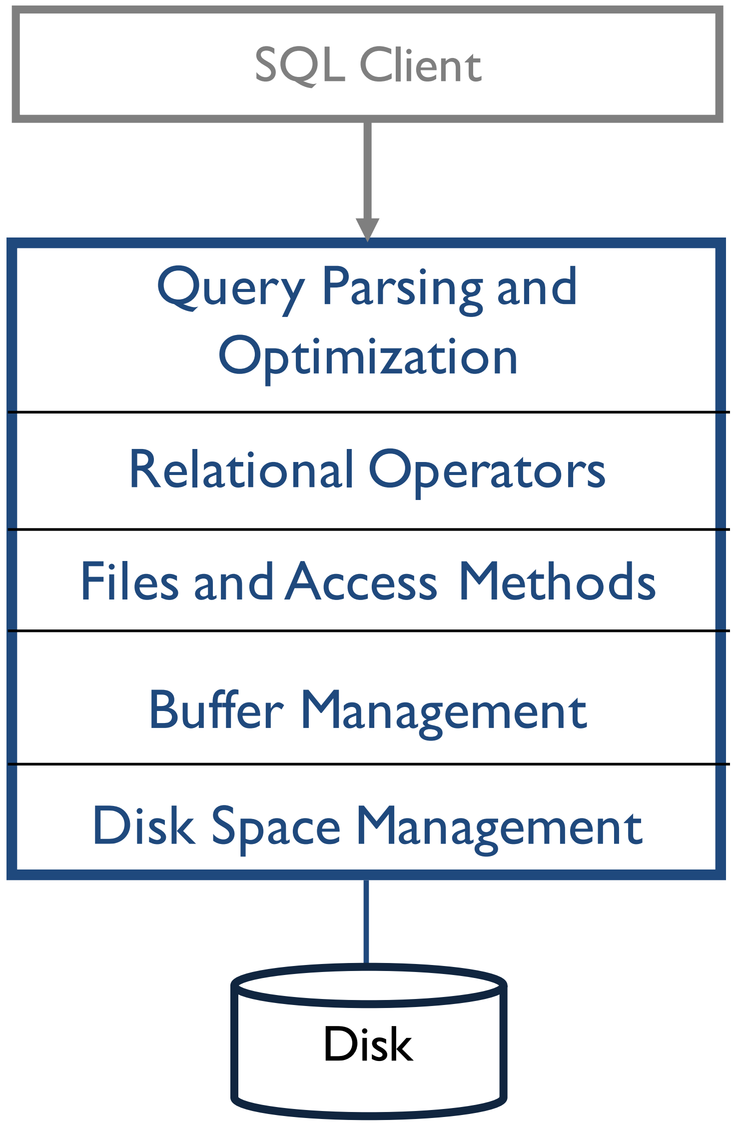
L8
Disk, Storage, and Indexing

Eugene Wu

DBMS Overview

Each layer provides a simple abstraction to layers above it, and makes assumptions about layers below it.

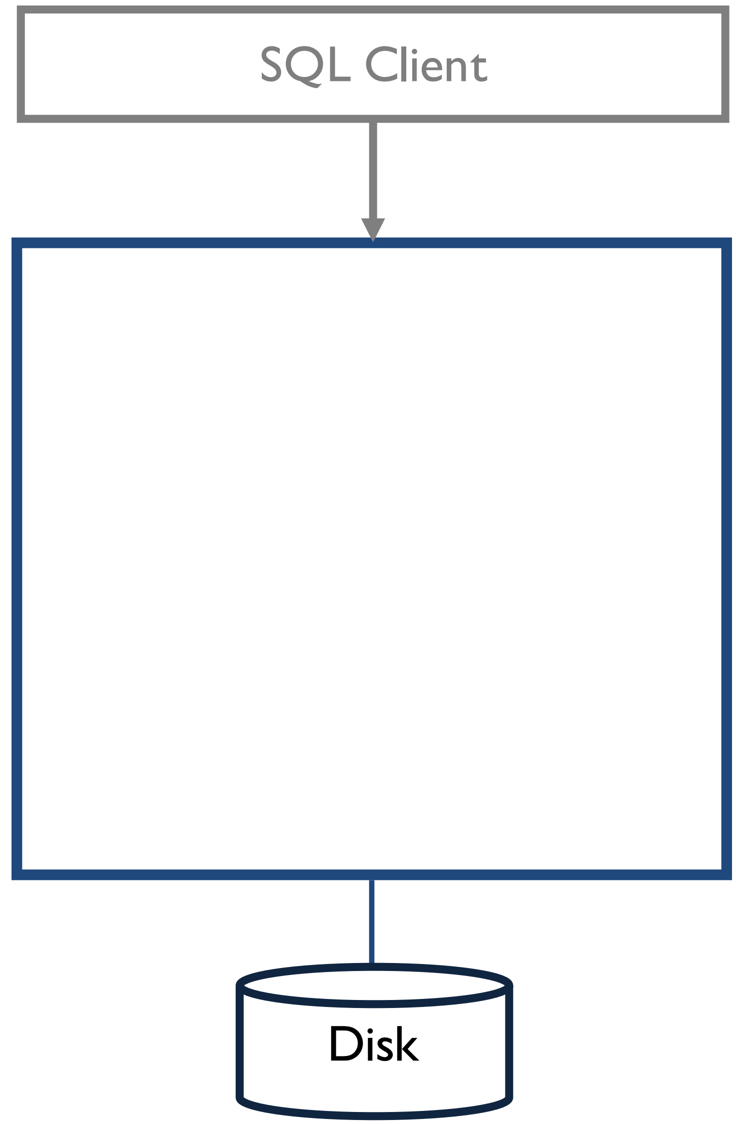
Requires careful design and assumptions for performance



DBMS Overview

Applications interact with SQL Client

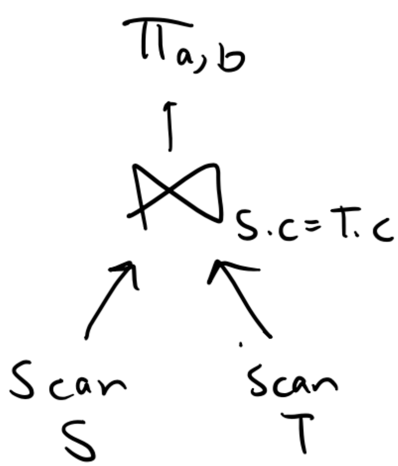
```
db.execute('''
  SELECT a, b
  FROM S, T
  WHERE S.c = T.c''')
```

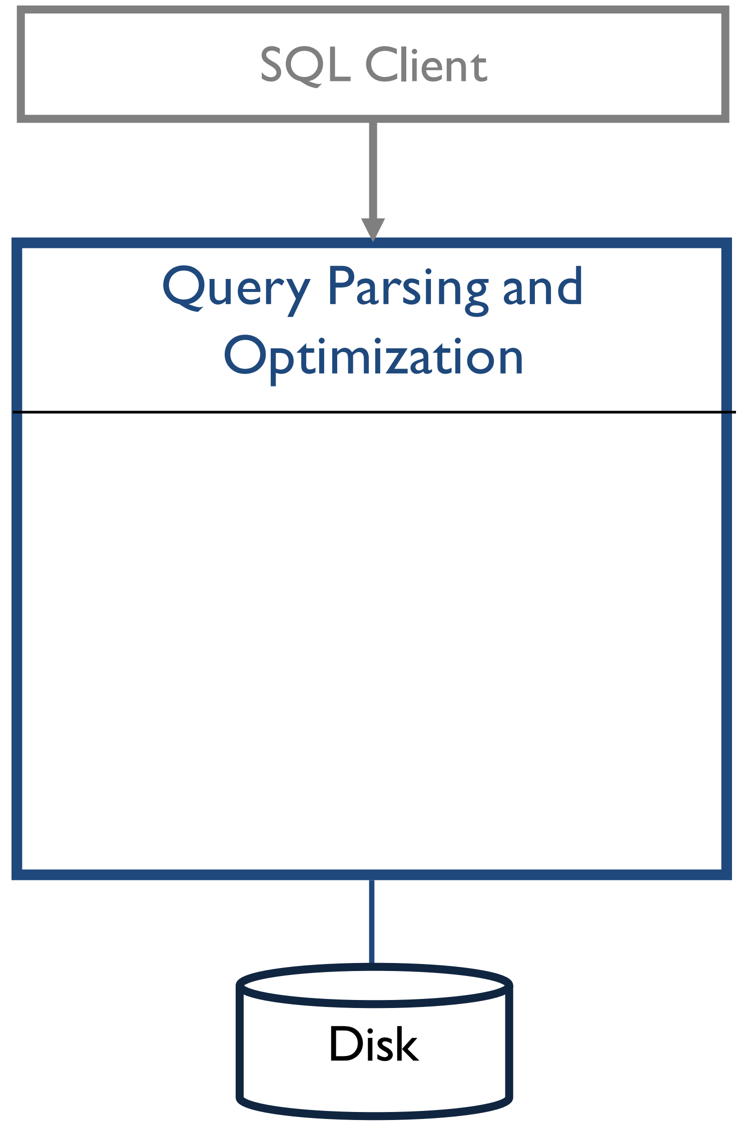


DBMS Overview

Parse, check, and verify the SQL query

Turn into efficient query plan

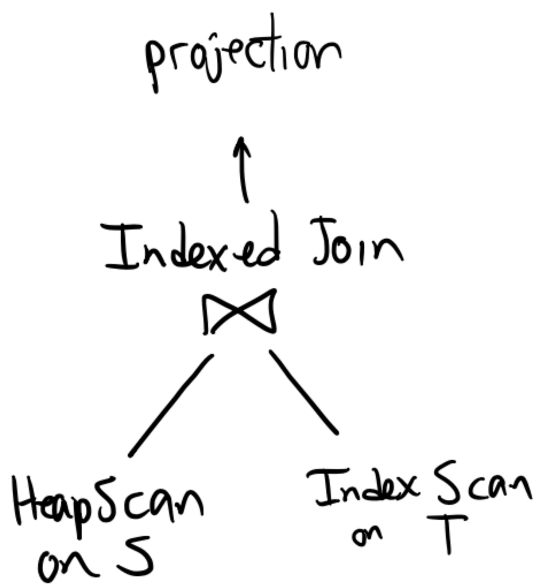


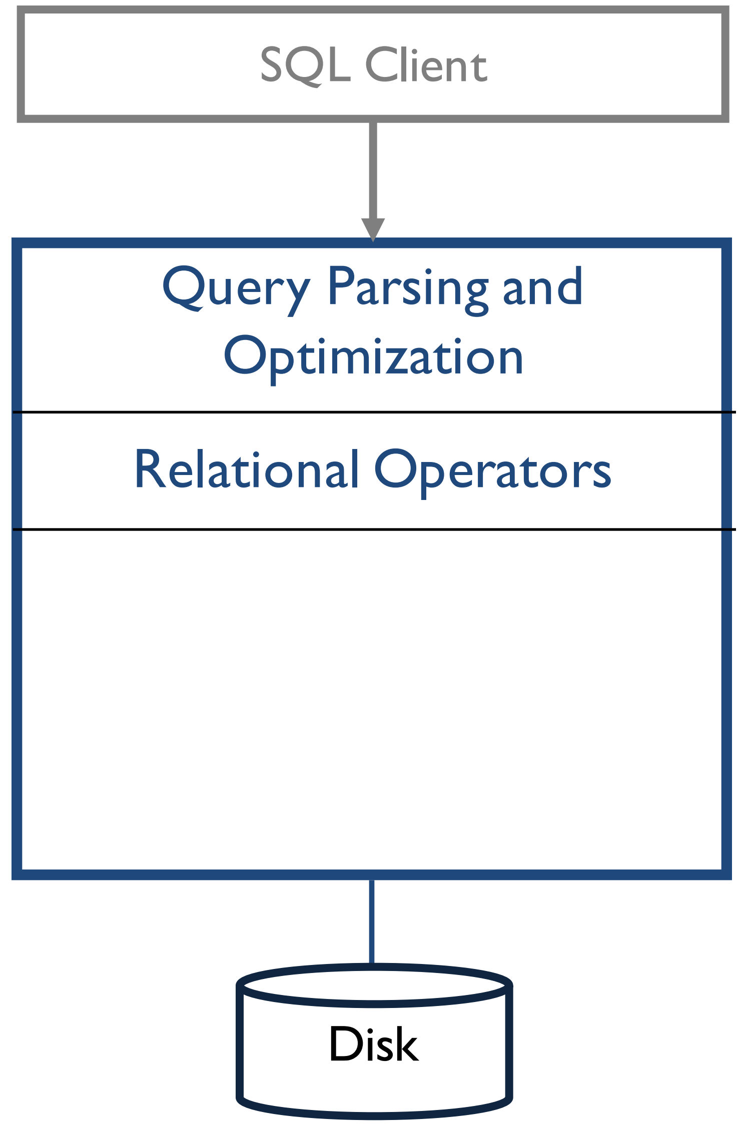


DBMS Overview

A query is represented as a relational data flow

Each operator is a specific implementation





DBMS Overview

Organizes tables, indexes, records as groups of pages in a "logical file"

API:

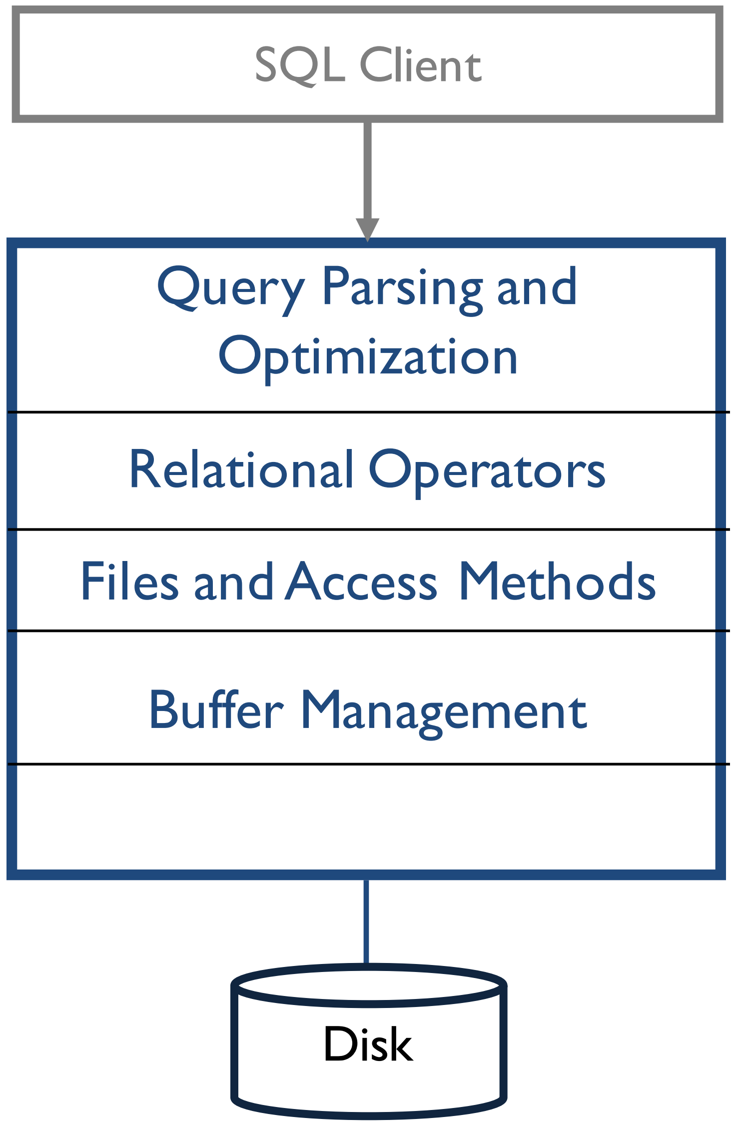
- Operators ask for records
- Logical files help read and write bytes on pages

DBMS Overview

Not all pages can fit into RAM.

Buffer manager provides illusion that all pages are accessible.

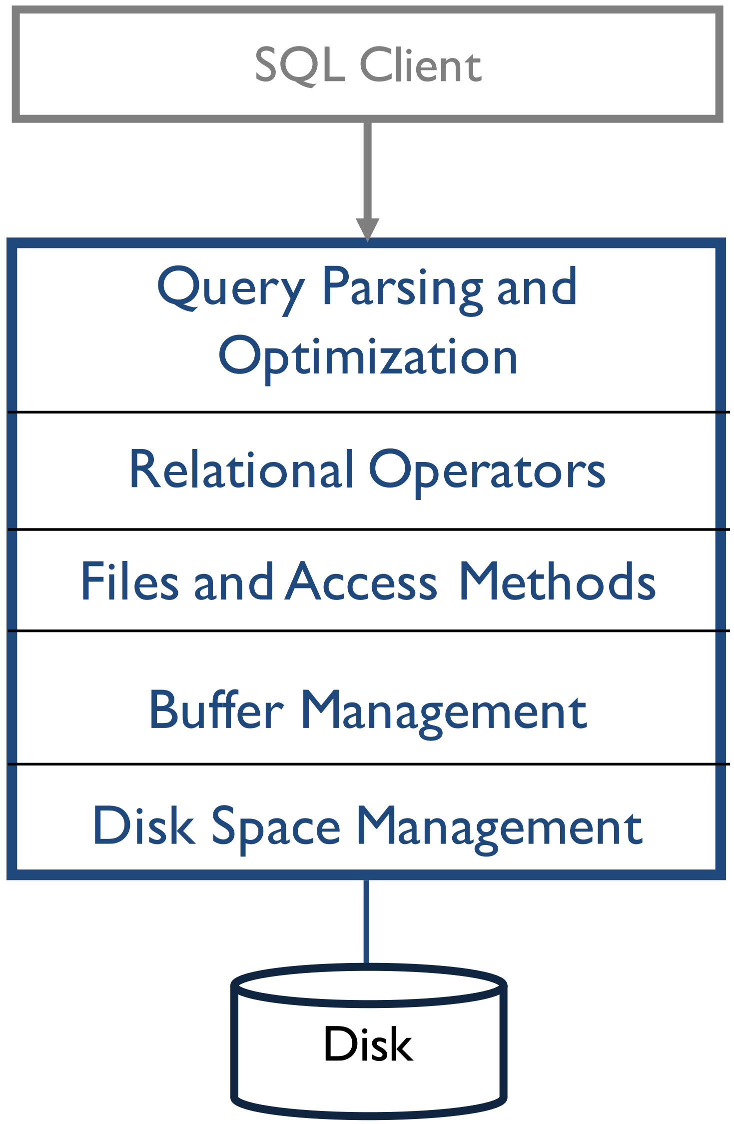
Files simply ask for pages.



DBMS Overview

Physically read and write bytes on one or more storage devices (hard drives, SSDs, etc)

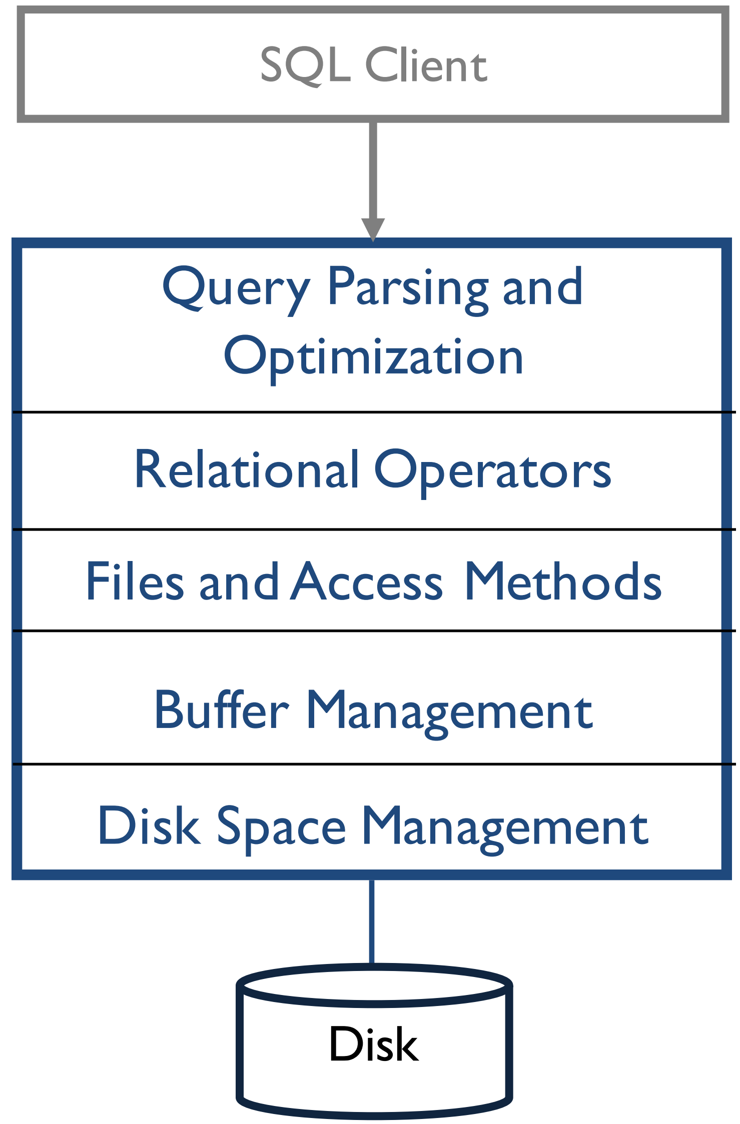
Storage performance properties dictate the design of layers above.



DBMS Overview

Layers help manage engineering complexity.

Requires assumptions about performance of lower layers. (cost models)



DBMS Overview

Physically read and write bytes on one or more storage devices (hard drives, SSDs, etc)

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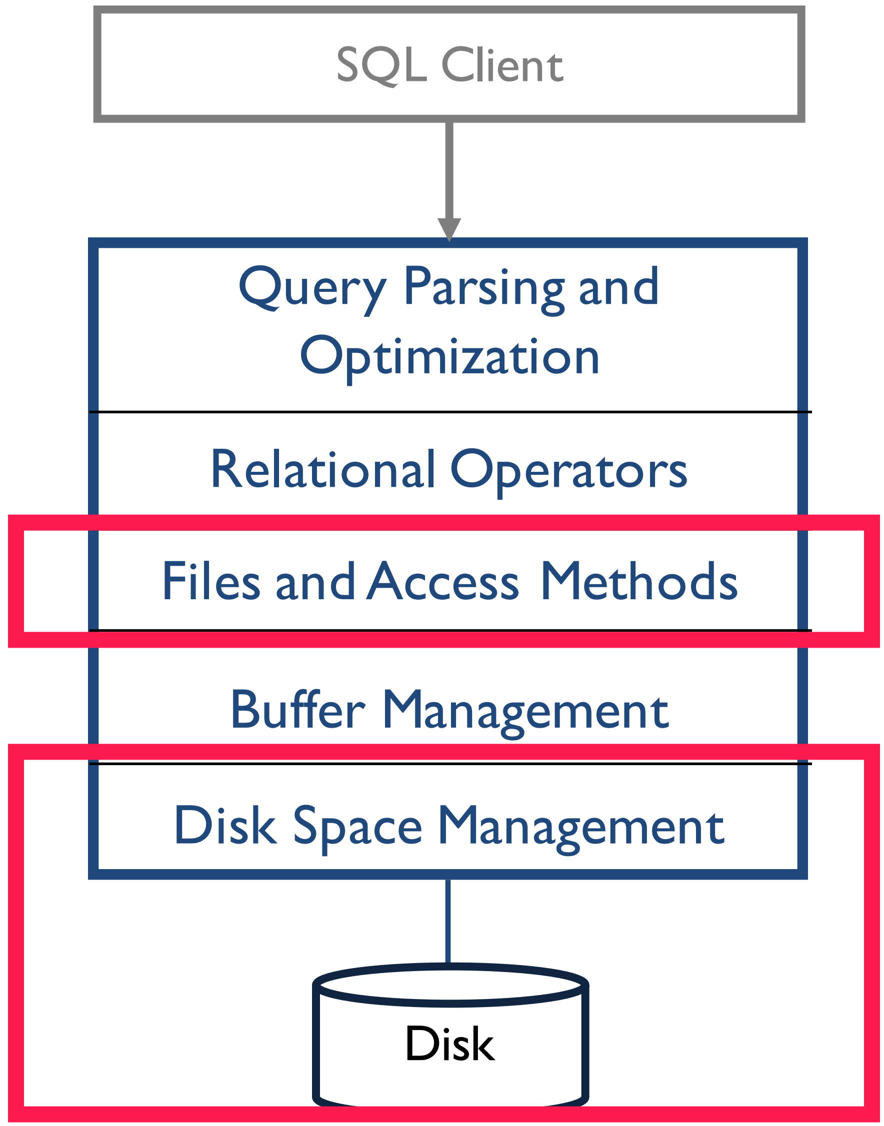


Storage Devices

Hard Drives vs SSDs vs RAM

Locality (random vs sequential)

Reads vs Writes

Performance and Monetary Costs

$ Matters

Why not store all in RAM?

- Costs too much
  - High-end Databases today ~Petabyte (1000TB) range.
  - SQL Hyperscale scales to 100TB+ (announced Sep 24, 2018)
    ~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

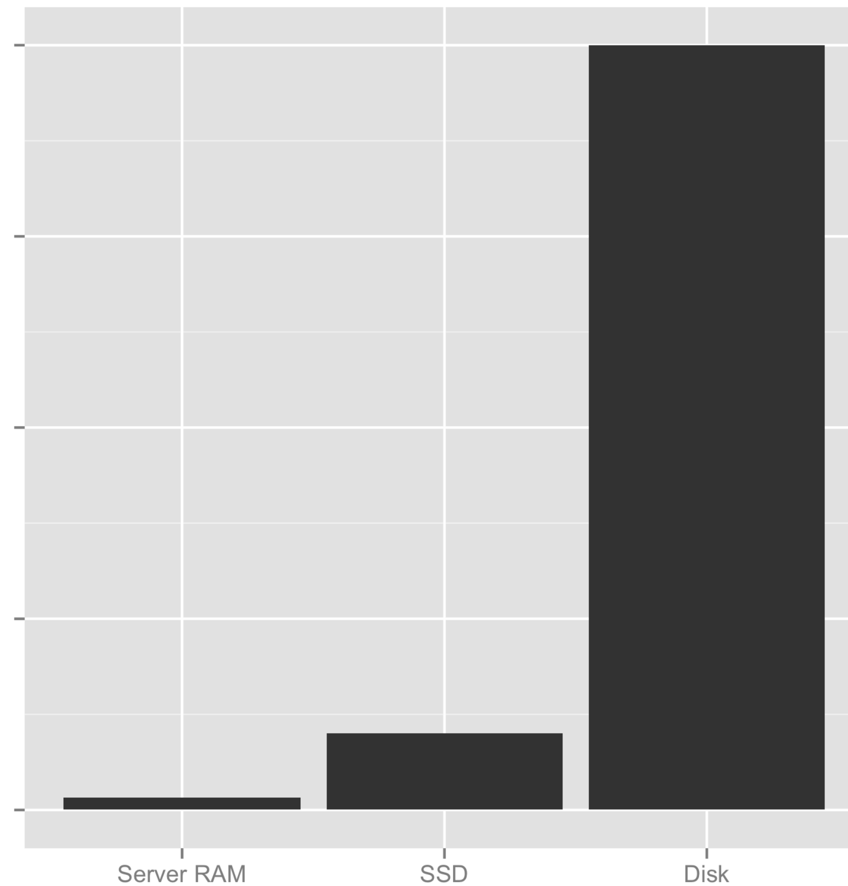
$ Matters

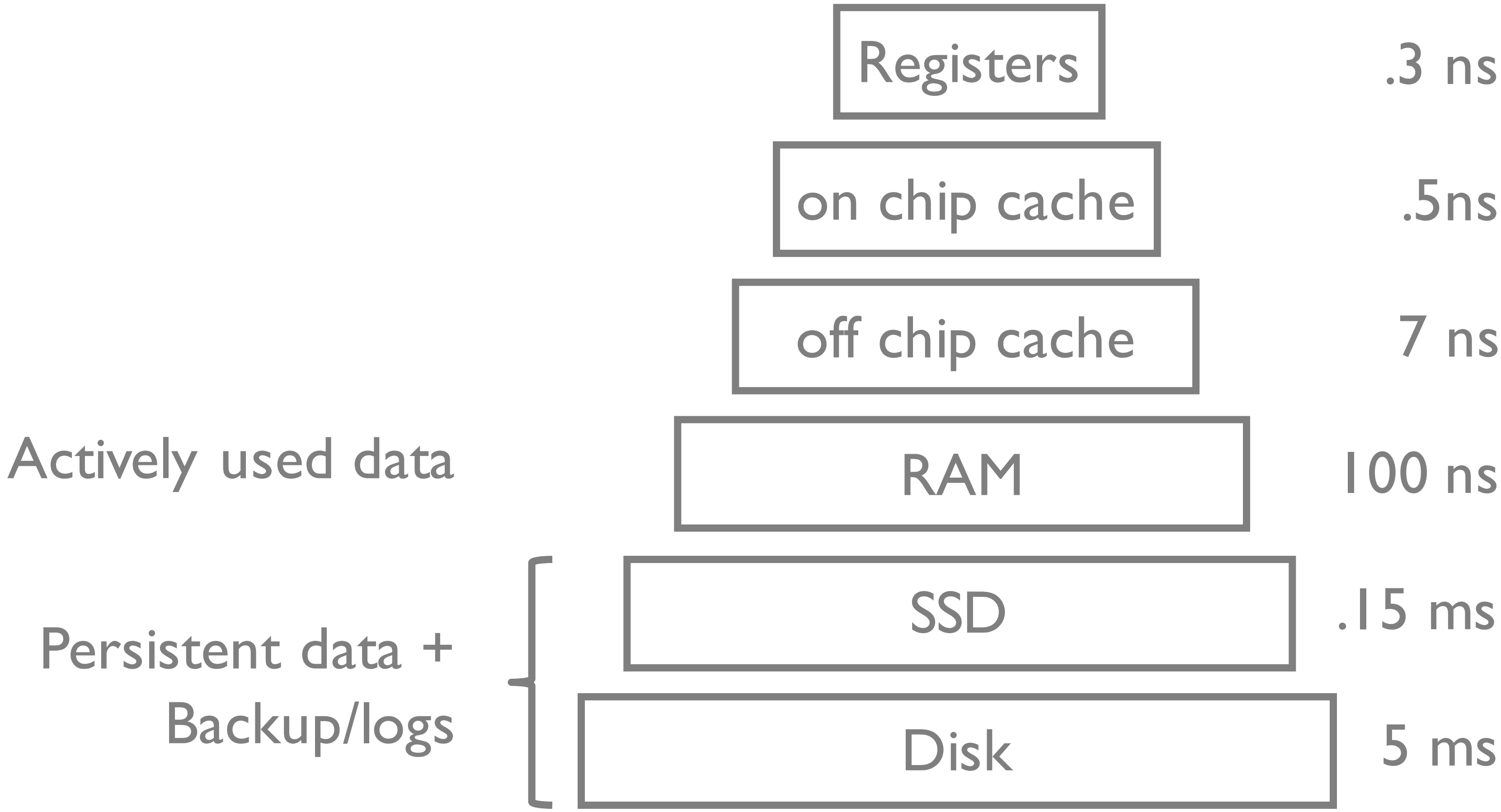
Newegg enterprise $1000

RAM: 0.08TB

SSD: ~2TB (25x)

Disk: ~40TB (500x)



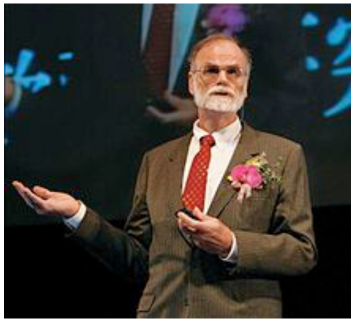


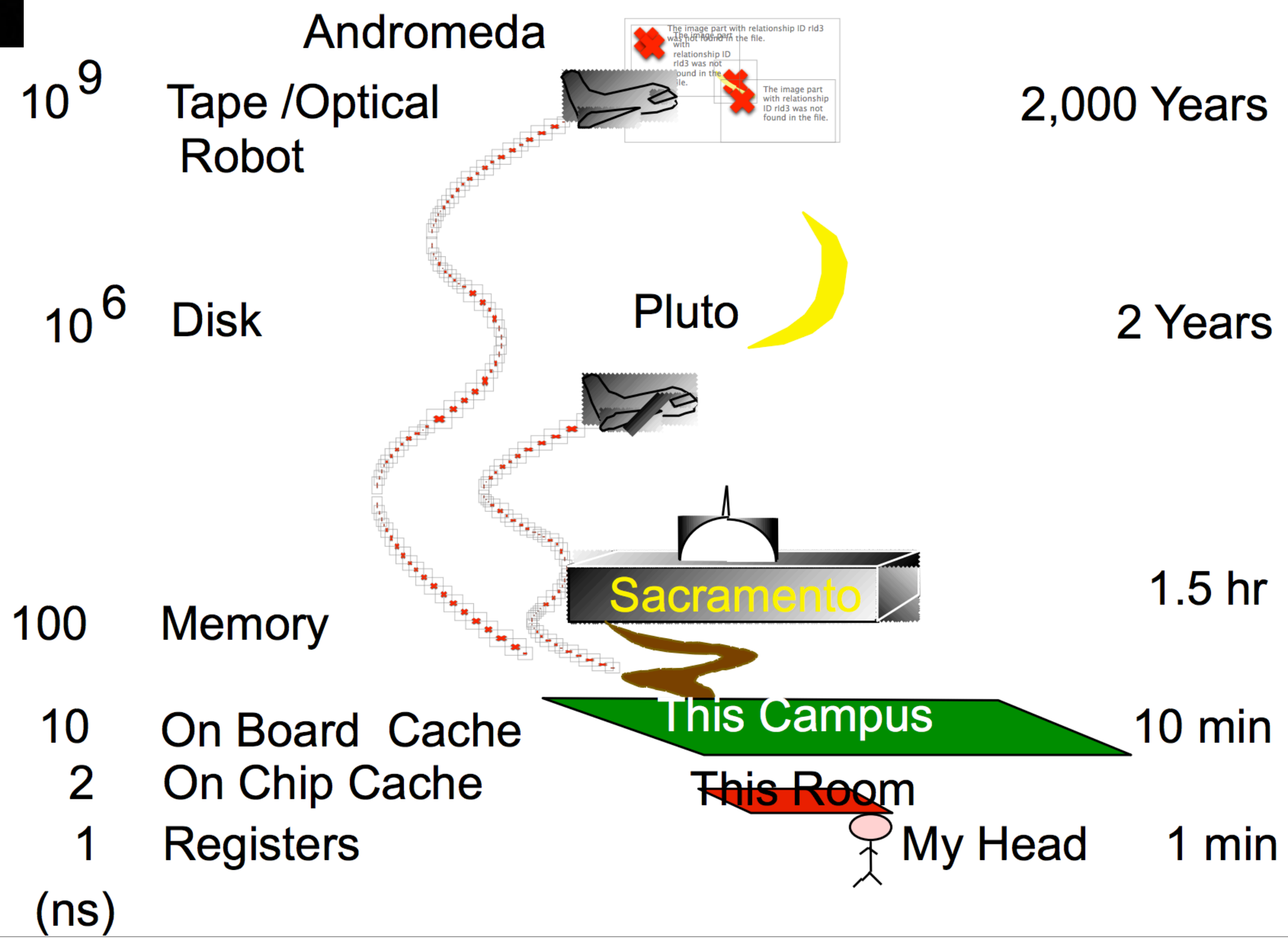
Interesting numbers

compress 1k bytes: 3000 ns

roundtrip in data center: .5 ms

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



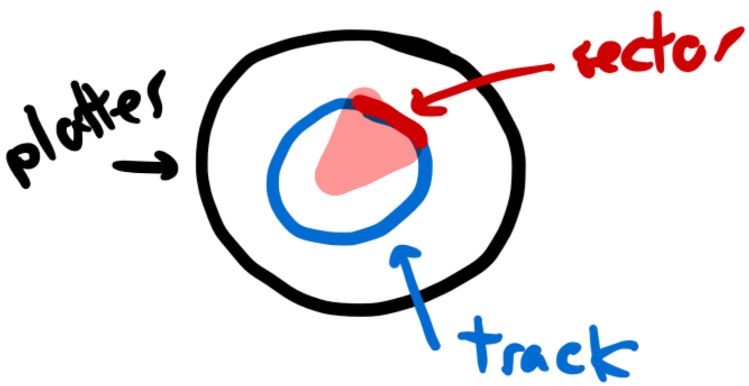


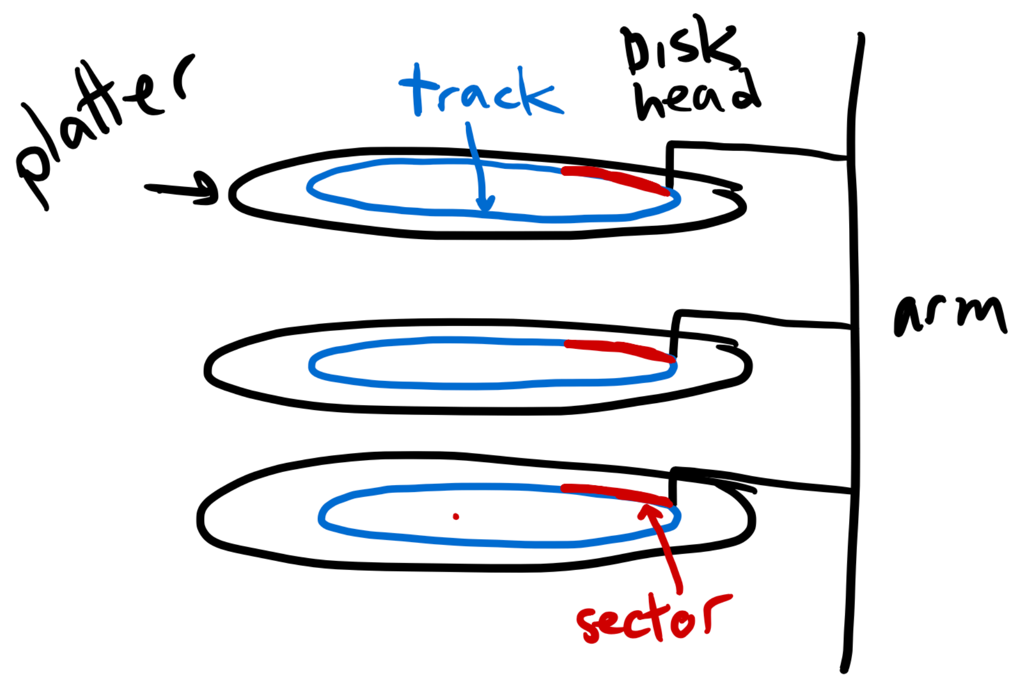
Andromeda
10^9 Tape /Optical Robot
2,000 Years
10^6 Disk
Pluto
2 Years
Sacramento
1.5 hr
100 Memory
10 On Board Cache
This Campus
10 min
2 On Chip Cache
This Room
1 Registers
My Head
1 min
(ns)

Spin speed: ~7200 RPM

Section = multiples of pages

Terminology: block same as page in this class





https://www.youtube.com/watch?v=BIB49F6ExkQ

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

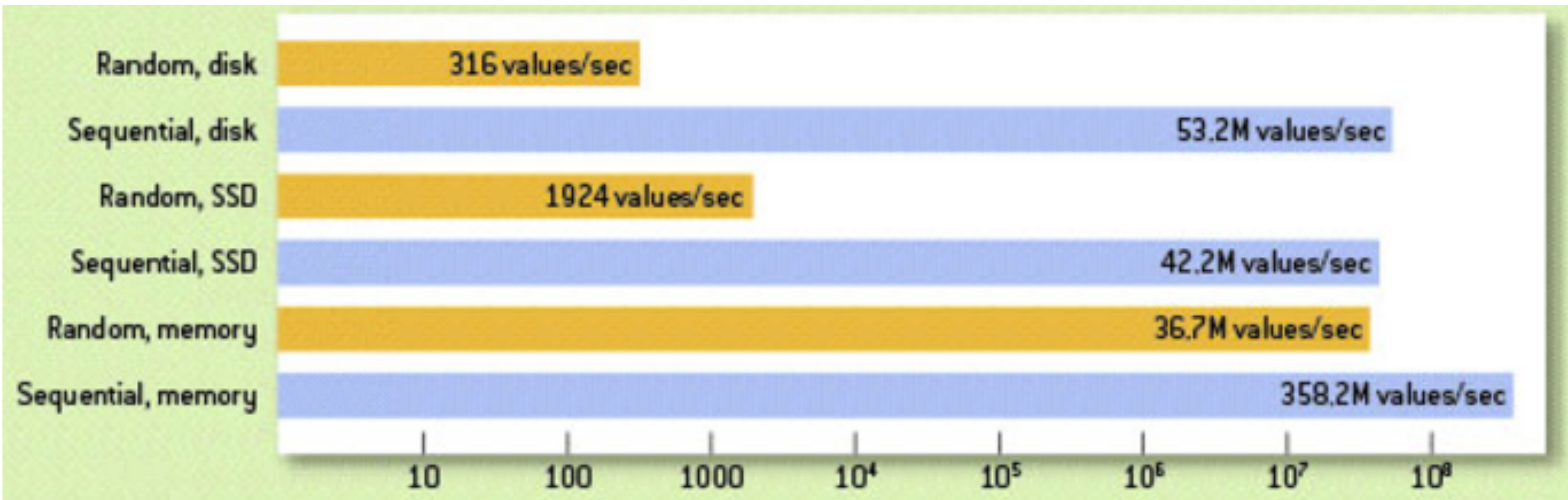
Throughput

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

Key: reduce seek and rotational delays

HW & SW approaches

of 4 byte values read per second



5 orders of magnitude

SSDs

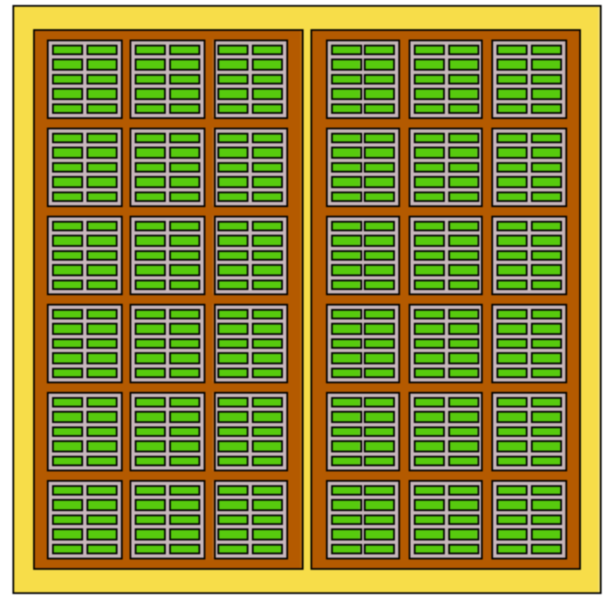
NAND memory

Small reads: 4-8k

Big writes: 1-2MB

2-3k writes before failure

wear leveling: distribute writes around



Write amplification: changing 4 bytes writes a 1-2MB chunk!

Need to think about wear, garbage collection, writing in bulk

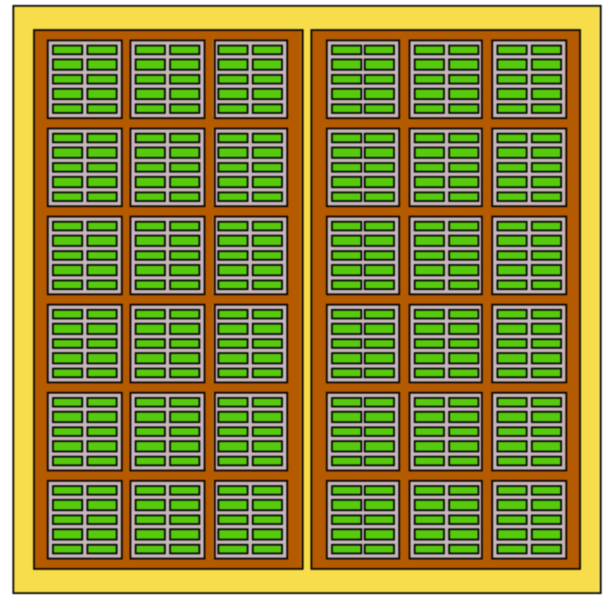
SSDs

Reads fast

- single read time: 0.03ms
- random reads: 500MB/s
- sequential reads: 525MB/s

Writes less predictable

- single write time: 0.03ms
- random writes: 120MB/s
- sequential writes: 480MB/s



What's Best? Depends on Application

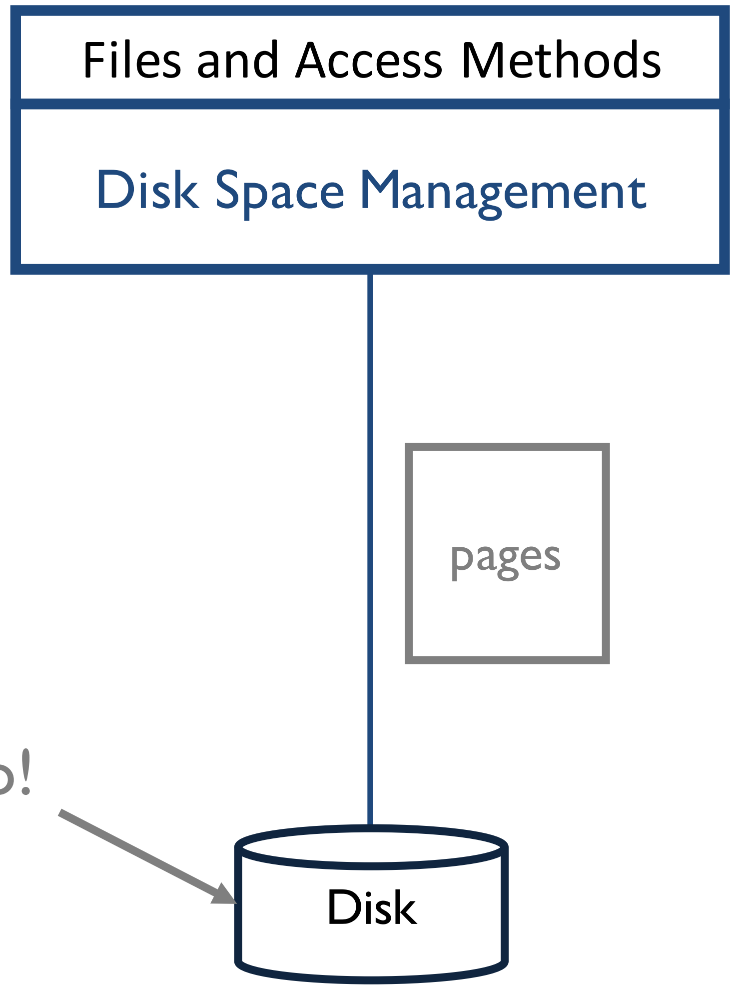
Small databases:

- All global daily weather since 1929: 20GB
- 2000 US Census: 200GB
- 2009 english wikipedia: 14GB
- Easily fits on an SSD or in RAM

Very Big databases

- Sensors easily generate TBs of data/day
- Boeing 787 generates ½ TB per flight
- Disk has best cost-capacity ratio
- SSDs help reduce read variance

Work from the bottom up



Like flying to Pluto!
How to be faster?

Strategies for Fast Data Access

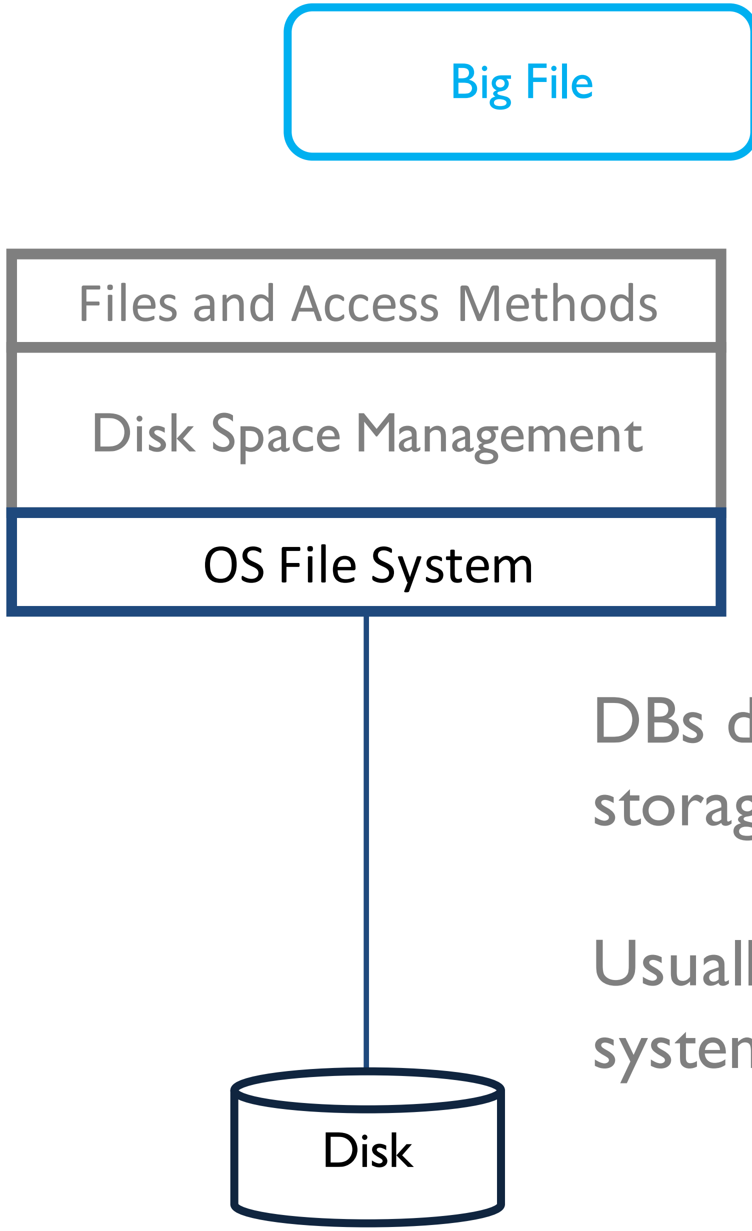
Big difference between random & sequential access

- Optimize for sequential accesses

Amortize sequentially read & write big chunks of bytes
Cache popular blocks
Pre-fetch what you will need later

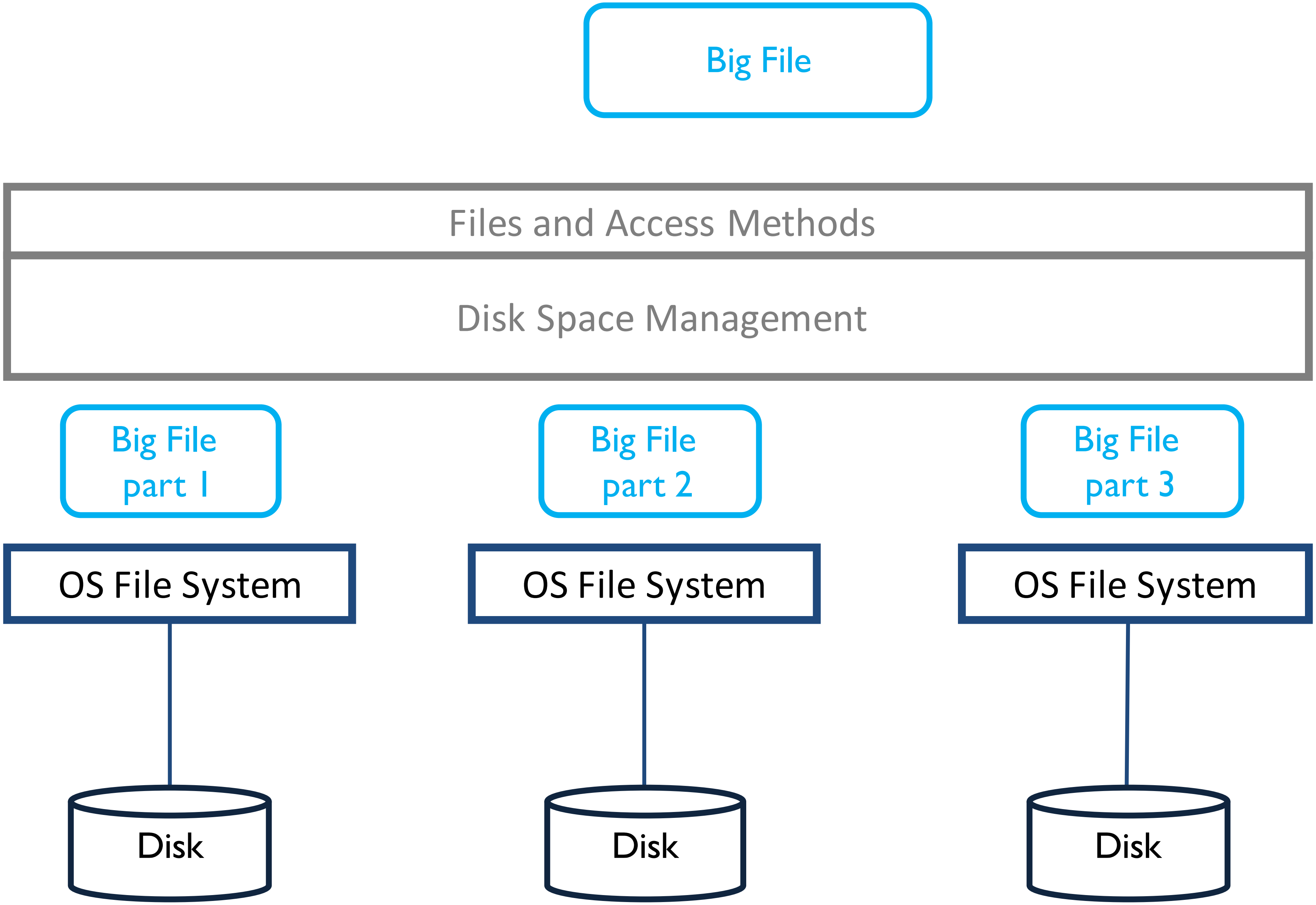
API

- read/write page
- read/write sequential pages
- notion of "next" page (upper layers can assume next is faster)



DBs don't directly talk to storage devices.

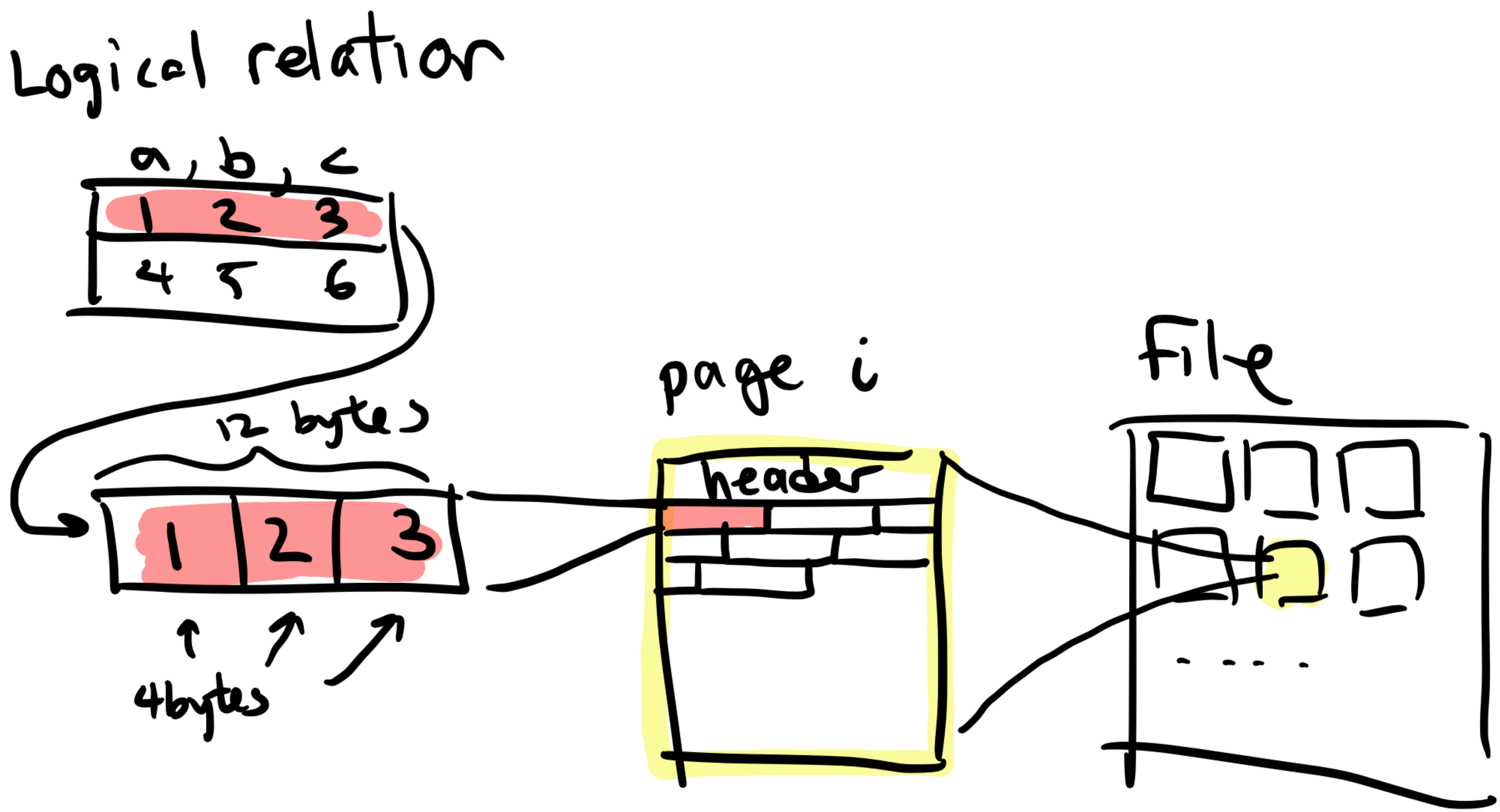
Usually go through OS file system


Big File
Files and Access Methods
Disk Space Management
Big File part 1
Big File part 2
Big File part 3
OS File System
OS File System
OS File System
Disk
Disk
Disk

PostgreSQL database stored in files

```
ewu@dyn-160-39-248-197 ~/d/p/base> cd 33883/
ewu@dyn-160-39-248-197 ~/d/p/b/33883> ls
112          12526        2601         2612         2659         2696         2840_vm      3456_fsm     3602
113          12528        2601_fsm     2612_fsm     2660         2699         2841         3456_vm      3602_fsm
1247         12529        2601_vm      2612_vm      2661         2701         2995         3466         3602_vm
1247_fsm     12529_fsm    2602         2613         2662         2702         2995_vm      3466_vm      3603
1247_vm      12529_vm     2602_fsm     2613_vm      2663         2703         2996         3467         3603_fsm
1249         12531        2602_vm      2615         2664         2704         3079         3468         3603_vm
1249_fsm     12533        2603         2615_fsm     2665         2753         3079_fsm     3501         3604
1249_vm      12534        2603_fsm     2615_vm      2666         2753_fsm     3079_vm      3501_vm      3605
12504        12536        2603_vm      2616         2667         2753_vm      3080         3502         3606
12504_fsm    12538        2604         2616_fsm     2668         2754         3081         3503         3607
12504_vm     1255         2604_vm      2616_vm      2669         2755         3085         3534         3608
12506        1255_fsm     2605         2617         2670         2756         3118         3541         3609
12508        1255_vm      2605_fsm     2617_fsm     2673         2757         3118_vm      3541_fsm     3712
12509        1259         2605_vm      2617_vm      2674         2830         3119         3541_vm      3764
12509_fsm    1259_fsm     2606         2618         2675         2830_vm      3164         3542         3764_fsm
12509_vm     1259_vm      2606_fsm     2618_fsm     2678         2831         3256         3574         3764_vm
12511        1417         2606_vm      2618_vm      2679         2832         3256_vm      3575         3766
12513        1417_vm      2607         2619         2680         2832_vm      3257         3576         3767
12514        1418         2607_fsm     2619_fsm     2681         2833         3258         3576_vm      548
12514_fsm    1418_vm      2607_vm      2619_vm      2682         2834         3394         3596         549
12514_vm     174          2608         2620         2683         2834_vm      3394_fsm     3596_vm      826
12516        175          2608_fsm     2620_vm      2684         2835         3394_vm      3597         826_vm
12518        2187         2608_vm      2650         2685         2836         3395         3598         827
12519        2328         2609         2651         2686         2836_vm      34002        3598_vm      828
12519_fsm    2328_vm      2609_fsm     2652         2687         2837         34004        3599         PG_VERSION
12519_vm     2336         2609_vm      2653         2688         2838         34004_fsm    3600         pg_filenode.map
12521        2336_vm      2610         2654         2689         2838_fsm     34004_vm     3600_fsm     pg_internal.init
12523        2337         2610_fsm     2655         2690         2838_vm      34008        3600_vm
12524        2600         2610_vm      2656         2691         2839         34031        3601
12524_fsm    2600_fsm     2611         2657         2692         2840         3455         3601_fsm
12524_vm     2600_vm      2611_vm      2658         2693         2840_fsm     3456         3601_vm
ewu@dyn-160-39-248-197 ~/d/p/b/33883>
```

Files



Logical relation
a, b, c
1 2 3
4 5 6
12 bytes
1 2 3
4bytes
page i
header
File

Files

Higher layers want to talk in terms of records, and files of records

File: collection of pages
Minimum API:
    insert/delete/modify record
    lookup record_id
    scan all records

Page: collection of records
    typically *fixed page sizes* (8 or 64kb in PostgreSQL)

These are logical.
Different page organizations in a file have different access costs

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
OK to not be exactly correct

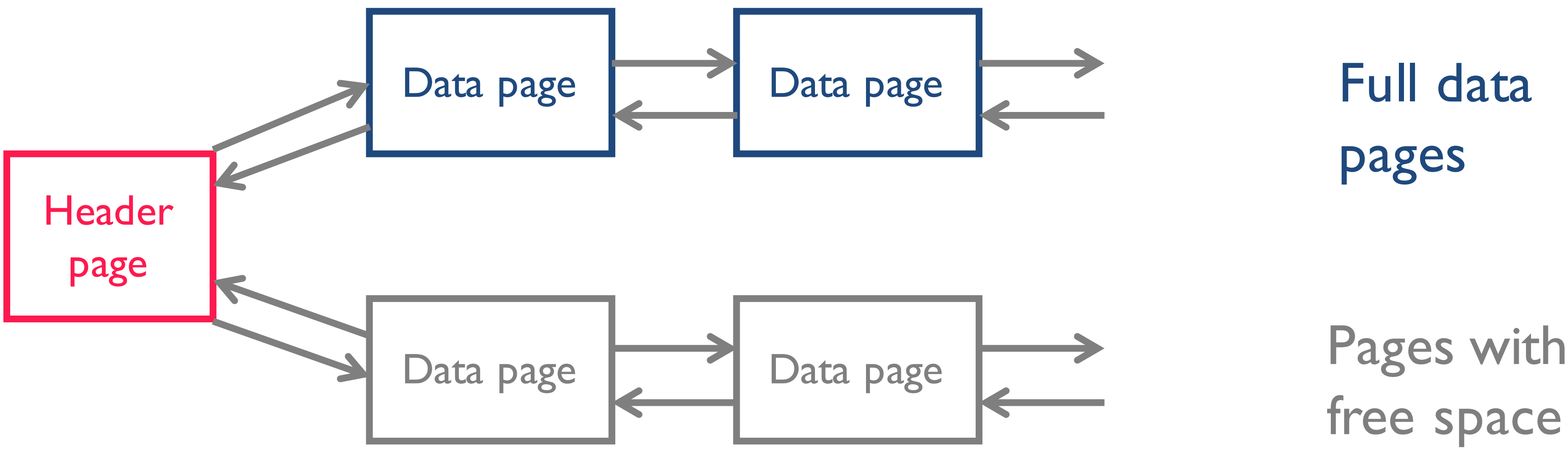
Unordered Heap Files

Collection of records (no order)

As we add records, pages allocated
As we remove records, pages removed

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

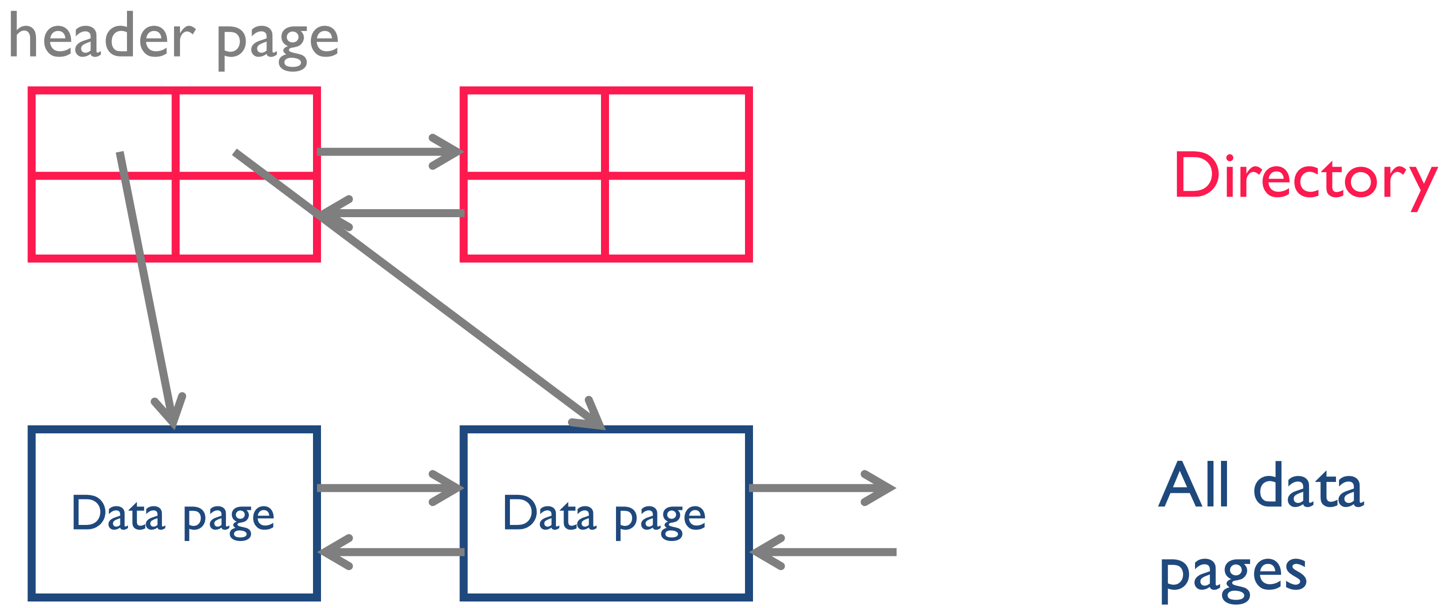
Heap File



Header page info stored in catalog
Data page contains: 2 pointers, free space, data

Need to scan pages to answer any query
Which page has enough free space for 100 bytes?

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 answers any query via a sequential scan

Queries use *qualifications* (predicates)

- find students here class = “CS”
- find students with age > 10

Indexes: file structures for value-based queries

- B+-tree index (~1970s)
- Hash index

Overview! Details in 4112

Indexes

Defined wrt a *search key*

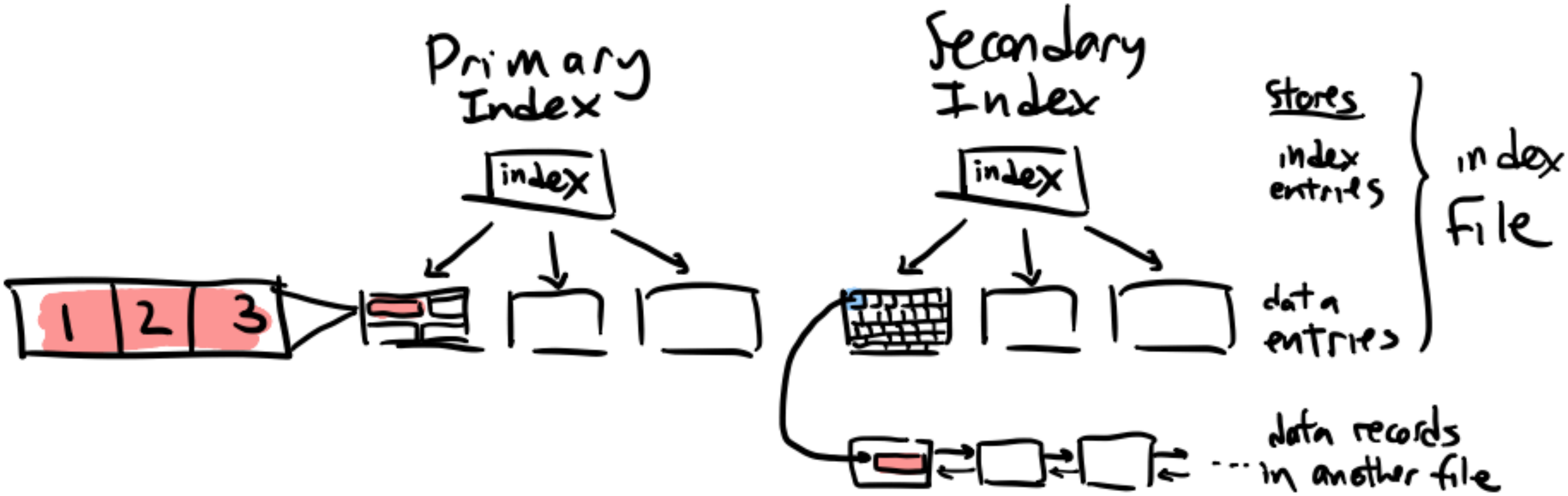
no relation to candidate keys!

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

Primary vs Secondary Index Files



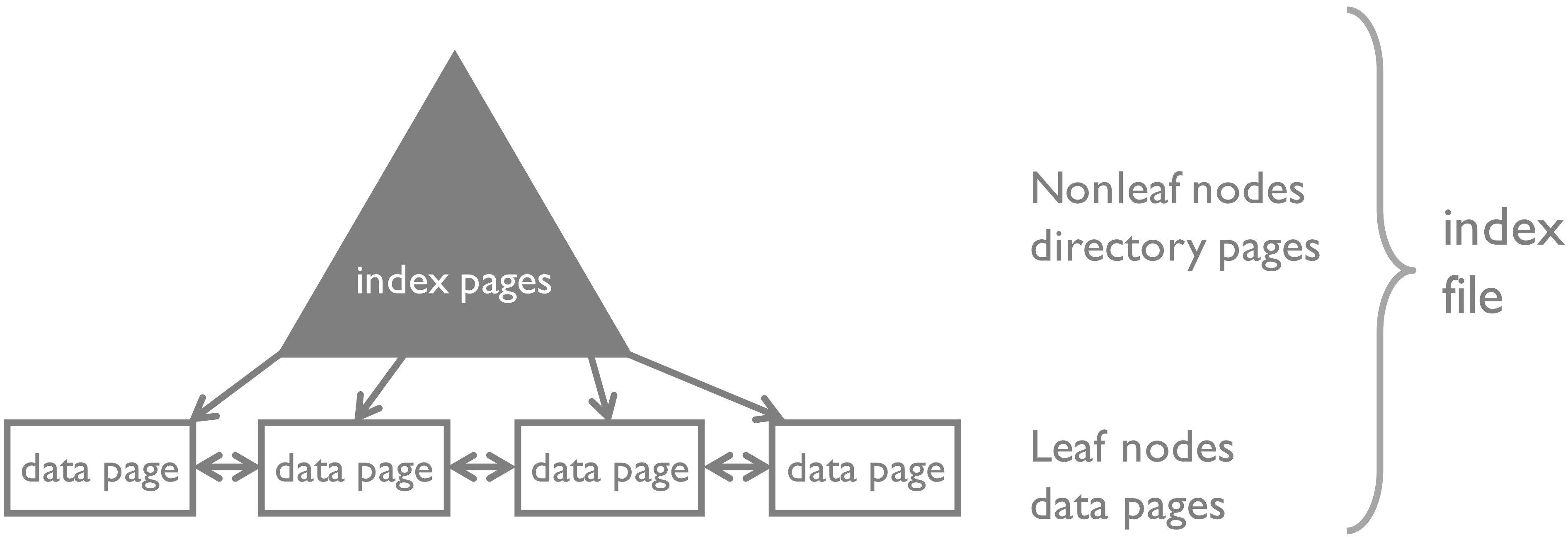
Primary: data entries contain data records in another file

Pros: directly access data

Secondary: data entries contain pointers <search key value, rid>

Pros: index is more compact

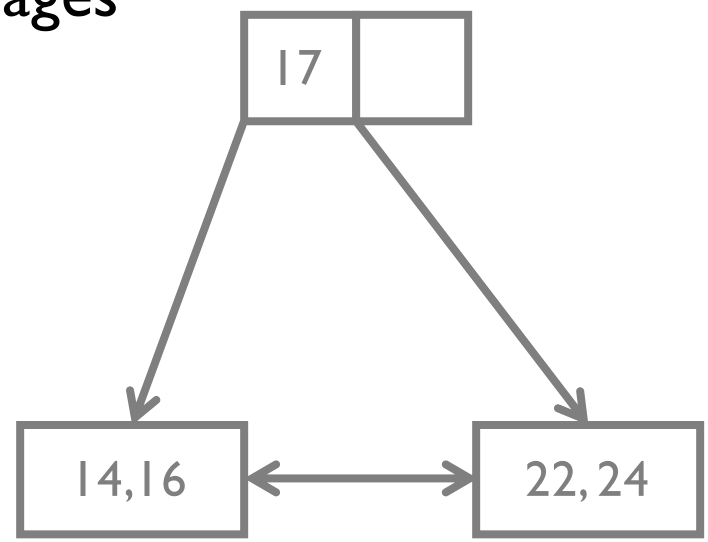
B+ Tree Index



Supports equality and range queries on search key
Self balancing
Leaf nodes are connected
Disk optimized
Node = Page
Height is with respect to directory pages (the gray part of the triangle)

B+ Tree on (age)

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

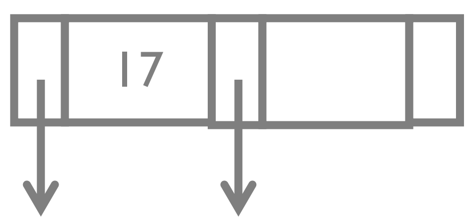


index & data
page contents
are in order

Leaf Data pages
data entries/tuples

Query: SELECT * WHERE age= 14

directory page

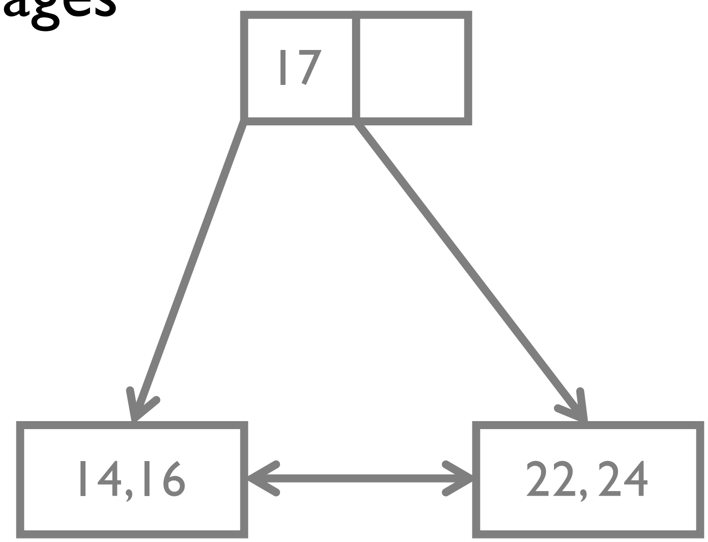


Index Only Queries: B+ Tree on (age)

Non-leaf Directory pages

m index entries

m+1 pointers



index & data page contents are in order

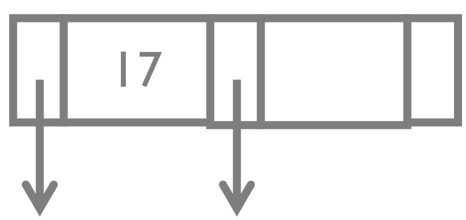
Leaf Data pages

data entries/tuples

Query: SELECT age WHERE age > 14

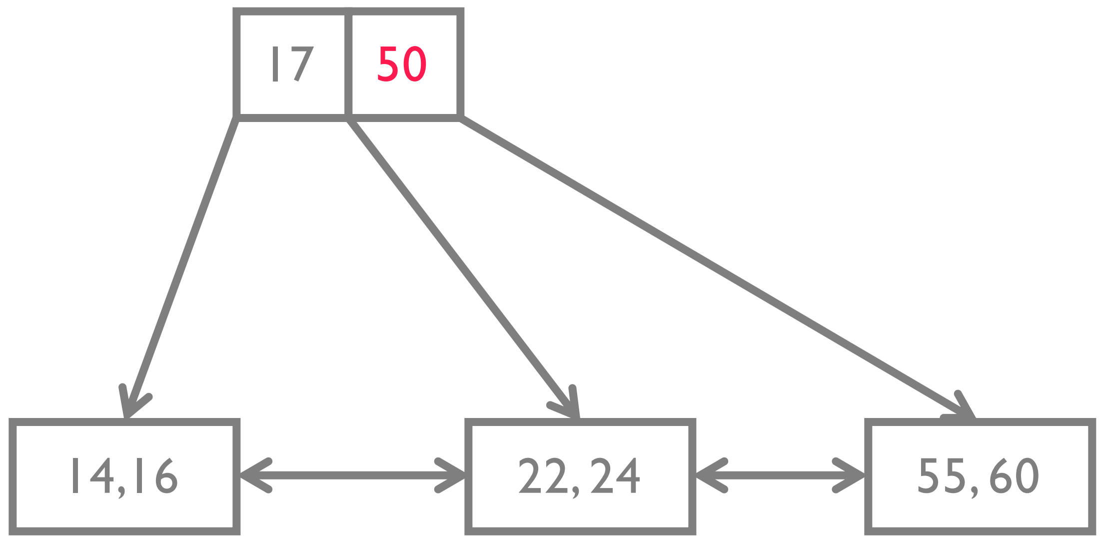
(index only!)

directory page



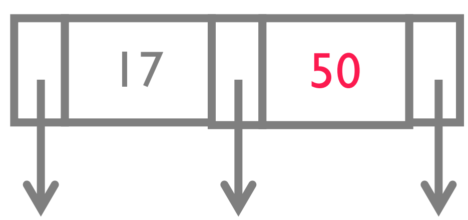
B+ Tree on (age)

Note: 50 not a data entry

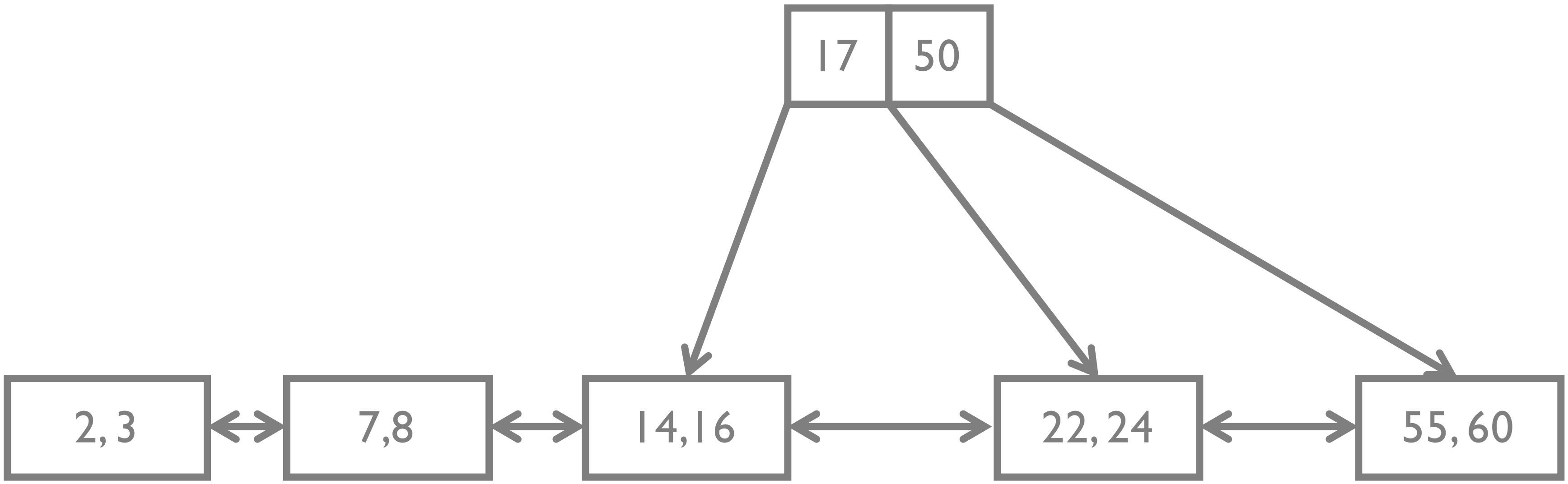


Query: SELECT * WHERE age = 55

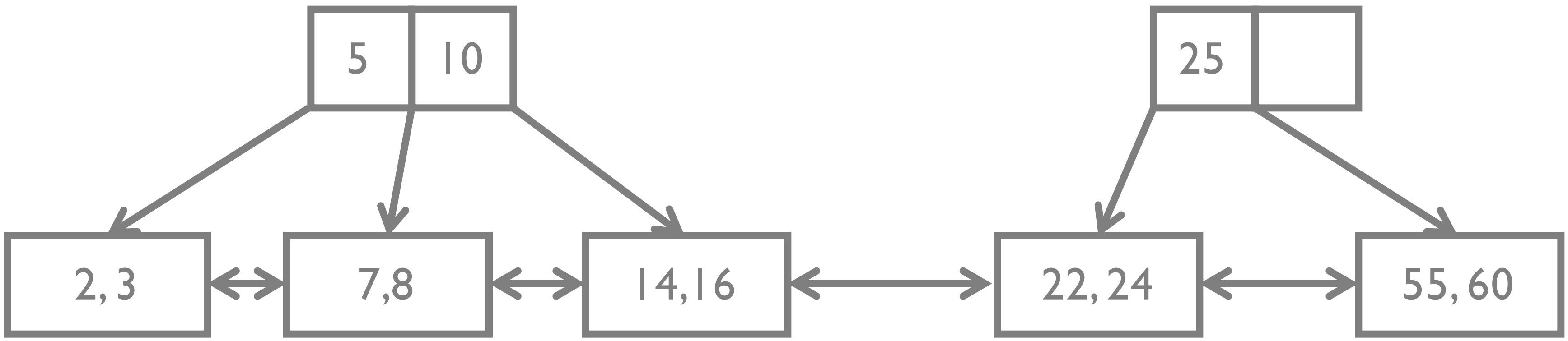
directory page



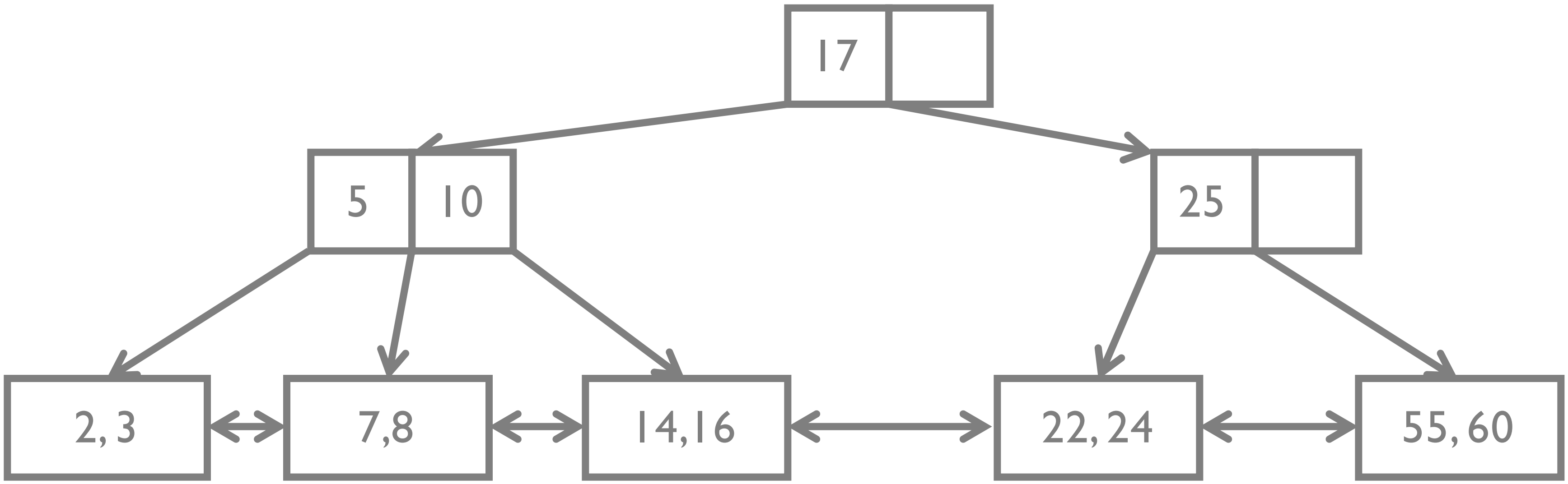
B+ Tree on (age)



B+ Tree on (age)

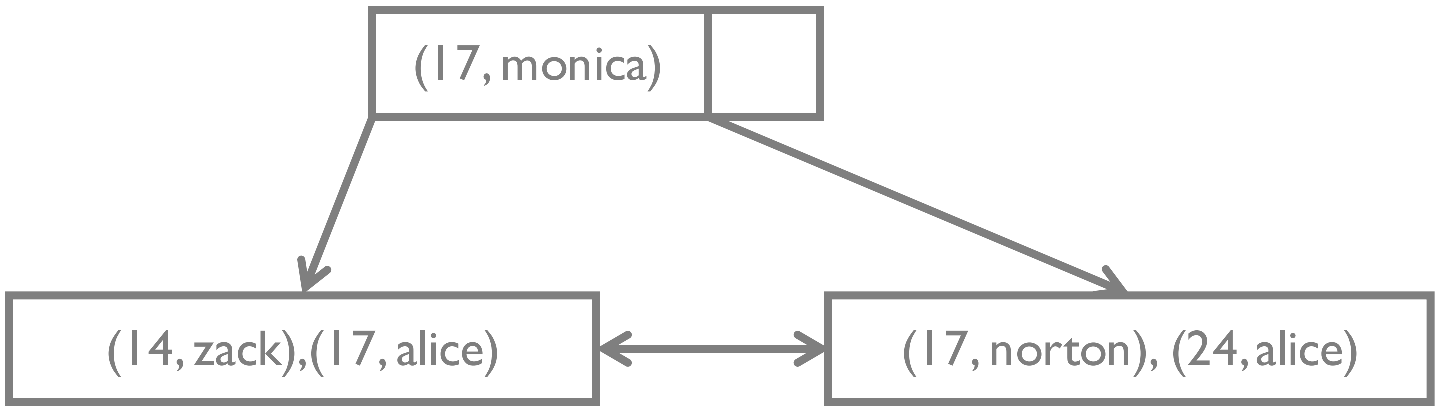


B+ Tree on (age)



Query: SELECT * WHERE age > 20

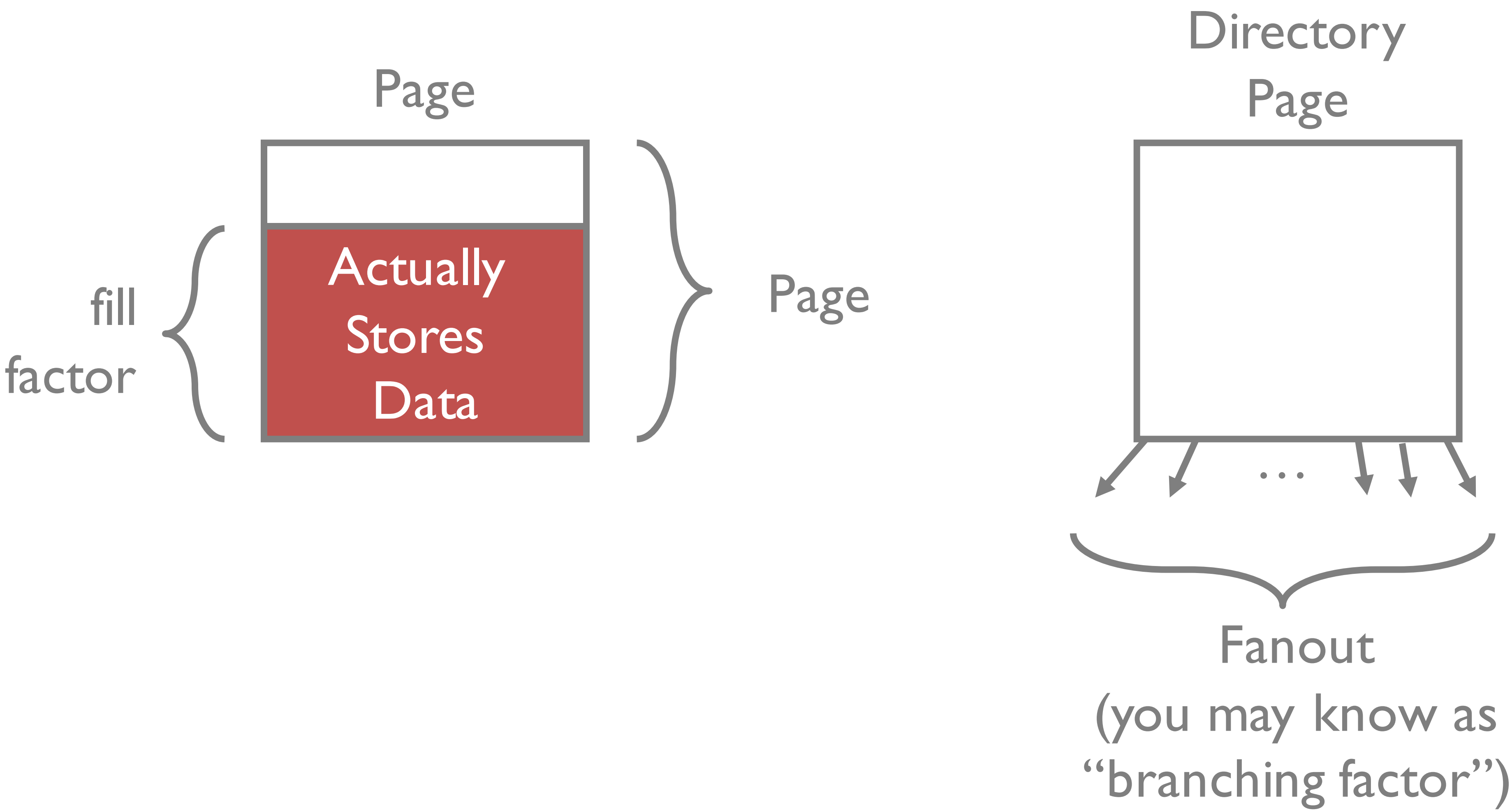
B+ Tree on (age, name)



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'
```

Terminology



Some numbers (8kb pages)

How many levels?

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

height 2: 300^3 ~ 27 Million entries assuming 300 tuples/pg

height 3: 300^4 ~ 8.1 Billion entries assuming 300 tuples/pg

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

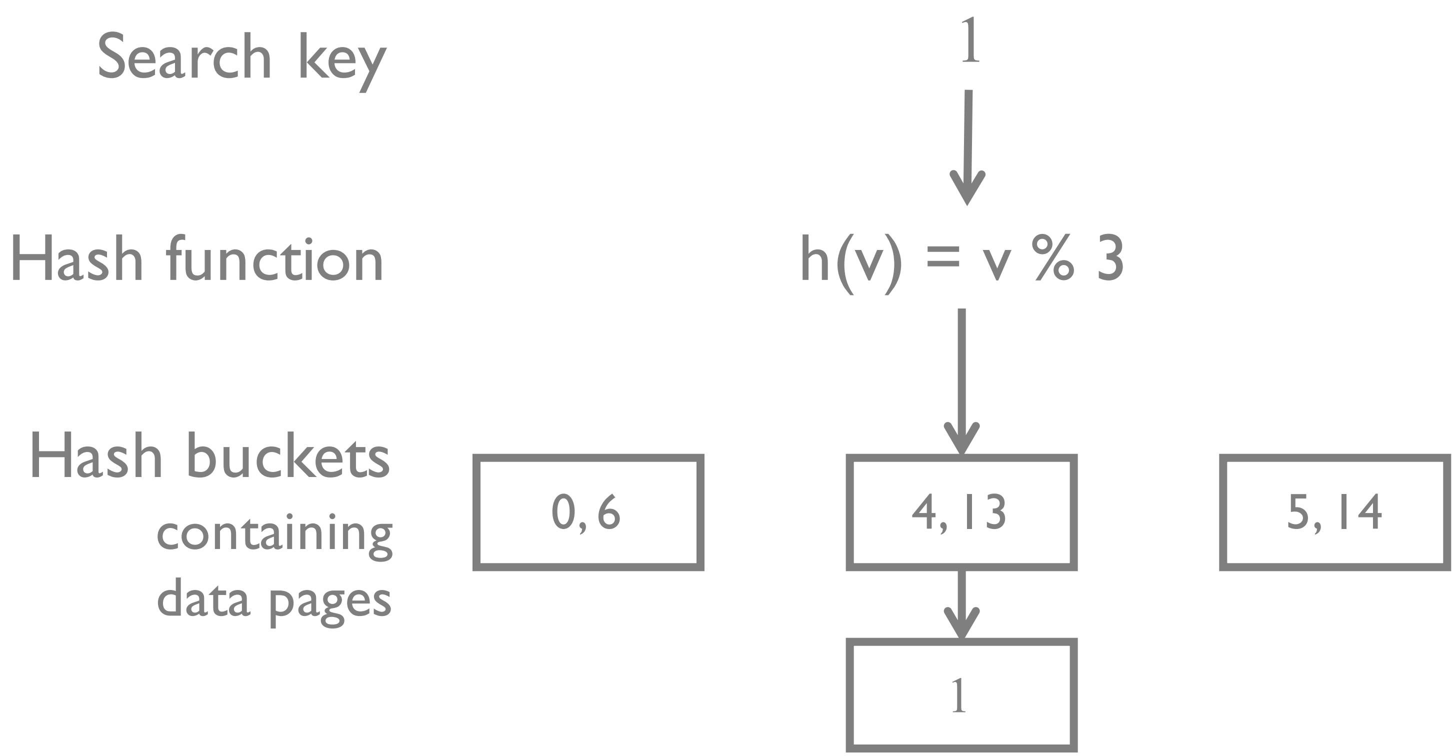
Hash Index on age

Hash function $h(v) = v \% 3$

Hash buckets containing data pages

0, 6	4, 13	5, 14

INSERT Hash Index on age

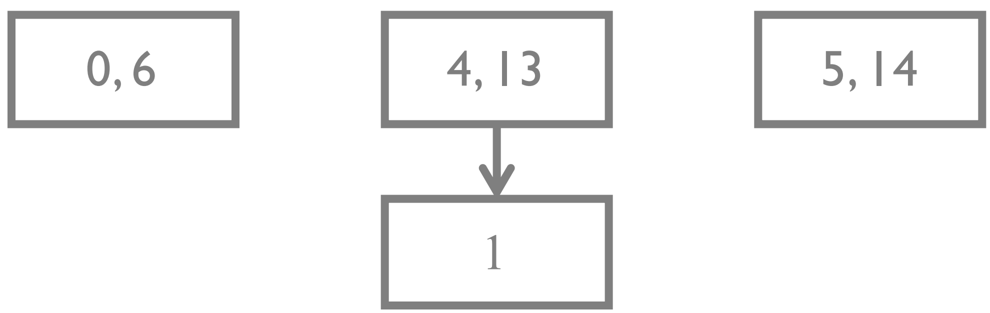


INSERT Hash Index on age

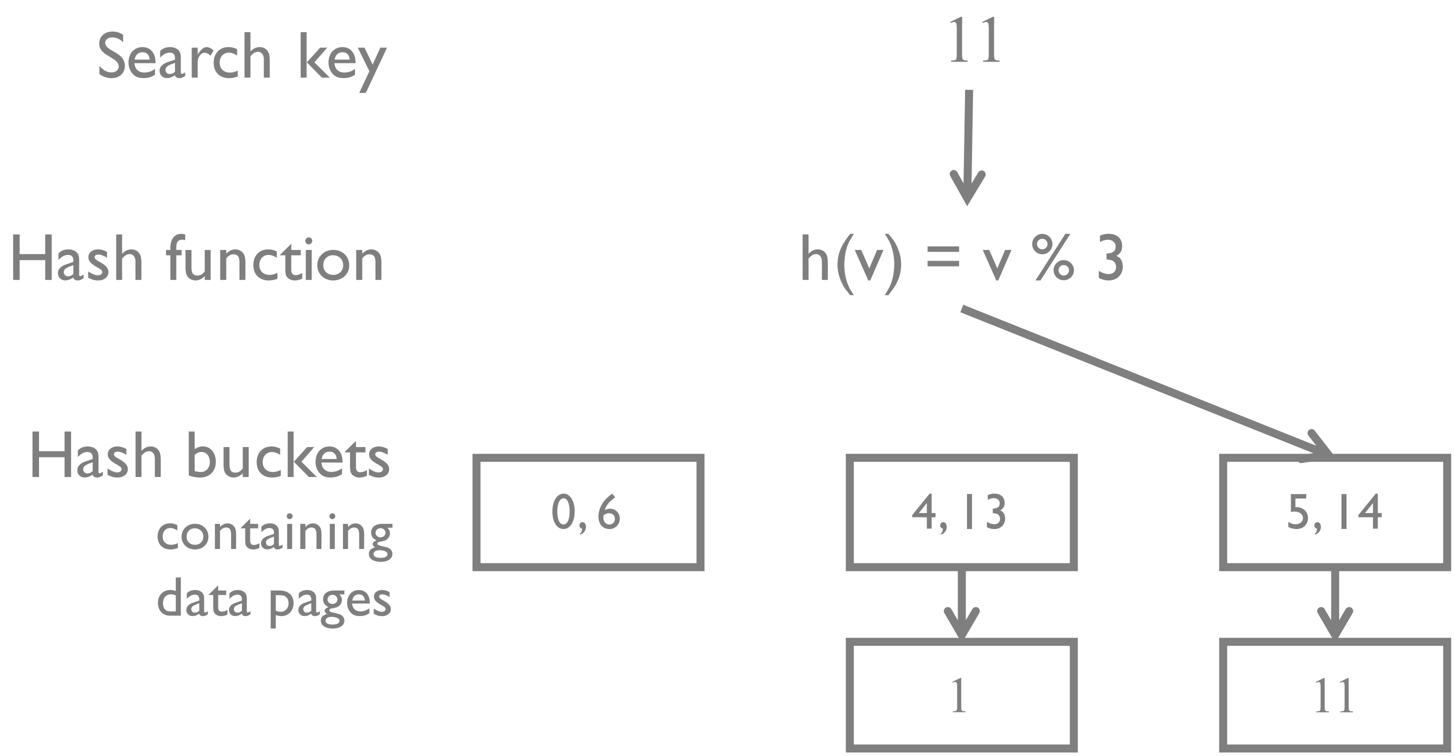
Search key 11

Hash function $h(v) = v \% 3$

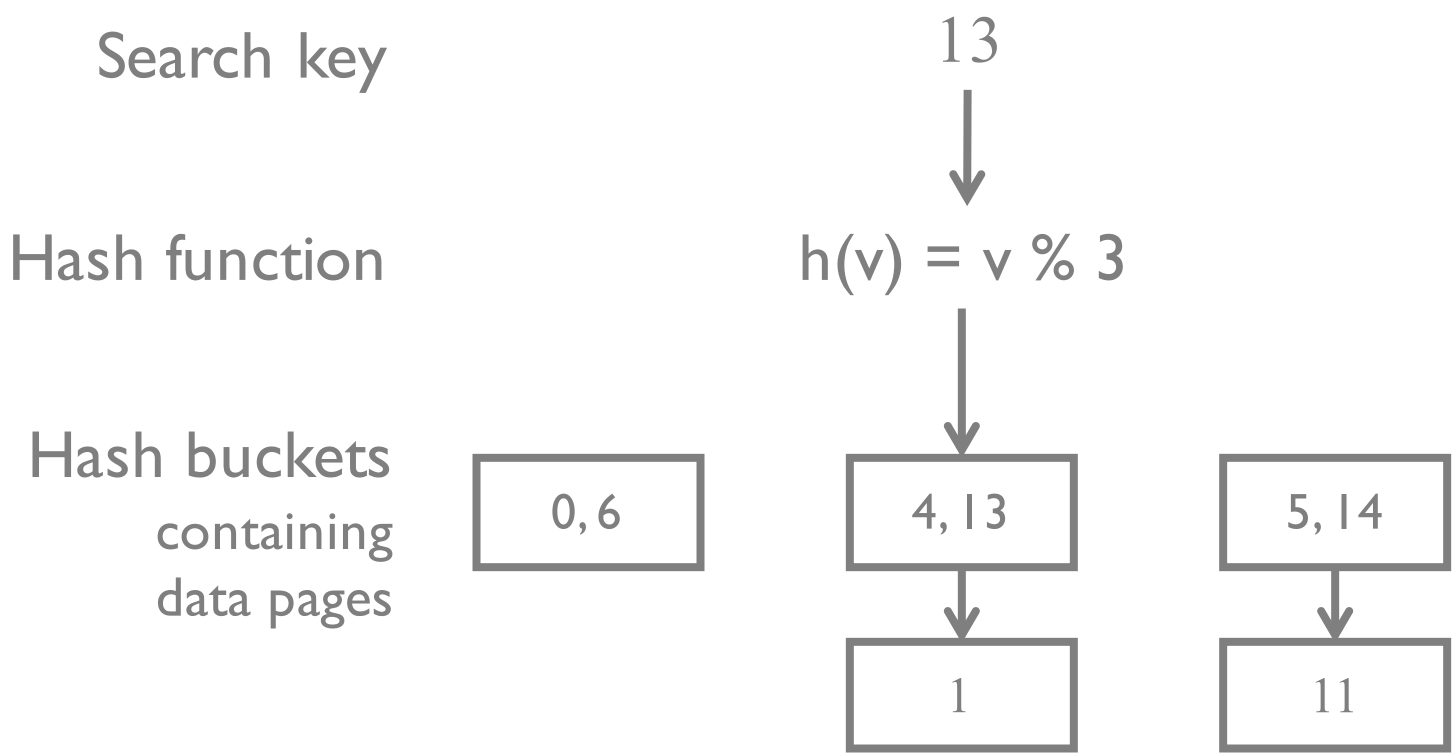
Hash buckets containing data pages



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	1.25BD	
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	$D(\log_{80} B + 2)$	
Delete	Search + D	Search + BD	$D(\log_{80} B + 2)$	

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	$D(\log_2 B)$	$D(\log_{80} B + 1)$	D
Range	BD	$D(\log_2 B + M)$	$D(\log_{80} B + M)$	1.25BD
Insert	2D	Search + BD	$D(\log_{80} B + 2)$	2D
Delete	Search + D	Search + BD	$D(\log_{80} B + 2)$	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

Where do B, D, M come from?

Estimated from more basic info

Assuming (we will be clear about this)

- fanout = number of directory entries
- pointer in secondary index same size as directory entry

Given:

- p: page size
- r: record size
- d: directory entry size
- f: fill factor
- n: # records

Estimate for primary and secondary index:

- size
- height
- access cost

Primary B+ Index

$p = 100$	records/page	$p / r = 10$
$r = 10$	direntries/page	$p / d = 20$
$d = 5$	fanout:	20
$f = 100\%$	# data pages	$n/(p/r) = 800$
$n = 8000$	height	$\log_{20}800 = 3$

Cost to look up a single record is
3 for directory pages + 1 data page

Secondary B+ Index

p = 100	records/page	p / r = 10
r = 10	direntries/page	p / d = 20
d = 5	fanout:	20
f = 100%	# data pages	n/(p/d) = 400
n = 8000	height	2

Cost to look up a single record is
2 for directory pages + 1 data page + 1 pointer lookup

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