Introduction to Data Management
CSE 344

Unit 4: RDBMS Internals

Logical and Physical Plans

Query Execution

Query Optimization

(3 lectures)

Introduction to Data Management
CSE 344

Lecture 15: Introduction to Query Evaluation

Announcements

Makeup lecture tomorrow, 4:30pm, BAG 131

HW6: we will use AWS. Do the setup early:

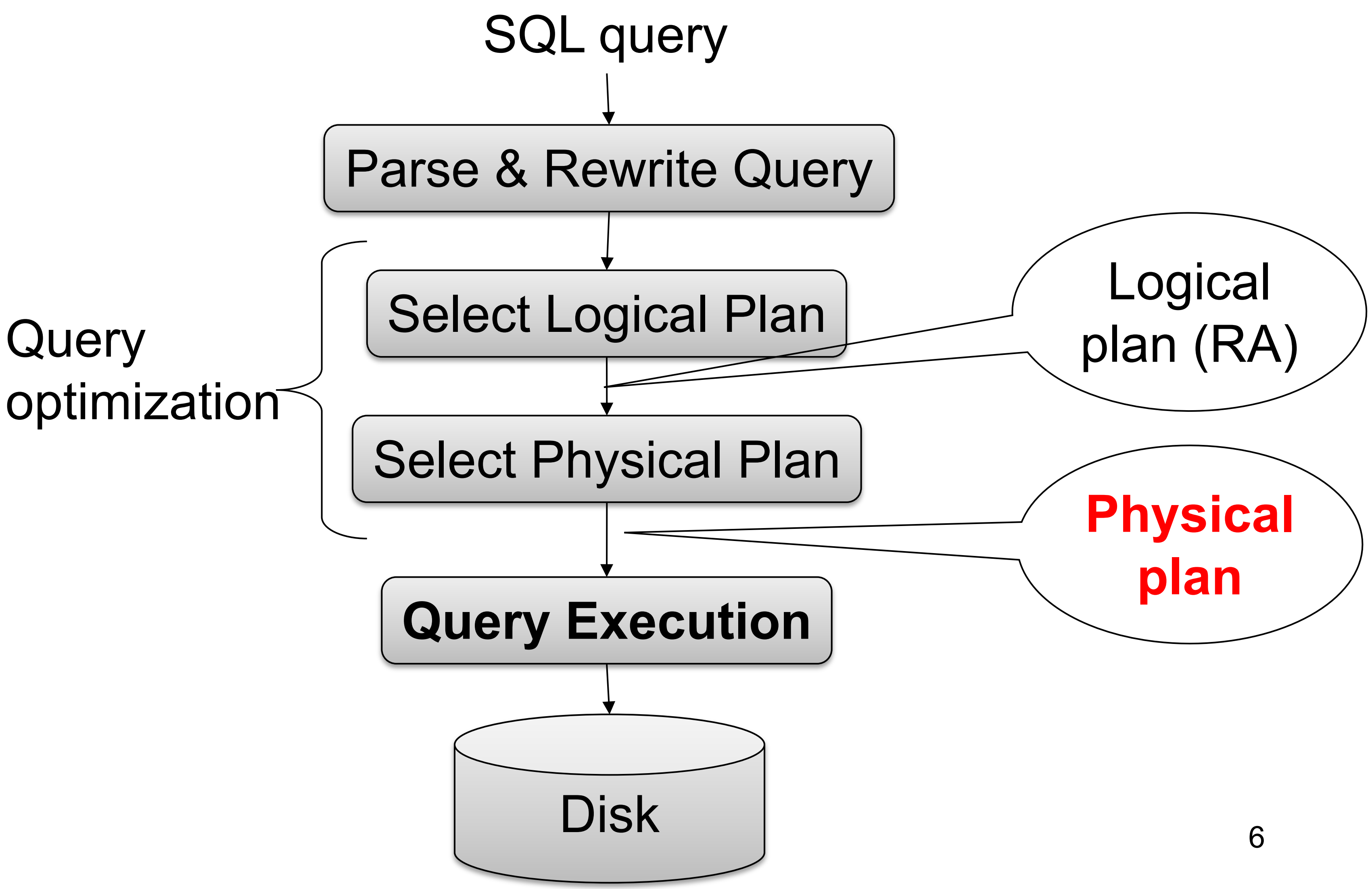
- If no account yet, sign up aws.amazon.com
- Request credits aws.amazon.com/awscredits

Class Overview

- Unit 1: Intro
- Unit 2: Relational Data Models and Query Languages
- Unit 3: Non-relational data
- Unit 4: RDMBS internals and query optimization
- Unit 5: Parallel query processing
- Unit 6: DBMS usability, conceptual design
- Unit 7: Transactions
- Unit 8: Advanced topics (time permitting)

From Logical RA Plans to Physical Plans

Query Evaluation Steps Review



Relational Algebra Operators

- Union ∪, ~~intersection ∩~~, difference -
- Selection σ
- Projection π
- Cartesian product ×, join ⋈
- (Rename ρ)
- Duplicate elimination δ
- Grouping and aggregation γ
- Sorting τ

RA

Extended RA

Physical Operators

- For each operators above, several possible algorithms
- Main memory or external memory algorithms
- Examples:
  - Main memory hash join
  - External memory merge join
  - External memory partitioned hash join
  - Sort-based group by
  - Etc, etc

$\bowtie$

γ

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Main Memory Algorithms

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

Propose three physical operators for the join, assuming the tables are in main memory:

1.

2.

3.

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Main Memory Algorithms

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Propose three physical operators for the join, assuming the tables are in main memory:

1. Nested Loop Join O(??)
2. Merge join O(??)
3. Hash join O(??)

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Main Memory Algorithms

Logical operator:

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Propose three physical operators for the join, assuming the tables are in main memory:

1. Nested Loop Join — $O(n^2)$
2. Merge join — $O(n \log n)$
3. Hash join — $O(n) \dots O(n^2)$

BRIEF Review of Hash Tables

A (naïve) hash function:

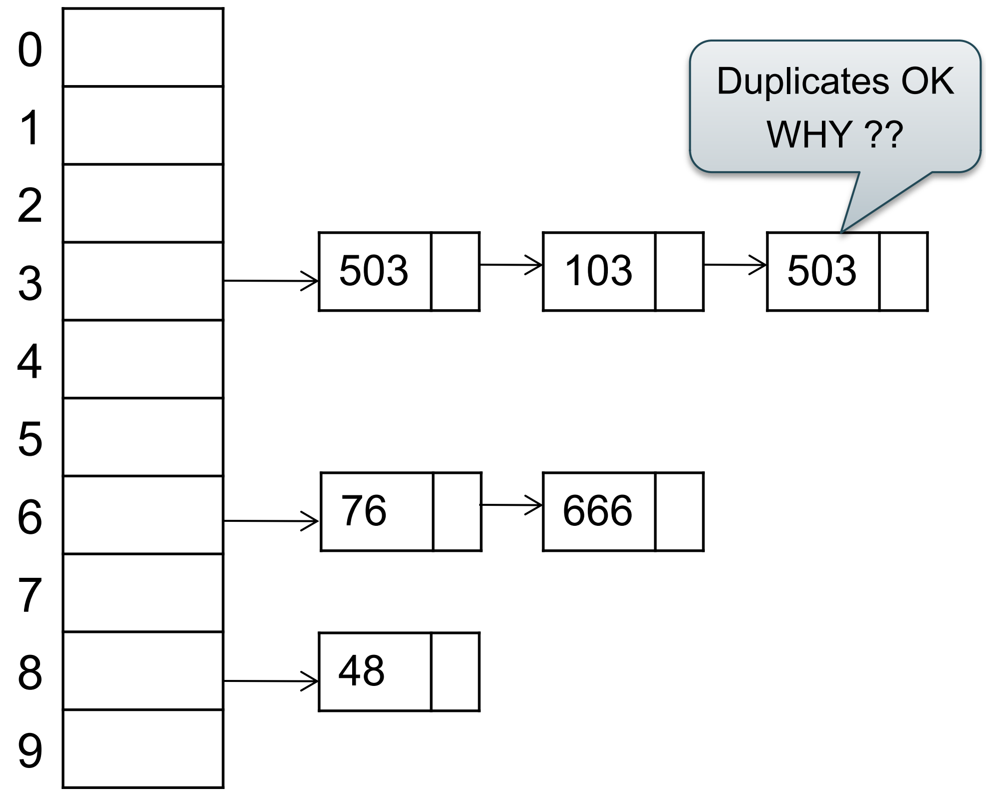
$h(x) = x \bmod 10$

Operations:

find(103) = ??

insert(488) = ??

Separate chaining:



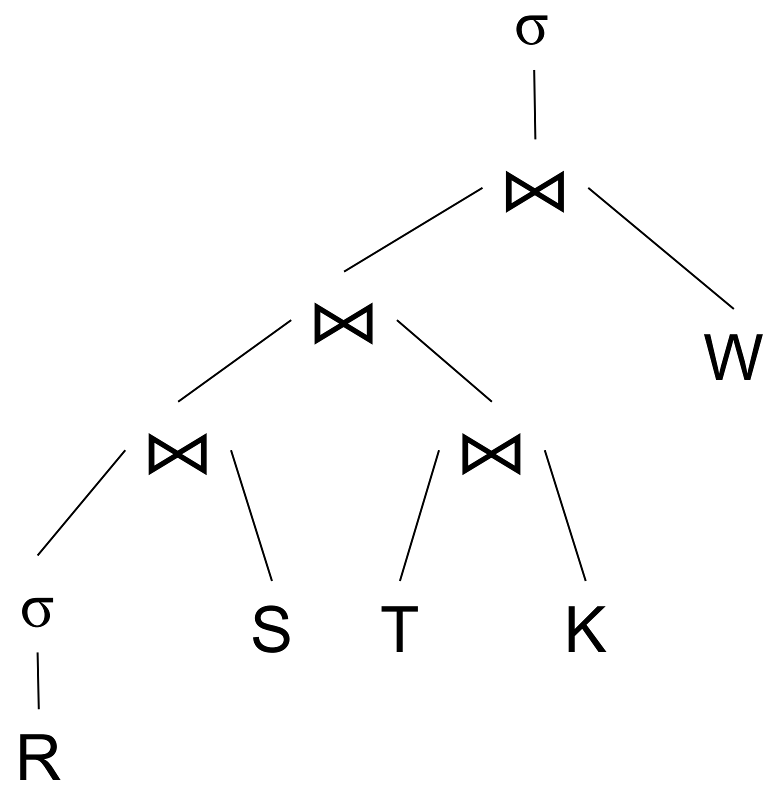
BRIEF Review of Hash Tables

- insert(k, v) = inserts a key k with value v
- Many values for one key
  - Hence, duplicate k's are OK
- find(k) = returns the ***list*** of all values v associated to the key k

Recap of Main Memory Algorithms

- Join $\bowtie$:
  - Nested loop join
  - Hash join
  - Merge join
- Selection σ
  - "on-the-fly"
  - Index-based selection (next lecture)
- Group by γ
  - Hash–based
  - Merge-based

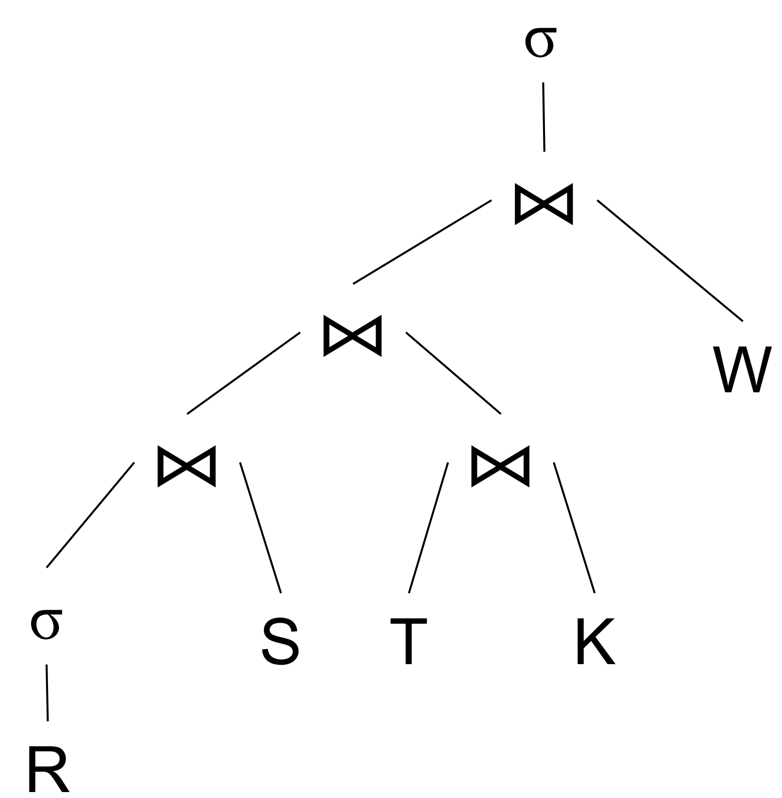
How Do We Combine Them?



How Do We Combine Them?

The *Iterator Interface*

- open()
- next()
- close()



Implementing Query Operators with the Iterator Interface

Example "on the fly" selection operator

```
interface Operator {









}
```

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  // initializes operator state
  // and sets parameters
  void open (...);










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  // processes an input tuple
  // produces output tuple(s)
  // returns null when done
  Tuple next ();




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```
class Select implements Operator {...
  void open (Predicate p,
             Operator c) {
    this.p = p; this.c = c; c.open();
    }
}
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    boolean found = false;
    Tuple r = null;
    while (!found) {
       r = c.next();
       if (r == null) break;
       found = p(r);
    }

  }
}
```

Implementing Query Operators with the Iterator Interface

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  Tuple next ();


  // cleans up (if any)
  void close ();
}
```

Query plan execution

```
Operator q = parse("SELECT ...");
q = optimize(q);

q.open();
while (true) {
  Tuple t = q.next();
  if (t == null) break;
  else printOnScreen(t);
}
q.close();
```

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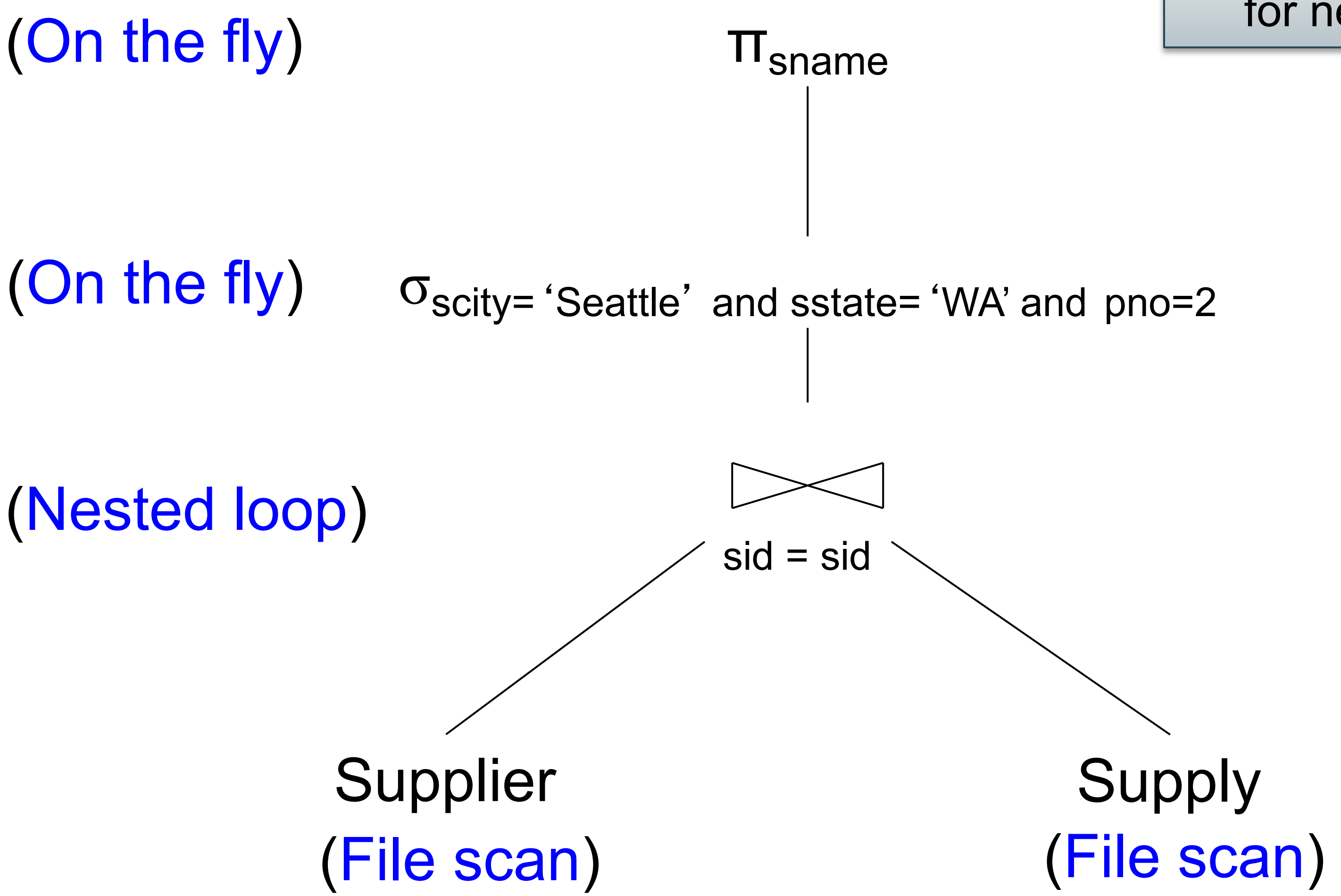
Pipelining

Discuss: open/next/close for nested loop join



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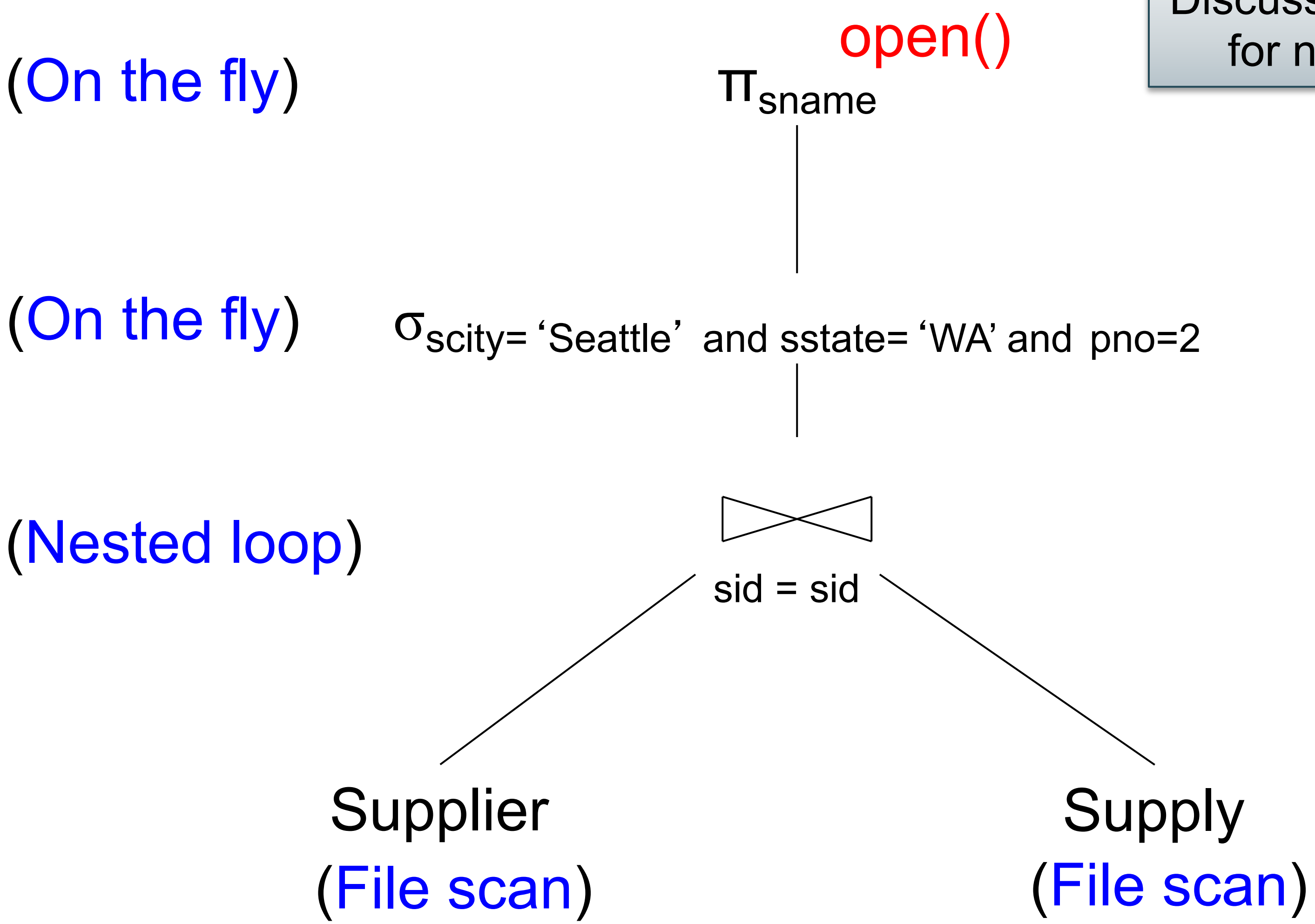

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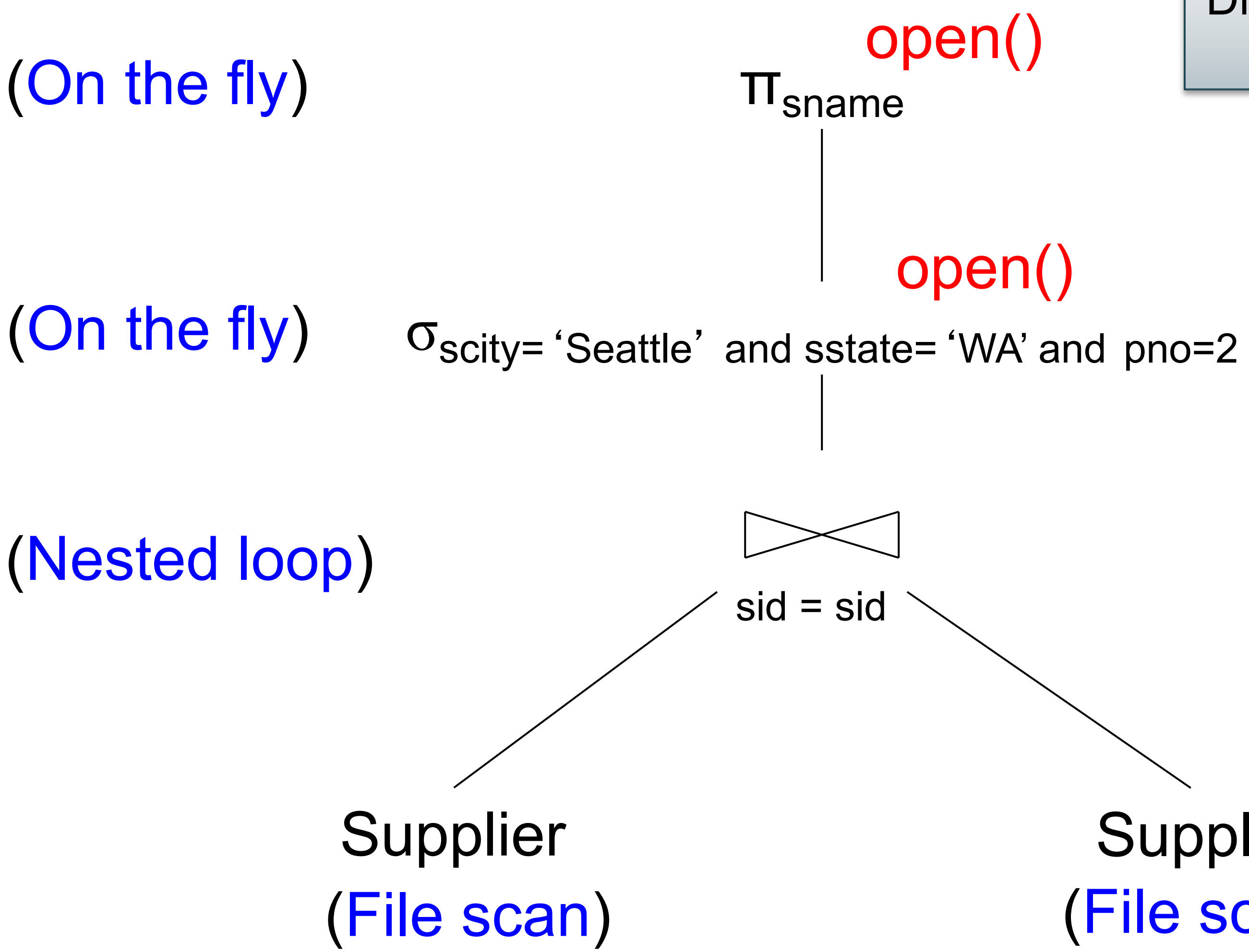

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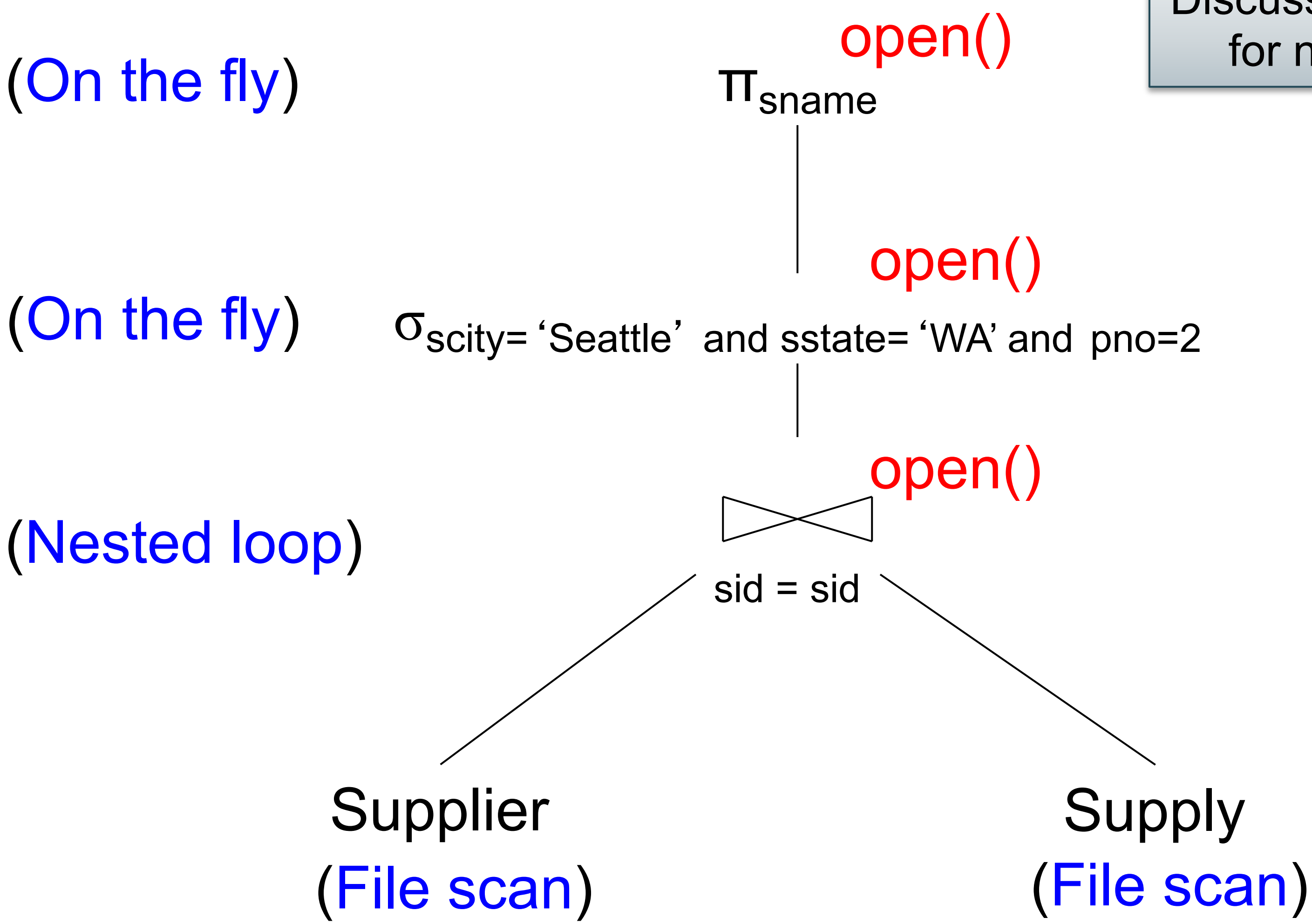

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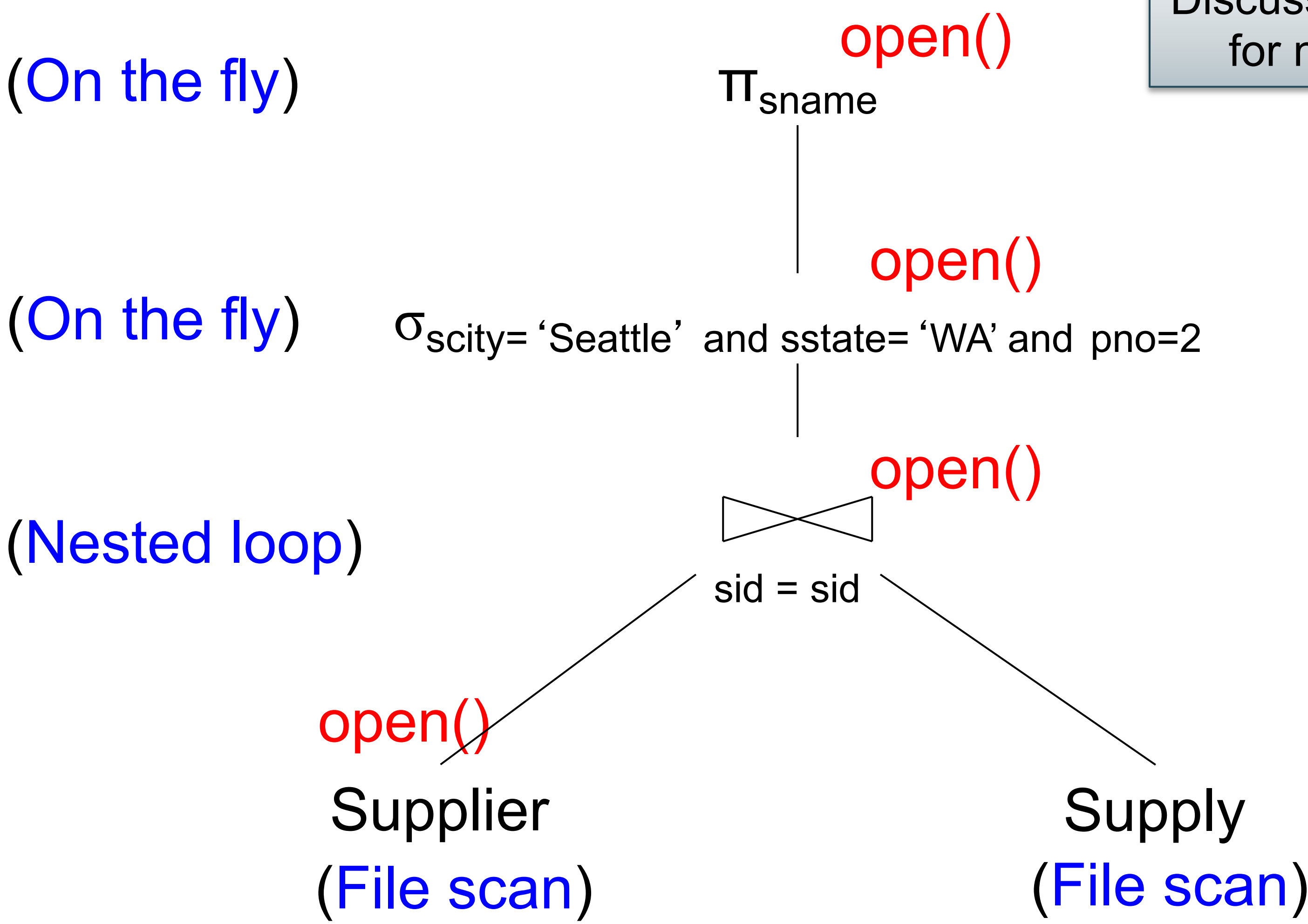

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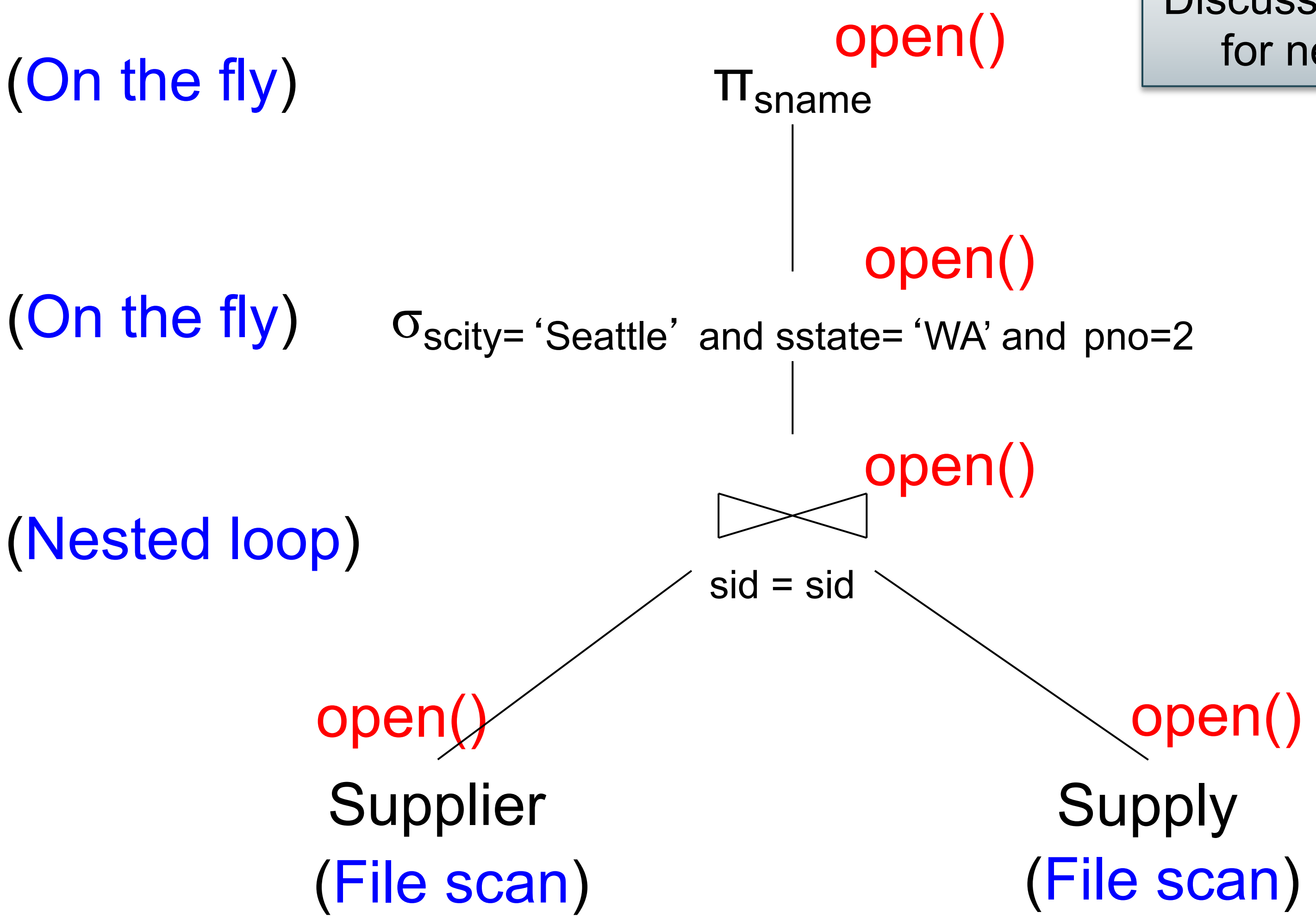

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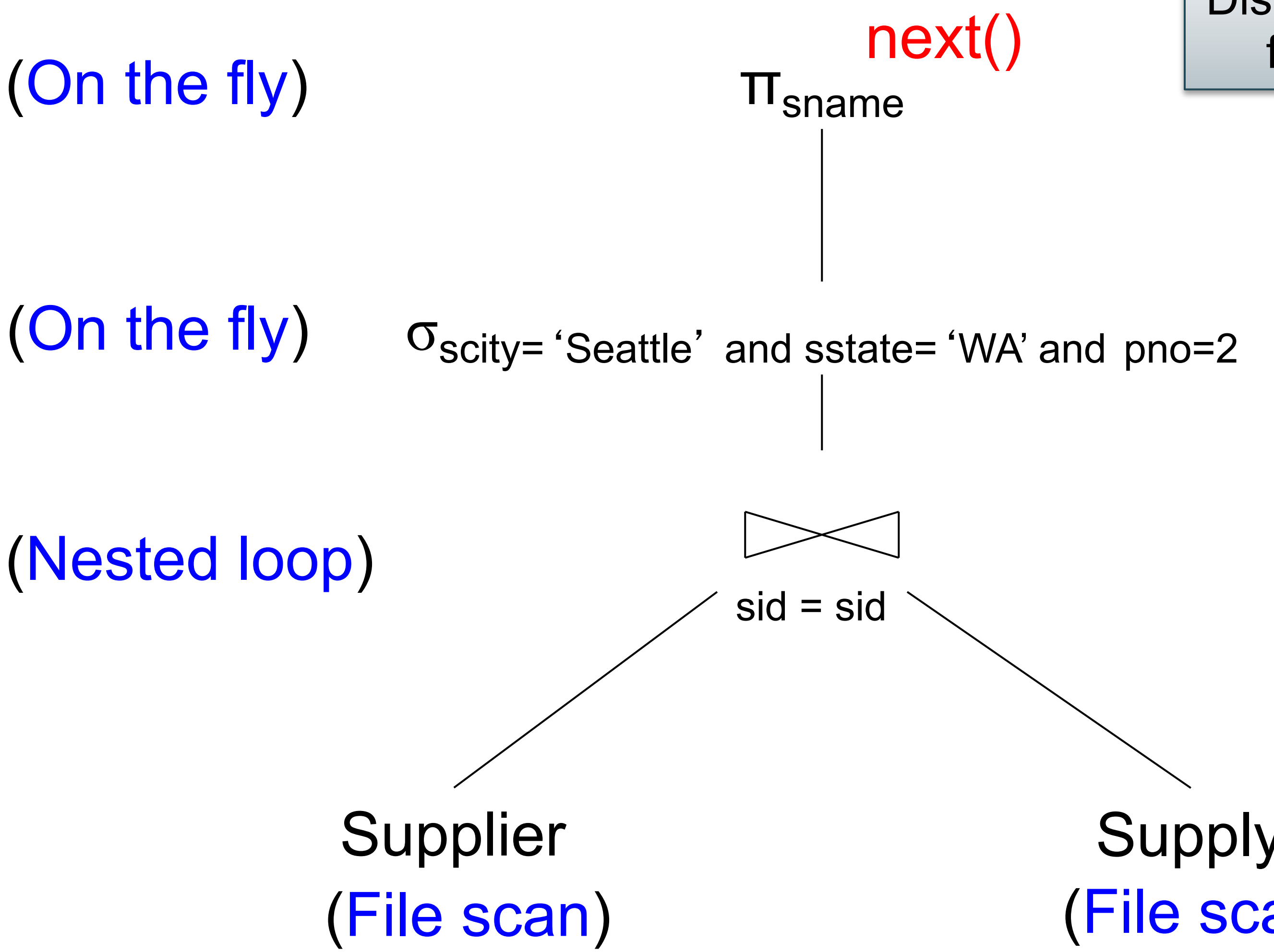

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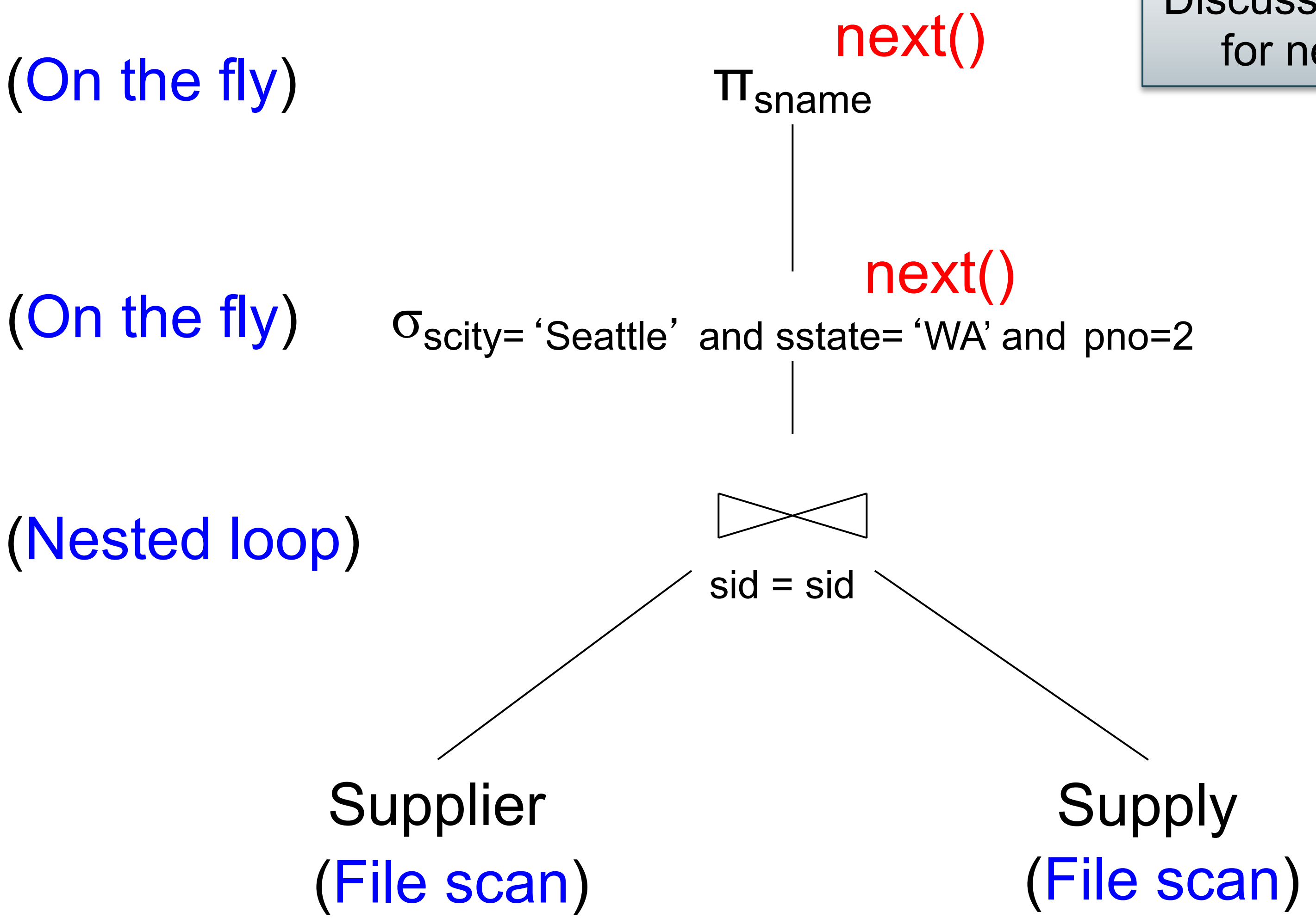

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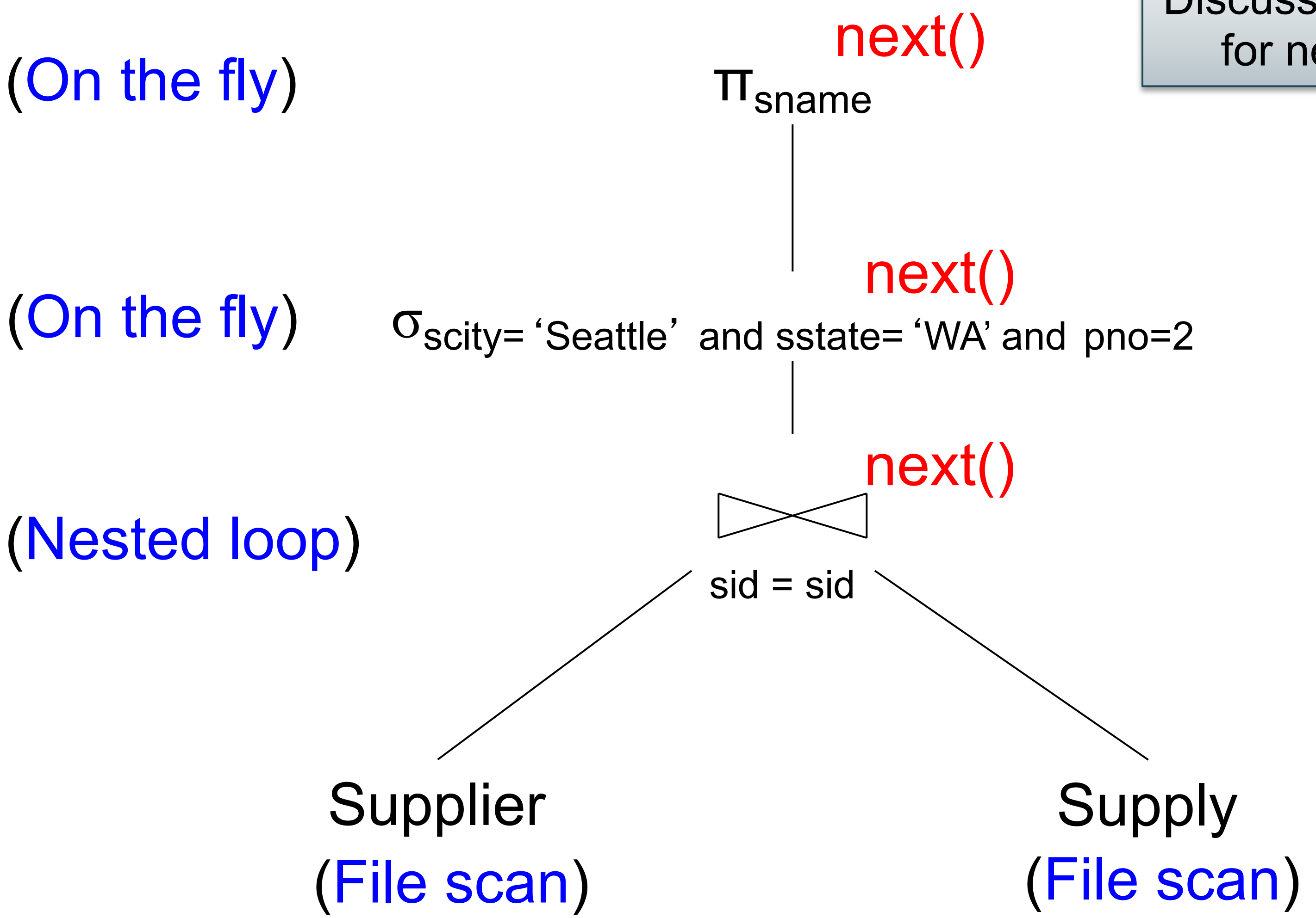

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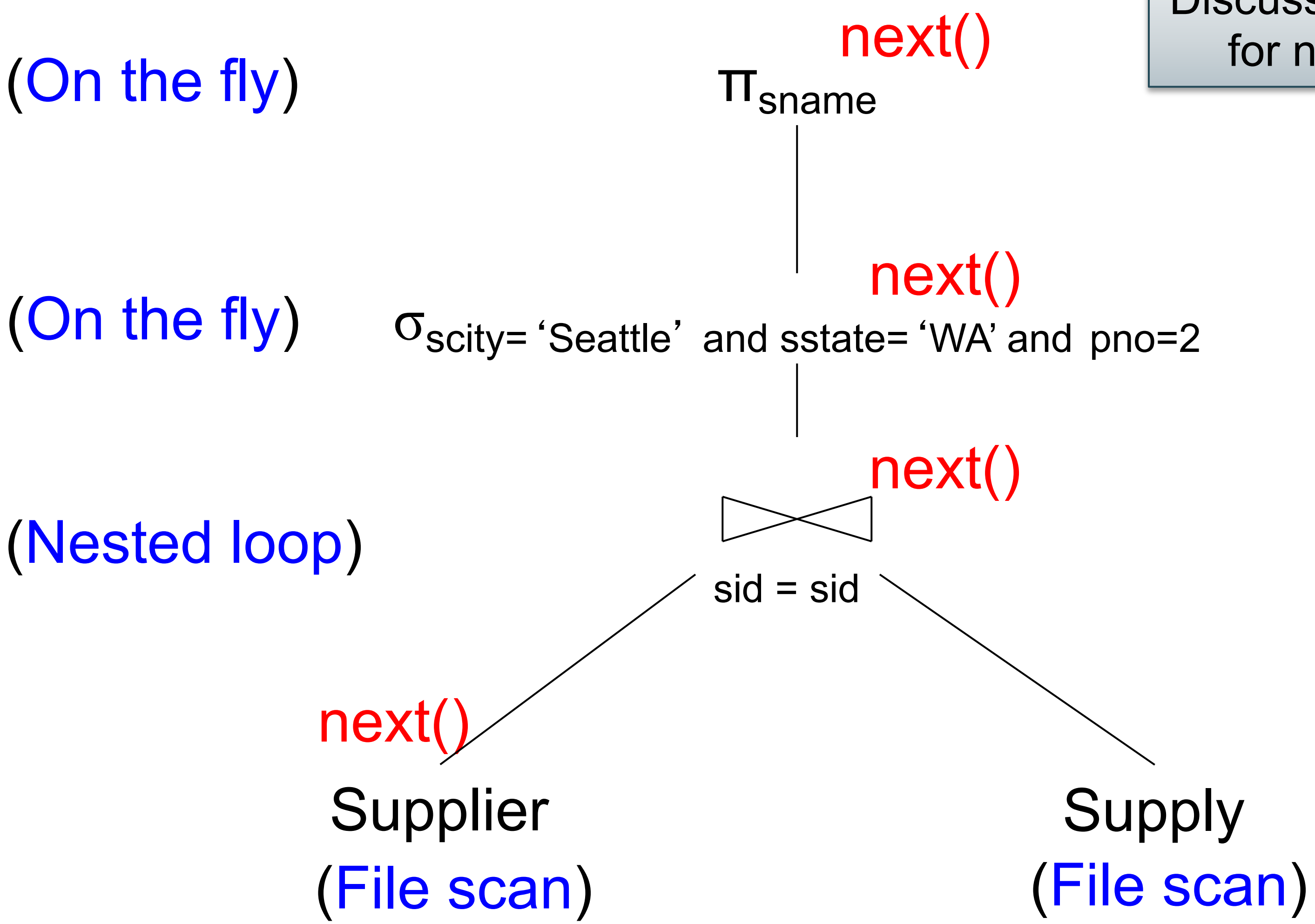

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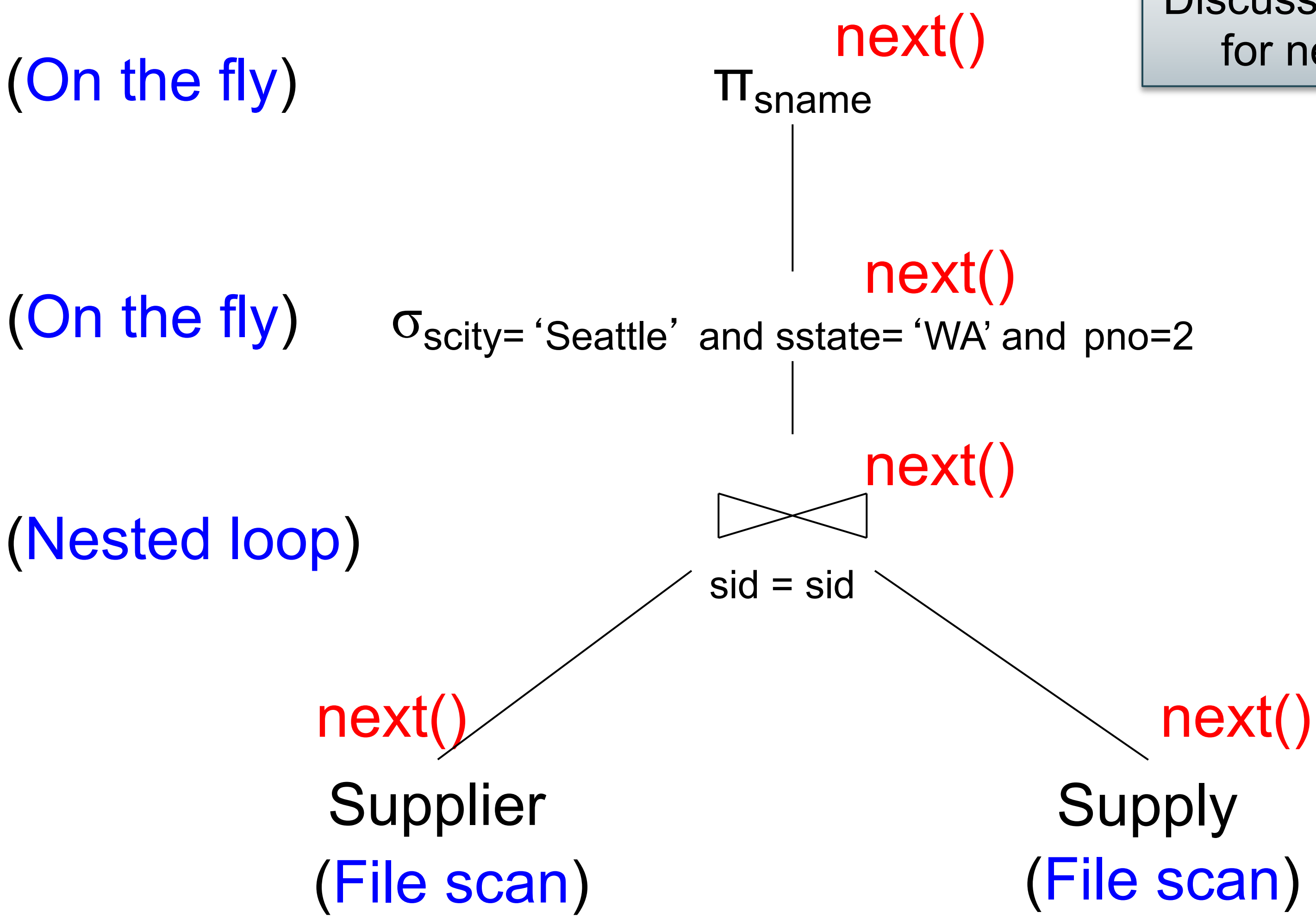

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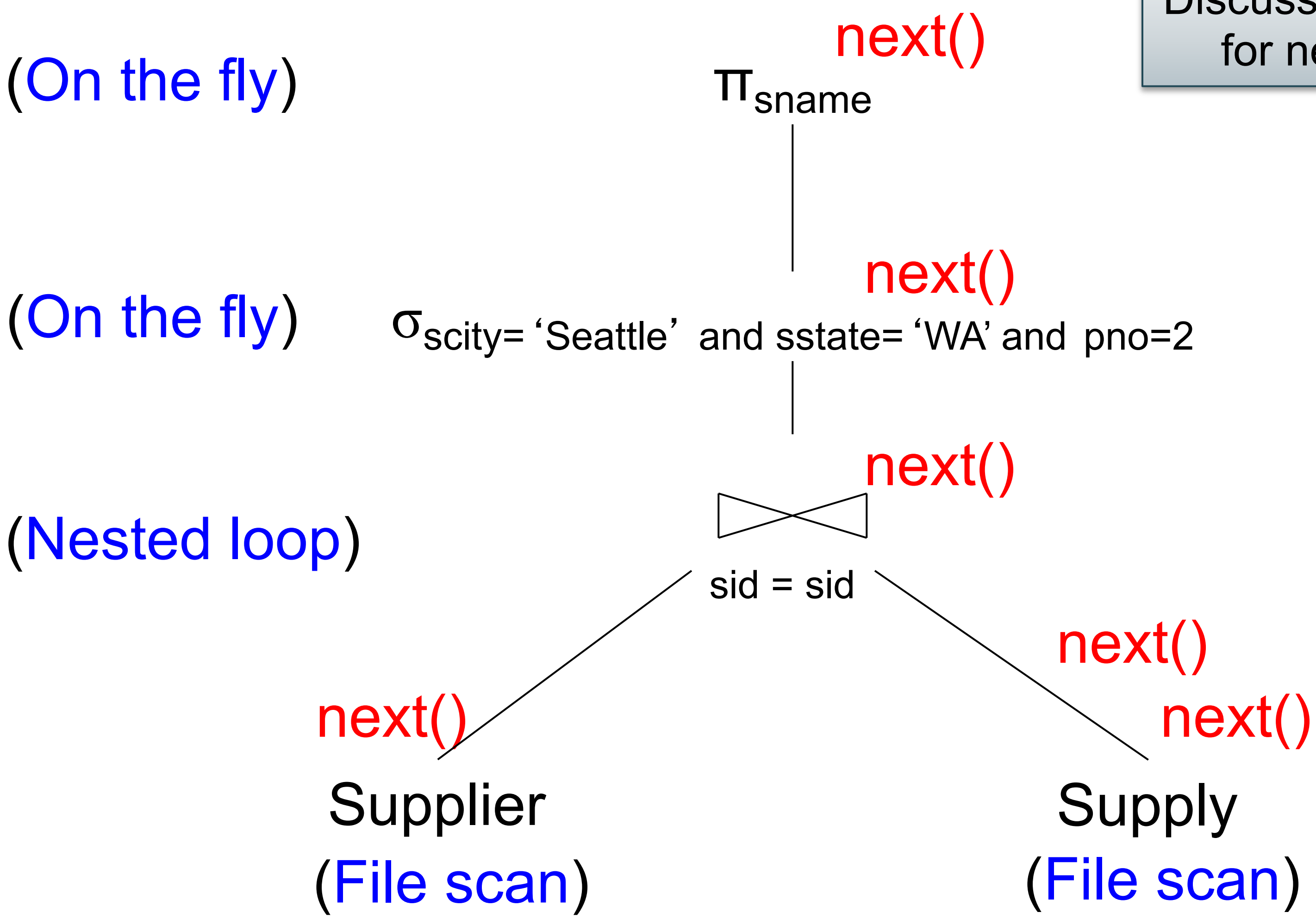

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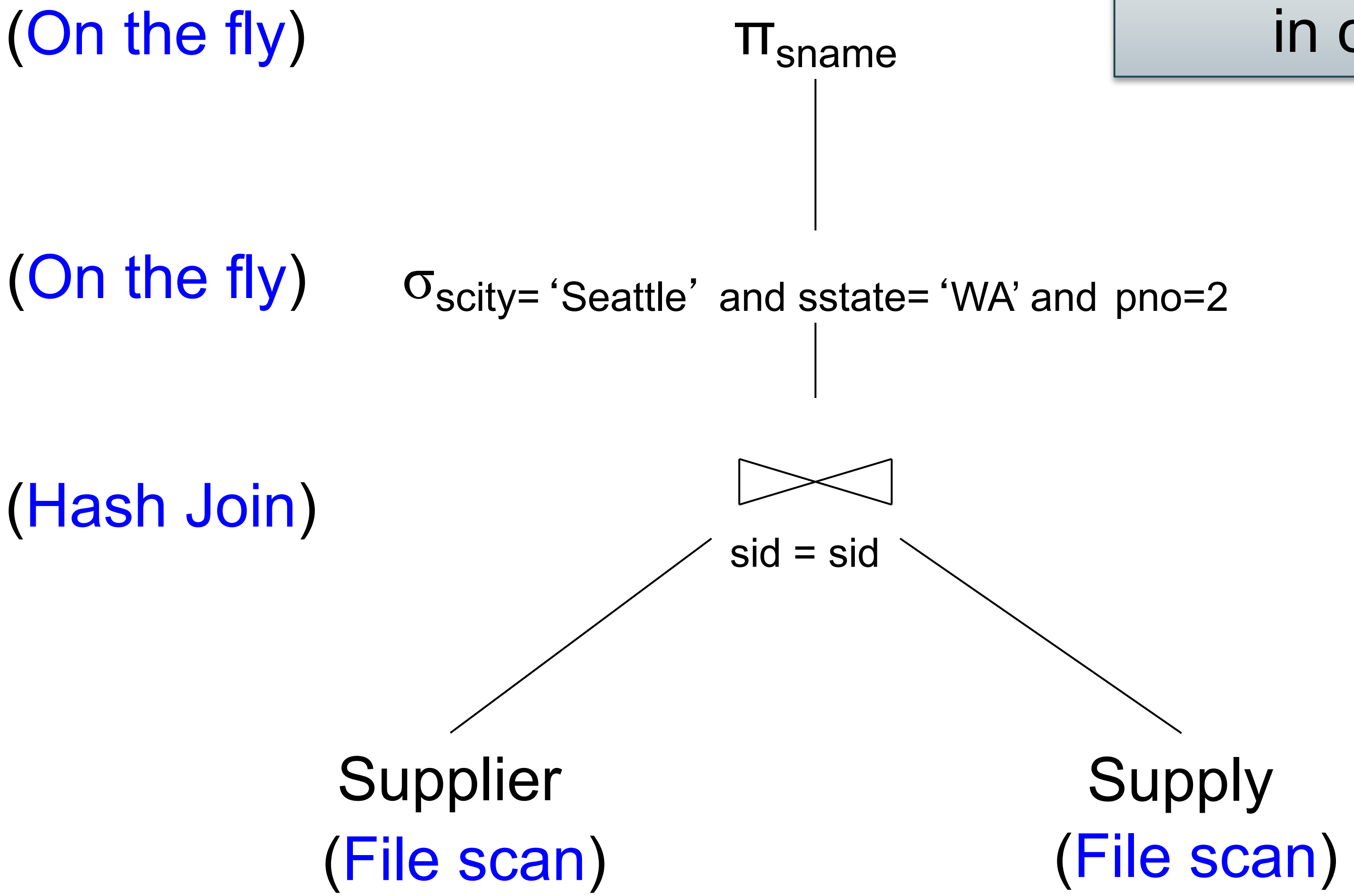
Pipelining

Discuss hash-join in class



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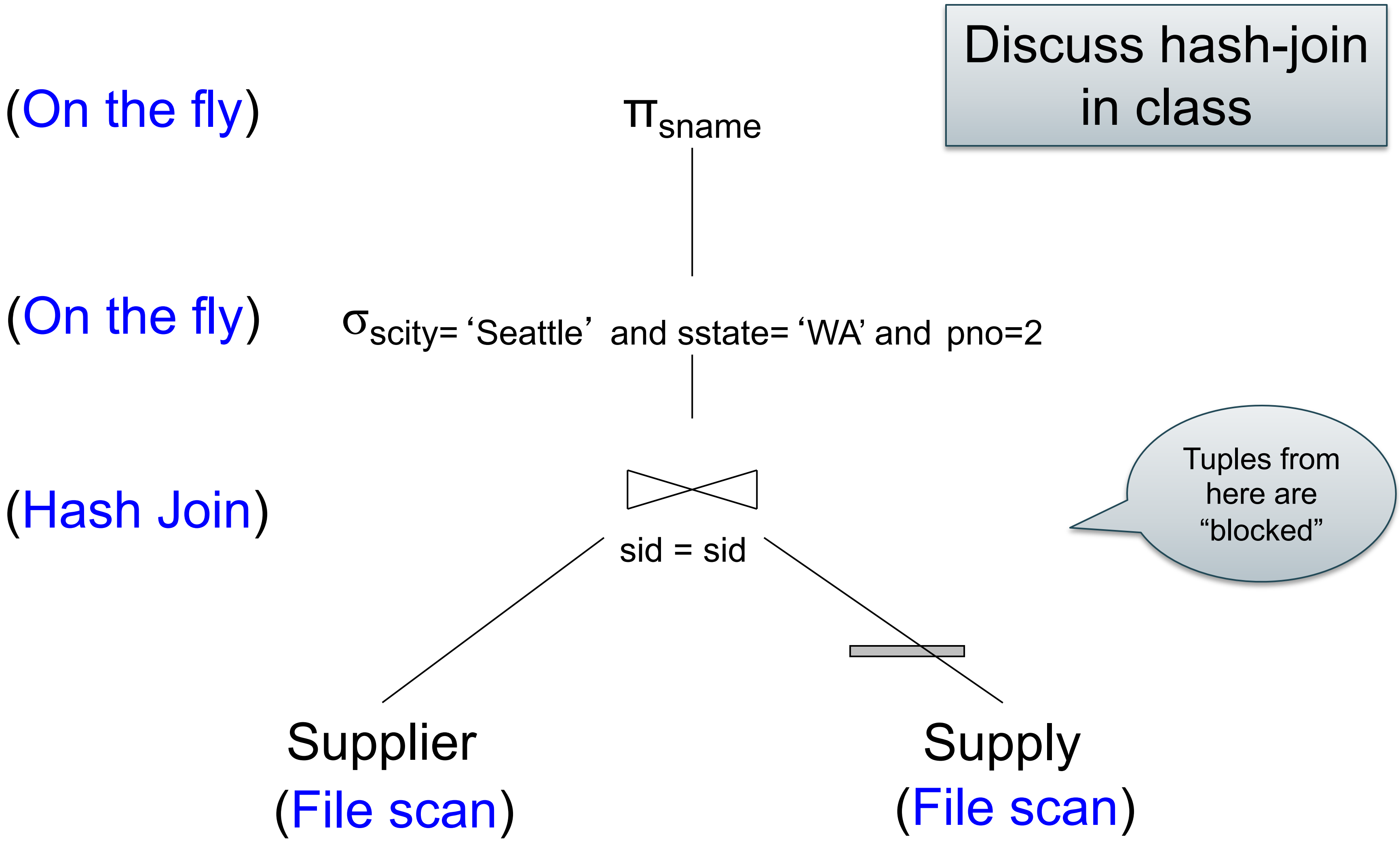

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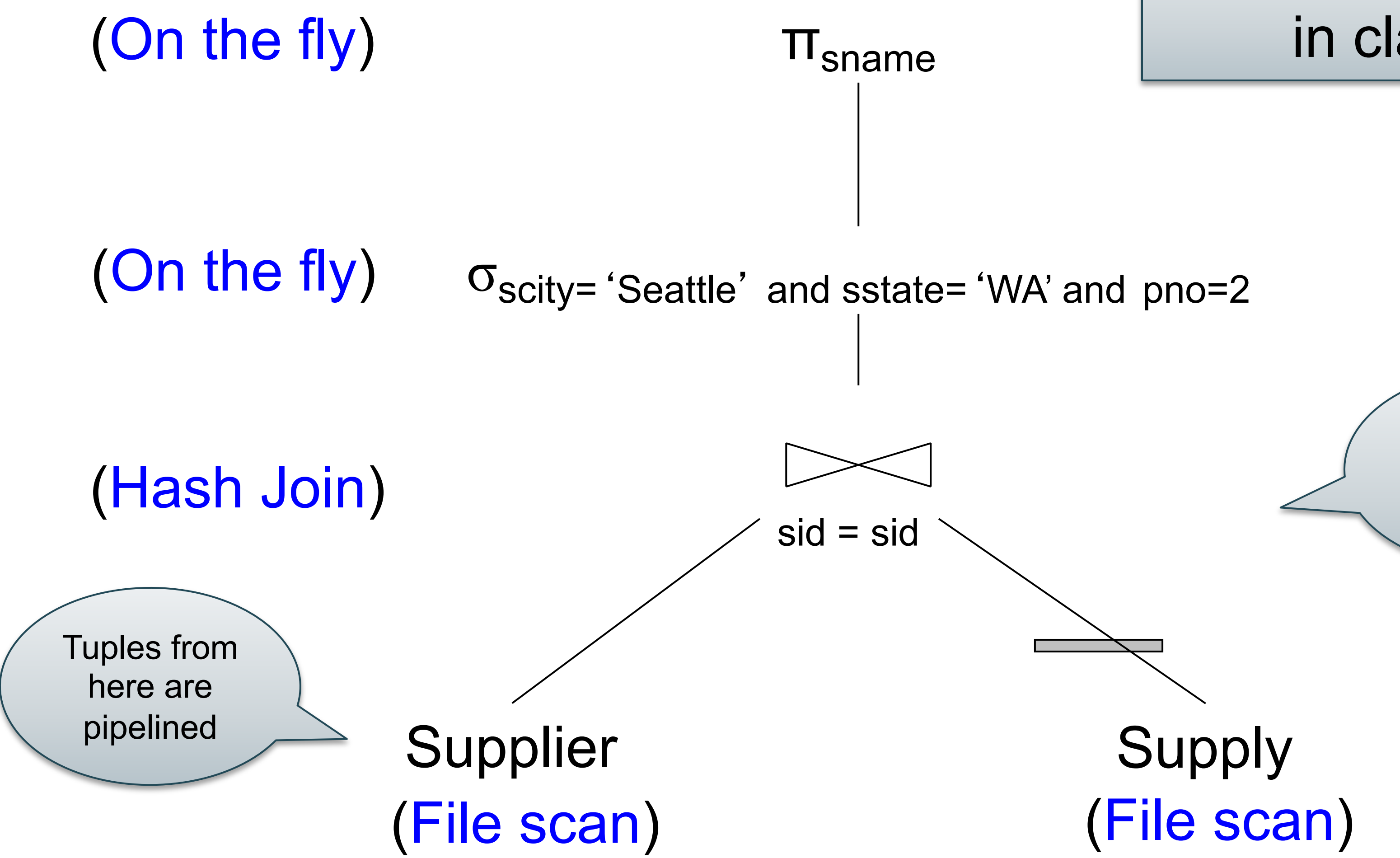

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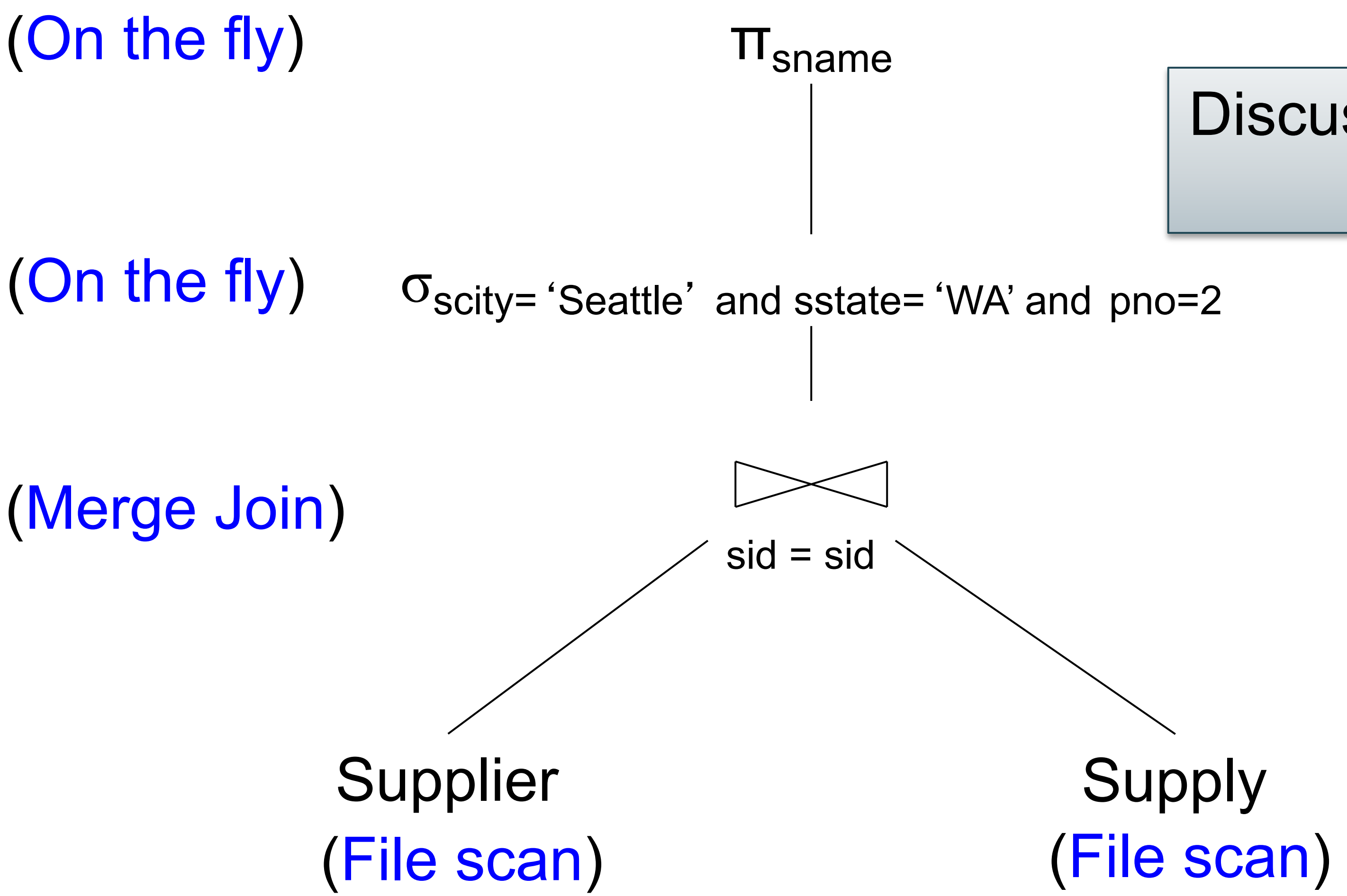
Blocked Execution



Discuss merge-join in class

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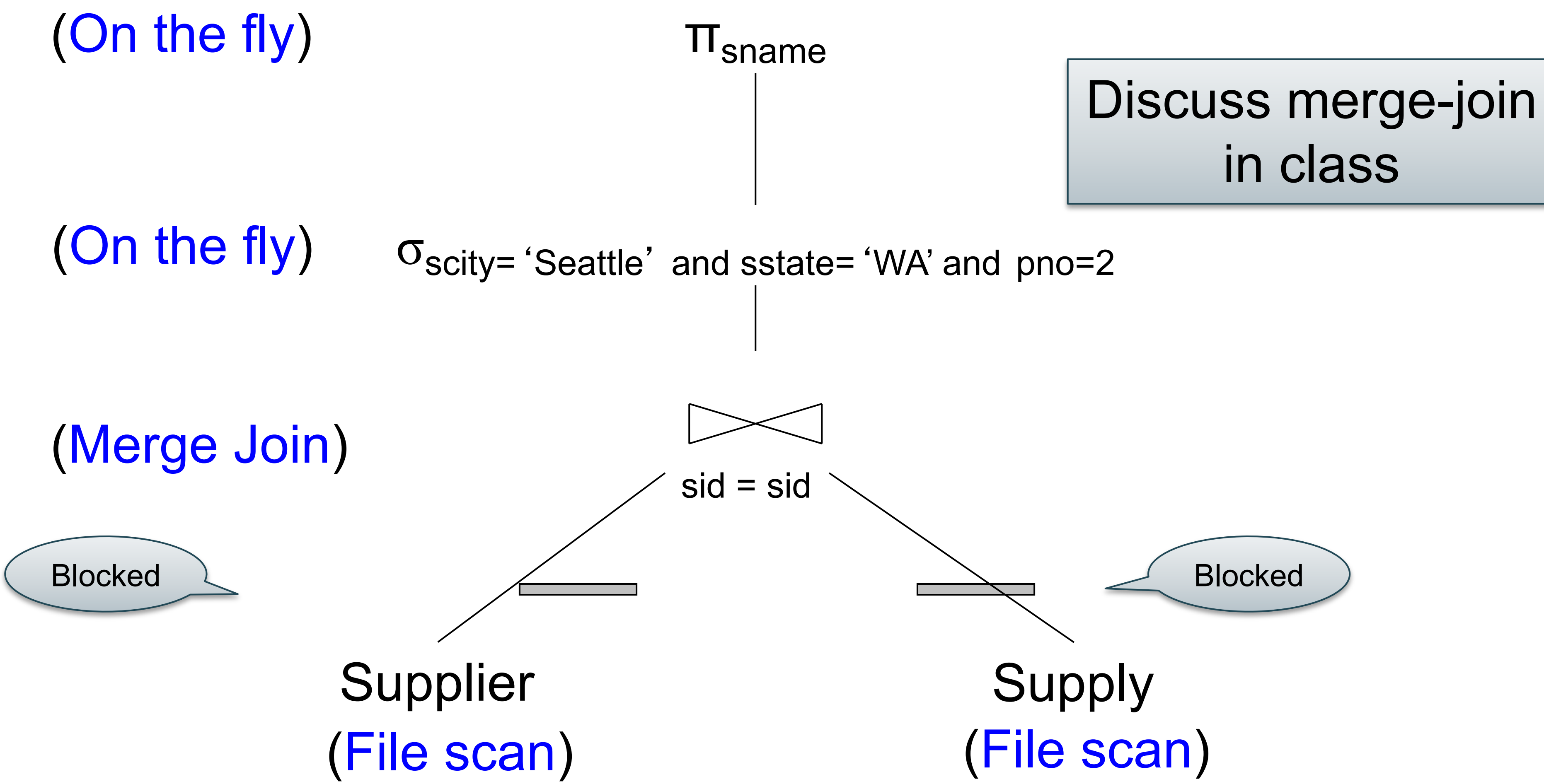
Supply(sid, pno, quantity)

Blocked Execution



Pipeline v.s. Blocking

- Pipeline
  - A tuple moves all the way through up the query plan
  - Advantages: speed
  - Disadvantage: need all hash at the same time in memory
- Blocking
  - The entire result of the subplan is computed (and stored to disk) before the first tuple is sent up the plan
  - Advantage: saves memory
  - Disadvantage: slower

Discussion on Physical Plan

More components of a physical plan:

- **Access path selection** for each relation
  - Scan the relation or use an index (next lecture)
- **Implementation choice** for each operator
  - Nested loop join, hash join, etc.
- **Scheduling decisions** for operators
  - Pipelined execution or intermediate materialization

Introduction to Database Systems
CSE 344

Lecture 16:
Basics of Data Storage and Indexes

Query Performance

To understand query performance, we need to understand:

- How is data organized on disk
- How to estimate query costs

- In this course we will focus on **disk-based** DBMSs

Hard Disk

- Disks are mechanical devices
- A *block* = unit of read/write
- Once in main memory we call it a *page*
- Read only at the rotation speed!
- Consequence: sequential scan faster than random
  - Good: read blocks 1,2,3,4,5,…
  - Bad: read blocks 2342, 11, 321,9, …
- Rule of thumb:
  - Random read 1-2% of file ≈ sequential scan entire file;
  - 1-2% decreases over time, because of increased density

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

Data Storage

- DBMSs store data in **files**
- Most common organization is row-wise storage
- On disk, a file is split into blocks
- Each block contains a set of tuples

10	Tom	Hanks	block 1
20	Amy	Hanks	
50	…	…	block 2
200	…		
220			block 3
240			
420			
800			

In the example, we have 4 blocks with 2 tuples each

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

Data File Types

The data file can be one of:

- Heap file
  - Unsorted
- Sequential file
  - Sorted according to some attribute(s) called *key*

Index

- An **additional** file, that allows fast access to records in the data file given a search key

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- The index contains (key, value) pairs:
  - Key = an attribute value (e.g., student ID or name)
  - Value = a pointer to the record OR the record itself

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- The index contains (key, value) pairs:
  - Key = an attribute value (e.g., student ID or name)
  - Value = a pointer to the record OR the record itself
- Could have many indexes for one table

Key = means here search key

This  Is Not A Key

Different keys:

- Primary key – uniquely identifies a tuple
- Key of the sequential file – how the data file is sorted, if at all
- Index key – how the index is organized

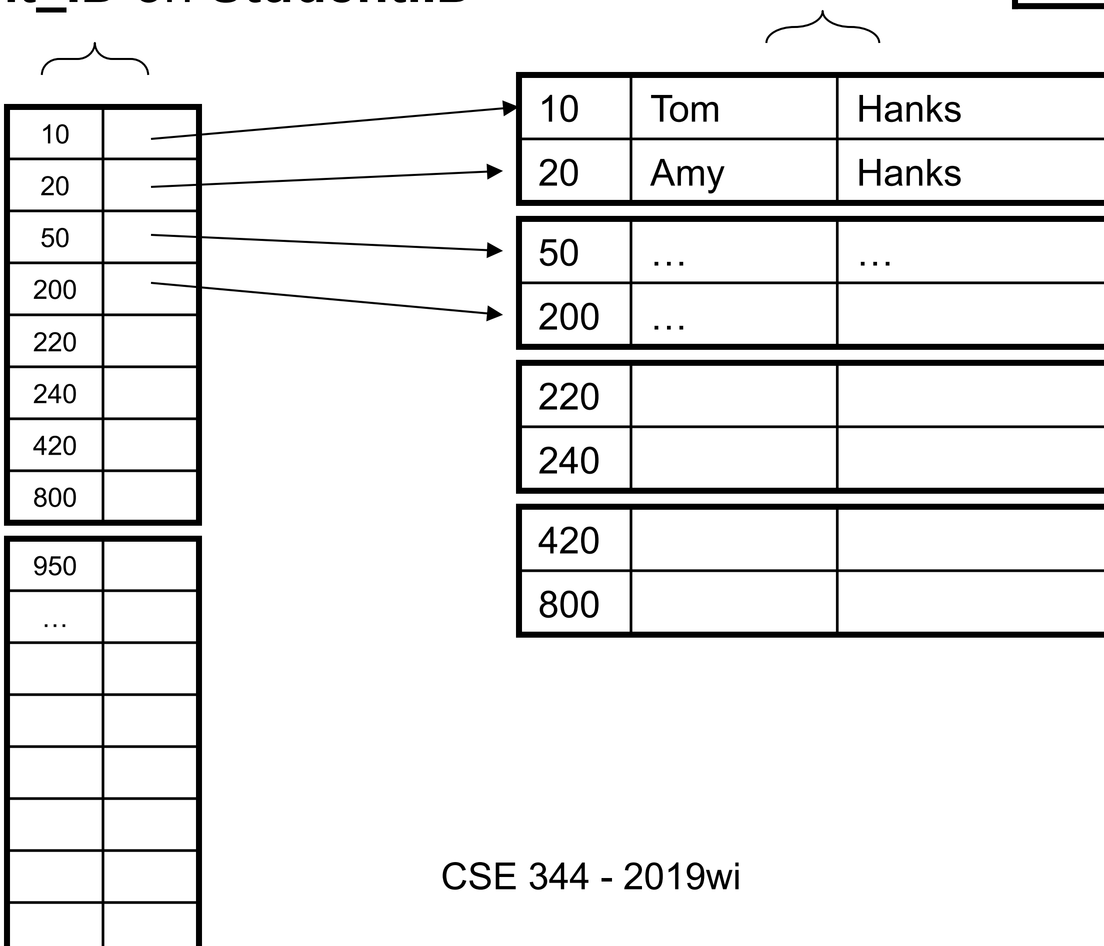
Example 1: Index on ID

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

Index **Student_ID** on **Student.ID**

Data File **Student**



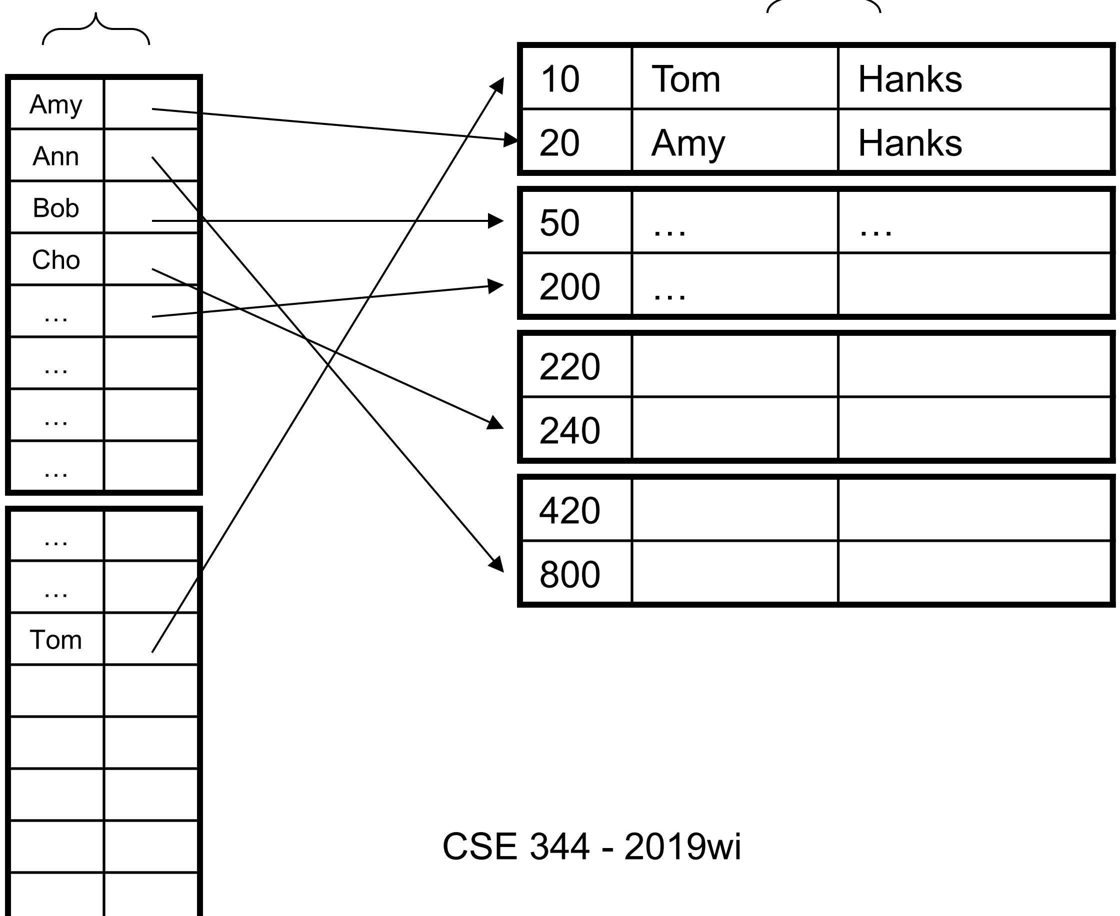
Example 2: Index on fName

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

Index **Student_fName** on **Student.fName**

Data File **Student**



Index Organization

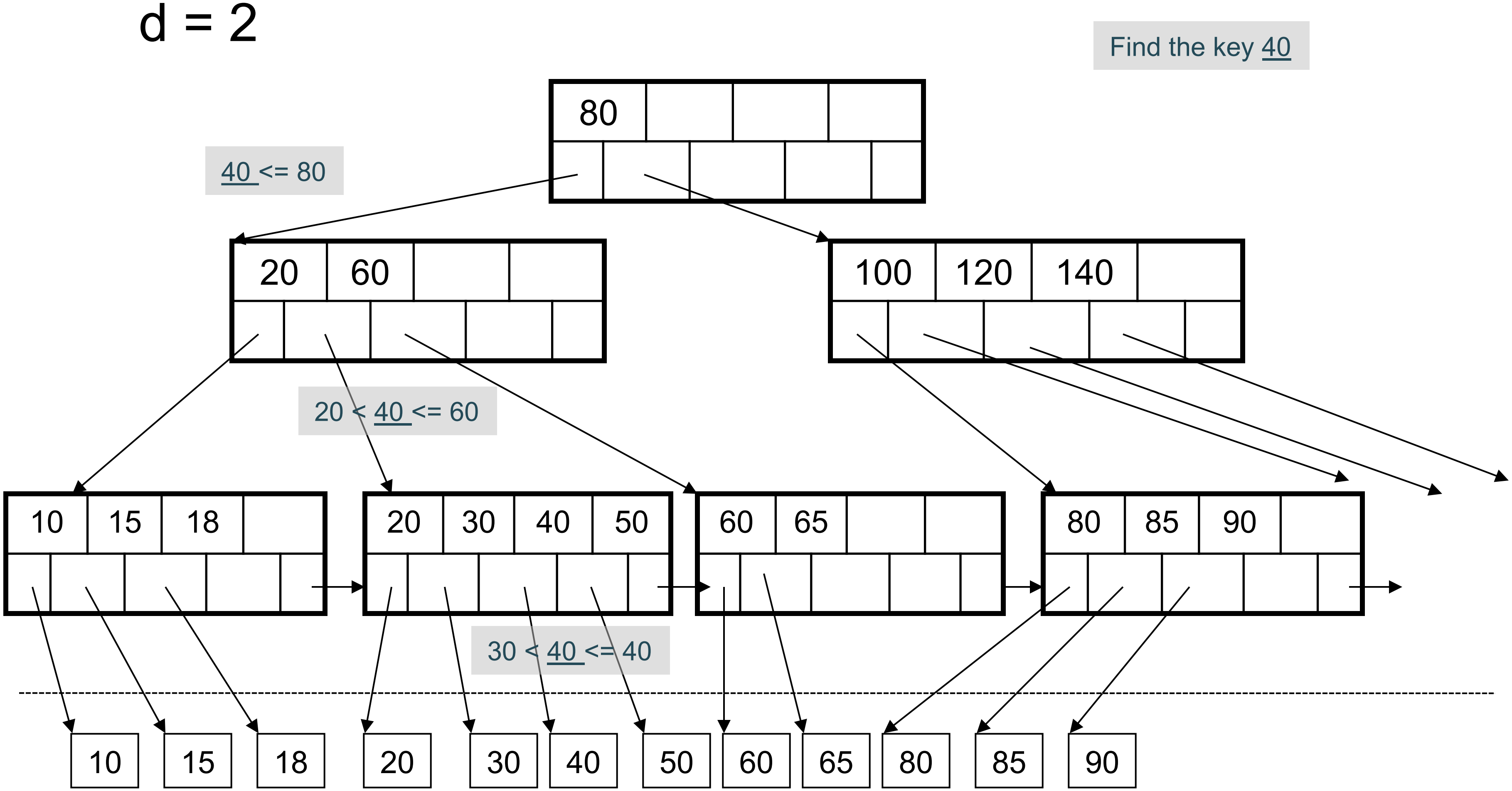
- Hash table

- B+ trees – most common
  - They are search trees, but they are not binary instead have higher fan-out
  - Will discuss them briefly next

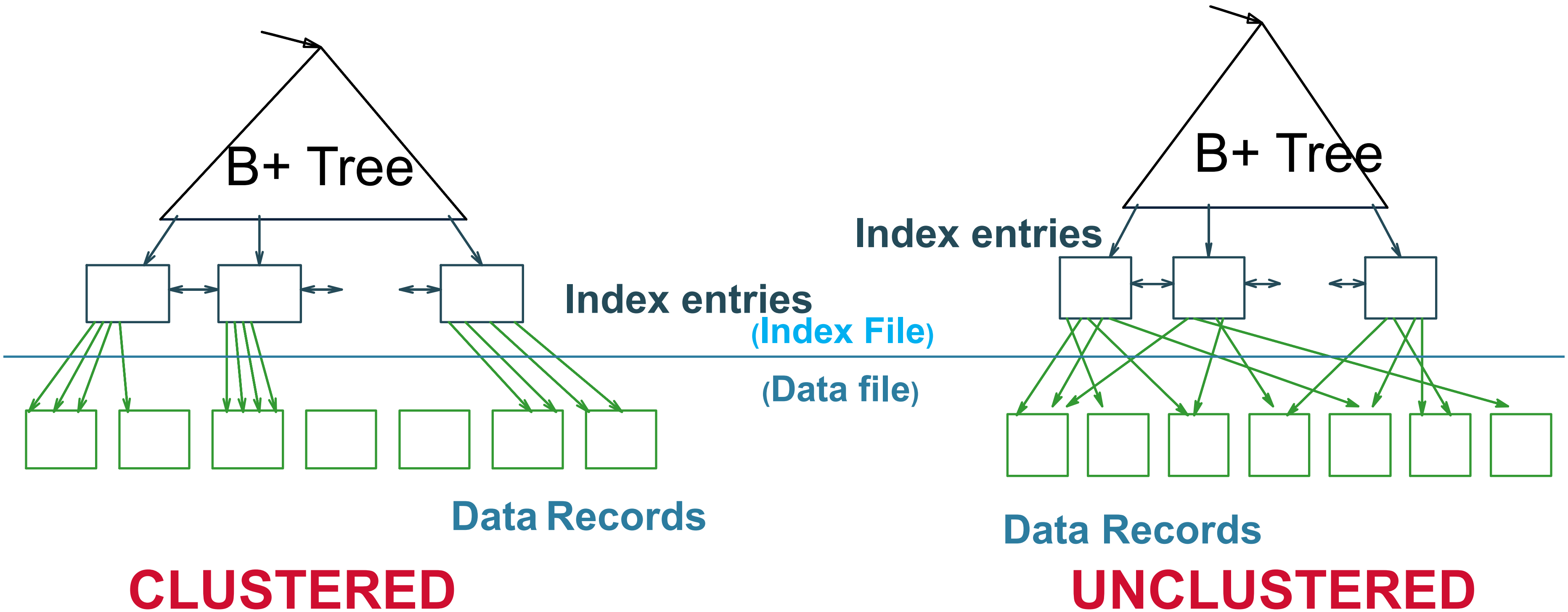
- Specialized indexes: bit maps, R-trees, inverted index

B+ Tree Index by Example

d = 2



Clustered vs Unclustered



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

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

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  - Meaning 1:
    - Primary = is over attributes that include the primary key
    - Secondary = otherwise
  - Meaning 2: means the same as clustered/unclustered

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- **Organization** B+ tree or Hash table

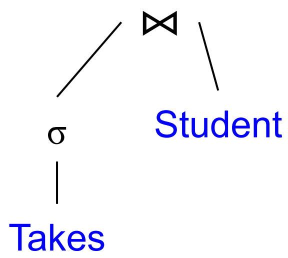
Summary So Far

- Index = a file that enables direct access to records in another data file
  - B+ tree / Hash table
  - Clustered/unclustered
- Data resides on disk
  - Organized in blocks
  - Sequential reads are efficient
  - Random access less efficient
  - Random read 1-2% of data worse than sequential

Student(<u>ID</u>, fname, lname)
Takes(studentID, courseID)

```
SELECT *
FROM  Student x, Takes y
WHERE x.ID=y.studentID AND y.courseID > 300
```

Example



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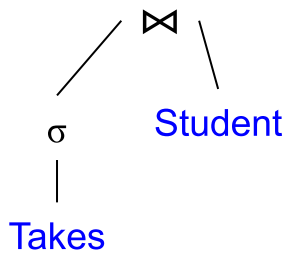


```
for y in Takes
   if courseID > 300 then
     for x in Student
         if x.ID=y.studentID
           output *
```

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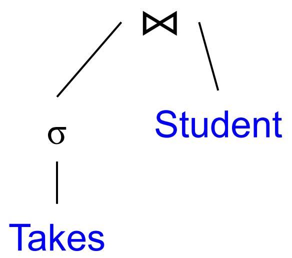



```
for y in Takes
  if courseID > 300 then
    for x in Student
        if x.ID=y.studentID
          output *
```

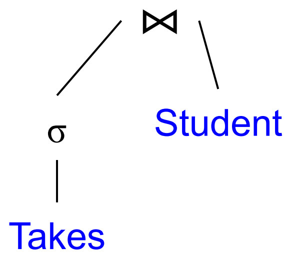
Assume the database has indexes on these attributes:

- **Takes_courseID** = index on Takes.courseID
- **Student_ID** = index on Student.ID

Student(<u>ID</u>, fname, lname)
Takes(studentID, courseID)

```
SELECT *
FROM  Student x, Takes y
WHERE x.ID=y.studentID AND y.courseID > 300
```

Example




```
for y in Takes
   if courseID > 300 then
     for x in Student
          if x.ID=y.studentID
            output *
```

Assume the database has indexes on these attributes:

- **Takes_courseID** = index on Takes.courseID
- **Student_ID** = index on Student.ID

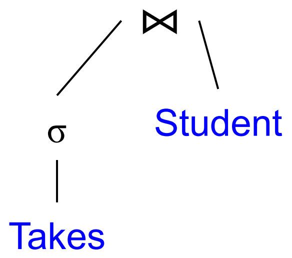
Index selection

```
for y' in Takes_courseID where y'.courseID > 300
```

Student(ID, fname, lname)
Takes(studentID, courseID)

```
SELECT *
FROM  Student x, Takes y
WHERE x.ID=y.studentID AND y.courseID > 300
```

Example




```
for y in Takes
   if courseID > 300 then
     for x in Student
         if x.ID=y.studentID
           output *
```

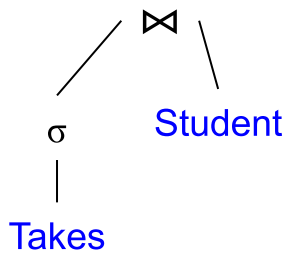
Assume the database has indexes on these attributes:

- **Takes_courseID** = index on Takes.courseID
- **Student_ID** = index on Student.ID

Index selection

```
for y' in Takes_courseID where y'.courseID > 300
  y = fetch the Takes record pointed to by y'
```

Student(<u>ID</u>, fname, lname)
Takes(studentID, courseID)

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SELECT *
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WHERE x.ID=y.studentID AND y.courseID > 300
```

Example

```
for y in Takes
   if courseID > 300 then
     for x in Student
          if x.ID=y.studentID
            output *
```

Assume the database has indexes on these attributes:

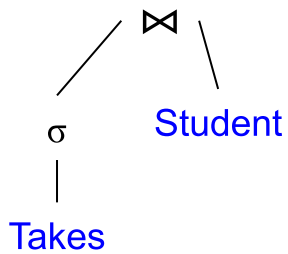
- **Takes_courseID** = index on Takes.courseID
- **Student_ID** = index on Student.ID

Index selection

```
for y' in Takes_courseID where y'.courseID > 300
  y = fetch the Takes record pointed to by y'
  for x' in Student_ID where x'.ID = y.studentID
        x = fetch the Student record pointed to by x'
```

Index join

Student(<u>ID</u>, fname, lname)
Takes(studentID, courseID)




```
SELECT *
FROM  Student x, Takes y
WHERE x.ID=y.studentID AND y.courseID > 300
```

Example

```
for y in Takes
  if courseID > 300 then
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        if x.ID=y.studentID
          output *
```

Assume the database has indexes on these attributes:

- **Takes_courseID** = index on Takes.courseID
- **Student_ID** = index on Student.ID

Index selection

```
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        x = fetch the Student record pointed to by x'
        output *
```
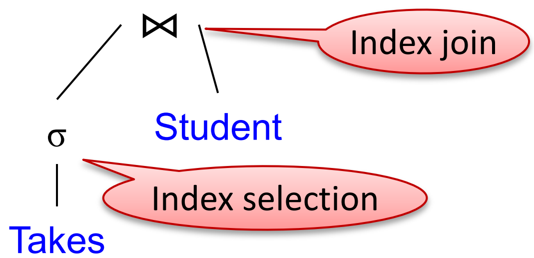

Index join

Student(ID, fname, lname)
Takes(studentID, courseID)

```
SELECT *
FROM  Student x, Takes y
WHERE x.ID=y.studentID AND y.courseID > 300
```

Example




```
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  if courseID > 300 then
    for x in Student
      if x.ID=y.studentID
        output *
```

Assume the database has indexes on these attributes:

- **Takes_courseID** = index on Takes.courseID
- **Student_ID** = index on Student.ID

Index selection

Index join

```
for y' in Takes_courseID where y'.courseID > 300
  y = fetch the Takes record pointed to by y'
  for x' in Student_ID where x'.ID = y.studentID
      x = fetch the Student record pointed to by x'
      output *
```

Getting Practical: Creating Indexes in SQL

```
CREATE  TABLE    V(M int,   N varchar(20),    P int);
```

```
CREATE  INDEX V1 ON V(N)
```

Getting Practical: Creating Indexes in SQL

```
CREATE TABLE   V(M int,   N varchar(20),   P int);
```

```
CREATE INDEX V1 ON V(N)
```

```
CREATE INDEX V2 ON V(P, M)
```

Getting Practical: Creating Indexes in SQL

```
CREATE TABLE   V(M int,   N varchar(20),    P int);
```

```
CREATE INDEX V1 ON V(N)
```

```
CREATE INDEX V2 ON V(P, M)
```

What does this mean?

Getting Practical: Creating Indexes in SQL

```
CREATE TABLE   V(M int,   N varchar(20),   P int);
```

```
CREATE INDEX V1 ON V(N)
```

```
CREATE INDEX V2 ON V(P, M)
```

What does this mean?

```
select *
from V
where P=55 and M=77
```

yes

Getting Practical: Creating Indexes in SQL

```
CREATE TABLE V(M int, N varchar(20), P int);
```

```
CREATE INDEX V1 ON V(N)
```

```
CREATE INDEX V2 ON V(P, M)
```

What does this mean?

yes

```
select *
from V
where P=55 and M=77
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```
select *
from V
where P=55
```

Getting Practical: Creating Indexes in SQL

```
CREATE TABLE   V(M int,   N varchar(20),   P int);
```

```
CREATE INDEX V1 ON V(N)
```

```
CREATE INDEX V2 ON V(P, M)
```

What does this mean?

```
select *
from V
where P=55 and M=77
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yes

```
select *
from V
where P=55
```

yes

Getting Practical: Creating Indexes in SQL

```
CREATE TABLE V(M int, N varchar(20), P int);
```

```
CREATE INDEX V1 ON V(N)
```

```
CREATE INDEX V2 ON V(P, M)
```

What does this mean?

```
select *
from V
where P=55 and M=77
```

yes

```
select *
from V
where P=55
```

yes

```
select *
from V
where M=77
```

Getting Practical: Creating Indexes in SQL

```
CREATE TABLE   V(M int,   N varchar(20),   P int);
```

```
CREATE INDEX V1 ON V(N)
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```
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What does this mean?

```
select *
from V
where P=55 and M=77
```

yes

```
select *
from V
where P=55
```

yes

```
select *
from V
where M=77
```

no

Getting Practical: Creating Indexes in SQL

```
CREATE TABLE   V(M int,   N varchar(20),   P int);
```

```
CREATE INDEX V1 ON V(N)
```

```
CREATE INDEX V2 ON V(P, M)
```

What does this mean?

```
CREATE INDEX V3 ON V(M, N)
```

```
CREATE UNIQUE INDEX V4 ON V(N)
```

```
CREATE CLUSTERED INDEX V5 ON V(N)
```

Not supported in SQLite

```
select *
from V
where P=55 and M=77
```

yes

```
select *
from V
where P=55
```

yes

```
select *
from V
where M=77
```

no

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

Which Indexes?

- How many indexes could we create?
- Which indexes should we create?

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

Which Indexes?

- How many indexes could we create?
- Which indexes should we create?

In general this is a very hard problem

Index Selection: Which Search Key

- Make some attribute K a search key if the WHERE clause contains:
  - An exact match on K
  - A range predicate on K
  - A join on K

The Index Selection Problem 1

```
V(M, N, P);
```

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

The Index Selection Problem 1

```
V(M, N, P);
```

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

What indexes ?

The Index Selection Problem 1

V(M, N, P);

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

A: V(N) and V(P) (hash tables or B-trees)

The Index Selection Problem 2

V(M, N, P);

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

What indexes ?

The Index Selection Problem 2

V(M, N, P);

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

A: definitely V(N) (must B-tree); unsure about V(P)

The Index Selection Problem 3

V(M, N, P);

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

1000000 queries:

```
SELECT *
FROM V
WHERE N=? and P>?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

What indexes ?

The Index Selection Problem 3

V(M, N, P);

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

1000000 queries:

```
SELECT *
FROM V
WHERE N=? and P>?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

A: V(N, P)

How does this index differ from:

1. Two indexes V(N) and V(P)?
2. An index V(P, N)?

The Index Selection Problem 4

V(M, N, P);

Your workload is this

1000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100000 queries:

```
SELECT *
FROM V
WHERE P>? and P<?
```

What indexes ?

The Index Selection Problem 4

```
V(M, N, P);
```

Your workload is this

1000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100000 queries:

```
SELECT *
FROM V
WHERE P>? and P<?
```

A: V(N) secondary, V(P) primary index

Two typical kinds of queries

```
SELECT *
FROM Movie
WHERE year = ?
```

- Point queries
- What data structure should be used for index?

```
SELECT *
FROM Movie
WHERE year >= ? AND
          year <= ?
```

- Range queries
- What data structure should be used for index?

Basic Index Selection Guidelines

- Consider queries in workload in order of importance
- Consider relations accessed by query
  - No point indexing other relations
- Look at WHERE clause for possible search key
- Try to choose indexes that speed-up multiple queries

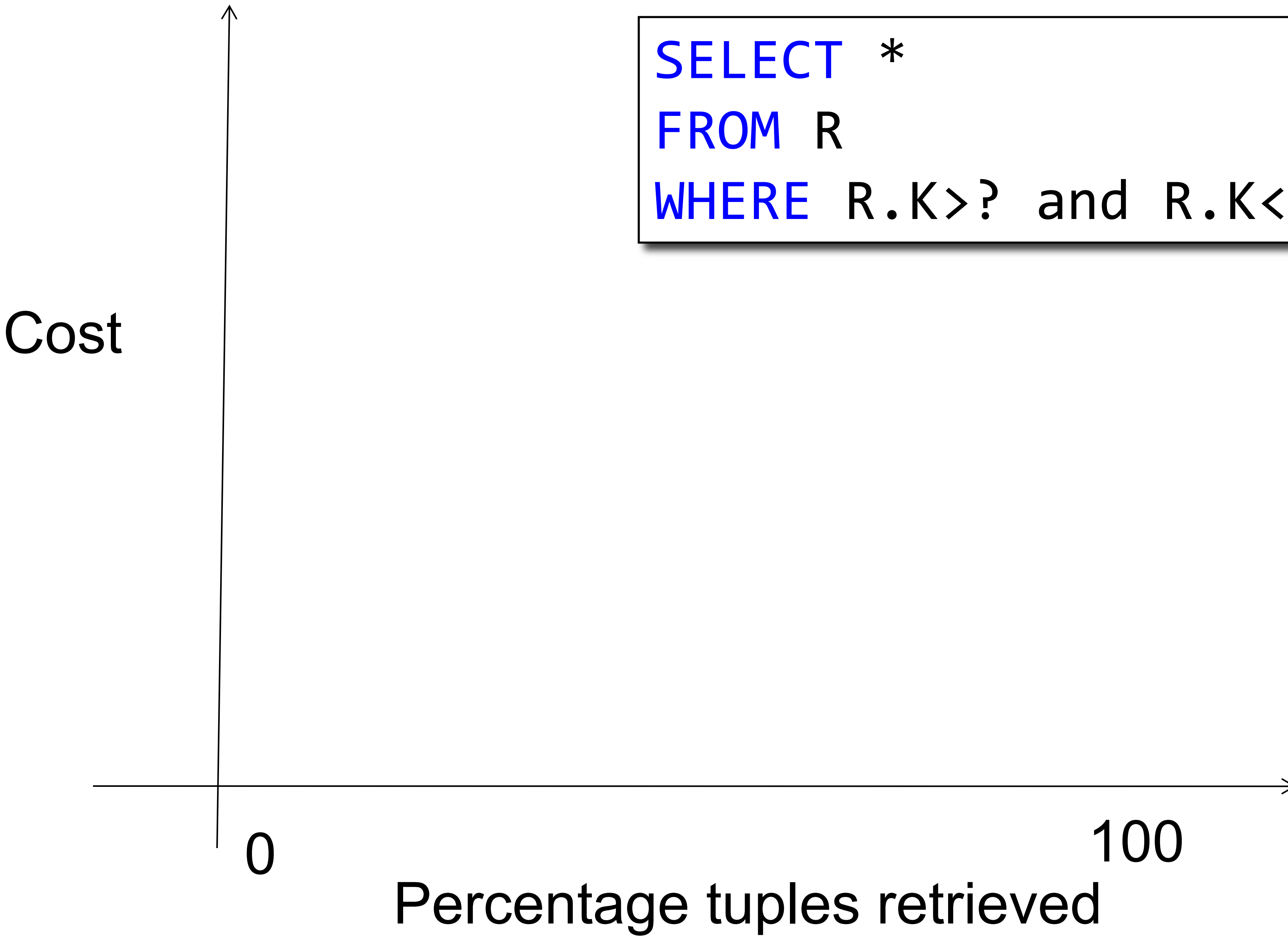
To Cluster or Not

Remember:

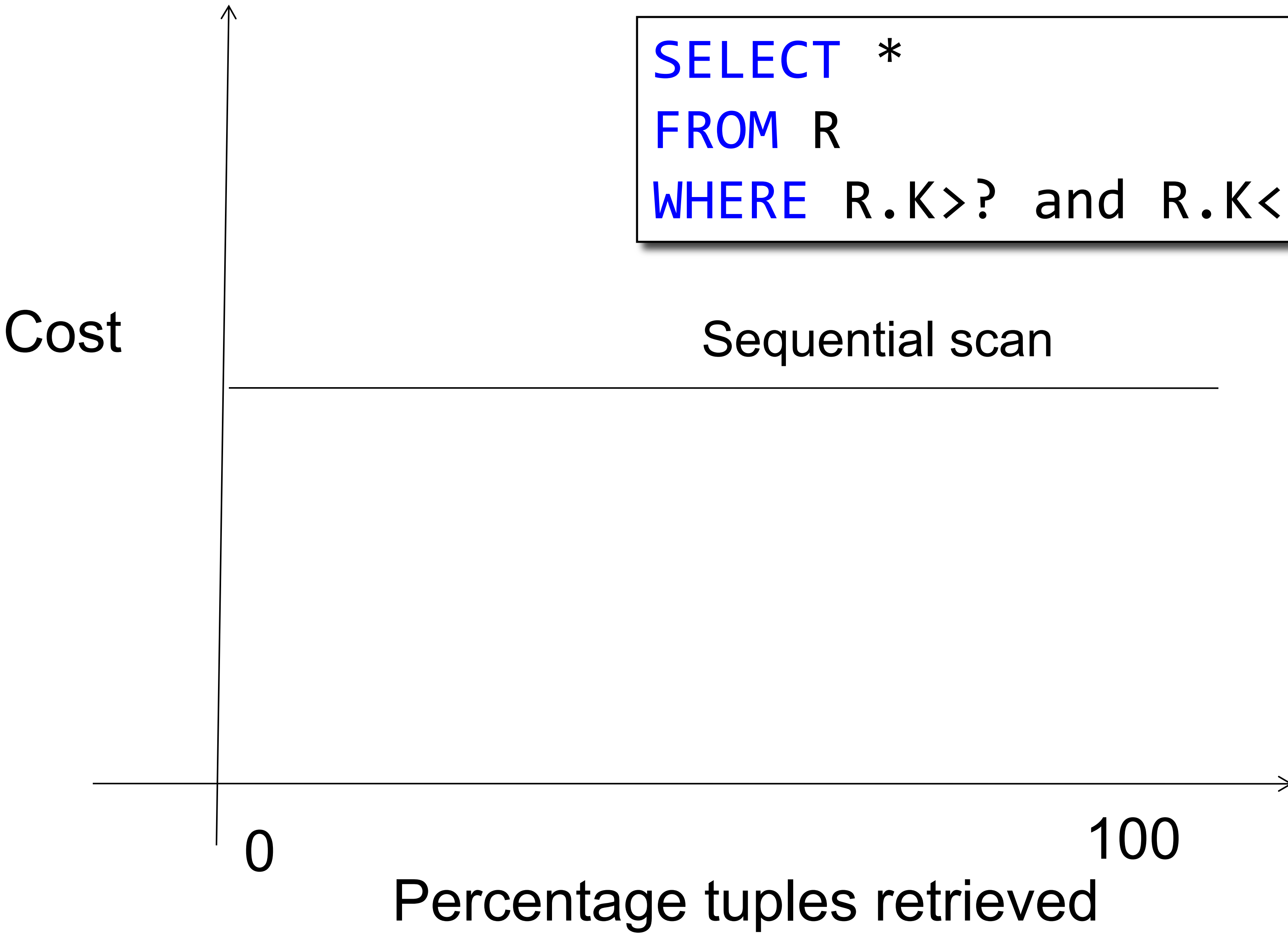
- Rule of thumb:
  Random reading 1-2% of file ≈ sequential scan entire file;

Range queries benefit mostly from clustering because they may read more than 1-2%

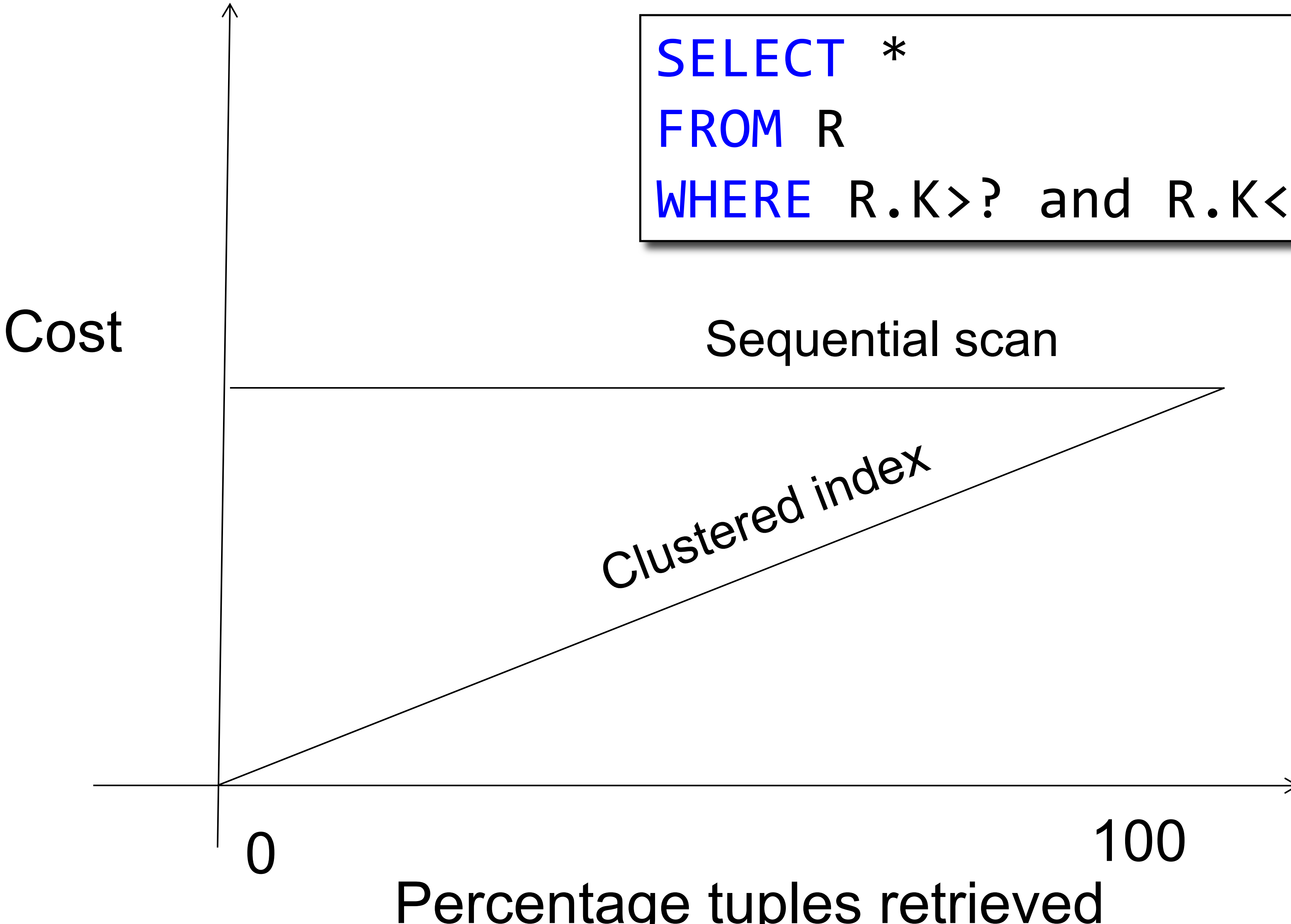
```
SELECT *
FROM R
WHERE R.K>? and R.K<?
```



```
SELECT *
FROM R
WHERE R.K>? and R.K<?
```



```sql
SELECT *
FROM R
WHERE R.K>? and R.K<?
```



```
SELECT *
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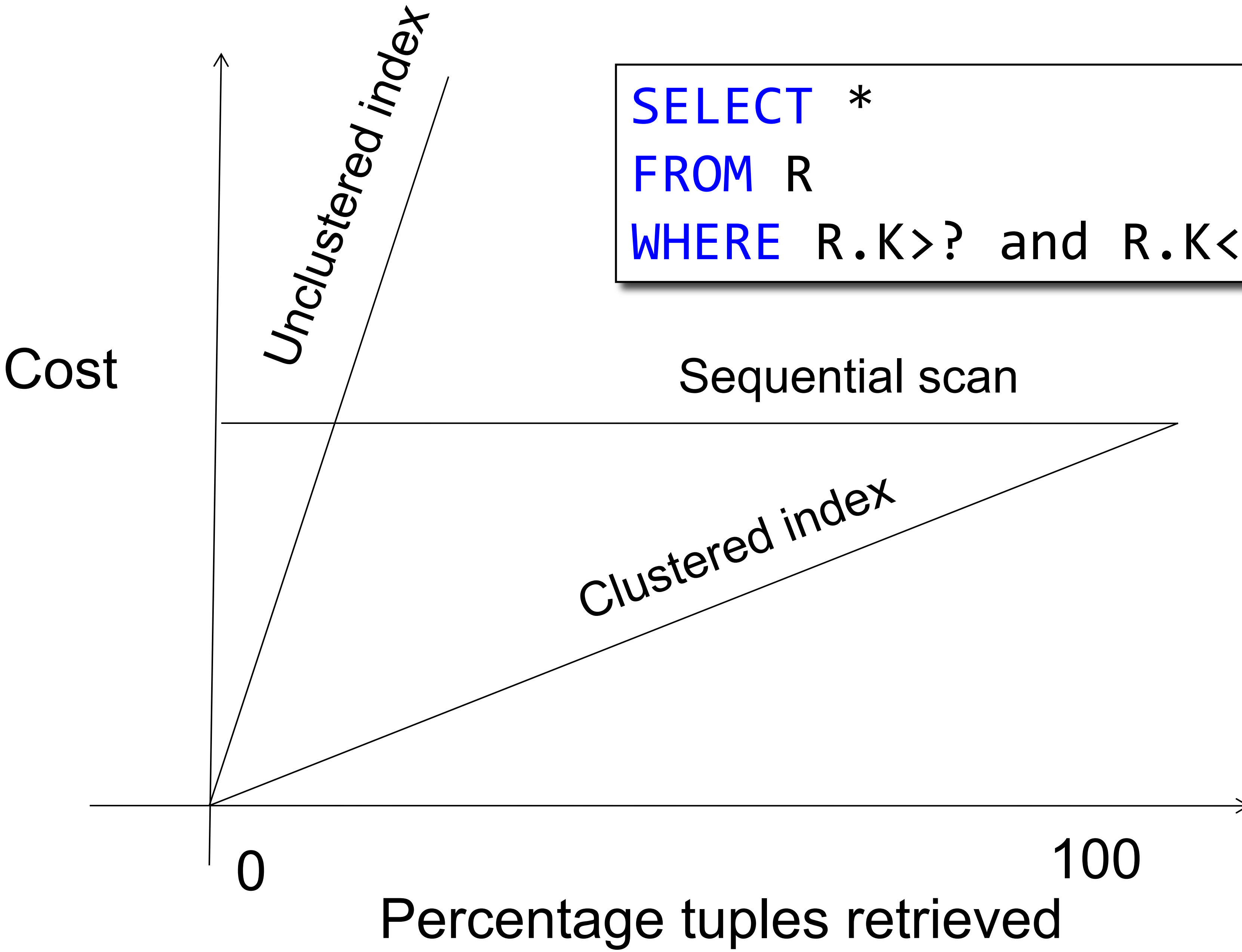
```



Introduction to Database Systems CSE 344

Lecture 17:
Basics of Query Optimization and Query Cost Estimation

Cost Estimation

- The optimizer considers several plans, estimates their costs, and chooses the cheapest
- This lecture: cost estimation for relational operators
- The cost is always dominated by the cost of reading from, or writing to disk

Cost of Reading Data From Disk

Cost Parameters

- Cost = I/O + CPU + Network BW
  - We will focus on I/O in this class
- Parameters (a.k.a. statistics):
  - **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

Cost Parameters

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  - **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

When **a** is a key, **V(R,a) = T(R)**

When **a** is not a key, **V(R,a)** can be anything <= **T(R)**

Cost Parameters

- Cost = I/O + CPU + Network BW
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  - **V(R, a)** = # of distinct values of attribute a

When **a** is a key, **V(R,a) = T(R)**
When **a** is not a key, **V(R,a)** can be anything <= **T(R)**

- DBMS collects statistics about base tables must infer them for intermediate results

Size Estimation

Main principle:

- Size of the output = some *fraction* of the size of the input
- The *fraction* is called the *selectivity factor*

Selectivity Factors for Conditions

- A = c   /* $\sigma_{A=c}(R)$ */
  – Selectivity f = 1/V(R,A)

Will use mostly this…

- A < c   /* $\sigma_{A<c}(R)$ */
  – Selectivity f = (c - min(R, A))/(max(R,A) - min(R,A))

- c1 < A < c2   /* $\sigma_{c1<A<c2}(R)$ */
  – Selectivity f = (c2 – c1)/(max(R,A) - min(R,A))

…and this

- Cond1 ∧ Cond2 ∧ Cond3 ∧ …
  – Selectivity = f1*f2*f3* …(assumes independence)

Cost of Reading Data From Disk

- Sequential scan for relation R costs **B(R)**
- Index-based selection
  - Estimate selectivity factor **f** (see previous slide)
  - Clustered index: f***B(R)**
  - Unclustered index f***T(R)**

Note: we ignore I/O cost for index pages

Index Based Selection

- Example:

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

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

- Table scan:
- Index based selection:

Index Based Selection

- Example:

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

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

- Table scan: B(R) = 2,000 I/Os
- Index based selection:

Index Based Selection

- Example:

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

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

- Table scan: B(R) = 2,000 I/Os
- Index based selection:
  - If index is clustered:
  - If index is unclustered:

Index Based Selection

- Example:

B(R) = 2000
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cost of $\sigma_{a=v}(R) = ?$

- Table scan: B(R) = 2,000 I/Os
- Index based selection:
  - If index is clustered: B(R) * 1/V(R,a) = 100 I/Os
  - If index is unclustered:

Index Based Selection

- Example:

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

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

- Table scan: $B(R) = 2{,}000$ I/Os
- Index based selection:
  - If index is clustered: $B(R) * 1/V(R,a) = 100$ I/Os
  - If index is unclustered: $T(R) * 1/V(R,a) = 5{,}000$ I/Os

Index Based Selection

- Example:

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

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

- Table scan: B(R) = 2,000 I/Os
- Index based selection:
  - If index is clustered: B(R) * 1/V(R,a) = 100 I/Os
  - If index is unclustered: T(R) * 1/V(R,a) = 5,000 I/Os

Lesson: Don't build unclustered indexes when V(R,a) is small !

Cost of Executing Operators (Focus on Joins)

Outline

- **Join operator algorithms**
  - One-pass algorithms (Sec. 15.2 and 15.3)
  - Index-based algorithms (Sec 15.6)

- Note about readings:
  - In class, we discuss only algorithms for joins
  - Other operators are easier: read the book

Join Algorithms

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

Join Example

Patient(pid, name, address)

Insurance(pid, provider, policy_nb)

Patient $\bowtie$ Insurance

Two tuples per page

Patient

1	'Bob'	'Seattle'
2	'Ela'	'Everett'

3	'Jill'	'Kent'
4	'Joe'	'Seattle'

Insurance

2	'Blue'	123
4	'Prem'	432

4	'Prem'	343
3	'GrpH'	554

Nested Loop Joins

- Tuple-based nested loop R ⋈ S
- R is the outer relation, S is the inner relation

```
for each tuple t1 in R do
   for each tuple t2 in S do
      if t1 and t2 join then output (t1,t2)
```

What is the Cost?

Nested Loop Joins

- Tuple-based nested loop R ⋈ S
- R is the outer relation, S is the inner relation

```
for each tuple t1 in R do
   for each tuple t2 in S do
      if t1 and t2 join then output (t1,t2)
```

What is the Cost?

- Cost: B(R) + T(R) B(S)
- Multiple-pass since S is read many times

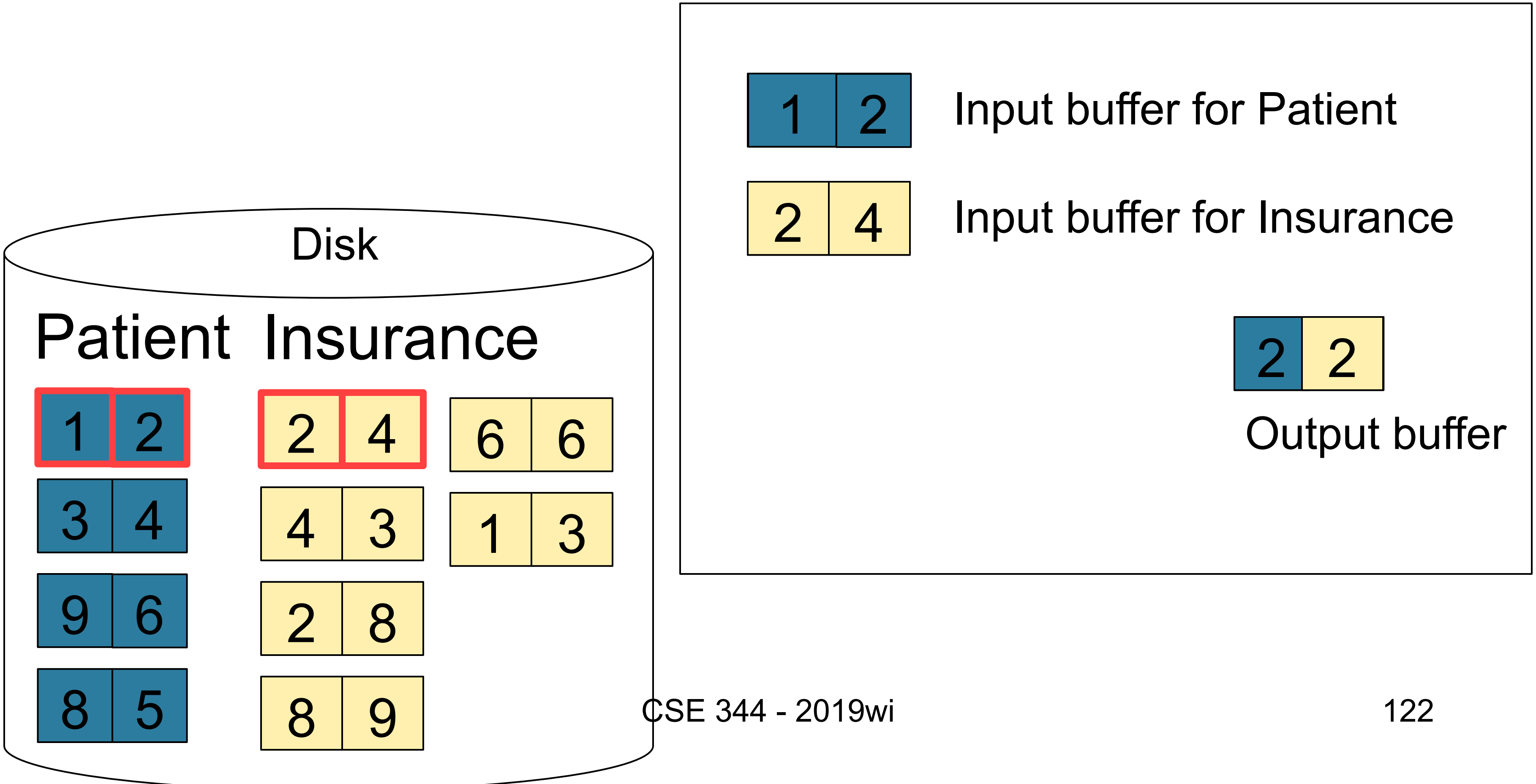
Page-at-a-time Refinement

```
for each page of tuples r in R do
   for each page of tuples s in S do
        for all pairs of tuples t1 in r, t2 in s
             if t1 and t2 join then output (t1,t2)
```

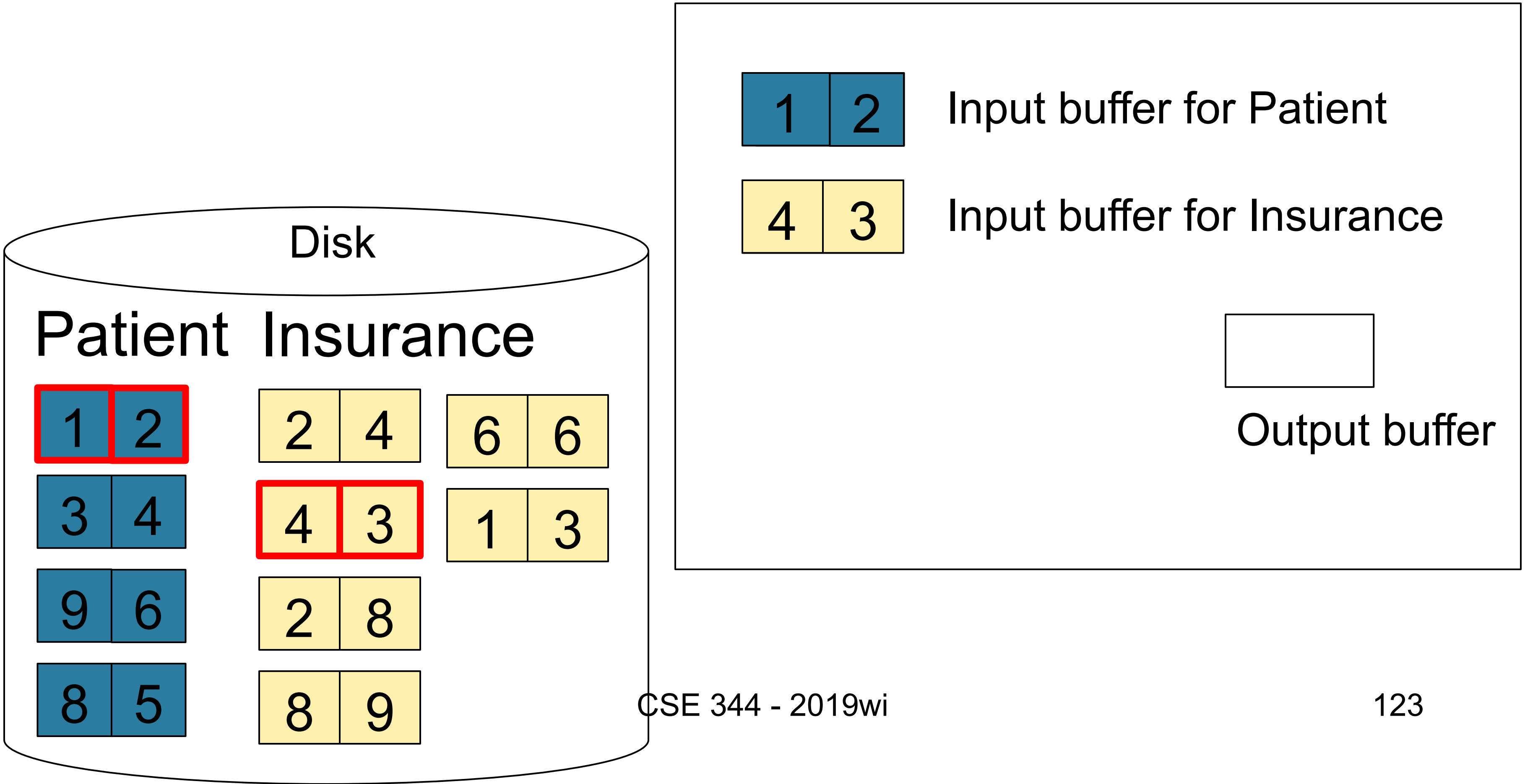
- Cost: B(R) + B(R)B(S)

What is the Cost?

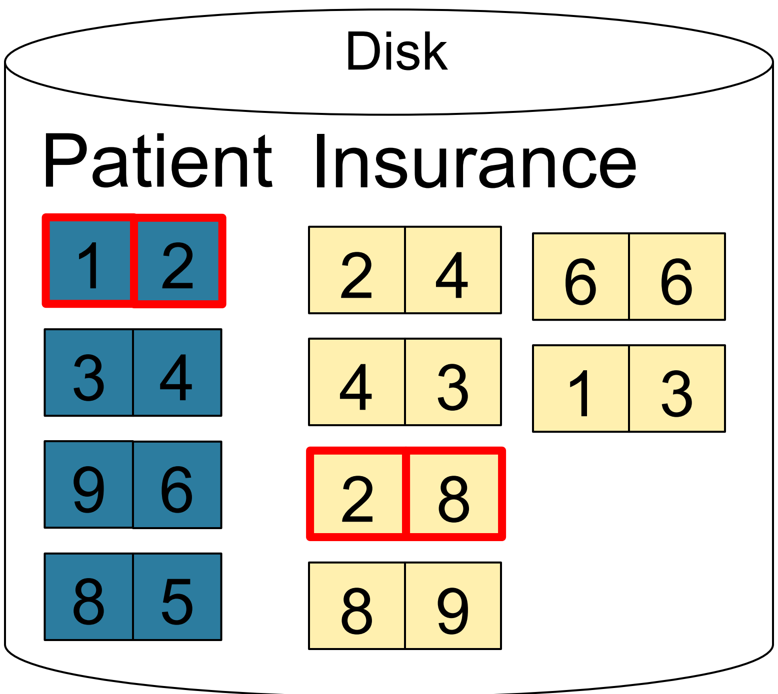
Page-at-a-time Refinement

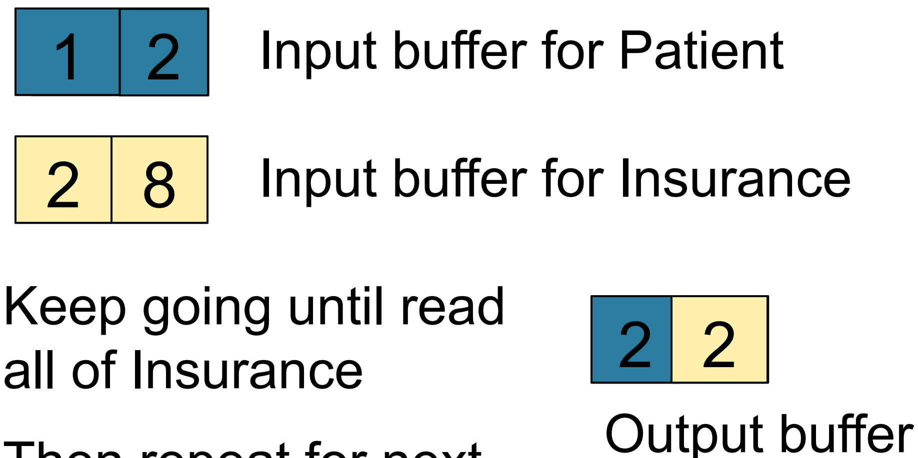


Page-at-a-time Refinement



Page-at-a-time Refinement





Keep going until read all of Insurance

Then repeat for next page of Patient… until end of Patient

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

Block-Nested-Loop Refinement

```
for each group of M-1 pages r in R do
   for each page of tuples s in S do
         for all pairs of tuples t1 in r, t2 in s
               if t1 and t2 join then output (t1,t2)
```

- Cost: B(R) + B(R)B(S)/(M-1)

What is the Cost?

Hash Join

Hash join: $R \bowtie S$

- Scan R, build buckets in main memory
- Then scan S and join
- Cost: $B(R) + B(S)$
- Which relation to build the hash table on?

Hash Join

Hash join: $R \bowtie S$

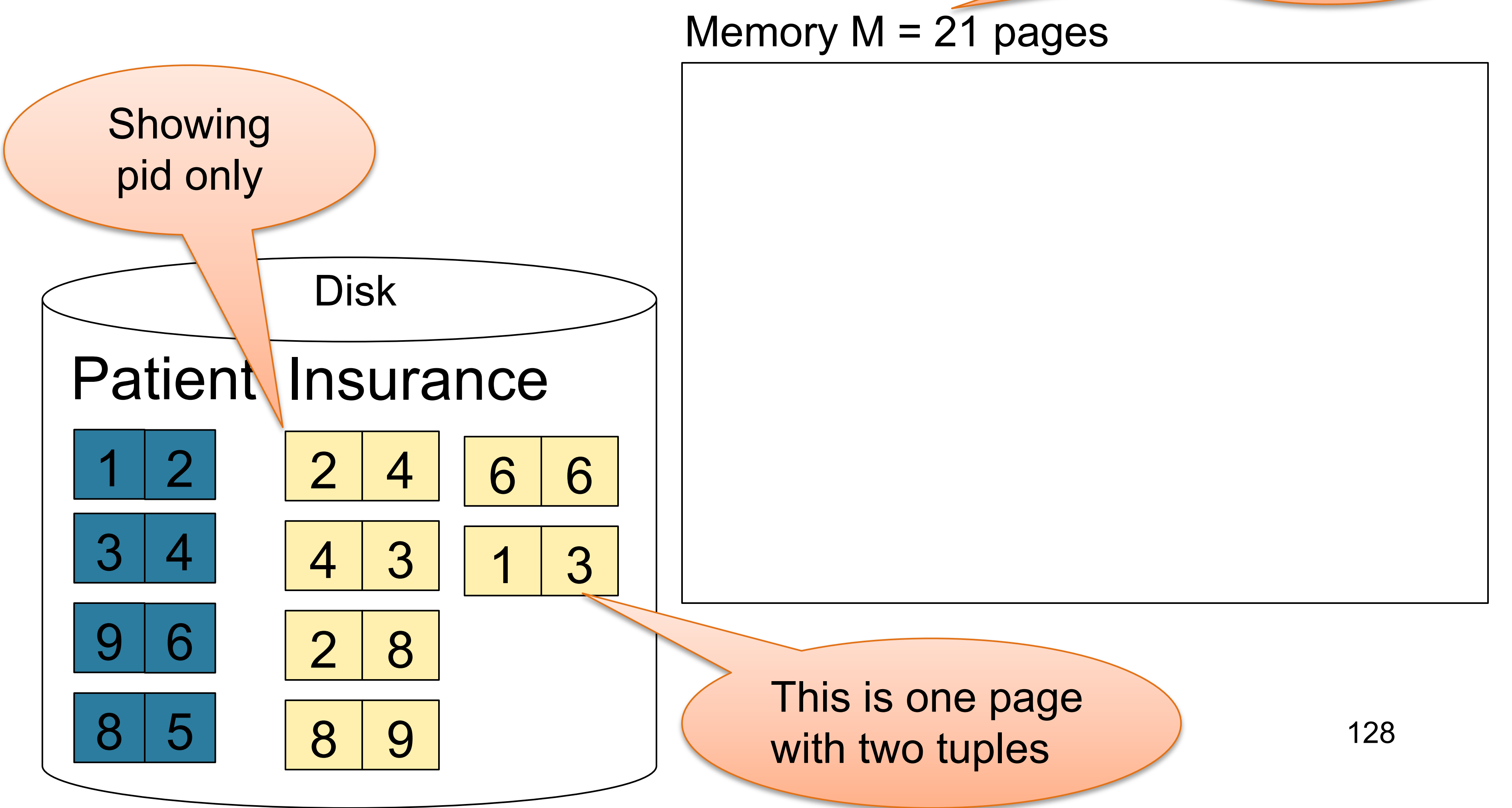
- Scan R, build buckets in main memory
- Then scan S and join
- Cost: B(R) + B(S)
- Which relation to build the hash table on?

- One-pass algorithm when $B(R) \leq M$
  - M = number of memory pages available

Hash Join Example

Patient $\bowtie$ Insurance

Some large-enough #

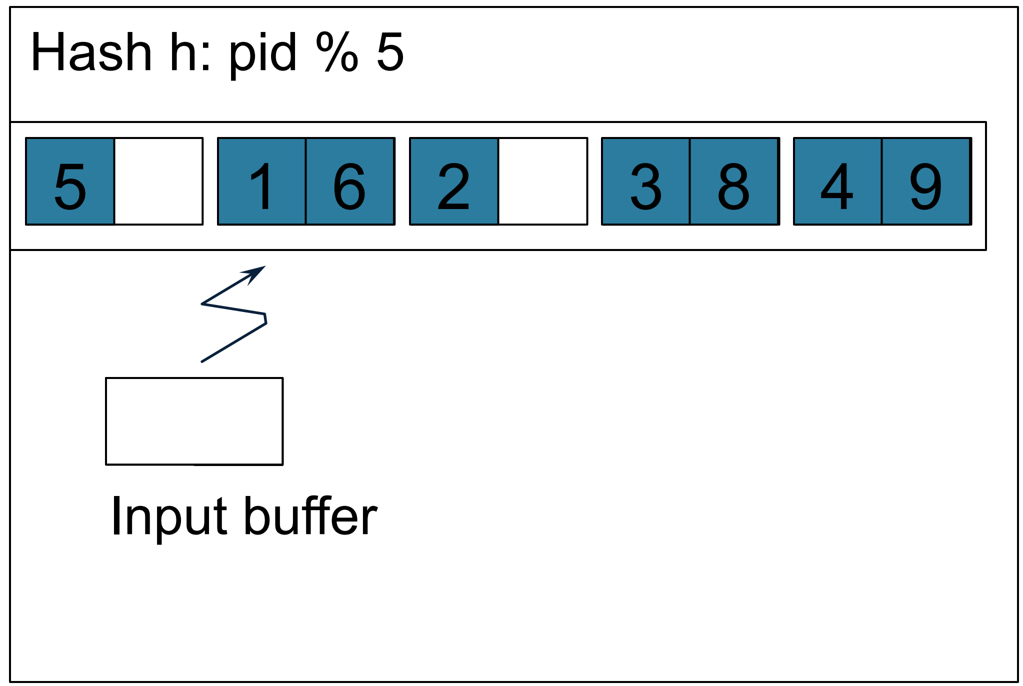


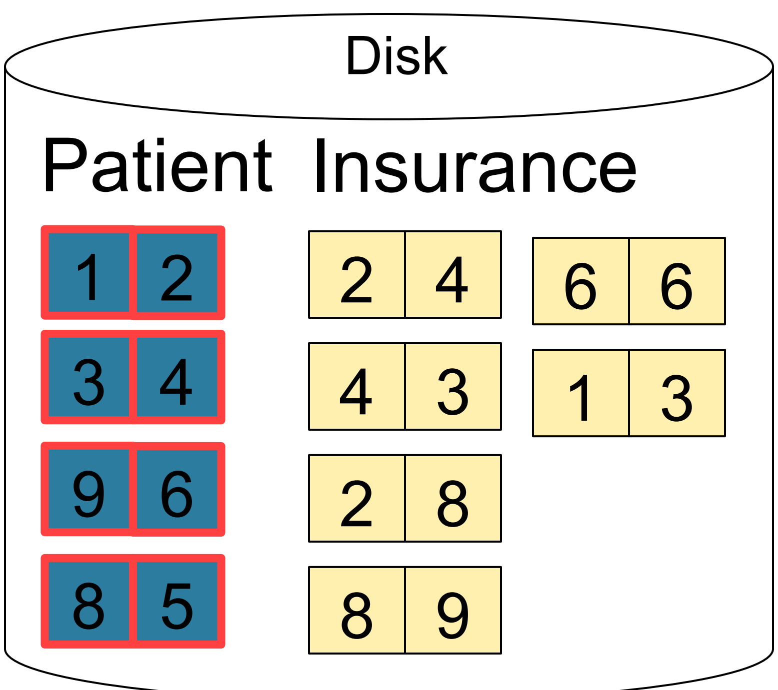
Hash Join Example

Step 1: Scan Patient and build hash table in memory

Can be done in method open()

Memory M = 21 pages

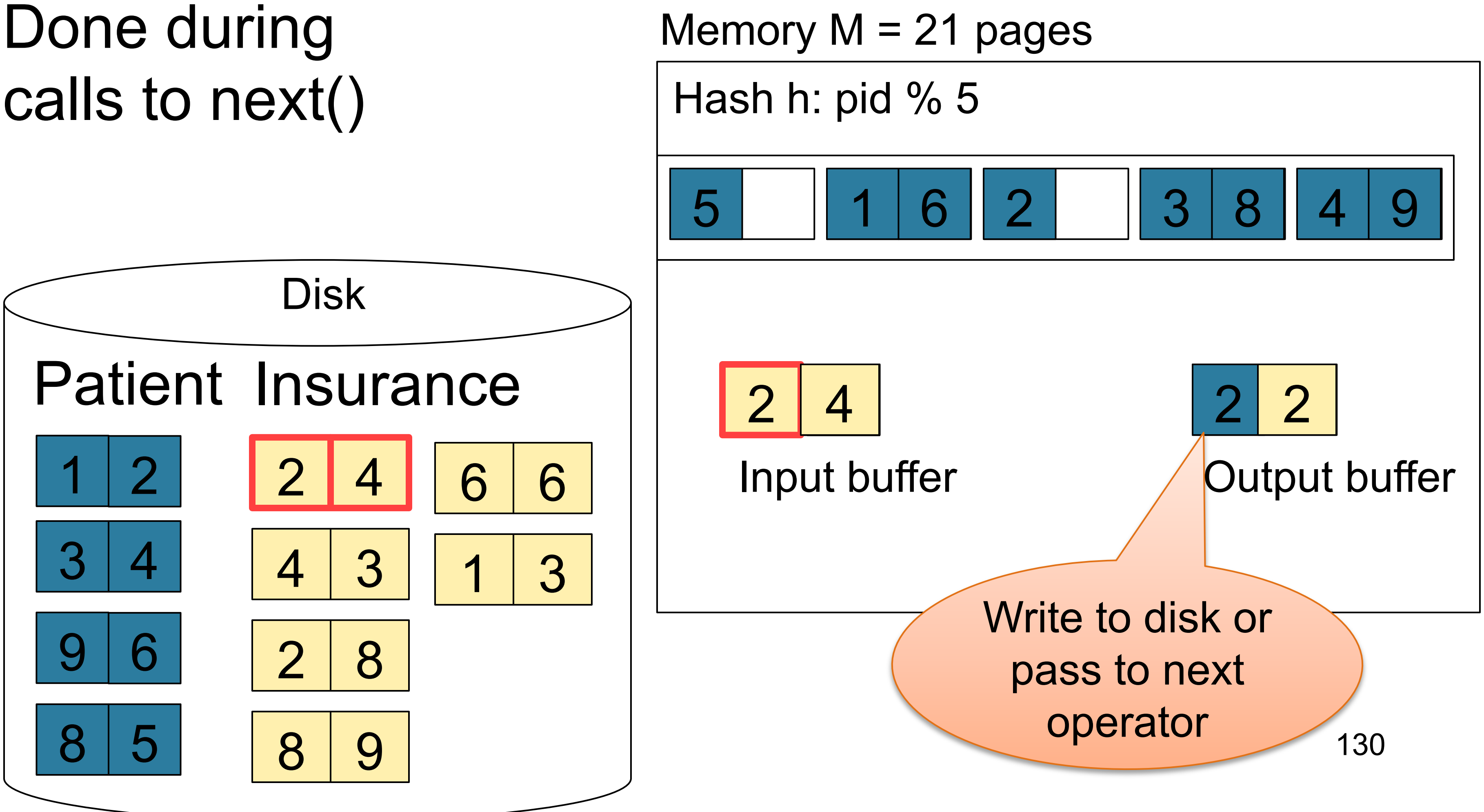




Hash Join Example

Step 2: Scan Insurance and probe into hash table

Done during calls to next()

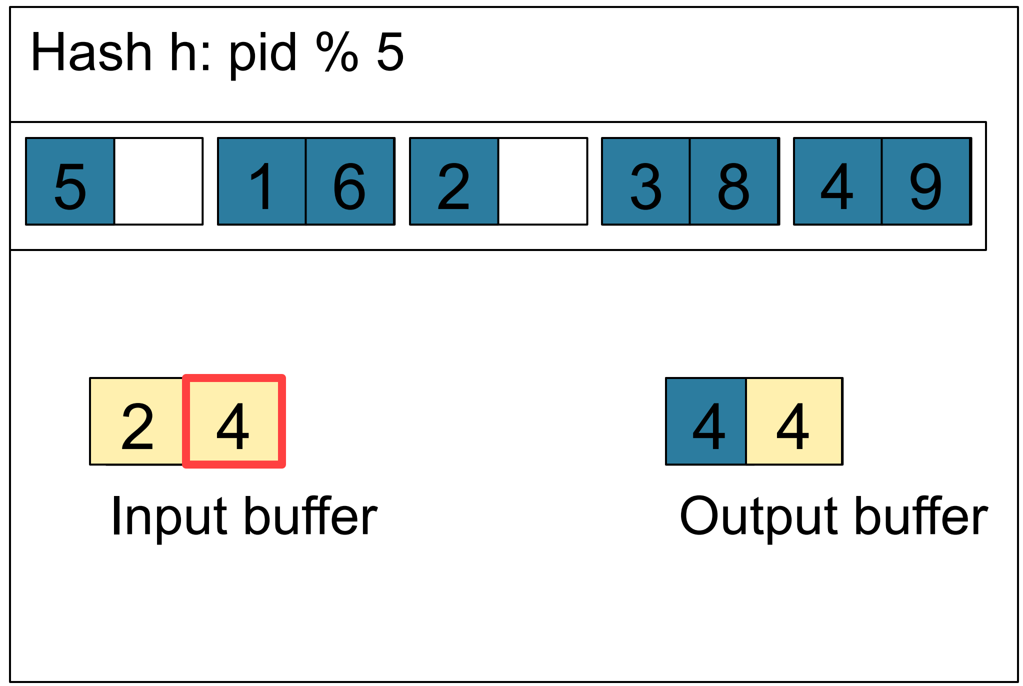


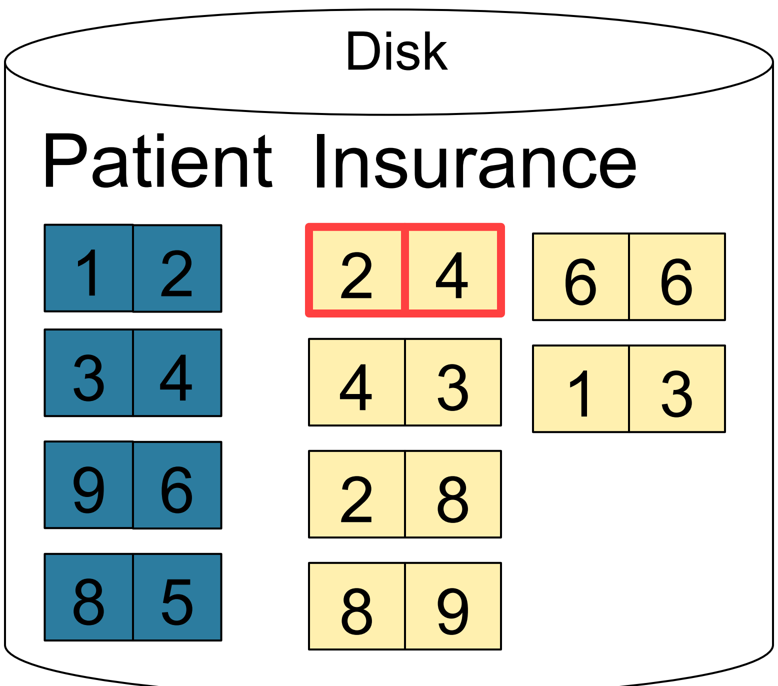
Hash Join Example

Step 2: Scan Insurance and probe into hash table

Done during calls to next()

Memory M = 21 pages

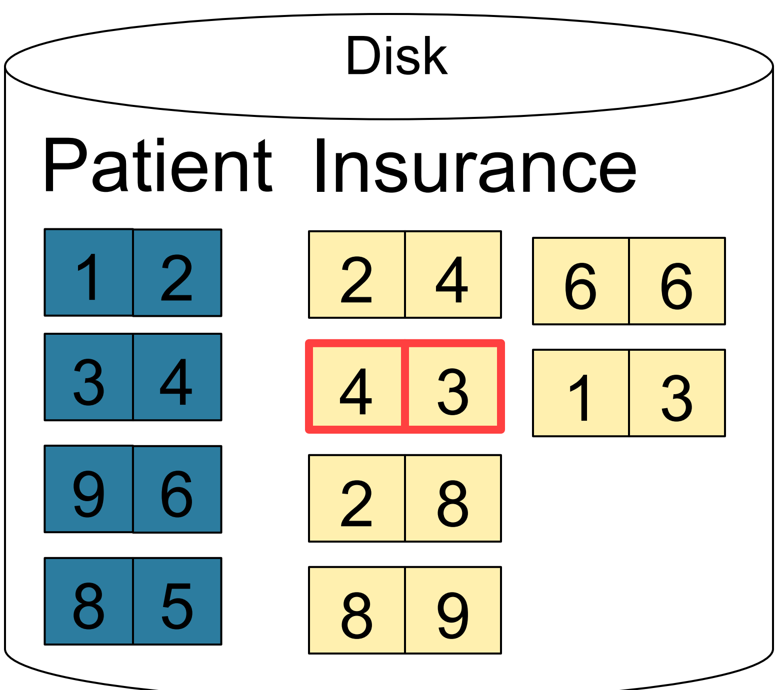




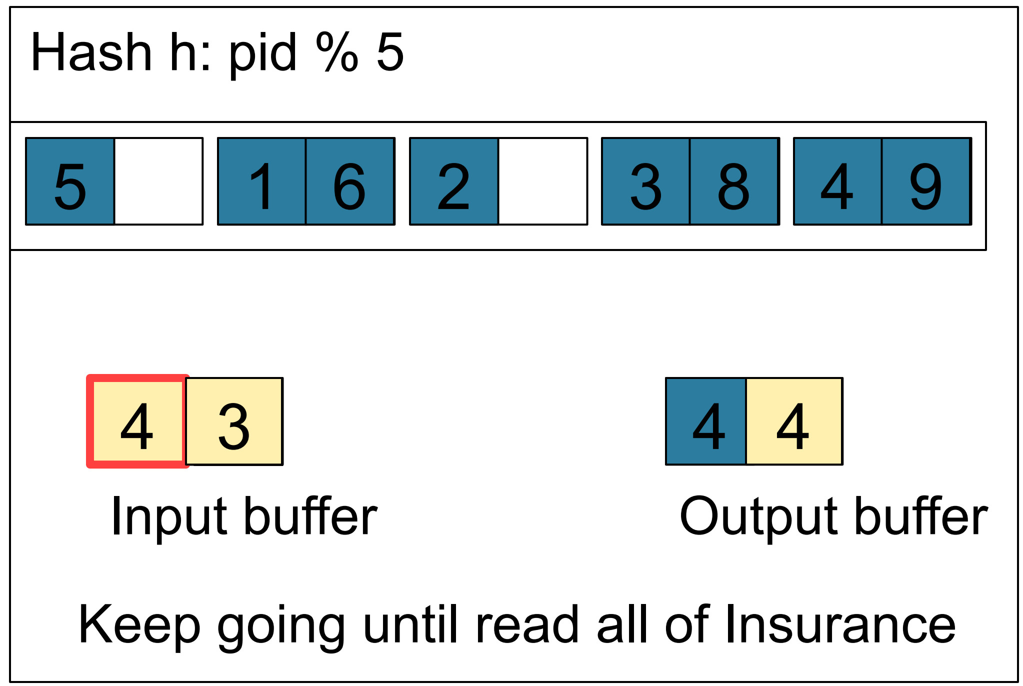
Hash Join Example

Step 2: Scan Insurance and probe into hash table

Done during calls to next()



Memory M = 21 pages



Cost: B(R) + B(S)

Sort-Merge Join

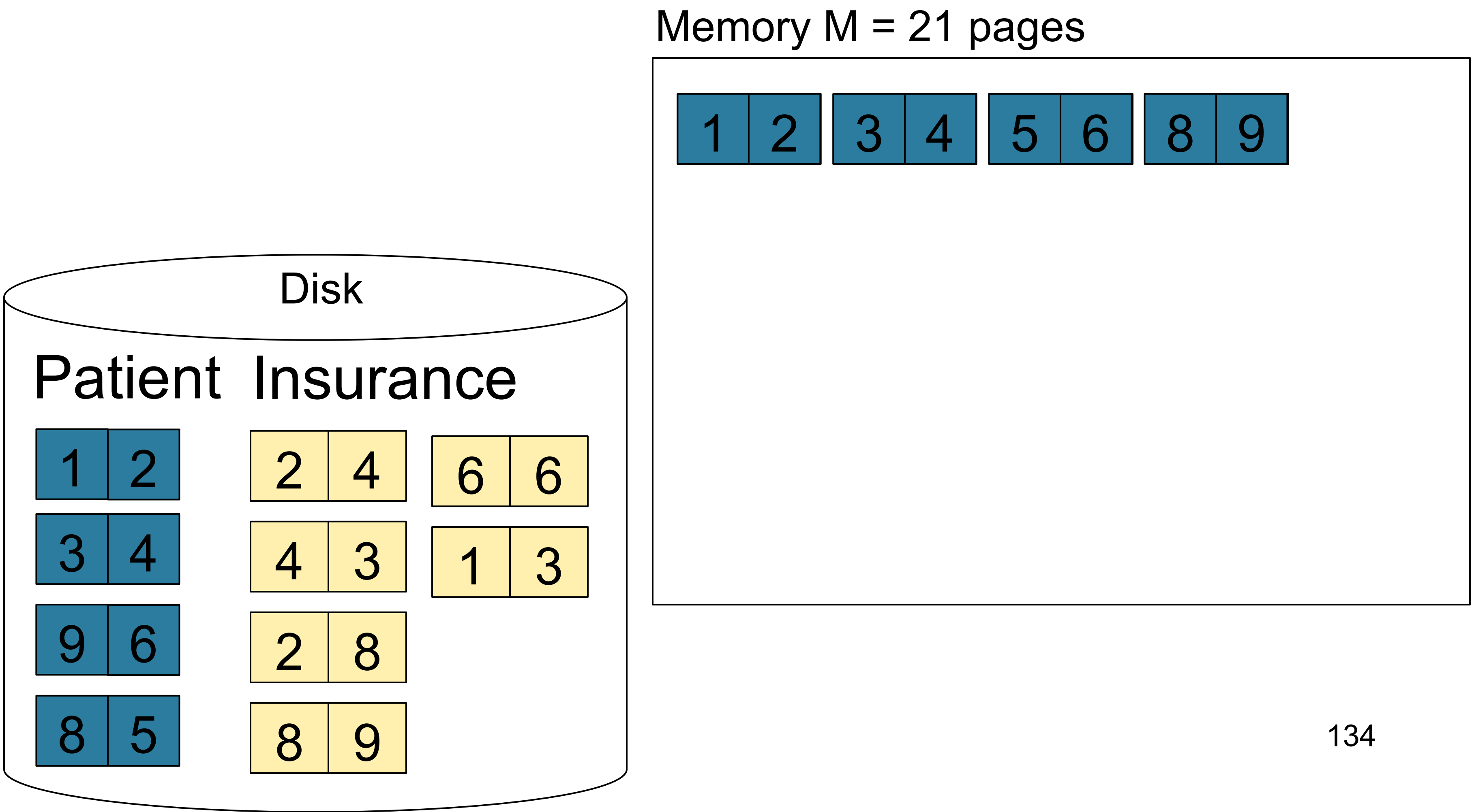
Sort-merge join: $R \bowtie S$

- 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

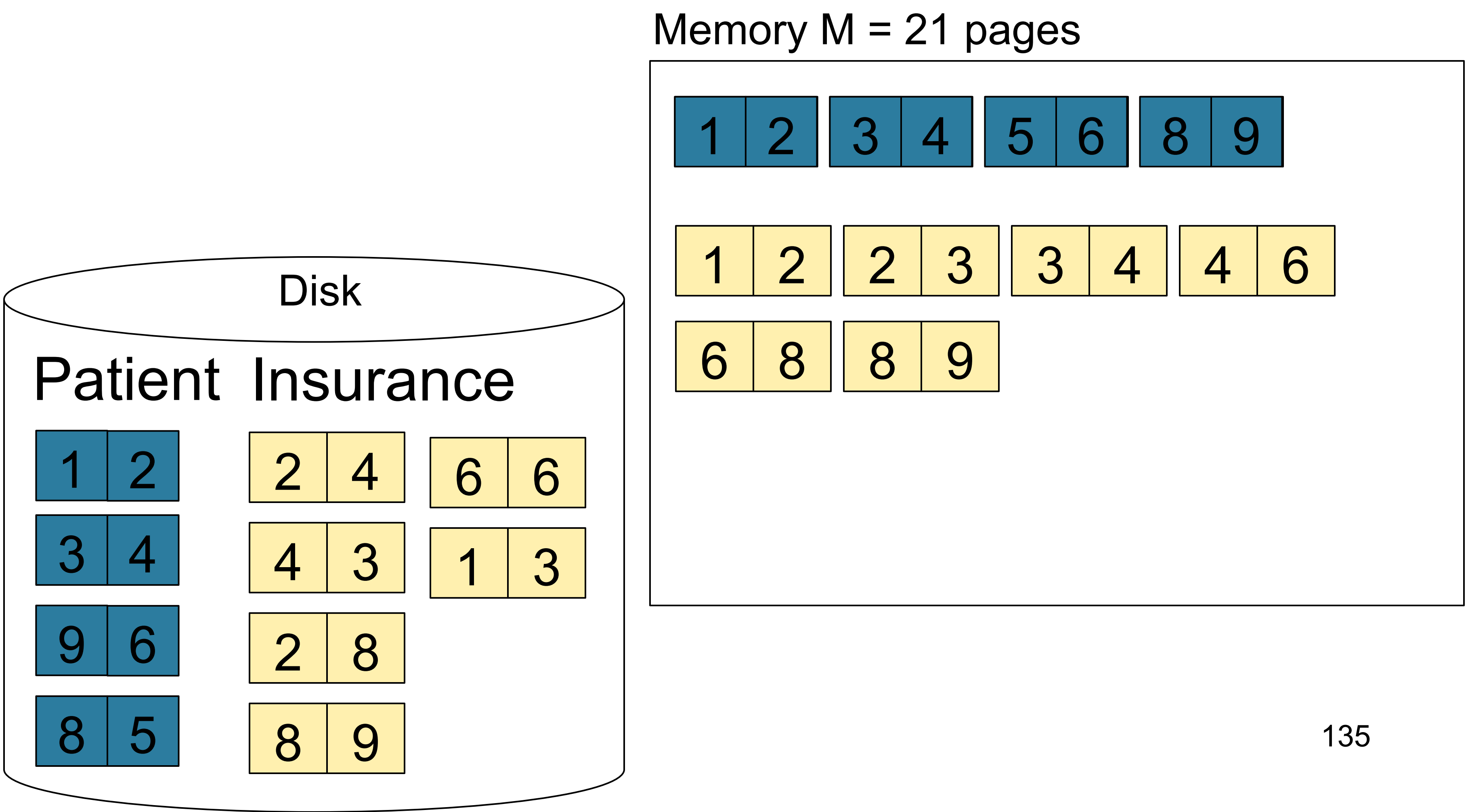
Sort-Merge Join Example

Step 1: Scan Patient and sort in memory



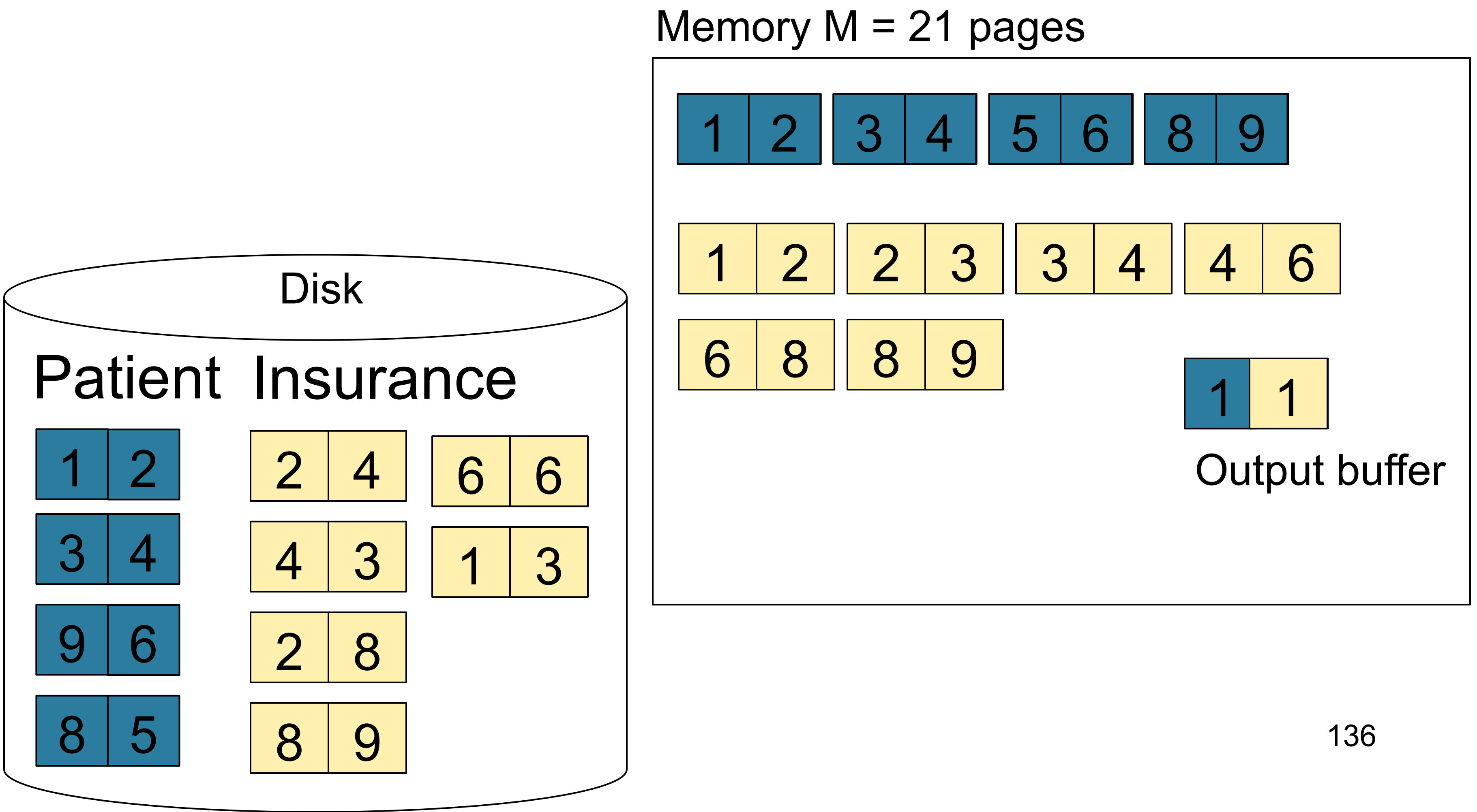
Sort-Merge Join Example

Step 2: Scan Insurance and sort in memory



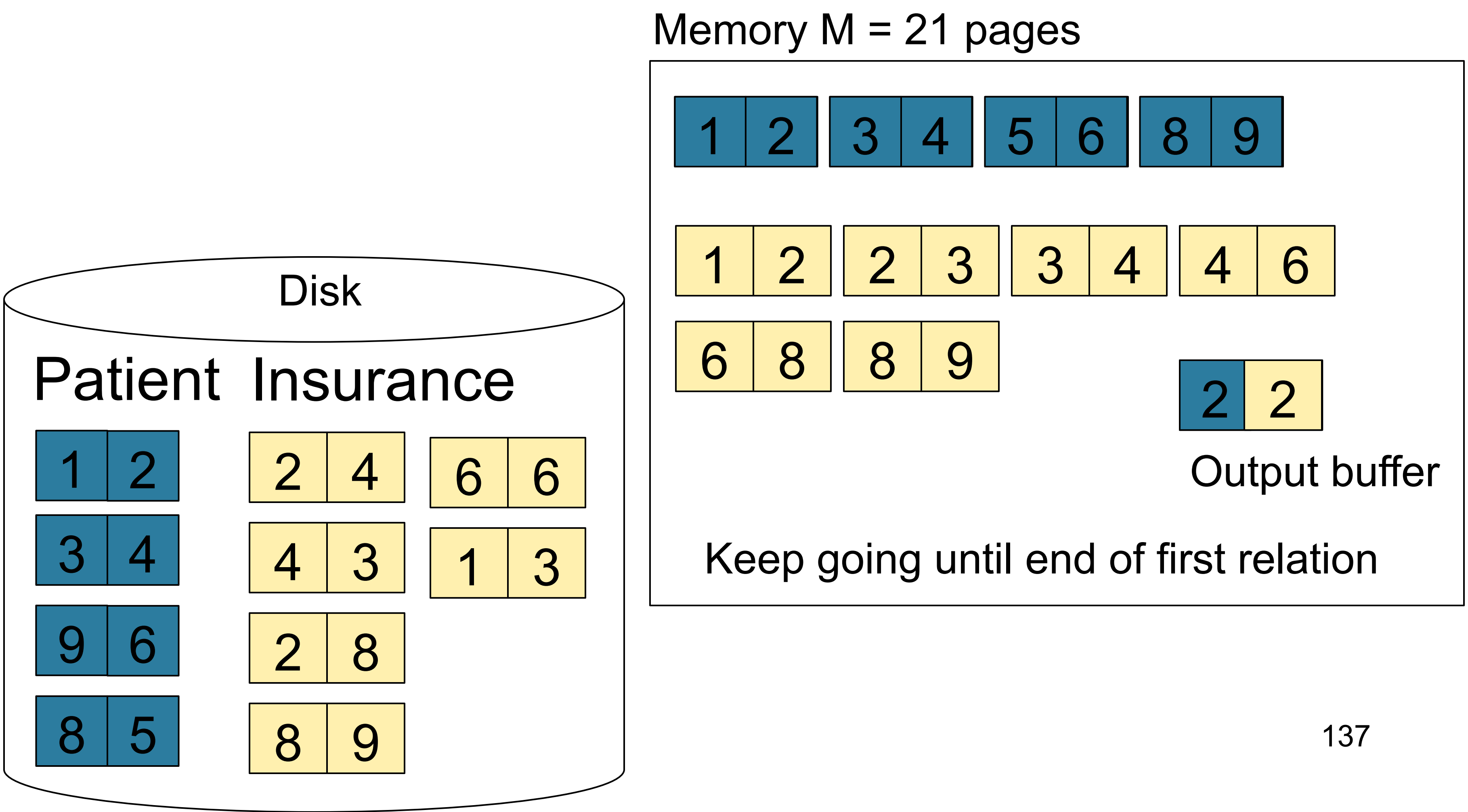
Sort-Merge Join Example

Step 3: Merge Patient and Insurance



Sort-Merge Join Example

Step 3: Merge Patient and Insurance



Index Join

$R \bowtie S$

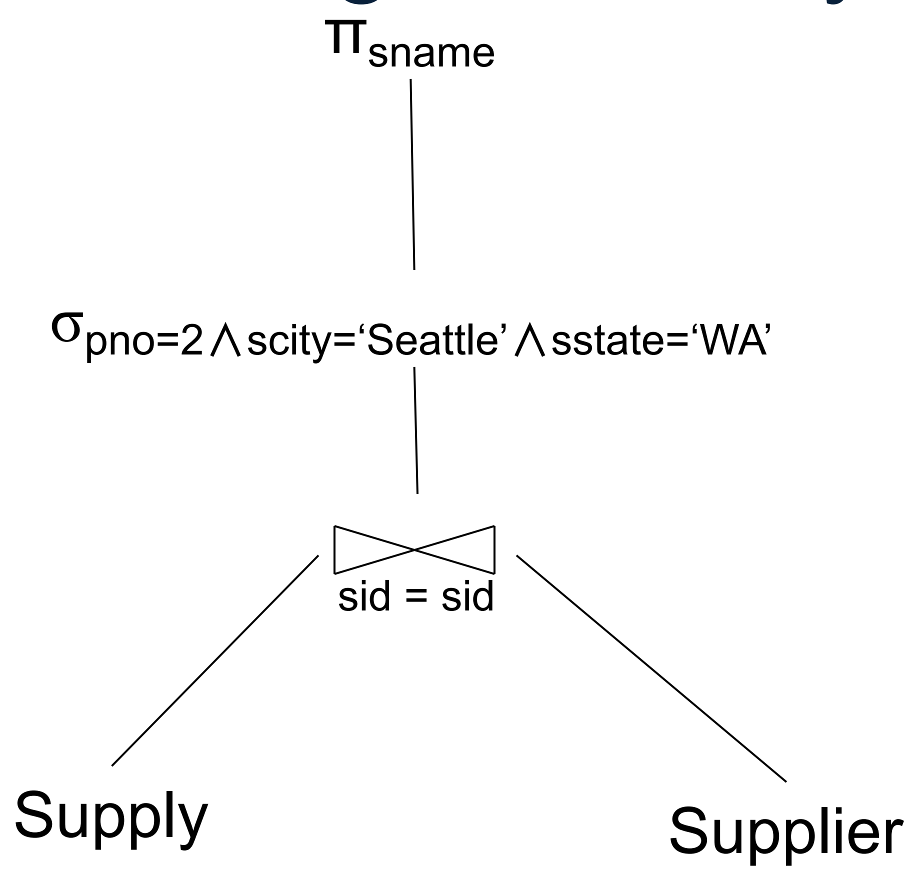
- Assume S has an index on the join attribute
- Iterate over R, for each tuple fetch corresponding tuple(s) from S

- Cost:
  - If index on S is clustered:
    B(R) + T(R) * (B(S) * 1/V(S,a))
  - If index on S is unclustered:
    B(R) + T(R) * (T(S) * 1/V(S,a))

Cost of Query Plans Example

Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)

Logical Query Plan 1




```
SELECT sname
FROM Supplier x, Supply y
WHERE x.sid = y.sid
    and y.pno = 2
    and x.scity = 'Seattle'
    and x.sstate = 'WA'
```

T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

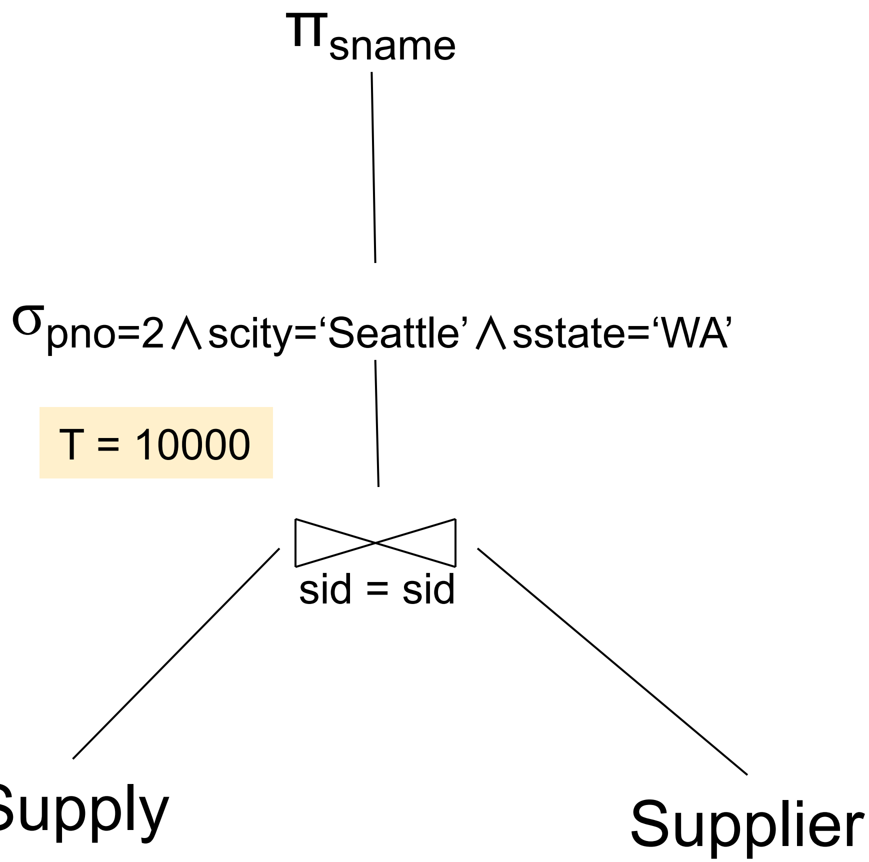
T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Logical Query Plan 1

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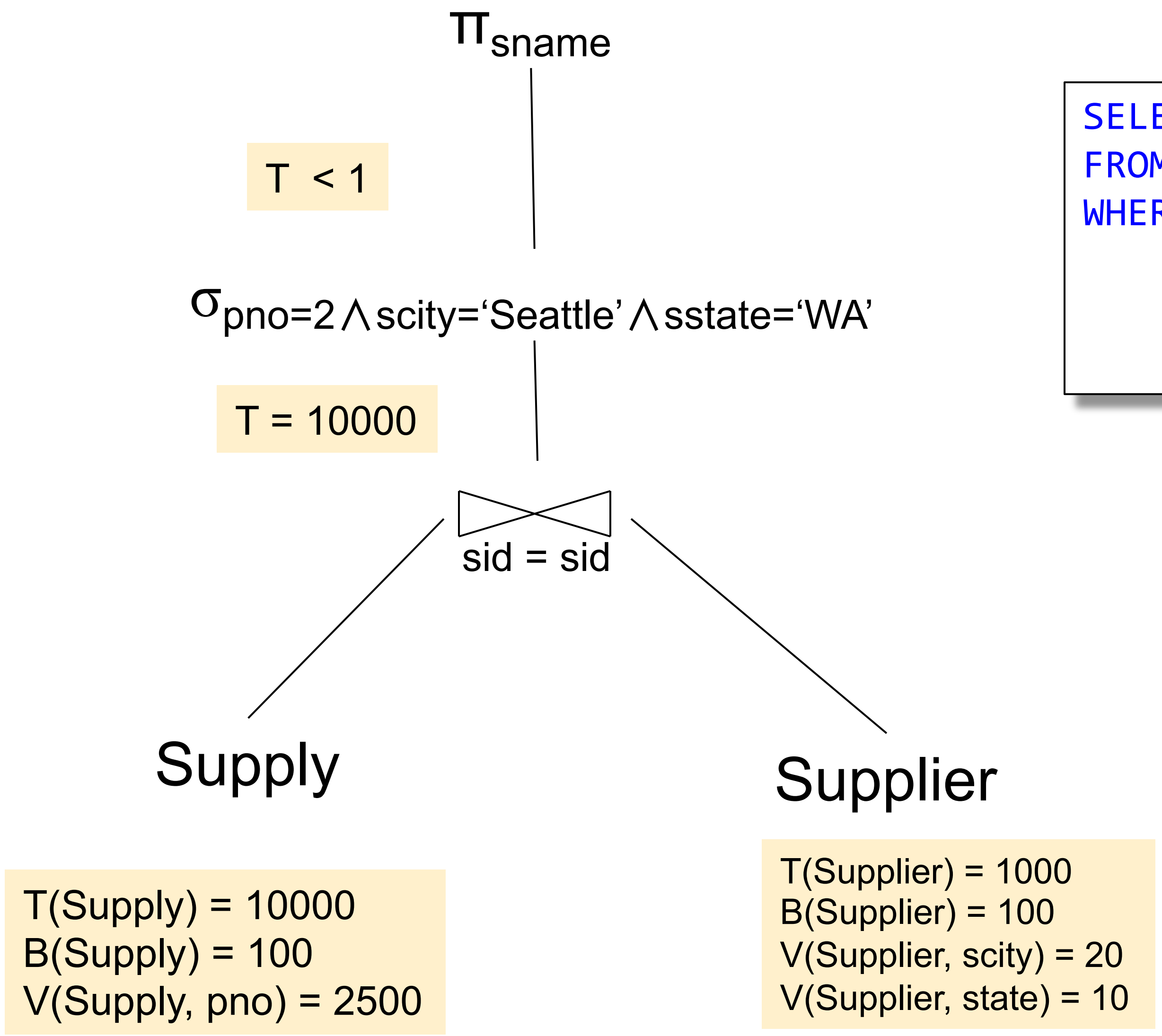
Supply(sid, pno, quantity)

Logical Query Plan 1

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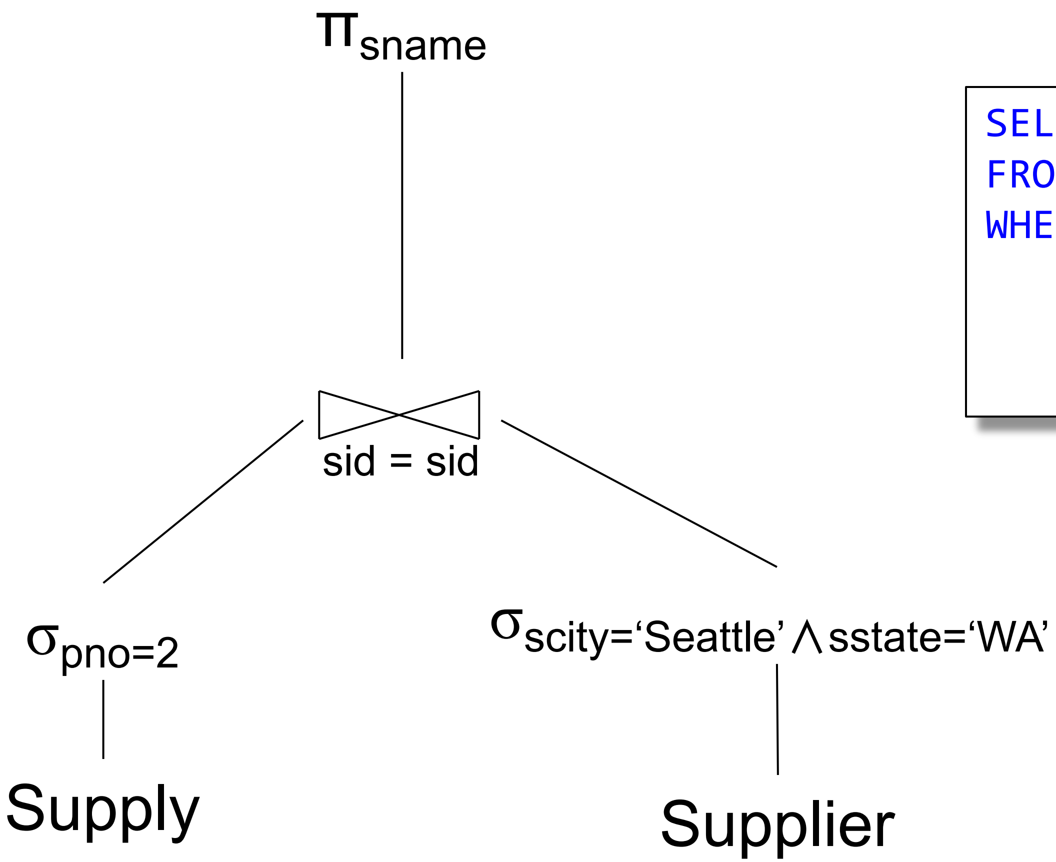
    and y.pno = 2
    and x.scity = 'Seattle'
    and x.sstate = 'WA'
```

M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Logical Query Plan 2




```
SELECT sname
FROM Supplier x, Supply y
WHERE x.sid = y.sid
    and y.pno = 2
    and x.scity = 'Seattle'
    and x.sstate = 'WA'
```

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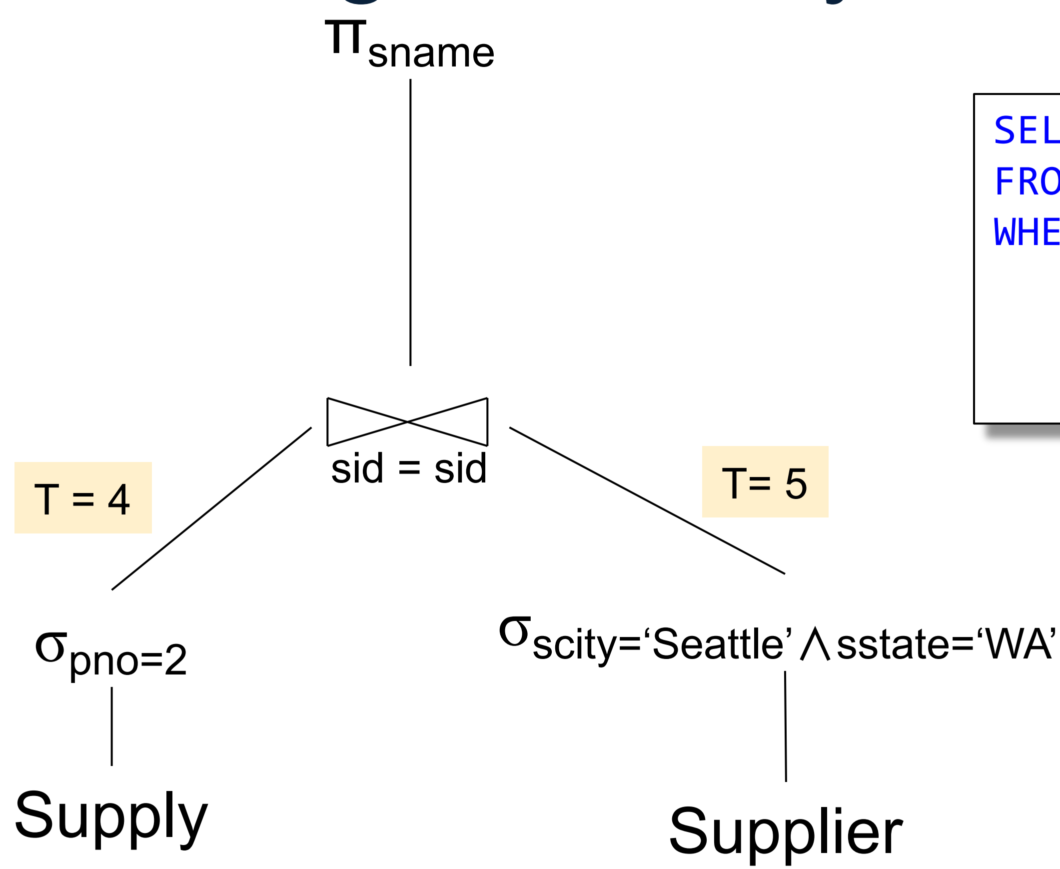
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Logical Query Plan 2

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Supply(sid, pno, quantity)

Logical Query Plan 2

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FROM Supplier x, Supply y
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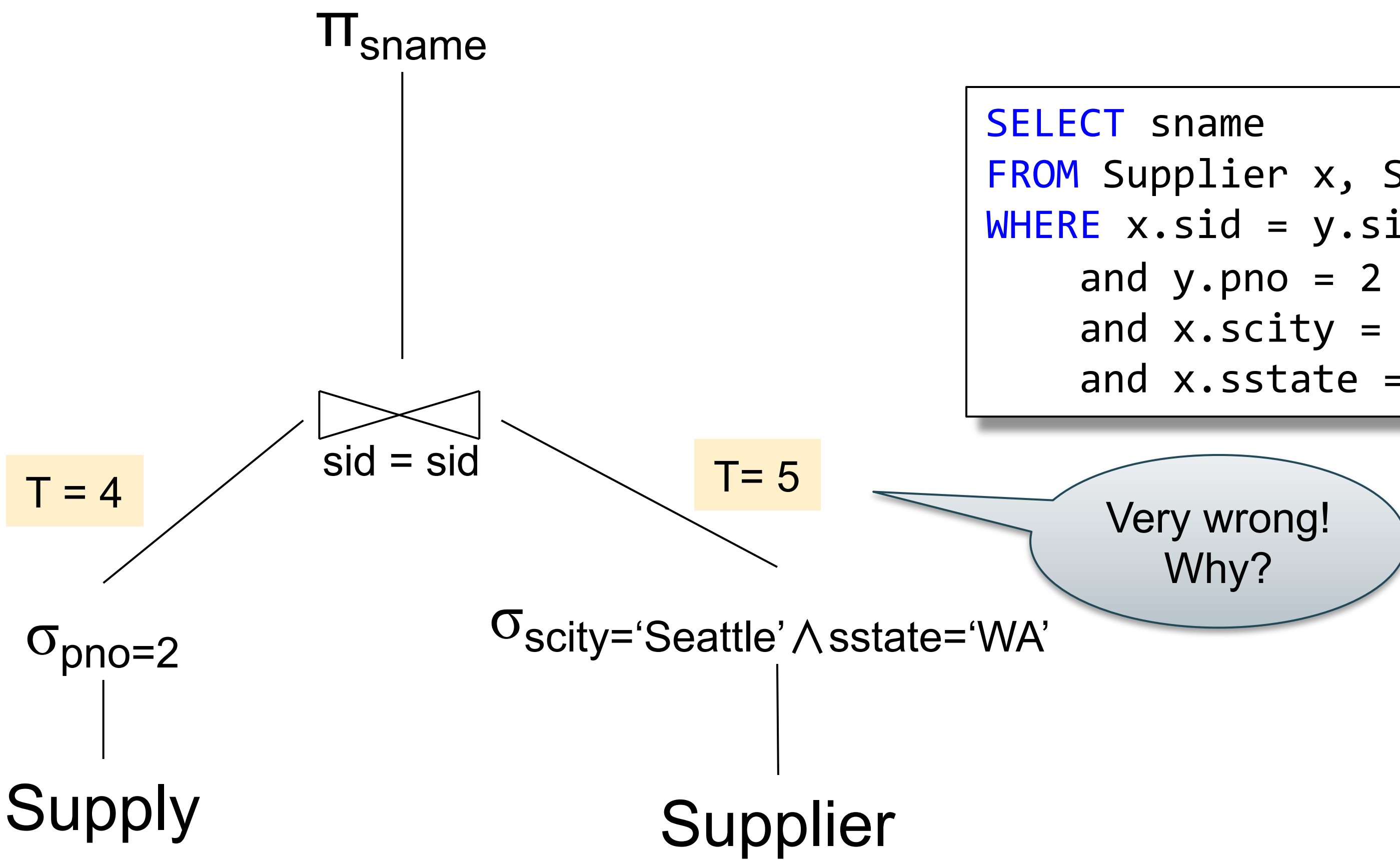
    and x.scity = 'Seattle'
    and x.sstate = 'WA'
```



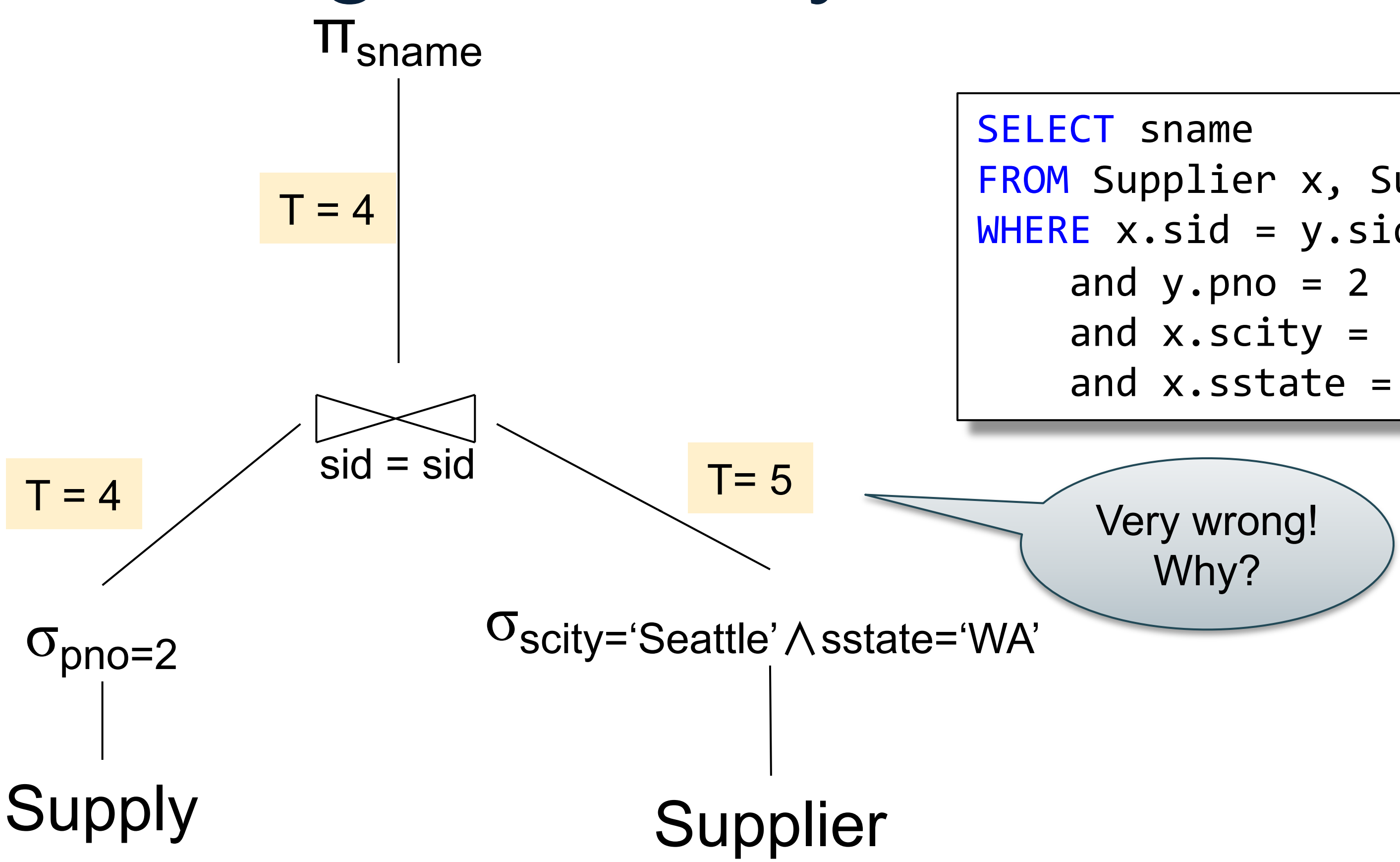
T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)

Logical Query Plan 2

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FROM Supplier x, Supply y
WHERE x.sid = y.sid
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    and x.sstate = 'WA'
```

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V(Supply, pno) = 2500

T(Supplier) = 1000
B(Supplier) = 100
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V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Logical Query Plan 2

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SELECT sname
FROM Supplier x, Supply y
WHERE x.sid = y.sid
    and y.pno = 2
    and x.scity = ‘Seattle’
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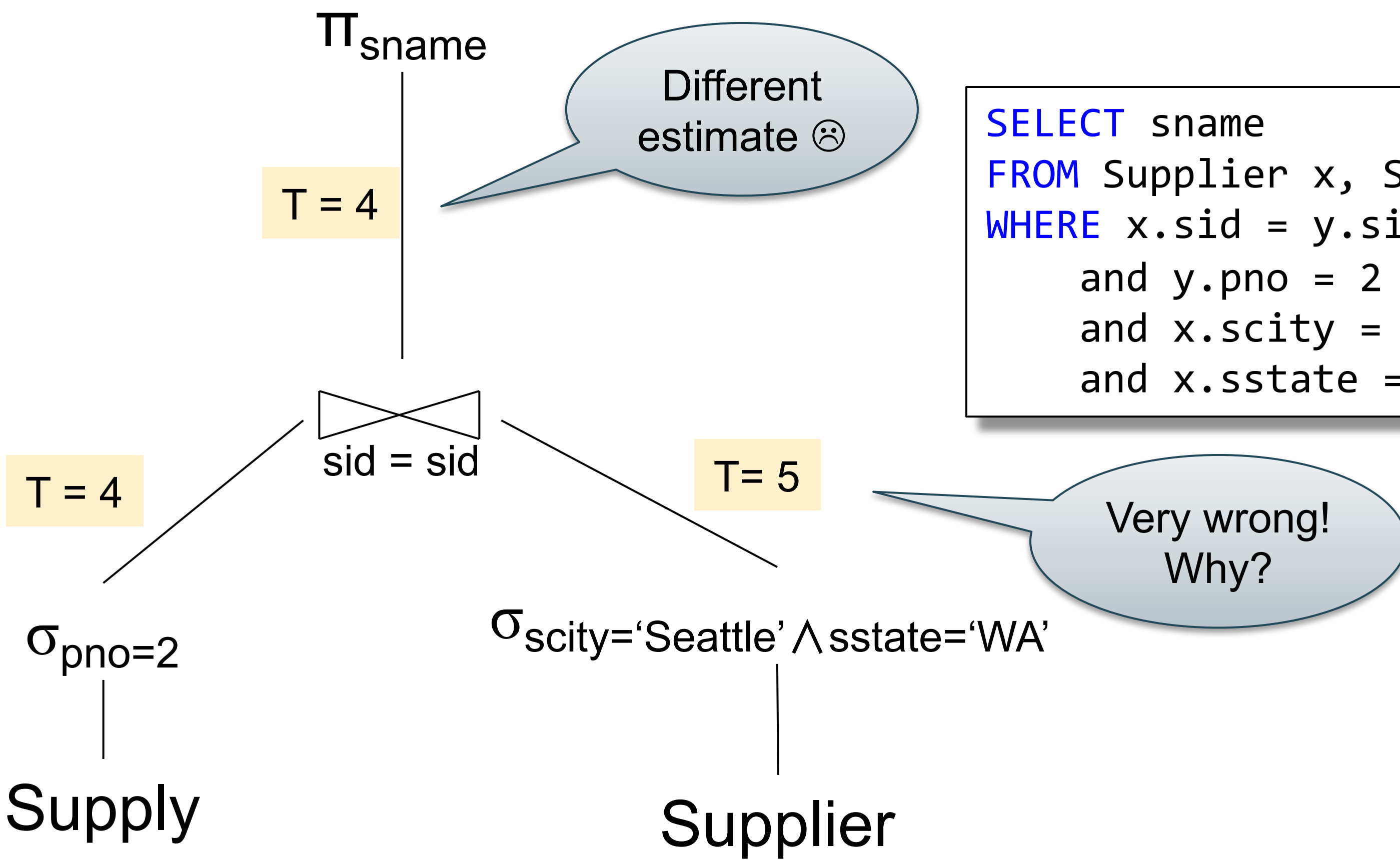


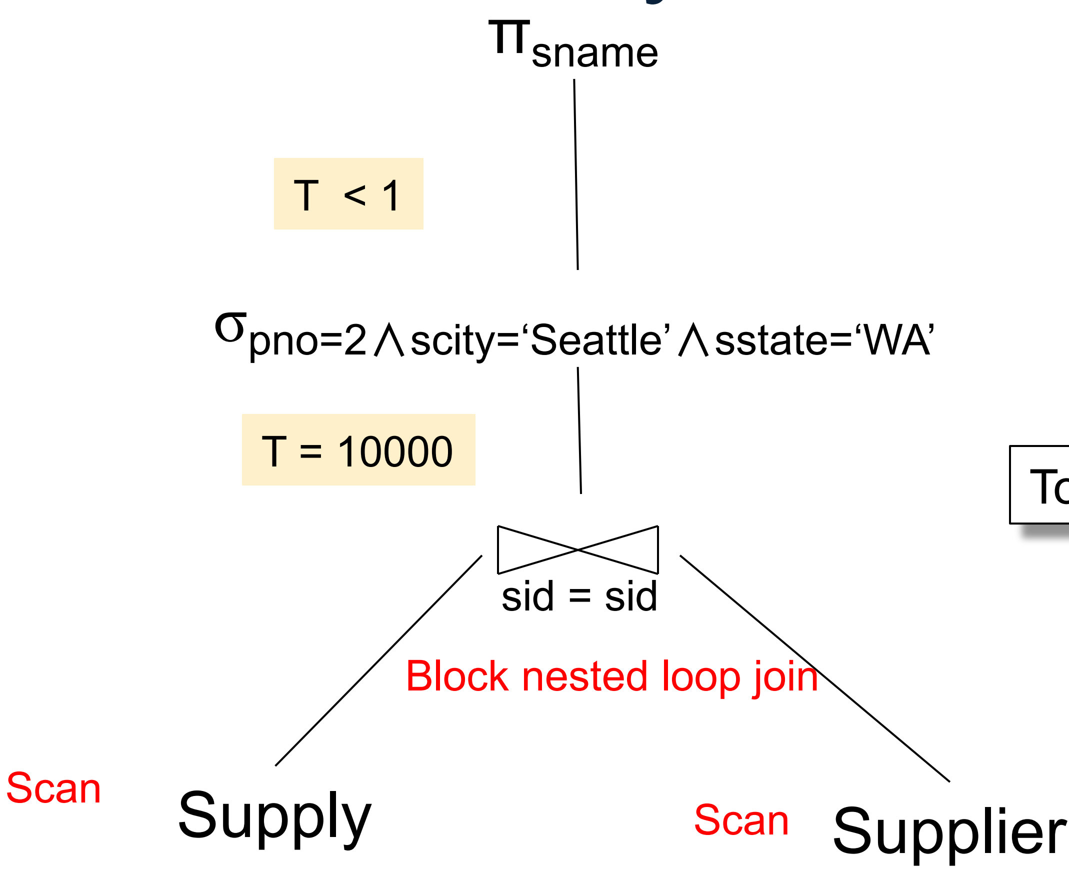
T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)

Physical Plan 1



Total cost:

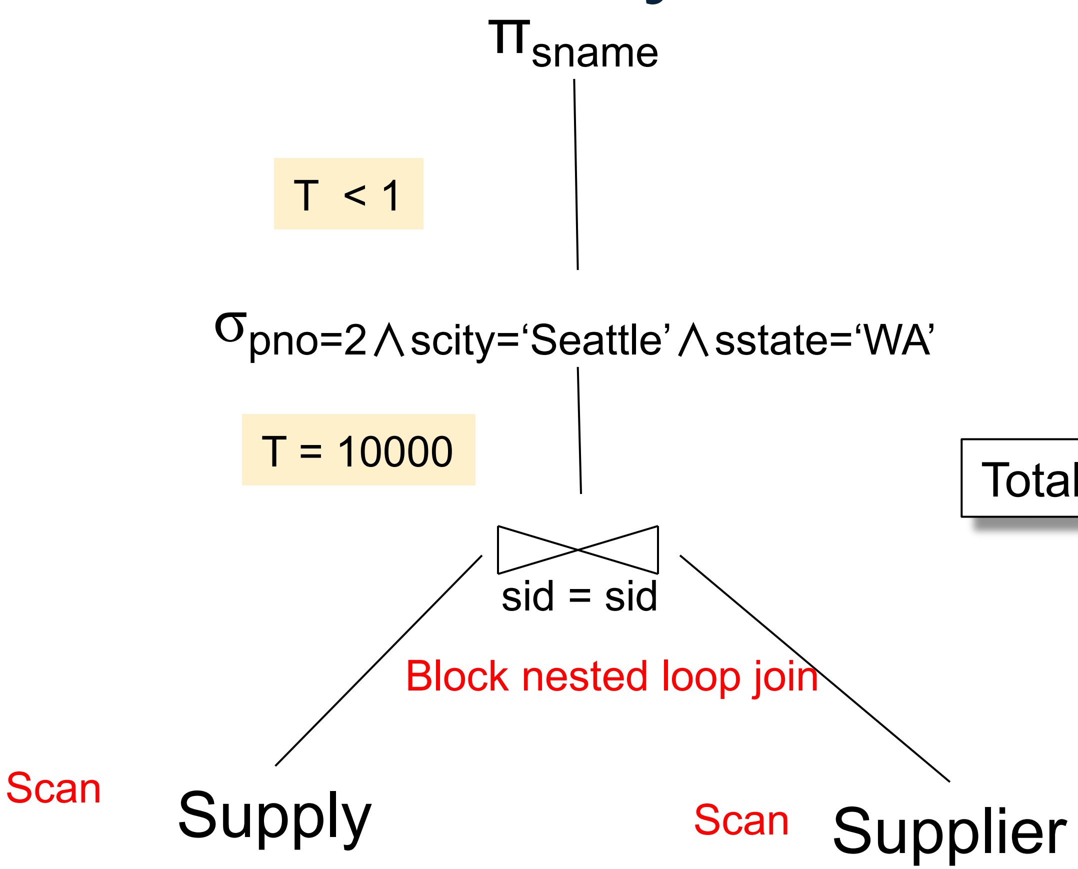
T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)

Physical Plan 1



Total cost: 100+100*100/10 = 1100

T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(<u>sid</u>, sname, scity, sstate)

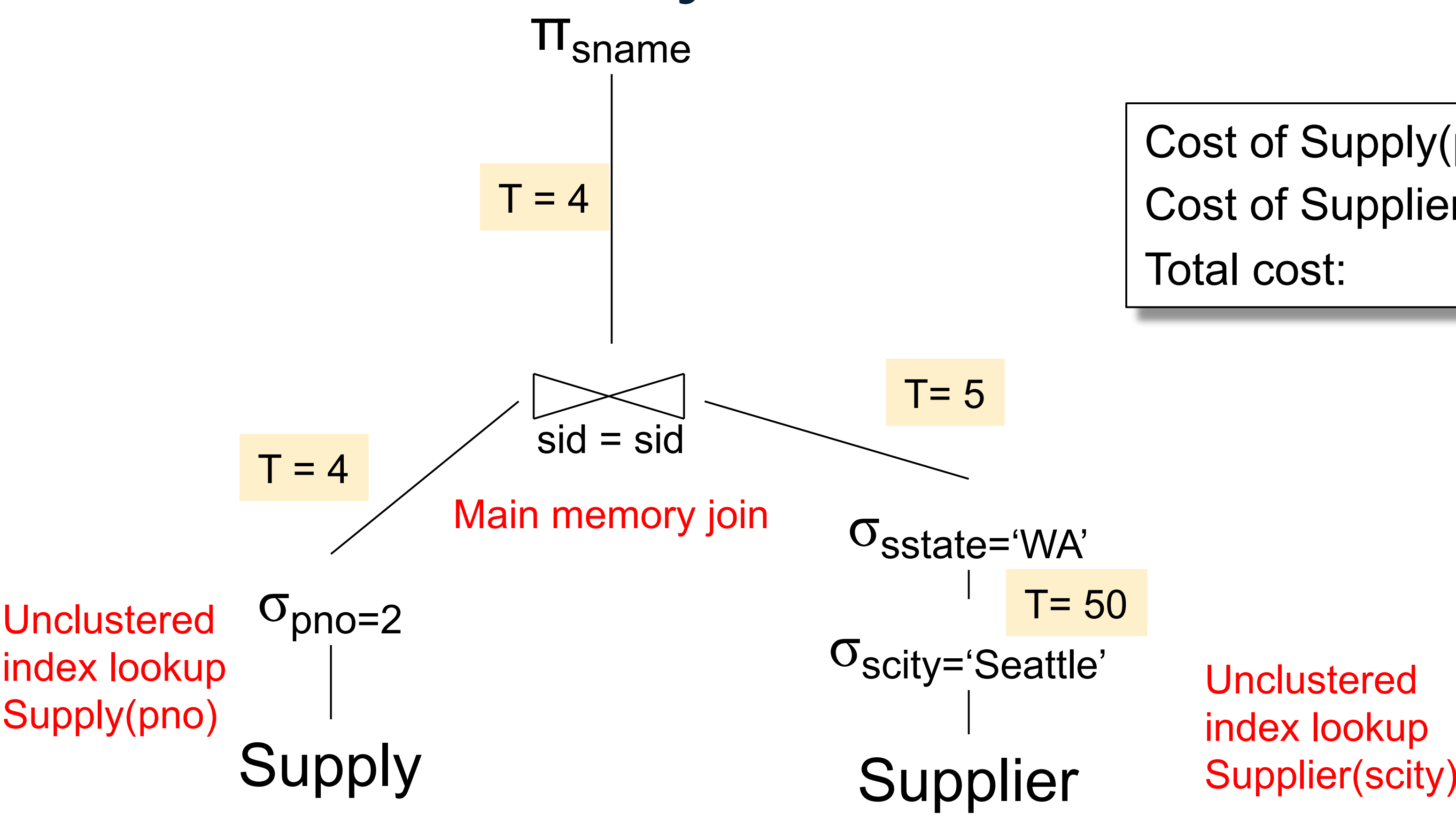
Supply(<u>sid, pno</u>, quantity)

Physical Plan 2

Cost of Supply(pno) =

Cost of Supplier(scity) =

Total cost:



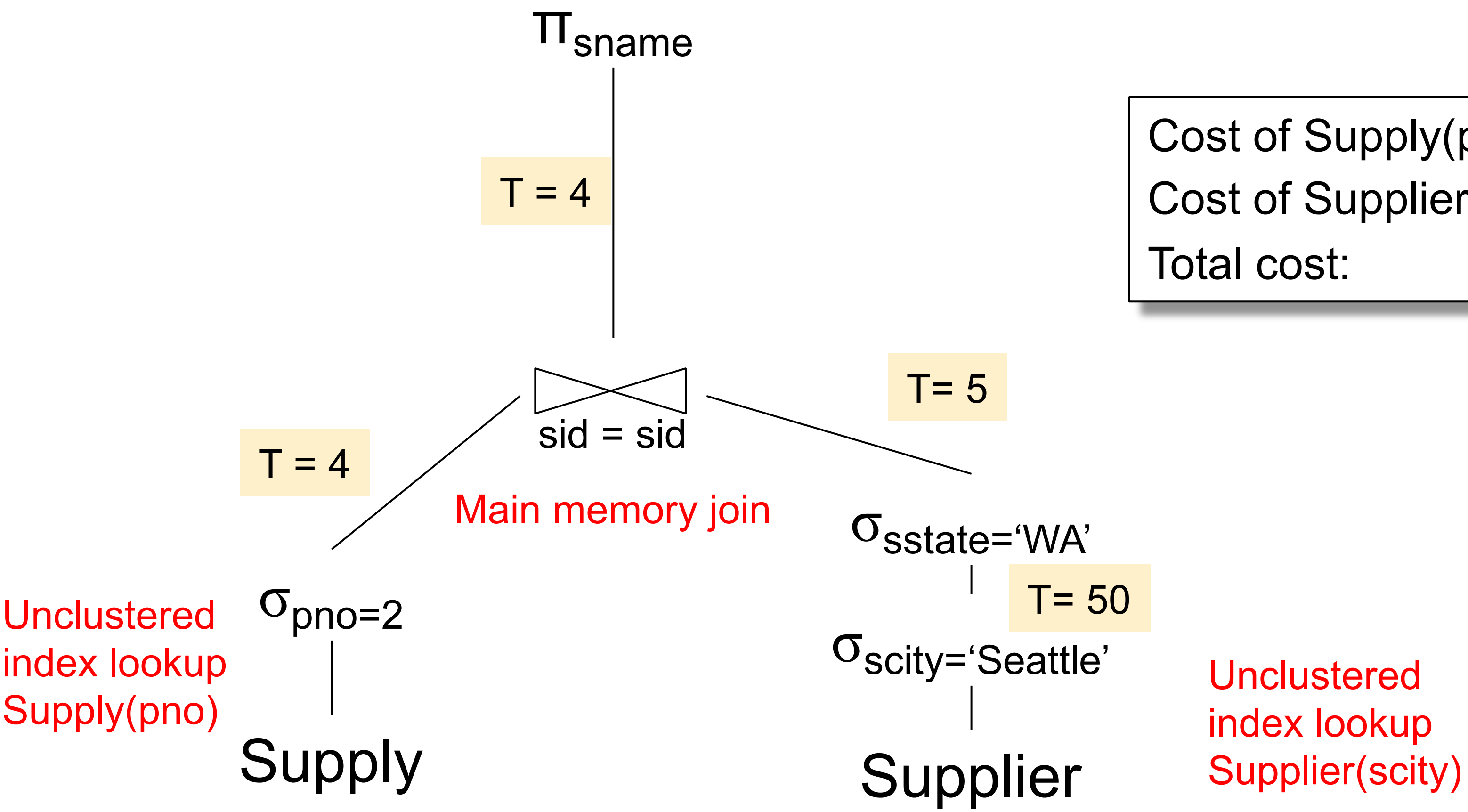
T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(<u>sid</u>, sname, scity, sstate)
Supply(<u>sid, pno</u>, quantity)

Physical Plan 2



Cost of Supply(pno) = 4
Cost of Supplier(scity) =
Total cost:

T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

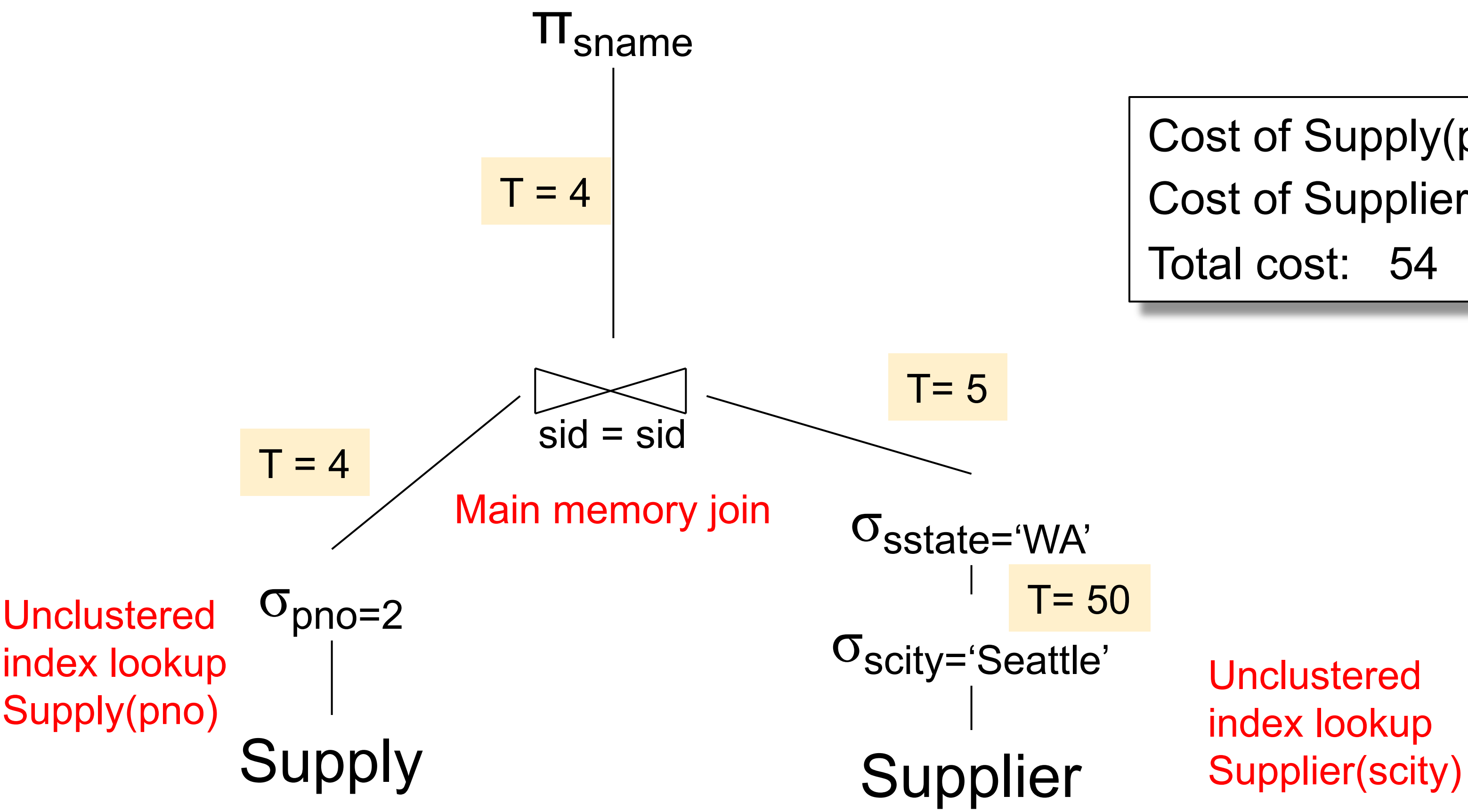
T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Physical Plan 2



Cost of Supply(pno) = 4
Cost of Supplier(scity) = 50
Total cost: 54

T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

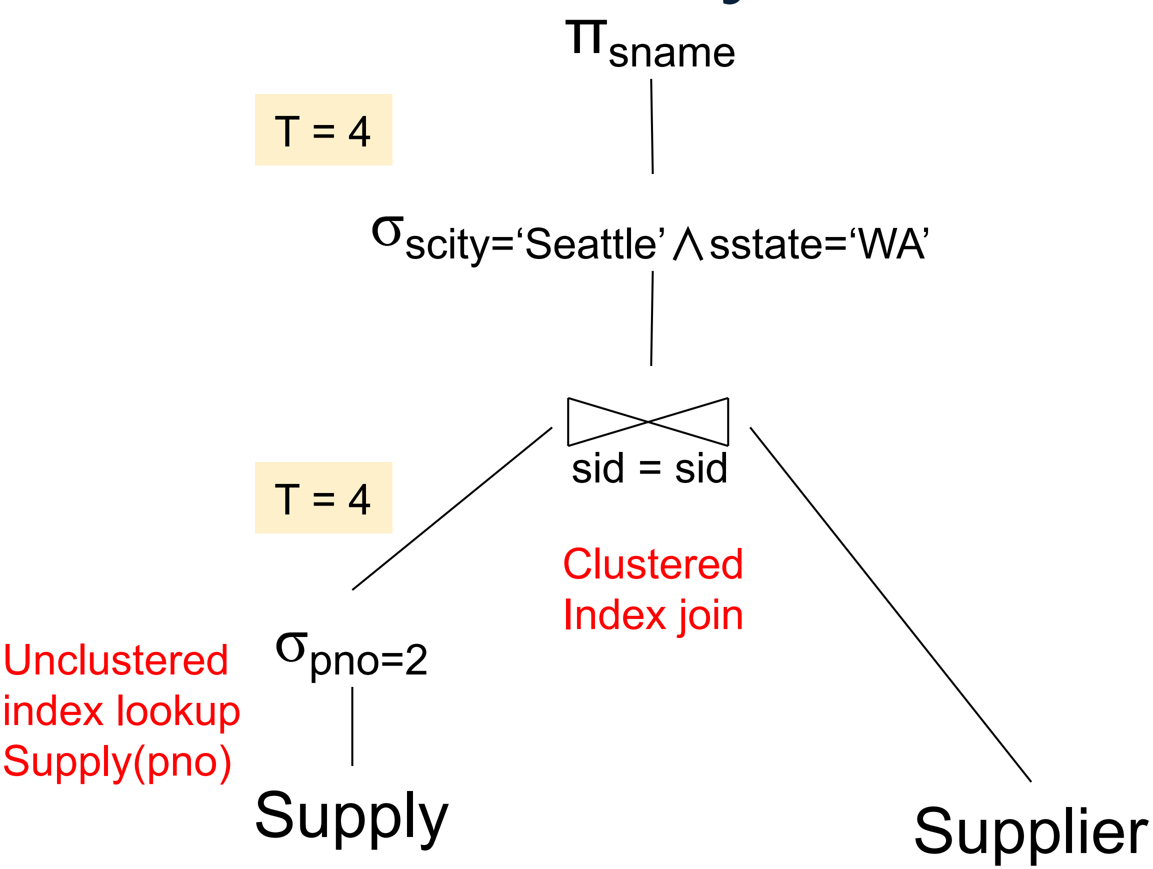
T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Physical Plan 3



Cost of Supply(pno) =

Cost of Index join =

Total cost:

T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

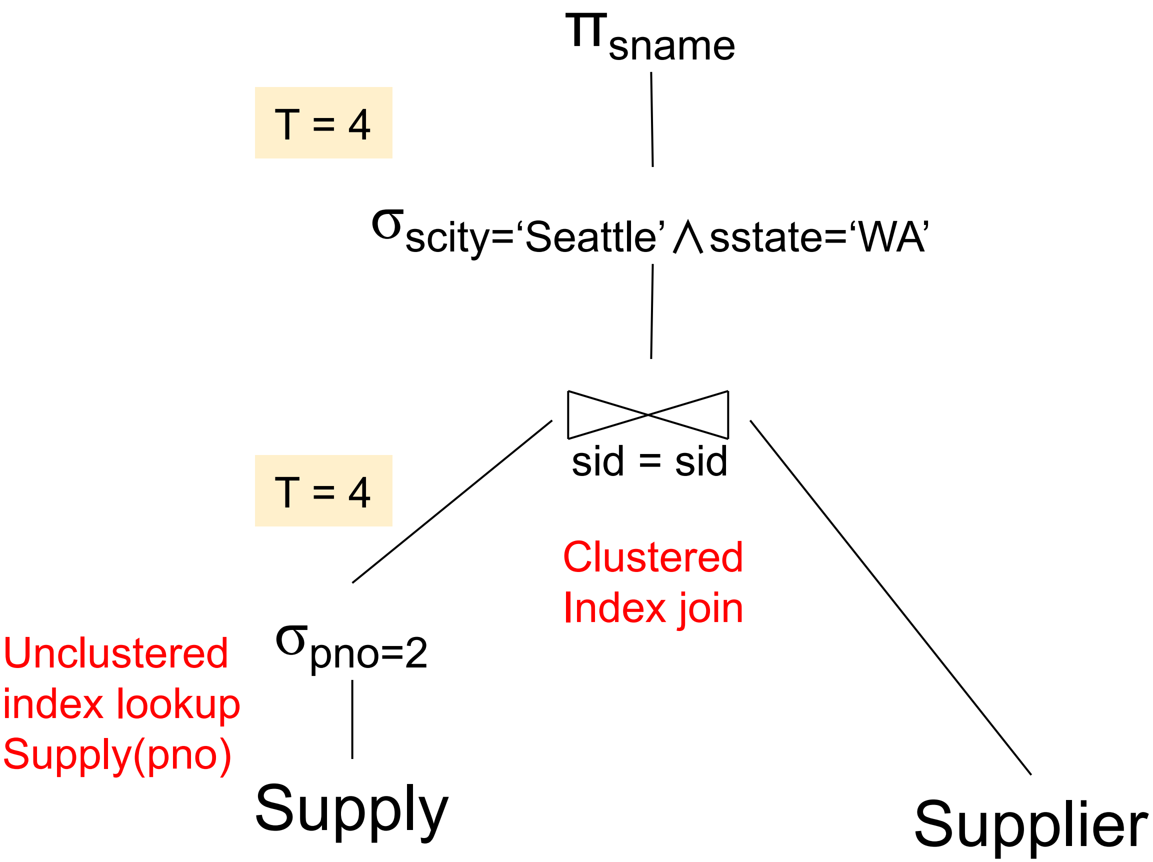
T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Physical Plan 3



Cost of Supply(pno) = 4

Cost of Index join =

Total cost:

T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

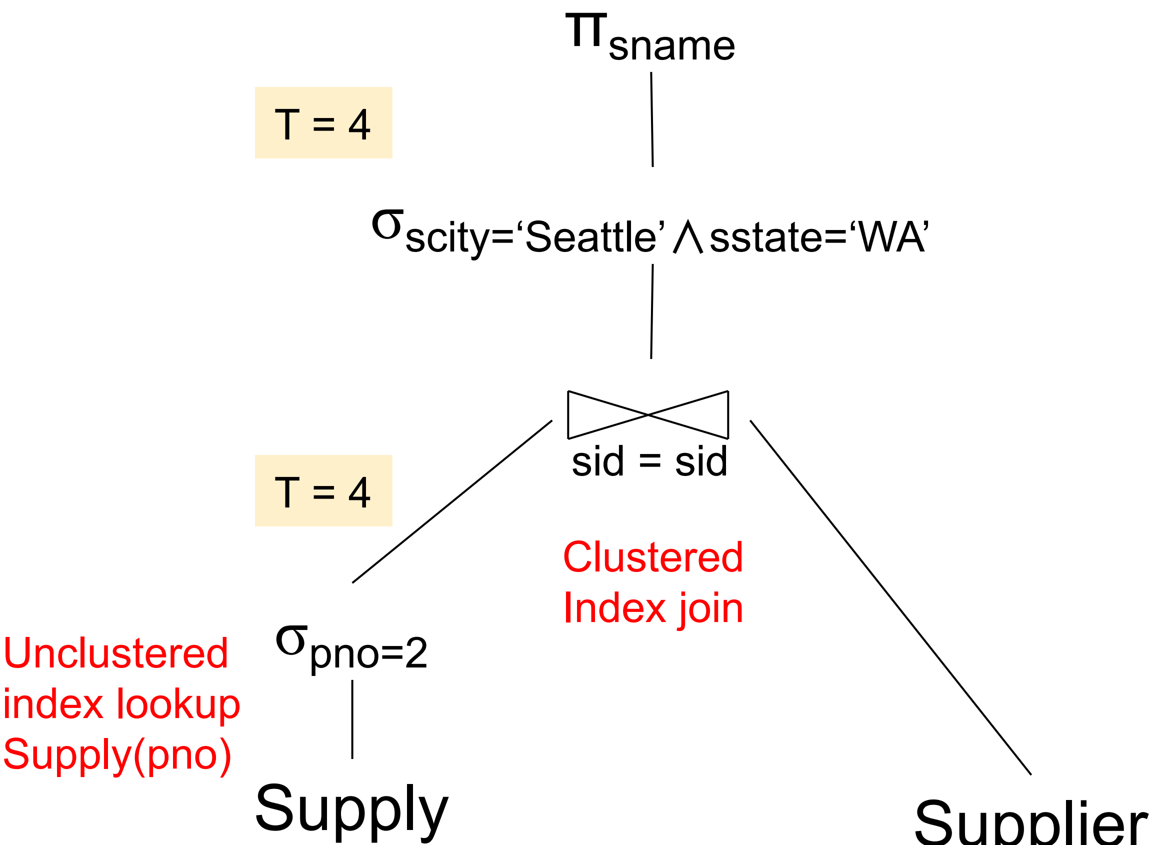
T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(<u>sid</u>, sname, scity, sstate)

Supply(<u>sid, pno</u>, quantity)

Physical Plan 3



Cost of Supply(pno) = 4

Cost of Index join = 4

Total cost: 8

T(Supply) = 10000

B(Supply) = 100

V(Supply, pno) = 2500

T(Supplier) = 1000

B(Supplier) = 100

V(Supplier, scity) = 20

V(Supplier, state) = 10

M=11

Query Optimizer Summary

- Input: A logical query plan
- Output: A good physical query plan
- Basic query optimization algorithm
  - Enumerate alternative plans (logical and physical)
  - Compute estimated cost of each plan
  - Choose plan with lowest cost

- This is called cost-based optimization