Introduction to Data Management
DATA 514

Unit 3: RDBMS Internals

Logical and Physical Plans
Query Execution
Query Performance & Optimization

Introduction to Data Management
DATA 514

Query Evaluation

Announcement

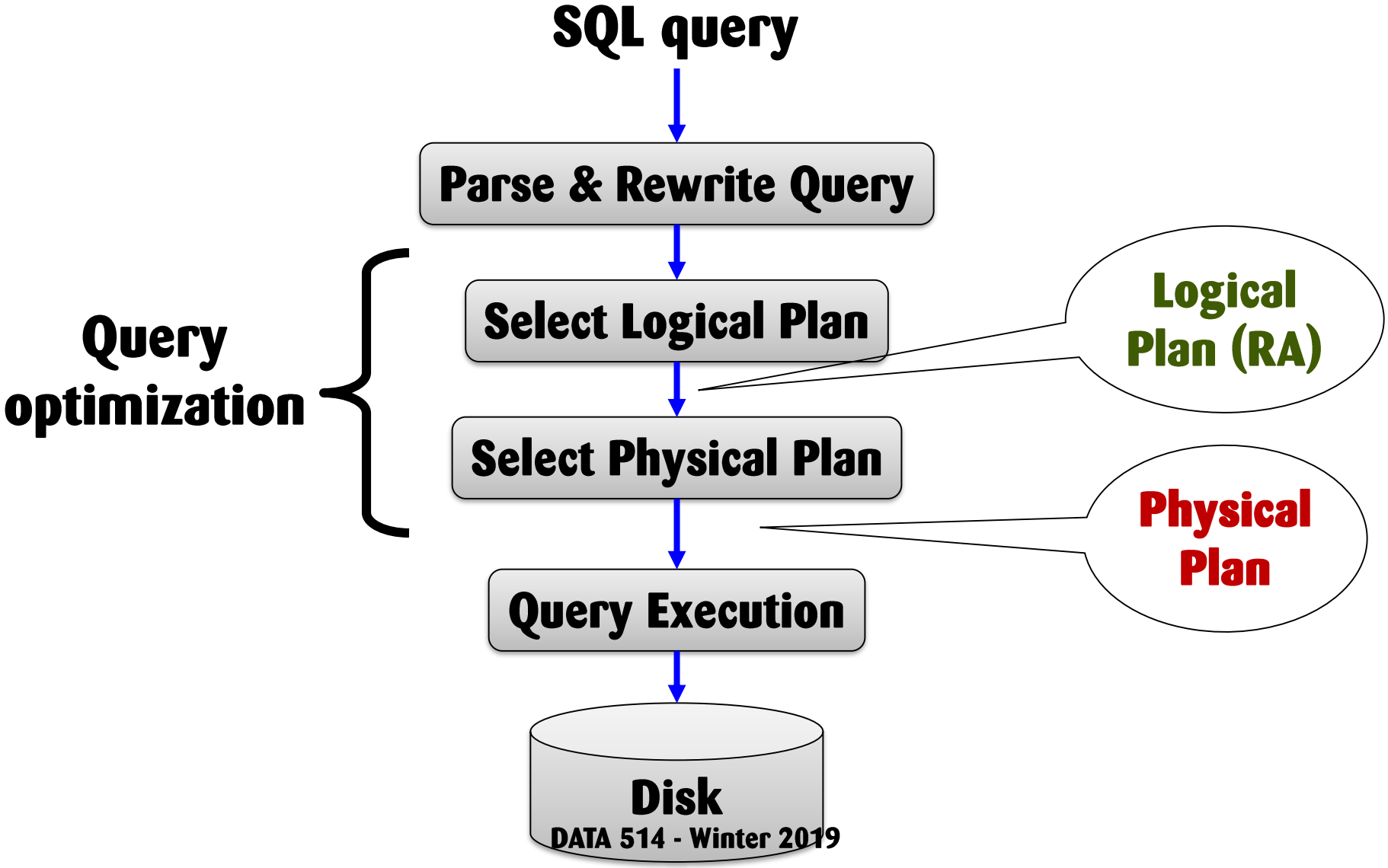
- Midterm: next Tuesday, 5-6pm in class
  - Open book (but you shouldn't need it)
  - Open computer: i.e., SQLite

Class Overview

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

From Logical RA Plans to Physical Plans

Query Evaluation Steps



Logical vs Physical Plans

- **Logical plans:**
  - Created by the parser from the input SQL text
  - Expressed as a Relational Algebra tree
  - Multiple possible logical plans

- **Physical plans:**
  - Goal is to choose an efficient implementation for each operation in the RA tree
  - Each logical plan has many possible physical plans

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Review: Relational Algebra

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

Relational algebra expression is also called the "logical query plan"

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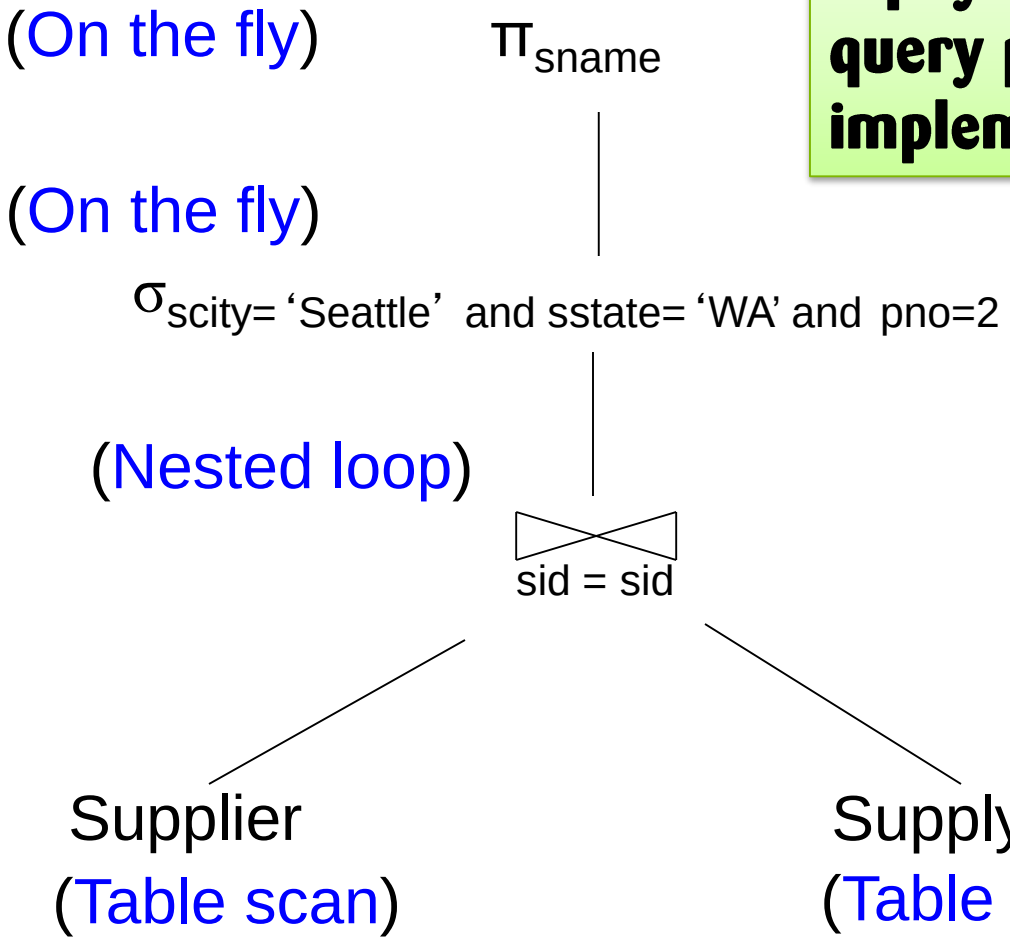
Physical Query Plan 1

A physical query plan is a logical query plan annotated with physical implementation details

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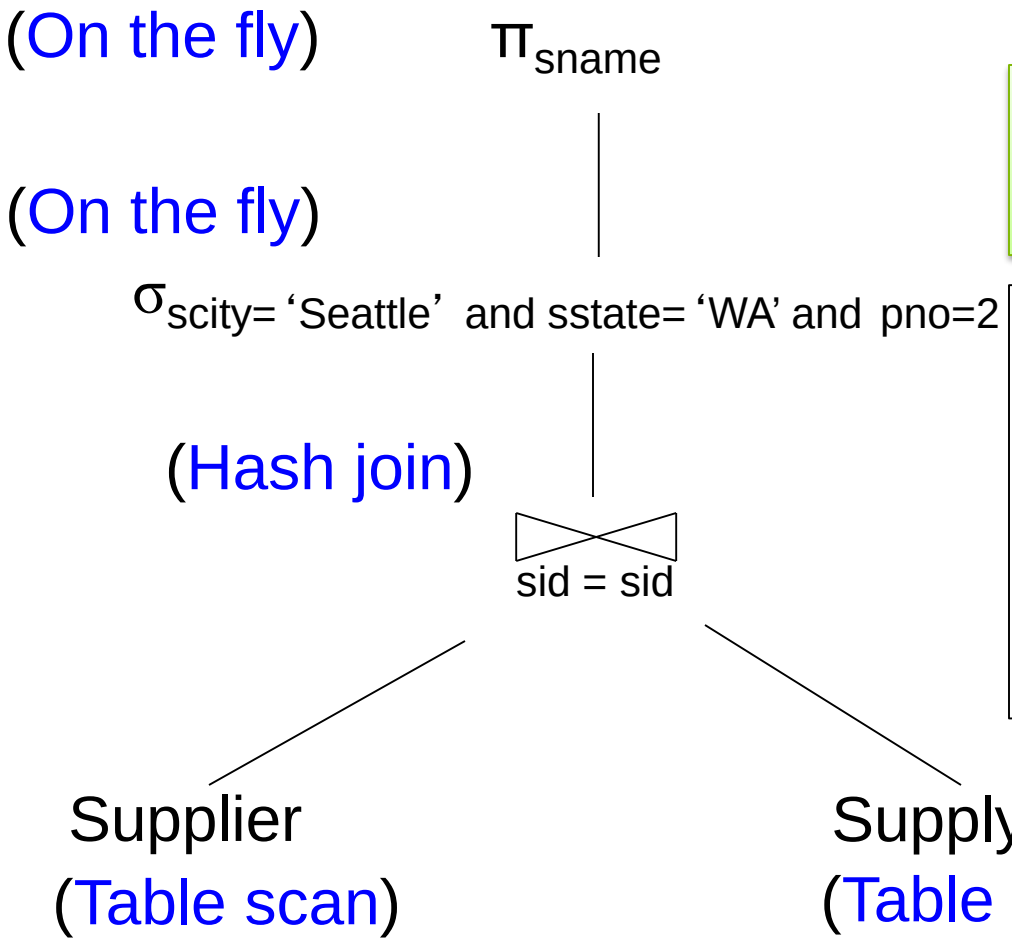
Physical Query Plan 2



Same logical query plan

Different physical plan

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

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

Physical Query Plan 3

Different but equivalent logical query plan; different physical plan

```
SELECT sname
FROM Supplier x, Supply y
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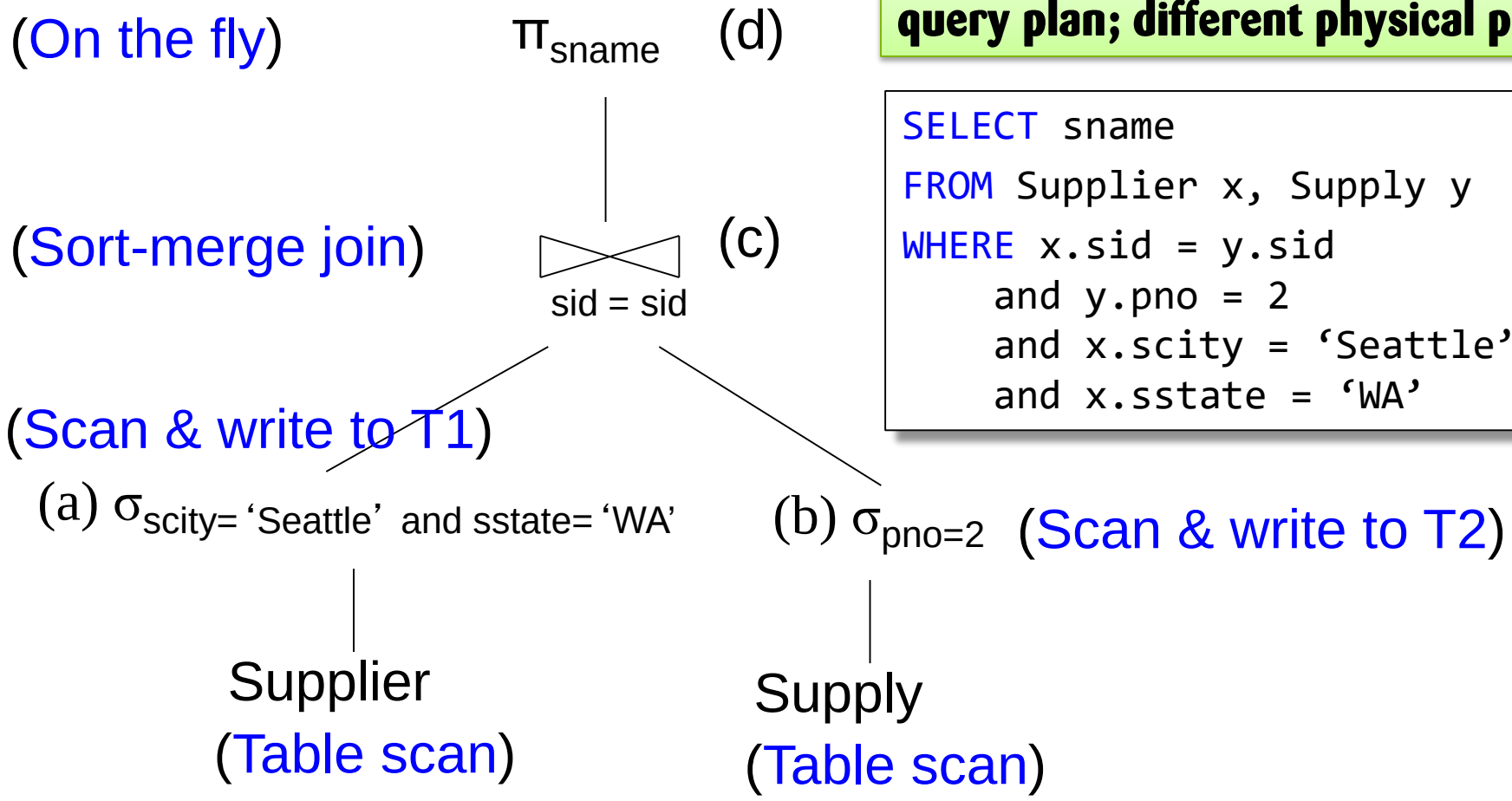

Query Optimization Problem

- For each SQL query… many logical plans
- For each logical plan… many physical plans
- Next: we will discuss physical operators;

How exactly is a query executed?

Query Execution

Physical Operators

Each of the logical operators may have one or more implementations = physical operators

Will discuss several basic physical operators, with a focus on join

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

Memory-resident Algorithms

- **Logical operation (JOIN):**

$$\textbf{Supplier} \bowtie_{\text{sid=sid}} \textbf{Supply}$$

- **Assuming the tables are both resident in main memory, consider three physical options:**

Option	Execution time
Nested Loop JOIN	?
Merge JOIN	?
Hash JOIN	?

Supplier(sid, sname, scity, sstate)
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Memory-resident Algorithms

- **Logical operation (JOIN):**

$$\text{Supplier} \bowtie_{\text{sid=sid}} \text{Supply}$$

- **Assuming the tables are both resident in main memory, consider three physical options:**

Nested Loop JOIN	$O(n^2)$
Merge JOIN	O(n log n)
Hash JOIN	$O(n \ldots n^2)$

Hash Tables

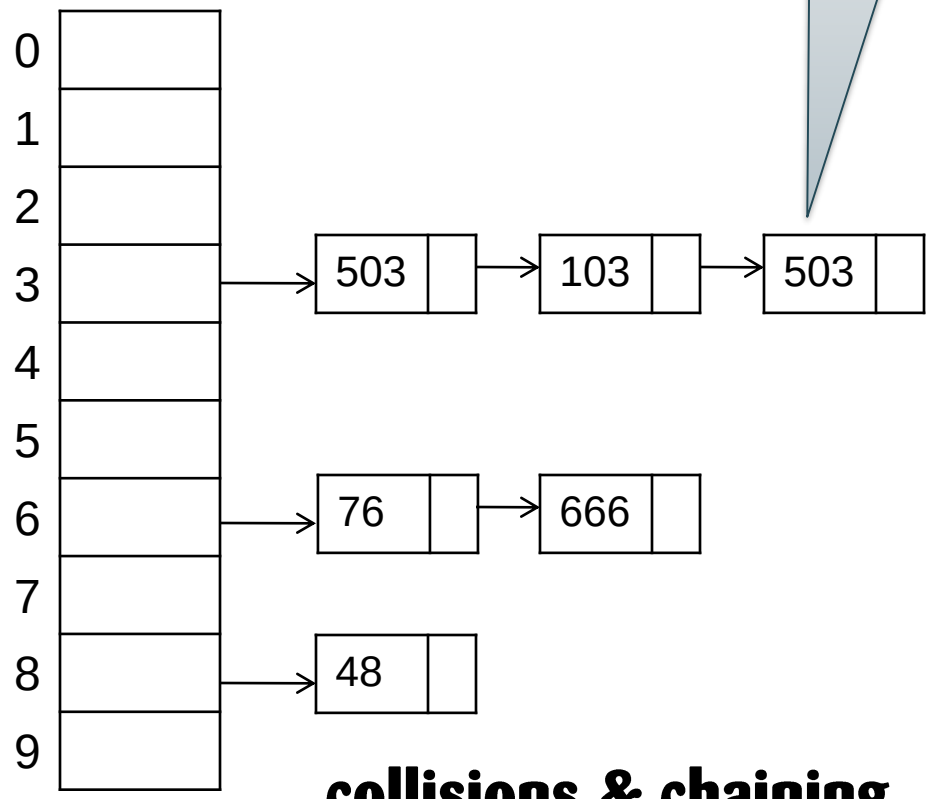
A (naïve) hash function:

```
h(x) = x mod 10
```

Operations:

find(103) = ??

insert(488) = ??



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 <u>all</u> values, **v** associated with the key **k**

Implementing Query Operators with the Iterator Interface

Each operator implements three methods:

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

Implementing Query Operators with the Iterator Interface

Example “on the fly” selection operator

```
interface Operator {




}
```

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

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Example "on the fly" selection operator

```
class Select implements Operator {...
  void open (Predicate p,
             Operator child) {
    this.p = p; this.child = child;
  }
                                    }
```

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    boolean found = false;
    Tuple r = null;
    while (!found) {
       r = child.next();
       if (r == null) break;
       found = p(in);
    }

  }
}
```

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    }
    return r;
  }
  void close () { child.close(); }
}
```

Implementing Query Operators with the Iterator Interface

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  // and sets parameters
  void open (...);


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


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

Query plan execution

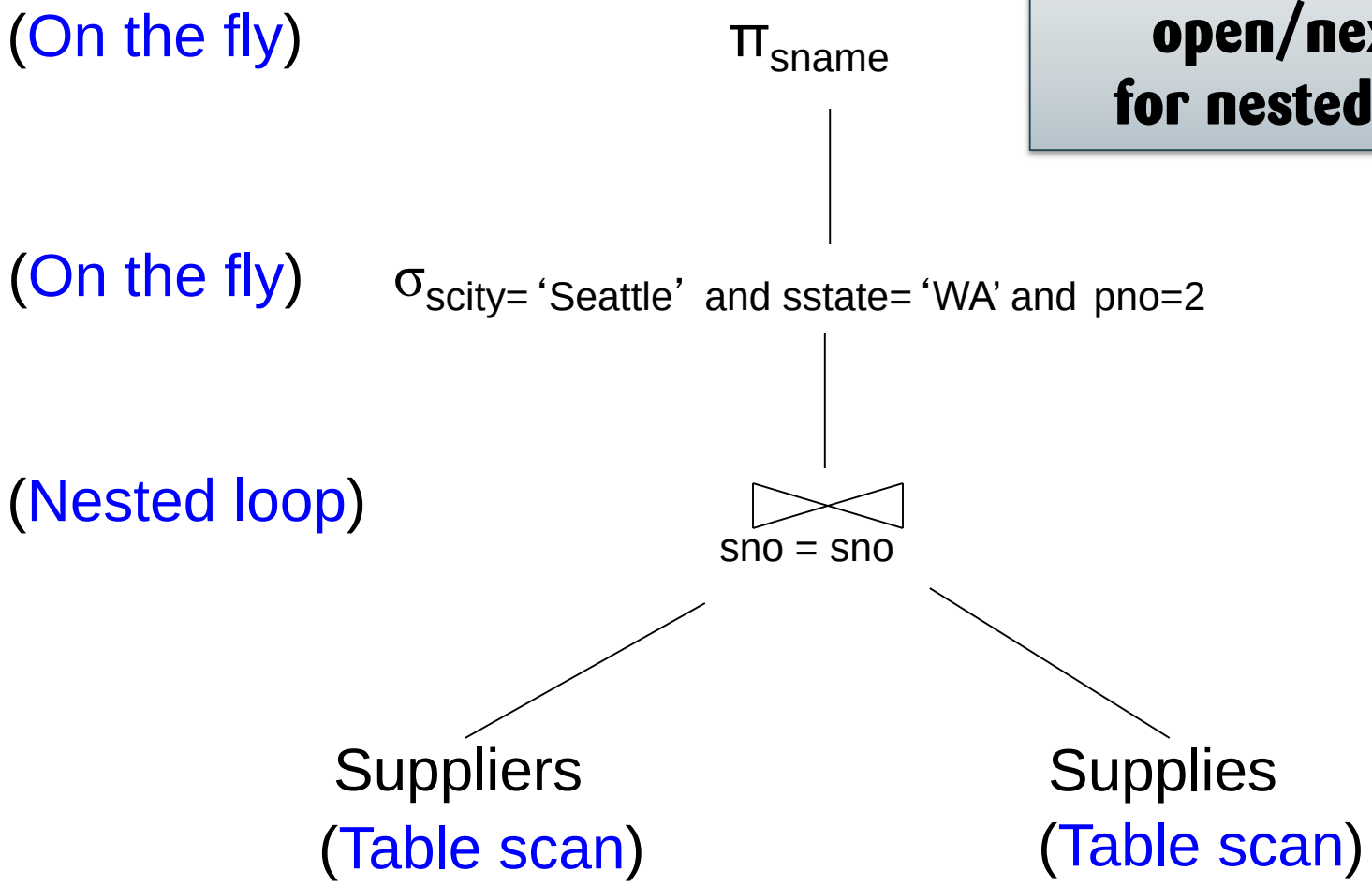
```
Operator q = parse("SELECT ...");
q = optimize(q);

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

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

Pipelining

Discuss: open/next/close for nested loop join



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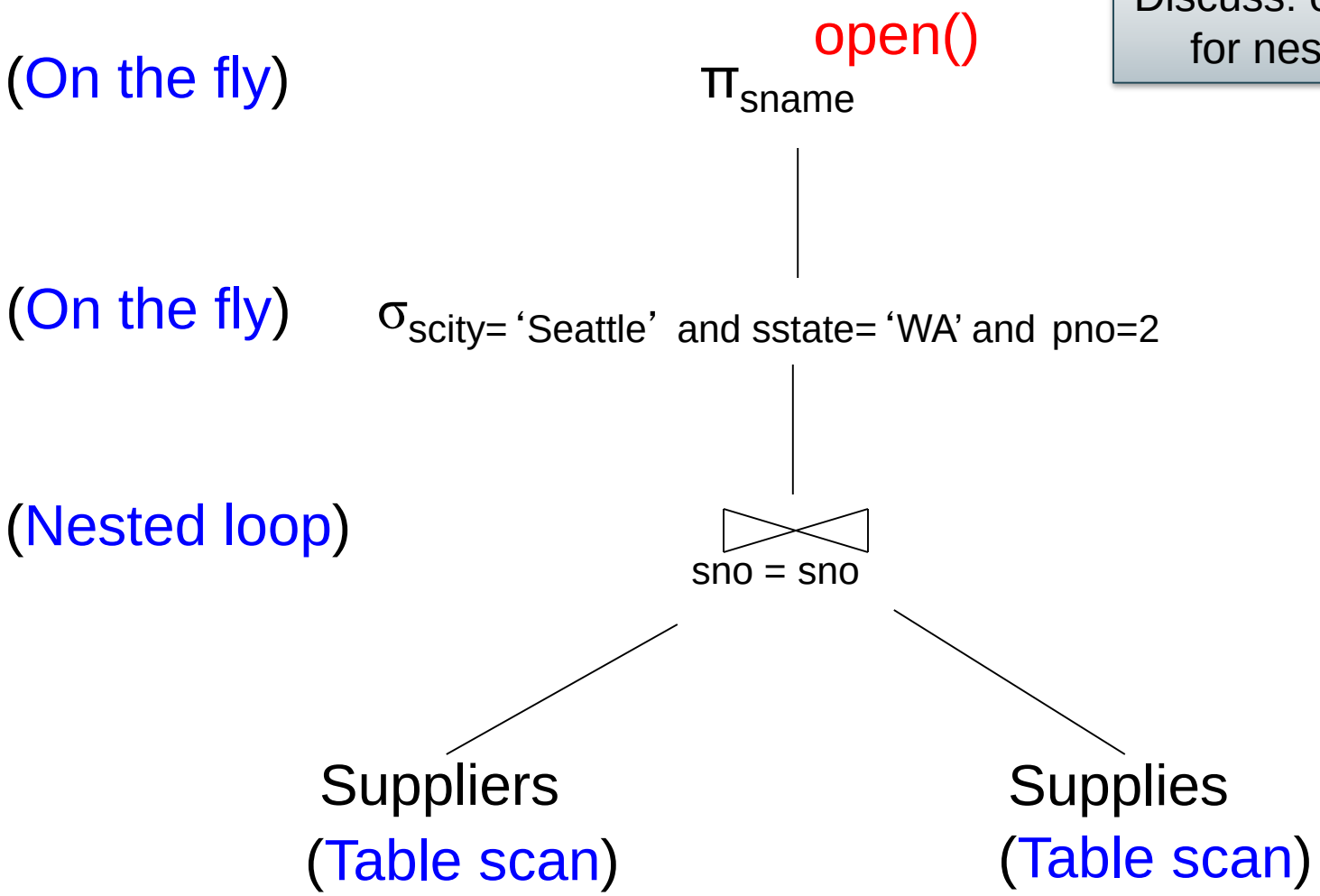

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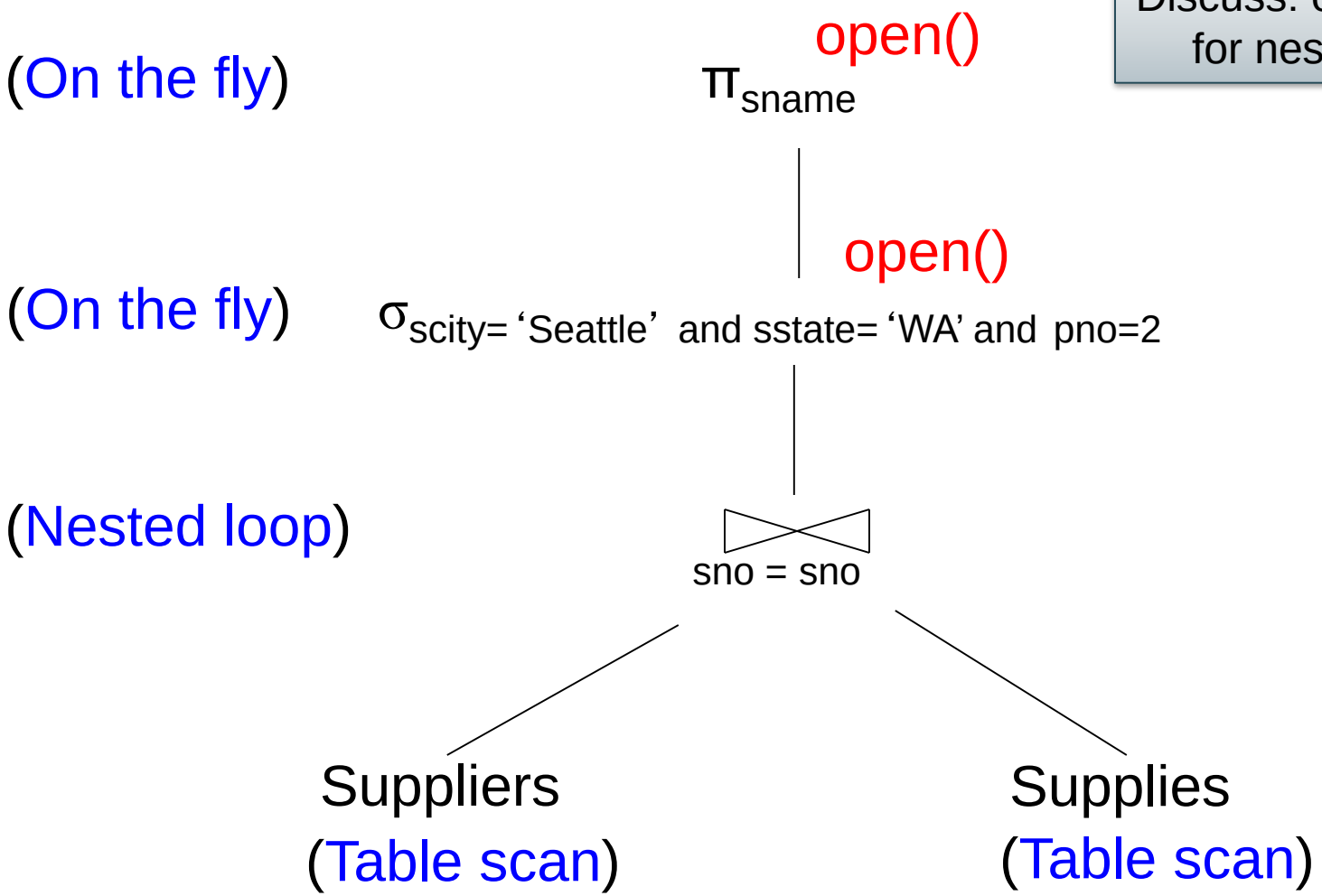

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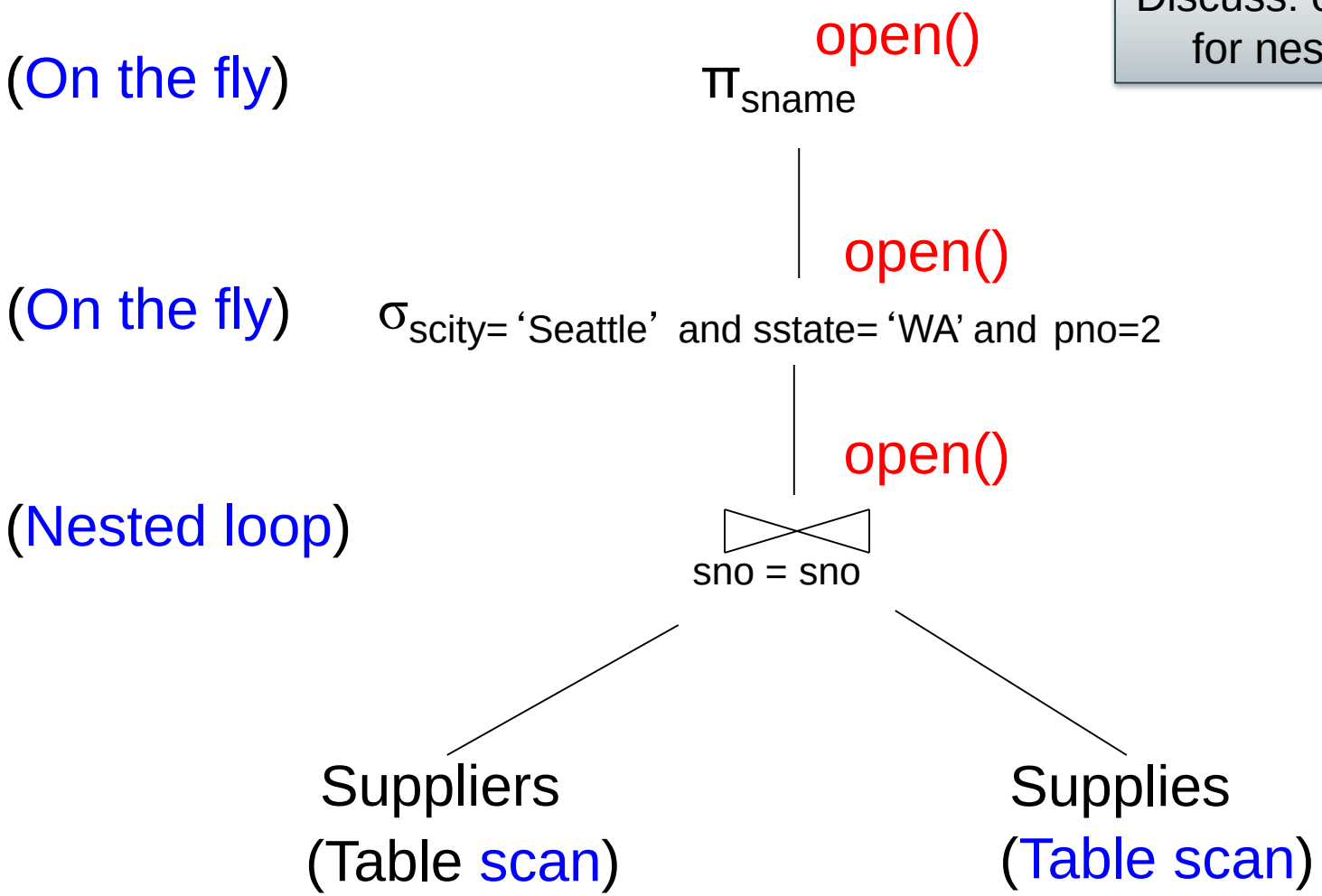

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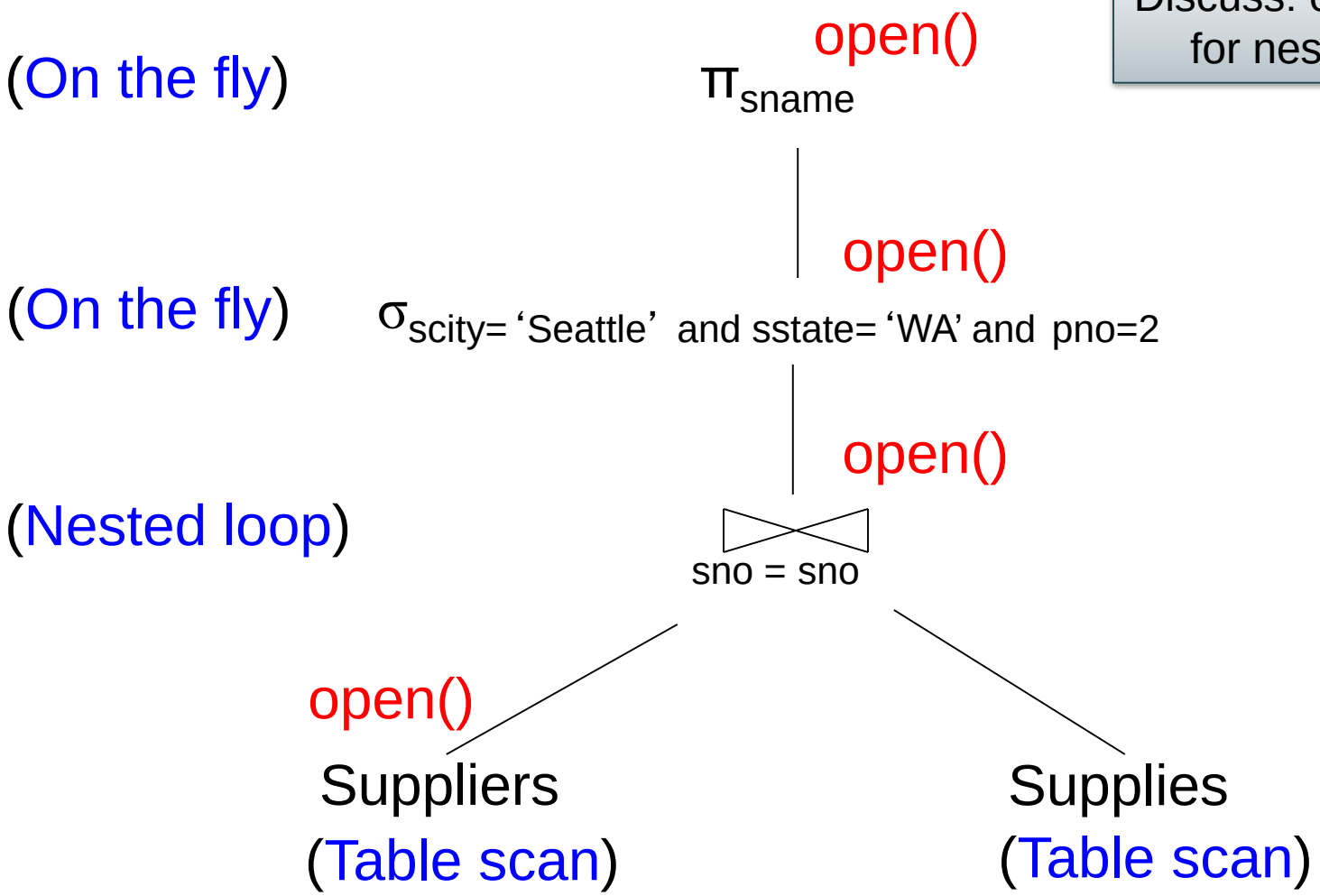

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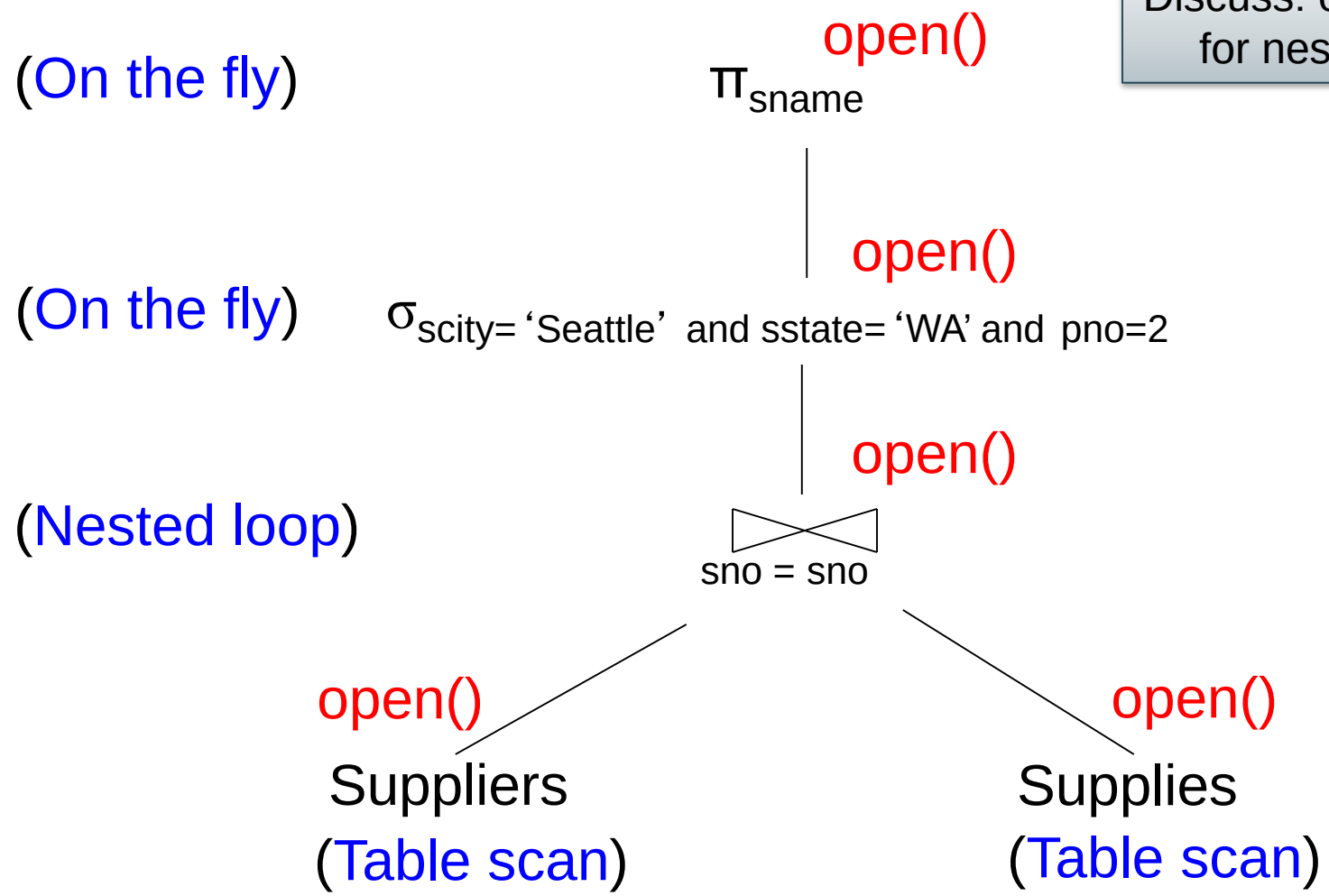

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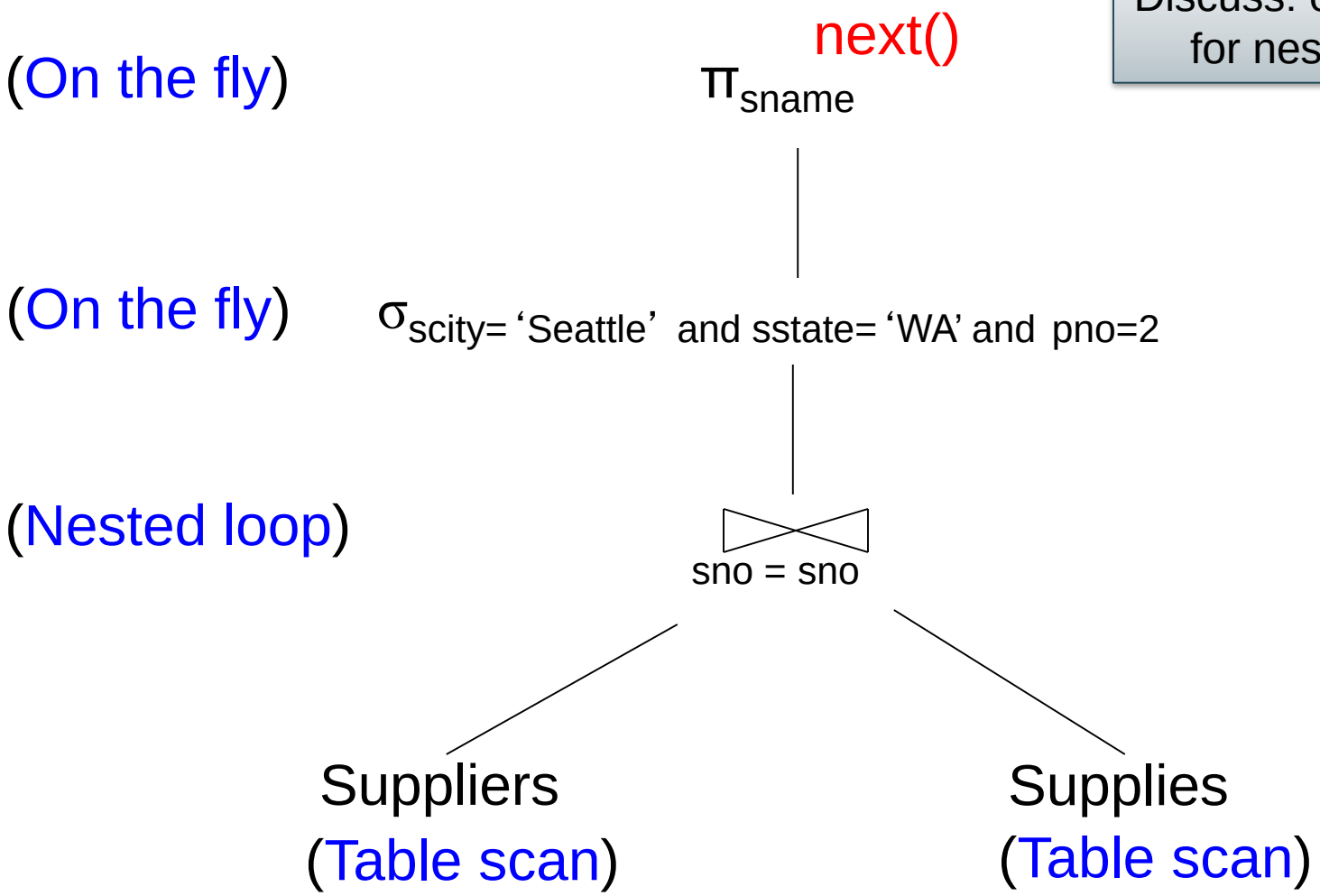

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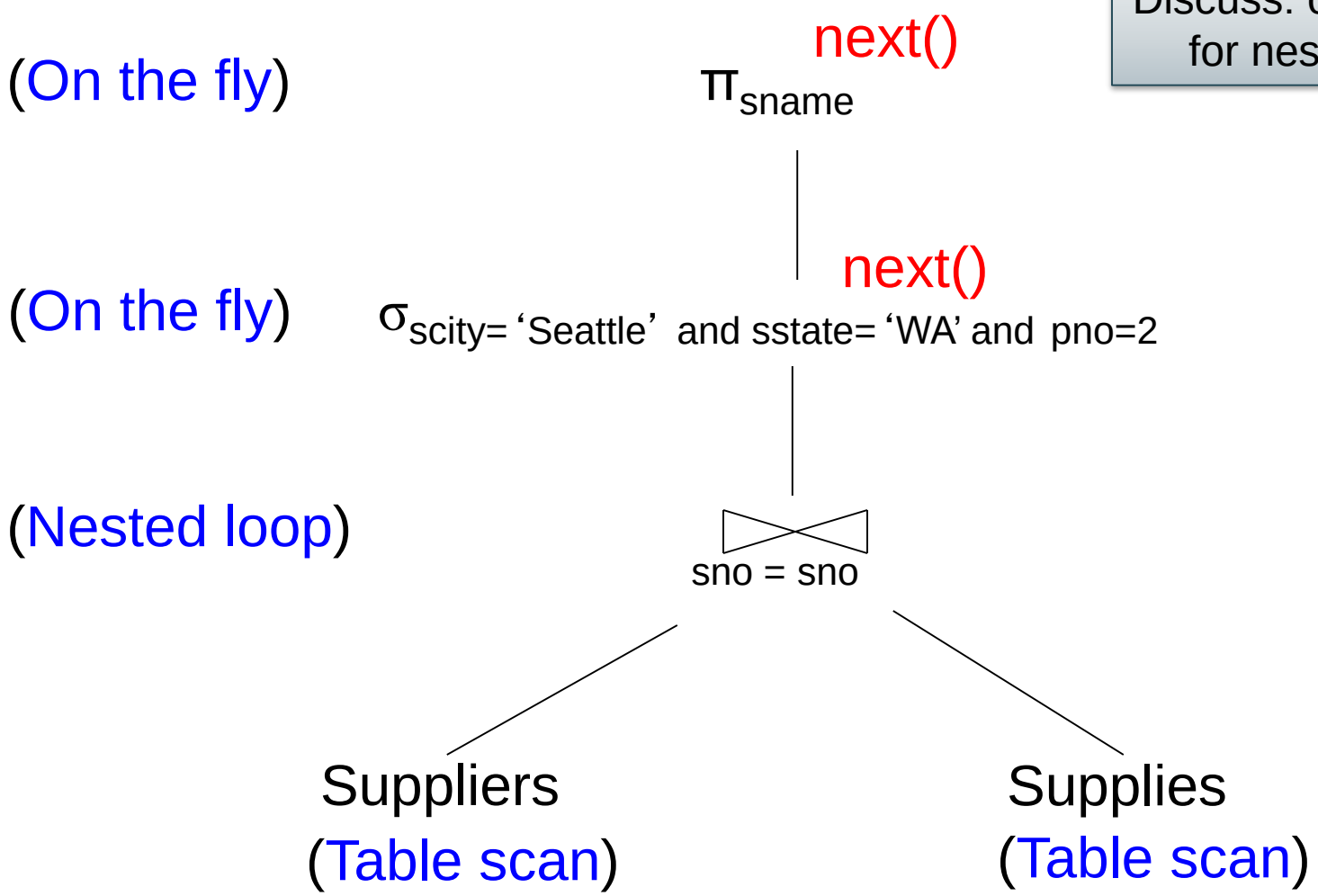

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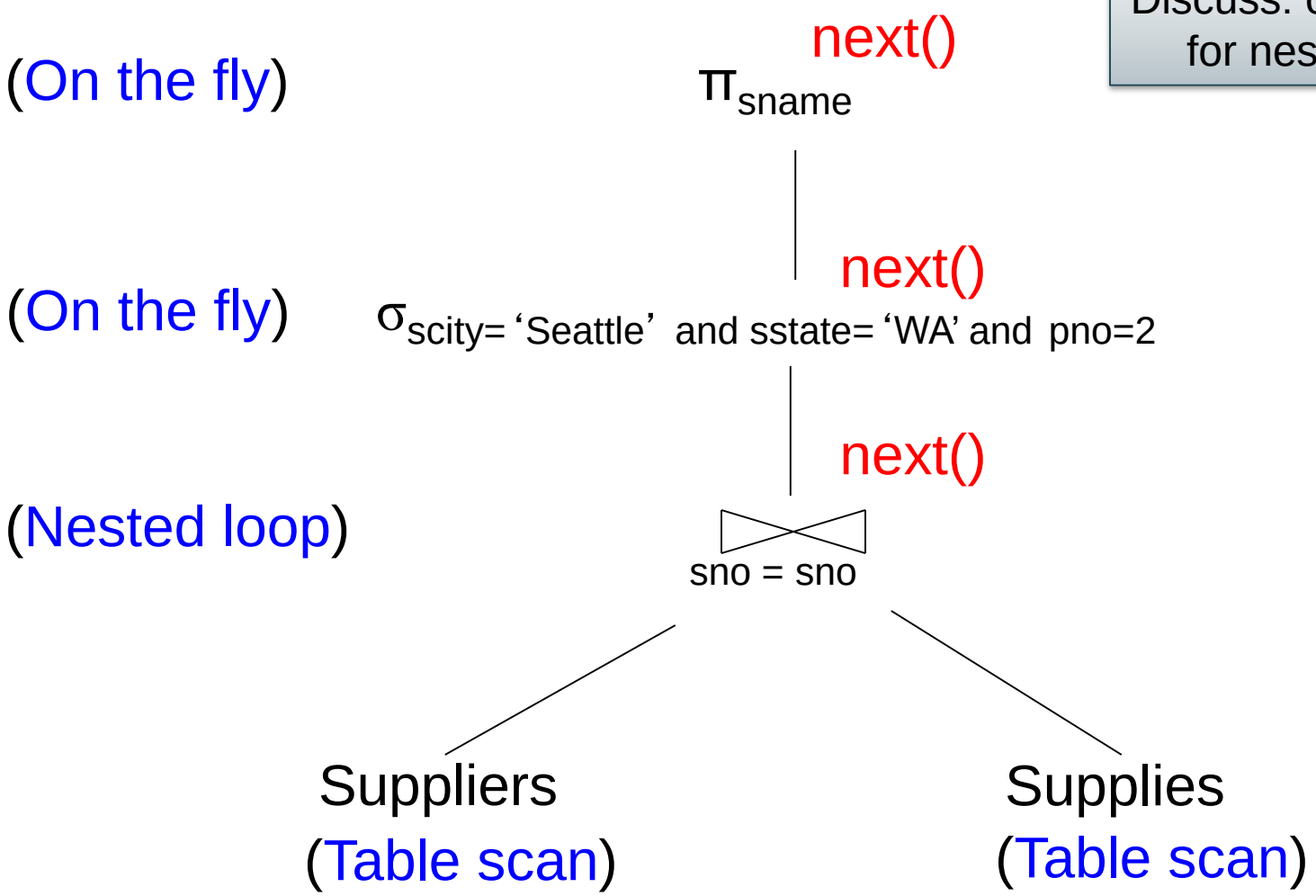

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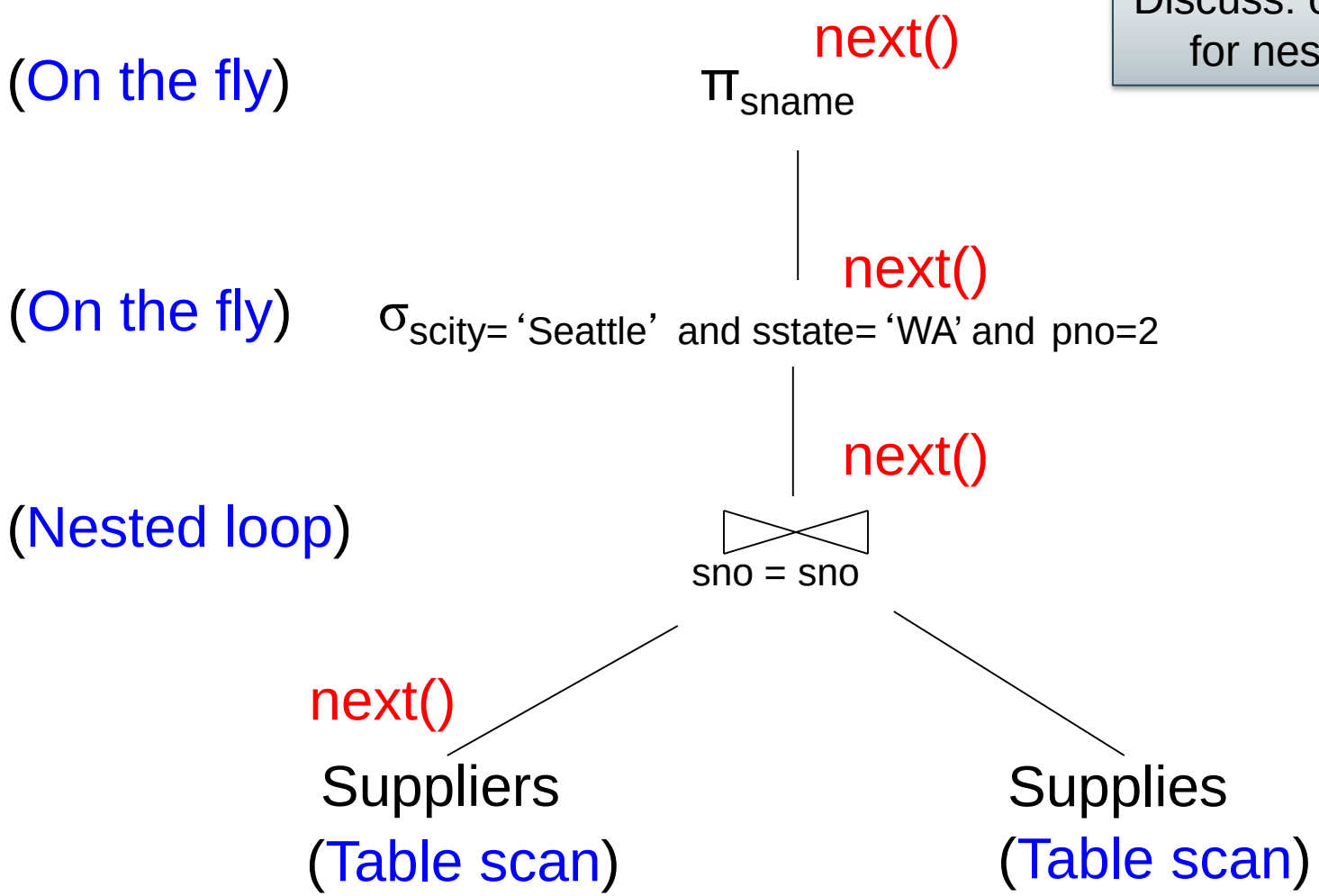

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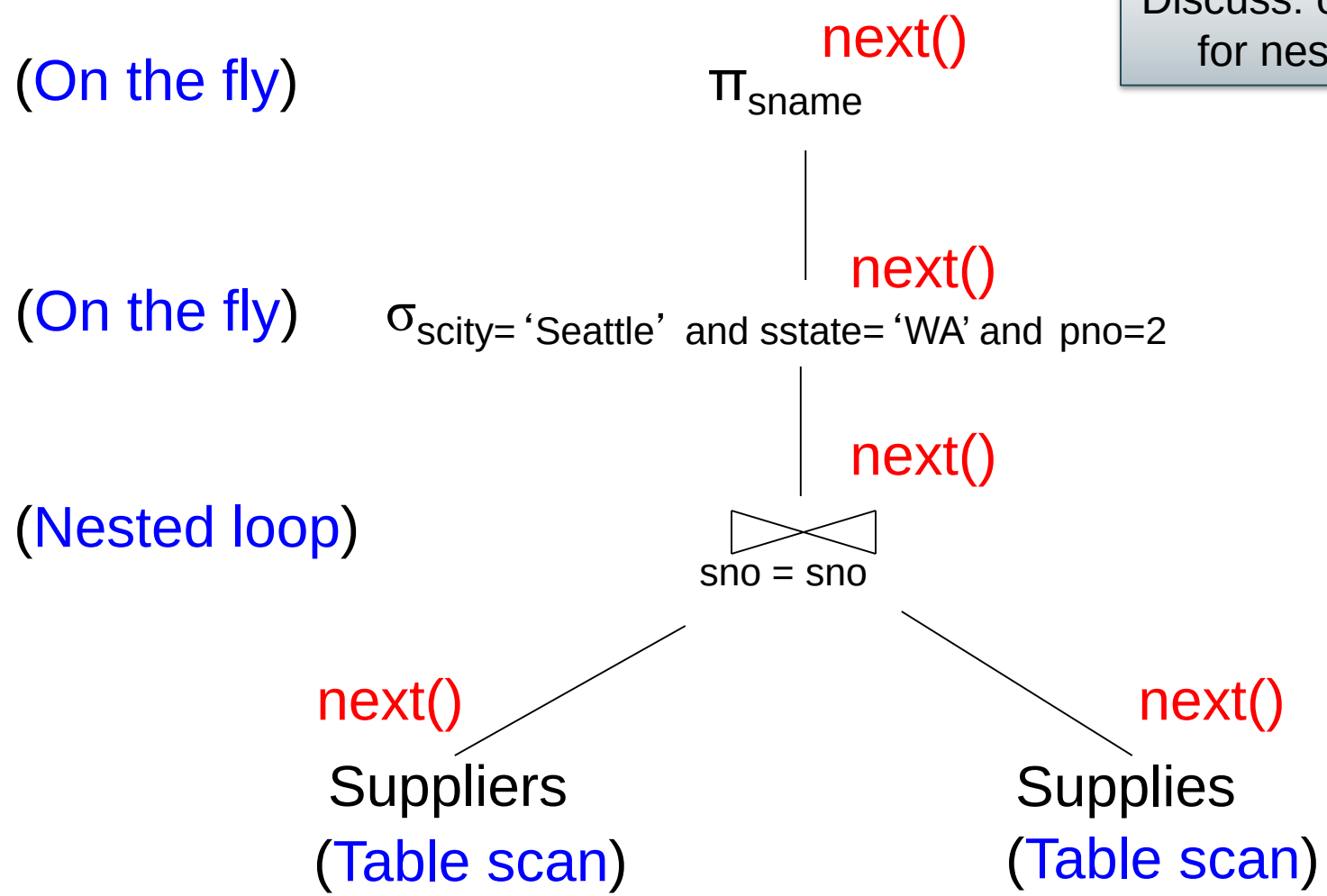

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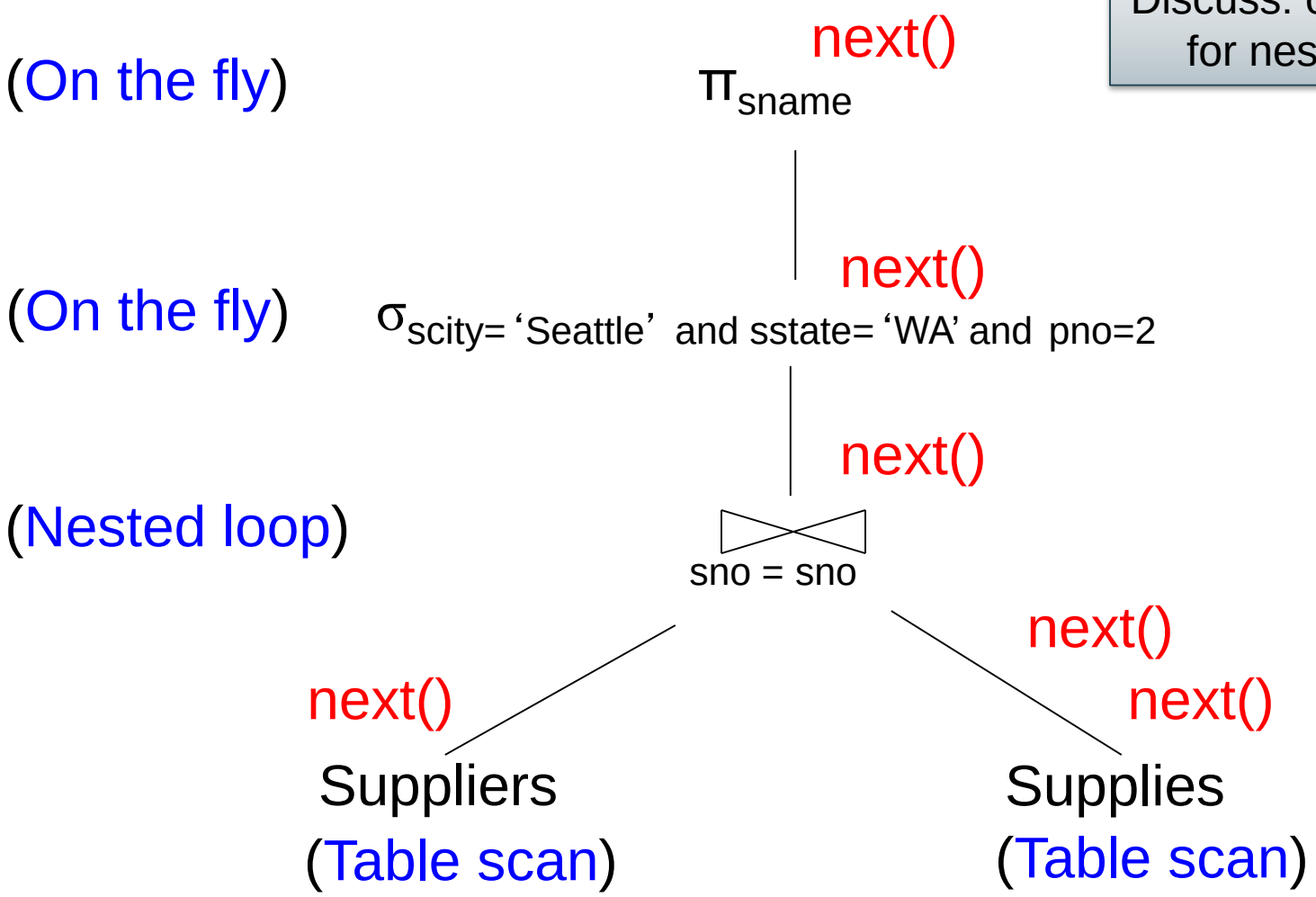

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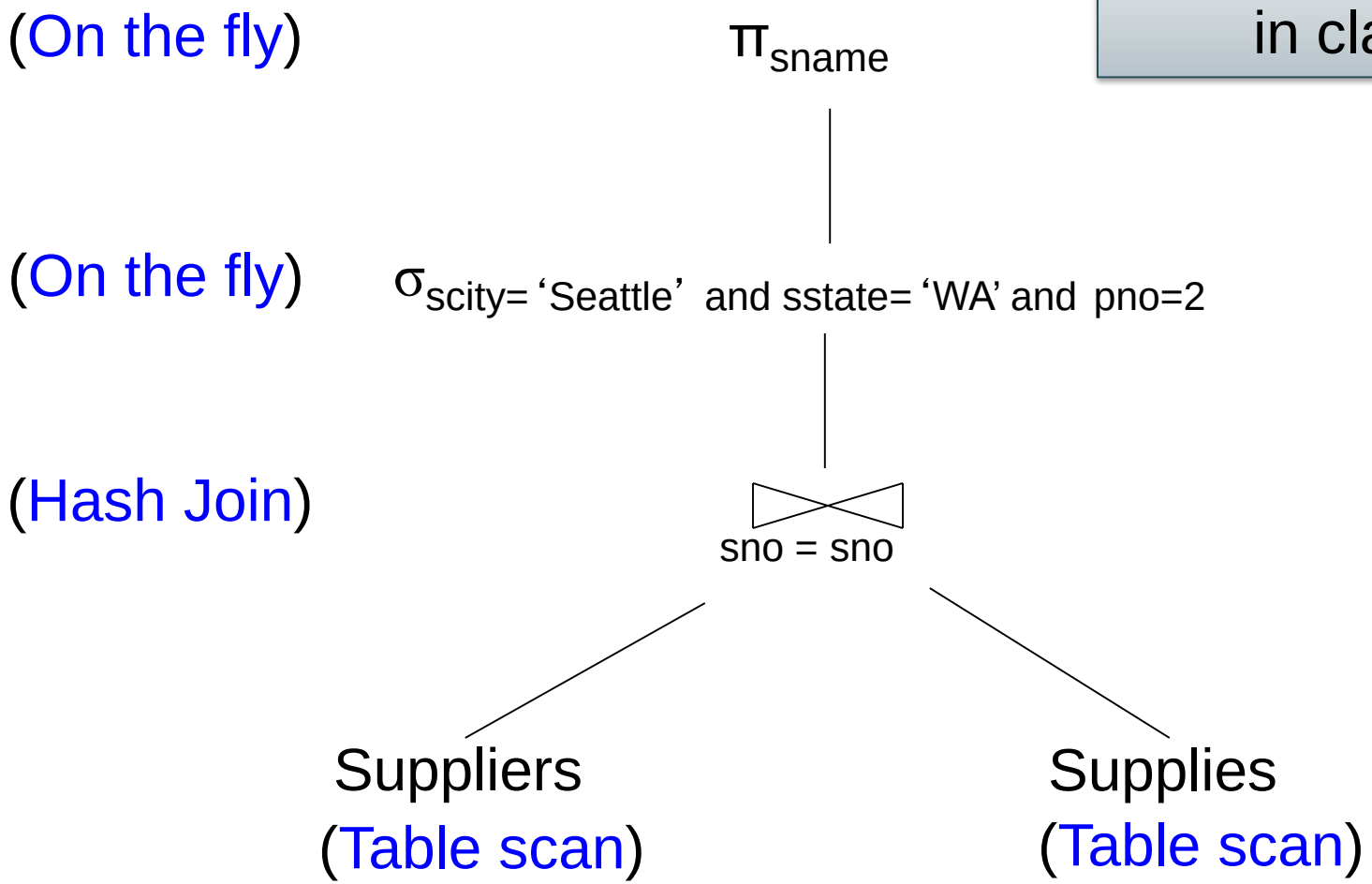
Pipelining

Discuss hash-join in class



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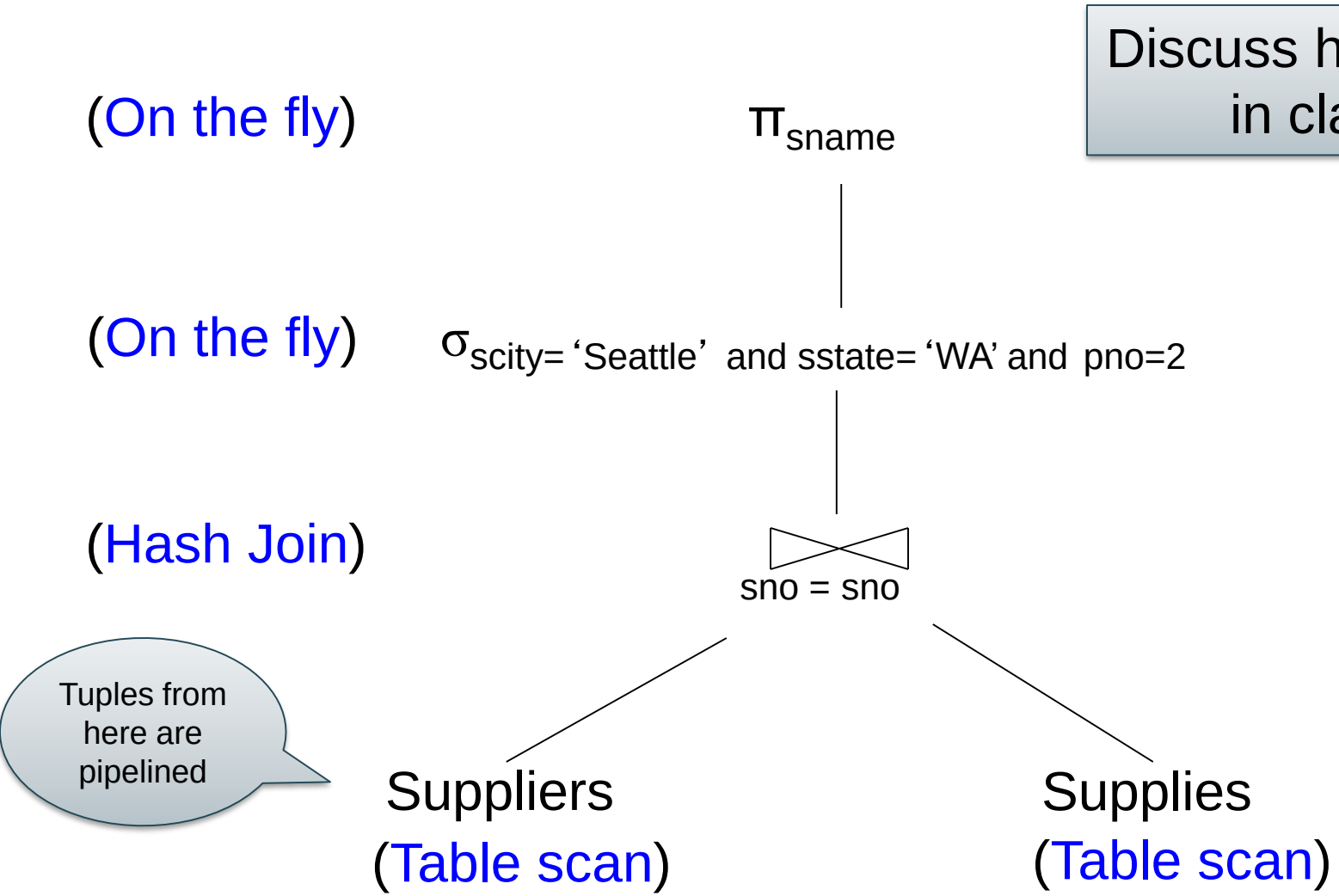

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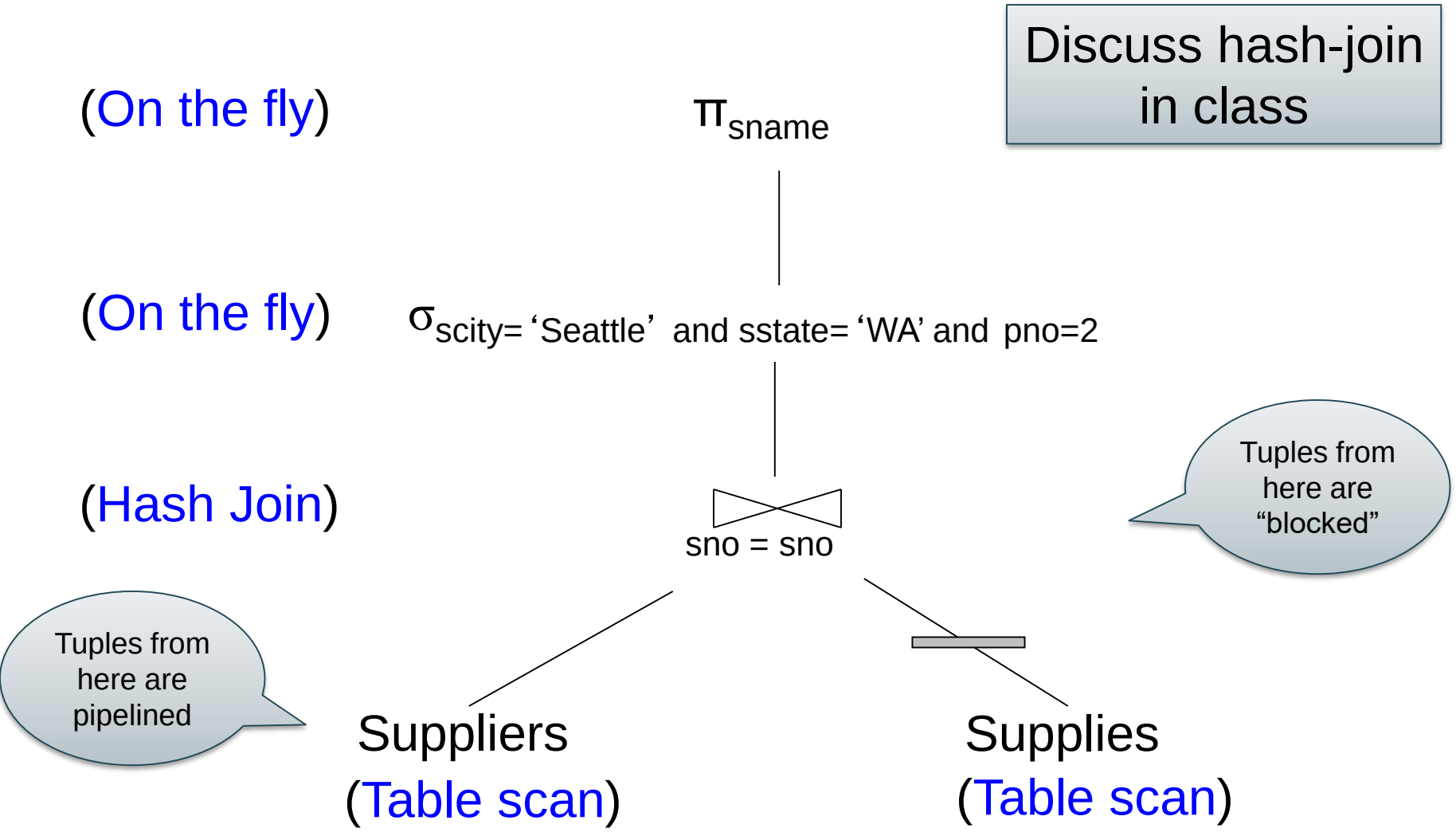

Supplier(sid, sname, scity, sstate)
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Blocked Execution

(On the fly) π_{sname}

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

(Merge Join) $\bowtie_{sno = sno}$

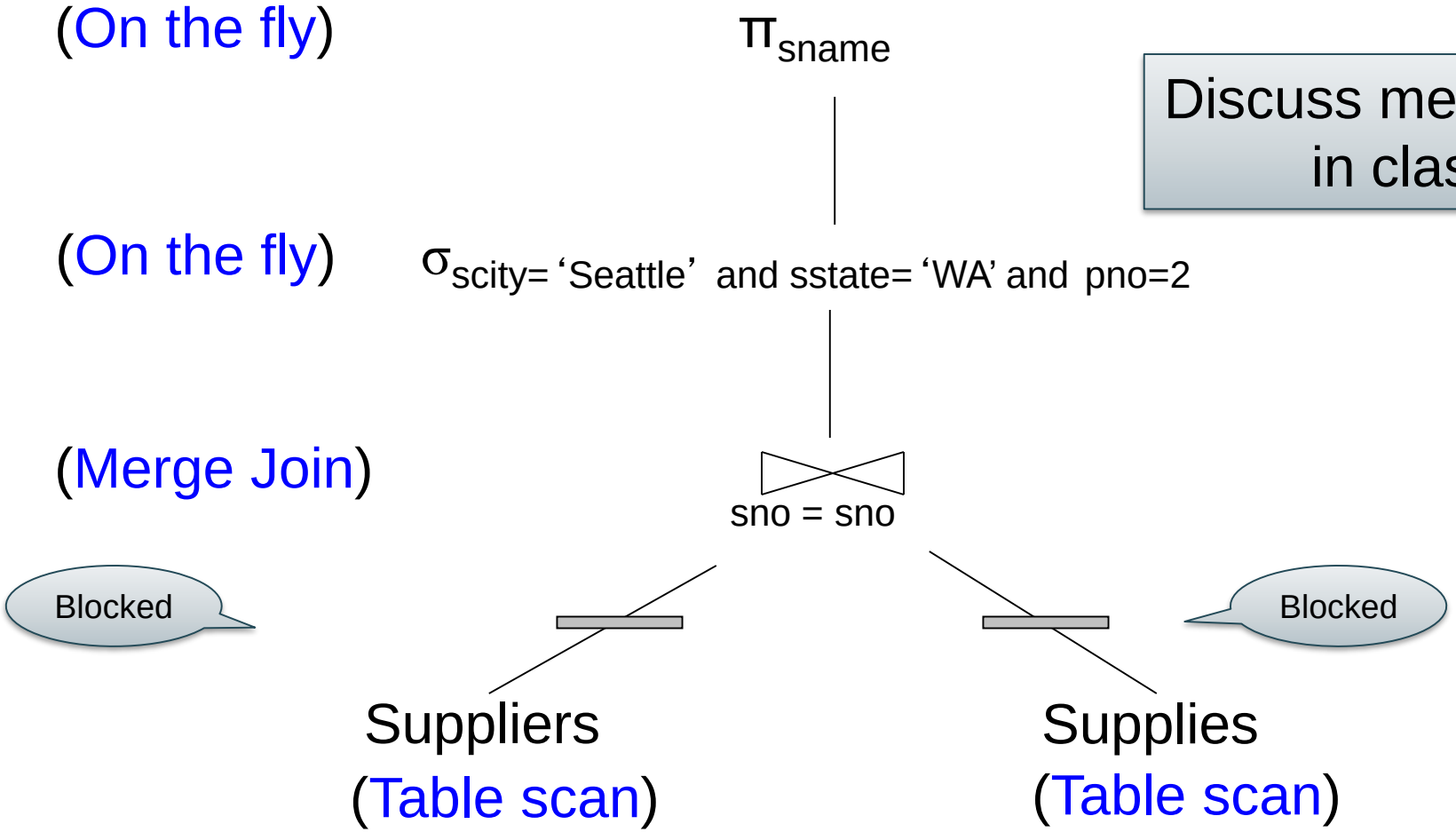
Suppliers (Table scan)

Supplies (Table scan)

Discuss merge-join in class

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

Blocked Execution



Discuss merge-join in class

Pipelined Execution

- Tuples generated by an operator are immediately sent to the parent
- Benefits:
  - No operator synchronization issues
  - No need to buffer tuples between operators
  - Saves cost of writing intermediate data to disk
  - Saves cost of reading intermediate data from disk
- This approach is used whenever possible

Query Execution Bottom Line

- SQL query transformed into 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
- Pipelined execution of physical plan

Recall: Physical Data Independence

- Applications are insulated from changes in physical storage details
- SQL and relational algebra facilitate physical data independence
  - Both languages input and output relations
  - Can choose different implementations for operators

Introduction to Database Systems
DATA 514

Lecture 15-16:
Basics of Data Storage and Indexes

Announcements

- HW4 (datalog) due tomorrow (Tuesday)
- Midterm: Wednesday
- No sections on Thursday!
- HW5 (SQL++) due next Tuesday

Query Performance

- My database application is too slow… why?
- One of the queries is very slow… why?

- To understand performance, we need to understand:
  - How is data organized on disk
  - How to estimate query costs

  - In this course the is focus on disk-based DBMSs

Data Storage

- DBMSs store data in files
  - Most common organization is row-wise storage
- On disk, the file(s) containing the database is organized into fixed-size blocks
  - Each block contains a set of tuples
  - example shows 4 blocks with 2 tuples each

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

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

Student

ID	fName	lName
10	Tom	Hanks
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…		

Data File Types

The data file can be one of:

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

Student

ID	fName	lName
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Data File Types

The data file can be one of:

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

Note: *key* here means something different from primary key: it just means that we order the file according to that attribute. In our example we ordered by **ID**. Might as well order by **fName,** if that seems a better idea for the applications running on our database.

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:
  - The key = an attribute value (e.g., student ID or name)
  - The value = a pointer to the record

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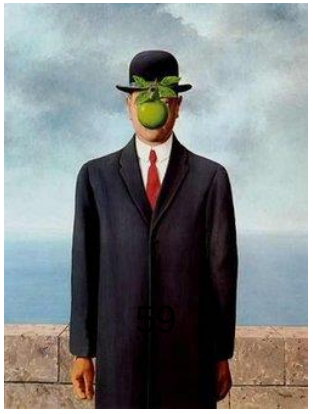
- The index contains (key, value) pairs:
  - The key = an attribute value (e.g., student ID or name)
  - The value = a pointer to the record
- Could have many indexes for one table

Here, Key = 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



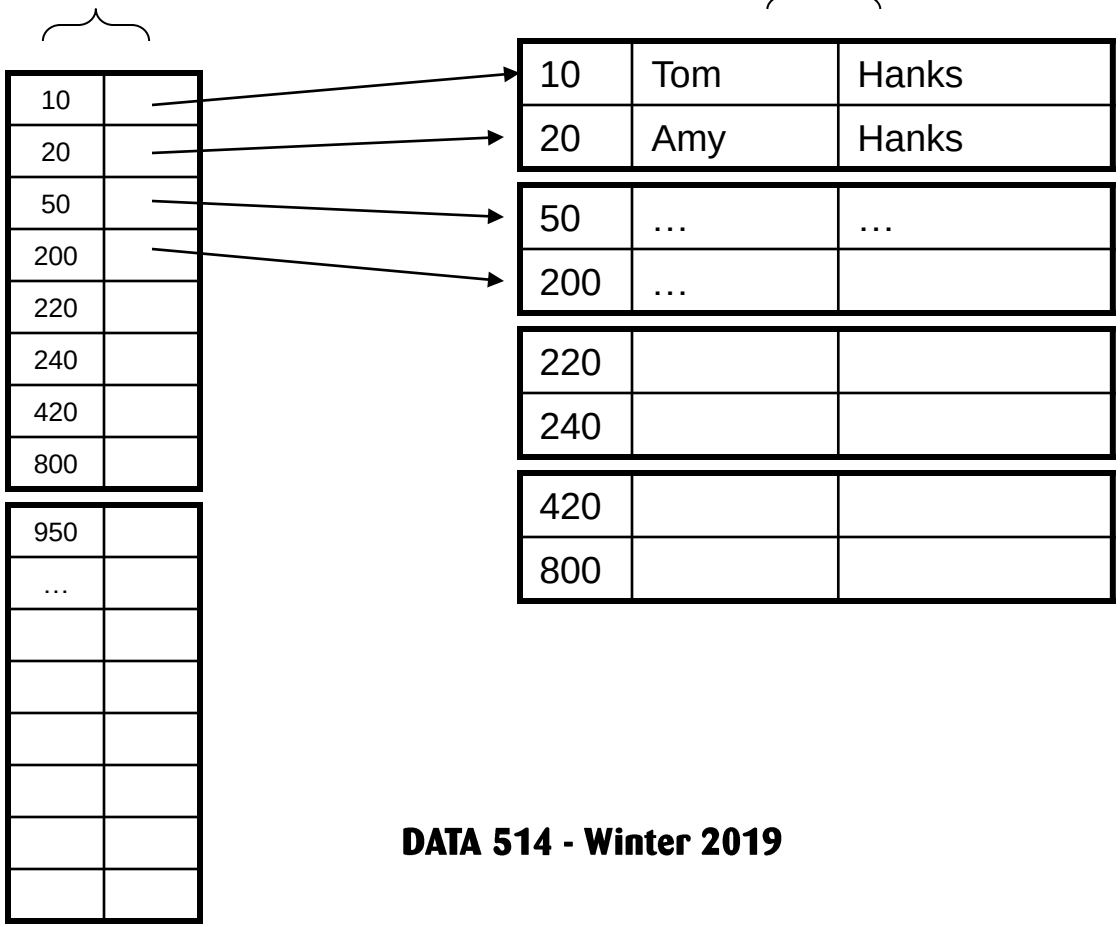
Example 1: Index on ID

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

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

Data File **Student**



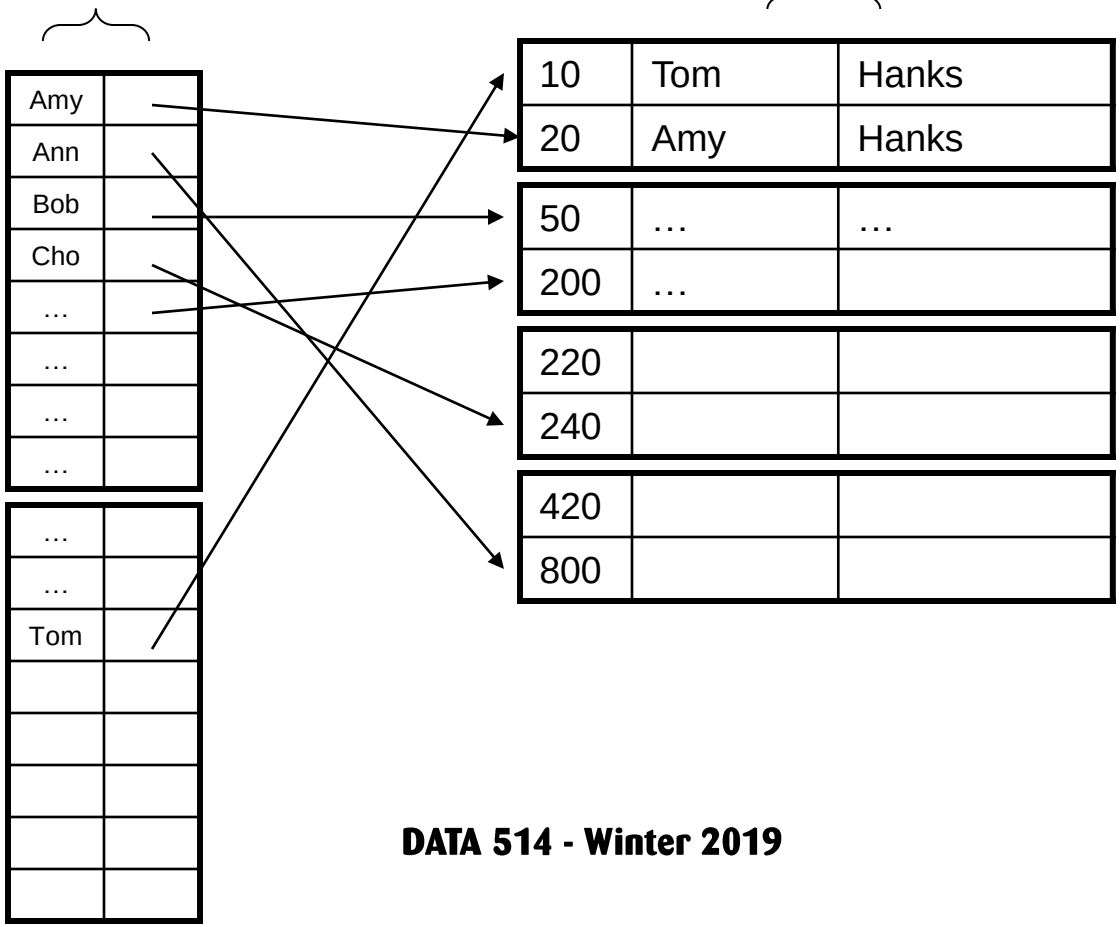
Example 2: Index on fName

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

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

Data File **Student**



Index Organization

We need a way to represent indexes after loading into memory so that they can be used

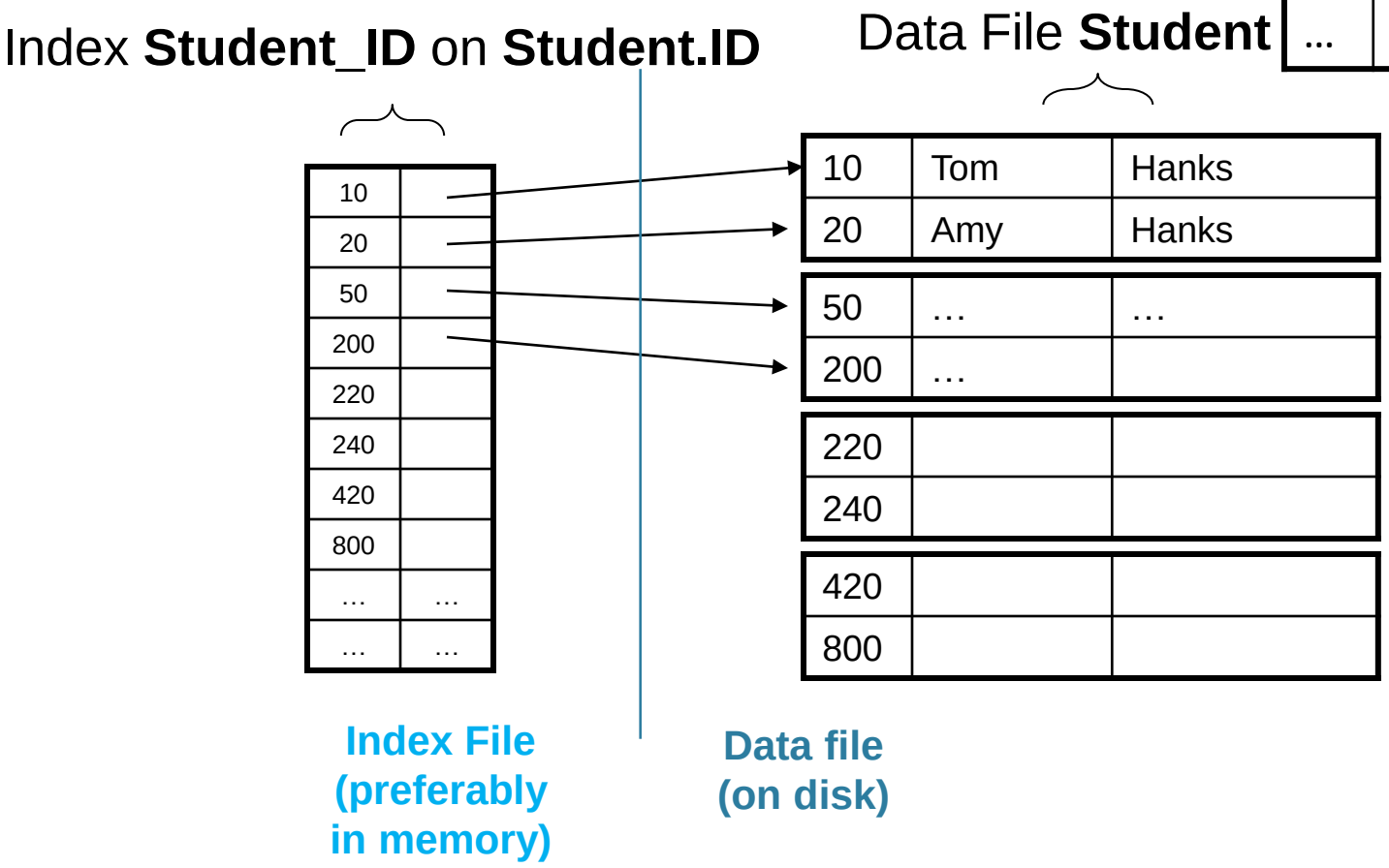
Several ways to do this:

- Hash table
- B+ trees – most popular
  - 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

Hash table example

Student

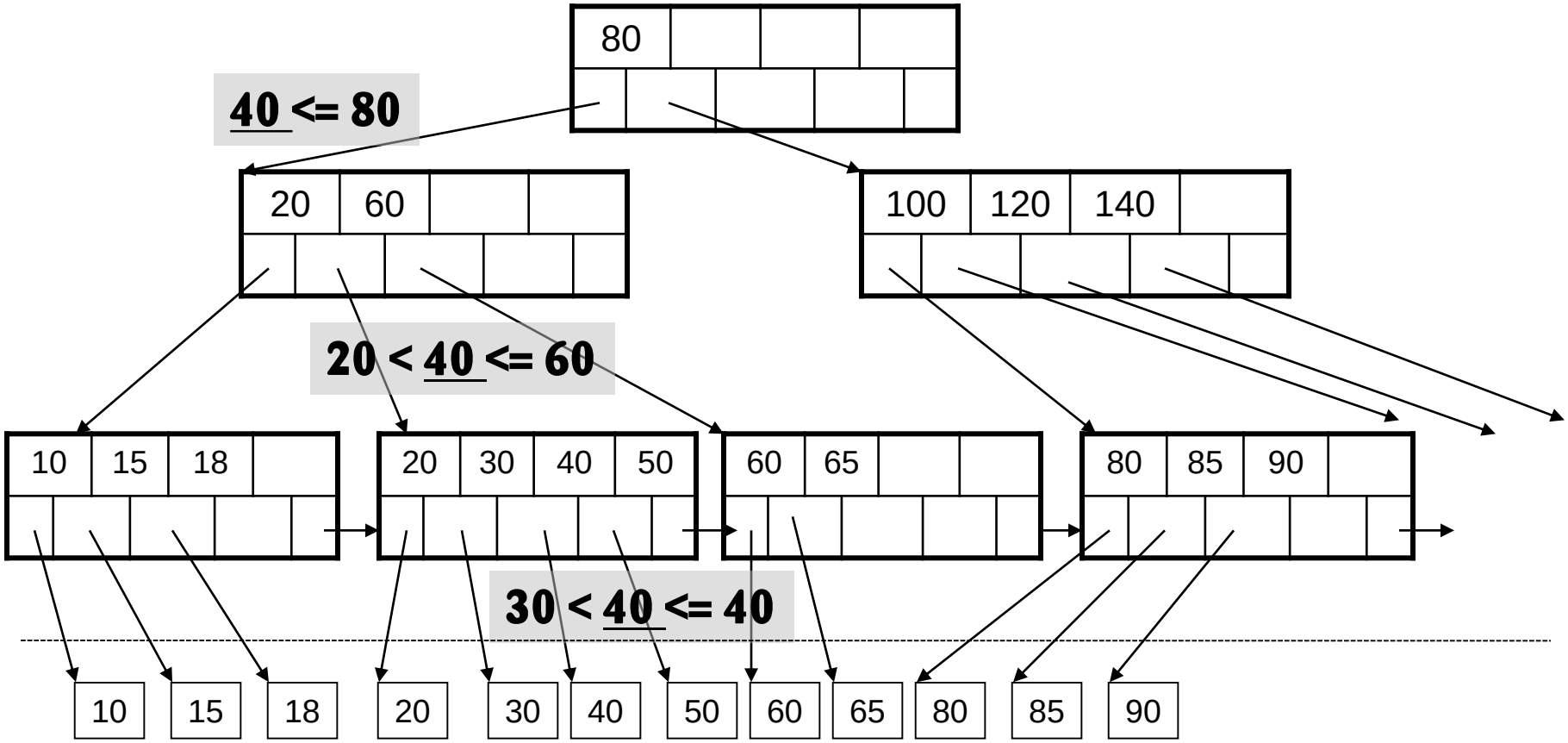
ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		



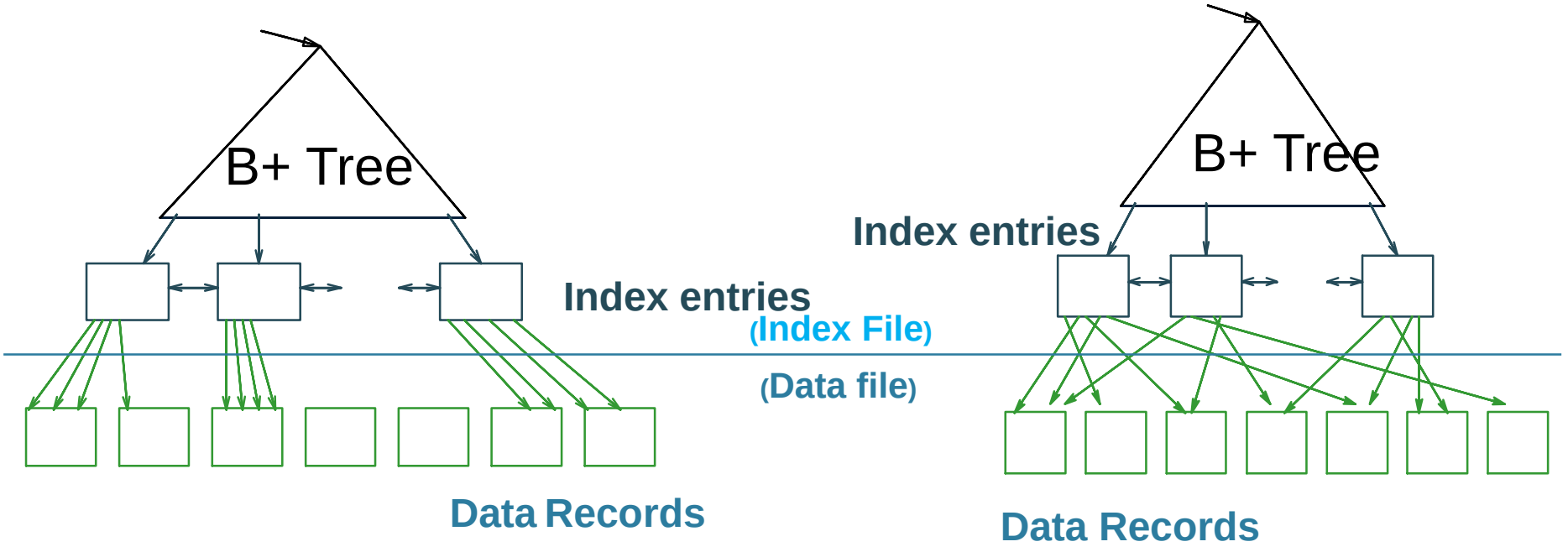
B+ Tree Index

Depth = 2

Find the key 40



Clustered vs Unclustered



Every table can have only one clustered index, but may have 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

Index Classification

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  - 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

Index Classification

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- **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

Scanning a Data File

- Disks are mechanical devices!
  - Technology from the 60s; density much higher now
- Read only at the rotation speed!
- Consequence:
  Sequential scan is MUCH FASTER than random reads
  - Good: read blocks 1,2,3,4,5,…
  - Bad: read blocks 2342, 11, 321,9, …
- Rule of thumb:
  - Random reading 1-2% of the file ≈ sequential scanning the entire file; this is decreasing over time (because of increased density of disks)
- Solid state (SSD): $$$ expensive; put indexes, other "hot" data there, still too expensive for everything

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 efficint
  - Random access less efficient
  - Random read 1-2% of data worse than sequential

Student(ID, fname, lname)

Takes(studentID, courseID)

Example

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

Student(ID, fname, lname)

Takes(studentID, courseID)

Example

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

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

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

Example

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```

Assume the database has indexes on these attributes:

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

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

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- **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(ID, fname, lname)
Takes(studentID, courseID)

Example

```
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Assume the database has indexes on these attributes:

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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'
```

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

Example

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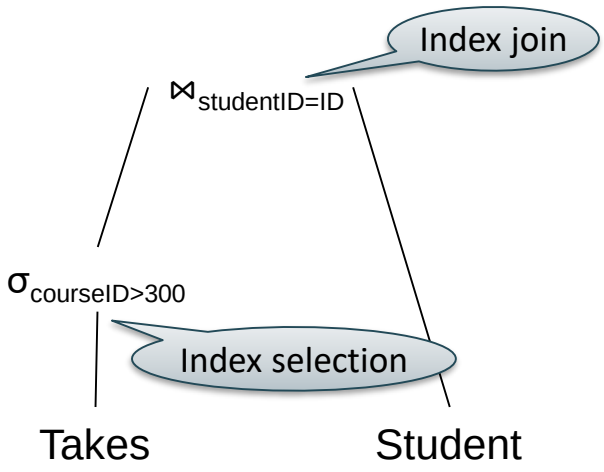

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Getting Practical: Creating Indexes in SQL

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

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

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

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

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

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

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What does this mean?

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

What does this mean?

Getting Practical: Creating Indexes in SQL

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

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yes

What does this mean?

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

yes

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

no

Not supported in SQLite

Which Indexes?

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

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

Which Indexes?

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

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

This is a very hard problem!

Which Indexes?

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

- The *index selection problem*
  - Given a table, and a "workload" (big Java application with lots of SQL queries), decide which indexes to create (and which ones NOT to create!)
- Who does index selection:
  - The database administrator DBA
  - Semi-automatically, using a database administration tool

Student

ID	fName	lName
10	Tom	Hanks
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…		

Which Indexes?

- The *index selection problem*
  - Given a table, and a "workload" (big Java application with lots of SQL queries), decide which indexes to create (and which ones NOT to create!)
- Who does index selection:
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  - Semi-automatically, using a database administration tool

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:

```
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WHERE N=?
```

100 queries:

```
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What indexes ?

The Index Selection Problem 1

V(M, N, P);

Your workload is this

100000 queries:

```
SELECT *
FROM V
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```

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?

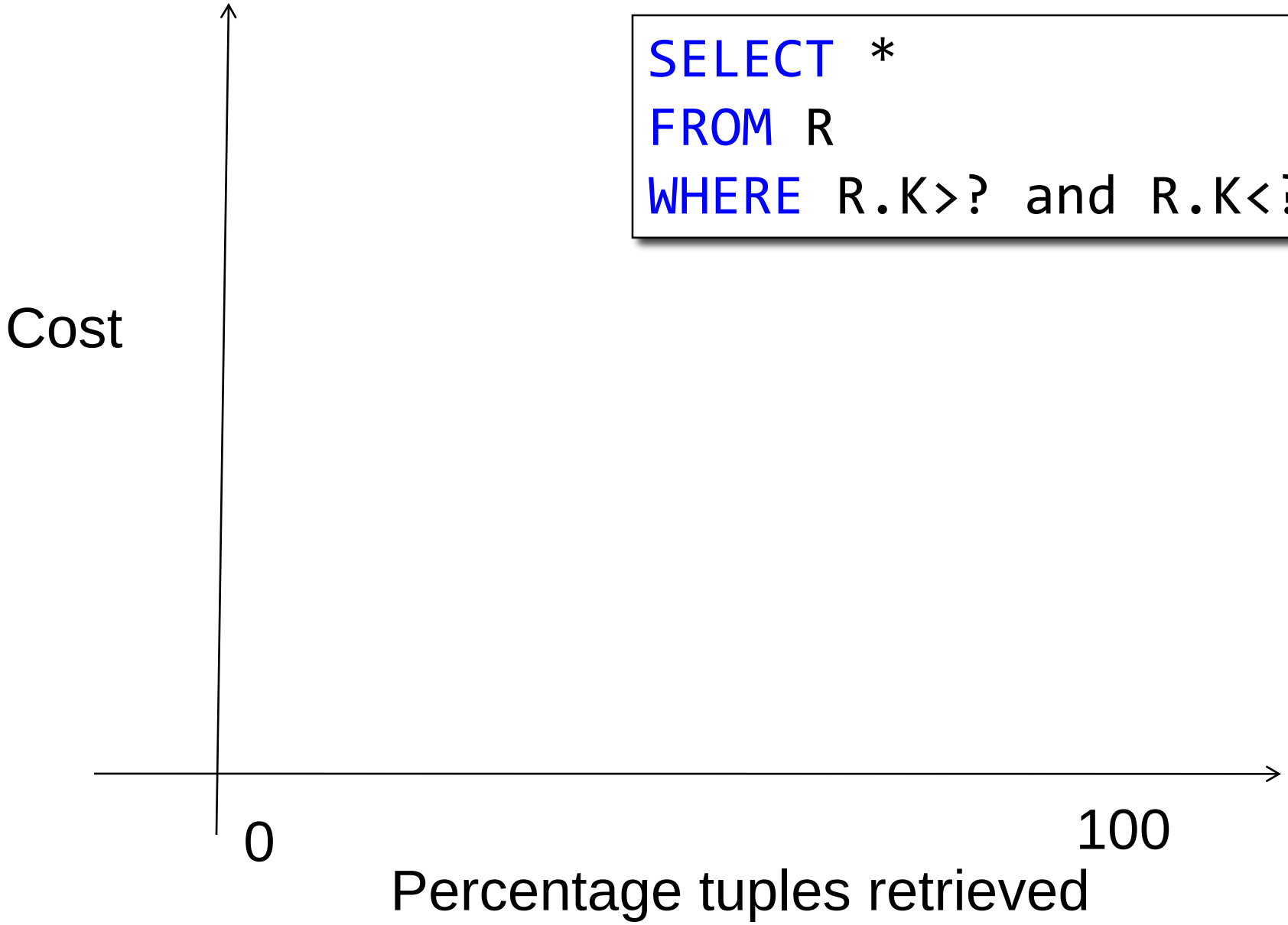
Basic Index Selection Guidelines

- 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

- Range queries benefit mostly from clustering
- Covering indexes do *not* need to be clustered: they work equally well unclustered

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



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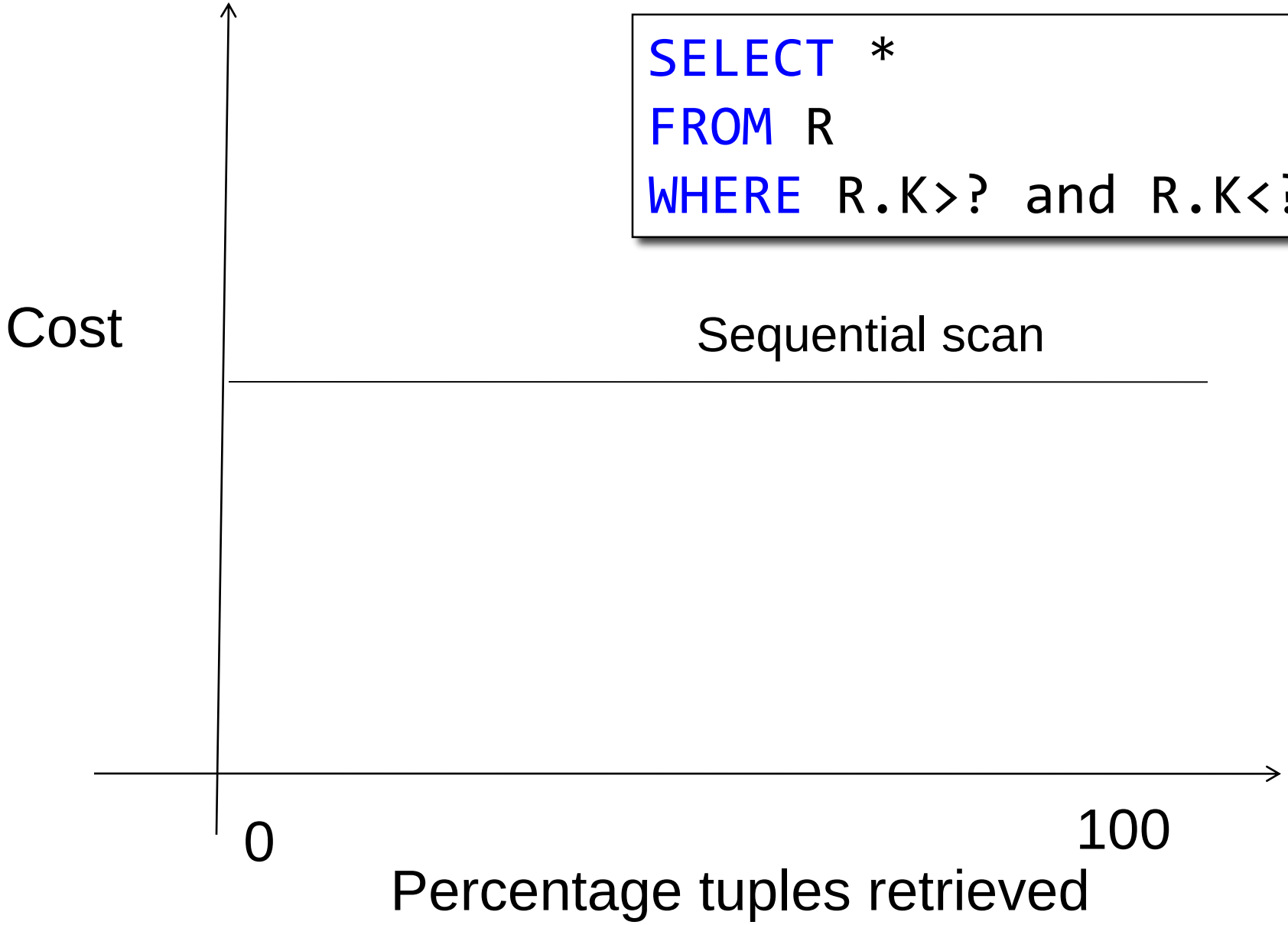

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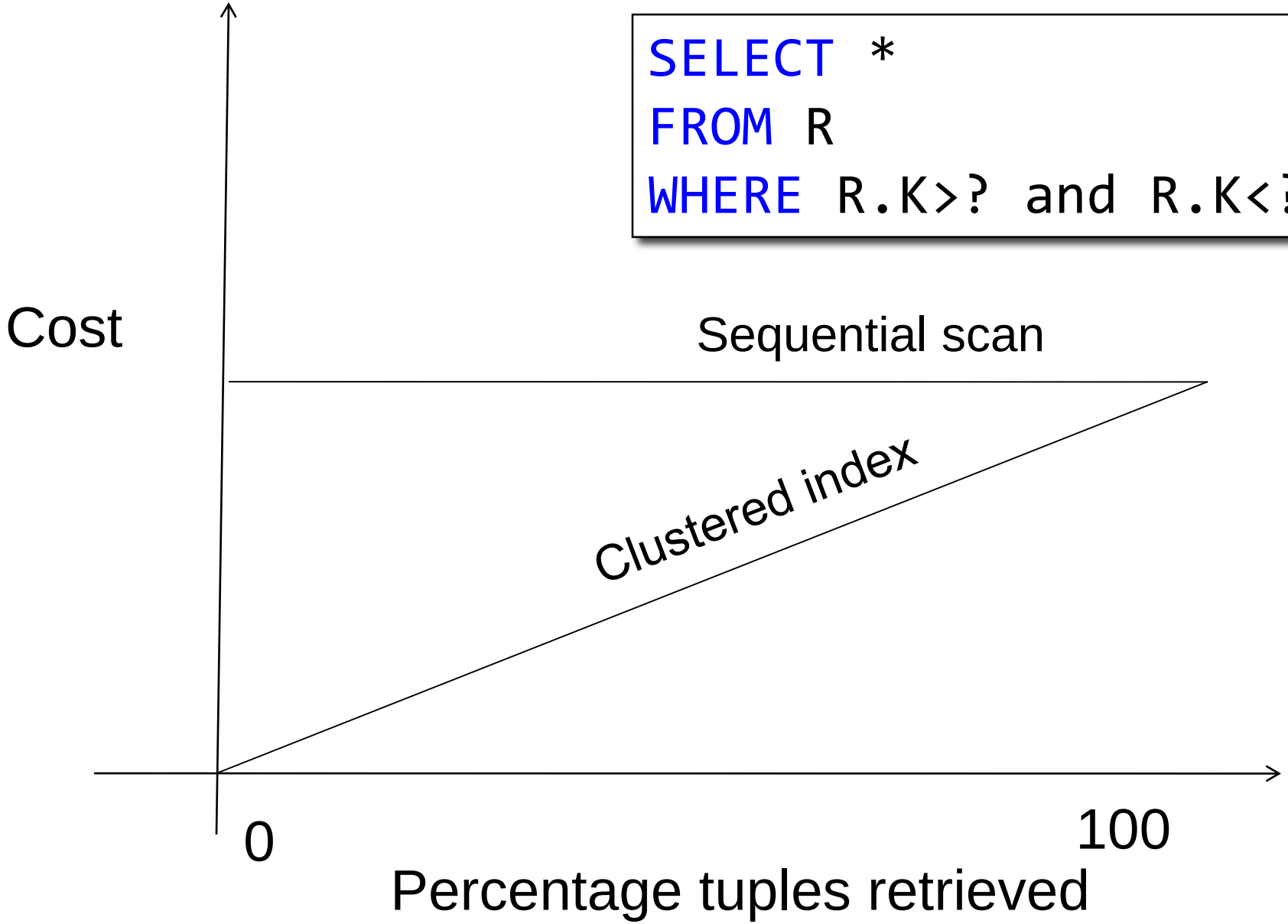

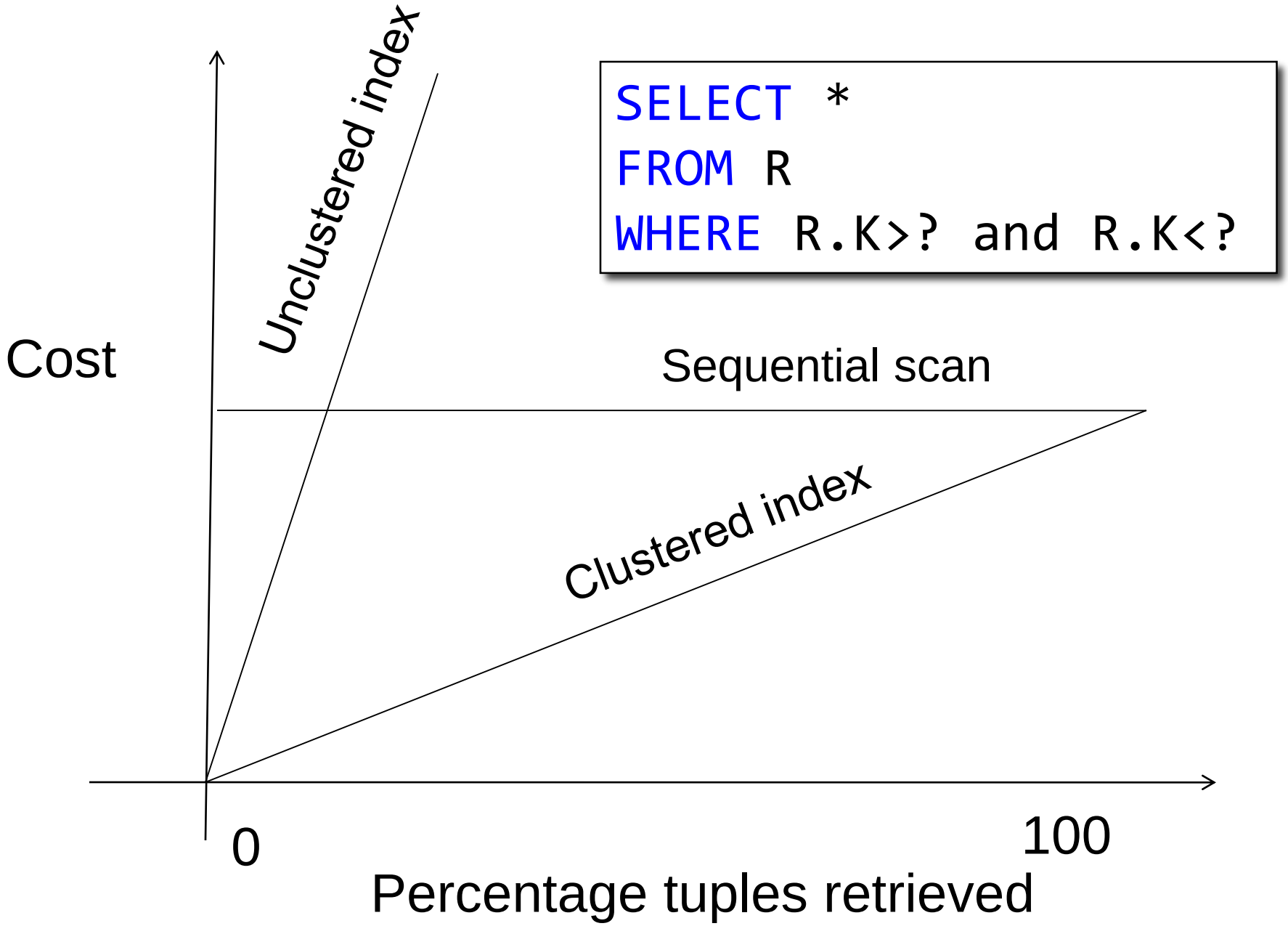
SELECT *
FROM R
WHERE R.K>? and R.K<?
Cost
Unclustered index
Sequential scan
Clustered index
0
100
Percentage tuples retrieved

Introduction to Database Systems
DATA 514

Lecture 17:
Basics of Query Optimization and Query Cost Estimation

Choosing Index is Not Enough

- To estimate the cost of a query plan, we still need to consider other factors:
  - How each operator is implemented
  - The cost of each operator
  - Let's start with the basics

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

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

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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**

Selectivity Factors for Conditions

- A = c /* $\sigma_{A=c}(R)$ */
  - Selectivity = 1/V(R,A)
- A < c /* $\sigma_{A<c}(R)$*/
  - Selectivity = (c - min(R, A))/(max(R,A) - min(R,A))
- c1 < A < c2 /* $\sigma_{c1<A<c2}(R)$*/
  - Selectivity = (c2 – c1)/(max(R,A) - min(R,A))

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:**

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- **Index based selection:**
  - **If index is clustered:**
  - **If index is unclustered:**

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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:**

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

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

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?

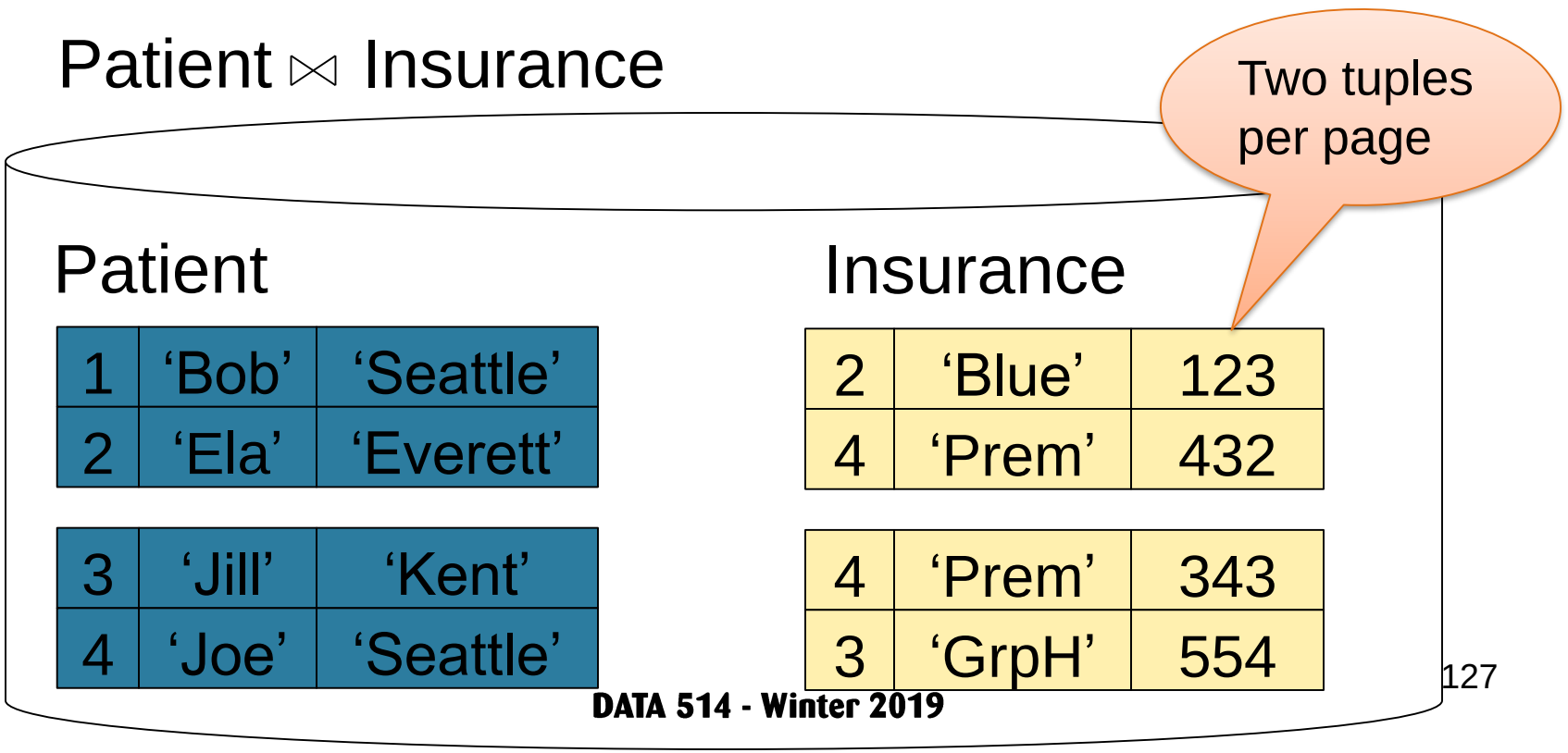
- One-pass algorithm when $B(R) \leq M$
  - M = number of memory pages available

Hash Join Example

Patient(pid, name, address)

Insurance(pid, provider, policy_nb)

Patient ⋈ Insurance



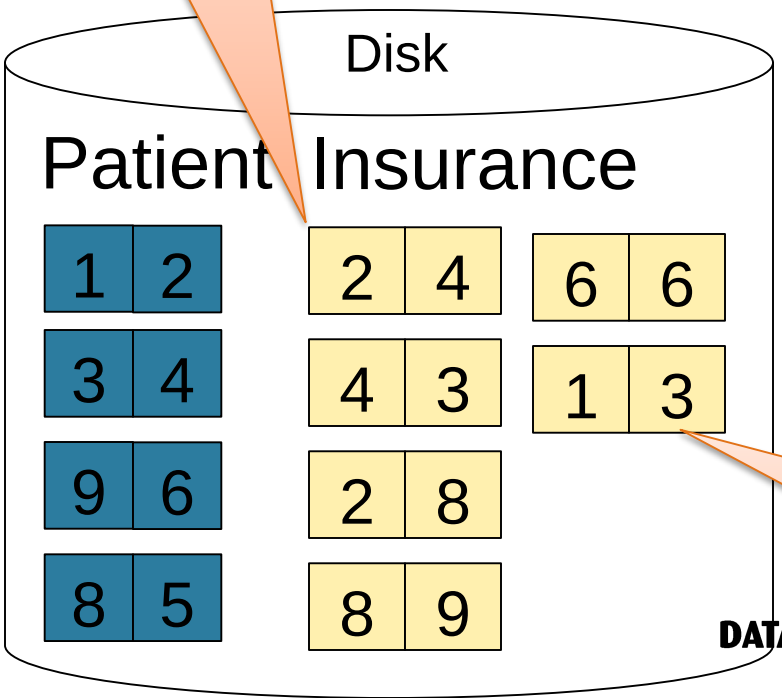
Hash Join Example

Patient ⋈ Insurance

Some large-enough #

Memory M = 21 pages

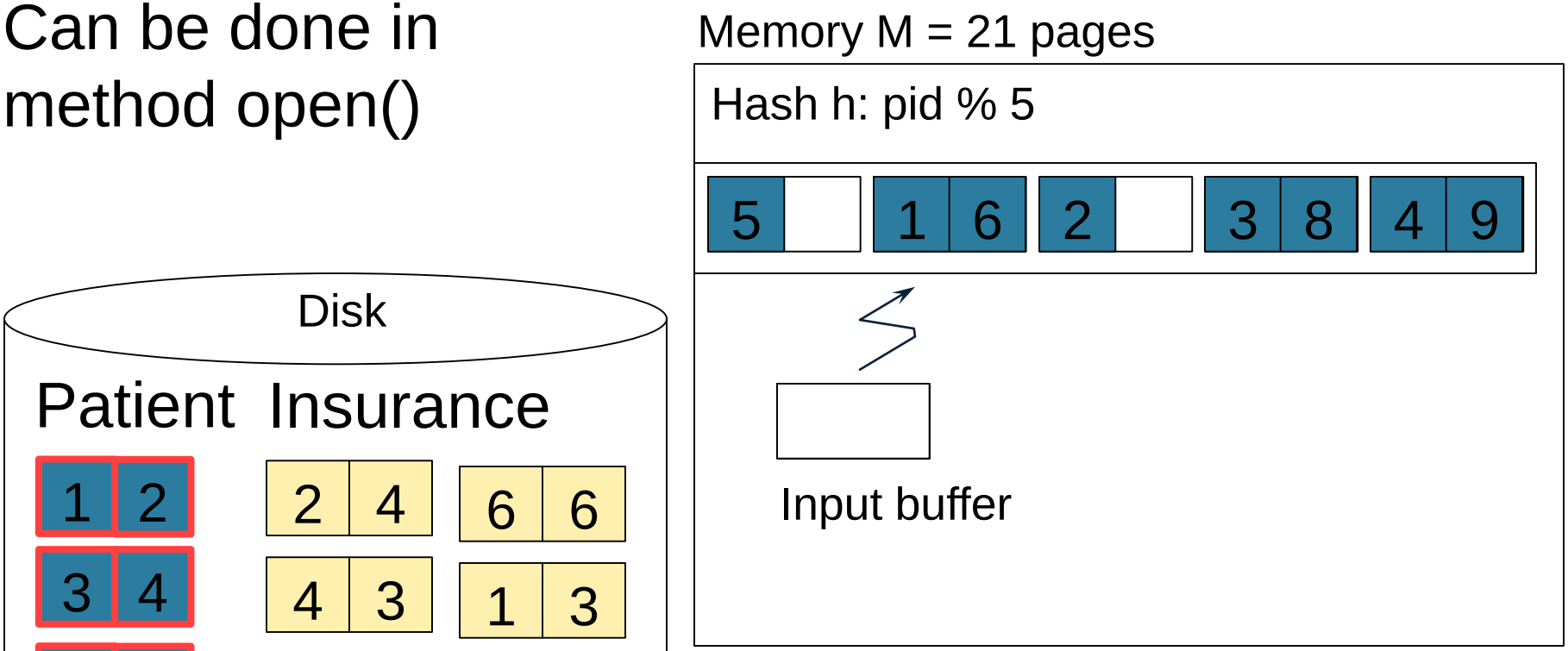
Showing pid only



This is one page with two tuples

Hash Join Example

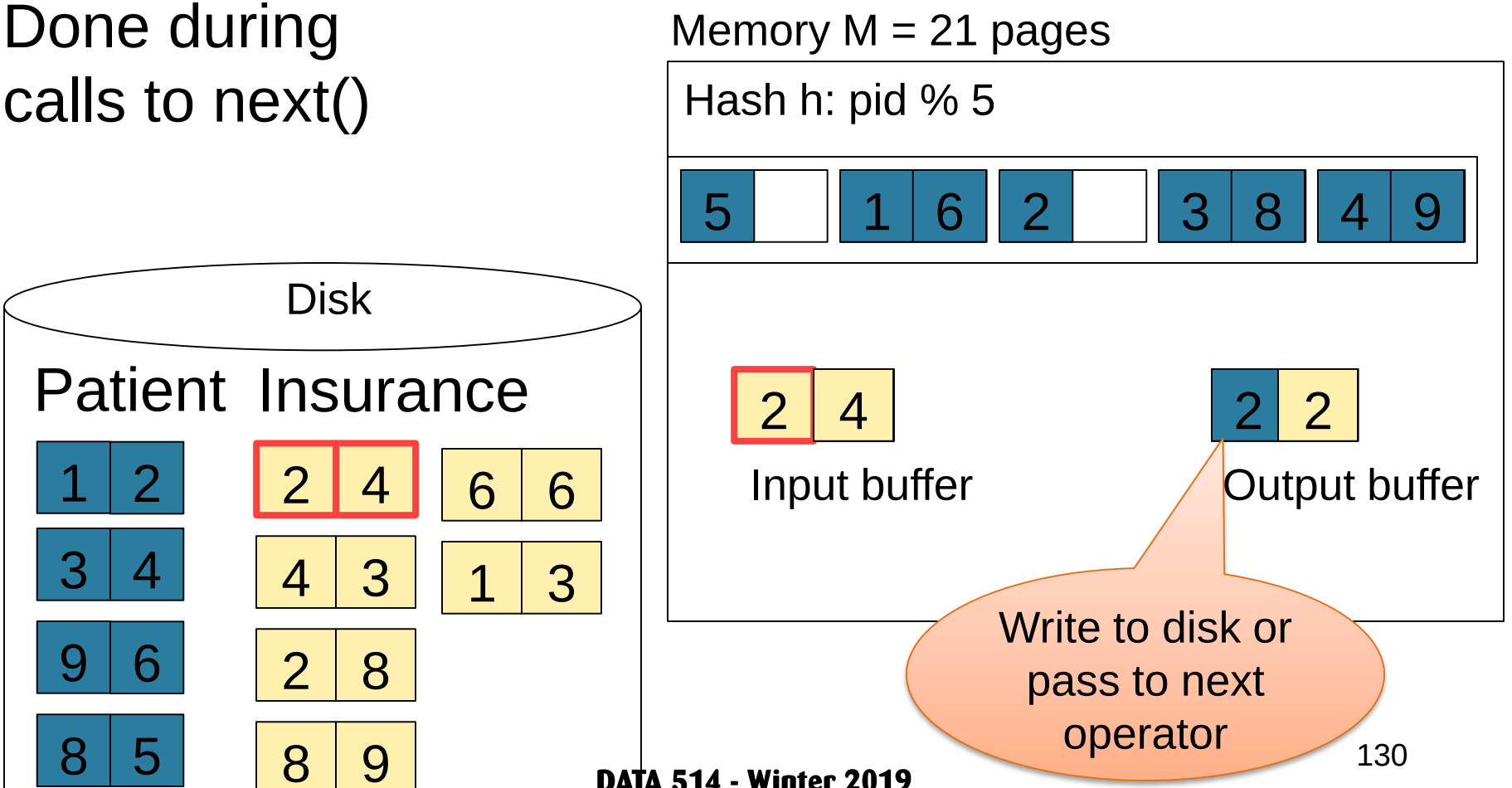
Step 1: Scan Patient and build hash table in memory
Can be done in
method open()



Hash Join Example

Step 2: Scan Insurance and probe into hash table

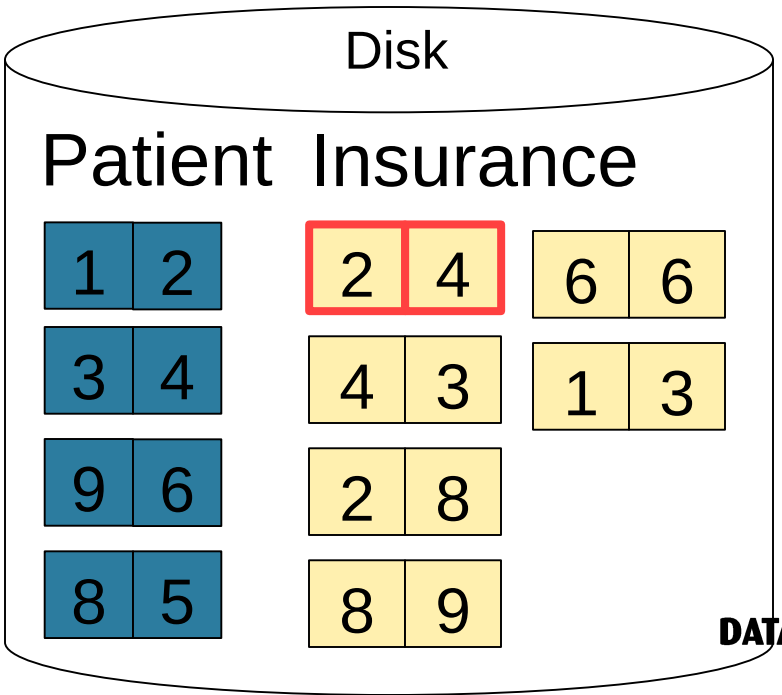
Done during calls to next()



Hash Join Example

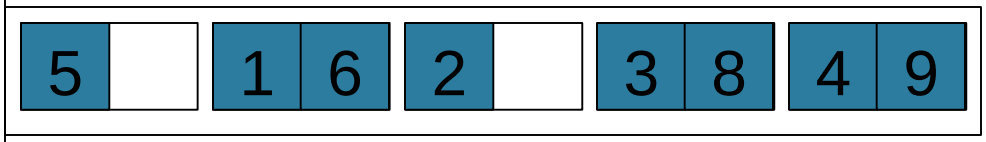
Step 2: Scan Insurance and probe into hash table

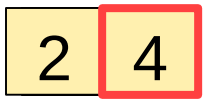
Done during
calls to next()



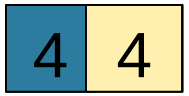
Memory M = 21 pages

Hash h: pid % 5





Input buffer

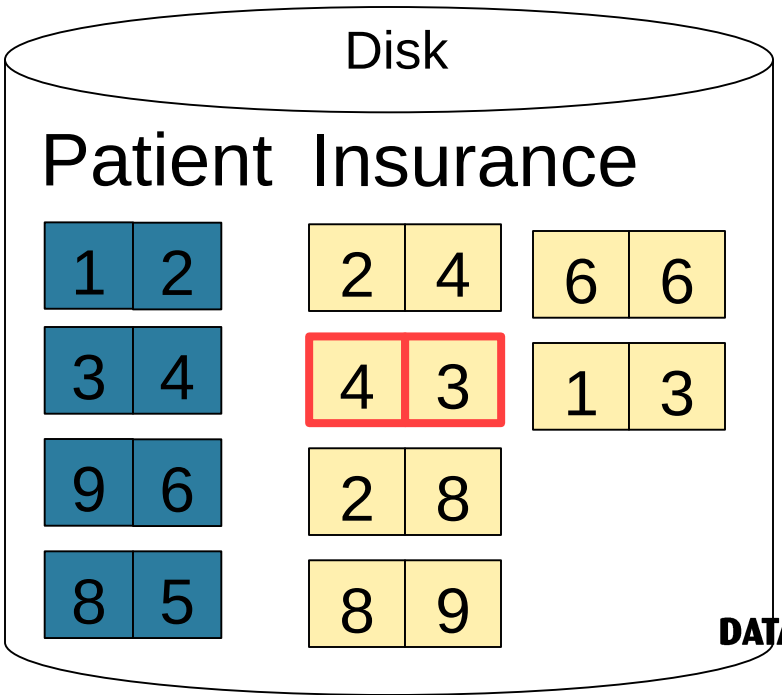


Output buffer

Hash Join Example

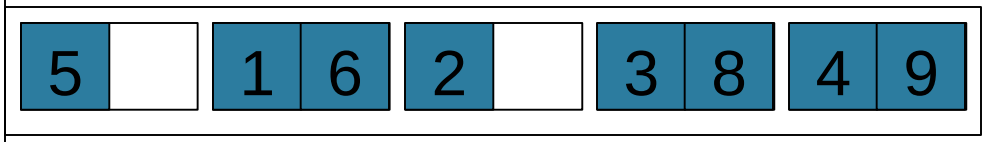
Step 2: Scan Insurance and probe into hash table

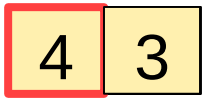
Done during calls to next()



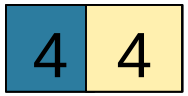
Memory M = 21 pages

Hash h: pid % 5





Input buffer



Output buffer

Keep going until read all of Insurance

Cost: B(R) + B(S)

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**

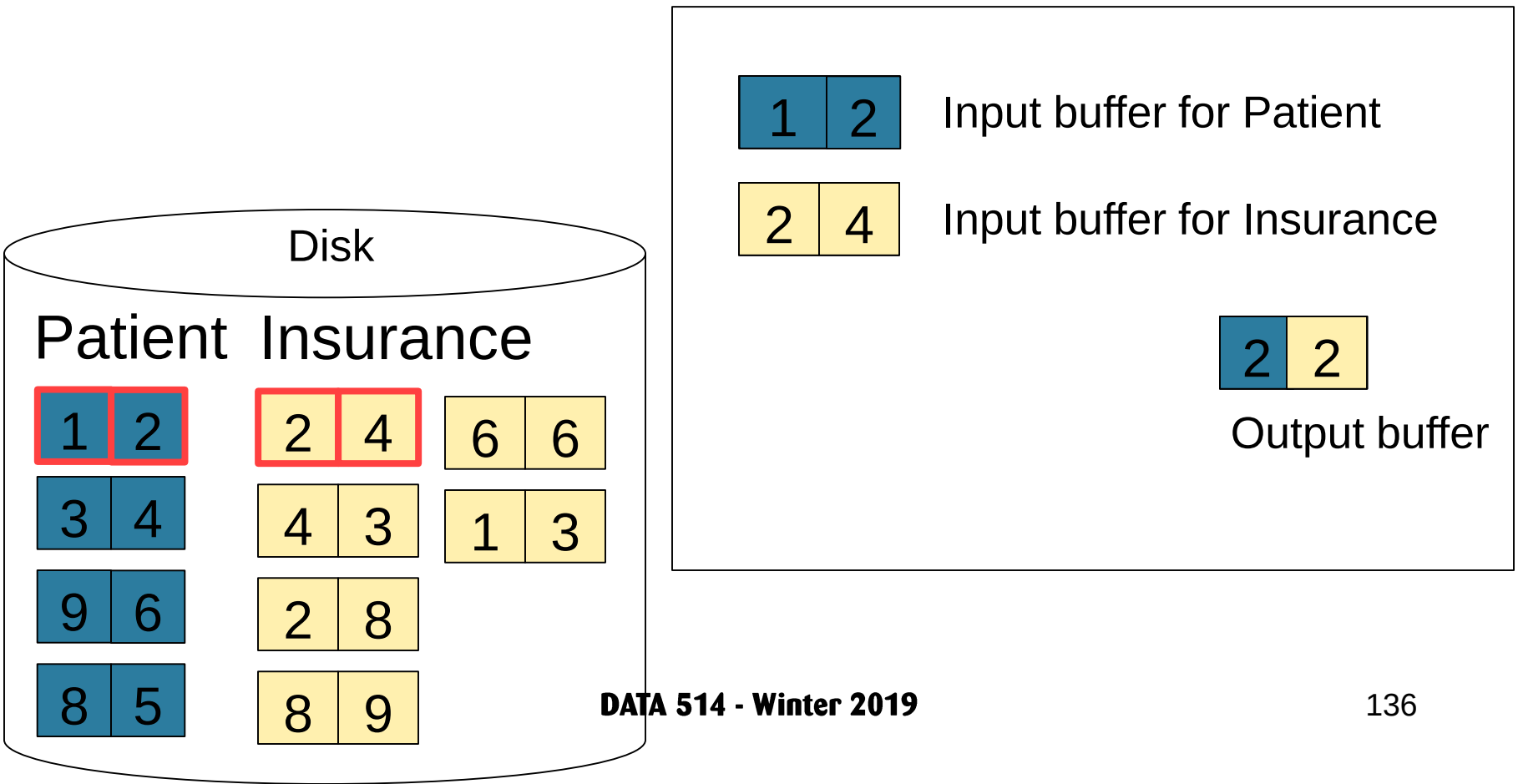
Page-at-a-time Refinement

```
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)
```

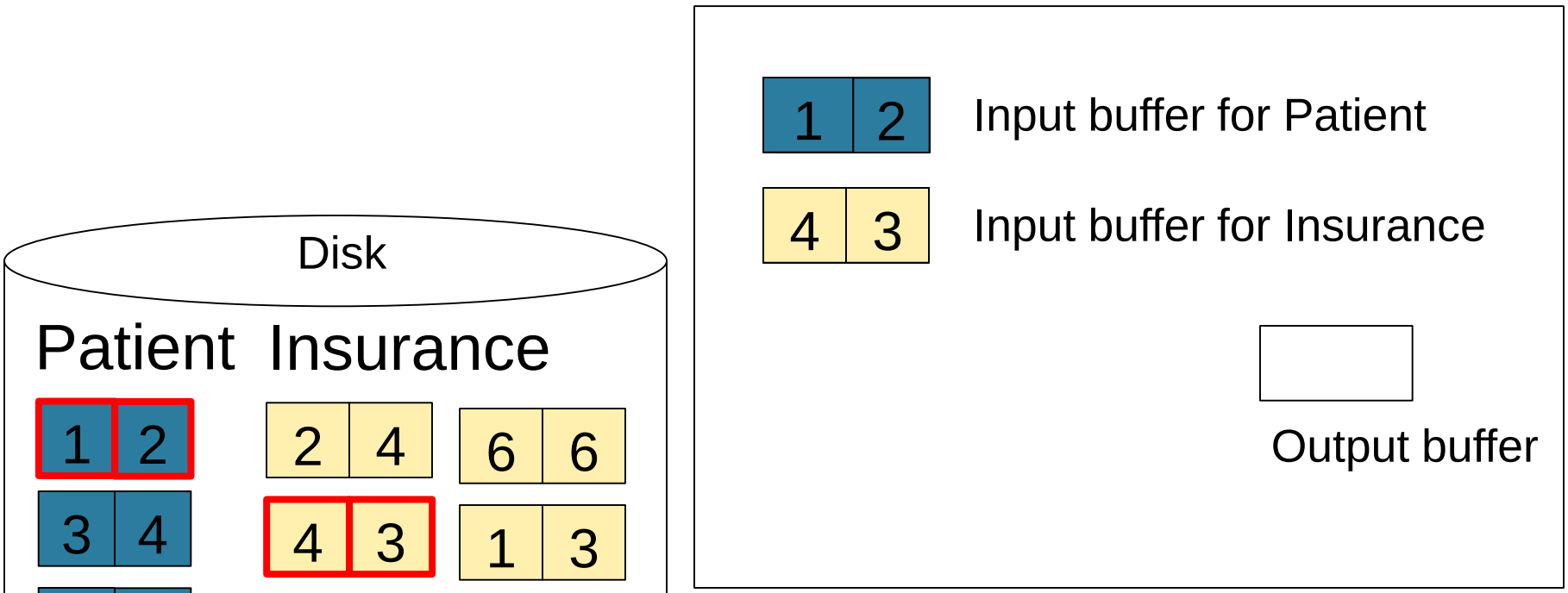
- **Cost: B(R) + B(R)B(S)**

What is the Cost?

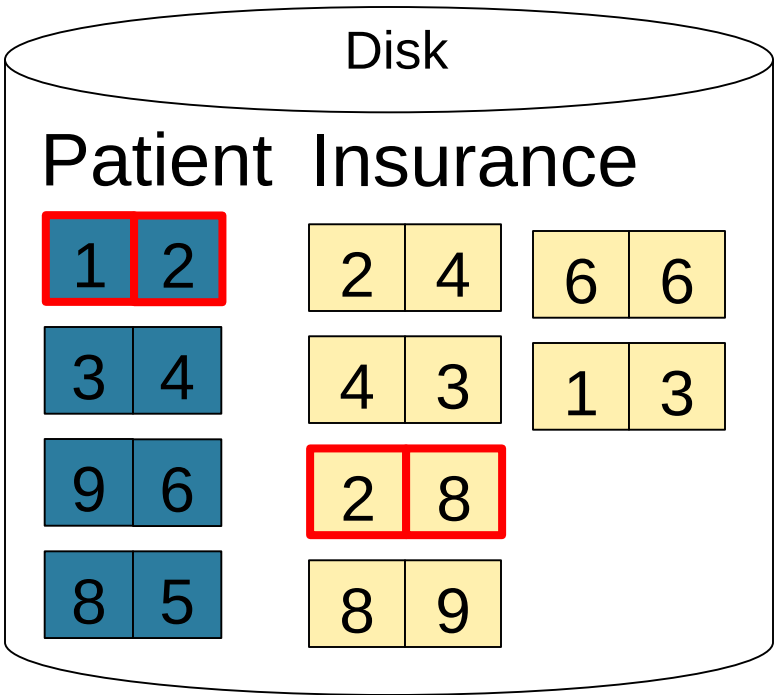
Page-at-a-time Refinement

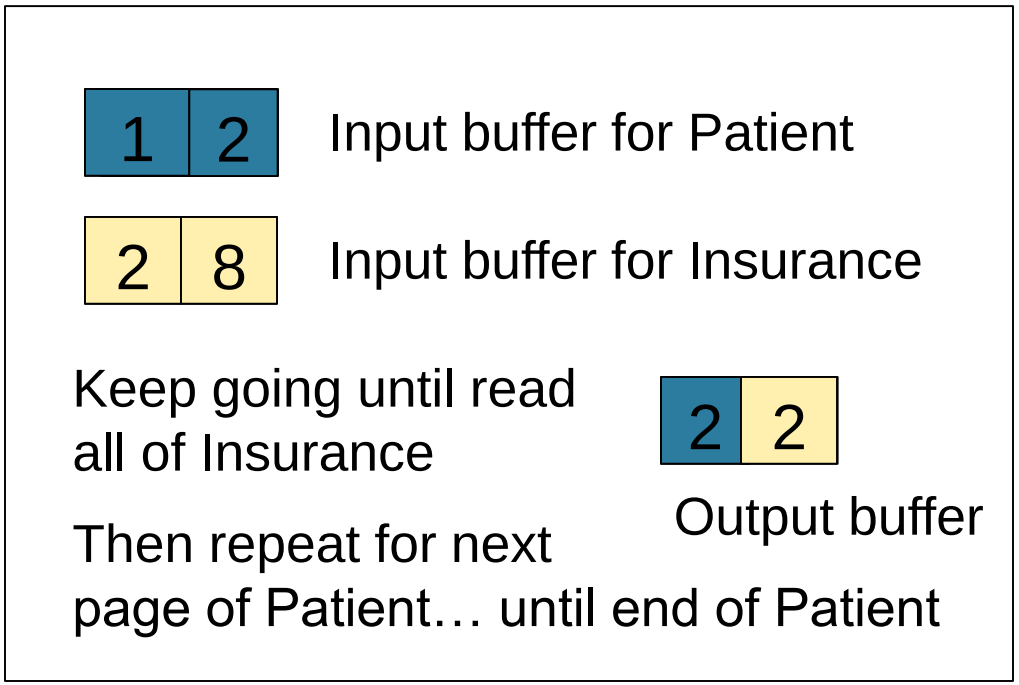


Page-at-a-time Refinement



Page-at-a-time Refinement





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?

Sort-Merge Join

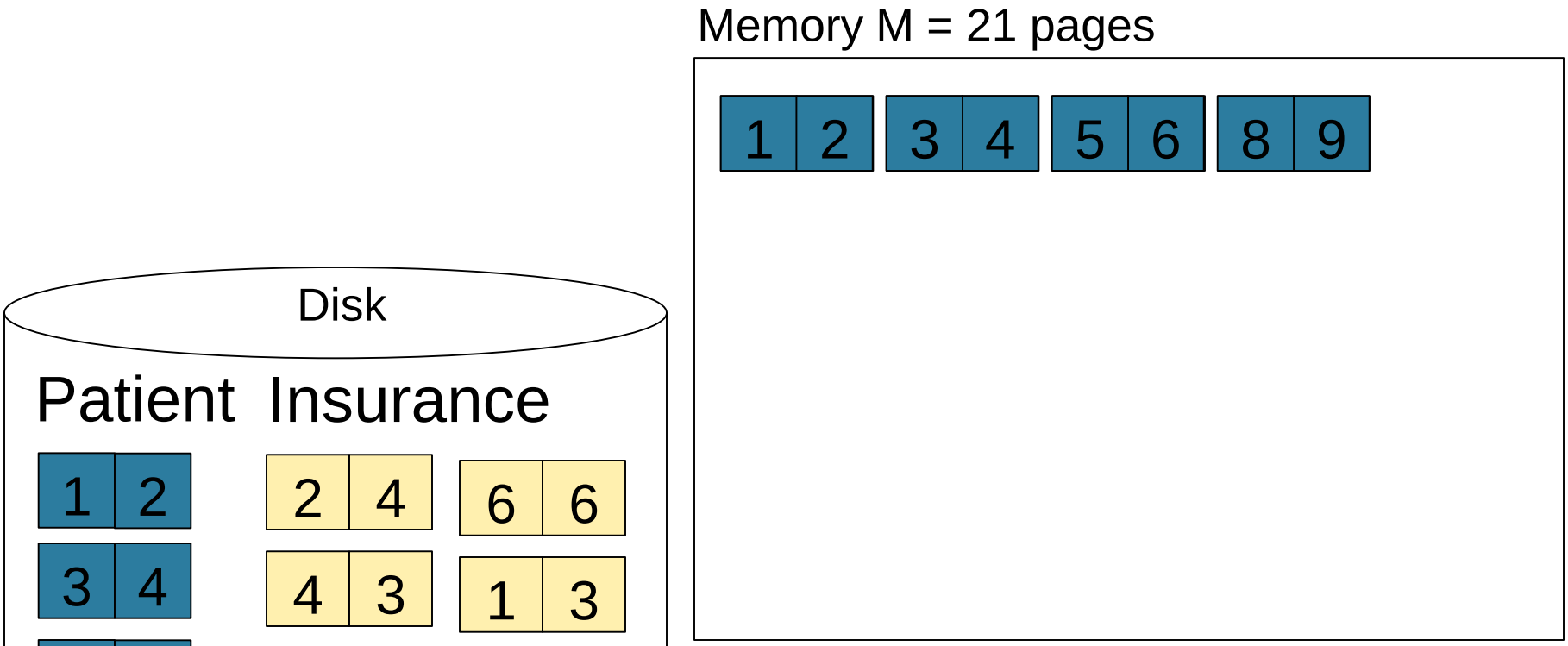
Sort-merge join: $R \bowtie S$

- 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

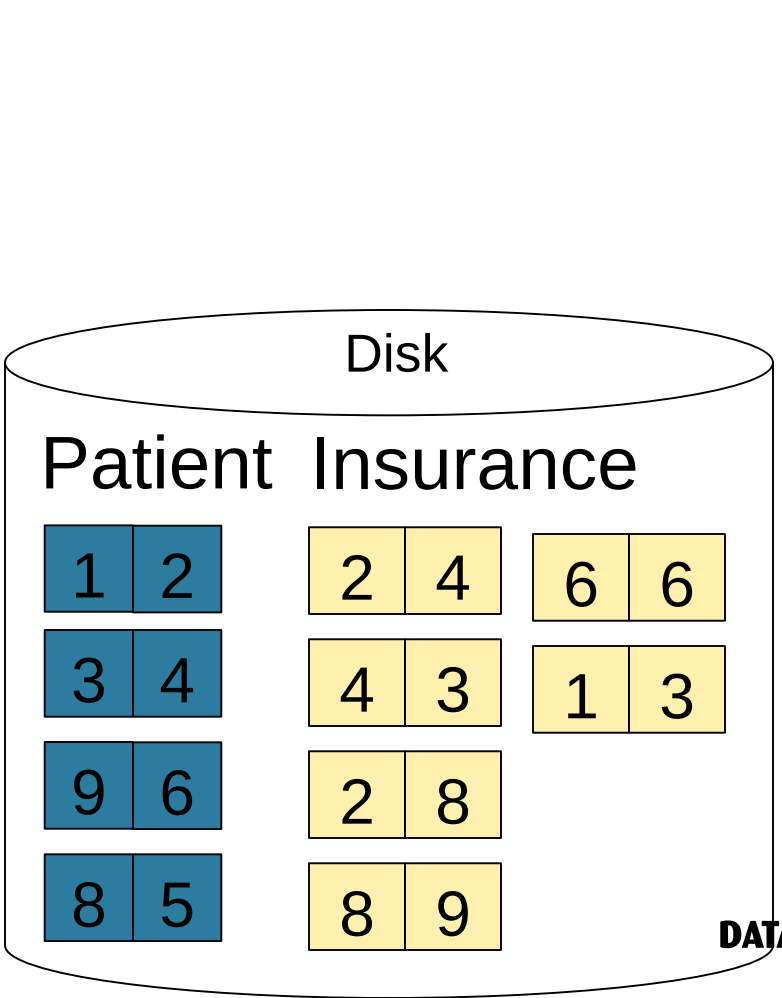
Sort-Merge Join Example

Step 1: Scan Patient and sort in memory

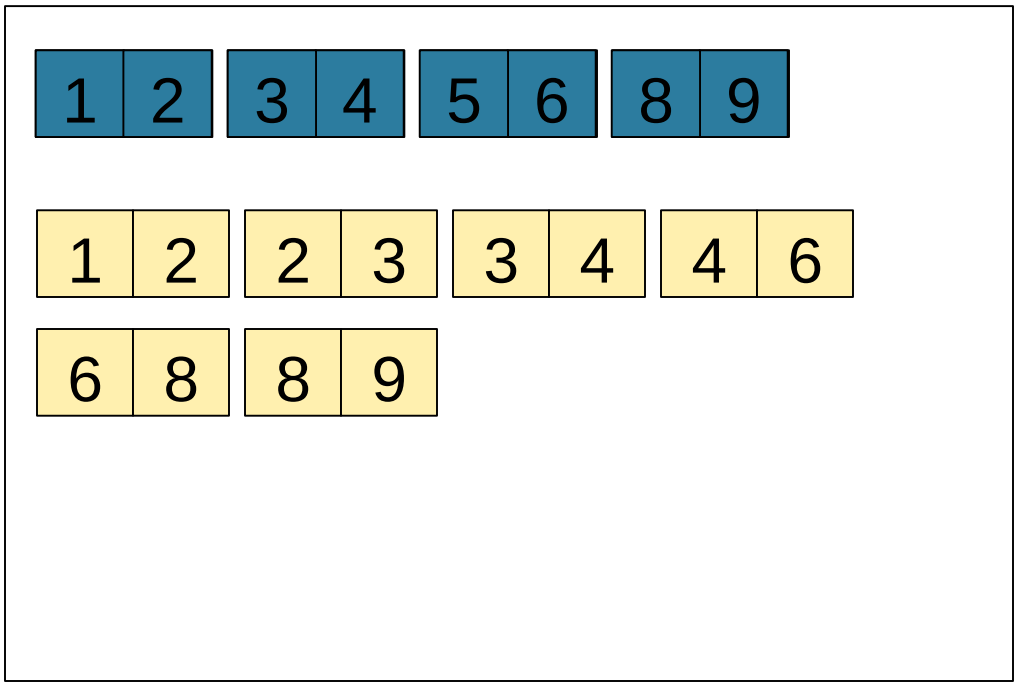


Sort-Merge Join Example

Step 2: Scan Insurance and sort in memory

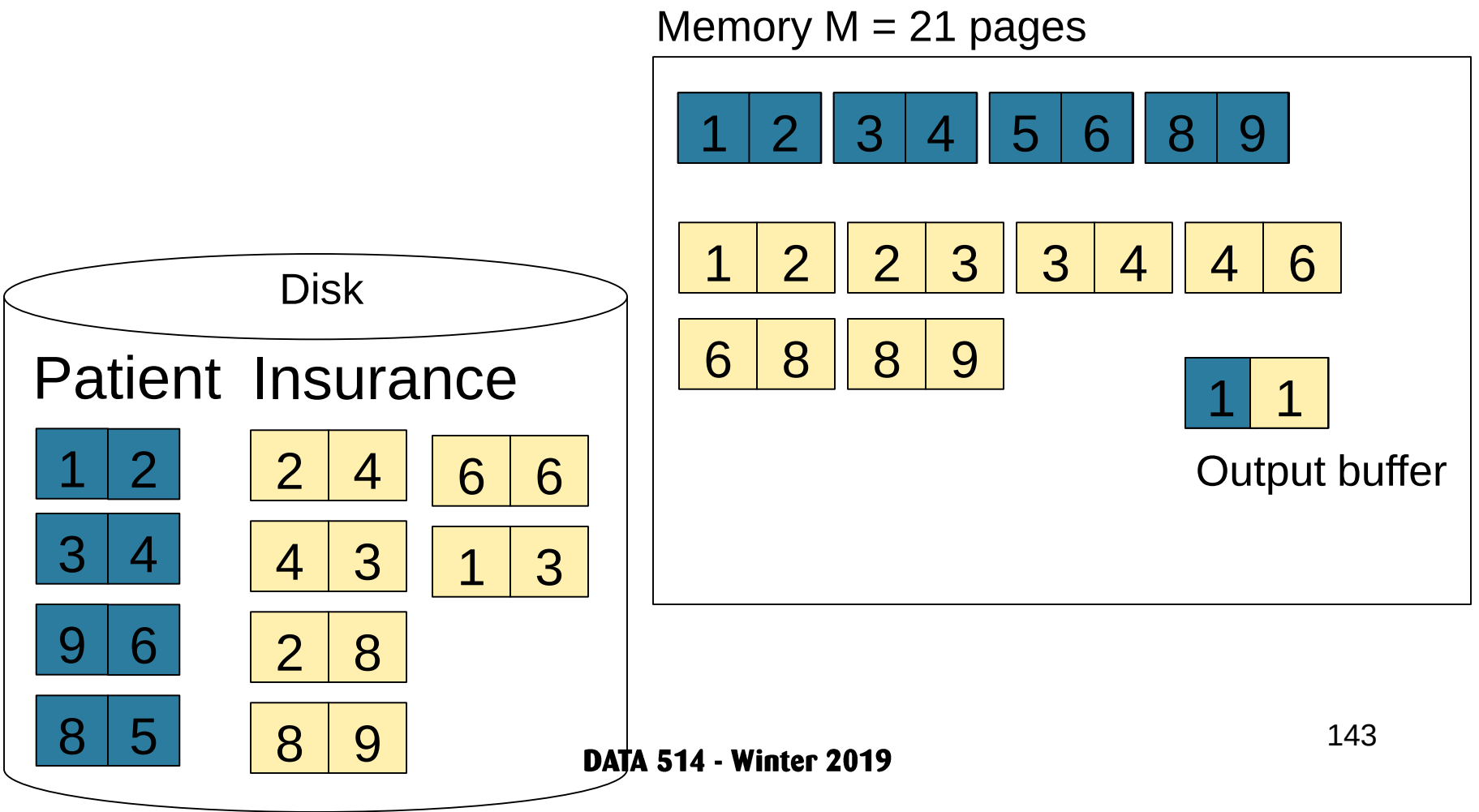


Memory M = 21 pages



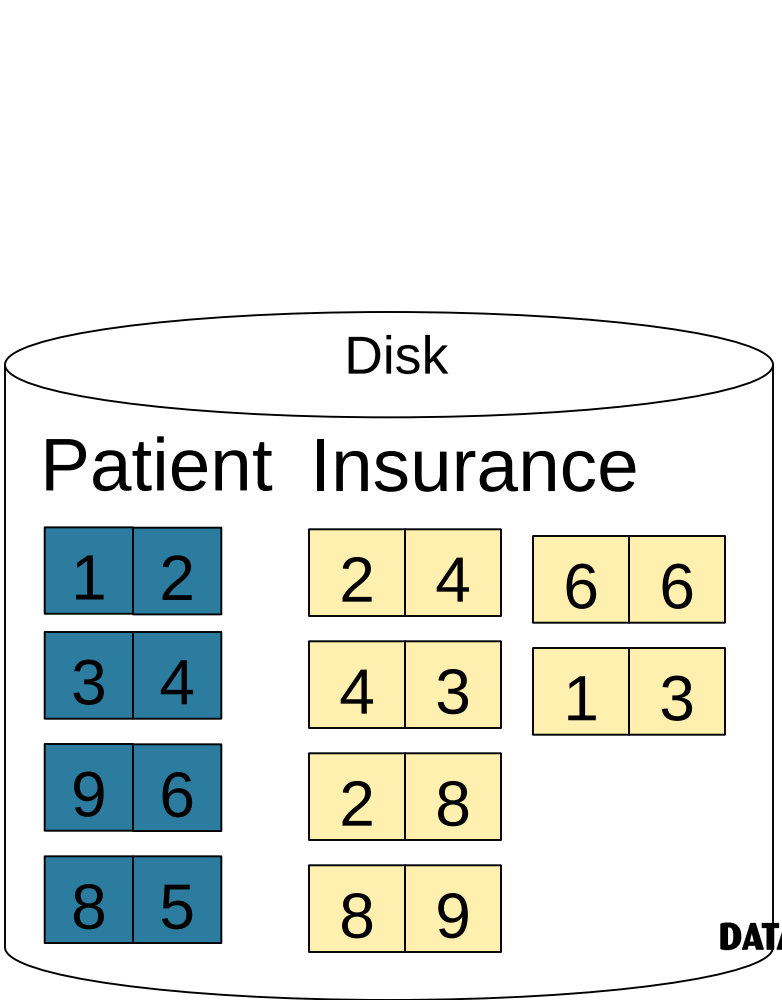
Sort-Merge Join Example

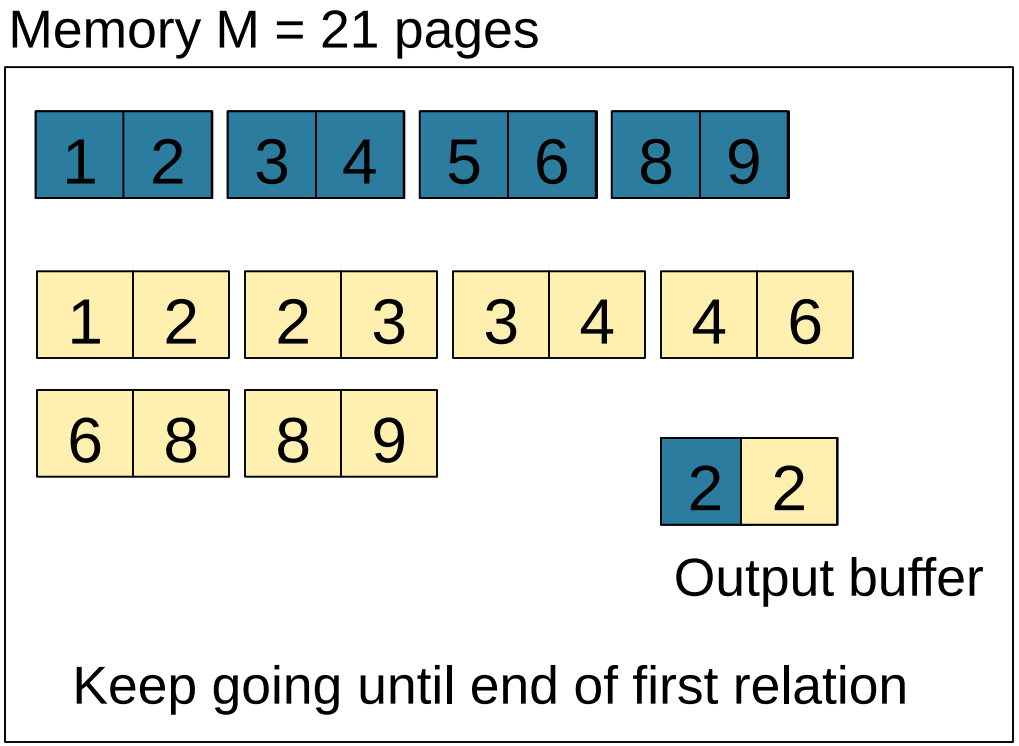
Step 3: Merge Patient and Insurance



Sort-Merge Join Example

Step 3: Merge Patient and Insurance





Index Nested Loop Join

R ⋈ S

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

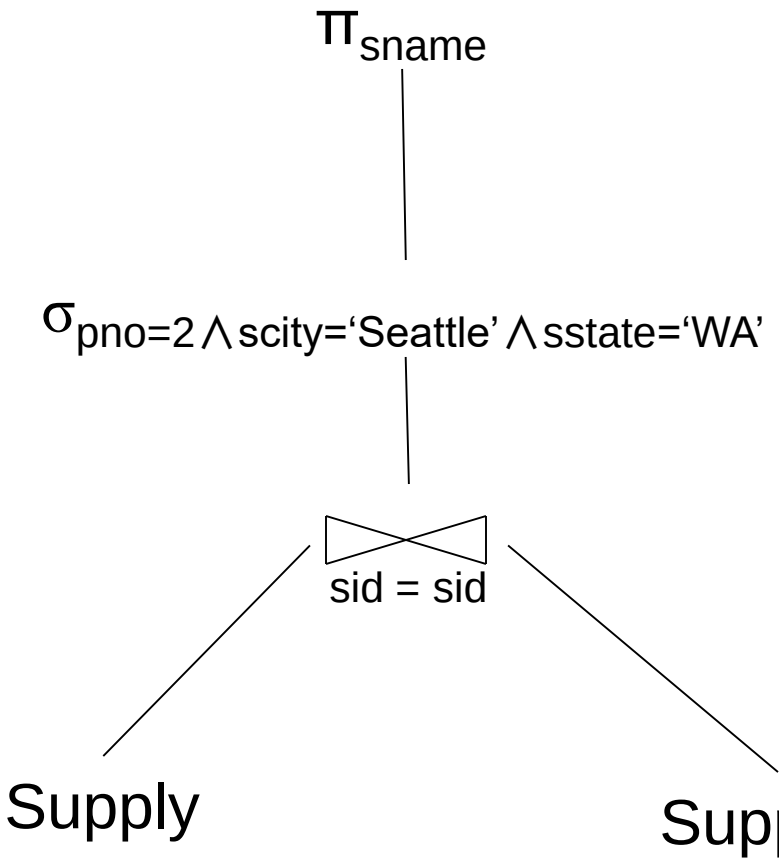
- **Cost**:
  - If index on S is clustered:
    B(R) + T(R) * (B(S) * 1/V(S,a))
  - If index on S is unclustered:
    B(R) + T(R) * (T(S) * 1/V(S,a))

Cost of Query Plans

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

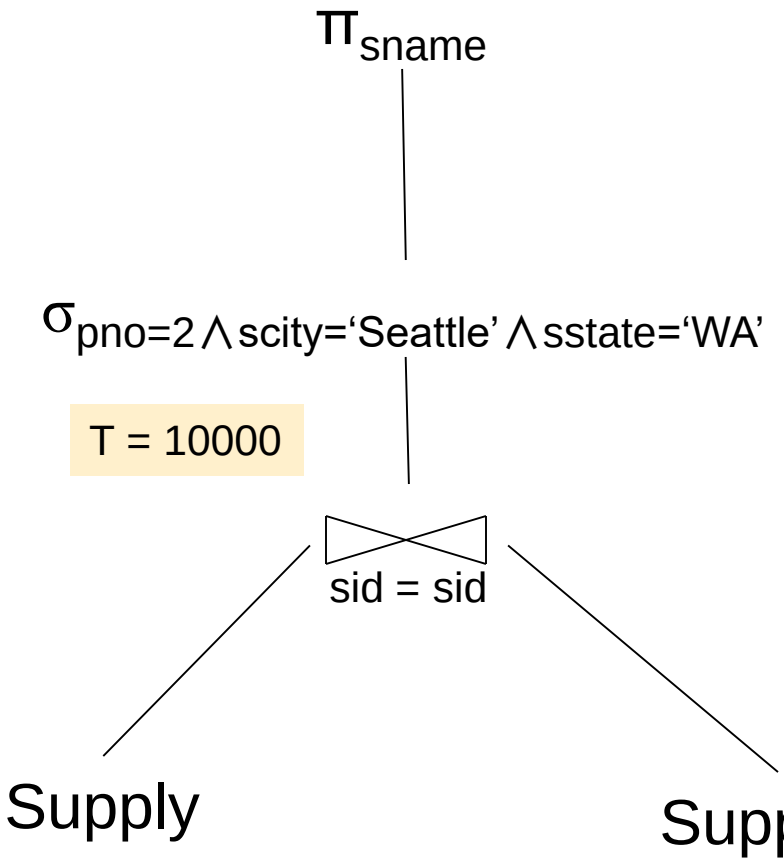
T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Logical Query Plan 1

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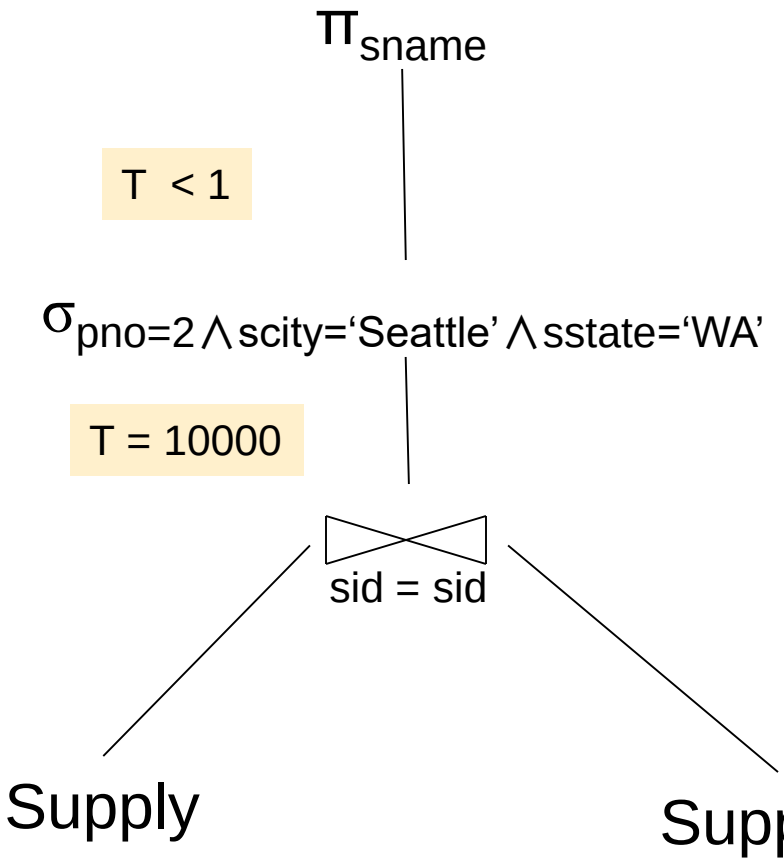
Logical Query Plan 1

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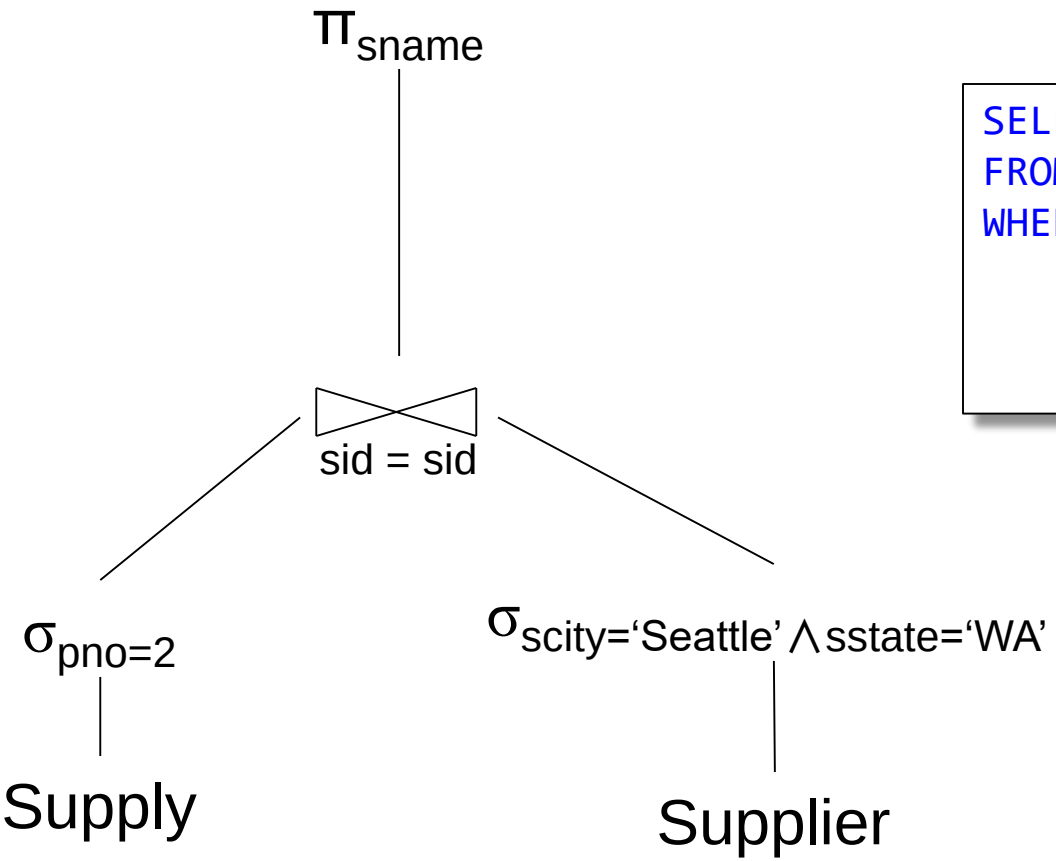
Logical Query Plan 2

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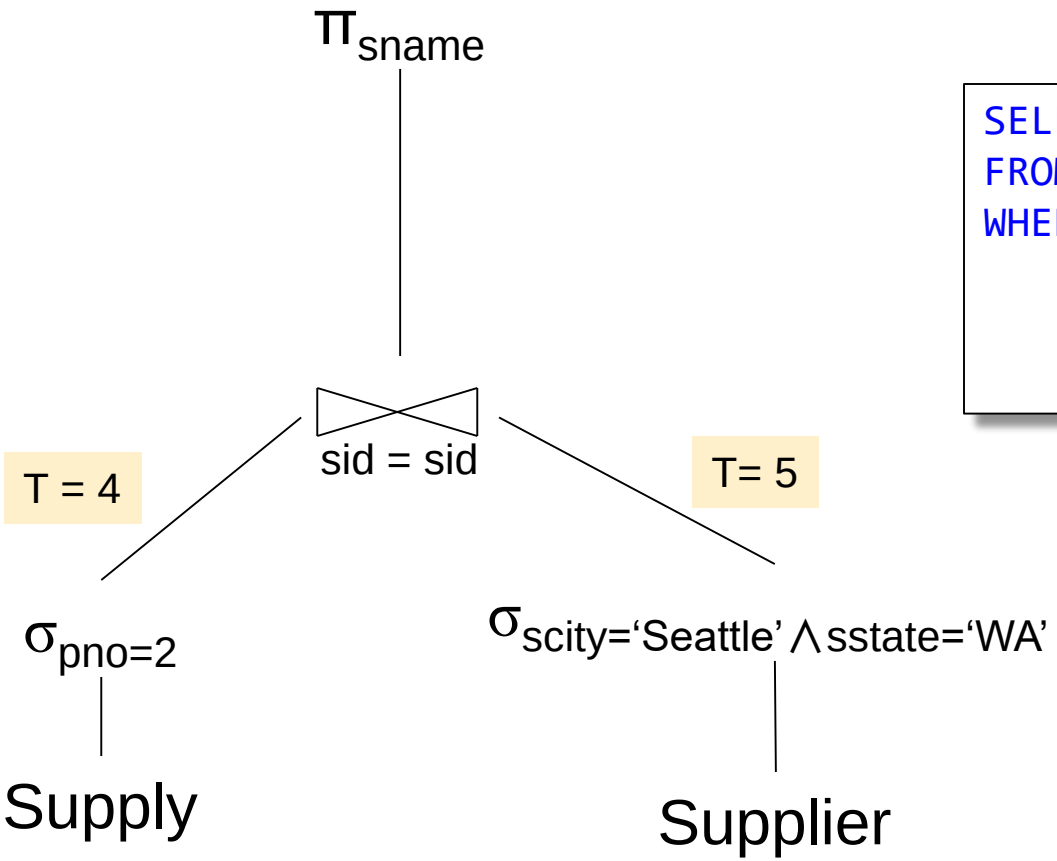


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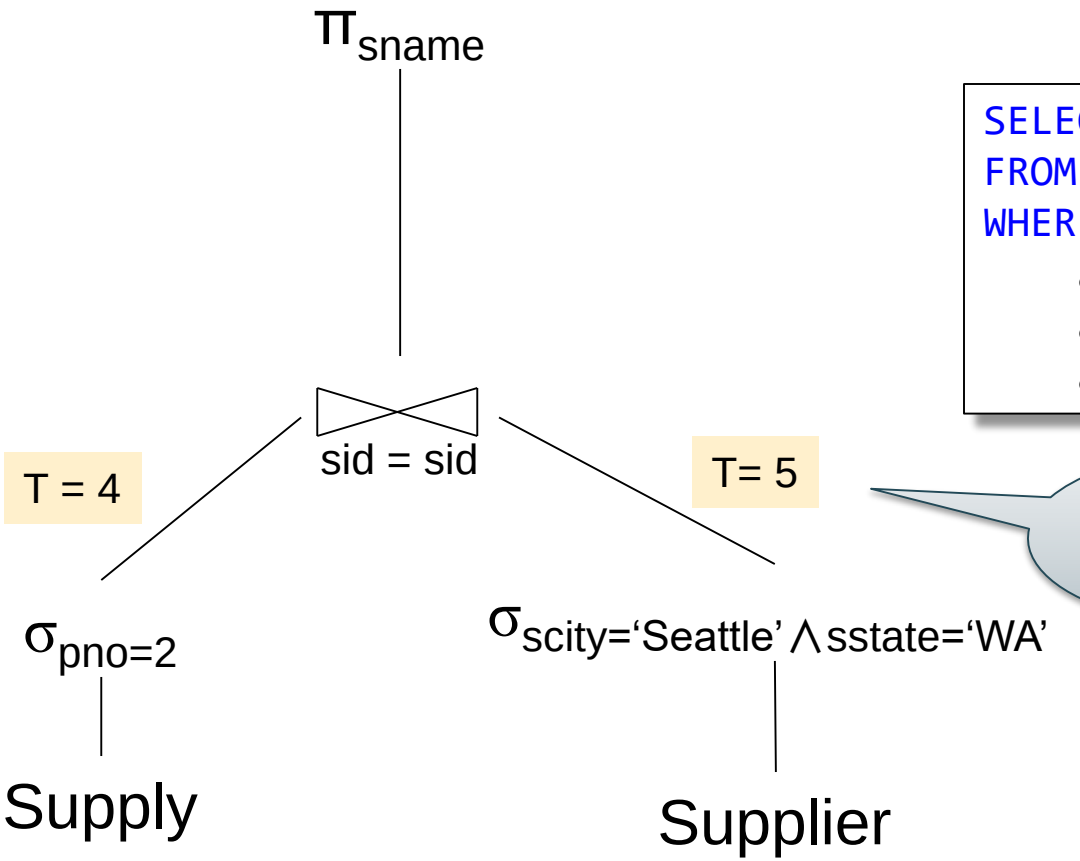


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Very wrong!
Why?

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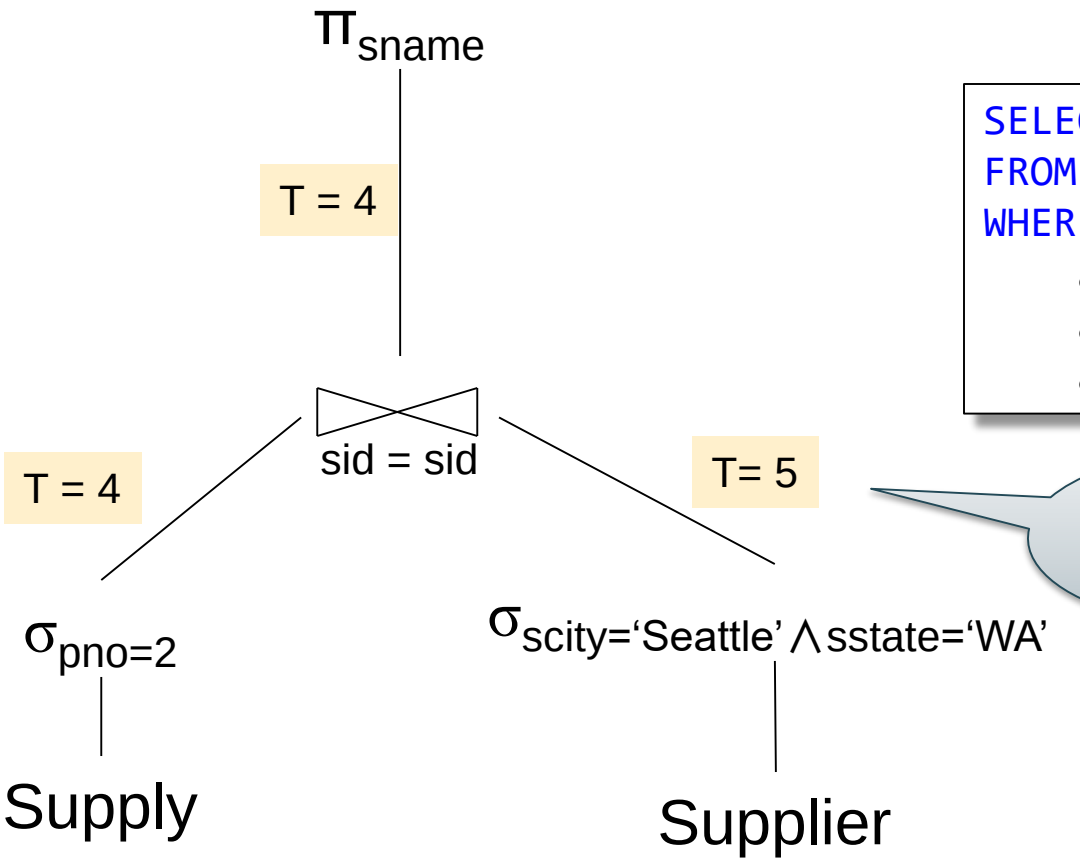
Logical Query Plan 2

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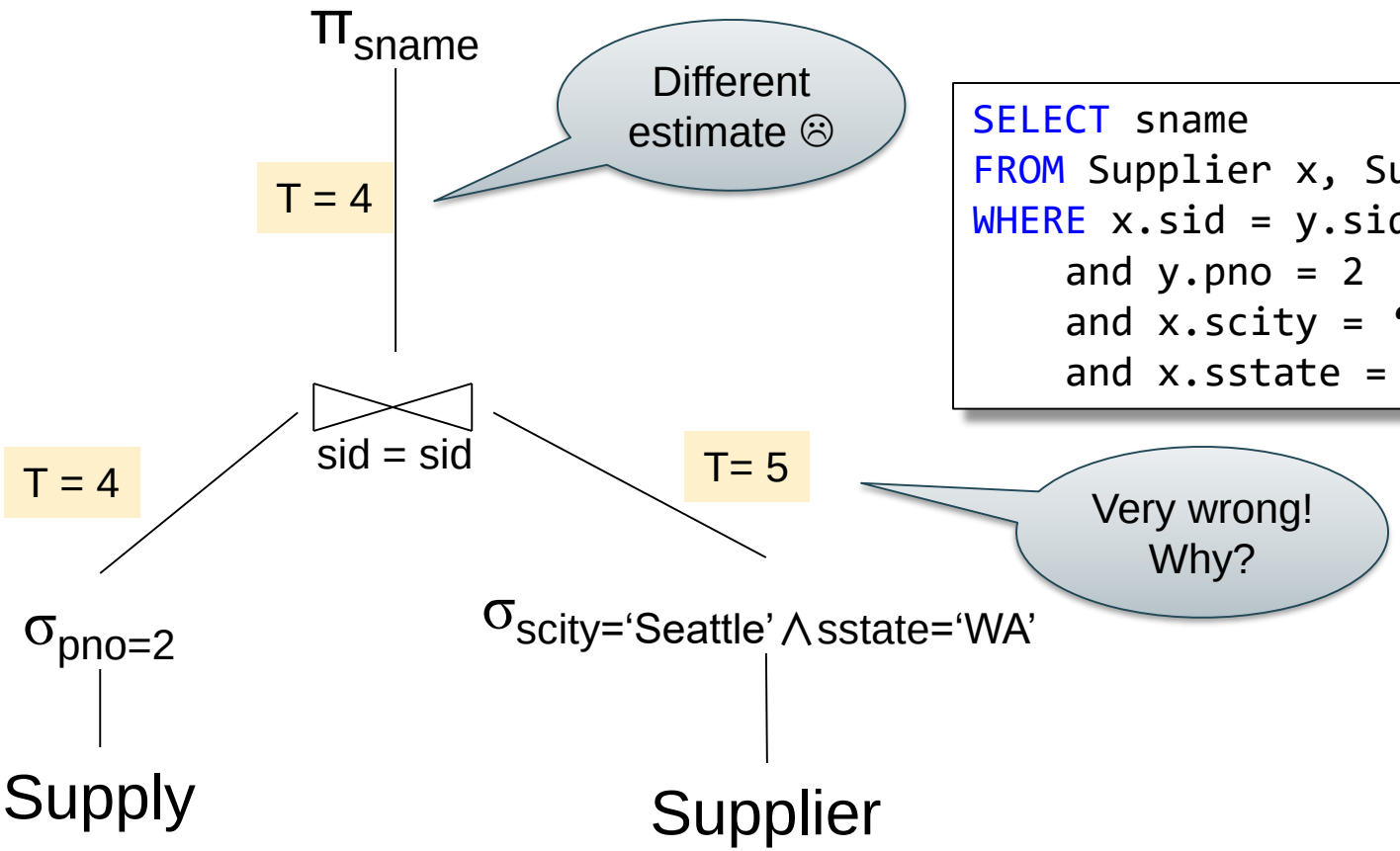
Supply(sid, pno, quantity)

Logical Query Plan 2

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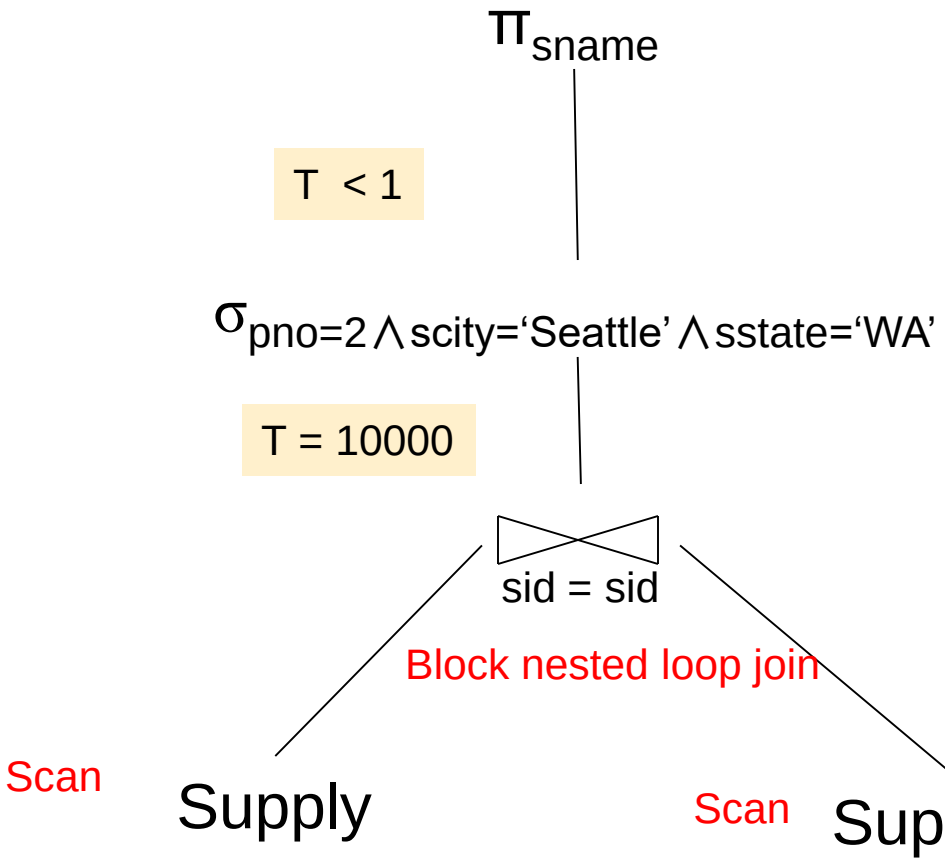
M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Physical Plan 1



Total cost:

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

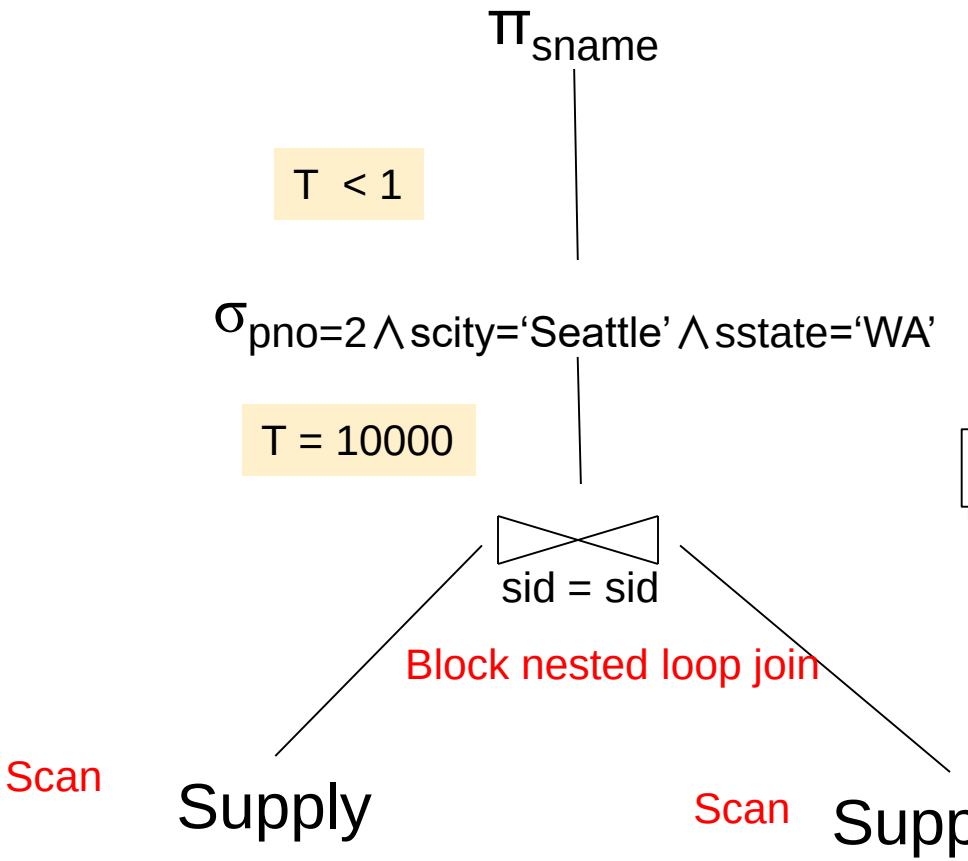
T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Physical Plan 1



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

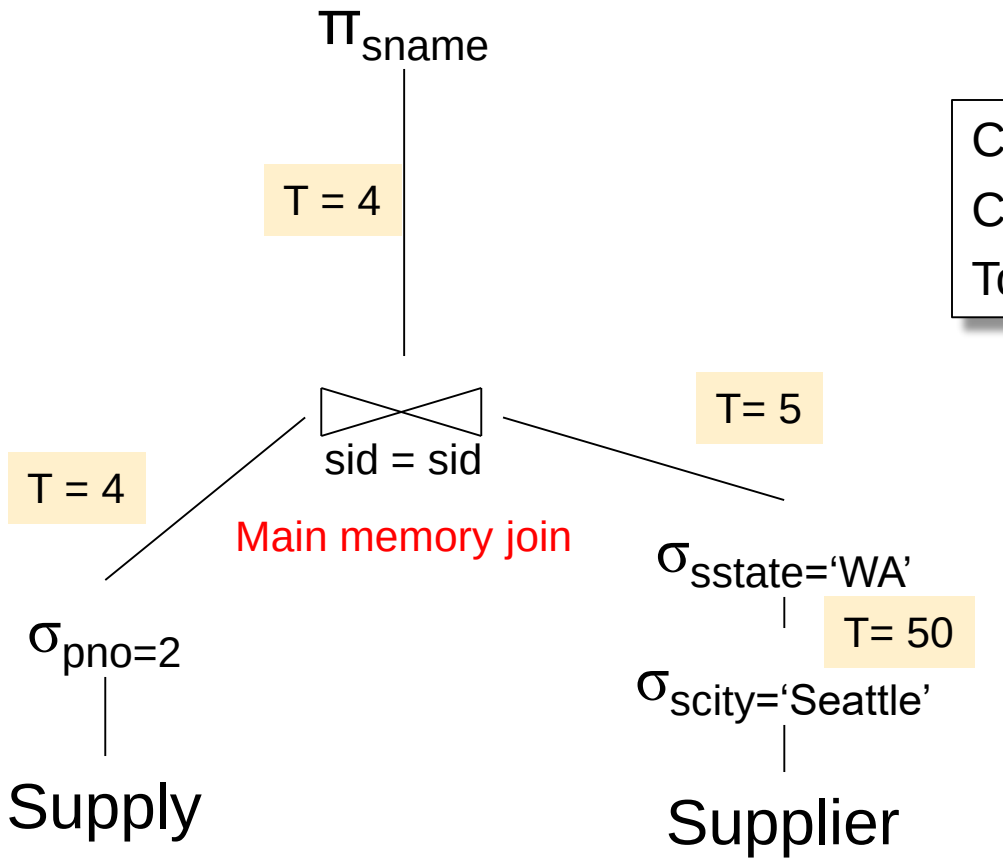
T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

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

M=11

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

Physical Plan 2



Unclustered index lookup Supply(pno)

Unclustered index lookup Supplier(scity)

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

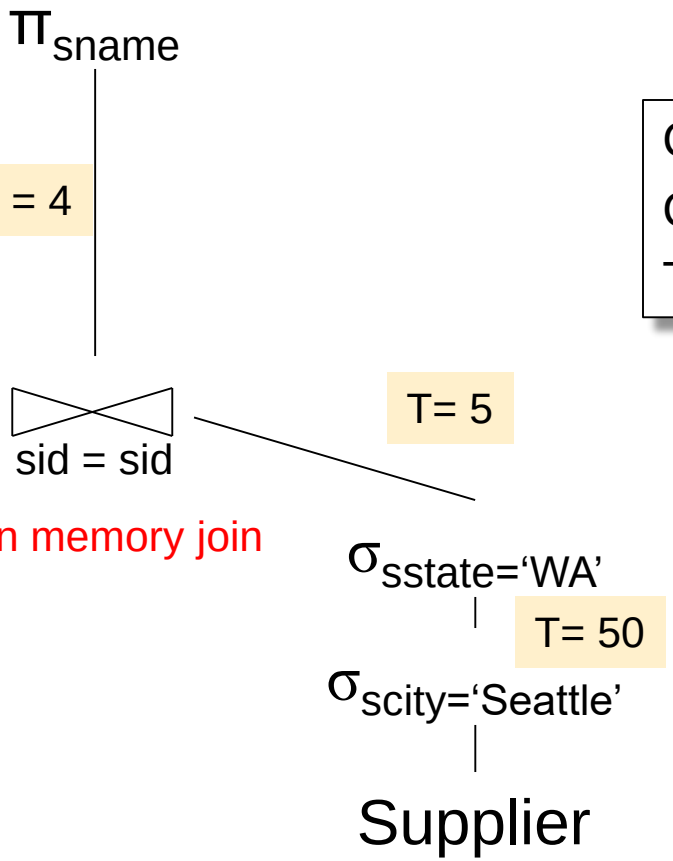
T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

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

M=11

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

Physical Plan 2



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

Unclustered index lookup Supply(pno)

Unclustered index lookup Supplier(scity)

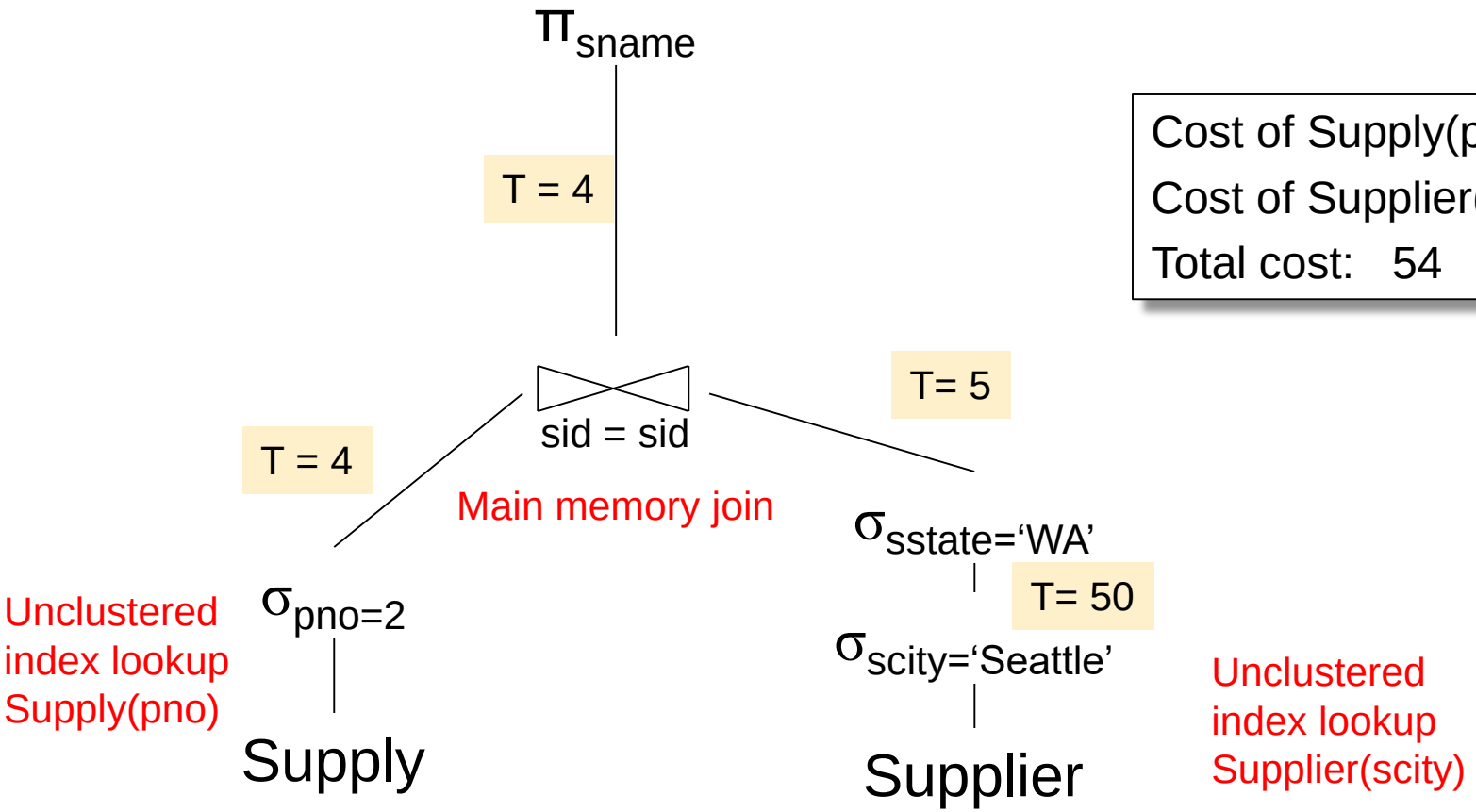
T(Supply) = 10000
B(Supply) = 100
V(Supply, pno) = 2500

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

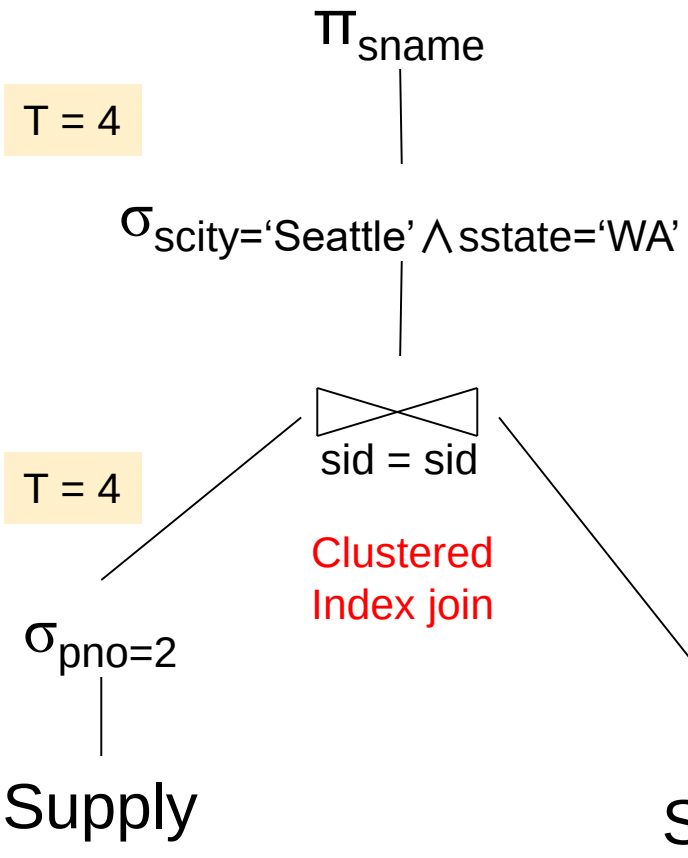
T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

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

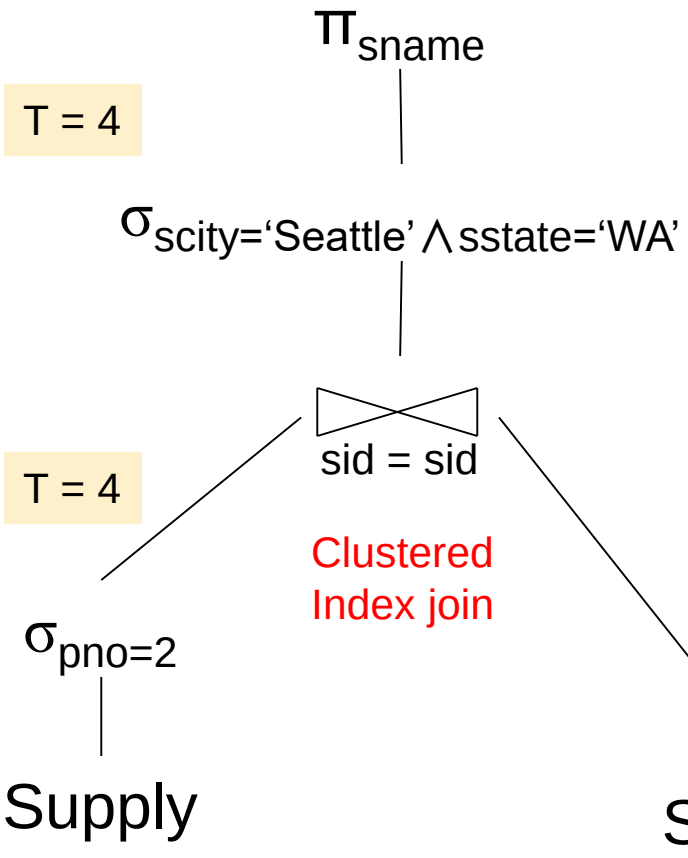
T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

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

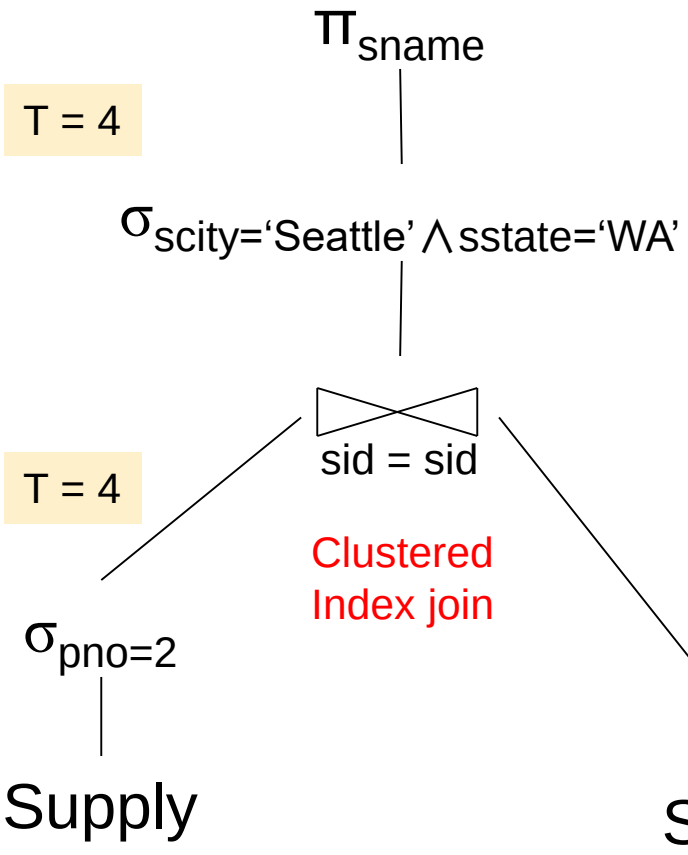
T(Supplier) = 1000
B(Supplier) = 100
V(Supplier, scity) = 20
V(Supplier, state) = 10

M=11

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, 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