CS 145 Final Review

The Best Of Collection (Master Tracks), Vol. 2

Course Summary

- We learned…

    1. **How to design a database**

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    1. How to design a database

    2. **How to query a database, even with concurrent users and crashes / aborts**

Course Summary

- We learned…

1. How to design a database
2. How to query a database, even with concurrent users and crashes / aborts
3. **How to optimize the performance of a database**

1. Intro

2-3. SQL

4. ER Diagrams

5-6. DB Design

7-8. TXNs

11-12. IO Cost

14-15. Joins

16. Rel. Algebra

Course Summary

- We learned…
  1. How to design a database
  2. How to query a database, even with concurrent users and crashes / aborts
  3. How to optimize the performance of a database
- We got a sense (as the old joke goes) of the three most important topics in DB research:
  - Performance, performance, and performance

1. Intro

2-3. SQL

4. ER Diagrams

5-6. DB Design

7-8. TXNs

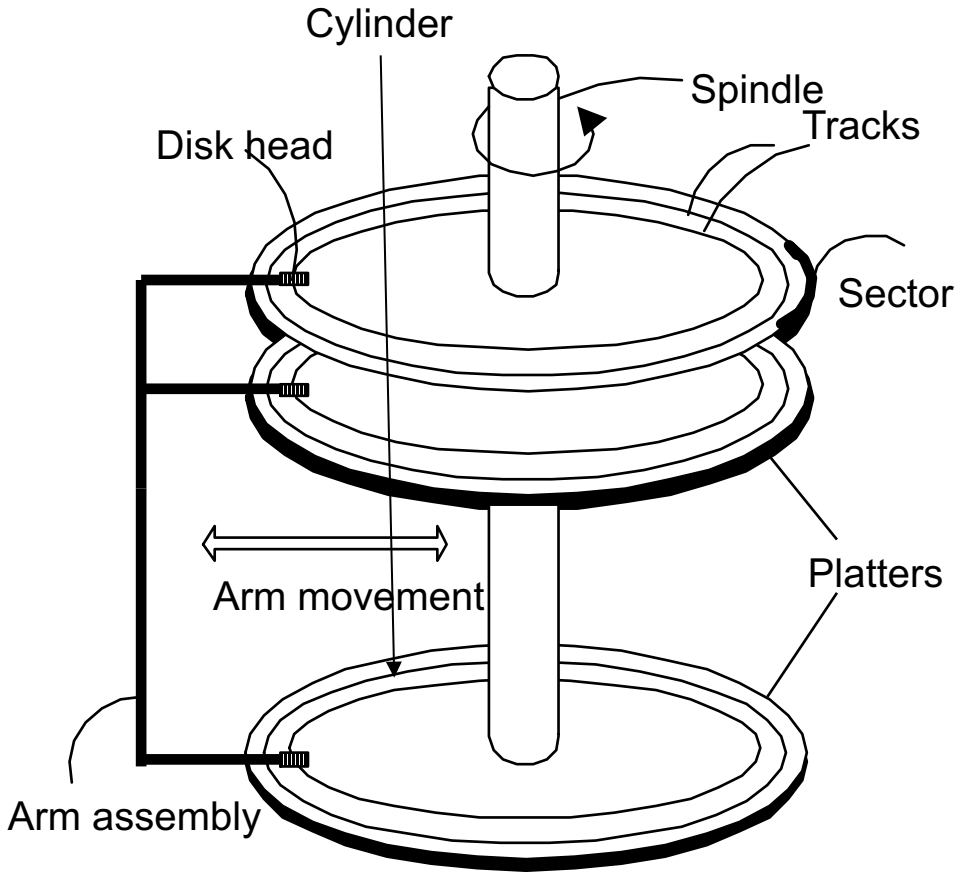
11-12. IO Cost

14-15. Joins

16. Rel. Algebra

High-level: Disk vs. Main Memory

- **Disk**:
  - *Slow*
    - Sequential access
      - (although fast sequential reads)
  - *Durable*
    - We will assume that once on disk, data is safe!
  - Cheap



High-level: Disk vs. Main Memory

- 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!

Transactions: Basic Definition

A **transaction ("TXN")** is a sequence of one or more ***operations*** (reads or writes) which reflects ***a single real-world transition***.

In the real world, a TXN either happened completely or not at all

```
START TRANSACTION
      UPDATE Product
      SET Price = Price – 1.99
      WHERE pname = 'Gizmo'
COMMIT
```

Motivation for Transactions

Grouping user actions (reads & writes) into *transactions* helps with two goals:

1. **Recovery & Durability**: Keeping the DBMS data consistent and durable in the face of crashes, aborts, system shutdowns, etc.

This lecture!

2. **Concurrency:** Achieving better performance by parallelizing TXNs *without* creating anomalies

Next lecture

Transaction Properties: ACID

- Atomic
  - State shows either all the effects of txn, or none of them
- Consistent
  - Txn moves from a state where integrity holds, to another where integrity holds
- Isolated
  - Effect of txns is the same as txns running one after another (ie looks like batch mode)
- Durable
  - Once a txn has committed, its effects remain in the database

ACID continues to be a source of great debate!

Basic Idea: (Physical) Logging

- Record UNDO information for every update!
  - Sequential writes to log
  - Minimal info (diff) written to log

- The **log** consists of **an ordered list of actions**
  - Log record contains:

    <XID, location, old data, new data>

This is sufficient to UNDO any transaction!

Why do we need logging for atomicity?

- Couldn't we just write TXN to disk **only** once whole TXN complete?
  - Then, if abort / crash and TXN not complete, it has no effect- atomicity!
  - *With unlimited memory and time, this could work…*

- However, we **need to log partial results of TXNs** because of:
  - Memory constraints (enough space for full TXN??)
  - Time constraints (what if one TXN takes very long?)

We need to write partial results to disk!
…And so we need a **log** to be able to ***undo*** these partial results!

Transaction Commit Process

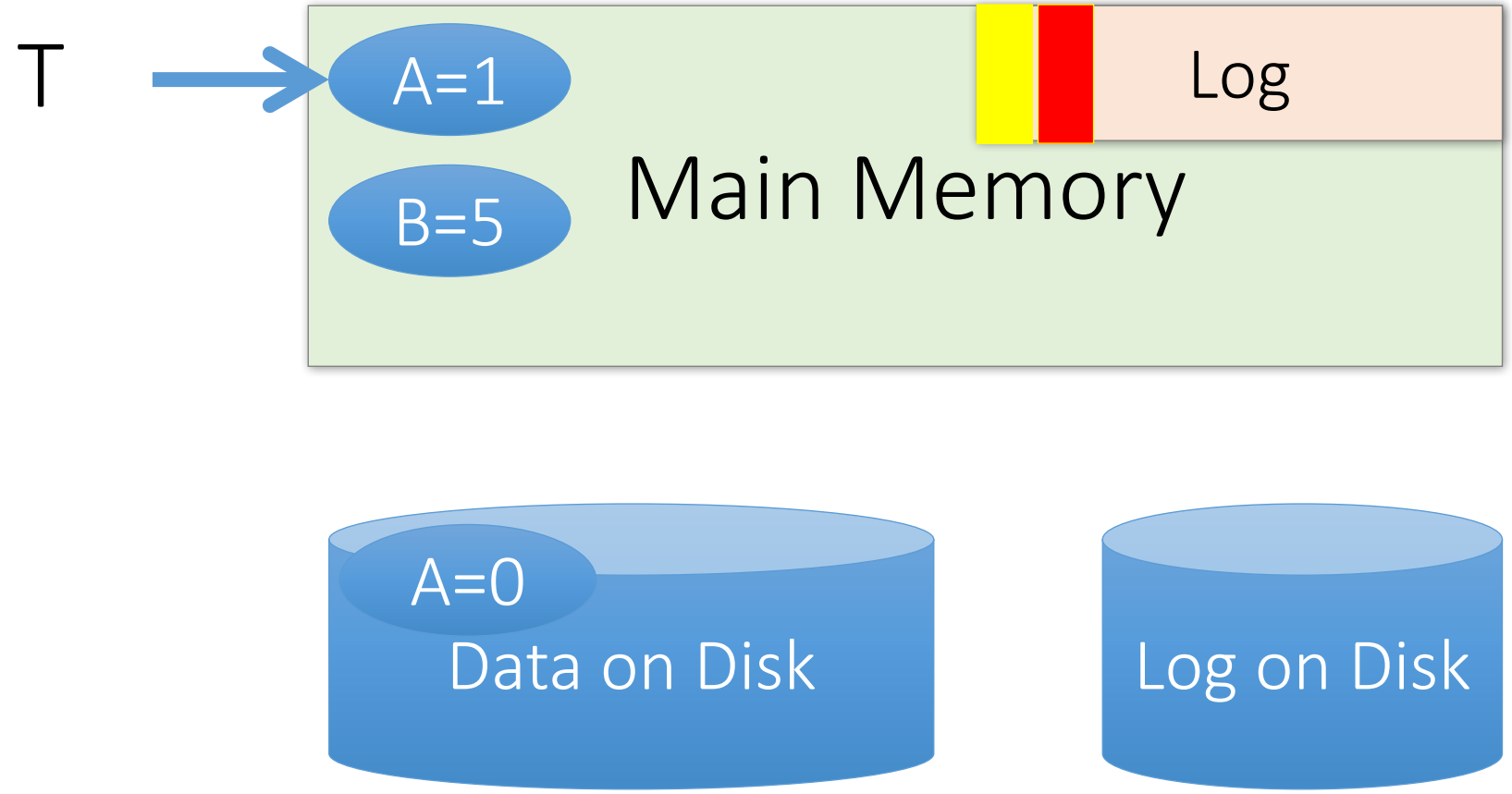
1. FORCE Write **commit** record to log
2. All log records up to last update from this TX are FORCED
3. Commit() returns

Transaction is committed *once commit log record is on stable storage*

Write-ahead Logging (WAL) Commit Protocol

T: R(A), W(A)

A: 0→1



This time, let's try committing ***after*** **we've written log to disk but *before* we've written data to disk**... this is WAL!

OK, Commit!

If we crash now, is T durable?

Write-ahead Logging (WAL) Commit Protocol

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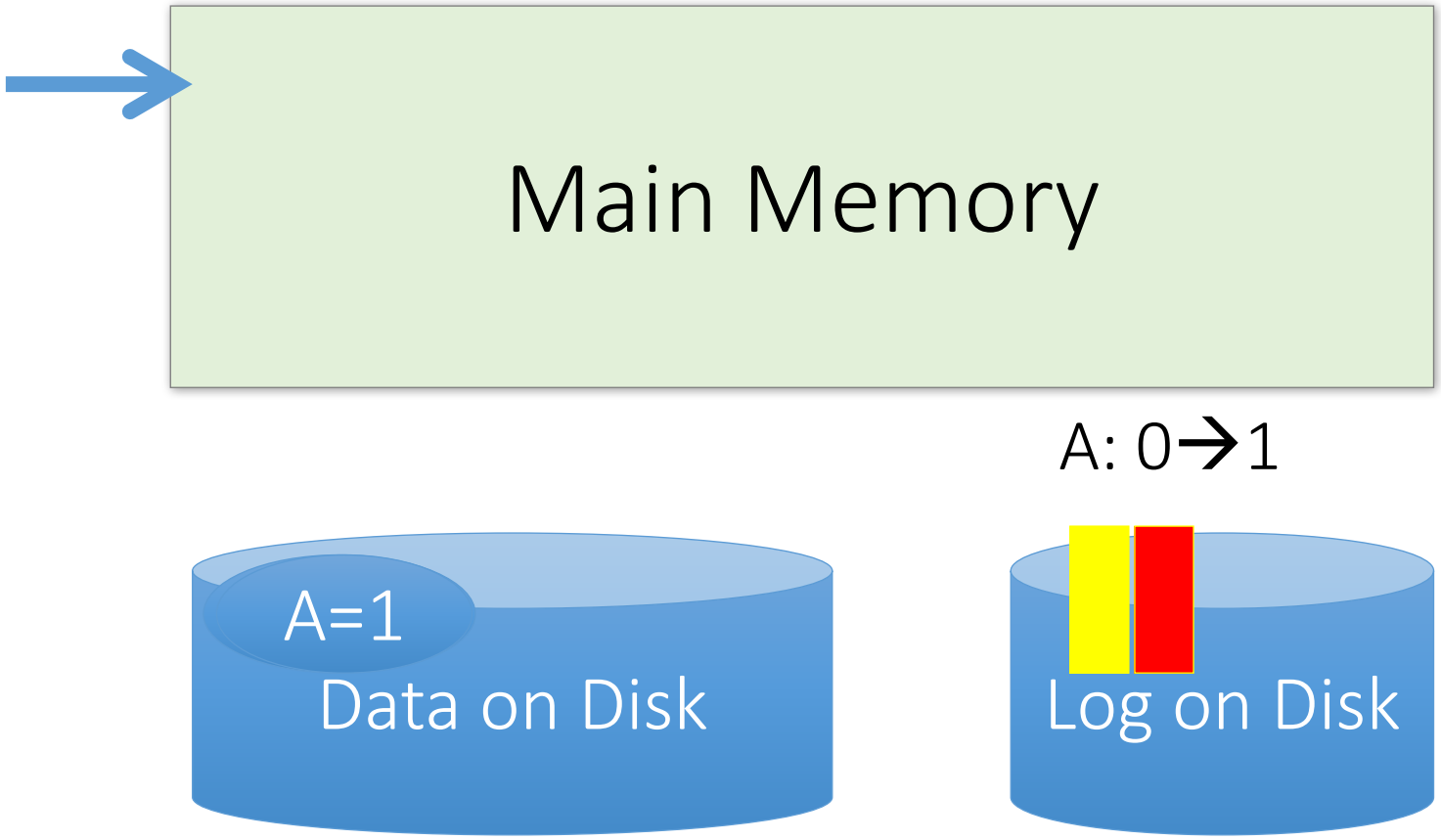
T



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OK, Commit!

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USE THE LOG!

Write-Ahead Logging (WAL)

- DB uses **Write-Ahead Logging (WAL)** Protocol:

Each update is logged! Why not reads?

1. Must *force log record* for an update *before* the corresponding data page goes to storage

→ Atomicity

2. Must *write all log records* for a TX *before commit*

→ Durability

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***

Scheduling Definitions

- A **serial schedule** is one that does not interleave the actions of different transactions

- A and B are **equivalent schedules** if, ***for any database state***, the effect on DB of executing A **is identical to** the effect of executing B

- *A* **serializable schedule** is a schedule that is equivalent to ***some*** serial execution of the transactions.

The word "**some**" makes this definition powerful & tricky!

Conflict Types

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

- Thus, there are three types of conflicts:
  - Read-Write conflicts (RW)
  - Write-Read conflicts (WR)
  - Write-Write conflicts (WW)

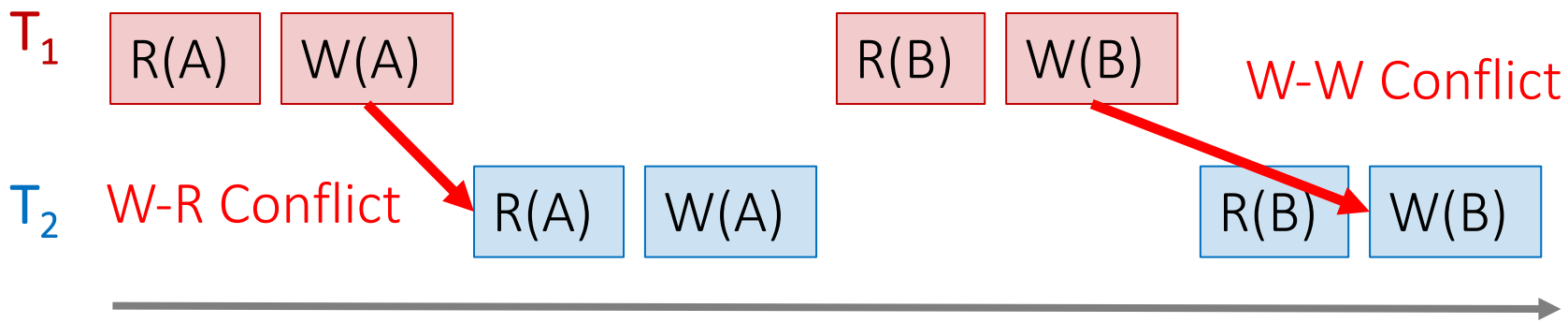
Why no "RR Conflict"?

Interleaving anomalies occur with / because of these conflicts between TXNs *(but these conflicts can occur without causing anomalies!)*

See next section for more!

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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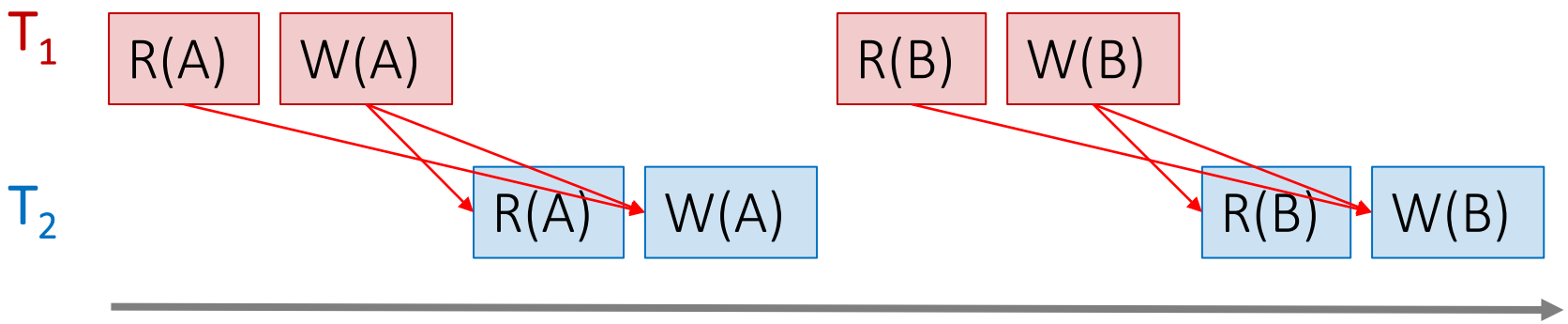

All “conflicts”!

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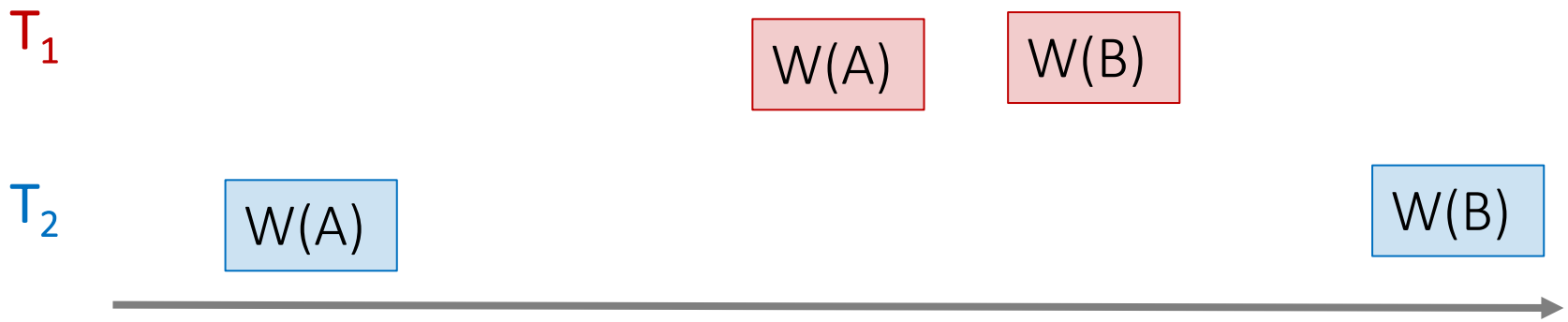
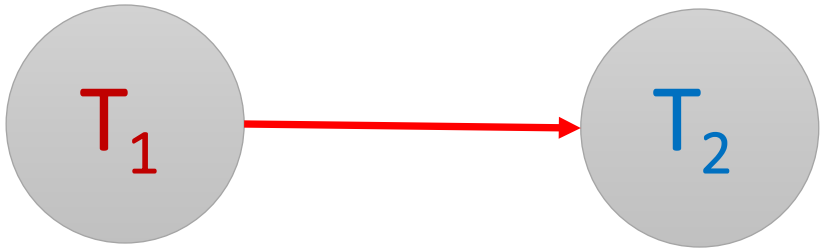


All "conflicts"!

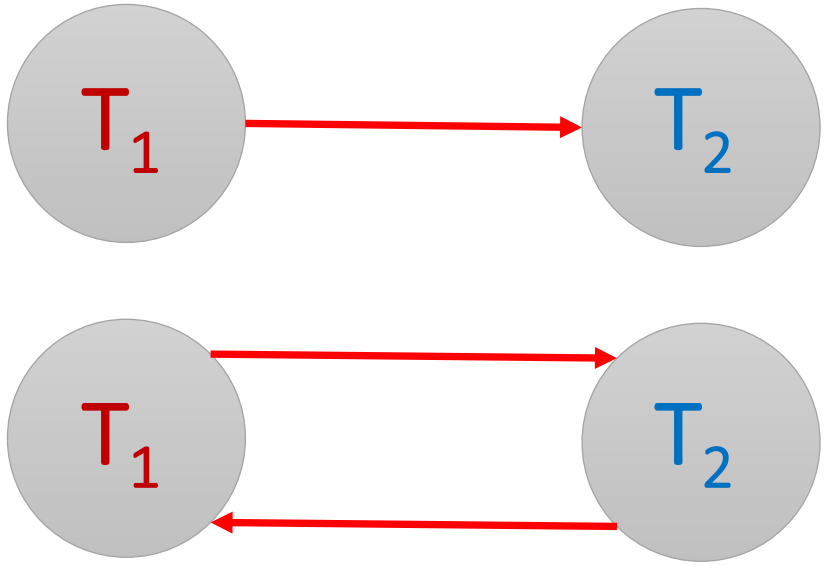
What can we say about "good" vs. "bad" conflict graphs?

Serial Schedule:



Simple!

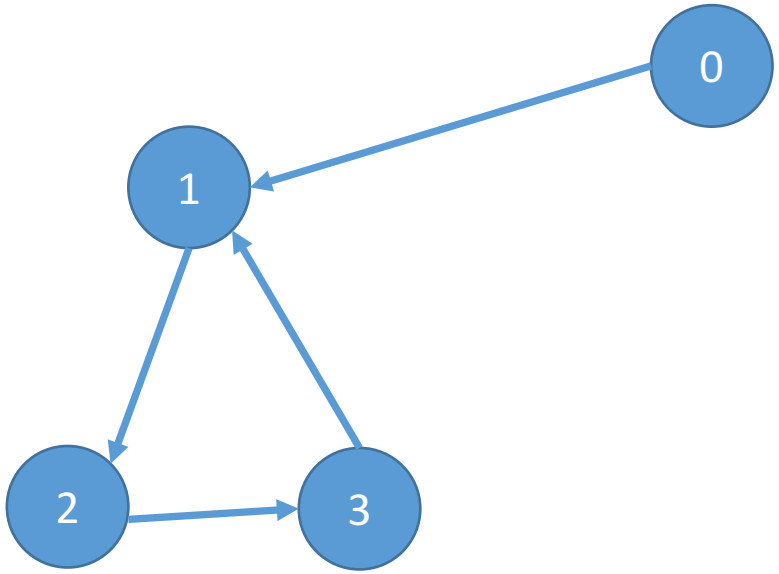
Interleaved Schedules:



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

DAGs & Topological Orderings

- Ex: What is one possible topological ordering here?



There is none!

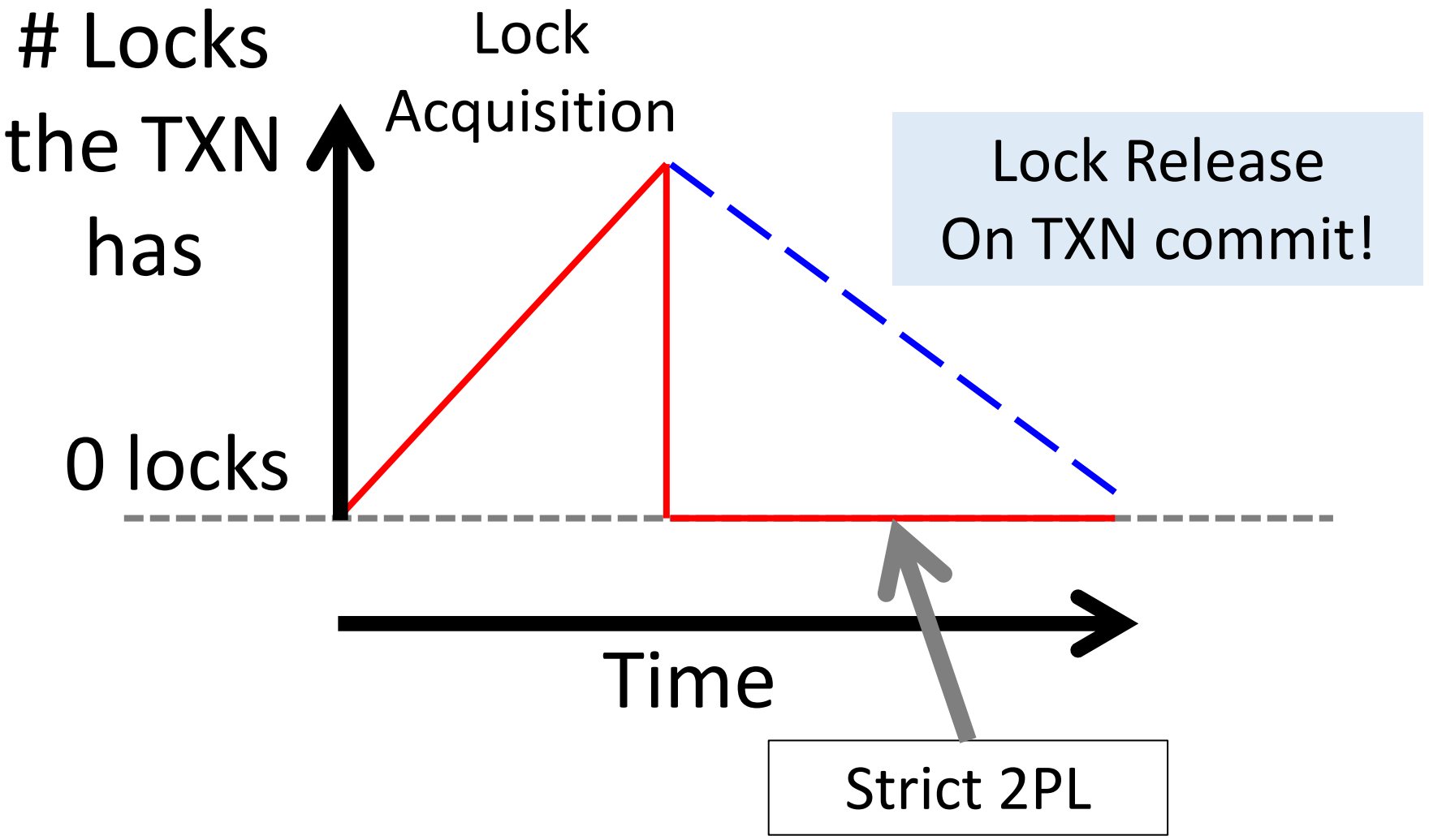
Strict Two-phase Locking (Strict 2PL) Protocol:

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!

Picture of 2-Phase Locking (2PL)



Deadlocks

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

- Two ways of dealing with deadlocks:

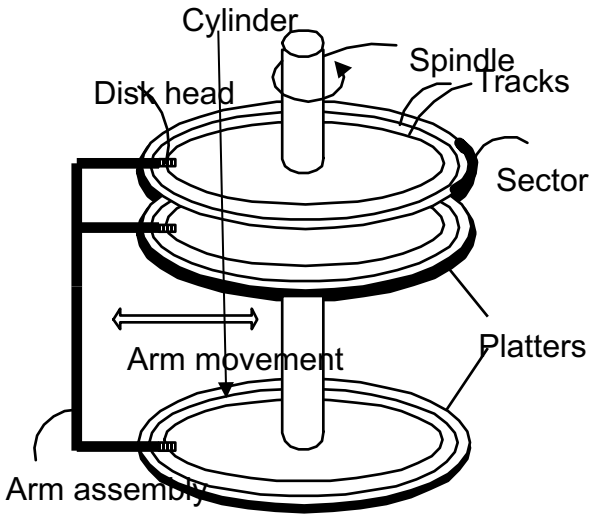
  1. Deadlock prevention

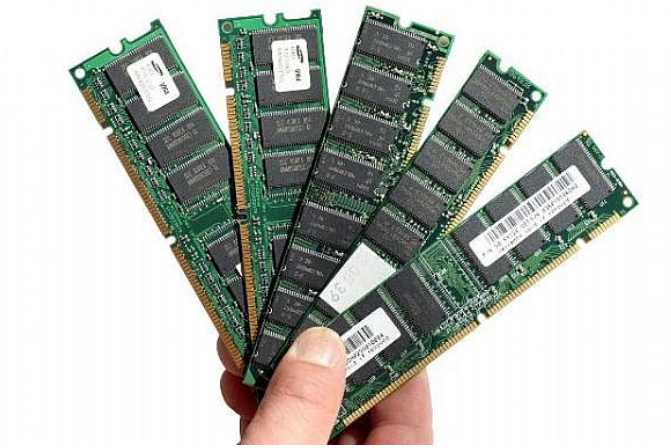
  2. Deadlock detection

High-Level: Lecture 11

- The ***buffer*** & simplified filesystem model
- Shift to ***IO Aware*** algorithms
- The ***external merge algorithm***

High-level: Disk vs. Main Memory





Disk:

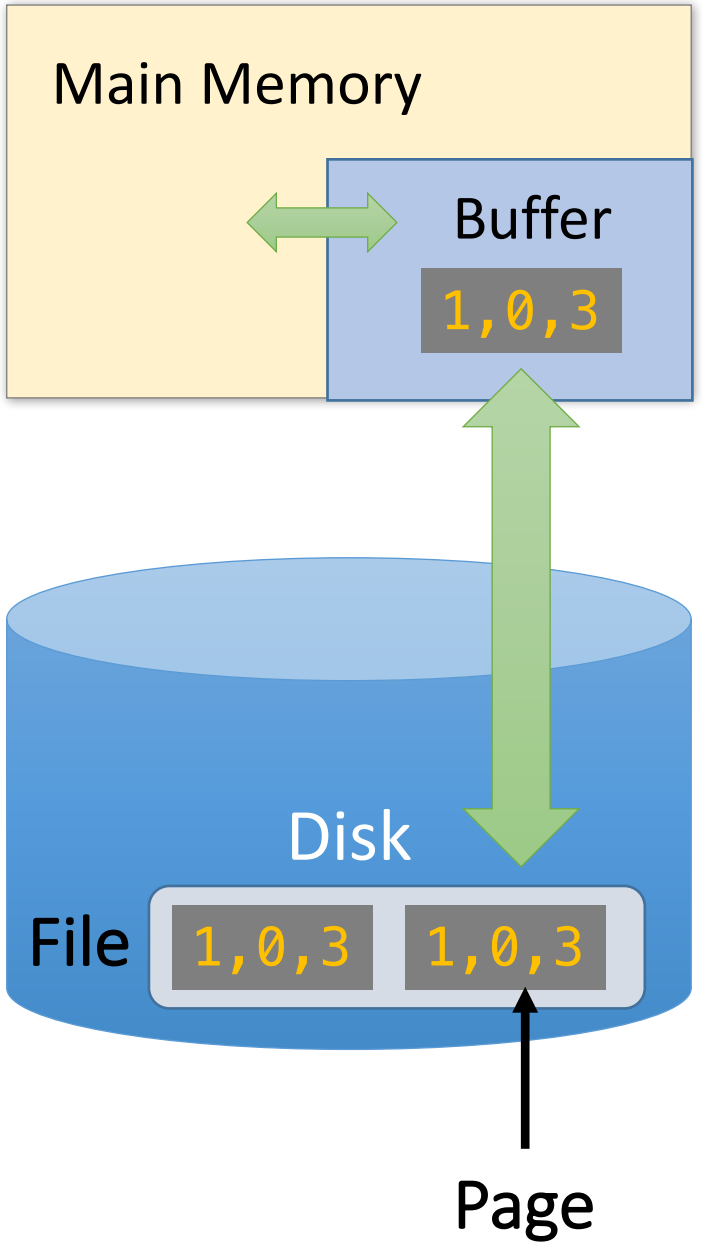
- ***Slow:*** Sequential *block* access
  - Read a blocks (not byte) at a time, so sequential access is cheaper than random
  - **Disk read / writes are expensive!**
- ***Durable:*** We will assume that once on disk, data is safe!
- ***Cheap***

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*
  - *Key Idea:* Reading / writing to disk is SLOW, need to cache data in main memory
  - Can **read** into buffer, **flush** back to disk, **release** from buffer
- DBMS manages its own buffer for various reasons (better control of eviction policy, force-write log, etc.)
- We use a simplified model:
  - A ***page*** is a fixed-length array of memory; **pages are the unit that is read from / written to disk**
  - A ***file*** is a variable-length list of pages on disk



IO Aware

- Key idea: Reading from / writing to disk- e.g. ***IO operations-*** is ***thousands*** of times slower than any operation in memory
    - → We consider a class of algorithms which try to minimize IO, and *effectively ignore cost of operations in main memory*

"IO aware" algorithms!

External Merge Algorithm

- ***Goal:*** Merge sorted files that are much bigger than buffer

- ***Key idea:*** Since the input files are sorted, we always know which file to read from next!

- ***Details:***

Given:	***B+1*** buffer pages
Input:	***B*** sorted files, $F_1,\ldots,F_B$, where F_i has $P(F_i)$ pages
Output:	One merged sorted file
IO COST:	$2 * \sum_{i=1}^{B} P(F_i)$ *(Each page is read & written once)*

High-Level: Lecture 12

- External Merge Sort Algorithm
  - Basic algorithm (including (B+1)-length initial runs & B-way merging)
  - Repacking optimization for longer initial runs
- Indexes Part I: Basics

See L13:11-27!

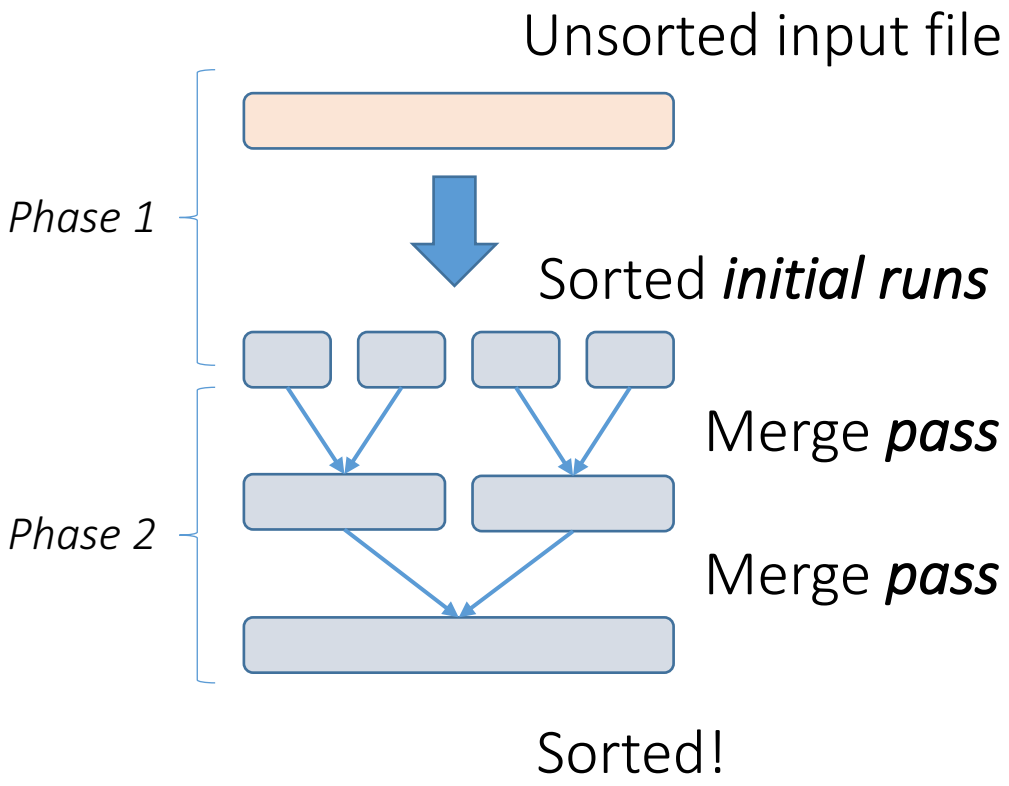
External Merge Sort Algorithm

- ***Goal:*** Sort a file that is much bigger than the buffer

- ***Key idea:***

  - *Phase 1:* Split file into smaller chunks ("initial runs") which can be sorted in memory

  - *Phase 2:* Keep merging (do "passes") using external merge algorithm until one sorted file!



External Merge Sort Algorithm

Given:	***B+1*** buffer pages	
Input:	Unsorted file of length ***N*** pages	
Output:	The sorted file	
IO COST:	$\boldsymbol{2N}\left(\left\lceil \log_{\boldsymbol{B}} \left\lceil \frac{\boldsymbol{N}}{\boldsymbol{B+1}} \right\rceil \right\rceil + \mathbf{1}\right)$	***Phase 1:*** Initial runs of length B+1 are created • There are $\left\lceil \frac{\boldsymbol{N}}{\boldsymbol{B+1}} \right\rceil$ of these • The IO cost is 2N ***Phase 2:*** We do passes of B-way merge until fully merged • Need $\left\lceil \log_{\boldsymbol{B}} \left\lceil \frac{\boldsymbol{N}}{\boldsymbol{B+1}} \right\rceil \right\rceil$ passes • The IO cost is 2N per pass

Indexes

- An *index* on a file speeds up selections on the *search key fields* for the index.
  - Where the *search key* could be any subset of fields, and does ***not*** need to be the same as *key of a relation*

By_Yr_Index

Published	BID
1866	002
1869	001
1877	003

By_Author_Title_Index

Author	Title	BID
Dostoyevsky	Crime and Punishment	002
Tolstoy	Anna Karenina	003
Tolstoy	War and Peace	001

Russian_Novels

BID	Title	Author	Published	Full_text
001	*War and Peace*	Tolstoy	1869	…
002	*Crime and Punishment*	Dostoyevsky	1866	…
003	*Anna Karenina*	Tolstoy	1877	…

Note this is the logical setup, not how data is actually stored!

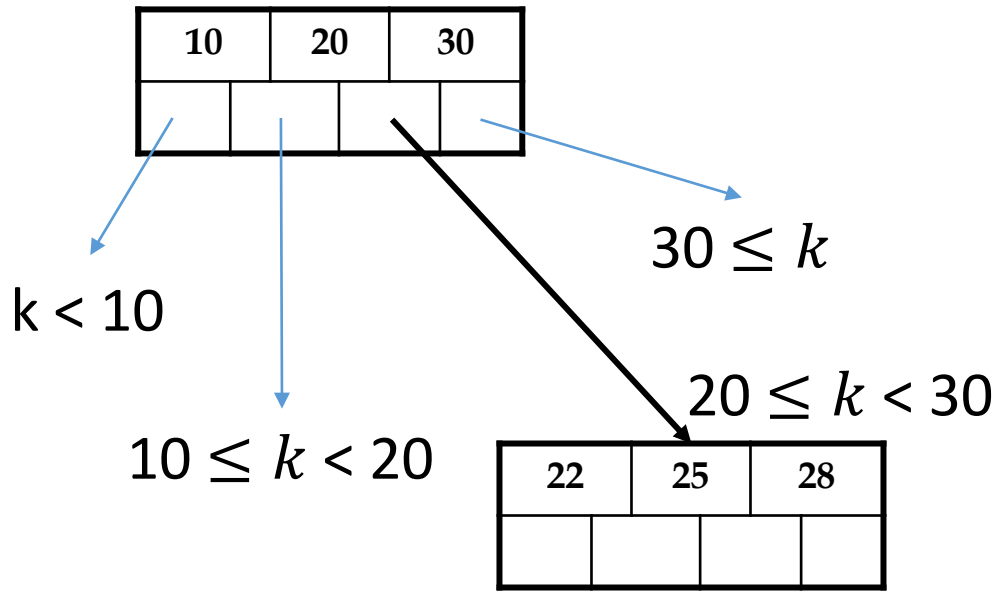
An index is **covering** *for a specific query* if the index contains all the needed attributes

High-Level: Lectures 14-15

- Indexes Pt. 2:
  - B+ Trees
  - Clustered vs. unclustered
- Join Algorithms:
  - Nested Loop Join Variants: NLJ, BNLJ, INLJ
  - SMJ
  - Hash Join

B+ Tree Basics

Non-leaf or *internal* node



Parameter ***d*** = the degree

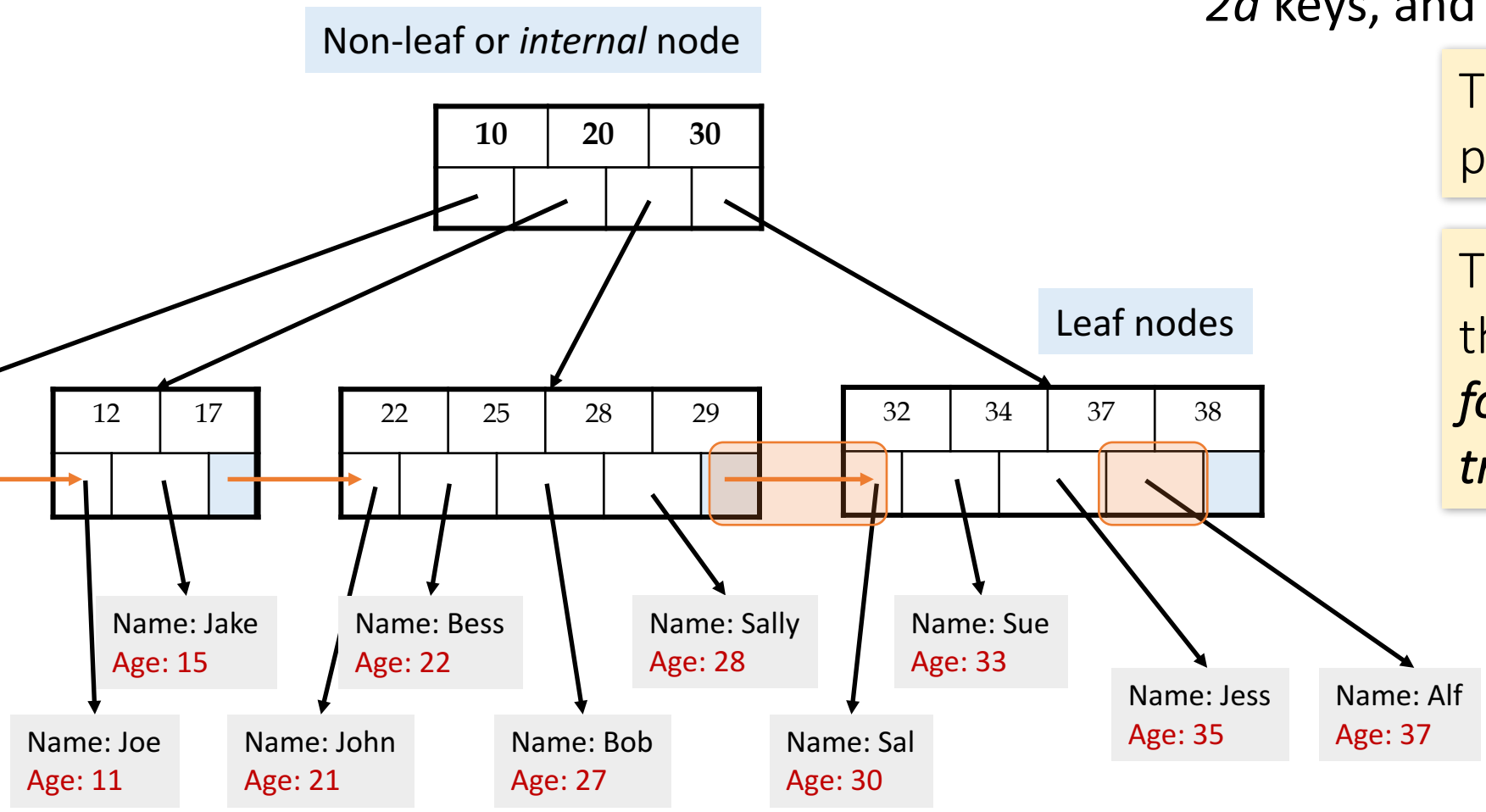
Each *non-leaf ("interior")* ***node*** has ≥ d and ≤ 2d ***keys****

The *n* keys in a node define *n+1* ranges

except for root node, which can have between **1 and 2d keys*

For each range, in a *non-leaf* node, there is a **pointer** to another node with keys in that range

B+ Tree Basics



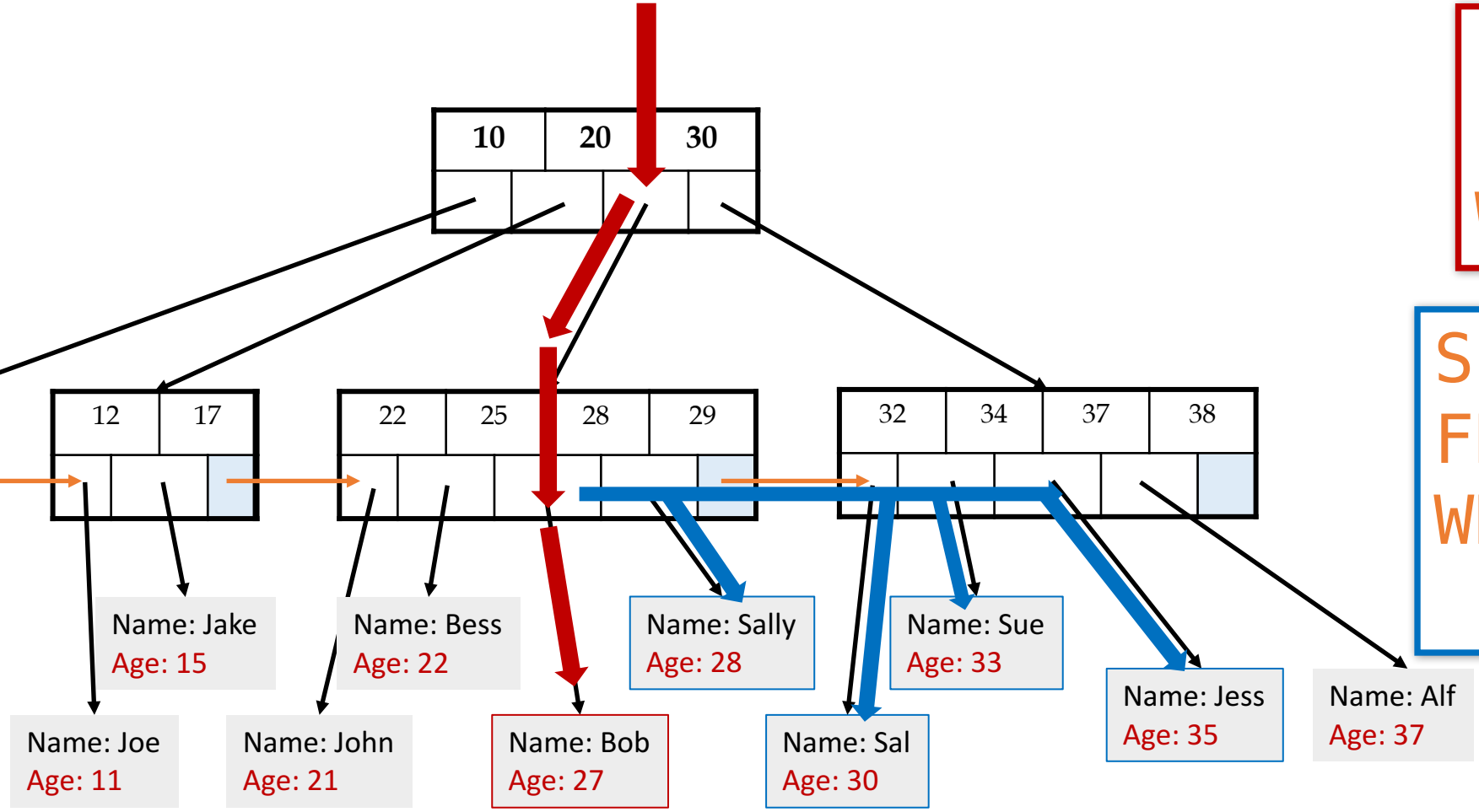
Leaf nodes also have between *d* and *2d* keys, and are different in that:

Their key slots contain pointers to data records

They contain a pointer to the next leaf node as well, ***for faster sequential traversal***

See L14-15:17-18!

Searching a B+ Tree




```
SELECT name
FROM   people
WHERE  age = 27
```

```
SELECT name
FROM   people
WHERE  27 <= age
  AND  age <= 35
```

B+ Tree Range Search

Note that exact search is just a special case of range search (R = 1)

- ***Goal:*** Get the results set of a range (or exact) query with minimal IO
- ***Key idea:***
  - A B+ Tree has high ***fanout (d ~= 10^2-10^3)***, which means it is very shallow → we can get to the right root node within a few steps!
  - Then just traverse the leaf nodes using the horizontal pointers
- ***Details:***
  - One node per page (thus page size determines *d*)
  - Fill only some of each node's slots (the ***fill-factor***) to leave room for insertions
  - We can keep some levels of the B+ Tree in memory!

The **fanout f** is the number of pointers coming out of a node. Thus:

$$d + 1 \leq f \leq 2d + 1$$

Note that we will often approximate f as constant across nodes!

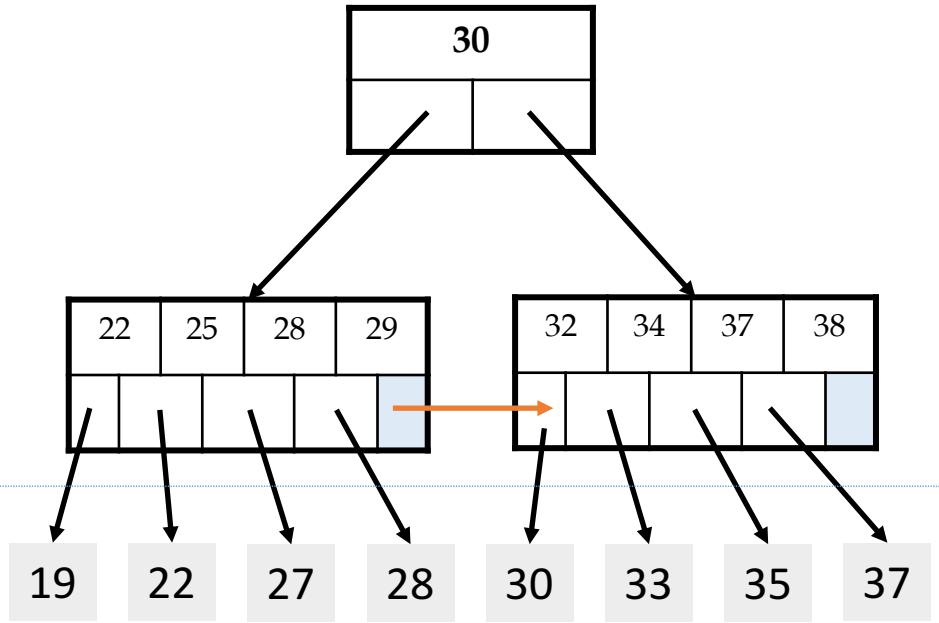
We define the ***height*** of the tree as counting the root node. Thus, *given constant fanout* ***f***, a tree of height ***h*** can index $\mathbf{f^h}$ pages and has $\mathbf{f^{h-1}}$ leaf nodes

See L14-15:22-24!

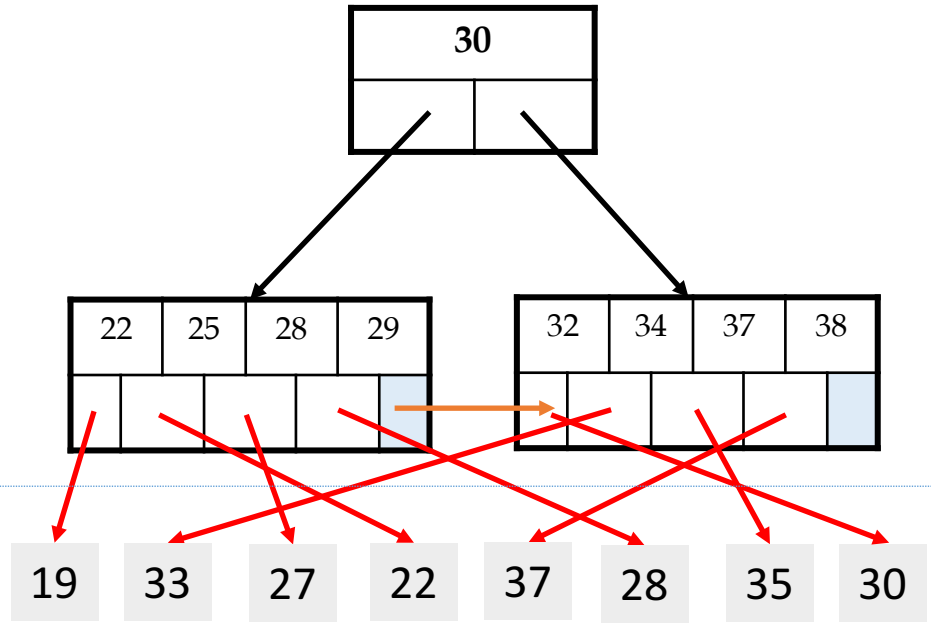
B+ Tree Range Search

Given:	• Parameter ***d*** • Fill-factor ***F*** • ***B*** available pages in buffer • A B+ Tree over ***N*** pages • **f** is the fanout [d+1,2d+1]	
Input:	A a range query.	
Output:	The ***R*** values that match	
IO COST:	$\left\lceil \log_f \frac{N}{F} \right\rceil - L_B + \mathbf{Cost}(Out)$ *where* $B \geq \sum_{l=0}^{L_B - 1} f^l$	***Depth of the B+ Tree:*** For each level of the B+ Tree we read in one node = one page ***# of levels we can fit in memory:*** These don't cost any IO! ***This equation*** is just saying that the sum of all the nodes for L_B levels must fit in buffer

Clustered vs. Unclustered Index



Index Entries



Data Records

Clustered

Unclustered

1 Random Access IO + Sequential IO
(# of pages of answers)

Random Access IO for each **value**
(i.e. # of tuples in answer)

Clustered can make a ***huge*** difference for range queries!

Joins: Example

$\mathbf{R} \bowtie \boldsymbol{S}$

```
SELECT R.A,B,C,D
FROM   R, S
WHERE  R.A = S.A
```

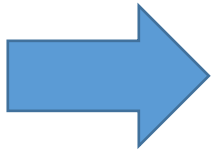
Example: Returns all pairs of tuples $\mathrm{r} \in R, s \in S$ *such that* $r.A = s.A$

R

A	B	C
1	0	1
2	3	4
2	5	2
3	1	1

S

A	D
3	7
2	2
2	3



A	B	C	D
2	3	4	2
2	3	4	3
2	5	2	2
2	5	2	3
3	1	1	7

Join Algorithms: Overview

For $R \bowtie S$ *on* A

- NLJ: An example of a *non*-IO aware join algorithm
- BNLJ: Big gains just by being IO aware & reading in chunks of pages!

Quadratic in P(R), P(S)
*I.e. O(P(R)*P(S))*

- SMJ: Sort R and S, then scan over to join!
- HJ: Partition R and S into buckets using a hash function, then join the (much smaller) matching buckets

Given sufficient buffer space, ***linear*** in P(R), P(S)
I.e. ~O(P(R)+P(S))

By only supporting equijoins & taking advantage of this structure!

Nested Loop Join (NLJ)

```
Compute R ⋈ S on A:
  for r in R:
    for s in S:
      if r[A] == s[A]:
        yield (r,s)
```

Note that IO cost based on number of ***pages*** loaded, not number of tuples!

Cost:

P(R) + T(R)*P(S) + OUT

1. Loop over the tuples in R
2. For every tuple in R, loop over all the tuples in S
3. Check against join conditions
4. **Write out (to page, then when page full, to disk)**

Have to read ***all of S*** from disk for ***every tuple in R!***

Block Nested Loop Join (BNLJ)

Given ***B+1*** pages of memory

```
Compute R ⋈ S on A:
  for each B-1 pages pr of R:
    for page ps of S:
      for each tuple r in pr:
        for each tuple s in ps:
          if r[A] == s[A]:
            yield (r,s)
```

Cost:

$$P(R) + \frac{P(R)}{B-1} P(S) + \text{OUT}$$

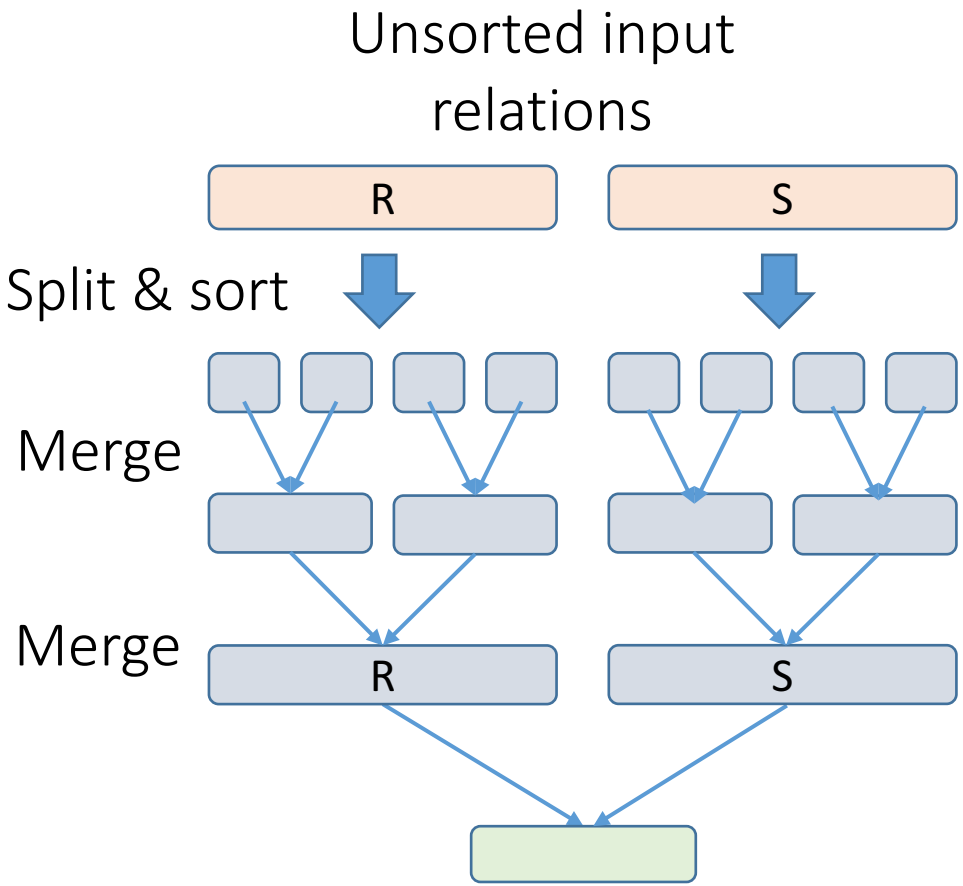
1. Load in B-1 pages of R at a time (leaving 1 page each free for S & output)
2. For each (B-1)-page segment of R, load each page of S
3. Check against the join conditions
4. **Write out**

Again, ***OUT*** could be bigger than P(R)*P(S)… but usually not that bad

See L14-15:63-69!

Sort Merge Join (SMJ)

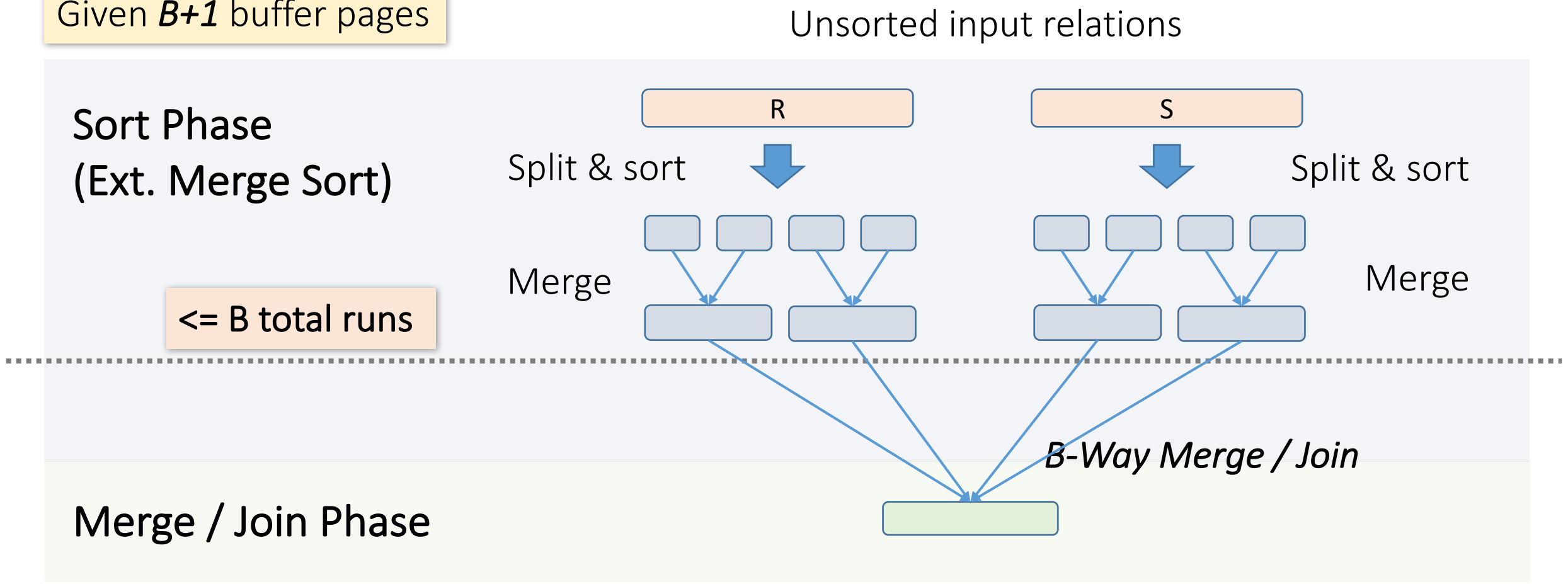
- ***Goal:*** Execute R ⋈ S on A
- ***Key Idea:*** We can sort R and S, then just scan over them!
- ***IO Cost:***
  - *Sort phase:* Sort(R) + Sort(S)
  - *Merge / join phase:* ~ P(R) + P(S) + OUT
    - ***Can be worse though- see next slide!***



See L14-15:78-81!

Simple SMJ Optimization

Given ***B+1*** buffer pages

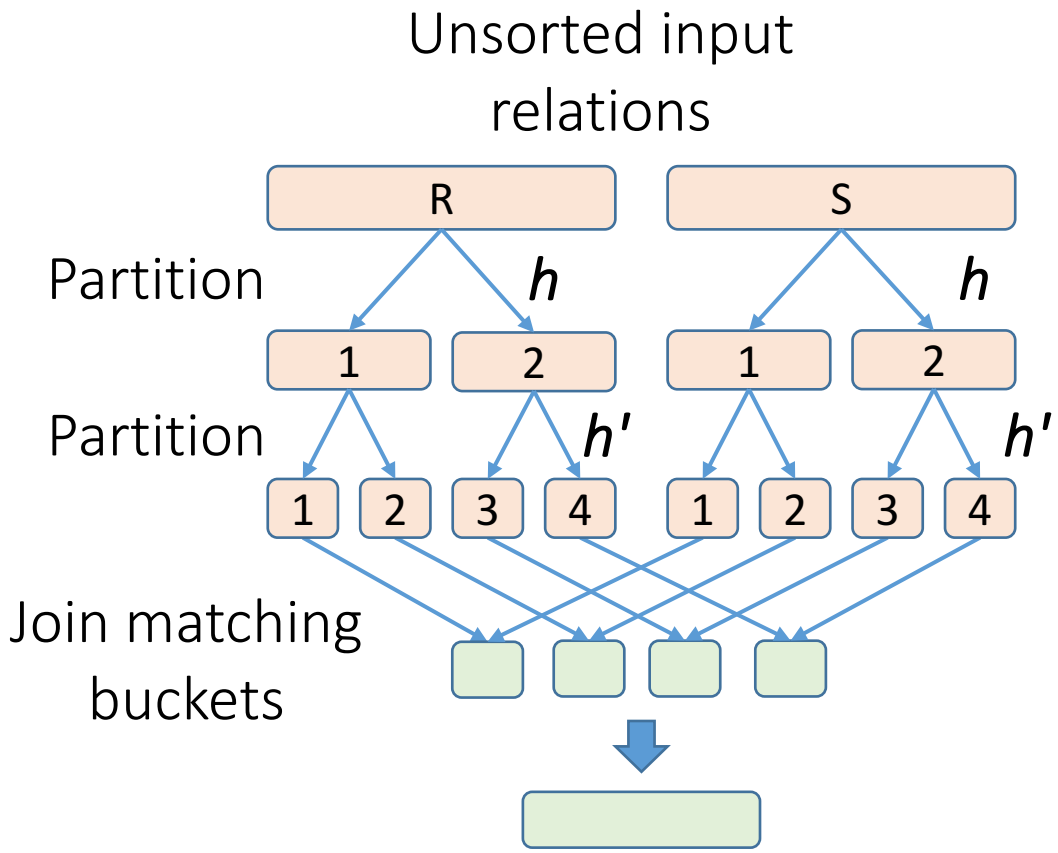


This allows us to "skip" the last sort & save 2(P(R) + P(S))!

See L14-15:88-!

Hash Join

- ***Goal:*** Execute R ⋈ S on A
- ***Key Idea:*** We can partition R and S into buckets by hashing the join attribute- then just join the pairs of (small) matching buckets!
- ***IO Cost:***
  - *Partition phase:* 2(P(R) + P(S)) each pass
  - *Join phase: Depends on size of the buckets… can be* ~ P(R) + P(S) + OUT if they are small enough!
    - ***Can be worse though- see next slide!***

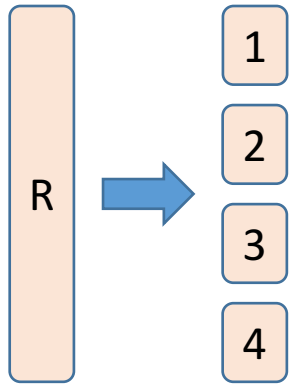


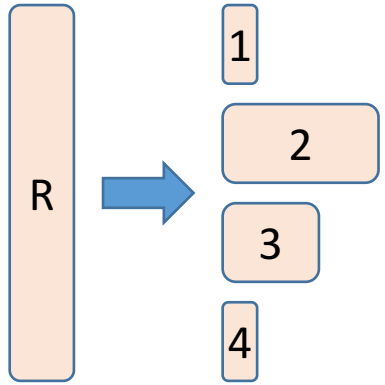
See L14-15:109-112!

HJ: Skew

- Ideally, our hash functions will partition the tuples *uniformly*

- However, hash collisions and *duplicate join key attributes* can cause ***skew***
  - For hash collisions, we can just partition again with a new hash function
  - Duplicates are just a problem… (Similar to in SMJ!)





R ⋈ S on A

Overview: SMJ vs. HJ

SMJ

Note: Ext. Merge Sort!

- We create ***initial sorted runs***
- We keep ***merging*** these runs until we have one sorted merged run for R, S
- We scan over R and S to complete the ***join***

HJ

- We keep ***partitioning*** R and S into progressively smaller buckets using hash functions h, h', h''…
- We ***join*** matching pairs of buckets (using BNLJ)

How many of these passes do we need to do?

R ⋈ S on A

How many passes do we need?

SMJ

# of passes	Length of runs	# of runs
0	1	N
1	B+1	$\left\lceil \frac{N}{B+1} \right\rceil$
2	B(B+1)	$\frac{1}{B}\left\lceil \frac{N}{B+1} \right\rceil$
…	…	…
k+1	$B^k(B+1)$	$\frac{1}{B^k}\left\lceil \frac{N}{B+1} \right\rceil$

Initial sorted runs

Fewer, longer runs by a factor of ***B***

HJ

# of passes	Avg. bucket size	# of buckets
0	N	1
1	$\left\lceil \frac{N}{B} \right\rceil$	B
2	$\frac{1}{B}\left\lceil \frac{N}{B} \right\rceil$	B^2
…	…	…
k+1	$\frac{1}{B^k}\left\lceil \frac{N}{B} \right\rceil$	B^{k+1}

More, smaller buckets by a factor of ***B***

Each pass, we get:

Each pass costs $2(P(R)+P(S))$

R ⋈ S on A

How many passes do we need?

SMJ

# of passes	Length of runs	# of runs
k+1	$B^k(B+1)$	$\frac{1}{B^k}\left\lceil\frac{N}{(B+1)}\right\rceil$

If (# of runs of R) + (# of runs of S) $\leq B$, then we are ready to complete the join in one pass*:

$$\mathrm{B} \geq \frac{\mathrm{P(R)}}{\mathrm{B^k(B+1)}} + \frac{\mathrm{P(S)}}{\mathrm{B^k(B+1)}}$$

$$B^{k+1}(B+1) \geq \mathrm{P(R)} + \mathrm{P(S)}$$

**Using the 'optimization' on slide 25*

HJ

# of passes	Avg. bucket size	# of buckets
k+1	$\frac{1}{B^k}\left\lceil\frac{N}{B}\right\rceil$	B^{k+1}

If *one of* the relations has bucket size $\leq B-1$, then we have partitioned enough to complete the join with single-pass BNLJ:

$$\mathrm{B}-1 \geq \frac{\min\{\mathrm{P(R)}, P(S)\}}{B^{k+1}}$$

$$B^{k+1}(\mathrm{B}-1) \geq \min\{\mathrm{P(R)}, P(S)\}$$

R ⋈ S on A

How many buffer pages for nice behavior?

Let's consider what B we'd need for k+1 = 1 passes (plus the final join):

SMJ

$$B(B+1) \geq \mathrm{P(R)} + \mathrm{P(S)}$$

If we use repacking, then we can satisfy the above if approximately:

$$B^2 \geq \max\{\mathrm{P(R)}, \mathrm{P(S)}\}$$

HJ

$$B(B-1) \geq \min\{\mathrm{P(R)}, \mathrm{P(S)}\}$$

So approximately:

$$B^2 \geq \min\{\mathrm{P(R)}, \mathrm{P(S)}\}$$

→ *Total IO Cost = **3(P(R) + P(S)) + OUT!***

Overview: SMJ vs. HJ

- HJ:
  - PROS: Nice linear performance is dependent on the *smaller relation*
  - CONS: Skew!

- SMJ:
  - PROS: Great if relations are already sorted; output is sorted either way!
  - CONS:
    - Nice linear performance is dependent on the *larger* relation
    - Backup!

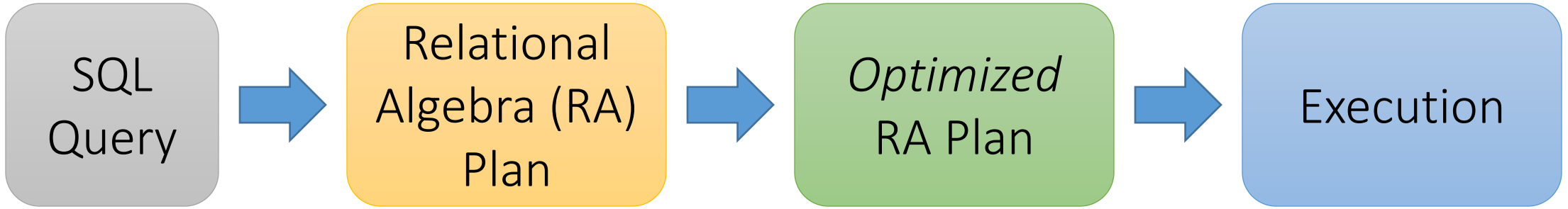
High-Level: Lecture 16

- Overall RDBMS architecture
- The Relational Model
- Relational Algebra

Check out the Relational Algebra practice exercises notebook!!

RDBMS Architecture

How does a SQL engine work ?



Declarative query (from user)

Translate to relational algebra expression

Find logically equivalent- but more efficient- RA expression

Execute each operator of the optimized plan!

The Relational Model: Data

An **attribute** (or **column**) is a typed data entry present in each tuple in the relation

Student

sid	name	gpa
001	Bob	3.2
002	Joe	2.8
003	Mary	3.8
004	Alice	3.5

The number of tuples is the **cardinality** of the relation

A **tuple** or **row** (or *record)* is a single entry in the table having the attributes specified by the schema

A **relational instance** is a ***set*** of tuples all conforming to the same *schema*

The number of attributes is the **arity** of the relation

Relational Algebra (RA)

- Five **basic** operators:
  1. Selection: σ
  2. Projection: Π
  3. Cartesian Product: $\times$
  4. Union: $\cup$
  5. Difference: -
- Derived or auxiliary operators:
  - Intersection, complement
  - Joins (natural,equi-join, theta join, semi-join)
  - Renaming: ρ
  - Division

1. Selection (σ)

- Returns all tuples which satisfy a condition
- Notation: $\sigma_c(R)$
- The condition c can be =, <, >, <>

```
Students(sid,sname,gpa)
```

SQL:

```
SELECT *
FROM Students
WHERE gpa > 3.5;
```

RA:

$$\sigma_{gpa>3.5}(Students)$$

2. Projection (Π)

- Eliminates columns, then removes duplicates
- Notation: $\Pi_{A1,\ldots,An}(R)$

```
Students(sid,sname,gpa)
```

SQL:

```
SELECT DISTINCT
   sname,
   gpa
FROM Students;
```

RA:

$$\Pi_{sname,gpa}(Students)$$

3. Cross-Product (×)

- Each tuple in R1 with each tuple in R2
- Notation: R1 × R2
- Rare in practice; mainly used to express joins

```
Students(sid,sname,gpa)
People(ssn,pname,address)
```

SQL:

```
SELECT *
FROM Students, People;
```

RA:

$$Students \times People$$

Renaming (ρ)

```
Students(sid,sname,gpa)
```

- Changes the schema, not the instance
- A 'special' operator- neither basic nor derived
- Notation: $\rho_{B1,\ldots,Bn}(R)$

- **Note: this is shorthand for the proper form (since names, not order matters!):**
  - $\rho_{A1 \rightarrow B1,\ldots,An \rightarrow Bn}(R)$

SQL:

```
SELECT
  sid AS studId,
  sname AS name,
  gpa AS gradePtAvg
FROM Students;
```

RA:

$$\rho_{studId,name,gradePtAvg}(Students)$$

We care about this operator *because* we are working in a *named perspective*

Natural Join (⋈)

- Notation: $R_1 \bowtie R_2$
- Joins R_1 and R_2 on *equality of all shared attributes*
  - If R_1 has attribute set A, and R_2 has attribute set B, and they share attributes $A \cap B = C$, can also be written: $R_1 \bowtie_C R_2$
- Our first example of a *derived* RA operator:
  - Meaning: $R_1 \bowtie R_2 = \Pi_{A \cup B}(\sigma_{C=D}(\rho_{C \to D}(R_1) \times R_2))$
  - Where:
    - The rename $\rho_{C \to D}$ renames the shared attributes in one of the relations
    - The selection $\sigma_{C=D}$ checks equality of the shared attributes
    - The projection $\Pi_{A \cup B}$ eliminates the duplicate common attributes

```
Students(sid,name,gpa)
People(ssn,name,address)
```

SQL:

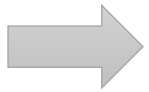
```
SELECT DISTINCT
  ssid, S.name, gpa,
  ssn, address
FROM
  Students S,
  People P
WHERE S.name = P.name;
```

RA:

$$Students \bowtie People$$

Converting SFW Query -> RA

```
SELECT DISTINCT A1,…,An
FROM            R1,…,Rm
WHERE           c1 AND … AND ck;
```



$$\Pi_{A_1,\ldots,An}(\sigma_{c_1} \ldots \sigma_{c_k}(R_1 \bowtie \cdots \bowtie R_m))$$

Why must the selections “happen before” the projections?

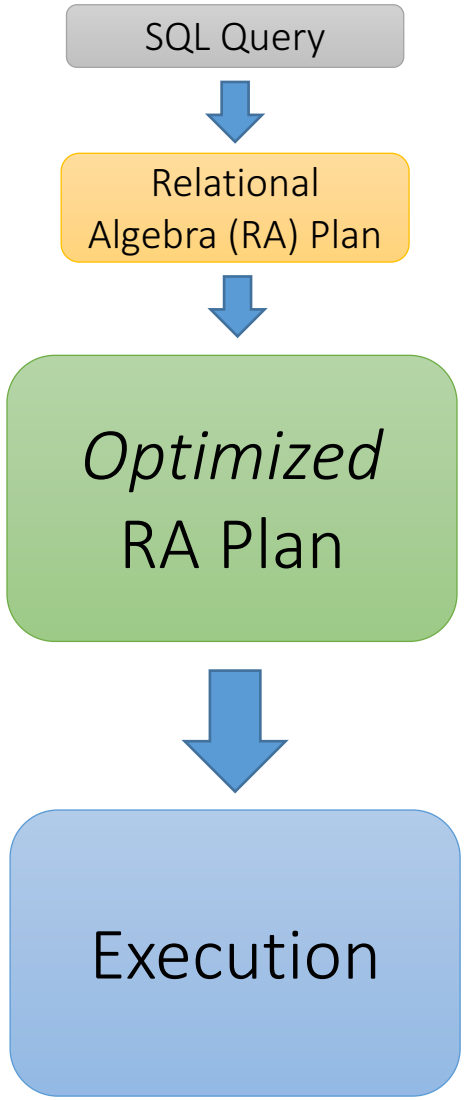
High-Level: Lecture 17

- Logical optimization
- Physical optimization
  - Index selections
  - IO cost estimation

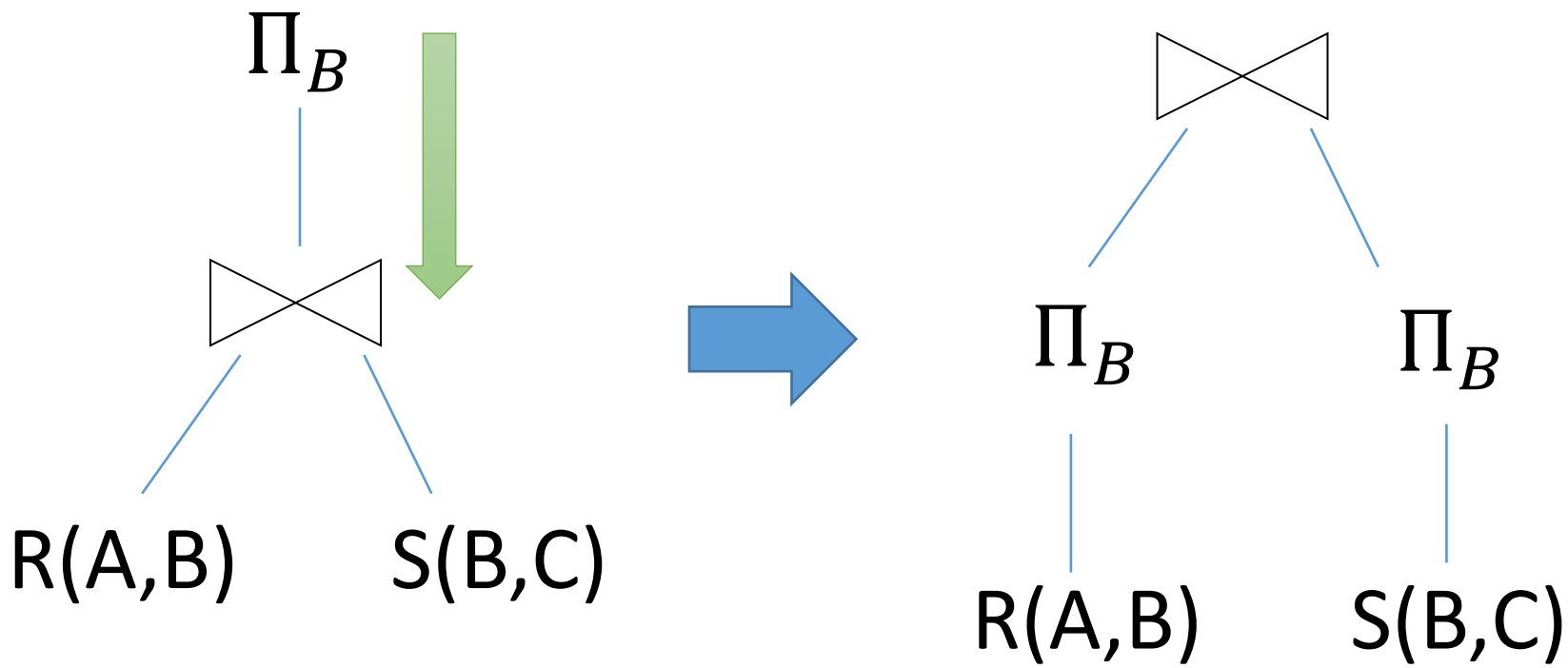
Logical vs. Physical Optimization

- **Logical optimization:**
  - Find equivalent plans that are more efficient
  - *Intuition: Minimize # of tuples at each step by changing the order of RA operators*

- **Physical optimization:**
  - Find algorithm with lowest IO cost to execute our plan
  - *Intuition: Calculate based on physical parameters (buffer size, etc.) and estimates of data size (histograms)*

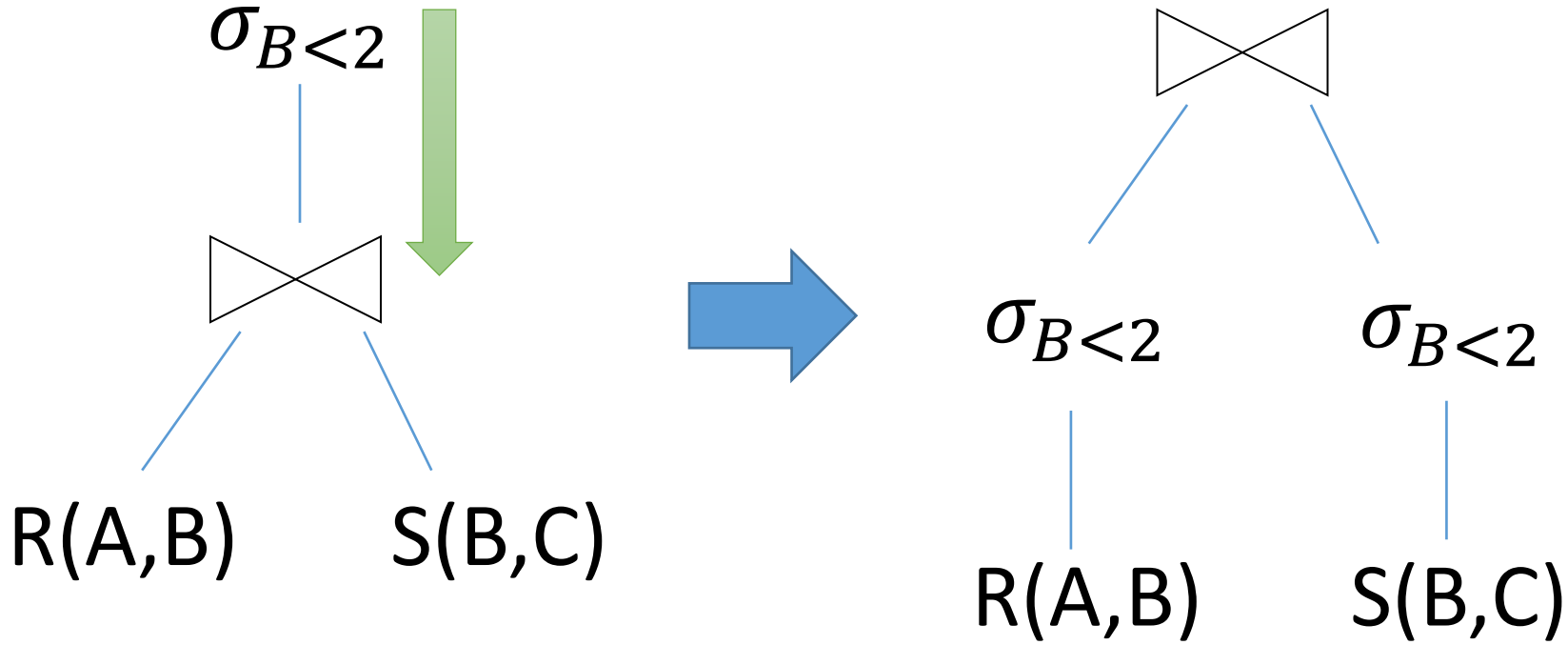


Logical Optimization: "Pushing down" projection



Why might we prefer this plan?

Logical Optimization: "Pushing down" selection



Why might we prefer this plan?

RA commutators

- The basic commutators:
  - Push **projection** through **(1) selection**, **(2) join**
  - Push **selection** through **(3) selection, (4) projection, (5) join**
  - *Also:* Joins can be re-ordered!

- Note that this is not an exhaustive set of operations
  - This covers *local re-writes; global re-writes possible but much harder*

This simple set of tools allows us to greatly improve the execution time of queries by optimizing RA plans!

Index Selection

Input:

- Schema of the database
- **Workload description:** set of (query template, frequency) pairs

Goal: Select a set of indexes that minimize execution time of the workload.

- Cost / benefit balance: Each additional index may help with some queries, but requires updating

This is an optimization problem!

IO Cost Estimation via Histograms

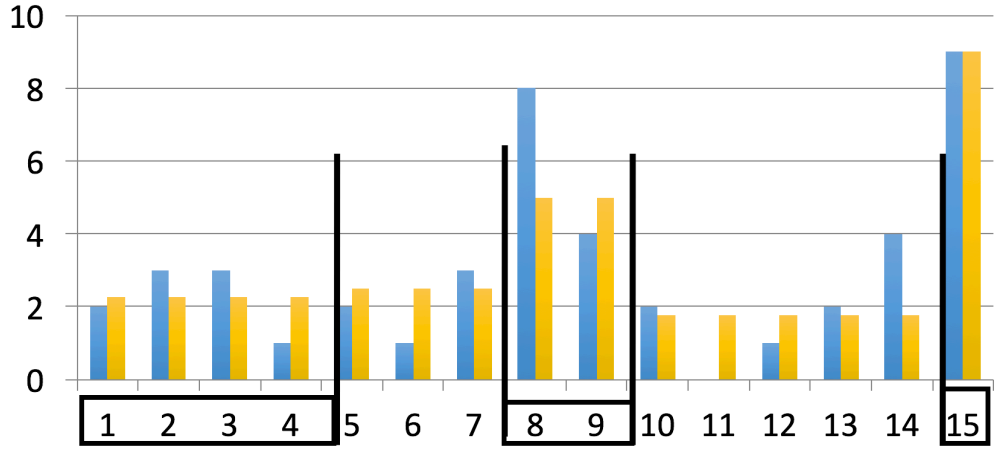
- For **index selection**:
  - What is the cost of an index lookup?
- Also for **deciding which algorithm to use**:
  - Ex: To execute $\mathrm{R} \bowtie S$, which join algorithm should DBMS use?
  - **What if we want to compute $\boldsymbol{\sigma_{A>10}(\mathrm{R}) \bowtie \sigma_{B=1}(S)}$?**
- In general, we will need some way to ***estimate intermediate result set sizes***

Histograms provide a way to efficiently store estimates of these quantities

Histogram types

Equi-depth

All buckets contain roughly the same number of items (total frequency)



Equi-width

All buckets roughly the same width