Administrivia

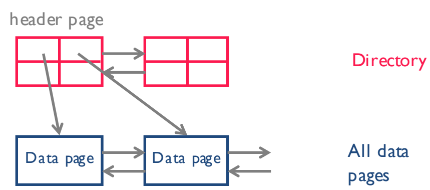
Proj 1 Part 3 Due 11:59PM EST

DB Connection issues

Virtual env + pip install vs sudo pip install

L20
Indexing Continued

Alternative: Use a directory



Directory entries track #free bytes on data pages

Directory is collection of pages

Indexes

"If I had eight hours to chop down a tree,
I'd spend six sharpening my ax."

Abraham Lincoln

Indexes

Heap files can get data by sequential scan

Queries use *qualifications* (predicates)
- find students in "CS"
- find students from CA

Indexes
- file structures for value-based queries
- B+-tree index (~1970s)
- Hash index

Overview! Details in 4112

Indexes

Defined wrt a *search key*

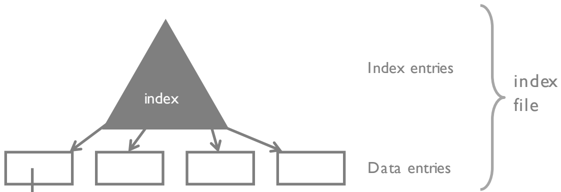
- different than a candidate key!

Faster access for WHERE clauses w/ search key

```
CREATE INDEX idx1 ON users USING btree (sid)
CREATE INDEX idx2 ON users USING hash  (sid)
CREATE INDEX idx3 ON users USING btree (age,name)
```

You will play around with indexes in HW4

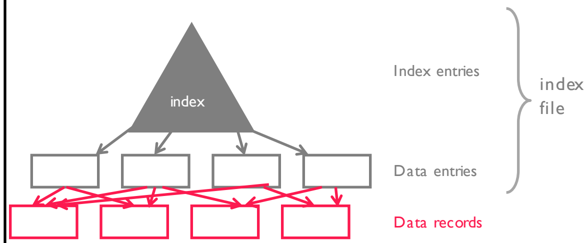
High level (Primary) index structure



<6, 18, josh, cs, swimming>
<2, 19, bob, cs, running>

What is a data entry?
actual data record

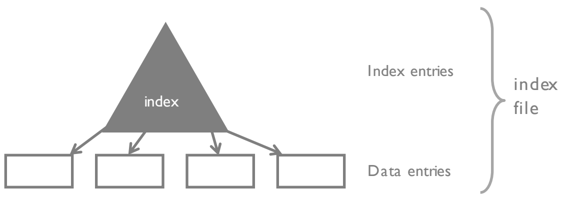
High level (Secondary) index structure



What is a data entry?
actual data record
<search key value, rid>

Tradeoffs
directly access tuple.
compact, fixed size entries

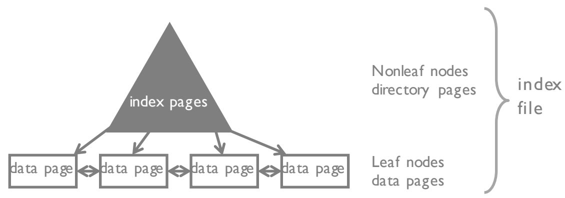
High level index structure



What is a data entry?
actual data record
<search key value, rid>

Tradeoffs
directly access tuple.
compact, fixed size entries

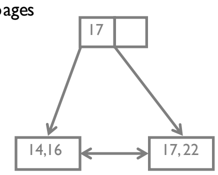
B+ Tree Index



Node = Page
Equality and range queries
Self balancing
Leaf nodes are connected
Disk optimized

B+ Tree on (age)

Non-leaf directory pages
m index entries
m+1 pointers

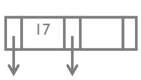


index & data
page contents
are in order

Leaf Data pages
data entries/tuples

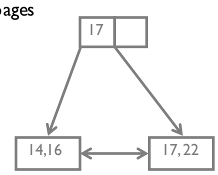
Query: SELECT * WHERE age= 14

directory page



Index Only Queries: B+ Tree on (age)

Non-leaf directory pages
m index entries
m+1 pointers

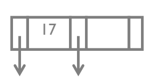


index & data
page contents
are in order

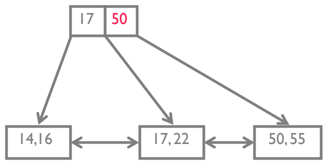
Leaf Data pages
data entries/tuples

Query: SELECT age WHERE age = 14
(index only!)

directory page

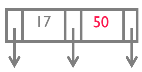


B+ Tree on (age)

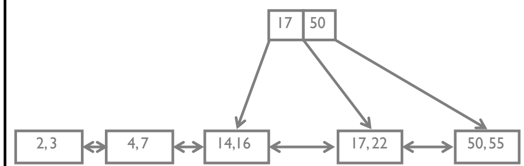


Query: SELECT * WHERE age = 50

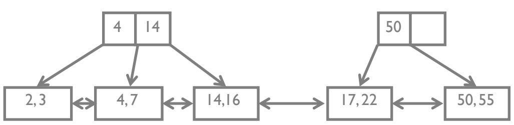
directory page



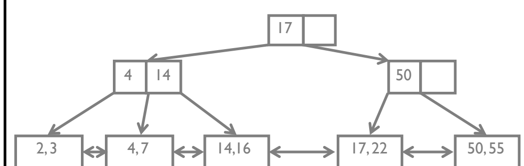
B+ Tree on (age)



B+ Tree on (age)

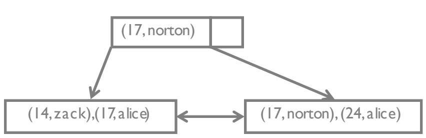


B+ Tree on (age)



Query: SELECT * WHERE age > 15

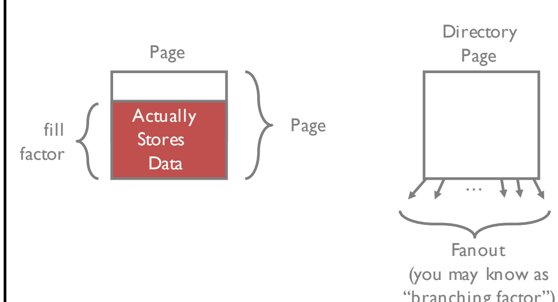
B+ Tree on (age, name)



How do the following queries use the index on (age, name)?

```
SELECT  age    WHERE  age  = 14
SELECT  *      WHERE  age  < 18  AND  name  <  'monica'
SELECT  age    WHERE  name  =  'bobby'
```

Terminology



Some numbers (8kb pages)

How many levels?

- fill-factor: ~66%
- ~300 entries per directory page

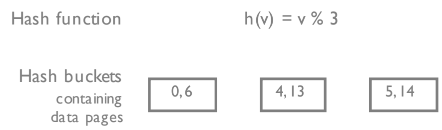
- height 2: 300^3 ~ 27 Million entries
- height 3: 300^4 ~ 8.1 Billion entries

Top levels often in memory

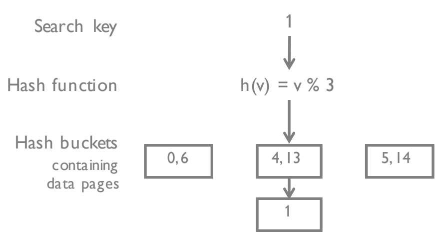
- height 2 only 300 pages ~2.4MB
- height 3 only 90k pages ~750MB

Cool B+ Tree viz: https://www.cs.usfca.edu/~galles/visualization/BPlusTree.html

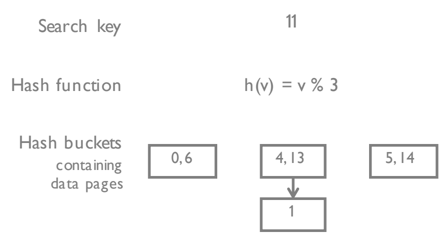
Hash Index on age



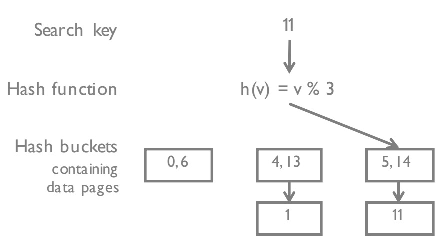
INSERT Hash Index on age



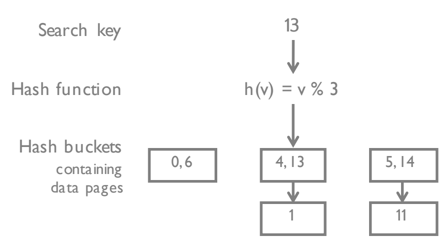
INSERT Hash Index on age



INSERT Hash Index on age



SEARCH Hash Index on age



Good for equality selections
Index = data pages + overflow data pages
Hash function h(v) takes as input the *search key*

Costs

Three file types

- Heap, B+ Tree, Hash

Operations we care about

- Scan all data SELECT * FROM R
- Equality SELECT * FROM R WHERE x = 1
- Range SELECT * FROM R WHERE 10 < x and x < 50
- Insert record
- Delete record

	Heap File	Sorted Heap	B+ Tree	Hash
Scan everything				
Equality				
Range				
Insert				
Delete				

B # *data* pages
D time to read/write page
M # pages in range query

	Heap File	Sorted Heap	B+ Tree	Hash
Scan everything	BD			
Equality	0.5BD (avg)			
Range	BD			
Insert	2D			
Delete	Search + D			

Heap File
- equality on a key. How many results?

B # *data* pages
D time to read/write page
M # pages in range query

	Heap File	Sorted Heap	B+ Tree	Hash
Scan everything	BD	BD		
Equality	0.5BD	D($\log_2$B)		
Range	BD	D($\log_2$B + M)		
Insert	2D	Search + BD		
Delete	Search + D	Search + BD		

Heap File
- equality on a key. How many results?

Sorted File
- files compacted after deletion

B # *data* pages
D time to read/write page
M # pages in range query

	Heap File	Sorted Heap	B+ Tree	Hash
Scan everything	BD	BD	1.25BD	
Equality	0.5BD	D($\log_2$B)	D($\log_{80}$1.25B + 1)	
Range	BD	D($\log_2$B + M)	D($\log_{80}$1.25B + M)	
Insert	2D	Search + BD	D($\log_{80}$1.25B + 2)	
Delete	Search + D	Search + BD	D($\log_{80}$1.25B + 2)	

Heap File
- equality on a key. How many results?

Sorted File
- files compacted after deletion

B+ Tree
- 100 entries/directory page
- 80% fill factor

B # *data* pages
D time to read/write page
M # pages in range query

	Heap File	Sorted Heap	B+ Tree	Hash
Scan everything	BD	BD	1.25BD	1.25BD
Equality	0.5BD	D($\log_2$B)	D($\log_{80}$1.25B + 1)	D
Range	BD	D($\log_2$B + M)	D($\log_{80}$1.25B + M)	1.25BD
Insert	2D	Search + BD	D($\log_{80}$1.25B + 2)	2D
Delete	Search + D	Search + BD	D($\log_{80}$1.25B + 2)	2D

Heap File
- equality on a key. How many results?

Sorted File
- files compacted after deletion

B+ Tree
- 100 entries/directory page
- 80% fill factor

Hash index
- no overflow
- 80% fill factor

B # *data* pages
D time to read/write page
M # pages in range query

How to pick?

Depends on your queries (workload)
- Which relations?
- Which attributes?
- Which types of predicates (=,<,>)
- *Selectivity*
- Insert/delete/update queries? how many?

Naïve Algorithm

```
get query workload
group queries by type
for each query type in order of importance
   calculate best cost using current indexes
   if new index IDX will further reduce cost
      create IDX
```

Why not create every index?
- updates are slower: upkeep costs
- takes up space

High level guidelines

Check the WHERE clauses
- attributes in WHERE are search/index keys
- equality predicate → hash index
- range predicate → tree index

Multi-attribute search keys supported
- order of attributes matters for range queries
- may enable queries that don't look at data pages (*index-only*)

Summary

Design depends on economics, access cost ratios
Disk still dominant wrt cost/capacity ratio
Many physical layouts for files
- same APIs, difference performance
- remember physical independence

Indexes
- Structures to speed up read queries
- Multiple indexes possible
- Decision depends on workload

Things to Know

- How a hard drive works and its major performance characteristics
- The storage hierarchy and rough performance differences between RAM, SSD, Hard drives
- What files, pages, and records are, and how they are different than the UNIX model
- Heap File data structure
- B+ tree and Hash indexes
- Performance characteristics of different file organizations

L20
Query Execution & Optimization

Steps for a New Application

Requirements
  what are you going to build?
Conceptual Database Design
  pen-and-pencil description
Logical Design
  formal database schema
Schema Refinement:
  fix potential problems, normalization
Physical Database Design
  optimize for speed/storage — Optimization
App/Security Design
  prevent security problems

Recall

Relational algebra
  equivalence: multiple stmts for same query
  some statements (much) faster than others

Which is faster?
  a. $\sigma_{v=1}(R \times T)$
  b. $\sigma_{v=1}(R) \times T$

  $|R| = |T| = 10$ pages. 100? 1M?
  \# unique values in R = 1. 100? 1M? ← selectivity!

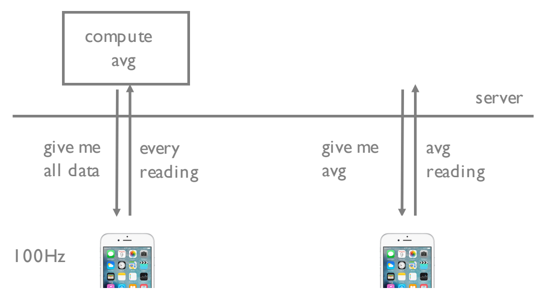
Overview of Query Optimization

SQL → query plan
How plans are executed
Some implementations of operators
Cost estimation of a plan
  Selectivity
System R dynamic programming

All ideas from System R's "Selinger Optimizer" 1979

iPhones as a database

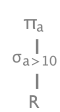
"avg acceleration over the past hour"



SQL → Query Plan

SELECT a FROM R — $\pi_a(R)$

SELECT a FROM R
WHERE a > 10 — $\pi_a(\sigma_{a>10}(R))$



SELECT a
FROM R JOIN S
ON R.b = S.b — $\pi_a(\bowtie_b(R,S))$