Review lecture - 2

CS348 Spring 2023

Instructor: Sujaya Maiyya

Sections: **002 & 004 only**

Announcements

- Milestone 2
  - Due Tuesday, June 11th
  - Late policy: 25% penalty per 24 hrs
- Assignment 3 - released
  - Due July 20th
  - Late policy: 15% penalty per 24 hrs
- Expect delays in grading due to a change in TA
  - We will announce on Piazza when grades are ready

Topics covered so far

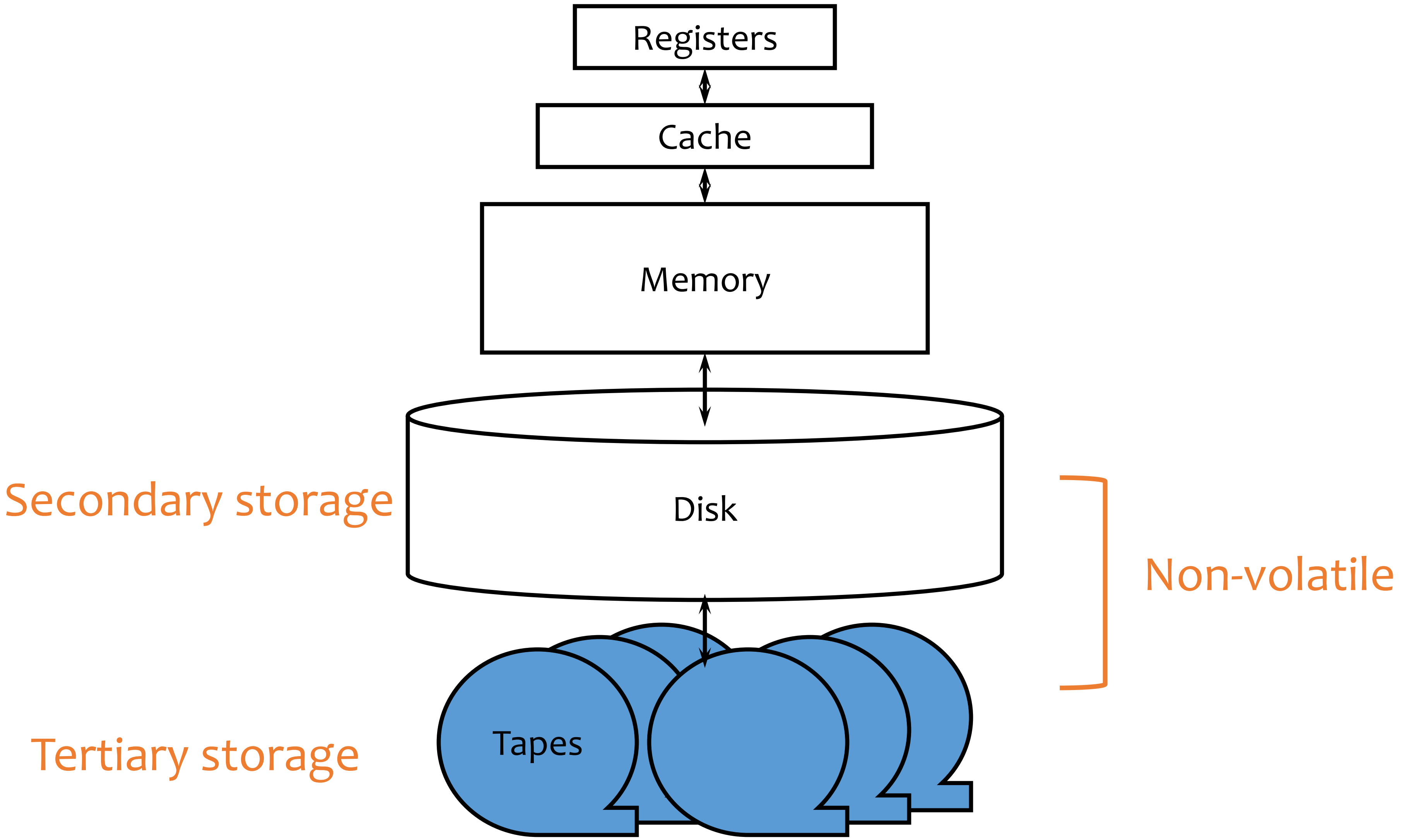
- Relational model (lecture 2)
- SQL (lectures 3-6)
- Database design (lectures 7-10)

Conceptual/Logical level

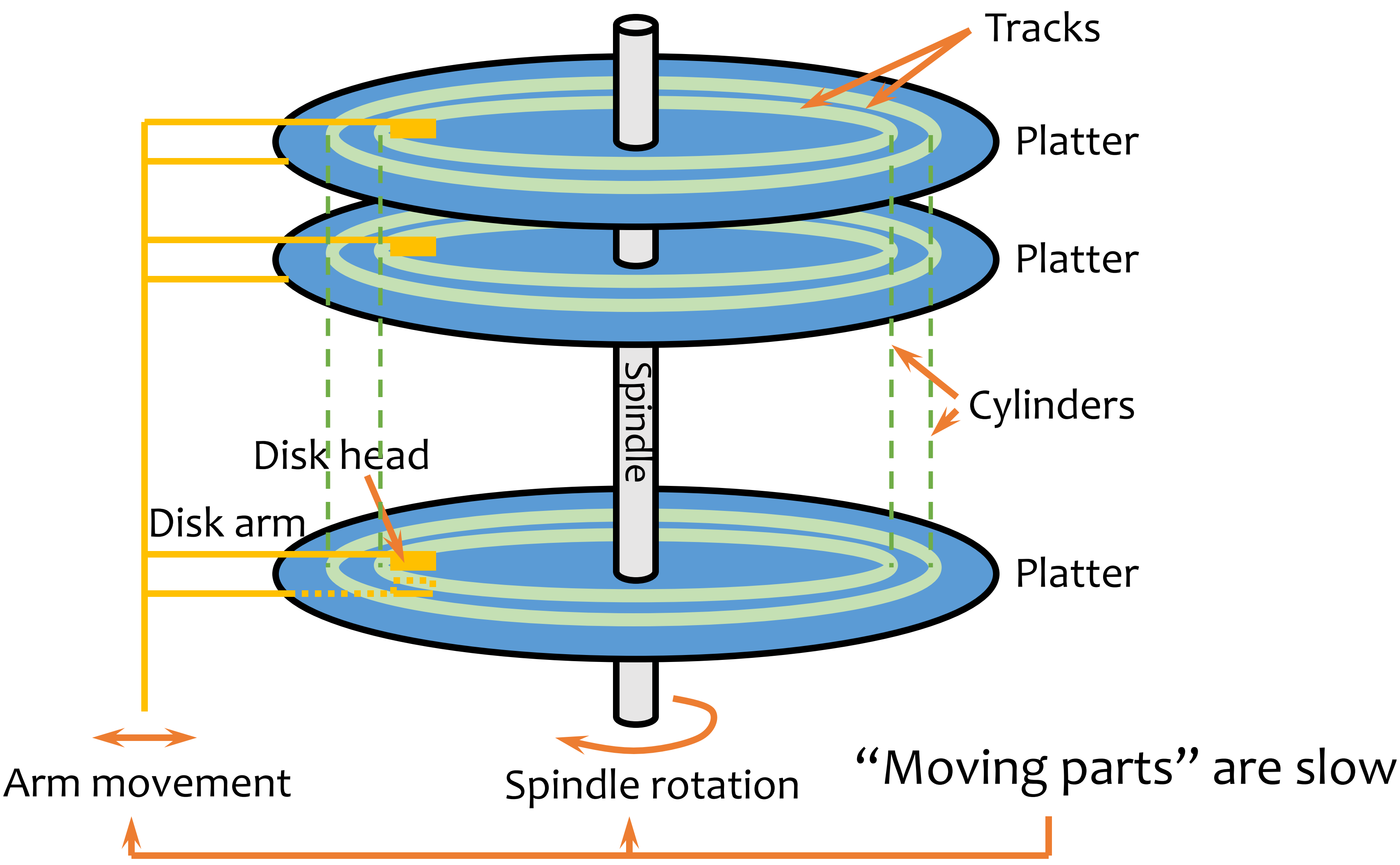
Review these topics

- Storage management & indexing (lectures 11-12)
- Query processing & optimizations (lectures 13-14)

Storage hierarchy

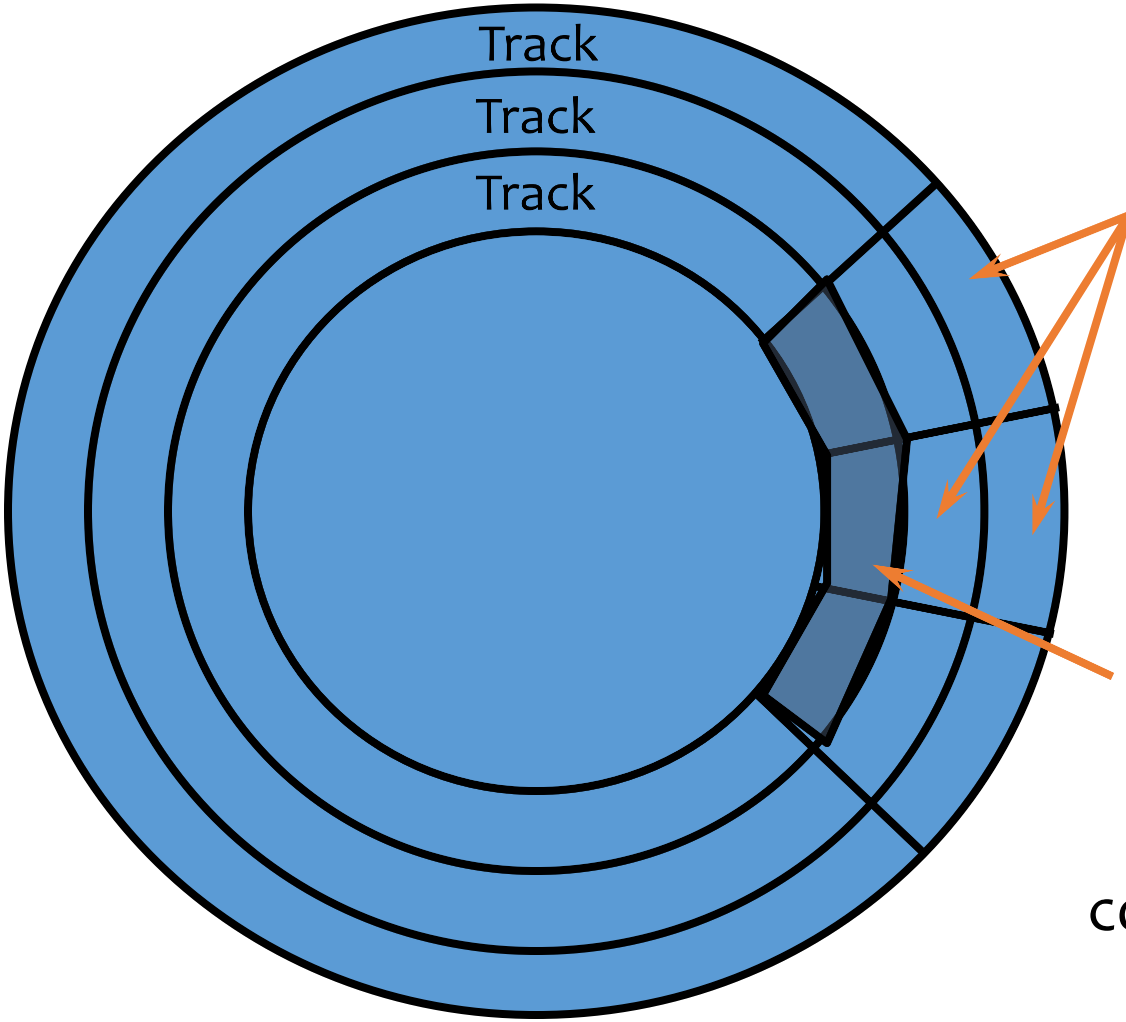


A typical hard drive



Top view

"Zoning": more sectors/data on outer tracks



A block is a logical unit of transfer consisting of one sector

Disk access time

Disk access time: time from when a read or write request is issued to when data transfer begins

Sum of:

- Seek time: time for disk heads to move to the correct cylinder
- Rotational delay: time for the desired block to rotate under the disk head

- Transfer time: time to read/write data in the block (= time for disk to rotate over the block)

- Total data access time = seek time + rotational delay + transfer time

Random disk access

→ Successive requests are for blocks that are randomly located on disk

Delay = Seek time + rotational delay + transfer time

- Average seek time
  - Seek the right cylinder for each access
  - "Typical" value: 5 ms

- Average rotational delay
  - Rotate for the right block for each access
  - "Typical" value: 4.2 ms (7200 RPM)

Sequential disk access

→ Successive requests are for successive block numbers, which are on the same track, or on adjacent tracks

Delay = Seek time + rotational delay + transfer time

- Seek time
  - 1 time delay: seek the right cylinder once
- Rotational delay
  - 1 time delay: rotate to the right block once
- Easily an order of magnitude faster than random disk access!

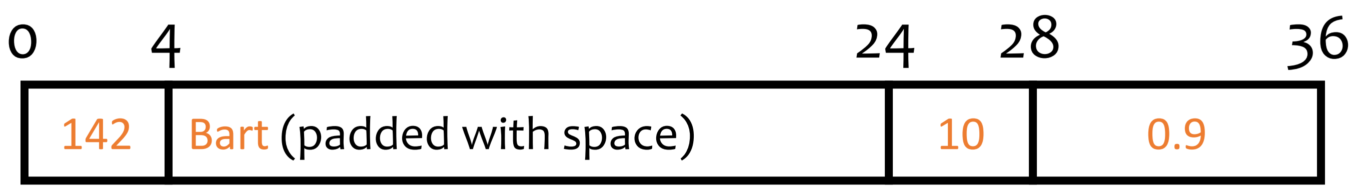
Record layout

Record = row in a table

- Variable-format records
  - Rare in DBMS—table schema dictates the format
  - Relevant for semi-structured data such as XML
- Focus on fixed-format records
  - With fixed-length fields only, or
  - With possible variable-length fields

Fixed-length fields

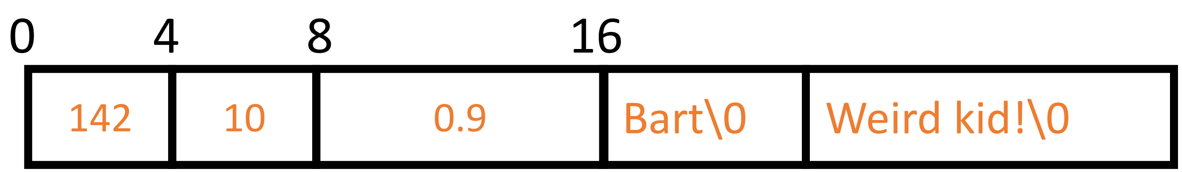
- All field lengths and offsets are constant
  - Computed from schema, stored in the system catalog
- Example: CREATE TABLE User(uid INT, name CHAR(20), age INT, pop FLOAT);



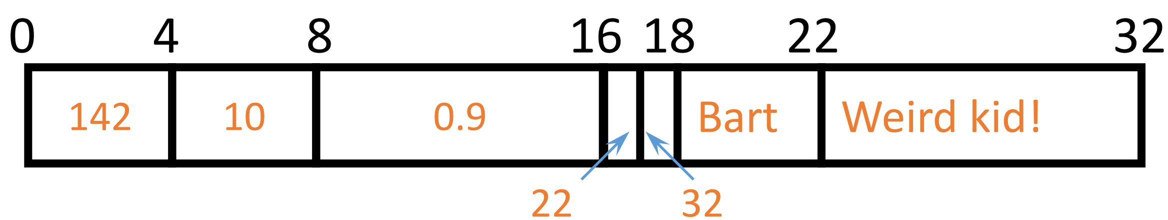
- If block size != 36, one row maybe split across multiple blocks or move to next block & leave the remaining space empty
- What about NULL?
  - Add a bitmap at the beginning of the record

Variable-length records

- Example: CREATE TABLE User(uid INT,
  name VARCHAR(20), age INT, pop FLOAT,
  comment VARCHAR(100));
- Put all variable-length fields at the end
- Approach 1: use field delimiters (‘\0’ okay?)



- Approach 2: use an offset array



- Scheme update is messy if it changes the length of a field

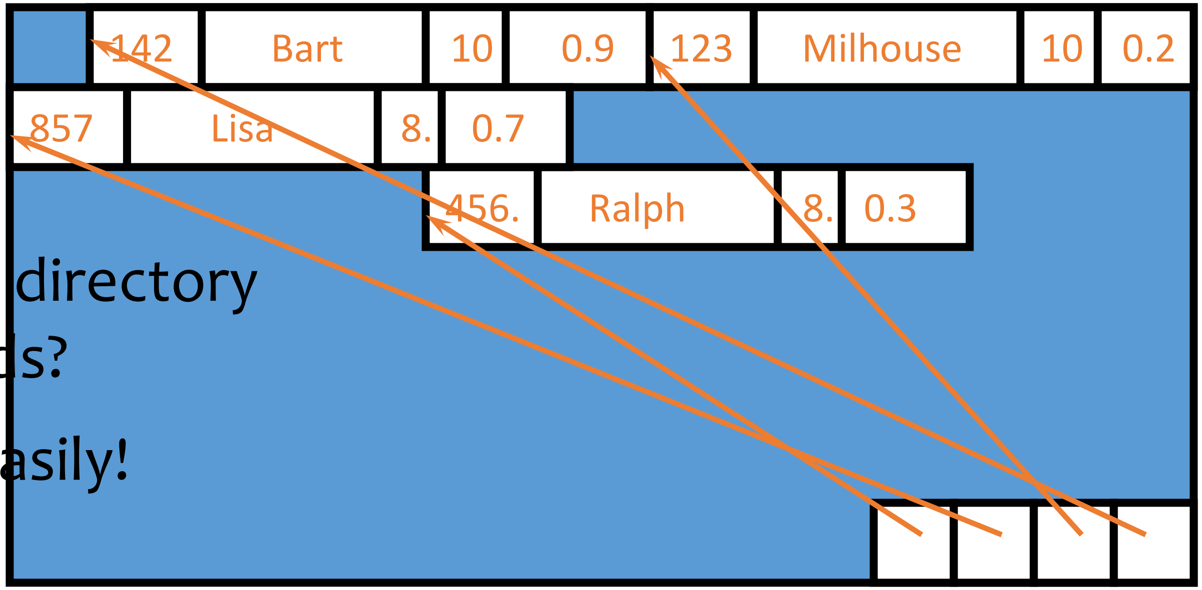
Block layout

How do you organize records in a block?

- NSM (N-ary Storage Model)
  - Most commercial DBMS
- PAX (Partition Attributes Across)
  - Ailamaki et al., *VLDB* 2001

NSM

- Store records from the beginning of each block
- Use a directory at the end of each block
  - To locate records and manage free space
  - Necessary for variable-length records

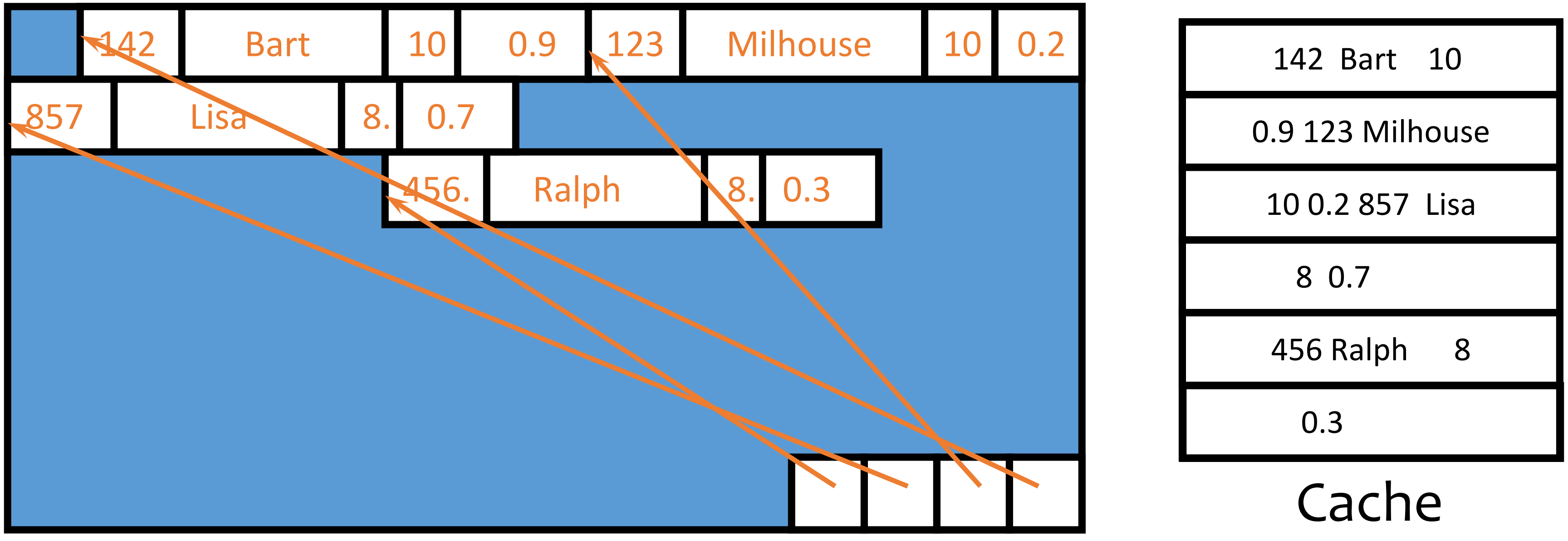


Why store data and directory at two different ends?

So both can grow easily!

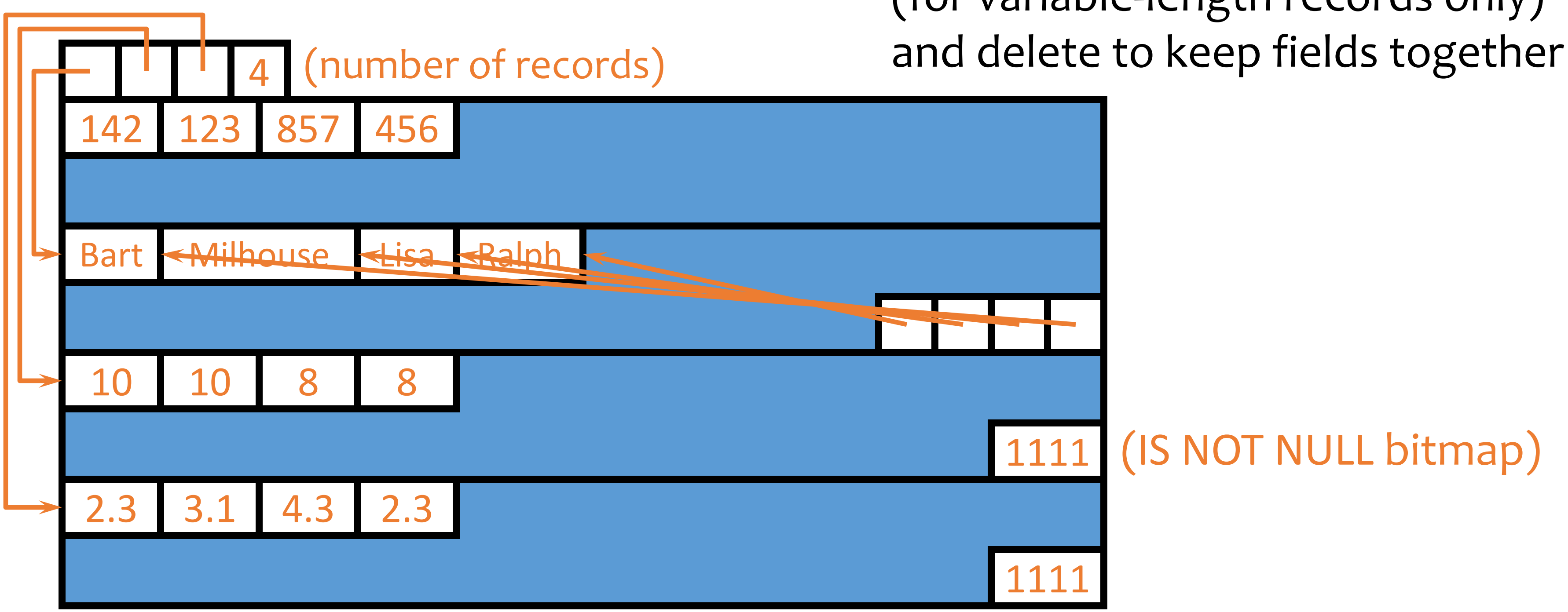
Cache behavior of NSM

- Query: SELECT uid FROM User WHERE pop > 0.8;
- Assumptions: no index, and cache line size < record size
- Lots of cache misses & wasted prefetching



PAX

- Most queries only access a few columns
- Cluster values of the same columns in each block
- Better sequential reads for queries that read a single column



Column vs. row oriented db

User:

uid	name	pop	age
1	Bart	.6	12
2	Lisa	.9	10
3	Abe	.3	65

Row oriented

1	Bart	.6	12
2	Lisa	.9	10
3	Abe	.3	65

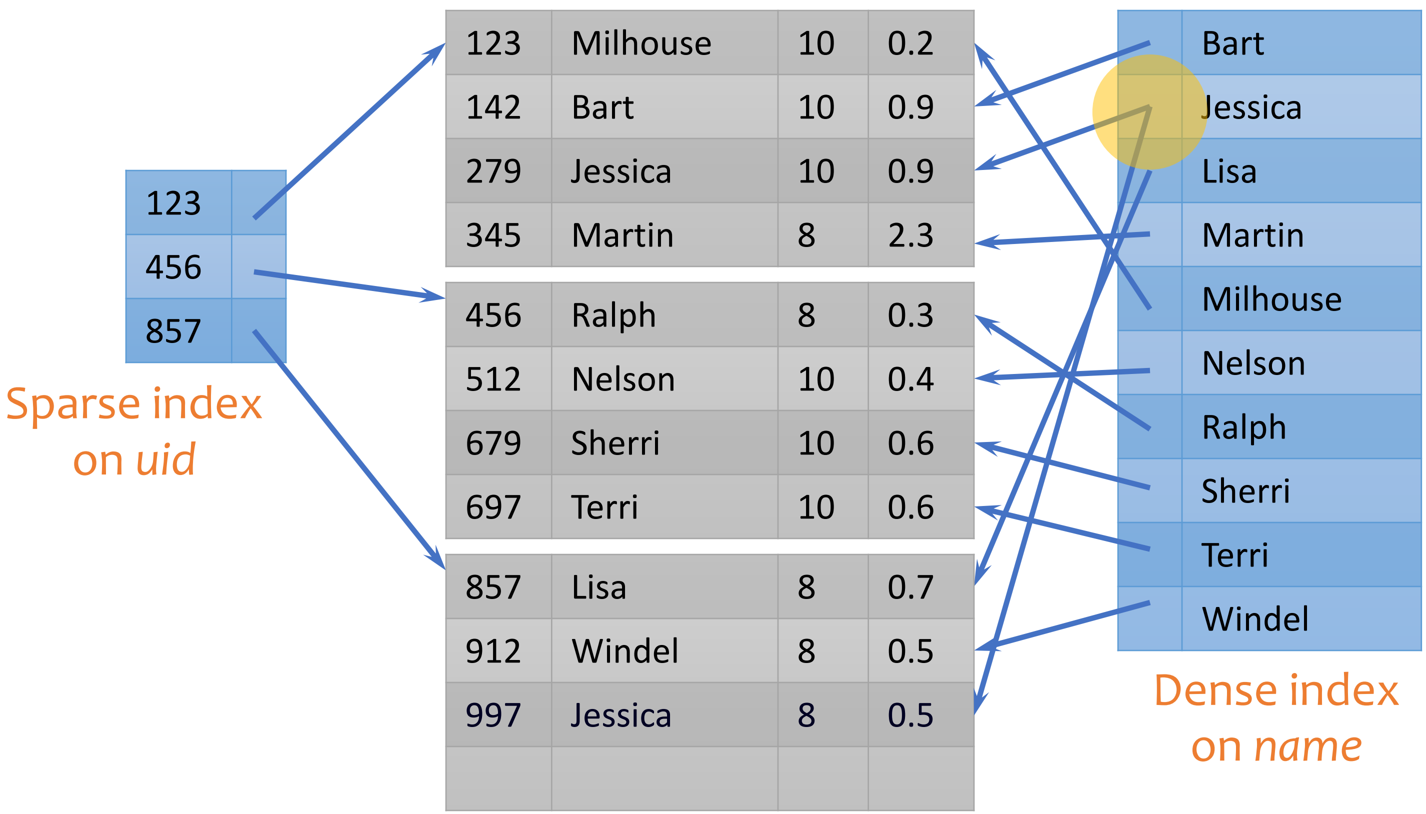
Column oriented

1	2	3
Bart	Lisa	Abe
.6	.9	.3
12	10	65

Indexes

Dense v.s. sparse indexes

- Dense: one index entry for each search key value
  - One entry may "point" to multiple records (e.g., two users named Jessica)
- Sparse: one index entry for each block
  - Records must be clustered according to the search key on disk



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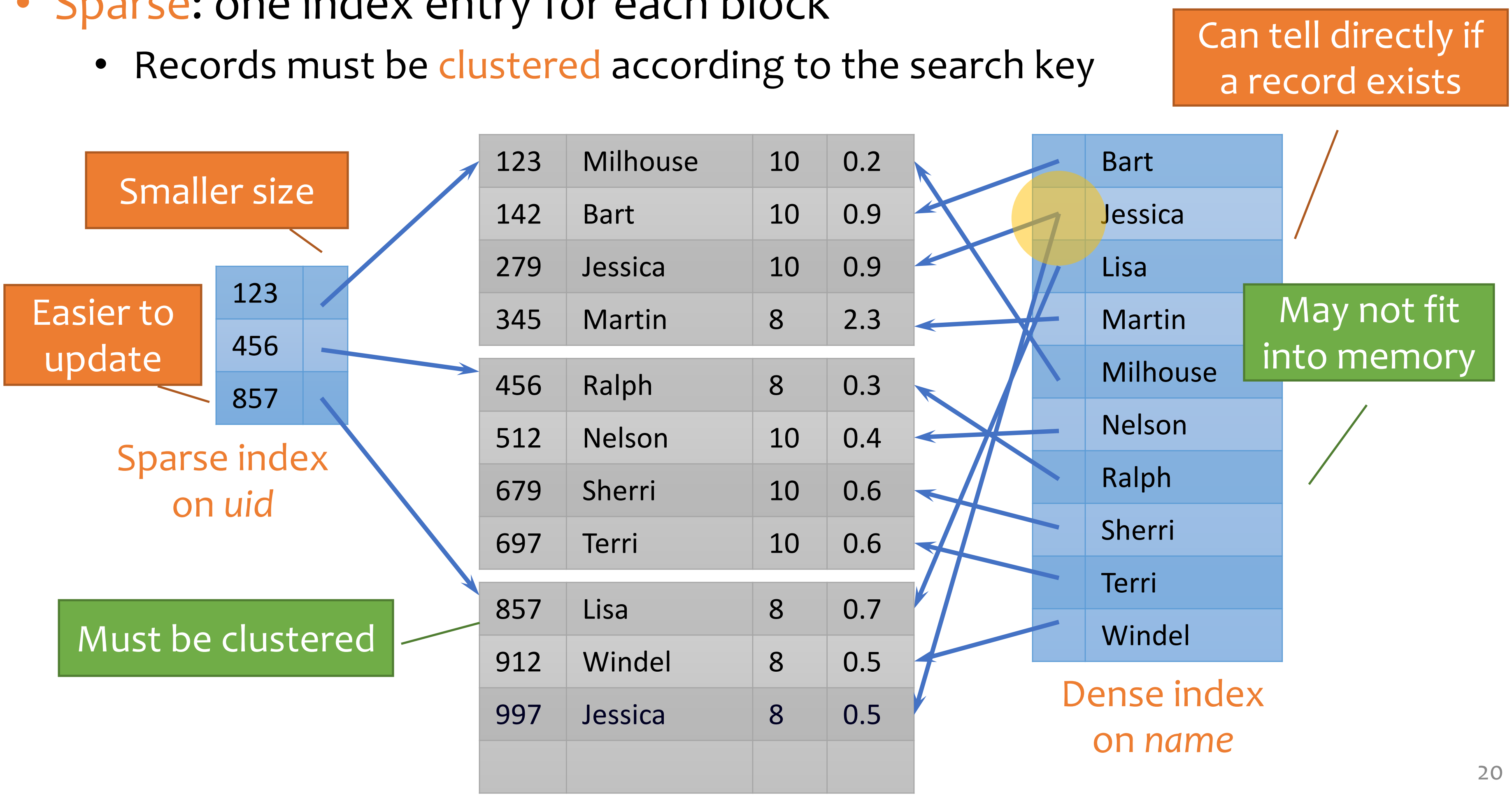
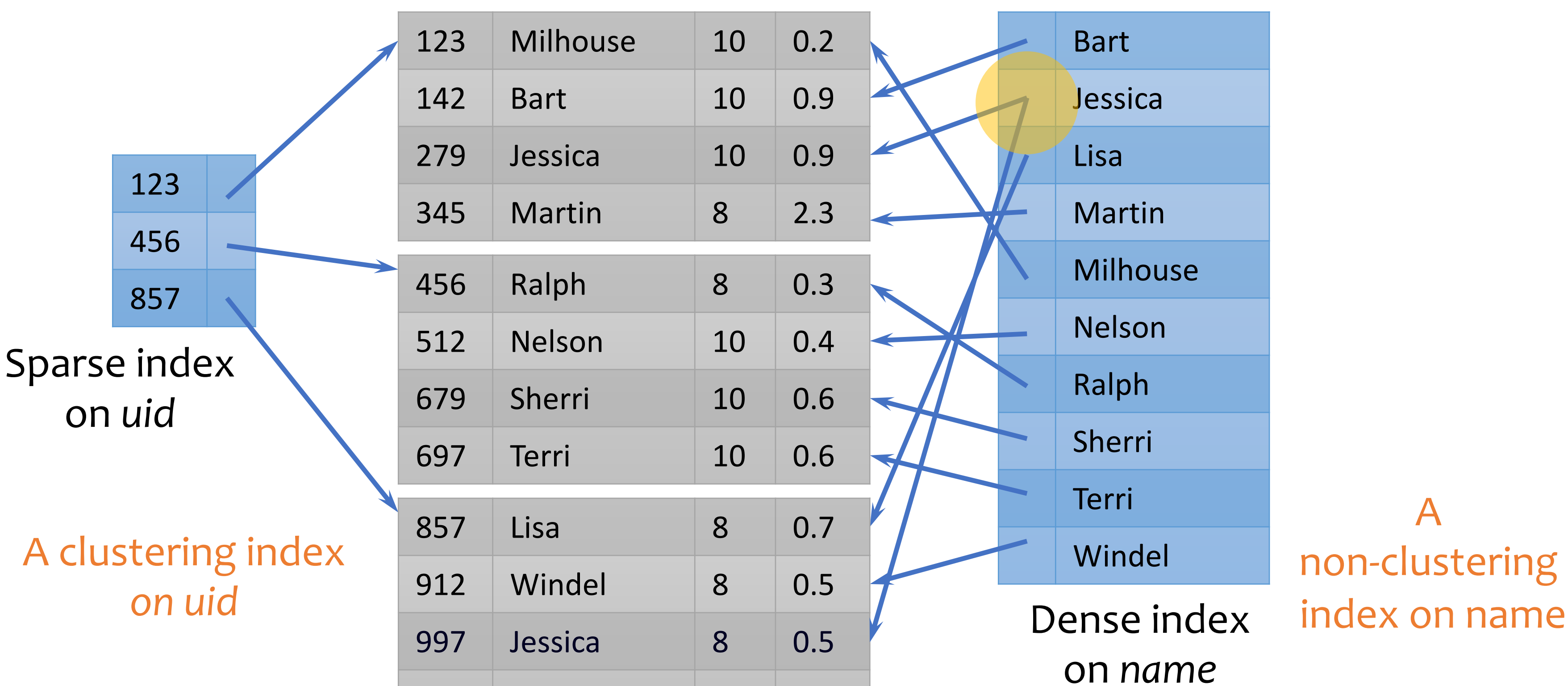


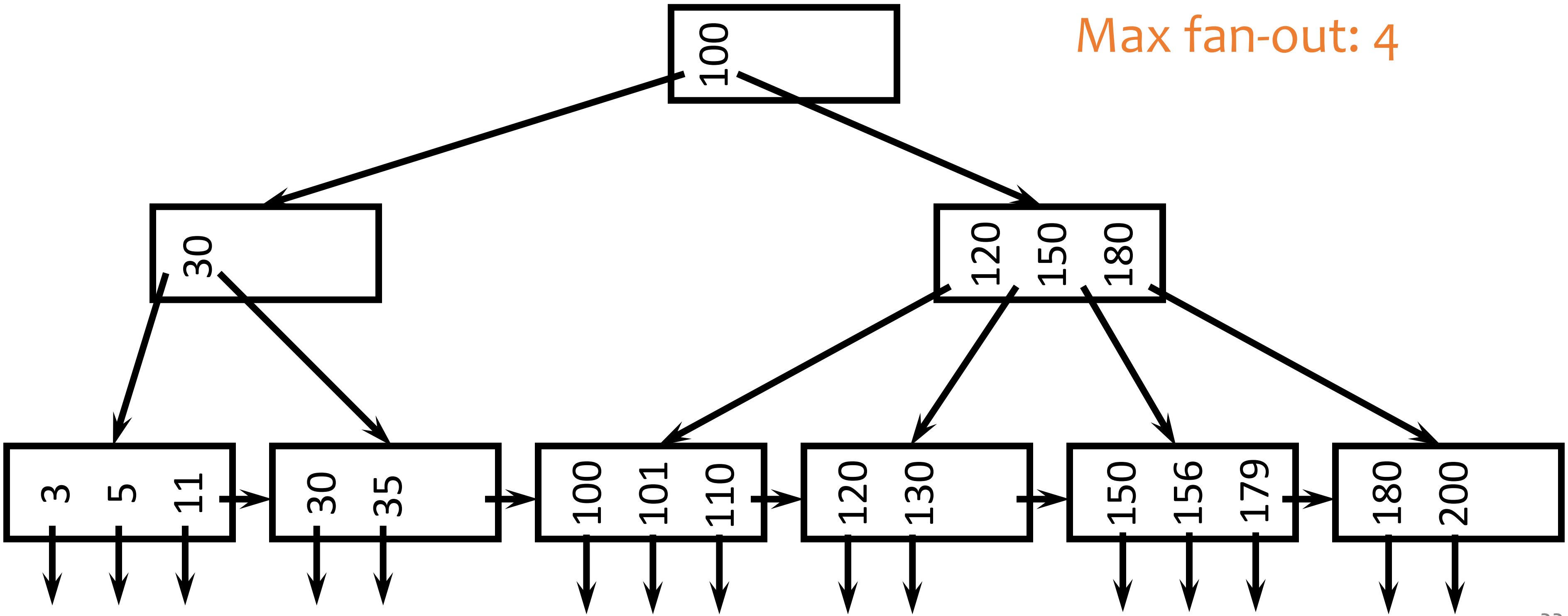
Clustering v.s. non-clustering indexes

- An index on attribute A is a clustering index if tuples in the relation with similar values for A are stored together in the same block.
- Other indices are non-clustering (or secondary) indices.
- Note: A relation may have at most one clustering index, and any number of non-clustering indices.

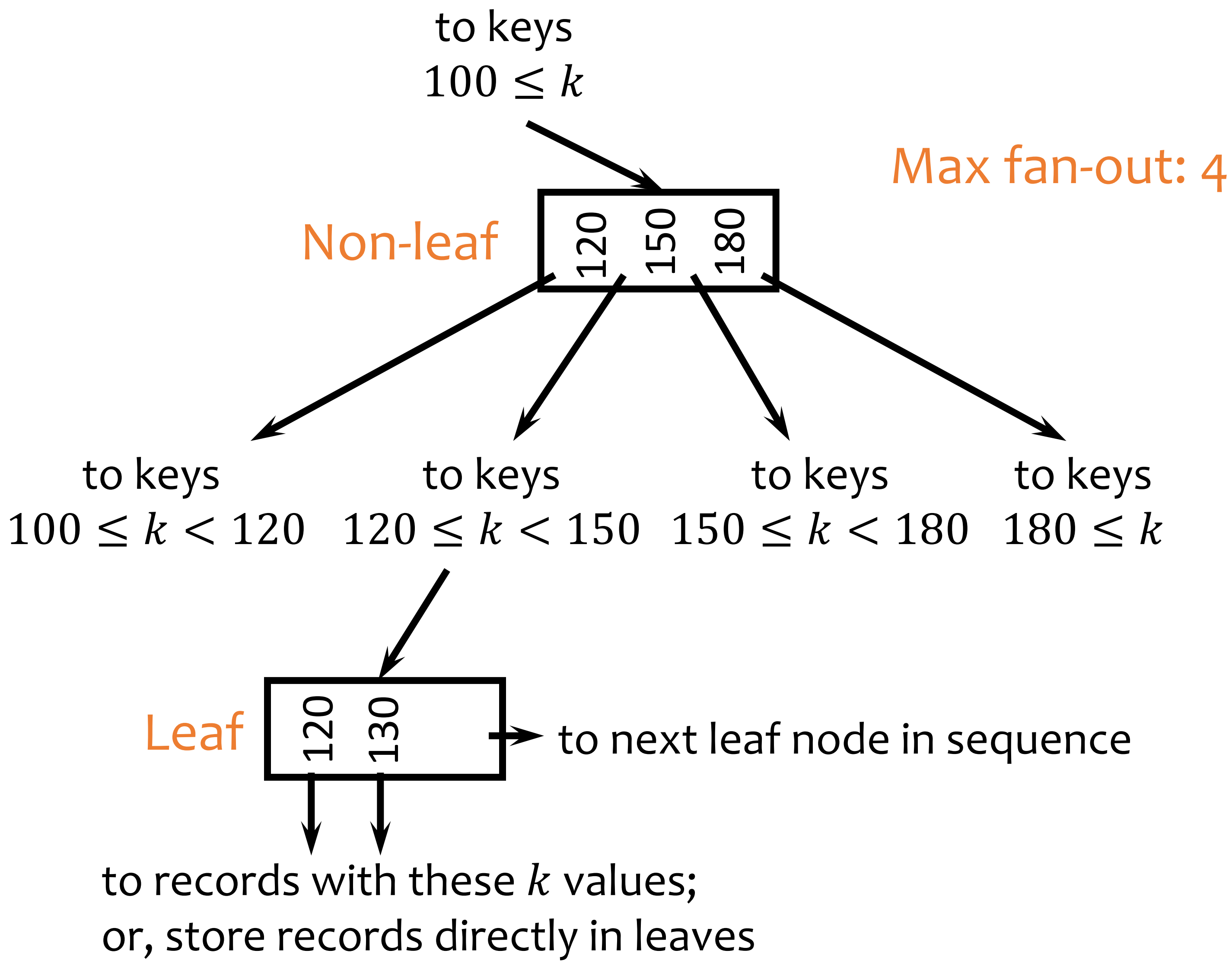


B+-tree

- A hierarchy of nodes with intervals
- Balanced: good performance guarantee
- Disk-based: one node per block; large fan-out

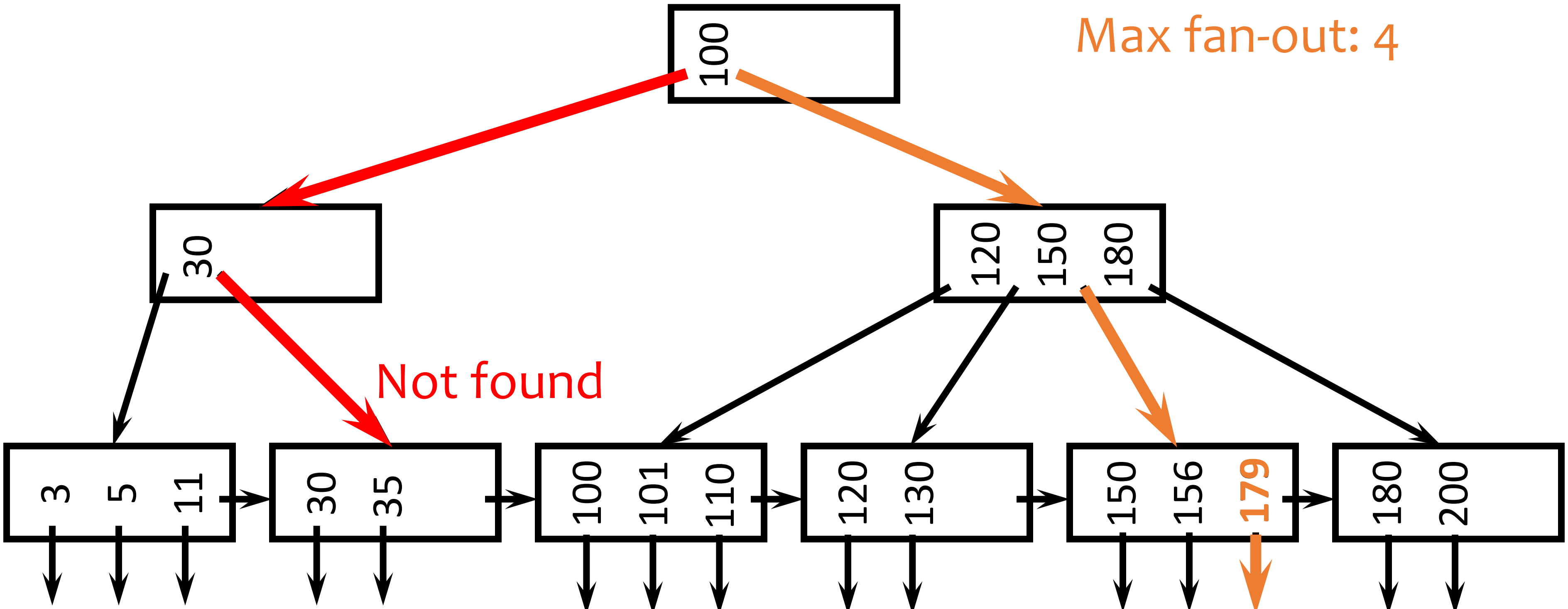


Sample B⁺-tree nodes



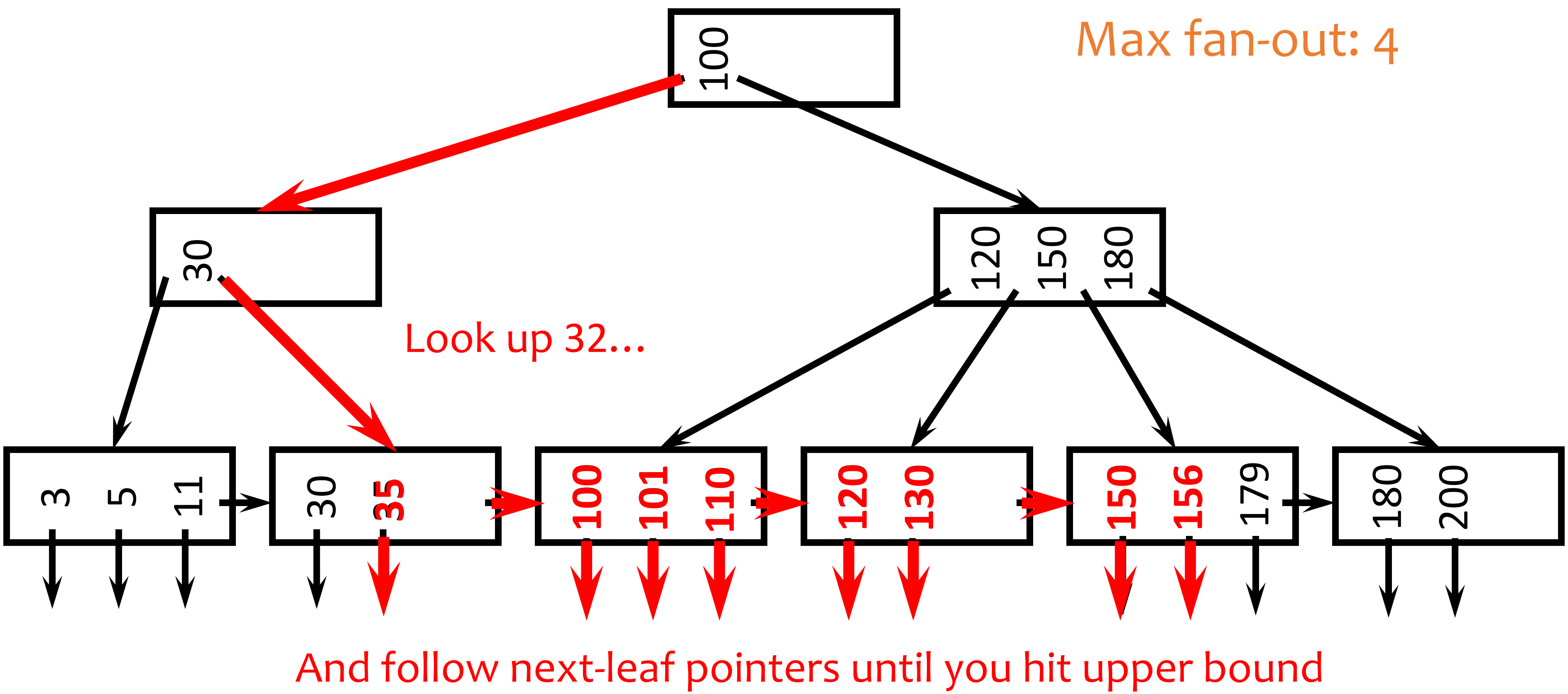
Lookups

- SELECT * FROM *R* WHERE *k* = 179;
- SELECT * FROM *R* WHERE *k* = 32;



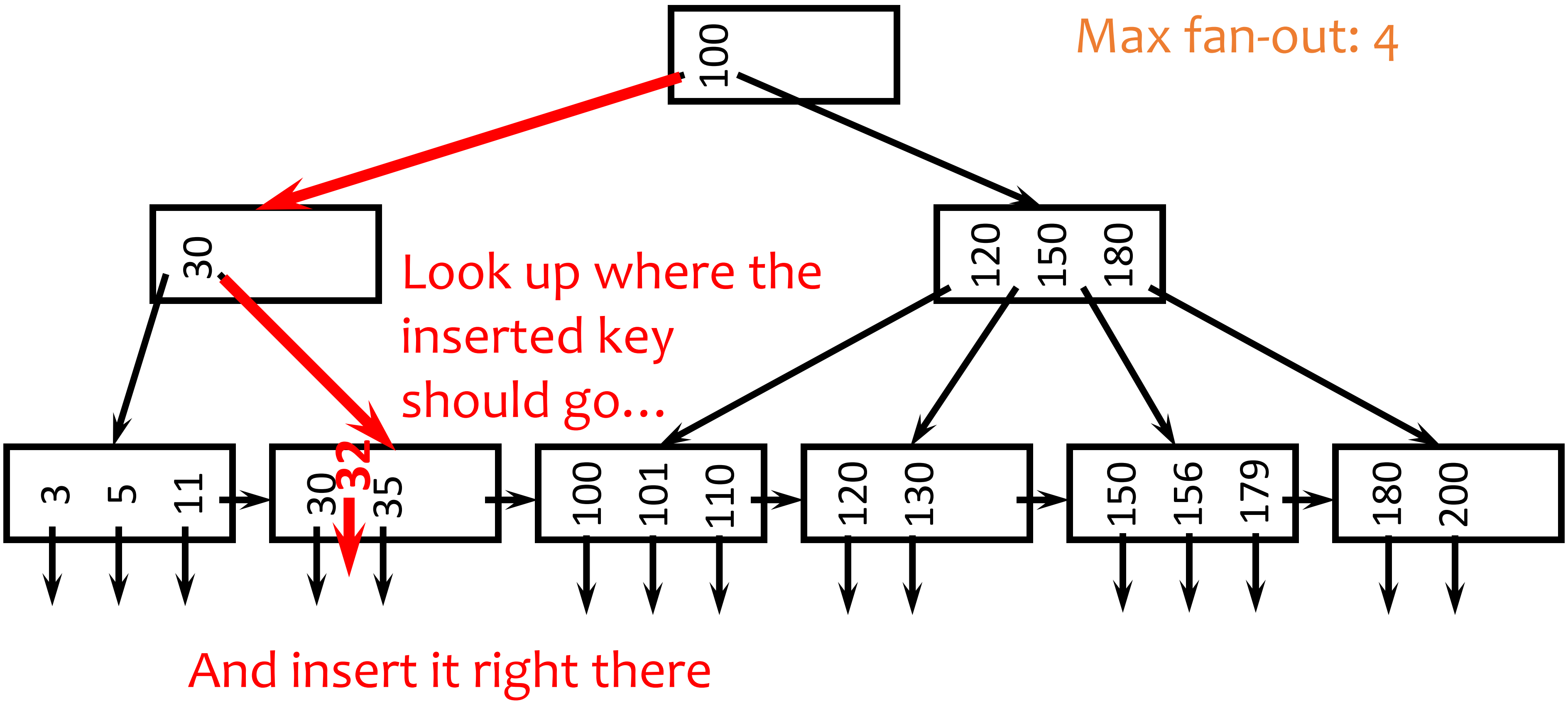
Range query

- SELECT * FROM *R* WHERE *k* > 32 AND *k* < 179;



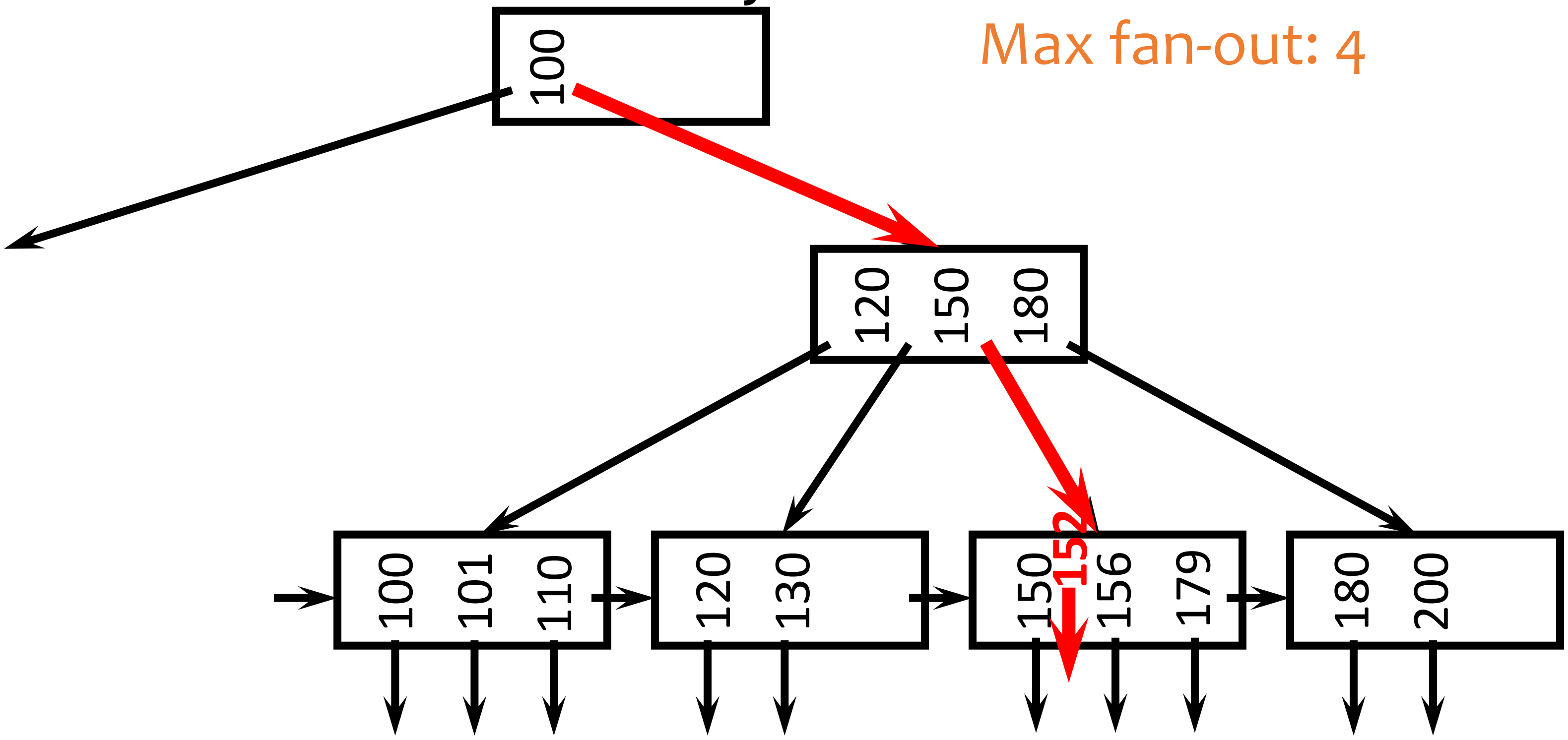
Insertion

- Insert a record with search key value 32

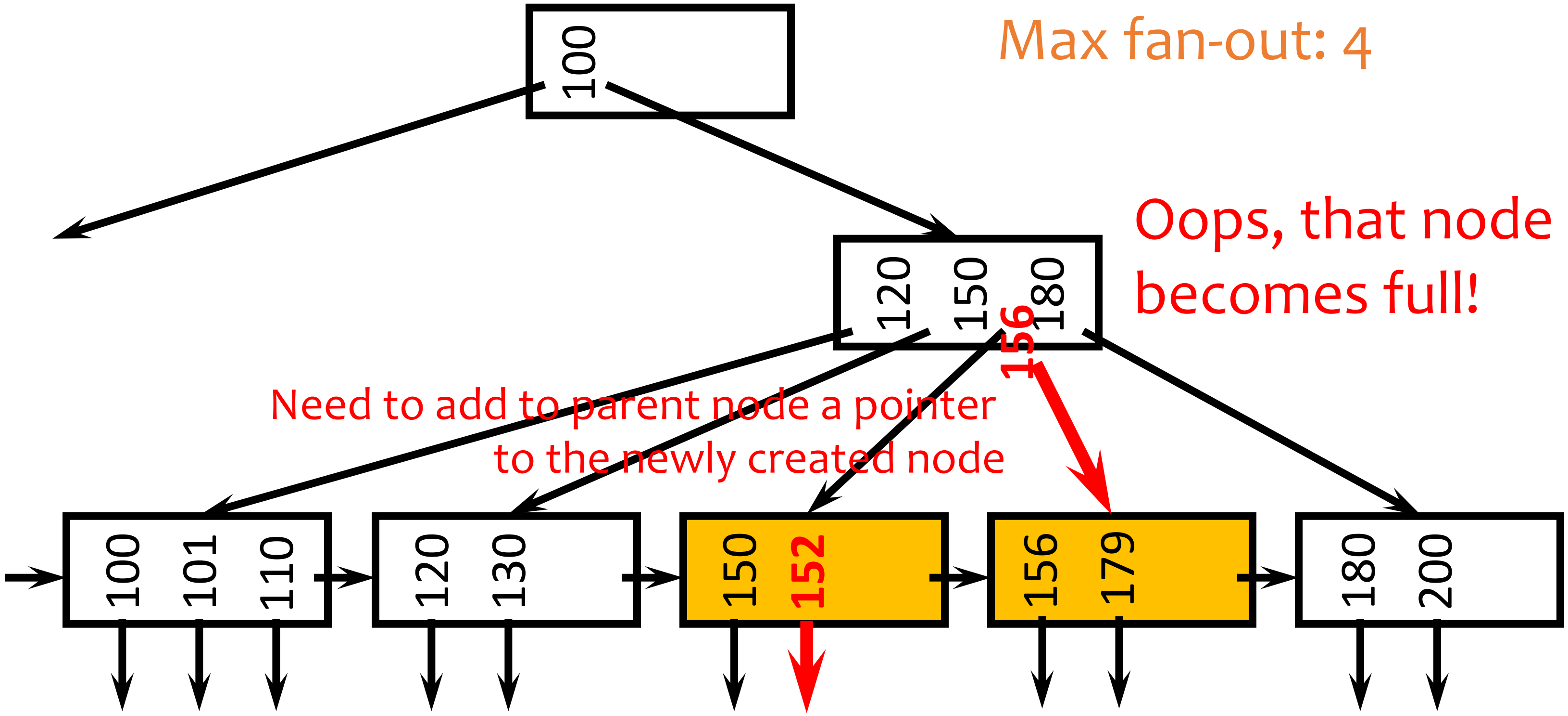


Another insertion example

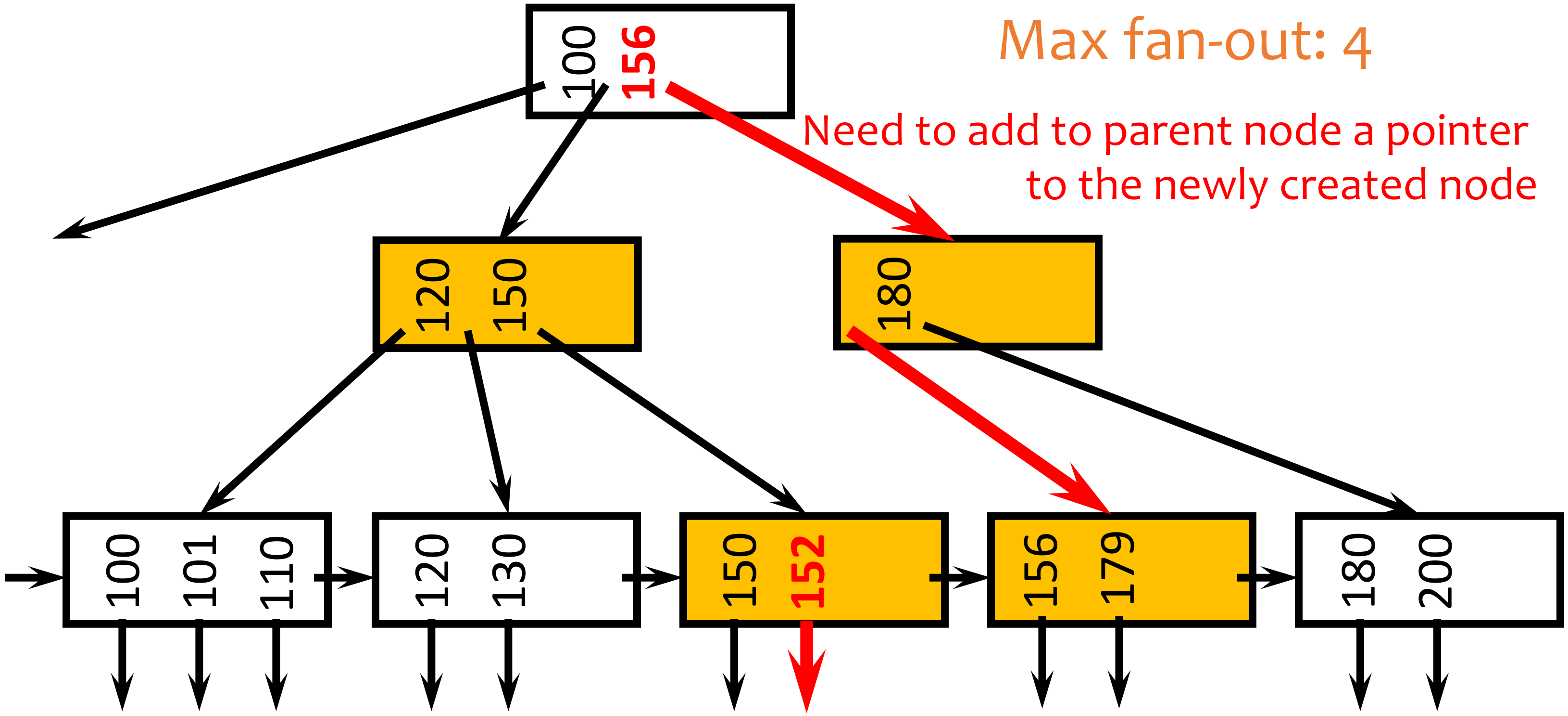
- Insert a record with search key value 152



Node splitting



More node splitting



- In the worst case, node splitting can "propagate" all the way up to the root of the tree (not illustrated here)
  - Splitting the root introduces a new root of fan-out 2 and causes the tree to grow "up" by one level

Index-only plan

- For example:
  - SELECT firstname, pop FROM User WHERE pop > ‘0.8’ AND firstname = ‘Bob’;
  - non-clustering index on (firstname, pop)

- A (non-clustered) index contains all the columns needed to answer the query without having to access the tuples in the base relation.
  - Avoid one disk I/O per tuple
  - The index is much smaller than the base relation

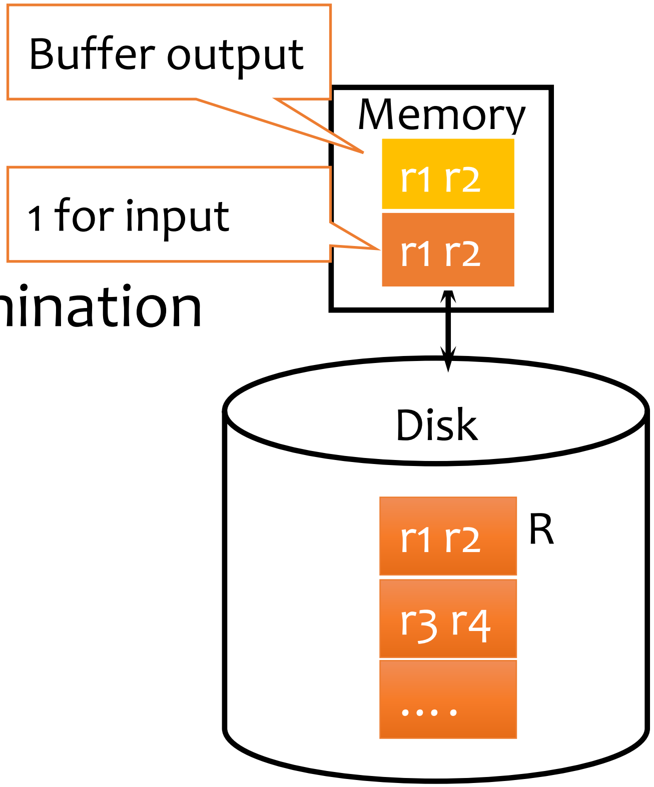
Query processing

Notation

- Relations: R, S
- Tuples: r, s
- Number of tuples: $|R|$, $|S|$
- Number of disk blocks: $B(R)$, $B(S)$
- Number of memory blocks available: M
- Cost metric
  - Number of I/O's
  - Memory requirement

Table scan

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



Basic nested-loop join

$R \bowtie_p S$

- `For each` r `in a block` B_R `of` R`:`
  - `For each` s `in a block` B_S `of` S`:`
    - `Output` rs `if` p `is true over` r `and` s

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

  Blocks of R are moved into memory only once

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

- Memory requirement: 3

Improvement: block nested-loop join

$R \bowtie_p S$

- For each block B_R of R:
    - For each block B_S of S:
        - For each r in B_R :
            - For each s in B_S:
                - Output rs if p is true over r and s

- I/O's: $B(R) + B(R) \cdot B(S)$

Blocks of R are moved into memory only once

Blocks of S are moved into memory B(R) number of times

- Memory requirement: 3

More improvements

- Stop early if the key of the inner table is being matched
- Make use of available memory
  - Stuff memory with as much of R as possible, stream S by, and join every S tuple with 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)

Indexes: 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 $R(B,A)$?

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

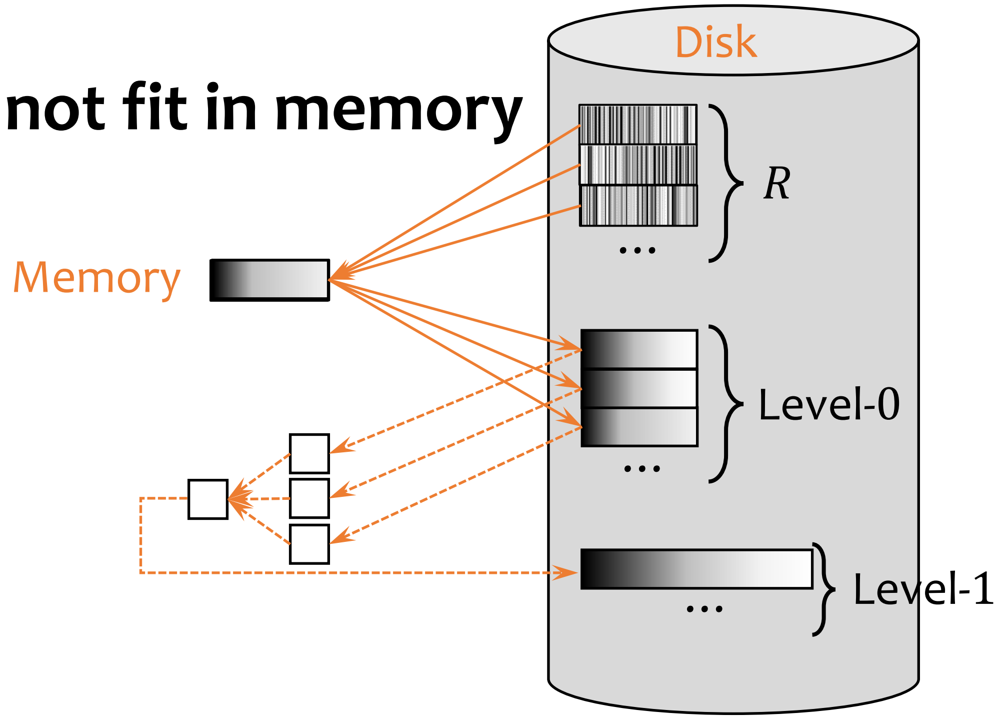
- I/O's: $B(R) + |R| \cdot (\text{index lookup}) + \text{I/O for record fetch}$
  - Typically, the cost of an index lookup is 2-4 I/O's (depending on the index tree height if B+ tree)
  - Beats other join methods if $|R|$ is not too big
  - Better pick R to be the smaller relation
- Memory requirement: 3 (extra memory can be used to cache index, e.g. root of B+ tree)

External merge sort

Recall in-memory merge sort: Sort progressively larger runs, 2, 4, 8, …, |R|, by merging consecutive "runs"

Problem: sort R, but R does not fit in memory

- 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

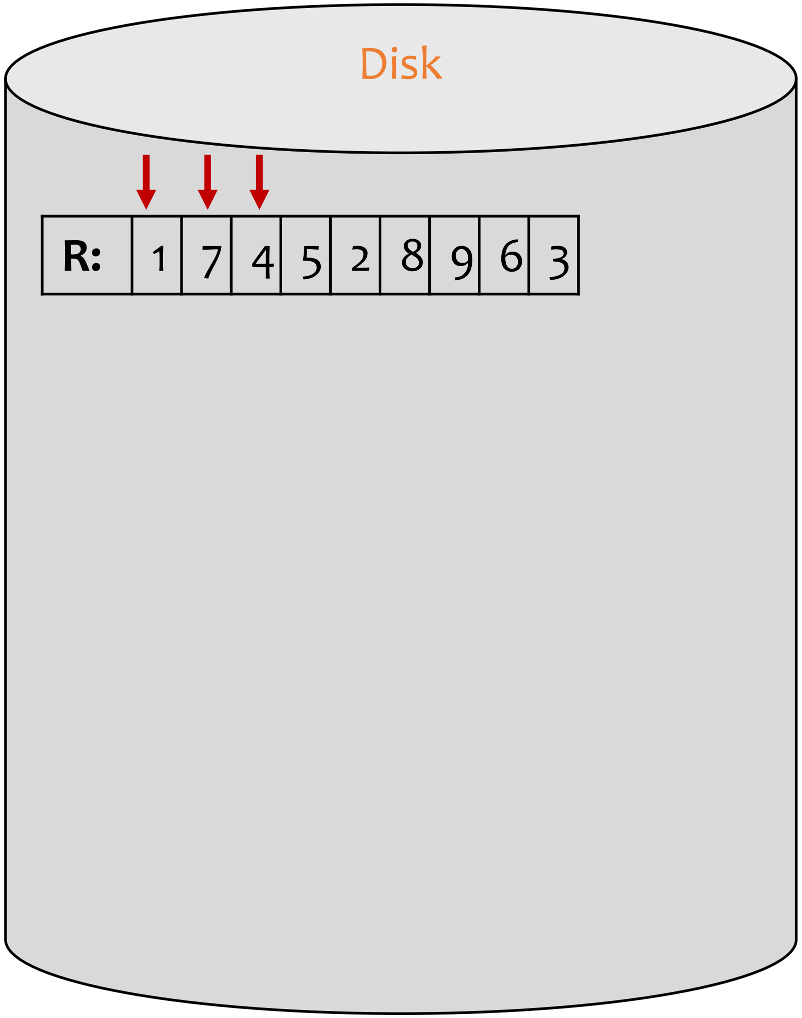
…

- 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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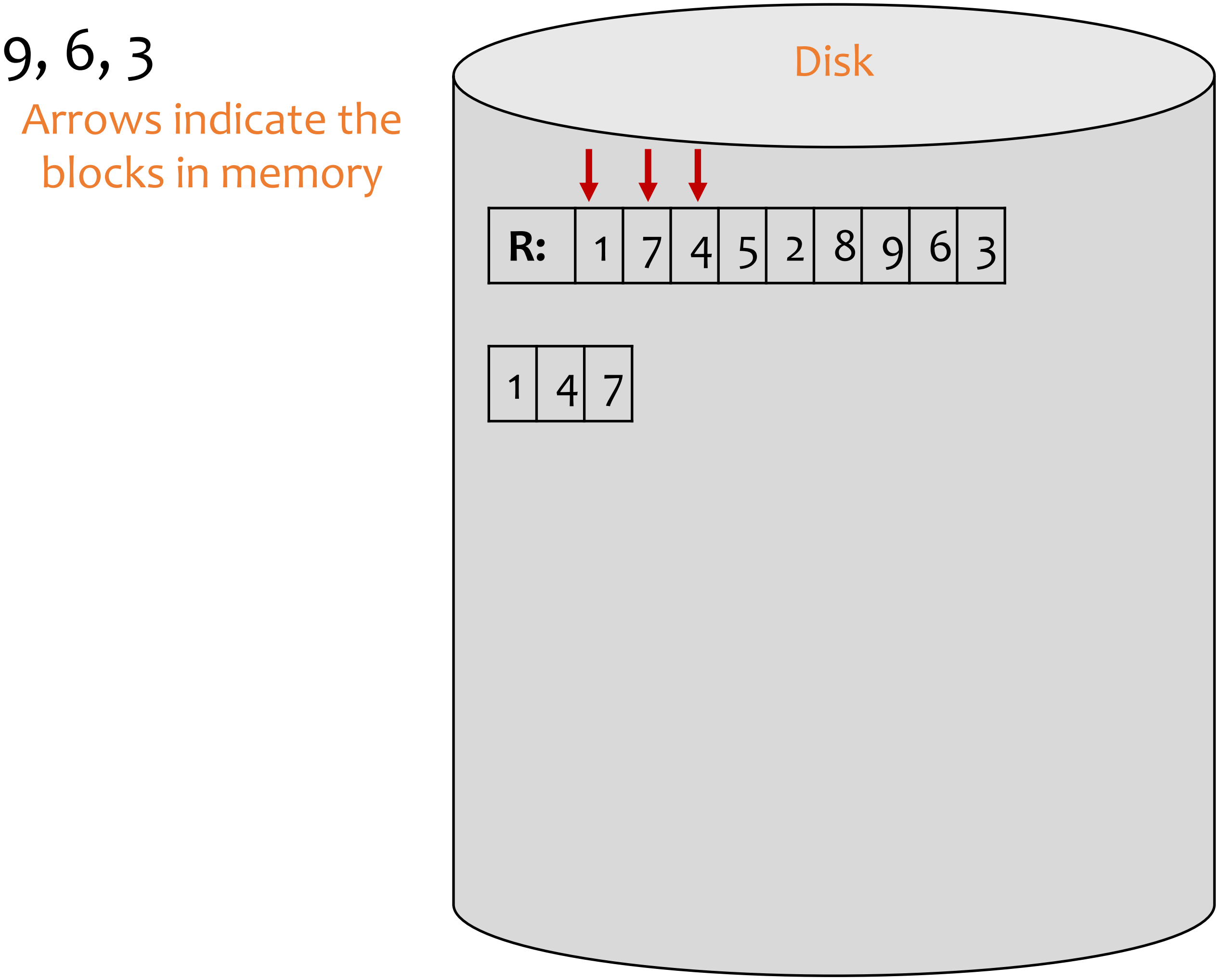

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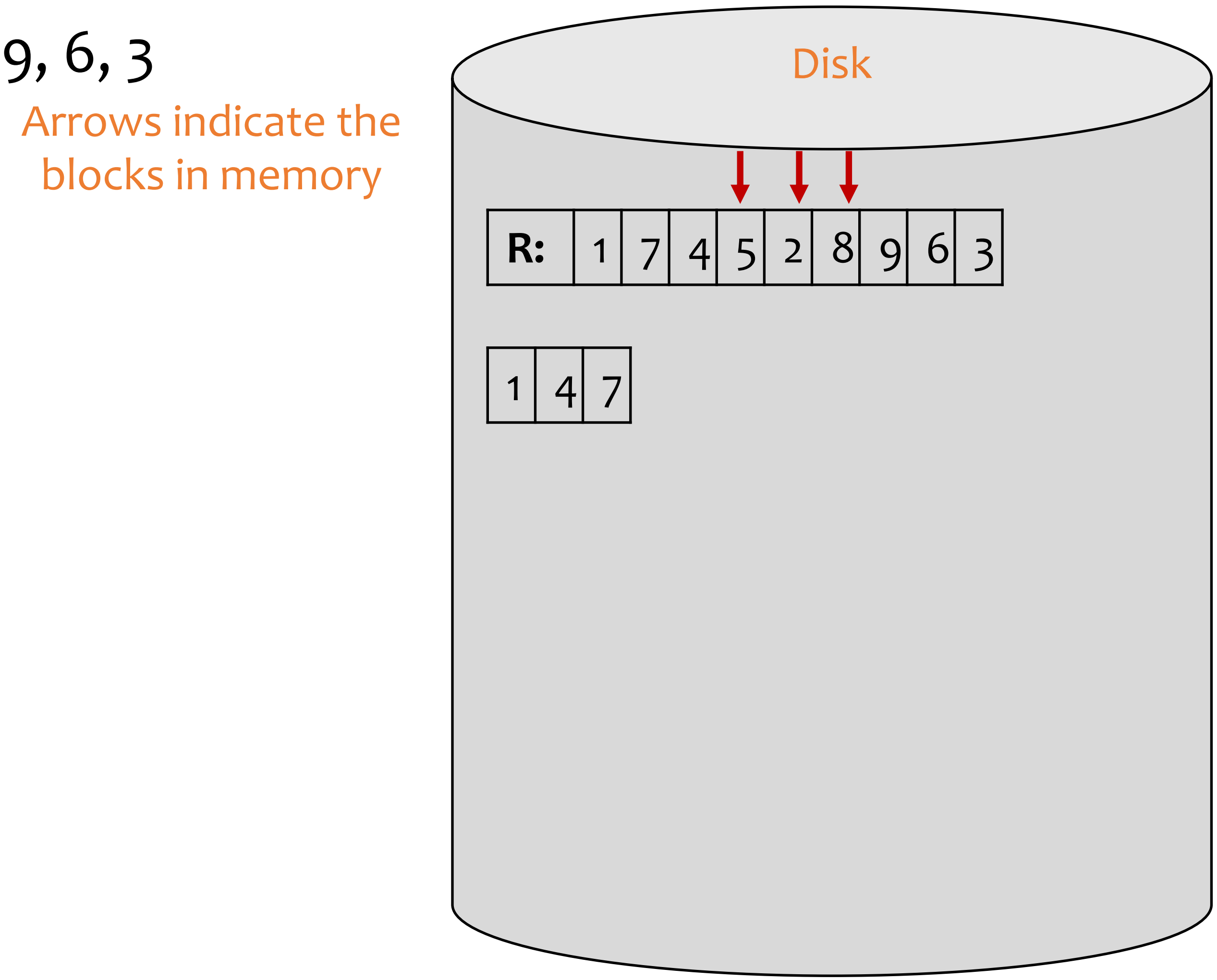

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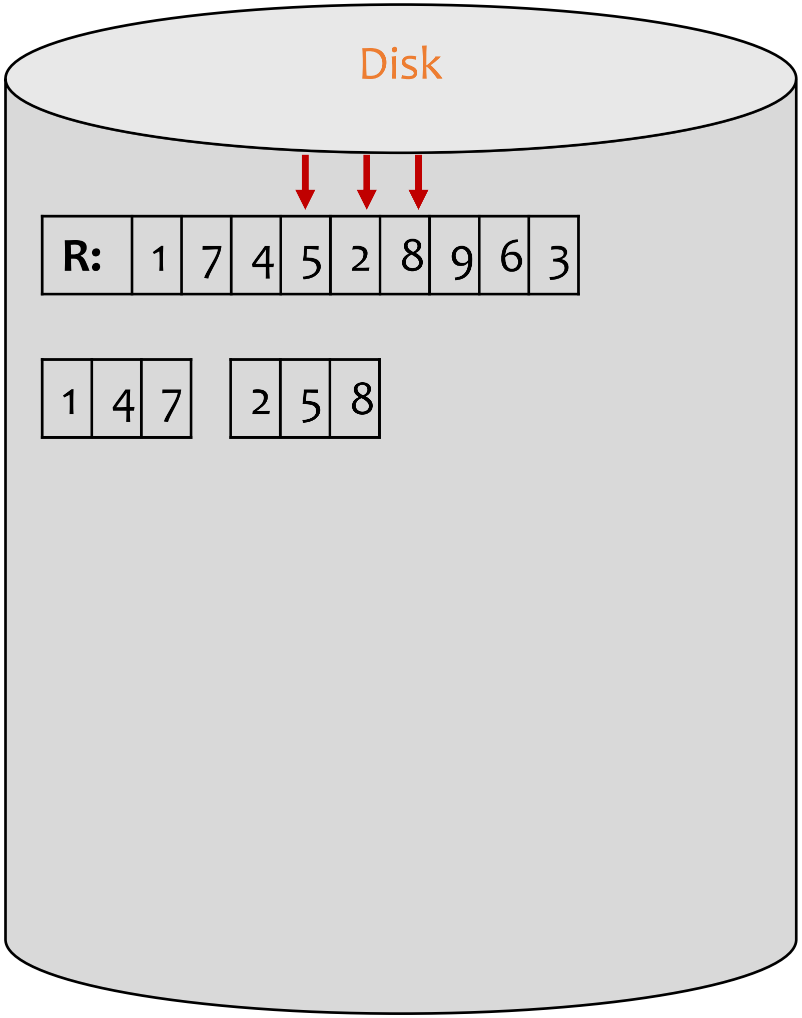

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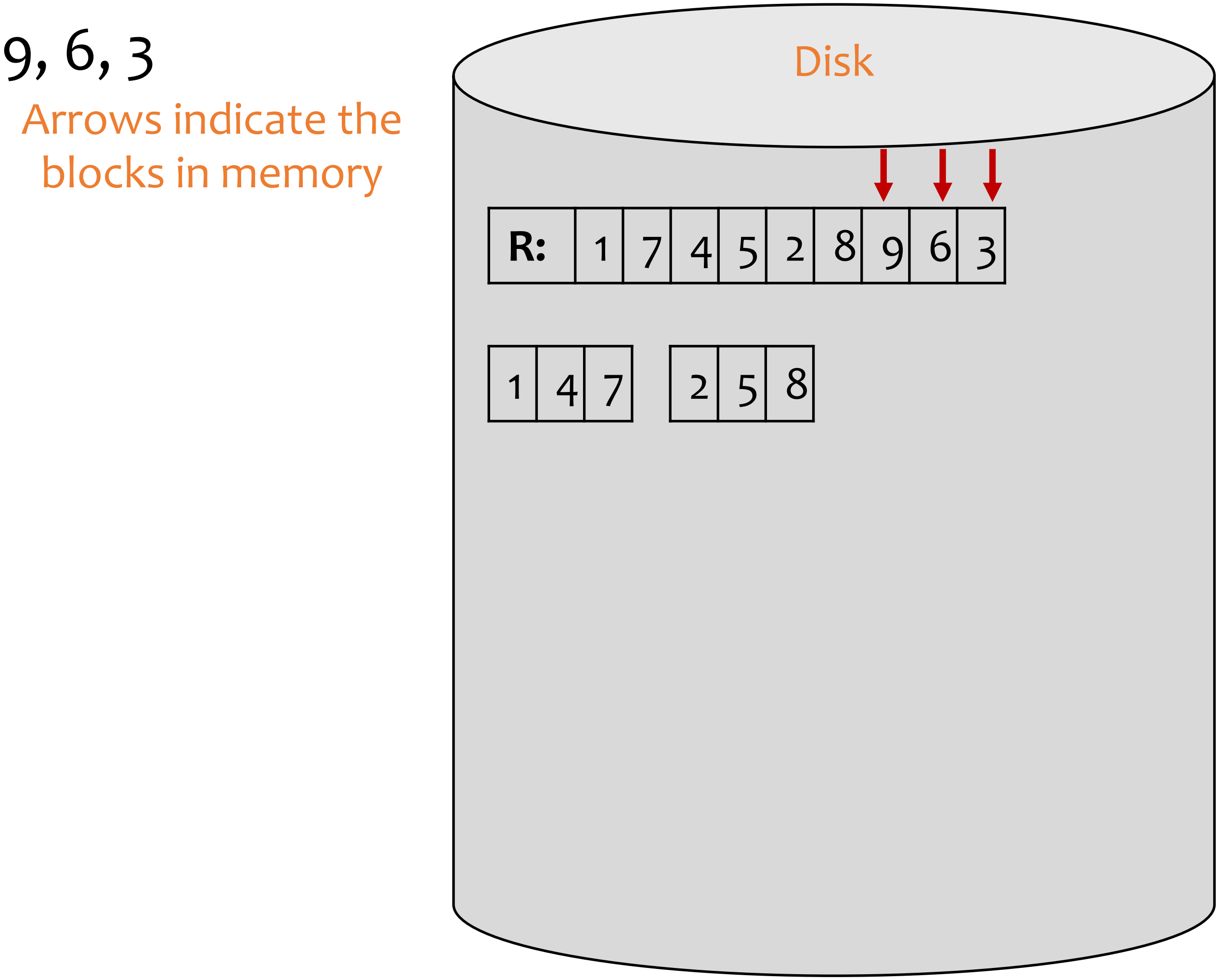

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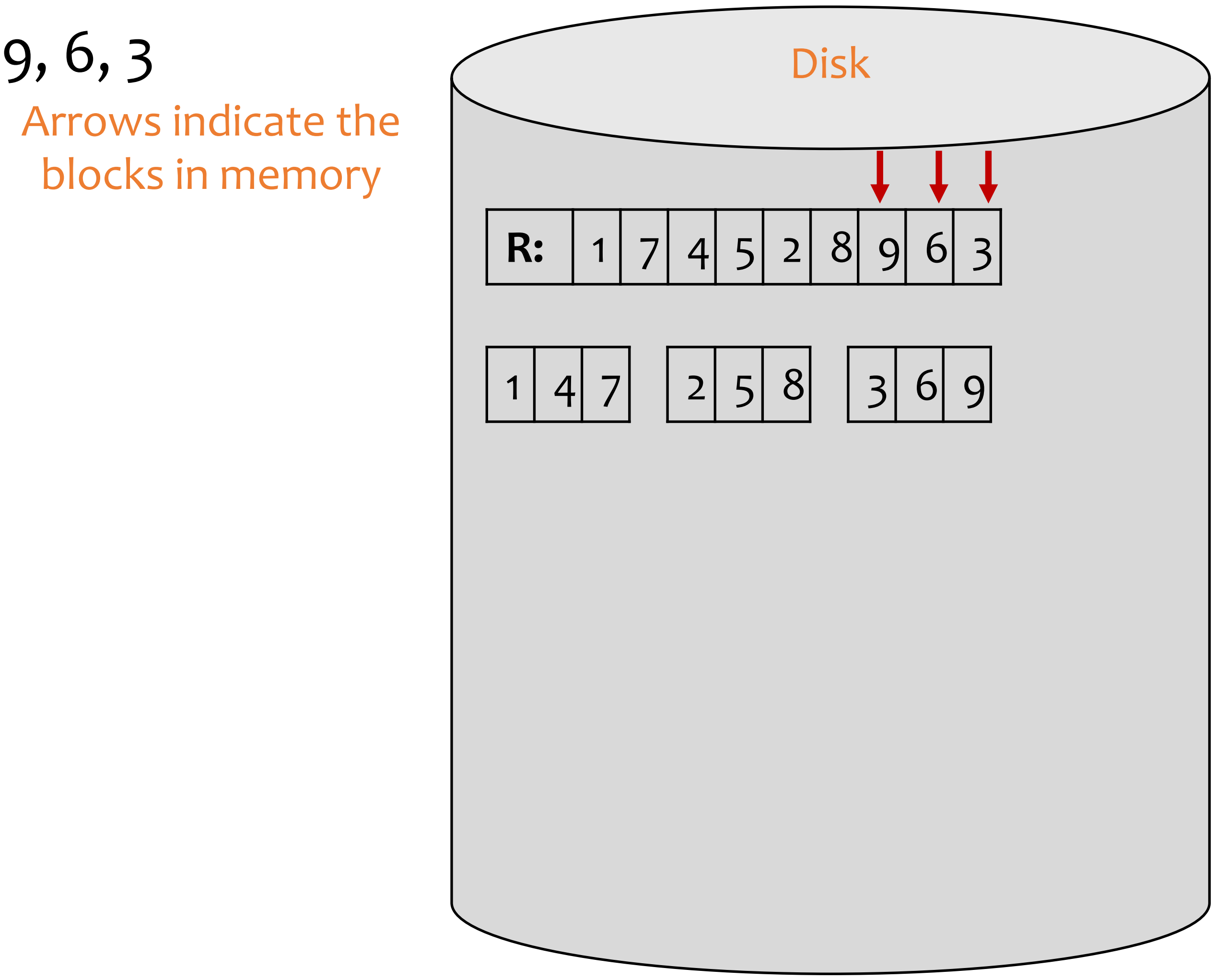

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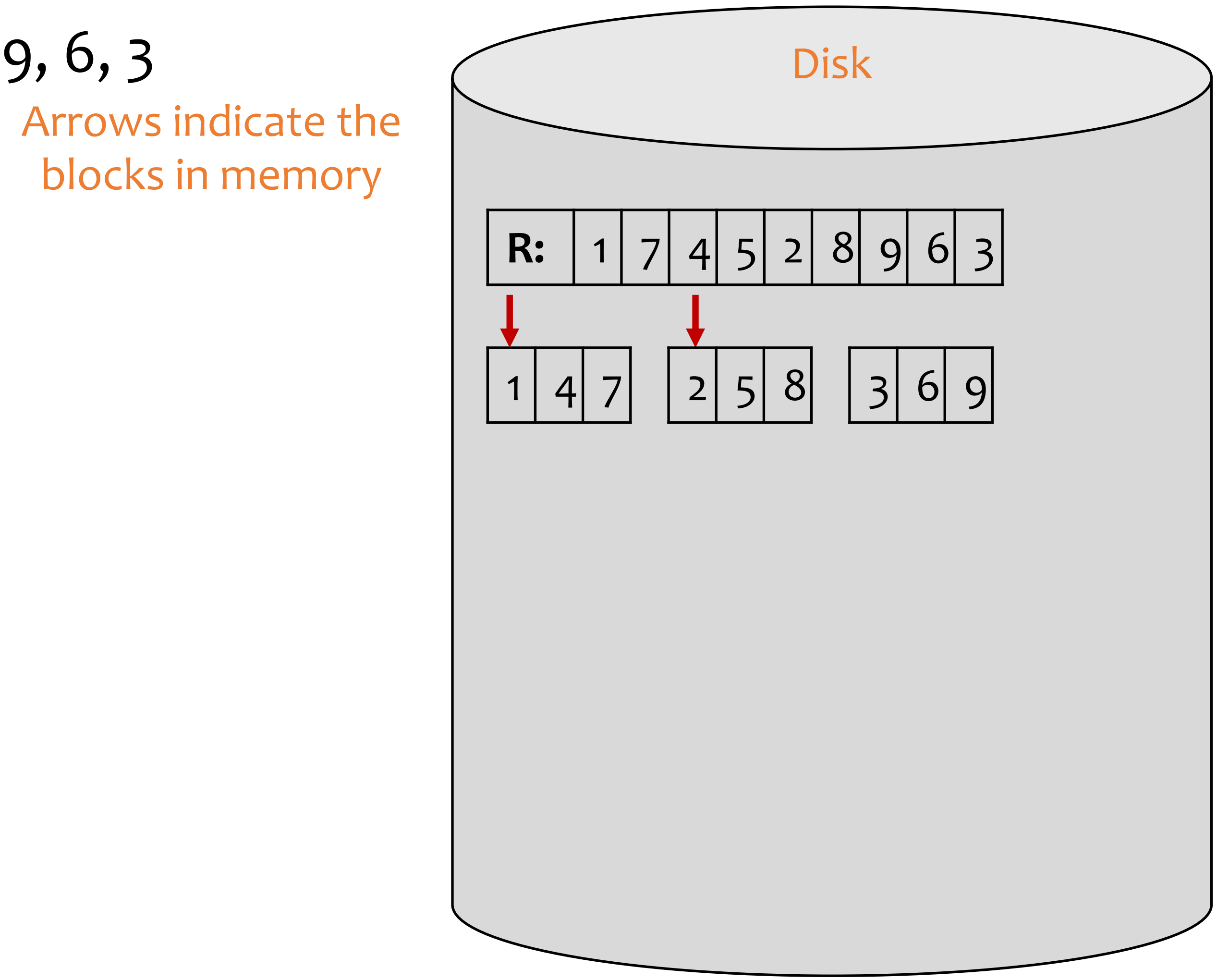

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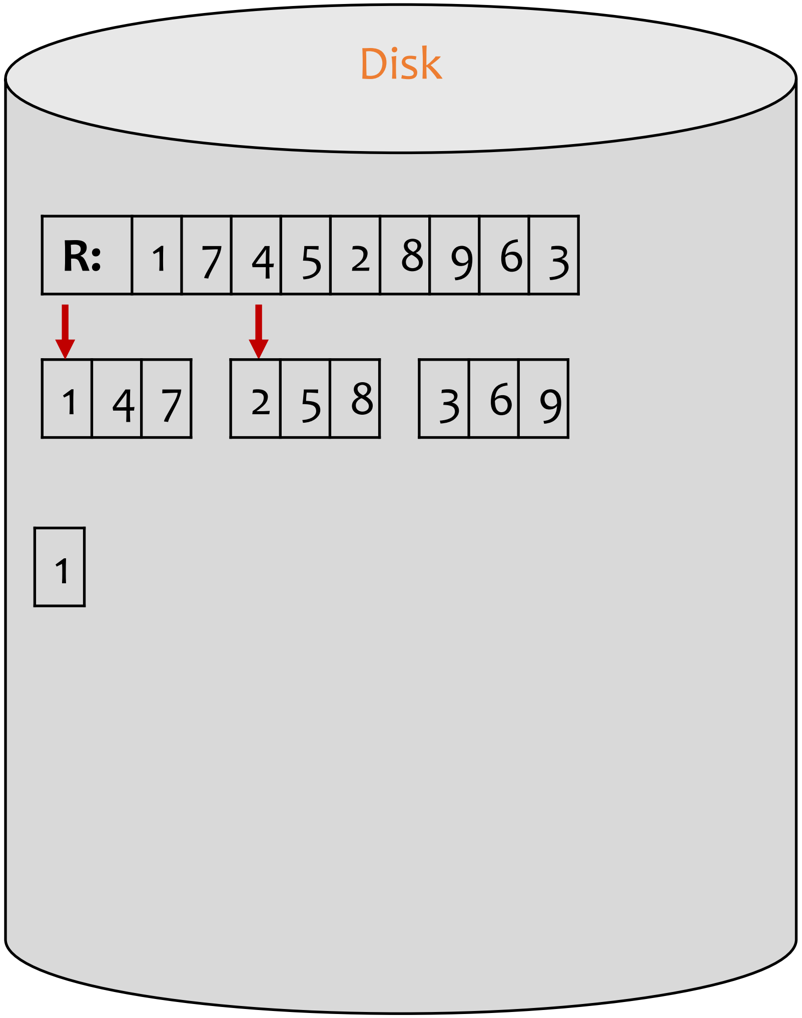

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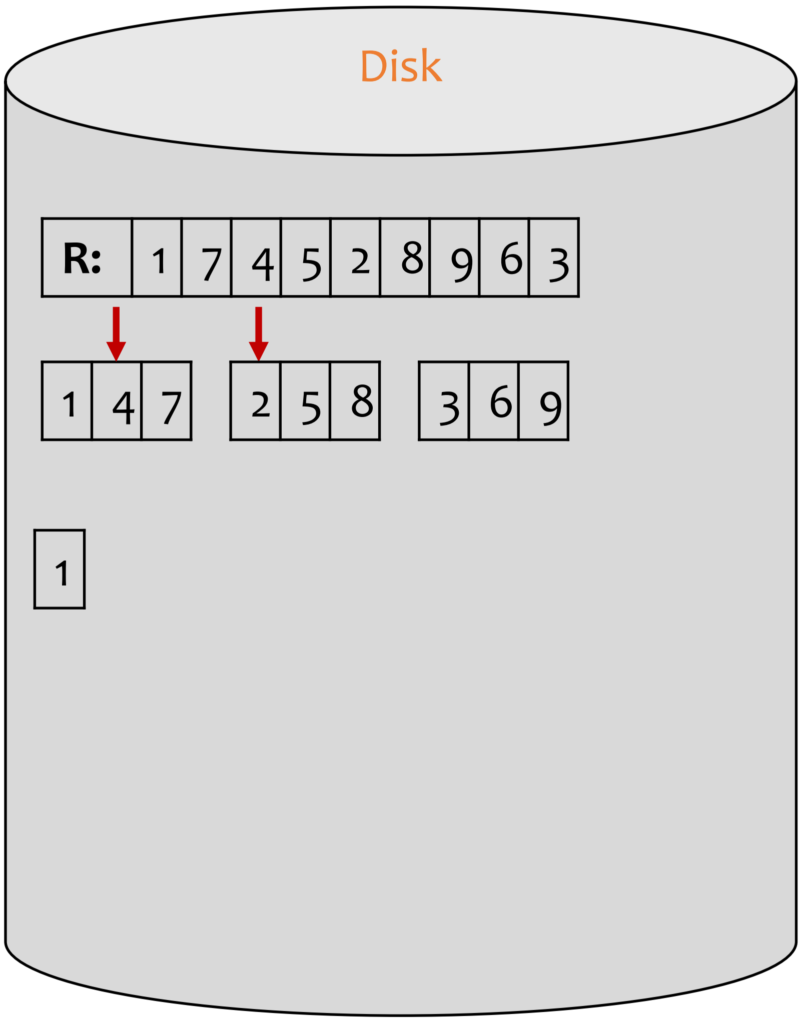

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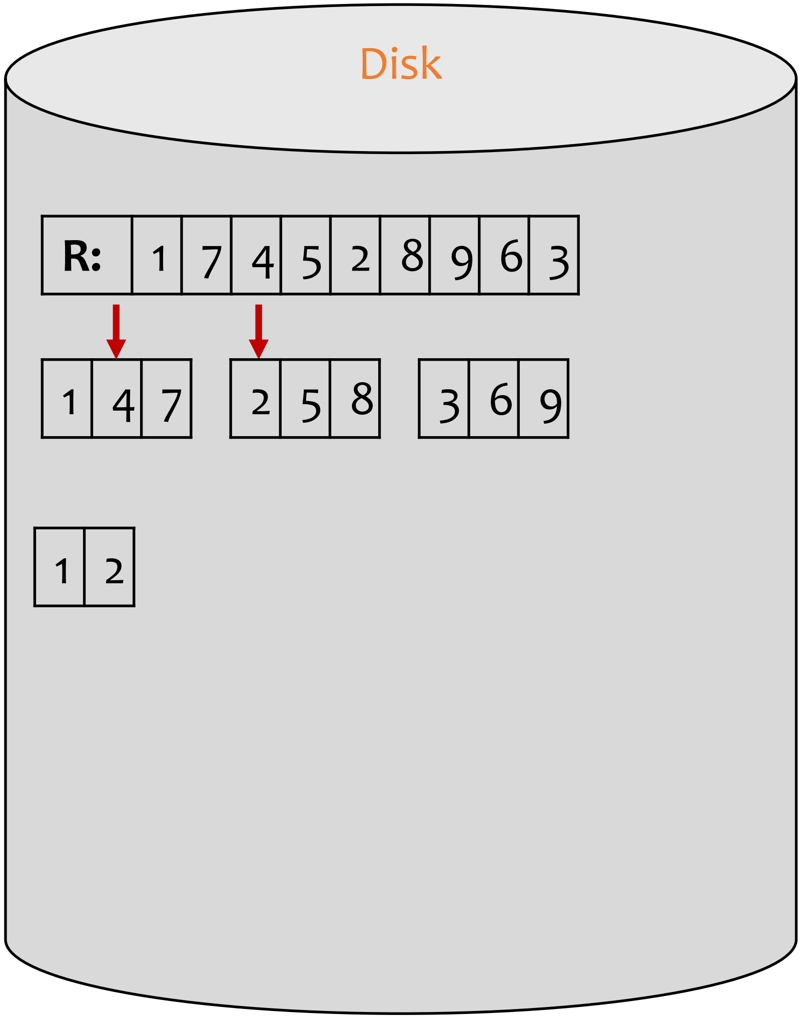

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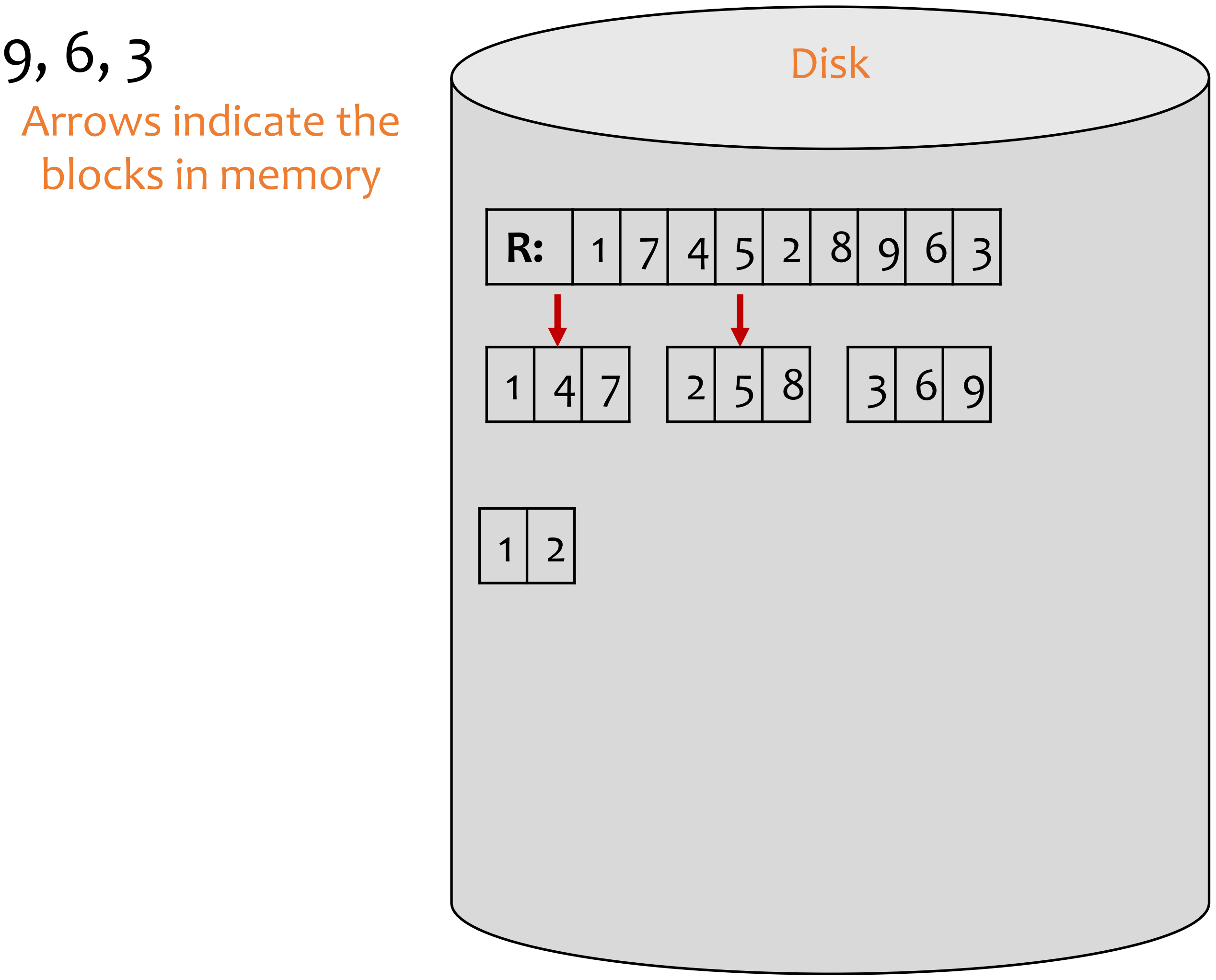

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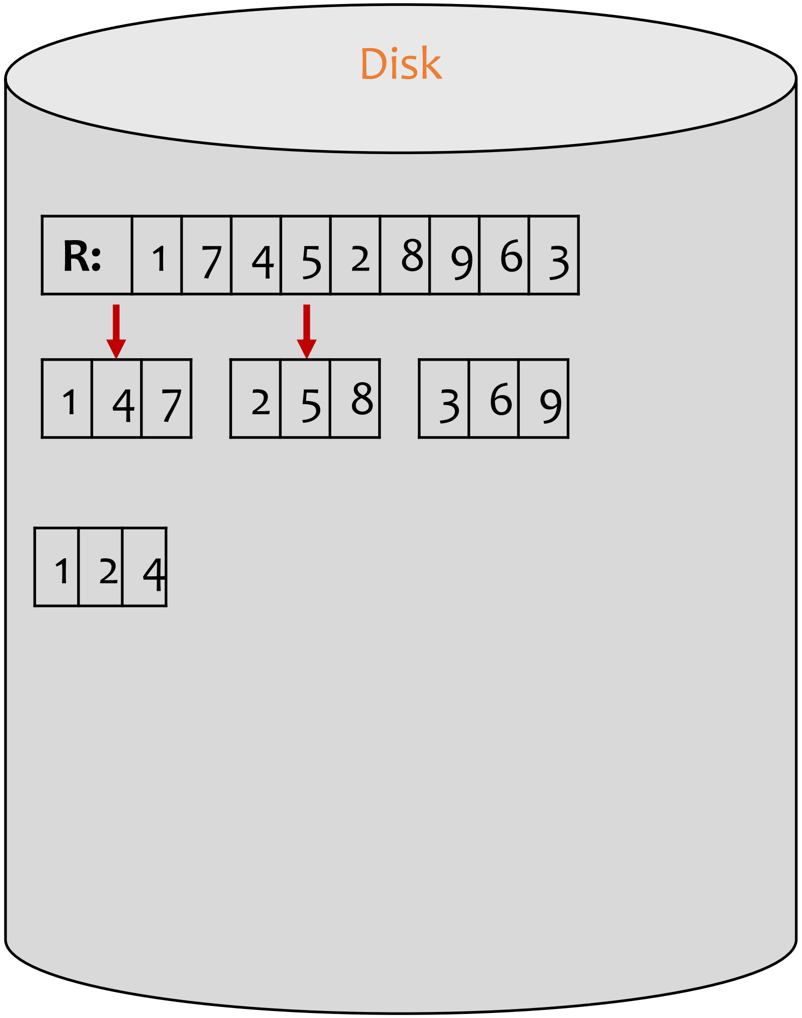

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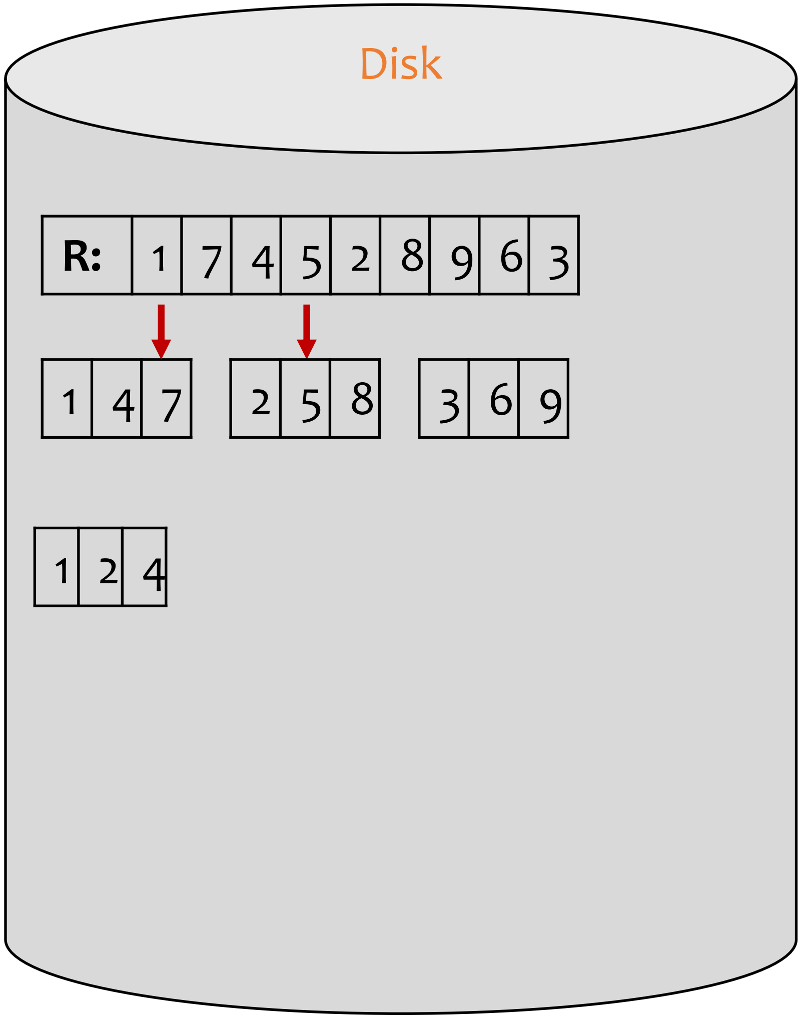

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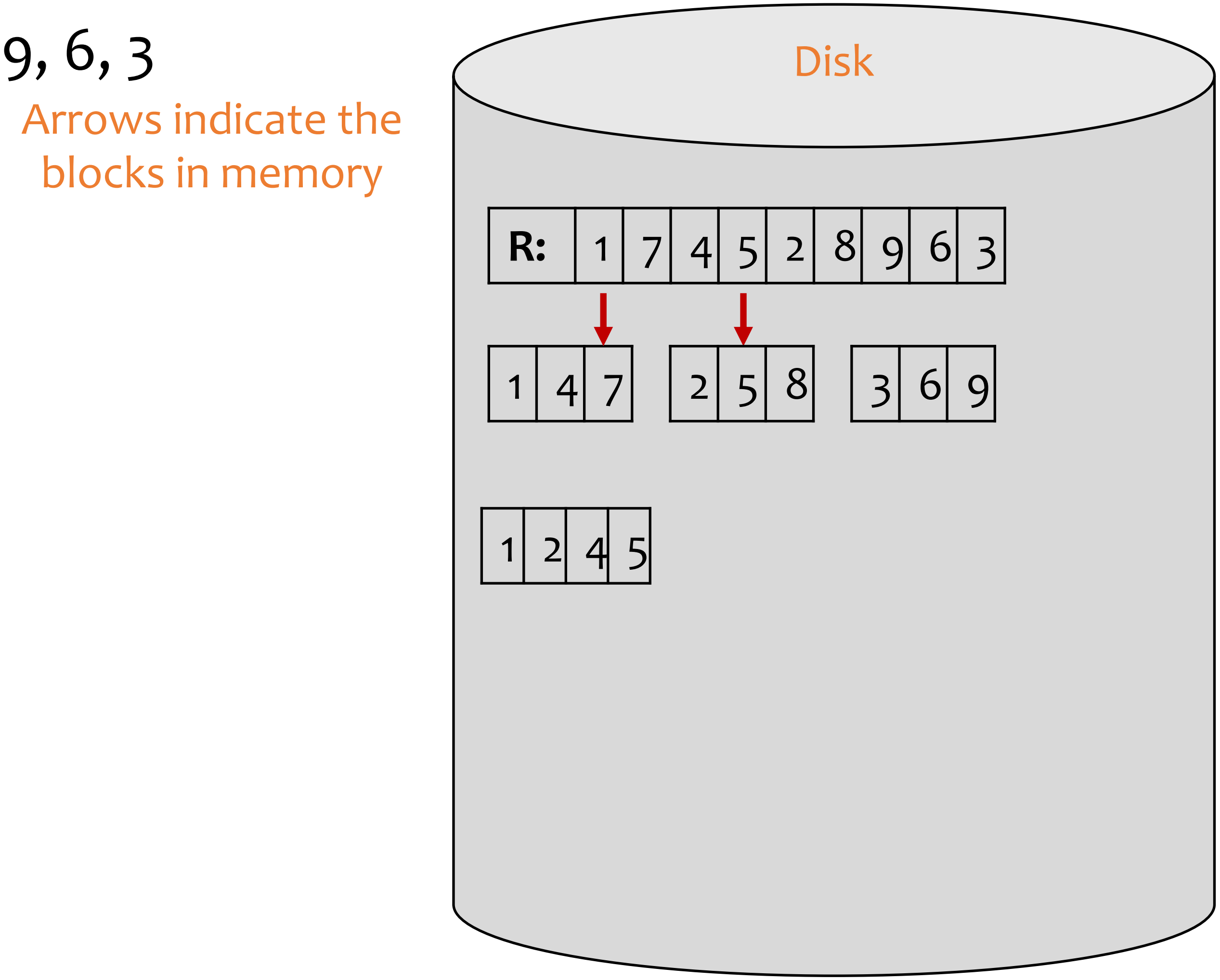

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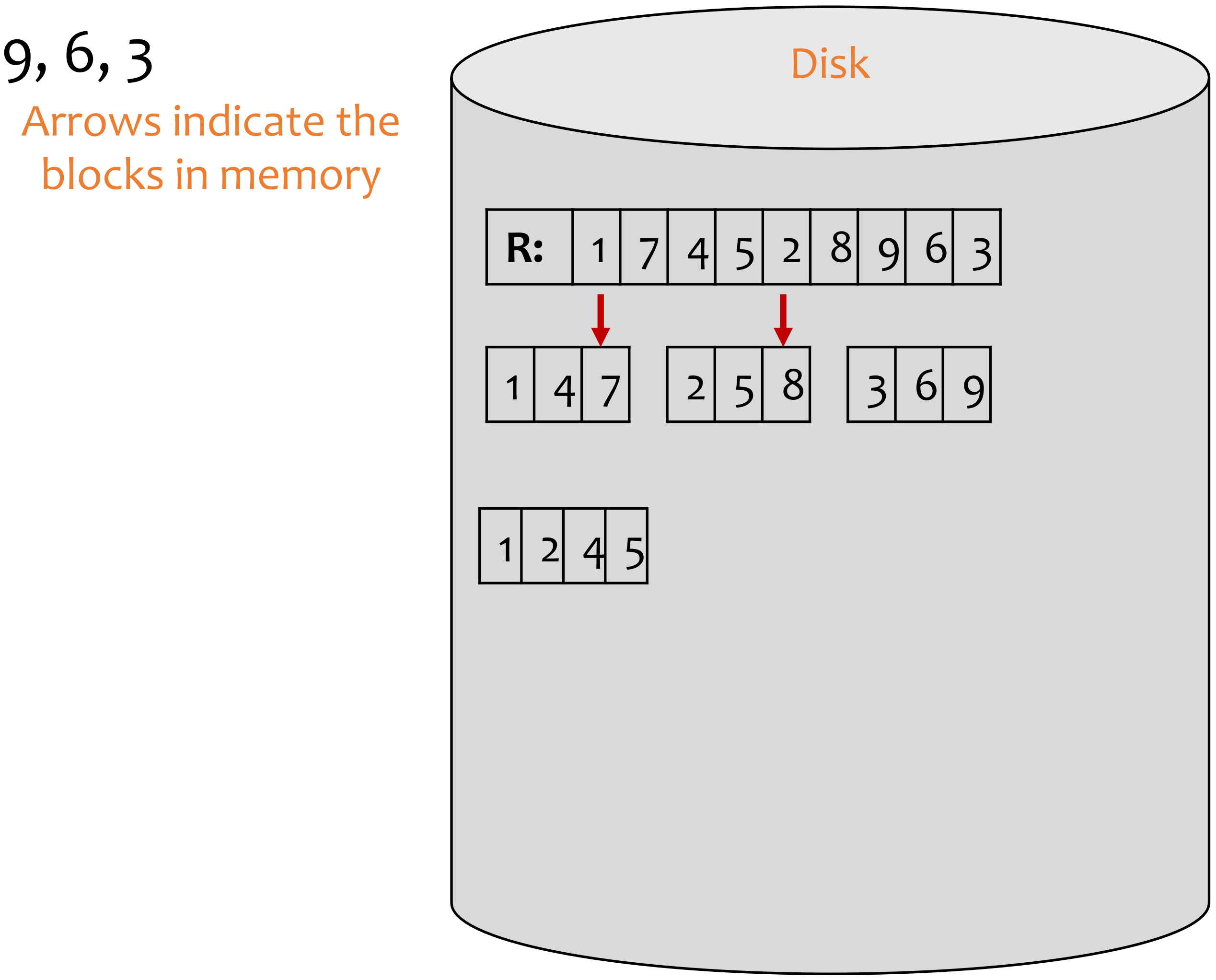

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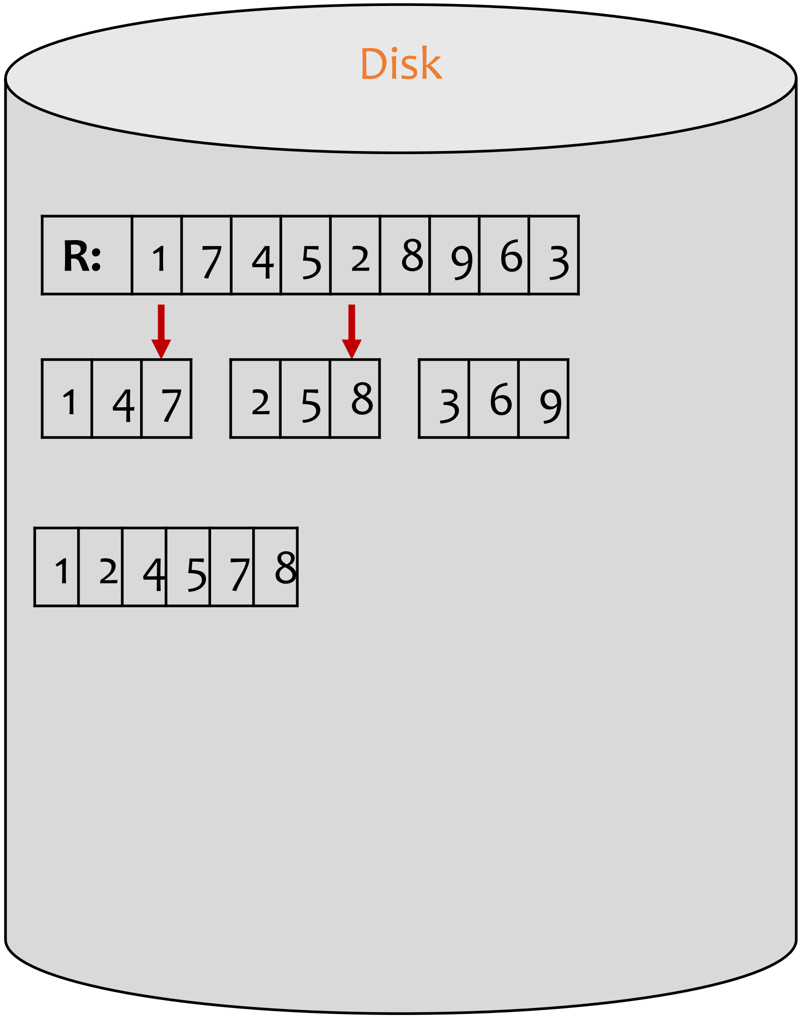

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- Phase 0
- Phase 1
- Phase 2 (final)

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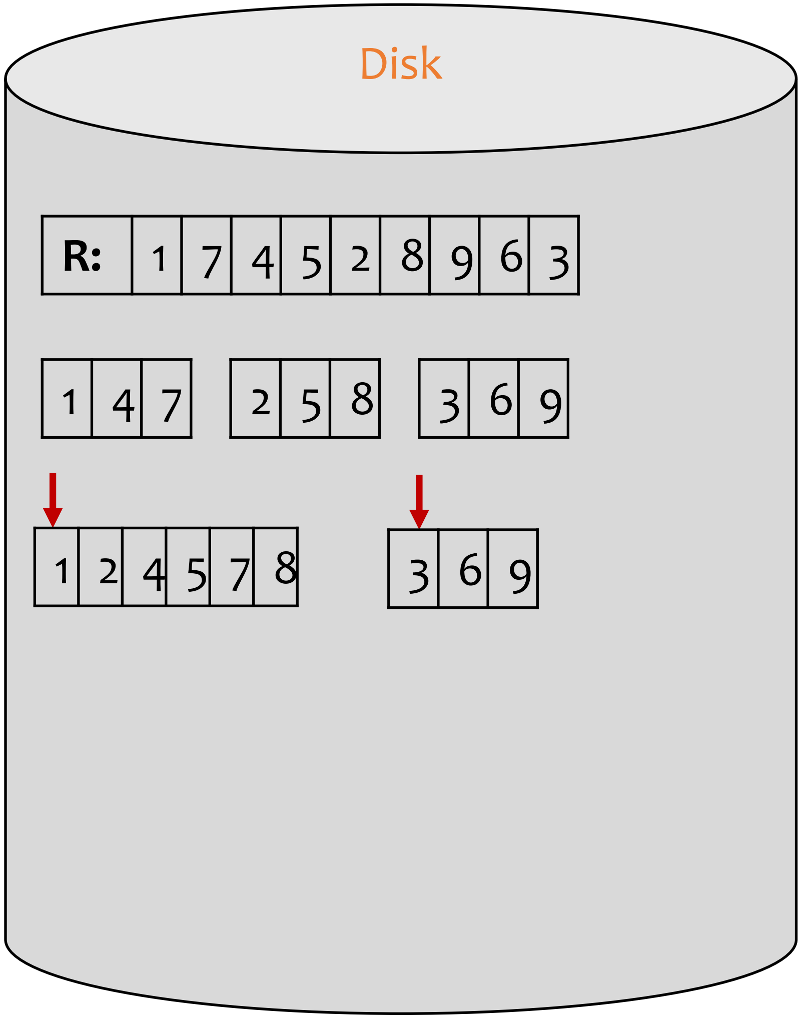

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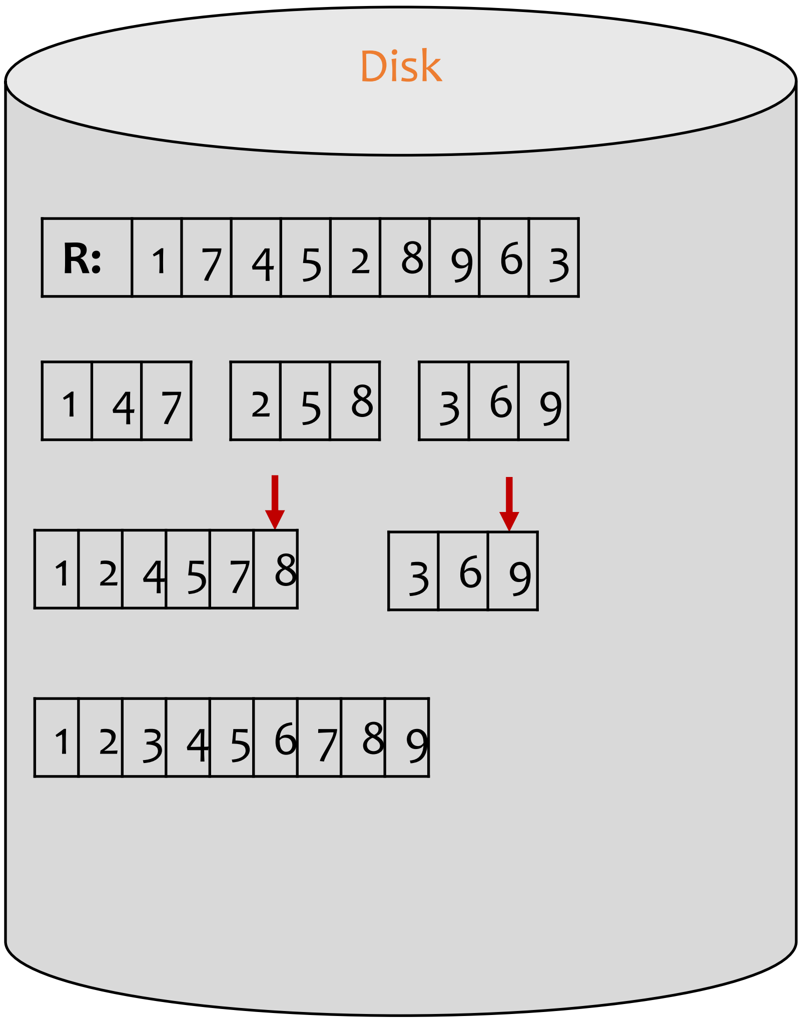


Sort-merge join

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

- 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 $r.A < s.B$

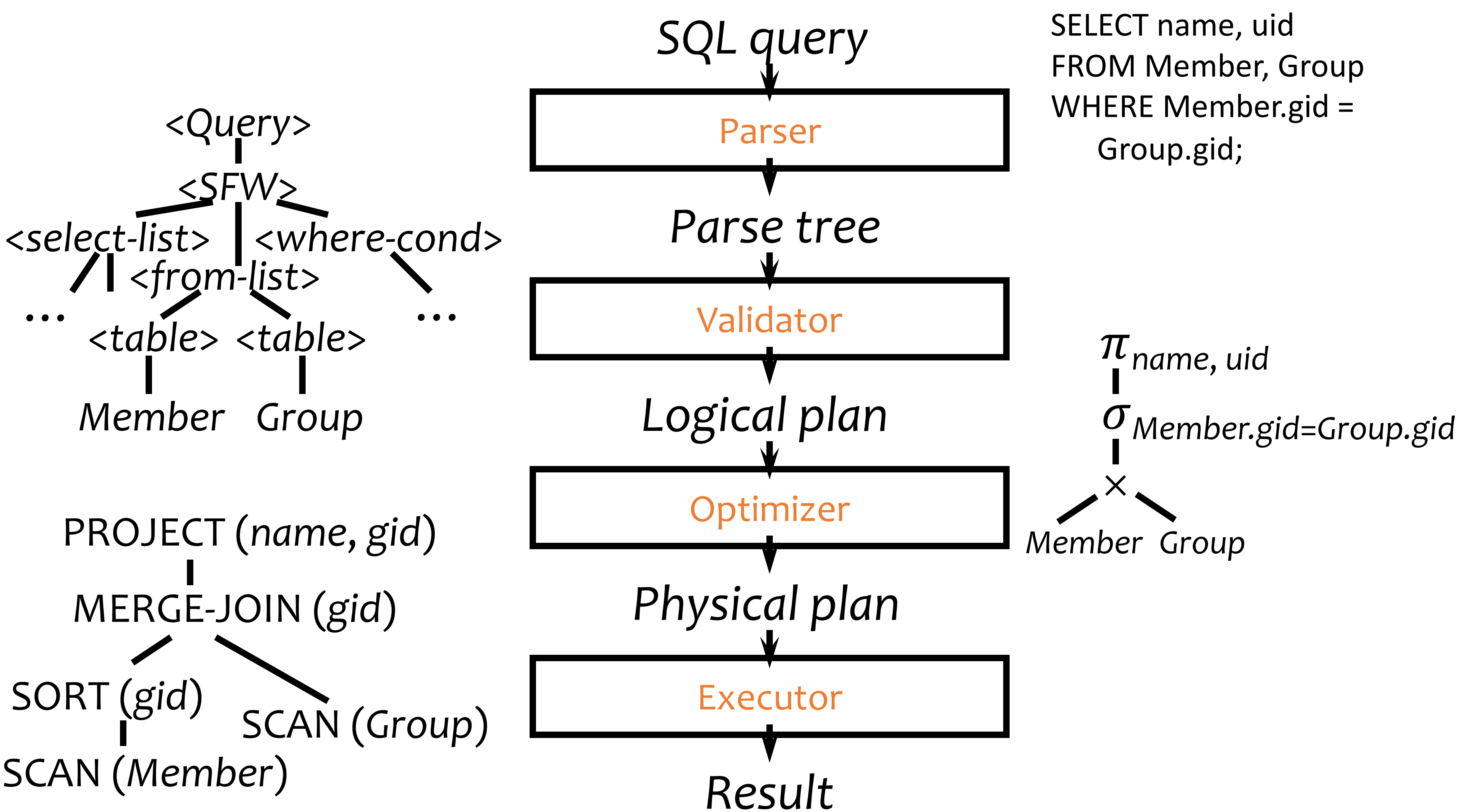
      then r = next tuple in R

    else output all matching tuples, and

      r, s = next in R and S
- I/O's: sorting $+O(B(R) + B(S))$
  - In most cases (e.g., join of key and foreign key)
  - Worst case is $B(R) \cdot B(S)$: everything joins

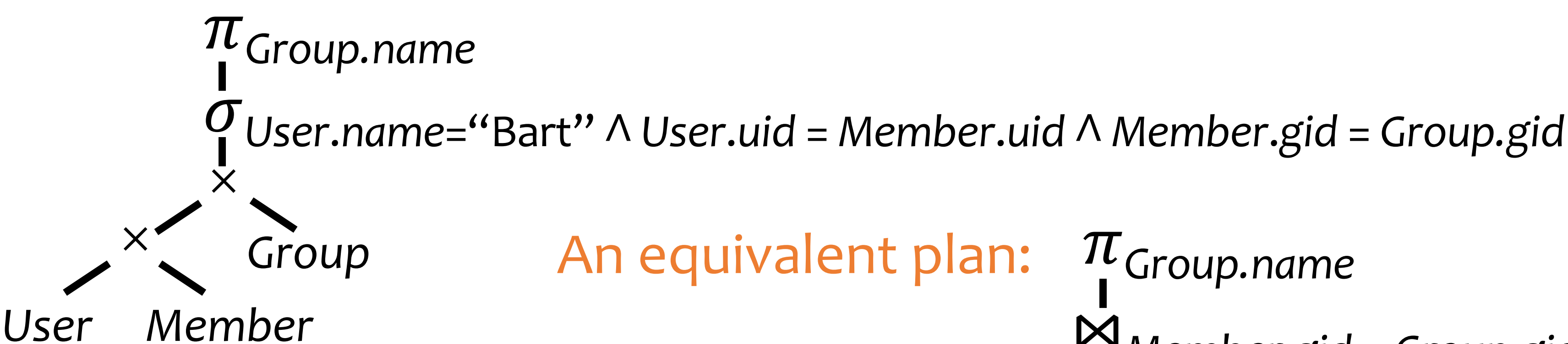
Query optimization

A query’s trip through the DBMS

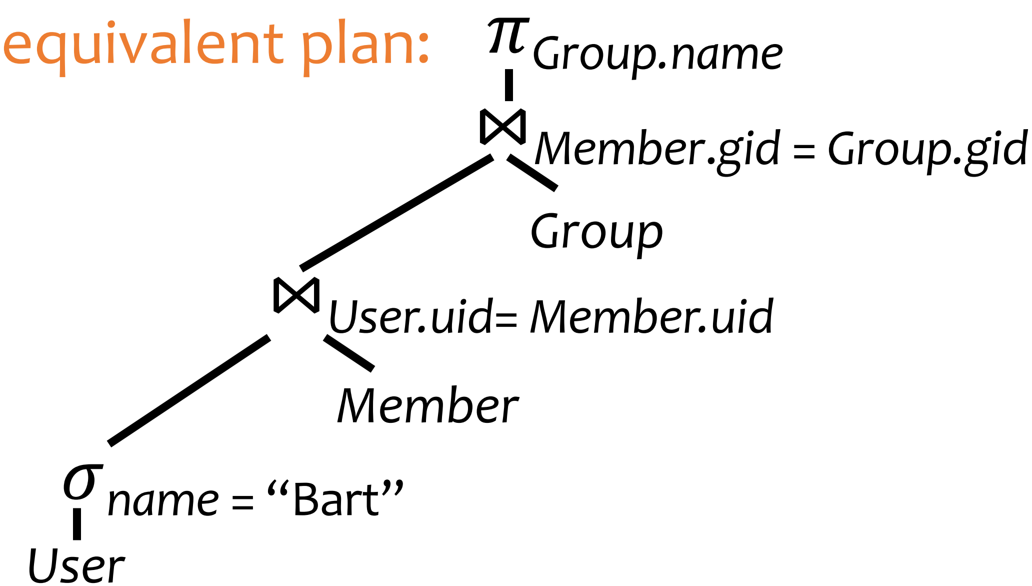


Logical plan

- Nodes are logical operators (often relational algebra operators)
- There are many equivalent logical plans



An equivalent plan:



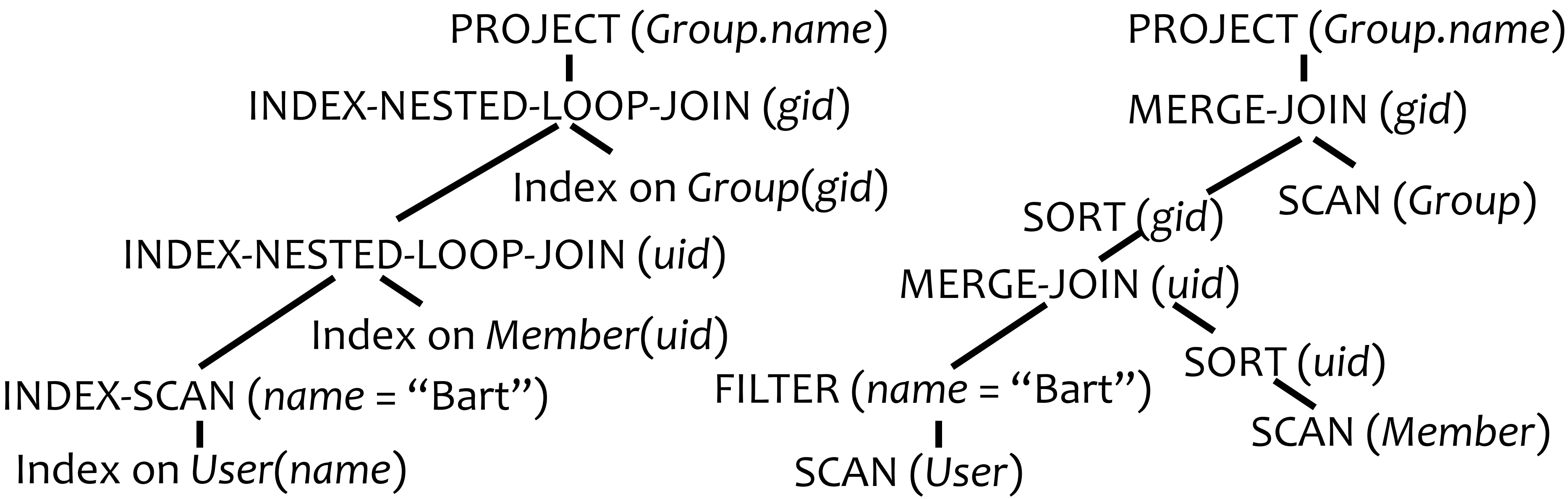
Physical (execution) plan

- A complex query may involve multiple tables and various query processing algorithms
  - E.g., table scan, basic & block nested-loop join, index nested-loop join, sort-merge join, … (Lecture 13)

- A physical plan for a query tells the DBMS query processor how to execute the query
  - A tree of physical plan operators
  - Each operator implements a query processing algorithm
  - Each operator accepts a number of input tables/streams and produces a single output table/stream

Examples of physical plans

SELECT Group.name
FROM User, Member, Group
WHERE User.name = 'Bart'
AND User.uid = Member.uid AND Member.gid = Group.gid;

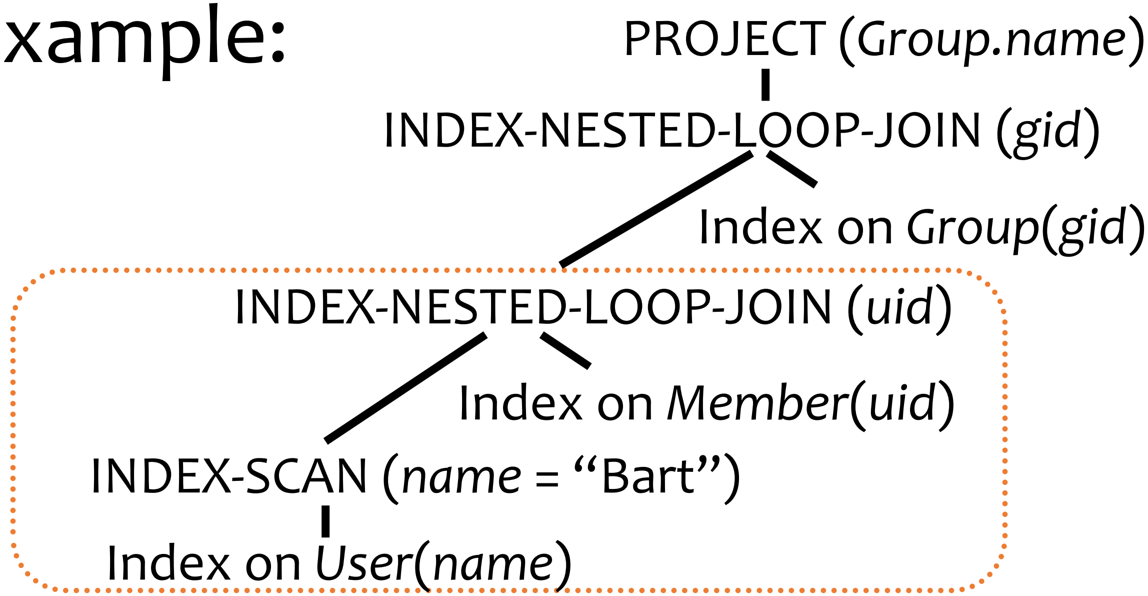


- Many physical plans for a single query
  - Equivalent results, but different costs and assumptions!

  ☞DBMS query optimizer picks the "best" possible physical plan

Cost estimation

Physical plan example:



Input to Join(*uid*):

What is its input size? How many tuples with name='Bart'?

Lecture 13

- We have: cost estimation for each operator
  - Example: INDEX-NESTED-LOOP-JOIN(*uid*) takes $O(B(R) + |R| \cdot (\text{index lookup} + \text{record fetch}))$
- We need: size of intermediate results

Cardinality estimation

Cardinality estimation for:

- Equality predicates
- Range predicates
- Joins

- Textbook has more operators

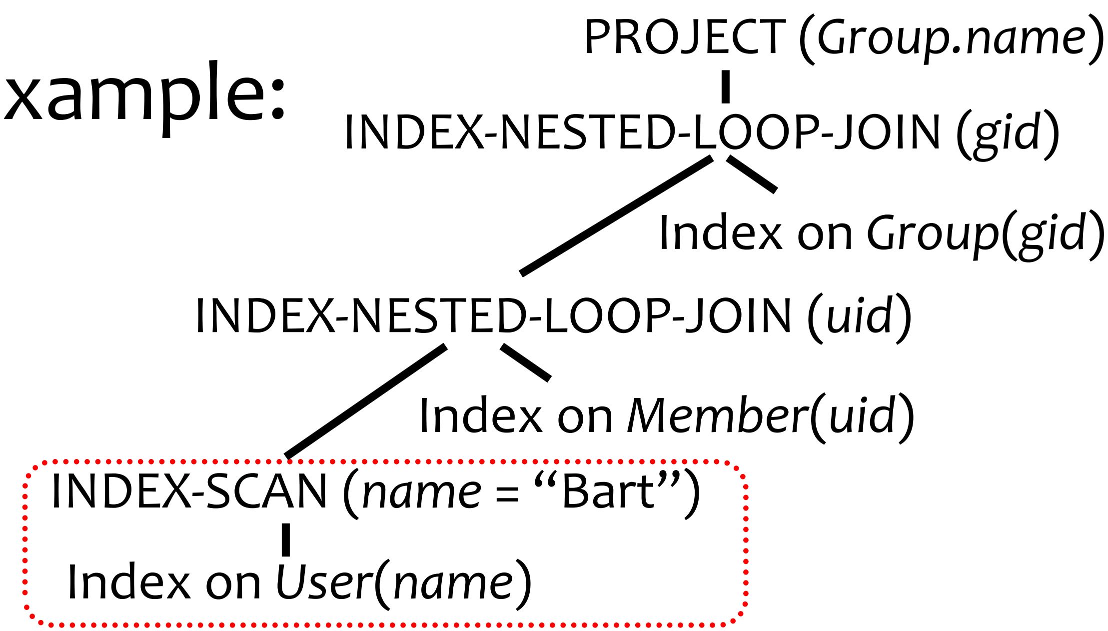
Selections with equality predicates

- Q: $\sigma_{A=v}R$
- DBMSs typically store the following in the catalog
  - Size of R: $|R|$
  - Number of distinct A values in R: $|\pi_A R|$
- Assumptions
  - Values of A are uniformly distributed in R

- $|Q| \approx {}^{|R|}/_{|\pi_A R|}$
  - Selectivity factor of $(A = v)$ is ${}^{1}/_{|\pi_A R|}$

Example

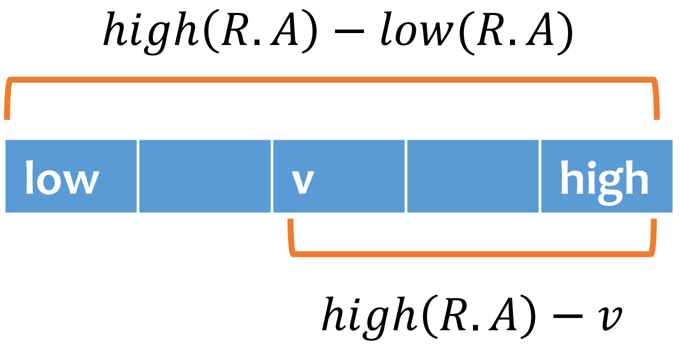
Physical plan example:



- |User|=1000, $|\pi_{name}(User)| = 50$ ➔ $|\sigma_{name="Bart"}(User)| = ?$
- Assumptions:
  - Values of $name$ are uniformly distributed in $User$
- $|\sigma_{name="Bart"}(User)| = \frac{1000}{50} = 20$

Range predicates

- Q: $\sigma_{A>v} R$
- Not enough information!
  - Just pick, say, $|Q| \approx |R| \cdot {}^1/_3$



- With more information
  - Largest R.A value: $\mathrm{high}(R.A)$
  - Smallest R.A value: $\mathrm{low}(R.A)$
  - $|Q| \approx |R| \cdot \frac{\mathrm{high}(R.A) - v}{\mathrm{high}(R.A) - \mathrm{low}(R.A)}$

Two-way equi-join

- Q: $R(A, B) \bowtie S(A, C)$
- Assumption: containment of value sets
  - Every tuple in the "smaller" relation (one with fewer distinct values for the join attribute) joins with some tuple in the other relation
    - That is, if $|\pi_A R| \leq |\pi_A S|$ then $\pi_A R \subseteq \pi_A S$
  - Certainly not true in general
  - But holds in the common case of foreign key joins
- $|Q| \approx \frac{|R| \cdot |S|}{\max(|\pi_A R|, |\pi_A S|)}$
  - Selectivity factor of $R.A = S.A$ is $1/_{\max(|\pi_A R|, |\pi_A S|)}$

Example

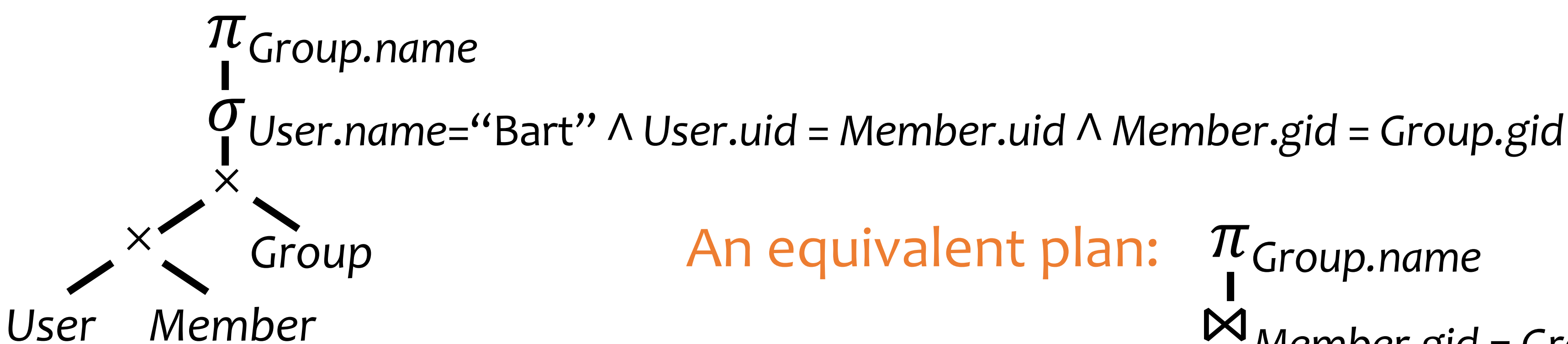
- Database:
  - User(uid, name, age, pop), Member(gid,uid,date), Group(gid, gname)
  - |User|=1000 rows, |Group|=100 rows, |Member|=50000 rows
  - $|\pi_{name}(User)| = 50$
  - $|\pi_{uid}(Member)| = 500$

- Estimate size $|User \bowtie Member| =?$
  - $|\ \pi_{uid}(User)| = 1000$
  - $|\pi_{uid}(Member)| = 500$
  - 1000*50000/max(500,1000)=50000

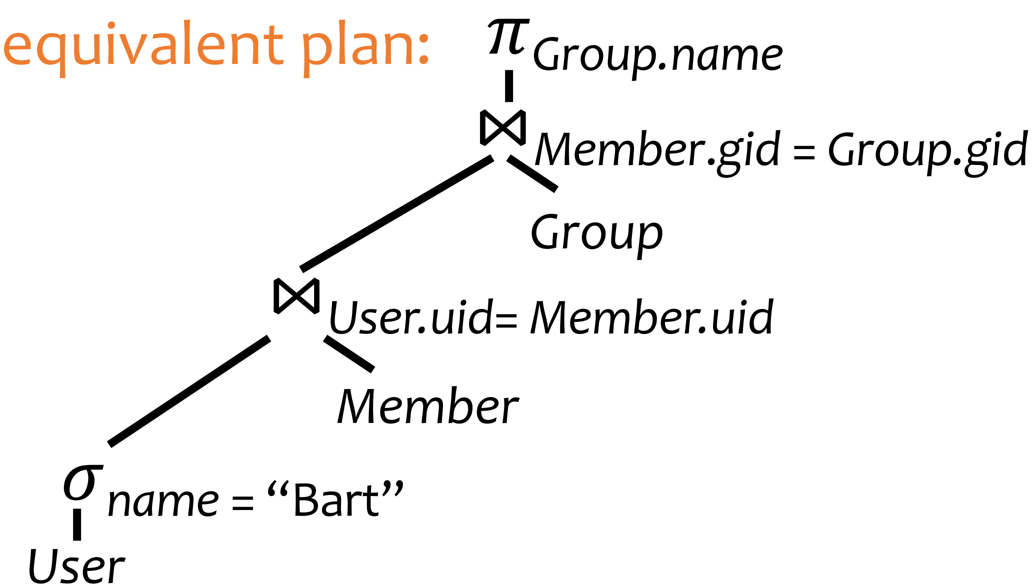
Search space is huge

- Characterized by "equivalent" logical query plans

SELECT Group.name FROM User, Member, Group WHERE User.name = 'Bart'
AND User.uid = Member.uid AND Member.gid = Group.gid;



An equivalent plan:



Do we need to exam all the logical plans?

No. We can apply heuristic transformation rules to find a cheaper logical plan

Transformation rules (a sample)

- Convert σ_p-$\times$ to/from $\bowtie_p$: $\sigma_p(R \times S) = R \bowtie_p S$
  - Example: $\sigma_{User.uid=Member.uid}(User \times Member) = User \bowtie Member$
- Merge/split σ's: $\sigma_{p_1}\left(\sigma_{p_2} R\right) = \sigma_{p_1 \wedge p_2} R$
  - Example: $\sigma_{age>20}\left(\sigma_{pop=0.8} User\ \right) = \sigma_{age>20 \wedge pop=0.8} User$
- Merge/split π's: $\pi_{L_1}\left(\pi_{L_2} R\right) = \pi_{L_1} R$, if $L_1 \subseteq L_2$
  - Example: $\pi_{age}\left(\pi_{age,pop} User\right) = \pi_{age} User$

Transformation rules (a sample)

- Push down/pull up σ:
  $\sigma_{p \wedge p_r \wedge p_s}(R \bowtie_{p'} S) = (\sigma_{p_r} R) \bowtie_{p \wedge p'} (\sigma_{p_s} S)$, where
  - p_r is a predicate involving only R columns
  - p_s is a predicate involving only S columns
  - p and p' are predicates involving both R and S columns
  - Example:

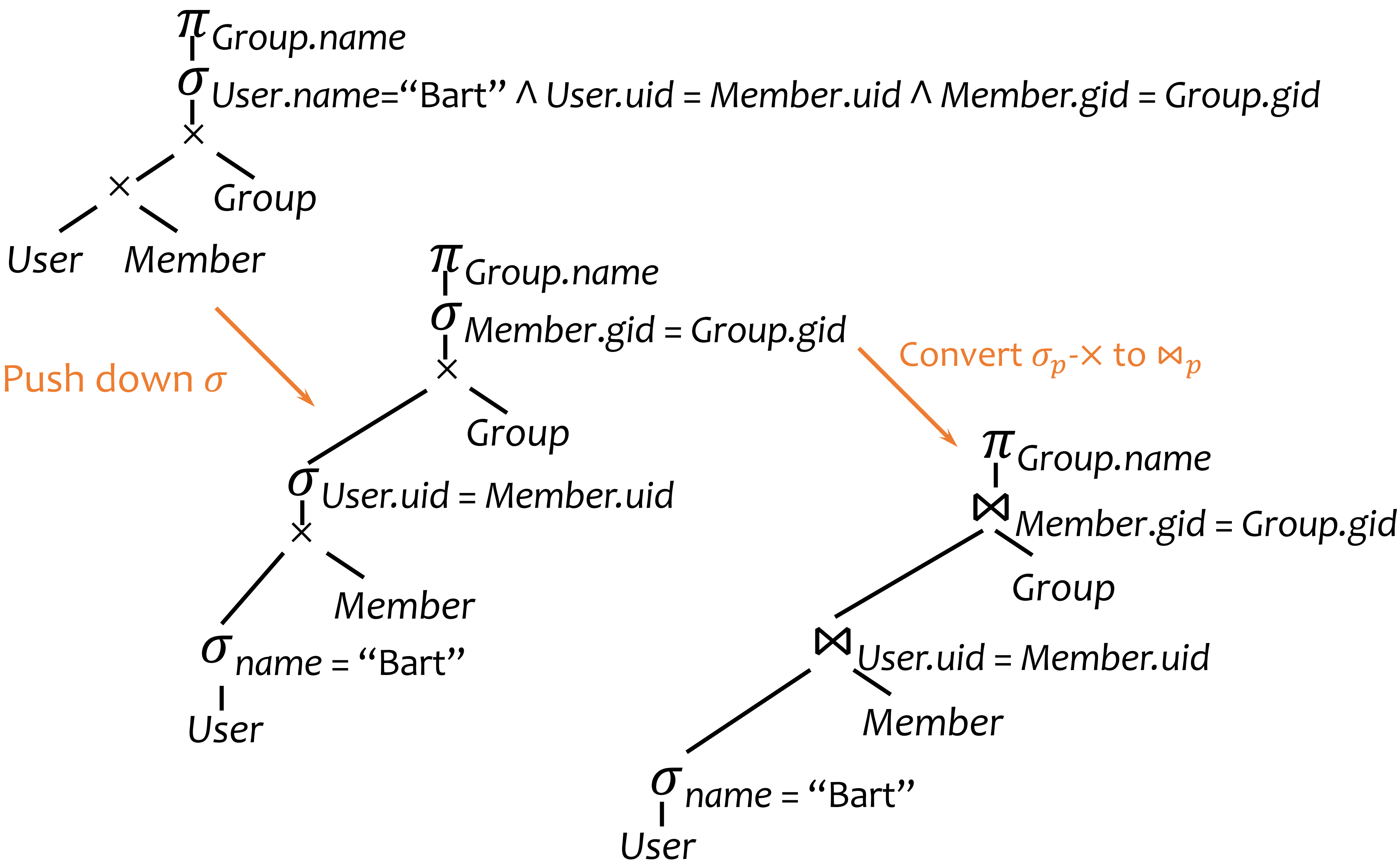
$$\sigma_{\text{U1.name=U2.name} \wedge U1.\text{pop}>0.8 \wedge U2.pop>0.8}(\rho_{U1} User \bowtie_{U1.uid \neq U2.uid} \rho_{U2} User)$$
$$= \sigma_{pop>0.8}(\rho_{U1} User) \bowtie_{U1.uid \neq U2.uid \wedge U1.name=U2.name} (\sigma_{pop>0.8}(\rho_{U2} User))$$

Transformation rules (a sample)

- Push down π: $\pi_L(\sigma_p R) = \pi_L\left(\sigma_p(\pi_{L,L'} R)\right)$, where
  - L' is the set of columns referenced by p that are not in L
  - Example:
    $\pi_{age}(\sigma_{pop>0.8} User) = \pi_{age}(\sigma_{pop>0.8}(\pi_{age,pop} User))$

- Many more (seemingly trivial) equivalences…
  - Can be systematically used to transform a plan to new ones

Relational query rewrite example



Heuristics-based query optimization

- Start with a logical plan
- Push selections/projections down as much as possible
  - Why? Reduce the size of intermediate results
- Join smaller relations first, and avoid cross product
  - Why? Joins are more optimized and have alternate implementations
- Convert the transformed logical plan to a physical plan (by choosing appropriate physical operators)