CS 348 Lectures 17-18

Query Processing Architecture and Algorithms

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Outline

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

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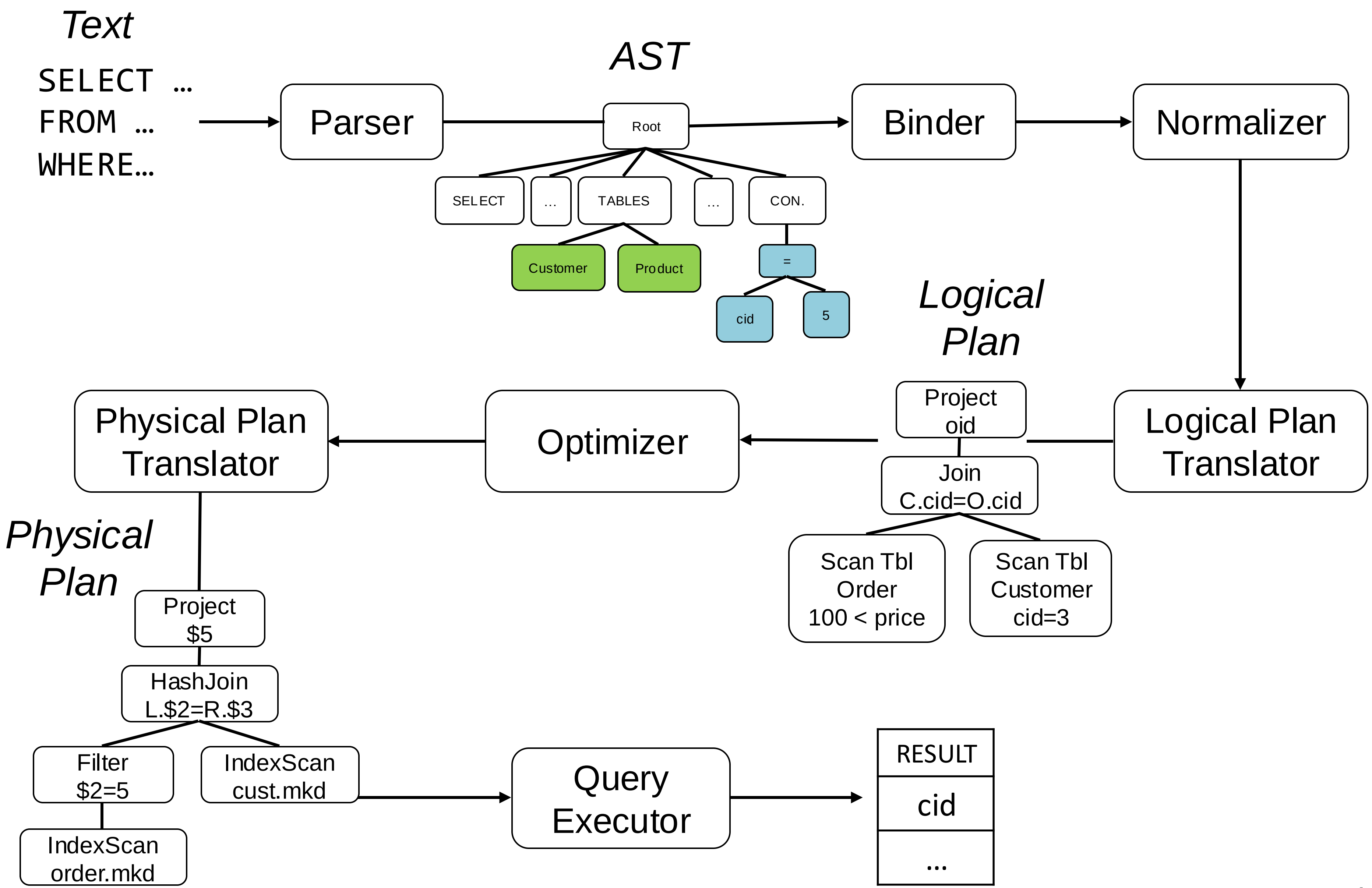
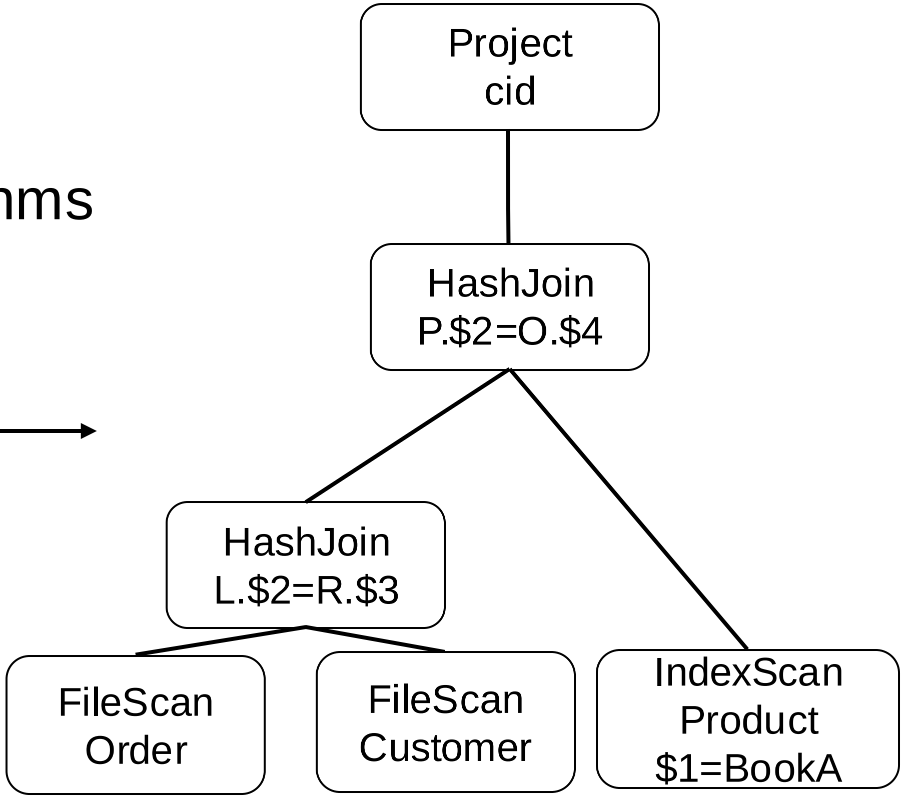
Recall: Overview of Compilation Steps



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
```

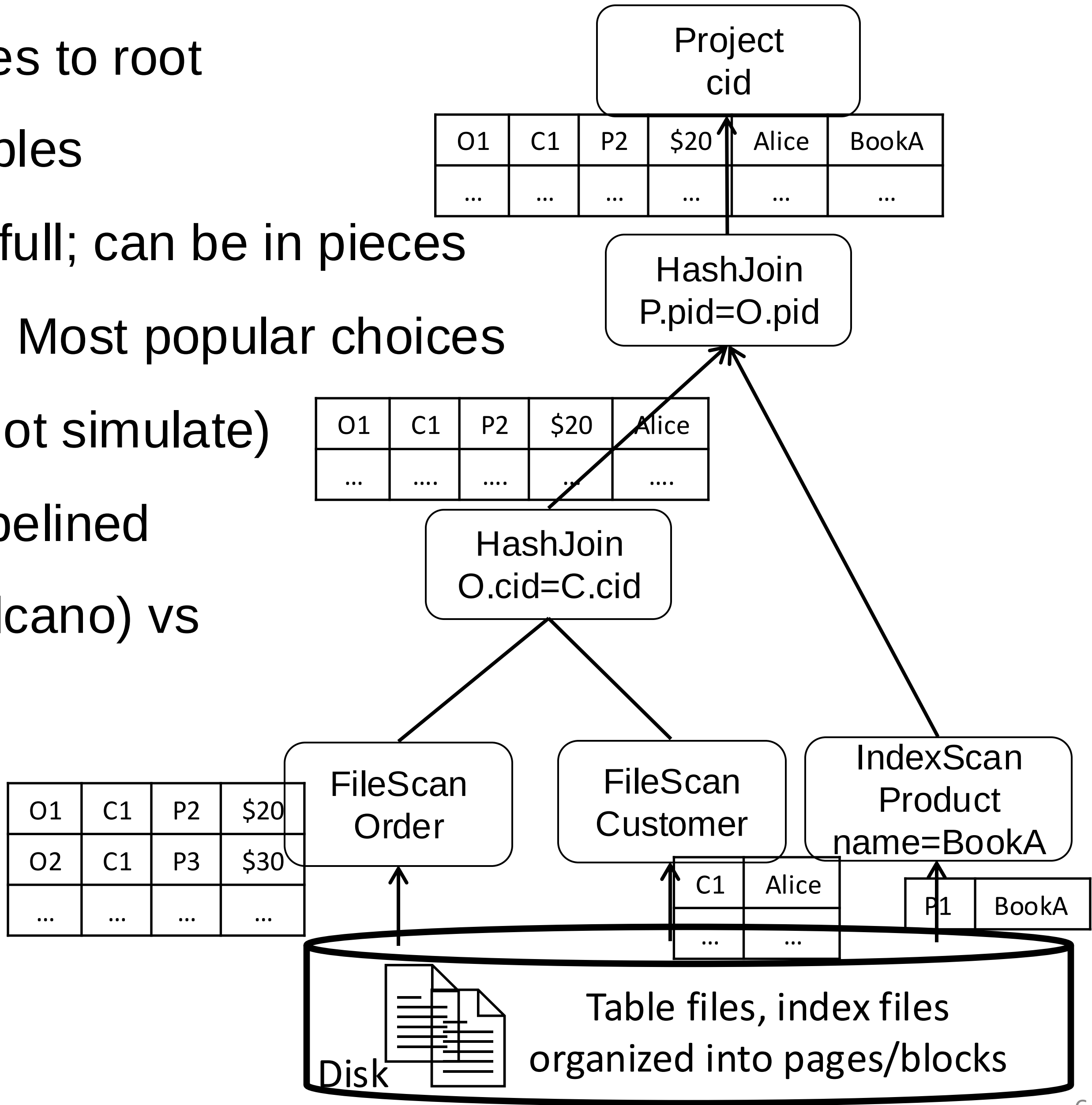


Note: the more operators a system has, the larger set of query plans (i.e., algorithms) it can stich together to evaluate queries

(Simplified) Physical Plan Architecture

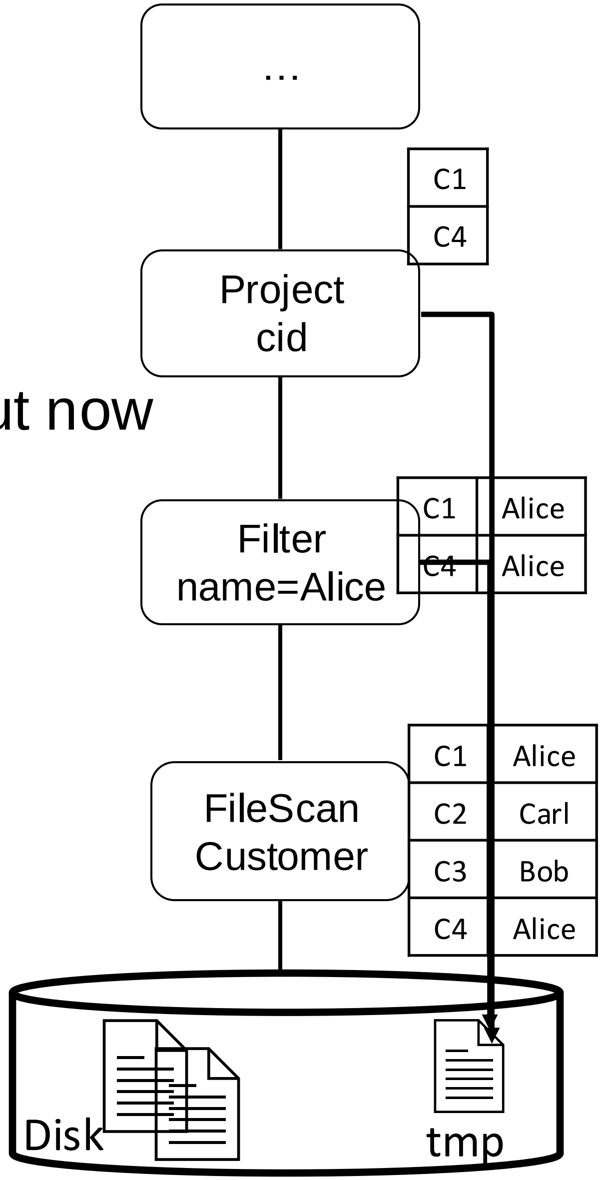
- Tuples flow from leaves to root
- Operators produce tables
  - not necessarily in full; can be in pieces
- Several designs exist. Most popular choices
  - push vs pull (will not simulate)
  - materialized vs pipelined
  - iterator model (Volcano) vs

    block-at-a-time



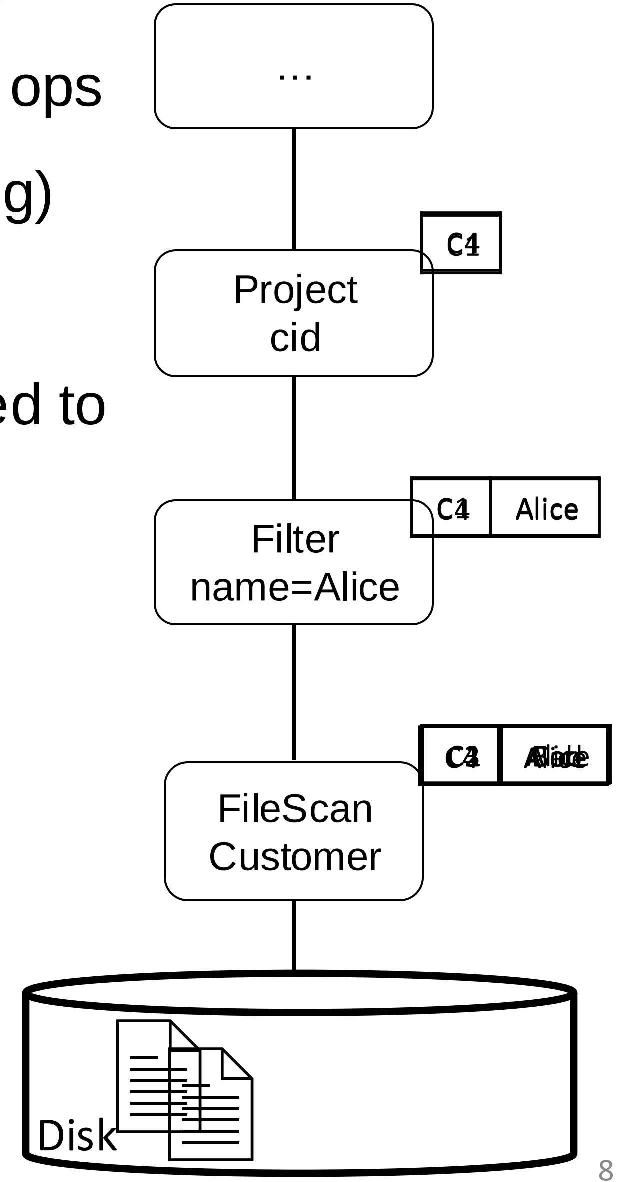
Materialized vs Pipelined (1)

- 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.



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Costs of Query Processing Algorithms

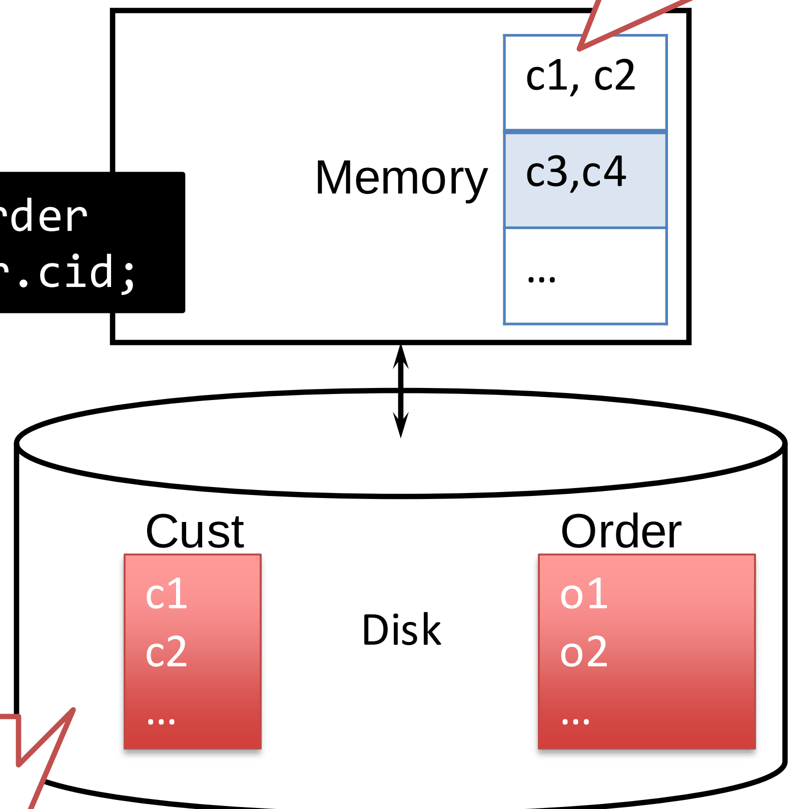
- In algorithm analysis often “runtime”, i.e., # CPU cycles is the metric
- In DBMSs, most algs (but not all) are linear time or almost-linear time (i.e., with O(log(|R|)) factors) in terms of runtime.
- Will use *I/O cost* to analyze the main algorithms because DBMSs are disk-based systems.
- Disclaimer 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

\# memory blocks (frames) available: M

```
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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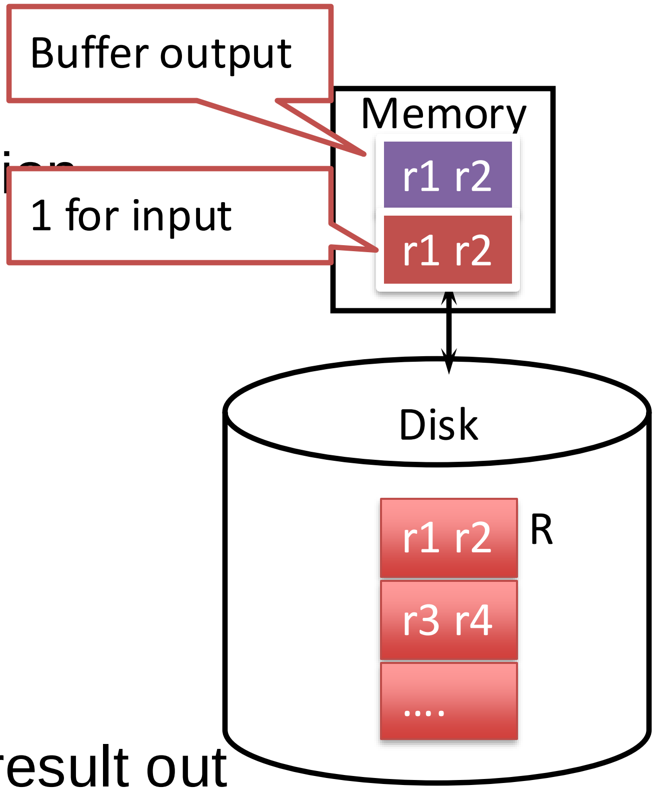
Table Scan Operators

- Scan table *R* and optionally perform a:
  - Selection over *R*
  - Projection of *R* without duplicate elimination
- 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

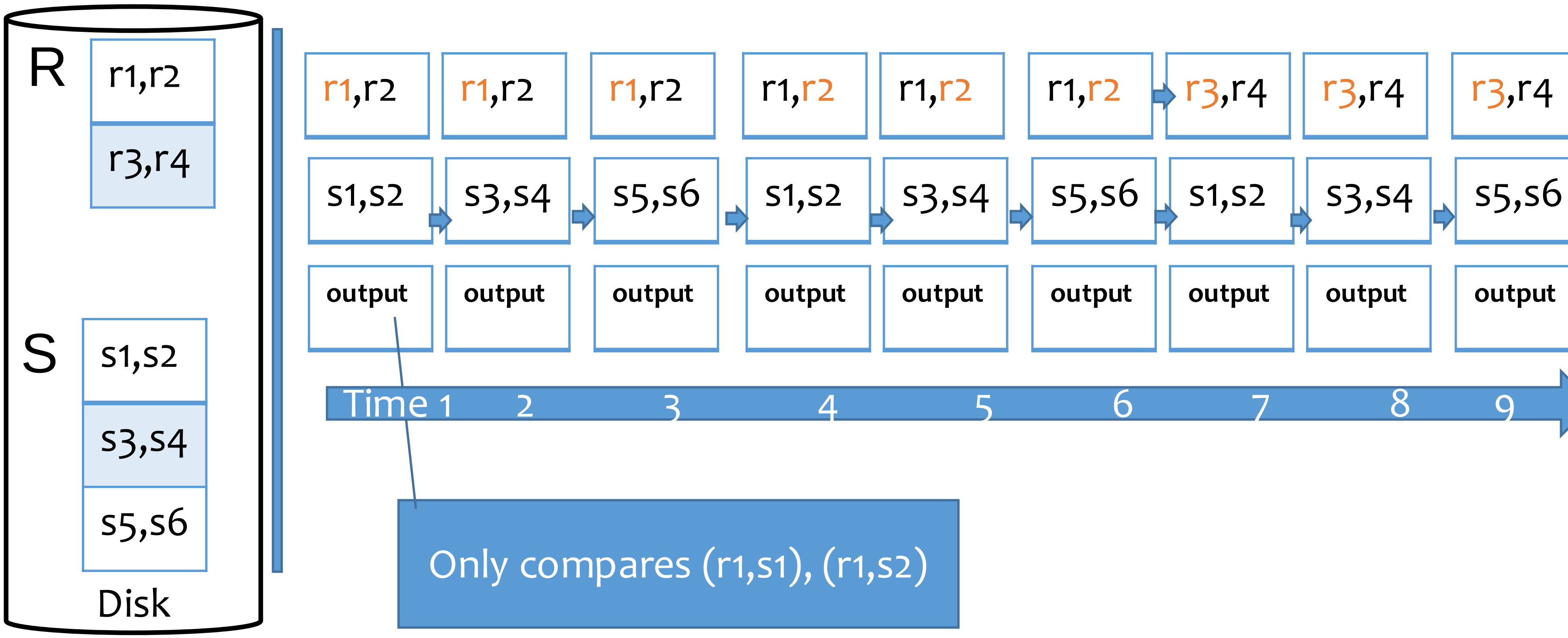
Blocks of R are moved into memory only once

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 (rather its optimized version next slide) 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

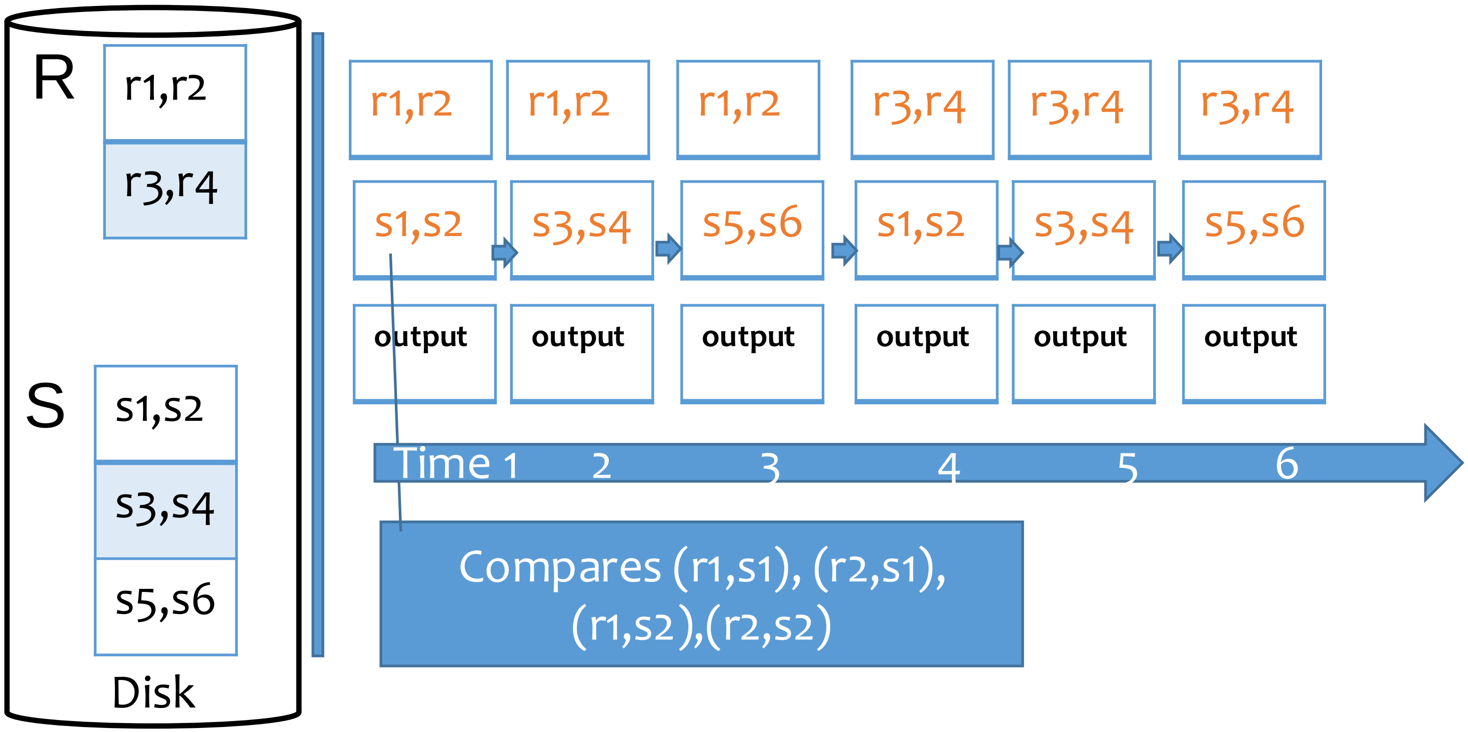
- Improvement: block-based nested-loop join

```
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:

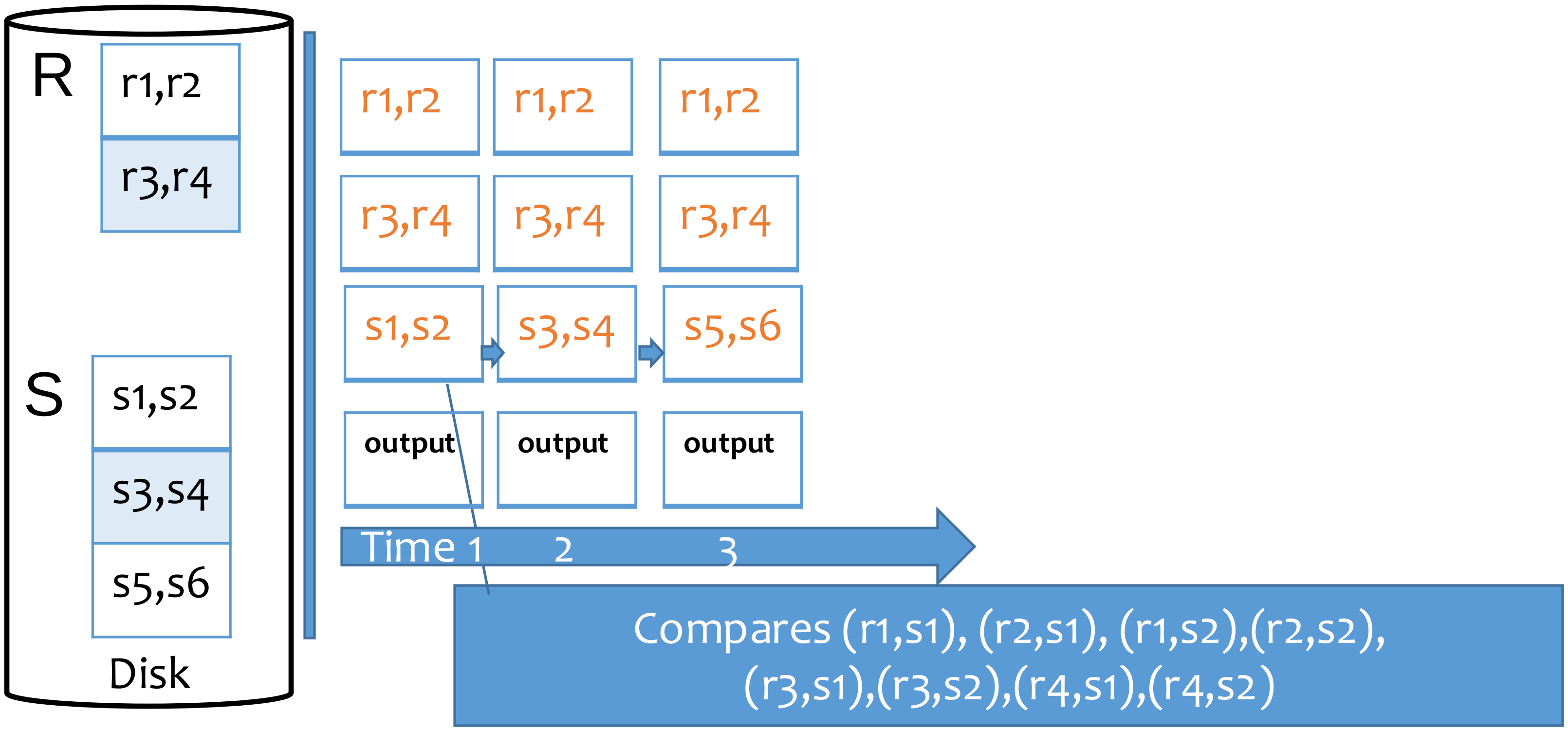
  B(R) + B(R)* B(S) = 2 blocks + 2 * 3 blocks = 8

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

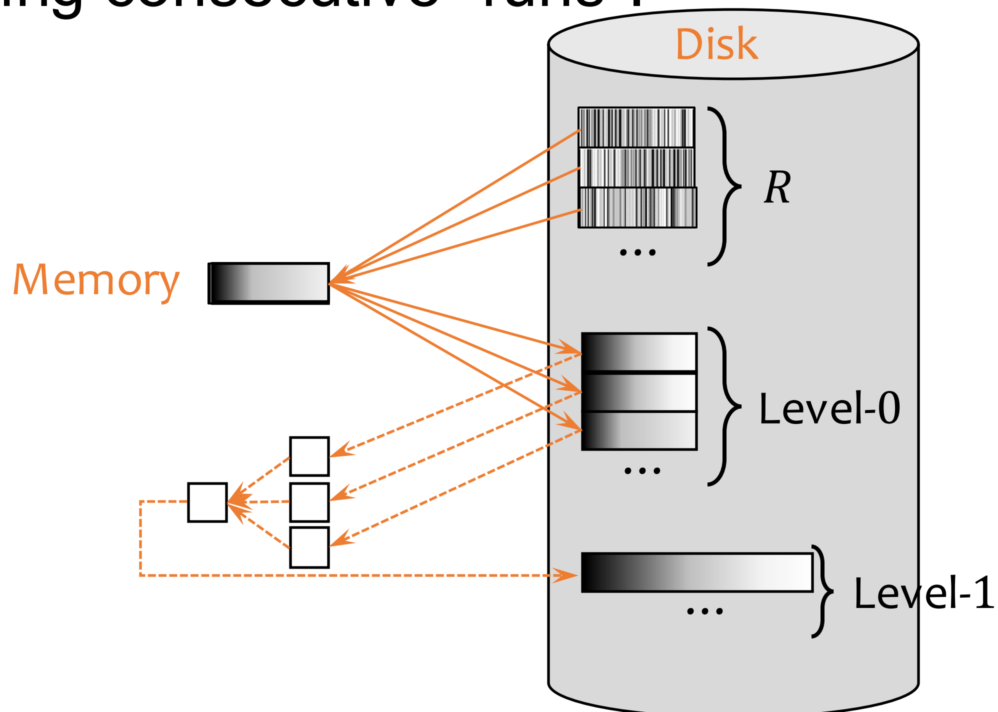
- At a high-level majority of DBMS operators require: (1) sorting; or (2) hashing of input tables.
- If you have a DBMS that has these core operators implemented in a very performant, robust, and scalable manner, you have a solid query processing foundation.
  - Key point: Keep optimizing these core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

Sorting Under Limited Memory

- A robust DBMS has solutions to the following problem:
- Consider an operator *o* that needs to sort a base table or an intermediate table R (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

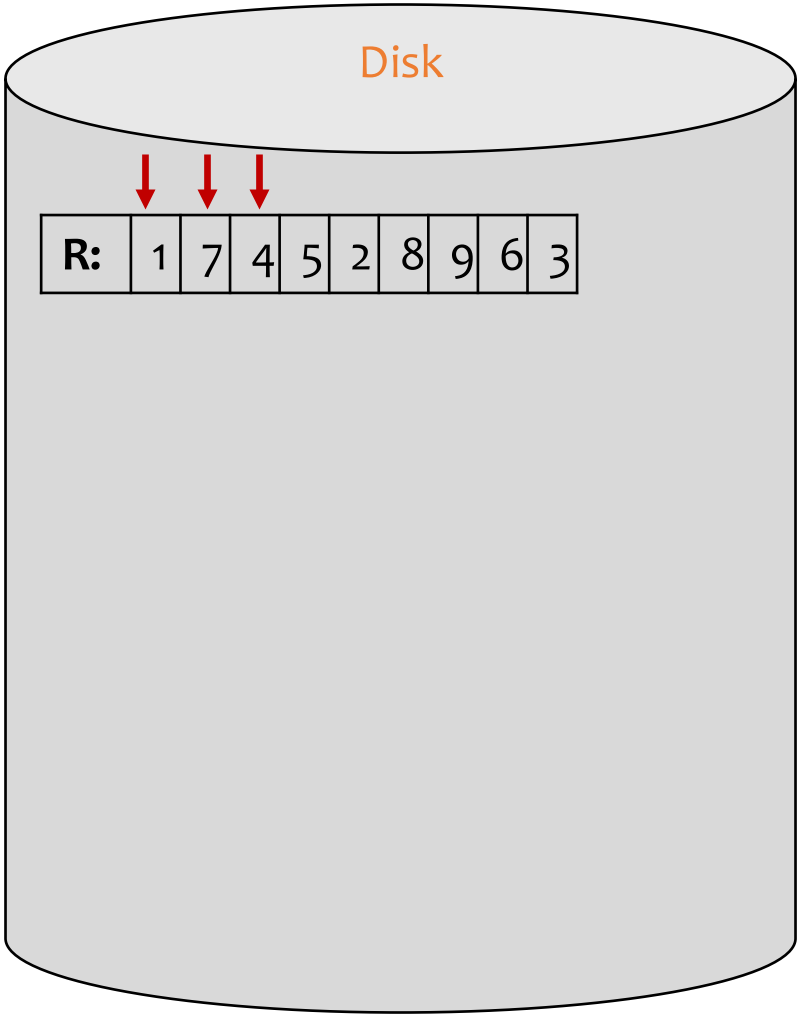
…

- 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

Arrows indicate the blocks in memory



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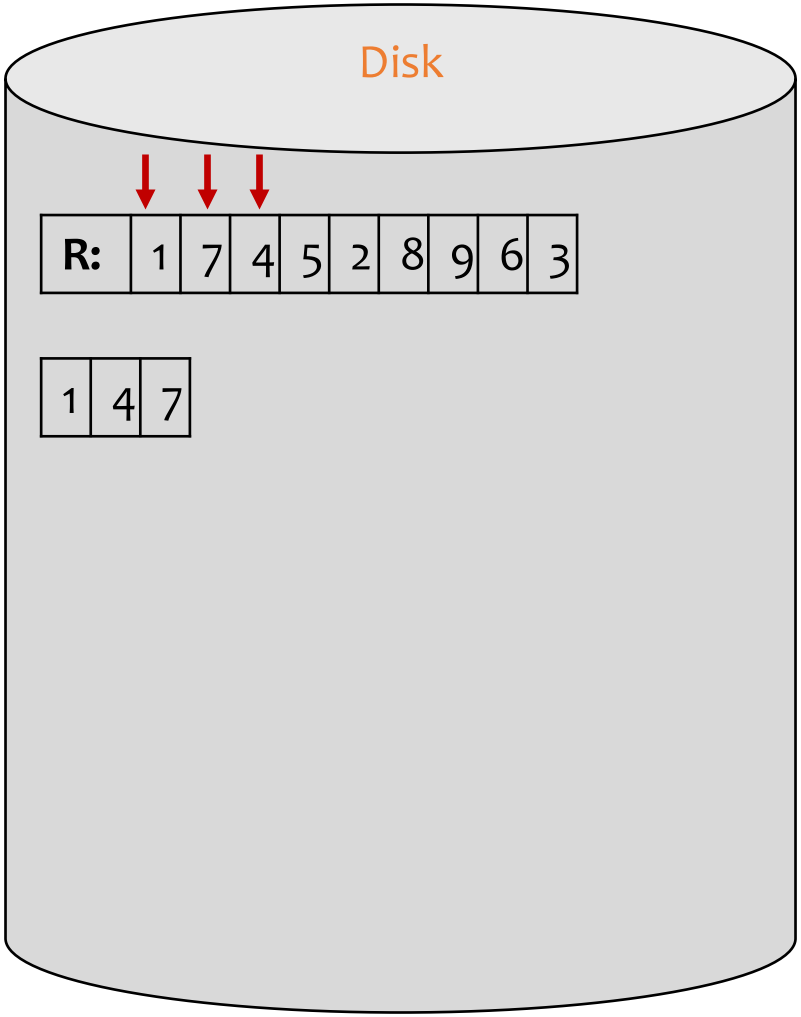

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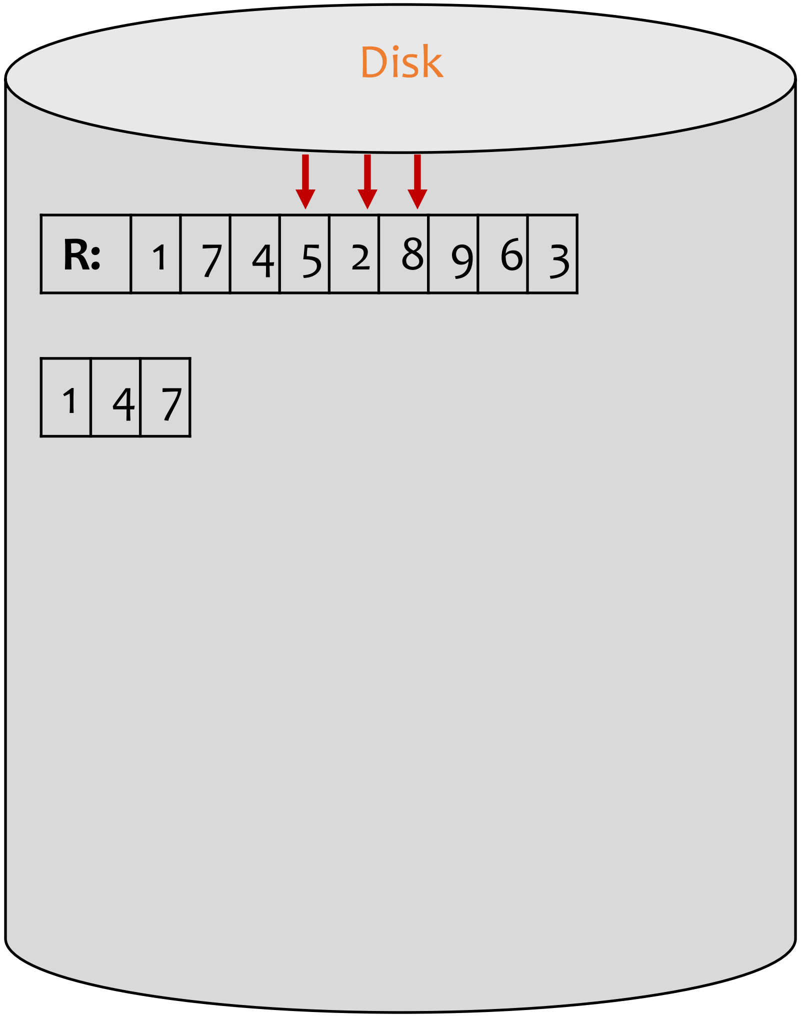

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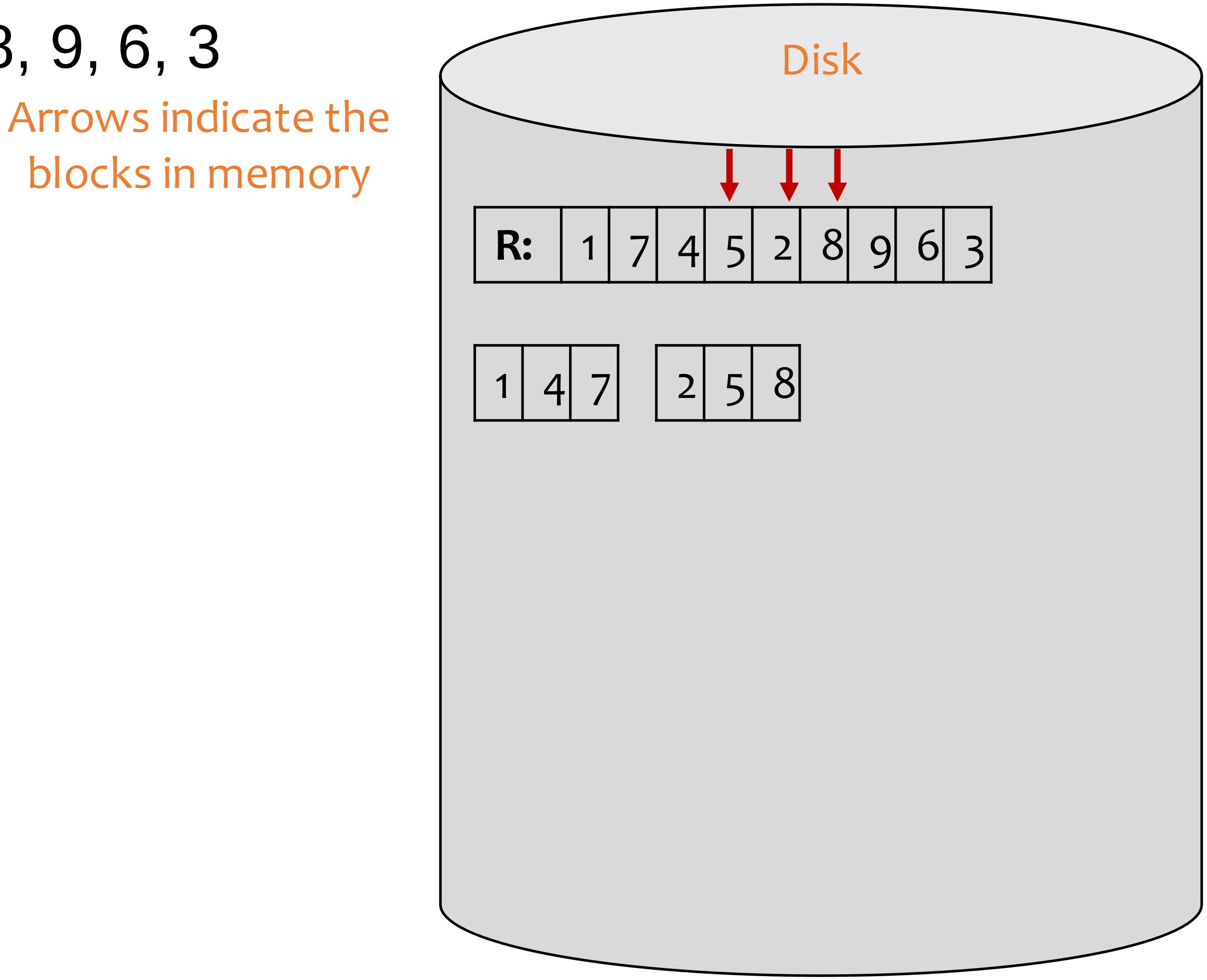

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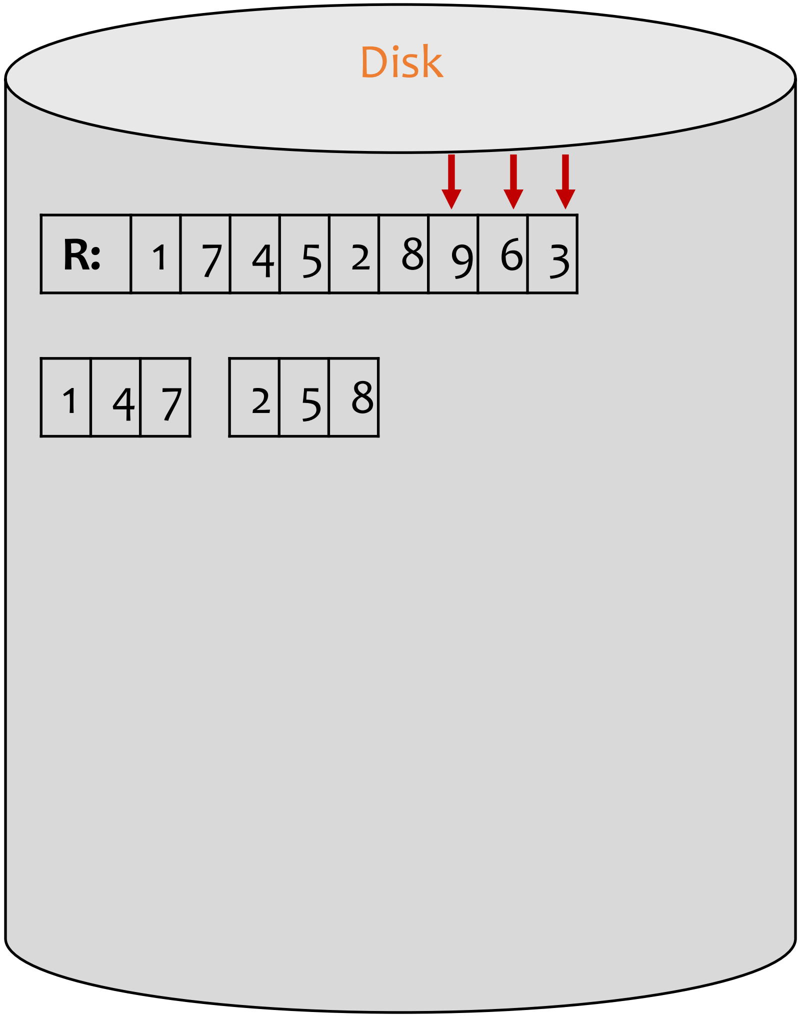

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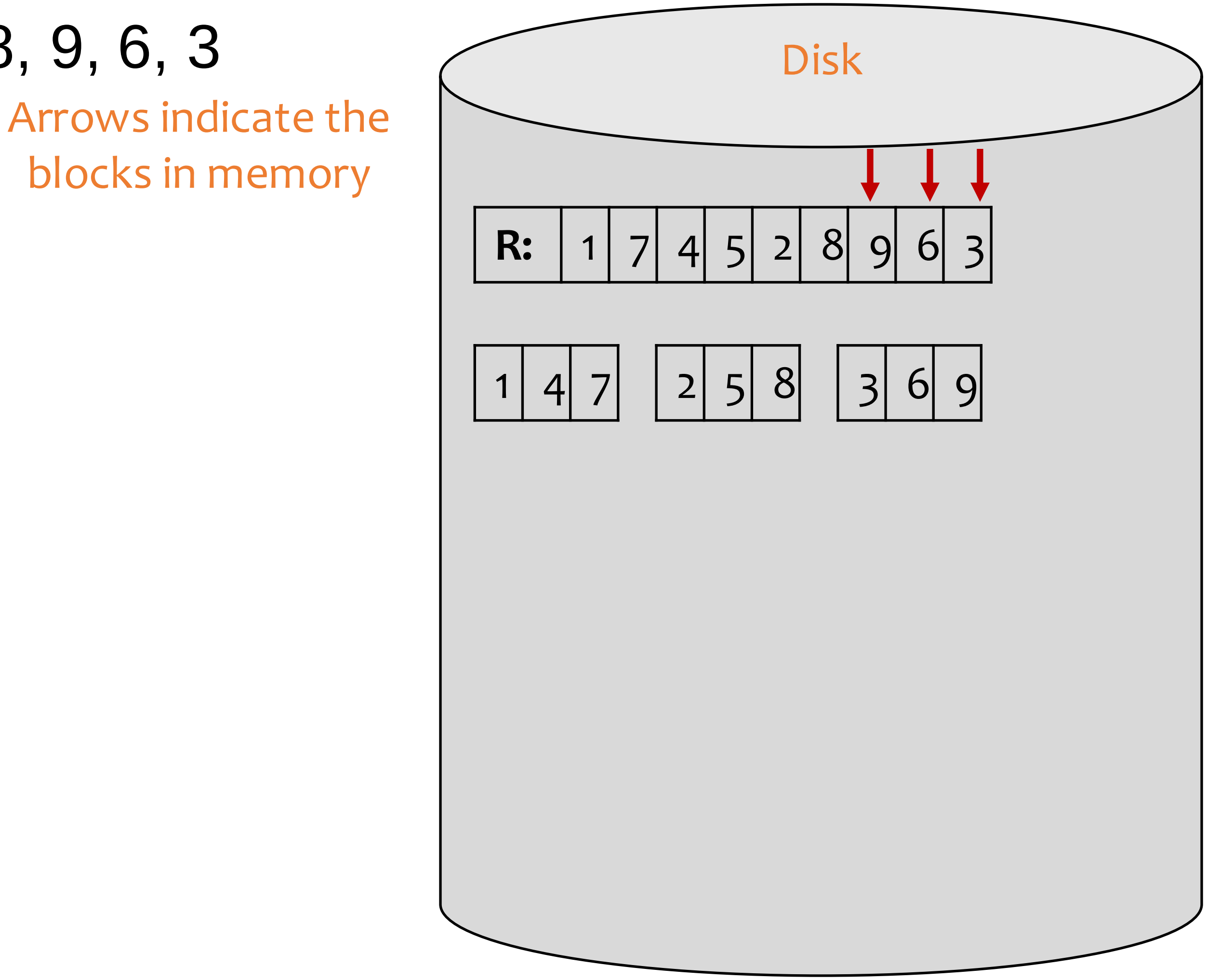

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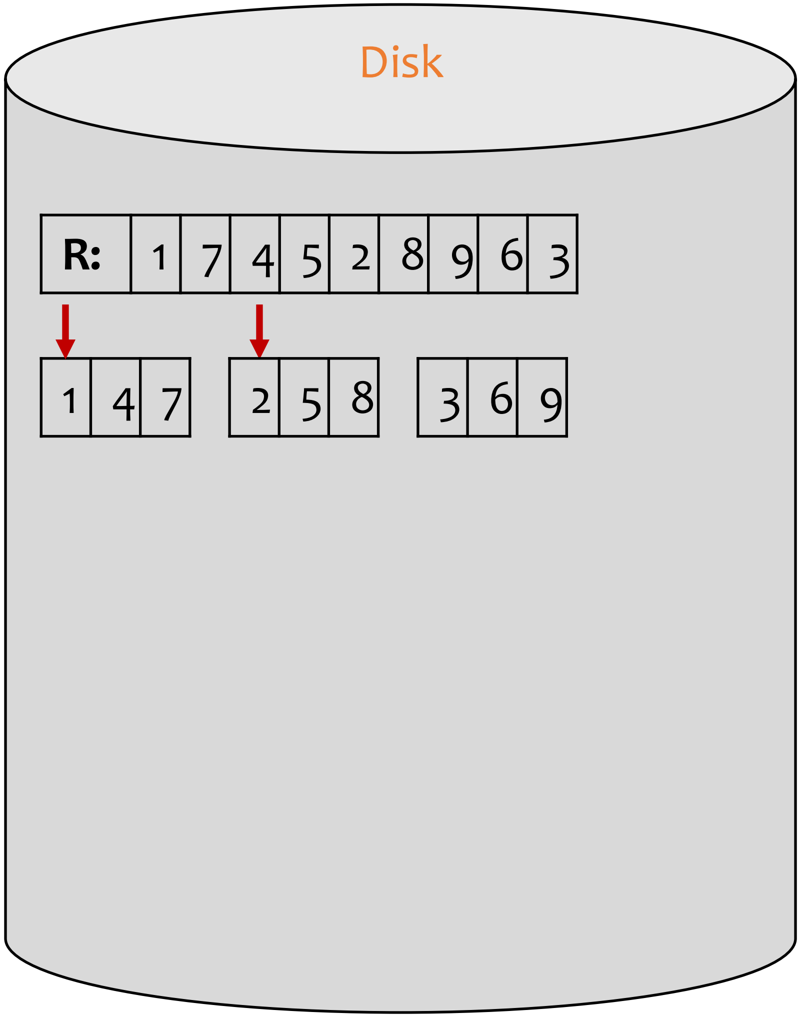

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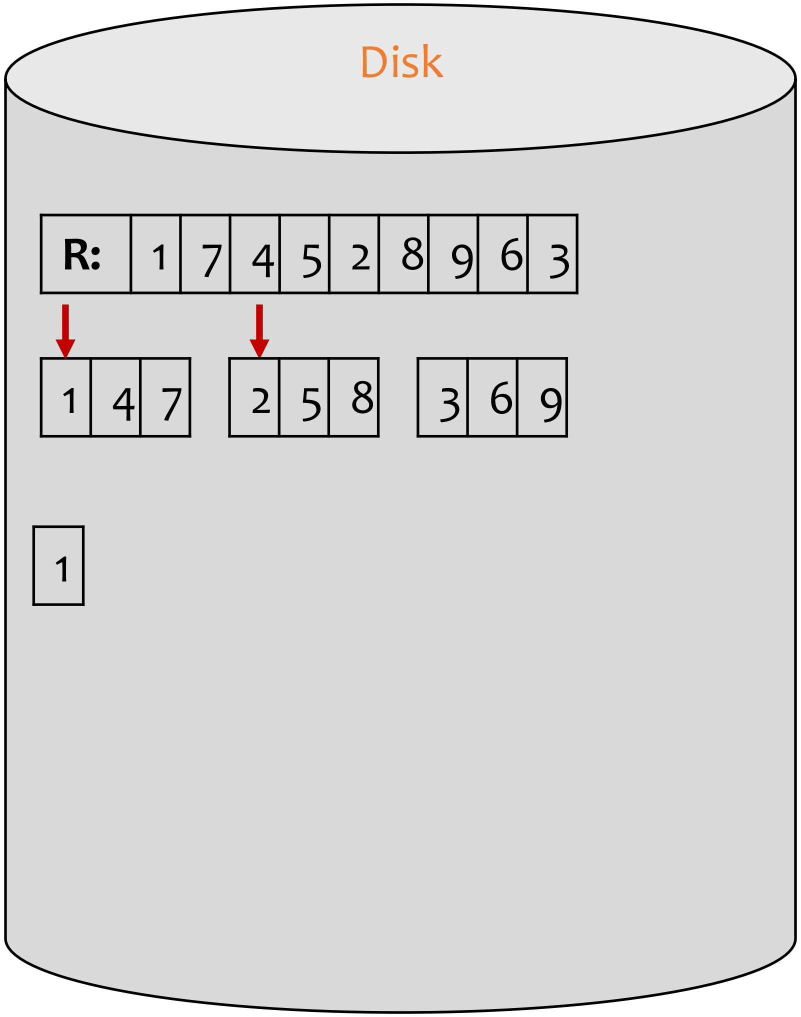

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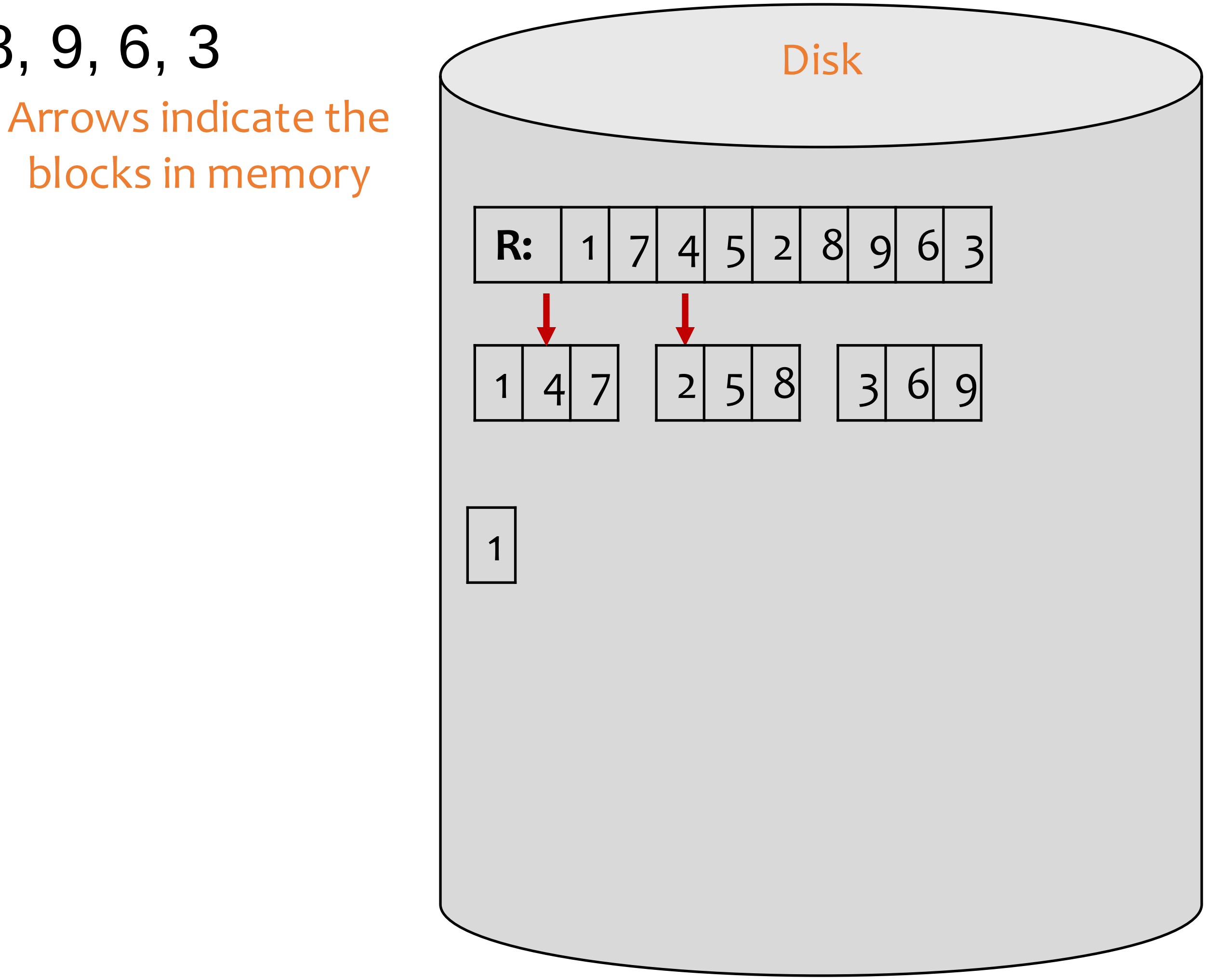

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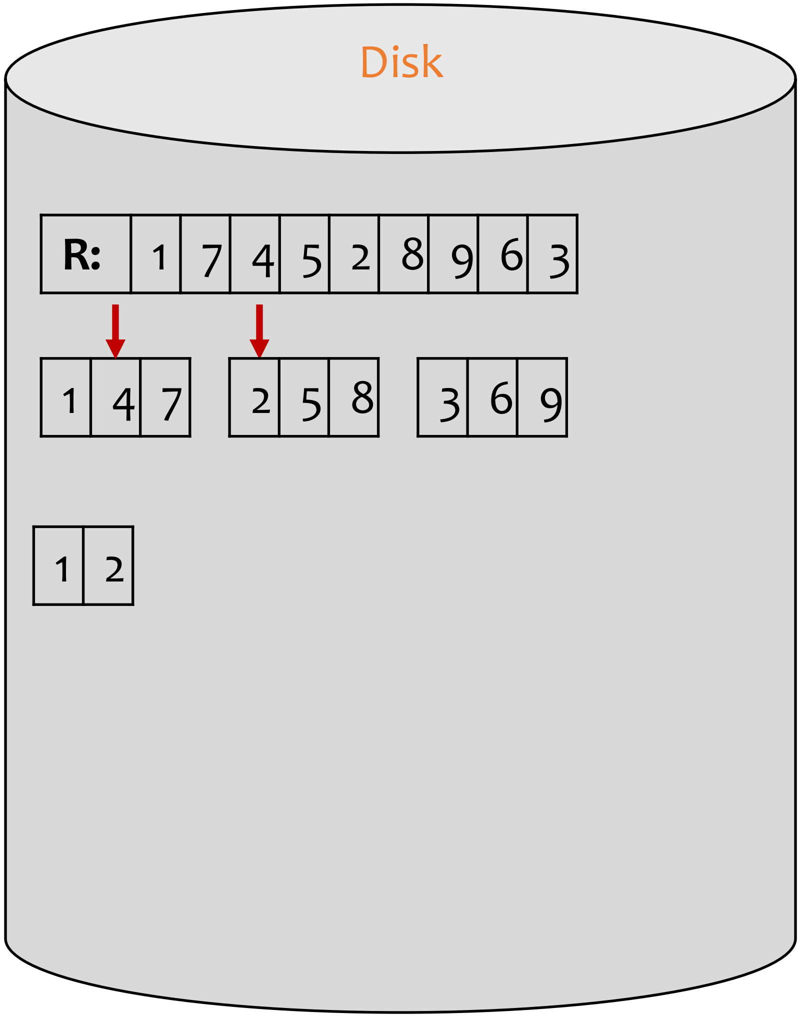

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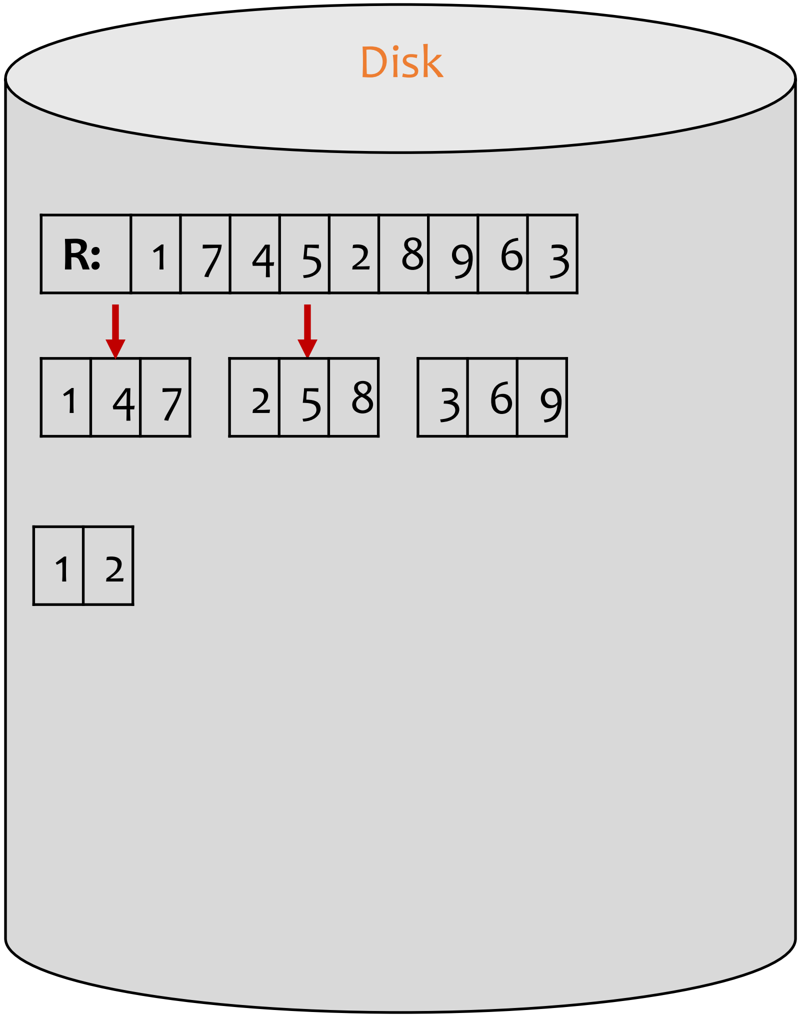

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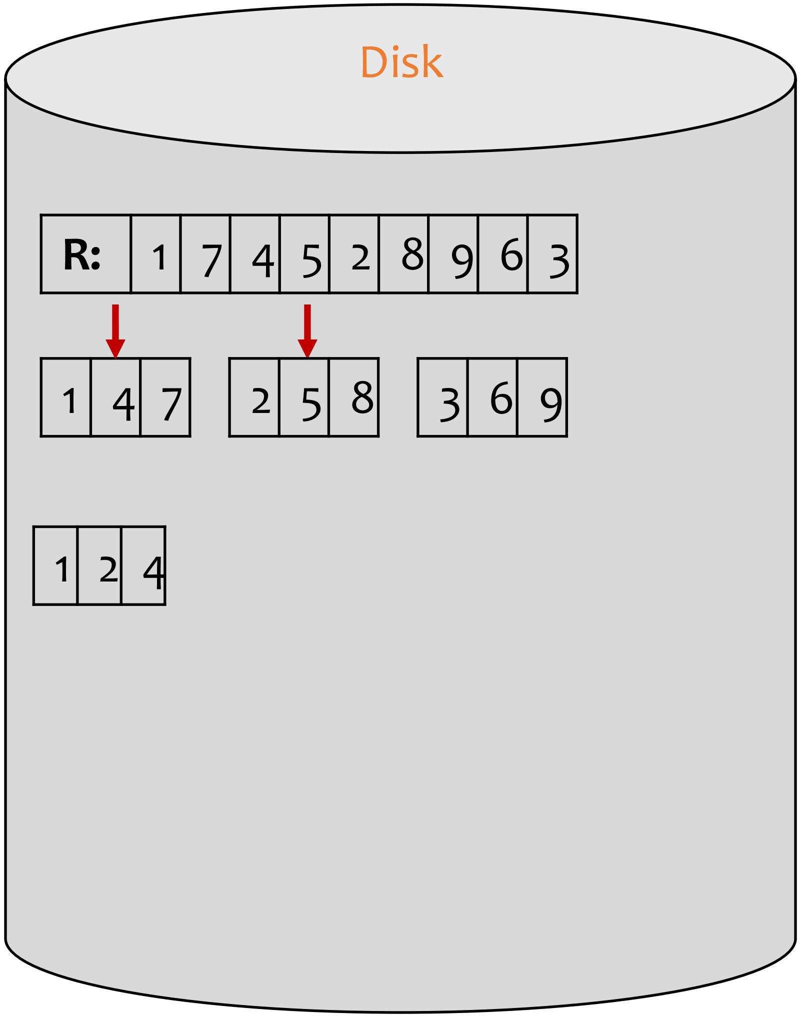

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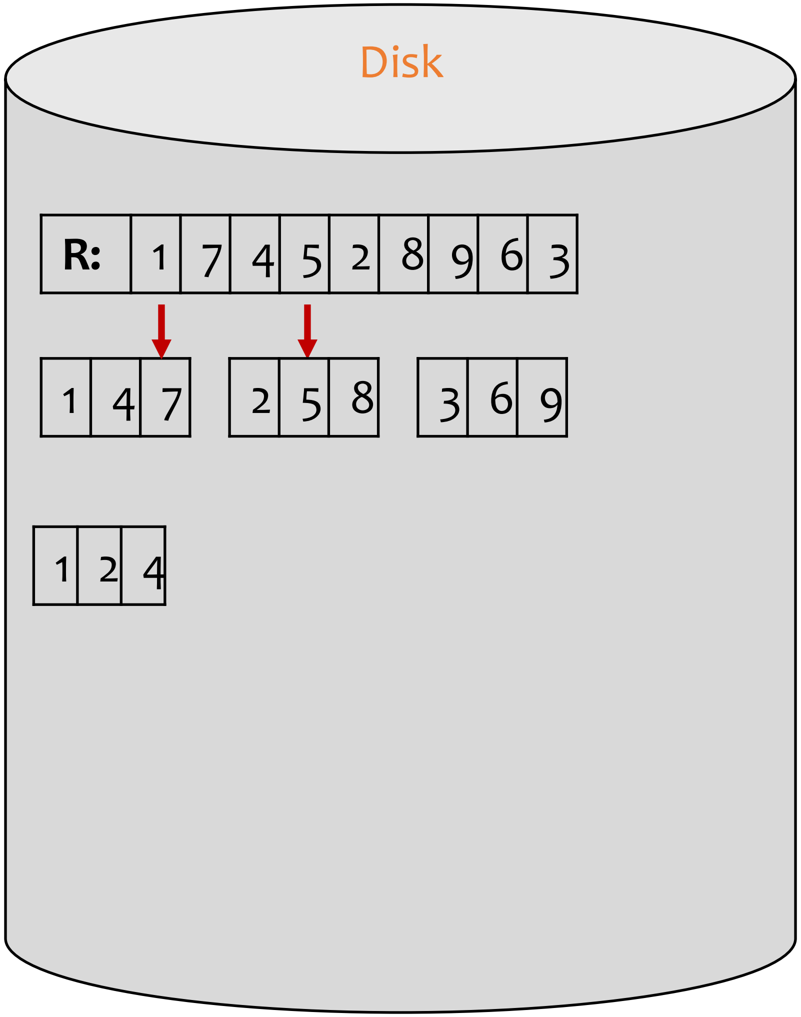

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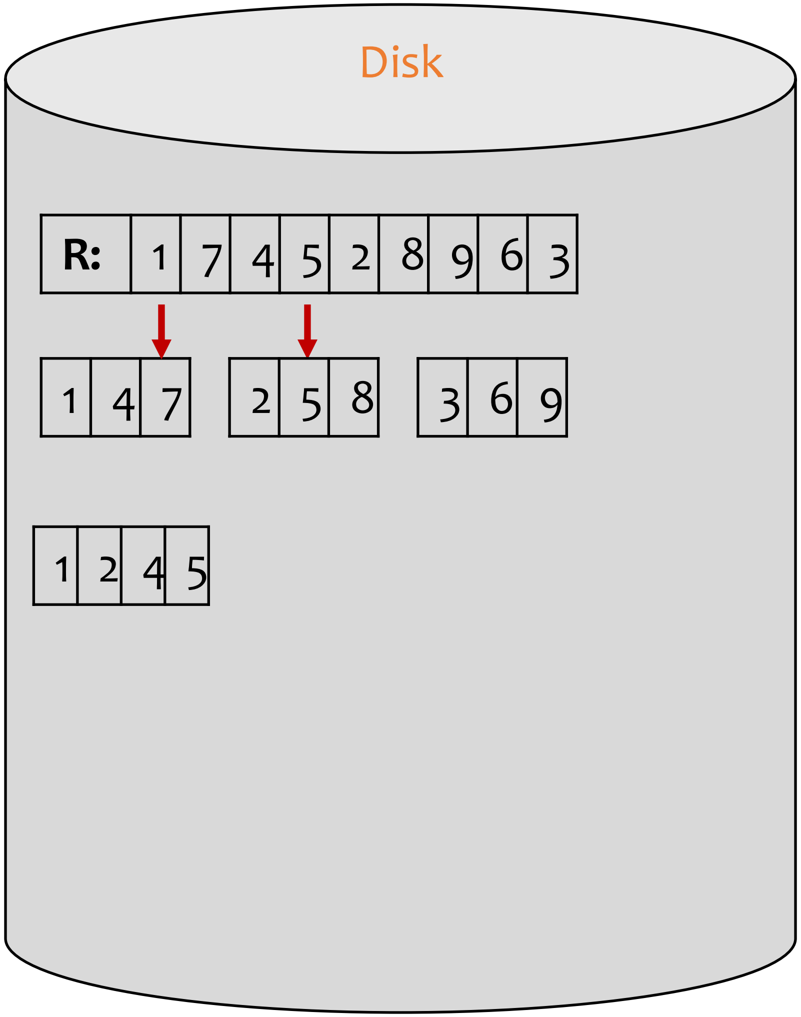

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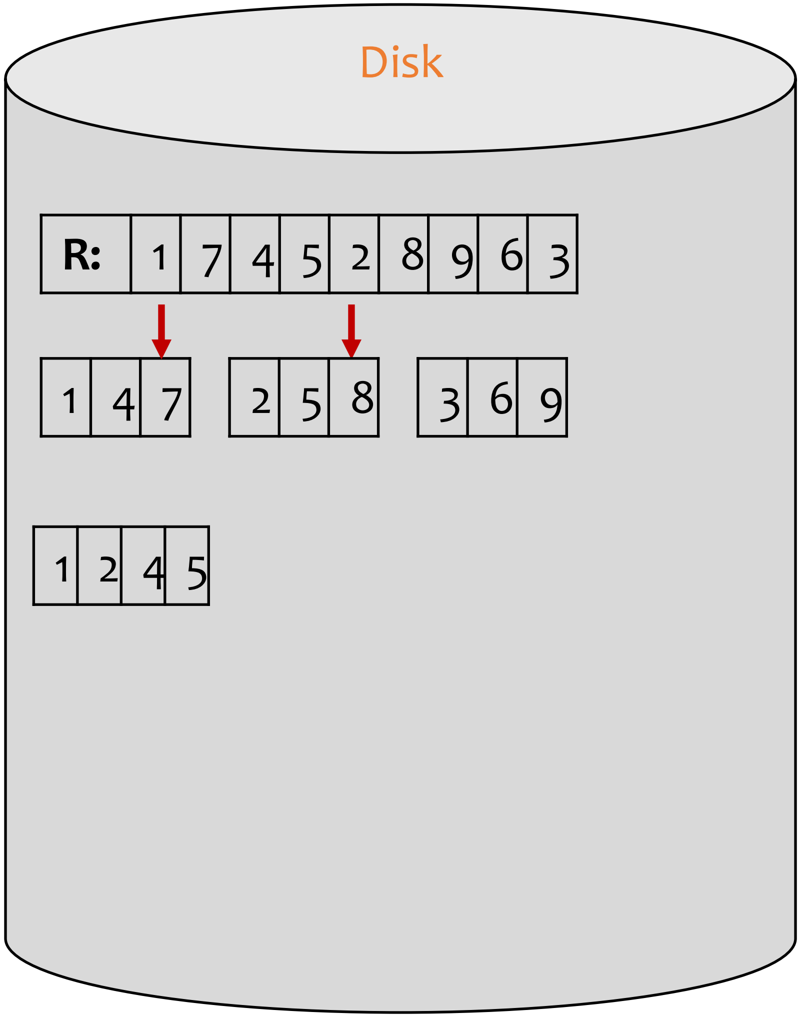

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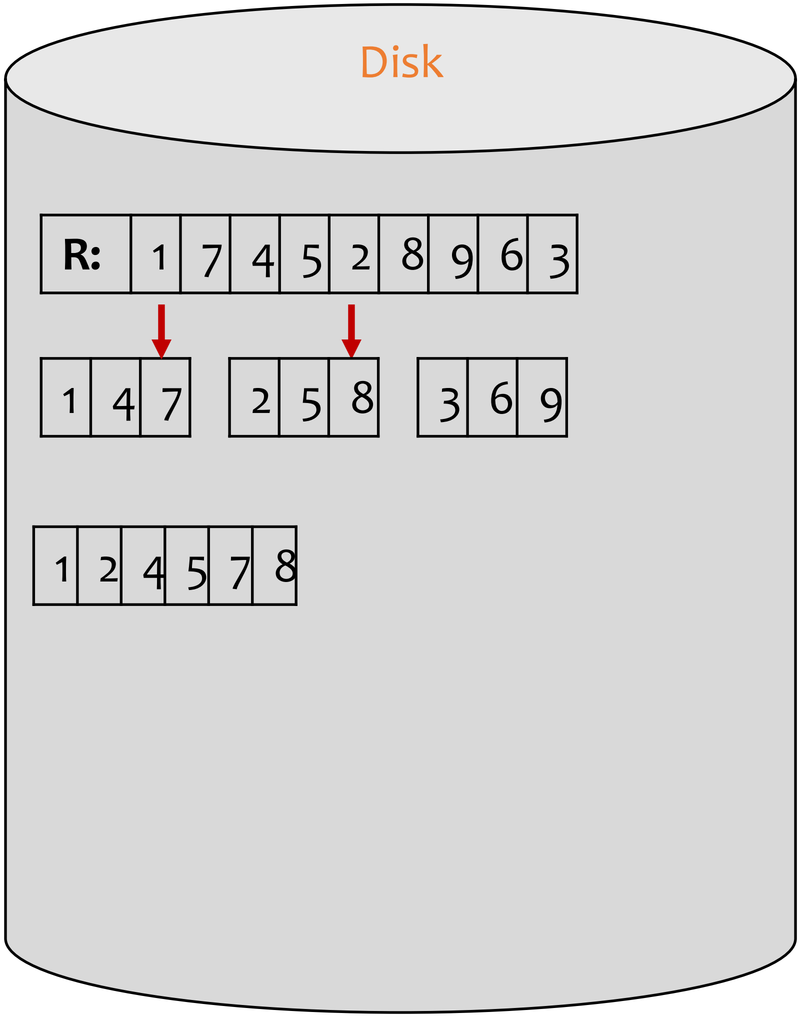
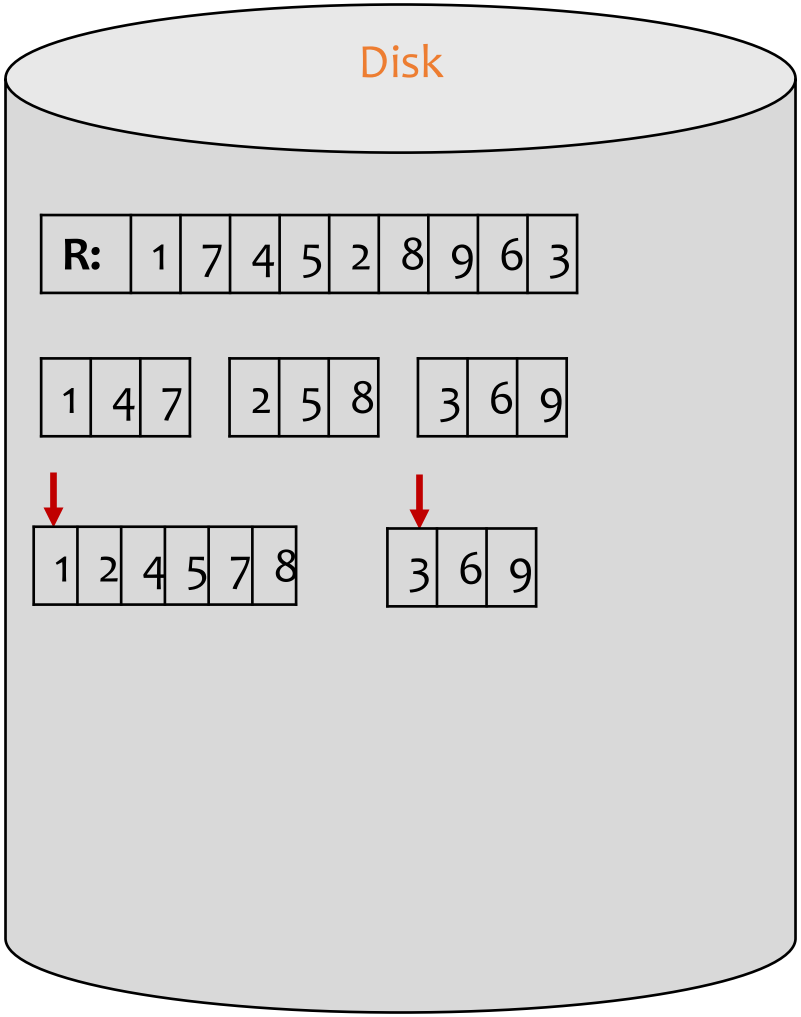


Example

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

Arrows indicate the blocks in memory



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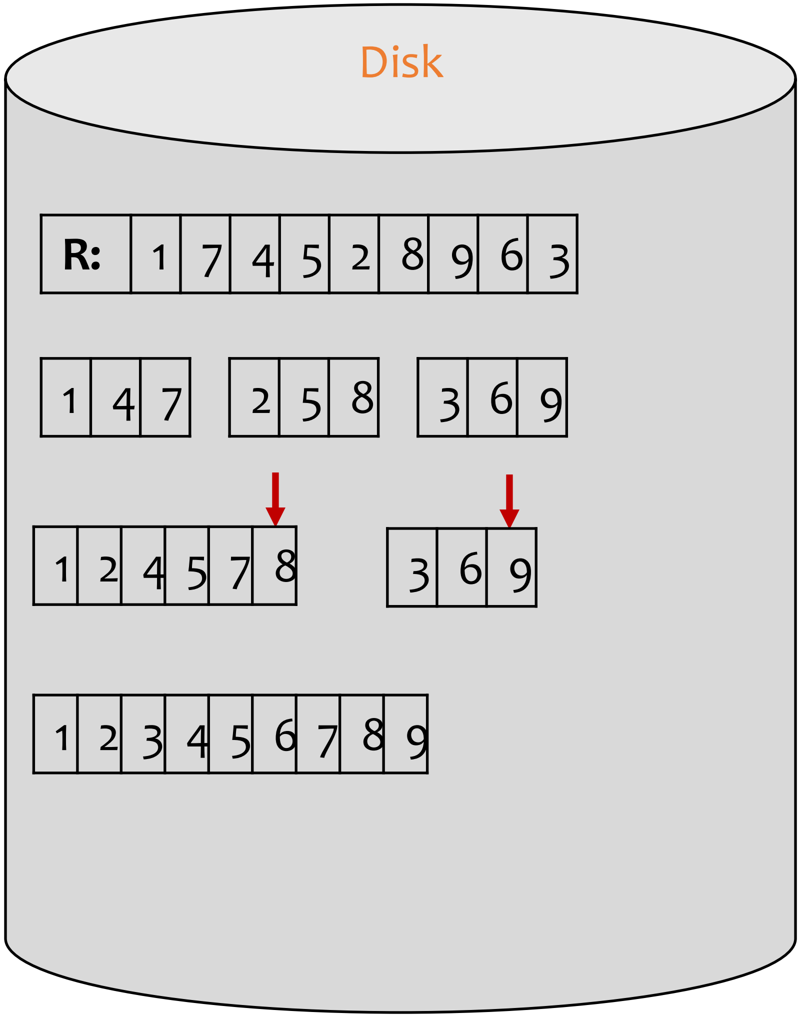

I/O Cost Analysis

- 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: $2\mathrm{B}(\mathrm{R}) \cdot \left(1 + \left\lceil \log_{M-1} \left\lceil \frac{B(R)}{M} \right\rceil \right\rceil\right) \approx 2B(R) \log_M(B(R))$
- 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 + B(R) + B(S)
  - If every r,s join (worst-case) sorting + $B(R) \cdot B(S)$:

Example

R:

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

S:

$s_1.B = 1$
$s_2.B = 2$
$s_3.B = 3$
$s_4.B = 3$
$s_5.B = 8$

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

$r_1 s_1$

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$R \bowtie_{R.A=S.B} S$:
$r_1 s_1$
$r_2 s_3$

Example

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

$r_1 s_1$

$r_2 s_3$

$r_2 s_4$

Example

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

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$r_4.A = 5$

$r_5.A = 7$

$r_6.A = 7$

$r_7.A = 8$

S:

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$s_2.B = 2$

$s_3.B = 3$

$s_4.B = 3$

$s_5.B = 8$

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

$r_1 s_1$

$r_2 s_3$

$r_2 s_4$

$r_3 s_3$

Example

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$r_2.A = 3$

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Outline

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

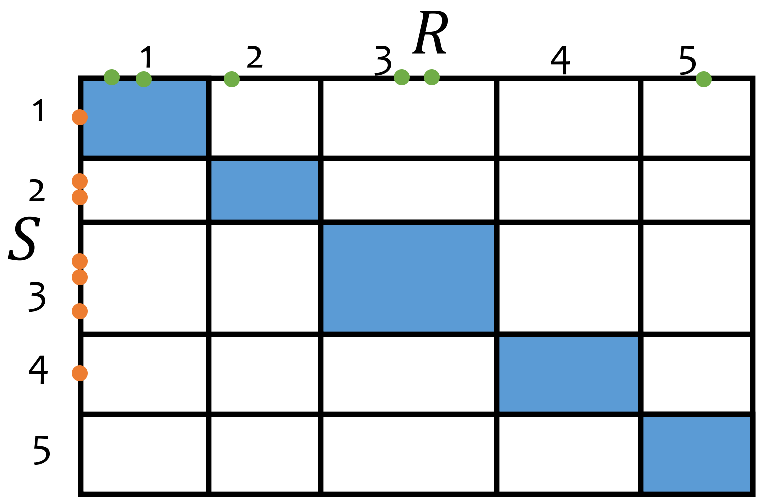
- Consider an equality join, e.g., join of R(X, A) ⋈ S(B, Y) where A=B.
- Let h be hash function hashing A or B values to 1, …, k
- If r ∈ R and s ∈ S “join”, i.e., r[A] = s[B] then:

  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



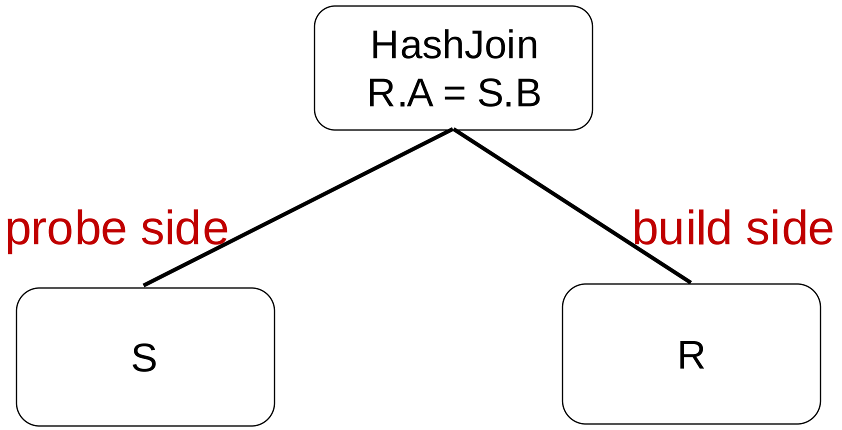
Nested-loop join considers all slots

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 s.t 1 part. of R & 1 part. of S (hopefully) fit in memory

```
Phase 1: partition R and S into k partitions using h
Phase 2:
for i = 1, …, k:
   read Ri and Si into memory and use in-memory hash-join alg.
   (i.e., build a hash table of Ri and probe Si tuples)
```



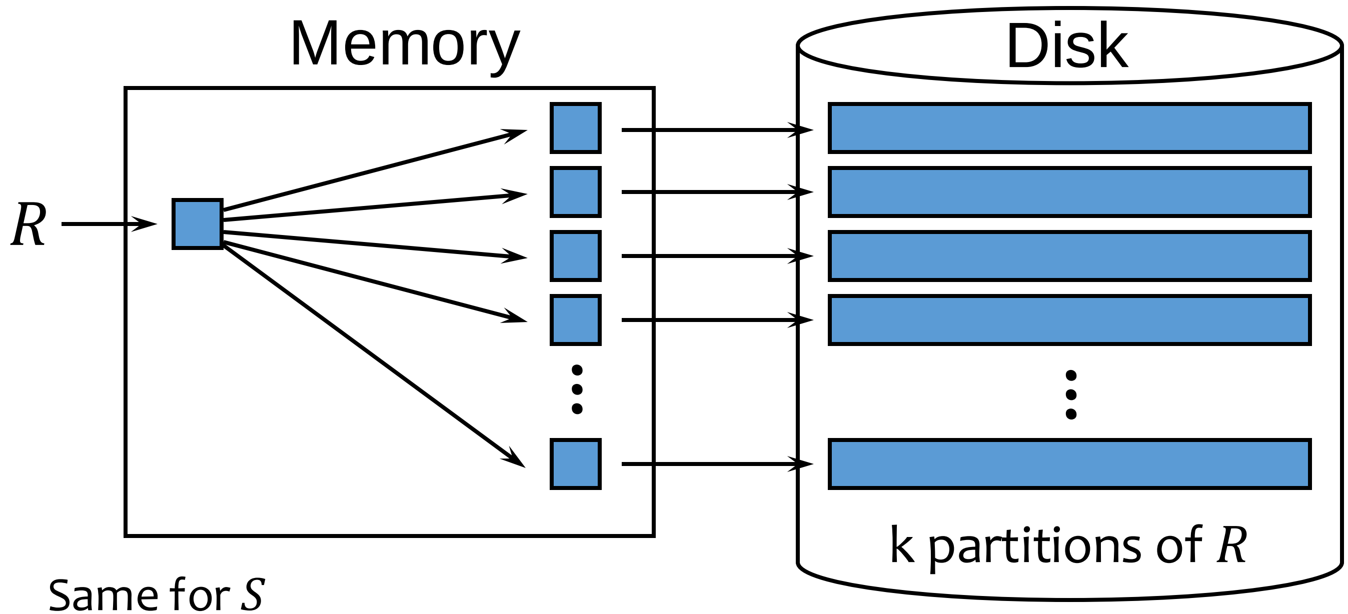
Q: Systems make the smaller (estimated) relation the build side? Why?

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

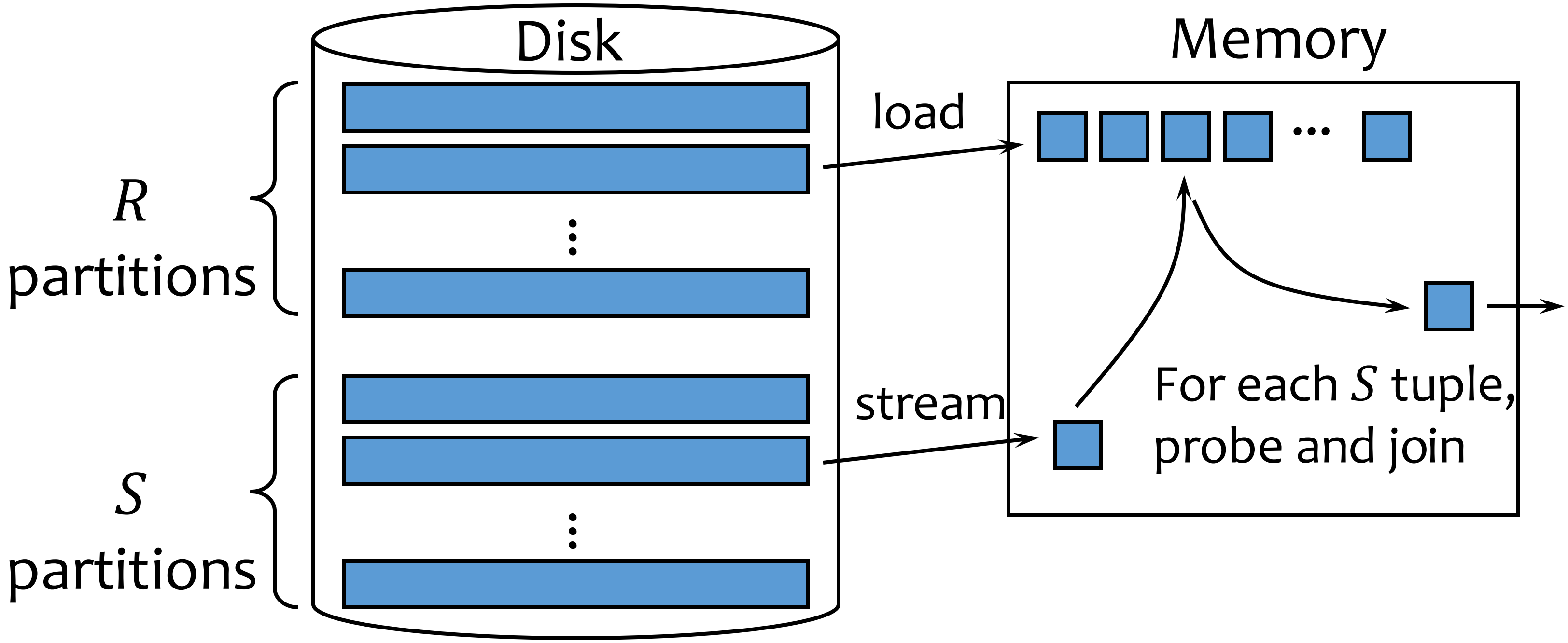
- Partition R and S according to the same hash function on their join attributes



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:

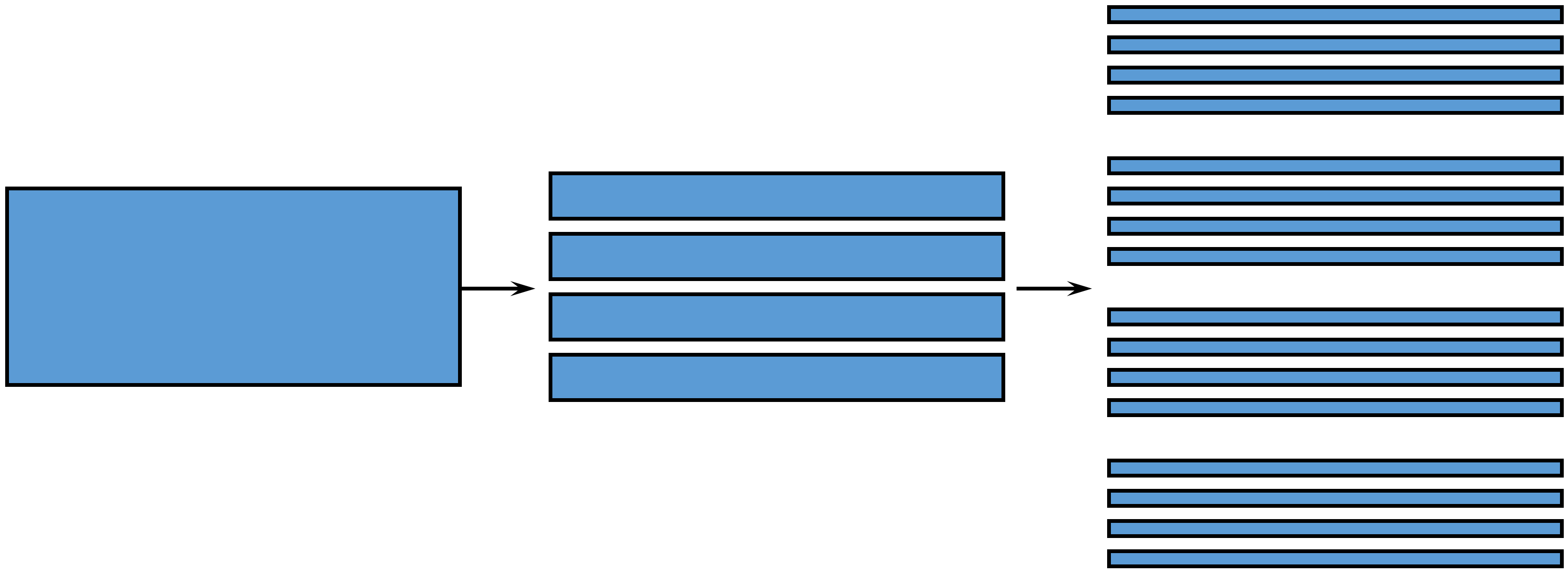
  I/O's: $3 \cdot \left(B(R) + B(S)\right)$

  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 a B+-tree, or hash index on $R(A)$

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

  Use an ordered index (e.g., 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 I/O commensurate with the height of the index (usually O(1)). 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 (Optional)

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

- 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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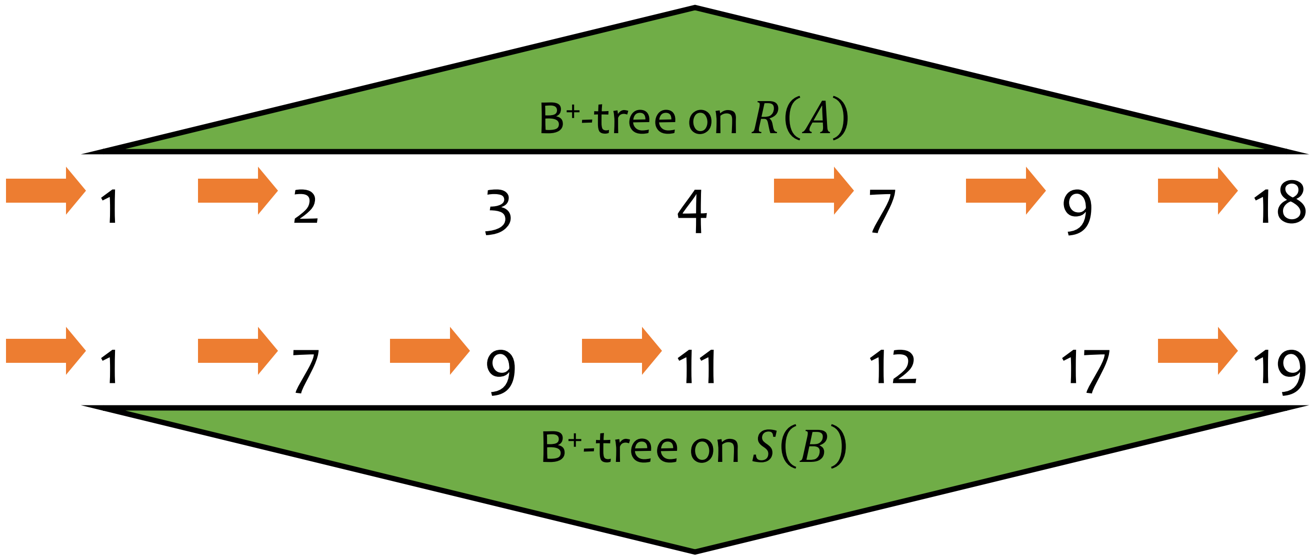
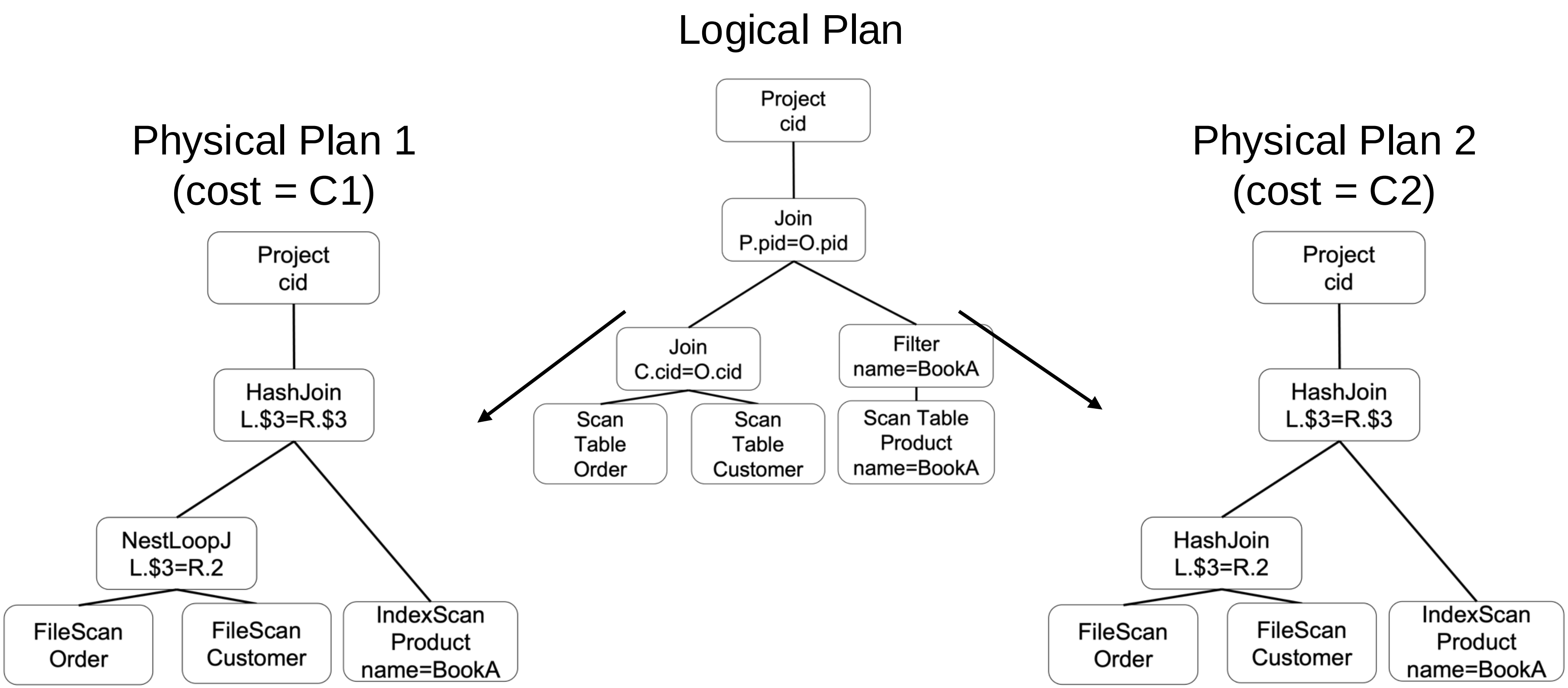


Note on Role of (I/O) Costs Of Operators For Picking Physical Plans

- 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.

Example

- System requirements:
  - Each disk/memory block can hold up to 10 rows (from any table);
  - All tables are stored compactly on disk (10 rows per block);
  - 8 memory blocks are available for query processing: M=8
- Database:
  - User(uid, age, pop), Member(gid,uid,date), Group(gid, gname)
  - |User|=1000 rows, |Group|=100 rows, |Member|=50000 rows
  - #of blocks: B(User)=1000/10=100; B(Group)=100/10=10; B(Member)=50000/10=5k
- Q1: select * from User where pop =0.8
  - I/O cost using table scan? $B(User) = 100$
- Q2: select * from User, Member where User.uid = Member.uid;
  - I/O cost using blocked-based nested loop join

$$B(User) + \left\lceil \frac{B(User)}{M-2} \right\rceil \cdot B(Member) = 100 + \left\lceil \frac{100}{8-2} \right\rceil \cdot 5000 = 85{,}100$$

Example

- Q3: select * from User order by age asc;
  - I/O cost using external merge sort?

Number of phases: $\left\lceil \log_{M-1} \left\lceil \frac{B(User)}{M} \right\rceil \right\rceil + 1 = \left\lceil \log_{(8-1)} \left\lceil \frac{100}{8} \right\rceil \right\rceil + 1 = 3$

$2*100*(1 + \left\lceil \log_7 \left\lceil \frac{100}{8} \right\rceil \right\rceil)) = 600$

There is nothing else to do in this query than to sort. So, you can also argue that the last writing of the sorted outputs can be omitted because the data is streamed to the user. Then you calculate the result as 600-100=500. In the assignment or an exam, as long as your assumptions are reasonable both calculations would be accepted.