CS 348 Lectures 13-14

Query Processing Architecture and Algorithms

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Mar 1st-3rd 2022

Announcements

- Assignment 4:
  - Out tonight.
  - Due Mar 18th midnight
  - Although the programming question is about query optimization (topic of next week) the question is completely self-contained, so you can start on it tonight.

Outline For Today

1. Wrap up Indices
2. DBMS Query Processing Architecture
3. Fundamental Query Processing Operators & Algorithms
    - Assumptions
    - Scan-based Operators
    - Sort-based Operators
    - Hashing-based Operators
    - Algorithms Using Indices

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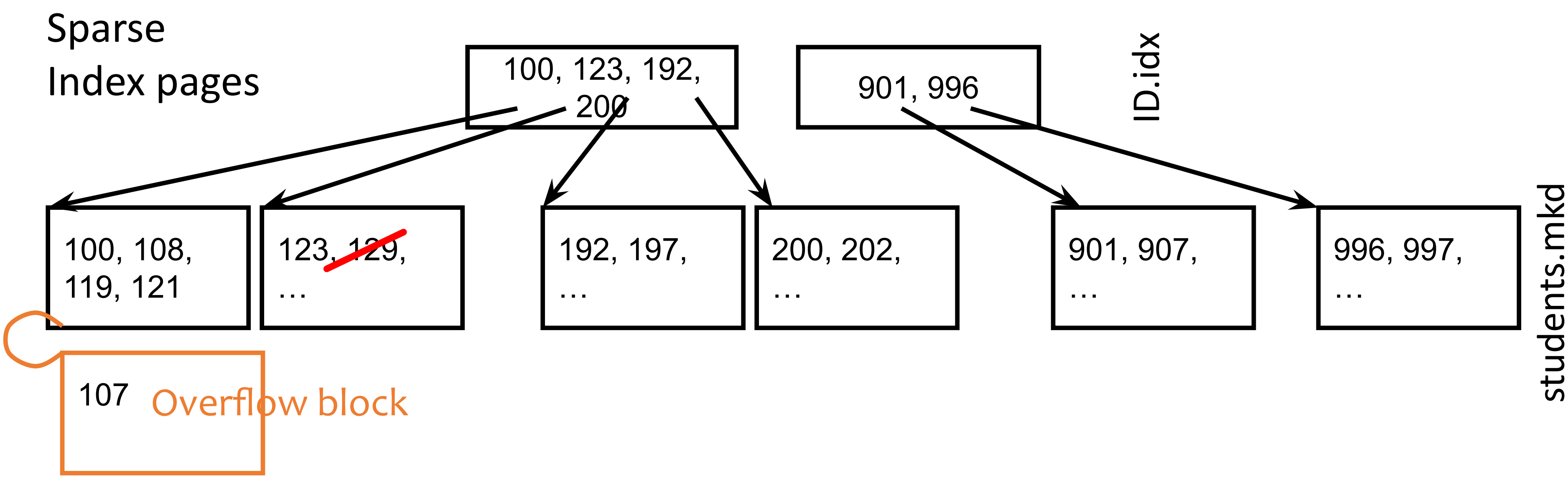
Recap: 1+4 Index Designs From Last Lecture

1. Index-less "Insertion Sort"
2. Single-level Dense Index
3. Single-level Sparse Index with Overflows



- Pros: Index size smaller than dense index
- Con 1: Sparse Index can still become very large (GBs) for large tables.
- Con 2: Overflows are not robust
- Con 3: Can lead to empty pages (but less of an issue in practice)

Recap: 1+4 Index Designs From Last Lecture

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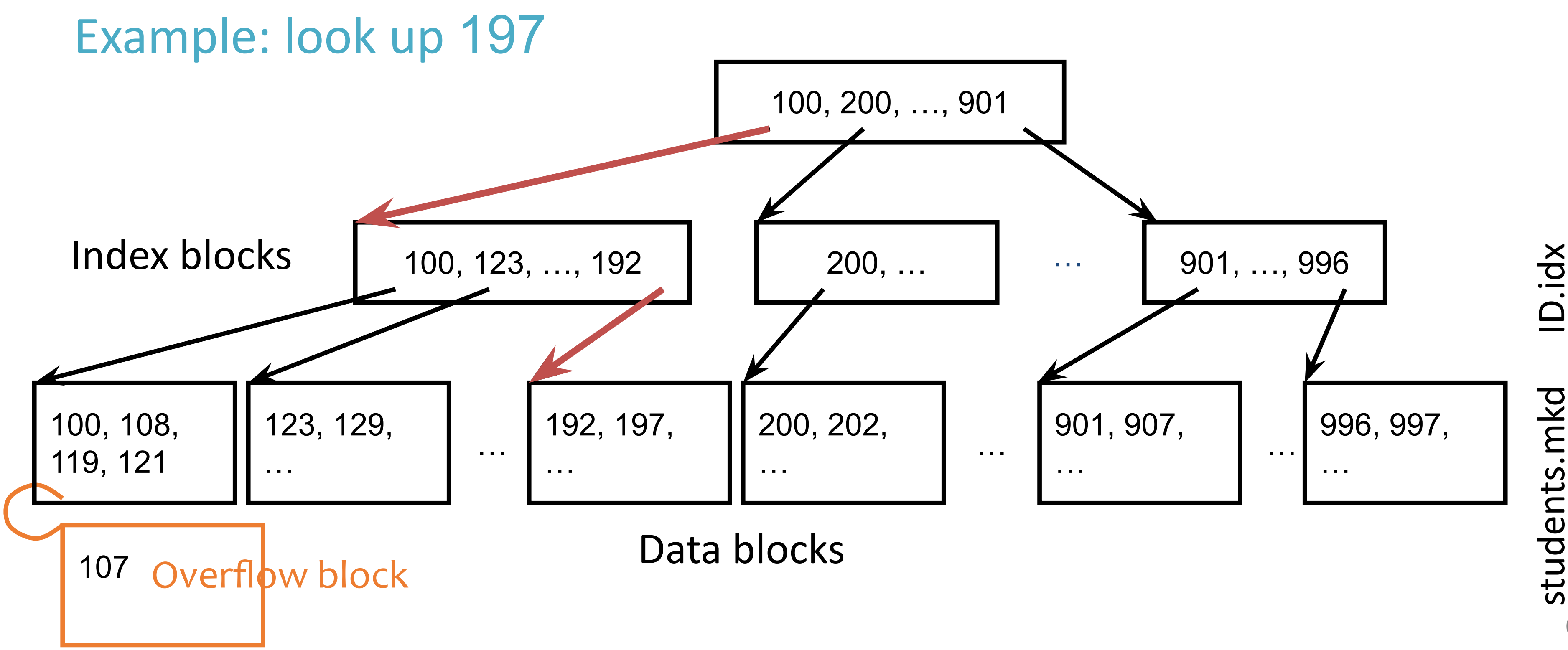
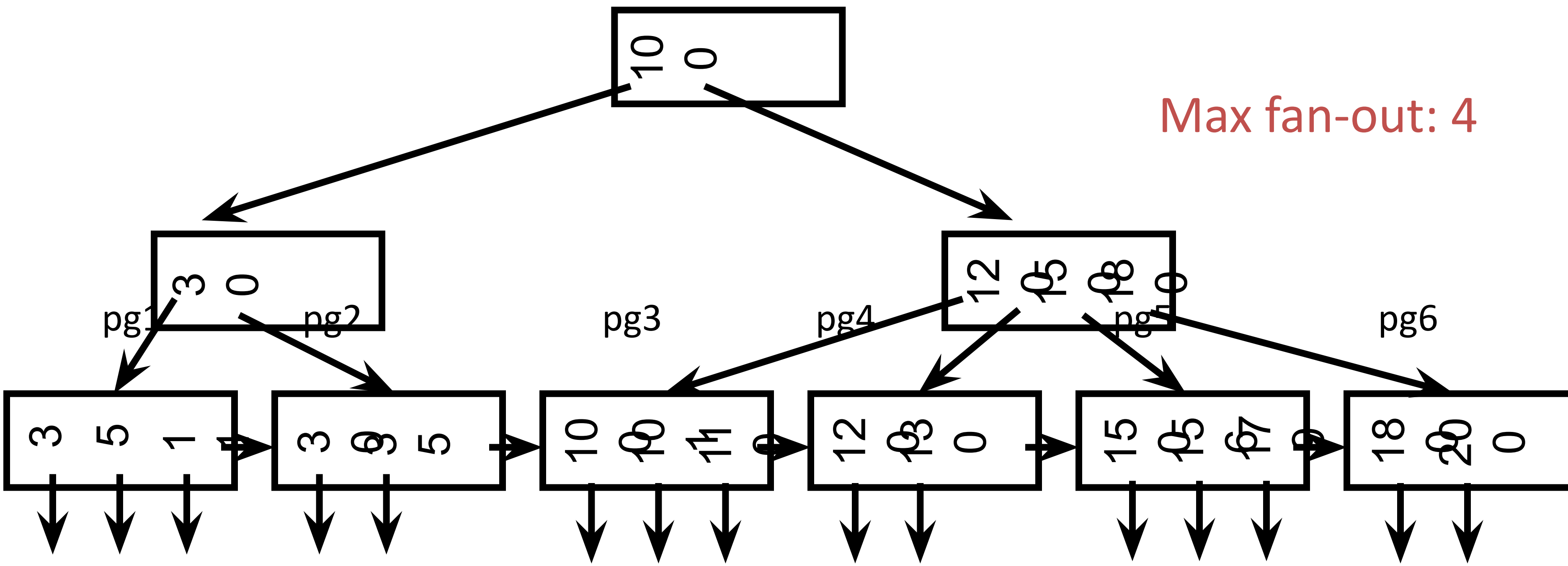
2. Single-level Dense Index
3. Single-level Sparse Index with Overflows
4. Multi-level Indices with Overflows



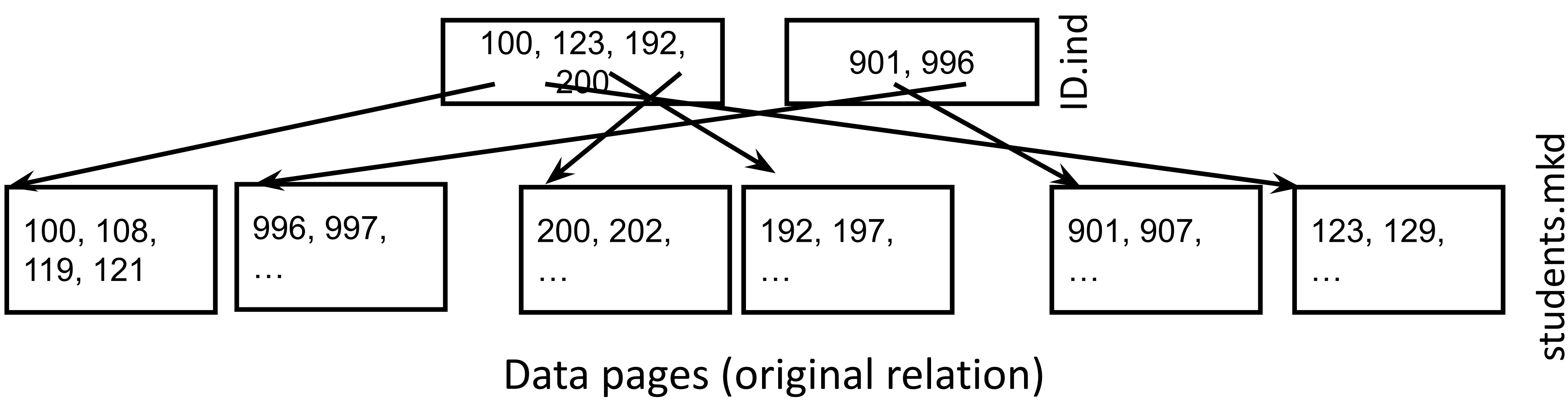
Recap: 5th Approach: B/B+ Tree Indices

- Multi-level sparse indices on a first level of pages that is either:
  - actual relation pages (if clustered)
  - dense index on the relation pages (works for clustered or unclustered)
  - leaf level consists of *chained pages*
- Forms a k-ary balanced tree
- Instead of overflow pages uses splitting and merging of pages at any layer



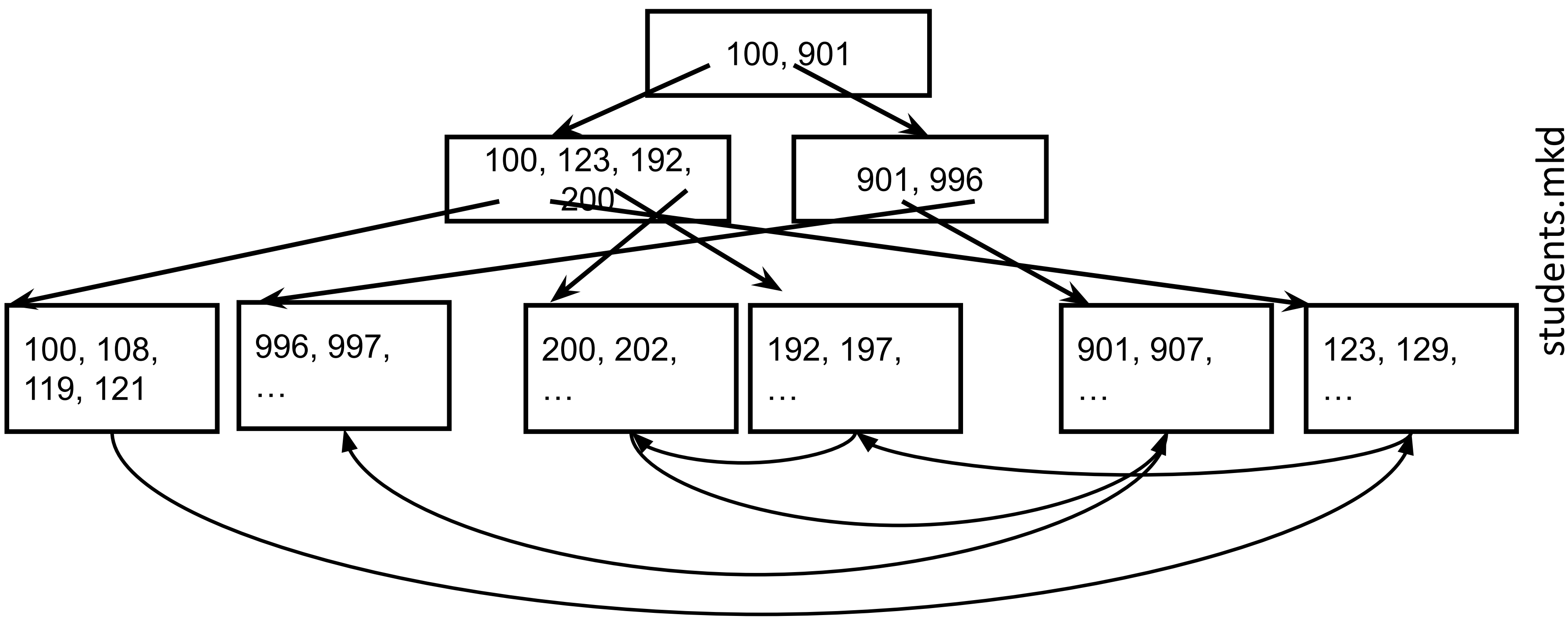
How to Keep A Table Sorted?

- Recall this key question
- Recall further note on clustered indices and page order: “When a relation file has a clustered index, i.e., when pages are sorted, we do not necessarily need the pages to be sorted.”



How to Keep A Table Sorted?

- Recall this key question
- Recall further note on clustered indices and page order.
- Again assume leaf nodes are tuples
- Many RDBMSs use “B+ tree files” to store the tables, i.e., entire file is a B+ tree index, with leaf nodes storing tuples (instead of pointers to tuples)

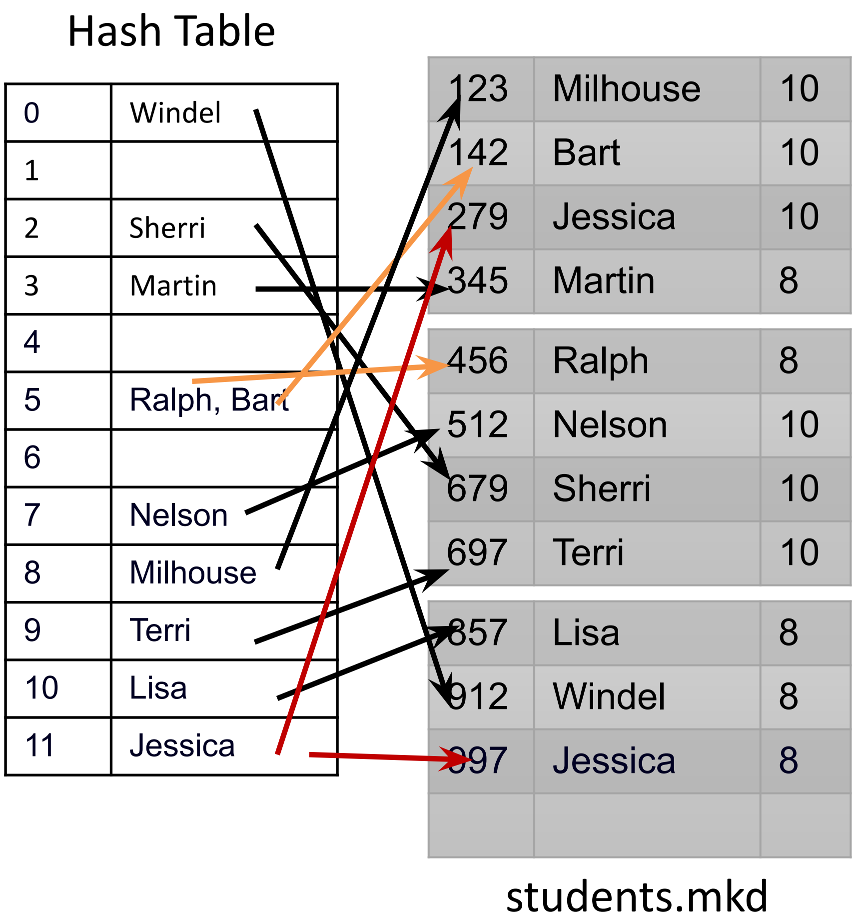


B+ tree file

Other Common Indices

- 2 Classes of Indices Overall

1. Tree-based: can do both lookups and range queries
   - B/B+ Trees, R Trees, Radix Tree
2. Hash-based
   - Can only do look ups. Cannot do range queries.
   - In practice: handle collisions
3. Many other indices: bitmap indices, probabilistic indices, suffix arrays, GiST or Inverted Index for different applications and data types.



Using Indices In Practice

Using Indices In Practice (1)

- Indices can be defined on one ore more attributes:
  - CREATE INDEX NameIndex ON User(Lastname,Firstname);
  - I.e., B+'s keys are (Lastname, Firstname) pairs and tuples are sorted first by LastName and then Firstname.
  - This index would be useful for these queries:

```
select * from User where Lastname = 'Smith'
select * from User where Lastname = 'Smith' and Firstname='John'
```

  - But not this query:

```
select * from User where Firstname='John'
```

- Many systems use indices by default on the primary key
- Many systems use indices to implement UNIQUE constraints

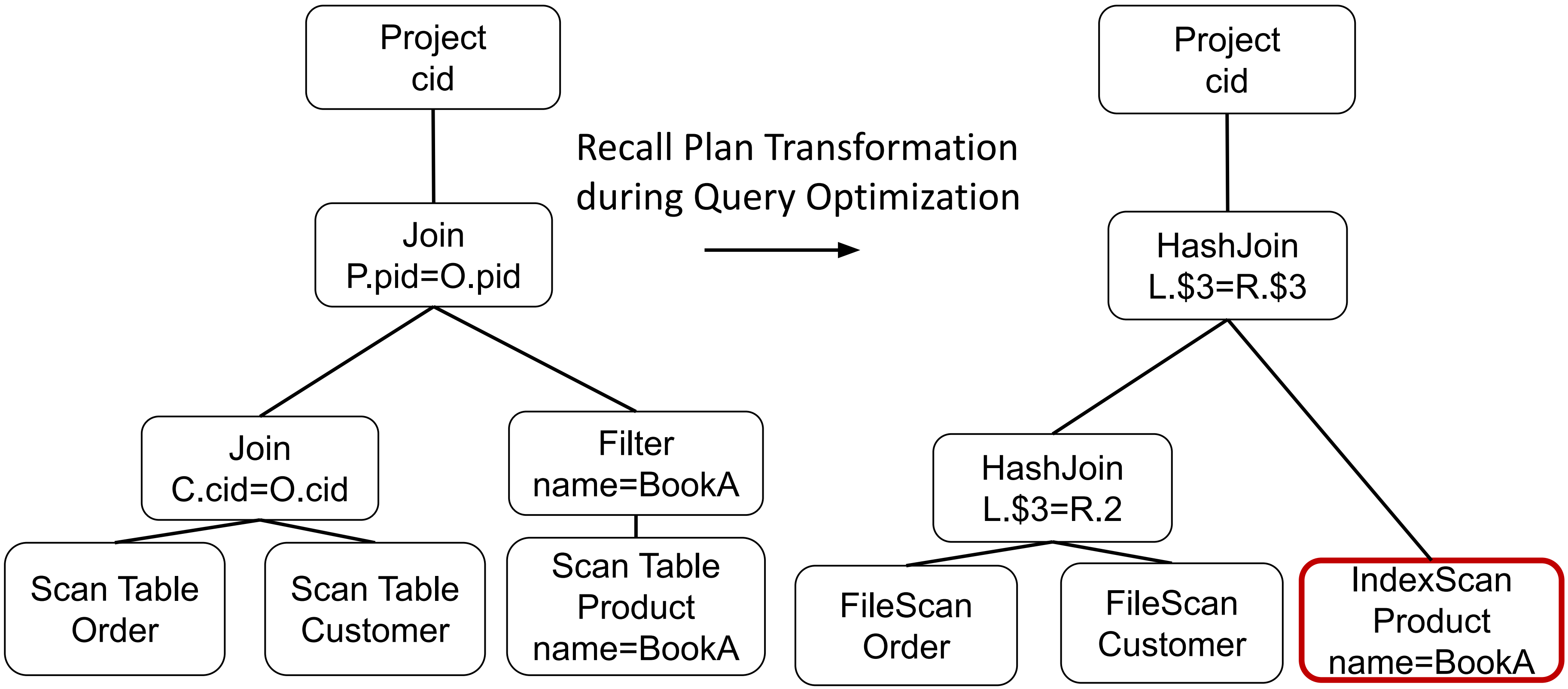
```
CREATE TABLE Students(
   studentID int,
   sinNumber varchar(16) UNIQUE
   PRIMARY KEY (studentID))
```

Will create 2 B+ indices:

1) on studentID;
2) 2) on sinNumber

Using Indices In Practice (2)

- Users only create indices. They do not refer to indices in queries.
- Pro: Some user queries will get much faster
  - B/c RDBMSs use indices during query evaluation
  - Ex: IndexScan operators, or IndexMergeJoin (in Oracle) or IndexNestedLoopJoin etc.



Using Indices In Practice (3)

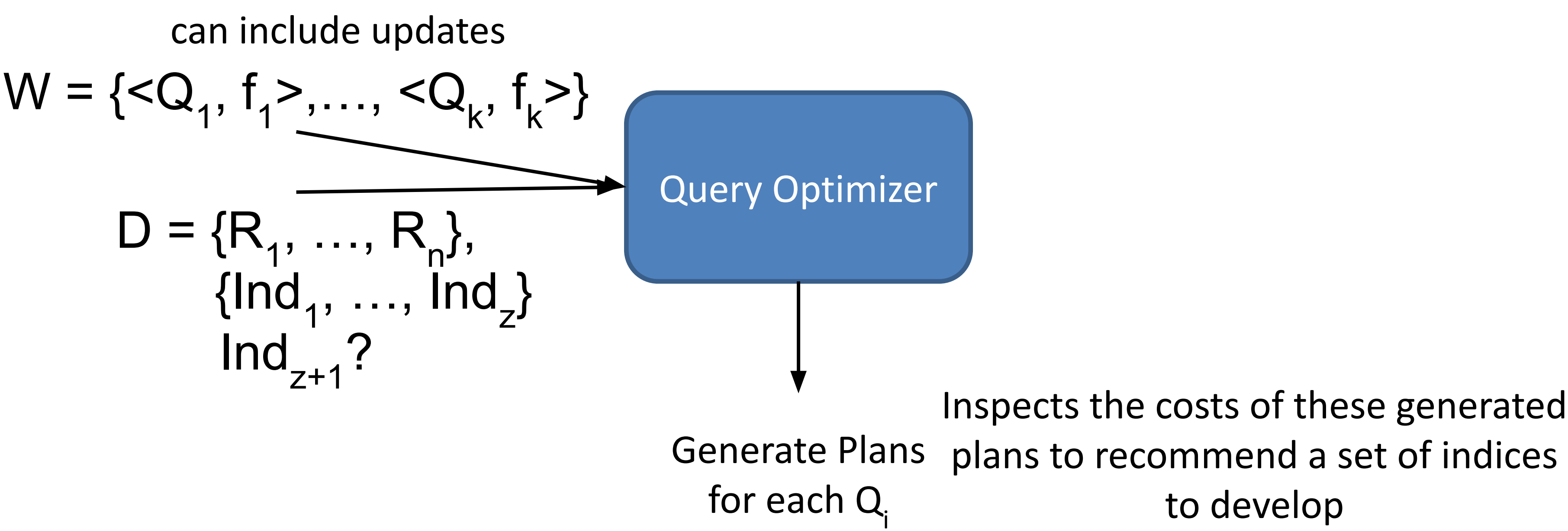
- Con: Updates will get slower because indices need to be maintained
- Q: How should users pick indices given a workload W (i.e., the set of queries an application asks and their frequencies)
- General Guideline:
  - Profile slow queries. Check if they have =, <, ≤, >, ≥ predicates

```
SELECT * FROM R WHERE A = value;
SELECT * FROM R WHERE A = value AND B = 27;
SELECT * FROM R, S WHERE R.A = S.C;
SELECT * FROM S WHERE D > 50;
```

  - E.g., above indices on R.A, R.A and R.B multicolumn, S.C, S.D are possible indices that can speed queries
  - But one should weigh these benefits against slow downs due to updates

Using Indices In Practice (4)

- Many RDBMSs have “Physical Design Advisor” (PDA) tool
- Input: Database D (w/ existing indices), workload W
- Output: A set of recommended indices
- Internally PDA does a “what if” analysis:
  - Uses Query Optimizer & inspects the estimated runtimes/costs of plans the system would use for queries in W with & without additional indices



The Halloween Problem: An Interesting Note On Challenging Problems a DBMS has to solve

- Story from the early days of System R:

```
UPDATE Payroll
SET salary = salary * 1.1
WHERE salary >= 100000;
```

  - There is a B^+-tree index on *Payroll*(*salary*)
  - The update never stopped (why?)
- Why?
- How could you try to solve this if you implemented System R.

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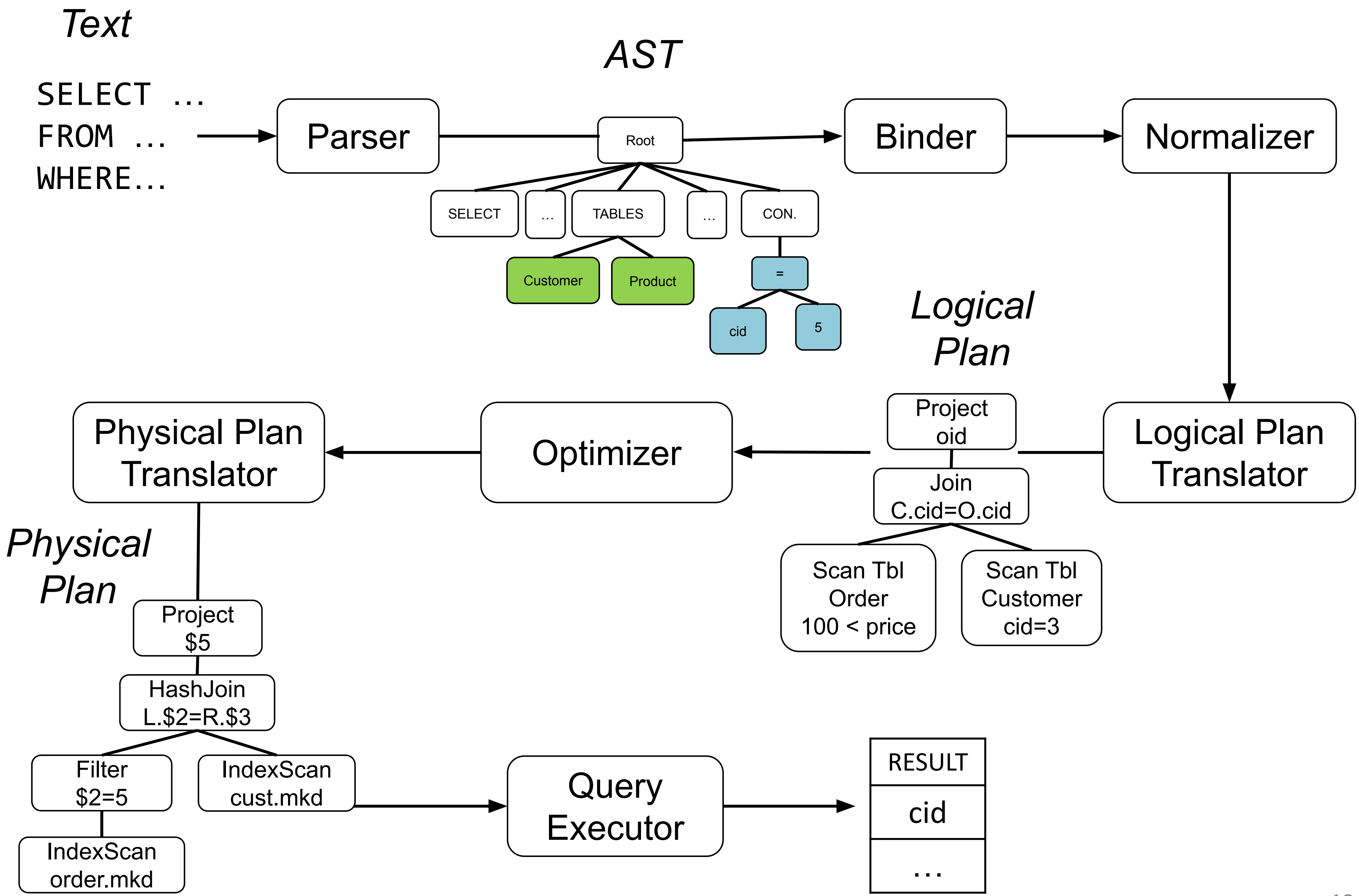
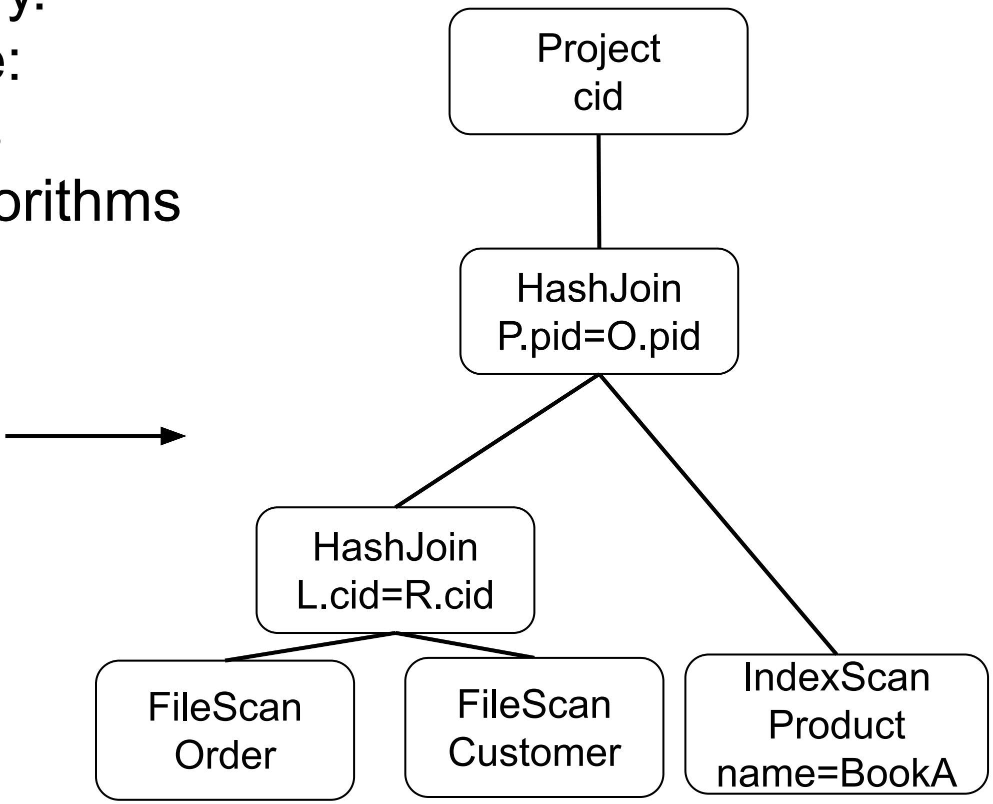
Recall: Overview of Compilation Steps



Query Processor of DBMSs

- The component that executes a *physical plan:*
  - A tree of operators that manipulate files and tuples to produce the output asked in a query.
  - Operators implement core:
    1. data access methods
    2. query processing algorithms

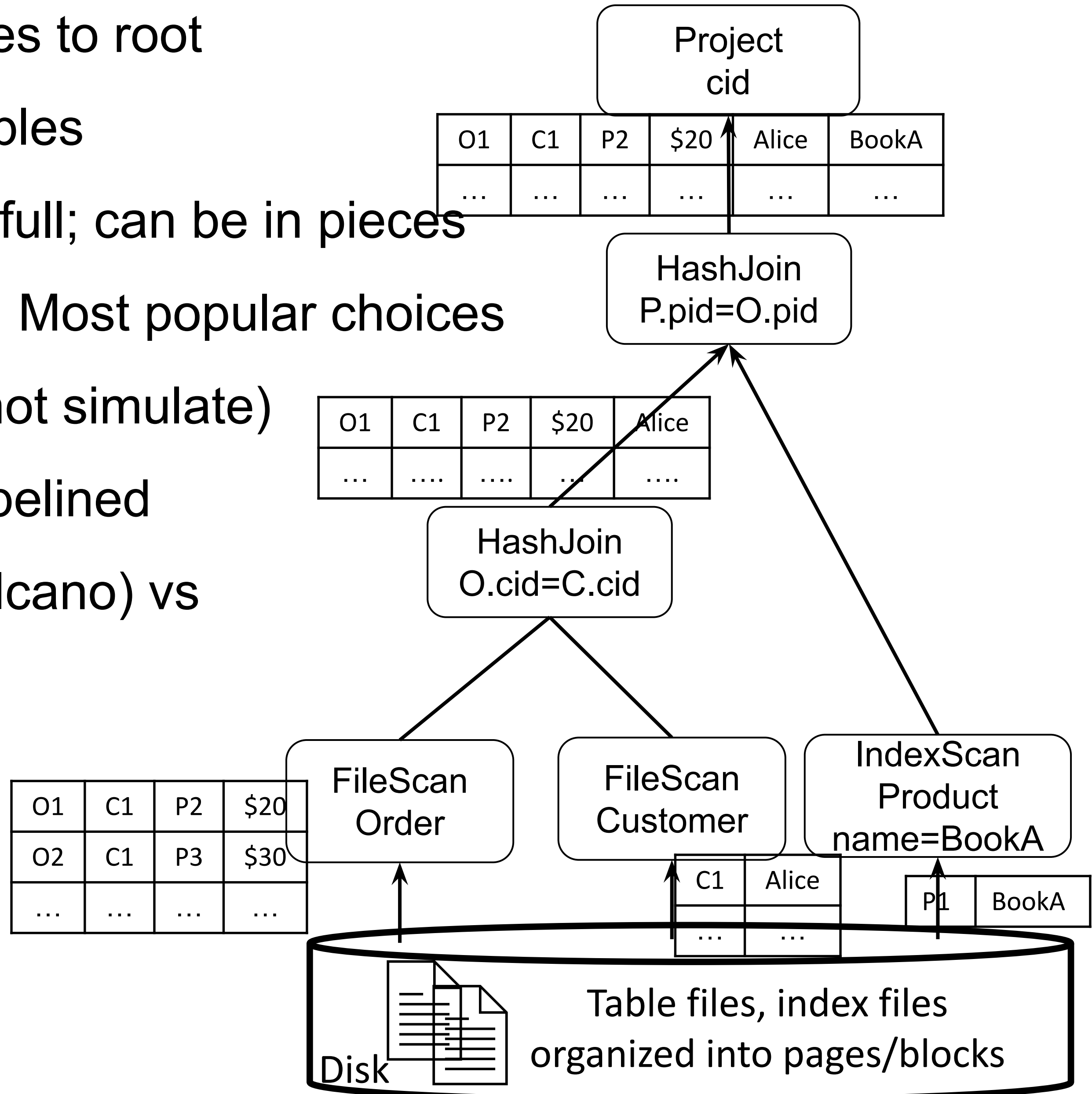
```
SELECT cid
FROM Customer C, Order O, Product P
WHERE C.cid = O.cid AND O.pid = P.pid
      AND P.name = BookA
```



Note: the more operators a system has, the larger set of query plans (i.e., algorithms) it can stich together to evaluate queries

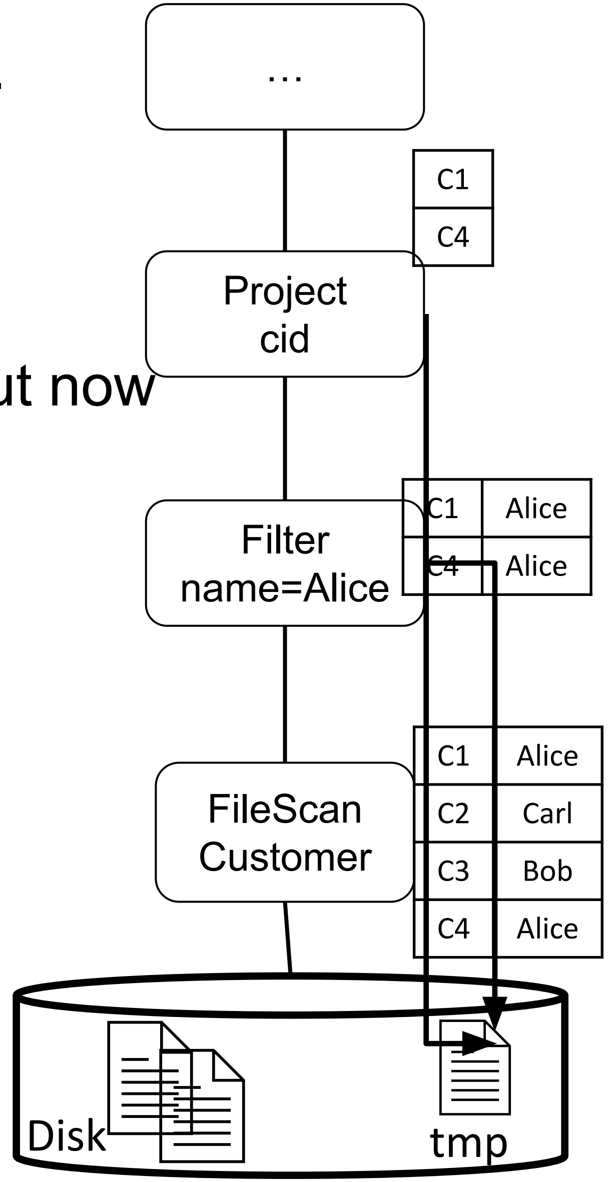
(Simplified) Physical Plan Architecture

- Tuples flow from leaves to root
- Operators produce tables
  - not necessarily in full; can be in pieces
- Several designs exist. Most popular choices
  - push vs pull (will not simulate)
  - materialized vs pipelined
  - iterator model (Volcano) vs block-at-a-time



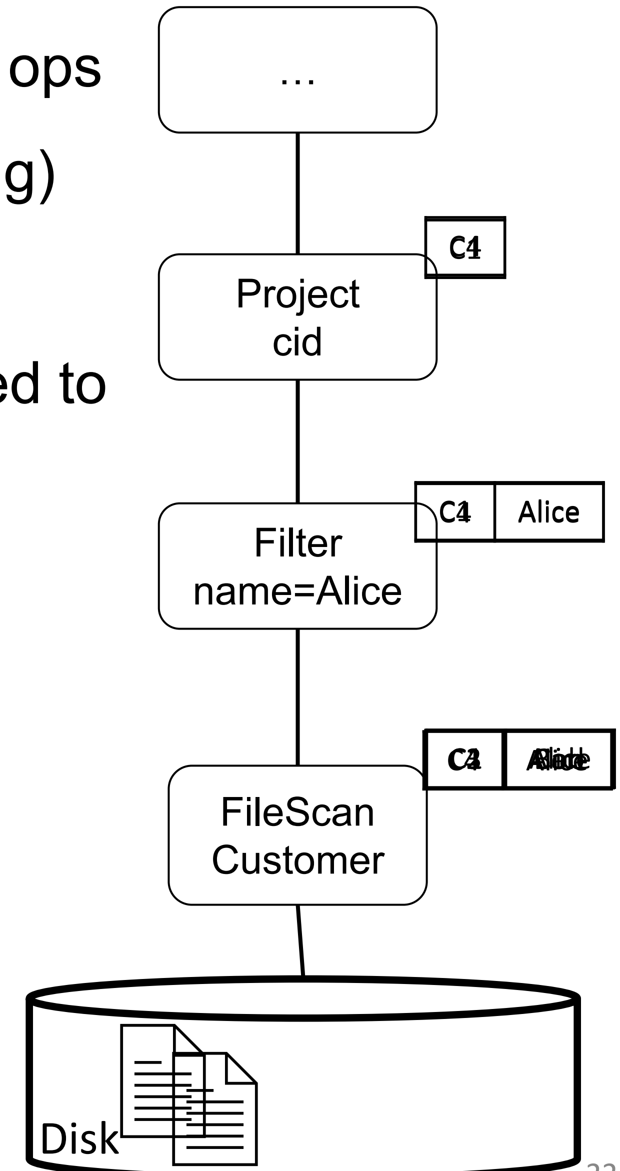
Materialized vs Pipelined (1)

- Materialized: All ops are “blocking”, i.e. materialize all their inputs to disk or temp. memory buffers
- Simple to implement
- Earlier DBMSs adopted materialization but now obsolete



Materialized vs Pipelined (2)

- Pipelined: When possible, ops take 1 or more tuples-at-a-time, process, and pass to parent ops
- More efficient (avoids temp file writing, reading)
- Not always possible: e.g., ORDER BY
  - to sort a table, cannot pipeline tuples. need to see all tuples before computing the order.

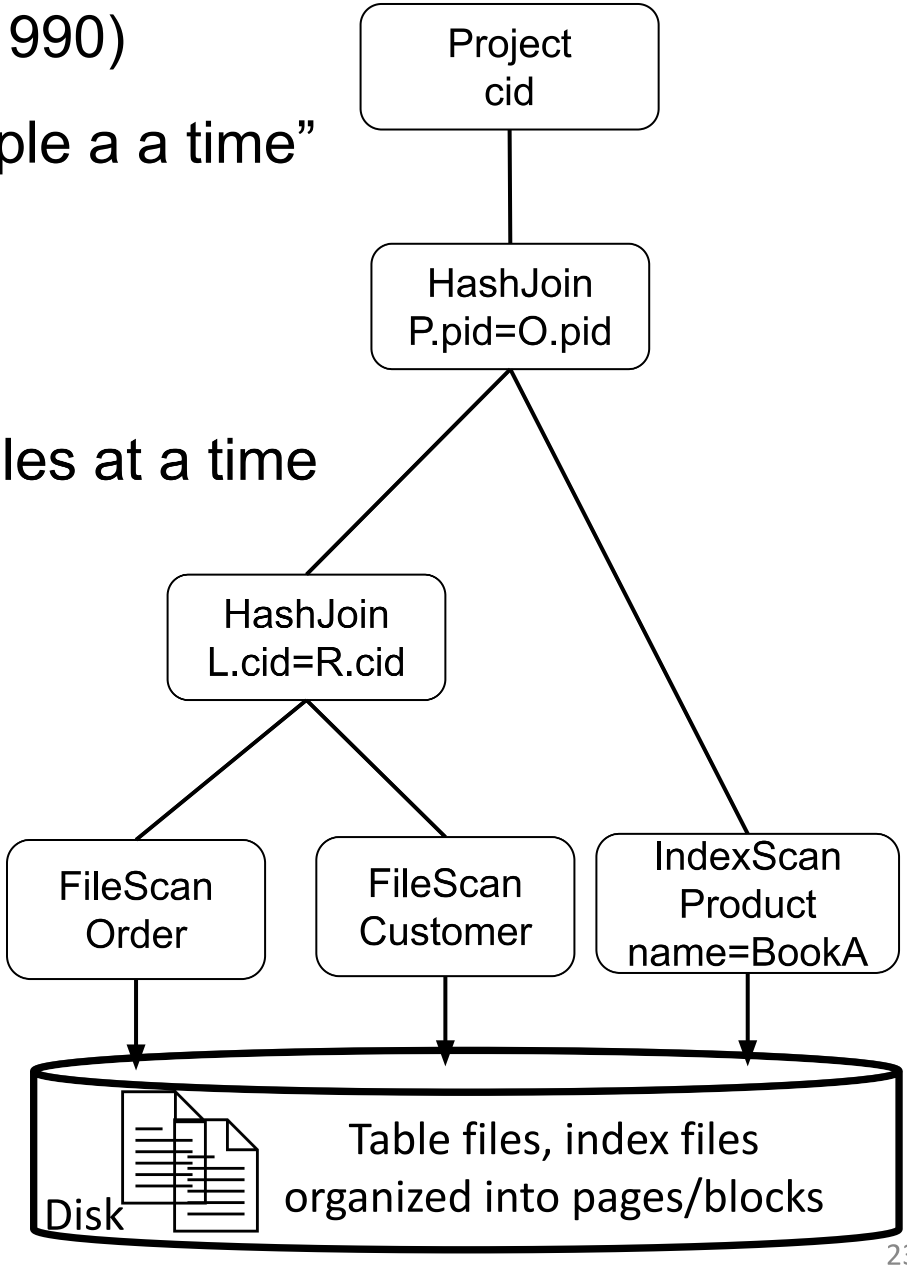


Iterator Model vs Block-at-a-time

- Iterator Model (by Goetz Graefe, 1990)
   - Pull data from children "one tuple a a time"
   - E.g.: PostgreSQL
- Block-at-a-time:
   - Pull data many, e.g., 1024, tuples at a time
   - Better CPU utilization b/c fewer function calls

Goetz Graefe

Main architect of first version of MS SQL Server



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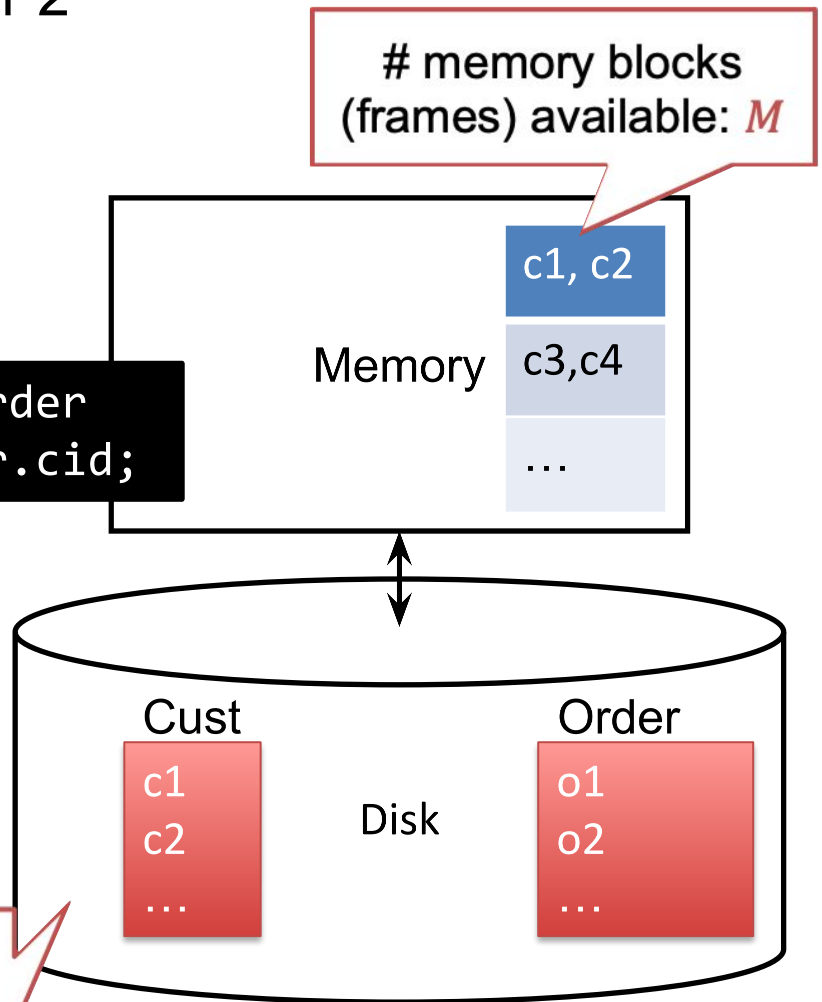
Costs of Query Processing Algorithms

- In algorithm analysis often “runtime”, i.e., # CPU cycles is the metric
- In DBMSs, most algs (but not all) are linear time or almost-linear time (i.e., with O(log(|R|)) factors) in terms of runtime.
- Will use *I/O cost* to analyze the main algorithms because DBMSs are disk-based systems.
- Disclaimer 1: Simplification to study the general behavior of algs
- Disclaimer 2: All of the algs we describe are integrated in many systems and have scenarios when one is used over the other

Setting

- Given operator *o* processing 1 or 2 tables (e.g., scan or join)
- Recall: *o* runs in memory

```
select * from Customer, Order
where Customer.cid = Order.cid;
```



Number of rows for a table $|Customer|$
Number of disk blocks for a table

$$B(Customer) = \frac{|Customer|}{\#\ of\ rows\ per\ block}$$

Notation

- Relations: R, S
- Tuples: r, s
- Number of tuples: $|R|$, $|S|$
- Number of disk blocks: $B(R)$, $B(S)$
- Assume row-oriented physical design (i.e., all column values of tuples are in the page/block)
- Number of memory blocks available: M
- Cost metric: # I/O's
  - And sometimes # memory blocks required

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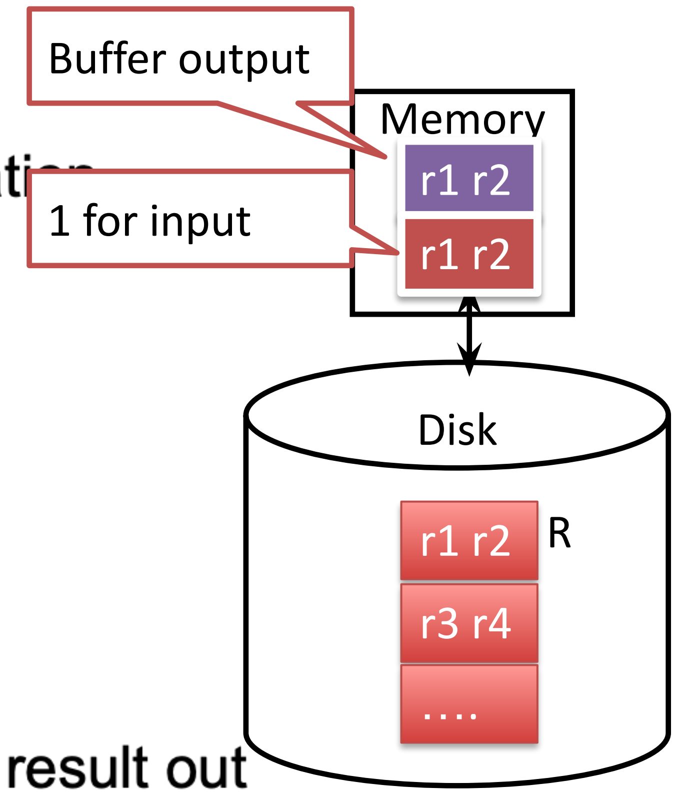
Table Scan Operators

- Scan table *R* and optionally perform a:
  - Selection over *R*
  - Projection of *R* without duplicate eliminati...
- I/O's: $B(R)$
  - Optimization for selection:
    - Stop early if it is a lookup by key
- Memory requirement: 2 (blocks)
  - 1 for input, 1 for buffer output
  - Increasing memory does not improve I/O
- Not counting I/O cost (if any), of writing the result out
  - Same for any algorithm!



Nested-loop Join Operator

- Takes 2 tables as inputs and implements: $R \bowtie_p S$
- Basic/Naive version:

```
for each block of R, and for each r in the block:
    for each block of S, and for each s in the block:
        output rs if p evaluates to true over r and s
```

- R is called the outer table; S is called the inner table
- I/O's: $B(R) + |R| \cdot B(S)$

Note: No other operation except table scan

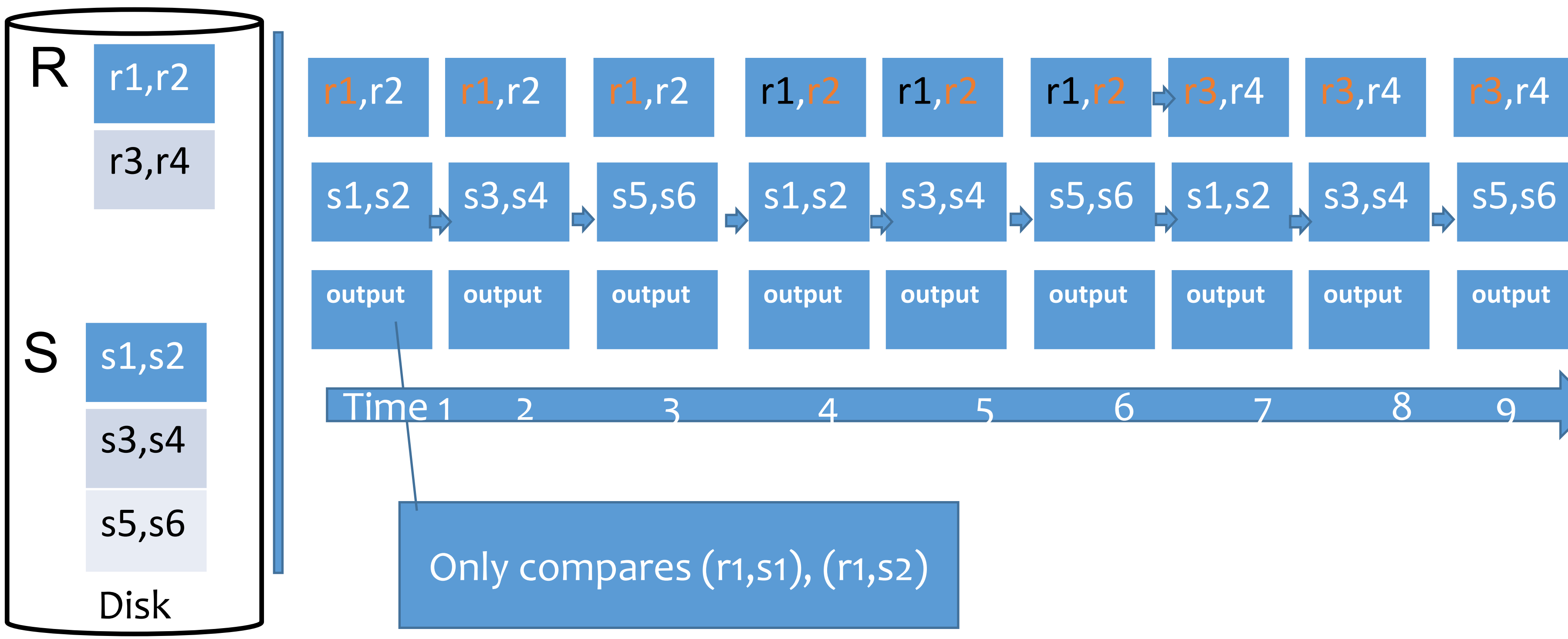
Blocks of R are moved into memory only once

Blocks of S are moved into memory with |R| number of times

- Memory requirement: 3
- This is a terribly slow algorithm: has quadratic runtime
- But when is it necessary?
  - When doing Cartesian product-like operations, e.g., "difficult" join conditions
  - SELECT * FROM R, P WHERE sqrt(R.A * S.B) > 5

Simulation of Basic Nested-loop Join

- 1 block = 2 tuples, 3 blocks of memory



- Number of I/O:

  B(R) + |R| * B(S) = 2 blocks + 4 * 3 blocks = 14

Block-Nested-loop join Operator

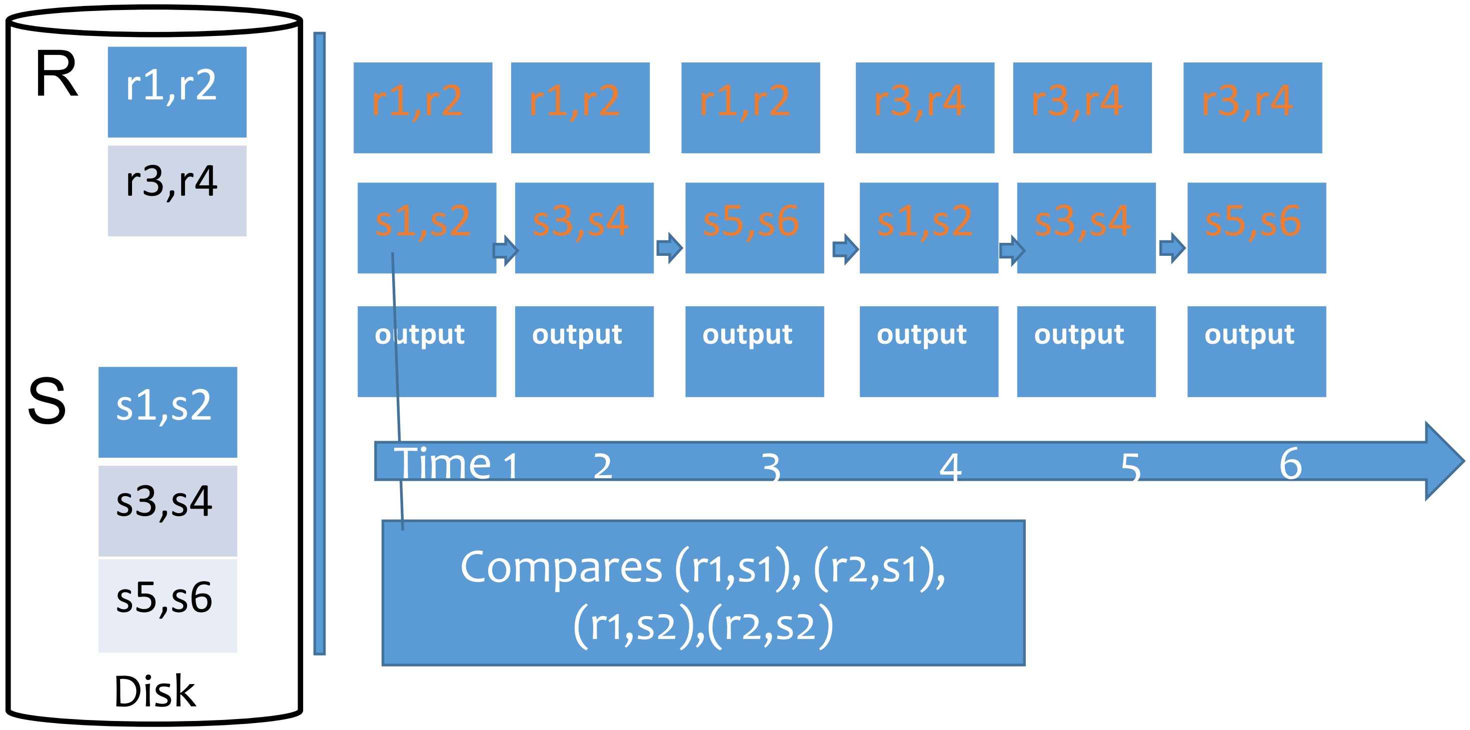
- Improvement: block-based nested-loop join

```
for each block of R, for each block of S:
    for each r in the R block, for each s in the S block:
    …
```

- I/O's: $B(R) + B(R) \cdot B(S)$
- Memory requirement: same as before

Simulation of Block Nested-loop Join

- 1 block = 2 tuples, 3 blocks of memory



- Number of I/O:

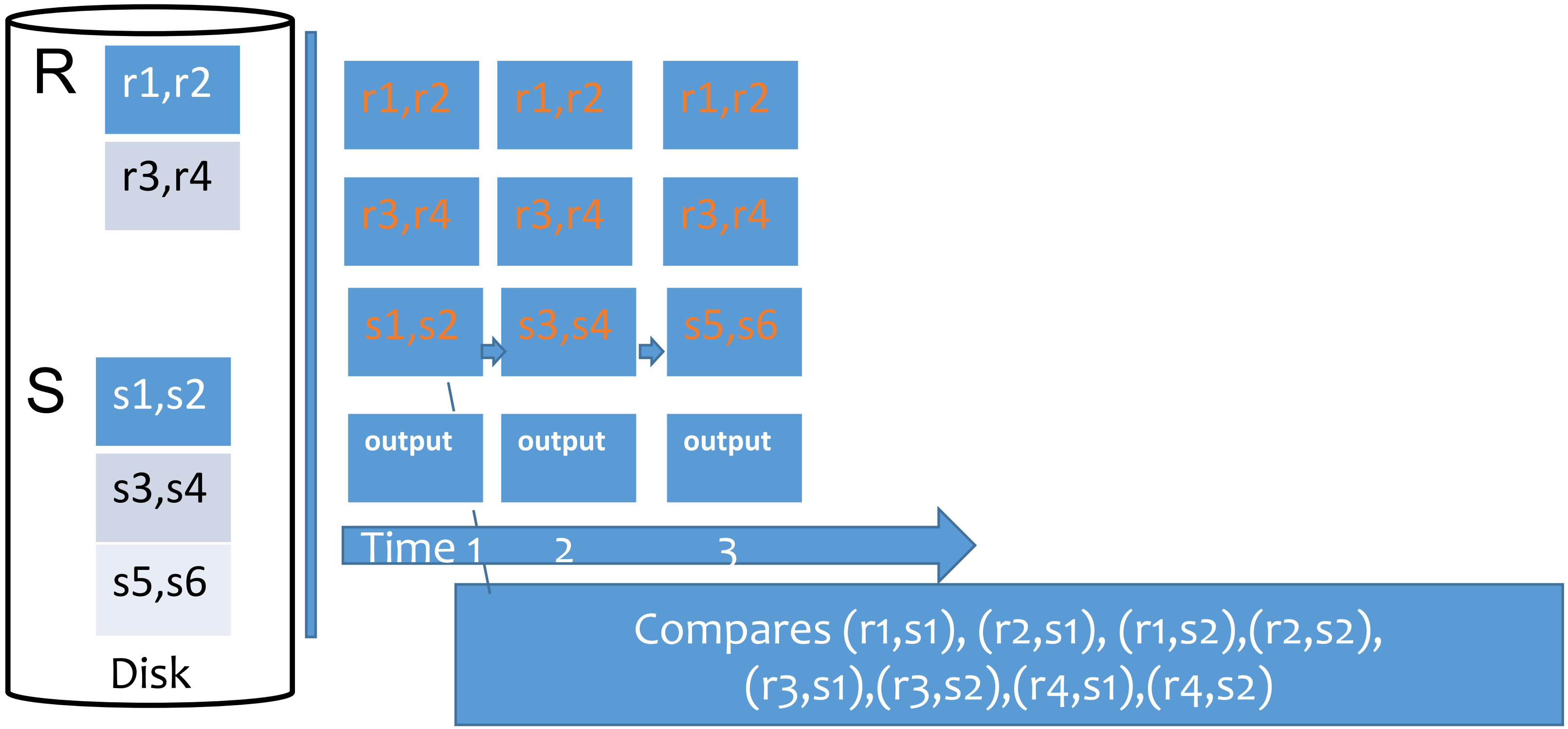
  B(R) + B(R)* B(S) = 2 blocks + 2 * 3 blocks = 8

Improvement to Block Nested Loop Join

- Make use of available memory
  - Read into memory as many blocks of R as possible, stream S by one-block at a time & join every S tuple w/ all R tuples in memory
  - I/O's: $B(R) + \left\lceil \frac{B(R)}{M-2} \right\rceil \cdot B(S)$
    - Or, roughly: $B(R) \cdot B(S)/M$
  - Memory requirement: M (as much as possible)
- Which table would you pick as the outer? (exercise)

Simulation After Improvement

- 1 block = 2 tuples, 4 blocks of memory



- Number of I/O:

  B(R) + B(R)/(M-2)* S(R) = 2 blocks + 1 * 3blocks = 5

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Two Core DBMS Operations

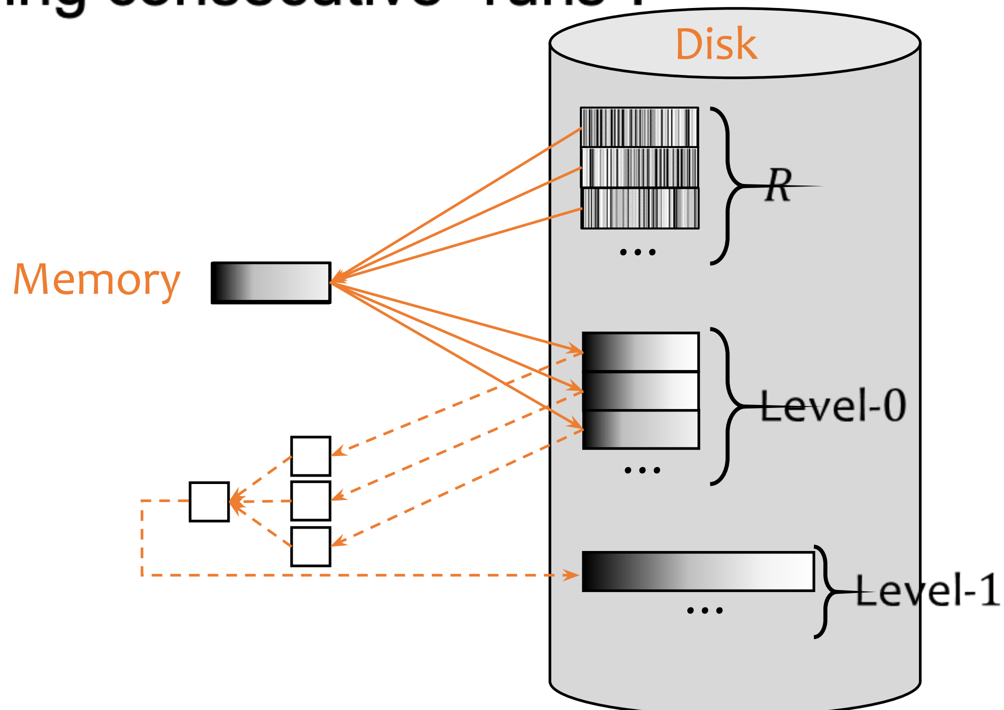
- At a high-level majority of DBMS operators require: (1) sorting; or (2) hashing of input tables.
- If you have a DBMS that has these core operators implemented in a very performant, robust, and scalable manner, you have a solid query processing foundation.
  - Key point: Keep optimizing these core algorithms!

Sorting Under Limited Memory

- A robust DBMS has solutions to the following problem:
- Consider an operator *o* that needs to sort a table R, maybe a base table or an intermediate table (e.g., implementing ORDER BY clause)
- Assume *o* is given M blocks of memory by system's memory manager but M << B(R). (Not an infrequent scenario)
- How can we sort if data does not fit into system's memory?

(External) Merge Sort Operator

- Recall in-memory merge sort: Sort progressively larger runs, 2, 4, 8, …, |R|, by merging consecutive "runs".
- Phase 0: read M blocks of R at a time, sort them, and write out a level-0 run
- Phase 1: merge $(M-1)$ level-0 runs at a time, and write out a level-1 run



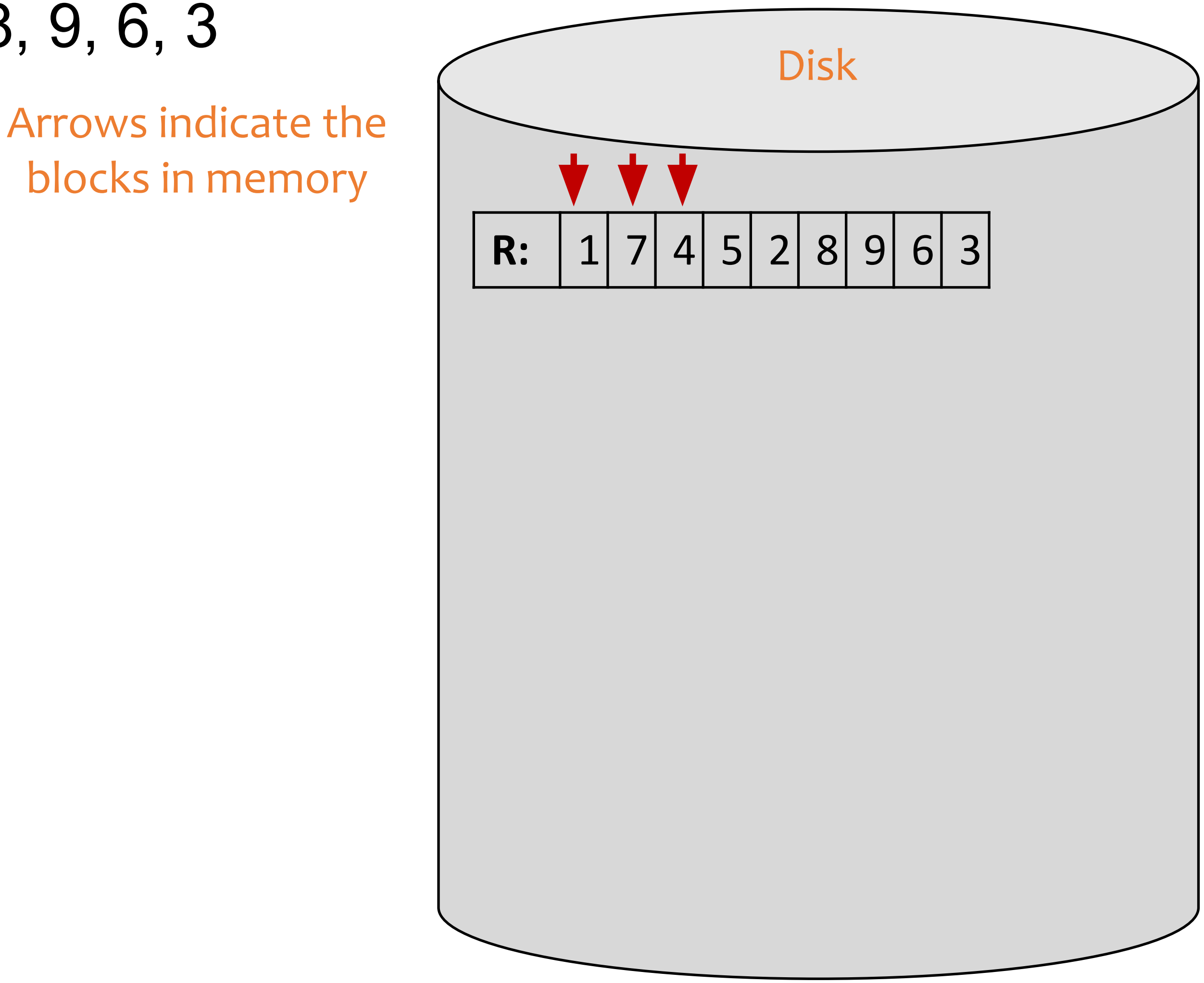
- Phase 2: merge $(M-1)$ level-1 runs at a time, and write out a level-2 run

…

- Final phase produces one sorted run

Example

- 3 memory blocks available; each holds one number
- Input: 1, 7, 4, 5, 2, 8, 9, 6, 3
- Phase 0



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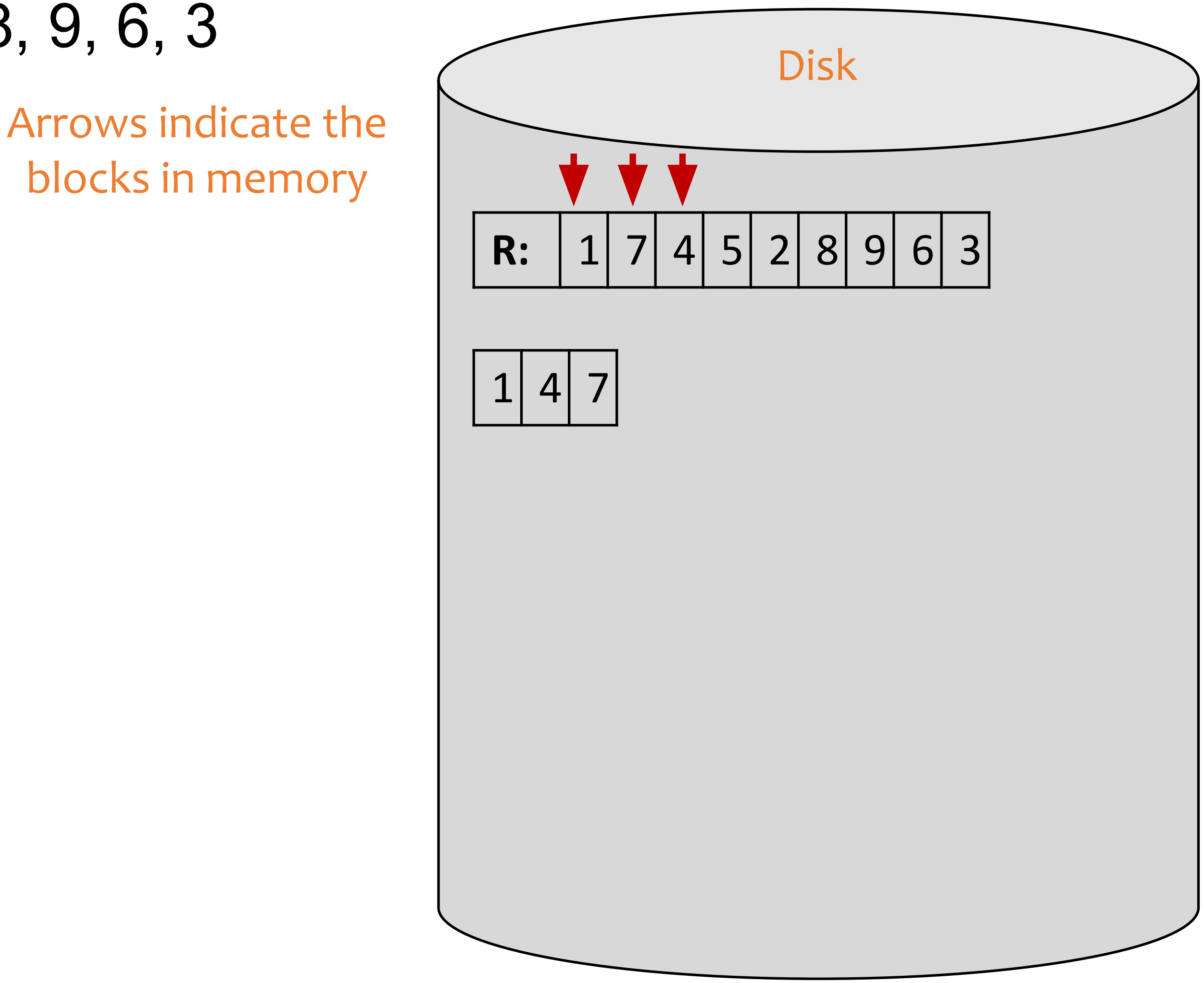

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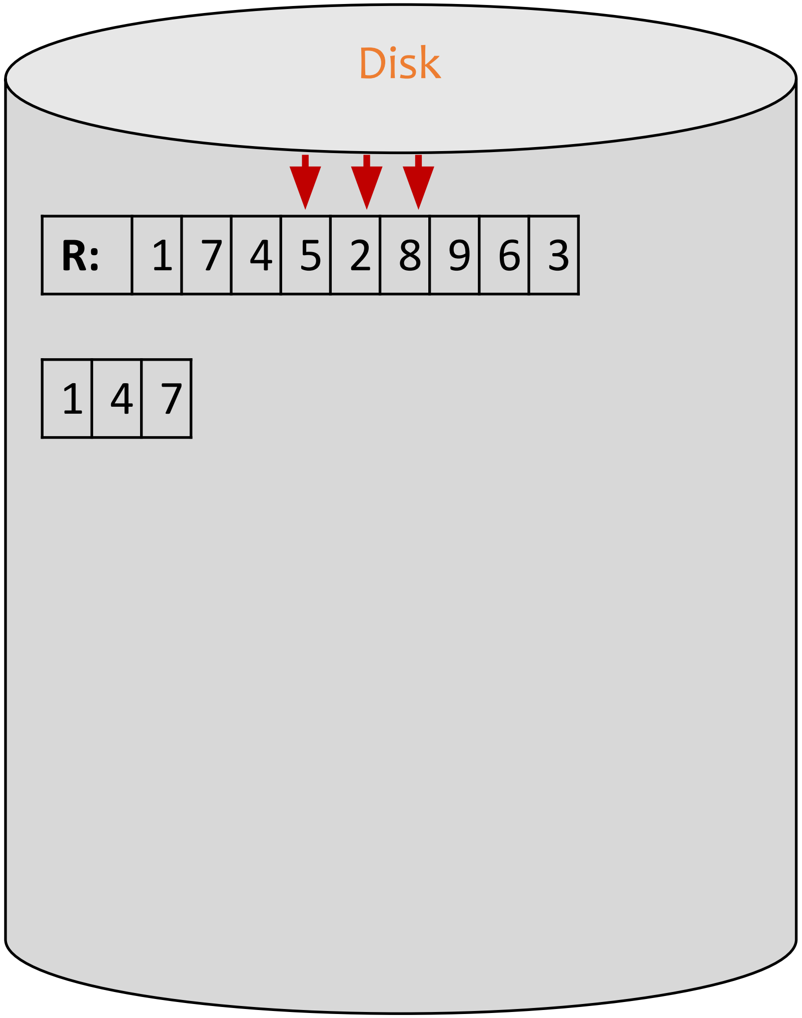

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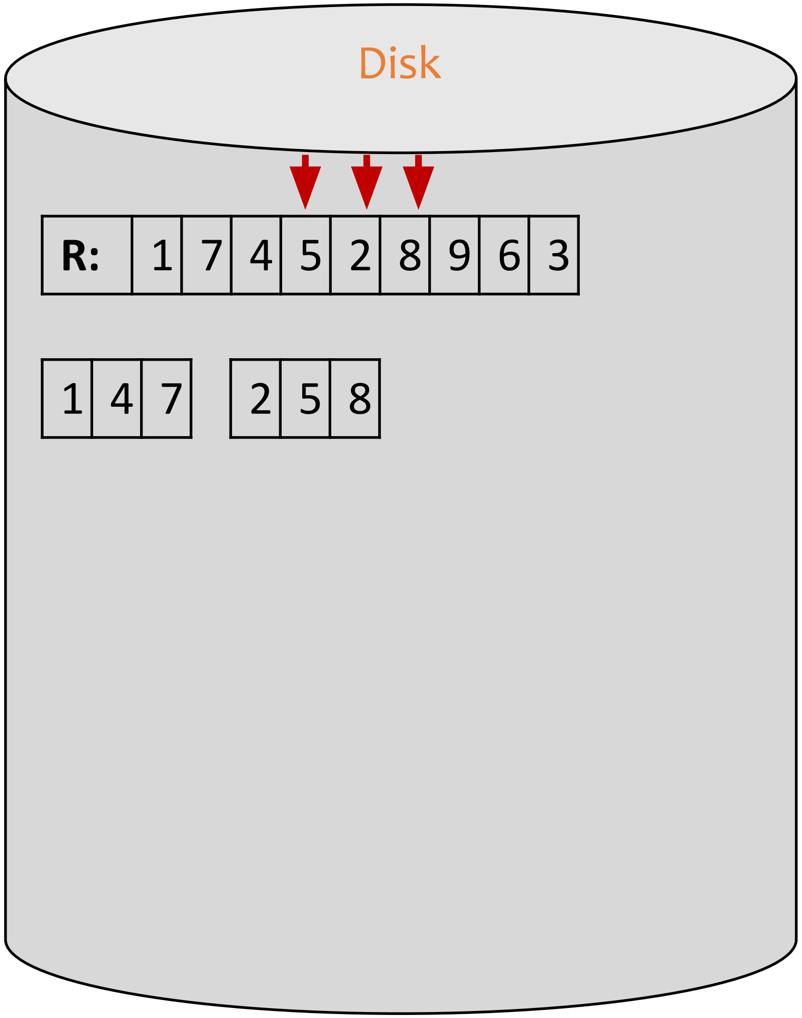

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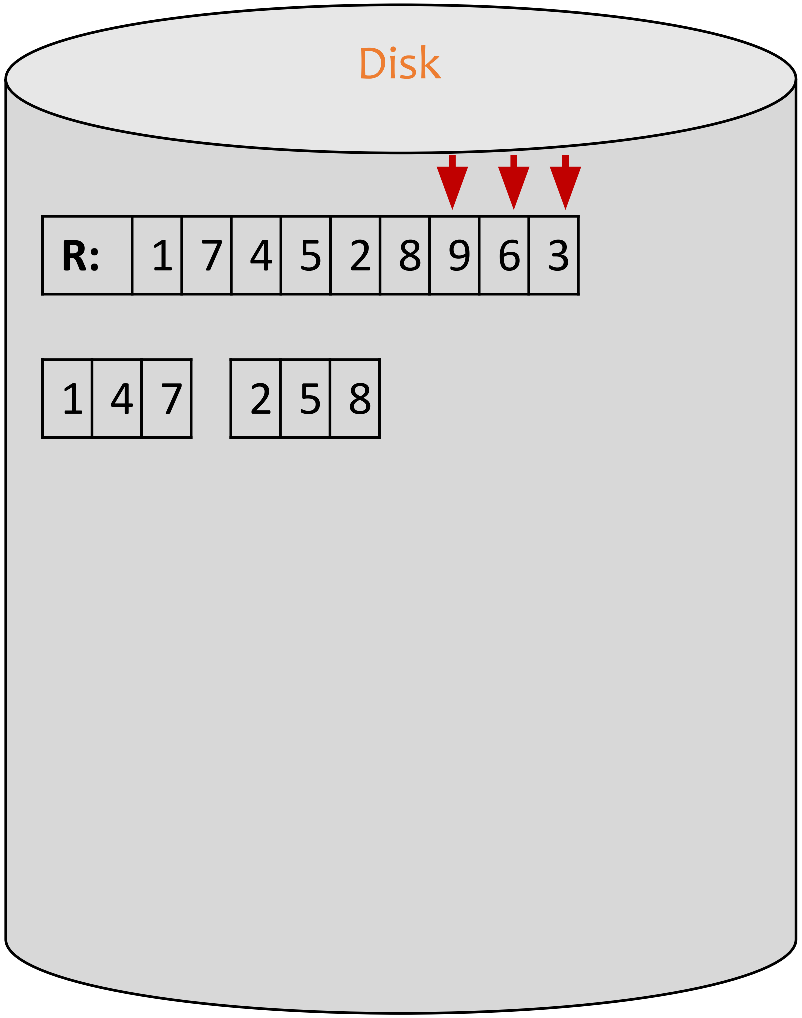

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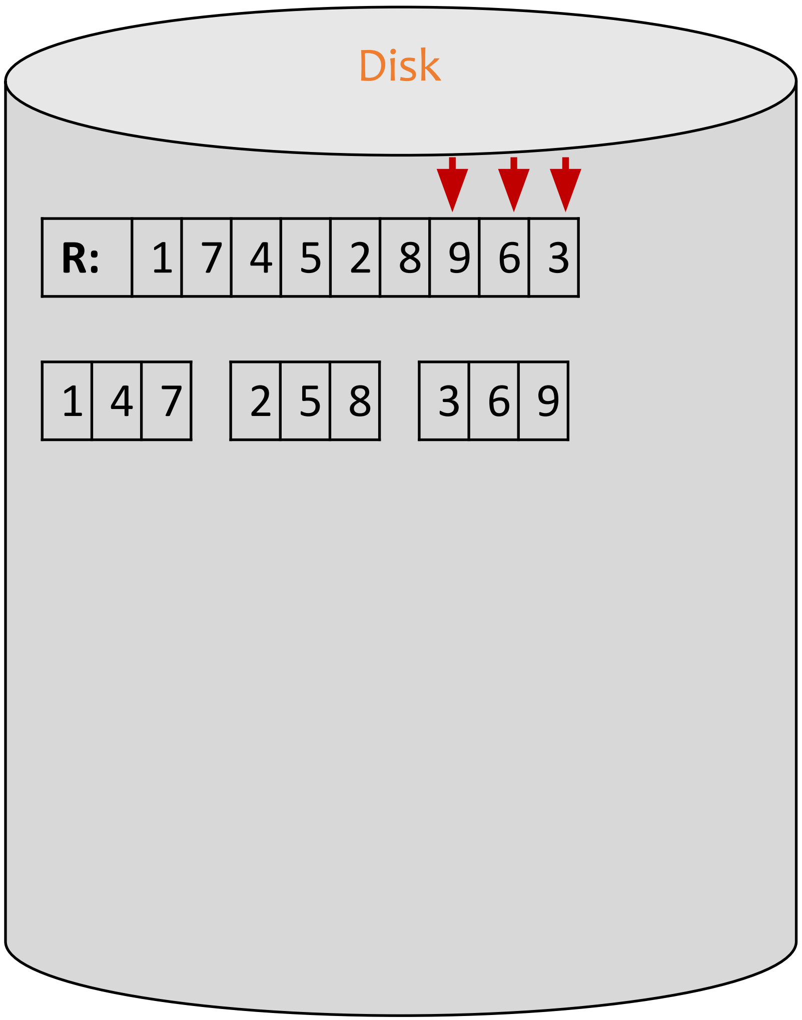

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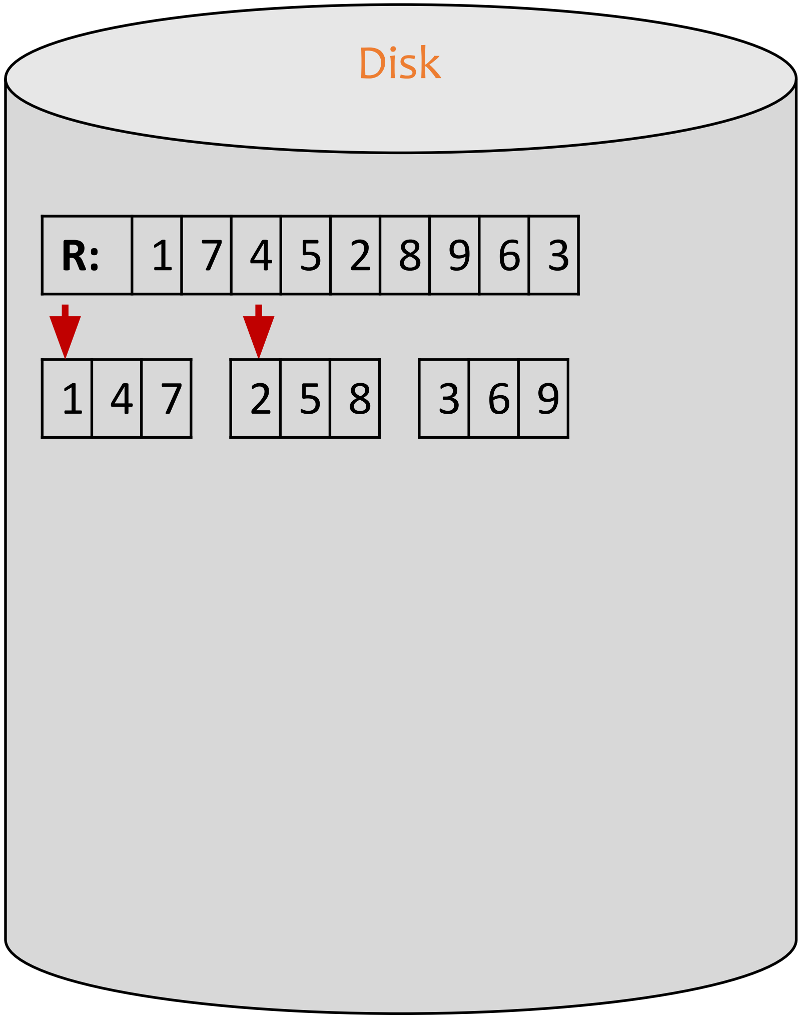

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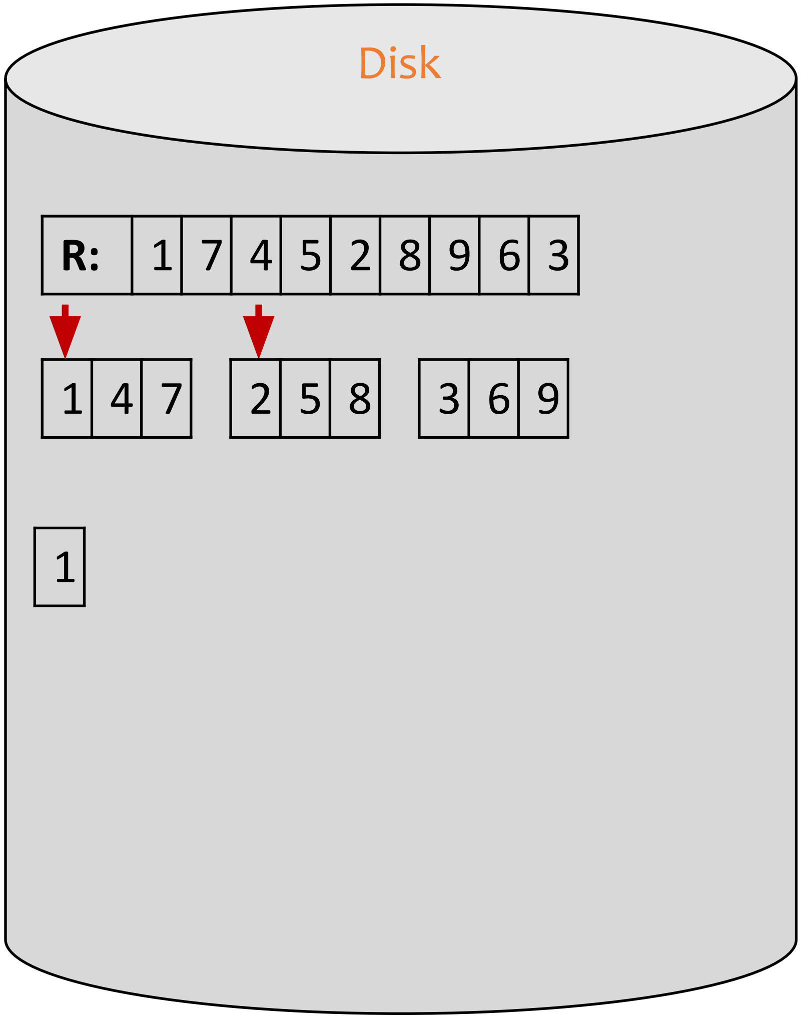

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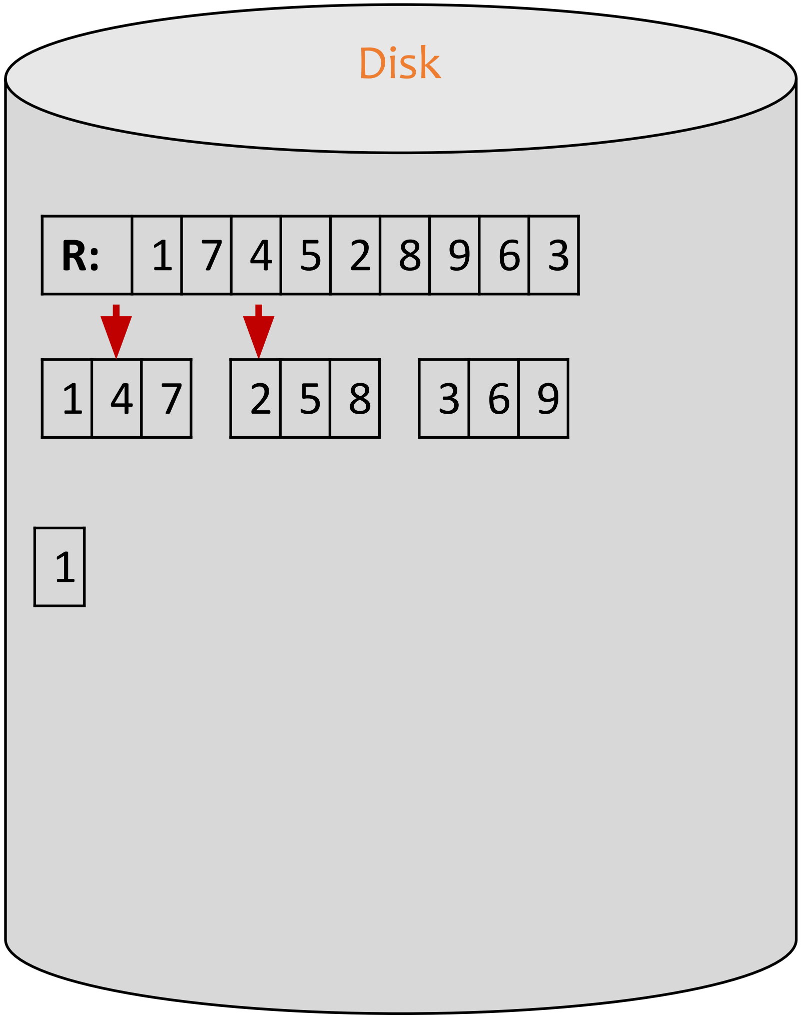

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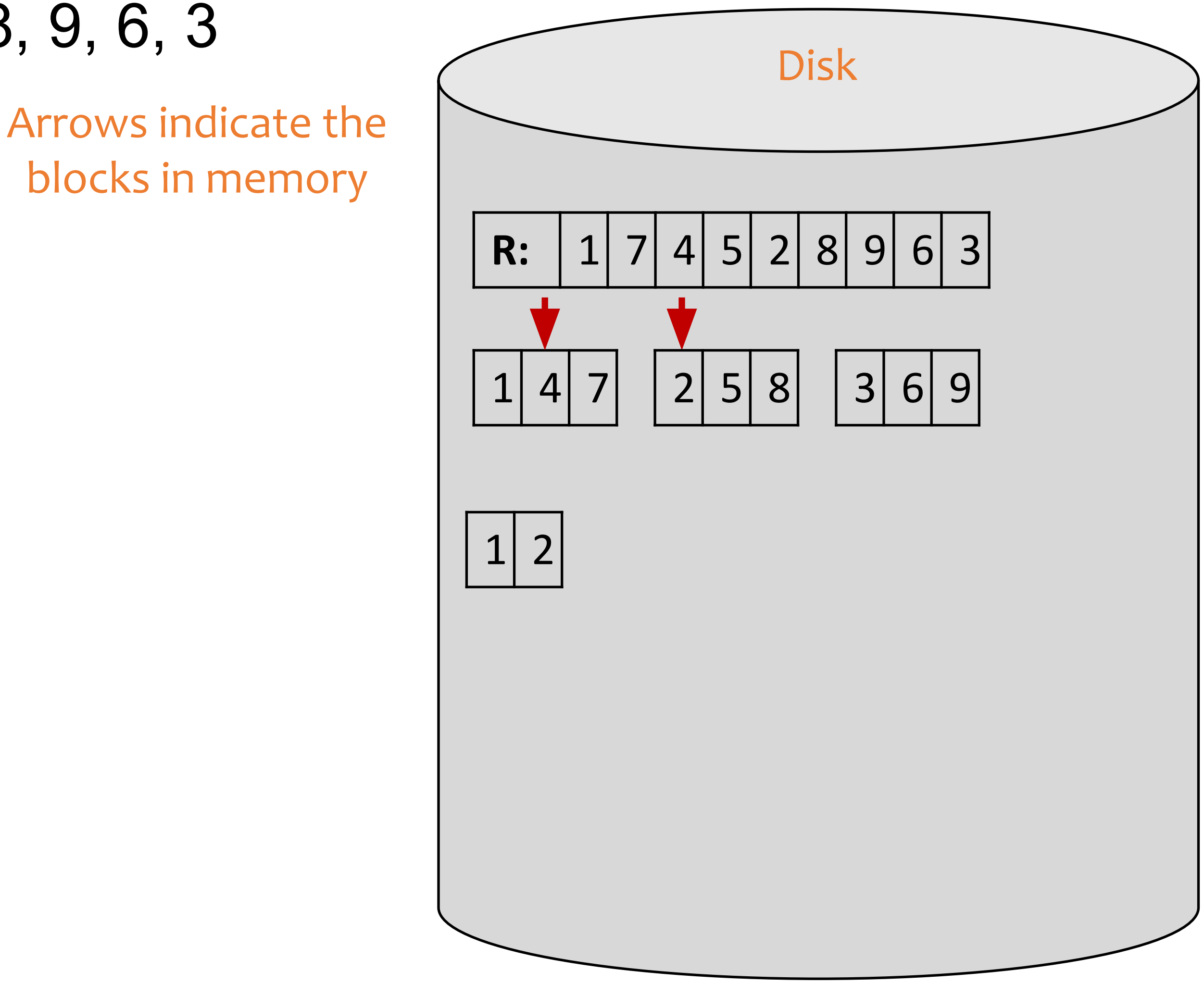

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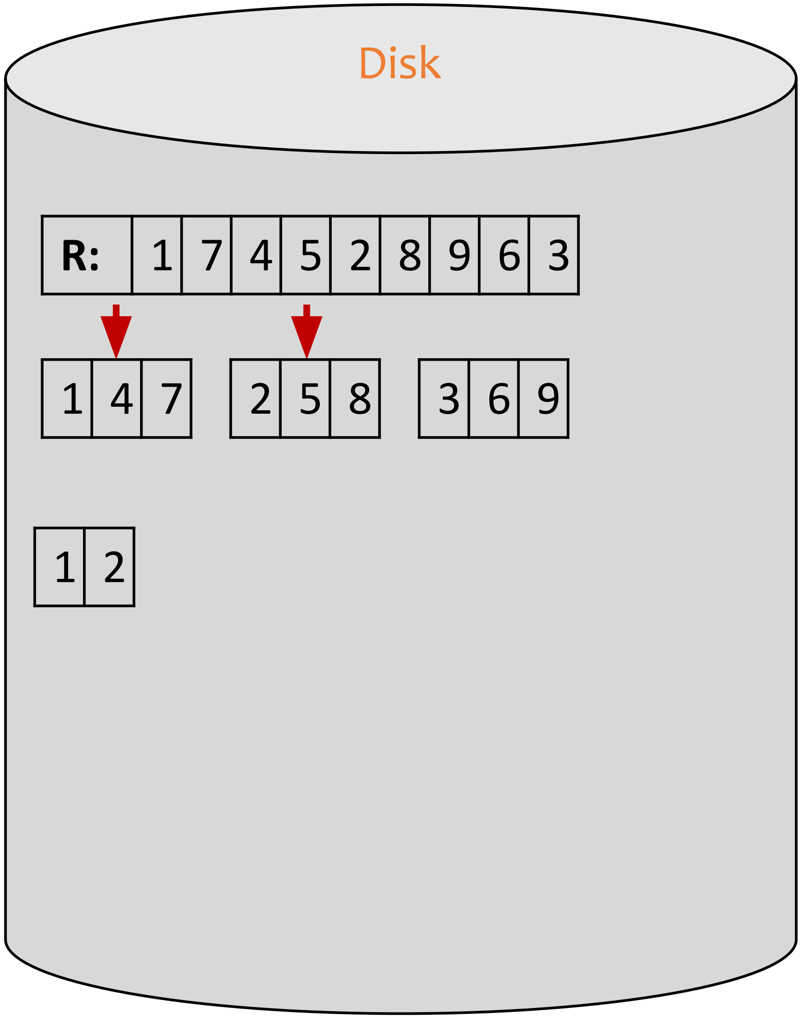

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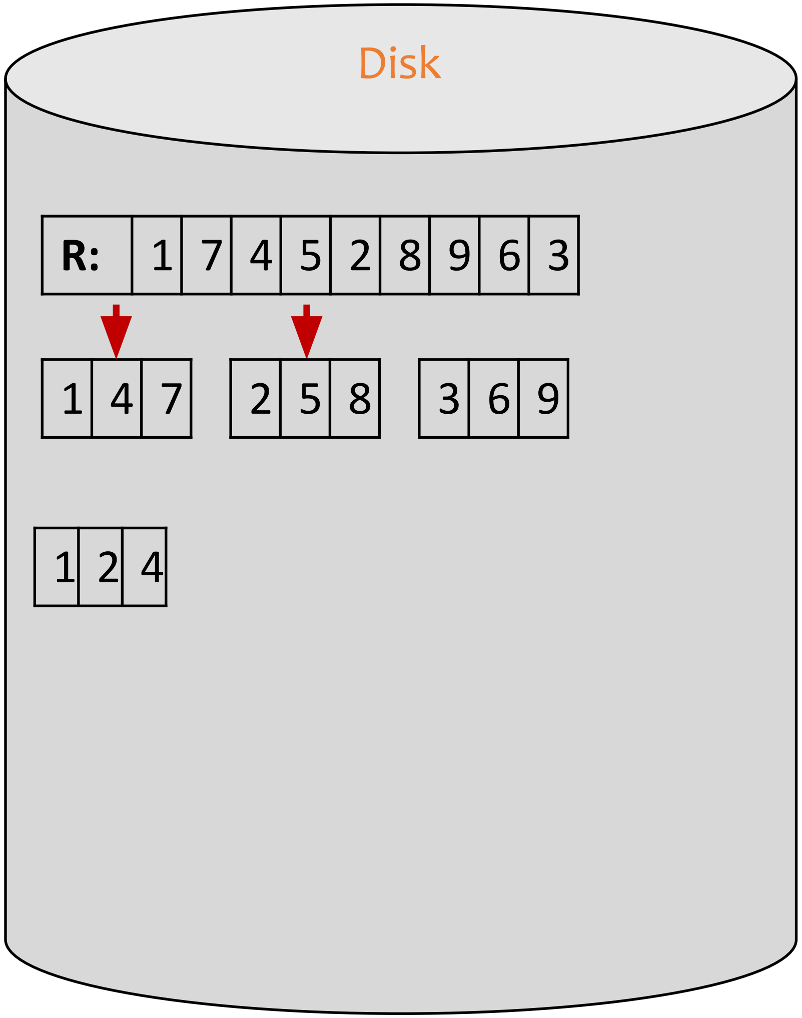

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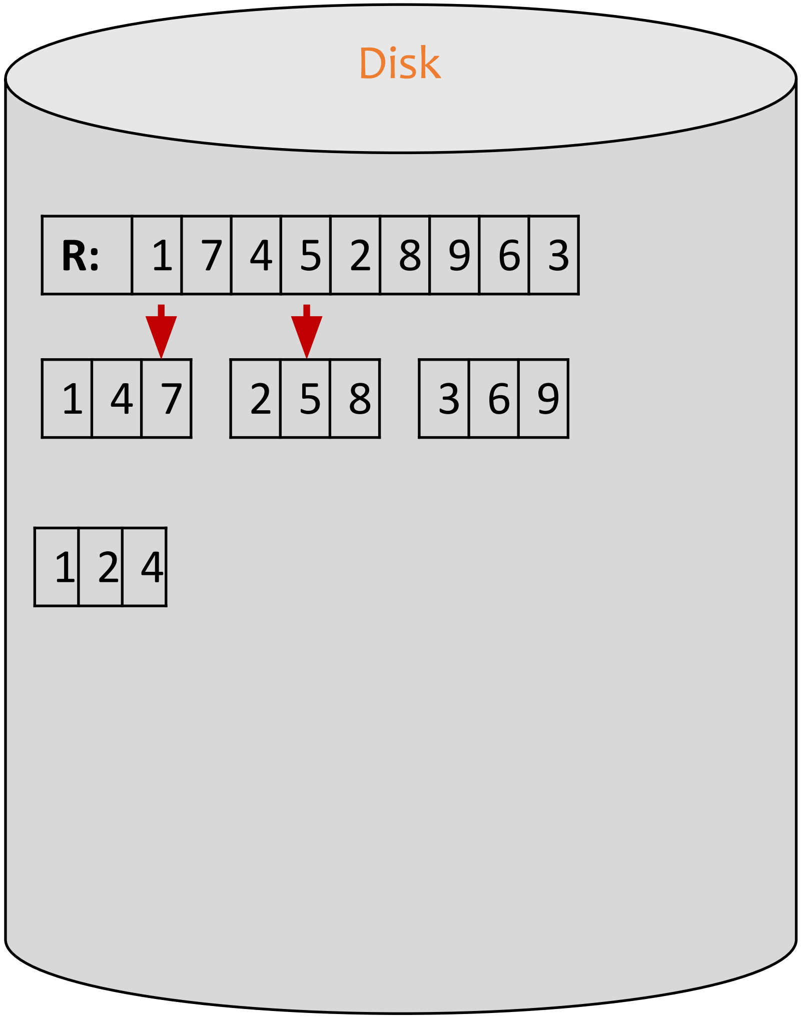

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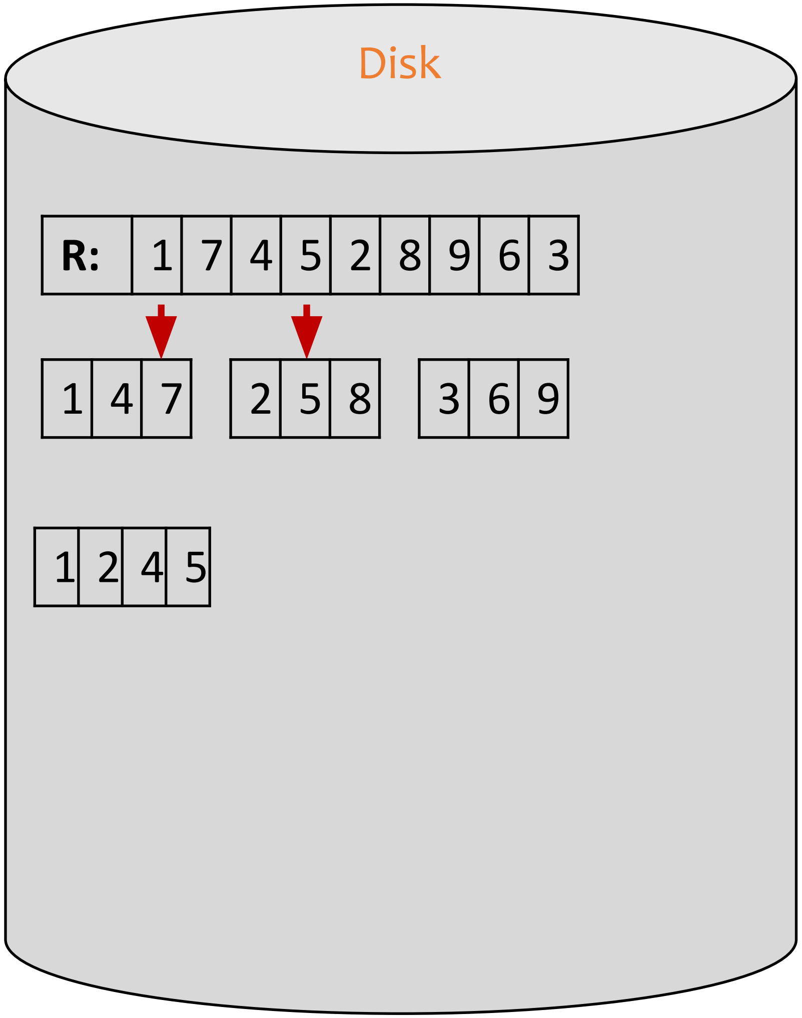

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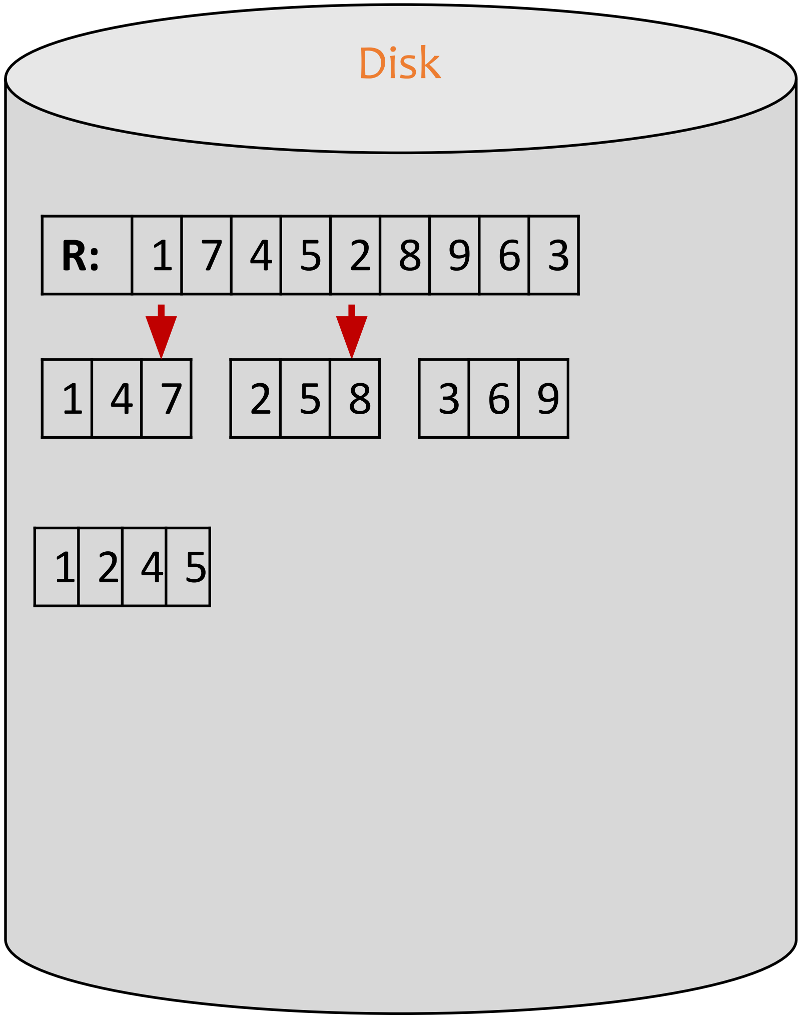

Example

- 3 memory blocks available; each holds one number
- Input: 1, 7, 4, 5, 2, 8, 9, 6, 3
- Phase 0
- Phase 1

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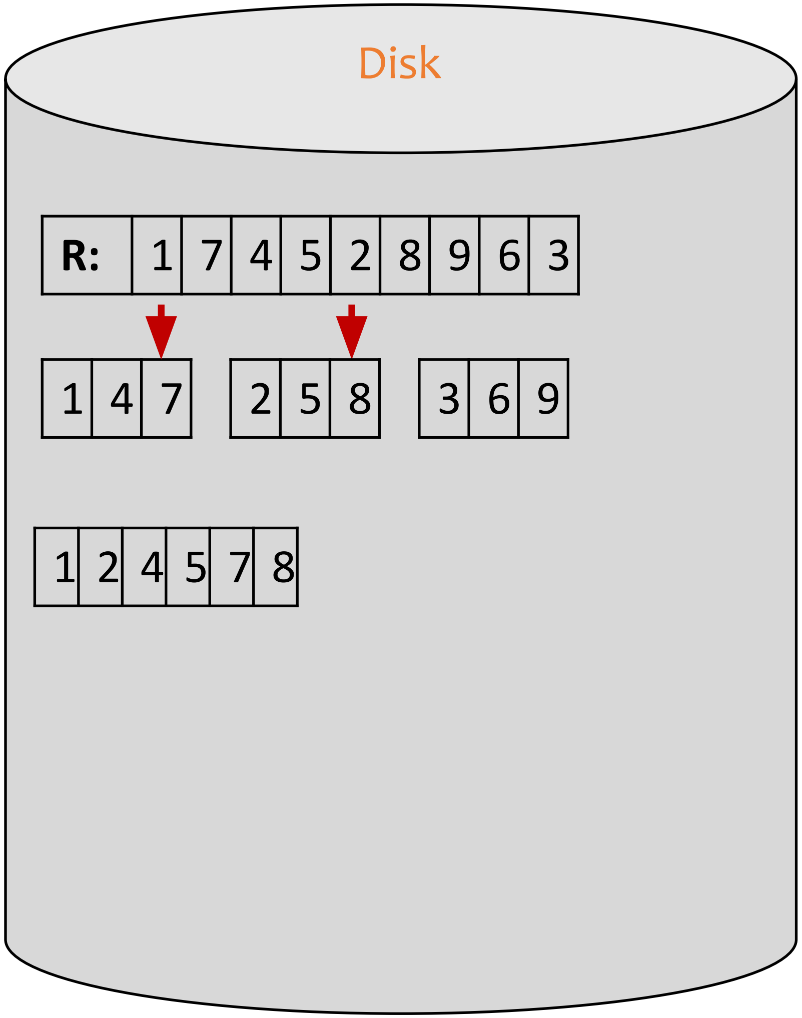

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- 3 memory blocks available; each holds one number
- Input: 1, 7, 4, 5, 2, 8, 9, 6, 3
- Phase 0
- Phase 1
- Phase 2 (final)

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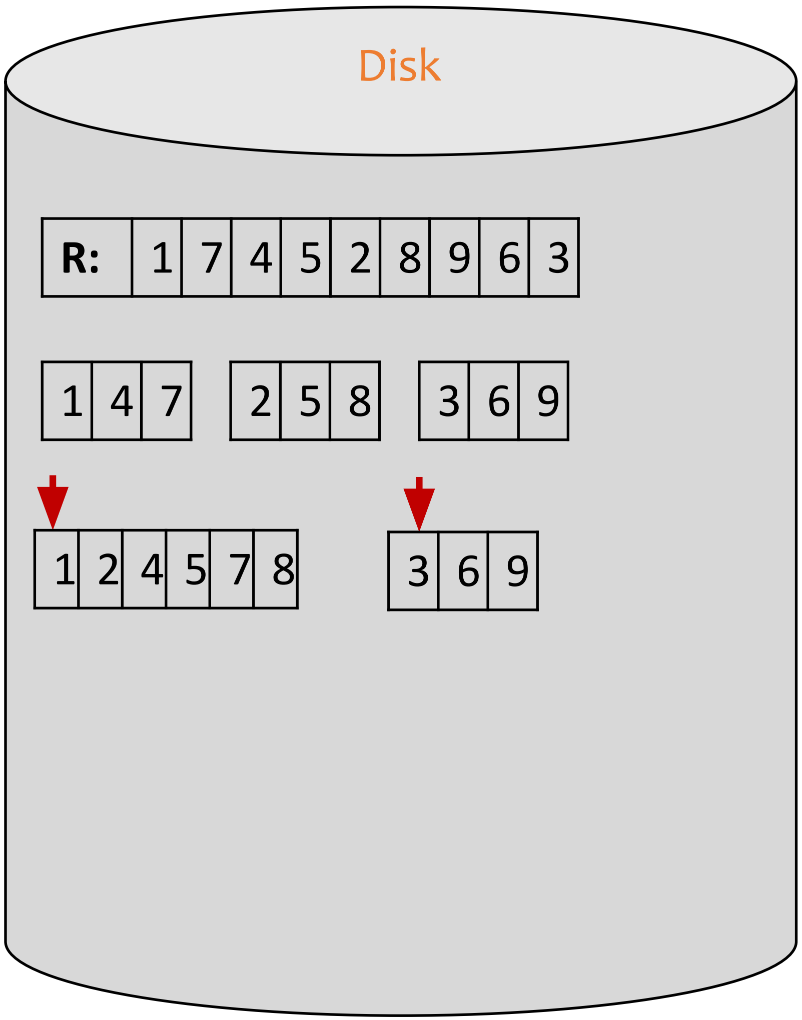

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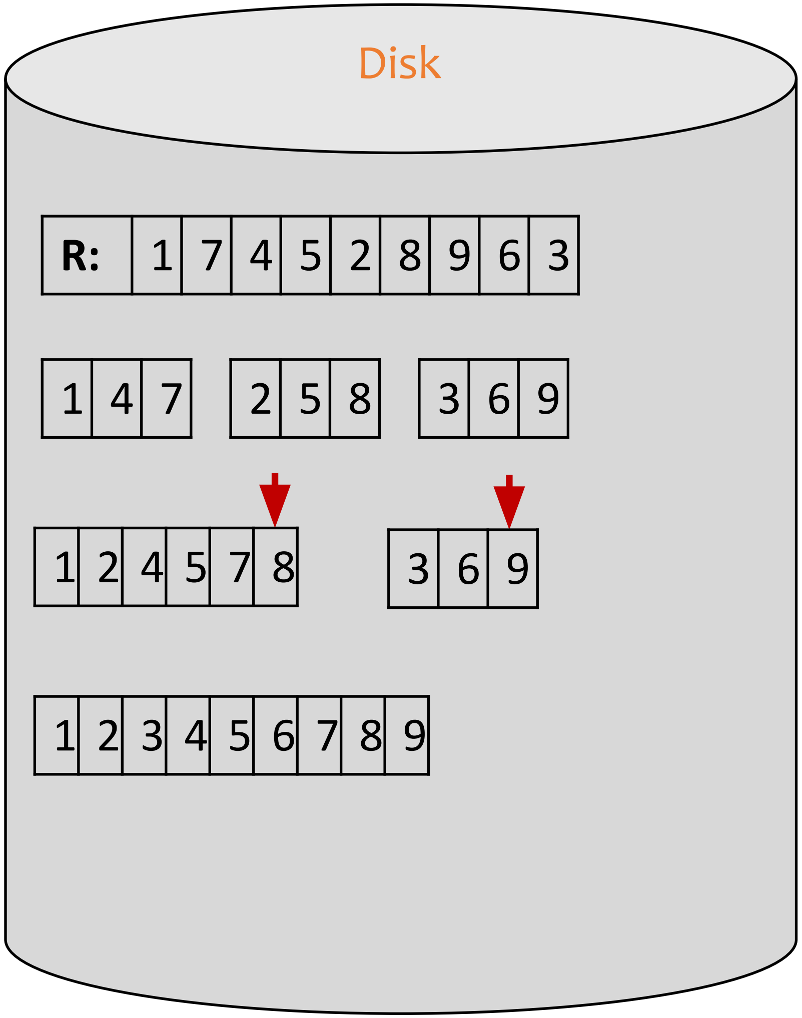

I/O Cost Analysis

- Phase 0: read M blocks of R at a time, sort them, and write out a level-0 run: 2*B(R) I/Os
  - There are $\left\lceil \frac{B(R)}{M} \right\rceil$ level-0 sorted runs

- Phase i: merge $(M-1)$ level-$(i-1)$ runs at a time, and write out a level-i run: 2* B(R) I/Os as well
- Total I/O: 2B(R) * Num phases
- # phases: 1 + $\left\lceil log_{M-1} \left\lceil \frac{B(R)}{M} \right\rceil \right\rceil$
- Total I/O: $2\mathrm{B(R)} \cdot \left(1 + \left\lceil \log_{M-1} \left\lceil \frac{B(R)}{M} \right\rceil \right\rceil \right) \approx 2B(R)\log_M(B(R))$
- Observe: As M increases cost decreases. E.g: when M is B(r) cost is 2B(R) as expected

Operators That Use Sorting

- Pure Sort: e.g., ORDER BY
- Set Union, Difference, Intersection, or Join or R and S (next slide): When the join condition is an equality condition e.g., R.A = S.B,
  - All can be implemented by walking relations “in tandem” as in the merge step of merge sort.
- Group-By-and-Aggregate: Exercise: Think about how you can implement group-by-and-aggregate with sorting?
- DISTINCT (Related to group-by-and-aggregate)

Sort-merge Join

- $$R \bowtie_{R.A=S.B} S$$

- Sort R and S by their join attributes; then merge

```
r, s = the first tuples in sorted R and S
Repeat until one of R and S is exhausted:
       If r.A > s.B then s = next tuple in S
       else if r.A < s.B then r = next tuple in R
       else output all matching tuples, and
           r, s = next in R and S
```

- I/O's: Depends on how many tuples match.
  - Common case each r matches 1 s: sorting$+O(B(R)+B(S))$
  - If every r,s join (worst-case) $B(R) \cdot B(S)$:

Example

- R:
  $r_1.A = 1$
  $r_2.A = 3$
  $r_3.A = 3$
  $r_4.A = 5$
  $r_5.A = 7$
  $r_6.A = 7$
  $r_7.A = 8$

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  $s_1.B = 1$
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  $r_1 s_1$

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Outline For Today

1. DBMS Query Processing Architecture
2. Fundamental Query Processing Operators & Algorithms
   - Assumptions
   - Scan-based Operators
   - Sort-based Operators
   - Hashing-based Operators
   - Algorithms Using Indices

Hash Join

- Consider an equality join, e.g., join of R(X, A) ⋈ S(B, Y) where A=B.
- Let h be hash function hashing A or B values to 1, …, k
- If r ∈ R and s ∈ S "join", i.e., r[A] = s[B] then:

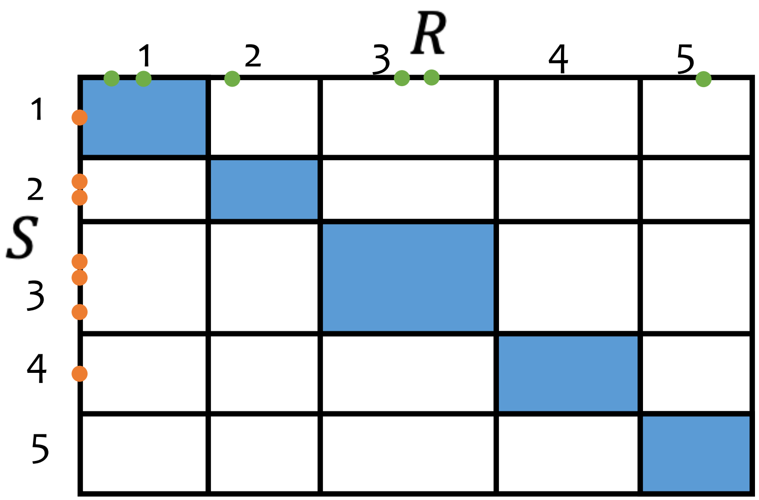
  h(r[A]) = h(s[B])

- Question: Why is this a useful observation?
- Answer: We can:
  1. partition R by hashing its tuples on A into R_1, …, R_k
  2. partition S by hashing its tuples on B into S_1, …, S_k
  3. where each partitions are (i) *much smaller tables* (e.g., they may fit in memory) & (ii) *tuples in R_i can only join with tuples in S_i*

If the join will be computed externally, i.e., using disk, hash join can be an efficient algorithm

Hash Join vs Nested Loop Join Pictorially

- $R \bowtie_{R.A=S.B} S$
- If $r.A$ and $s.B$ get hashed to different partitions, they don't join



Nested-loop join considers all slots

Hash join considers only those along the diagonal!

(External) Hash Join Algorithm

- let h be a hash function mapping A or B columns into 1, …, k
- Pick k < M (why?)

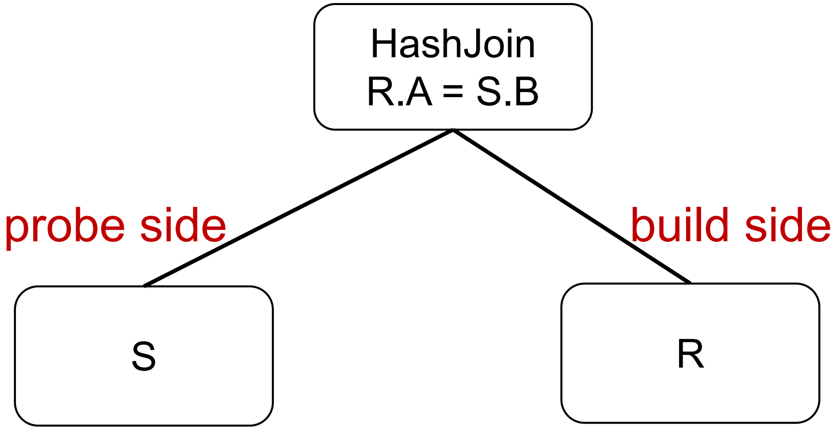
```
Phase 1: partition R and S into k partitions using h

Phase 2:

for i = 1, …, k:

   read R_i and S_i into memory and use in-memory hash-join alg.

   (i.e., build a hash table of R_i and probe S_i tuples)
```



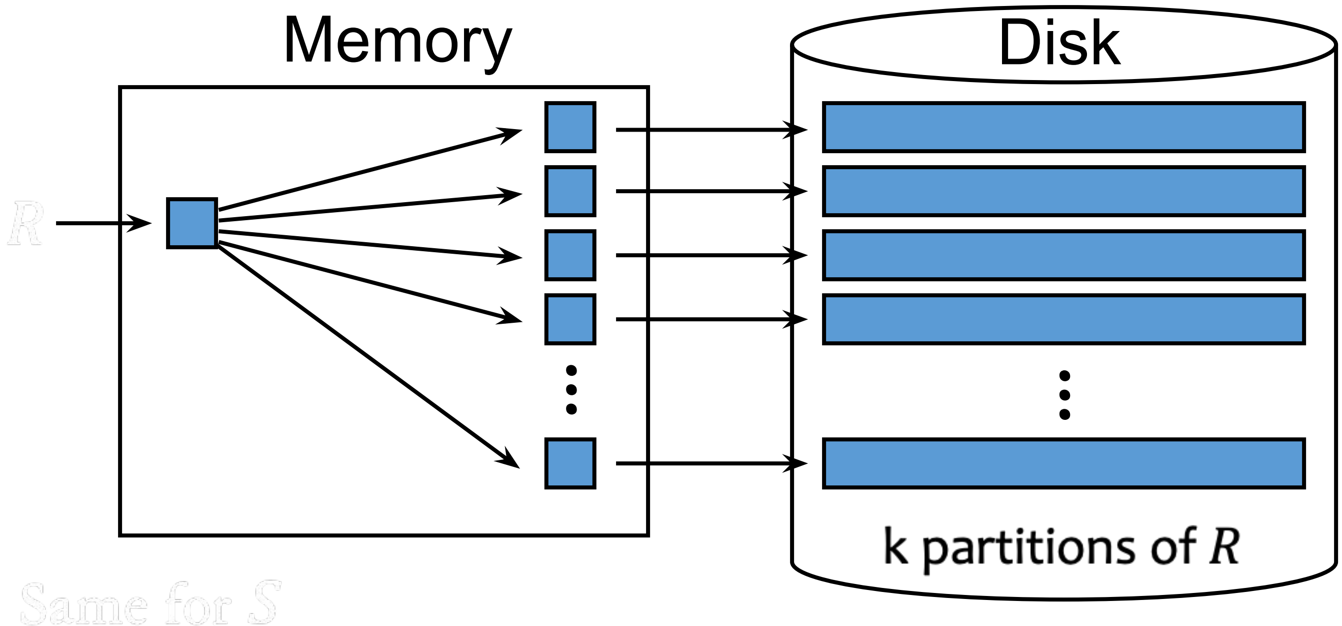
Q: Systems make the smaller (estimated) relation the build side? Why?

1. Quicker to build & search in hash table

Note: do not have to use any memory for probe side, e.g., can just stream S.

Phase 1: Partitioning

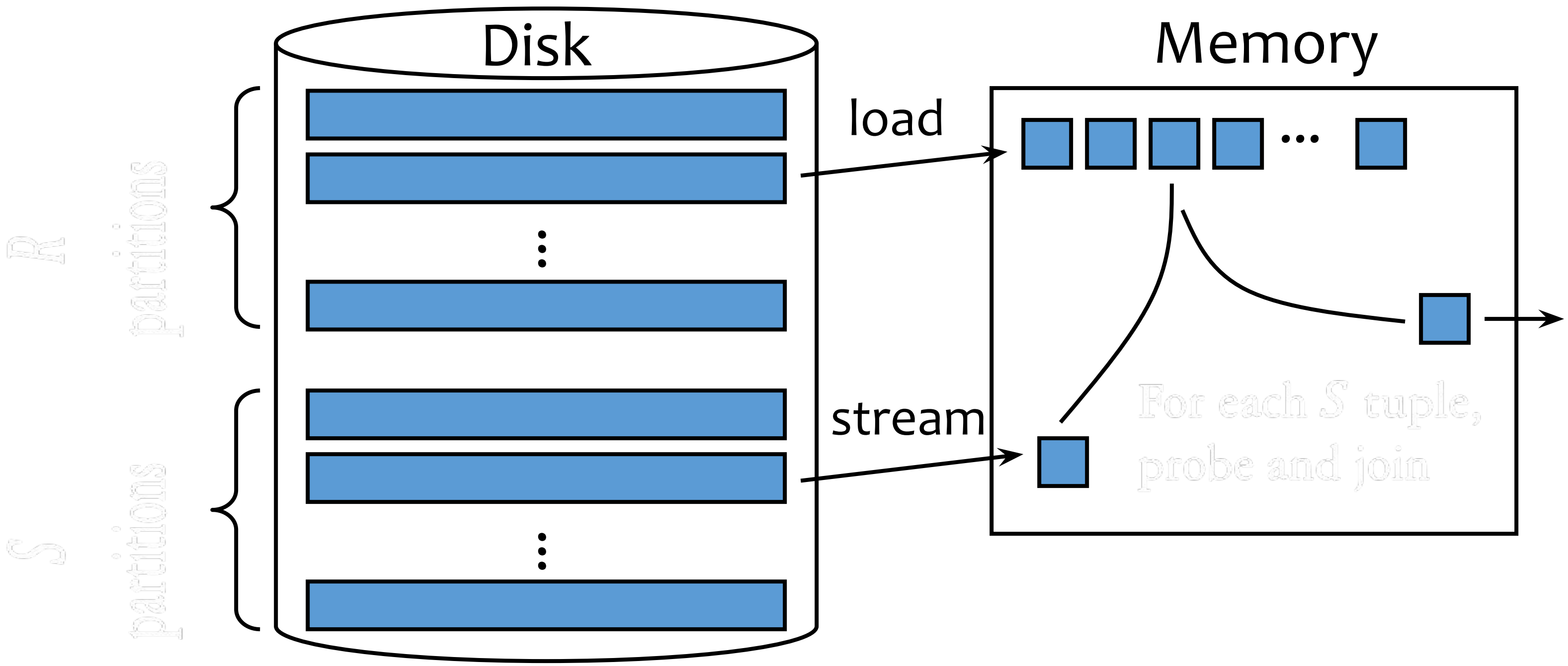
- Partition R and S according to the same hash function on their join attributes



Each partition takes ~ B(R)/k blocks

Phase 2: Probing

- Read in R_i, stream in the corresponding partition S_i and join
  - Typically use in-memory hash join: build a hash table of R_i
    - often use a different hash function for in-memory hash join

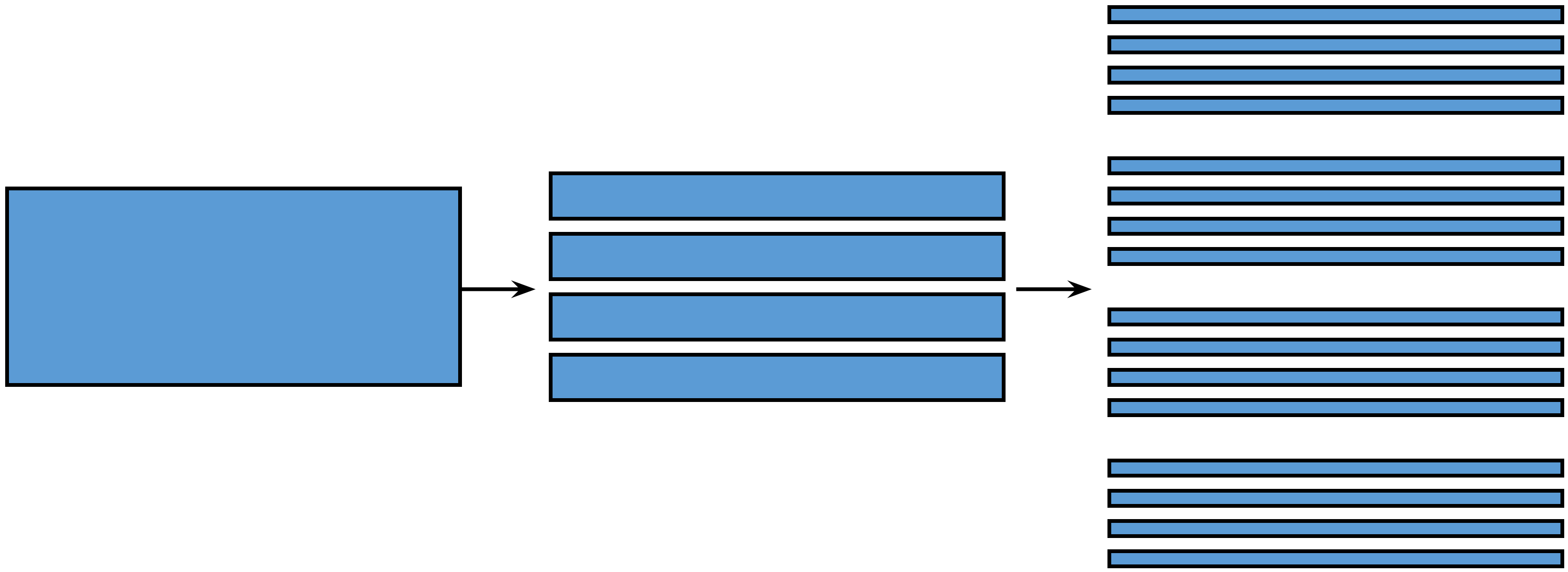


I/O Cost of Hash Join

- Assuming no edges cases (e.g., a very large hash partition) and hash join completes in two phases:
  - I/O's: $3 \cdot \left(B(R) + B(S)\right)$
    - Phase 1: read B(R) + B(S) into memory to partition and write partitioned B(R) +B(S) to disk
    - Phase 2: read B(R) + B(S) into memory to perform the join

What if R_i Does Not Fit In Memory

- Read it back in and partition it again!
- Note however, in the worst-case all A or B values could be the same and one simply cannot generate useful partitions.
- Systems either fail in such cases or fall back to alternative slower solutions



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Selection Using Index

- Equality predicate: $\sigma_{A=v}(R)$

  Use an ISAM, B$^+$-tree, or hash index on $R(A)$

- Range predicate: $\sigma_{A>v}(R)$

  Use an ordered index (e.g., ISAM or B$^+$-tree) on $R(A)$

  Hash index is not applicable

- Indexes other than those on $R(A)$ may be useful
  - Example: B$^+$-tree index on $R(A, B)$
  - How about B$^+$-tree index on $R(B, A)$?
    - Not useful because A values will be scattered.

Index vs Table Scan (1)

- Situations where index clearly is the better choice:
- Index-only equality queries on a unique column (e.g., primary key)
  - E.g. $\sigma_{A=v}(R)$ where A is a unique column and has an index.
    - Index guarantees 1 I/O. Table scan can lead up to B(R) I/Os.
- Index-only range queries on clustered indices:
  - $\sigma_{A>v}(R)$: guarantee that only the blocks that contain answers are read (aside from blocks of the index)

Index vs Table Scan (2)

- BUT(!): Consider $\sigma_{A>v}(R)$ and a secondary, non-clustered index on $R(A)$
  - Need to follow pointers to get the actual result tuples
  - Say that 20% of R satisfies $A > v$
    - Could happen even for equality predicates
  - Back-of-the-envelope calculation:

    I/O's for table scan: $B(R)$

    I/O's for index scan up to: lookup + 20% $|R|$ (assume no cache hits)

    Table scan is faster if a block contains more than 5 tuples!

    B(R) = |R|/5 < 20%|R|+lookup

Systems should not do this to be safe. Table scan might be slow but its slowness is bounded by B(R) and not a function of R.

Index Nested-loop Join

$R \bowtie_{R.A=S.B} S$

- Idea: use a value of $R.A$ to probe the index on $S(B)$

```
for each block of R, and for each r in the block:
    use the index on S(B) to retrieve s with s.B = r.A
    output rs
```

- I/O's: $B(R) + |R| \cdot$ (index lookup)
  - Let's assume the cost of an index lookup is 2-4 I/O's (depends on the index tree height if B+ tree)
  - Key takeaway 1: Can be faster than hash/sort-merge join if $|R|$ is small
  - Key takeaway 2: Better pick R to be the smaller relation

- Memory requirement: $O(1)$ (extra memory can be used to cache index, e.g. root of B+ tree).

Zig-zag Join Using Ordered Indexes

$R \bowtie_{R.A=S.B} S$

- Idea: use the ordering provided by the indexes on $R(A)$ and $S(B)$ to eliminate the sorting step of sort-merge join
- Use the larger key to probe the other index

  Possibly skipping many keys that don't match

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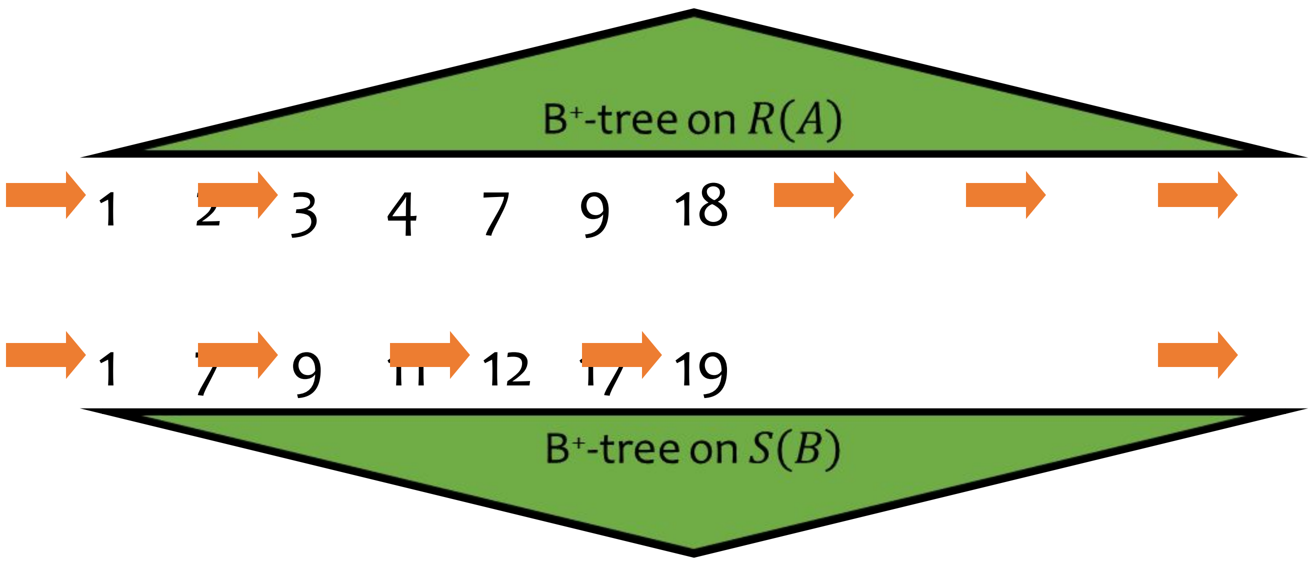
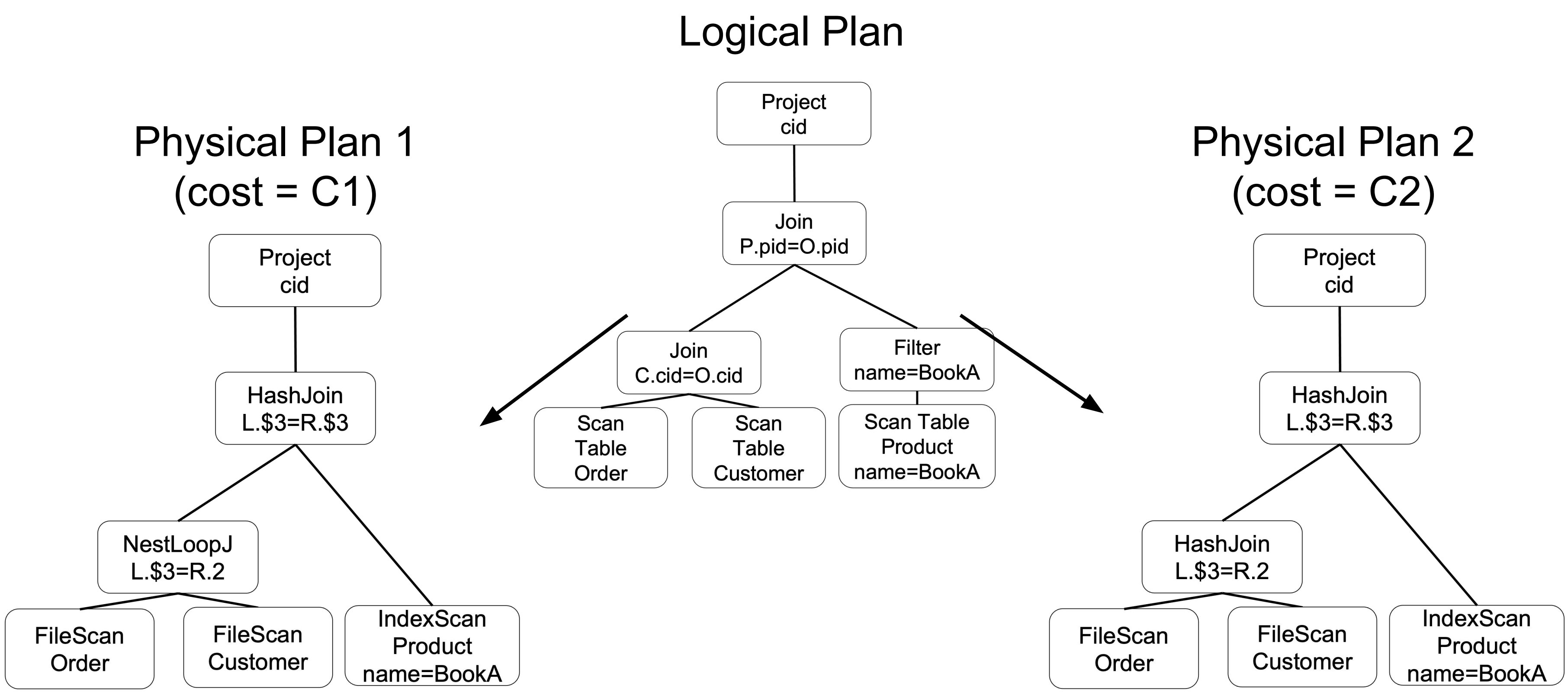


Note on Role of (I/O) Costs Of Operators For Picking Physical Plans

- Some systems use estimated I/O costs of core ops to pick how to translate logical to physical plans, i.e., logical-physical plan translation is a cost-based optimization:



Note on Role of (I/O) Costs Of Operators For Picking Physical Plans

- Some systems use estimated I/O costs of core ops to pick how to translate logical to physical plans, i.e., logical-physical plan translation is a cost-based optimization:
  1. Enumerate different physical plan translations
  2. Estimate the cost of each physical plan
  3. Pick the minimum cost estimated plan
  - Next lecture on cost-based optimization at logical plan picking level
- Others pick physical operators in a rule-based manner, so the I/O costs are there to determine these rules.
  - Always make scans IndexScans if possible
  - All equality joins should be HashJoins except if the tables are already sorted, in which case use SortMerge Join.
  - All other types of joins should be NesteLoopJoins etc.