Database Systems
CSE 344

Lecture 10:
Basics of Data Storage and Indexes
(Ch. 8.3-4, 14.1-1.7, & skim 14.2-3)

Announcements

- WQ3 - Due Tonight at 11pm

- HW3 is due **next** Tuesday
  - please get started on software setup

Index Objectives

- To understand performance, need to understand a bit about how a DBMS works
  - my database application is too slow… why?
  - one of the queries is very slow… why?
- Understanding query optimization
  - we have seen SQL query ~> logical plan (RA), but not much about RA ~> physical plan
- Choice of indexes is often up to you

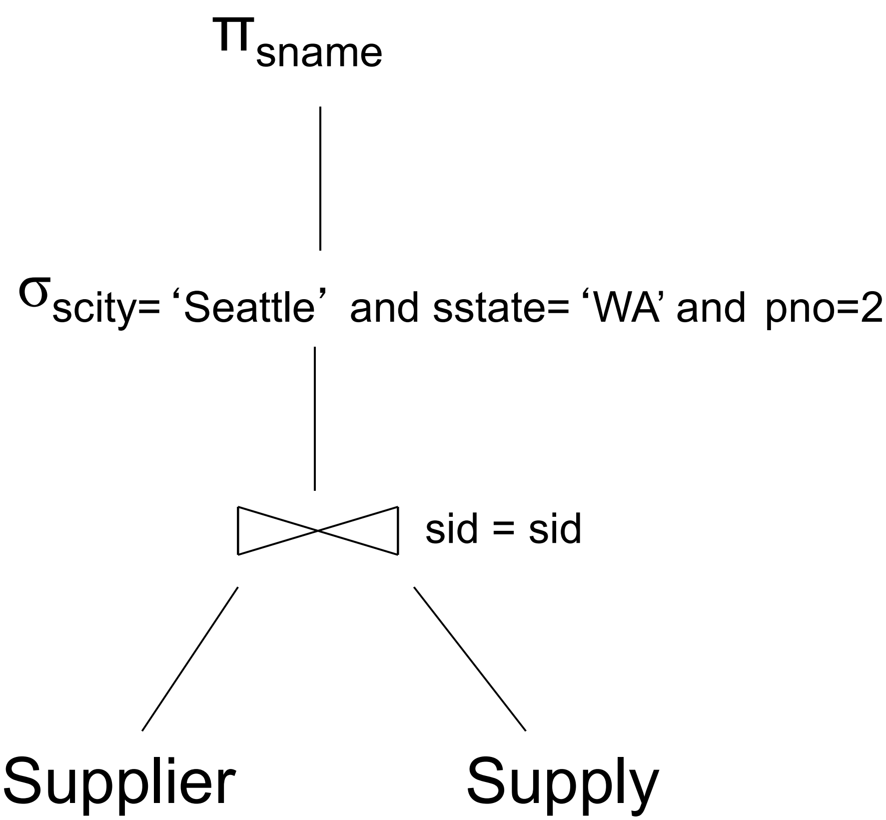
Review

- Logical plans
- Physical plans
- Overview of query optimization and execution

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

Review: Relational Algebra

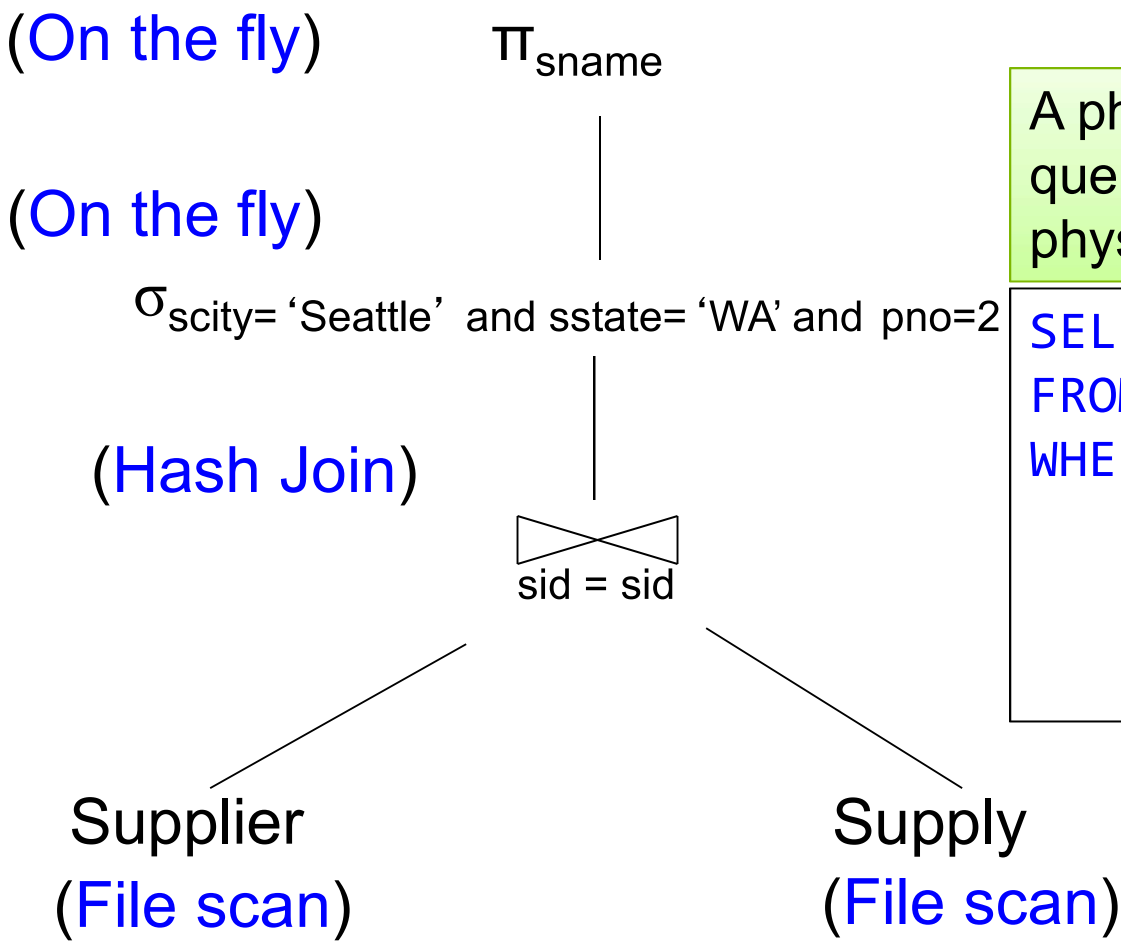
```
SELECT sname
FROM Supplier x, Supply y
WHERE x.sid = y.sid
    and  y.pno = 2
    and x.scity = 'Seattle'
    and x.sstate = 'WA'
```



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

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

Review: Physical Query Plan Example



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

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

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

  - For most of this course we will focus on **disk-based** DBMSs

Data Storage

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

- DBMSs store data in **files**
- Most common organization is row-wise storage:
  - File is split into blocks
  - Each block contains a set of tuples
- DBMS reads entire block

block 1

10	Tom	Hanks
20	Amy	Hanks

block 2

50	…	…
200	…	

block 3

220		
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*

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 using our DB.

Index

- An **additional** file, that allows fast access to records in the data file given a search key
- The index contains (key, value) pairs:
  - The key = an attribute value (e.g., student ID or name)
  - The value = a pointer to the record Blok, offset
- Could have many indexes for one table

Key = means here search key

This  Is Not A Key

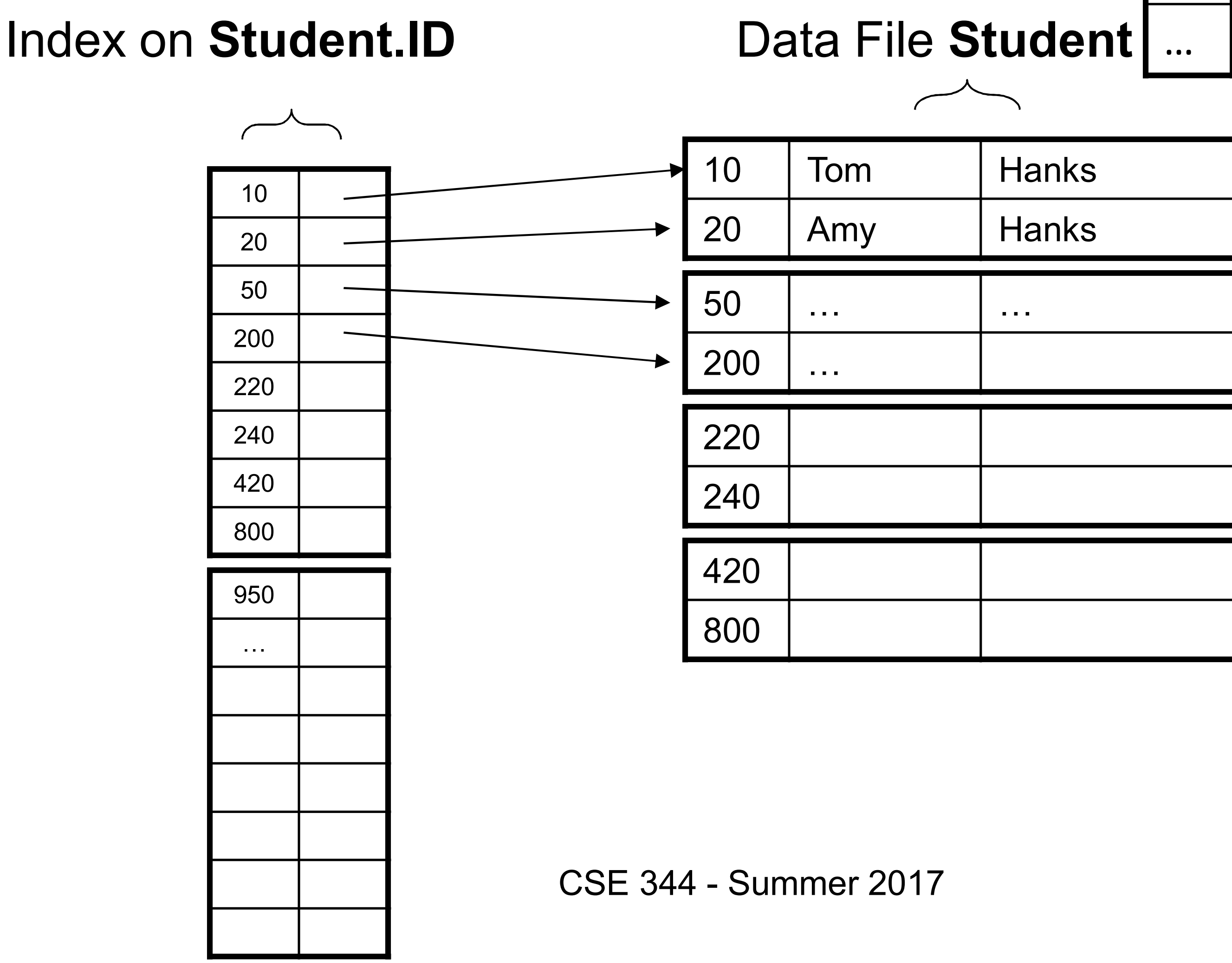
Different keys:

- 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

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

Example 1: Index on ID



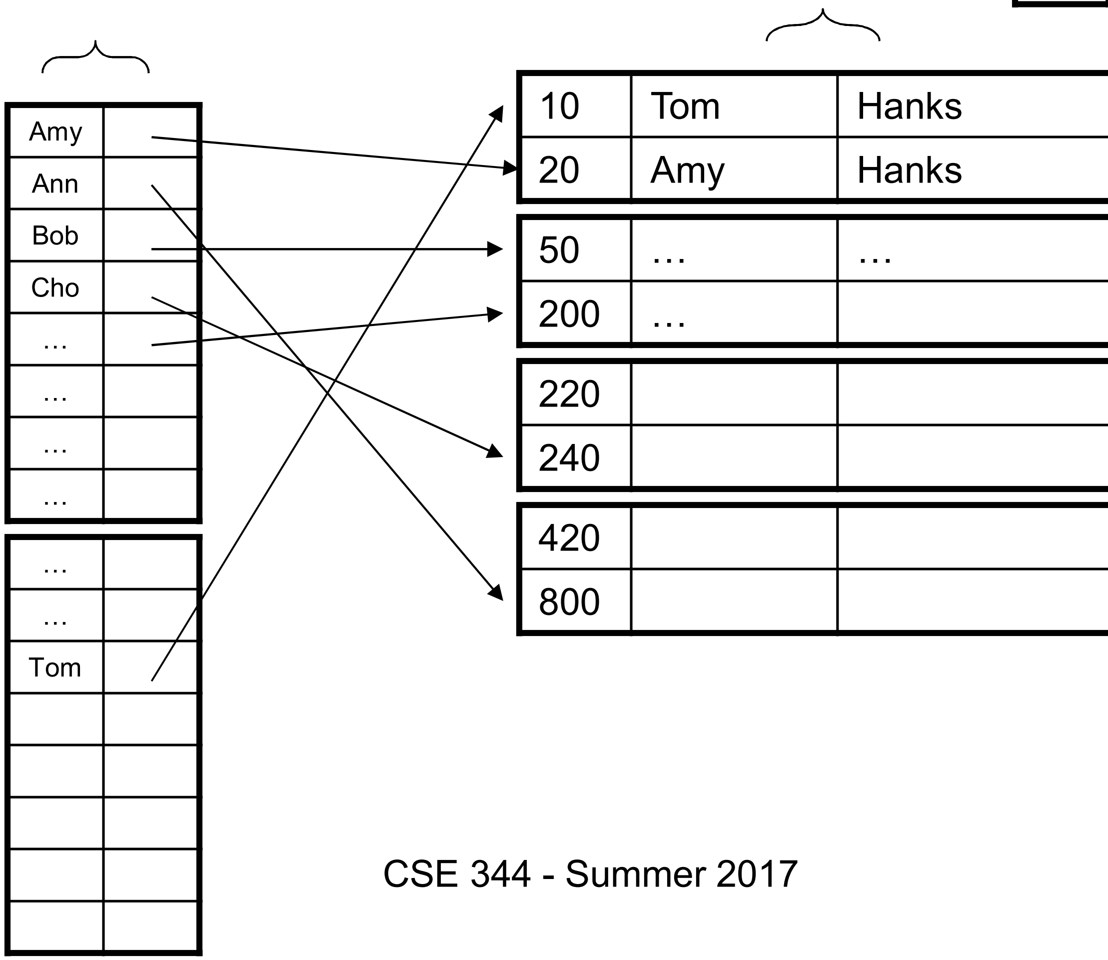
Example 2: Index on fName

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

Index on **Student.fName**

Data File **Student**



Index Organization

We need a way to represent indexes after loading into memory

Several ways to do this:

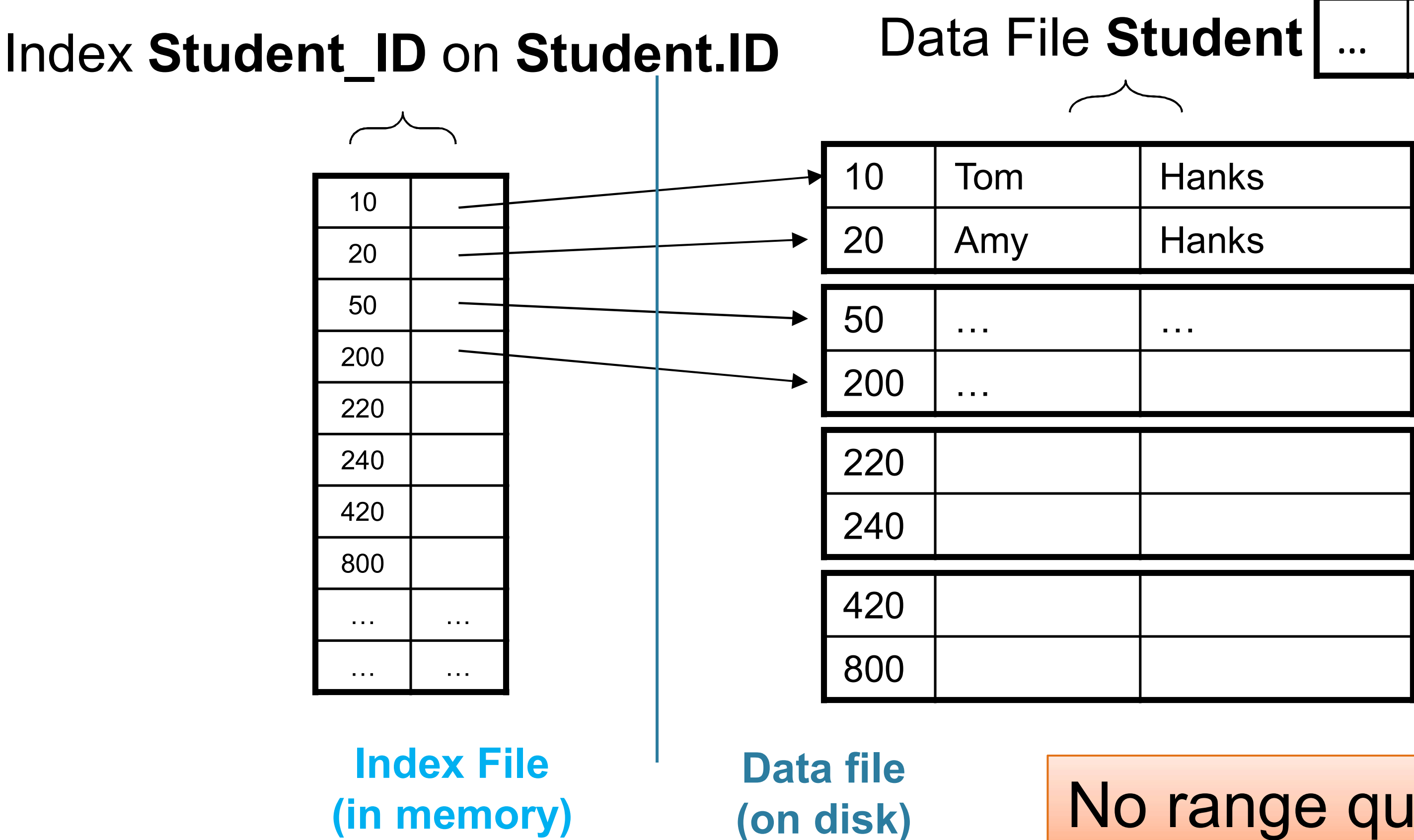
- Hash table
- B+ trees – most popular
  - They are search trees, but they are not binary instead have higher fanout
  - Will discuss them briefly next
- Specialized indexes: bit maps, R-trees, inverted index

↳ Boolean

Hash table example

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		



No range queries!

(Each level is a fraction of the size of the one below)

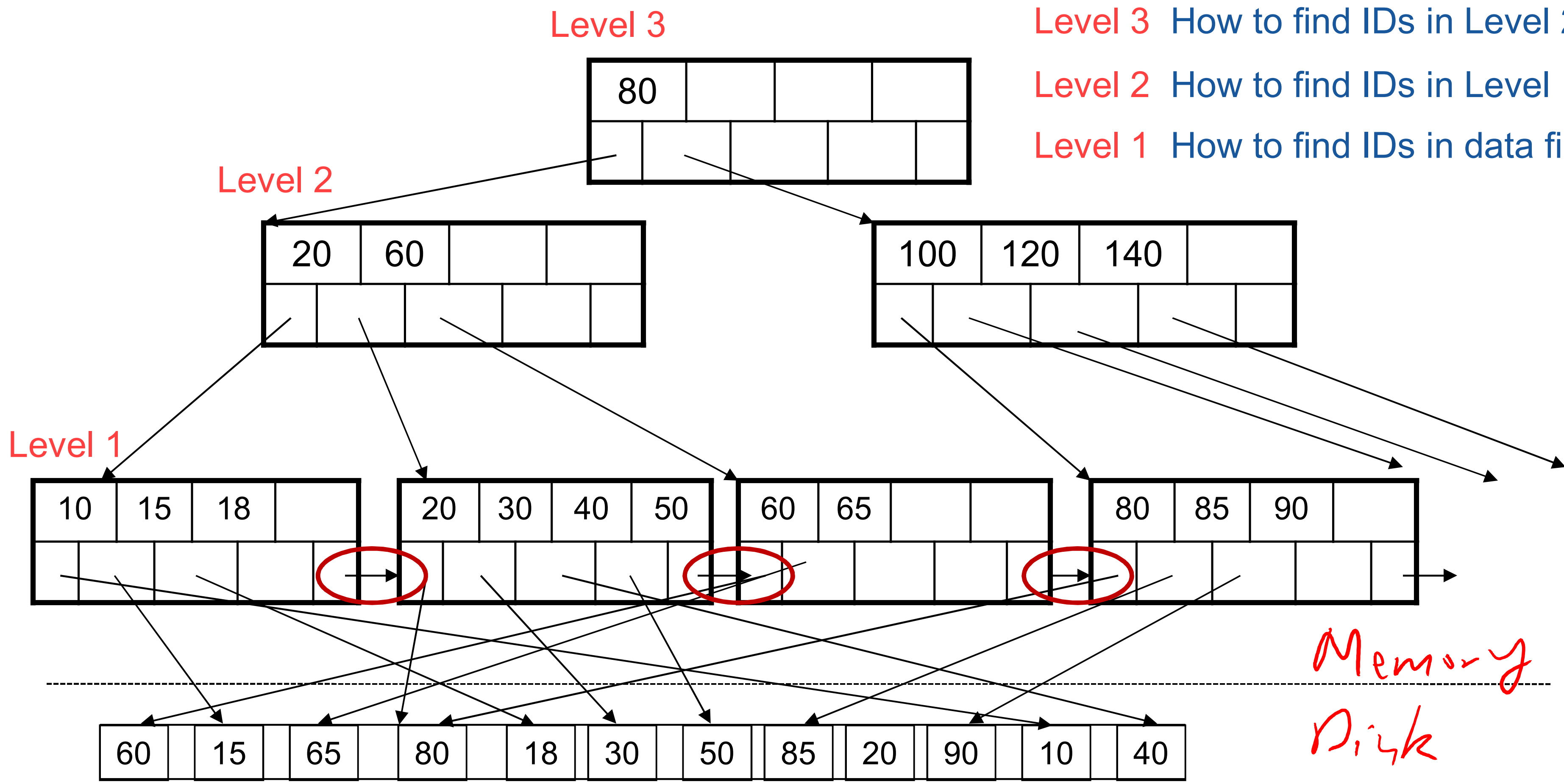
Recap: B+ Tree

…

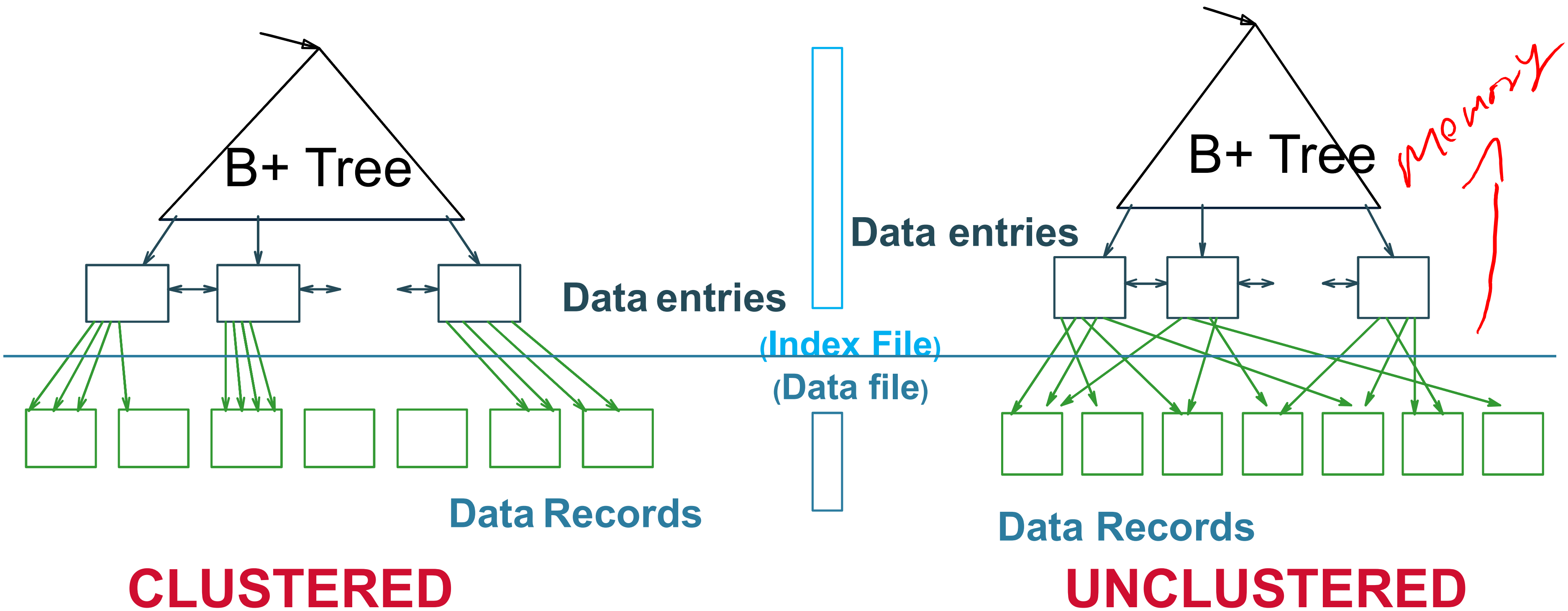
Level 3 How to find IDs in Level 2

Level 2 How to find IDs in Level 1

Level 1 How to find IDs in data file



Clustered vs Unclustered



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

SQL Server defaults to cluster by **primary key**

Index Classification

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

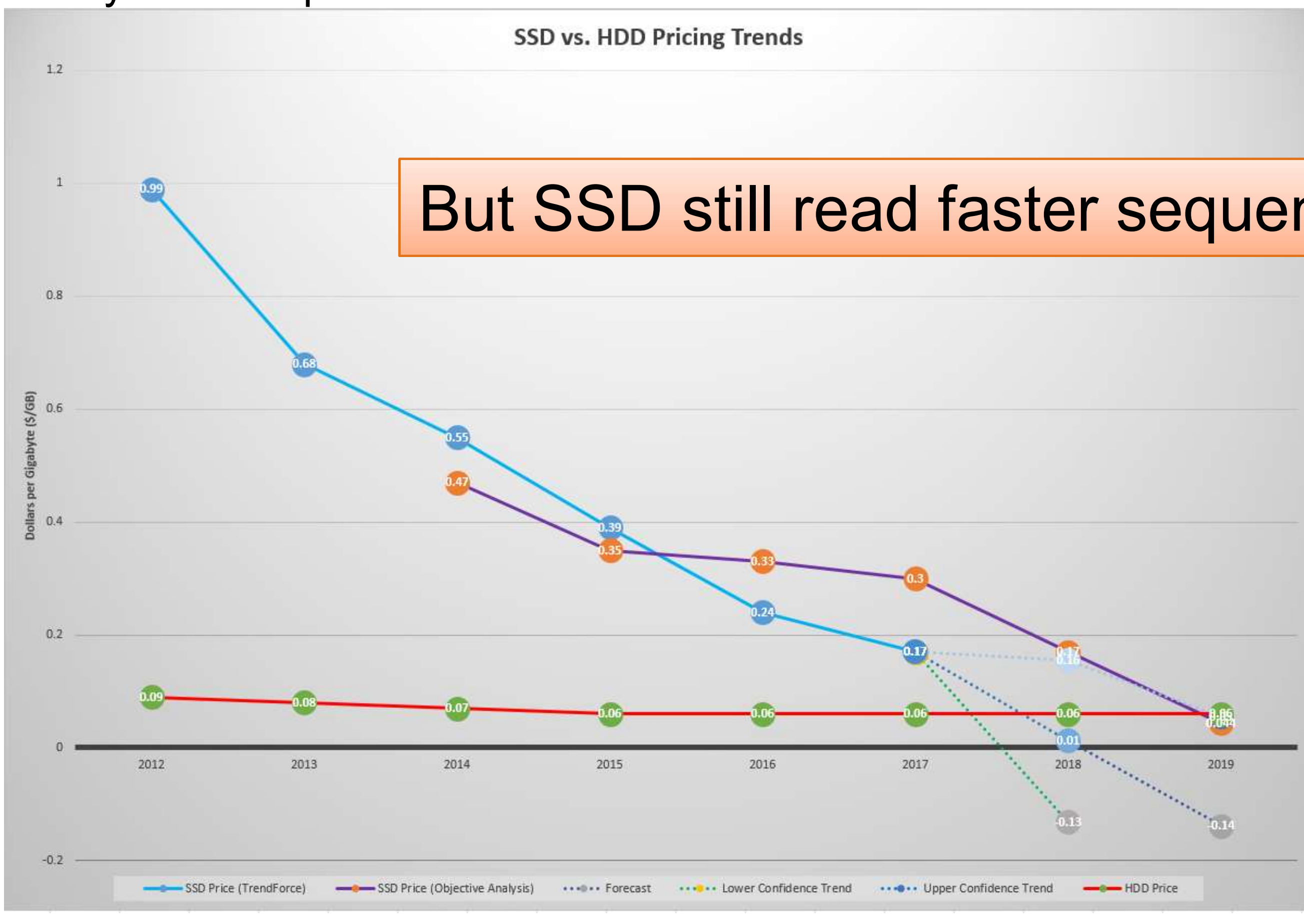
Scanning a Data File

- Hard disks are mechanical devices!
  - Technology from the 60s; density much higher now
- We 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, … jumping around

- 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)

HDD ~> SSD

- Solid state (SSD): used to be too expensive… not any more
  - entirely different performance characteristics!



But SSD still read faster sequentially

Takes(studentID, courseID)

Student(studentID, name, …)

Example

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

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

Assume the database has indexes on these attributes:

- **index_takes_course** = index on Takes.courseID
- **index_studentID** = index on Student.ID

Index selection

Index join

```
for y1 in index_takes_course where y1.courseID = 300
   for y in y1.Takes
       for x1 in index_studentID where x.ID = y.studentID
          for x in x1.Student
            output x.*,y.*
```

Getting Practical: Creating Indexes in SQL

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

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

Drop index V1;

```
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

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

Which Indexes?

- How many indexes could we create?

15, eg: (ID), (fName), (lName), (ID,fName),(fName,ID),…

- Which indexes should we create?

→ create index after import

Few! Each new index slows down updates to Student

Index selection is a hard problem

Student

ID	fName	lName
10	Tom	Hanks
20	Amy	Hanks
…		

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:
  - database administrator DBA
  - 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

Index Selection Problem

V(M, N, P);

Suppose the database has the index I1 below. Discuss physical query plans for these queries.

INDEX I1 on V(M)

```
SELECT *
FROM V
WHERE V.M = 33
```

```
Scan V
For each record:
  if M=33 then output
```

```
Lookup key 33 in I1
For each record: output
```

```
SELECT *
FROM V
WHERE V.M = 33 and V.P = 55
```

```
Scan V
For each record:
  if M=33 and P=55 then output
```

```
Lookup key 33 in I1
For each record
  if P=55 then output
```

Index Selection Problem 1

V(M, N, P);

Your workload is this (and nothing else)

100000 queries:

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

100 queries:

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

What indexes ?

Index Selection Problem 1

V(M, N, P);

Your workload is this (and nothing else)

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)

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 ?

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)

Index Selection Problem 3

V(M, N, P);

Your workload is this

100,000 queries:

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

1,000,000 queries:

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

100,000 queries:

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

What indexes ?

Index Selection Problem 3

V(M, N, P);

Your workload is this

100,000 queries:

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

no P

1,000,000 queries:

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

100,000 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)?

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 ?

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

Index Selection Problem 5

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

```
SELECT *
FROM V
WHERE V.M = 33
```

```
SELECT *
FROM V
WHERE V.M = 33 and V.P = 55
```

Suppose the database has these indexes. Which ones can the optimizer use?

INDEX I1 on V(M)

INDEX I2 on V(M,P)

INDEX I3 on V(P,M)

Recap – Indexes

V(M, N, P);

```
SELECT *
FROM V
WHERE V.M = 33
```

Yes

```
SELECT *
FROM V
WHERE V.M = 33 and V.P = 55
```

Suppose the database has these indexes. Which ones can the optimizer use?

INDEX I1 on V(M)

INDEX I2 on V(M,P)

INDEX I3 on V(P,M)

Recap – Indexes

V(M, N, P);

Suppose the database has these indexes. Which ones can the optimizer use?

```
SELECT *
FROM V
WHERE V.M = 33
```

Yes (why?)

INDEX I1 on V(M)

INDEX I2 on V(M,P)

Yes

```
SELECT *
FROM V
WHERE V.M = 33 and V.P = 55
```

INDEX I3 on V(P,M)

Recap – Indexes

V(M, N, P);

```
SELECT *
FROM V
WHERE V.M = 33
```

```
SELECT *
FROM V
WHERE V.M = 33 and V.P = 55
```

Suppose the database has these indexes. Which ones can the optimizer use?

INDEX I1 on V(M)

INDEX I2 on V(M,P)

No! (why?)

Yes

INDEX I3 on V(P,M)

Recap – Indexes

Movie(mid, title, year)

CLUSTERED INDEX I on Movie(id)
INDEX J on Movie(year)

```
SELECT *
FROM Movie
WHERE year = 2010
```

```
SELECT *
FROM Movie
WHERE year = 1910
```

The system uses the index J for one of the queries, but not for the other.

Which and why?

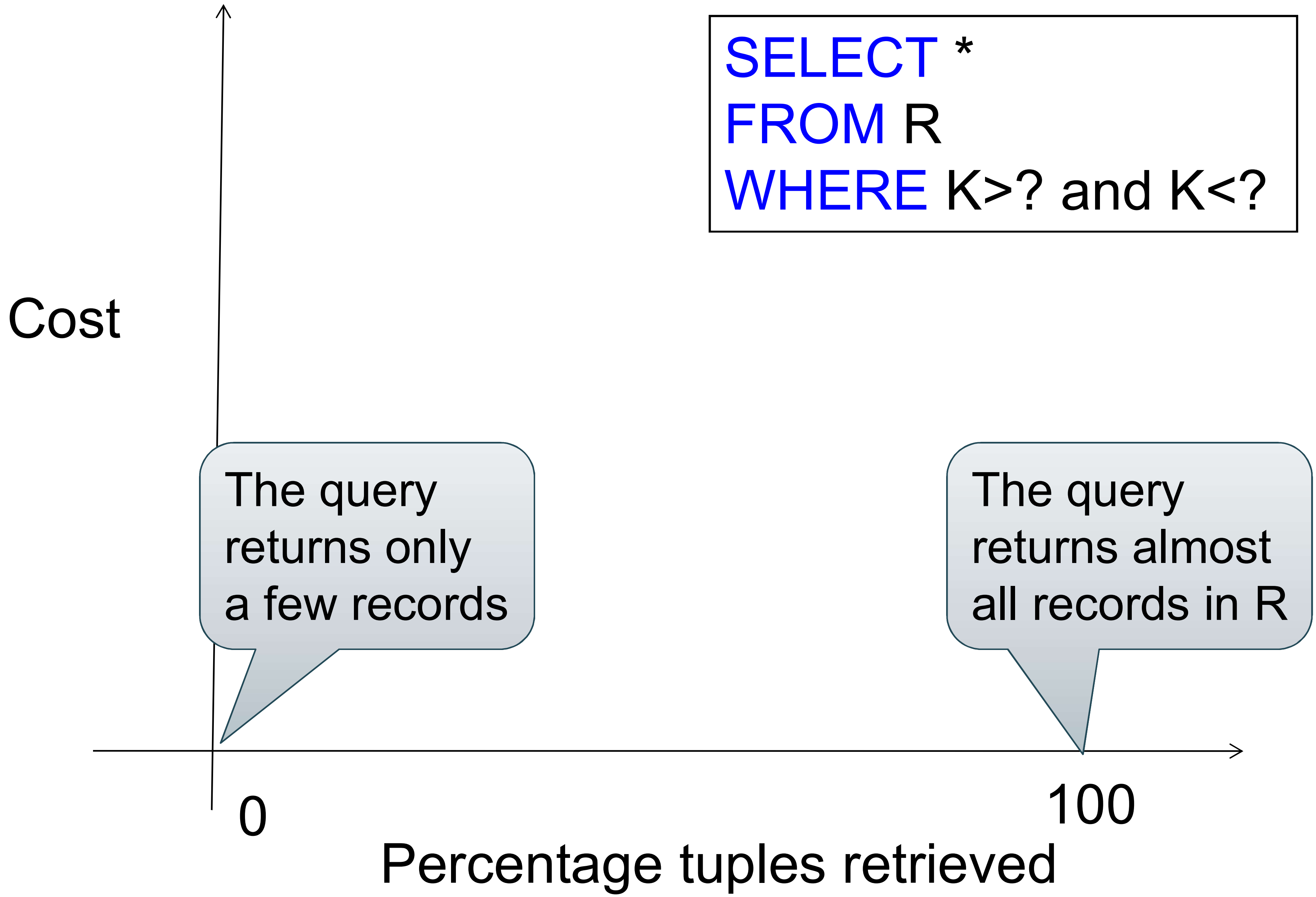
Basic Index Selection Guidelines

- Consider queries in workload in order of importance
  - ignore infrequent queries if you also have many writes
- 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
  - (a covering index for a query is one where every attribute mentioned in the query is part of the index's search key)
  - in that case, index has all the info you need anyway

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



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