CS660: Intro to Database Systems

Class 14: Query Processing with Relational Operations

Instructor: Manos Athanassoulis

https://bu-disc.github.io/CS660/

Query Processing

Overview

Selections

Projections

Nested loop joins

Sort-merge and hash joins

General joins and aggregates

Query Processing

Overview

Readings: Chapter 12

Selections

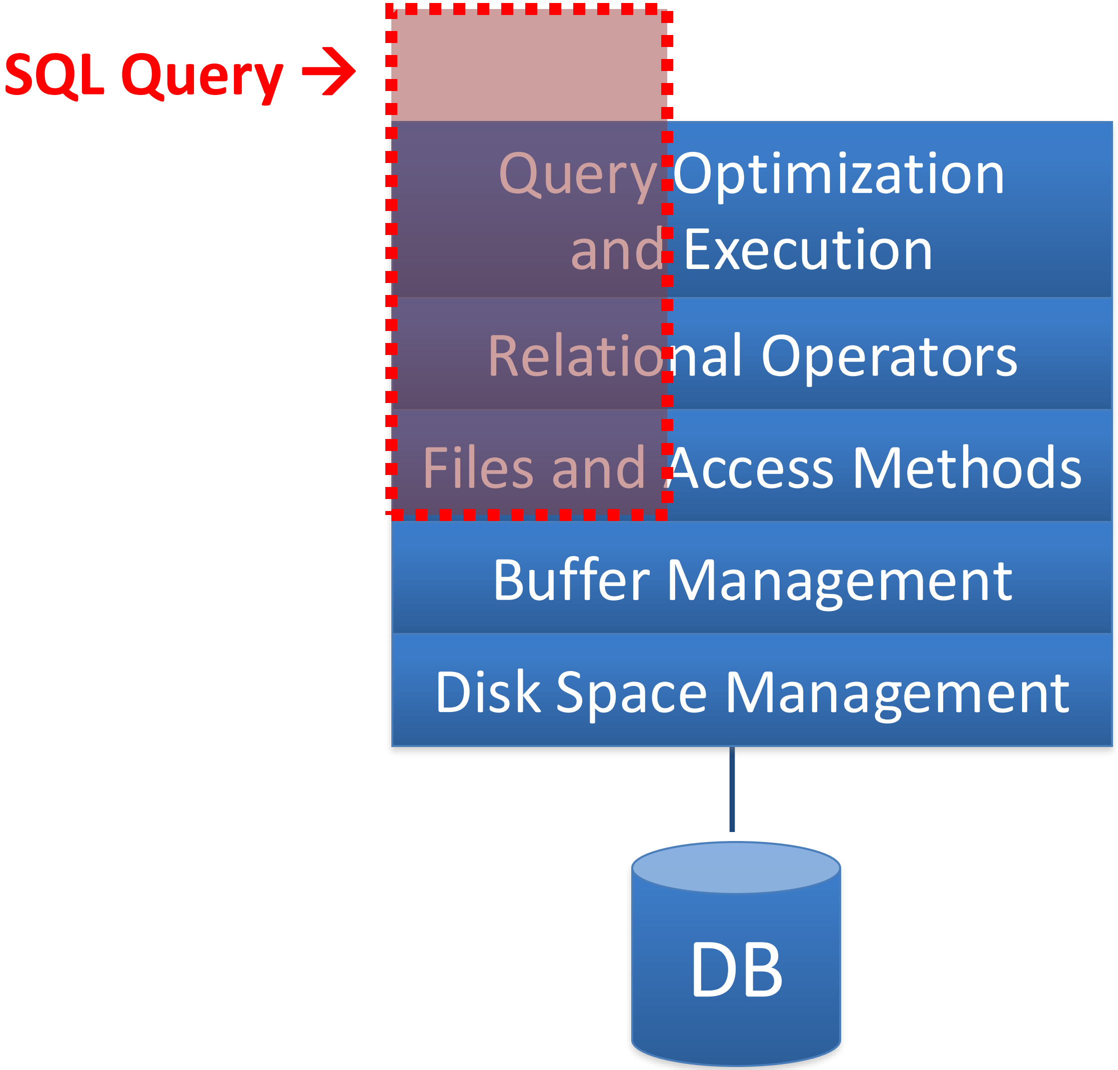
Projections

Nested loop joins

Sort-merge and hash joins

General joins and aggregates

DBMS Layer-Cake



SINGLE-TABLE QUERIES

Basic Single-Table Queries

```
SELECT [DISTINCT] <column expression list>
FROM <single table>
[WHERE <predicate>]
[GROUP BY <column list>
[HAVING <predicate>] ]
[ORDER BY <column list>]
```

Basic Single-Table Queries

```
SELECT [DISTINCT] <column expression list>
FROM <single table>
[WHERE <predicate>]
[GROUP BY <column list>
[HAVING <predicate>] ]
[ORDER BY <column list>]
```

Simplest version is straightforward:

- Produce **all tuples** in the table that **satisfy the predicate**
- Output the **expressions** in the **SELECT** list
  - Expression can be a **column reference**, or an **arithmetic expression over column references**

Basic Single-Table Queries

```
SELECT S.name, S.gpa
FROM Students S
WHERE S.dept="CS"
[GROUP BY <column list>
[HAVING <predicate>] ]
[ORDER BY <column list>]
```

Simplest version is straightforward:

- Produce **all tuples** in the table that **satisfy the predicate**
- Output the **expressions** in the **SELECT** list
  - Expression can be a **column reference**, or an **arithmetic expression over column references**

SELECT DISTINCT

```
SELECT DISTINCT S.name, S.gpa
FROM Students S
WHERE S.dept=“CS”
[GROUP BY <column list>
[HAVING <predicate>] ]
[ORDER BY <column list>]
```

The **DISTINCT** flag specifies removal of duplicates before output

ORDER BY

```
SELECT DISTINCT S.name, S.gpa, 2023-S.age AS YOB
FROM Students S
WHERE S.dept=“CS”
[GROUP BY <column list>
[HAVING <predicate>] ]
ORDER BY S.gpa, S.name, YOB
```

ORDER BY clause specifies that output should be sorted

- Lexicographic ordering again!

Obviously must refer to **columns in the output (SELECT clause)**

- Note the **AS** clause for naming output columns!

ORDER BY

```
SELECT DISTINCT S.name, S.gpa
FROM Students S
WHERE S.dept="CS"
[GROUP BY <column list>
[HAVING <predicate>] ]
ORDER BY S.gpa DESC, S.name ASC
```

Ascending order by default, but can be overridden

- **DESC** flag for descending, **ASC** for ascending
- Can **mix and match**, lexicographically

AGGREGATES

```
SELECT [DISTINCT] AVERAGE(S.gpa)
FROM Students S
WHERE S.dept="CS"
[GROUP BY <column list>
[HAVING <predicate>] ]
[ORDER BY <column list>]
```

Before producing output, compute a **summary** (a.k.a. an **aggregate**) of some **arithmetic expression**

- Produces **1 row of output**
  - with <u>one column in this case</u>
- Other aggregates: **SUM**, **COUNT**, **MAX**, **MIN**

Note: can use **DISTINCT** inside the aggregate function (what is the difference?)

- SELECT **COUNT(DISTINCT S.name)** FROM Students S
- vs. SELECT **DISTINCT COUNT (S.name)** FROM Students S;

GROUP BY

```
SELECT [DISTINCT] AVERAGE(S.gpa), S.dept
FROM Students S
[WHERE <predicate>]
GROUP BY S.dept
[HAVING <predicate>] ]
[ORDER BY <column list>]
```

Partition the table into **groups** that have the **same value on GROUP BY columns**

- Can group by a list of columns

Produce an **aggregate result per group**

- Cardinality of output = # of distinct group values

Note: can put grouping columns in SELECT list

- For aggregate queries, SELECT list can contain aggs and GROUP BY columns only!
- ➢ What would it mean if we said SELECT S.name, AVERAGE(S.gpa) above?

HAVING

```
SELECT [DISTINCT] AVERAGE(S.gpa), S.dept
FROM Students S
[WHERE <predicate>]
GROUP BY S.dept
HAVING COUNT(*)>5
[ORDER BY <column list>]
```

The **HAVING predicate** is applied **after grouping and aggregation**

- Hence can contain anything that could go in the **SELECT** list
- i.e. aggregates or **GROUP BY** columns

It is an **optional** clause

Putting it All Together

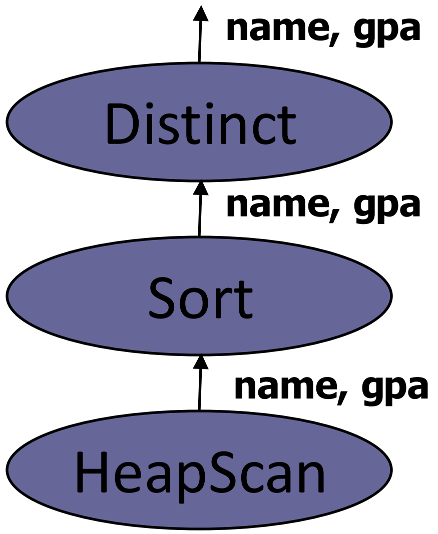
```
SELECT [DISTINCT] AVERAGE(S.gpa), S.dept
FROM Students S
WHERE S.age = 20
GROUP BY S.dept
HAVING COUNT(*)>5
ORDER BY S.dept;
```

Query Processing Overview

- The *query parser and optimizer* translates SQL to a special internal "language"
  - Query Plans
- The *query executor* is an *interpreter* for query plans
- Think of query plans as "box-and-arrow" *dataflow* diagrams
  - Each **box** implements a ***relational operator***
  - **Edges** represent a **flow of tuples** (columns as specified)
  - For **single-table queries**, these diagrams are **straight-line graphs**

SELECT DISTINCT name, gpa
FROM Students

Query Parsing & Optimization →



Query processing

Some database operations are EXPENSIVE

Can greatly improve performance by being 'smart'

- e.g., can speed up 1,000,000x over naïve approach

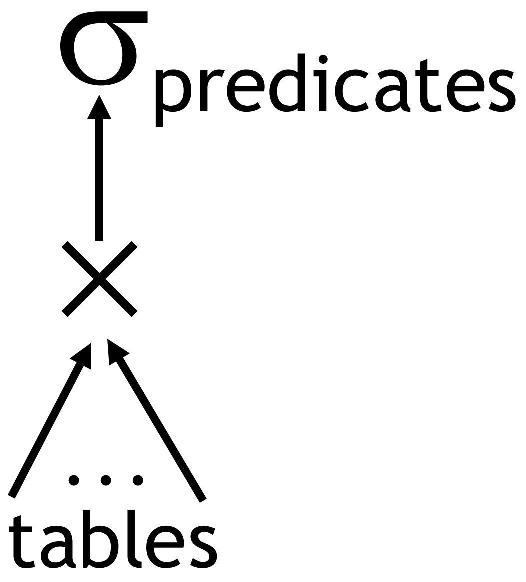
Main weapons are:

1. Clever (fast) implementation techniques for operators
2. exploiting 'equivalencies' of relational operators
3. using statistics and cost models to choose among these

A Really Bad Query Optimizer

For each Select-From-Where query block

- Create a plan that:
  - Forms the Cartesian product of the FROM clause
  - Applies the WHERE clause
  - Incredibly inefficient
    - Huge intermediate results!



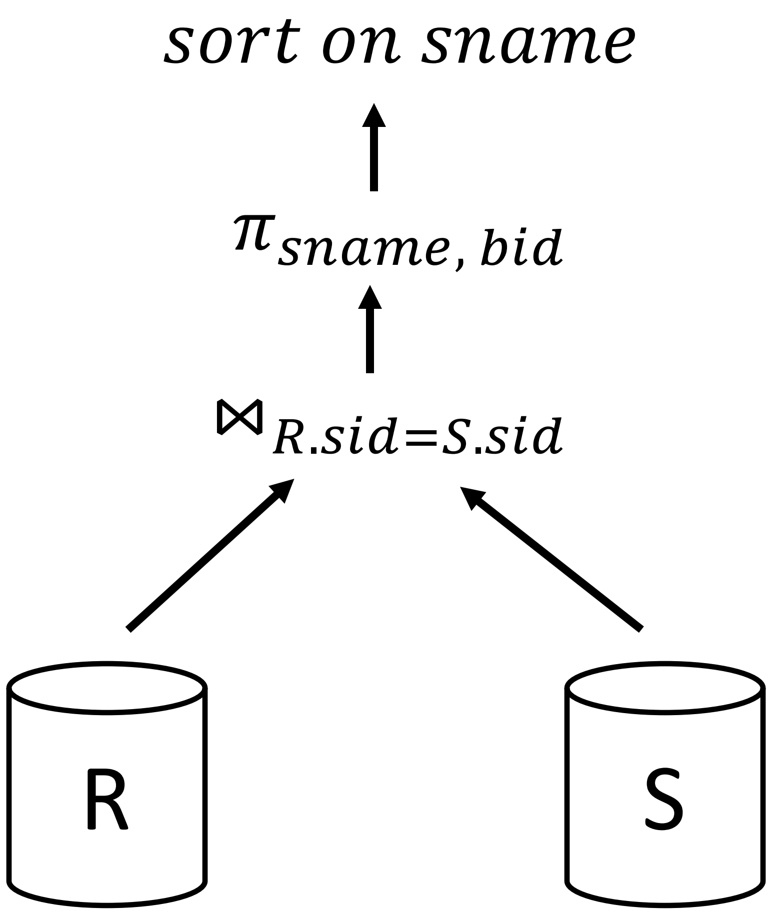
Then, as needed:

- Apply the GROUP BY clause
- Apply the HAVING clause
- Apply any projections and output expressions
- Apply duplicate elimination and/or ORDER BY

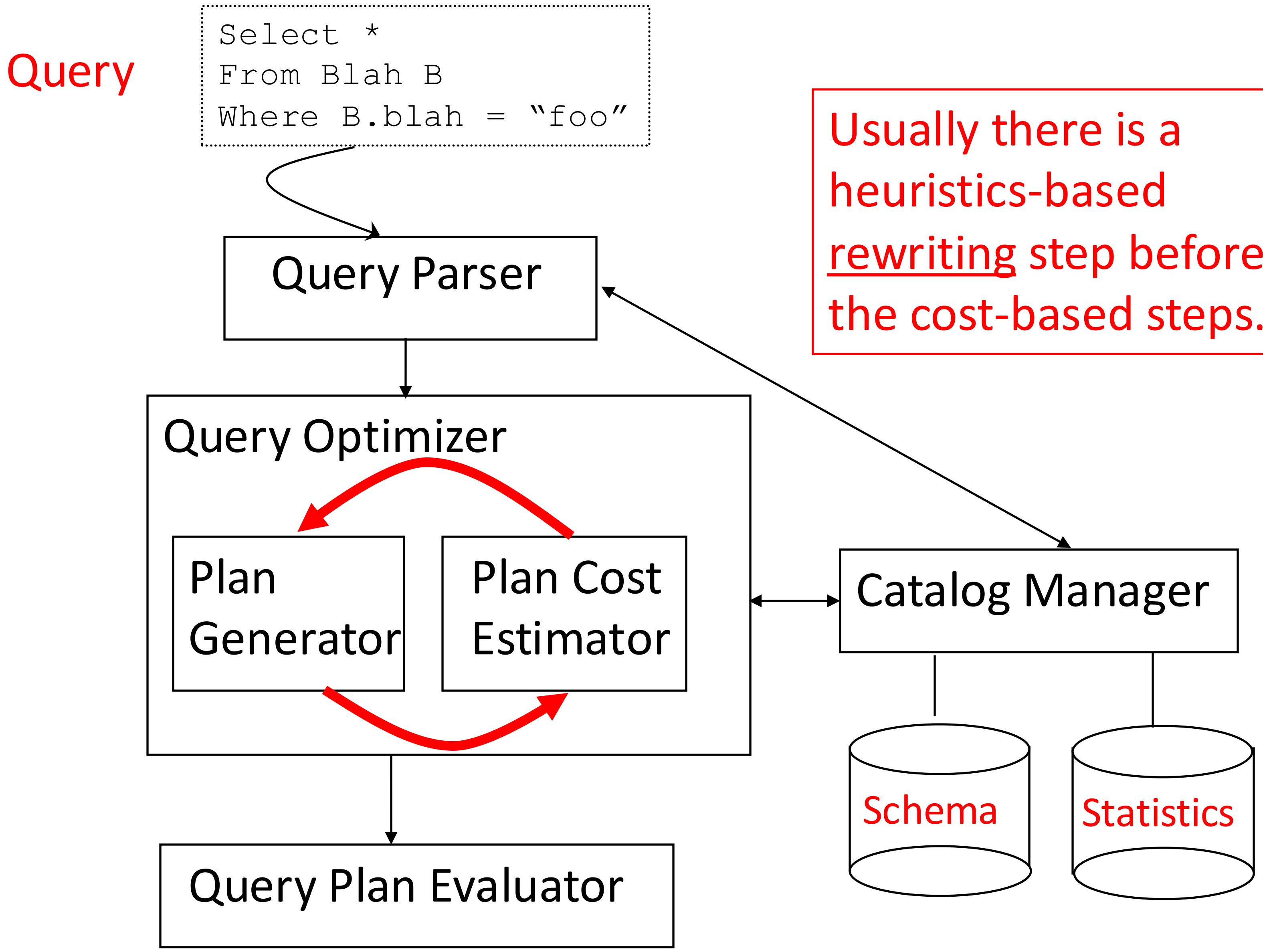
Correct BUT (very) slow!

A (multi-table)Query Plan

```
SELECT    sname, bid
FROM      R, S
WHERE     R.sid=S.sid
ORDER BY  sname
```



Query execution



Usually there is a heuristics-based rewriting step before the cost-based steps.

The Query Optimization Game

‘Optimizer’ is a bit of a misnomer

Goal: pick a ‘good’ (i.e., low expected cost) plan

- Involves choosing access methods, physical operators, operator orders, …
- Notion of cost is based on an abstract ‘cost model’

Roadmap for this topic:

- First: basic operators
- Then: joins
- After that: optimizing multiple operators

Relational Operations

We will consider how to implement:

- *Selection* (σ) Selects a subset of rows from relation
- *Projection* (π) Deletes unwanted columns from relation
- *Join* (⋈) Allows us to combine two relations
- *Set-difference* (−) Tuples in relation 1, but not in relation 2
- *Union* (∪) Tuples in relation 1 and in relation 2
- *Aggregation* (SUM, MIN, etc.) and GROUP BY

Today

Operators can be *composed* !

Next: *optimizing* queries by composing them

Common Techniques

Indexing

use an index to examine tuples satisfying a specific condition

Iteration

examine all tuples one after the other

Partitioning (e.g., sorting or hashing)

decompose a problem into a less expensive collection of operations on partitions

Schema for Examples

S: N=500, p_s=80, ts=50b
R: M=1000, p_R=100, ts=40b

Sailors (*sid*: integer, *sname*: string, *rating*: integer, *age*: real)
Reserves (*sid*: integer, *bid*: integer, *day*: dates, *rname*: string)

Similar to old schema; *rname* added for variations.

Sailors:

- Each tuple is 50 bytes long, 80 tuples per page, 500 pages
- N=500, p_S=80, t_S=50

Reserves:

- Each tuple is 40 bytes long, 100 tuples per page, 1000 pages
- M=1000, p_R=100, t_S=40

Query Processing

Overview

Selections

Readings: Chapters 14.1-14.2

Projections

Nested loop joins

Sort-merge and hash joins

General joins and aggregates

Simple Selections

```
SELECT   *
FROM     Reserves R
WHERE    R.rname < 'C%'
```

Of the form: $\sigma_{R.attr\ \boldsymbol{op}\ value}(R)$

Question: how best to perform? Depends on:

- available indexes/access paths
- expected size of the result (# of tuples and/or # of pages)

Size of result approximated as

*size of R * reduction factor*

- "reduction factor" is usually called <u>*selectivity*</u>
- estimate of selectivity is based on statistics

Alternatives for Simple Selections

R: M=1000, p_R=100, ts=40b

With no index, unsorted:

- Must essentially scan the whole relation
- cost is M (#pages in R); for "reserves" = 1000 I/Os

With no index, sorted:

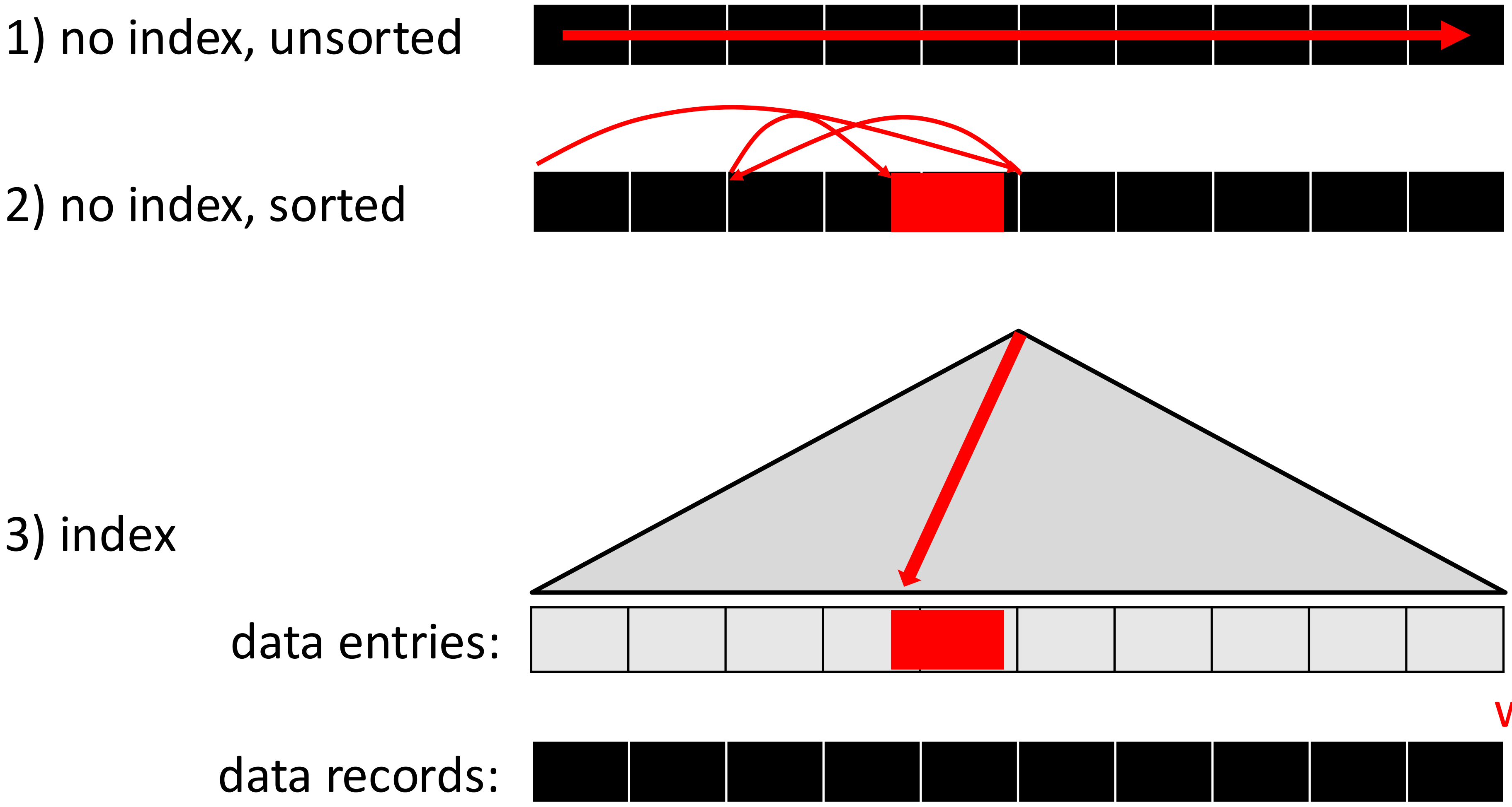
- cost of binary search + number of pages containing results.
- For reserves = $\log_2(1000)$ = 10 I/Os + $\lceil$selectivity*#pages$\rceil$

With an index on selection attribute:

1. Use index to find qualifying data entries,
2. then retrieve corresponding data records
   - Note: Hash index useful only for equality selections

Simple Selections – Explained

R: M=1000, p_R=100, ts=40b



scan everything
cost=1000 I/O

binary search: $\log_2 M$
qualifying pages: $\lceil f \cdot M \rceil$
selectivity

index search: $\log_B M$

what is the cost to access the qualifying pages?

Using an Index for Selections

R: M=1000, p_R=100, ts=40b

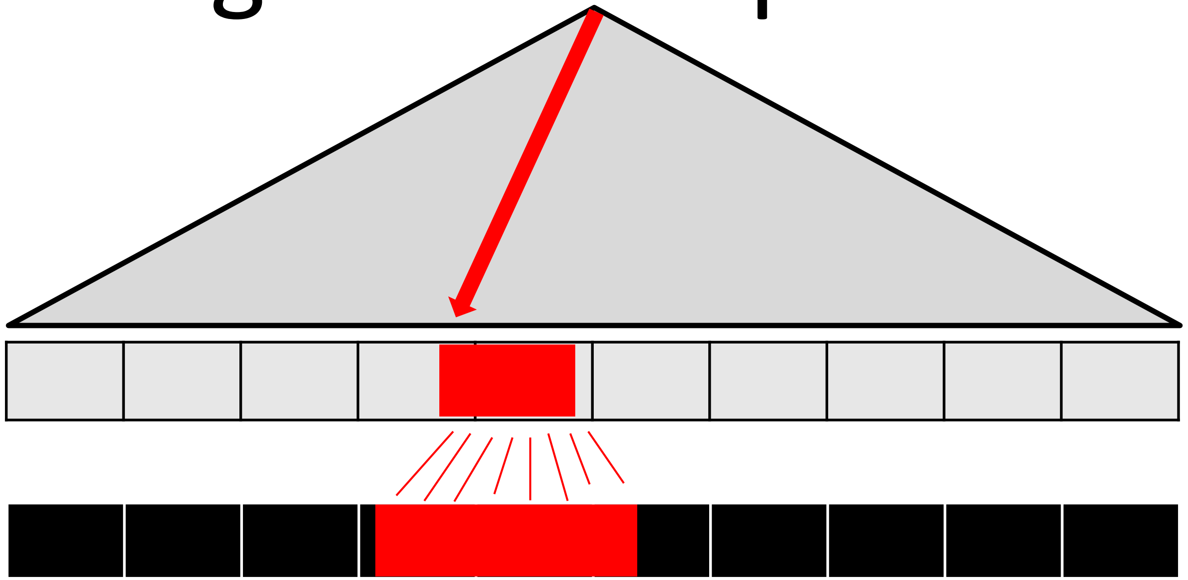
Cost ~ #qualifying tuples, clustering

- Cost factors:
  - find qualifying data entries (typically small)
  - retrieve records (could be large w/o clustering)
- Our example, "reserves" relation:
  if 10% of tuples qualify (100 pages, 10000 tuples)
  - *clustered* index → a bit more than 100 I/Os
  - *unclustered* → could be up to 10000 I/Os!

Selections using Index– Explained

R: M=1000, p_R=100, ts=40b

A) clustered



data entries:

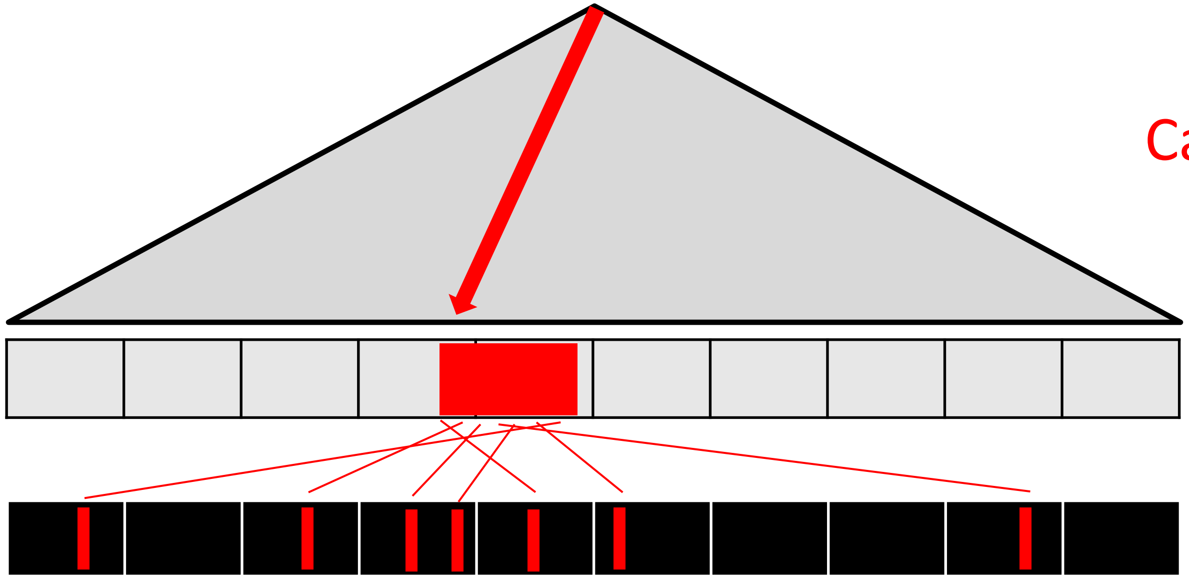
data records:

index search: $\log_B M$

$\lceil f \cdot M \rceil =$
$= 10\% \cdot 1000 = 100$

Can we do better?

B) unclustered



data entries:

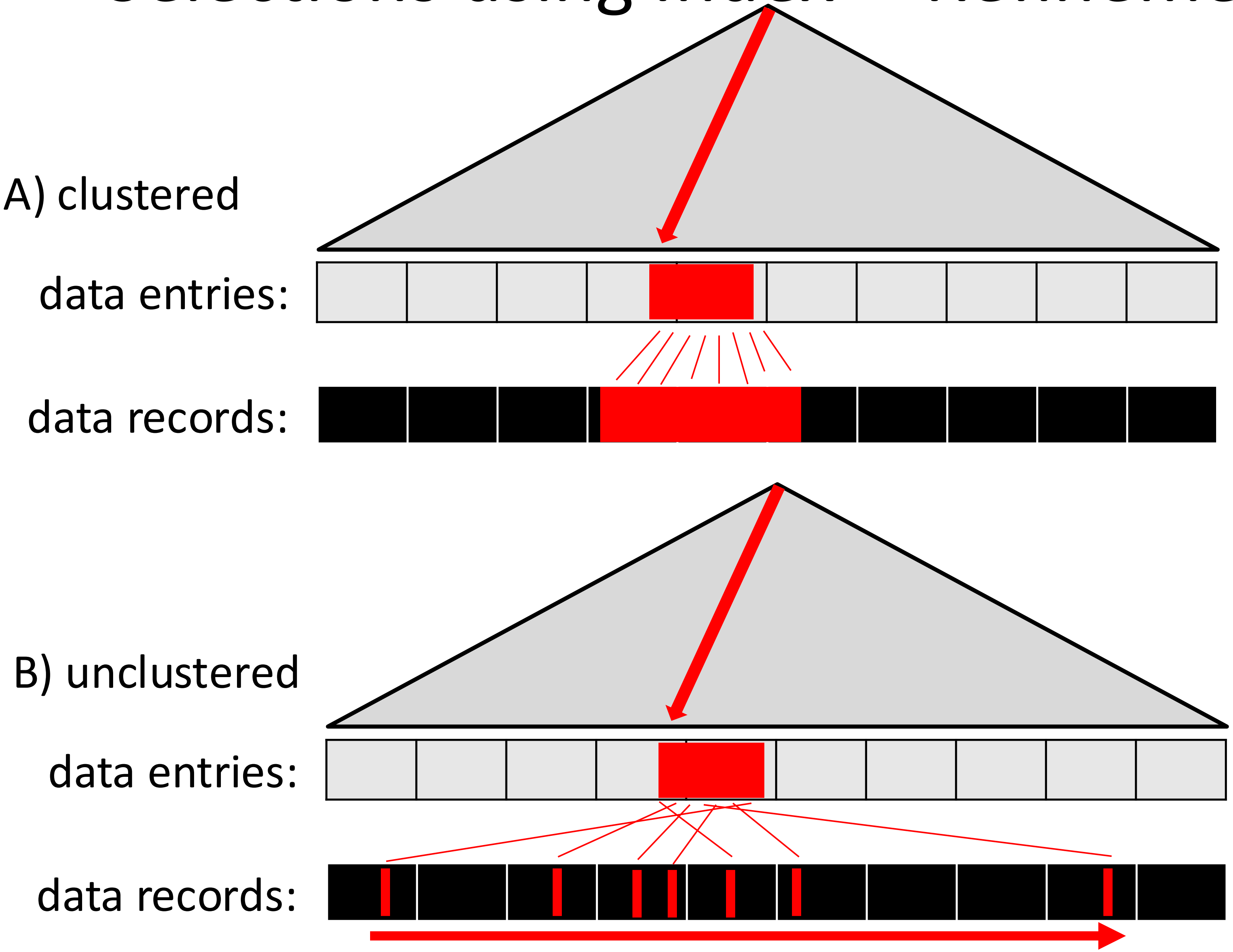
data records:

index search: $\log_B M$

$\lceil f \cdot M \cdot p_R \rceil =$
$= 10\% \cdot 1000 \cdot 100 = 10000$

Selections using Index -- Refinement

R: M=1000, p_R=100, ts=40b



Important refinement (for unclustered):

1. Find qualifying data entries
2. Sort the rid's of the data records to be retrieved
3. Fetch rids in order

   Each data page is accessed once

No need for clustered!

General Selection Conditions

- *(day<8/9/94 AND rname= 'Paul') OR bid=5 OR sid=3*

First converted to [*conjunctive normal form* (CNF)]

- *(day<8/9/94 OR bid=5 OR sid=3) AND (rname= 'Paul' OR bid=5 OR sid=3)*

We assume no ORs (conjunction of <*attr op value*>)

A B-tree index ***matches*** (a conjunction of) terms that involve only attributes in a *prefix* of the search key

- Index on *<a, b, c>* matches *a=5 AND b=3*, but not *b=3*

Hash indexes must have all attributes in search key

Hash indexes support only…?

Selections – 1st approach

1. Find the *cheapest access path*
2. Retrieve tuples using it
3. Apply the terms that don't match the index (if any):
   - *Cheapest access path*
     An index or file scan with the fewest estimated page I/Os
   - Terms that match this index reduce the # of tuples *retrieved*
   - Other terms are used to discard some retrieved tuples, but do not affect number of tuples/pages fetched

Cheapest Access Path - Example

Consider *day < 8/9/94 AND bid=5 AND sid=3*

A B+ tree index on *day* can be used;

- then, *bid=5* and *sid=3* must be checked for each retrieved tuple

Similarly, a hash index on <*bid, sid*> could be used;

- *Then, day<8/9/94* must be checked

How about a B+tree on <rname,day>?

How about a B+tree on <day, rname>?

How about a Hash index on <day, rname>?

Selections – 2nd approach: Intersecting RIDs

If we have 2 or more matching indexes (w/Alt. (2) or (3) for data entries):

1. Get sets of rids of data records using each matching index
2. Then *intersect* these sets of rids
3. Retrieve the records and apply any remaining terms

EXAMPLE: Consider *day<8/9/94 AND bid=5 AND sid=3*

– With (i) a B+ tree index on *day* and (ii) an index on *sid*:

1. a) Retrieve rids of records satisfying *day<8/9/94* using the first
   b) Retrieve rids of records satisfying *sid=3* using the second
2. Intersect
3. Retrieve records and check *bid=5*

Selections: summary

Simple selections

- On sorted or unsorted data, with or without index

General selections

- Expressed in conjunctive normal form (expr1 AND expr2 AND …)
- Retrieve tuples and then filter them through other conditions
- Intersect RIDs of matching tuples for non-clustered indexes

Choices depend on selectivity of each access method

Break: The Halloween Problem

Story from the early days of System R.

While testing the optimizer on 10/31/76(?), the following update was run:

```
UPDATE payroll
SET salary = salary*1.1
WHERE salary < 25K;
```

AND IT STOPPED WHEN ALL HAD salary ≥ 25K!

Can you guess why? (hint: it was an optimizer bug…)

Query Processing

Overview

Selections

Projections

Readings: Chapter 14.3

Nested loop joins

Sort-merge and hash joins

General joins and aggregates

The Projection Operation

SELECT DISTINCT R.sid, R.bid
FROM Reserves R

Issue is removing duplicates

Reserves (*sid*: integer, *bid*: integer, *day*: dates, *rname*: string)

R: M=1000, p_R=100, ts=40b

output tuple size: 10b

Basic approach is to use sorting

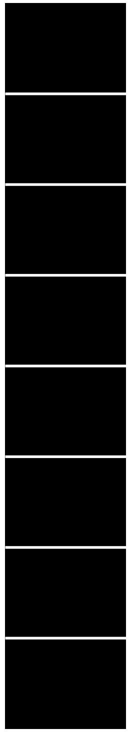
- 1. Scan R, extract only the needed attributes (why do this first?)
- 2. Sort the resulting set
- 3. Remove adjacent duplicates

- Cost: Reserves with size ratio 0.25 = 250 pages
  With 20 buffer pages can sort in 2 passes $(1 + \lceil log_{19}(^{250}/_{20}) \rceil)$, so:
  1000 +250 + 2 * 2 * 250 + 250 = 2500 I/Os

Projection - Sorting (explained)

R: M=1000, p_R=100, ts=40b

output tuple size: 10b



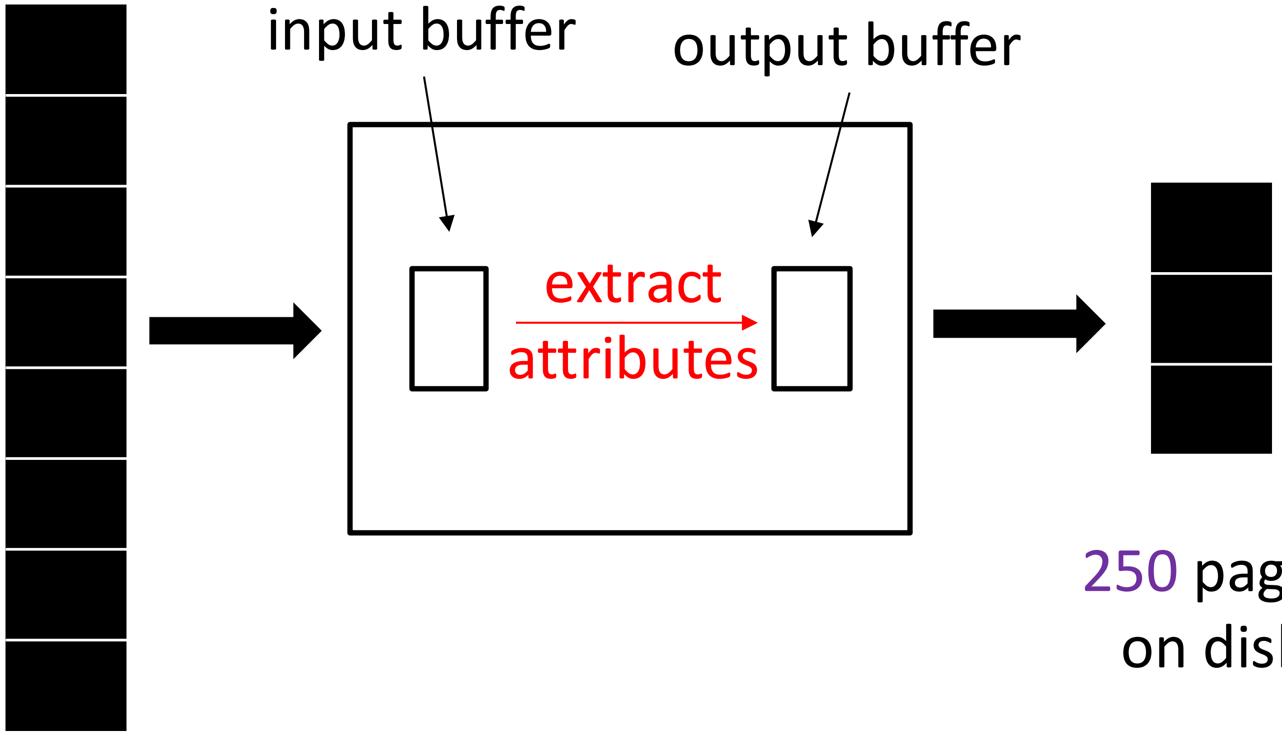
1000 pages
on disk

Remember the streaming paradigm?

Projection - Sorting (explained)

R: M=1000, p_R=100, ts=40b

output tuple size: 10b



1000 pages on disk

250 pages on disk

Note: if $B < \sqrt{M}$

1000+250+#passes*2*250+250

Sorting to remove duplicates

B=20

Pass 0: $\left\lceil \frac{250}{20} \right\rceil = 13$ runs

Pass 1: final merge

Remove adjacent duplicates in final pass

Total cost:

1000+250+2*2*250+250=2500

Can we do better?

Projection: Yes, we can do better!

SELECT DISTINCT R.sid, R.bid
FROM Reserves R

R: M=1000, p_R=100, ts=40b

output tuple size: 10b

Modify external sort algorithm (see chapter 13):

- Modify Pass 0 of external sort to eliminate unwanted fields
- Modify merging passes to eliminate duplicates
- Cost for above case:
  read 1000 pages, write out 250 in runs of 40 pages,
  merge runs = 1000 + 250 +250 = 1500

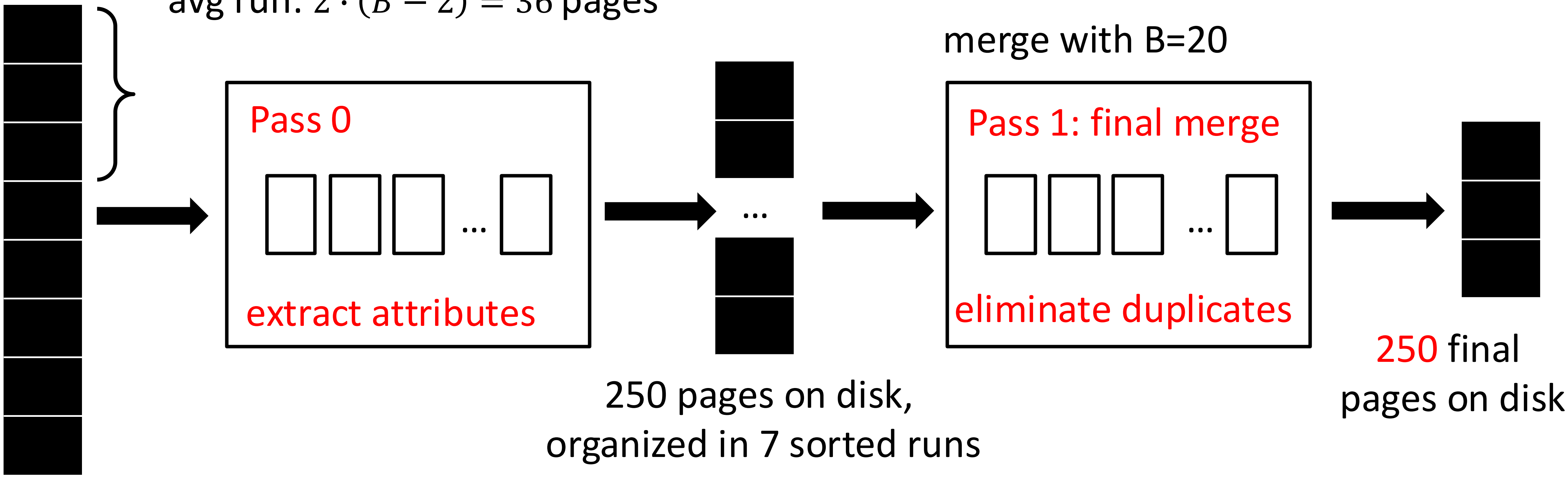
Projection - Sorting (explained)

R: M=1000, p_R=100, ts=40b

output tuple size: 10b

heapsort with B=20

avg run: $2 \cdot (B-2) = 36$ pages



1000 pages on disk

Pass 0: $\left\lceil \frac{250}{36} \right\rceil = 7$ runs

Total cost:

1000+250+250=1500

Projection Based on *Hashing*

Partitioning phase:

- Read R using one input buffer
- For each tuple:
  - Discard unwanted fields
  - Apply hash function *h1* to choose one of B-1 output buffers
- Result is B-1 partitions (of tuples with no unwanted fields)
  - 2 tuples from different partitions guaranteed to be distinct

Projection Based on *Hashing*

Duplicate elimination phase:

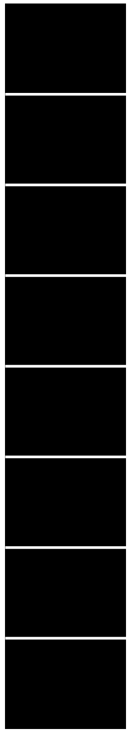
- For each partition
  - Read it and build an in-memory hash table
    - using hash function *h2* (<> *h1*) on all desired fields
  - while discarding duplicates
- If partition does not fit in memory
  - Apply hash-based projection algorithm recursively to this partition

Projection - Hashing (explained)

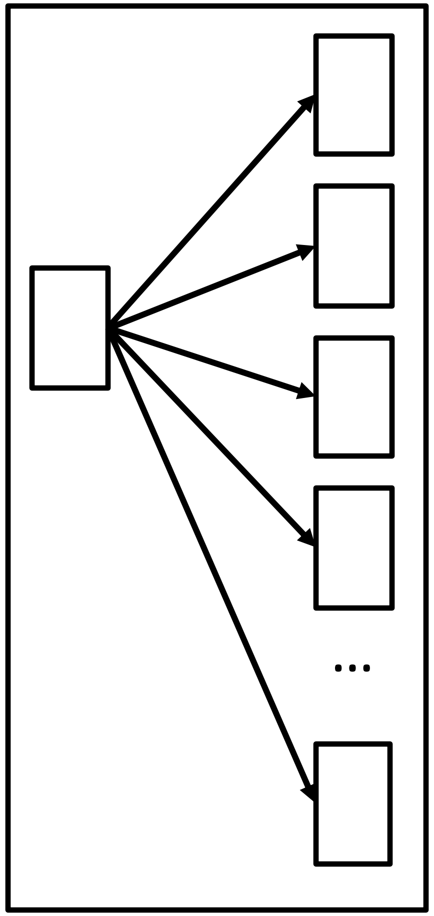
R: M=1000, p_R=100, ts=40b

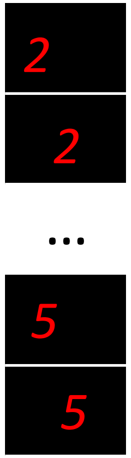
output tuple size: 10b

hash partitioning with B=20



1000 pages on disk

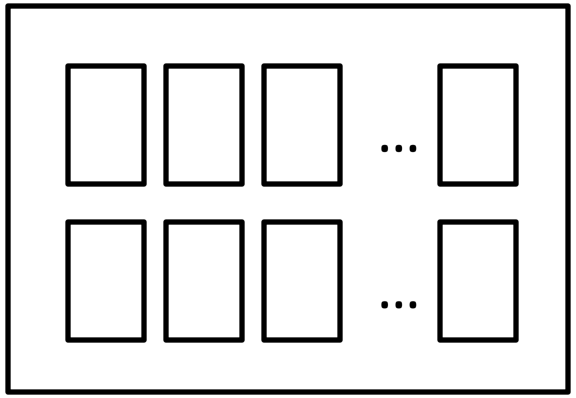




250 pages on disk, in B-1 partitions

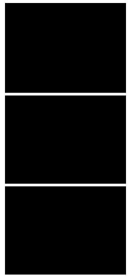
(any duplicates will be in the same partitions)

duplicate elimination with B=20



if all partitions fit in B pages, i.e., $B \geq \sqrt{M}$

(if not apply the hash partitioning algorithm recursively)



250 pages on disk

Total cost:

1000+250+250=1500

Discussion of Projection (1/2)

Sort-based approach is standard

– Better handling of skew, and result is sorted

If there are enough buffers, both have same I/O cost:

$$M + 2T$$

where:

– M is #pages in R,

– T is #pages of R with unneeded attributes removed

Although many systems don't use the specialized sort

Discussion of Projection (2/2)

If all wanted attributes are indexed
→ *index-only* scan

- Apply projection techniques to data entries (much smaller!)

If all wanted attributes are indexed as prefix of the search key
→ even better:

- Retrieve data entries in order (index-only scan)
- Discard unwanted fields
- Compare adjacent tuples to check for duplicates

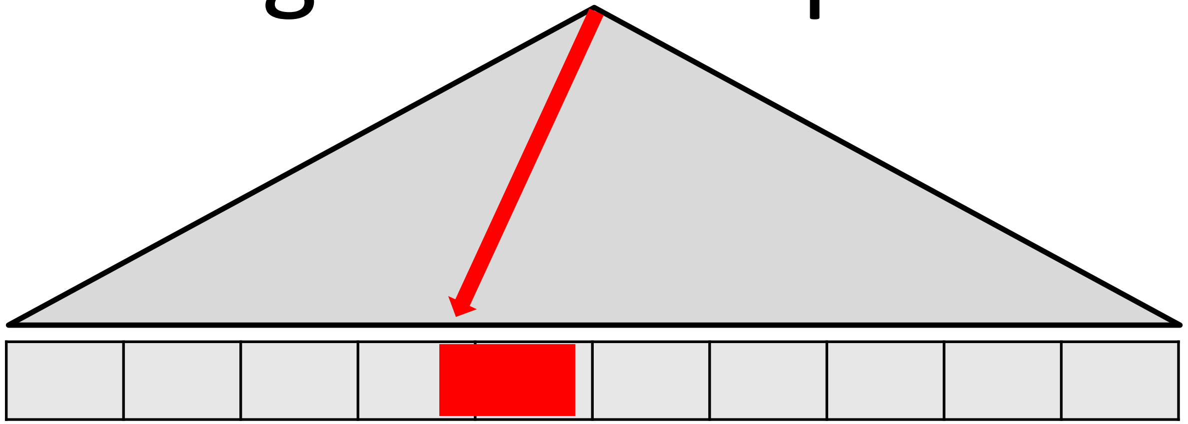
Projections using Index– Explained

R: M=1000, p_R=100, ts=40b

```
SELECT   DISTINCT
           R.sid, R.bid
FROM     Reserves R
```

A) indexed

data entries:



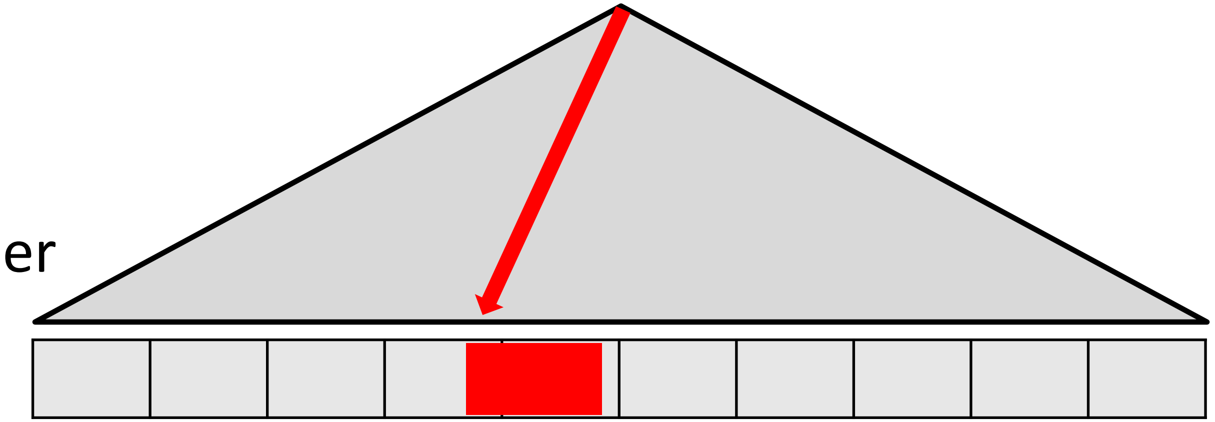
Index on <sid, day, bid>

no need to access the base data!

apply sort-based or hash-based projection only on the desired attributes

A) indexed in prefix order

data entries:



Index on <sid, bid, day >

retrieve entries sorted

discard unwanted fields & duplicates on the fly

Projections: summary

Projection based on *sorting*

Projection based on *hashing*

Can use *indexes* if they cover *relevant attributes*

Query Processing

Overview

Selections

Projections

Nested loop joins

Readings: Chapters 14.4-14.4.1

Sort-merge and hash joins

General joins and aggregates

Joins…

…are very common.
…can be very expensive (cross product in the worst case).

➔ Many approaches to reduce join cost!

Join techniques we will cover:

1. Nested-loops join
2. Index-nested loops join
3. Sort-merge join
4. Hash join

Equality Joins With One Join Column

```
SELECT  *
FROM    Reserves R1, Sailors S1
WHERE   R1.sid=S1.sid
```

In algebra: $R \bowtie S$. Common! Must be carefully optimized. R X S is large; so, R X S followed by a selection is inefficient

Remember, join is associative and commutative

Assume:

- M pages in R, p_R tuples per page
- N pages in S, p_S tuples per page
- In our examples, R is Reserves and S is Sailors

We will consider more complex join conditions later

Cost metric : # of I/Os

We will ignore output costs

Simple Nested Loops Join

```
foreach tuple r in R do
    foreach tuple s in S do
        if r_i == s_j then add <r, s> to result
```

For each tuple in the *outer* relation R, we scan the entire *inner* relation S

How much does this Cost?

$(p_R * M) * N + M = 100*1000*500 + 1000$ I/Os

- At 10ms/IO, Total: ???

What if smaller relation (S) was outer?

What assumptions are being made here?

Q: What is cost if one relation can fit entirely in memory?

Page-Oriented Nested Loops Join

foreach page b_R in R do
  foreach page b_S in S do
    foreach tuple r in b_R do
      foreach tuple s in b_S do
        if $r_i == s_j$ then add <r, s> to result

For each *page* of R
- get each *page* of S
- write out matching pairs of tuples <r, s>, where r is in R-page and S is in S-page

What is the cost of this approach?

M*N + M= 1000*500 + 1000
- If smaller relation (S) is outer, cost = 500*1000 + 500

Index Nested Loops Join

```
foreach tuple r in R do
    foreach tuple s in S where r_i == s_j do
        add <r, s> to result
```

If there is an index on the join column of one relation (say S), can make it the inner and exploit the index

- Cost: M + ((M*p_R) * cost of finding matching S tuples)

For each R tuple, cost of probing S index is about 1.2 for hash index, 2-4 for B+ tree. Cost of then finding S tuples (assuming Alt. (2) or (3) for data entries) depends on clustering

Clustered index: 1 I/O per page of matching S tuples

Unclustered: up to 1 I/O per matching S tuple

Examples of Index Nested Loops (1/2)

Hash-index (Alt. 2) on *sid* of Sailors (inner):

- Scan Reserves: 1000 page I/Os, 100*1000 tuples
- For each Reserves tuple:
  - 1.2 I/Os to get data entry in index,
  - plus 1 I/O to get (the exactly one) matching Sailors tuple

Examples of Index Nested Loops (2/2)

Hash-index (Alt. 2) on *sid* of Reserves (inner):

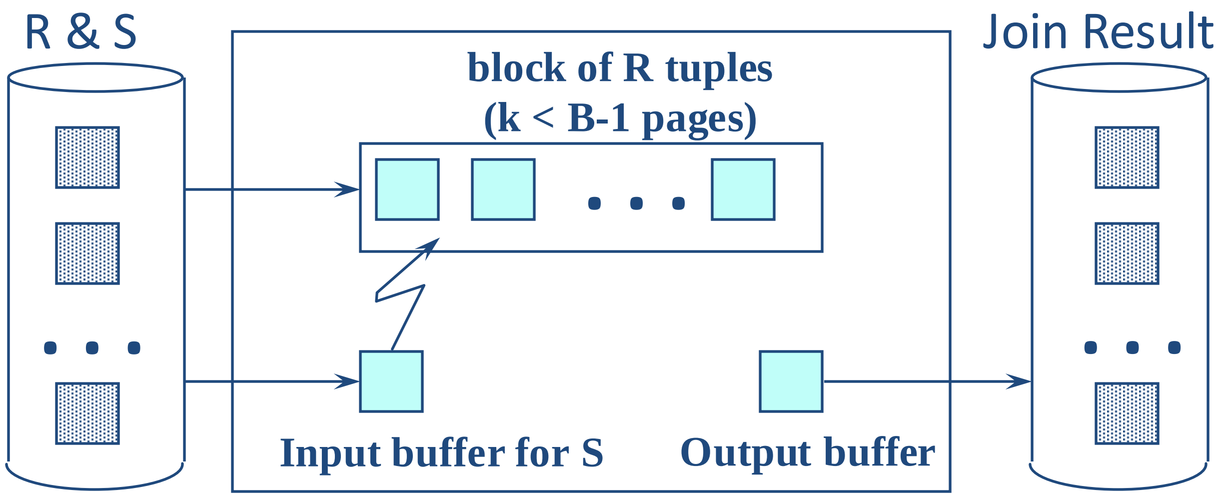
- Scan Sailors: 500 page I/Os, 80*500 tuples
- For each Sailors tuple:
  - 1.2 I/Os to find index page with data entries,
  - plus cost of retrieving matching Reserves tuples
  - Assuming uniform distribution, 2.5 reservations per sailor (100,000 / 40,000). Cost of retrieving them is 1 or 2.5 I/Os depending on whether the index is clustered

Block Nested Loops Join

Page-oriented NL doesn't exploit extra buffers

Alternative approach: Use one page as an input buffer for scanning the inner S, one page as the output buffer, and use all remaining pages to hold ‘block’ of outer R

For each matching tuple r in R-block, s in S-page, add <r, s> to result. Then read next R-block, scan S, etc



Examples of Block Nested Loops

Cost: Scan of outer + #outer blocks * scan of inner

- #outer blocks = $\lceil \# \; of \;\; pages \; of \;\; outer \; / \; blocksize \rceil$

With Reserves (R) as outer, and 100 pages of R:

- Cost of scanning R is 1000 I/Os; a total of 10 *blocks*
- Per block of R, we scan Sailors (S); 10*500 I/Os

With 100-page block of Sailors as outer:

- Cost of scanning S is 500 I/Os; a total of 5 blocks
- Per block of S, we scan Reserves; 5*1000 I/Os

With *sequential reads* considered, analysis changes: may be best to divide buffers evenly between R and S

Nested loop joins: summary

Simple nested loops

- Optimized by page-oriented access

Index nested loops

- Costs depend on the type of index

Block nested loops

- Optimization of page nested loops which uses memory buffers

Query Processing

Overview

Selections

Projections

Nested loop joins

Sort-merge and hash joins

Readings: Chapters 14.4.2-14.4.3

General joins and aggregates

Sort-Merge Join $(R \bowtie_{i=j} S)$

Sort R and S on the join column, then scan them to do a ‘merge’ (on join column), and output result tuples

Useful if

- one or both inputs are already sorted on join attribute(s)
- output is required to be sorted on join attributes(s)

‘Merge’ phase can require some back tracking if duplicate values appear in join column

R is scanned once; each S group is scanned once per matching R tuple. Note: Multiple scans of an S group will probably find needed pages in buffer

Example of Sort-Merge Join

sid	sname	rating	age
22	dustin	7	45.0
28	yuppy	9	35.0
31	lubber	8	55.5
44	guppy	5	35.0
58	rusty	10	35.0

sid	bid	day	rname
28	103	12/4/96	guppy
28	103	11/3/96	yuppy
31	101	10/10/96	dustin
31	102	10/12/96	lubber
31	101	10/11/96	lubber
58	103	11/12/96	dustin

Cost: Sort R +Sort S + (M+N)

- The cost of scanning, M+N, could be M*N (very unlikely!)

With 35, 100 or 300 buffer pages, both Reserves and Sailors can be sorted in 2 passes; total join cost: 2*#passes*(M+N)+(M+N)=7500

(BNL cost: 2500 to 15000 I/Os)

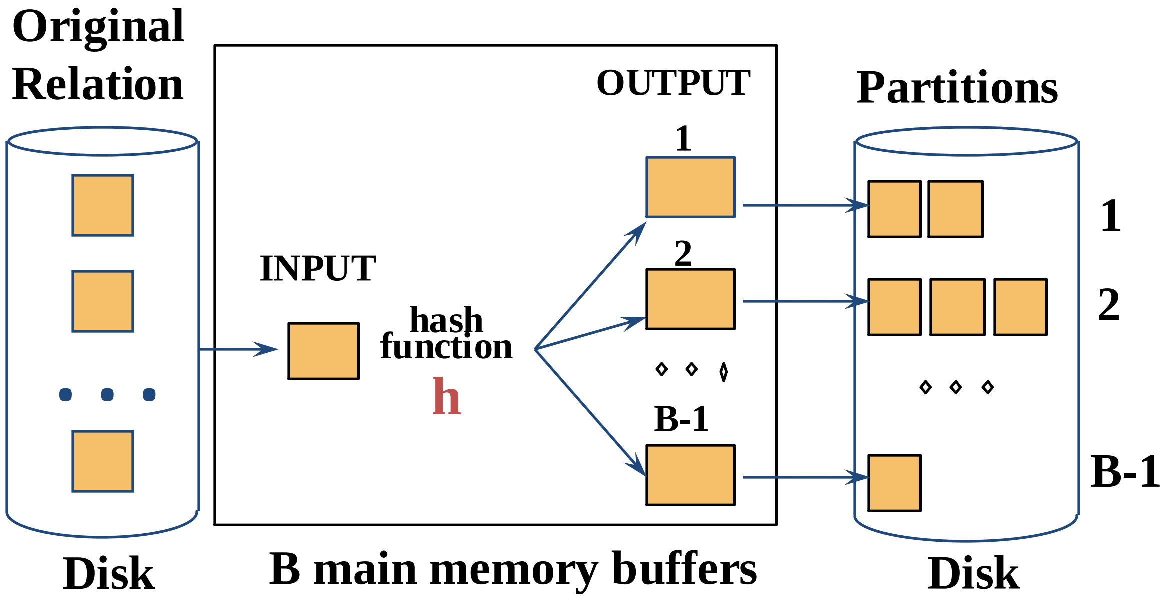
Refinement of Sort-Merge Join

We can combine the merging phases in the *sorting* of R and S with the merging required for the join

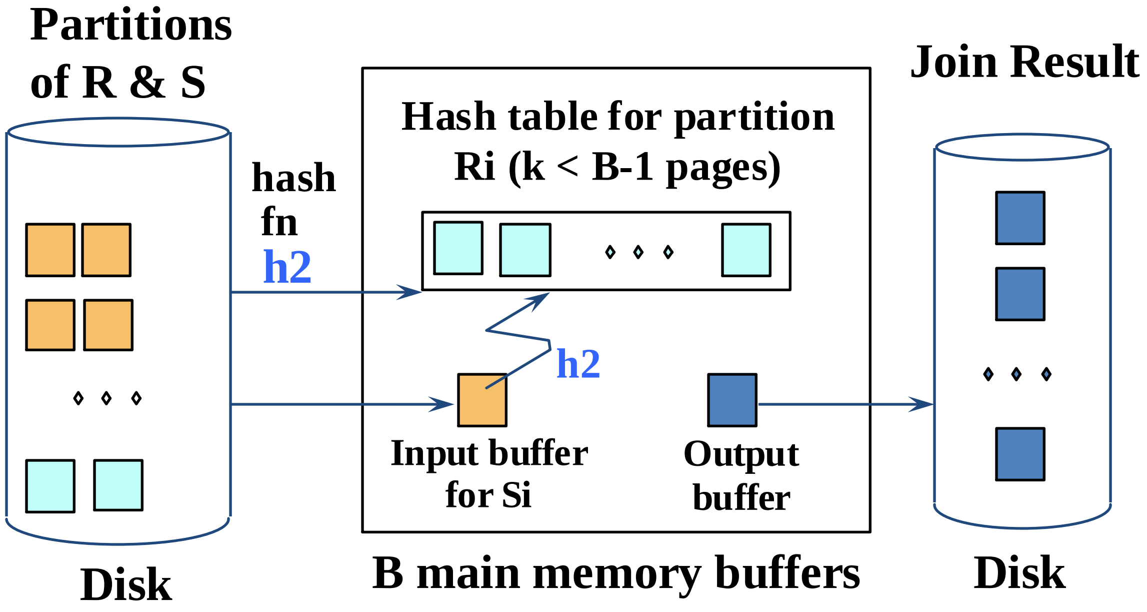
- Allocate 1 page per run of each relation, and 'merge' while checking the join condition
- With B > $\sqrt{L}$, where *L* is the size of the larger relation, using the sorting refinement that produces runs of length 2B in Pass 0, #runs of each relation is < B/2
- Cost: read+write each relation in Pass 0 + read each relation in (only) merging pass (+ writing of result tuples)
- In example, cost goes down from 7500 to 4500 I/Os

Hash-Join

Partition both relations using hash funtion h: R tuples in partition *i* will only match S tuples in partition *i*



Read in a partition of R, hash it using h2 (<> h!). Scan matching partition of S, probe hash table for matches



Observations on Hash-Join

First pass creates B-1 partitions, each of size S_i = N/(B-1)

Need each $S_i \leq$ B-2 in order to fit in memory for 2nd pass

→Need N/(B-1) ≤ B-2

… or, roughly: $\mathrm{B} > \sqrt{N}$ (we consider a fudge factor, f, so: $\mathrm{B} > f\sqrt{N}$)

where N is size of smaller relation

More Observations on Hash-Join

Since we build an in-memory hash table to speed up the matching of tuples in the second phase, a little more memory is needed

If the hash function does not partition uniformly, one or more R partitions may not fit in memory. We can apply hash-join technique recursively to do the join of this R-partition with corresponding S-partition

Cost of Hash-Join

In partitioning phase, **read and write** both relations; 2(M+N)

In matching phase, **read** both relations; M+N I/Os

In our running example, this is a total of 4500 I/Os

Sort-Merge Join vs. Hash Join

Given a minimum amount of memory (*what is this, for each?*) both have a cost of 3(M+N) I/Os

Hash Join Pros:

- Superior if relation sizes differ greatly
- Shown to be highly parallelizable *(beyond scope of class)*

Sort-Merge Join Pros:

- Less sensitive to data skew
- Result is sorted (may help "upstream" operators)
- Goes faster if one or both inputs already sorted

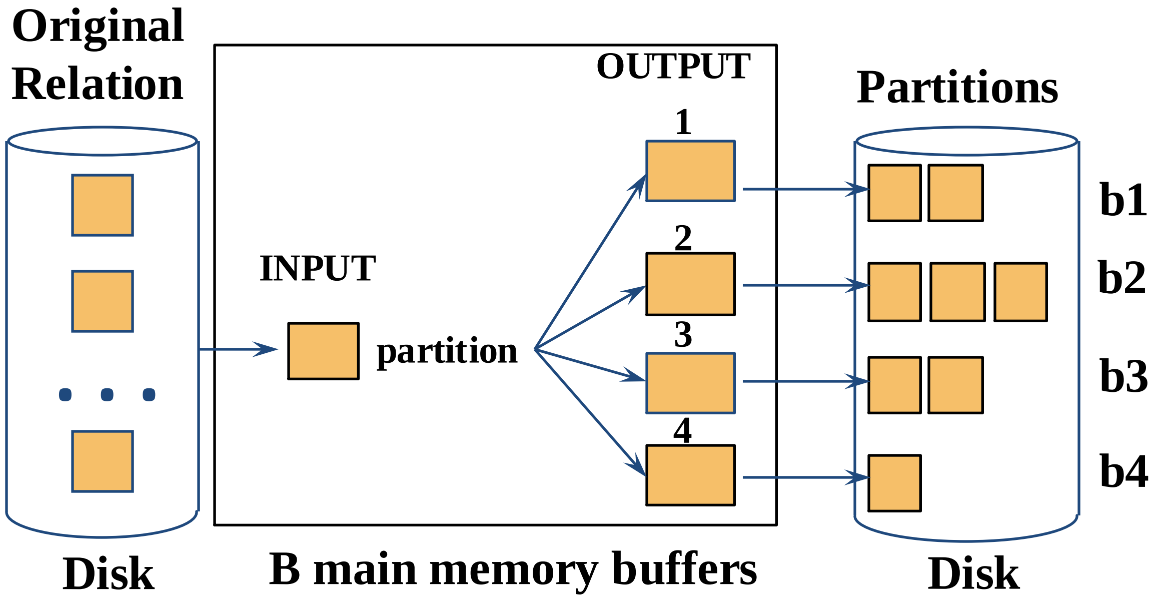
Hash-Join

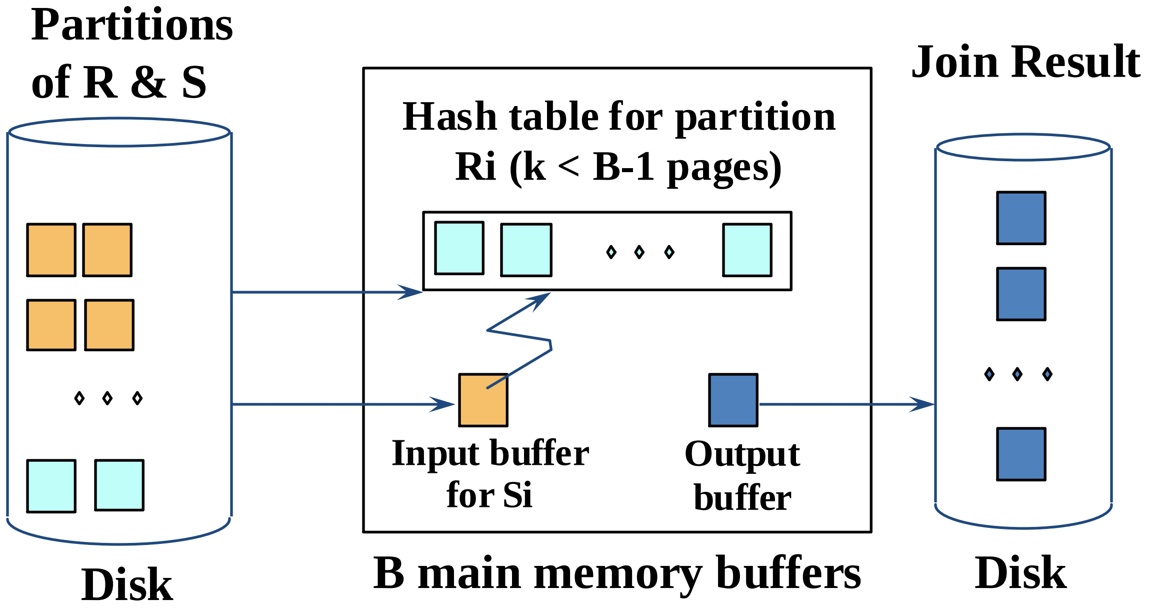
Let B = 5

Buckets:

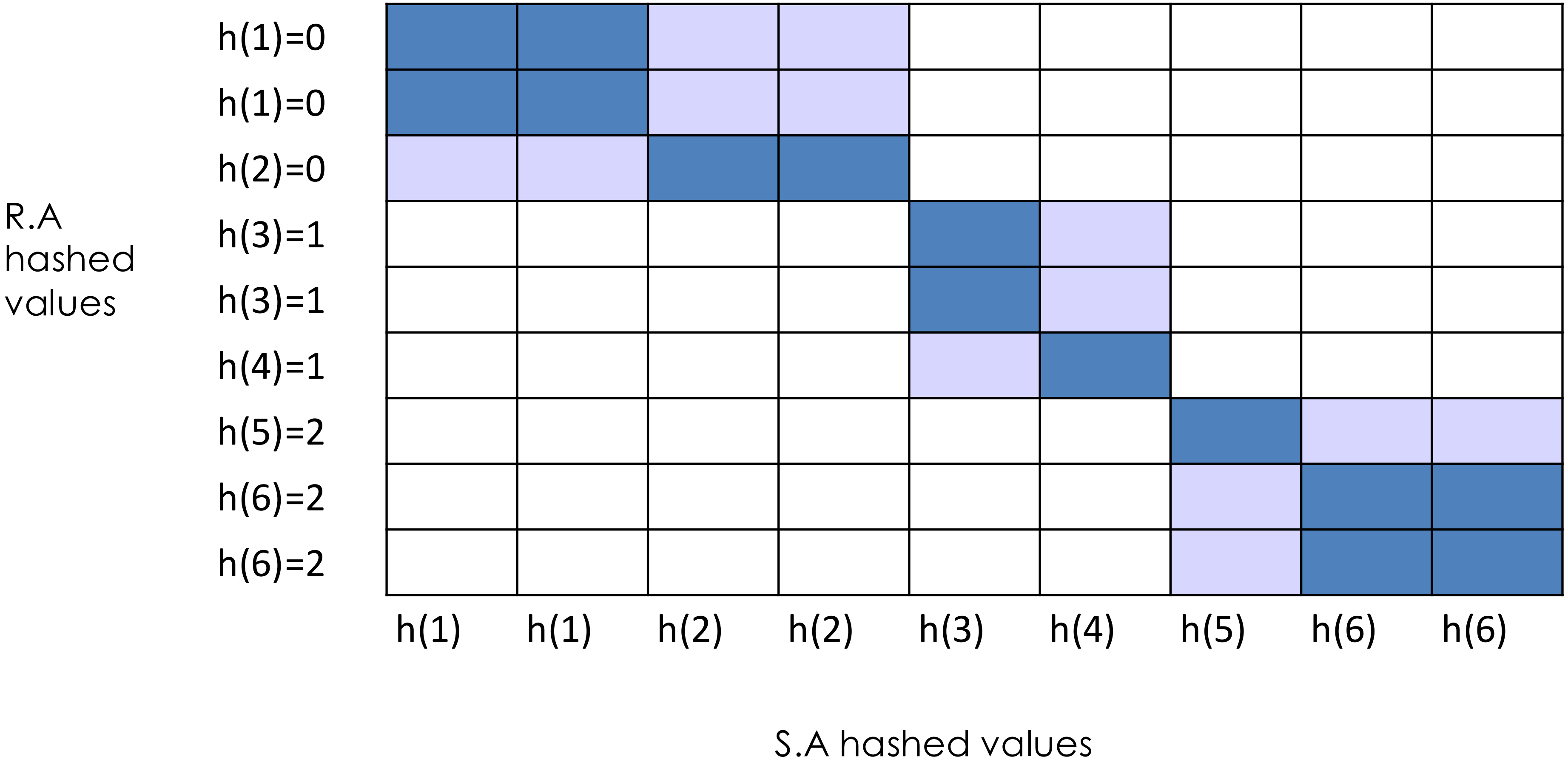
- b1: h ∈ [1,25]
- b2: h ∈ [26,50]
- b3: h ∈ [51,75]
- b4: h ∈ [76,100]

If |F| ≤ |M|, in second phase build in-memory hash table on F partitions, and stream M partitions through memory



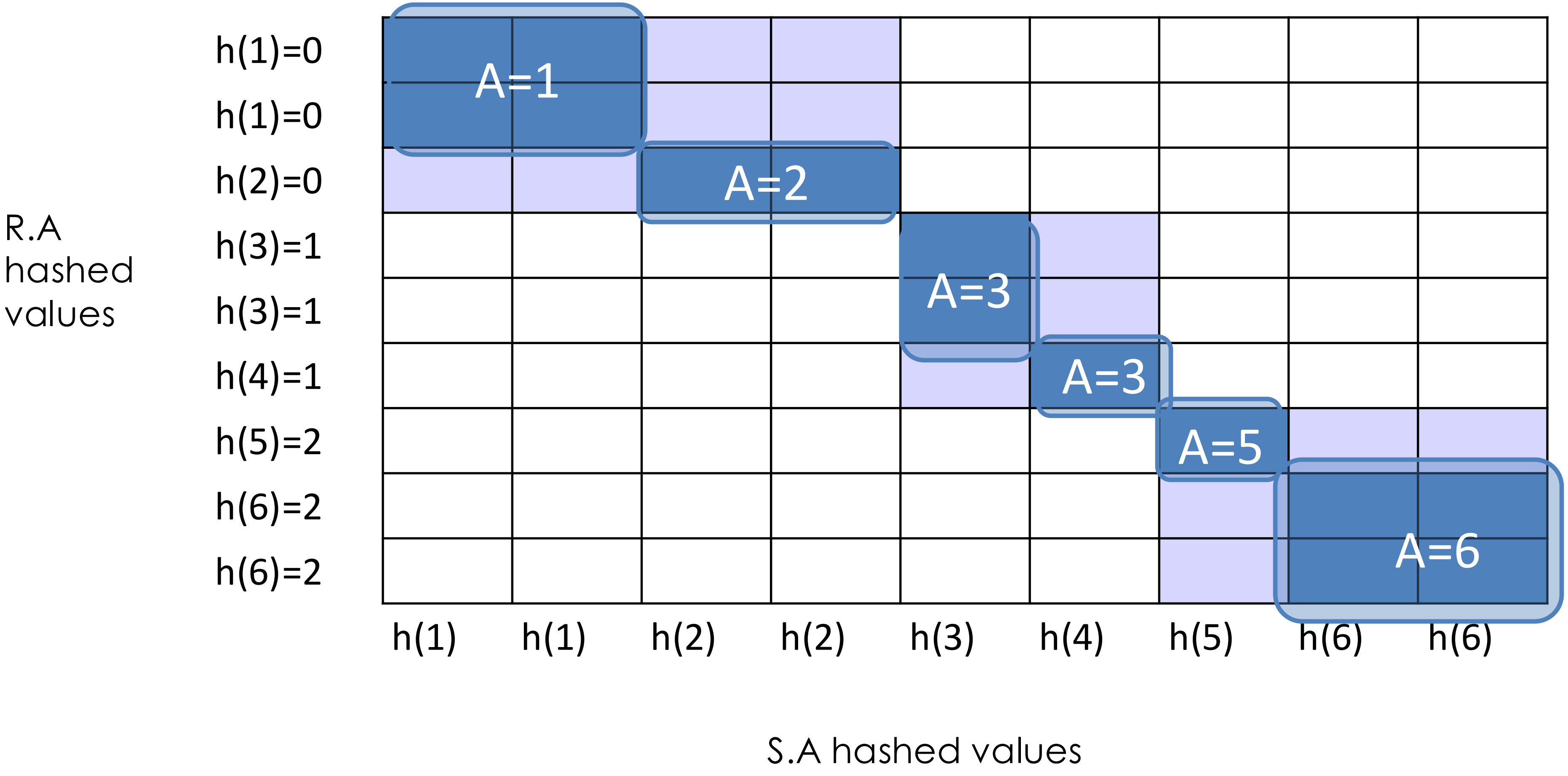


Hash Join Phase 2: Matching



$R \bowtie S \ on \ A$

Hash Join Phase 2: Matching

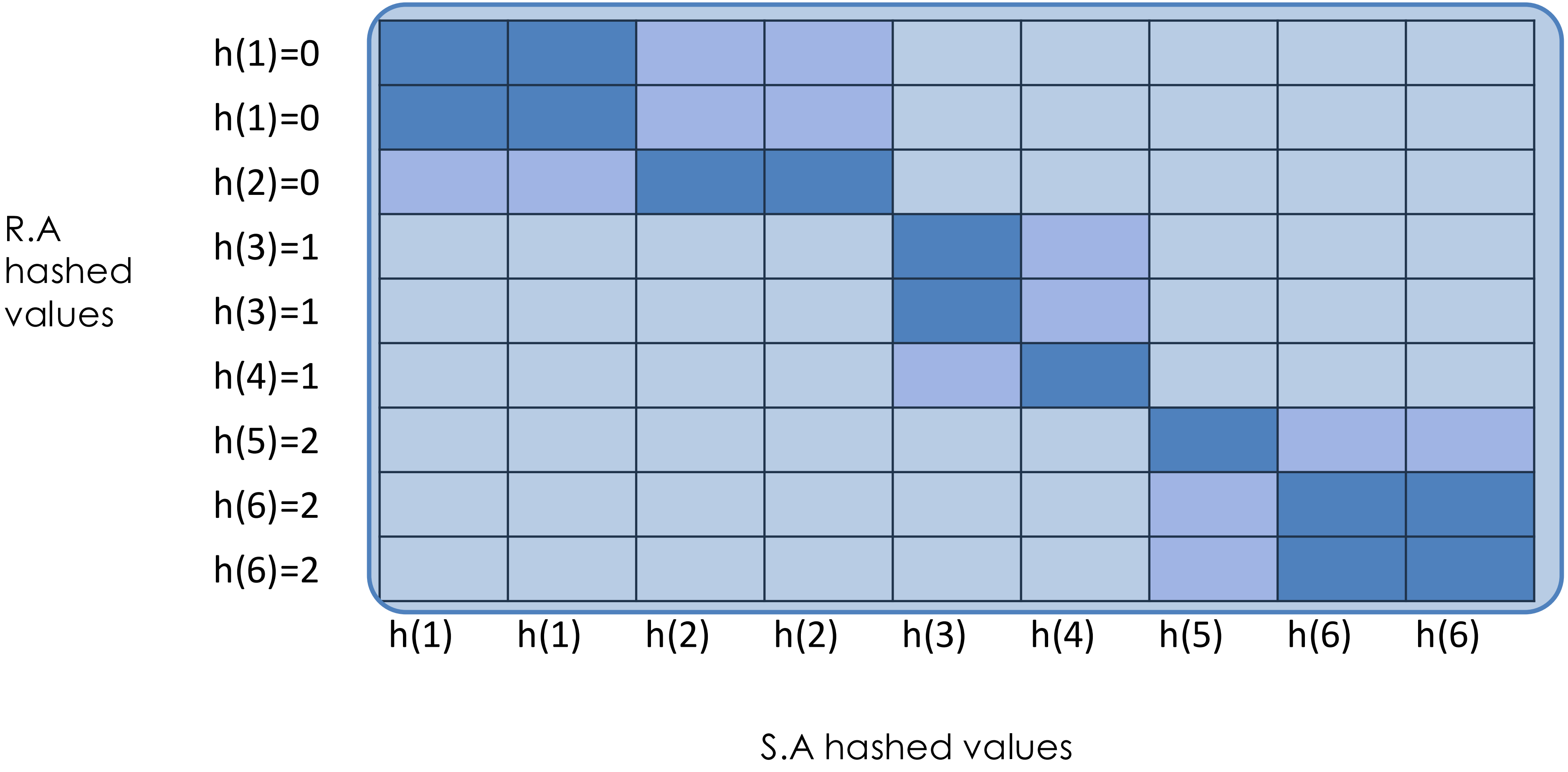


$R \bowtie S \text{ on } A$

To perform the join, we ideally just need to explore the dark blue regions

= the tuples with same values of the join key A

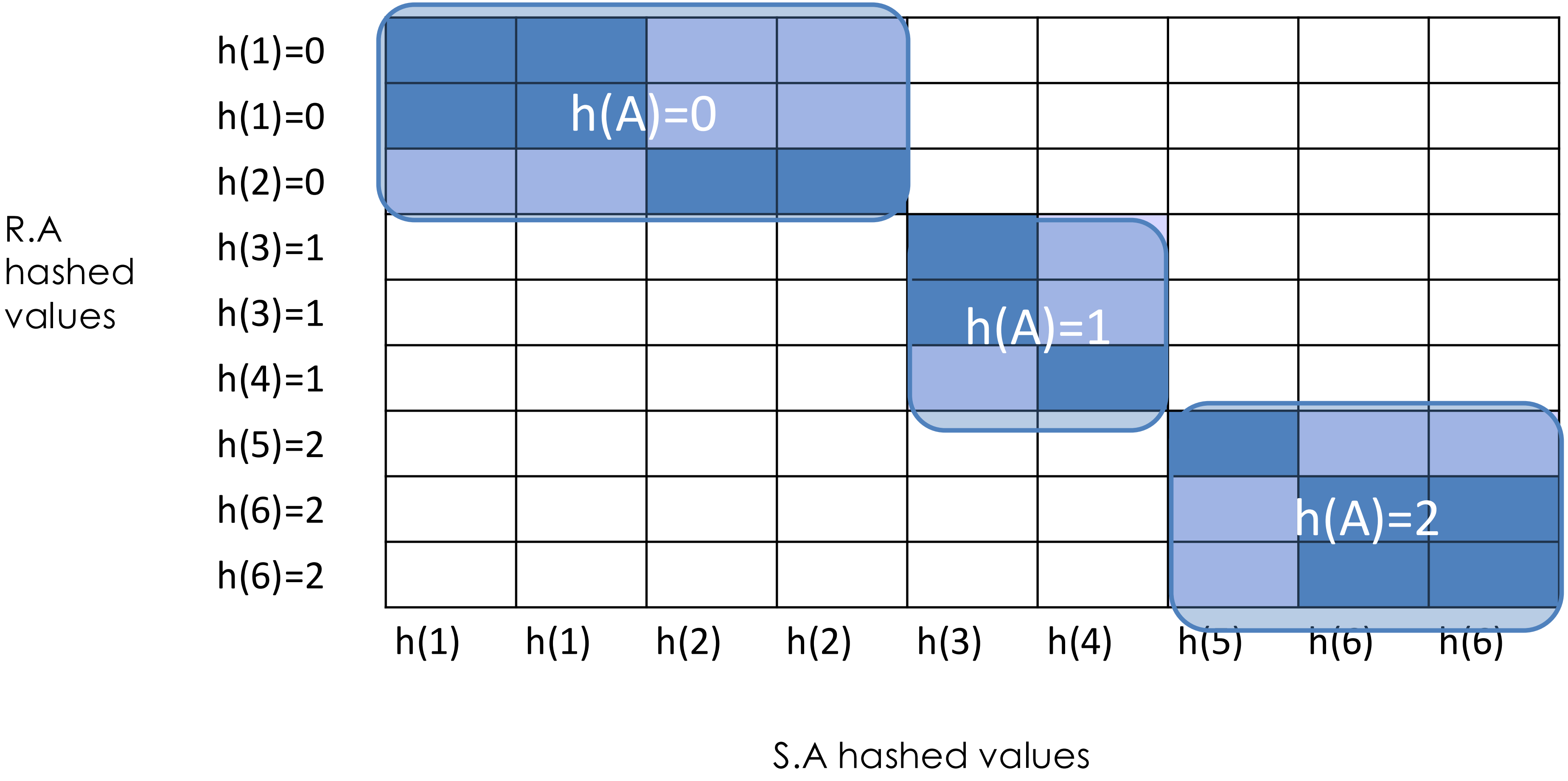
Hash Join Phase 2: Matching



$R \bowtie S \; on \; A$

With a join algorithm like BNLJ that doesn't take advantage of equijoin structure, we'd have to explore this whole grid!

Hash Join Phase 2: Matching



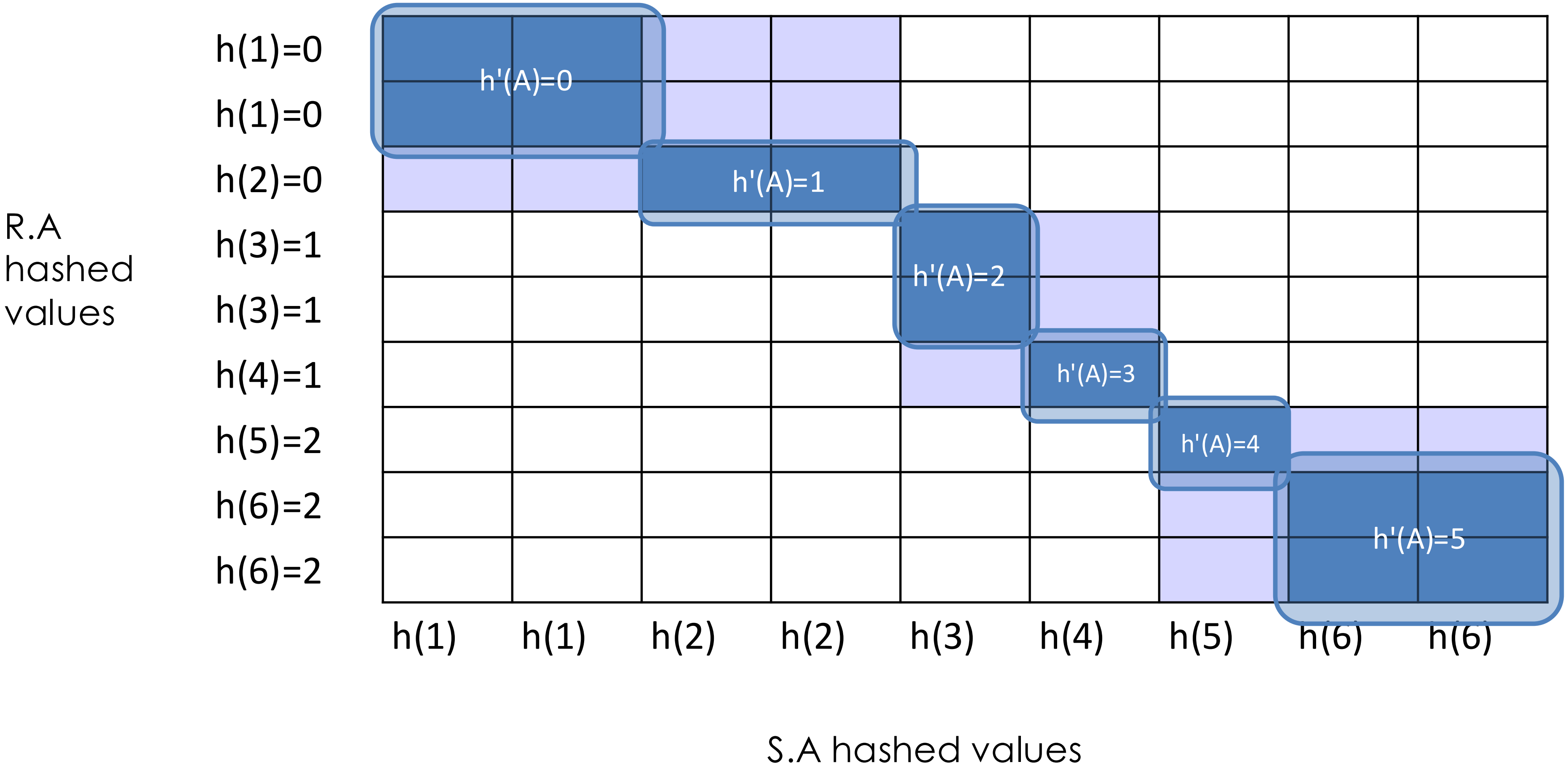
$R \bowtie S$ on A

With HJ, we only explore the blue regions

= the tuples with same values of h(A)!

We can apply BNLJ to each of these regions

Hash Join Phase 2: Matching



$R \bowtie S \text{ on } A$

An alternative to applying BNLJ:

We could also hash again, and keep doing passes in memory to reduce further!

Summary

Sort merge join

- Relies on the sorted order of join attributes
- Produces sorted output

Hash join

- Uses little memory
- Great when one relations is much smaller than the other
- Has problems with data skew

Query Processing

Overview

Selections

Projections

Nested loop joins

Sort-merge and hash joins

General joins and aggregates

Readings: Chapters 14.4.5-14.7

General Join Conditions

Equalities over several attributes (e.g., *R.sid=S.sid* AND *R.rname=S.sname*):

- For Index NL, build index on *<sid, sname>* (if S is inner); or use existing indexes on *sid* or *sname*
- For Sort-Merge and Hash Join, sort/partition on combination of the two join columns

Inequality conditions (e.g., *R.rname < S.sname*):

- For Index NL, need (clustered!) B+ tree index
  - Range probes on inner; # matches likely to be much higher than for equality joins
- Hash Join, Sort Merge Join not applicable!
- Block NL quite likely to be the best join method here

Set Operations

Intersection and ***cross-product*** special cases of join

Union (Distinct) and **Except** similar; we'll do union:

Sorting based approach to union:

- Sort both relations (on combination of all attributes)
- Scan sorted relations and merge them
- *Alternative*: Merge runs from Pass 0 for *both* relations

Hash based approach to union:

- Partition R and S using hash function *h*
- For each S-partition, build in-memory hash table (using *h2*), scan corresponding R-partition and add tuples to table while discarding duplicates

Aggregate Operations (AVG, MIN, etc.)

Without grouping:

- In general, requires ***scanning*** the relation
- Given ***index*** whose search key ***includes all attributes in the SELECT or WHERE*** clauses, can do index-only scan

Example: SELECT avg(salary) FROM EMPLOYEES WHERE age>35

can use an index on <age, salary> without going to the base data

Aggregate Operations (AVG, MIN, etc.)

With grouping:

- (a) **sort** on group-by attributes
  (b) scan relation and compute aggregate for each group
  Note: we can improve upon this by ***combining*** sorting and aggregation
- Similar approach based on **hashing** on group-by attributes
- Given tree **index** whose search key **includes all attributes in SELECT, WHERE and GROUP BY** clauses, we can do index-only scan
- If **group-by attributes form prefix of the search key**, we can retrieve data entries/tuples in group-by order

Impact of Buffering

If several operations are executing concurrently, estimating the number of available buffer pages is guesswork

Repeated access patterns interact with buffer replacement policy

- e.g., Inner relation is scanned repeatedly in Simple Nested Loop Join. With enough buffer pages to hold inner, replacement policy does not matter. Otherwise, MRU is best, LRU is worst (*sequential flooding*)
- Does replacement policy matter for Block Nested Loops?
- What about Index Nested Loops?

Summary

A virtue of relational DBMSs: queries are composed of a few basic operators

- Implementation of operators can be carefully tuned
- Important to do this!

Many alternative implementations for each operator

- No universally superior technique for most operators

Must consider alternatives for each operation in a query and choose best one based on system statistics…

- Part of the broader task of optimizing a query composed of several operators