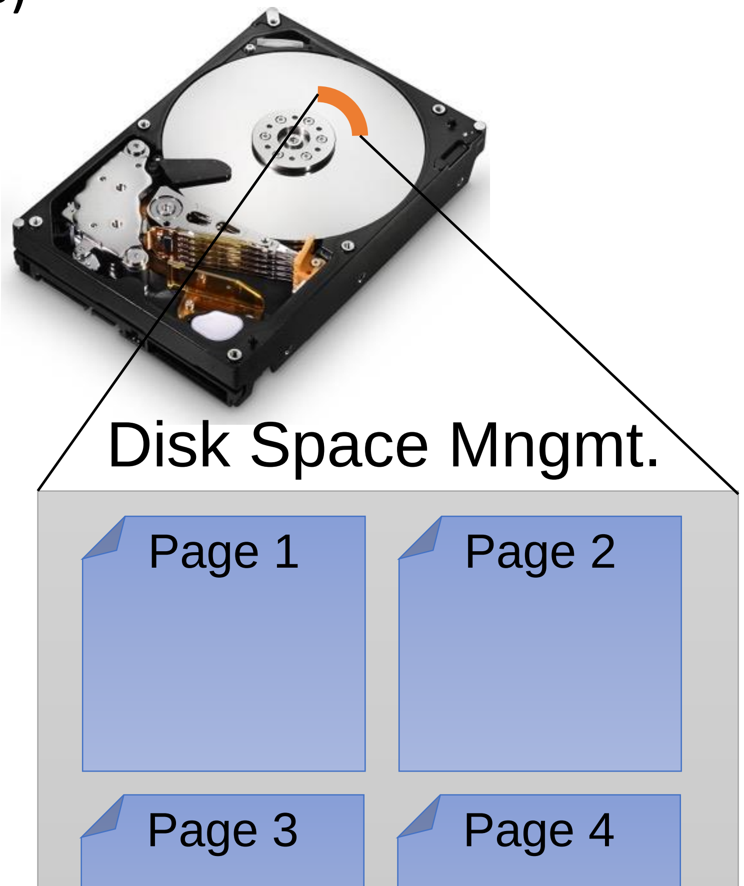
3. External Merge Algorithm

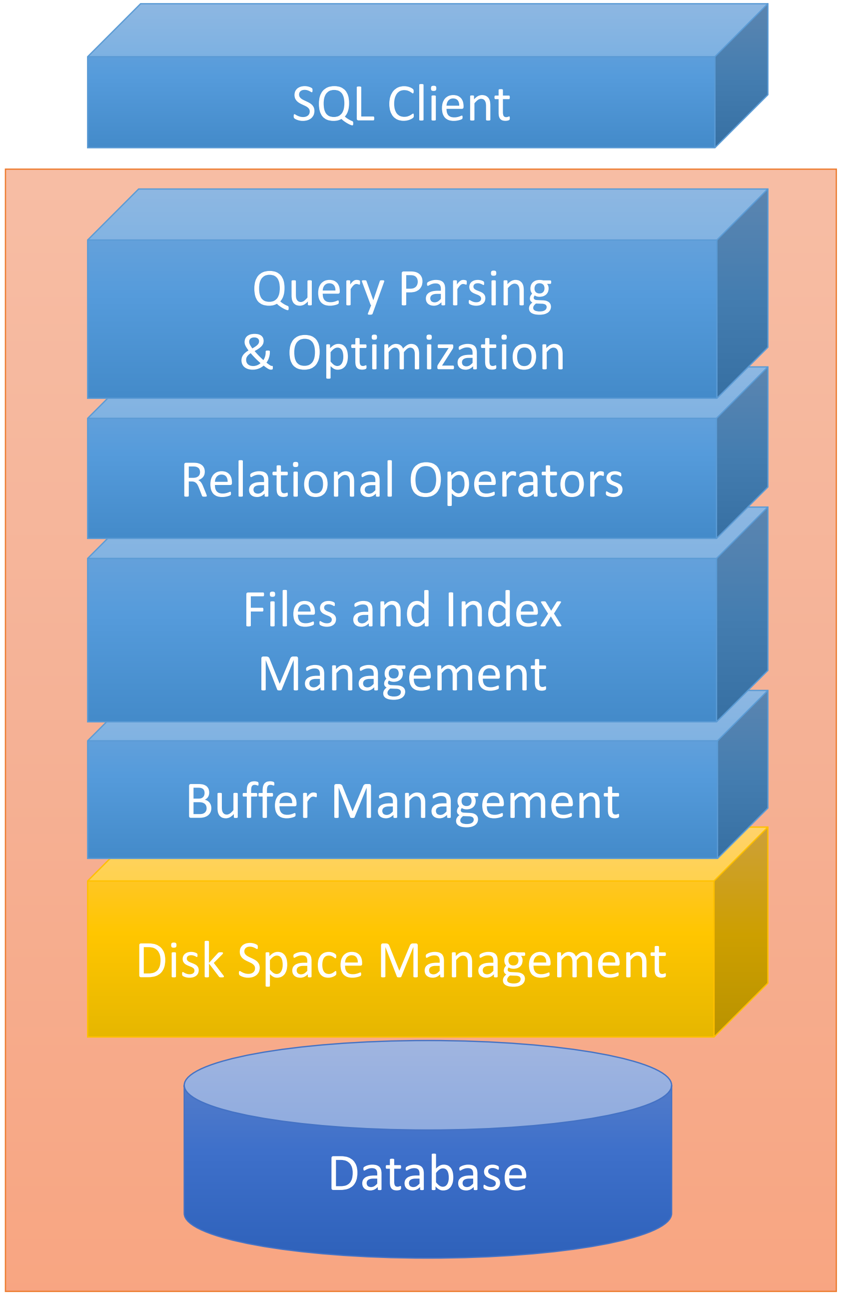
4. External Merge Sort Algorithm

1. The Disk and Files

Architecture of a DBMS

Translates page requests into physical bytes on one or more device(s)



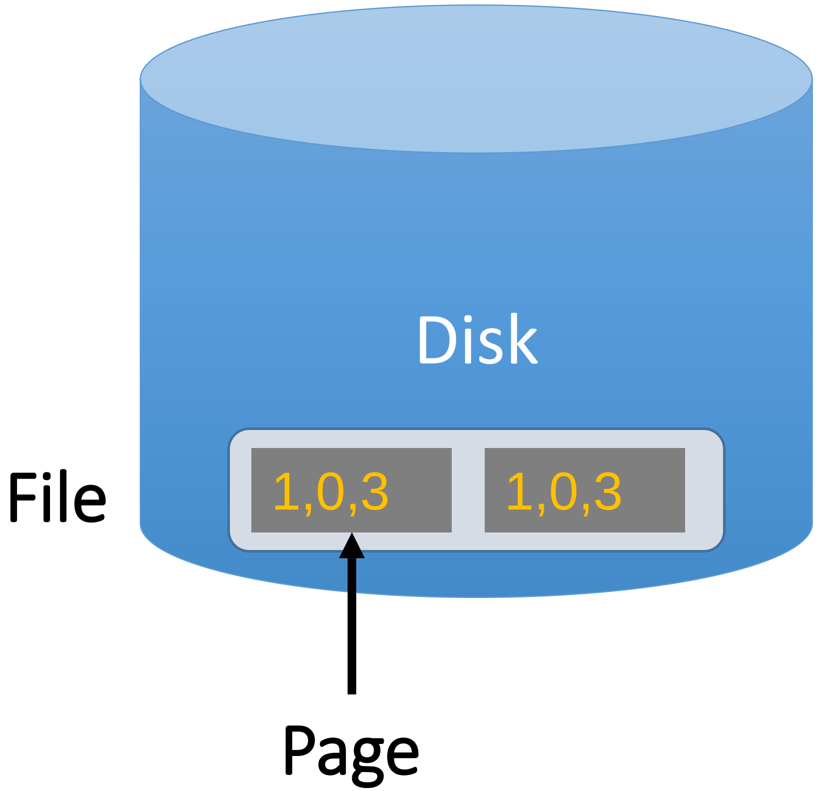


Overview: Files of Pages of Records

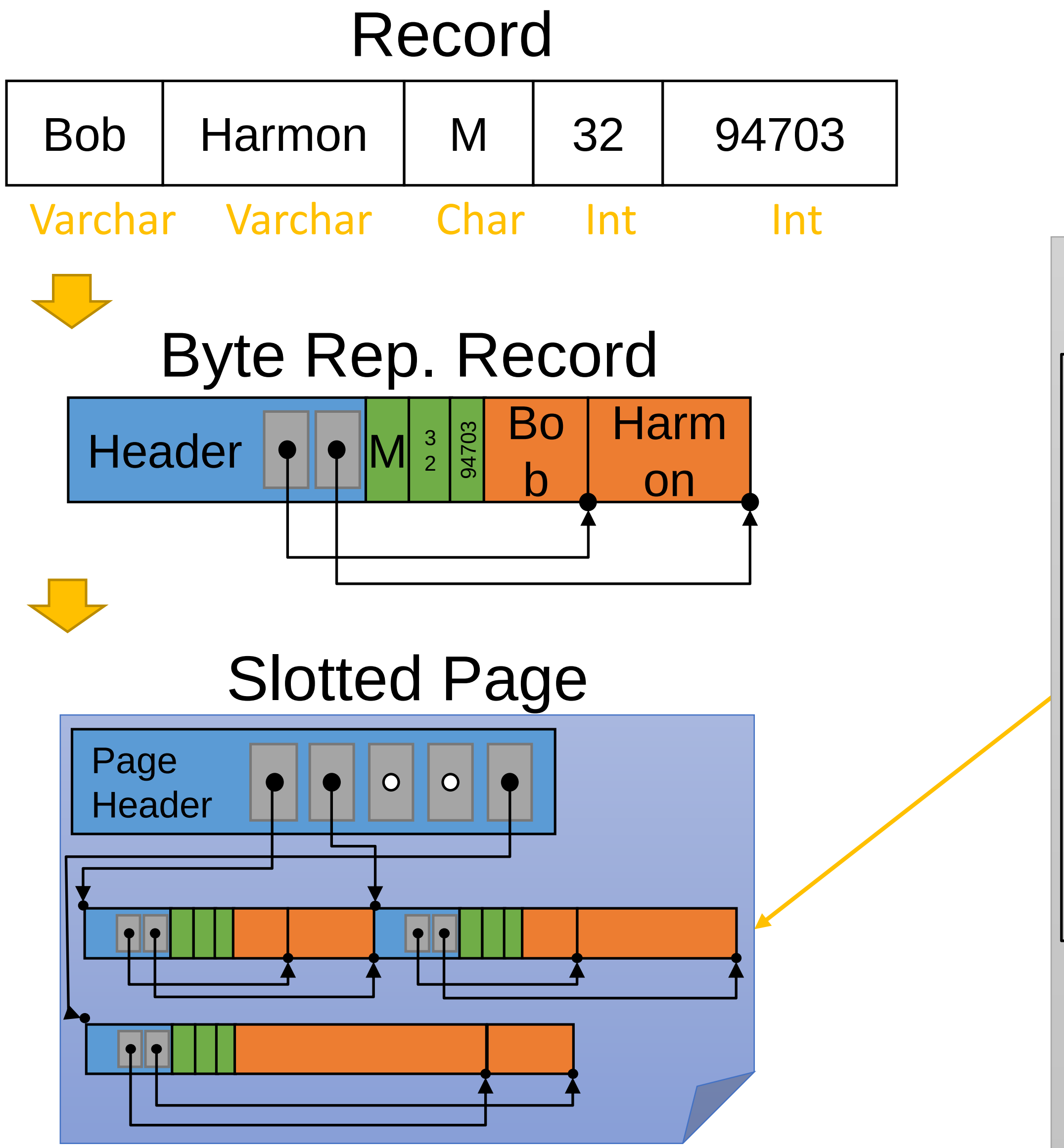
- Tables stored as a *logical files* consisting of *pages* each containing a collection of *records*
- Pages are managed
  - in memory by the buffer manager: higher levels of database only operate in memory
  - on disk by the disk space manager: reads and writes pages to physical disk/files

A Simplified Filesystem Model

- For us, a **<u>page</u>** is a ***fixed-sized array*** of memory
  - Think: One or more disk blocks
  - Interface:
    - write to an entry (called a **slot**) or set to “None”
  - DBMS also needs to handle variable length fields
    - Page layout is important for good hardware utilization as well (see next next lecture)
- And a **<u>file</u>** is a *variable-length list* of pages
  - Interface: create / open / close; next_page(); etc.

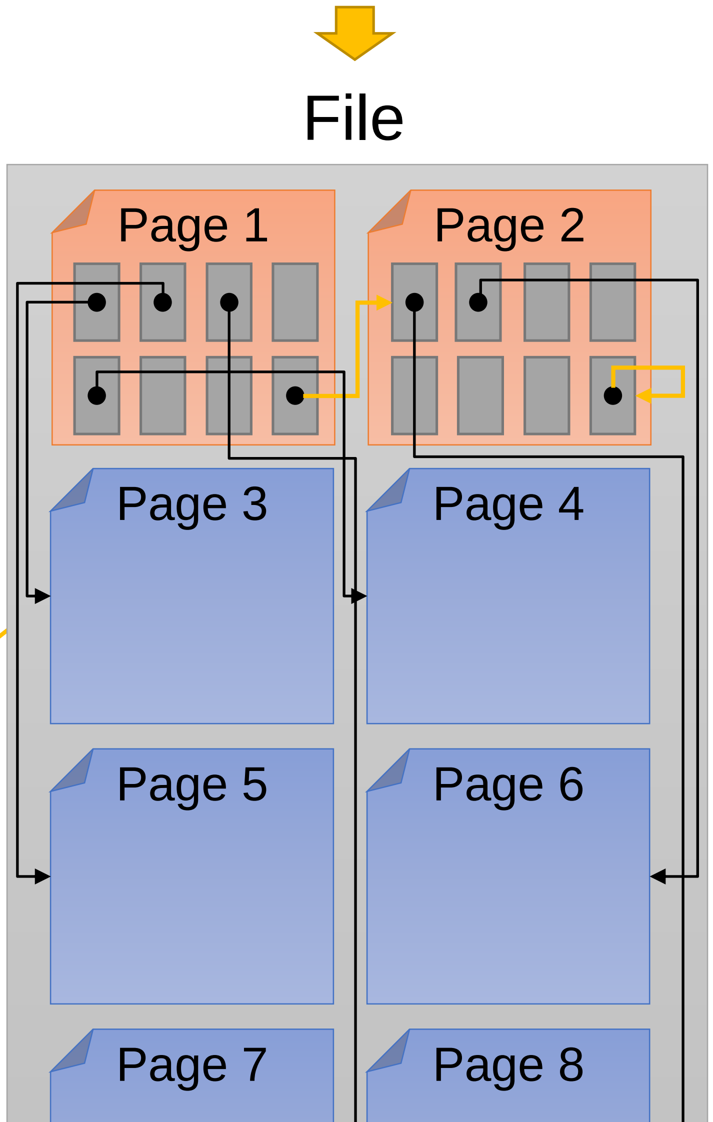


Overview



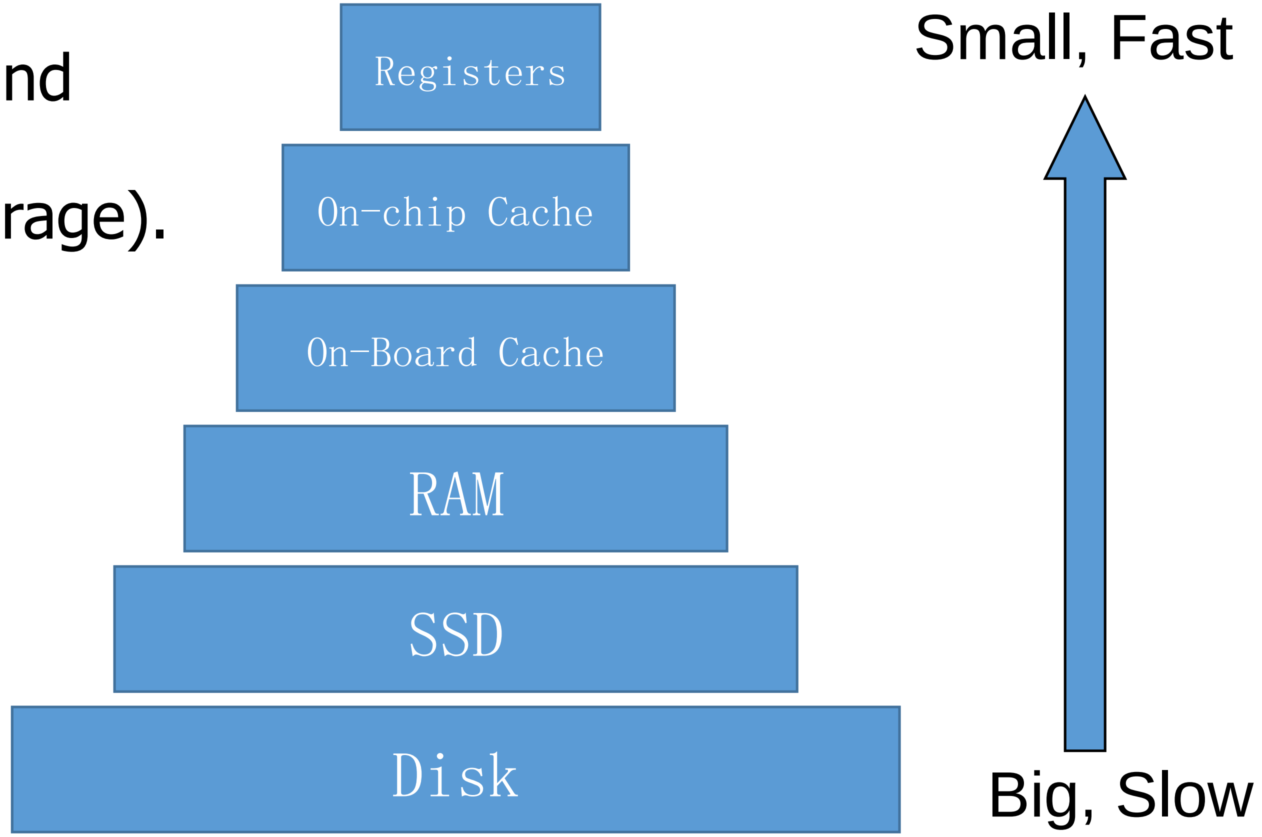
Table

Name	Addr	Sex	Age	Zip
Bob	Harmon	M	32	94703
Alice	Mabel	F	33	94703
Jose	Chavez	M	31	94110
Jane	Chavez	F	30	94110



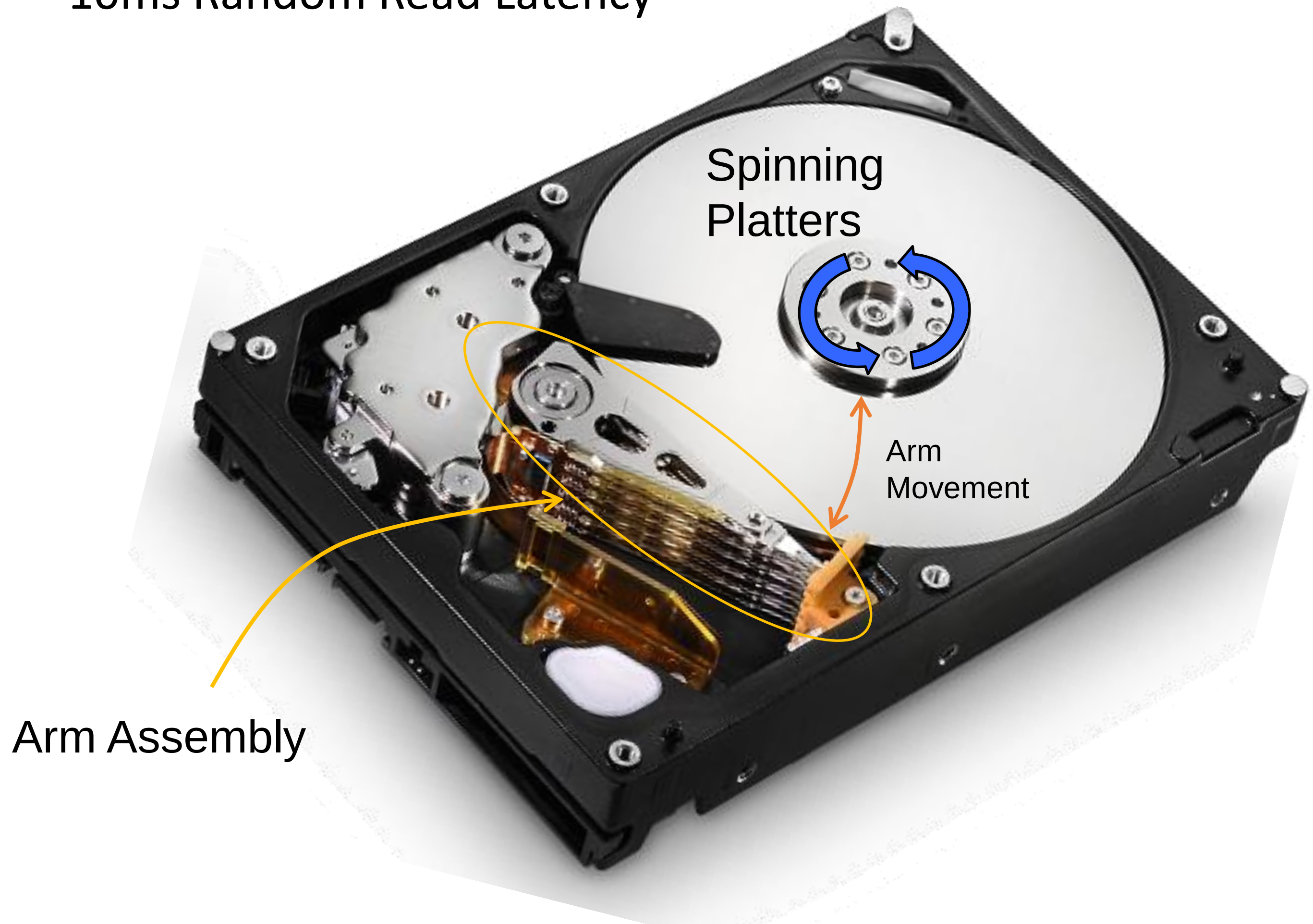
The Storage Hierarchy

- Main memory (RAM) for currently used data.
- Disk for main database and backups/logs (secondary & tertiary storage).
- The role of Flash (SSD) varies by deployment
  - Sometimes the DB
  - Sometimes a cache



Disks

- DBMS stores information on Disks and SSDs.
  - Disks are a mechanical anachronism (slow!)
    - 10ms Random Read Latency



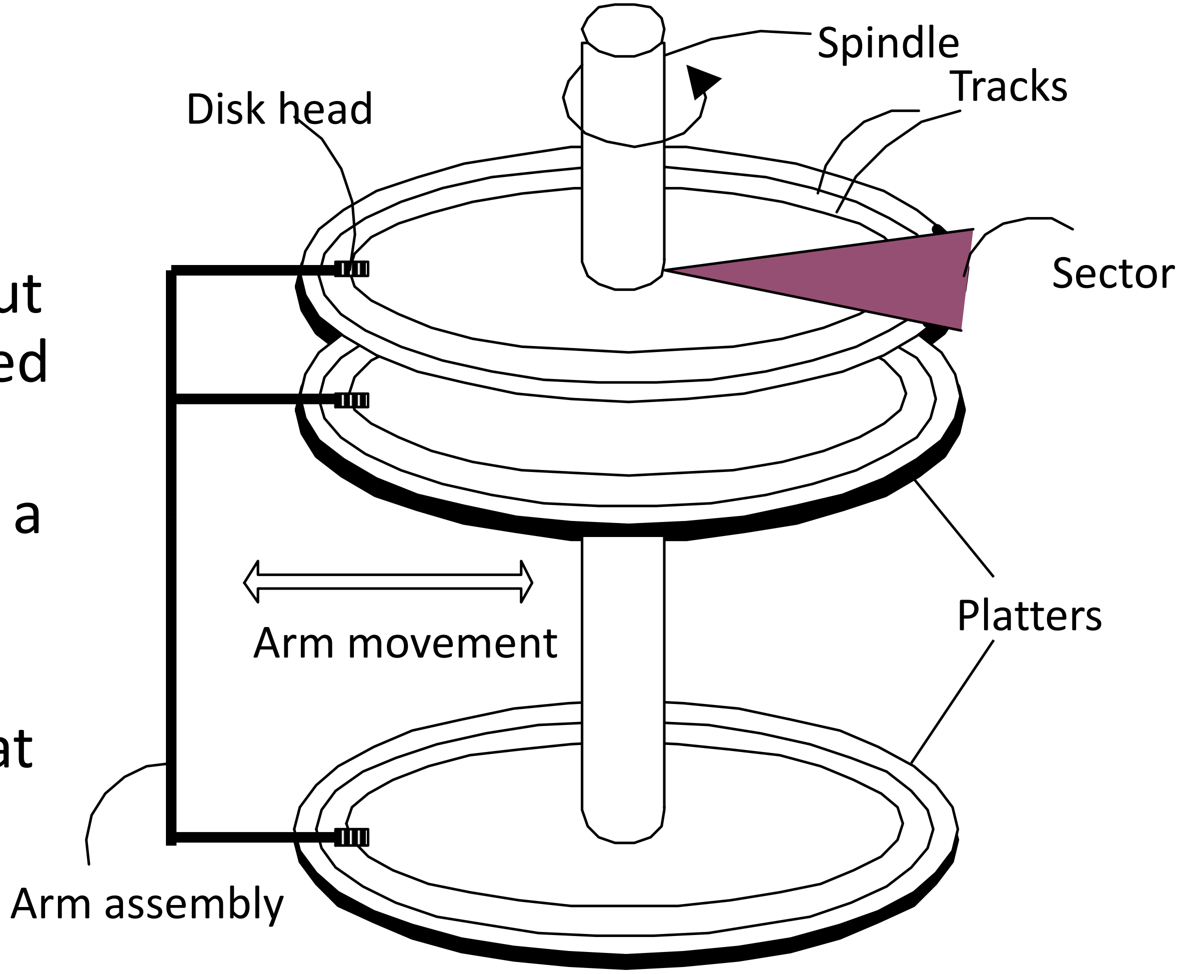
Components of a Disk

- Platters spin (say 15000 rpm)

- Arm assembly 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/page size is a multiple of (fixed) sector size

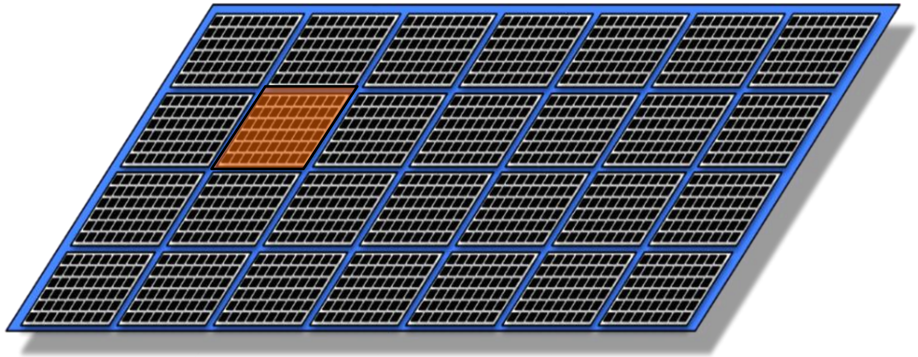


Arranging Pages on Disk

- *"Next"* page concept:
  - pages on same track, followed by
  - pages on same cylinder, followed by
  - pages on adjacent cylinder
- Arrange file pages sequentially on disk
  - minimize seek and rotational delay.
- For a sequential scan, *pre-fetch*
  - several pages at a time!
- Read large consecutive blocks

Notes on Flash (SSD)

- Issues in current generation (NAND)
  - 4-8K reads, 1-2MB writes
  - Only 2k-3k erasures before failure, so move writes around ("wear leveling")
  - *Write amplification*: big units, need to reorg for garbage collection & wear
- So... read is fast and *predictable*
  - Single read access time: 0.03 ms
  - 4KB random reads: ~500MB/sec
  - Sequential reads: ~525MB/sec
  - 64K: 0.48msec
- But.. write is not! Slower for random
  - Single write access time: 0.03ms
  - 4KB random writes: ~120MB/sec
  - Sequential writes: ~480MB/sec



Disks and Files

- DBMS stores information on **Disks** and **SSDs**.
  - Disks are a mechanical **anachronism** (slow!)
  - SSDs faster, **slow relative to memory**, costly writes
- DBMS operate at **Block Level**
  - Read and Write large **chunks seq. bytes**
    - Leverage cache hierarchy and HW pre-fetch
    - Amortize seek delays on HDDs and Writes on SSD
  - *Sequentially: Next* disk block is fastest
  - Maximize usage of data per R/W
- Organize data for fast in memory processing (i.e., mapping)

A note on (confusing) terminology

Block = Unit of transfer for disk read/write

- 64KB - 128KB is a good number today
- Book says 4KB

Page = Fixed size contiguous chunk of memory

- Assume same size as block
- Refer to corresponding blocks on disk

For simplicity we use Block and Page interchangeably.

Disk Space Management

Lowest layer of DBMS, manages space on disk

- Mapping pages to locations on disk
- Loading pages from disk to memory
- Saving pages back to disk & ensuring writes

Higher levels call upon this layer to:

- read/write a pages
- allocate/de-allocate logical pages

Request for a *sequence* of pages best satisfied by pages stored sequentially on disk

- Physical details hidden from higher levels of system
- Higher levels may assume **Next Page** is fast!

Disk Space Management Implementation

Proposal 1: Talk to the device directly

- Could be very fast if you knew the device well
- What happens when devices change?

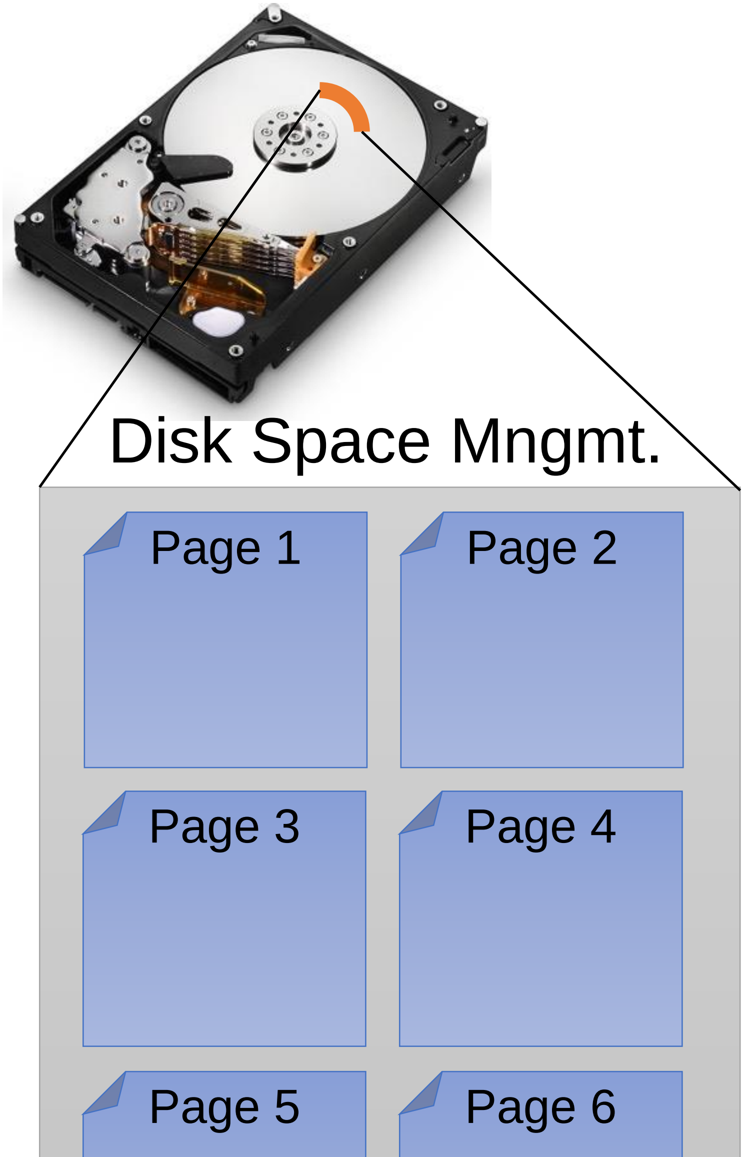
Proposal 2: Run over filesystem (FS)

- Allocate single large “contiguous” file and assume sequential / nearby byte access are fast
- Most FS optimize for sequential access and temporal locality (buffer cache on hot items)
  - Sometimes disable FS buffering
- May span multiple files on multiple disks / machines

Typically sits on top of local file system

Get Page 4 Get Page 5

Disk Space Management

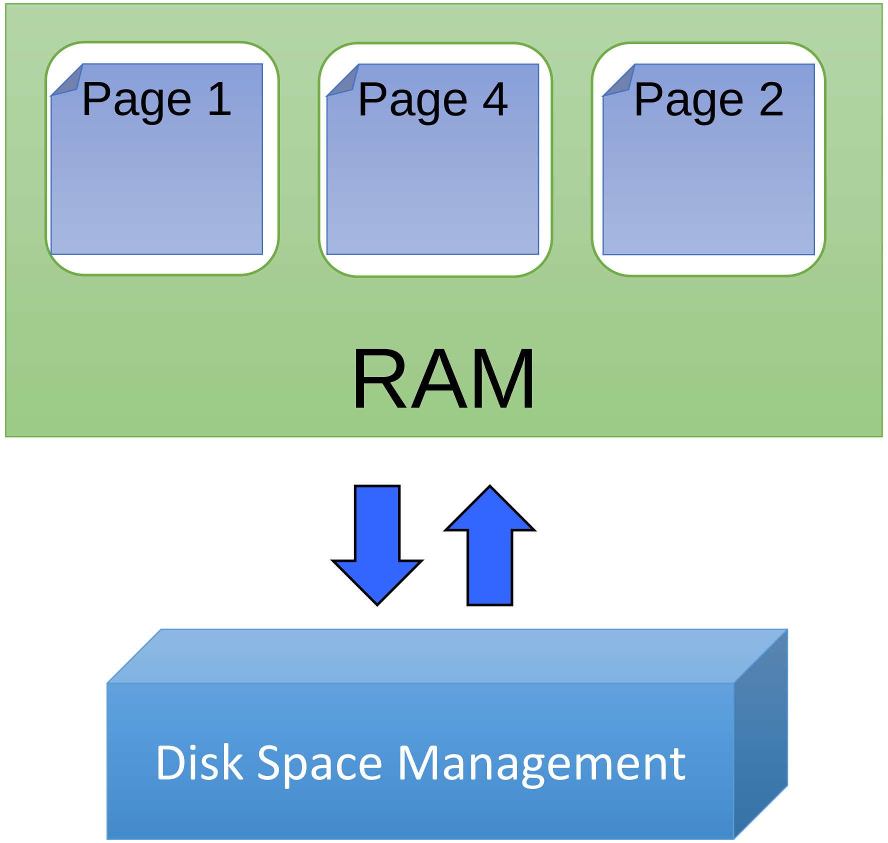


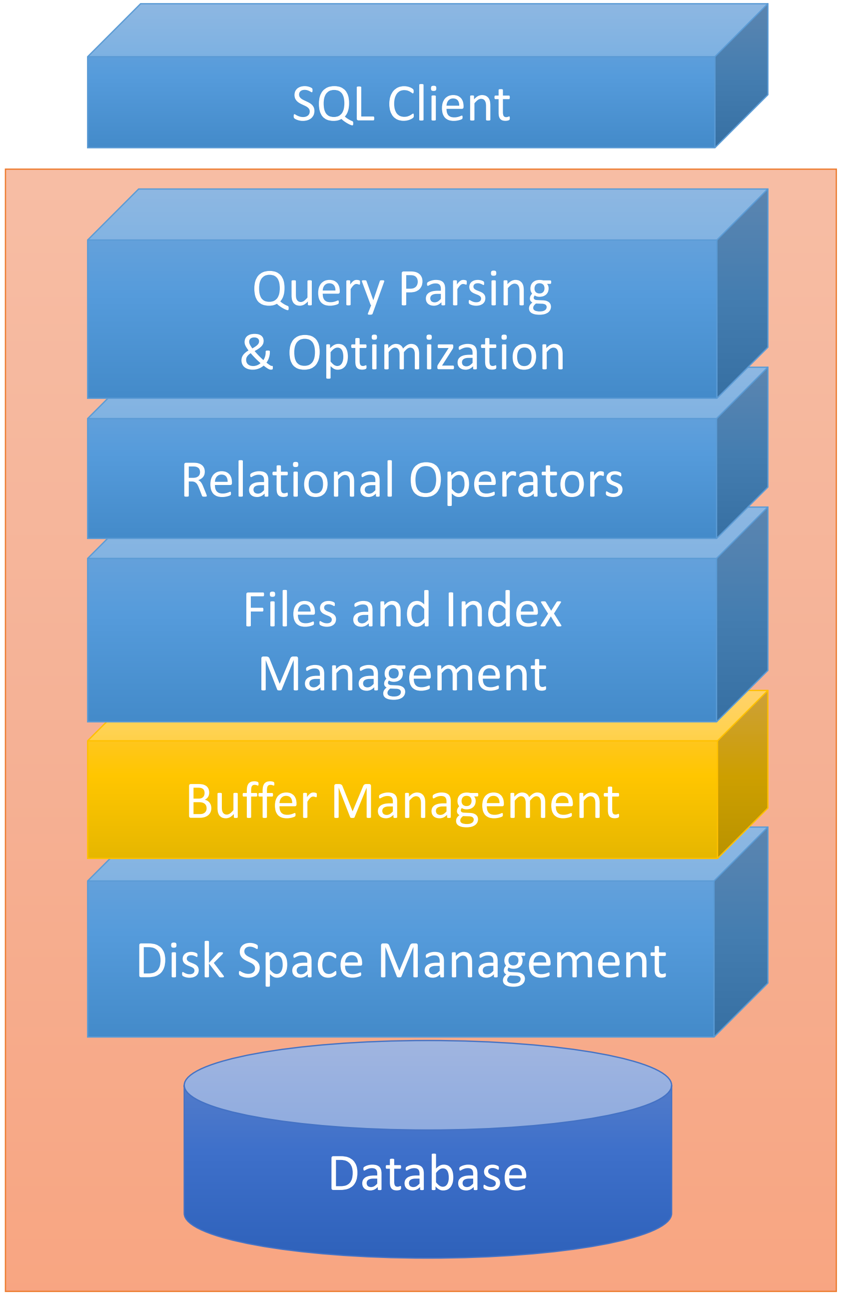
- Provide API to read and write pages to device
- Pages: block level organization of bytes on disk
- Ensures next locality and abstracts FS/Device details

2. The Buffer

Architecture of a DBMS

Illusion of operating in memory



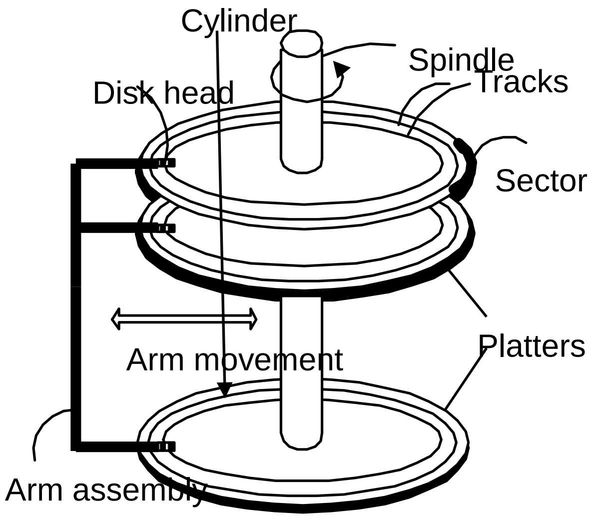


What you will learn about in this section

1. RECAP: Storage and memory model

2. Buffer primer

High-level: Disk vs. Main Memory



Disk:

- ***Slow:*** Sequential *block* access
  - Read a blocks (not byte) at a time, so sequential access is cheaper than random
  - **Disk read / writes are expensive!**
- ***Durable:*** We will assume that once on disk, data is safe!
- ***Cheap***

Random Access Memory (RAM) or Main Memory:

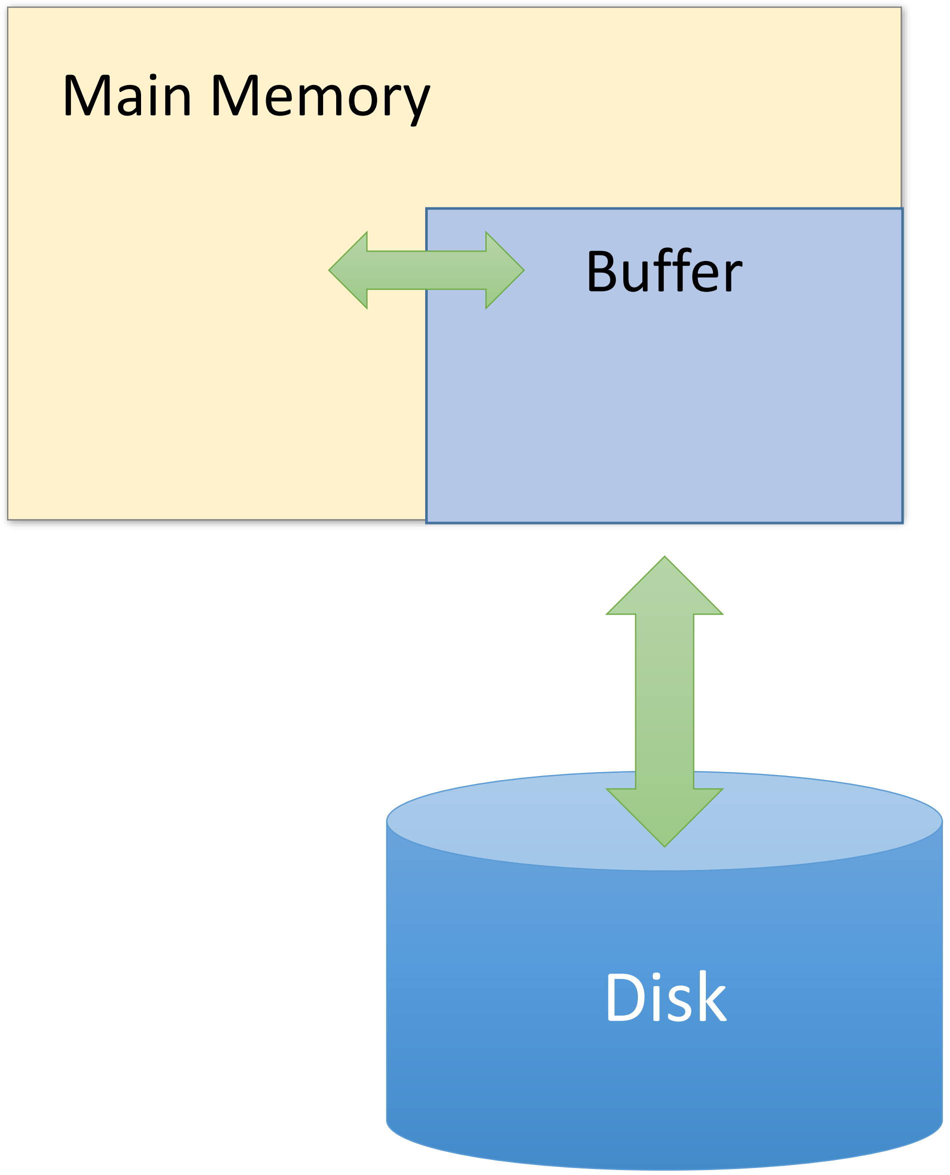
- ***Fast:*** Random access, byte addressable
  - ~10x faster for sequential access
  - ~100,000x faster for random access!
- ***Volatile:*** Data can be lost if e.g. crash occurs, power goes out, etc!
- ***Expensive:*** For $100, get 16GB of RAM vs. 2TB of disk!

The Buffer

- A **buffer** is a region of physical memory used to store *temporary data*

    - *In this lecture:* a region in main memory used to store **intermediate data between disk and processes**

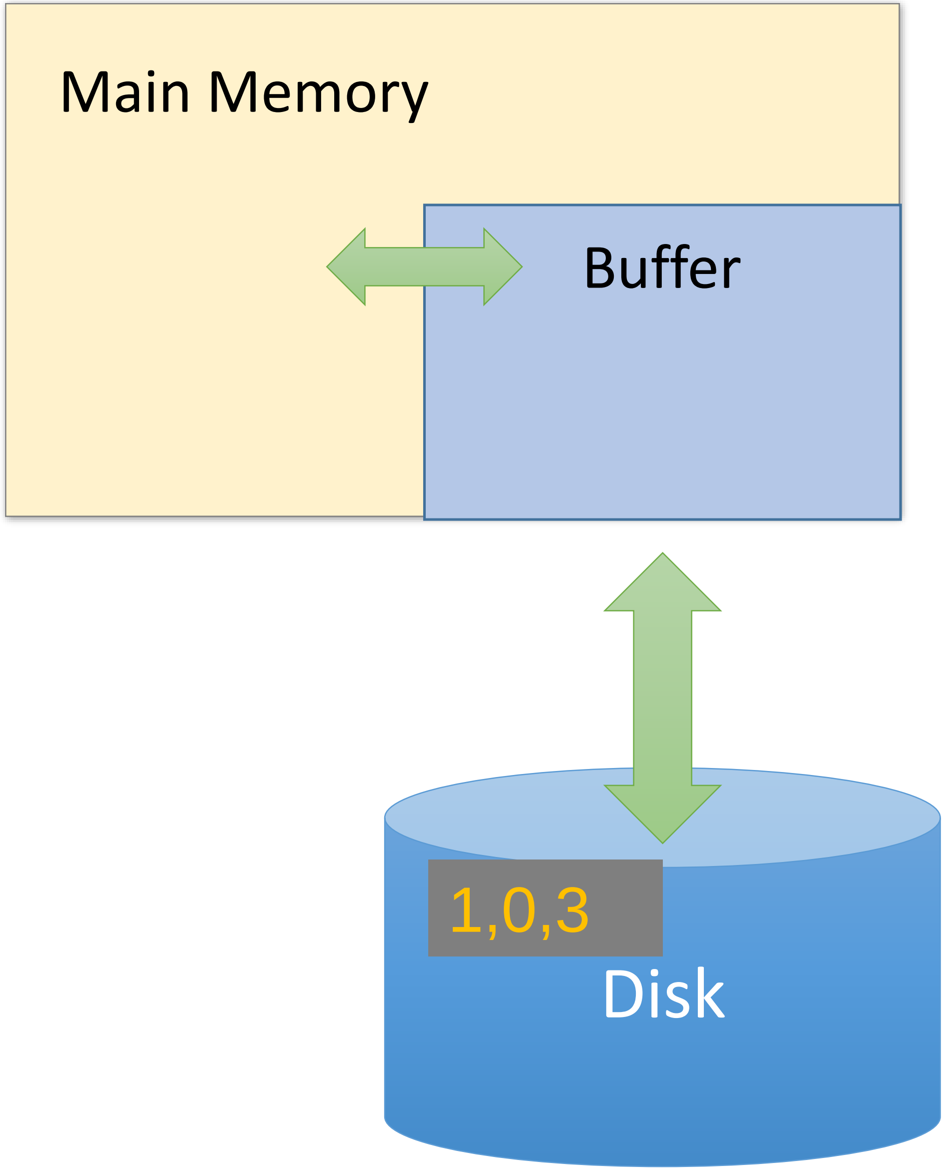
- *Key idea:* Reading / writing to disk is slow- need to cache data!



The (Simplified) Buffer

- In this class: We'll consider a buffer located in **main memory** that operates over **pages** and **files**:

  - <u>**Read(page):**</u> Read page from disk -> buffer *if not already in buffer*



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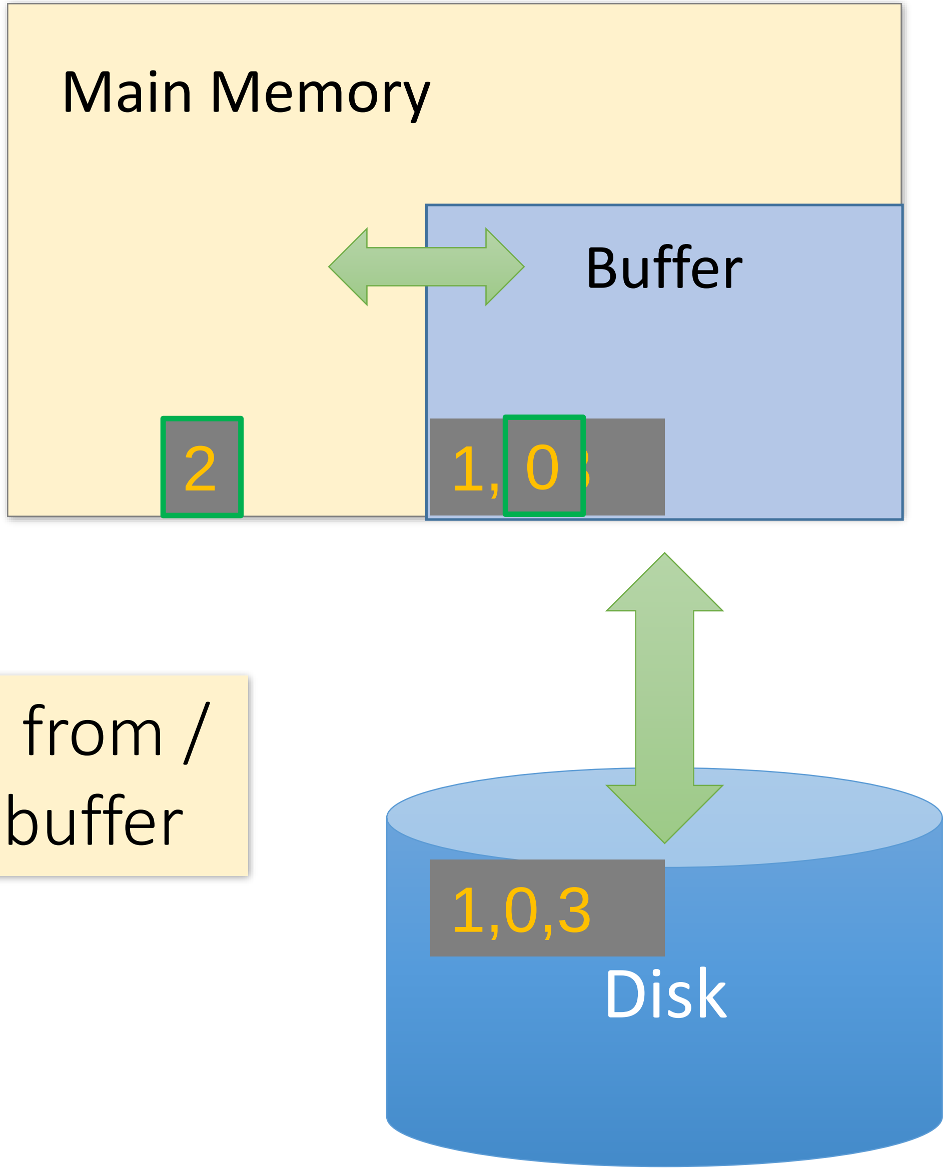
  - **<u>Read(page):</u>** Read page from disk -> buffer *if not already in buffer*

Processes can then read from / write to the page in the buffer



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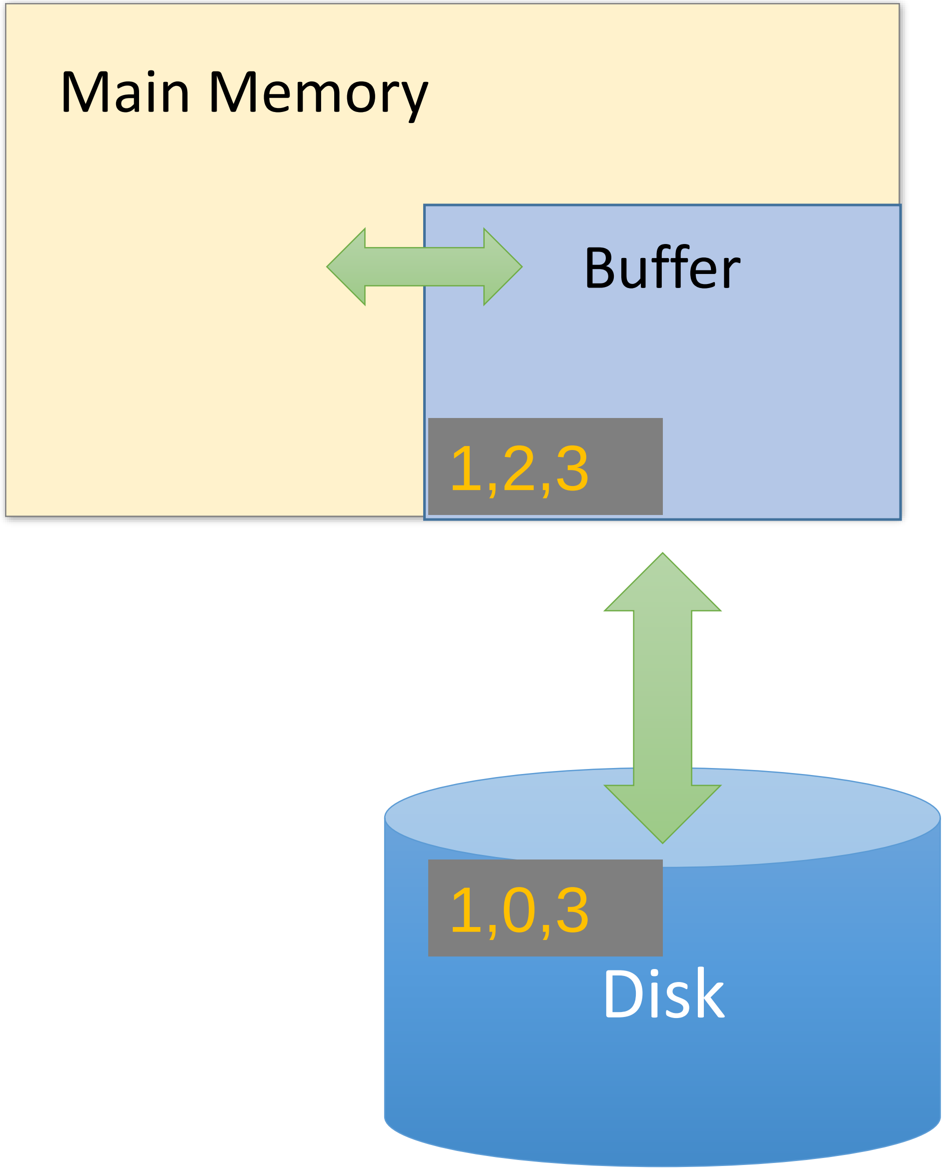
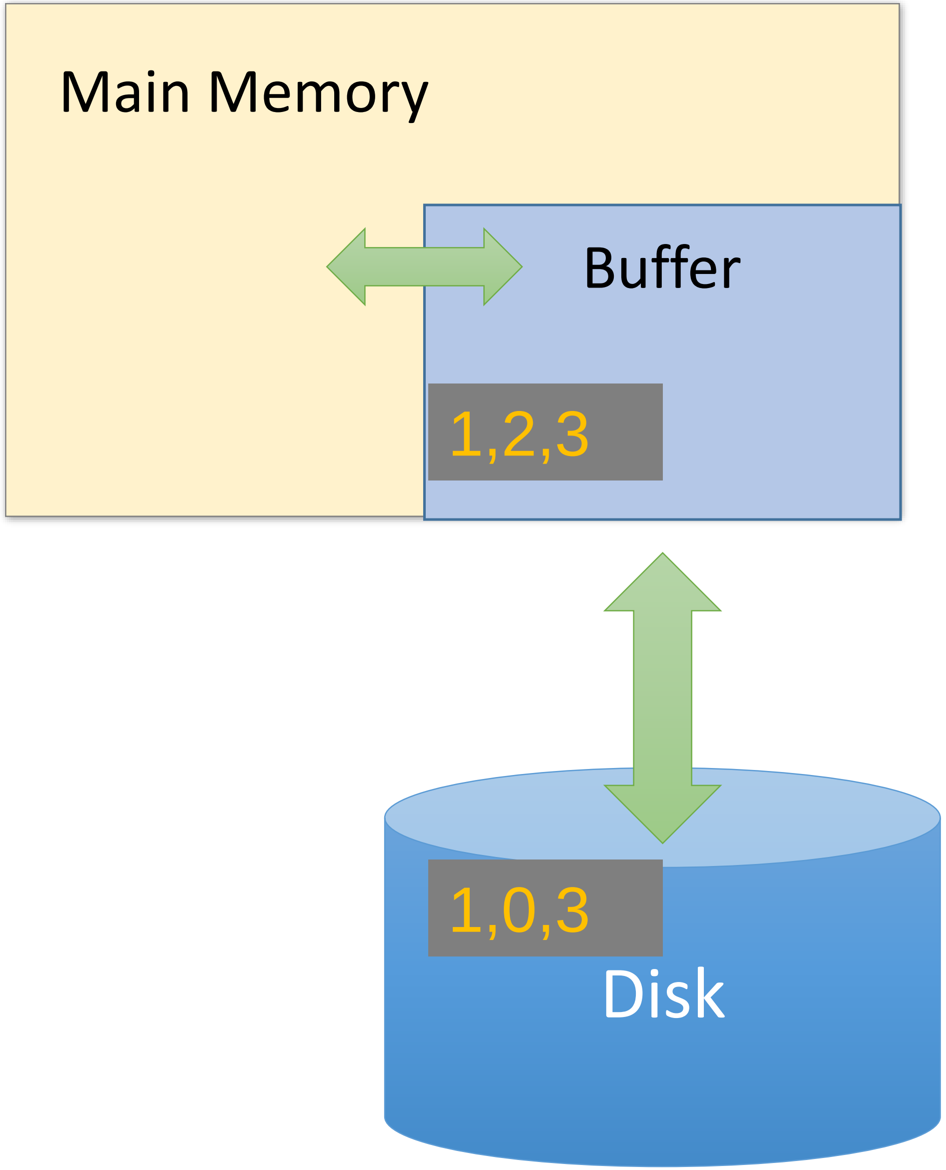
  - **<u>Read(page):</u>** Read page from disk -> buffer *if not already in buffer*
  - **<u>Flush(page):</u>** Evict page from buffer & write to disk



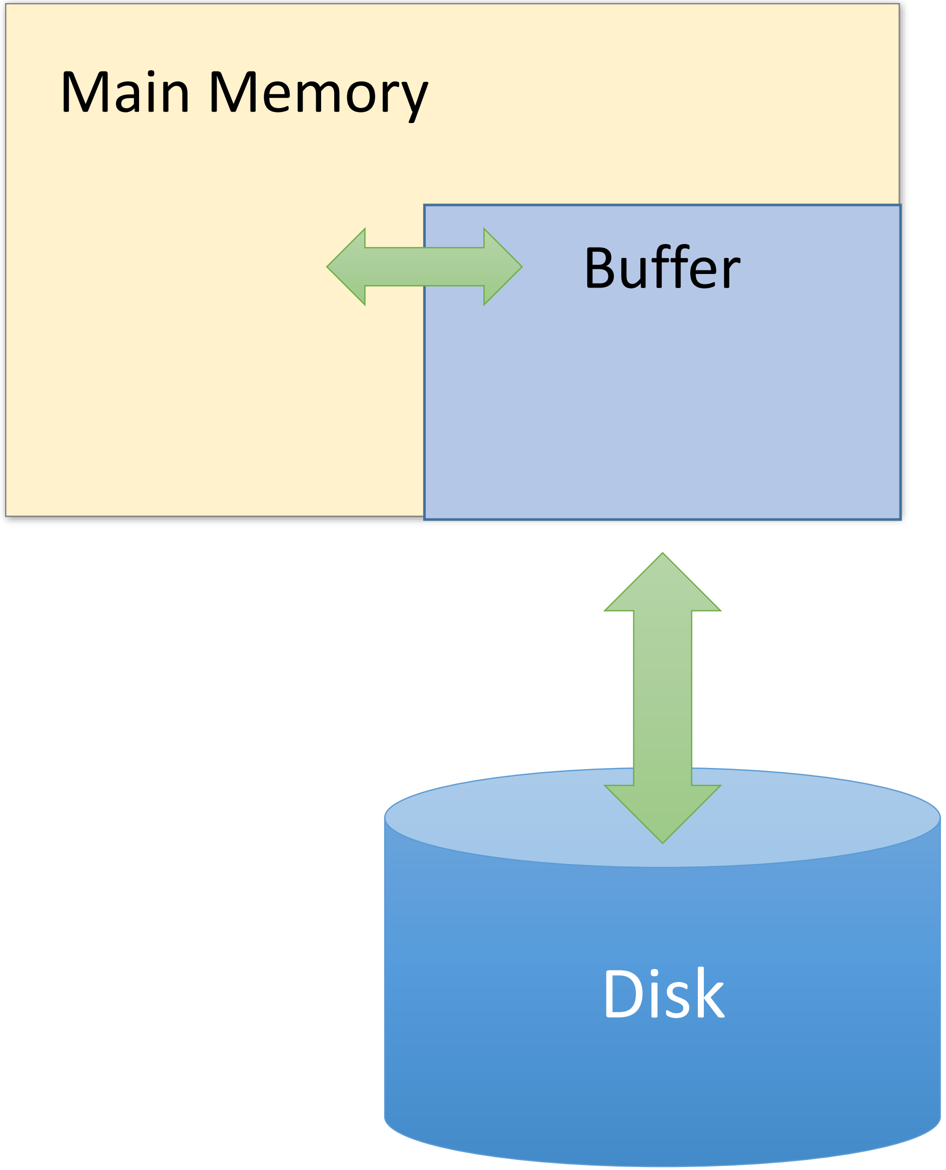
The (Simplified) Buffer

- In this class: We'll consider a buffer located in **main memory** that operates over **pages** and **files**:
  - **<u>Read(page):</u>** Read page from disk -> buffer *if not already in buffer*
  - **<u>Flush(page):</u>** Evict page from buffer & write to disk
  - **<u>Release(page):</u>** Evict page from buffer *without* writing to disk



Managing Disk: The DBMS Buffer

- Database maintains its own buffer
  - Why? The OS already does this…
  - DB knows more about access patterns.
    - Watch for how this shows up! (cf. *Sequential Flooding*)
  - Recovery and logging require ability to **flush** to disk.



When a Page is Requested ...

- Buffer pool information "table" contains:
  <frame#, pageid, pin_count, dirty>

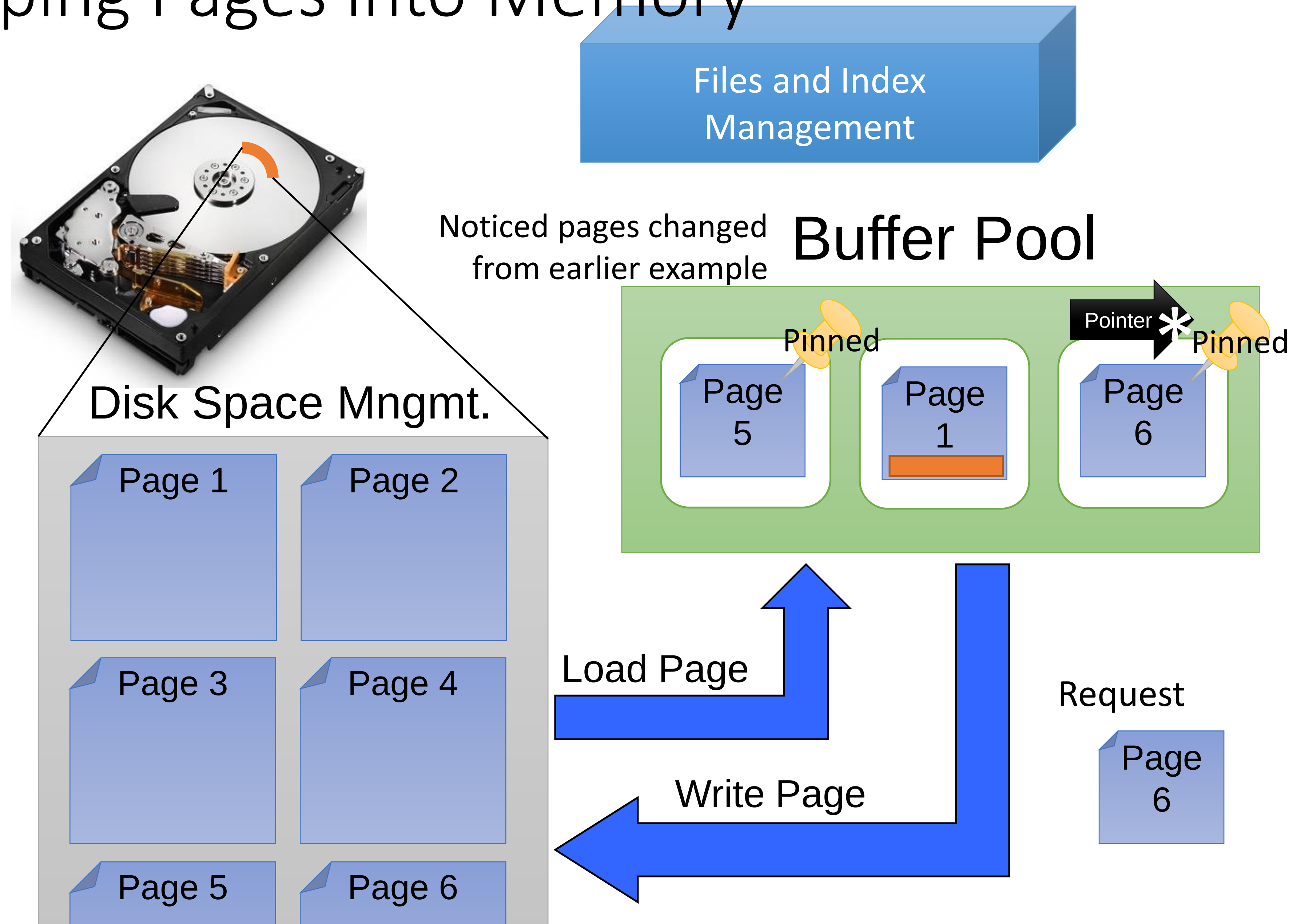
1. If requested page is not in pool:
   a. Choose a frame for *replacement.*
      Only "un-pinned" pages are candidates!
   b. If frame "dirty", write current page to disk
   c. Read requested page into frame

2. *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!

Mapping Pages into Memory



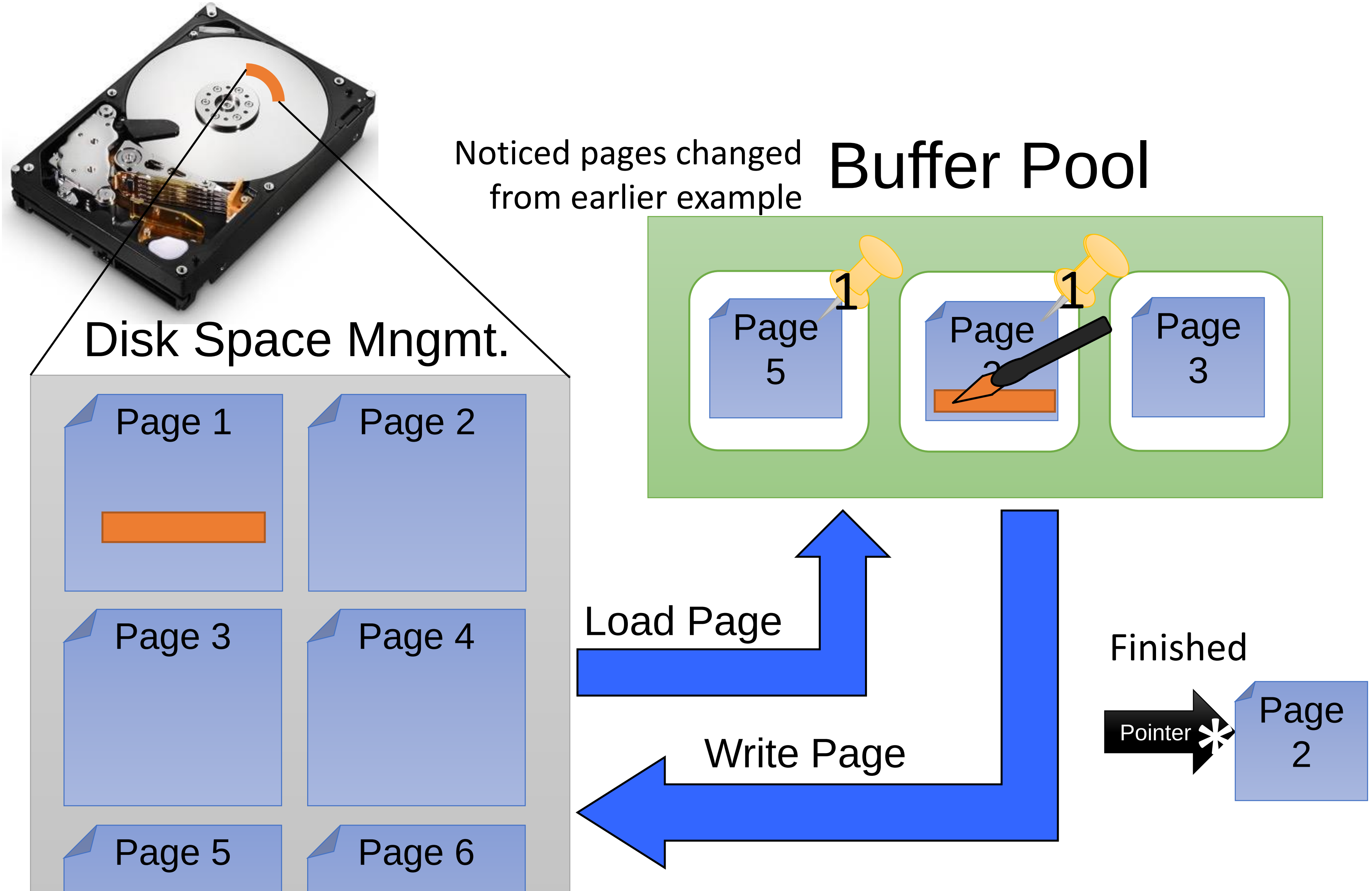
After Requestor Finishes

- Requestor of page must:
  1. indicate whether page was modified via *dirty* bit.
  2. *unpin* it (soon preferably!) why?

- Page in pool may be requested many times,
  - a *pin count* is used.
  - To pin a page: pin_count++
  - A page is a candidate for replacement iff
    pin count == 0 (“unpinned”)

- CC & recovery may do additional I/Os upon replacement.
  - *Write-Ahead Log* protocol; more later!

Mapping Pages into Memory



Page Replacement Policy

- Page is chosen for replacement by a *replacement policy:*
  - Least-recently-used (LRU), Clock
  - Most-recently-used (MRU)

- Policy can have big impact on #I/O’s;
  - Depends on the *access pattern.*

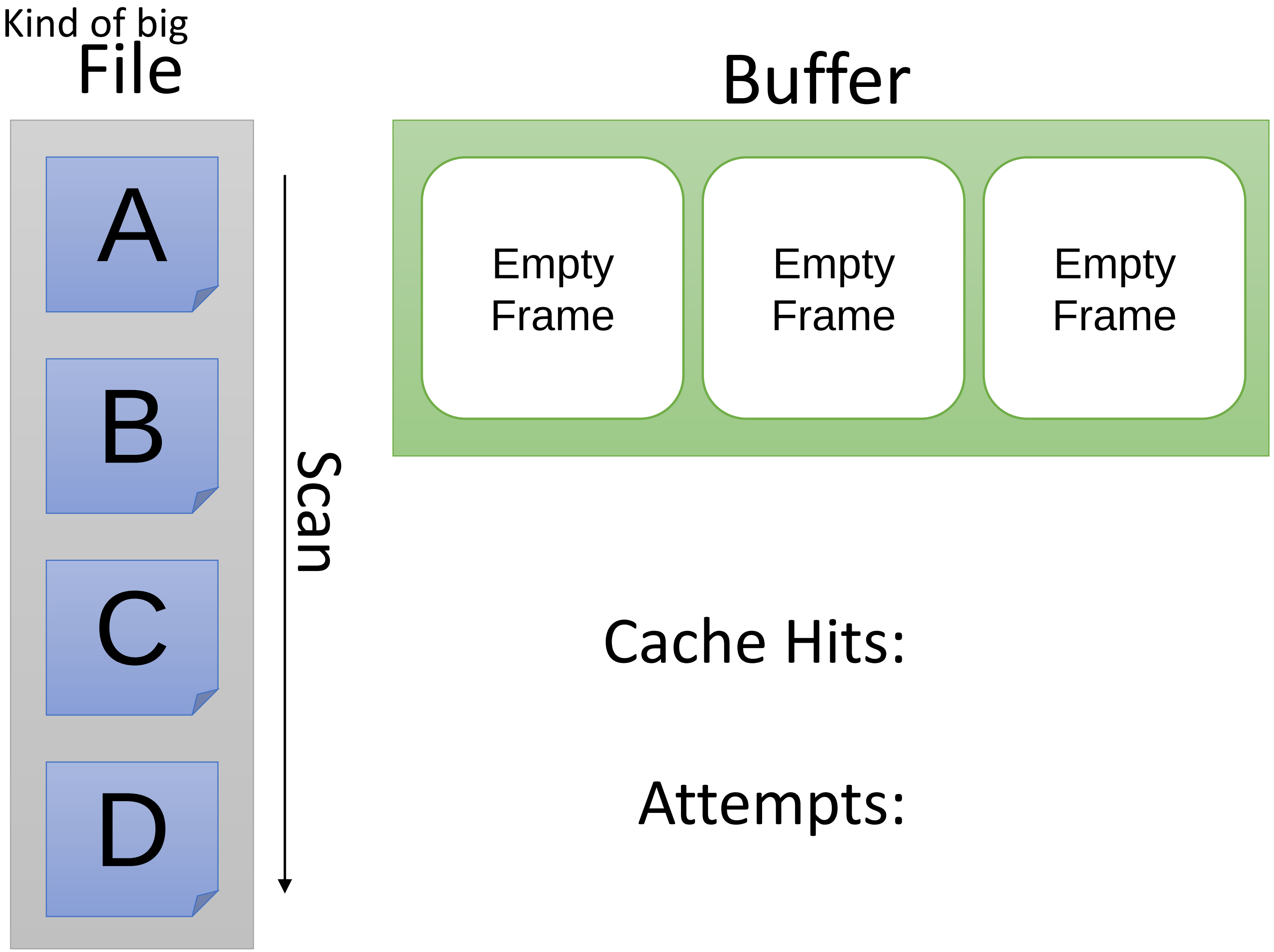
LRU Replacement Policy

- *Least Recently Used (LRU)*
  - Pinned Frame: not available to replace
  - track time each frame last *unpinned* (end of use)
  - replace the frame which least recently unpinned
- Very common policy: intuitive and simple
  - Works well for repeated accesses to popular pages (temporal locality)
  - *Can be costly. Why?*
    - *Need to maintain heap data-structure*
    - *Solution?*

Is LRU/Clock Always Best?

- Very common policy: *intuitive* and *simple*
- Works well for repeated accesses to popular pages
  - temporal locality
- LRU can be costly → Clock policy is cheap
- When might it perform poorly
  - *What about repeated scans of big files?*

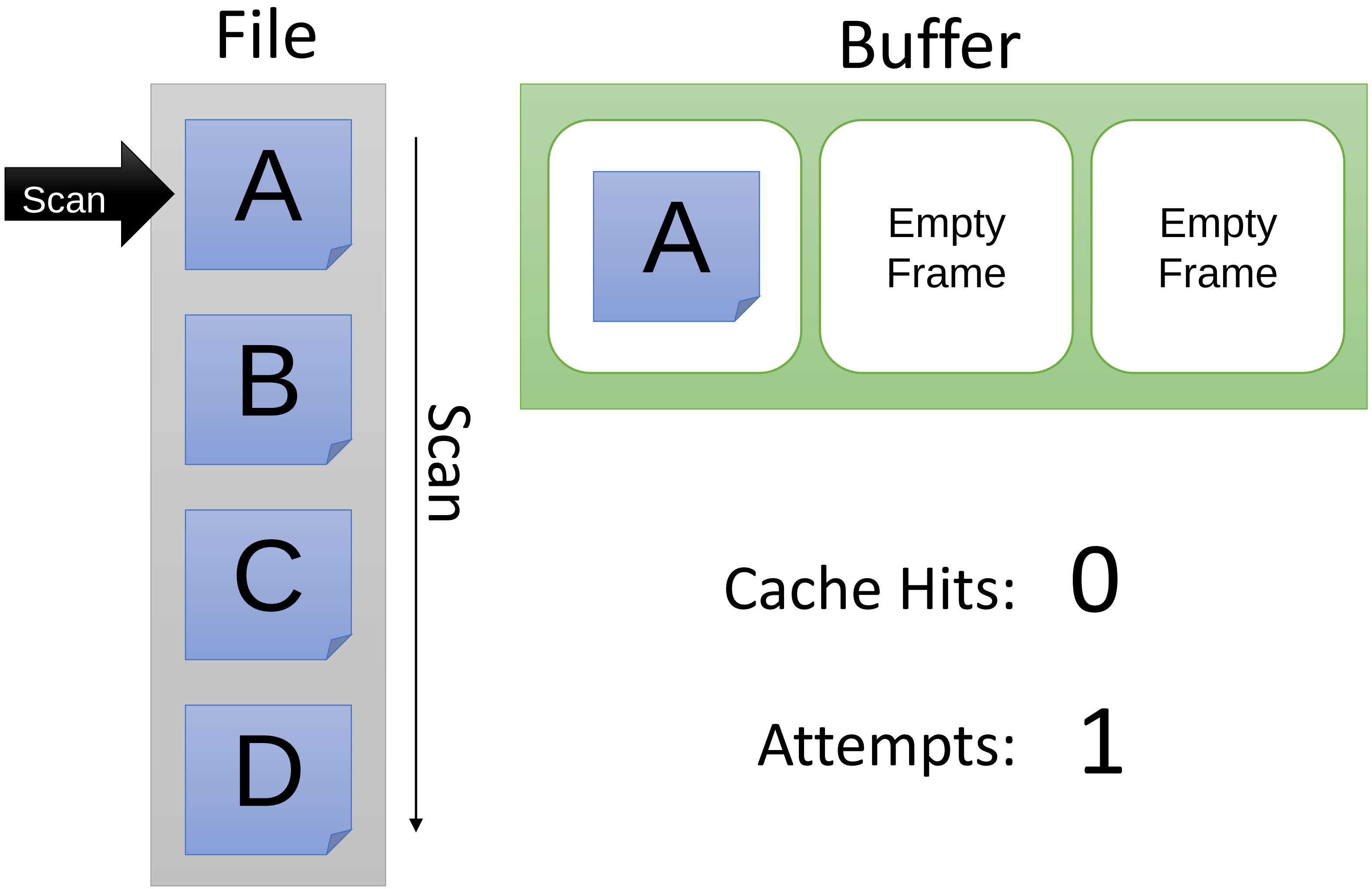
Repeated Scan of Big File (LRU)



Cache Hits:

Attempts:

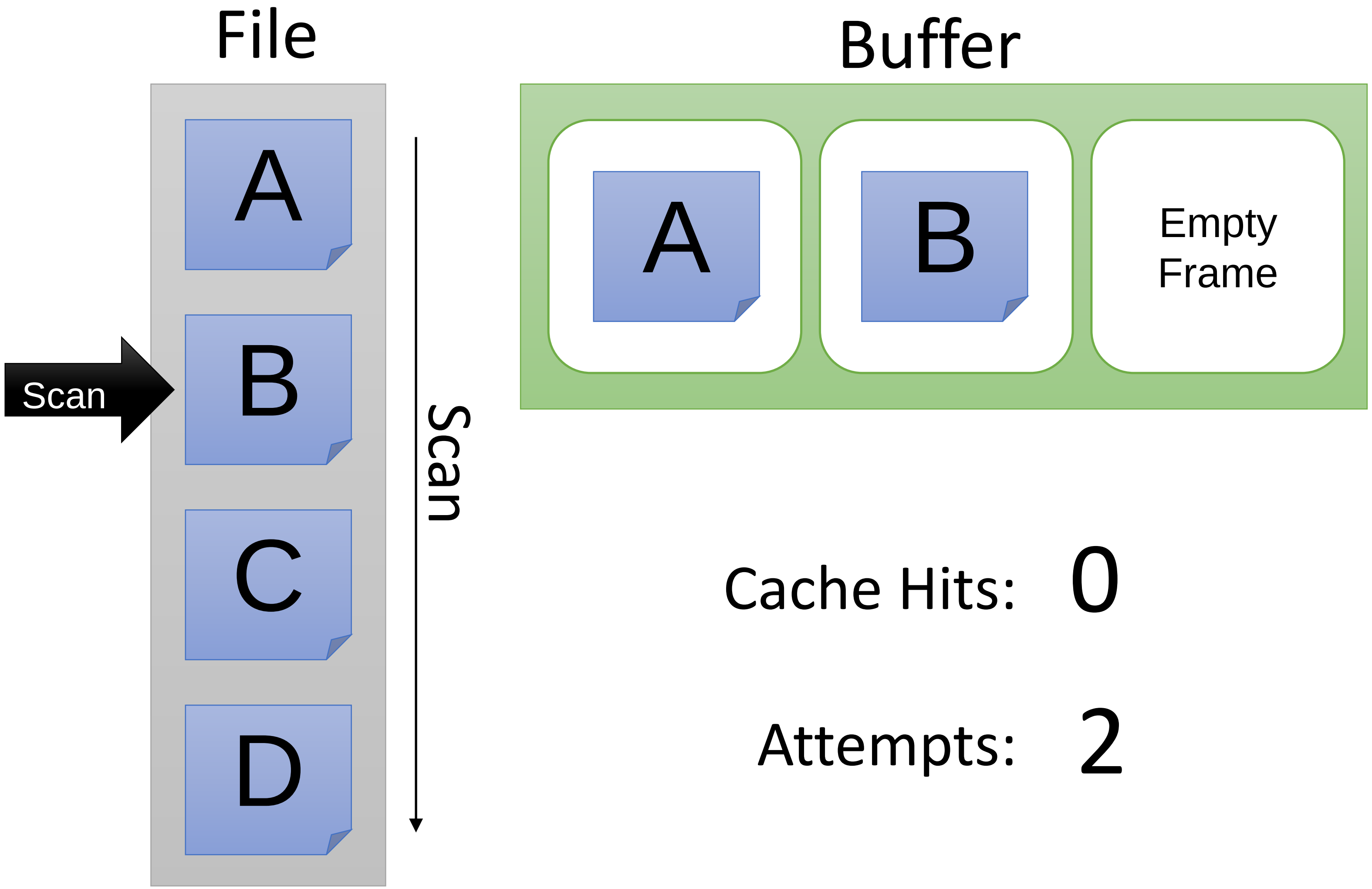
Repeated Scan of Big File (LRU)



Cache Hits: 0

Attempts: 1

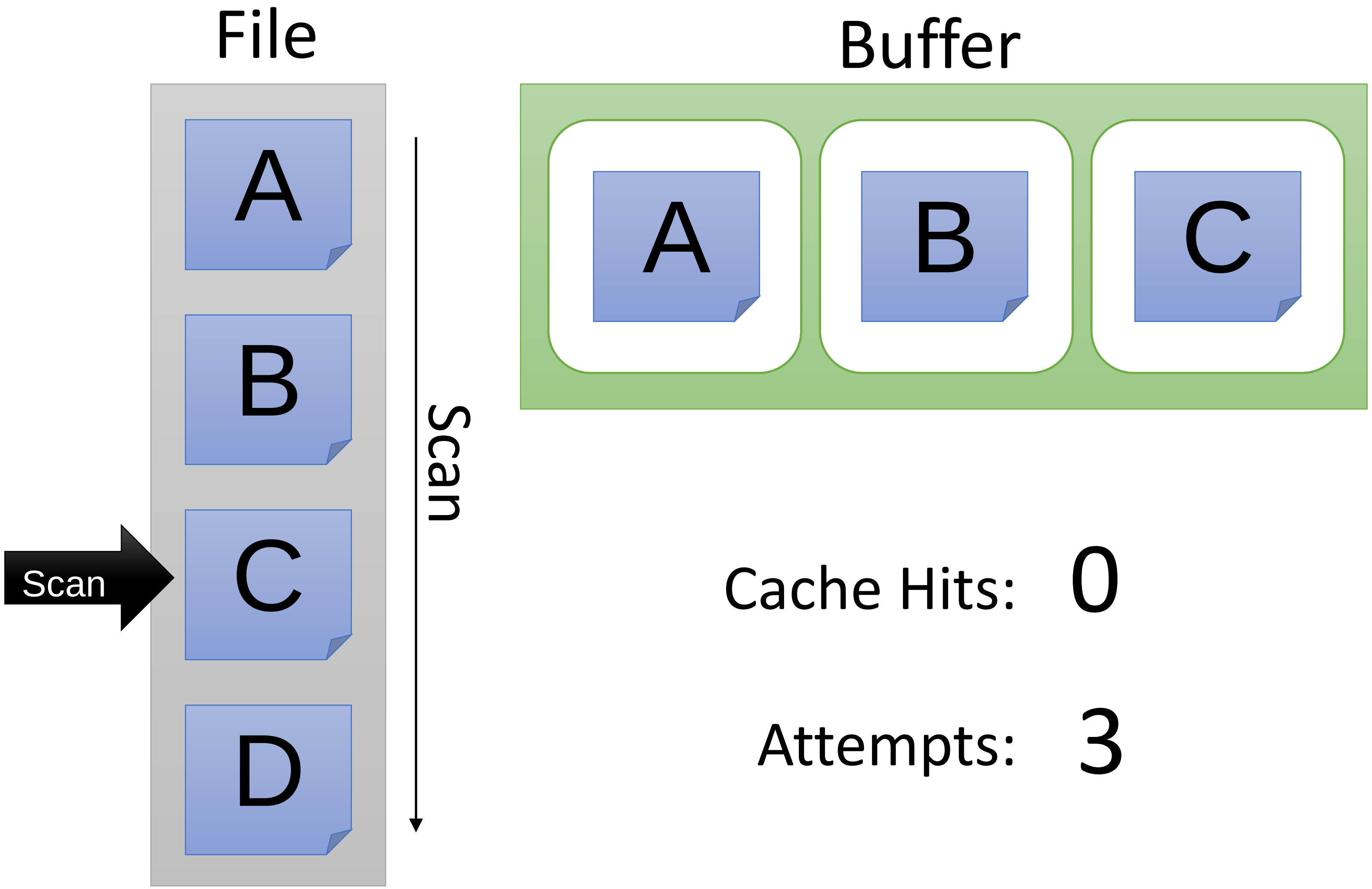
Repeated Scan of Big File (LRU)



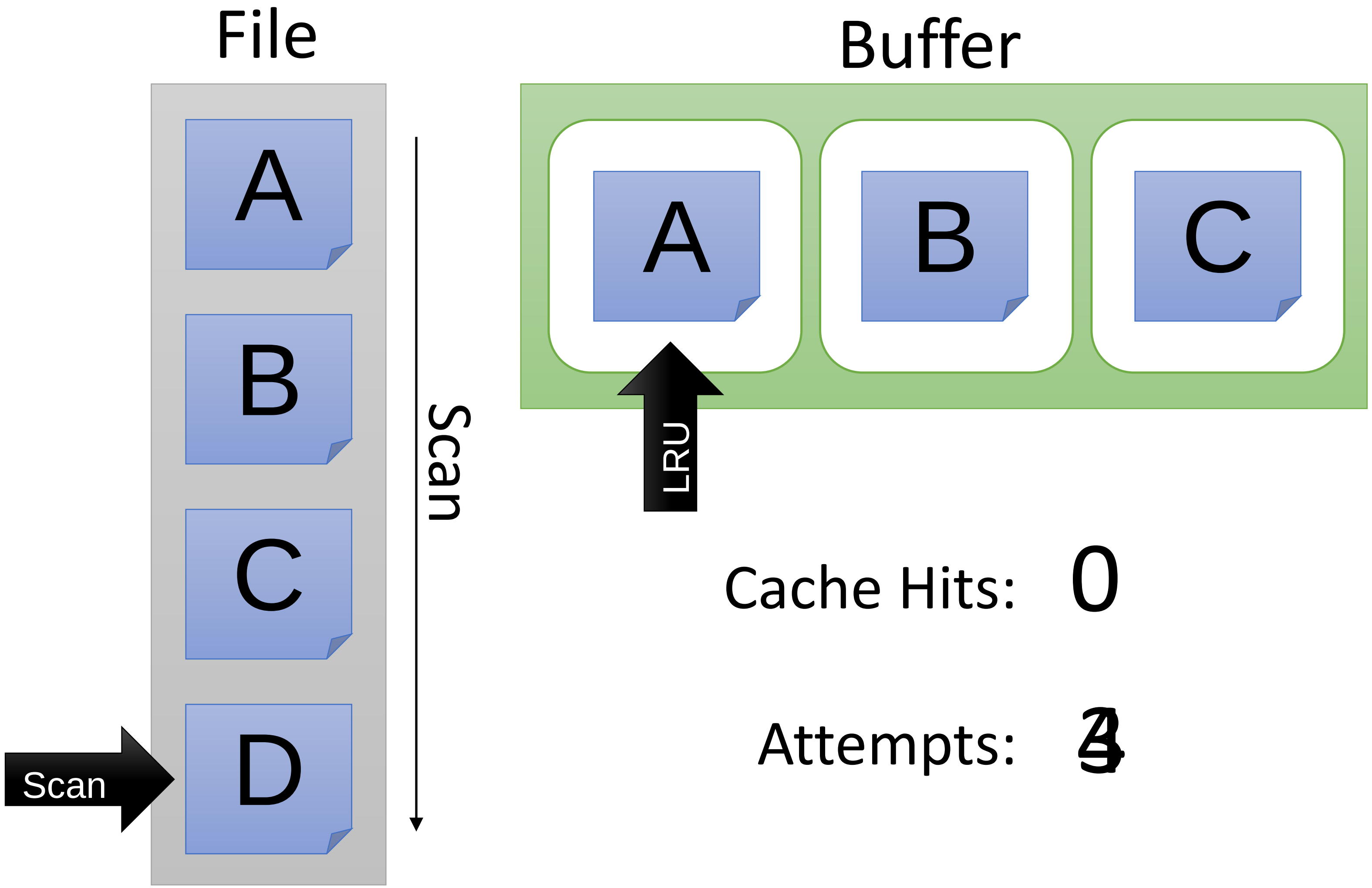
Cache Hits: 0

Attempts: 2

Repeated Scan of Big File (LRU)



Repeated Scan of Big File (LRU)



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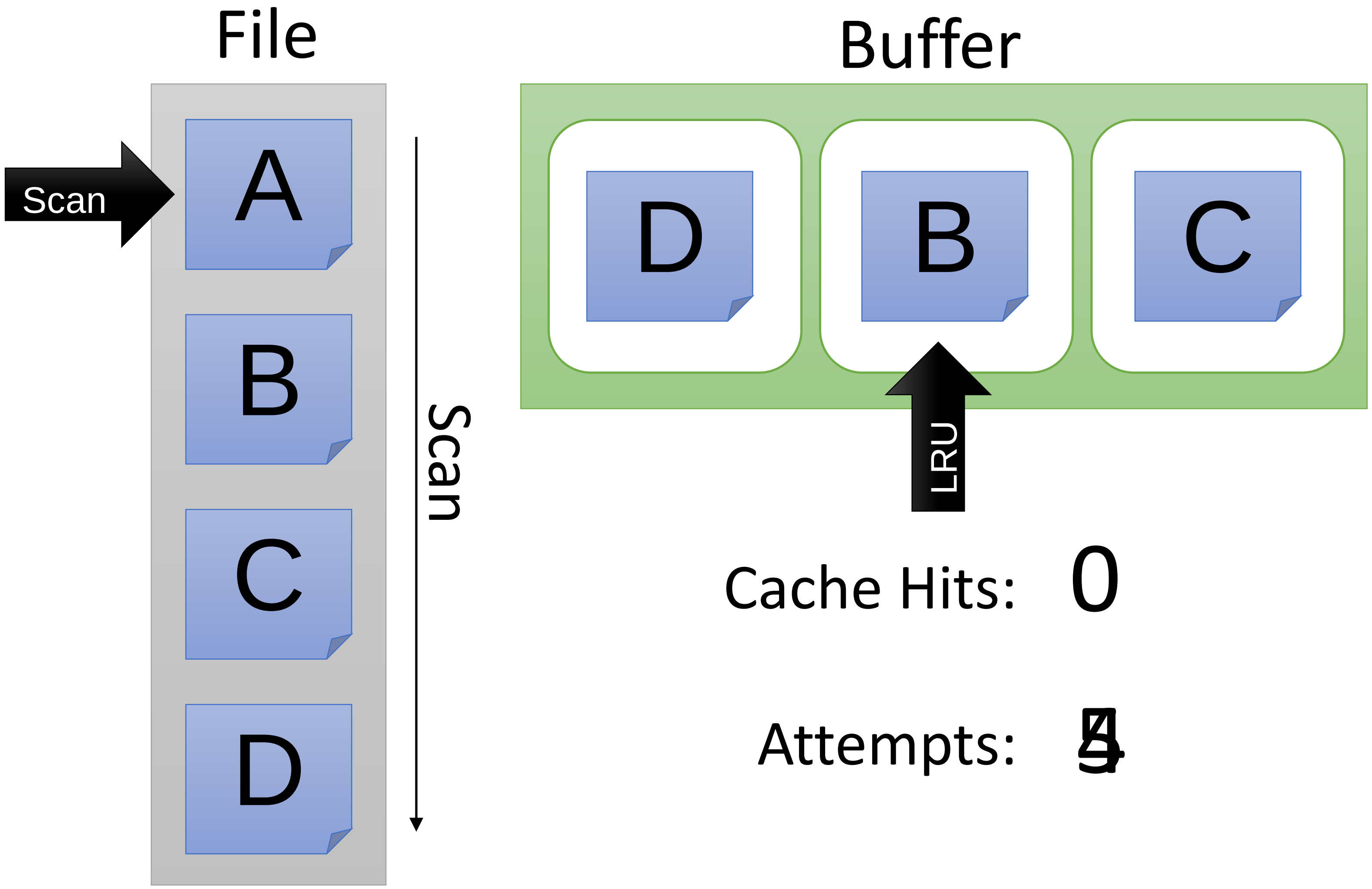

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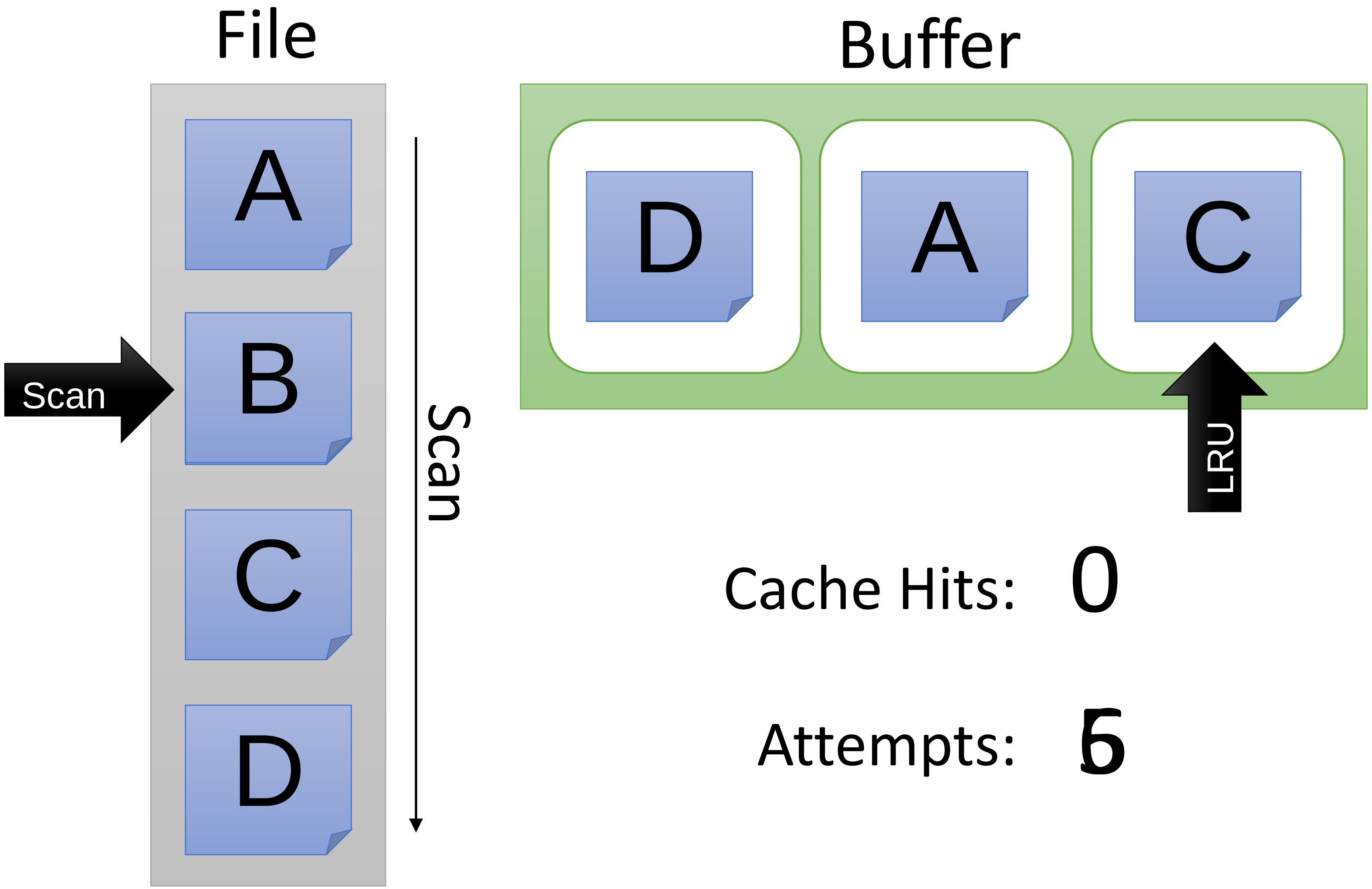

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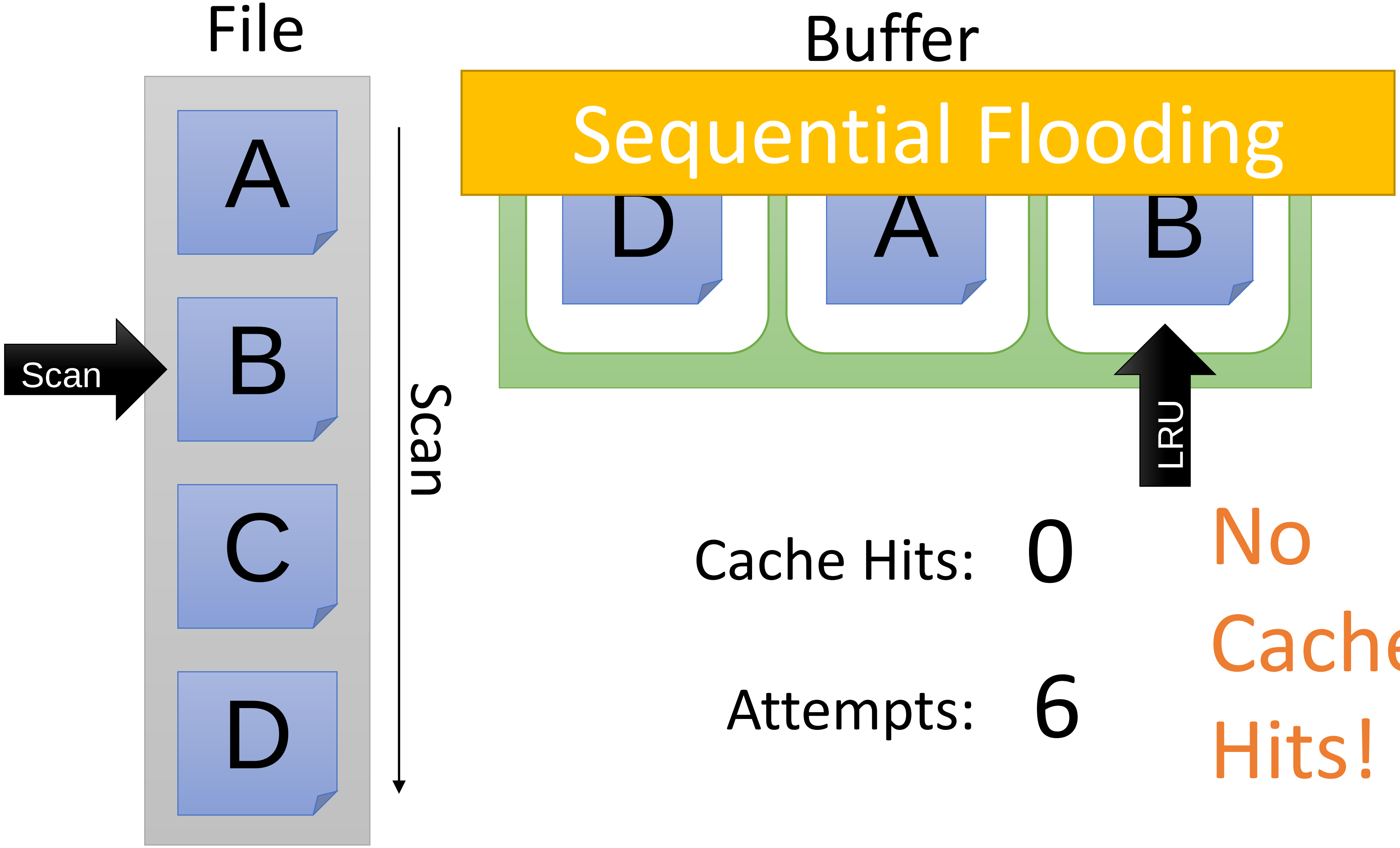


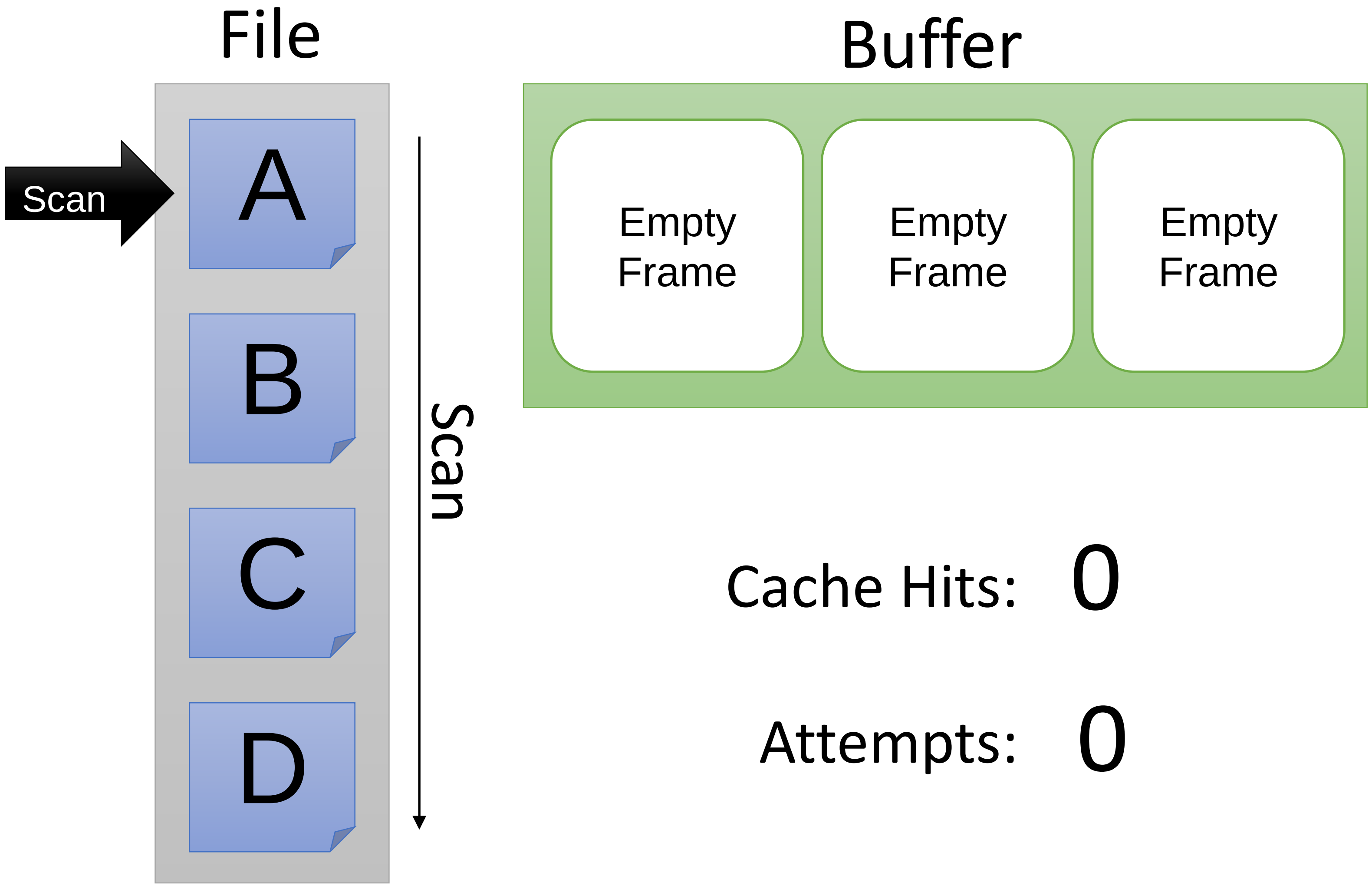
Cache Hits: 0

Attempts: 6

No Cache Hits!

Repeated Scan of Big File **(MRU)**

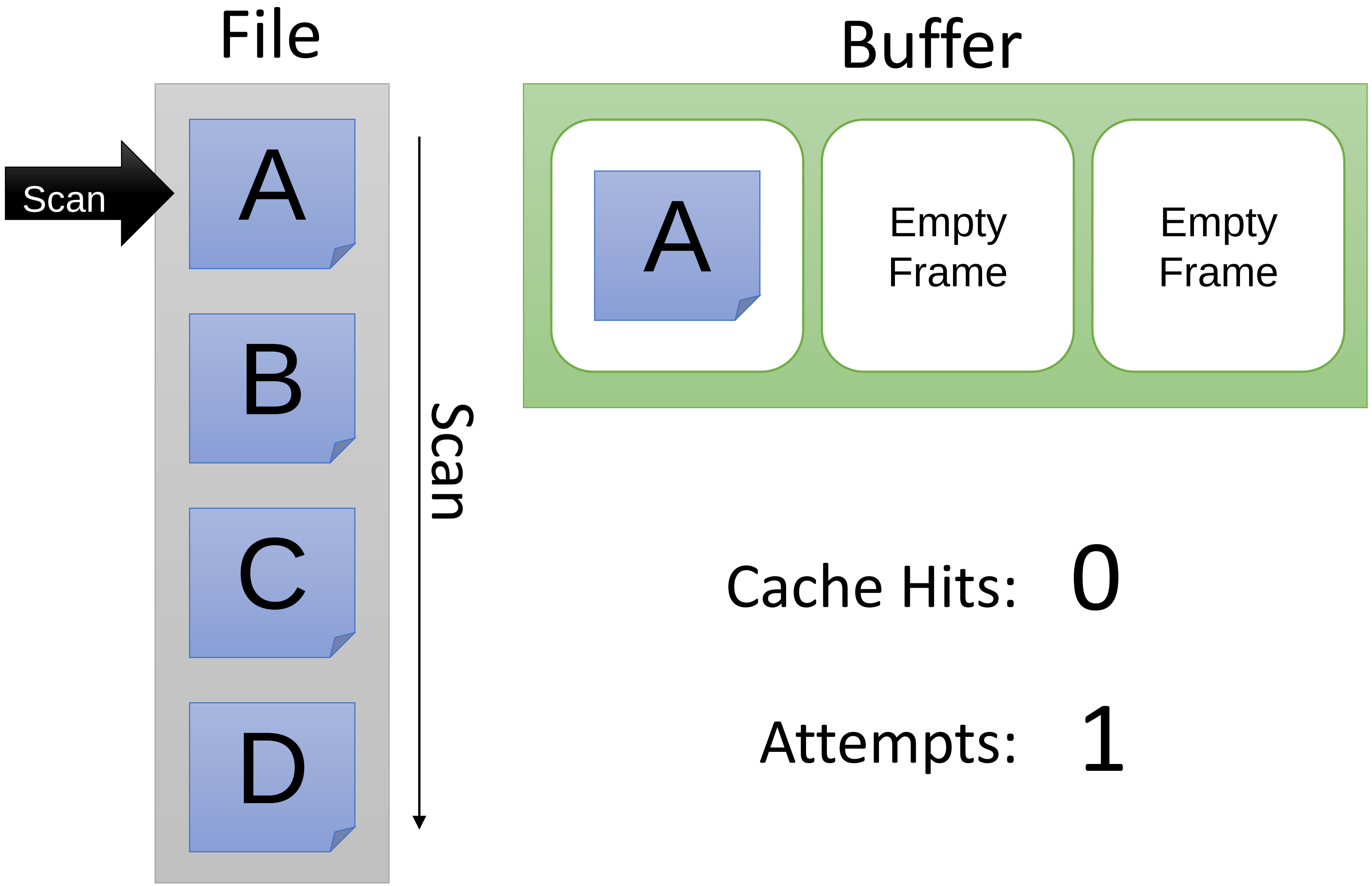
Most Recently Used



Cache Hits: 0

Attempts: 0

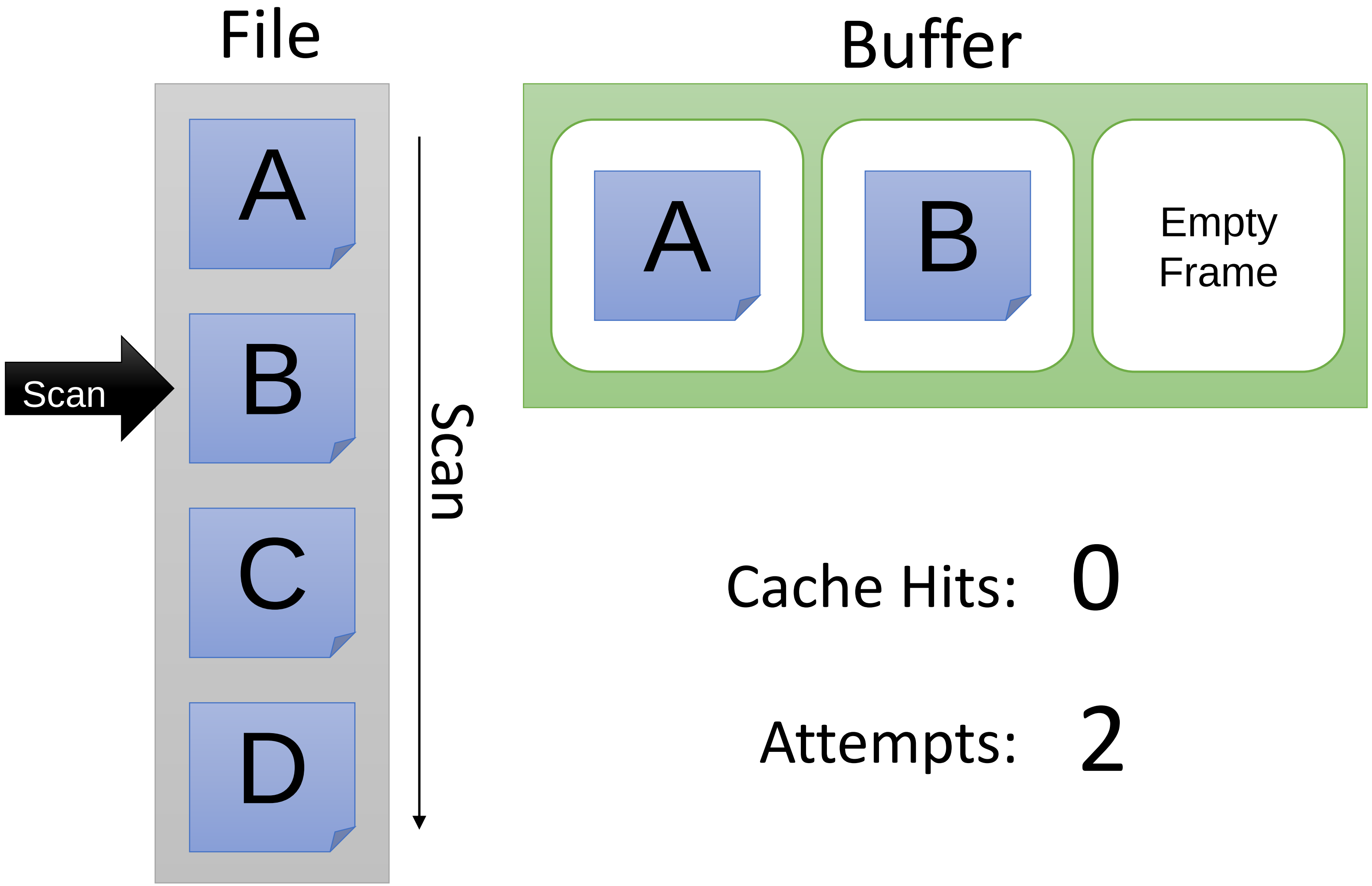
Repeated Scan of Big File (MRU)



Cache Hits: 0

Attempts: 1

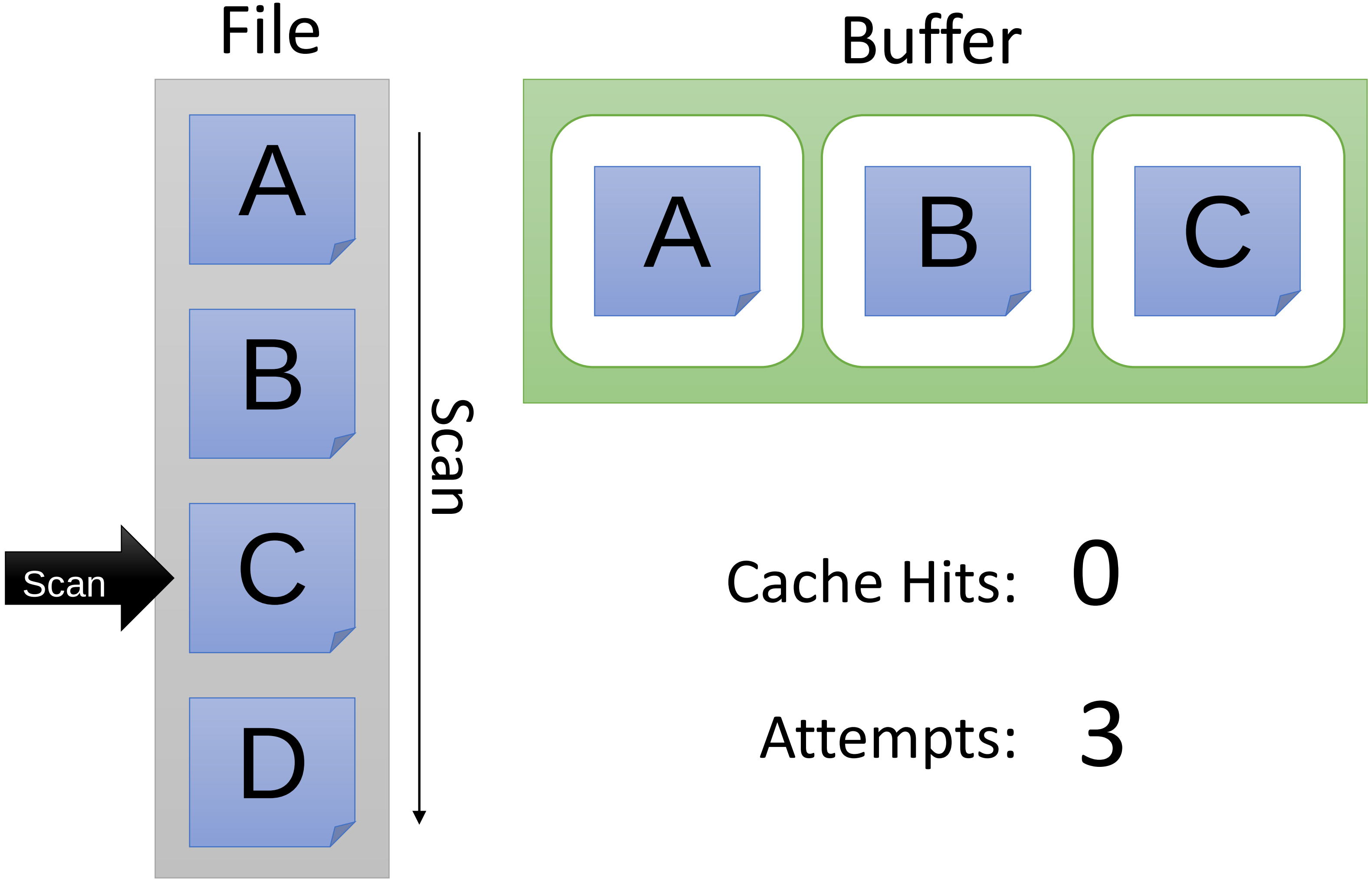
Repeated Scan of Big File (MRU)



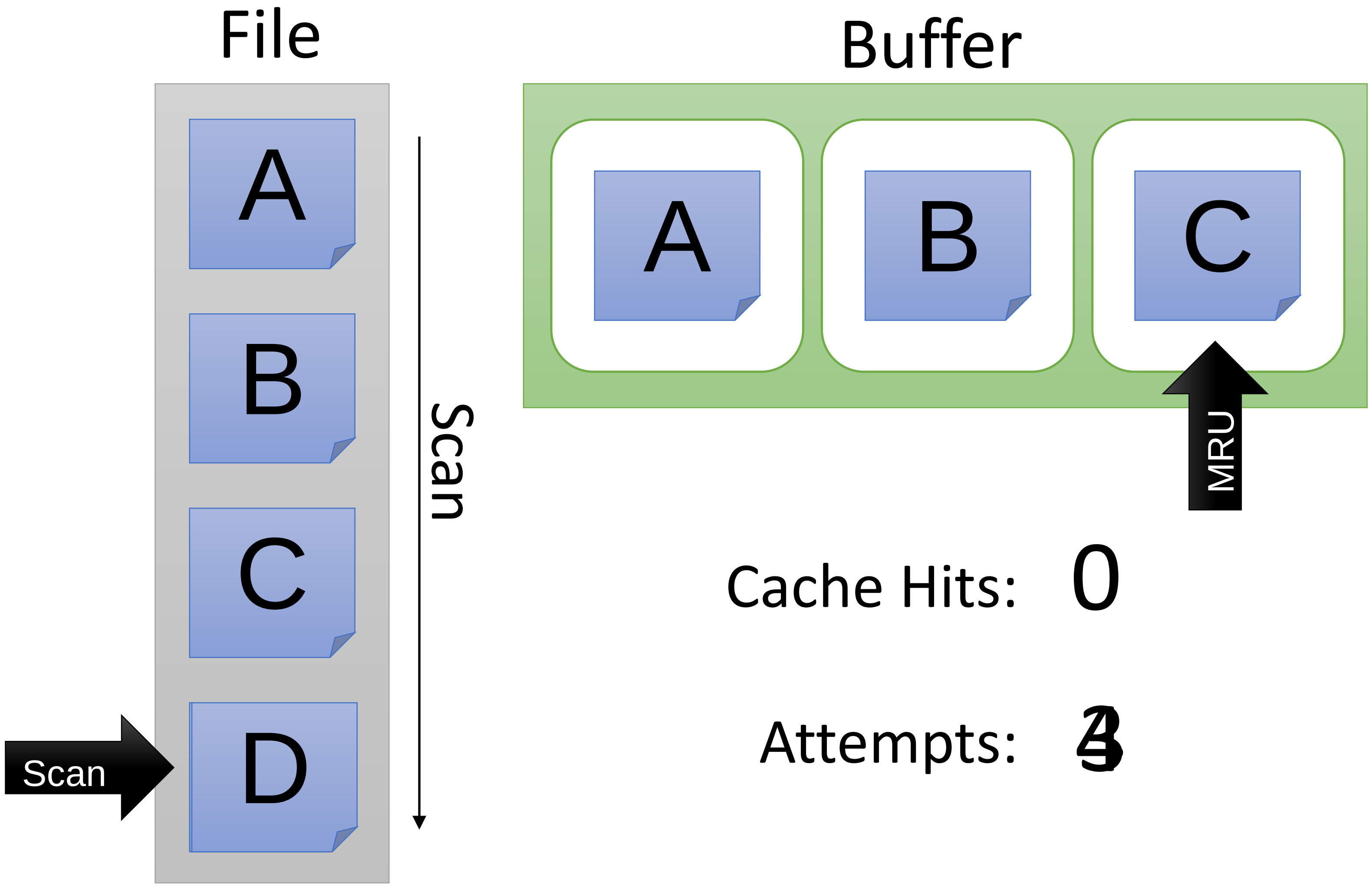
Cache Hits: 0

Attempts: 2

Repeated Scan of Big File (MRU)



Repeated Scan of Big File (MRU)



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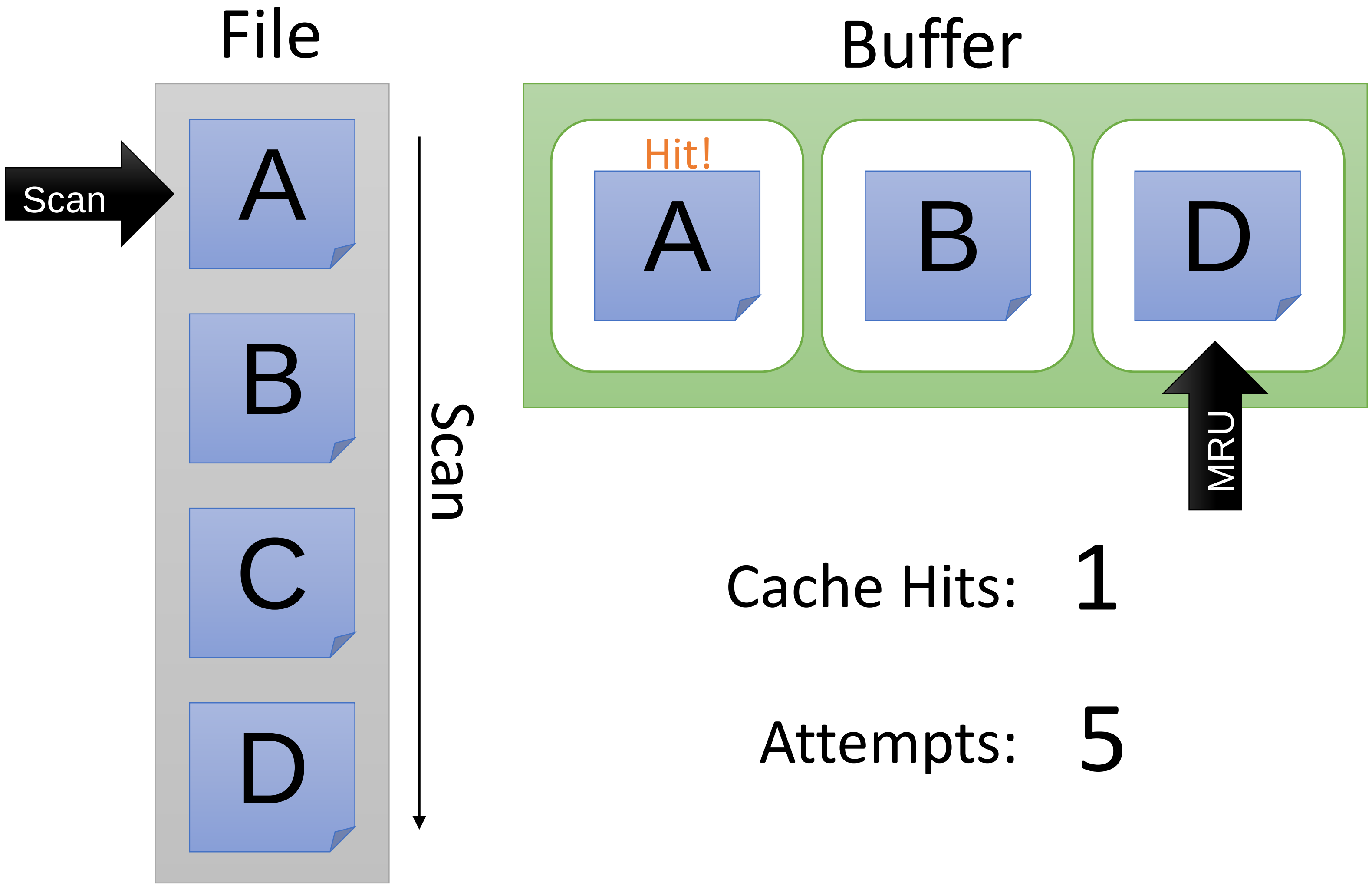
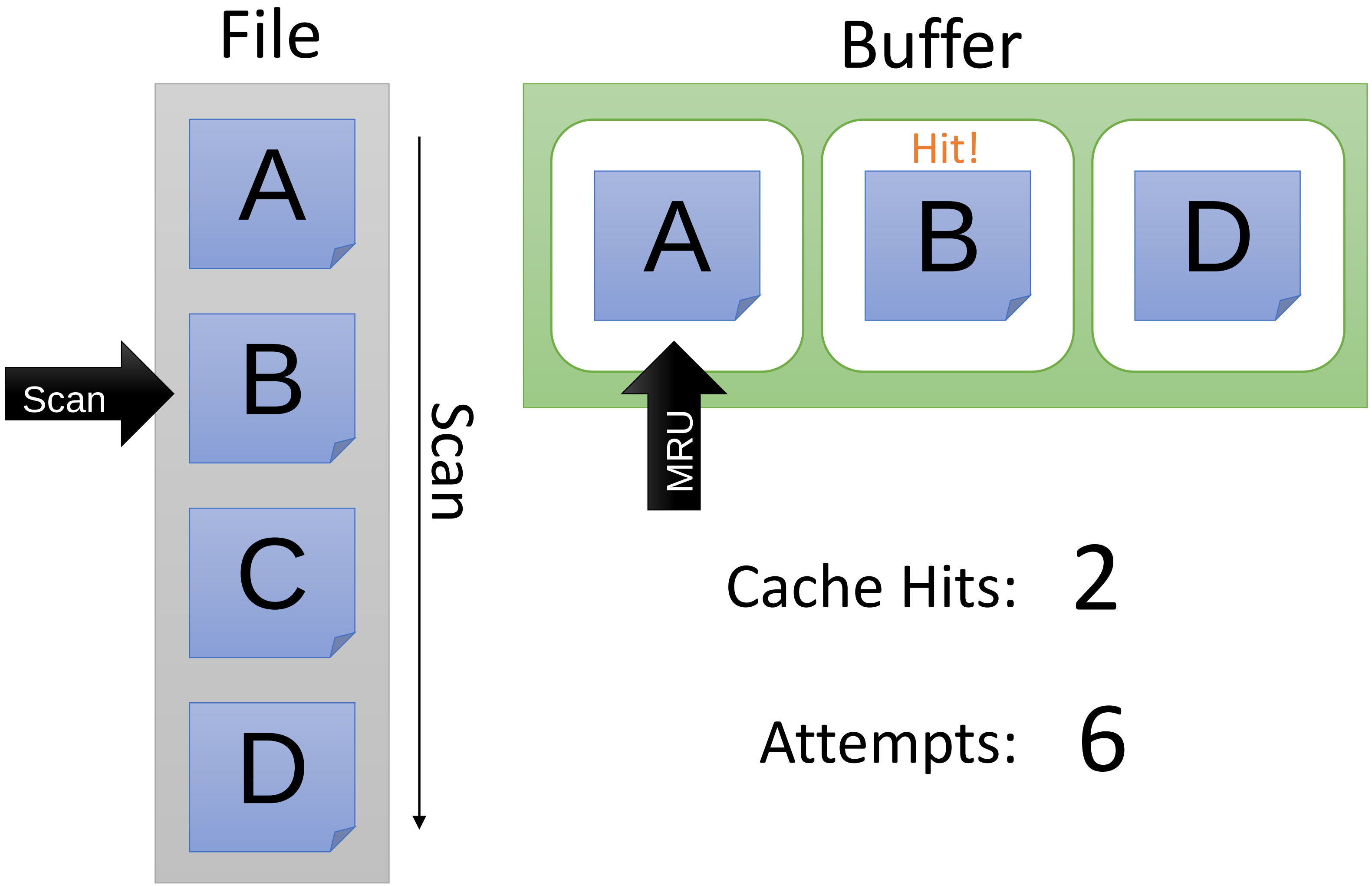


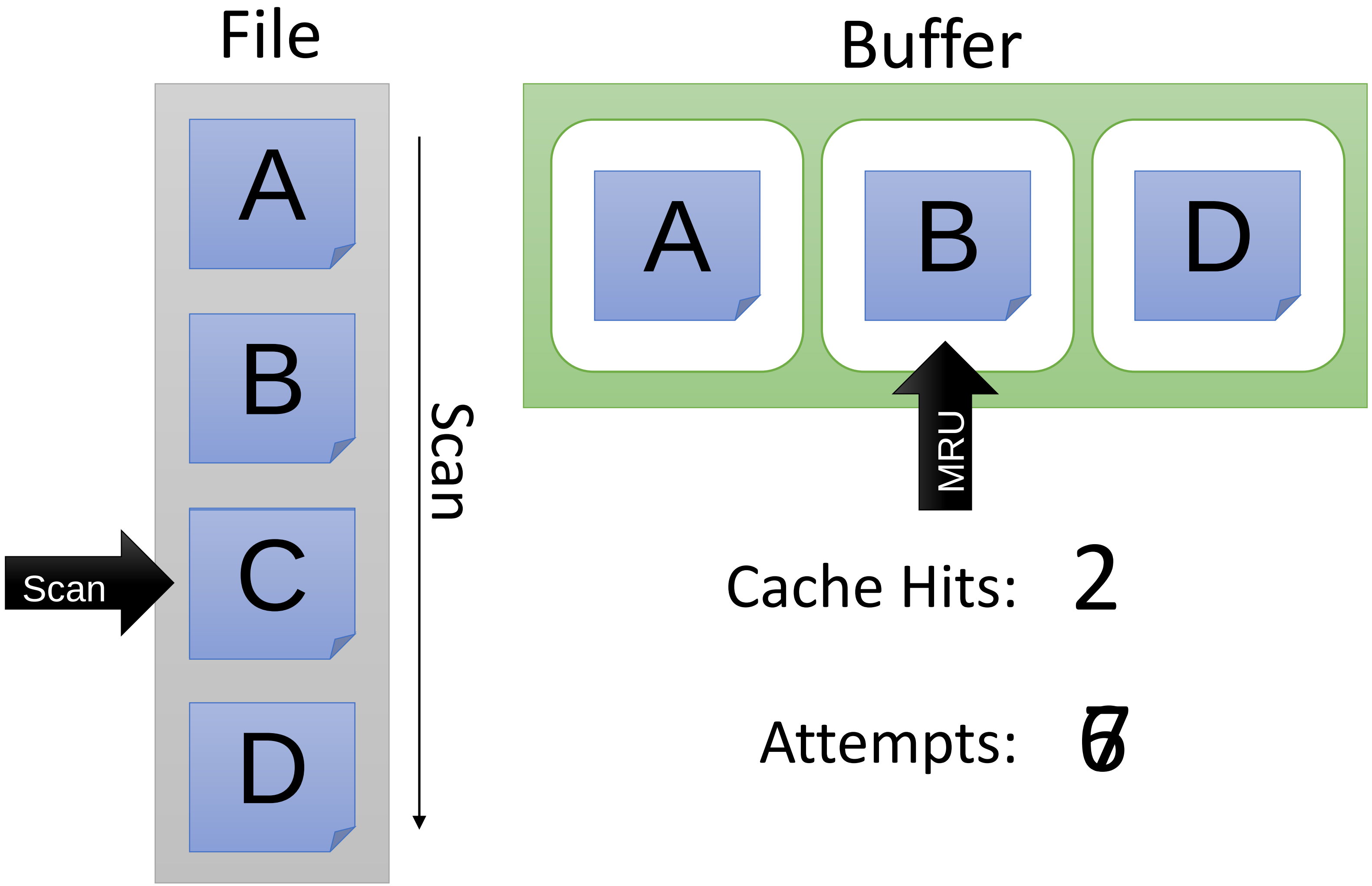
Cache Hits: 1

Attempts: 5

Repeated Scan of Big File (MRU)



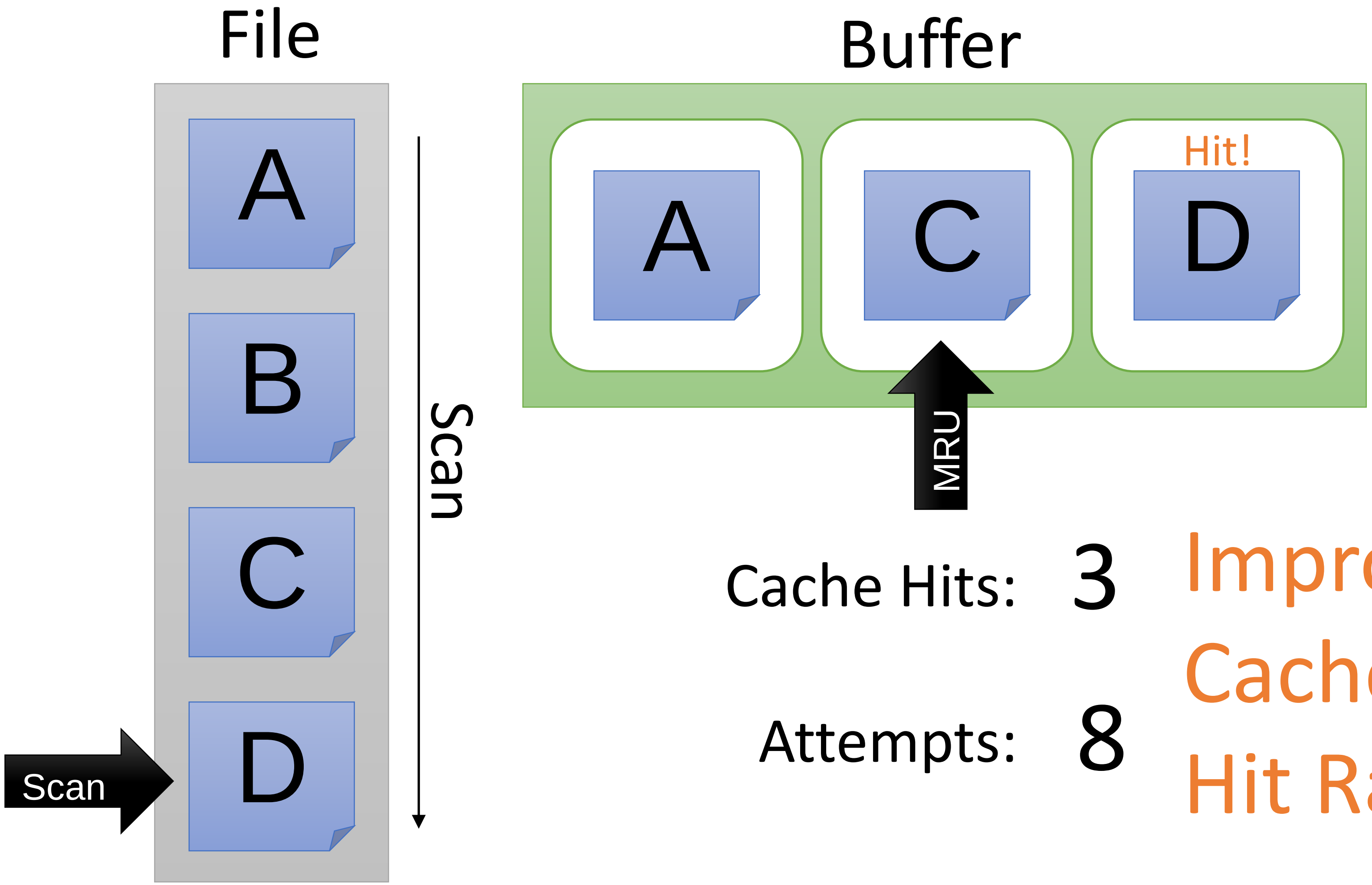
Repeated Scan of Big File (MRU)



Cache Hits: 2

Attempts: 7

Repeated Scan of Big File (MRU)

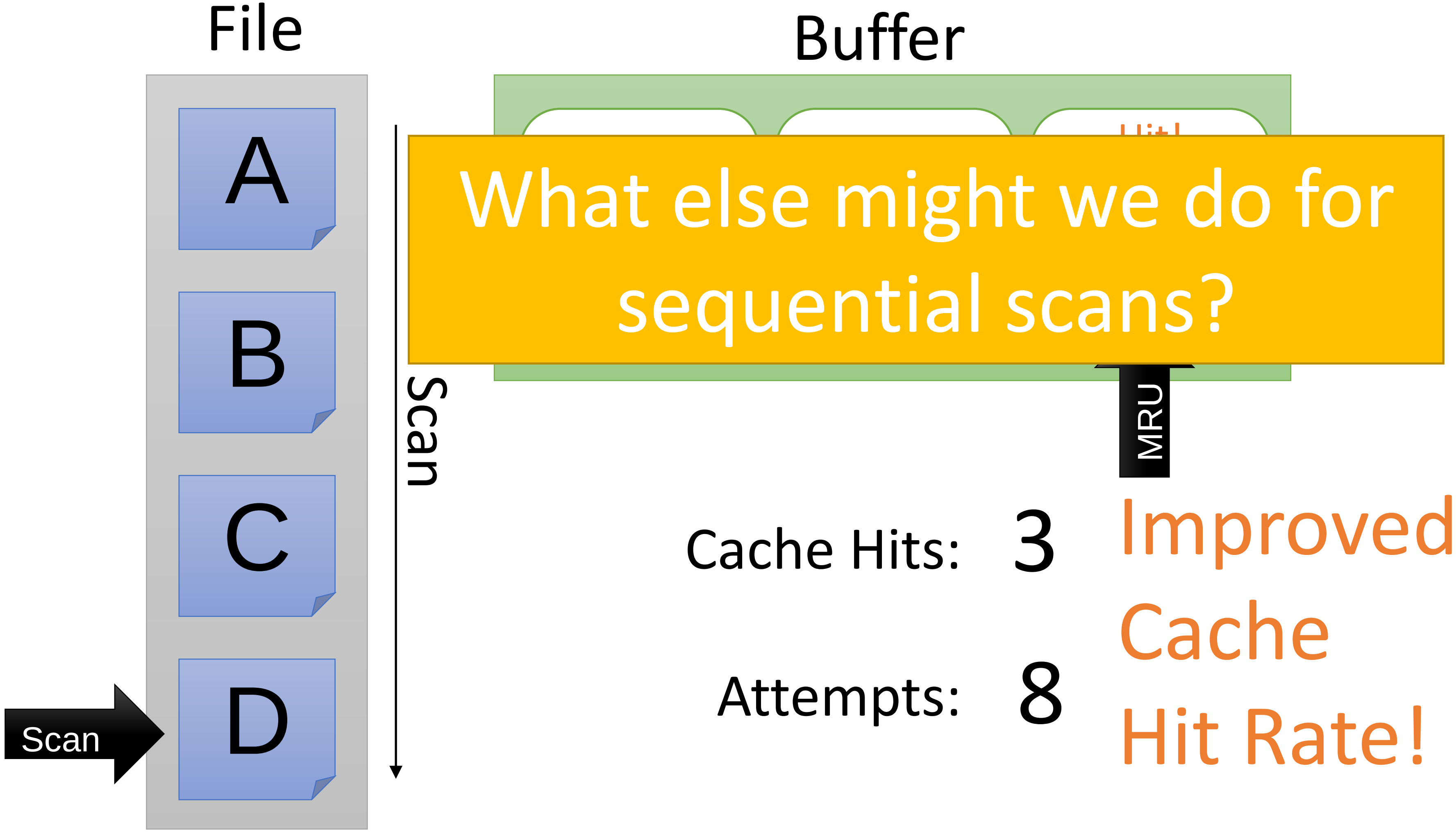


Cache Hits: 3

Attempts: 8

Improved Cache Hit Rate!

Repeated Scan of Big File (MRU)

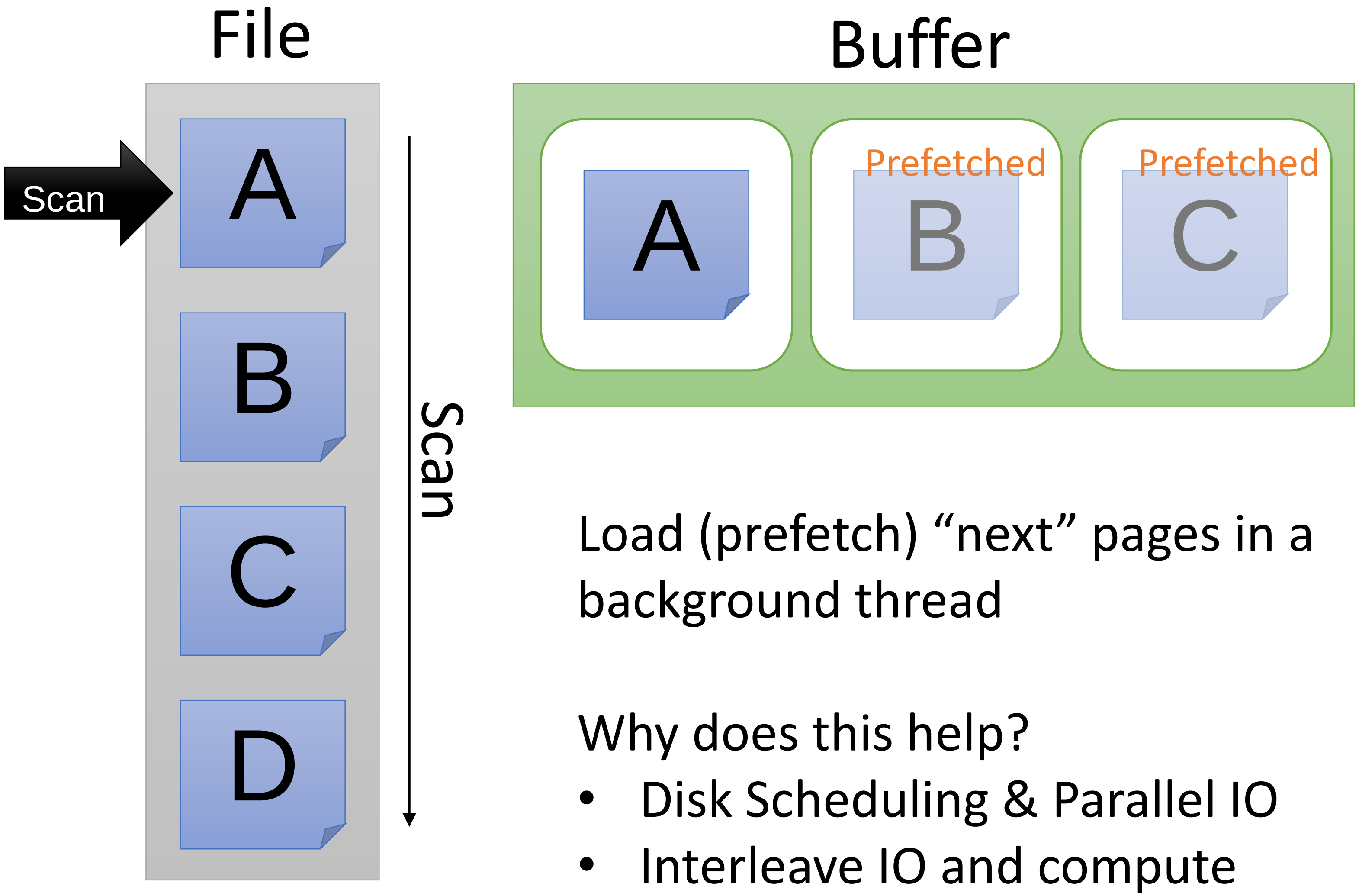


Cache Hits: 3

Attempts: 8

Improved Cache Hit Rate!

Background Prefetching



Load (prefetch) “next” pages in a background thread

Why does this help?

- Disk Scheduling & Parallel IO
- Interleave IO and compute

The Buffer Manager

- A **buffer manager** handles supporting operations for the buffer:
  - Primarily, handles & executes the "replacement policy"
    - i.e. finds a page in buffer to flush/release if buffer is full and a new page needs to be read in
  - DBMSs typically implement their own buffer management routines

3. External Merge Algorithm

Challenge: Merging Big Files with Small Memory

- How do we *efficiently* merge two sorted files when both are much larger than our main memory buffer?

- **Key point:** Disk IO (R/W) dominates the algorithm cost

Our first example of an **“IO aware”** algorithm / cost model

External Merge Algorithm

- **Input**: 2 sorted lists of length M and N

- **Output:** 1 sorted list of length M + N

- **Required:** At least 3 Buffer Pages

- **IOs**: 2(M+N)

Key (Simple) Idea

To find an element that is no larger than all elements in two lists, one only needs to compare minimum elements from each list.

If:

$$A_1 \leq A_2 \leq \cdots \leq A_N$$
$$B_1 \leq B_2 \leq \cdots \leq B_M$$

Then:

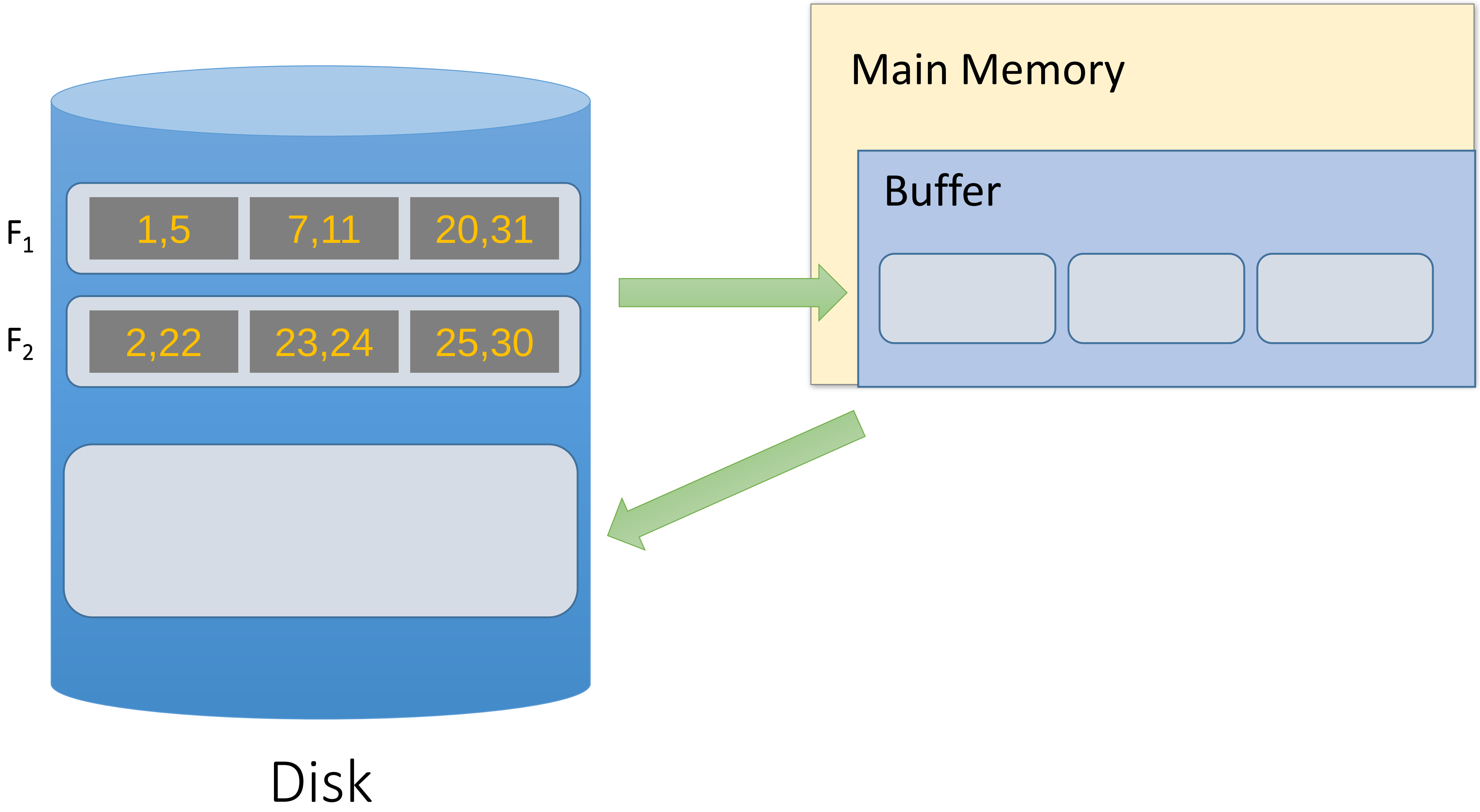
$$Min(A_1, B_1) \leq A_i$$
$$Min(A_1, B_1) \leq B_j$$

for i=1….N and j=1….M

External Merge Algorithm

Input:
Two sorted
files

Output:
One *merged*
sorted file



External Merge Algorithm

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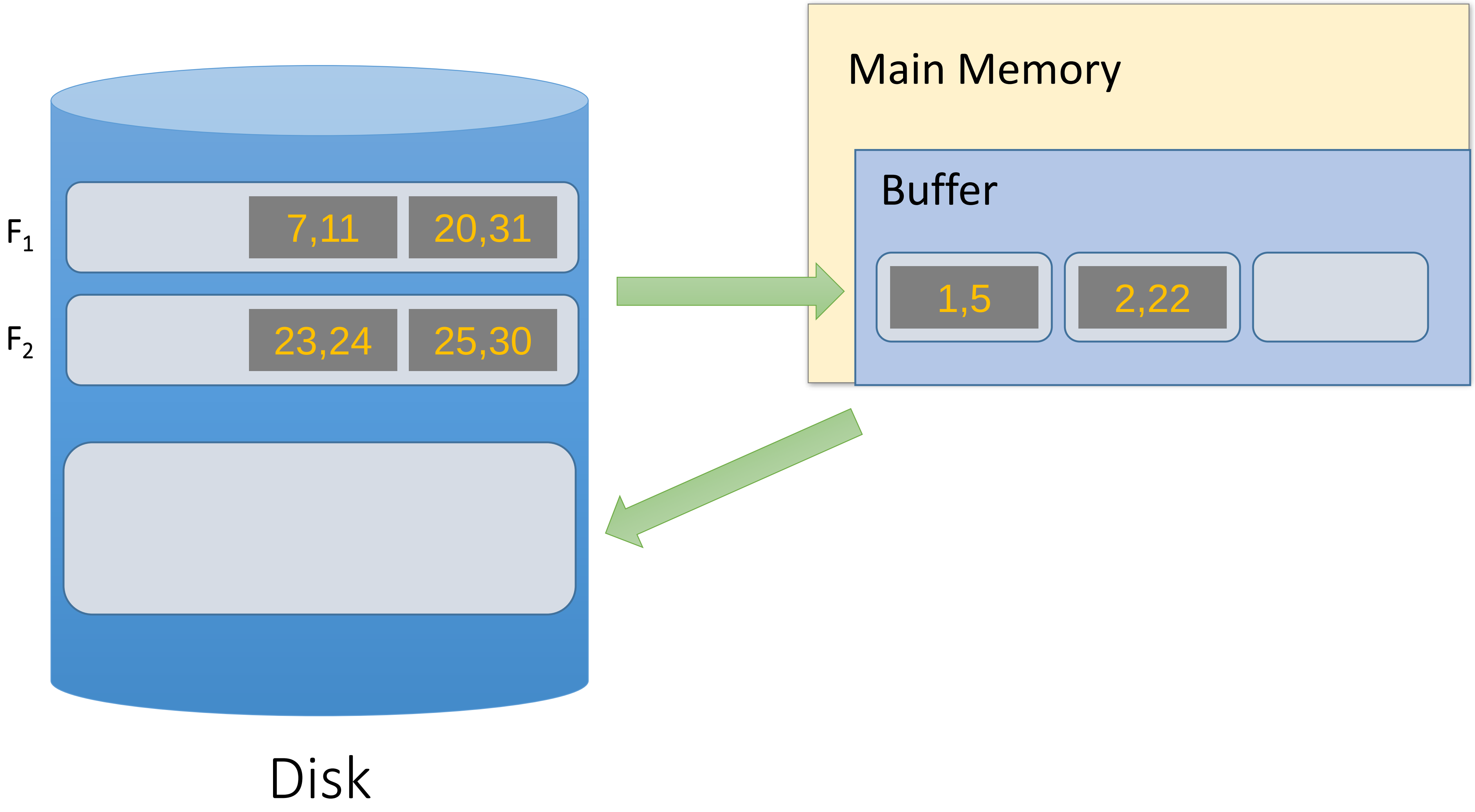
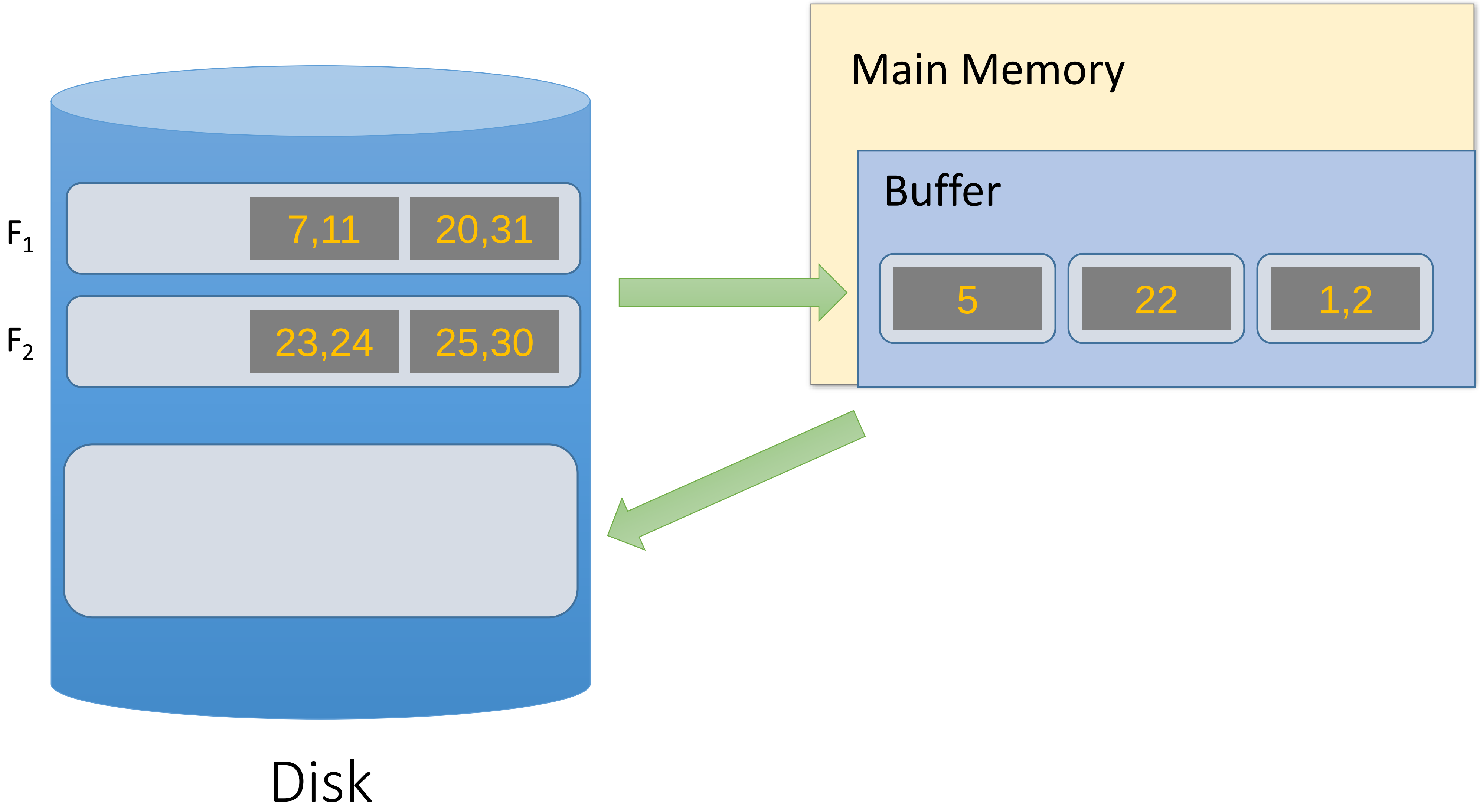
Output:
One *merged* sorted file



External Merge Algorithm

Input:
Two sorted
files

Output:
One *merged*
sorted file



External Merge Algorithm

Input:
Two sorted
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Output:
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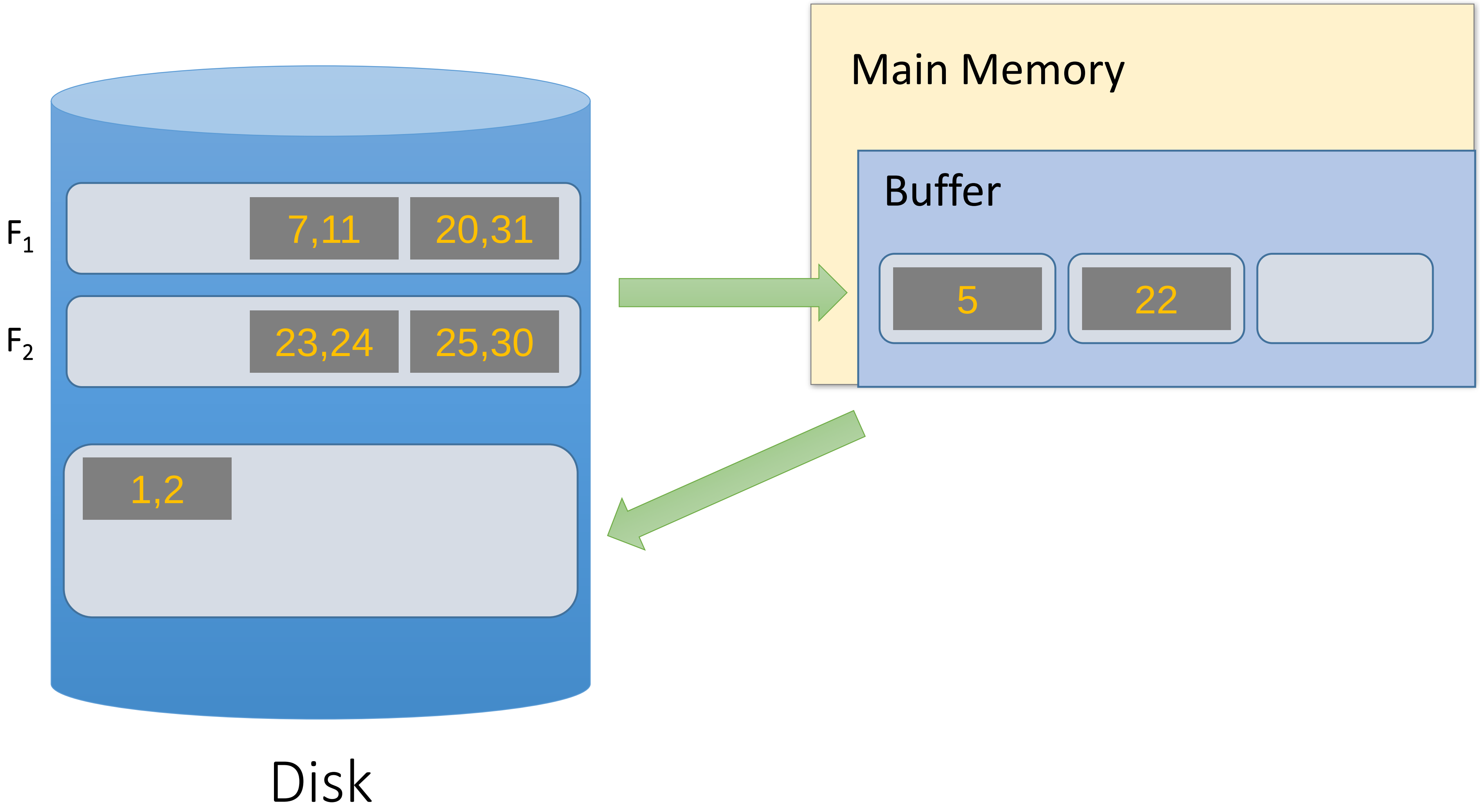
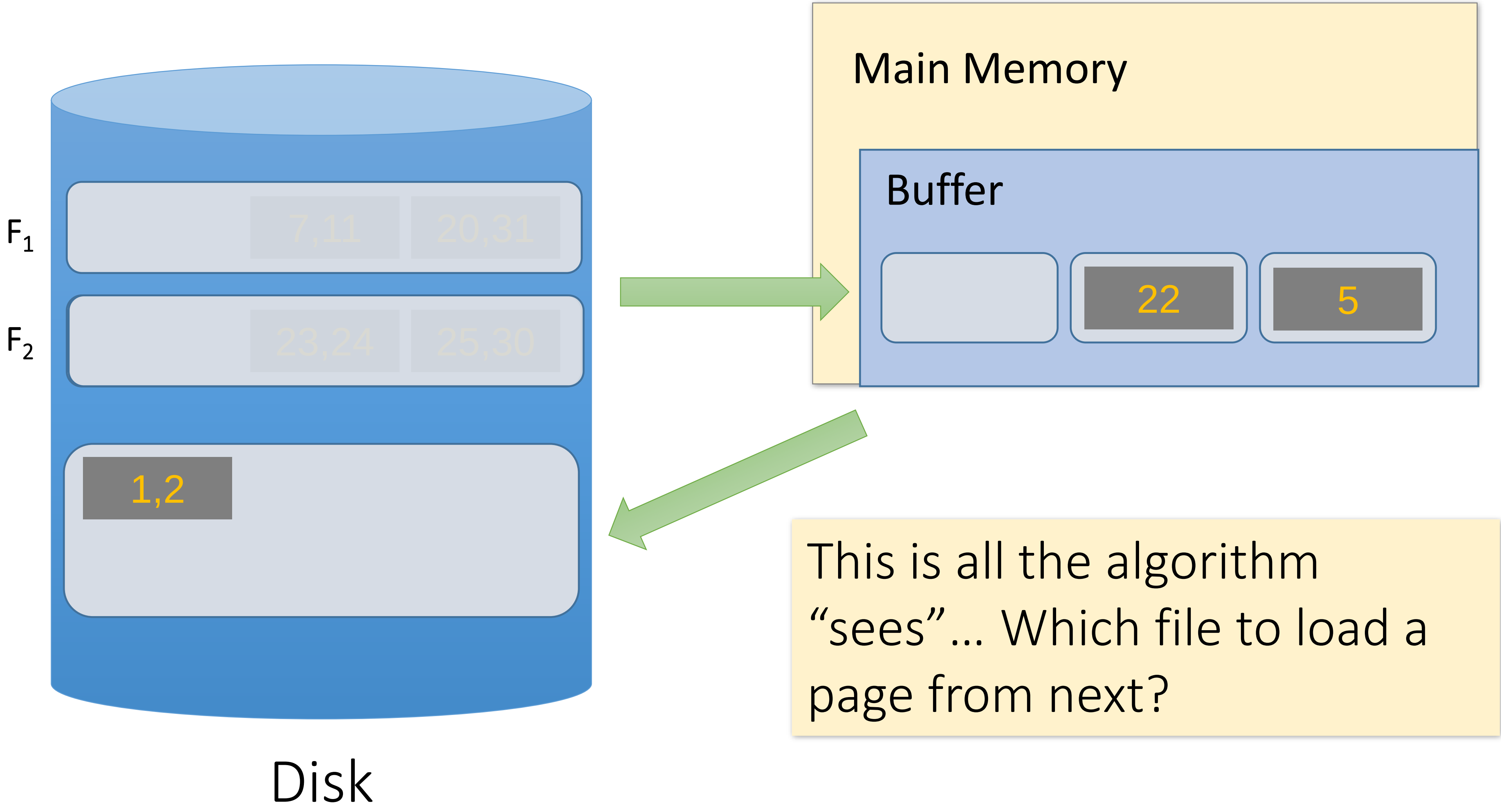


External Merge Algorithm

Input:
Two sorted files

Output:
One *merged* sorted file

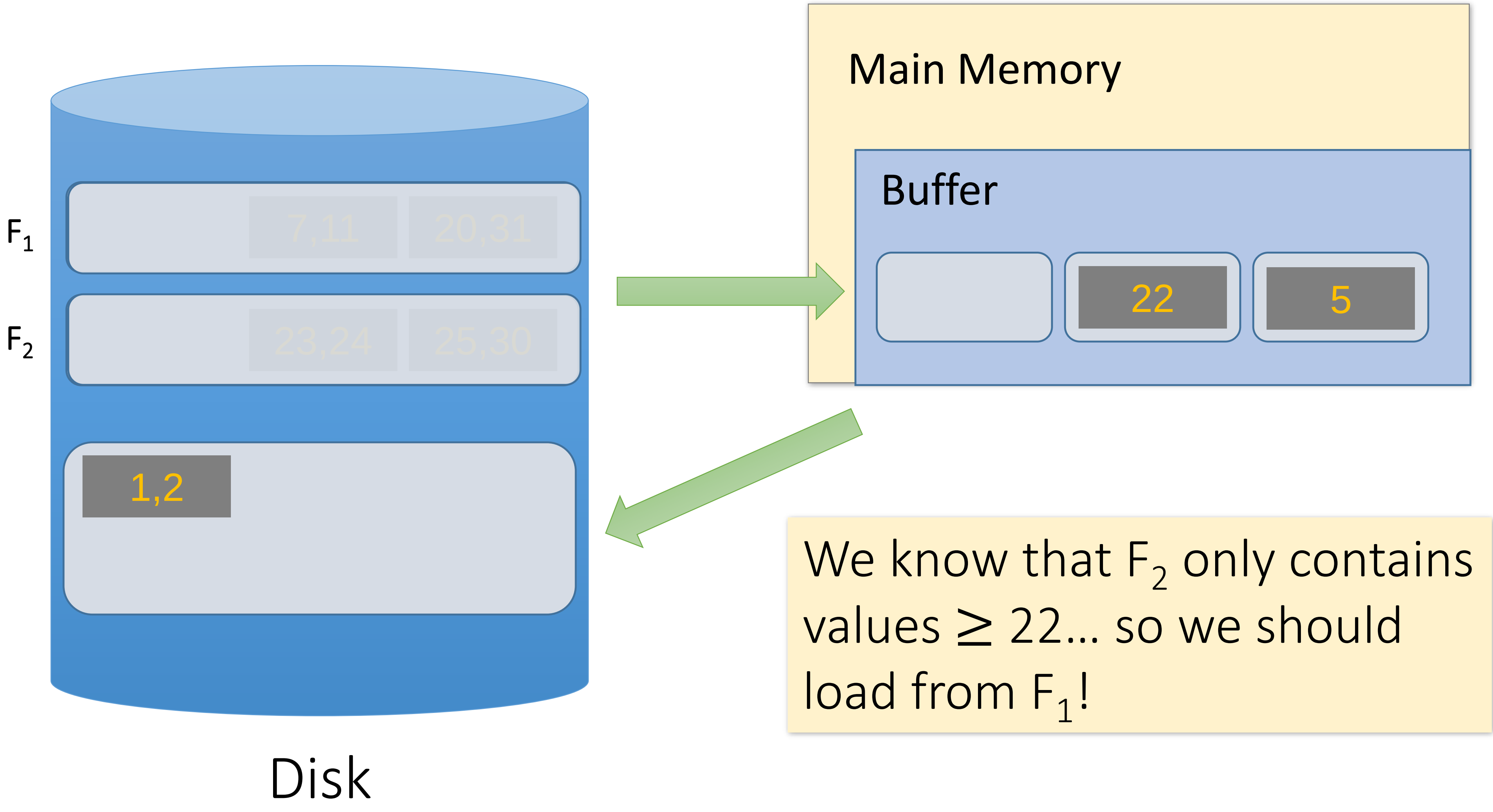


This is all the algorithm "sees"… Which file to load a page from next?

External Merge Algorithm

Input:
Two sorted files

Output:
One *merged* sorted file

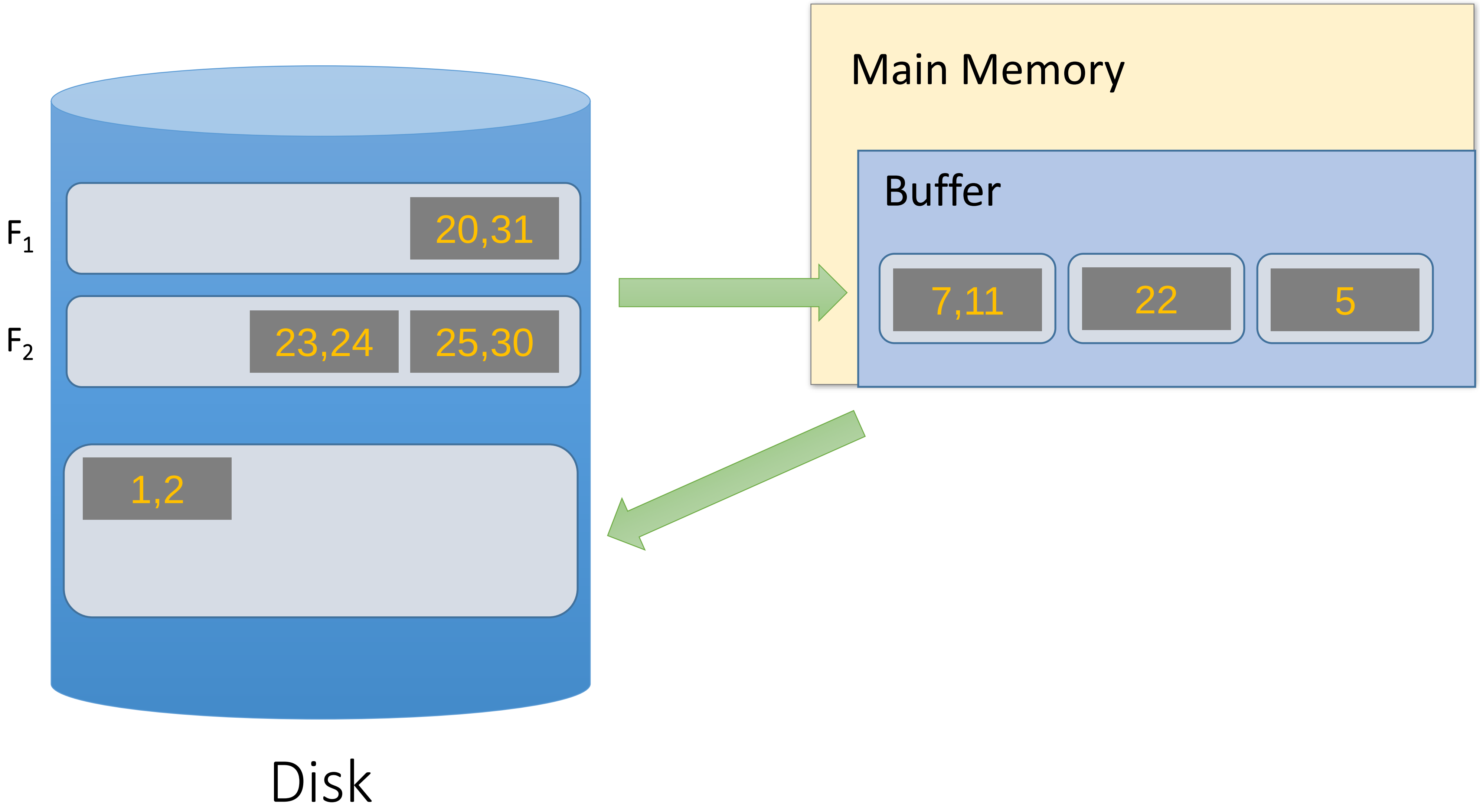


We know that F$_2$ only contains values ≥ 22… so we should load from F$_1$!

External Merge Algorithm

Input:
Two sorted
files

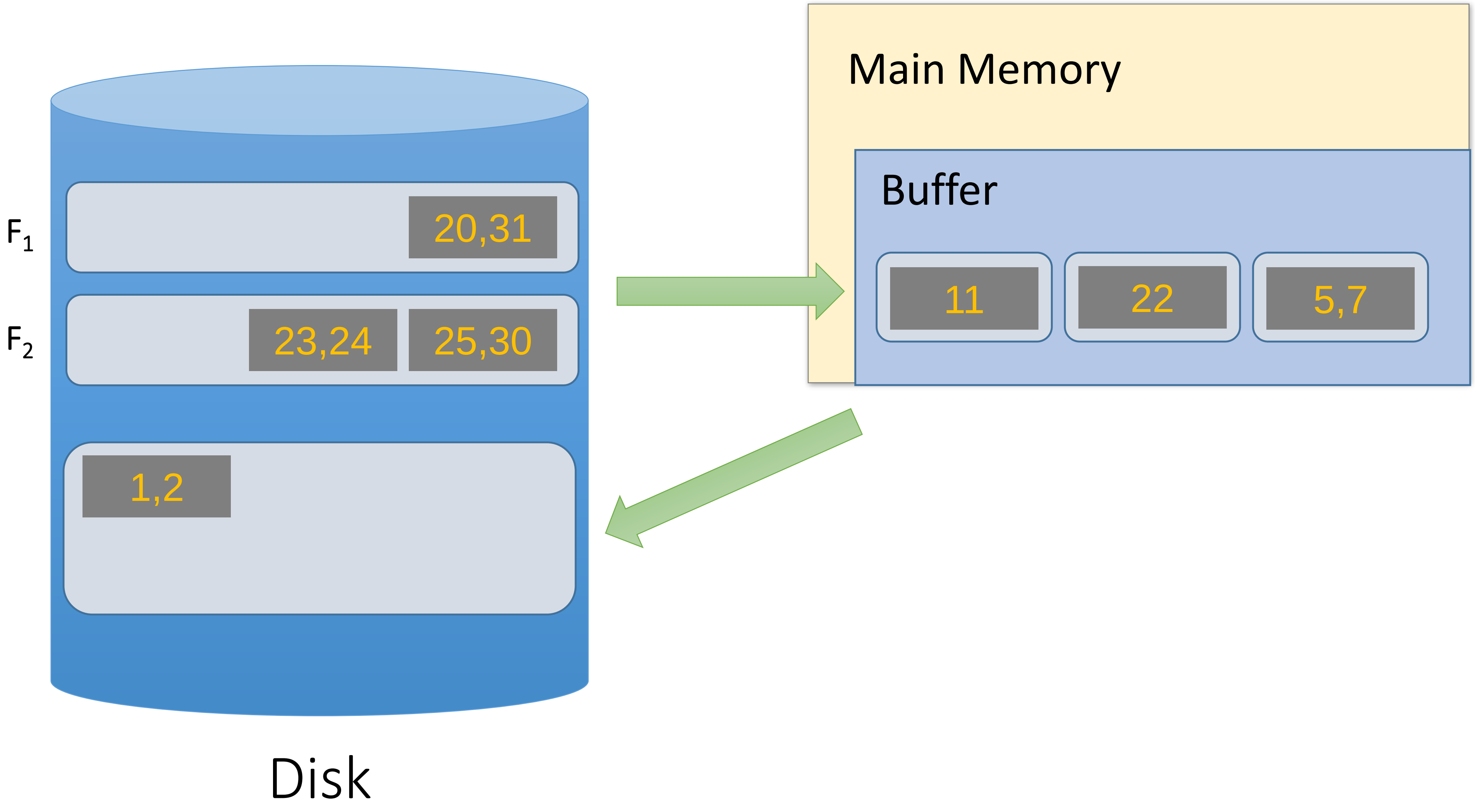
Output:
One *merged*
sorted file



External Merge Algorithm

Input:
Two sorted
files

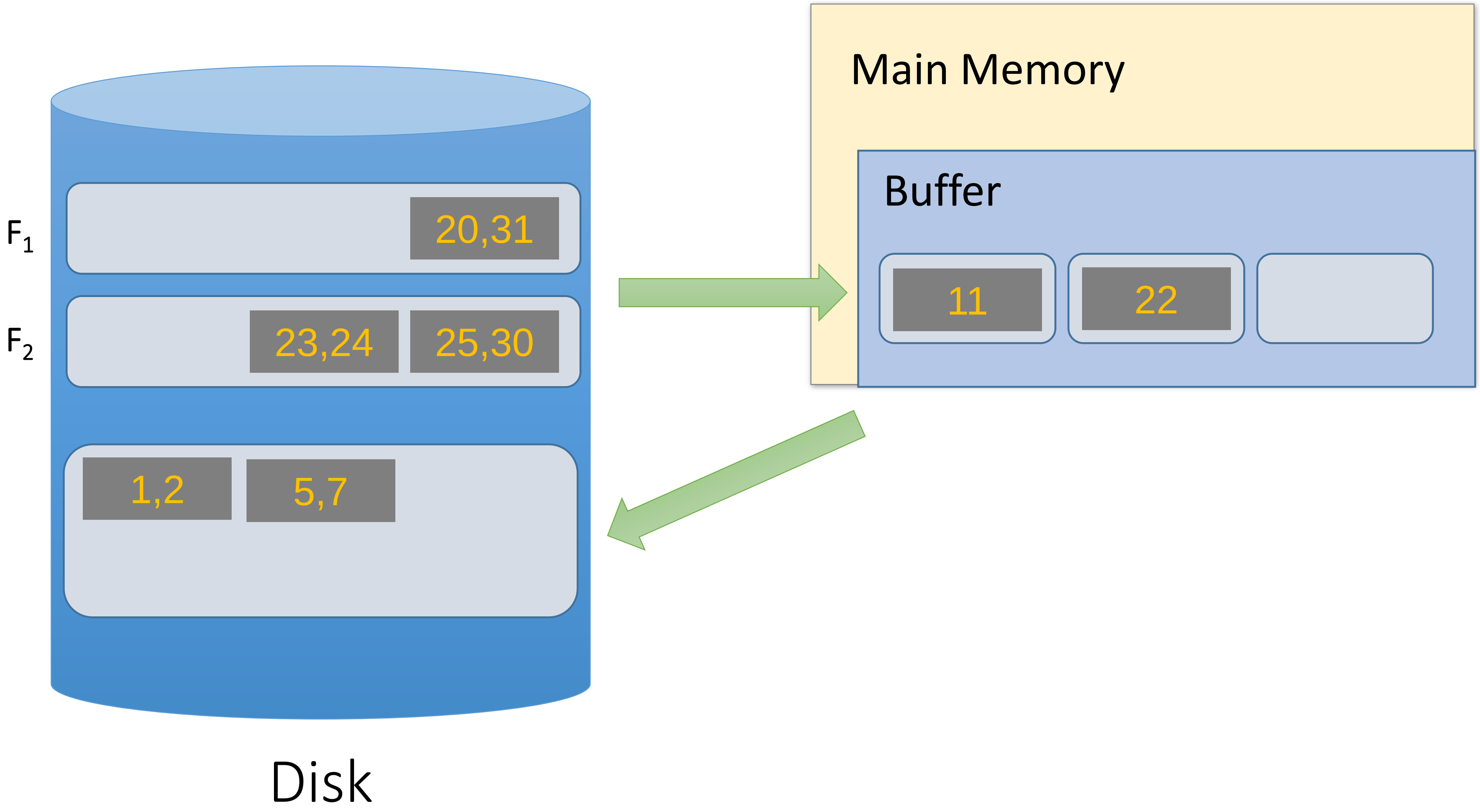
Output:
One *merged*
sorted file



External Merge Algorithm

Input:
Two sorted
files

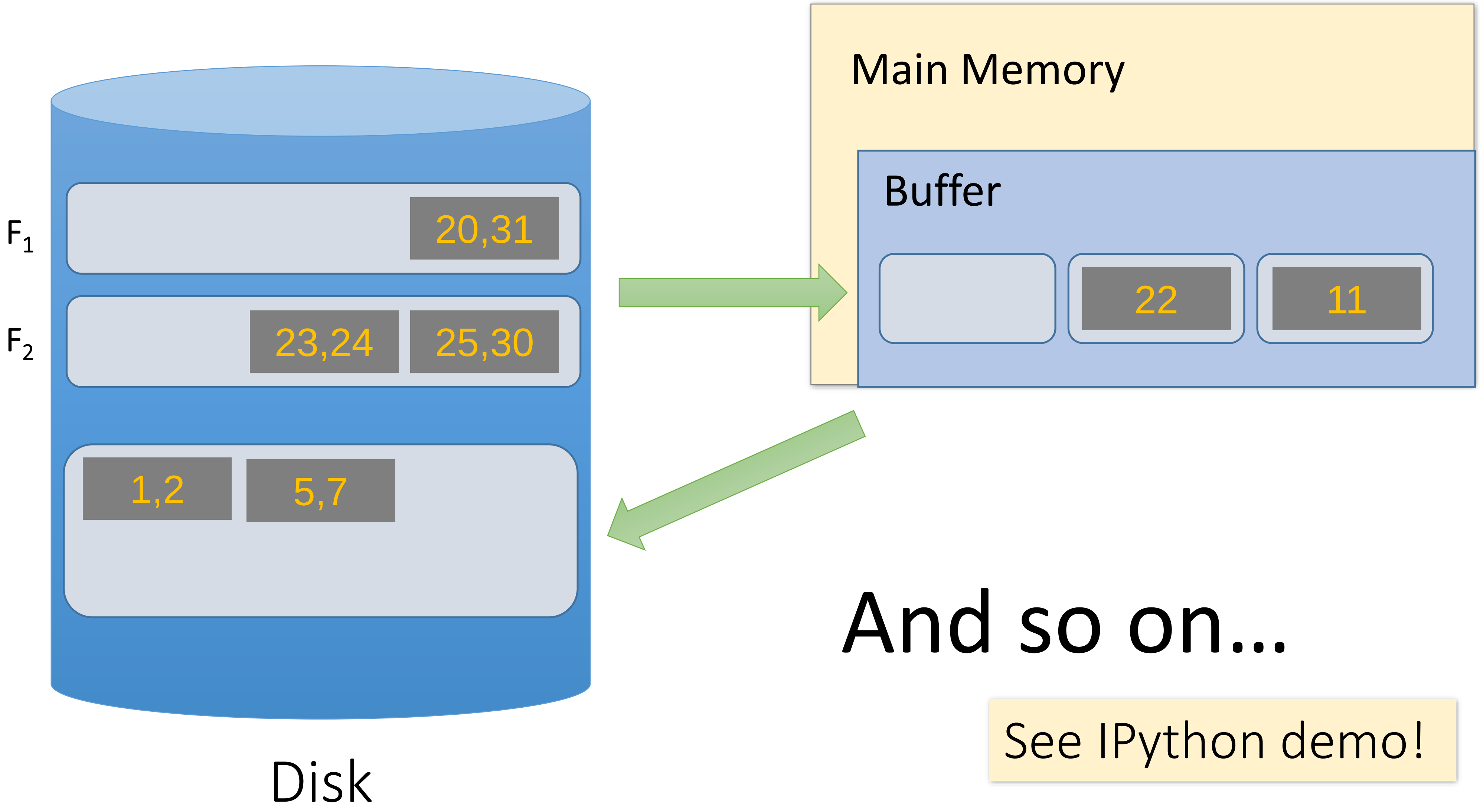
Output:
One *merged*
sorted file



External Merge Algorithm

Input:
Two sorted
files

Output:
One *merged*
sorted file



And so on…

See IPython demo!

We can merge lists of **arbitrary length** with *only* 3 buffer pages.

If lists of size M and N, then

Cost: 2(M+N) IOs

Each page is read once, written once

With B+1 buffer pages, can merge B lists. How?

Recap: External Merge Algorithm

- Suppose we want to merge two **sorted** files both much larger than main memory (i.e. the buffer)

- We can use the **external merge algorithm** to merge files of ***arbitrary length*** in **2*(N+M) IO** operations with only **3 buffer pages**!

Our first example of an "IO aware" algorithm / cost model

4. External Merge Sort

Why are Sort Algorithms Important?

- Data requested from DB in sorted order is **extremely common**
  - e.g., find students in increasing GPA order

- **Why not just use quicksort in main memory??**
  - What about if we need to sort 1TB of data with 1GB of RAM…

A classic problem in computer science!

More reasons to sort…

- Sorting useful for eliminating *duplicate copies* in a collection of records (Why?)

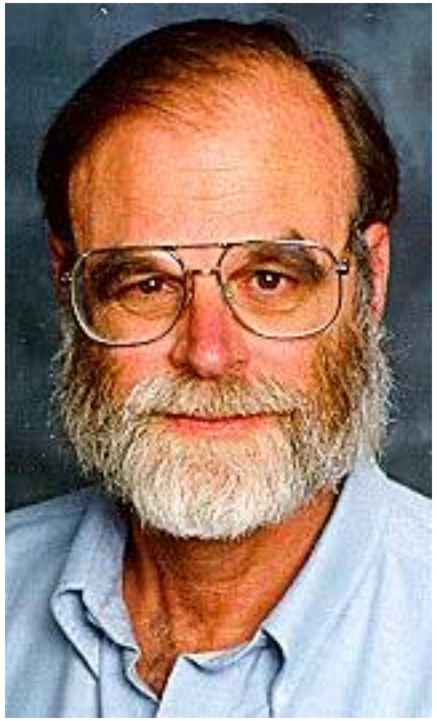
- Sorting is first step in *bulk loading* B+ tree index.

- *Sort-merge* join algorithm involves sorting

Next lectures

Do people care?

http://sortbenchmark.org



Sort benchmark bears his name

So how do we sort big files?

1. Split into chunks small enough to **sort in memory *("runs")***

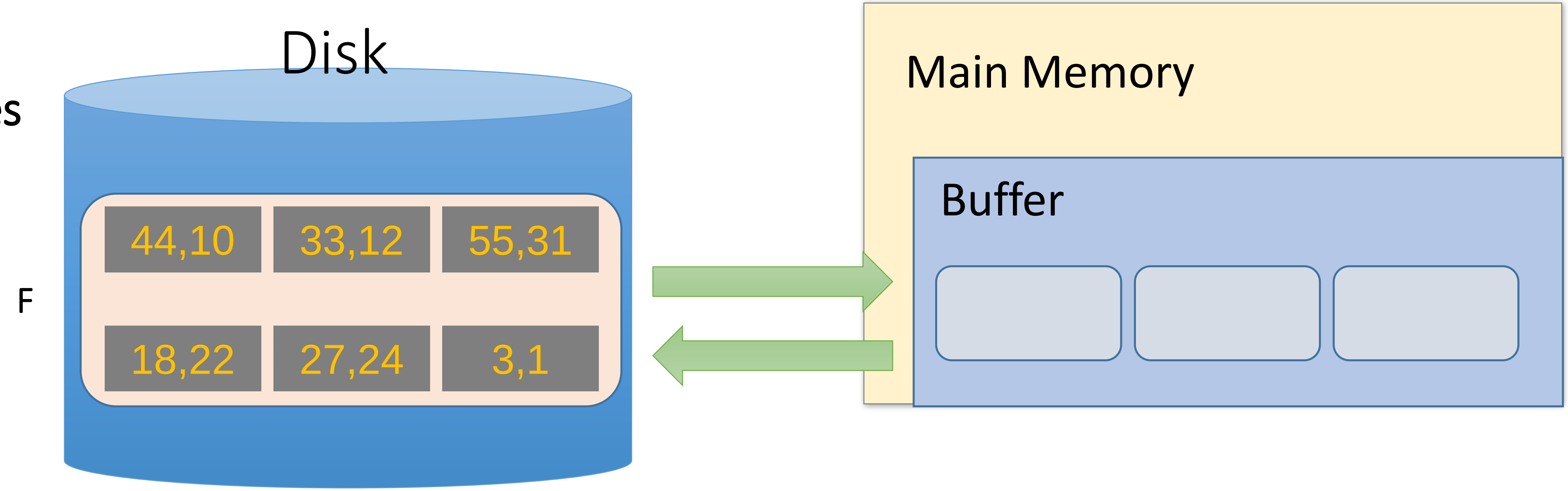
2. **Merge** pairs (or groups) of runs ***using the external merge algorithm***

3. **Keep merging** the resulting runs ***(each time = a "pass")*** until left with one sorted file!

External Merge Sort Algorithm

Example:
- 3 Buffer pages
- 6-page file

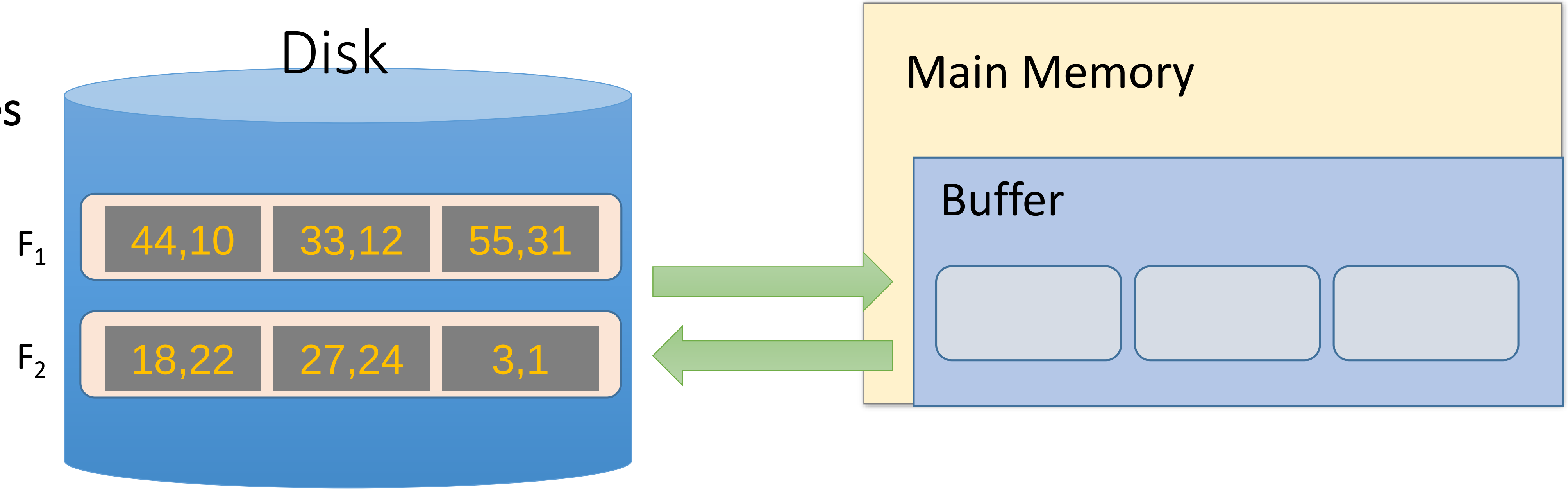
Orange file = unsorted



1. Split into chunks small enough to **sort in memory**

External Merge Sort Algorithm

Example:
- 3 Buffer pages
- 6-page file



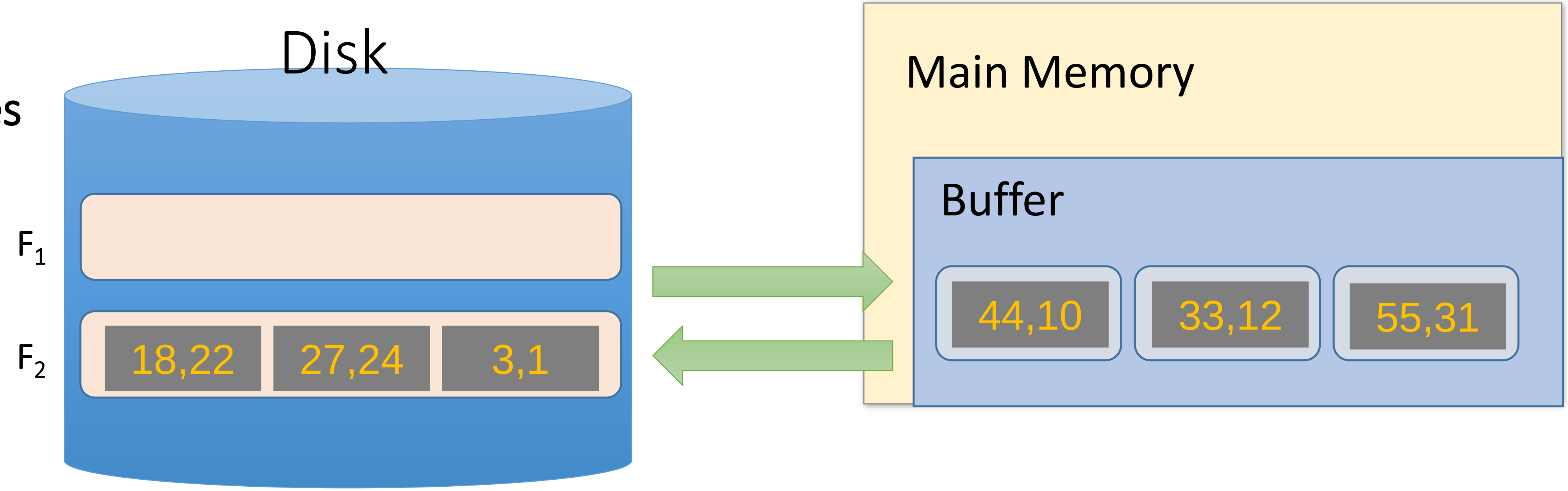
Orange file = unsorted

1. Split into chunks small enough to **sort in memory**

External Merge Sort Algorithm

Example:
- 3 Buffer pages
- 6-page file

Orange file = unsorted

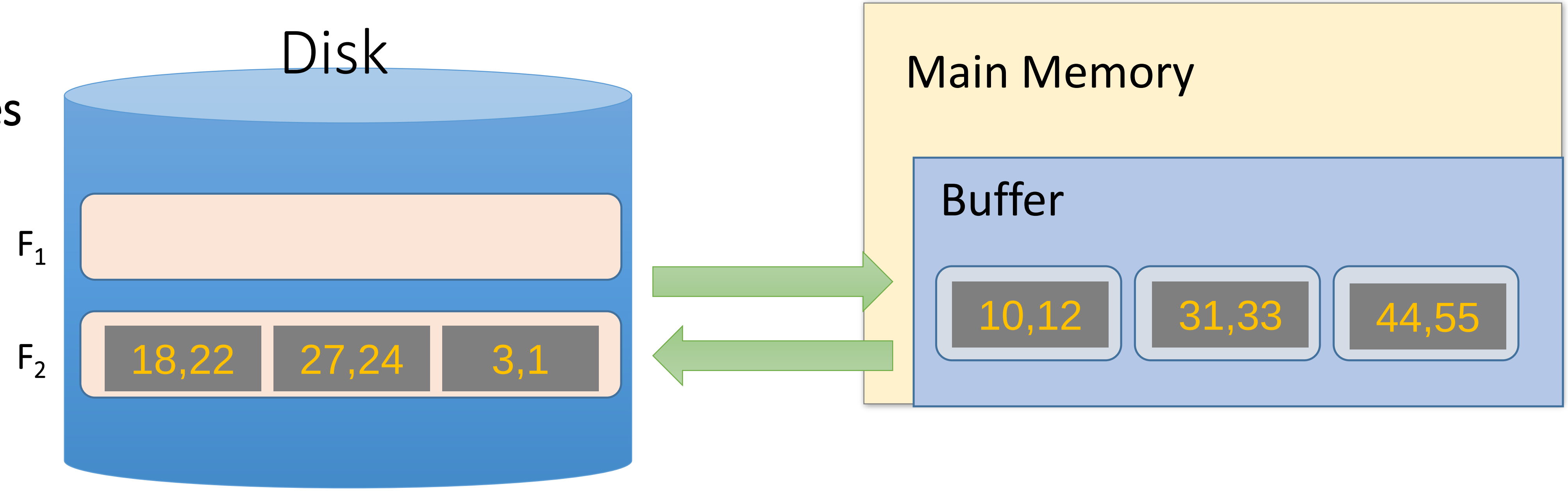


1. Split into chunks small enough to **sort in memory**

External Merge Sort Algorithm

Example:

- 3 Buffer pages
- 6-page file



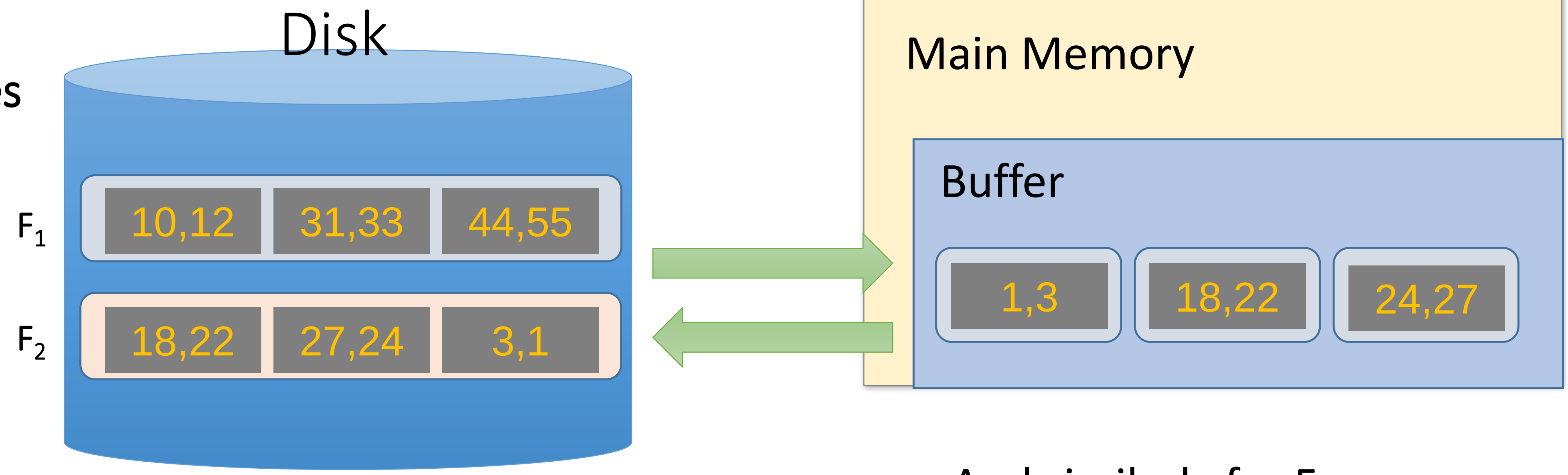
Orange file = unsorted

1. Split into chunks small enough to **sort in memory**

External Merge Sort Algorithm

Example:
- 3 Buffer pages
- 6-page file

Each sorted file is a called a *run*

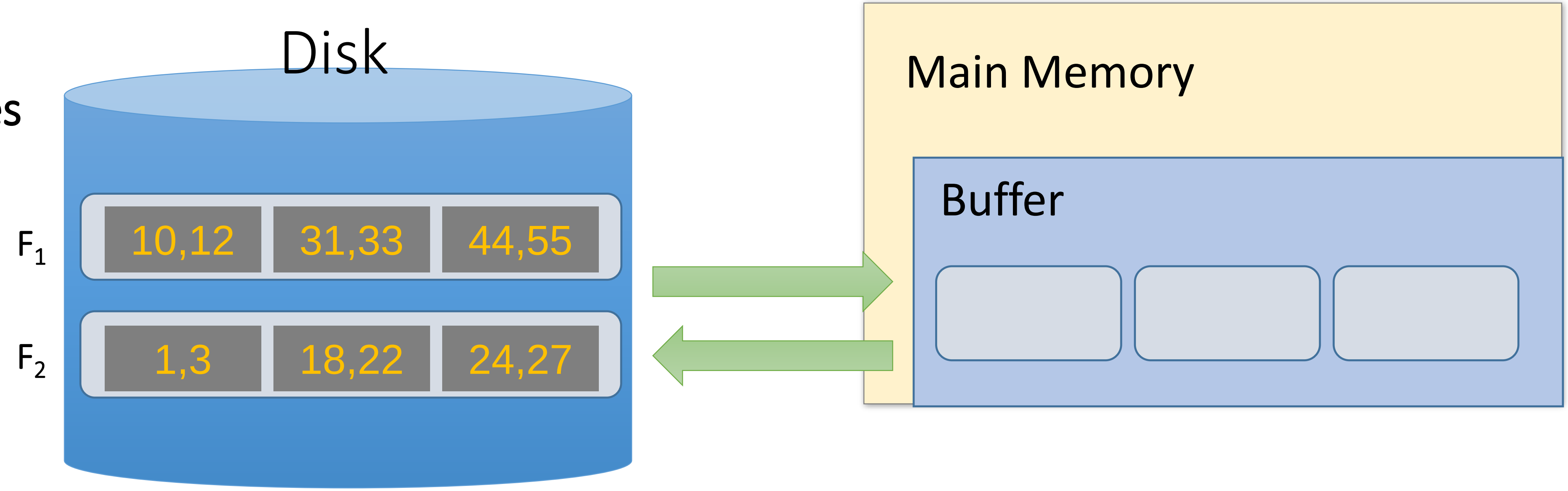


And similarly for F_2

1. Split into chunks small enough to **sort in memory**

External Merge Sort Algorithm

Example:
- 3 Buffer pages
- 6-page file



2. Now just run the **external merge** algorithm & we're done!

Calculating IO Cost

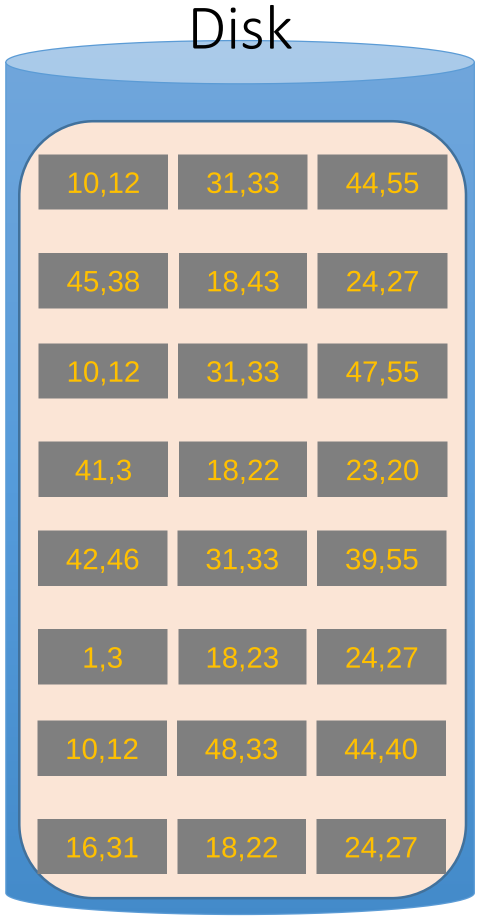
For 3 buffer pages, 6 page file:

1. Split into **<u>two 3-page files</u>** and **sort in memory**
   1. **= 1 R + 1 W for each page = 2*(3 + 3) = 12 IO operations**

2. **Merge** each pair of sorted chunks ***using the external merge algorithm***
   1. **= 2*(3 + 3) = 12 IO operations**

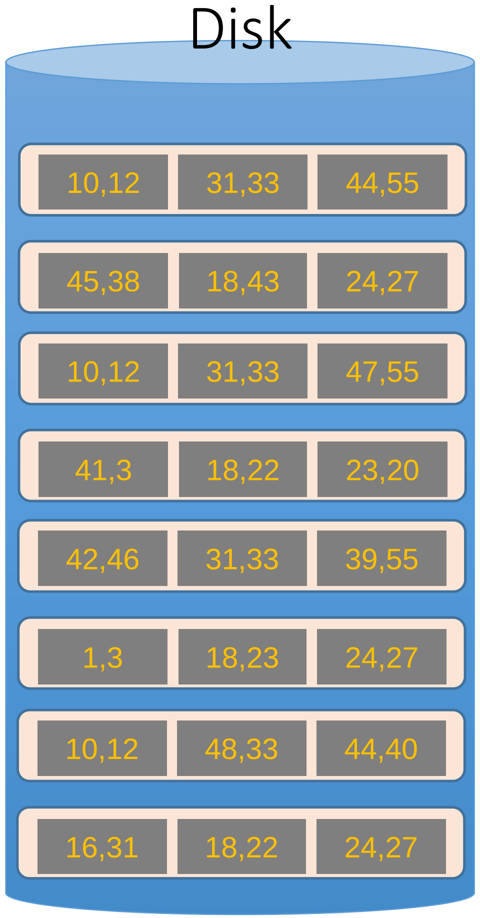
3. **Total cost = 24 IO**

Running External Merge Sort on Larger Files



Assume we still only have *3* buffer pages *(Buffer not pictured)*

Running External Merge Sort on Larger Files



1. Split into files small enough to sort in buffer…

Assume we still only have *3* buffer pages *(Buffer not pictured)*

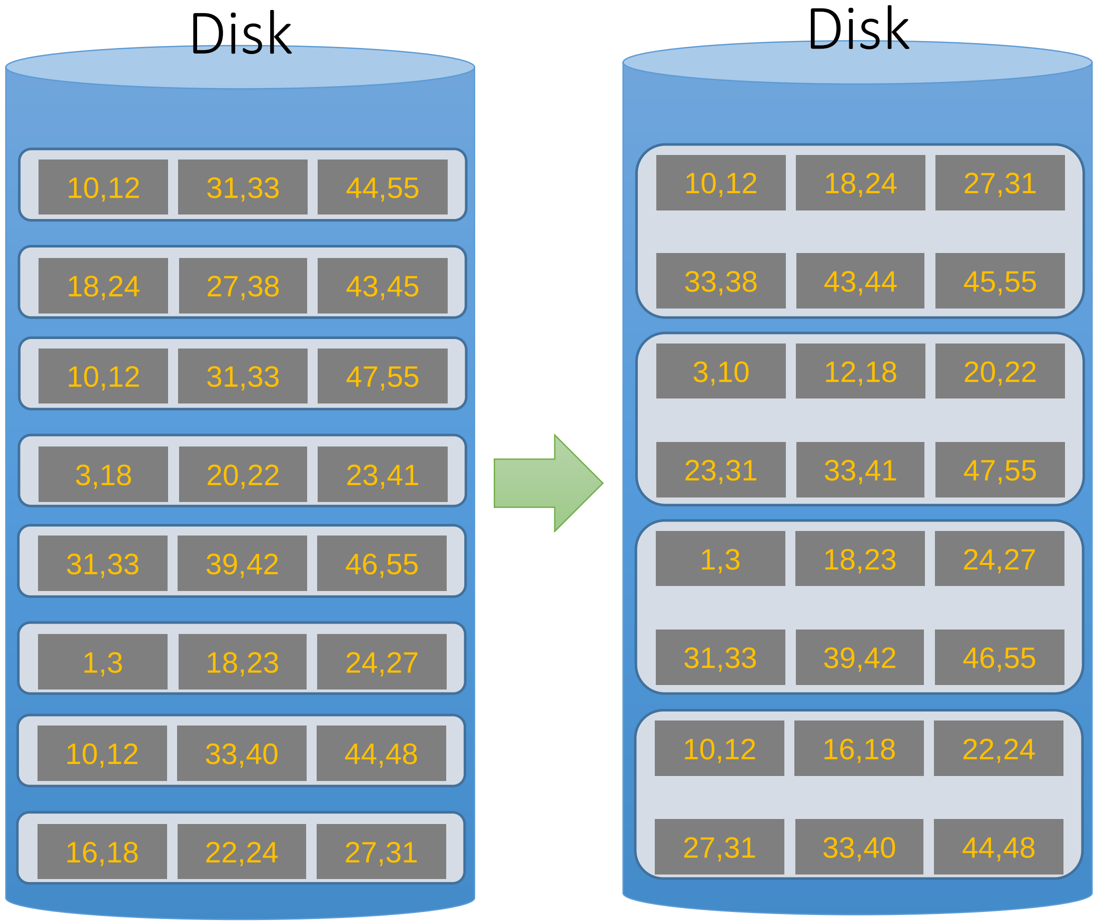
Running External Merge Sort on Larger Files

1. Split into files small enough to sort in buffer… and sort

Assume we still only have *3* buffer pages *(Buffer not pictured)*

Call each of these sorted files a ***run***

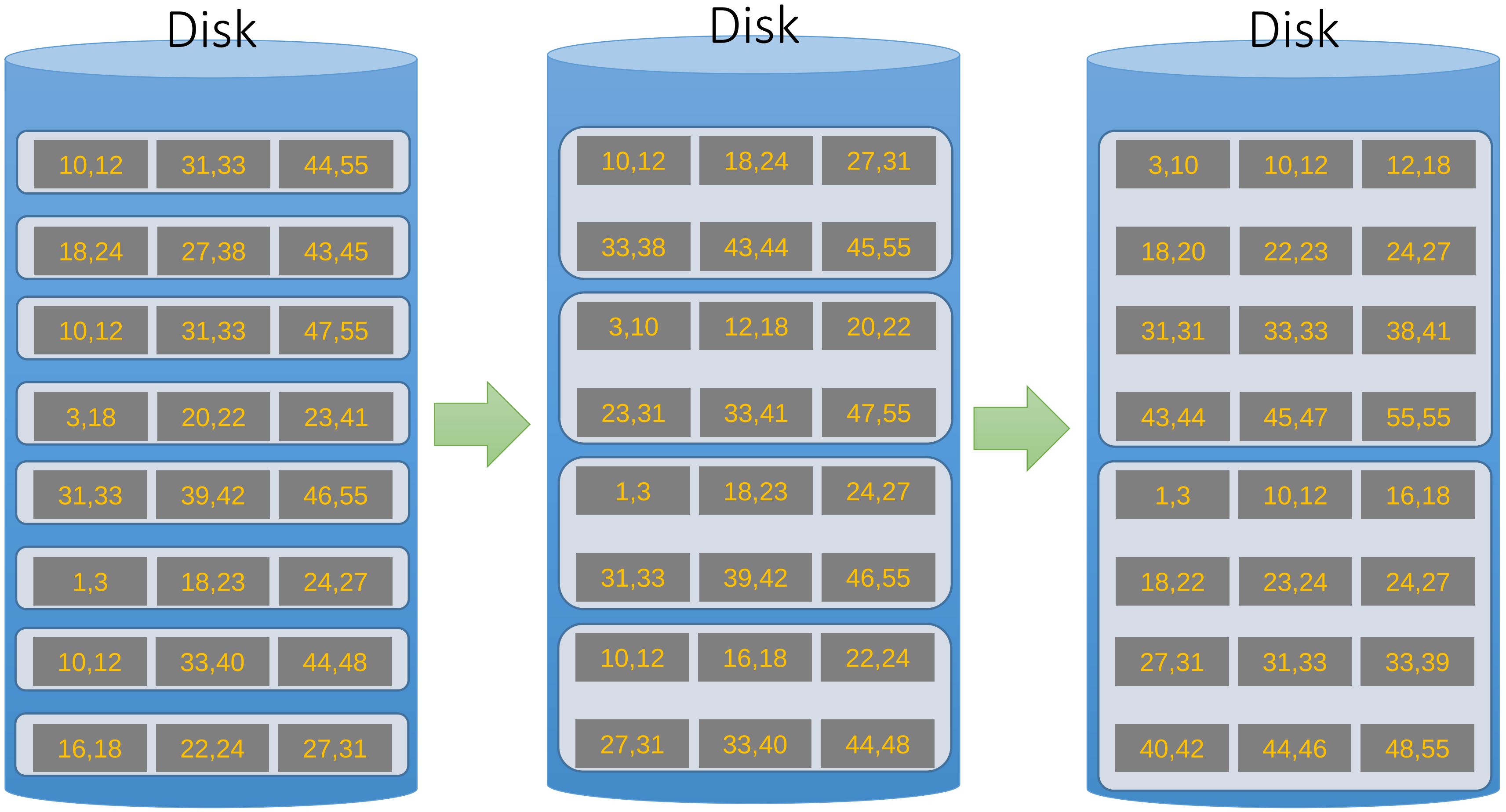
Running External Merge Sort on Larger Files



Assume we still only have *3* buffer pages *(Buffer not pictured)*

2. Now merge pairs of (sorted) files… **the resulting files will be sorted!**

Running External Merge Sort on Larger Files

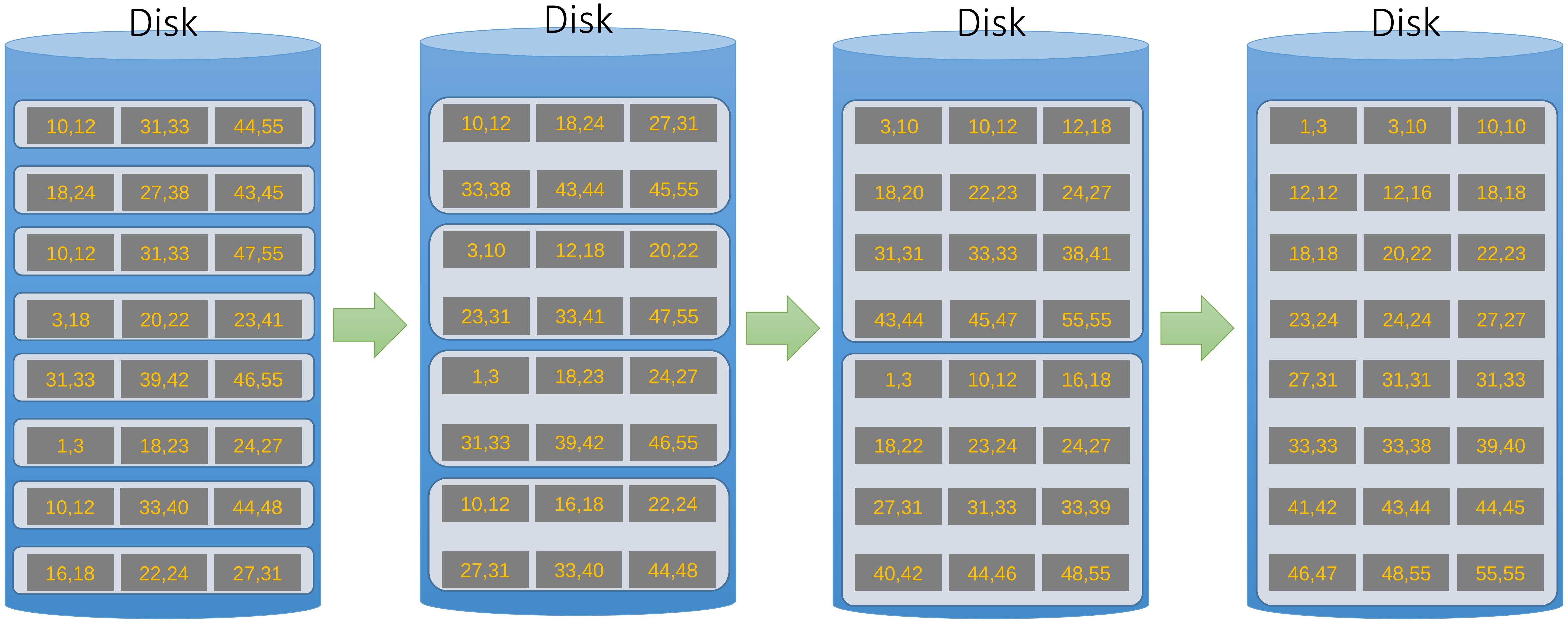


Assume we still only have *3* buffer pages *(Buffer not pictured)*

3. And repeat…

Call each of these steps a ***pass***

Running External Merge Sort on Larger Files

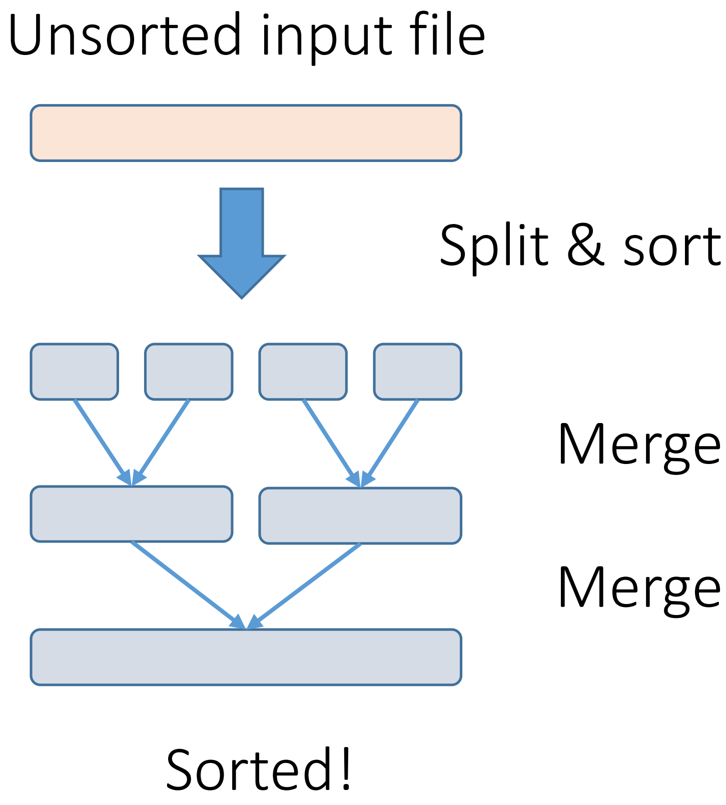


4. And repeat!

Simplified 3-page Buffer Version

Assume for simplicity that we split an N-page file into N single-page ***runs*** and sort these; then:

- First pass: Merge **N/2 *pairs* of runs** each of length **1 page**
- Second pass: Merge **N/4 *pairs* of runs** each of length **2 pages**
- In general, for **N** pages, we do $\lceil \log_2 N \rceil$ passes
  - +1 for the initial split & sort
- Each pass involves reading in & writing out all the pages = ***2N IO***



→ 2N*($\lceil \log_2 N \rceil$+1) total IO cost!