Lecture 12: The IO Model & External Sorting

Today's Lecture

1. *[From 9-2]:* Conflict Serializability & Deadlock
2. The Buffer
3. External Merge Sort

1. Conflict Serializability & Deadlock

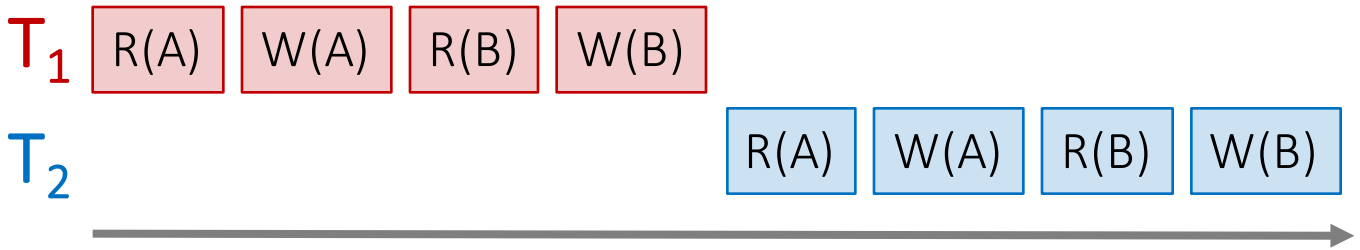
Recap from Lecture 9-2

What you will learn about in this section

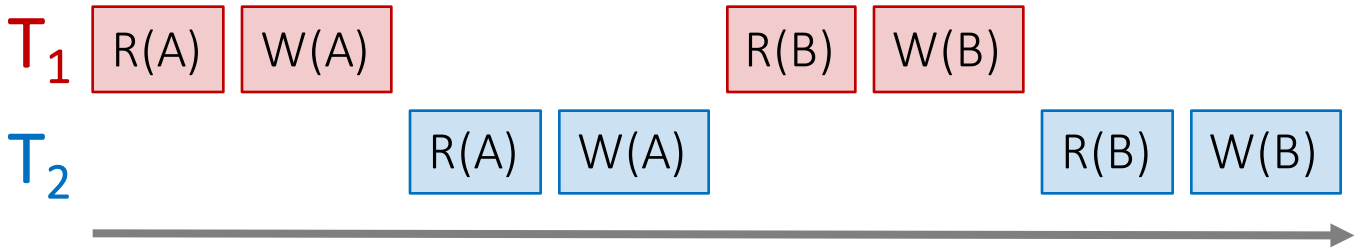
1. RECAP: Concurrency
2. RECAP: Conflicts vs. Anomalies
3. DAGs & Topological Orderings
4. Conflict Serializability
5. Deadlocks

Recall: Concurrency as Interleaving TXNs

Serial Schedule:



Interleaved Schedule:



- For our purposes, having TXNs occur concurrently means **interleaving their component actions (R/W)**

We call the particular order of interleaving a **schedule**

Recall: Why Interleave TXNs?

- Interleaving TXNs might lead to anomalous outcomes… why do it?

- Several important reasons:
  - Individual TXNs might be *slow*- don't want to block other users during!

  - Disk access may be *slow*- let some TXNs use CPUs while others accessing disk!

All concern large differences in ***performance***

Recall: Must Preserve Consistency & Isolation

- The DBMS has freedom to interleave TXNs
- However, it must pick an interleaving or **schedule** such that isolation and consistency are maintained
  - Must be *as if* the TXNs had executed serially!

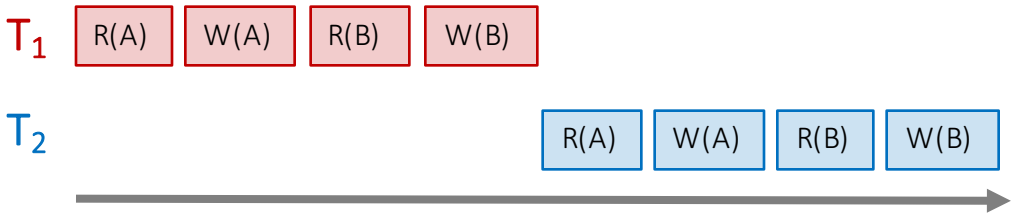
"With great power comes great responsibility"

ACID

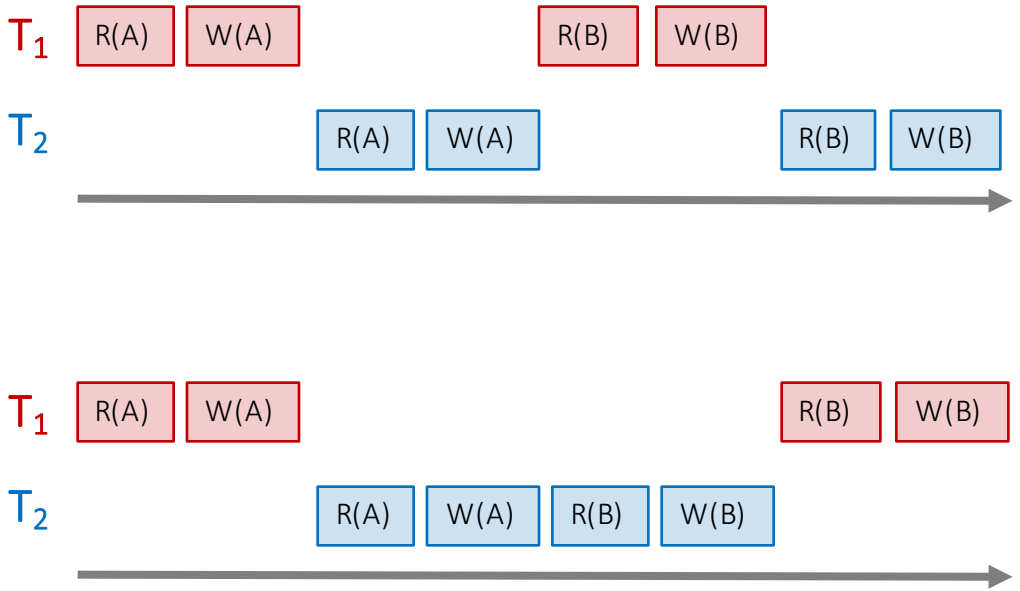
DBMS must pick a schedule which maintains isolation & consistency

Recall: "Good" vs. "bad" schedules

Serial Schedule:



Interleaved Schedules:



Why?

We want to develop ways of discerning "good" vs. "bad" schedules

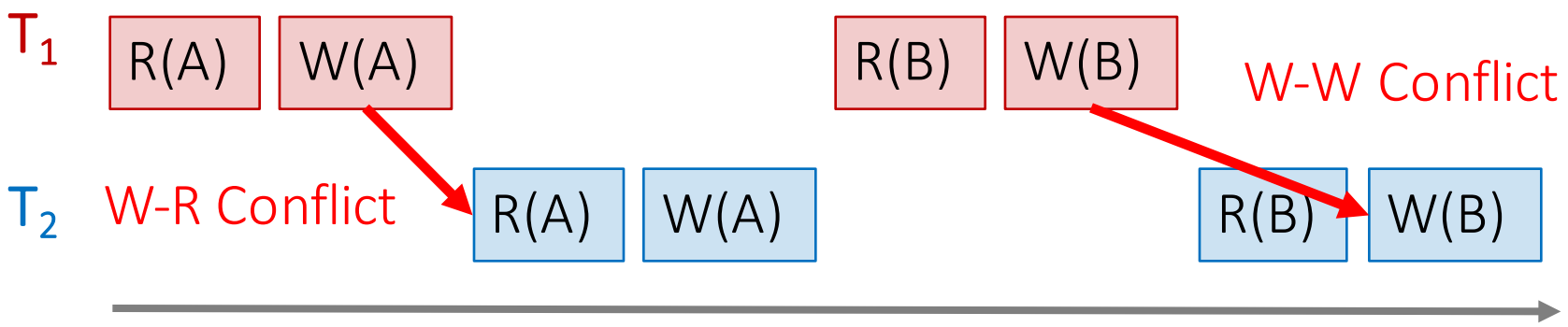
Ways of Defining "Good" vs. "Bad" Schedules

- Recall from last time: we call a schedule ***serializable*** if it is equivalent to *some* serial schedule
  - We used this as a notion of a "good" interleaved schedule, since **a serializable schedule will maintain isolation & consistency**
- Now, we'll define a stricter, but very useful variant:
  - ***Conflict serializability***

We'll need to define *conflicts* first..

Conflicts

Two actions **conflict** if they are part of different TXNs, involve the same variable, and at least one of them is a write



Conflicts

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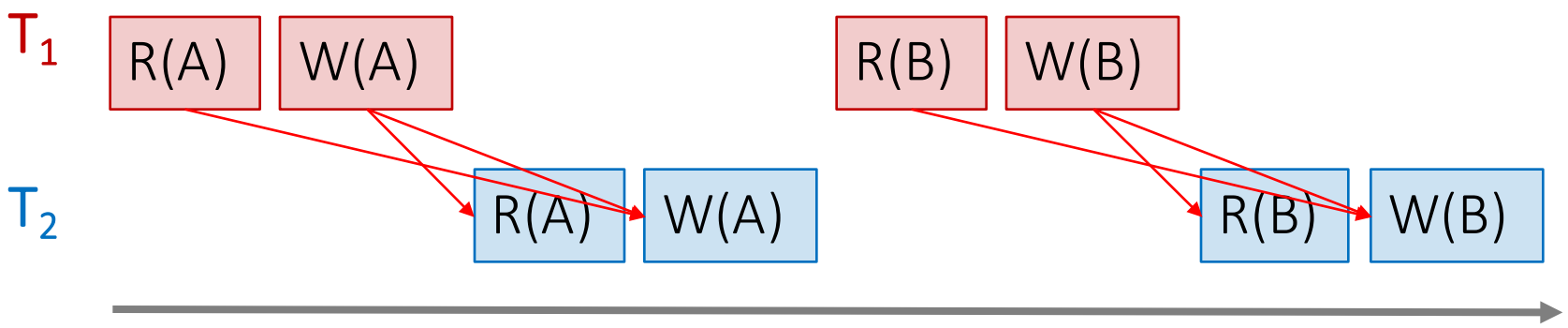


All “conflicts”!

Conflict Serializability

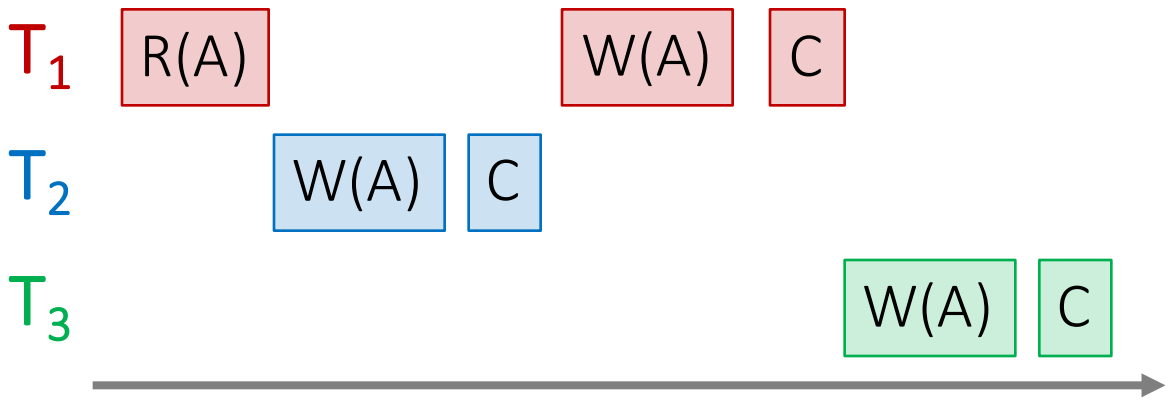
- Two schedules are **conflict equivalent** if:
  - They involve *the same actions of the same TXNs*
  - Every *pair of conflicting actions* of two TXNs are *ordered in the same way*
- Schedule S is **conflict serializable** if S is *conflict equivalent* to some serial schedule

Conflict serializable ⇒ serializable

So if we have conflict serializable, we have consistency & isolation!

Note: Serializable vs. Conflict Serializable

Example of a schedule that is serializable but ***not*** conflict serializable:



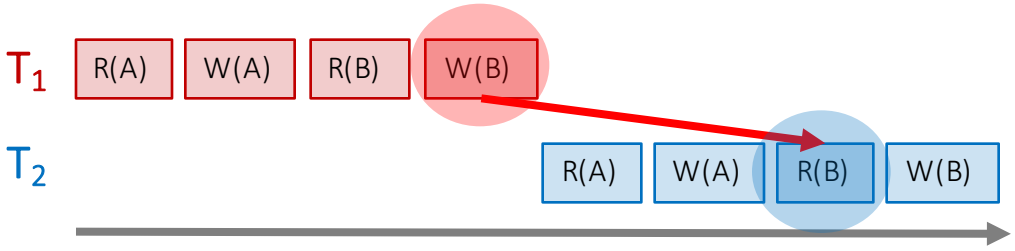
This is ***equivalent*** to T_1,T_2,T_3, so serializable

But not conflict ***equivalent*** to T_1,T_2,T_3 (or any other serial schedule) so not conflict serializable!

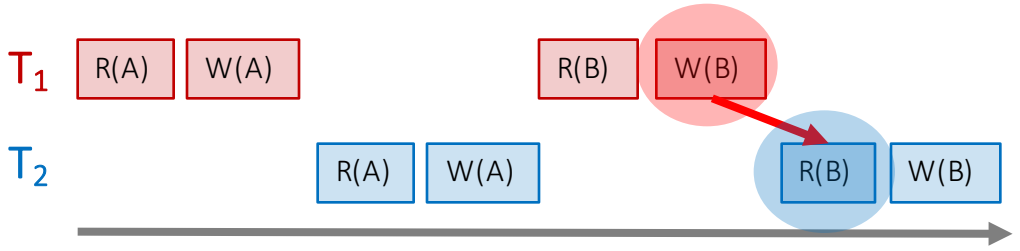
Conflict serializable ⇒ serializable, but not the other way around

Recall: "Good" vs. "bad" schedules

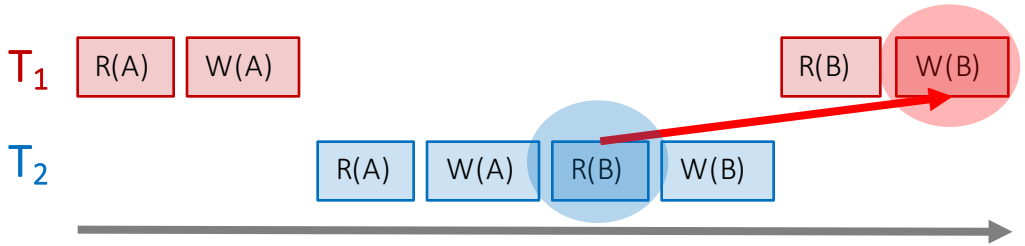
Serial Schedule:



Interleaved Schedules:



X



Note that in the "bad" schedule, the ***order of conflicting actions is different than the above (or any) serial schedule!***

Conflict serializability also provides us with an operative notion of "good" vs. "bad" schedules!

Note: Conflicts vs. Anomalies

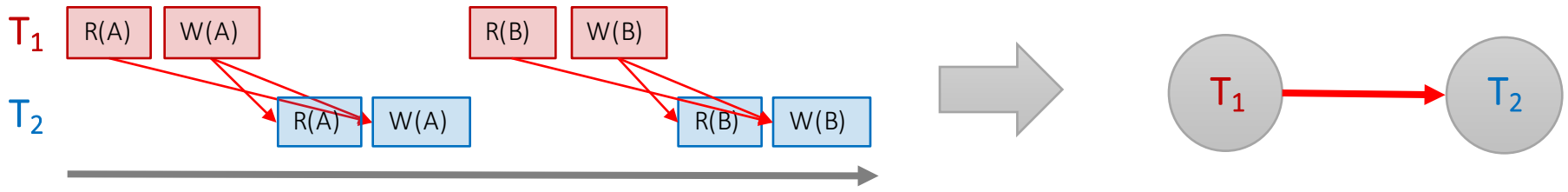
- **Conflicts** are things we talk about to help us characterize different schedules
  - Present in both “good” and “bad” schedules

- **Anomalies** are instances where isolation and/or consistency is broken because of a “bad” schedule
  - We often characterize different anomaly types by what types of conflicts predicated them

The Conflict Graph

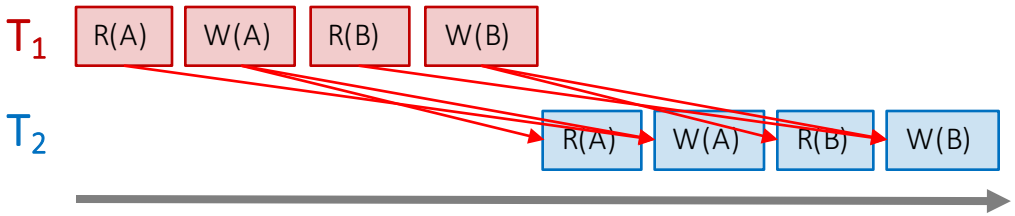
- Let's now consider looking at conflicts **at the TXN level**

- Consider a graph where the **nodes are TXNs**, and there is an edge from $T_i \rightarrow T_j$ **if any actions in T_i precede and conflict with any actions in T_j**

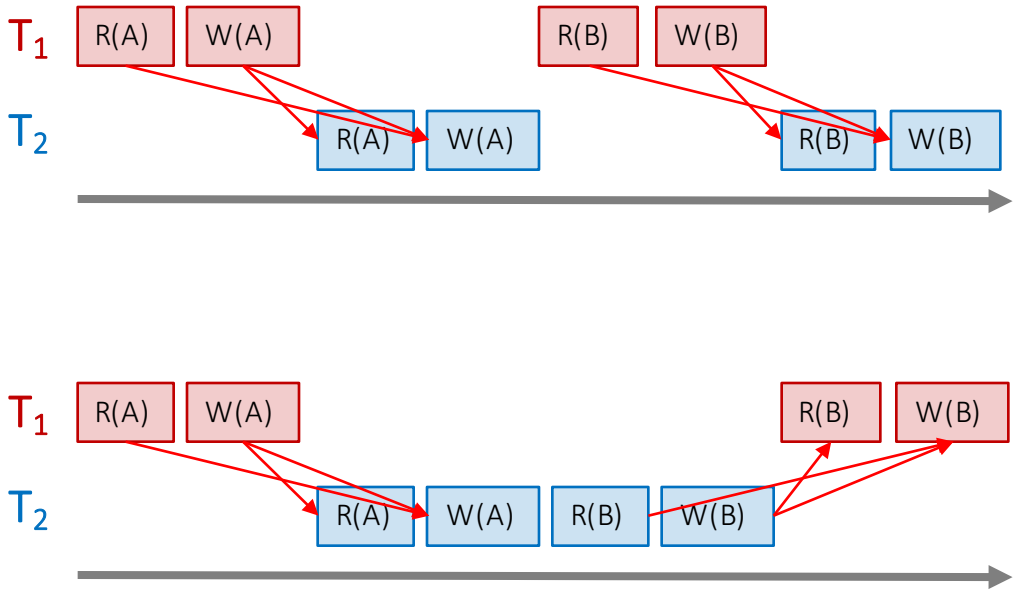


What can we say about "good" vs. "bad" conflict graphs?

Serial Schedule:



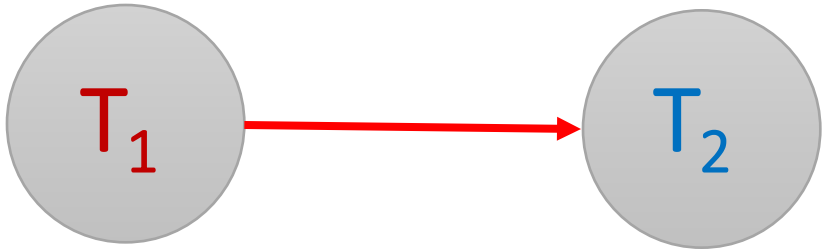
Interleaved Schedules:



A bit complicated…

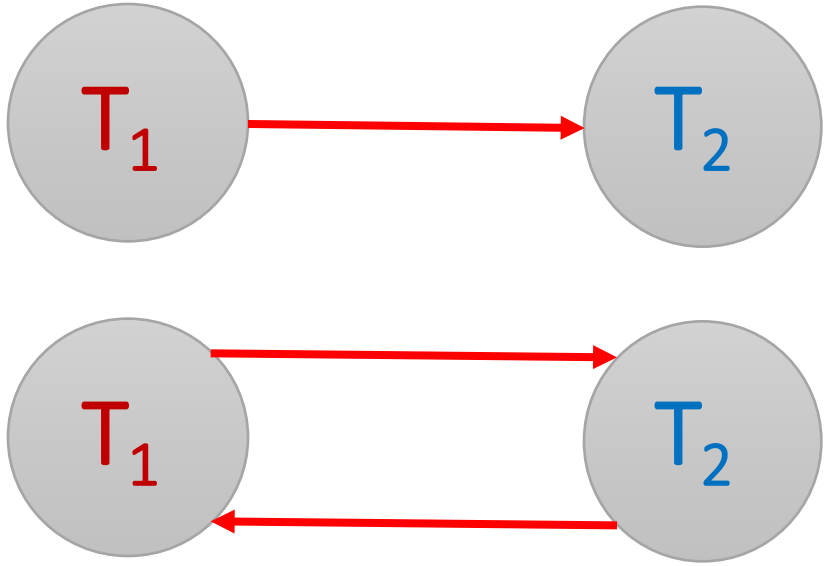
What can we say about "good" vs. "bad" conflict graphs?

Serial Schedule:



Simple!

Interleaved Schedules:



Theorem: Schedule is **conflict serializable** if and only if its conflict graph is **acyclic**

Let’s unpack this notion of acyclic conflict graphs…

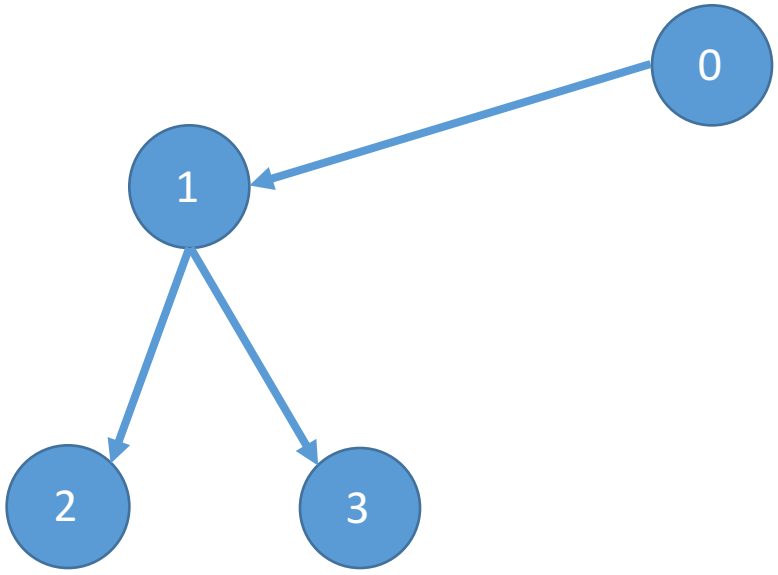
DAGs & Topological Orderings

- A **topological ordering** of a directed graph is a linear ordering of its vertices that respects all the directed edges

- A directed **acyclic** graph (DAG) always has one or more **topological orderings**
  - (And there exists a topological ordering *if and only if* there are no directed cycles)

DAGs & Topological Orderings

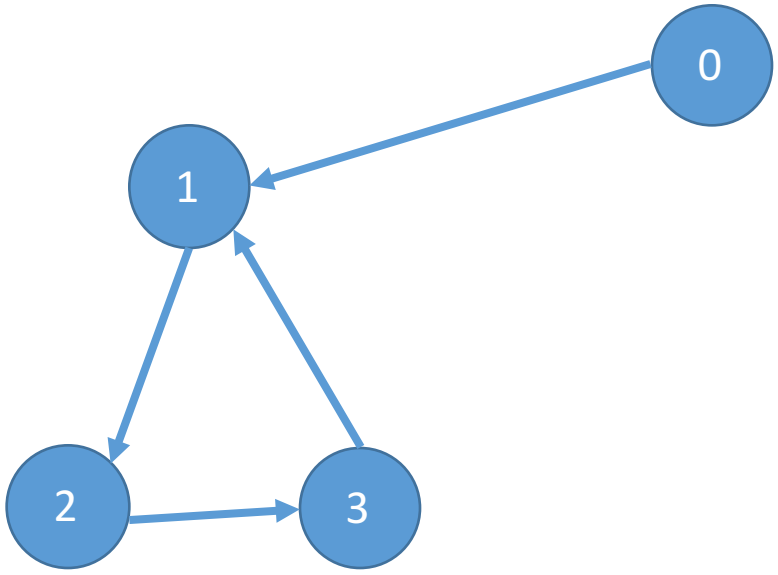
- Ex: What is one possible topological ordering here?



Ex: 0, 1, 2, 3 (or: 0, 1, 3, 2)

DAGs & Topological Orderings

- Ex: What is one possible topological ordering here?



There is none!

Connection to conflict serializability

- In the conflict graph, a topological ordering of nodes corresponds to **a serial ordering of TXNs**

- Thus an **acyclic** conflict graph → conflict serializable!

Theorem: Schedule is **conflict serializable** if and only if its conflict graph is **acyclic**

Strict Two-Phase Locking

- We consider **locking**- specifically, *strict two-phase locking*- as a way to deal with concurrency, because is **guarantees conflict serializability**

- Also fairly straightforward to implement, and transparent to the user!

Strict Two-phase Locking (Strict 2PL) Protocol:

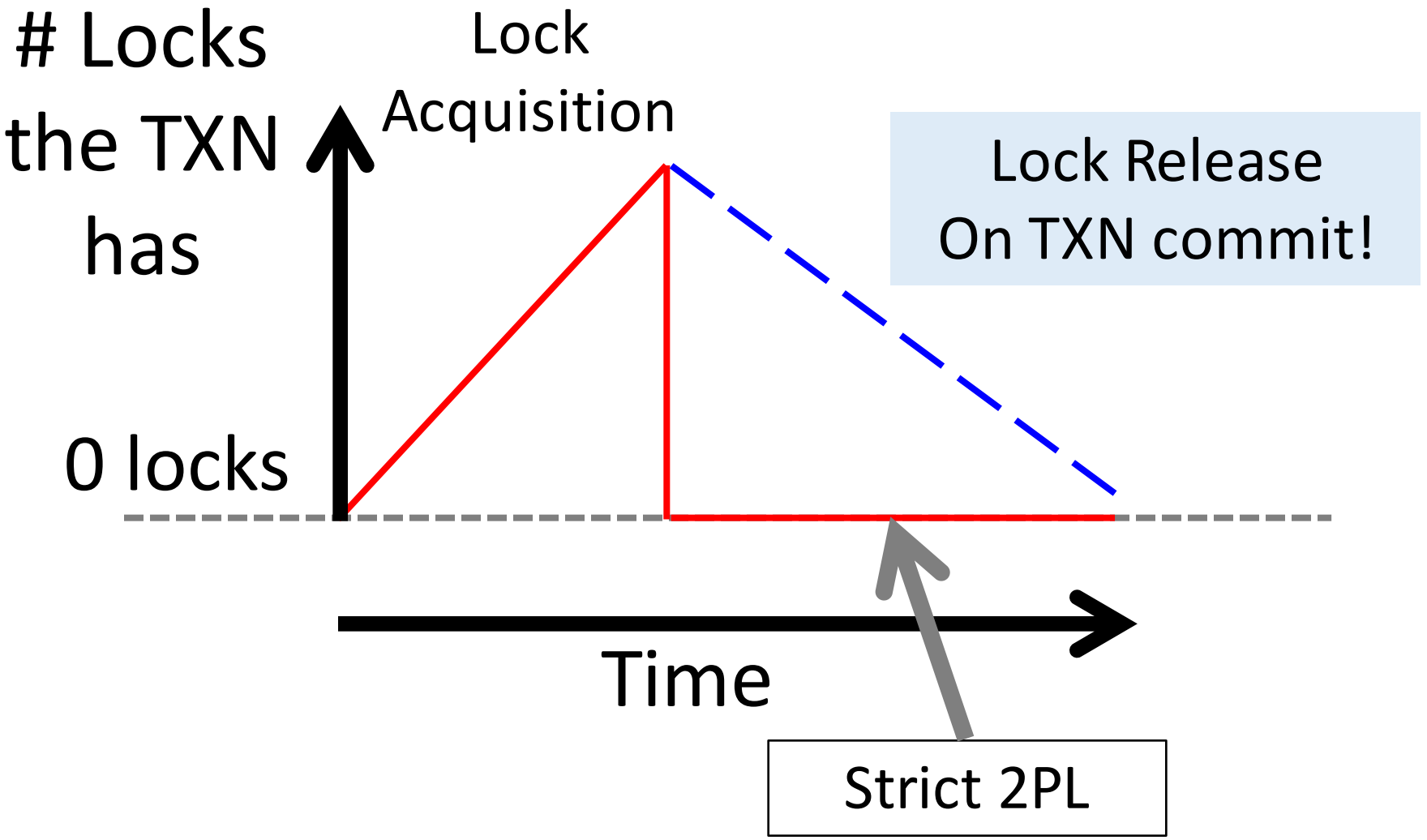
TXNs obtain:

- An **X (*exclusive*) lock** on object before **writing**.
  - If a TXN holds, no other TXN can get a lock (S or X) on that object.
- An **S (*shared*) lock** on object before **reading**
  - If a TXN holds, no other TXN can get *an X lock* on that object
- All locks held by a TXN are released when TXN completes.

Note: Terminology here- "exclusive", "shared"- meant to be intuitive- no tricks!

These policies ensure that no conflicts (RW/WR/WW) occur!

Picture of 2-Phase Locking (2PL)



Strict 2PL

Theorem: Strict 2PL allows only schedules whose dependency graph is acyclic

Proof Intuition: In strict 2PL, if there is an edge $T_i \rightarrow T_j$ (i.e. T_i and T_j conflict) then T_j needs to wait until T_i is finished – so *cannot* have an edge $T_j \rightarrow T_i$

Therefore, Strict 2PL only allows conflict serializable ⇒ serializable schedules

Strict 2PL

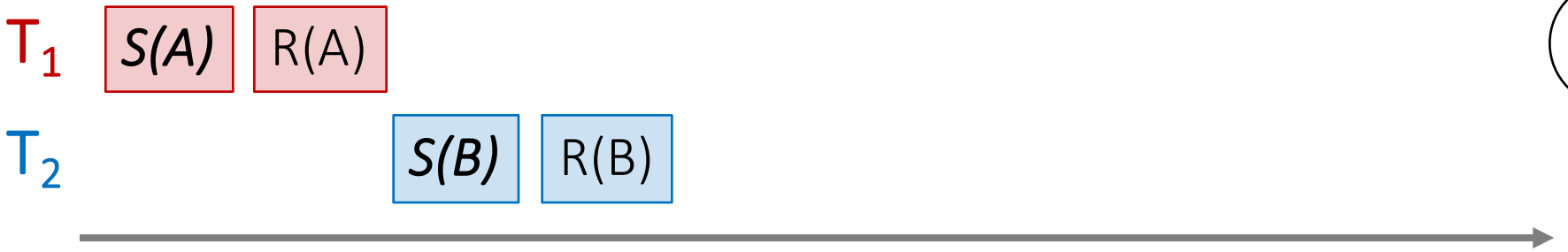
- If a schedule follows strict 2PL and locking, it is conflict serializable…
  - …and thus serializable
  - …and thus maintains isolation & consistency!
- Not all serializable schedules are allowed by strict 2PL.
- So let's use strict 2PL, what could go wrong?

Deadlock Detection: Example

Waits-for graph:

First, T_1 requests a shared lock on A to read from it

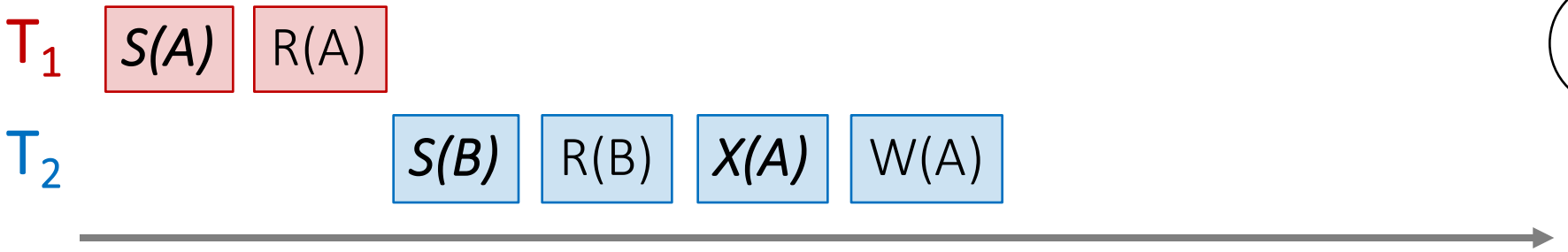
Deadlock Detection: Example



Waits-for graph:

Next, T_2 requests a shared lock on B to read from it

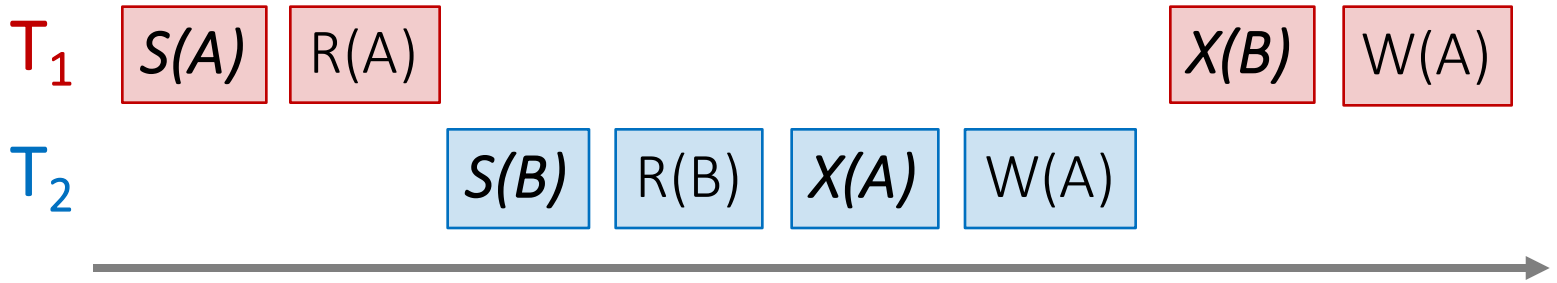
Deadlock Detection: Example



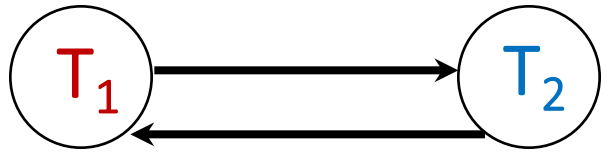
Waits-for graph:

T_2 then requests an exclusive lock on A to write to it- **now T_2 is waiting on T_1…**

Deadlock Detection: Example



Waits-for graph:

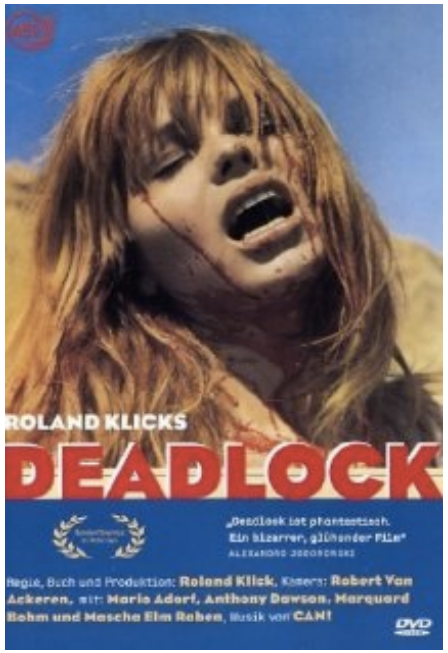


Cycle = DEADLOCK

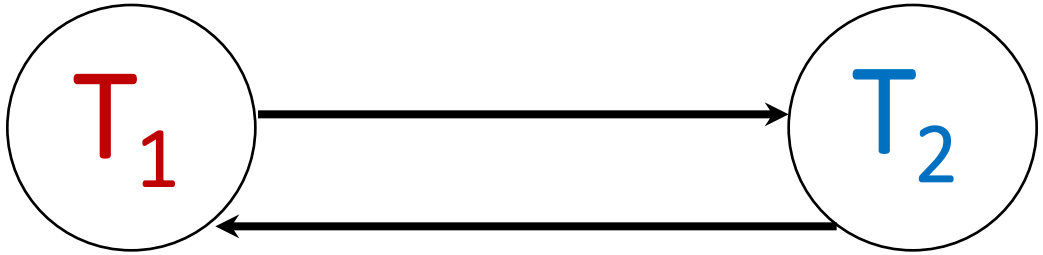
Finally, T_1 requests an exclusive lock on B to write to it- **now T_1 is waiting on T_2… DEADLOCK!**

```
sqlite3.OperationalError: database is locked
```

```
ERROR:  deadlock detected
DETAIL:  Process 321 waits for ExclusiveLock on tuple of
relation 20 of database 12002; blocked by process 4924.
Process 404 waits for ShareLock on transaction 689; blocked
by process 552.
HINT:  See server log for query details.
```



The problem? Deadlock!??!



NB: Also movie called wedlock (deadlock) set in a futuristic prison…
I haven't seen either of them…

Deadlocks

- **Deadlock**: Cycle of transactions waiting for locks to be released by each other.

- Two ways of dealing with deadlocks:

  1. Deadlock prevention

  2. Deadlock detection

Deadlock Detection

- Create the **waits-for graph**:
  - Nodes are transactions
  - There is an edge from $T_i \rightarrow T_j$ if T_i is *waiting for T_j to release a lock*
- Periodically check for (***and break***) cycles in the waits-for graph

Summary

- *Last lecture:* Concurrency achieved by **interleaving TXNs** such that **isolation** & **consistency** are maintained
  - We formalized a notion of **serializability** that captured such a "good" interleaving schedule

- Now, we defined **conflict serializability**, which implies serializability

- **Locking** allows only conflict serializable schedules
  - If the schedule completes- it may deadlock!

Candy Break

2. The Buffer

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

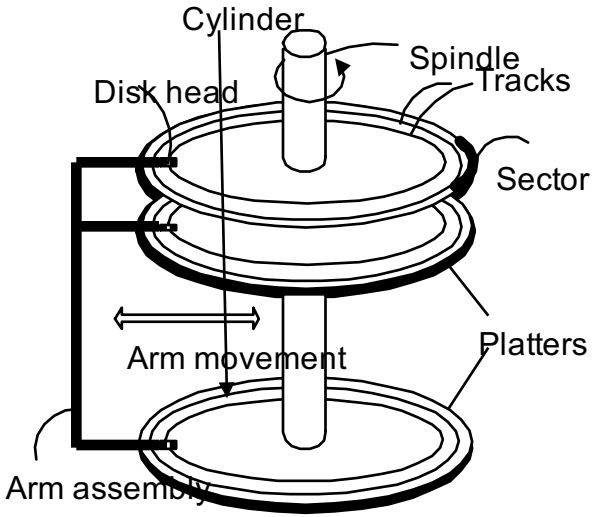
2. Many **mechanisms** have become **stand-alone systems**
    - **Indexing** to Key-value stores
    - Embedded join processing
    - SQL-like languages take some aspect of what we discuss (PIG, Hive)

What you will learn about in this section

1. RECAP: Storage and memory model

2. Buffer primer

High-level: Disk vs. Main Memory



Disk:

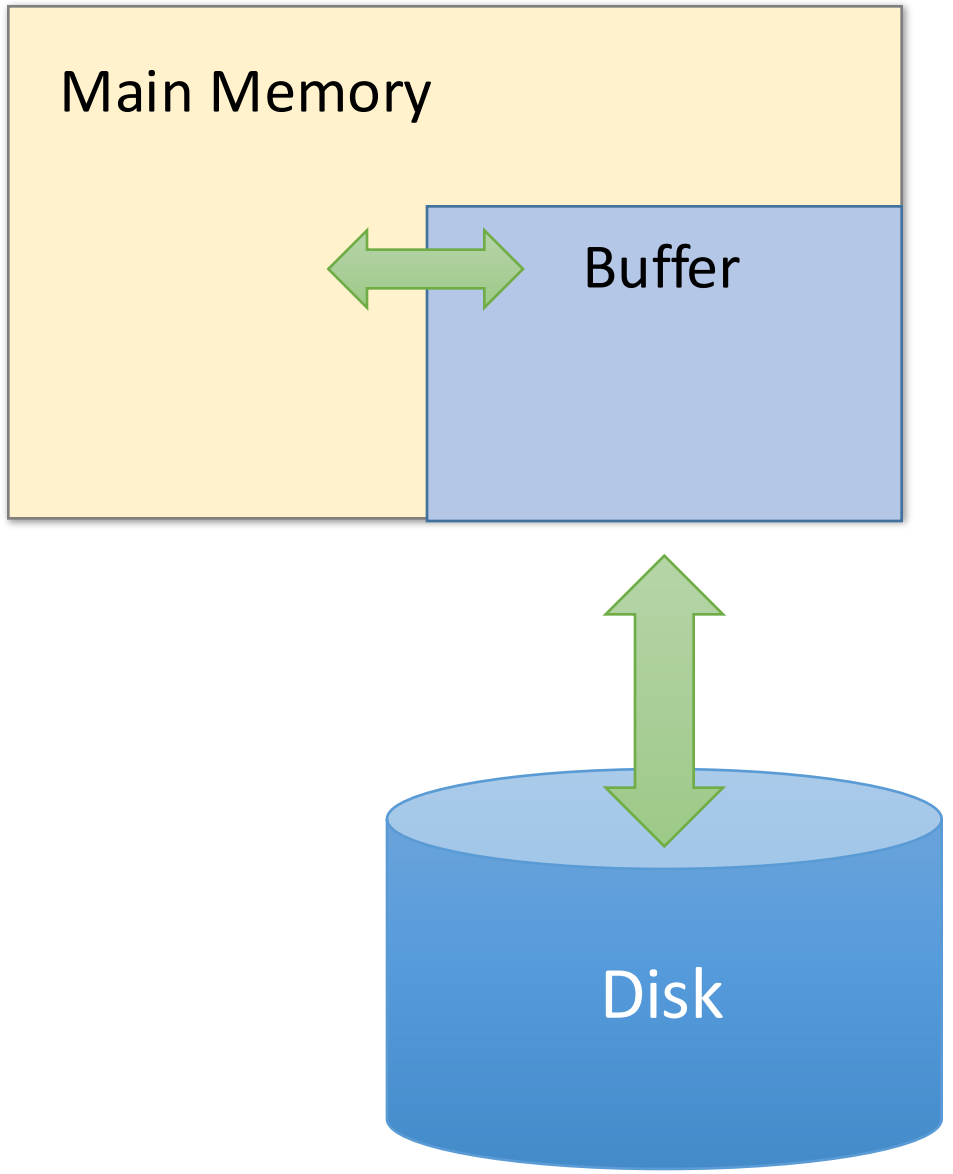
- ***Slow:*** Sequential *block* access
  - Read a blocks (not byte) at a time, so sequential access is cheaper than random
  - **Disk read / writes are expensive!**
- ***Durable:*** We will assume that once on disk, data is safe!
- ***Cheap***

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!

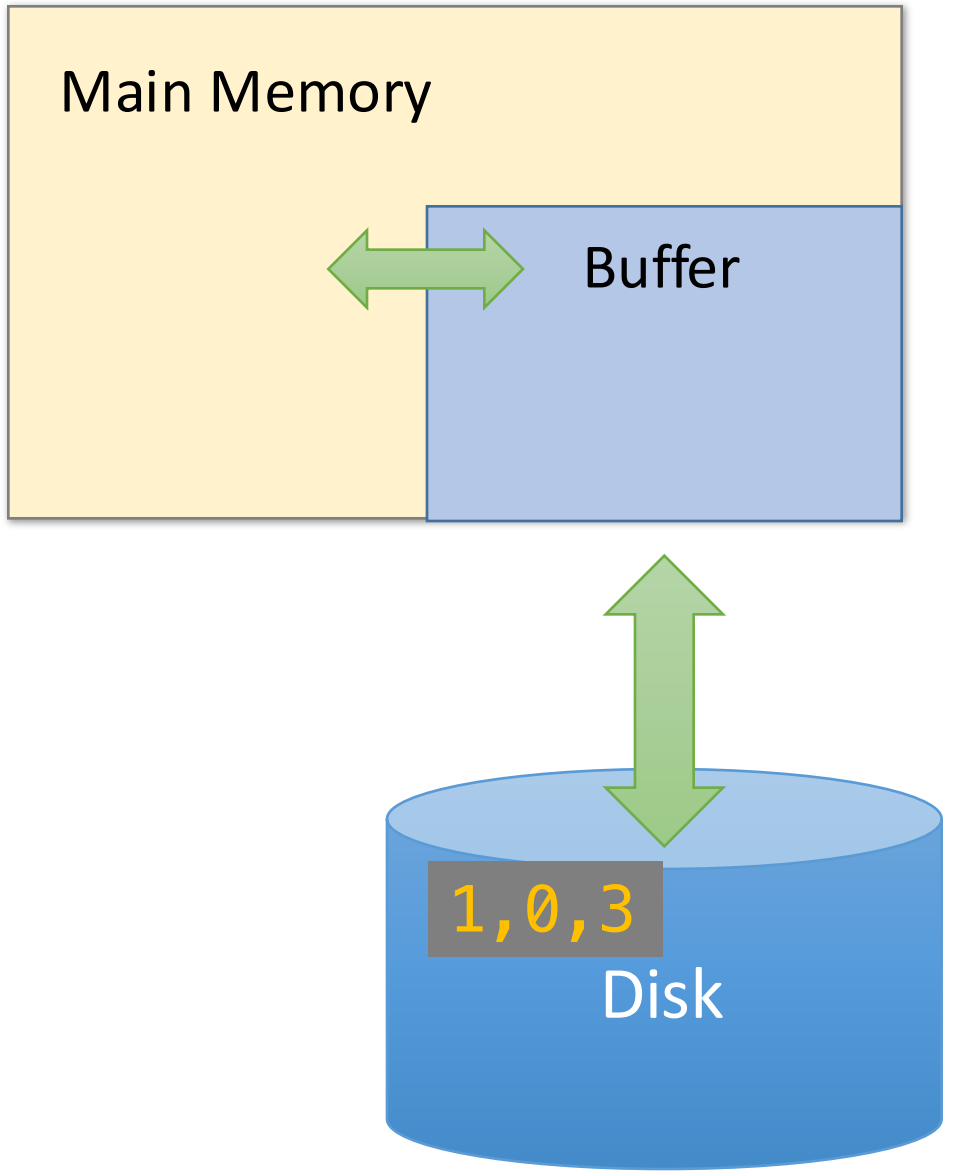
The Buffer

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



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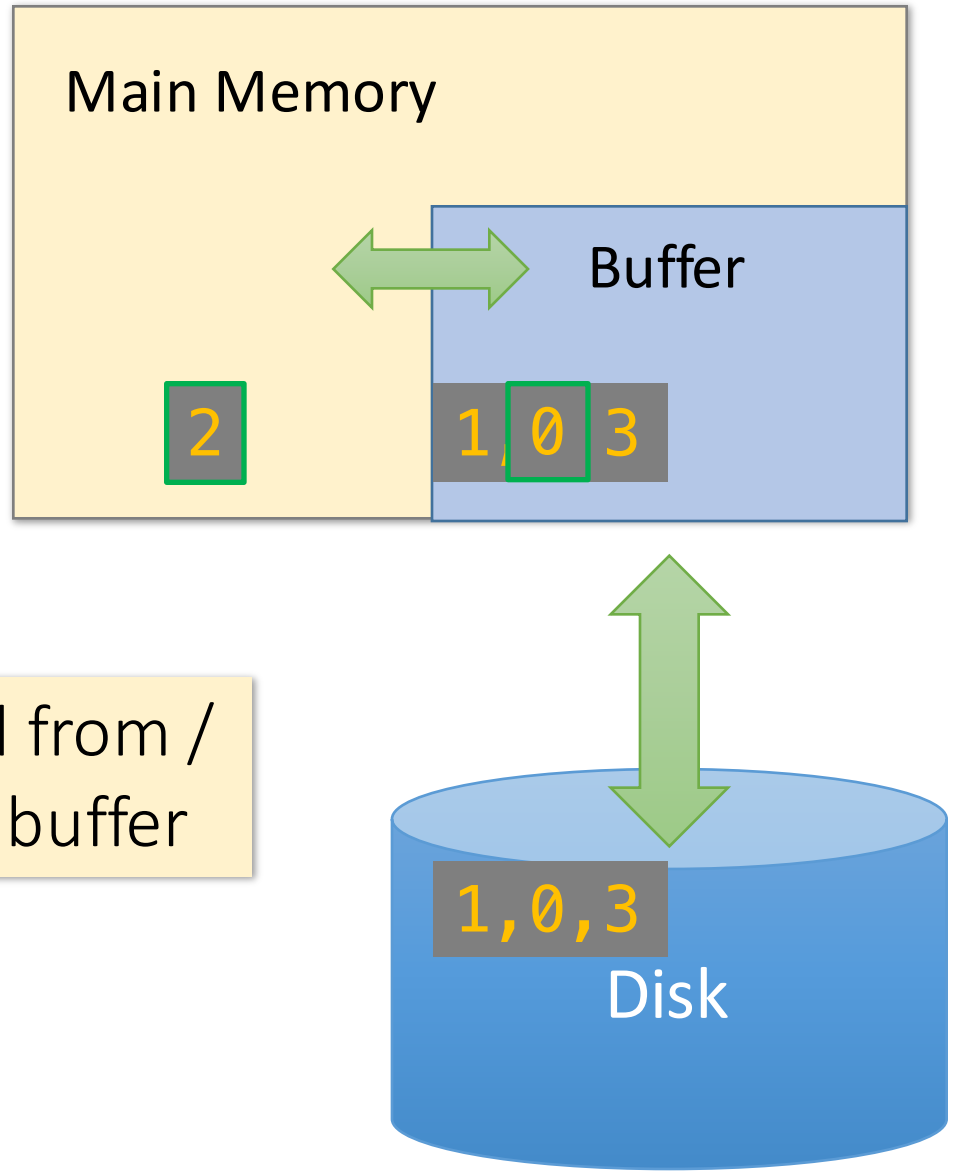

Processes can then read from / write to the page in the buffer

The (Simplified) Buffer

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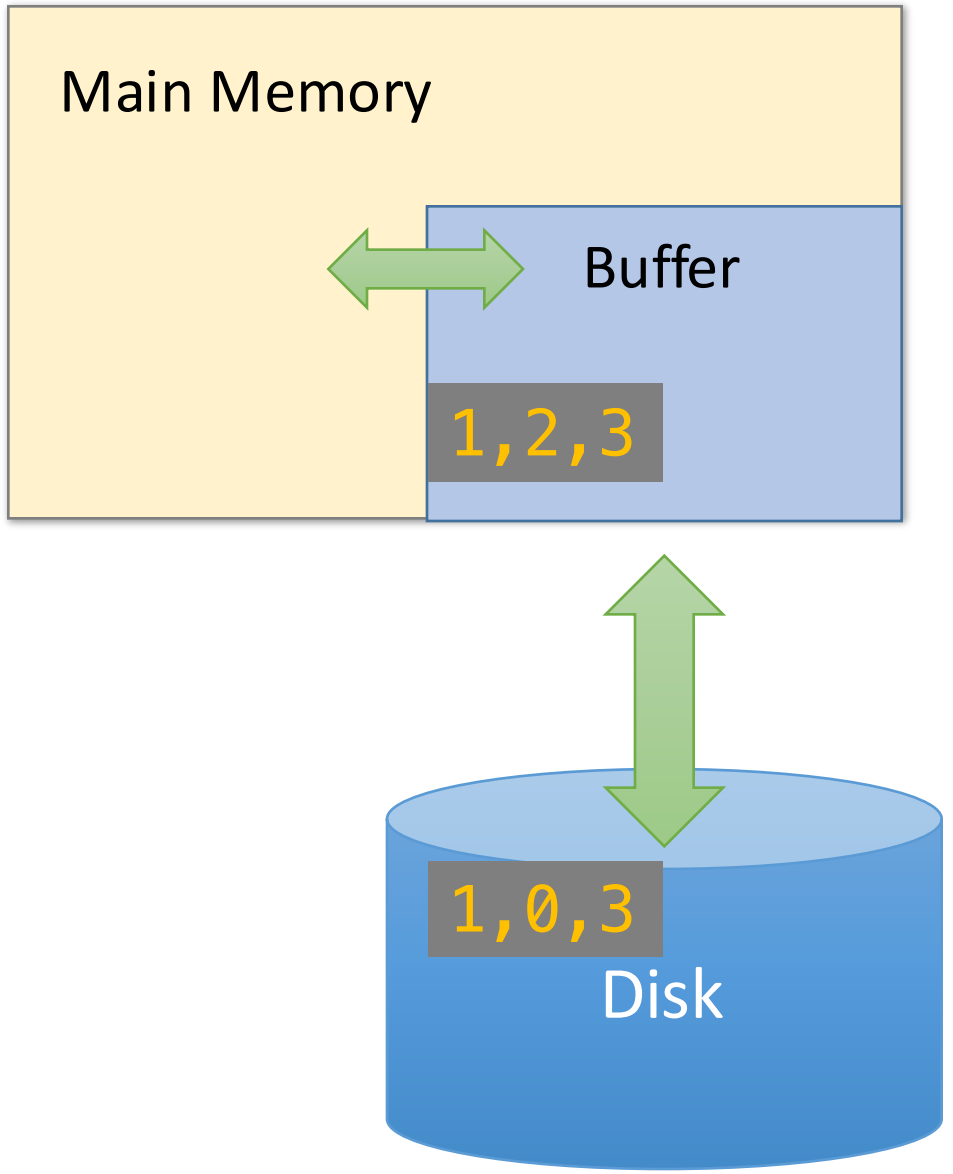
  - **Flush(page):** Evict page from buffer & write to disk



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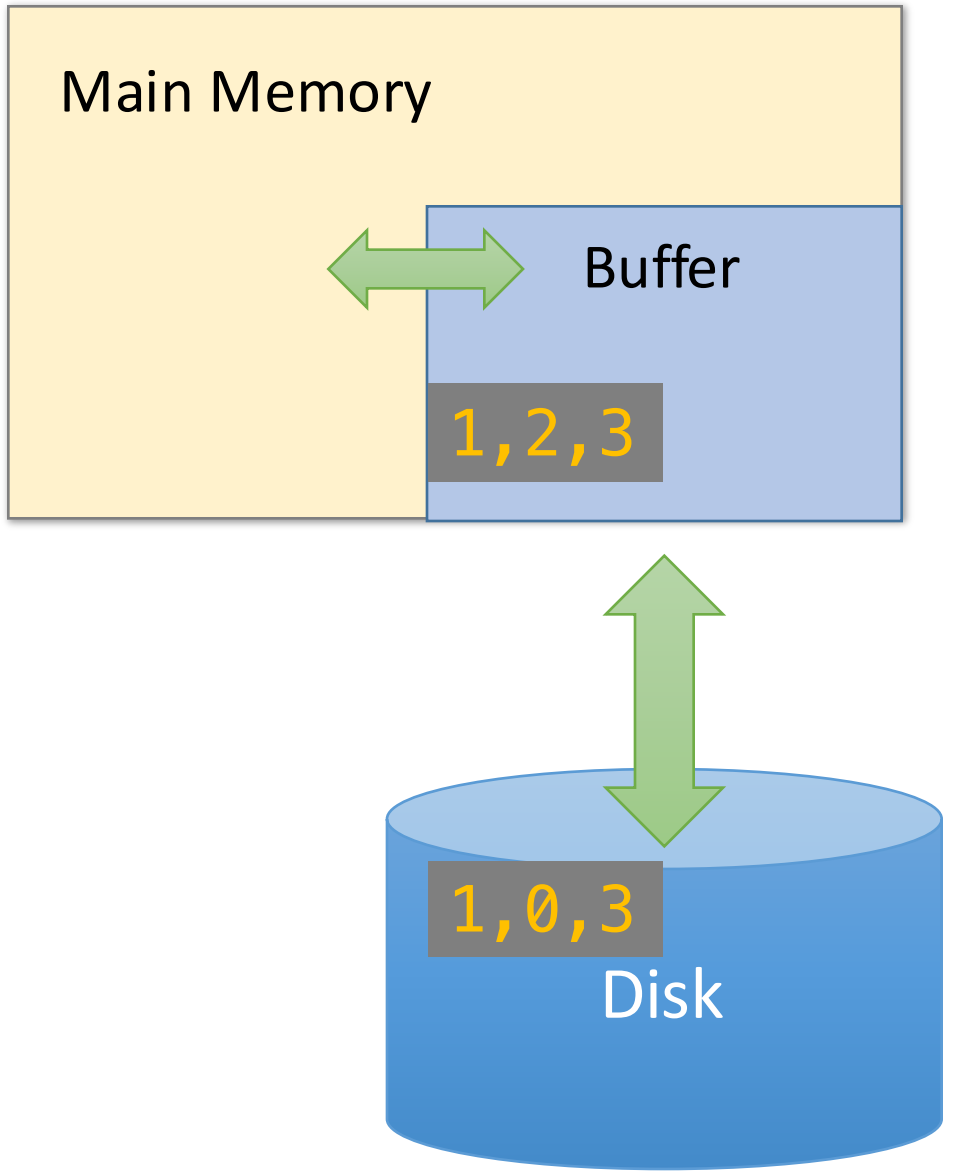
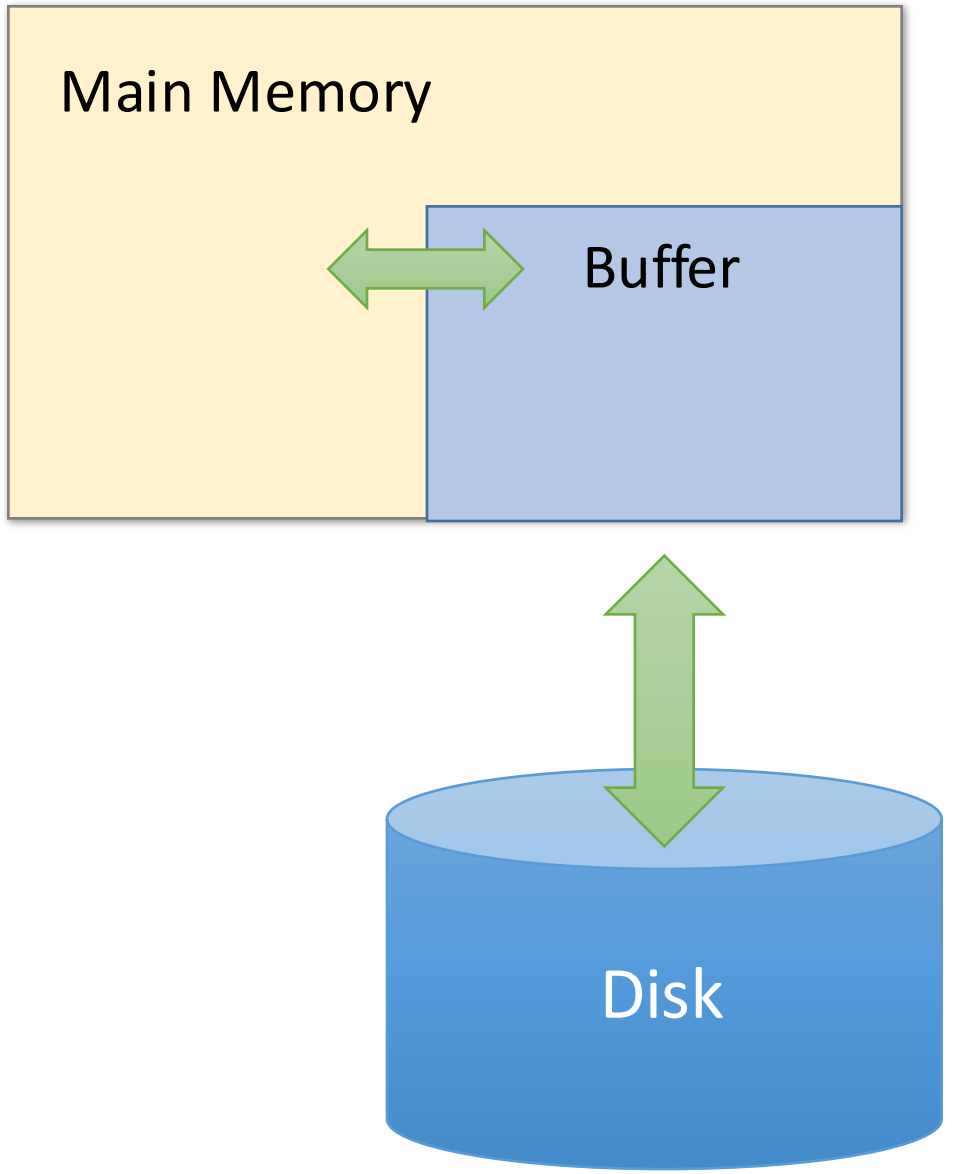
  - **Read(page):** Read page from disk -> buffer *if not already in buffer*
  - **Flush(page):** Evict page from buffer & write to disk
  - **Release(page):** Evict page from buffer *without* writing to disk



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.

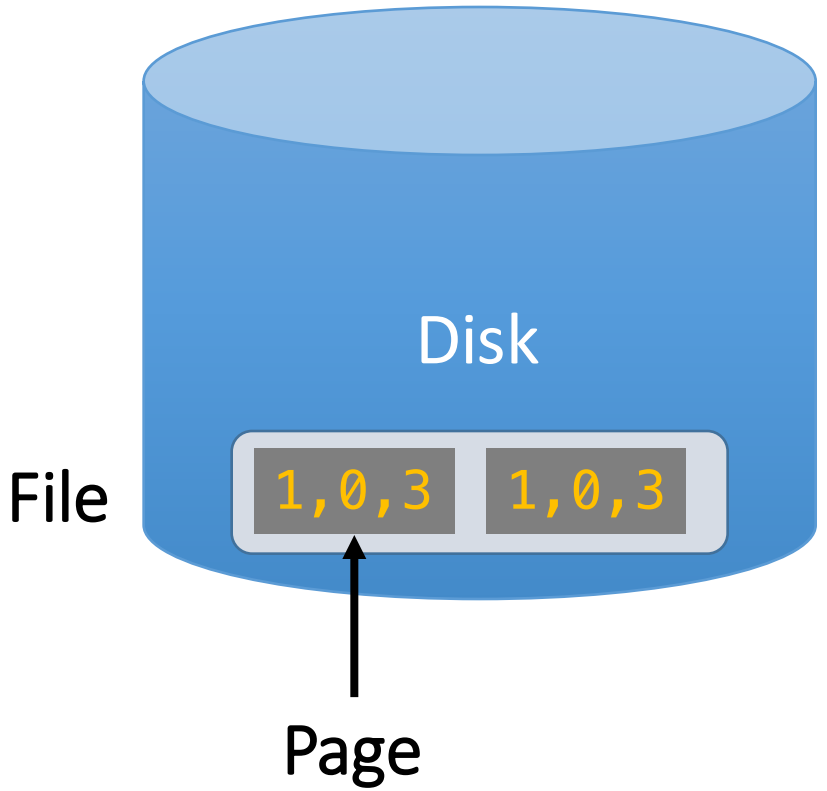


The Buffer Manager

- 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

A Simplified Filesystem Model

- For us, a **page** 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 346)
- And a **file** is a *variable-length list* of pages
  - Interface: create / open / close; next_page(); etc.



2. External Merge & Sort

What you will learn about in this section

1. External Merge- Basics
2. External Merge- Extensions
3. External Sort

External Merge

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?

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:

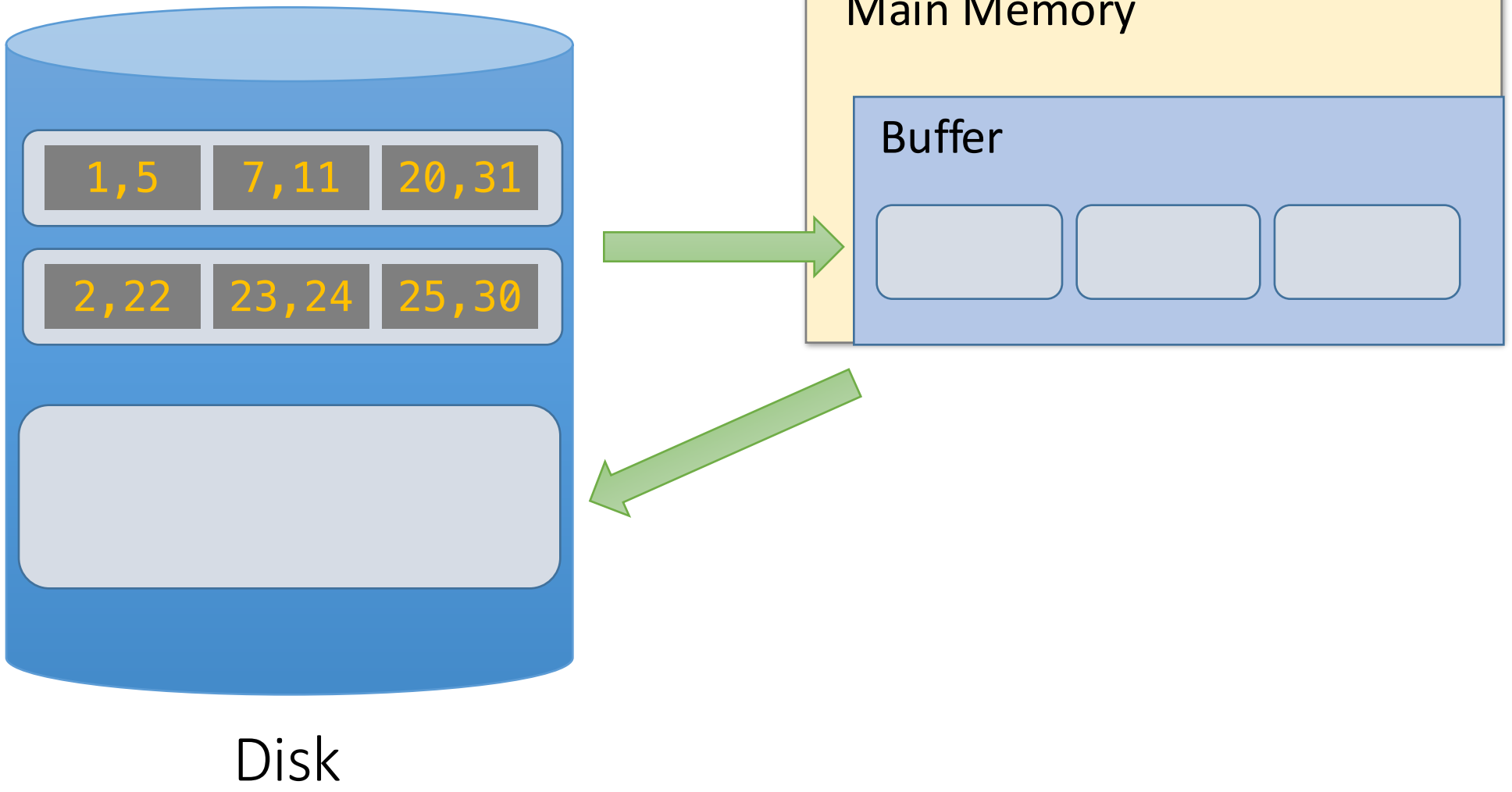
$$Min(A_1, B_1) \leq A_i$$
$$Min(A_1, B_1) \leq B_j$$

for i=1….N and j=1….M

External Merge Algorithm

Input:
Two sorted
files

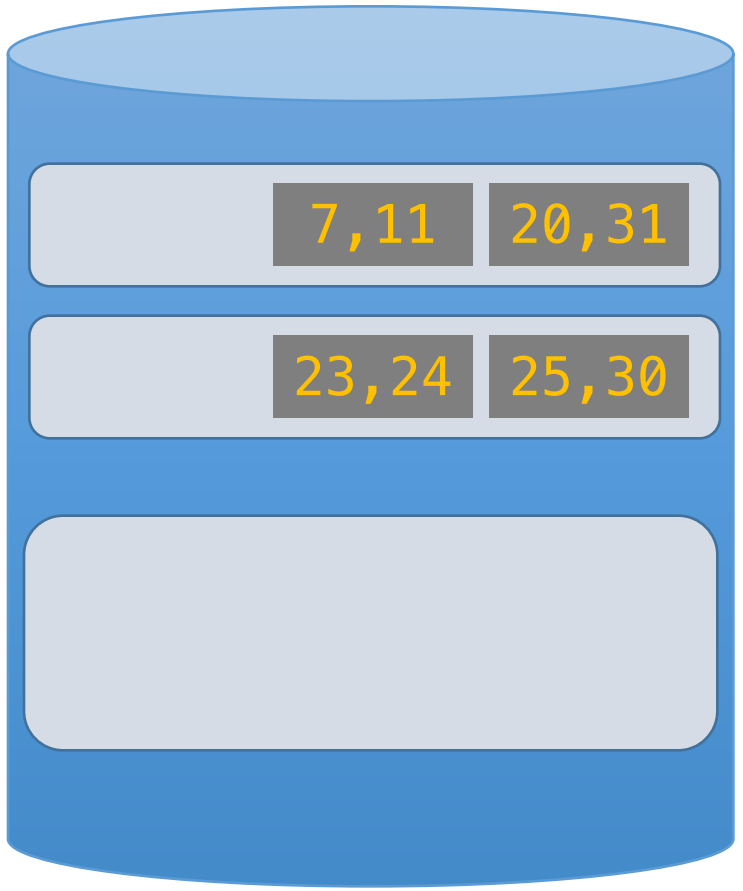
Output:
One *merged*
sorted file



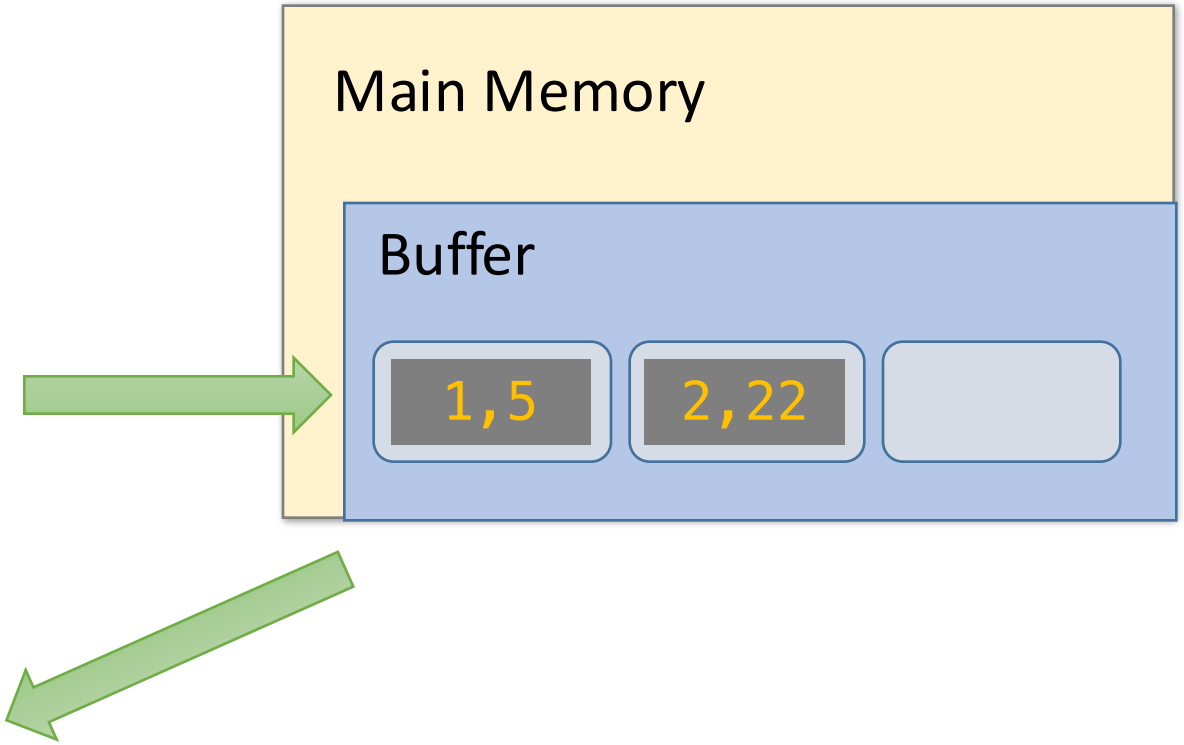
External Merge Algorithm

Input:
Two sorted
files

Output:
One *merged*
sorted file



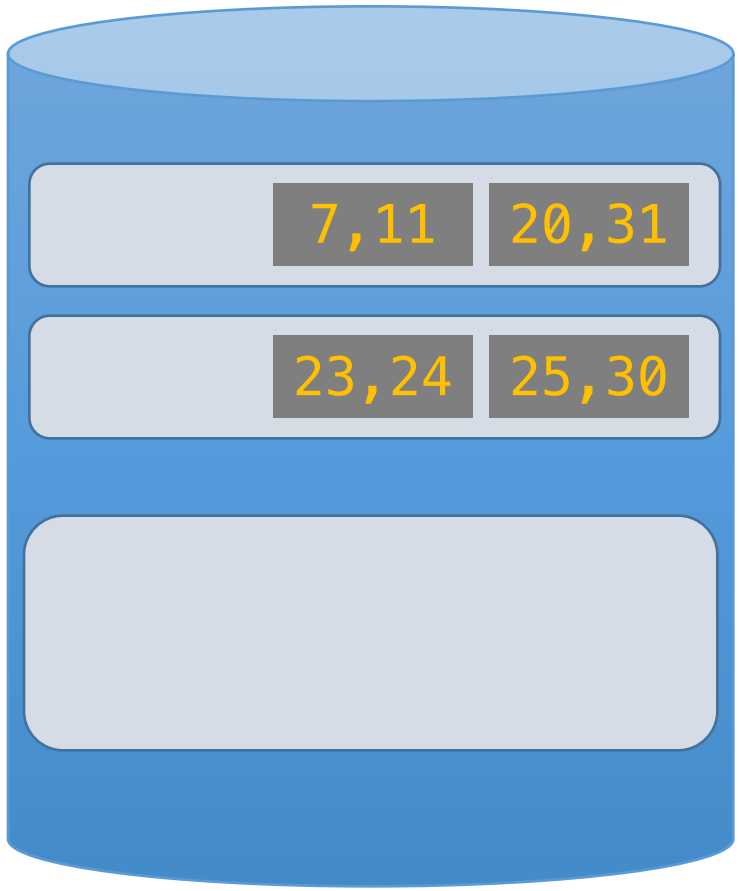
Disk



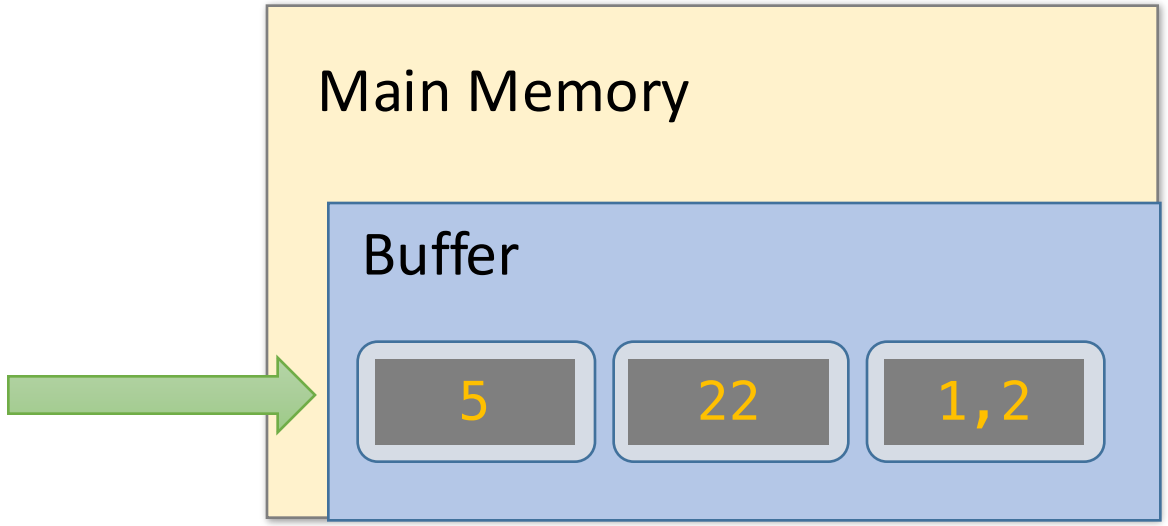
External Merge Algorithm

Input:
Two sorted
files

Output:
One *merged*
sorted file



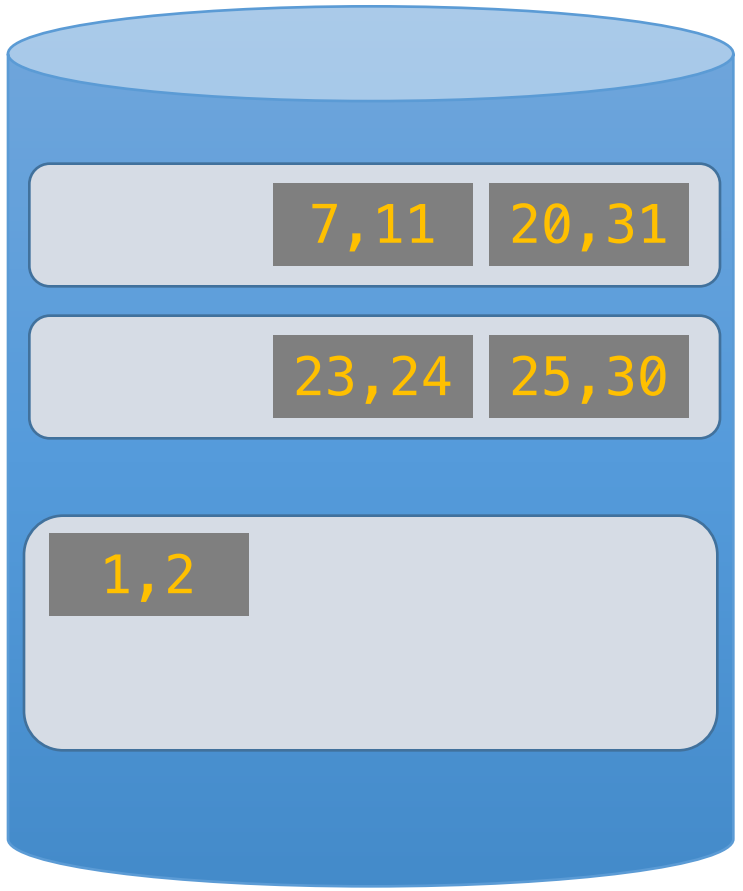
Disk



External Merge Algorithm

Input:
Two sorted
files

Output:
One *merged*
sorted file



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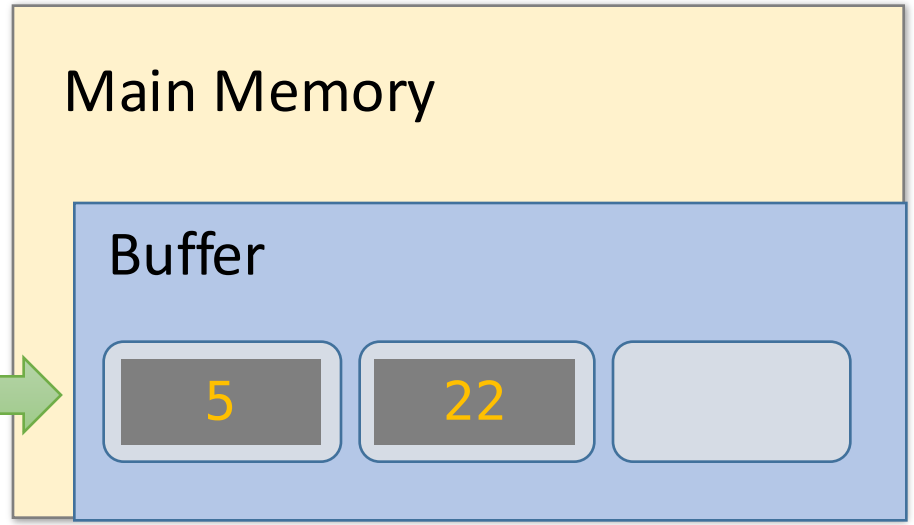
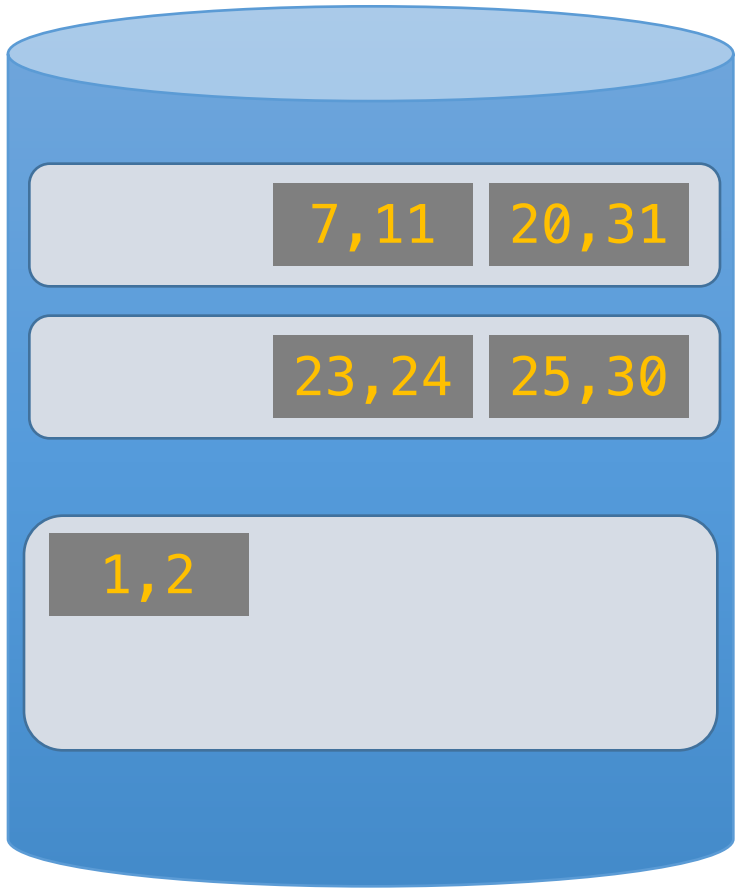


External Merge Algorithm

Input:
Two sorted files

Output:
One *merged* sorted file



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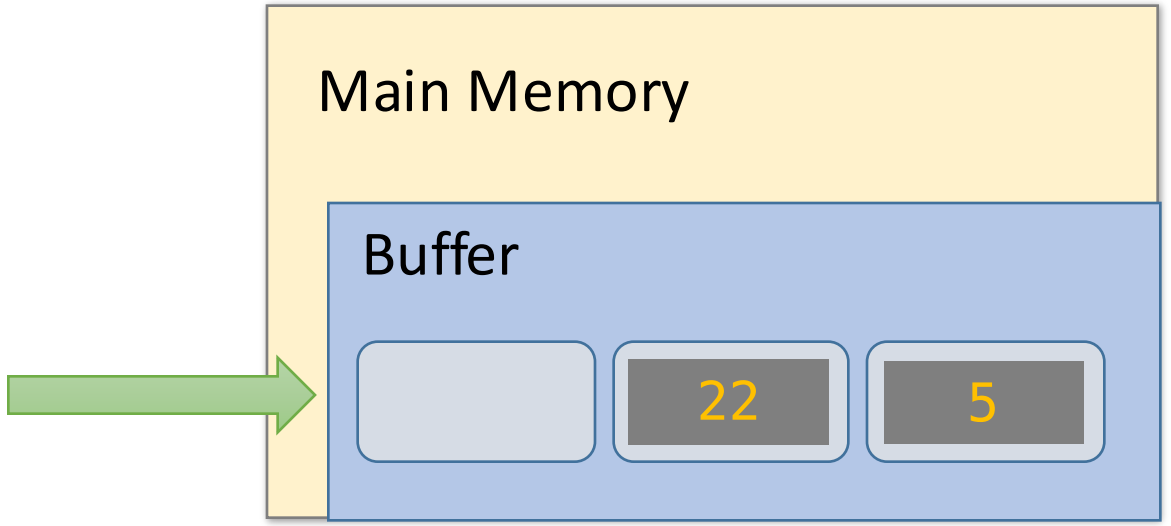
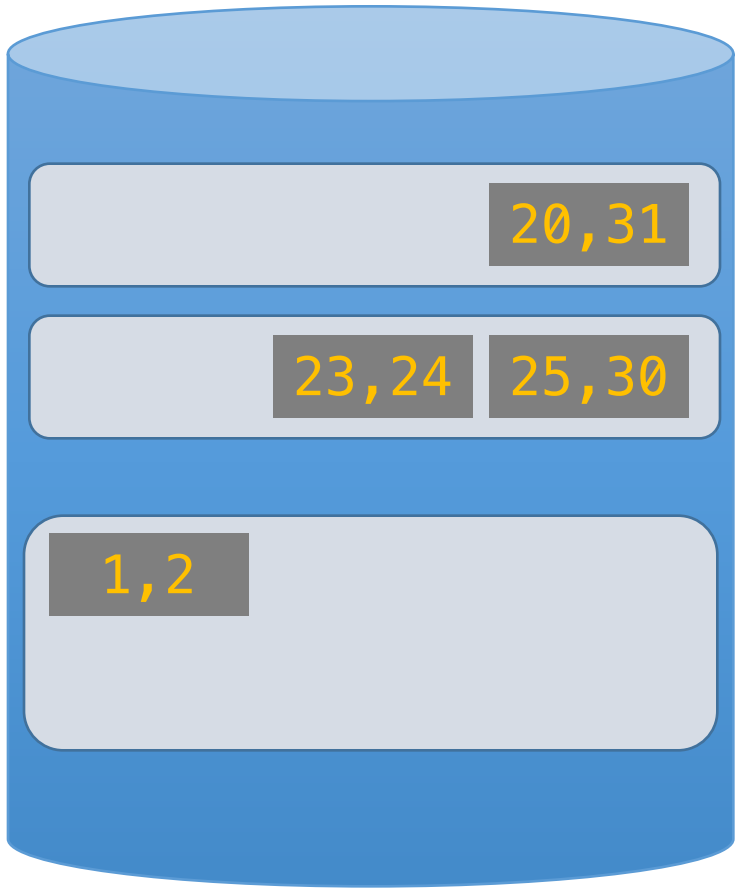


Which page to load next? We know that all values in F_2 are ≥ 22... so load from F_1

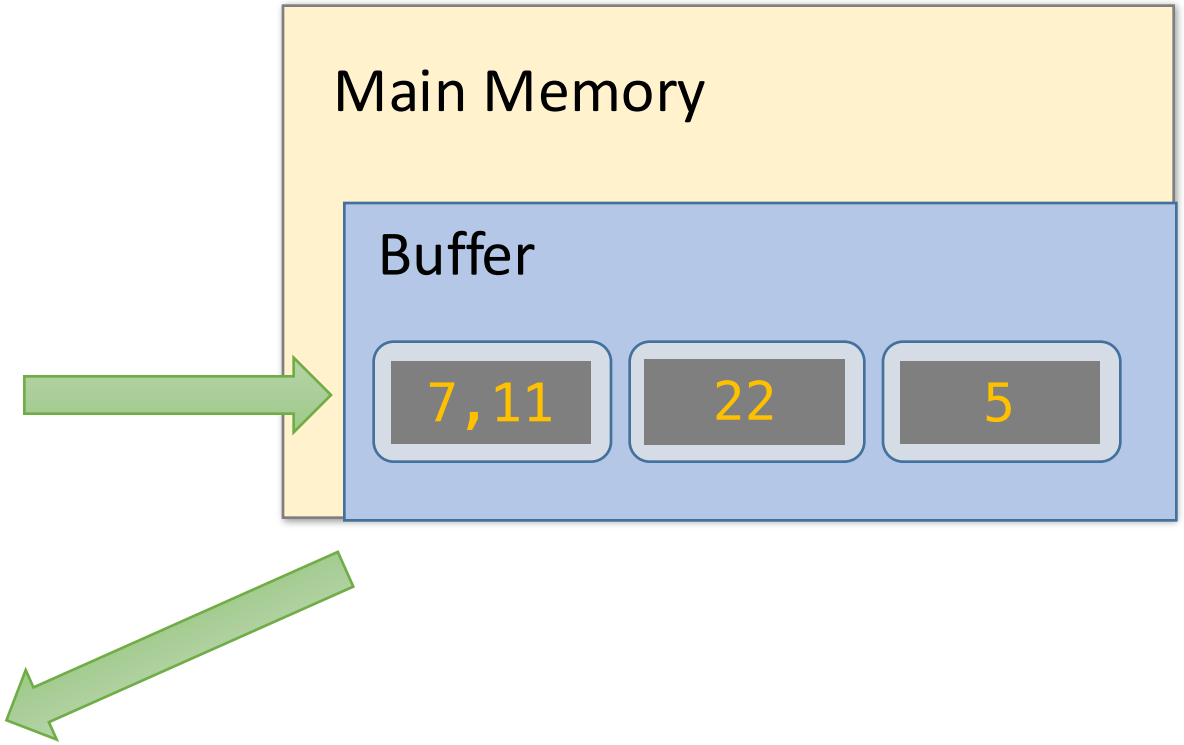
External Merge Algorithm

Input:
Two sorted
files

Output:
One *merged*
sorted file



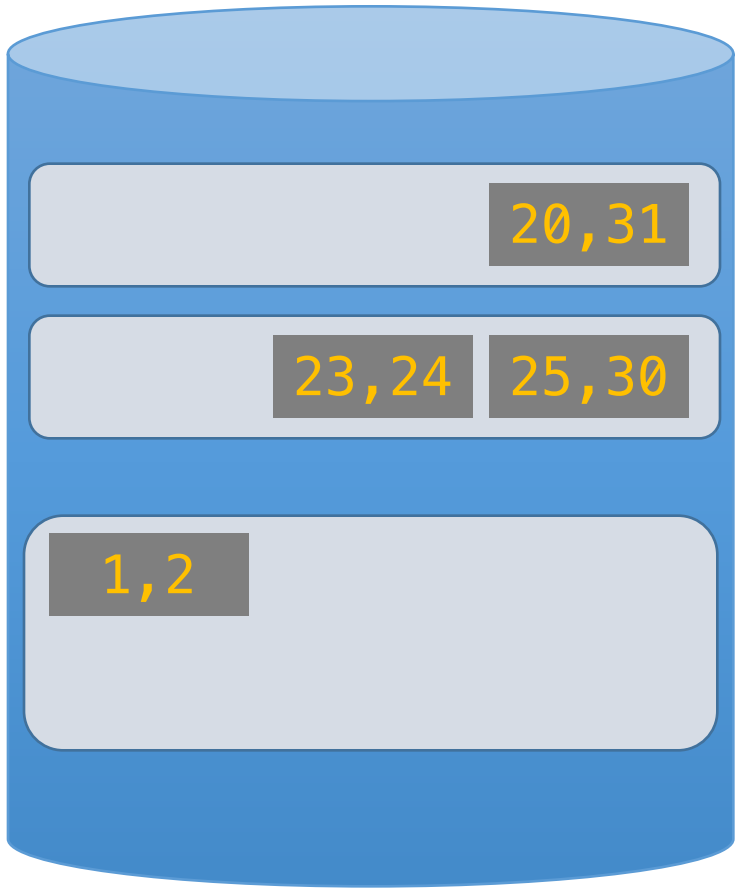
Disk



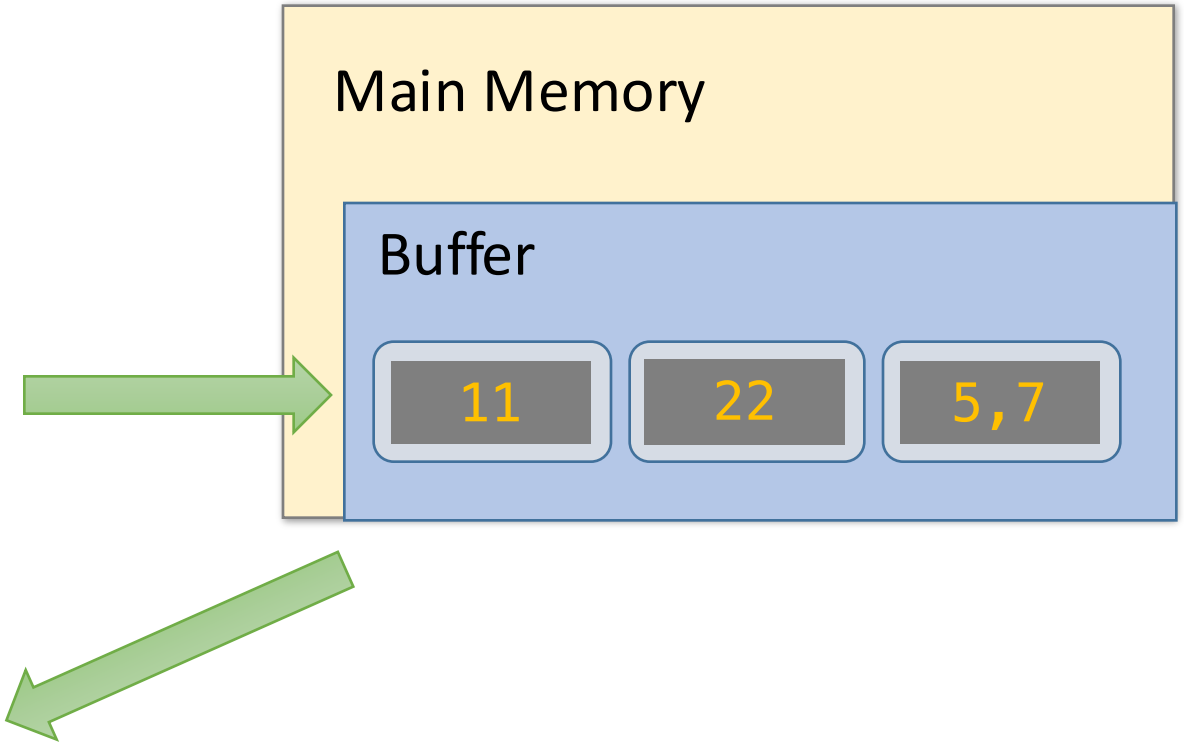
External Merge Algorithm

Input:
Two sorted
files

Output:
One *merged*
sorted file



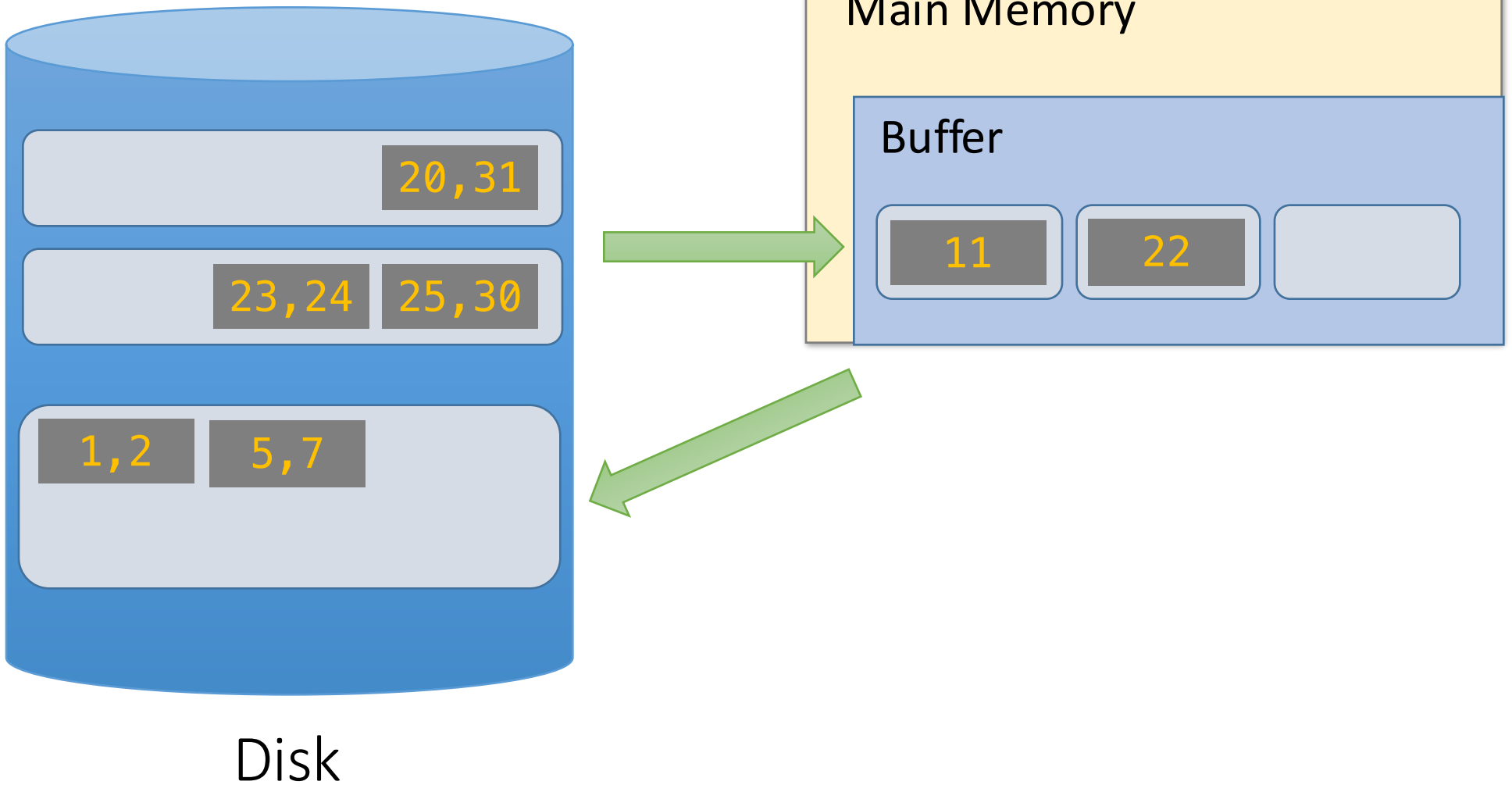
Disk



External Merge Algorithm

Input:
Two sorted
files

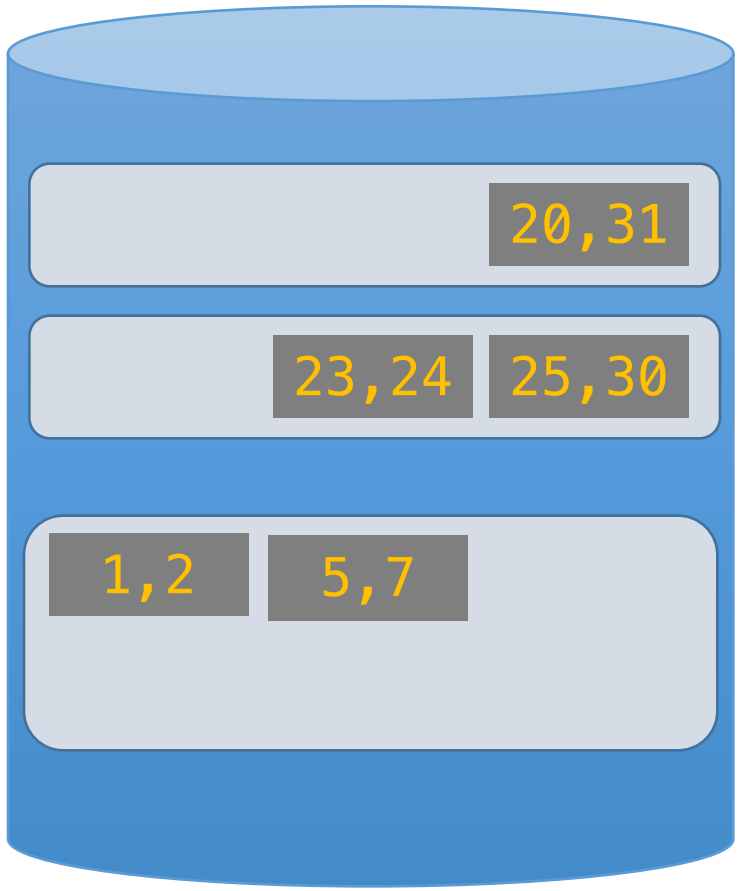
Output:
One *merged*
sorted file



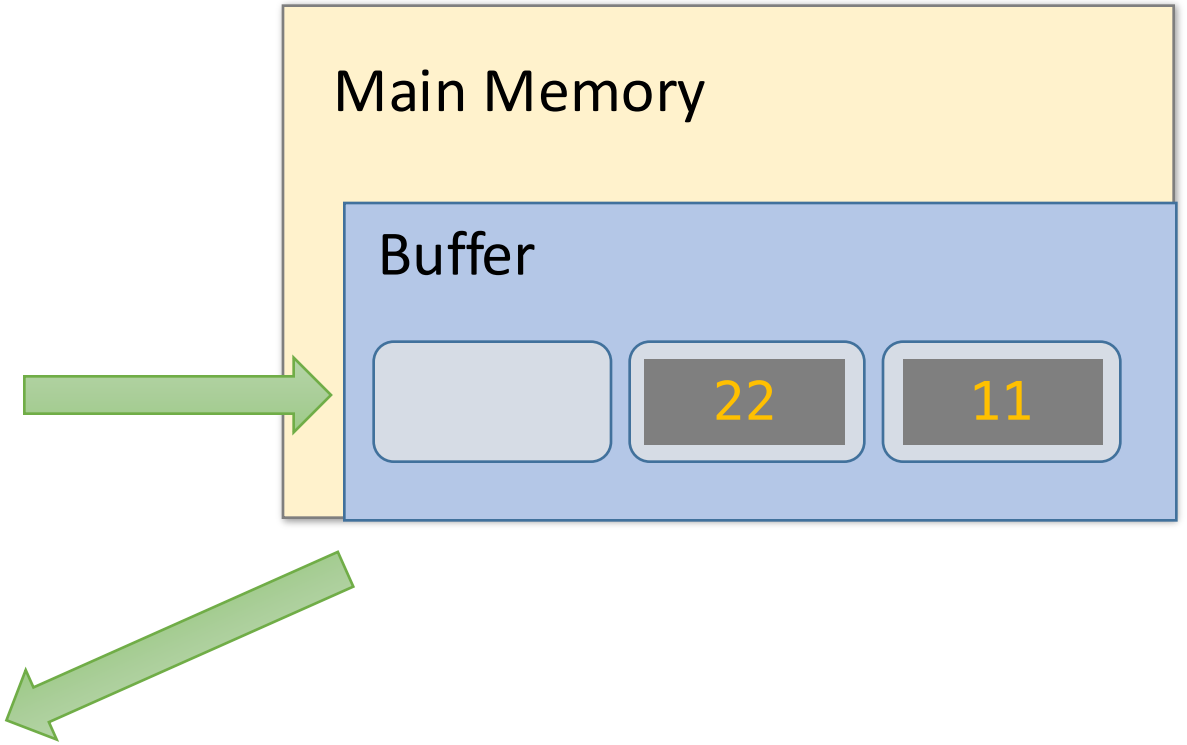
External Merge Algorithm

Input:
Two sorted
files

Output:
One *merged*
sorted file



Disk



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?

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.

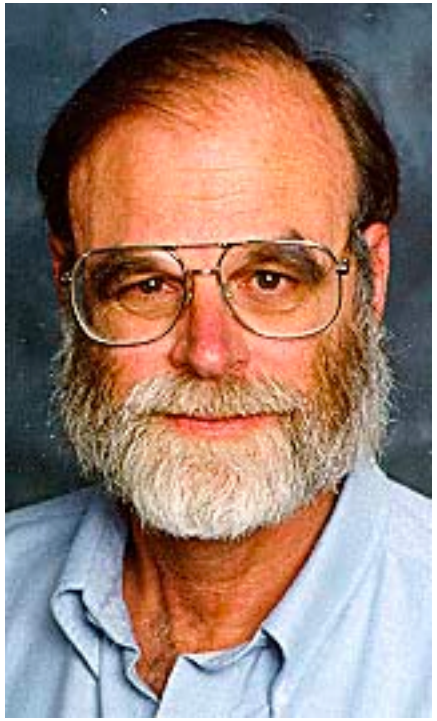
Next lecture!

- *Sort-merge* join algorithm involves sorting

The lecture after next…

Do people care?

http://sortbenchmark.org



Sort benchmark bears his name

Simplified External Sorts.

So how do we sort big files?

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

2. **Merge** each pair of sorted chunks ***using the external merge algorithm***

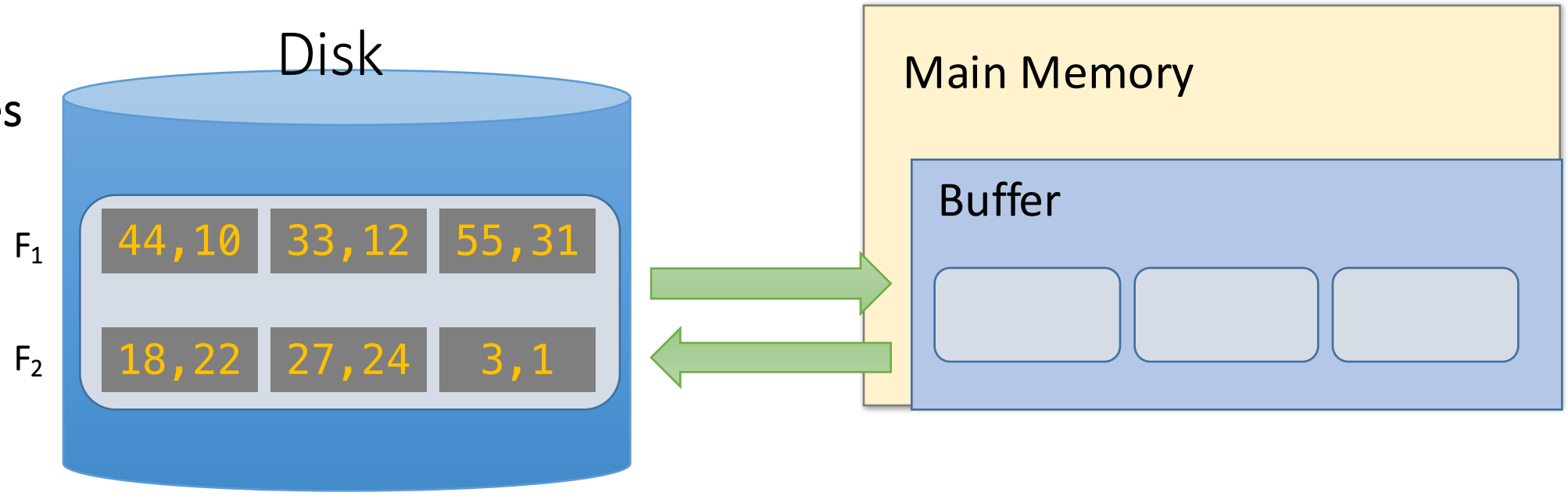
3. **Merge** pairs of these resulting chunks…

4. **Repeat** until all merged (and sorted!)

External Merge Sort Algorithm

Example:

- 3 Buffer pages
- 6-page file

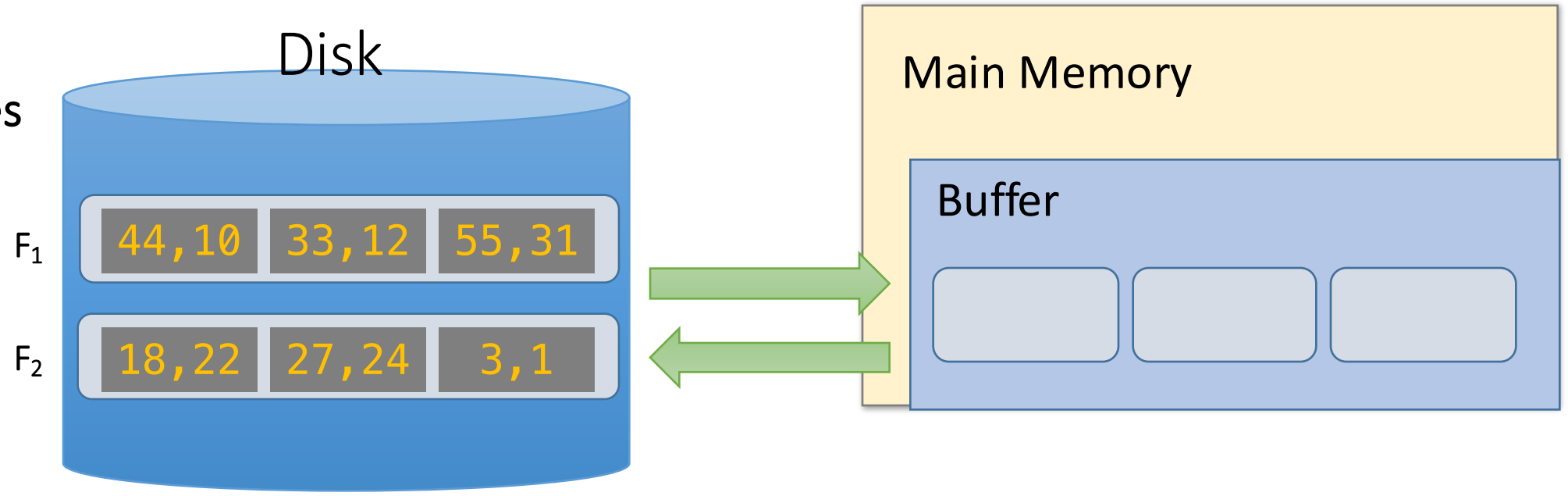


1. Split into chunks small enough to **sort in memory**

External Merge Sort Algorithm

Example:

- 3 Buffer pages
- 6-page file

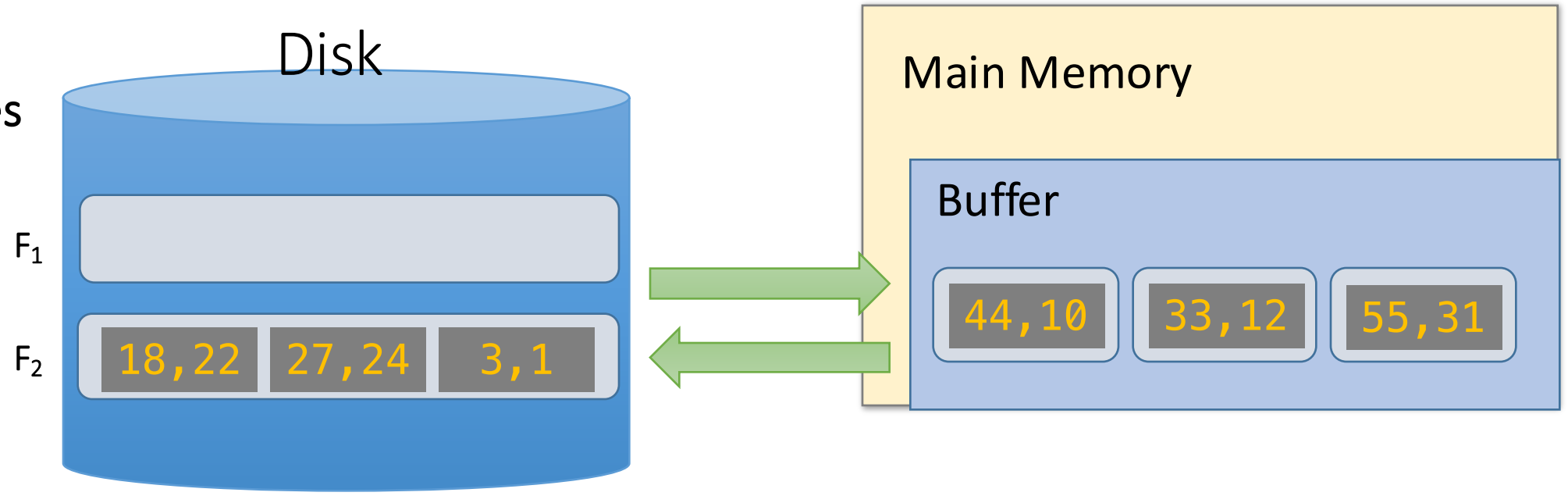


1. Split into chunks small enough to **sort in memory**

External Merge Sort Algorithm

Example:

- 3 Buffer pages
- 6-page file

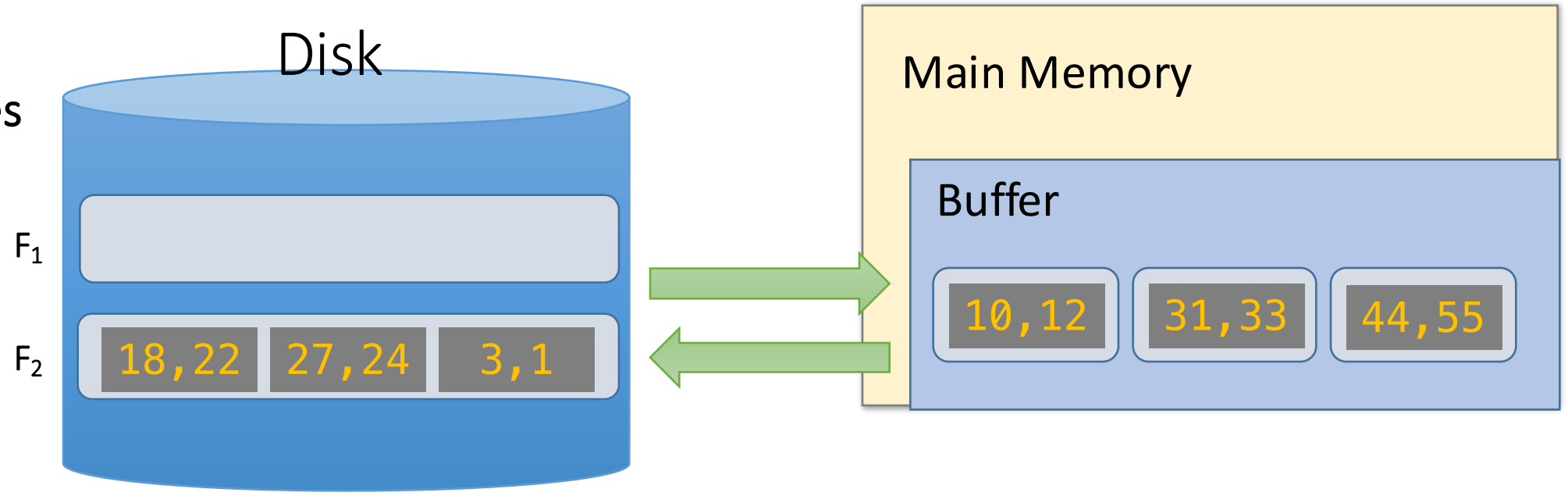


1. Split into chunks small enough to **sort in memory**

External Merge Sort Algorithm

Example:

- 3 Buffer pages
- 6-page file

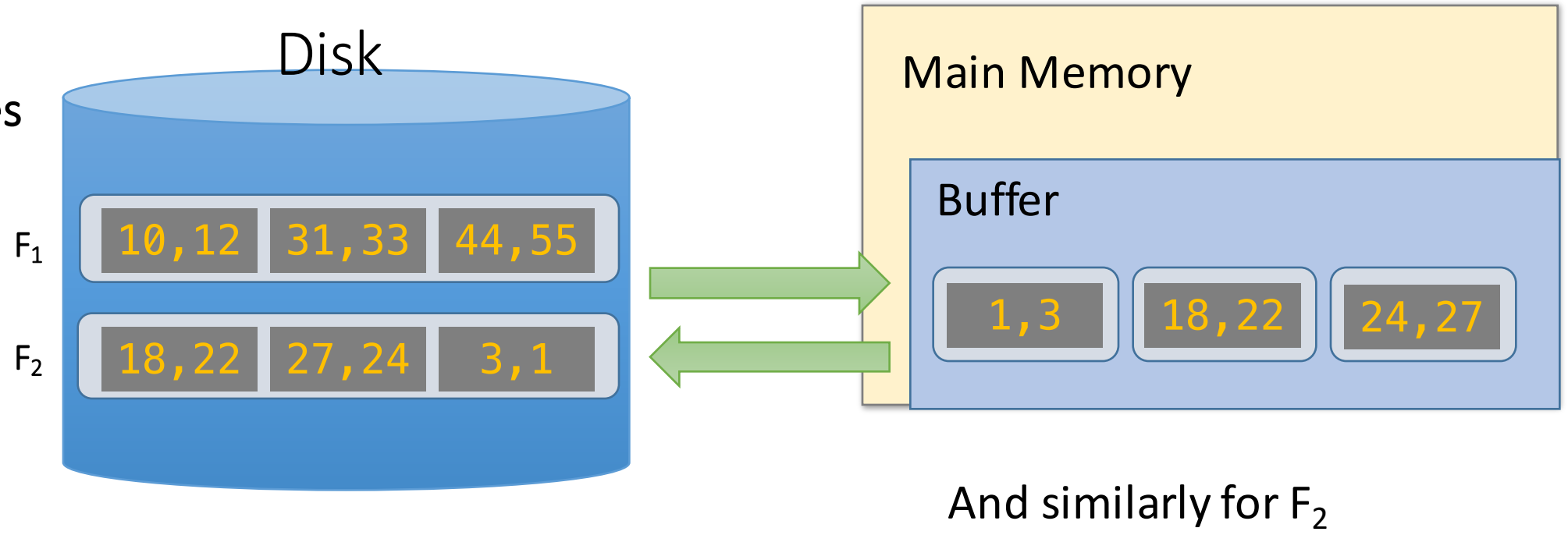


1. Split into chunks small enough to **sort in memory**

External Merge Sort Algorithm

Example:

- 3 Buffer pages
- 6-page file

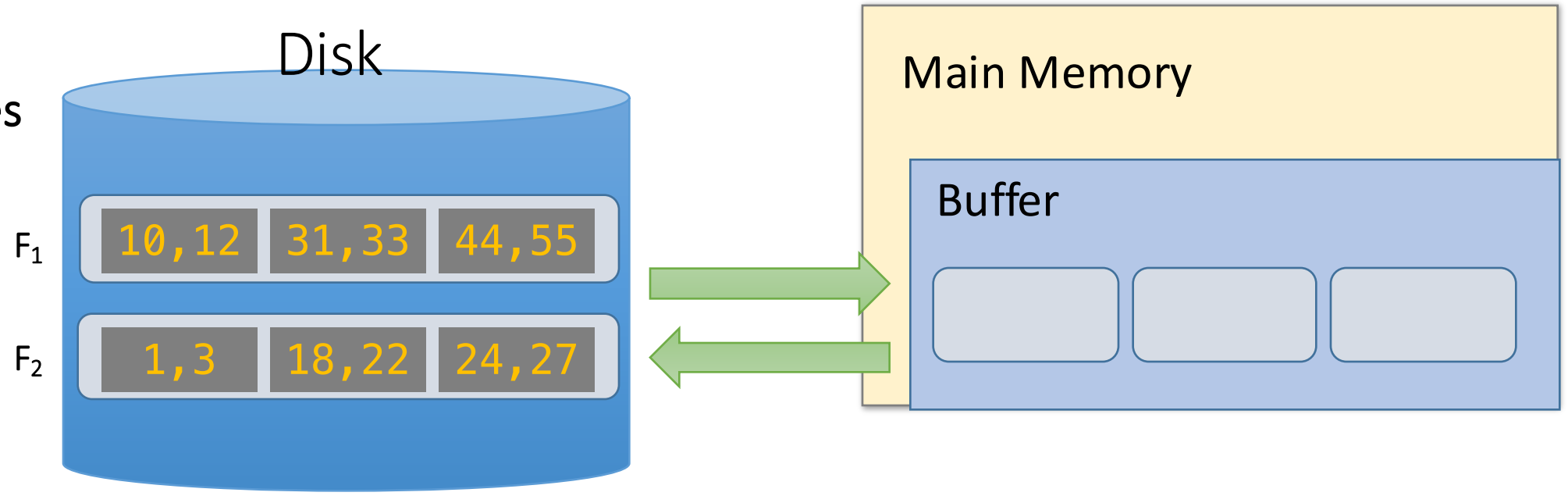


1. Split into chunks small enough to **sort in memory**

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 **two 3-page files** and **sort in memory**
    1. **= 1 R + 1 W for each file = 2*2 = 4 IO operations**

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

Calculating IO Cost

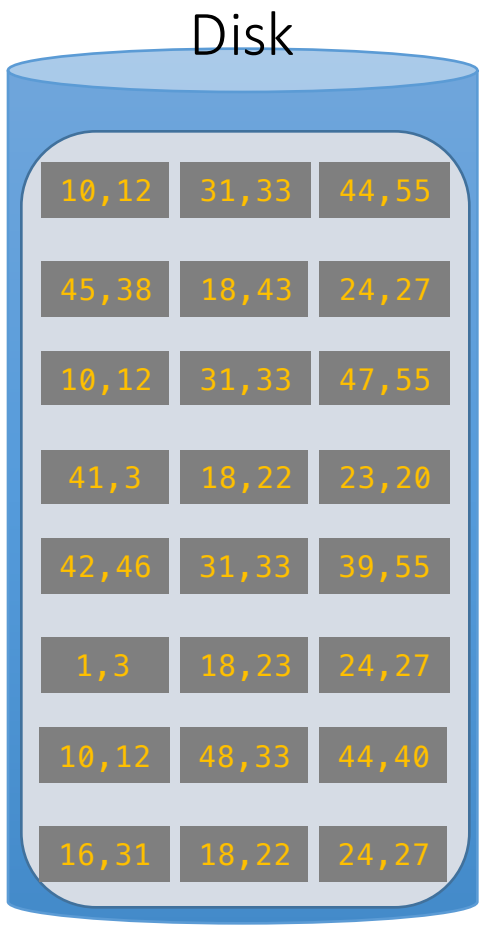
For ***B*** buffer pages, ***2*B*** page file:

1. Split into **two B-page files** and **sort in memory**
    1. **= 1 R + 1 W for each file = 2*2 = 4 IO operations**

2. **Merge** each pair of sorted chunks ***using the external merge algorithm***
    1. **= 2*(B + B) = 4B IO operations**

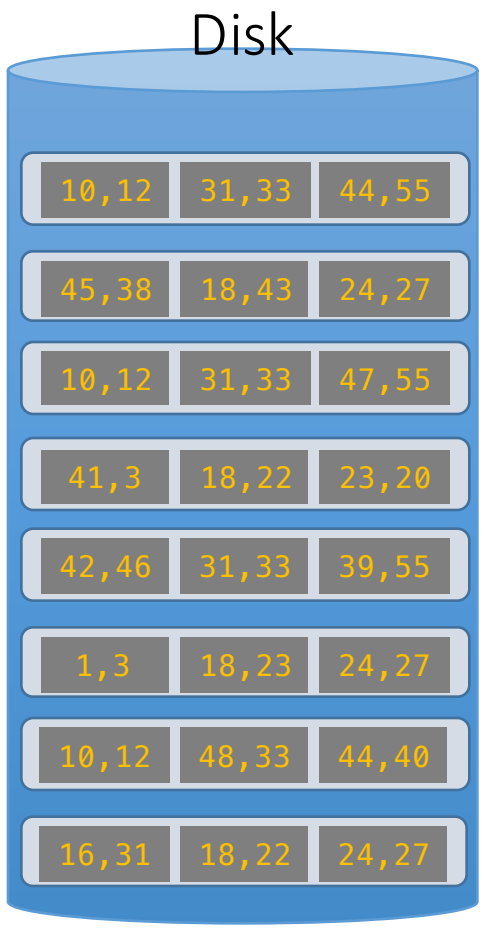
= 4*(B+1) IO Operations

Running External Merge Sort on Larger Files



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

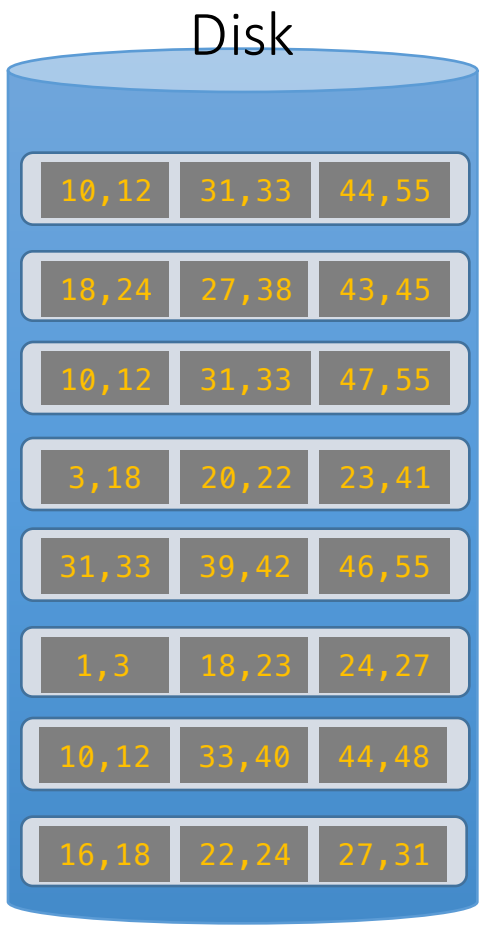
Running External Merge Sort on Larger Files



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

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

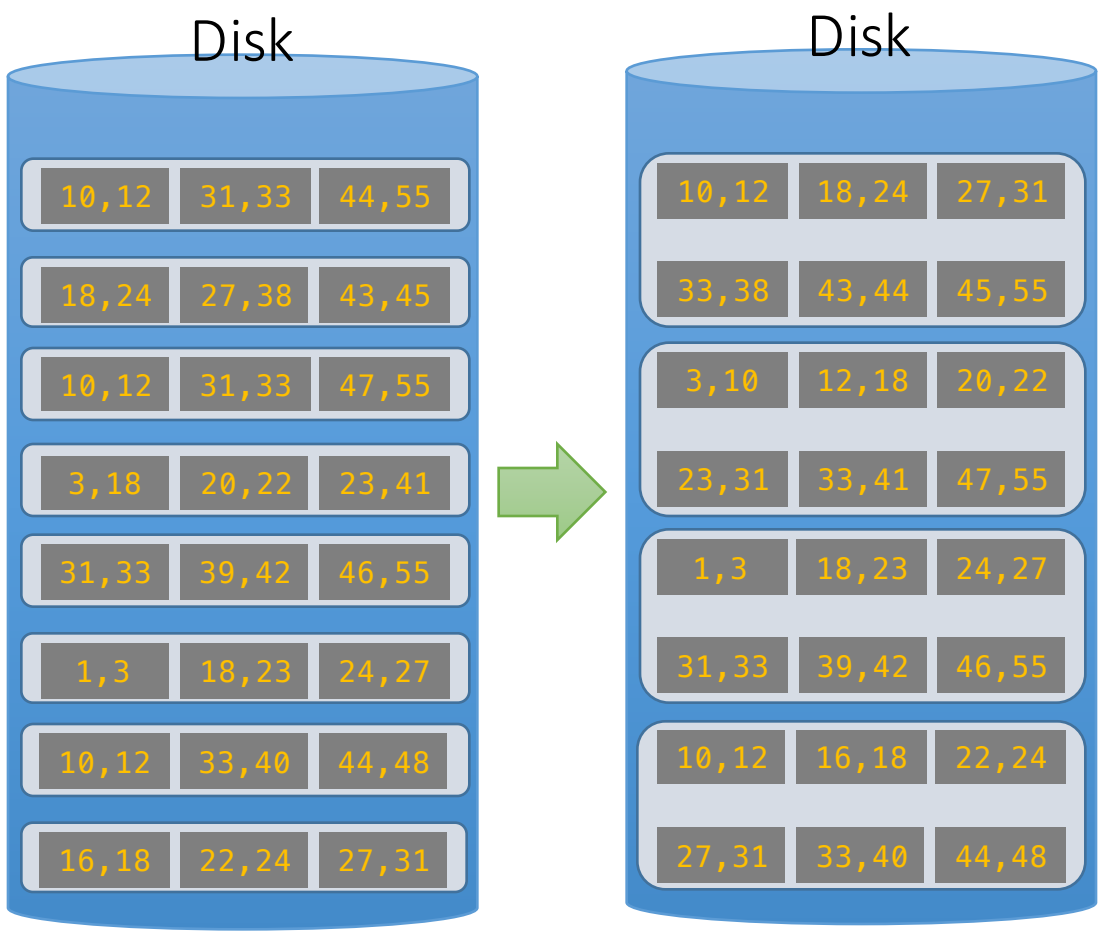
Running External Merge Sort on Larger Files



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

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

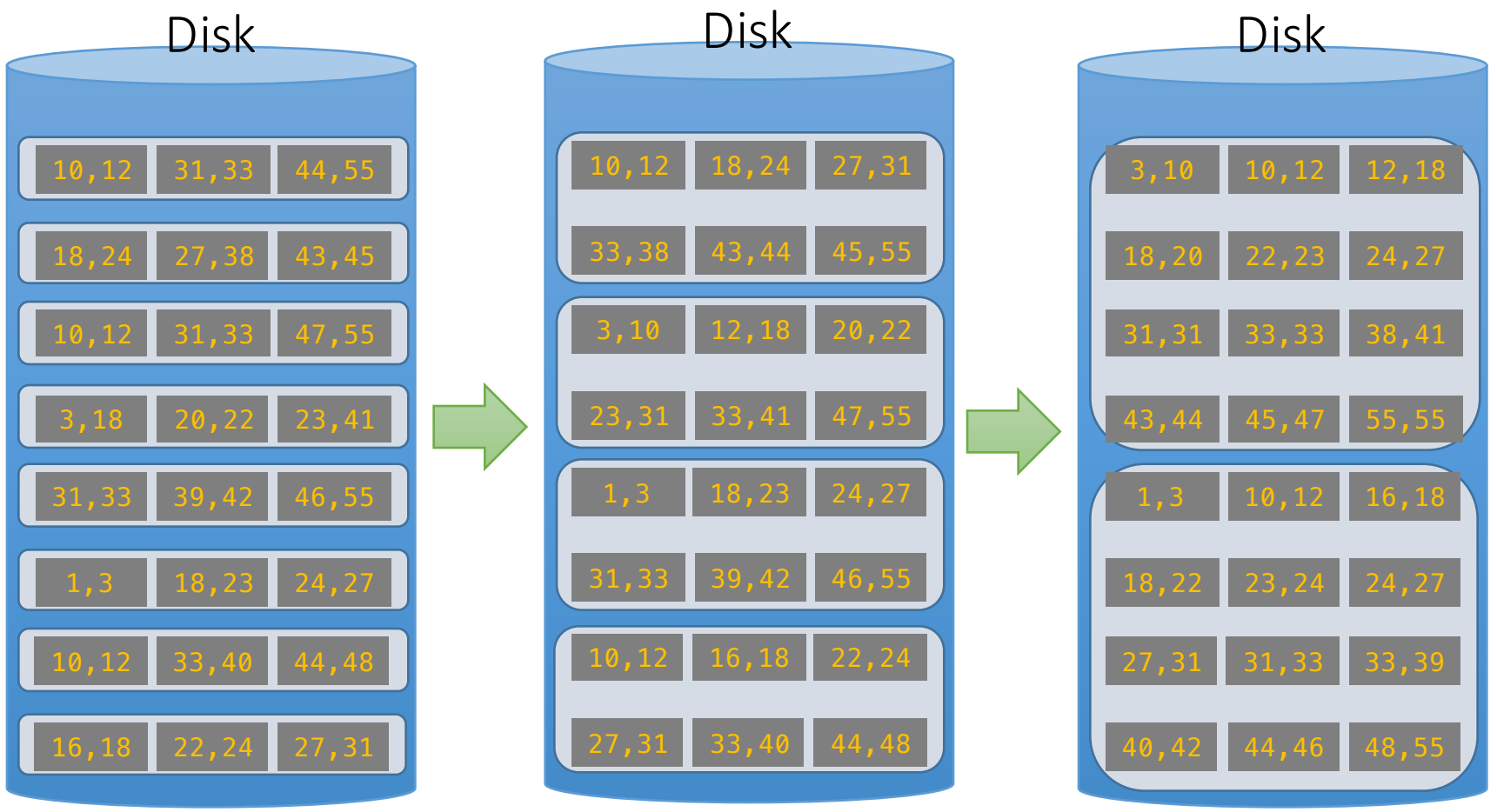
Running External Merge Sort on Larger Files



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

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

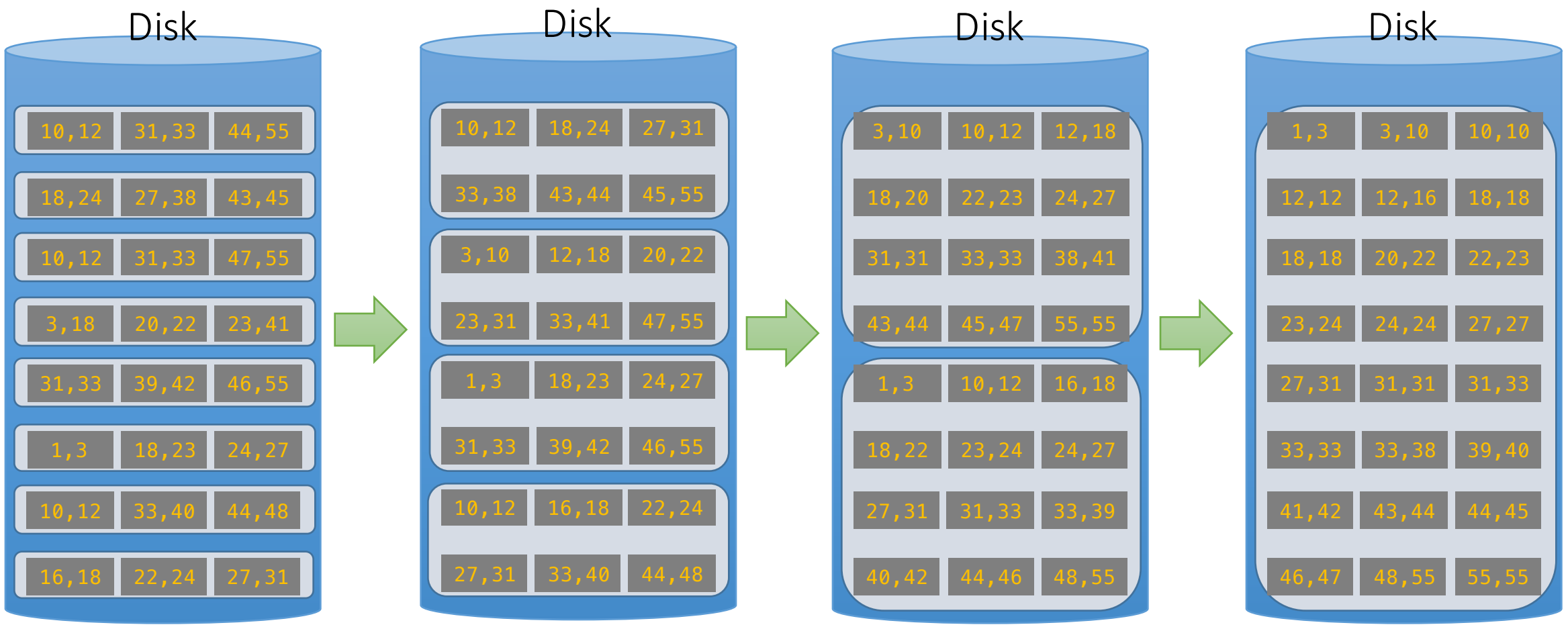
Running External Merge Sort on Larger Files



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

3. And repeat…

Running External Merge Sort on Larger Files

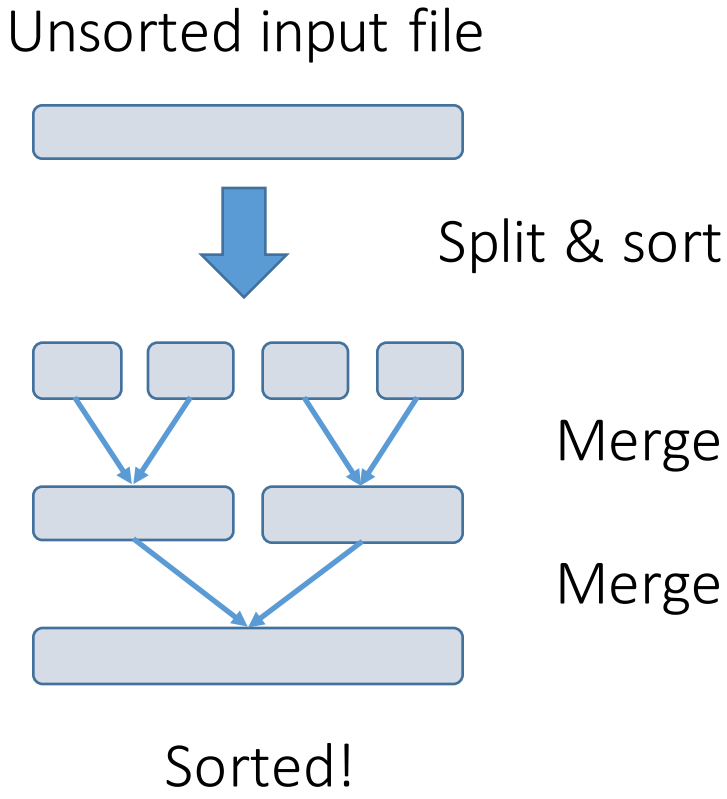


4. And repeat!

Simplified 3-page Buffer Version

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

- We merge **N/2 pairs** of length **1 page**
  - Each one takes 2*(1+1) = **4 IO**
- Then we merge **N/4 pairs** of length **2 pages**
  - Each one takes 2*(2+2) = **8 IO**
- … In general, each step will take ***2N*** IO!



For N pages, there will be $\lceil \log_2 N \rceil$+1 steps → 2N*($\lceil \log_2 N \rceil$+1) total IO cost!

Using B+1 buffer pages to reduce passes

Goal: Reduce *the number* of passes.

- Suppose we have B+1 buffer pages and a file with N pages.
- Each pass still takes 2N IOs.

1. **Increase length of initial runs**. Sort B at a time!
   - From N of length 1 to N/(B+1) runs each of length B

2. **Perform a B way merge.**
   - Given M runs each of length L, produce M/B runs of length LB.

IO Cost:

$$2N(\lceil \log_2 N \rceil + 1)$$

$$2N\left(\left\lceil \log_2 \frac{\boldsymbol{N}}{\boldsymbol{B+1}} \right\rceil + 1\right)$$

$$2N\left(\left\lceil \log_{\boldsymbol{B}} \frac{N}{B+1} \right\rceil + 1\right)$$

Summary

- Basics of IO and buffer management.
  - See notebook for more fun! (Learn about *sequential flooding*)
- We introduced the IO cost model using **sorting**.
  - Saw how to do merges with few IOs,
  - Works better than main-memory sort algorithms.
- Described a few optimizations for sorting

Number of Passes of External Sort

N	B=3	B=5	B=9	B=17	B=129	B=257
100	7	4	3	2	1	1
1,000	10	5	4	3	2	2
10,000	13	7	5	4	2	2
100,000	17	9	6	5	3	3
1,000,000	20	10	7	5	3	3
10,000,000	23	12	8	6	4	3
100,000,000	26	14	9	7	4	4
1,000,000,000	30	15	10	8	5	4

Engineer's rule of thumb:

You sort in 3 passes

Even longer initial runs

Suppose we have B+1 buffer pages.

- Produce longer runs by "merging" as we read.
- Read B buffer pages and merge them.
- **Twist: when input page is empty, read in a new page.**
- **Issue**: Some values on new page may be smaller than already output value.
  - Can't output, these values call them **frozen**.
- Try to consolidate frozen values in pages, to free up more pages.
  - **Alternatively**: Just use a priority queue—called tournament sort!

- **How long are the runs if input file is sorted in desired order?**
  - Nothing is frozen!
- **How long are the runs if input file is sorted in reverse order?**
  - All new values are frozen

Engineers approximation: Runs will have ~ 2(B+1) length.

Double Buffering

Which IOs are sequential in sorting?

- Initial runs, both reading and writing are sequential writes.
- **Merge phase**: writing is sequential, reading is **not**!

Can Improve performance by using bigger buffers to “prefetch” or “double buffer” to hide reads in merge-phase.

- **Prefetch**: Hide latency
- **Bigger Batch Sizes**: Amortize expensive random reads and writes, but reduce available buffer pages.

Surprisingly useful trick.