L8
Disk, Storage, and Indexing

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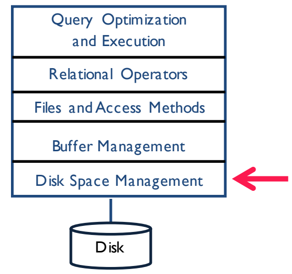
Fall 2015

Work from the bottom up



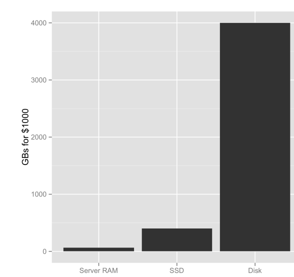
$ Matters

Why not store all in RAM?
- Costs too much
  - High-end Databases today ~Petabyte (1000TB) range.
  - ~60% cost of a production system is in the disks.
- Main memory not persistent
  - Obviously important if DB stops/crashes

Some systems are *main-memory* DBMSes, topic for advanced DB course

$ Matters

Newegg enterprise $1000
- RAM: 64
- SSD: 400
- Disk: 4000

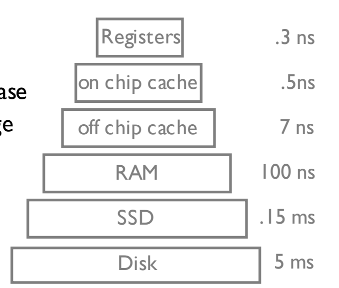


RAM for active data

Disk for main database
- secondary storage

Tapes for archive

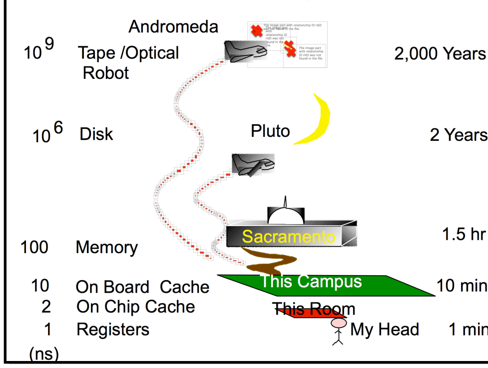
SSD is still in flux, some in use

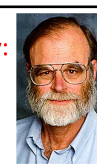


Interesting numbers
- compress 1k bytes: 3000 ns
- roundtrip in data center: .5 ms

https://gist.github.com/jboner/2841832

Jim Gray's Storage Latency Analogy: How Far Away is the Data?

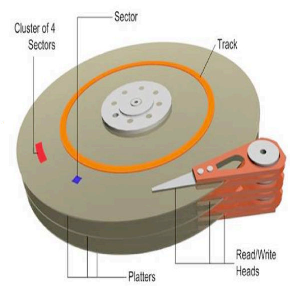




Jim Gray
Turing Award
B.S. Cal 1966
Ph.D. Cal 1969!

Spin speed: ~7200 RPM

Arm moved in/out to position head over a track



Time to access (read or write) a disk block

seek time	2-4 msec avg
rotational delay	2-4 msec
transfer time	0.3 msec/64kb page

Throughput

read	~150 MB/sec
write	~50 MB/sec

Key: reduce seek and rotational delays
- HW & SW approaches

Next block concept (in order of speed)
- blocks on same track
- blocks on same cylinder
- blocks on adjacent cylinder

Sequentially arrange files
- minimize seek and rotation latency

When sequentially scanning: Pre-fetch
- >1 page/block at once

SSD maybe

Fast changing, not yet stabilized

Read small & fast

single read:	0.03ms
4kb random reads:	500MB/sec
seq reads:	525MB/sec

Write is slower for random

single write:	0.03ms
4kb random writes:	120MB/sec
seq writes:	120MB/sec

Write endurance limited
- 2-3k cycle lifetimes
- 6-10 months

4 byte values read per second

Pragmatics of Databases

Most databases are pretty small
- All global daily weather since 1929: 20GB
- 2000 US Census: 200GB
- 2009 english wikipedia: 14GB

Data sizes grow faster than moore's law

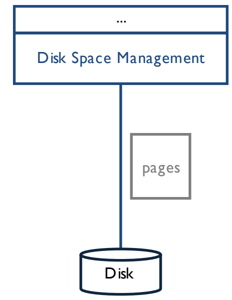
Disk Space Management

VLDBs SSDs: reduce variance
Small DBs interesting data is small

Huge data exists
Many interesting data is small

People will still worry about magnetic disk.
May not care about it

Work from the bottom up



Disk Space Management

Lowest layer of DBMS, manages space on disk

Low level IO interface:
- allocate/deallocate a page
- read/write page

Sequential performance desirable
- try to ensure sequential pages are sequential on disk
- hidden from rest of DBMS
- but algorithms may assume sequential performance

Files

Pages are IO interface
Higher levels work on records and files (of records)

File: collection of pages
- insert/delete/modify record
- get(record_id) a record
- scan all records

Page: collection of records
- typically *fixed size* (8kb in PostgreSQL)

May be stored in multiple OS files spanning multiple disks

Units that we'll care about

Ignore CPU cost
Ignore RAM cost

B # *data* pages on disk for relation
R # records per data page
D avg time to read/write data page to/from disk

Simplifies life when computing costs
Very rough approximation, but OK for now
- ignores prefetching, bulk writes/reads, CPU/RAM

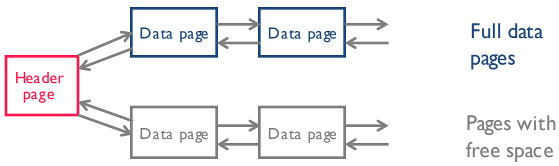
Unordered Heap Files

Collection of records (no order)

As add/rm records, pages de/allocated

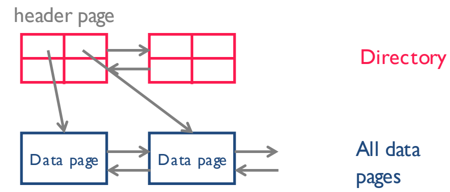
To support record level ops, need to track:
- pages in file
- free space on pages
- records on page

Heap File



Header page and heap file pointers stored in catalog
Data page = 2 pointers + data

Use a directory



Directory entries track #free bytes on data pages
Directory is collection of pages

Administrivia

Project 1 evaluations this week
(very important for your grade)

HW3 has been out

Project 2 destined to be out on Wednesday

HW4 next Monday

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 rid
- 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*

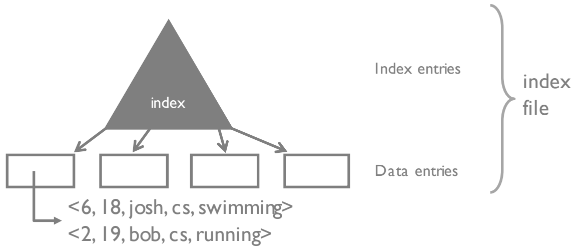
no relation to candidate keys!

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)
```

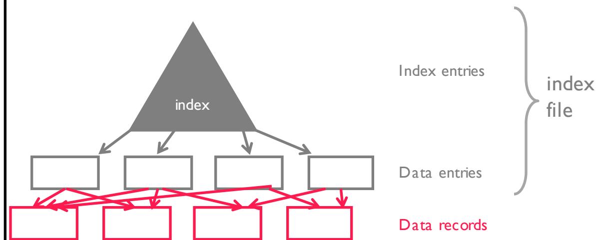
You will play around with indexes in HW4

High level index structure



What is a data entry?
actual data record

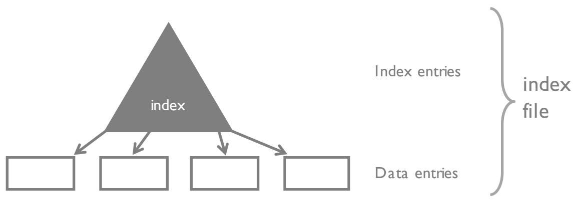
High level index structure



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

Tradeoffs
directly access tuple.
compact, fixed size entries
more compact, variable size entries

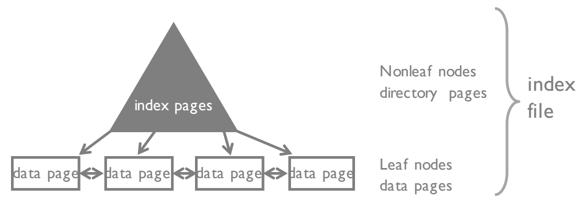
High level index structure



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

Tradeoffs
directly access tuple.
compact, fixed size entries
more compact, variable size entries

B+ Tree Index

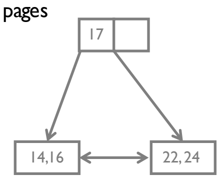


Node = Page
Equality and range queries
Self balancing
Leaf nodes are connected
Disk optimized

B+ Tree on (age)

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

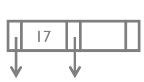
Leaf Data pages
data entries/tuples



index & data
page contents
are in order

Query: SELECT * WHERE age= 14

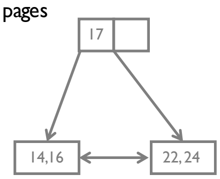
directory page



Index Only Queries: B+ Tree on (age)

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

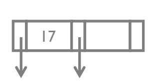
Leaf Data pages
data entries/tuples



index & data
page contents
are in order

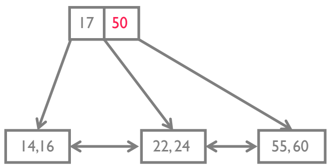
Query: SELECT age WHERE age= 14
(index only!)

directory page



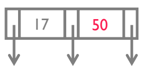
B+ Tree on (age)

Note: 50 not a data entry

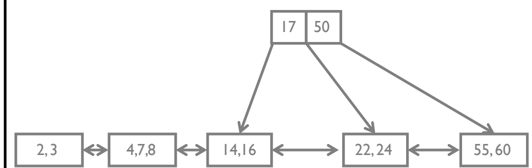


Query: SELECT * WHERE age = 55

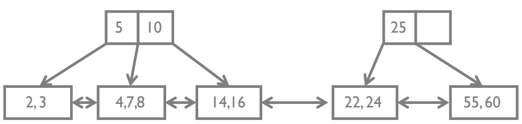
directory page



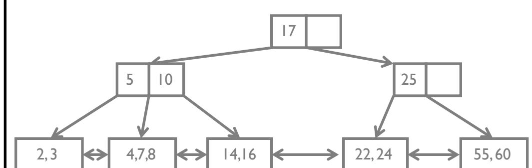
B+ Tree on (age)



B+ Tree on (age)

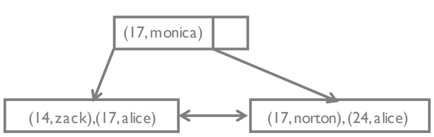


B+ Tree on (age)



Query: SELECT * WHERE age > 20

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'
```

Some numbers (8kb pages)

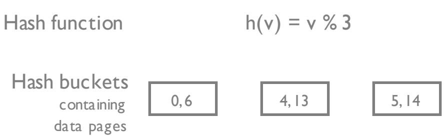
How many levels?
- fill-factor: ~66%
- ~300 entries per directory page

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

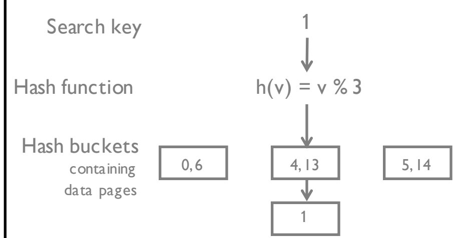
Top levels often in memory
- height 2 only 300 pages ~2.4MB
- height 3 only 90k pages ~750MB

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

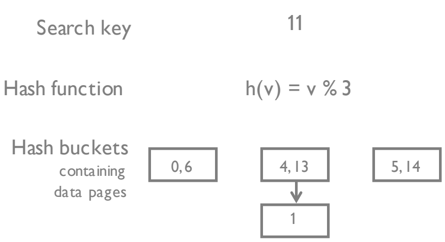
Hash Index on age



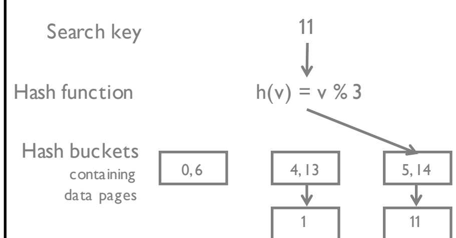
INSERT Hash Index on age



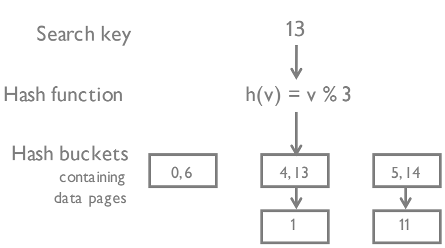
INSERT Hash Index on age



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 x > 10 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			
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	1.2BD	
Equality	0.5BD	D($\log_2$B)	D($\log_{80}$B + 1)	
Range	BD	D($\log_2$B + M)	D($\log_{80}$B + M)	
Insert	2D	Search + BD	D($\log_{80}$B)	
Delete	Search + D	Search + BD	D($\log_{80}$B)	

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	1.2BD	1.2BD
Equality	0.5BD	D($\log_2$B)	D($\log_{80}$B + 1)	D
Range	BD	D($\log_2$B + M)	D($\log_{80}$B + M)	1.2BD
Insert	2D	Search + BD	D($\log_{80}$B)	2D
Delete	Search + D	Search + BD	D($\log_{80}$B)	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?

How to choose indexes?

Considerations
- which relations should have indexes?
- on what attributes?
- how many indexes?
- what type of index (hash/tree)?

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?
- update queries slowed down (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