CSE 544
Principles of Database Management Systems

Fall 2016

Lecture 7: Lifecycle of a Query

Recommended Readings

- Join processing in database systems with large main memories. Leonard Shapiro. ACM Transactions on Database Systems 11(3), 1986. Also in Red Book (3rd and 4th ed)
- The Anatomy of a Database System. J. Hellerstein and M. Stonebraker. **Section 4**. Red Book. 4th Ed.
- Database management systems.

  Ramakrishnan and Gehrke.

  Third Ed. **Chapters 12, 13 and 14.**

Outline

- **Steps involved in processing a query**
  - Logical query plan
  - Physical query plan
  - Query execution overview
- **Operator implementations**
  - One pass algorithms
  - Two-pass algorithms
  - Index-based algorithms

Example Database Schema

```
Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)
```

View: Suppliers in Seattle

```
CREATE VIEW NearbySupp AS
SELECT sno, sname
FROM Supplier
WHERE scity='Seattle' AND sstate='WA'
```

Example Query

- Find the names of all suppliers in Seattle who supply part number 2

```
SELECT sname FROM NearbySupp
WHERE sno IN ( SELECT sno
               FROM Supplies
               WHERE pno = 2 )
```

Lifecycle of a Query (1)

- **Step 0: admission control**
  - User connects to the db with username, password
  - User sends query in text format
- **Step 1: Query parsing**
  - Parses query into an internal format
  - Performs various checks using catalog: Correctness, authorization, integrity constraints
- **Step 2: Query rewrite**
  - View rewriting, flattening, decorrelation, etc.

View Rewriting, Flattening

Original query:

```
SELECT sname
FROM NearbySupp
WHERE sno IN ( SELECT sno
               FROM Supplies
               WHERE pno = 2 )
```

View rewriting
= view inlining
= view expansion

Flattening
= unnesting

Rewritten query:

```
SELECT S.sname
FROM Supplier S, Supplies U
WHERE S.scity='Seattle' AND S.sstate='WA'
AND S.sno = U.sno
AND U.pno = 2;
```

Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)

Decorrelation

```
SELECT  Q.sno
FROM Supplier Q
WHERE  Q.sstate = 'WA'
    and not exists
      (SELECT *
       FROM Supply P
       WHERE P.sno = Q.sno
            and P.price > 100)
```

Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)

Decorrelation

```
SELECT  Q.sno
FROM Supplier Q
WHERE  Q.sstate = 'WA'
   and not exists
     (SELECT *
      FROM Supply P
      WHERE P.sno = Q.sno
          and P.price > 100)
```

Correlation !

Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)

Decorrelation

```
SELECT  Q.sno
FROM Supplier Q
WHERE  Q.sstate = 'WA'
    and not exists
      (SELECT *
       FROM Supply P
       WHERE P.sno = Q.sno
             and P.price > 100)
```

De-Correlation

```
SELECT  Q.sno
FROM Supplier Q
WHERE  Q.sstate = 'WA'
    and Q.sno not in
      (SELECT P.sno
       FROM Supply P
       WHERE P.price > 100)
```

Decorrelation

Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)

Un-nesting

```
(SELECT  Q.sno
 FROM Supplier Q
 WHERE  Q.sstate = 'WA')
   EXCEPT
(SELECT P.sno
  FROM Supply P
  WHERE P.price > 100)
```

```
SELECT  Q.sno
FROM Supplier Q
WHERE  Q.sstate = 'WA'
    and Q.sno not in
      (SELECT P.sno
       FROM Supply P
       WHERE P.price > 100)
```

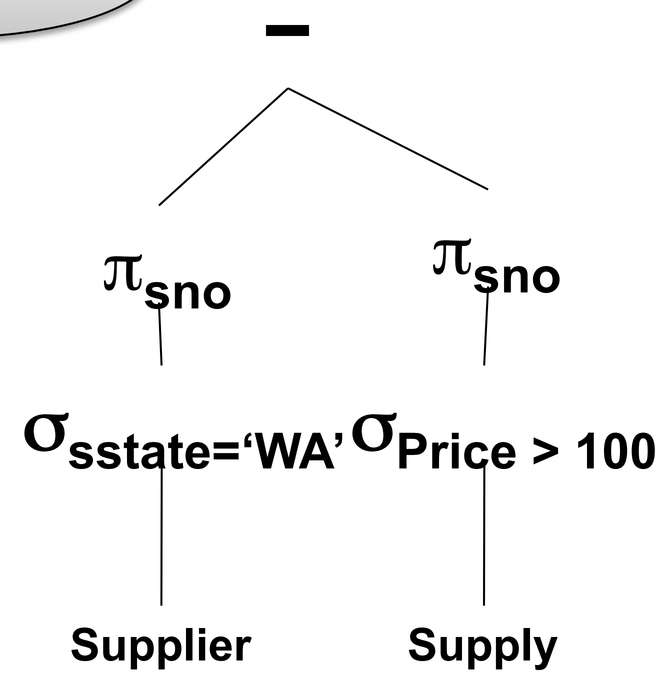
EXCEPT = set difference

Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)

Decorrelation

```
(SELECT  Q.sno
 FROM Supplier Q
 WHERE  Q.sstate = 'WA')
   EXCEPT
(SELECT P.sno
  FROM Supply P
  WHERE P.price > 100)
```

Finally…



Lifecycle of a Query (2)

- **Step 3: Query optimization**
  - Find an efficient query plan for executing the query
  - We will spend next lecture on this topic

- A **query plan** is
  - **Logical query plan**: an extended relational algebra tree
  - **Physical query plan**: with additional annotations at each node

Extended Algebra Operators

- Union $\cup$, intersection $\cap$, difference -
- **S**election σ
- **P**rojection π
- Join $\bowtie$
- **D**uplicate elimination δ
- **G**rouping and aggregation γ
- **S**orting τ
- **R**ename ρ

Bag semantics!

Logical Query Plan

π_{sname}

$\sigma_{\text{sscity='Seattle'} \wedge \text{sstate='WA'} \wedge \text{pno=2}}$

$\bowtie_{\text{sno = sno}}$

Suppliers   Supplies

Query Block

- Most optimizers operate on individual query blocks

- A query block is an SQL query with **no nesting**
  - **Exactly one**
    - SELECT clause
    - FROM clause
  - **At most one**
    - WHERE clause
    - GROUP BY clause
    - HAVING clause

Typical Plan For Block

$\sigma_{\text{having-condition}}$

$\gamma_{\text{ fields, sum/count/min/max(fields)}}$

$\pi_{\text{ fields}}$

$\sigma_{\text{where-condition}}$

$\bowtie$

join condition

… …

SELECT-PROJECT-JOIN
Query

Physical Query Plan

(On the fly) π_{sname}

(On the fly) $\sigma_{\text{sscity='Seattle'} \wedge \text{sstate='WA'} \wedge \text{pno=2}}$

(Nested loop) $\bowtie_{\text{sno = sno}}$

Algorithm

Suppliers (File scan)

Supplies (Index lookup)

Access path

Physical plan=
Logical plan
+ choice of algorithms
+ choice of access path

Final Step in Query Processing

- **Step 4: Query execution**
  - How to synchronize operators?
  - How to pass data between operators?

- Standard approach:
  - Iterator interface and
  - Pipelined execution or
  - Intermediate result materialization

Iterator Interface

- Each **operator implements this interface**
- Interface has only three methods
- **open()**
  - Initializes operator state
  - Sets parameters such as selection condition
- **get_next()**
  - Operator invokes get_next() recursively on its inputs
  - Performs processing and produces an output tuple
- **close()**: clean-up state

Pipelined Execution

- Applies parent operator to tuples directly as they are produced by child operators
- Benefits
  - No operator synchronization issues
  - Saves cost of writing intermediate data to disk
  - Saves cost of reading intermediate data from disk
  - Good resource utilizations on single processor
- This approach is used whenever possible

Pipelined Execution

(On the fly) π_{sname}

(On the fly) $\sigma_{\text{sscity='Seattle'} \wedge \text{sstate='WA'} \wedge \text{pno=2}}$

(Nested loop) $\bowtie_{\text{sno = sno}}$

Suppliers (File scan)

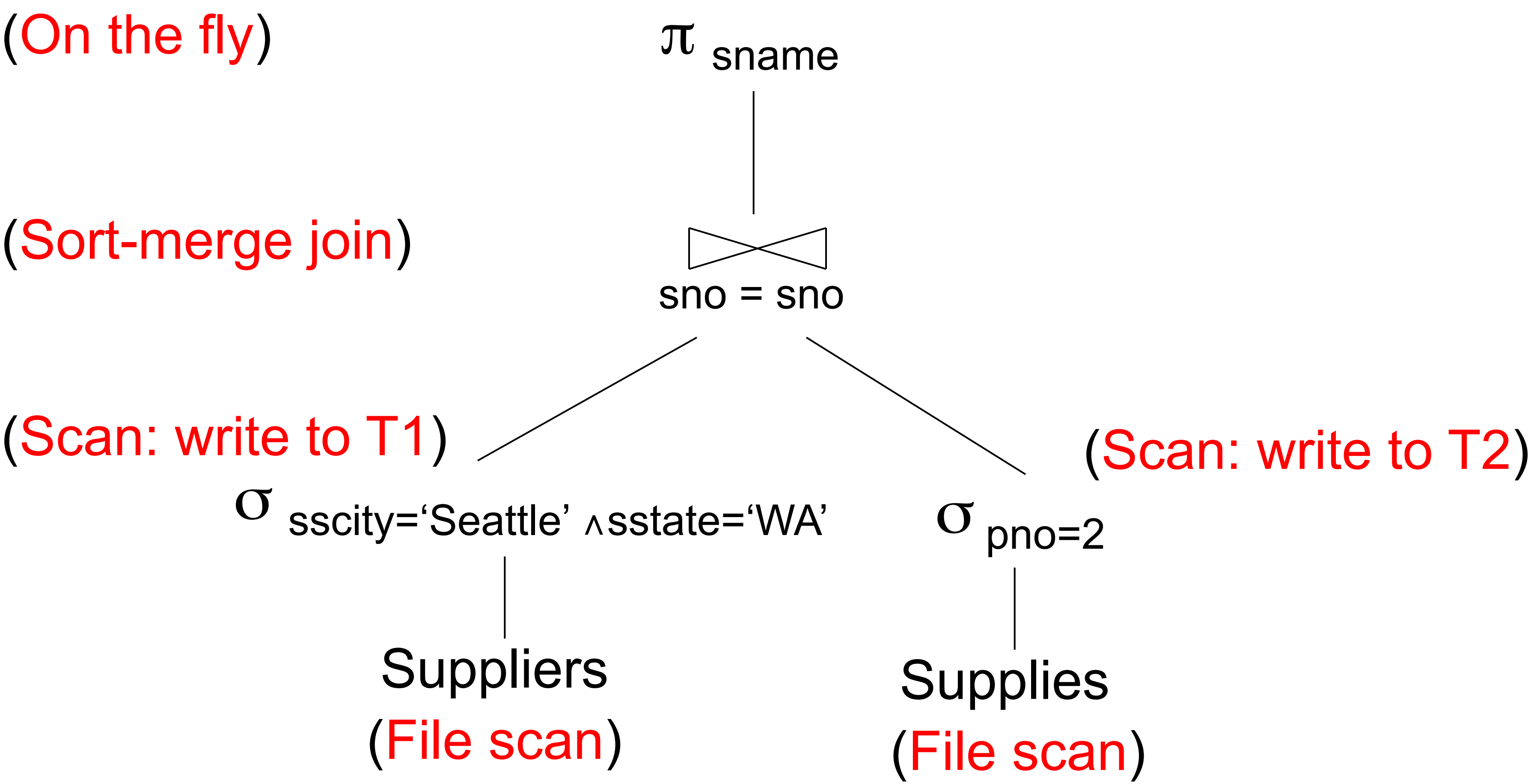
Supplies (Index lookup)

Intermediate Tuple Materialization

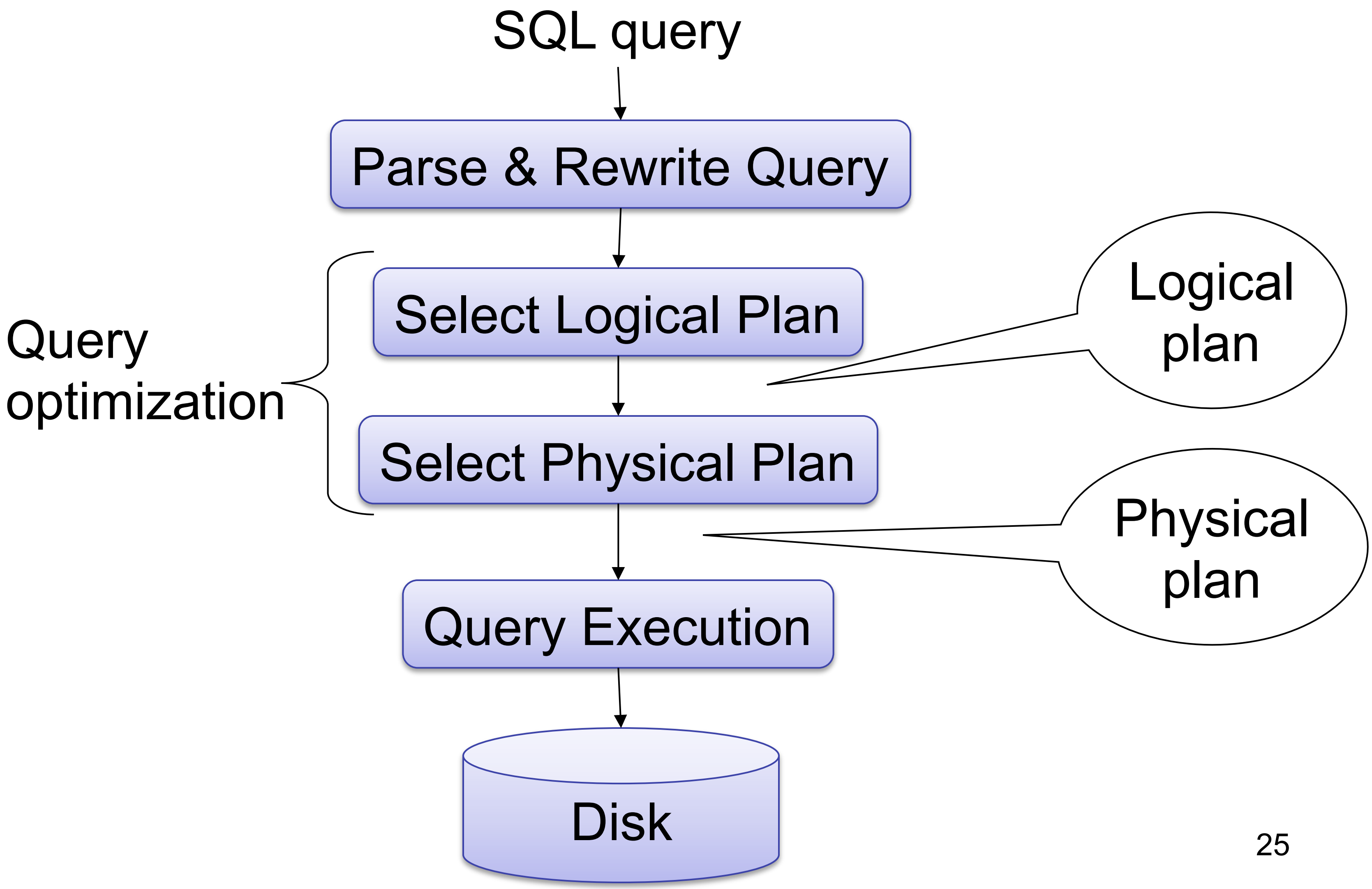
- Writes the results of an operator to an intermediate table on disk

- Necessary for some operator implementations
- When operator needs to examine the same tuples multiple times

Intermediate Tuple Materialization



Lifecycle of a Query



Outline

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Cost Parameters

- In database systems the data is on disk

- Parameters:
  - B(R) = # of blocks (i.e., pages) for relation R
  - T(R) = # of tuples in relation R
  - V(R, a) = # of distinct values of attribute a
  - M = # pages available in main memory

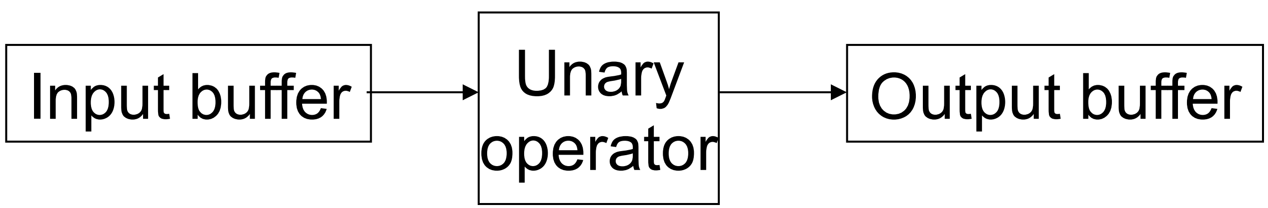
- Cost = total number of I/Os

- Convention: writing the final result to disk is *not included*

One-pass Algorithms

Selection $\sigma(R)$, projection $\Pi(R)$

- Both are ***tuple-at-a-time*** algorithms
- Cost: B(R), the cost of scanning the relation



Main Memory Join Algorithms

Three standard main memory algorithms:

- Hash join
- Nested loop join
- Sort-merge join

Review in class

One Pass Hash Join

Hash join: R $\bowtie$ S

- Scan R, build buckets in main memory
- Then scan S, probe hash table to join

- Cost: B(R) + B(S)

- One pass algorithm when B(R) <= M

Nested Loop Joins

- Tuple-based nested loop $R \bowtie S$
- R is the outer relation, S is the inner relation

```
for each tuple r in R do
   for each tuple s in S do
      if r and s join then output (r,s)
```

- Cost: B(R) + T(R) B(S)

Page-at-a-time Refinement

```
for each page of tuples r in R do
   for each page of tuples s in S do
         for all pairs of tuples
               if r and s join then output (r,s)
```

- Cost: B(R) + B(R)B(S)

Nested Loop Joins

- We can be much more clever

- How would you compute the join in the following cases ? What is the cost ?

  – $B(R) = 1000$, $B(S) = 2$, $M = 4$

  – $B(R) = 1000$, $B(S) = 3$, $M = 4$

  – $B(R) = 1000$, $B(S) = 6$, $M = 4$

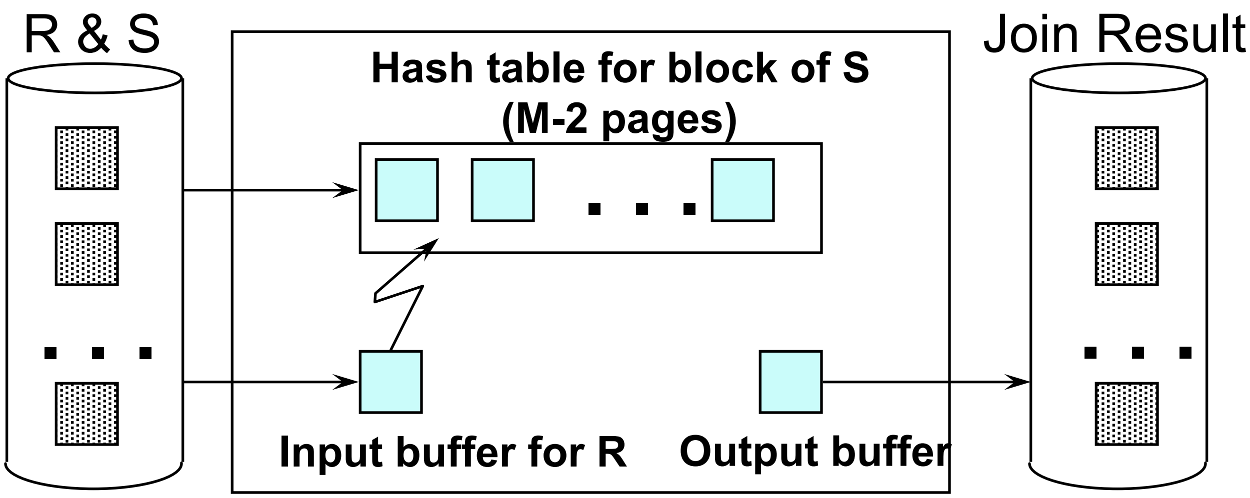
Nested Loop Joins

- Block Nested Loop Join
- Group of (M-2) pages of S is called a "block"

```
for each (M-2) pages ps of S do
   for each page pr of R do
      for each tuple s in ps
         for each tuple r in pr do
            if r and s join then output(r,s)
```

Main memory hash-join
ps ⋈ pr

Nested Loop Joins



Nested Loop Joins

Cost of block-based nested loop join

- Read S once: $B(S)$
- Outer loop runs $B(S)/(M-2)$ times, each iteration reads the entire R: $B(S)B(R)/(M-2)$
- Total cost: $B(S) + B(S)B(R)/(M-2)$

Notice: it is better to iterate over the smaller relation first

Sort-Merge Join

Sort-merge join: R $\bowtie$ S

- Scan R and sort in main memory
- Scan S and sort in main memory
- Merge R and S

- Cost: B(R) + B(S)
- One pass algorithm when B(S) + B(R) <= M
- Typically, this is NOT a one pass algorithm

Example

Grouping:

Product(name, department, quantity)

$\gamma_{\text{department, sum(quantity)}}$ (Product) → Answer(department, sum)

In class: describe a one-pass algorithms. Cost=?

Outline

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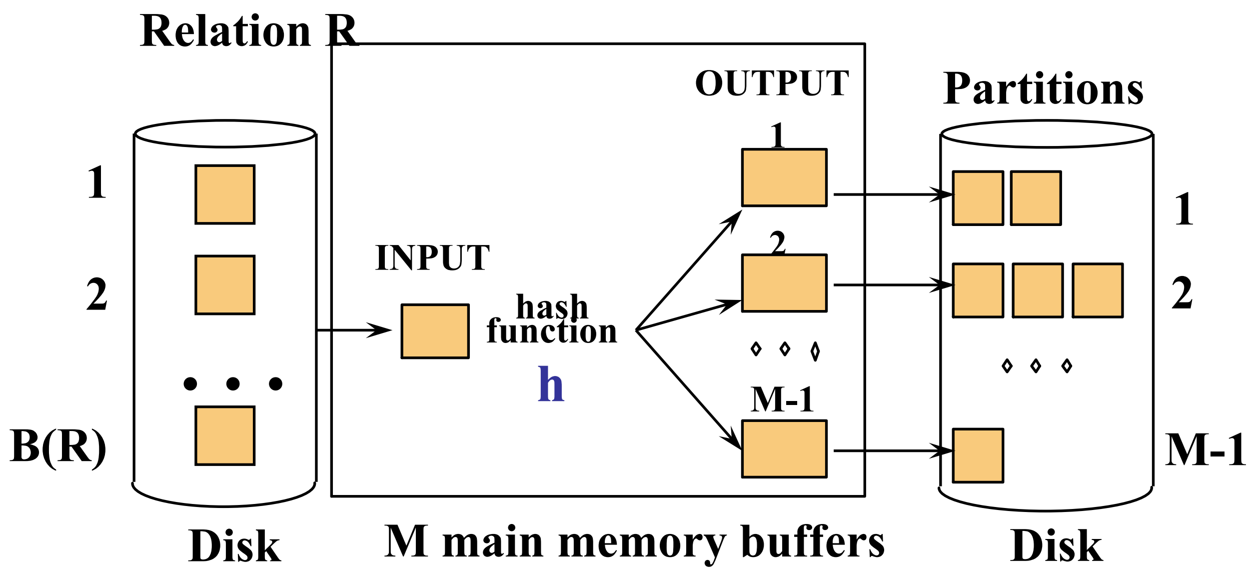
Two-Pass Algorithms

- When data is larger than main memory, need two or more passes
- Two key techniques
  - Hashing
  - Sorting

Two Pass Algorithms Based on Hashing

- Idea: partition a relation R into buckets, on disk
- Each bucket has size approx. B(R)/M



- Does each bucket fit in main memory ?
  - Yes if B(R)/M <= M, i.e. $B(R) <= M^2$

Hash Based Algorithms for γ

- Recall: $\gamma(R)$ = grouping and aggregation

- Step 1. Partition R into buckets
- Step 2. Apply γ to each bucket

- Cost: 3B(R)
- Assumption: $B(R) <= M^2$

Simple Hash Join

Will skip in class
See [Shapiro]

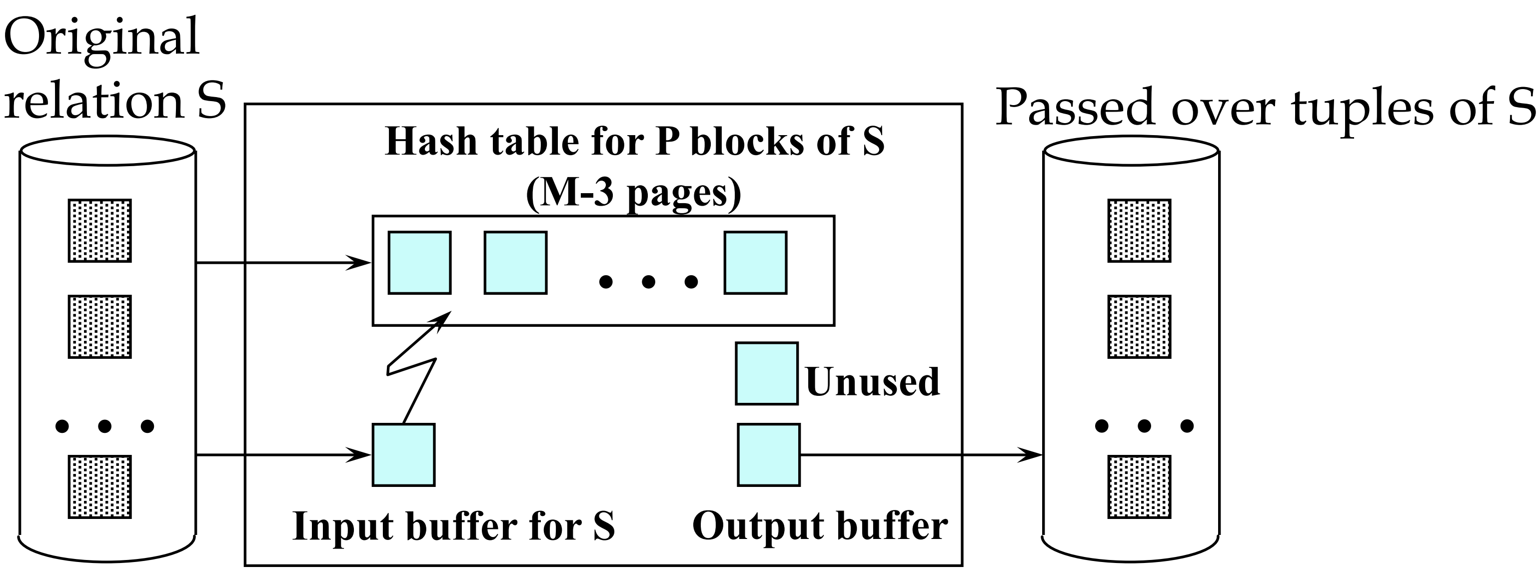
$R \bowtie S$

- Step 1:
  - P = min(M-3, B(S))
  - Choose hash function h and set of hash values s.t. P blocks of S tuples will hash into that set
  - Hash S and either insert tuple into hash table or write to disk
- Step 2
  - Hash R and either probe the hash table for S or write to disk
- Step 3
  - Repeat steps 1 and 2 until all tuples are processed

Simple Hash Join

Will skip in class
See [Shapiro]

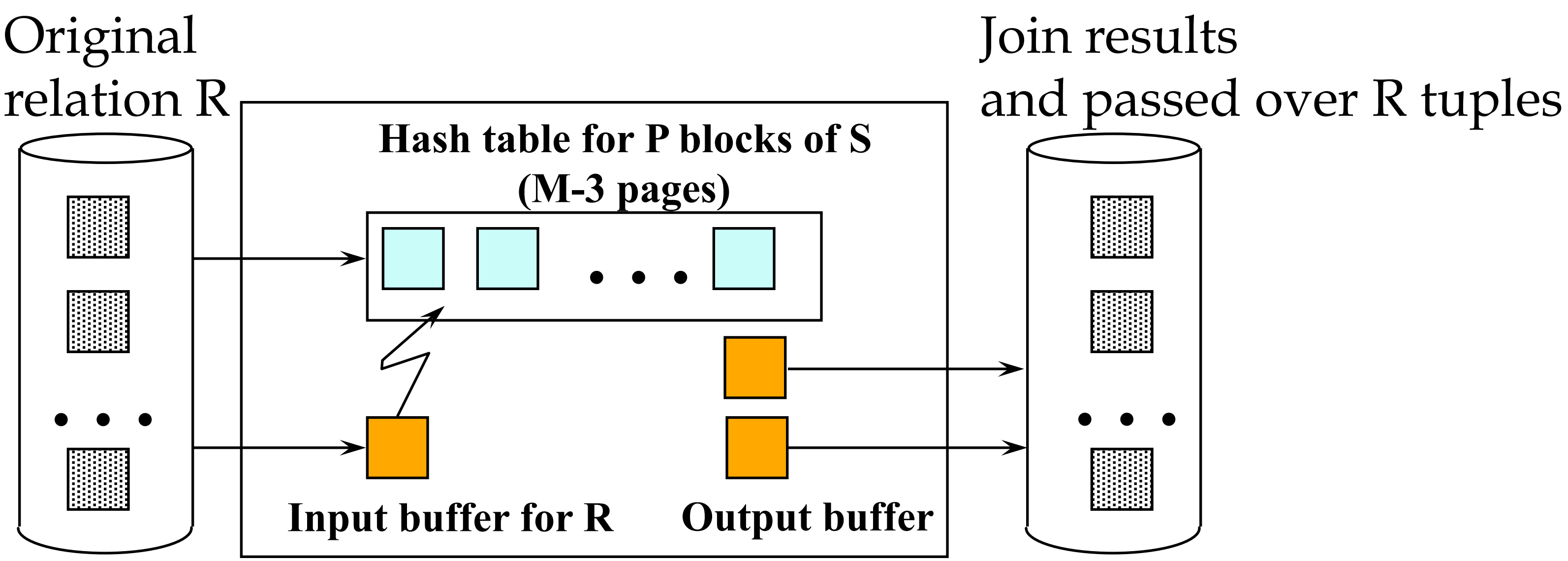
- Build a hash-table for M-3 pages of S
- Write remaining pages of S back to disk



Simple Hash Join

Will skip in class
See [Shapiro]

- Hash R using the same hash function
- Probe hash table for S or write tuples of R back to disk



- Repeat these two steps until all tuples are processed
- Requires many passes

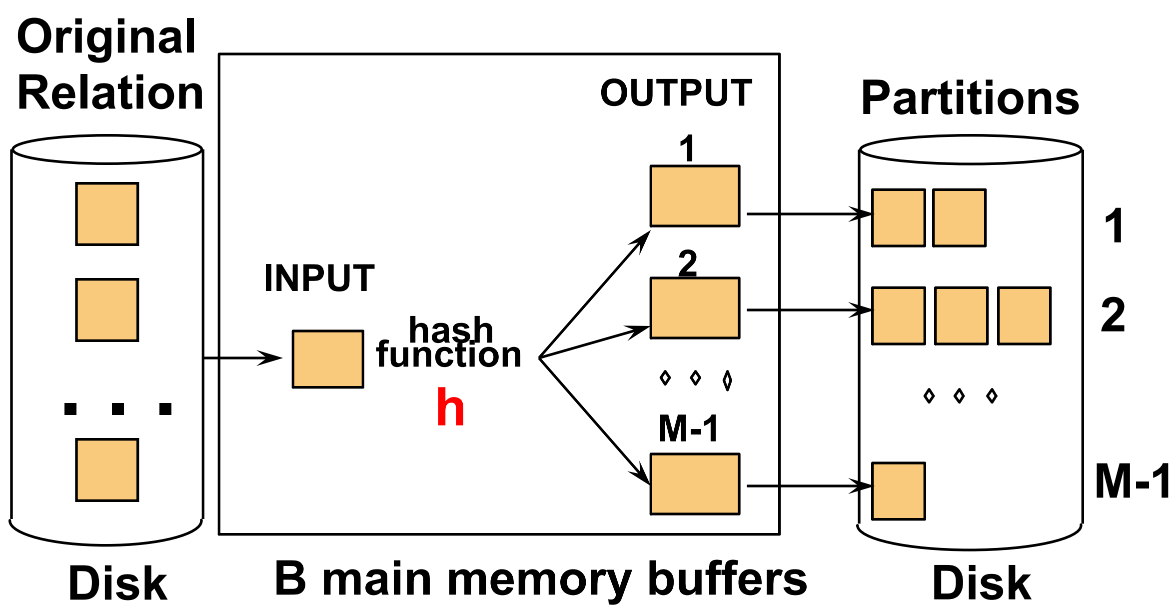
Partitioned (Grace) Hash Join

$R \bowtie S$

- Step 1:
  - Hash S into M-1 buckets
  - Send all buckets to disk
- Step 2
  - Hash R into M-1 buckets
  - Send all buckets to disk
- Step 3
  - Join every pair of buckets

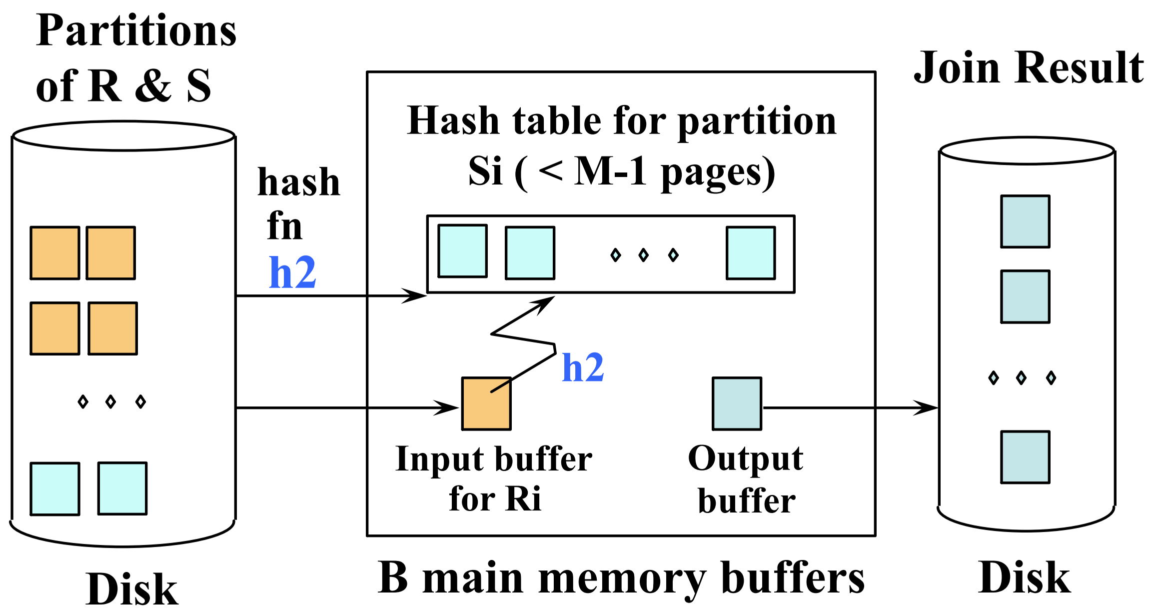
Partitioned Hash Join

- Partition both relations using hash fn **h**
- R tuples in partition i will only match S tuples in partition i.



Partitioned Hash Join

- Read in partition of R, hash it using h2 (≠ h)
  - Build phase
- Scan matching partition of S, search for matches
  - Probe phase



Partitioned Hash Join

- Cost: 3B(R) + 3B(S)
- Assumption: min(B(R), B(S)) <= M^2

Hybrid Hash Join Algorithm

- Assume we have extra memory available

- Partition S into k buckets

  t buckets S_1 , …, S_t stay in memory

  k-t buckets S_{t+1}, …, S_k to disk

- Partition R into k buckets
  - First t buckets join immediately with S
  - Rest k-t buckets go to disk

- Finally, join k-t pairs of buckets:

  (R_{t+1},S_{t+1}), (R_{t+2},S_{t+2}), …, (R_k,S_k)

Hybrid Hash Join Algorithm

- How to choose k and t ?
  - The first t buckets must fin in M: $t/k * B(S) \leq M$
  - Need room for k-t additional pages: $k\text{-}t \leq M$
  - Thus: $t/k * B(S) + k\text{-}t \leq M$

- Assuming $t/k * B(S) \gg k\text{-}t$: $t/k = M/B(S)$

Hybrid Hash Join Algorithm

- How many I/Os ?

- Cost of partitioned hash join: 3B(R) + 3B(S)

- Hybrid join saves 2 I/Os for a t/k fraction of buckets
- Hybrid join saves 2t/k(B(R) + B(S)) I/Os

- Cost: (3-2t/k)(B(R) + B(S)) = (3-2M/B(S))(B(R) + B(S))

External Sorting

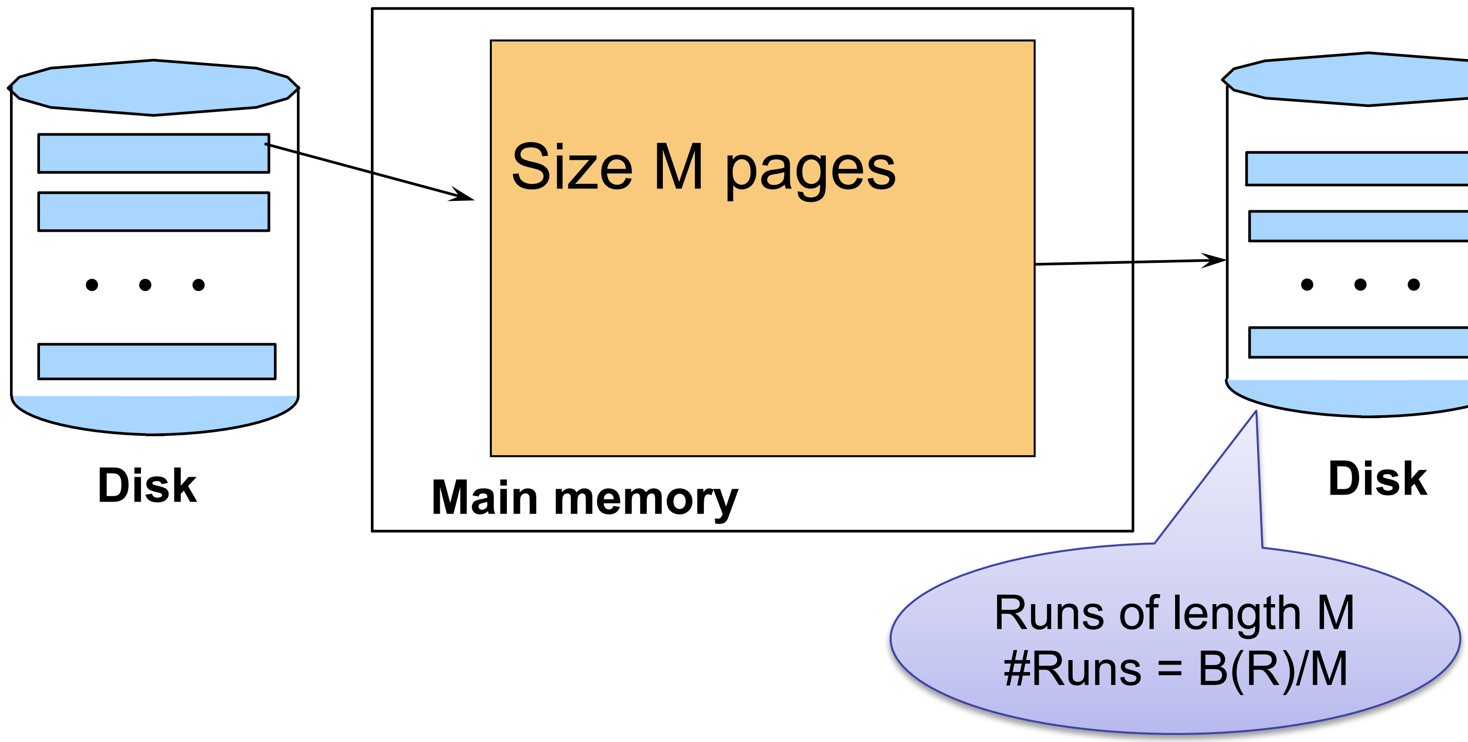
- Problem: Sort a file of size B with memory M

- Where we need this:
  - ORDER BY in SQL queries
  - Several physical operators
  - Bulk loading of B+-tree indexes.

- Will discuss only 2-pass sorting, for when $B < M^2$

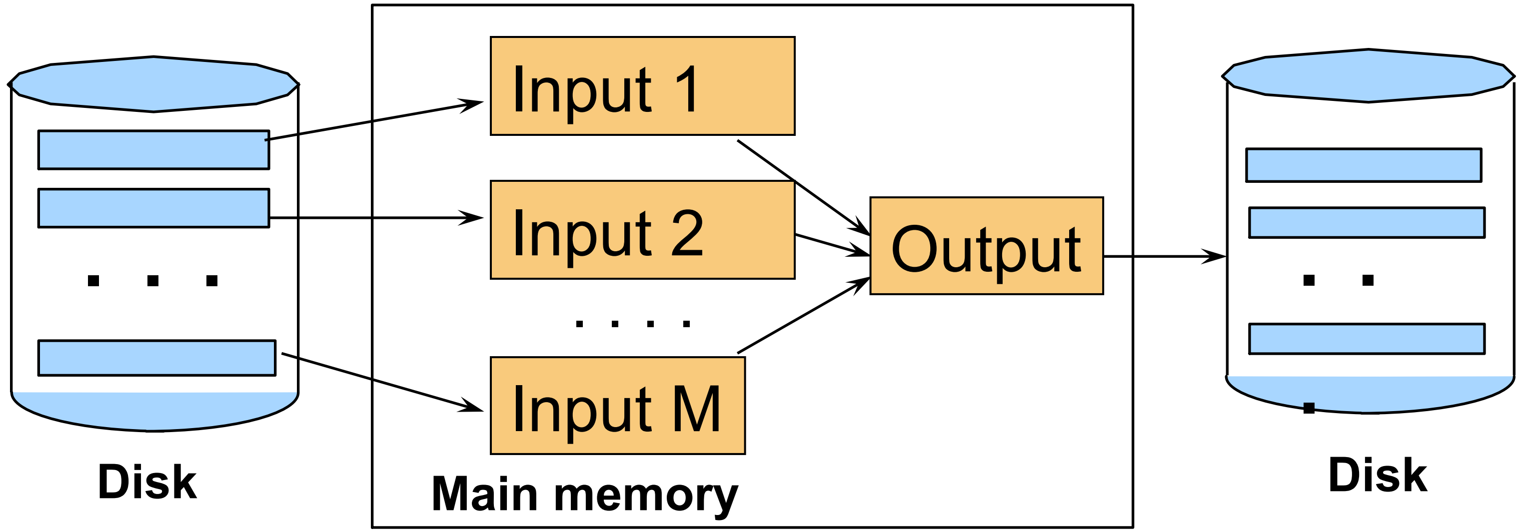
External Merge-Sort: Step 1

- Phase one: load M pages in memory, sort



External Merge-Sort: Step 2

- Merge M – 1 runs into a new run
- Result: runs of length M (M – 1) $\approx M^2$



If B <= M^2 then we are done

External Merge-Sort

- Cost:
  - Read+write+read = 3B(R)
  - Assumption: B(R) <= M^2

- Other considerations
  - In general, a lot of optimizations are possible

Two-Pass Algorithms Based on Sorting

Grouping: $\gamma_{a,\ sum(b)}$ (R)

Sort, then compute the sum(b) for each group of a's

- Step 1: sort chunks of size M, write
  - cost 2B(R)
- Step 2: merge M-1 runs, combining groups by addition
  - cost B(R)
- Total cost: 3B(R), Assumption: B(R) <= M^2

Two-Pass Algorithms Based on Sorting

Join R $\bowtie$ S

- Start by creating initial runs of length M, for R and S:
  - Cost: 2B(R)+2B(S)
- Merge (and join) M_1 runs from R, M_2 runs from S:
  - Cost: B(R)+B(S)
- Total cost: 3B(R)+3B(S)
- Assumption:
  - R has M_1=B(R)/M runs, S has M_2=B(S)/M runs
  - $M_1 + M_2 \leq M$
  - Hence: $B(R)+B(S) \leq M^2$

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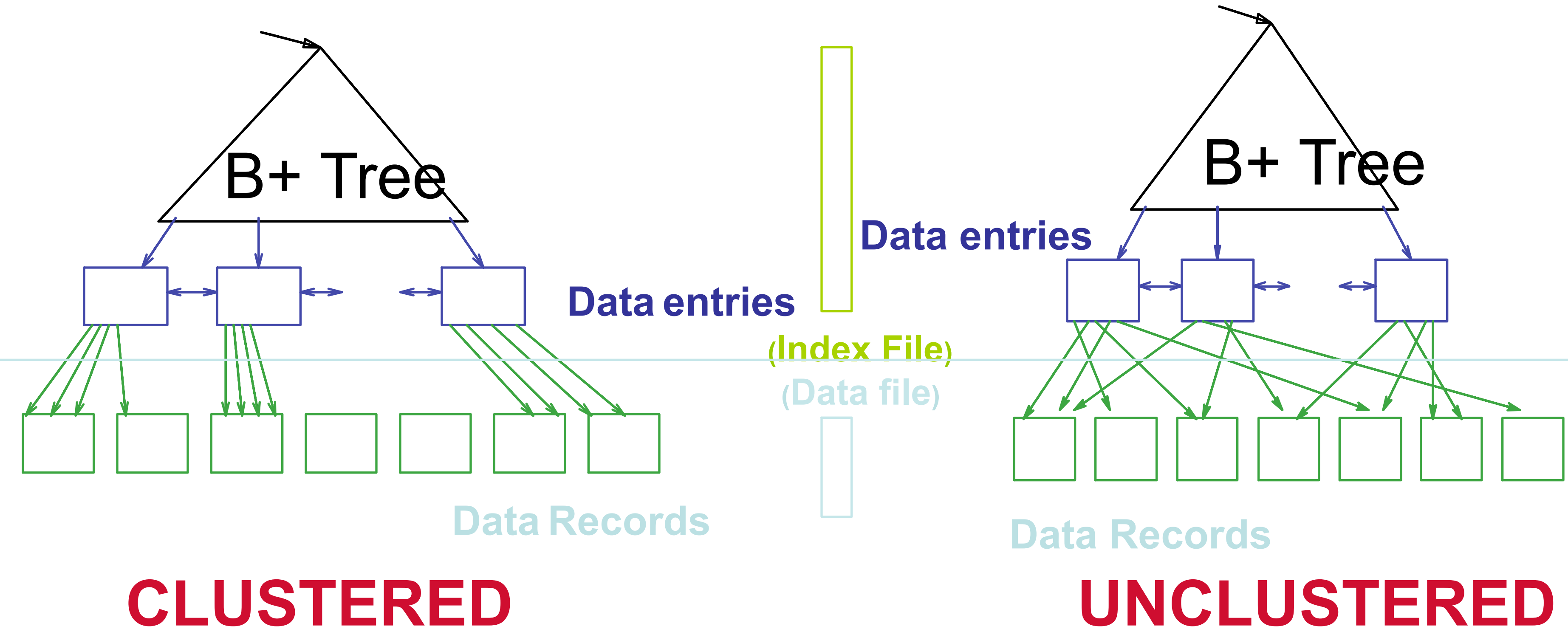
Review: Index Classification

- **Clustered/unclustered**
  - Clustered = records close in index are close in data
    - Option 1: Data inside data file is sorted on disk
    - Option 2: Store data directly inside the index (no separate files)
  - Unclustered = records close in index may be far in data
- **Primary/secondary**
  - Meaning 1:
    - Primary = is over attributes that include the primary key
    - Secondary = otherwise
  - Meaning 2: means the same as clustered/unclustered
- **Organization** B+ tree or Hash table

Clustered vs Unclustered



Every table can have **only one** clustered and **many** unclustered indexes

Index Based Selection

- Selection on equality: $\sigma_{a=v}(R)$
- V(R, a) = # of distinct values of attribute a
- Clustered index on a: cost B(R)/V(R,a)
- Unclustered index on a: cost T(R)/V(R,a)
- Note: we ignored the I/O cost for the index pages (why?)

Index Based Selection

- Example:

B(R) = 2000
T(R) = 100,000
V(R, a) = 20

cost of $s_{a=v}(R)$ = ?

- Table scan (assuming R is clustered)
  - B(R) = 2,000 I/Os
- Index based selection
  - If index is clustered: B(R)/V(R,a) = 100 I/Os
  - If index is unclustered: T(R)/V(R,a) = 5,000 I/Os
- Lesson
  - Don't build unclustered indexes when V(R,a) is small !

Index Based Selection

- Example:

$B(R) = 2000$
$T(R) = 100{,}000$
$V(R, a) = 20$

cost of $s_{a=v}(R) = ?$

- Table scan (assuming R is clustered)
  - $B(R) = 2{,}000$ I/Os
- Index based selection
  - If index is clustered: $B(R)/V(R,a) = 100$ I/Os
  - If index is unclustered: $T(R)/V(R,a) = 5{,}000$ I/Os
- Lesson
  - Don't build unclustered indexes when V(R,a) is small !

The 2% rule!

Note: the "2" in 2% decreases yearly (why?)

Index Nested Loop Join

$R \bowtie S$

- Assume S has an index on the join attribute
- Iterate over R, for each tuple fetch corresponding tuple(s) from S

- Cost:
  - Assuming R is clustered
  - If index on S is clustered: $B(R) + T(R)B(S)/V(S,a)$
  - If index on S is unclustered: $B(R) + T(R)T(S)/V(S,a)$

Summary of External Join Algorithms

- Block Nested Loop Join: $B(R) + B(R)*B(S)/M$
- Hybrid Hash Join: $(3-2M/B(S))(B(R) + B(S))$
  Assuming $t/k * B(S) >> k-t$
- Sort-Merge Join: $3B(R)+3B(S)$
  Assuming $B(R)+B(S) <= M^2$
- Index Nested Loop Join: $B(R) + T(R)B(S)/V(S,a)$
  Assuming R is clustered and S has clustered index on a