Administrivia

Updated Midterm/Final grading policy

- if your final has a higher score, we will drop your midterm 1 score and weigh the final represent both exams

Administrivia

HW4

- Query optimization
- EXPLAIN query

Project 2

- Graph analysis using SQL
- Extra Credit: recursive WITH clauses

Both Due 11/21

Real-world Example of FDs

Airport Dataset

```
"id","ident","type","name","latitude_deg","longitude_deg","elevation_ft","continent","iso_country","iso_region","municipality","sche
6523,"00A","heliport","Total Rf Heliport",40.07080078125,-74.93360137939453,11,"NA","US","US-PA","Bensalem","no","00A",,"00A",,,
323361,"00AA","small_airport","Aero B Ranch Airport",38.704022,-101.473911,3435,"NA","US","US-KS","Leoti","no","00AA",,"00AA",,,
6524,"00AK","small_airport","Lowell Field",59.947733,-151.692524,450,"NA","US","US-AK","Anchor Point","no","00AK",,"00AK",,,
6525,"00AL","small_airport","Epps Airpark",34.86479949951172,-86.77030181884766,820,"NA","US","US-AL","Harvest","no","00AL",,"00AL",
6526,"00AR","closed","Newport Hospital & Clinic Heliport",35.6087,-91.254898,237,"NA","US","US-AR","Newport","no",,,,,,"00AR"
322127,"00AS","small_airport","Fulton Airport",34.9428028,-97.8180194,1100,"NA","US","US-OK","Alex","no","00AS",,"00AS",,,
6527,"00AZ","small_airport","Cordes Airport",34.305599212646484,-112.16500091552734,3810,"NA","US","US-AZ","Cordes","no","00AZ",,"00
6528,"00CA","small_airport","Goldstone (GTS) Airport",35.35474,-116.885329,3038,"NA","US","US-CA","Barstow","no","00CA",,"00CA",,,
324424,"00CL","small_airport","Williams Ag Airport",39.427188,-121.763427,87,"NA","US","US-CA","Biggs","no","00CL",,"00CL",,,
322658,"00CN","heliport","Kitchen Creek Helibase Heliport",32.7273736,-116.4597417,3350,"NA","US","US-CA","Pine Valley","no","00CN",
6529,"00CO","closed","Cass Field",40.622202,-104.344002,4830,"NA","US","US-CO","Briggsdale","no",,,,,,"00CO"
6531,"00FA","small_airport","Grass Patch Airport",28.64550018310547,-82.21900177001953,53,"NA","US","US-FL","Bushnell","no","00FA",,
6532,"00FD","closed","Ringhaver Heliport",28.8466,-82.345398,25,"NA","US","US-FL","Riverview","no",,,,,,"00FD"
6533,"00FL","small_airport","River Oak Airport",27.230899810791016,-80.96920013427734,35,"NA","US","US-FL","Okeechobee","no","00FL",
534,"00GA","small_airport","Lt World Airport",33.76750183105469,-84.06829833984375,700,"NA","US","US-GA","Lithonia","no","00GA",,"0
6535,"00GE","heliport","Caffrey Heliport",33.887982,-84.736983,957,"NA","US","US-GA","Hiram","no","00GE",,"00GE",,,
6536,"00HI","heliport","Kaupulehu Heliport",19.832881,-155.978347,43,"OC","US","US-HI","Kailua-Kona","no","00HI",,"00HI",,,
```

TPC-H Warehousing Benchmark

```
LineID, OrderID, PartID, SupplierID, Qty, Discount, Tax,
CustomerID, OrderTotalPrice, OrderDate,
AvailQty, SupplyCost,
PartName, Brand, Type
SupplierName, Address

Order → CustomerID, OrderTotalPrice, OrderDate
PartID,SupplierID → AvalQty, SupplyCost
PartID → PartName, Brand, Type
SupplierID → SupplierName, Address
LineID → OrderID, PartID, SupplierID, Qty, Discount, Tax
```

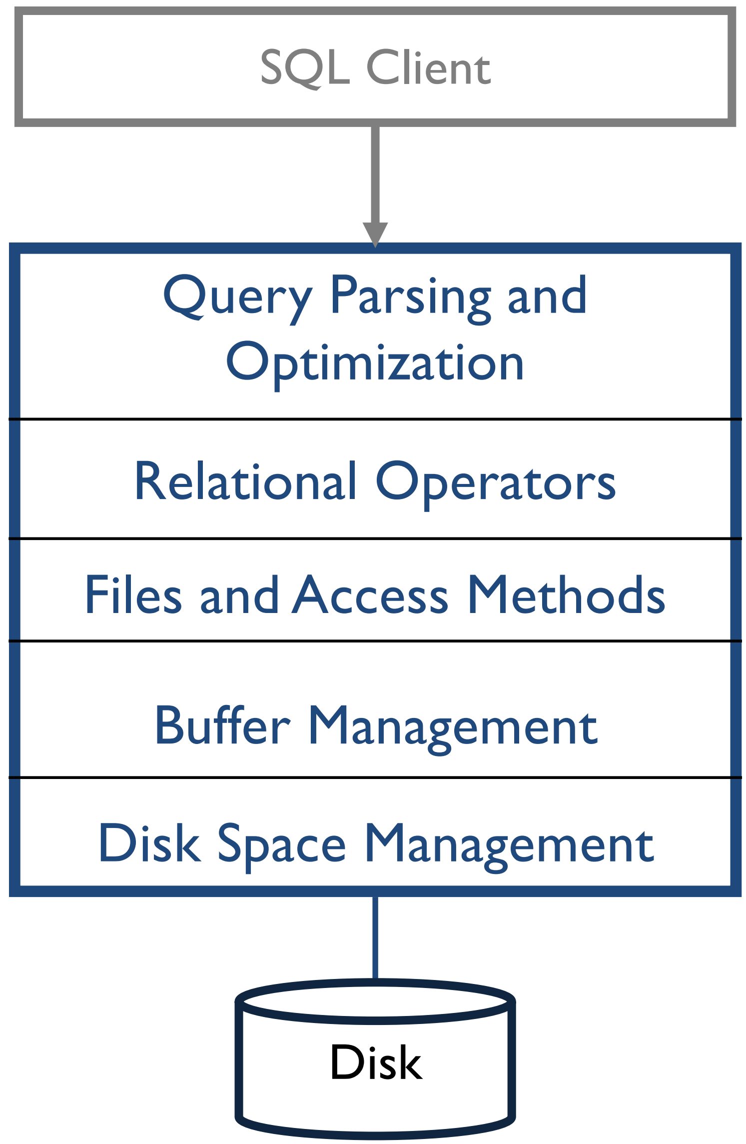
Disk, Storage, and Indexing

Eugene Wu

DBMS Overview

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

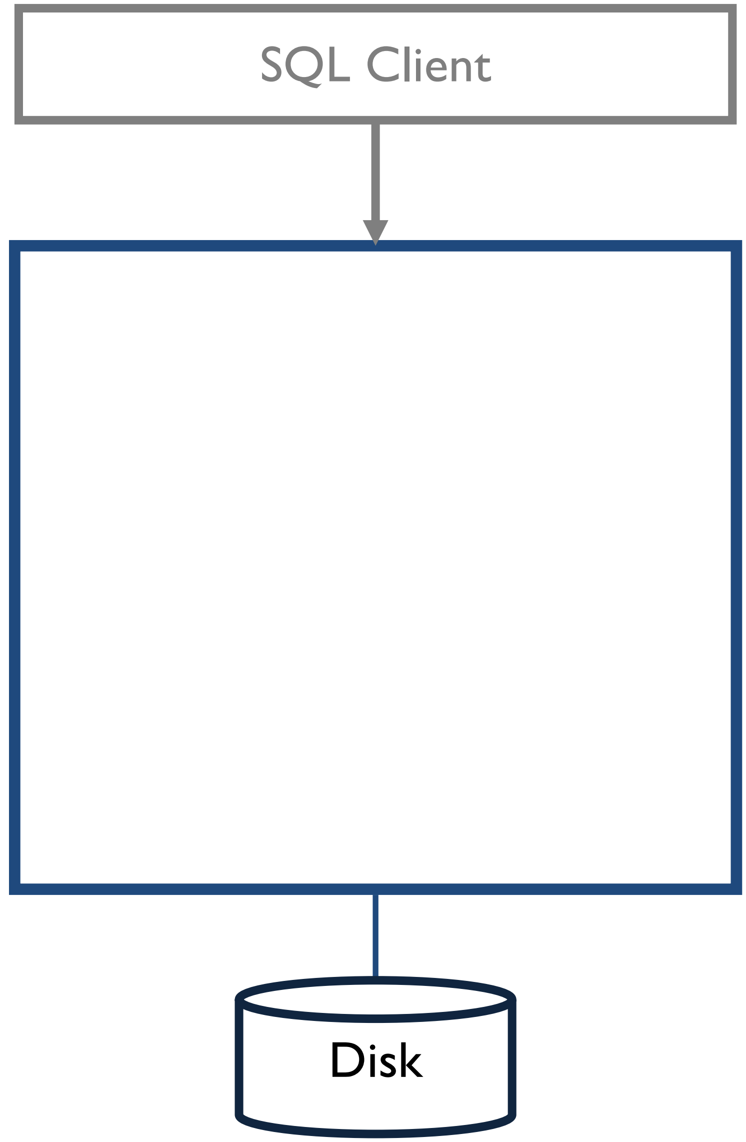
Requires careful design and assumptions for performance



DBMS Overview

Apps interact w/ SQL Client

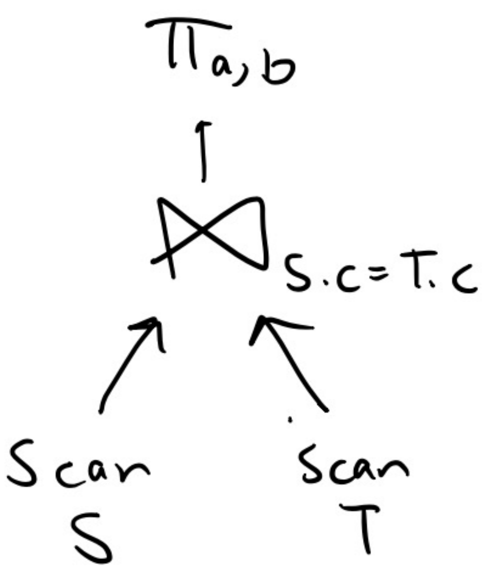
```
db.execute(‘‘‘
  SELECT a, b
    FROM S, T
   WHERE S.c = T.c
’’’)
```

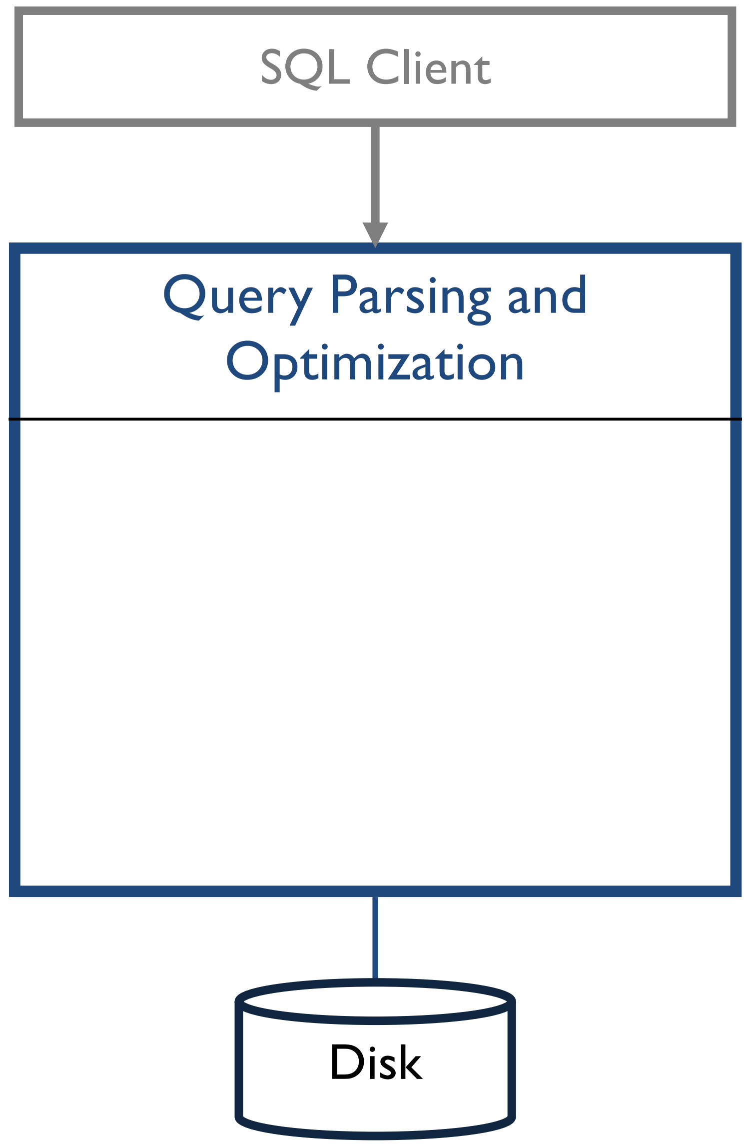


DBMS Overview

Parse, check, & verify SQL query

Turn into efficient query plan composed of logical operators

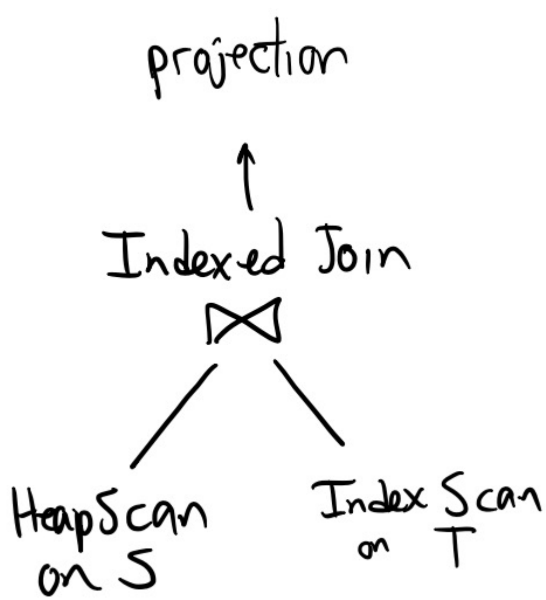


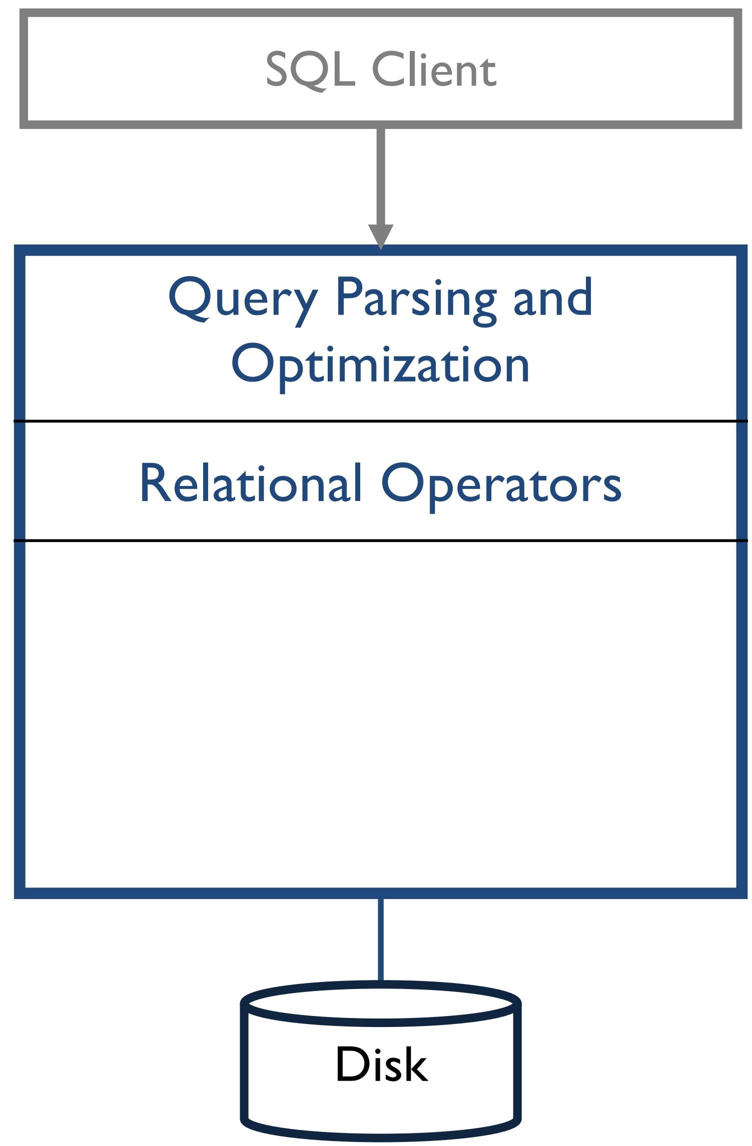


DBMS Overview

Query is modeled 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:

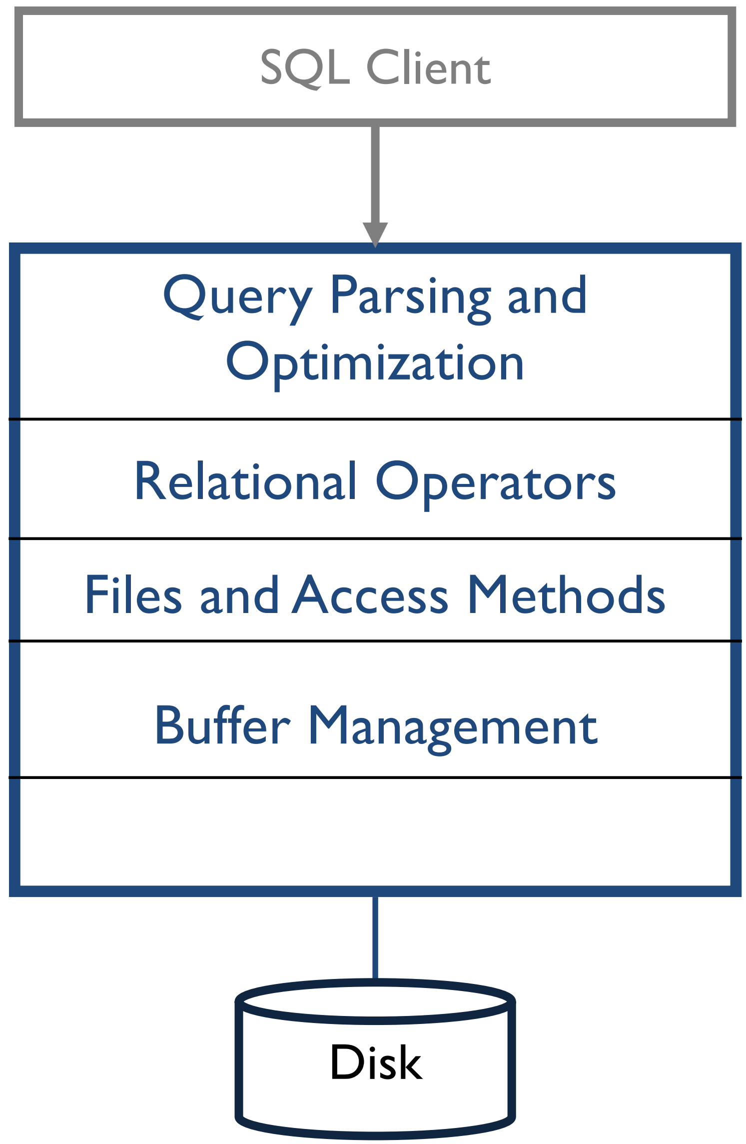
- Operators ask for records
- Logical files help read and write bytes on pages

DBMS Overview

Not all pages can fit into RAM.

Buffer manager provides illusion that all pages are accessible.

Files simply ask for pages.

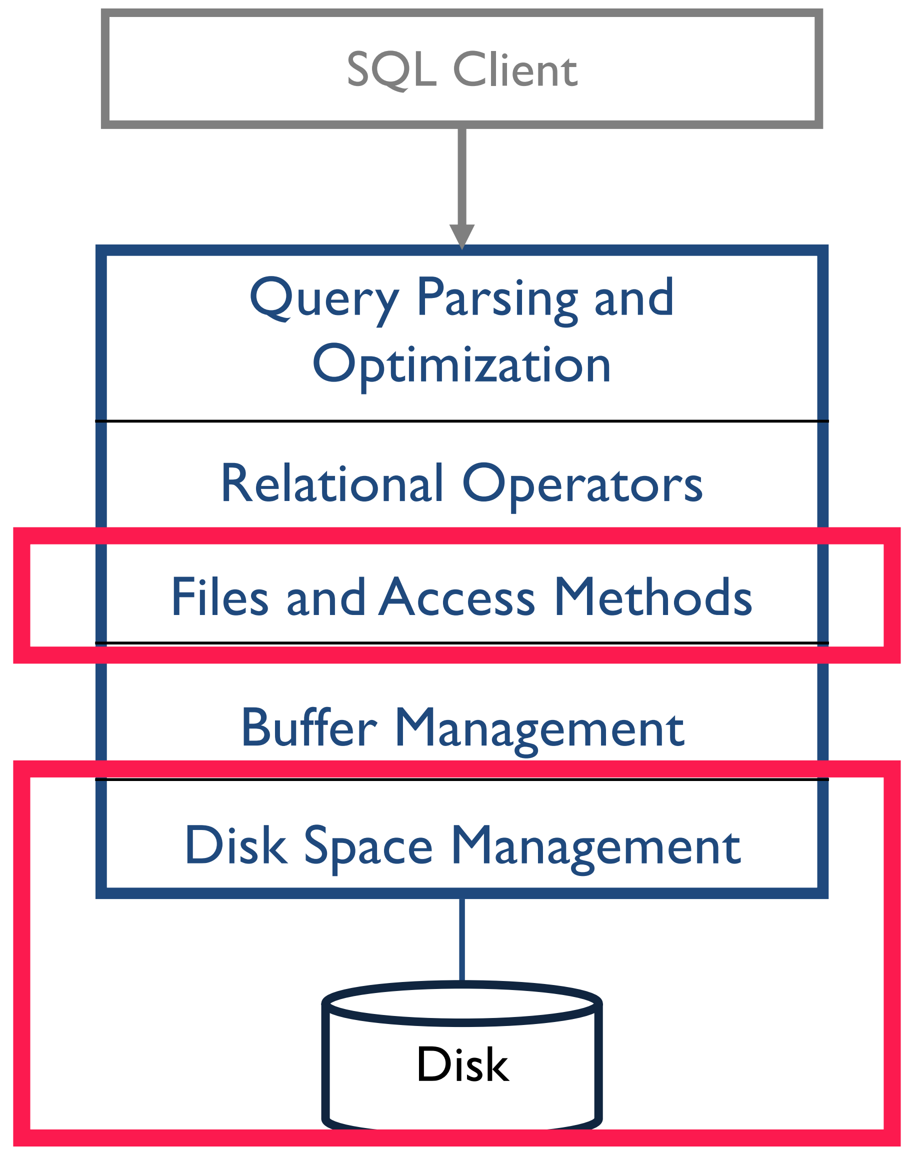


DBMS Overview

Physically read and write bytes on one or more storage devices

(hard drives, SSDs, etc)

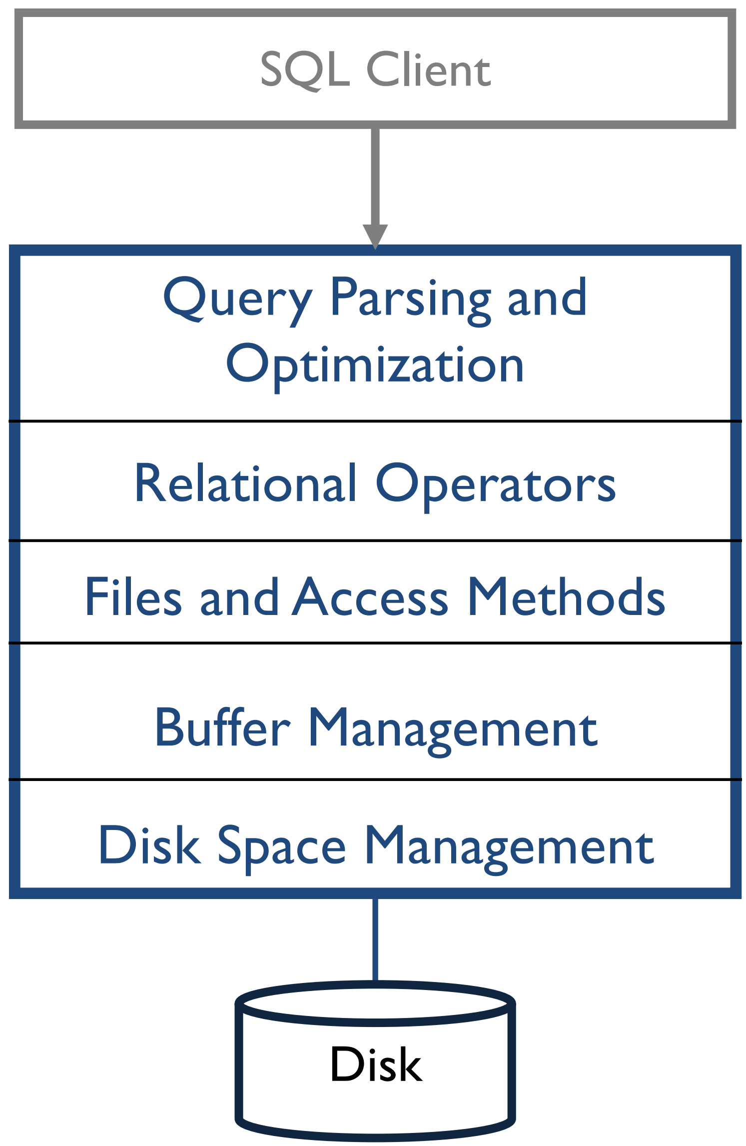
Storage performance properties dictate the design of layers above.



DBMS Overview

Layers help manage engineering complexity.

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



Storage Devices

Hard Drives vs SSDs vs RAM

Locality (random vs sequential)

Reads vs Writes

Performance and Monetary Costs

Why not store all in RAM? $$$

Too much $$$

- High-end DBs: ~Petabyte (1000TB).
- SQL Hyperscale: 100TB+ (2018)
- Disks are ~60% cost of a production system

Main memory not persistent

- Obviously important if DB stops/crashes

main-memory DBMSes discussed in advanced DB course

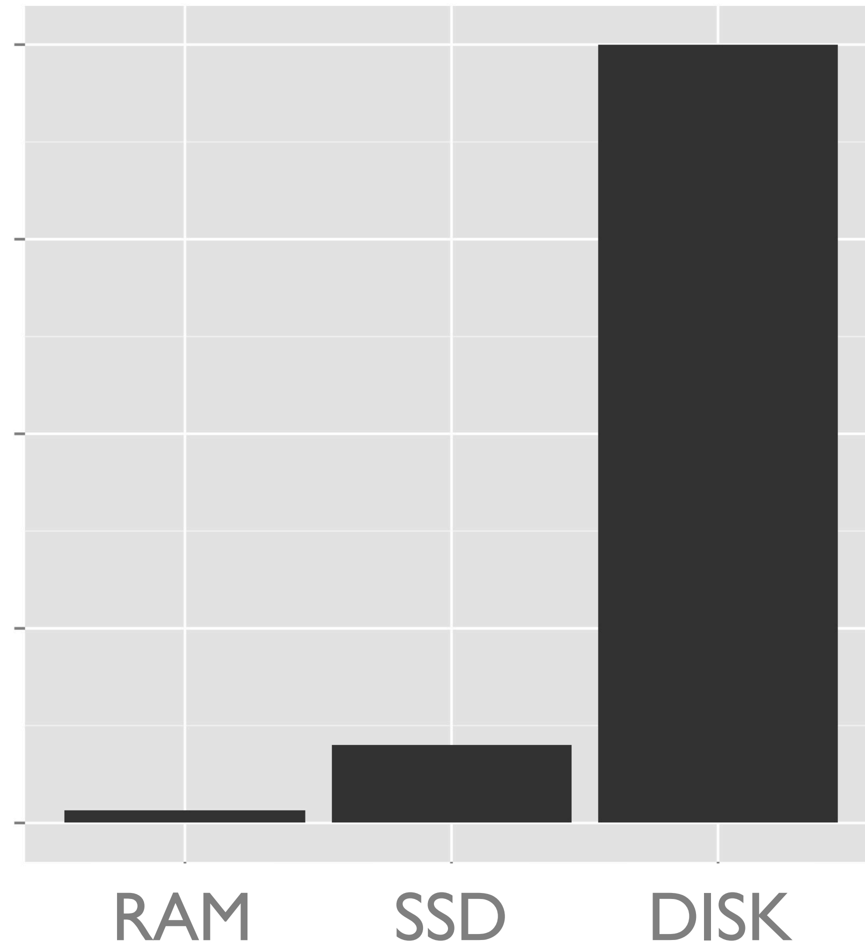
$ Matters

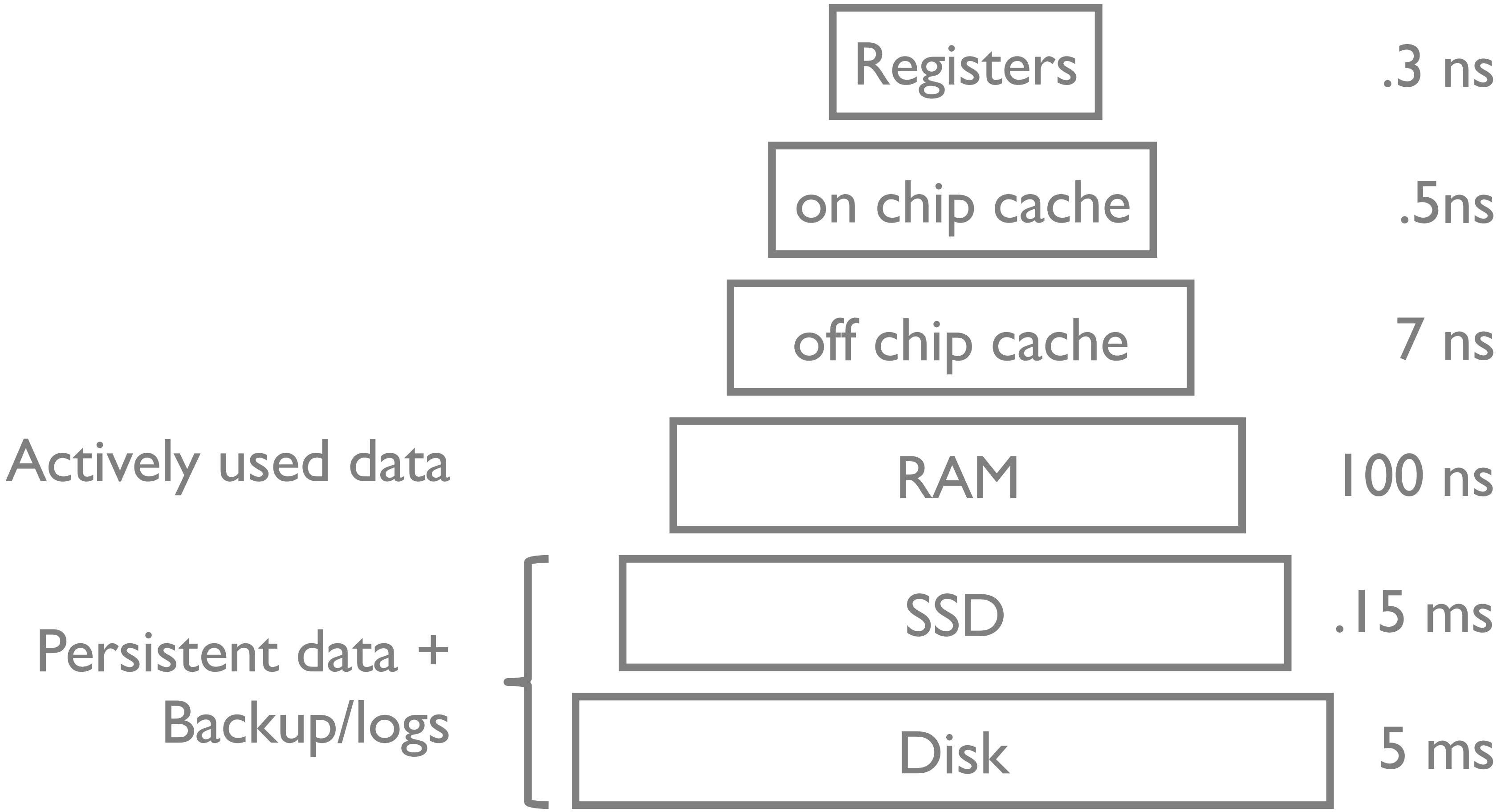
Newegg enterprise $1000

RAM: 0.08TB

SSD: ~2TB (25x)

Disk: ~40TB (500x)



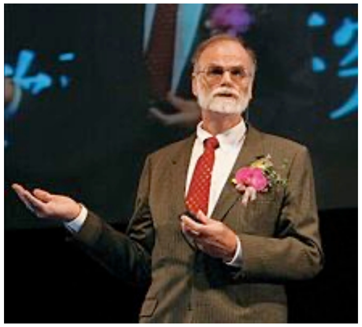


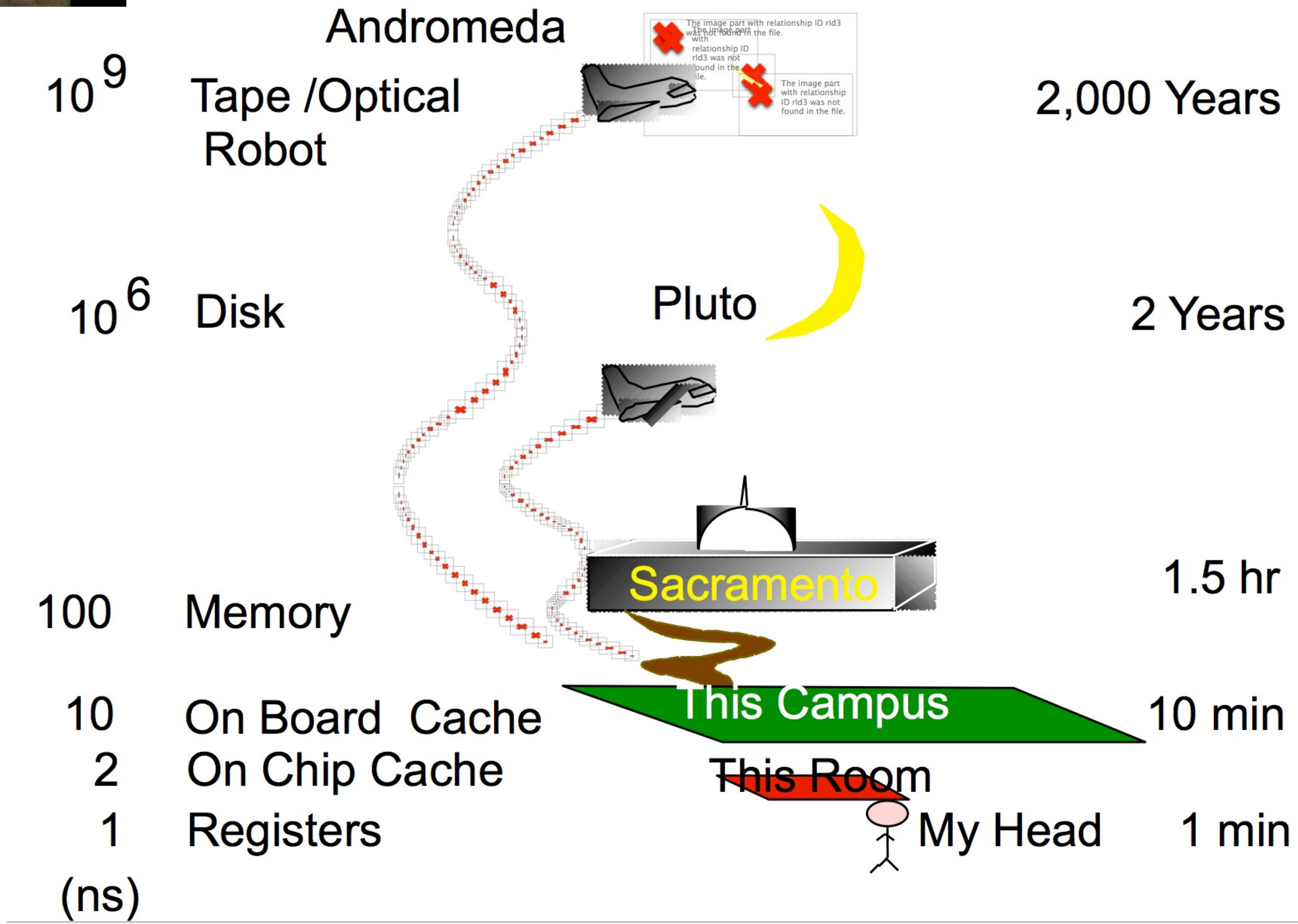
Interesting numbers

compress 1k bytes: 3000 ns

roundtrip in data center: .5 ms

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



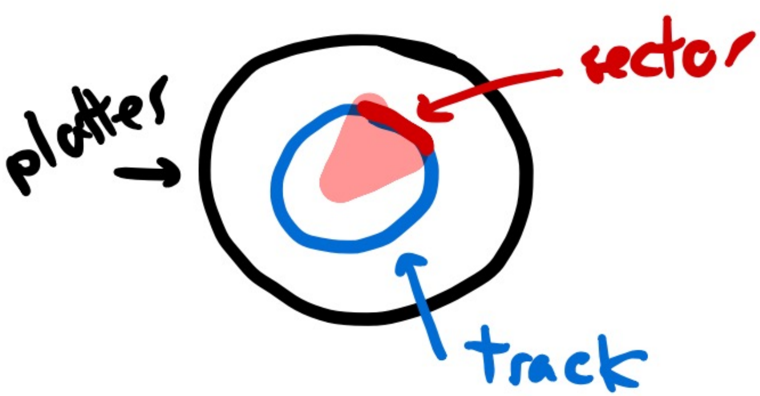

Andromeda
10^9
Tape /Optical Robot
2,000 Years
10^6
Disk
Pluto
2 Years
100
Memory
Sacramento
1.5 hr
10
On Board Cache
This Campus
10 min
2
On Chip Cache
This Room
1
Registers
My Head
1 min
(ns)
The image part with relationship ID rId3 was not found in the file.

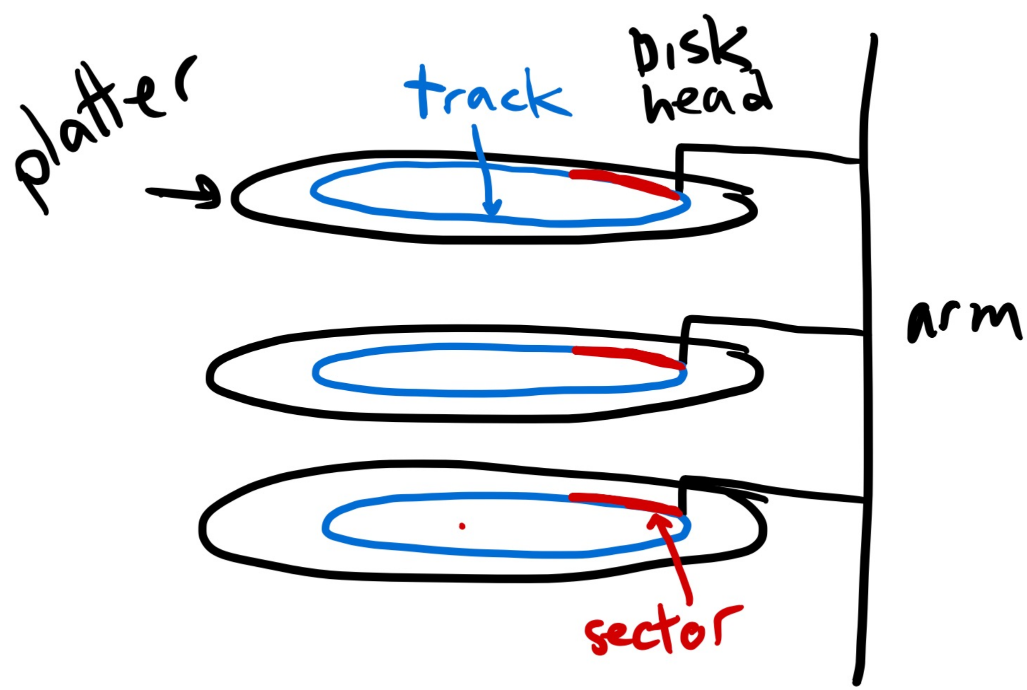
Spin speed: ~7200-15K RPM.   10K RPM ~ 6ms/rotation

Sector: multiples of pages.

More sectors further from center

Terminology: block = 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

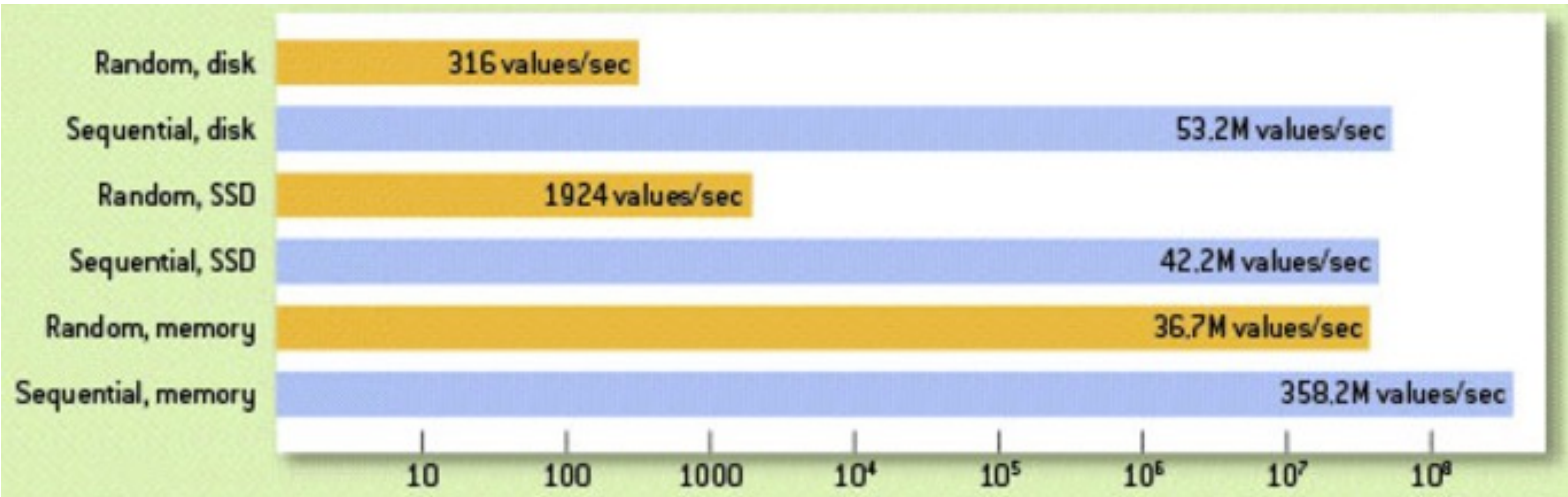
Throughput

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

Key: reduce seek and rotational delays

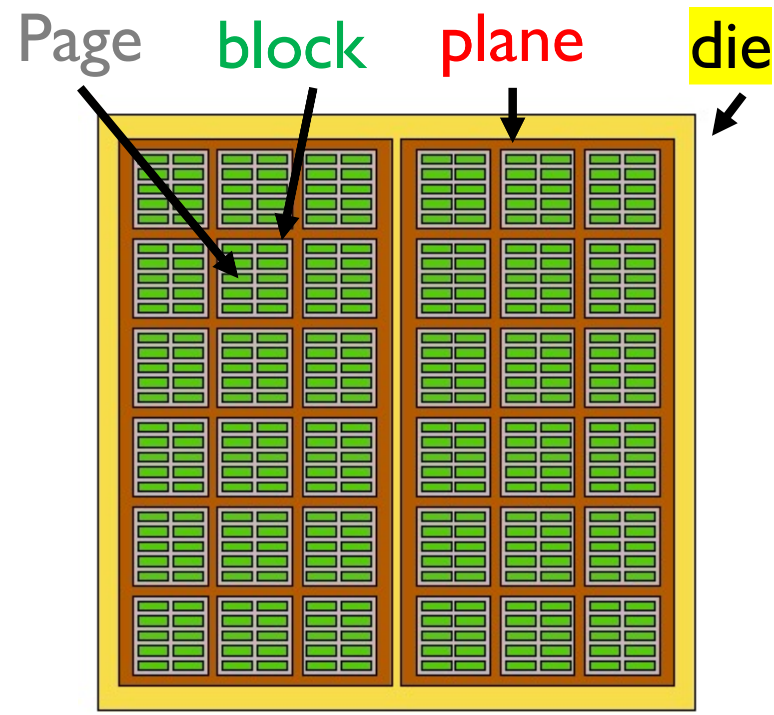
HW & SW approaches

of 4 byte values read per second



5 orders of magnitude

SSDs



NAND memory

Small reads: 4-8k sized page

Big writes: 1-2MB block

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

https://www.anandtech.com/show/2738/5

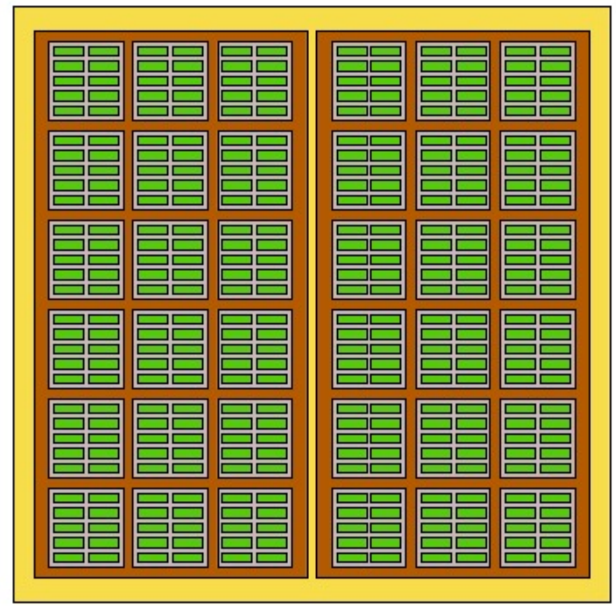
SSDs

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: SSD/RAM

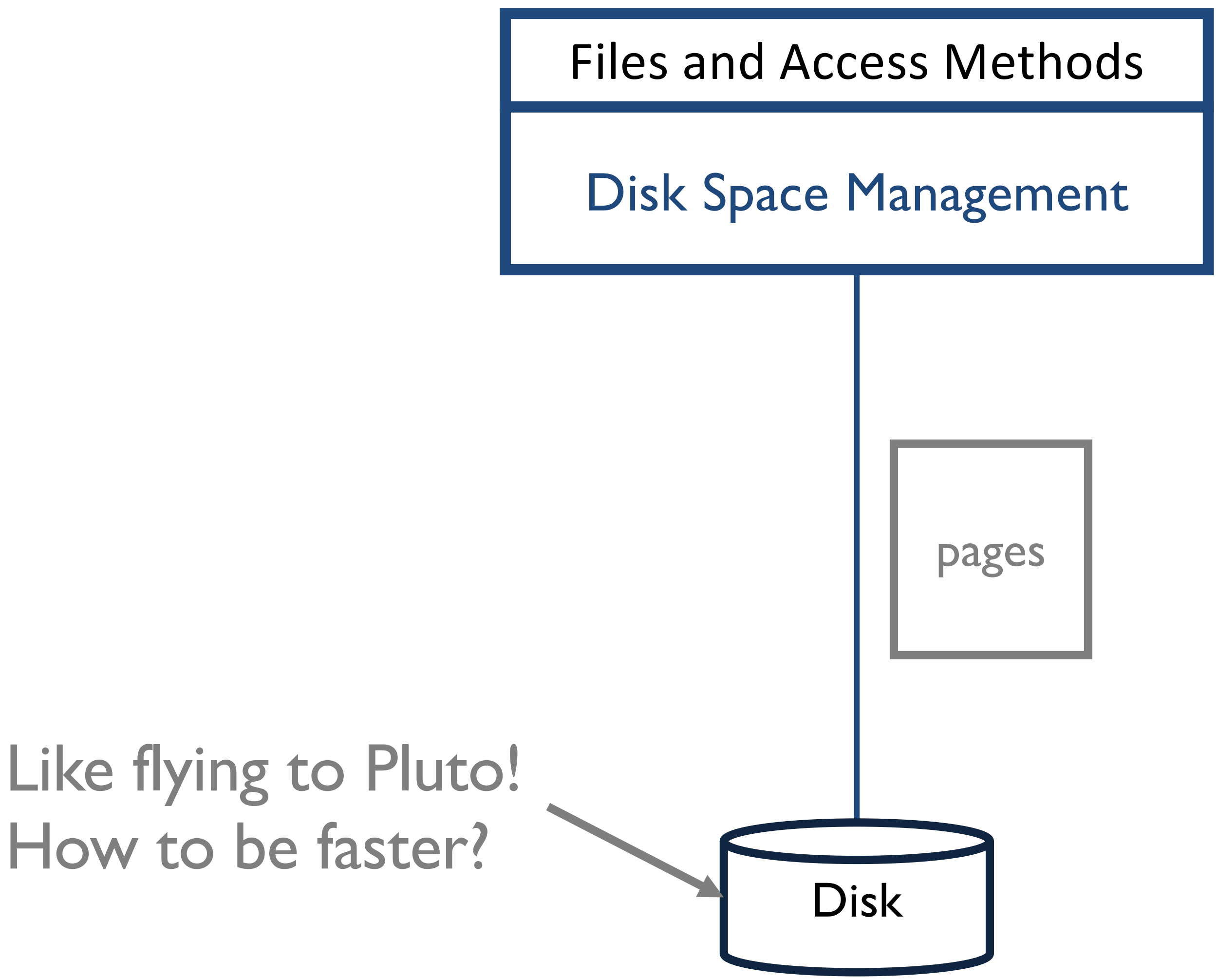
- All global daily weather since 1929: 20GB
- 2000 US Census: 200GB
- 2009 english wikipedia: 14GB
- Easily fits on an SSD or in RAM

Big databases: Disk

- 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

AWS h1.16xlarge: 64 vCPU, 256GB ram, 8x2T hard drives

Work from the bottom up



Strategies for Fast Data Access

(think about going to the store)

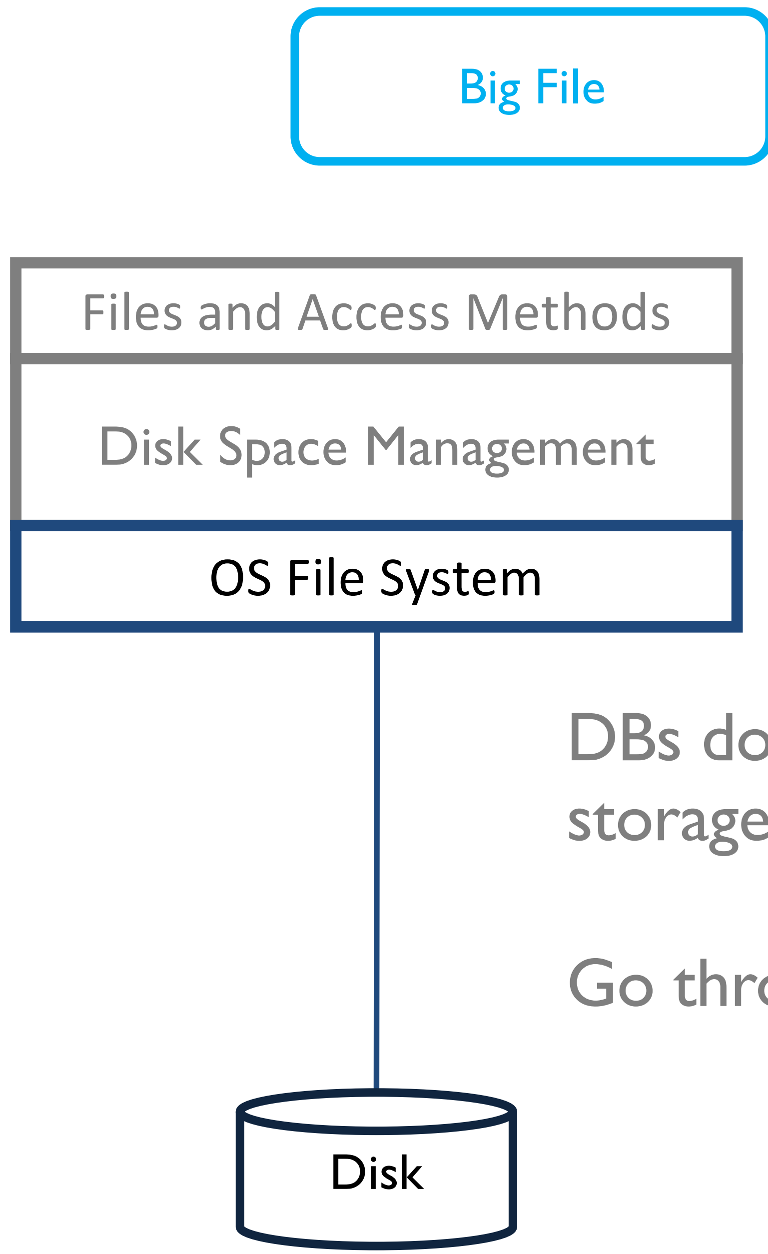
Big difference between random & sequential access

- Optimize for sequential accesses

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

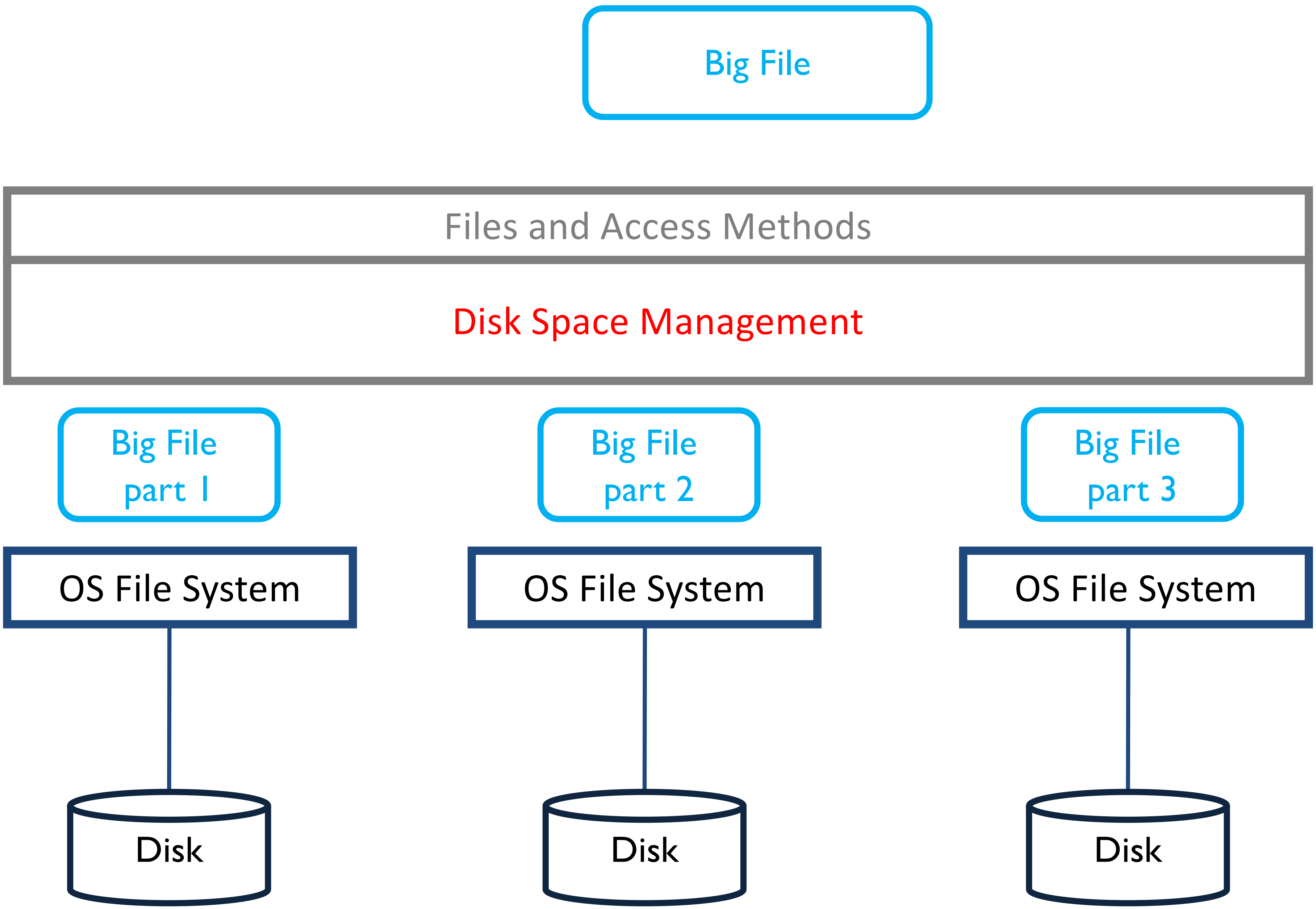
API

- 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.

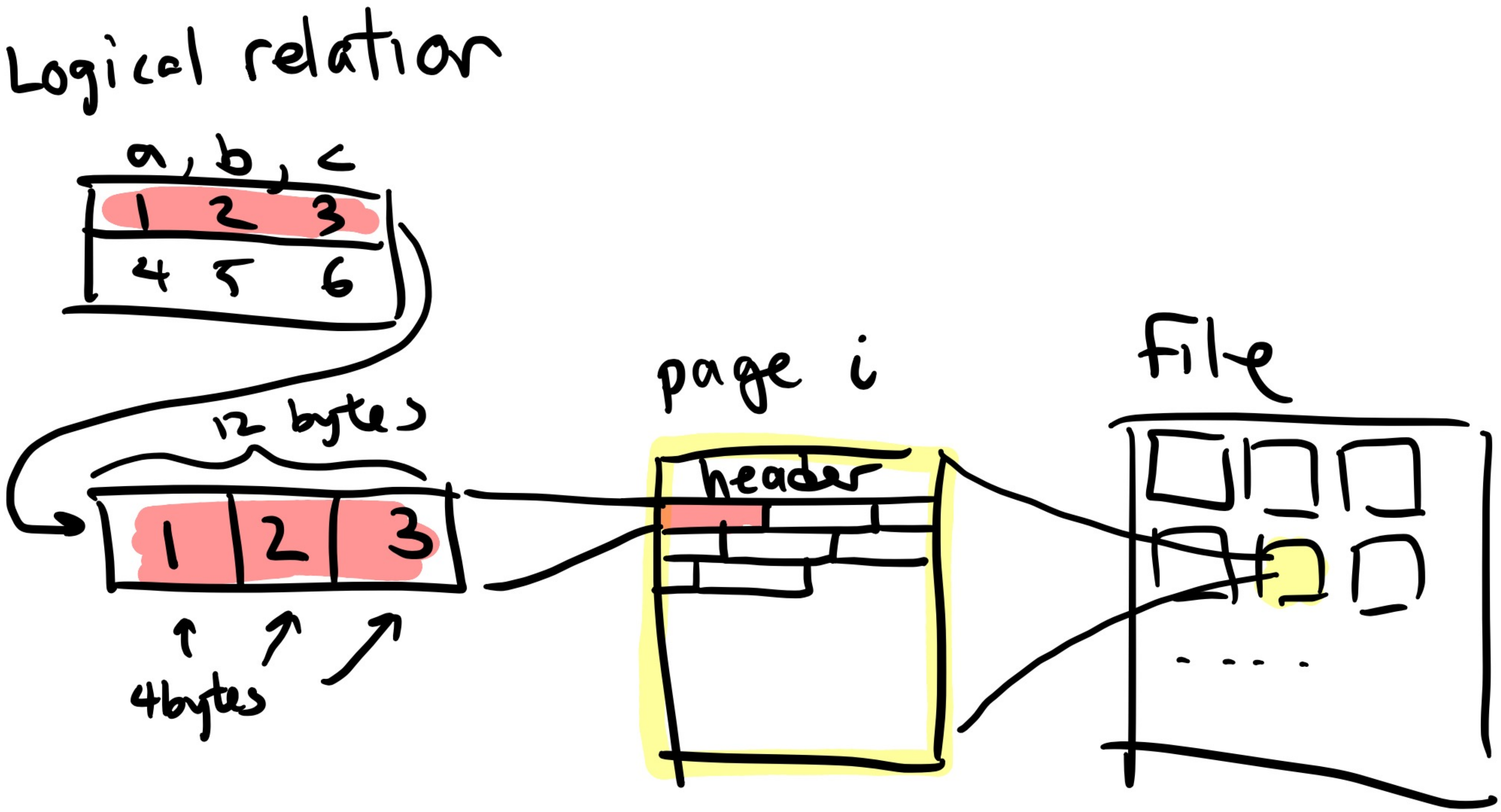
Go through OS file system


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.

File Organizations Overview

What do pages store, and how to organize pages?

- Unordered heap file
- Heap file
- B+ tree index
- Hash index

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

Ok, let's design that

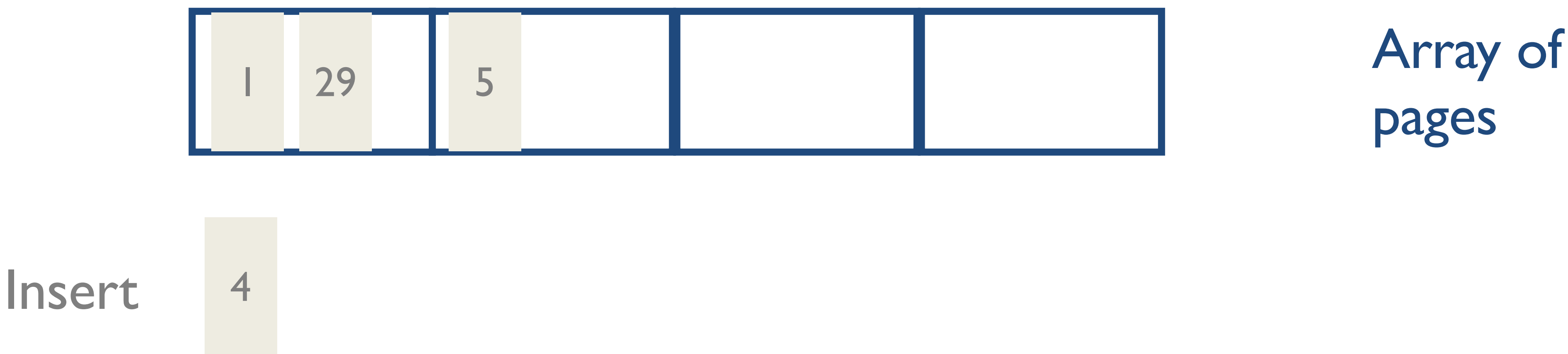
Super Naïve Design

Big array
of bytes

Heap is a big array of bytes.

First split into array of pages

Super Naïve Design

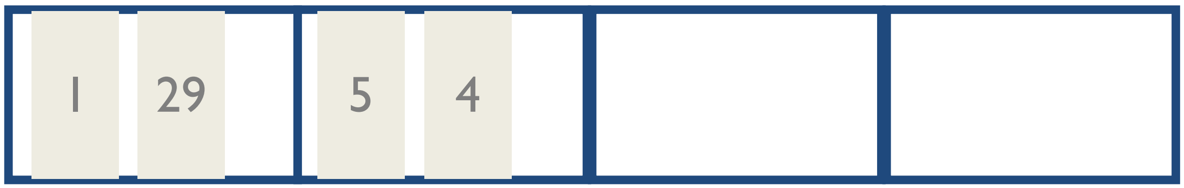


Each each page from disk sequentially

Check if there's an open spot

Insert 4 into open spot.

Super Naïve Design

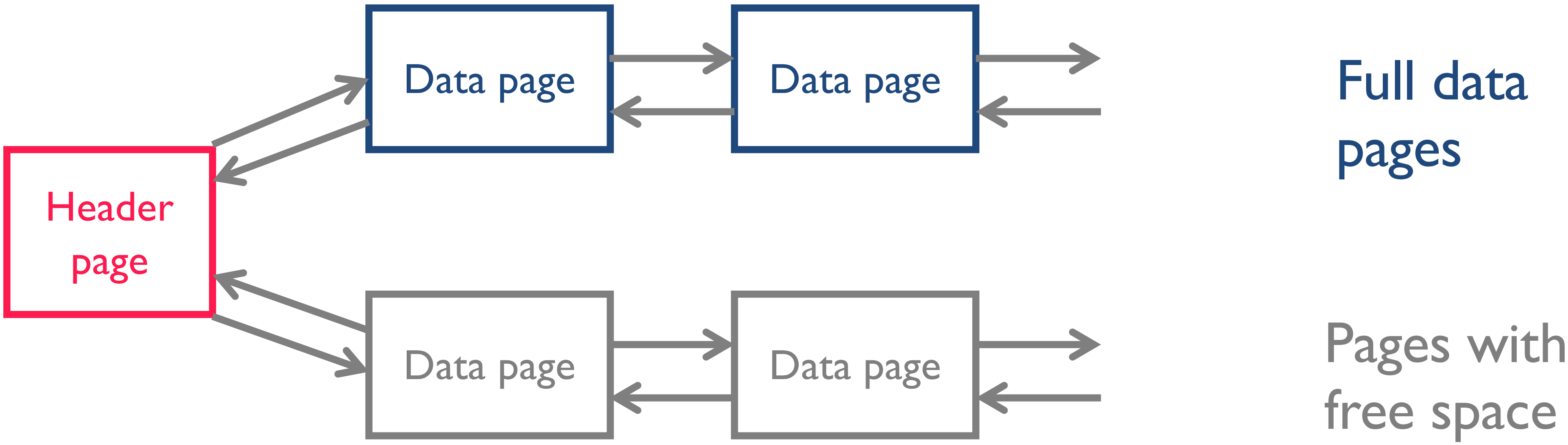


Array of pages

Some problems include

- Slow to know what pages are empty, full, have space
- Slow to find a particular value
- Fragmentation

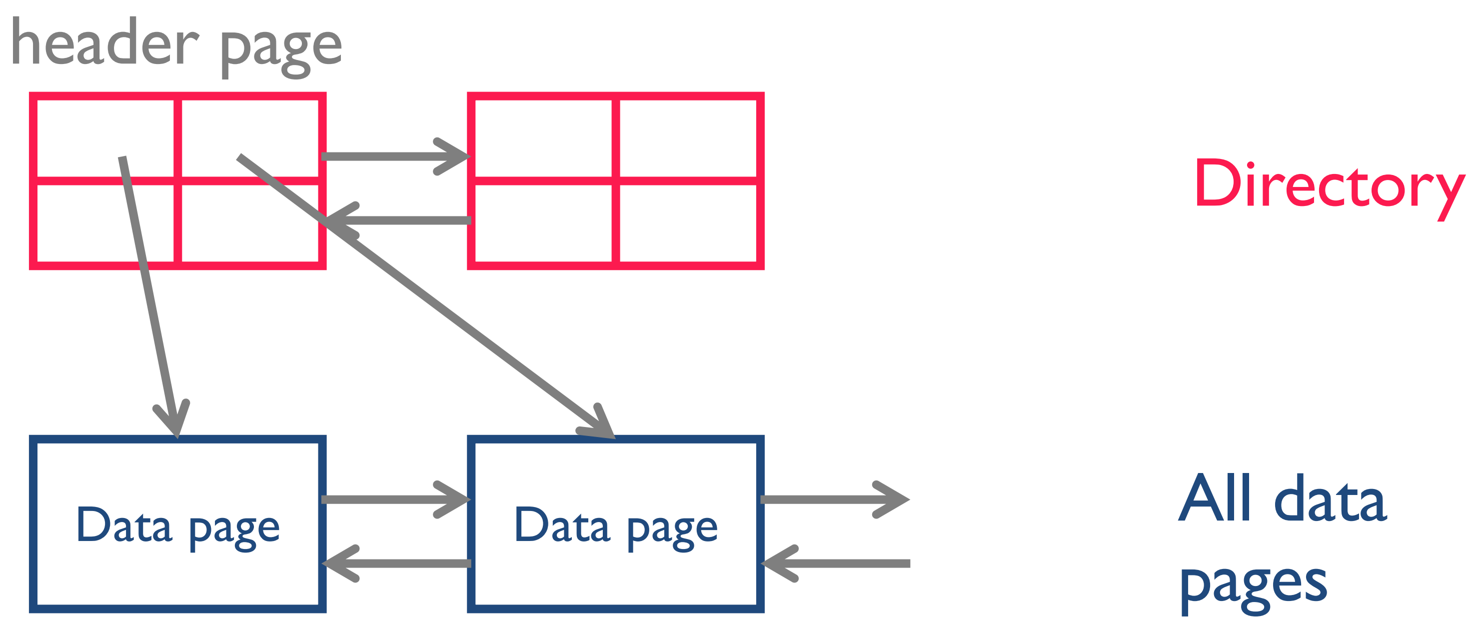
Heap File



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

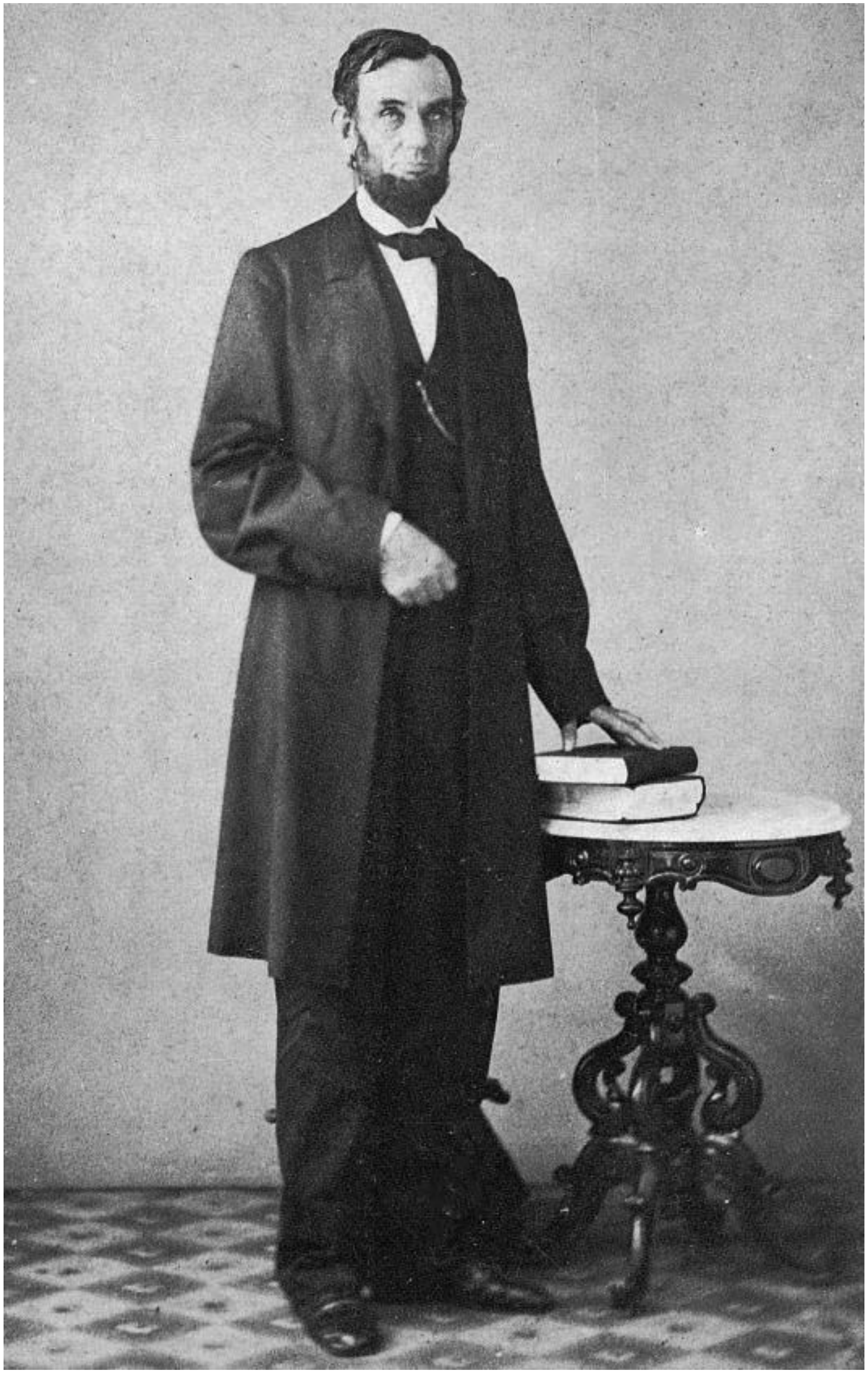
Need to scan pages to answer any query
Which page has enough free space for 100 bytes?

Use a directory



Directory entries track # free bytes on data pages

Directory is collection of pages



Indexes

"If I had 8 hours to chop down a tree, I'd spend 6 sharpening my ax."

Abraham Lincoln

Indexes

Heap files answer any query via a sequential scan, but…

Queries use *qualifications* (predicates)

find students where 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 with respect to a *search key*

don't confuse with candidate keys!!

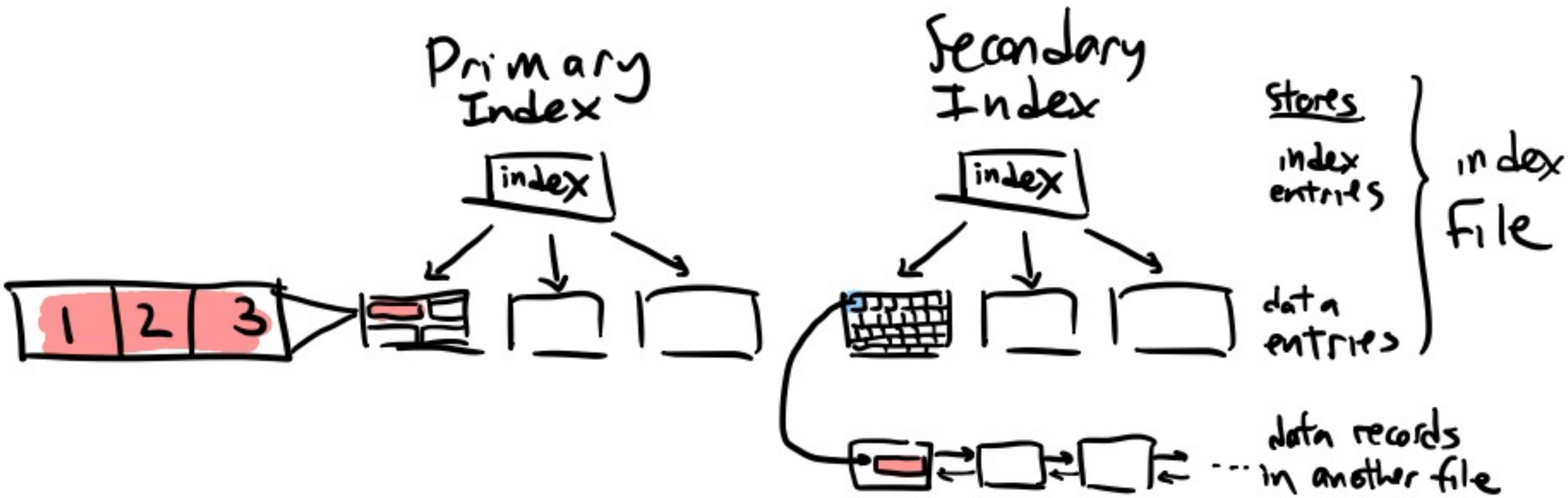
Faster access for WHERE clauses w/ search key

```
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

https://www.postgresql.org/docs/11/sql-createindex.html

Primary vs Secondary Index Files



Primary

Data entries contain actual tuples

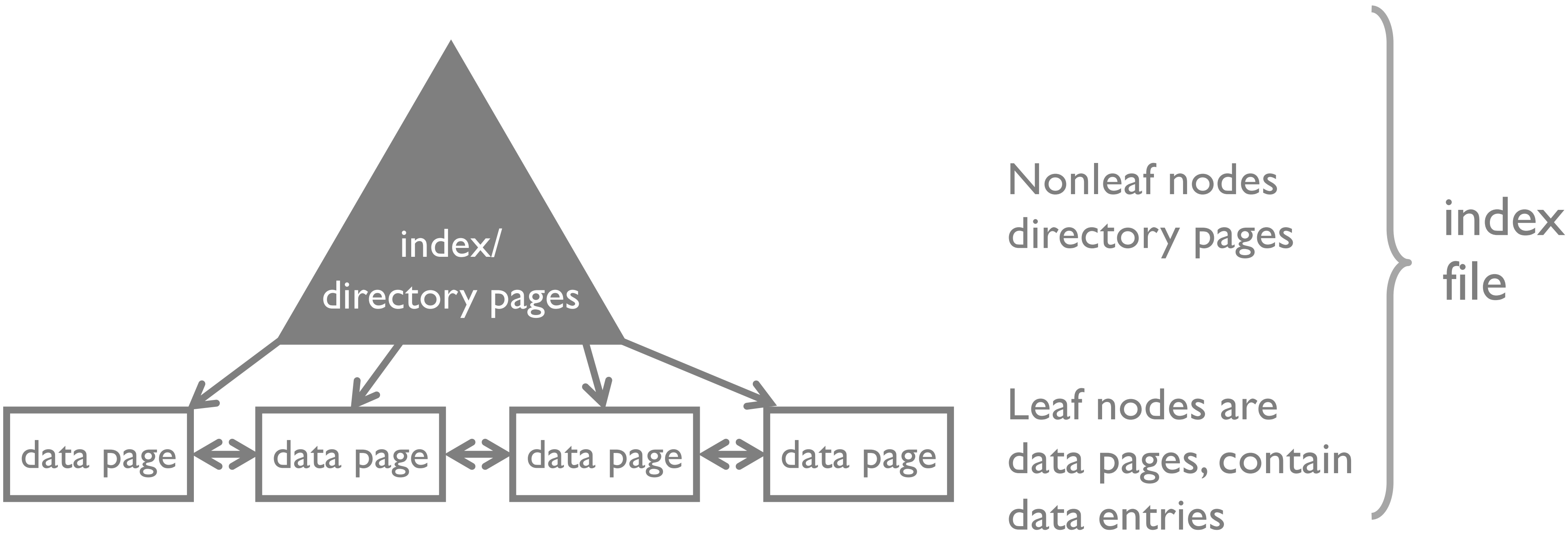
Pros: directly access data.

Secondary

Data entries contain <search key val, rid> pointers into another file

Pros: index is more compact

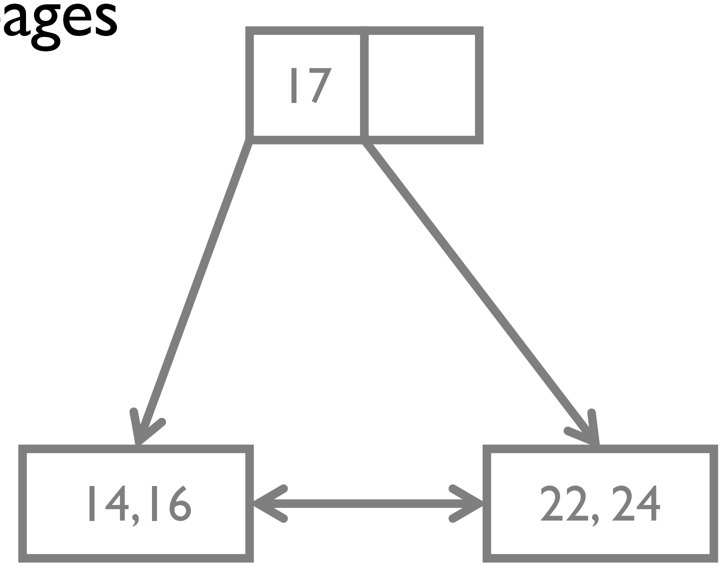
B+ Tree Index: disk-optimized index



Node = Page
Supports equality and range queries on search key
Self balancing (path to any leaf is almost the same)
Leaf nodes are connected via doublely linked list
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

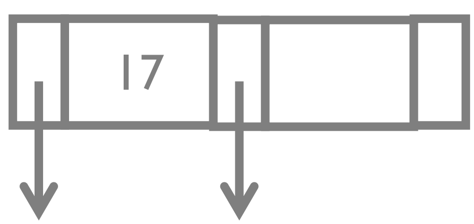


At each level in the tree, index & data page contents are sorted by search key

Leaf Data pages
data entries/tuples

Query: SELECT * WHERE age= 14

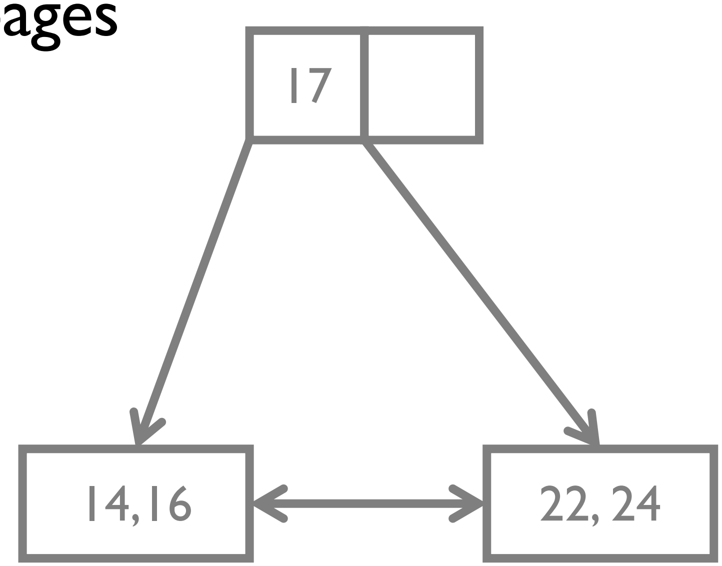
directory page



Index Only Queries: B+ Tree on (age)

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

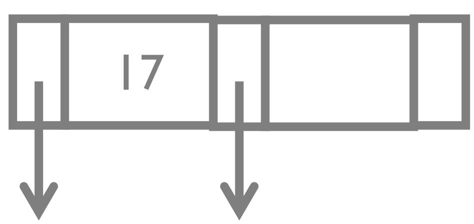
Leaf Data pages
data entries/tuples



At each level in the tree, index & data page contents are sorted by search key

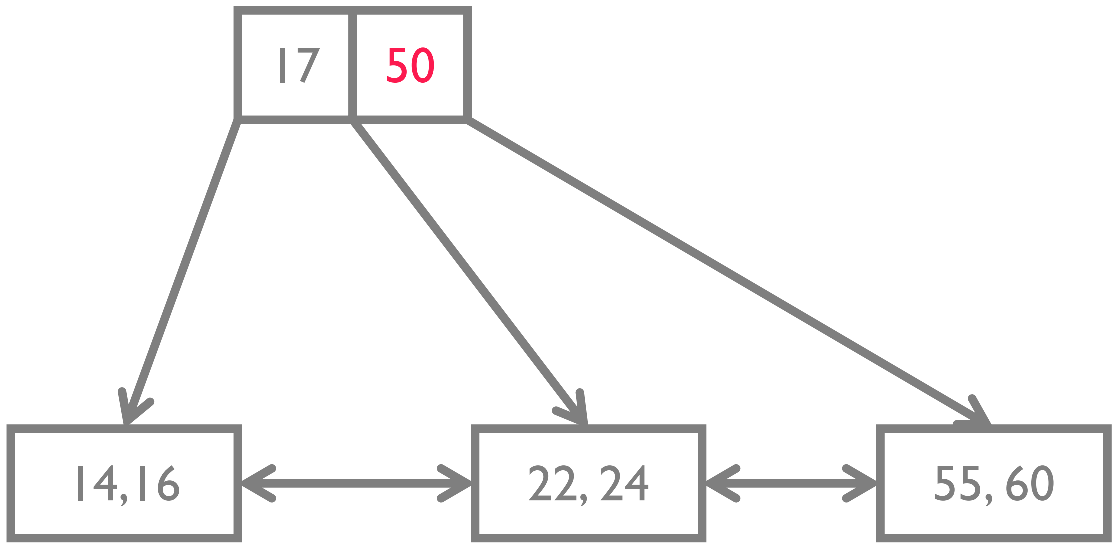
Query: SELECT age WHERE age > 14
(index only!)

directory page



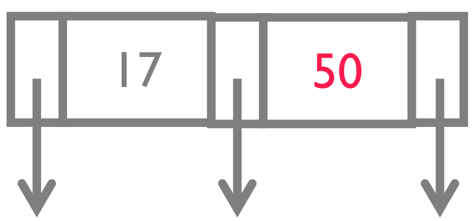
B+ Tree on (age)

Note: 50 not a data entry



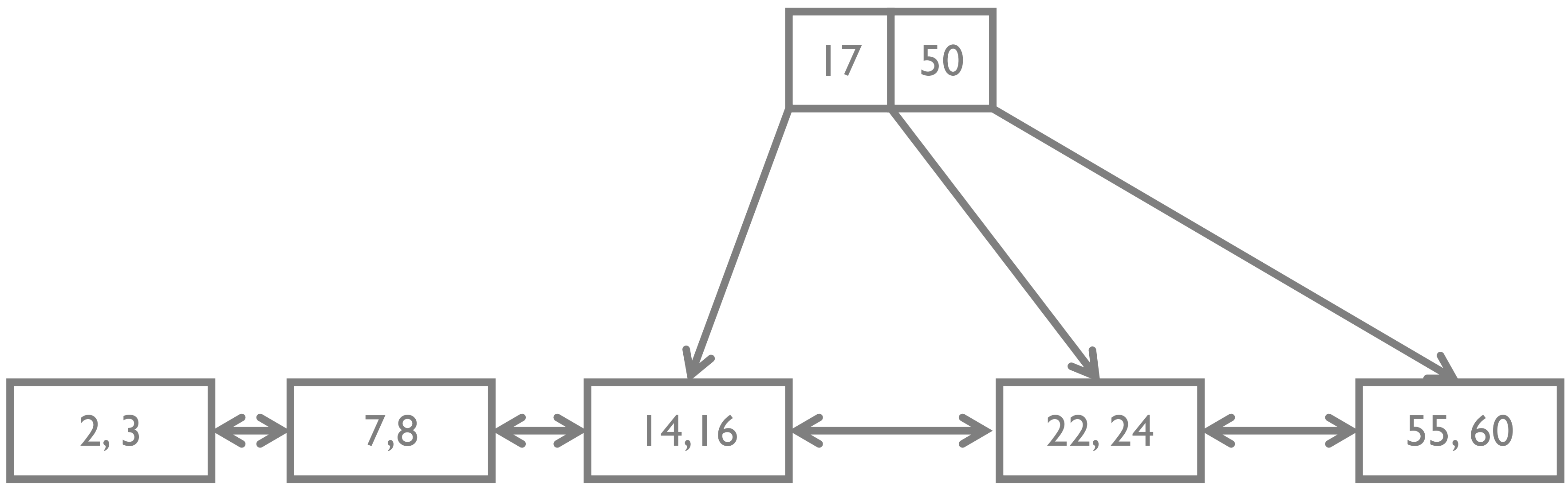
Query: SELECT * WHERE age = 55

directory page



In this class for cost estimation, we will assume number of pointers same as number of directory entries

B+ Tree on (age)

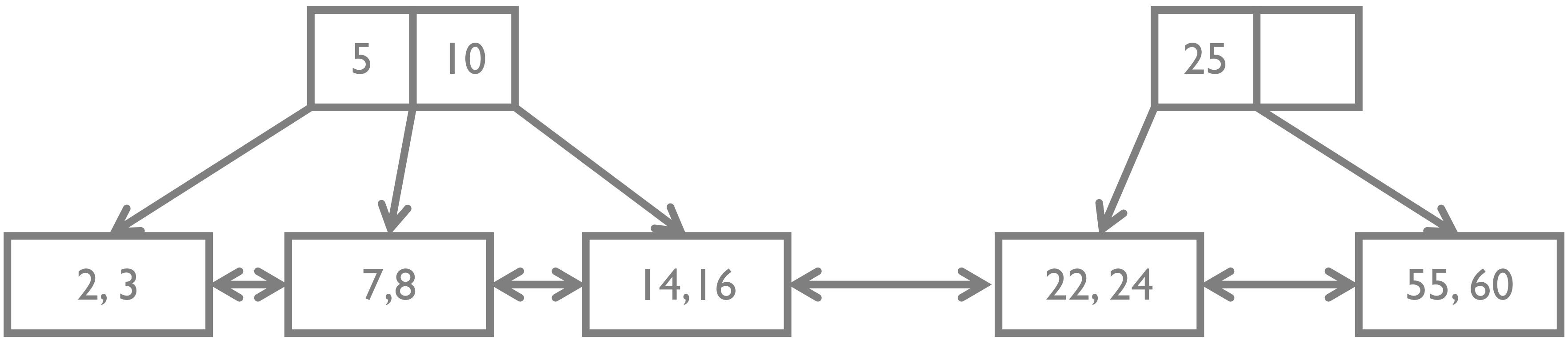


When directory page is full, can't add more pointers

Split directory page and reorganize tree

(don't need to know details of how splits are done)

B+ Tree on (age)

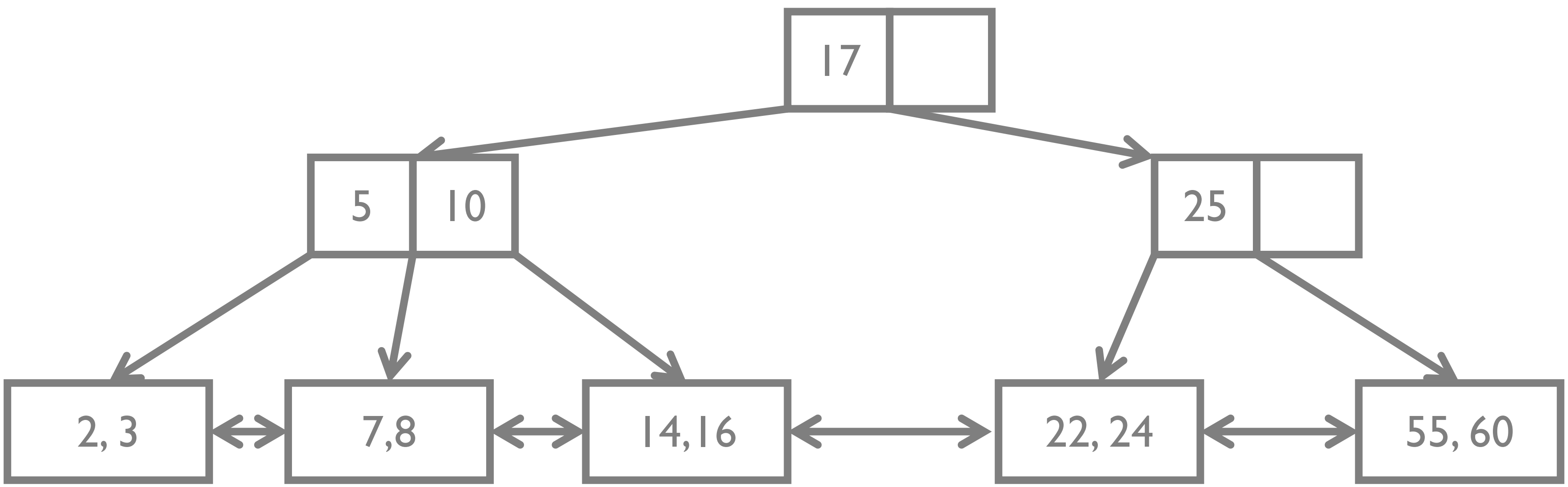


When directory page is full, can't add more pointers

Split directory page and reorganize tree

(don't need to know details of how splits are done)

B+ Tree on (age)

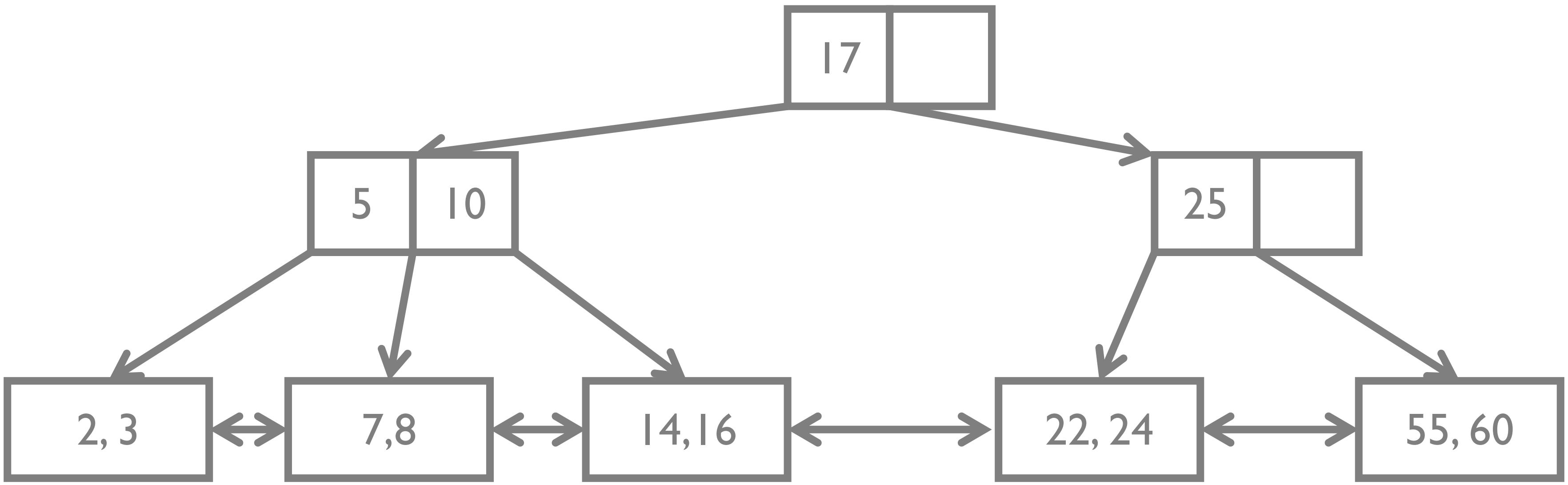


When directory page is full, can't add more pointers

Split directory page and reorganize tree

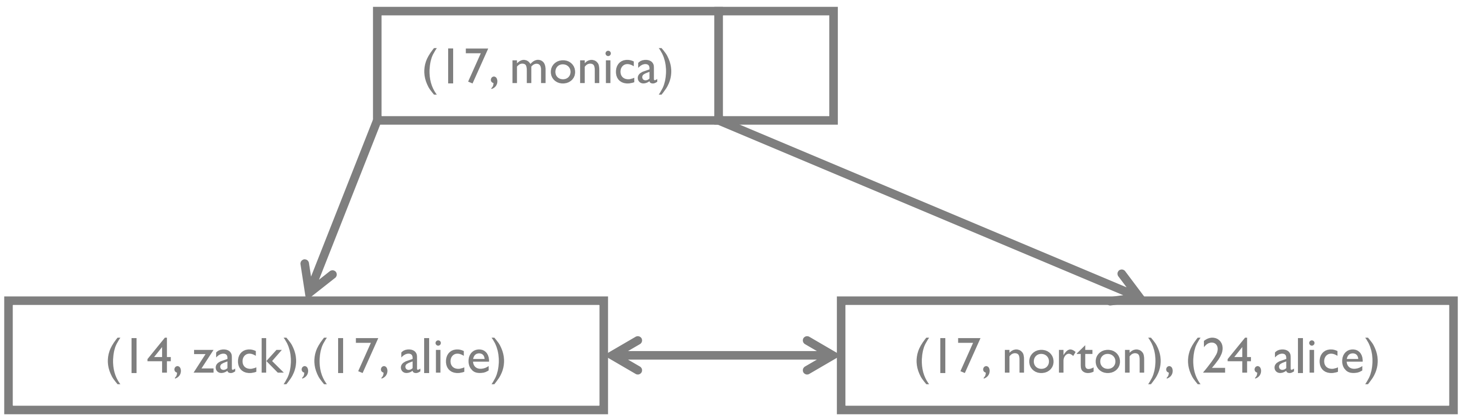
(don't need to know details of how splits are done)

B+ Tree on (age)



Query: SELECT * WHERE age > 20

Composite Keys: B+ Tree on (age, name)

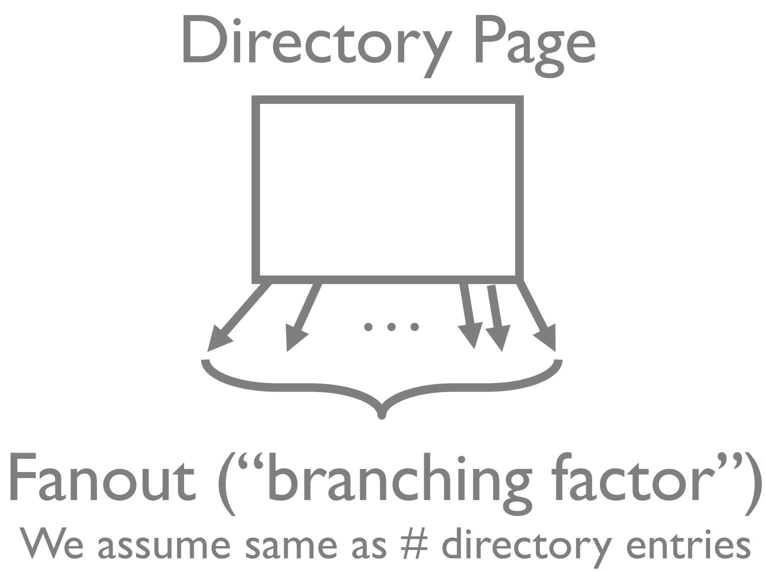


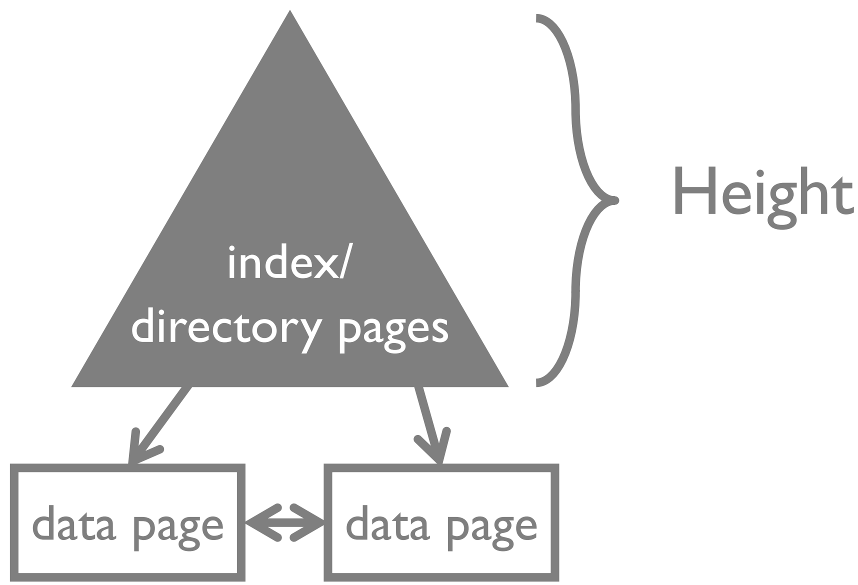
How do the following queries use the index on (age, name)?

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

Terminology

Keep free space for fast inserts
Reduce "fill factor" parameter





Example using 8kb pages

How many entries in the index's data pages?

- 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

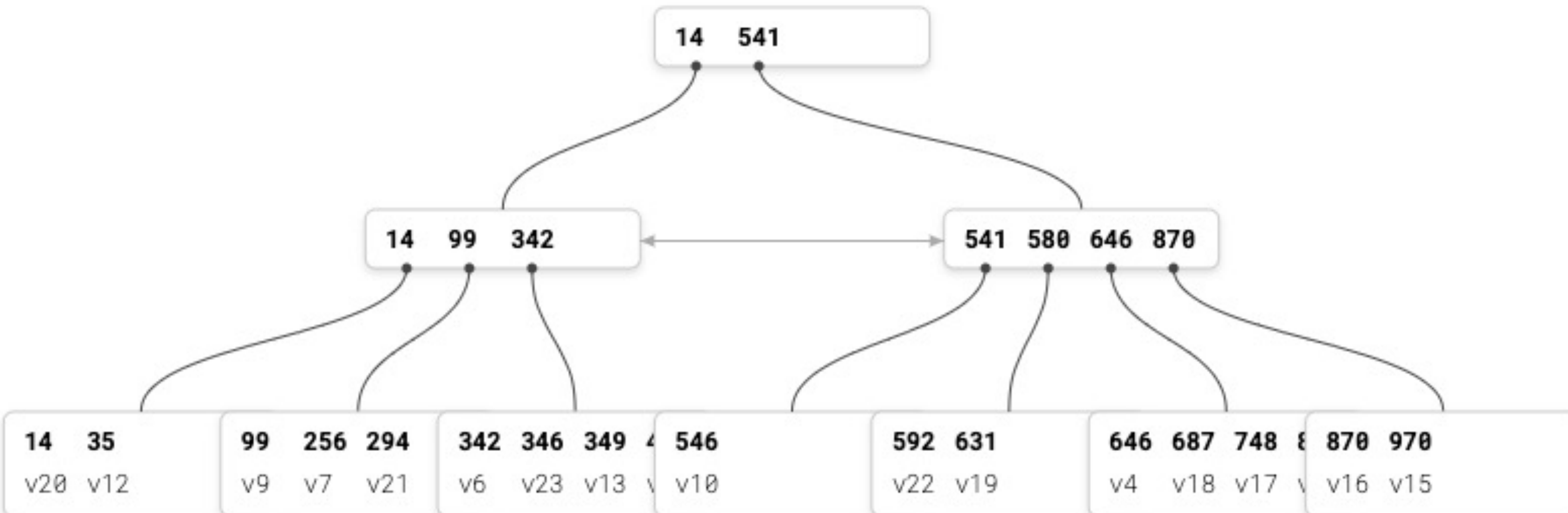
Cool B+Tree viz: https://www.cs.usfca.edu/~galles/visualization/BPlusTree.html

For Real?

problem. We have run TB range databases on Raspberry PI with 4GB of RAM and hammered that in benchmarks (far exceeding the memory capacity). The interesting thing here is that the B+Tree nature means that the upper tiers of the tree were already in memory, so we mostly ended up with a single page fault per request.

https://ayende.com/blog/196161-C/re-are-you-sure-you-want-to-use-mmap-in-your-database-management-system

https://bplustree.app/



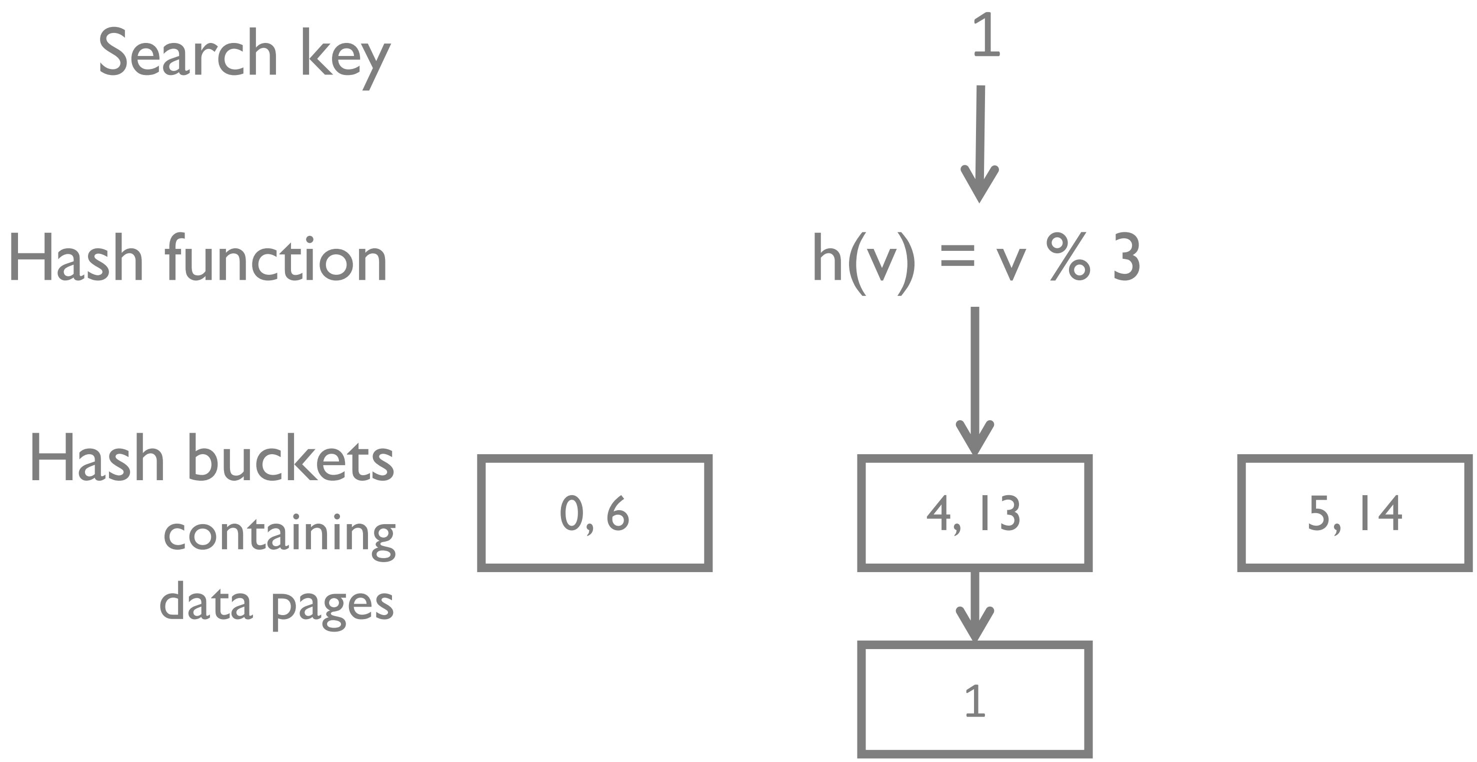
Hash Index on age

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

Hash buckets containing data pages

0, 6	4, 13	5, 14

INSERT Hash Index on age

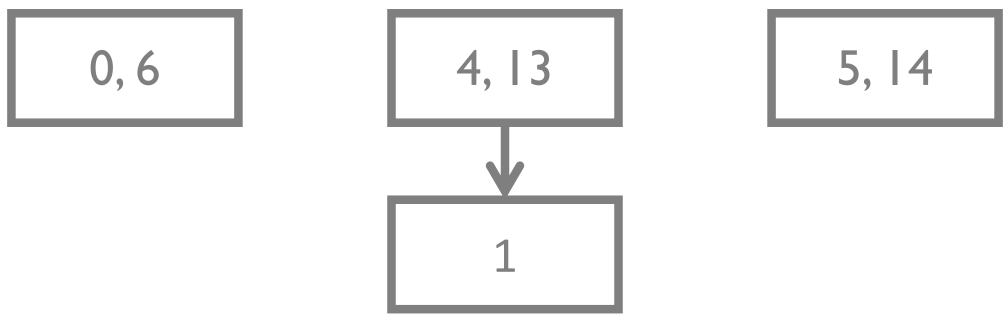


INSERT Hash Index on age

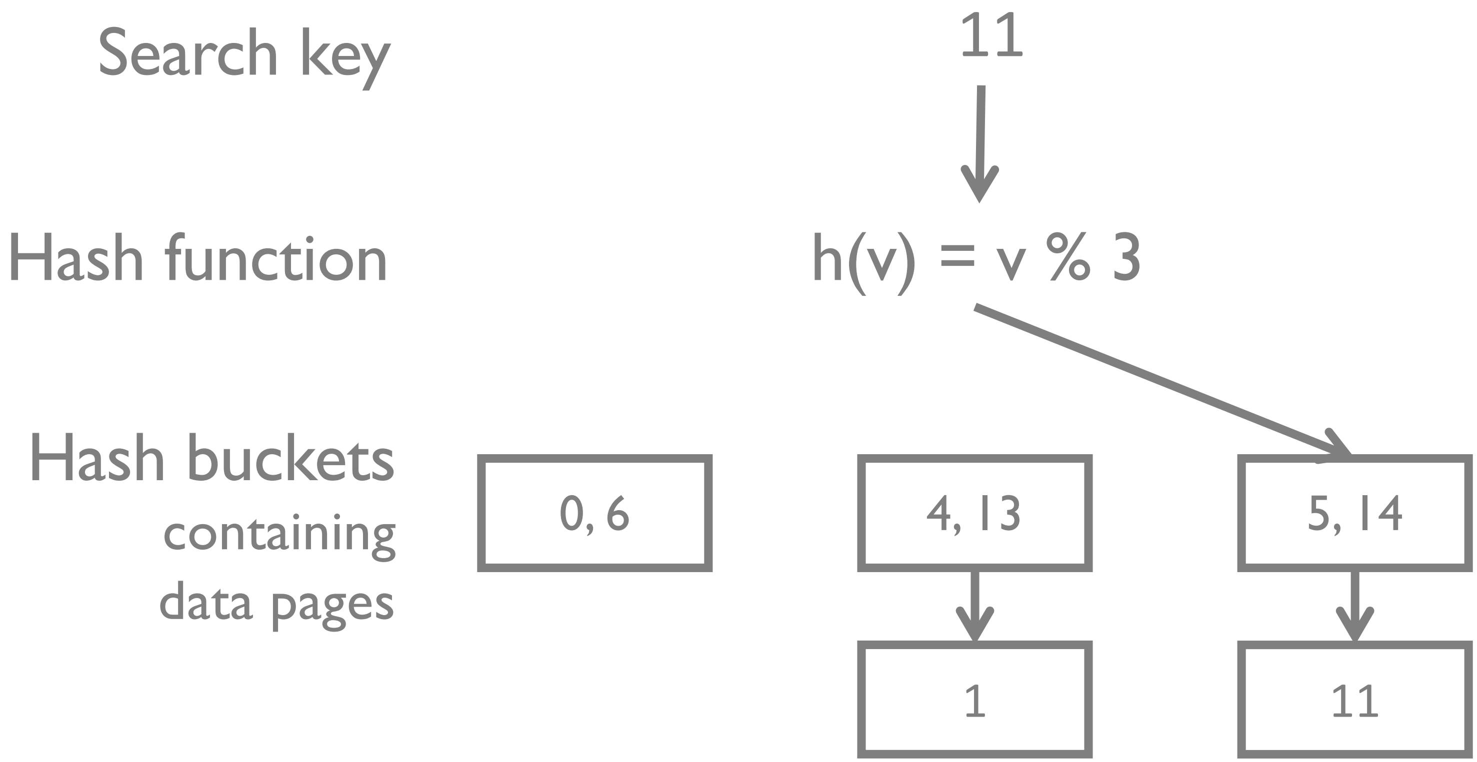
Search key 11

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

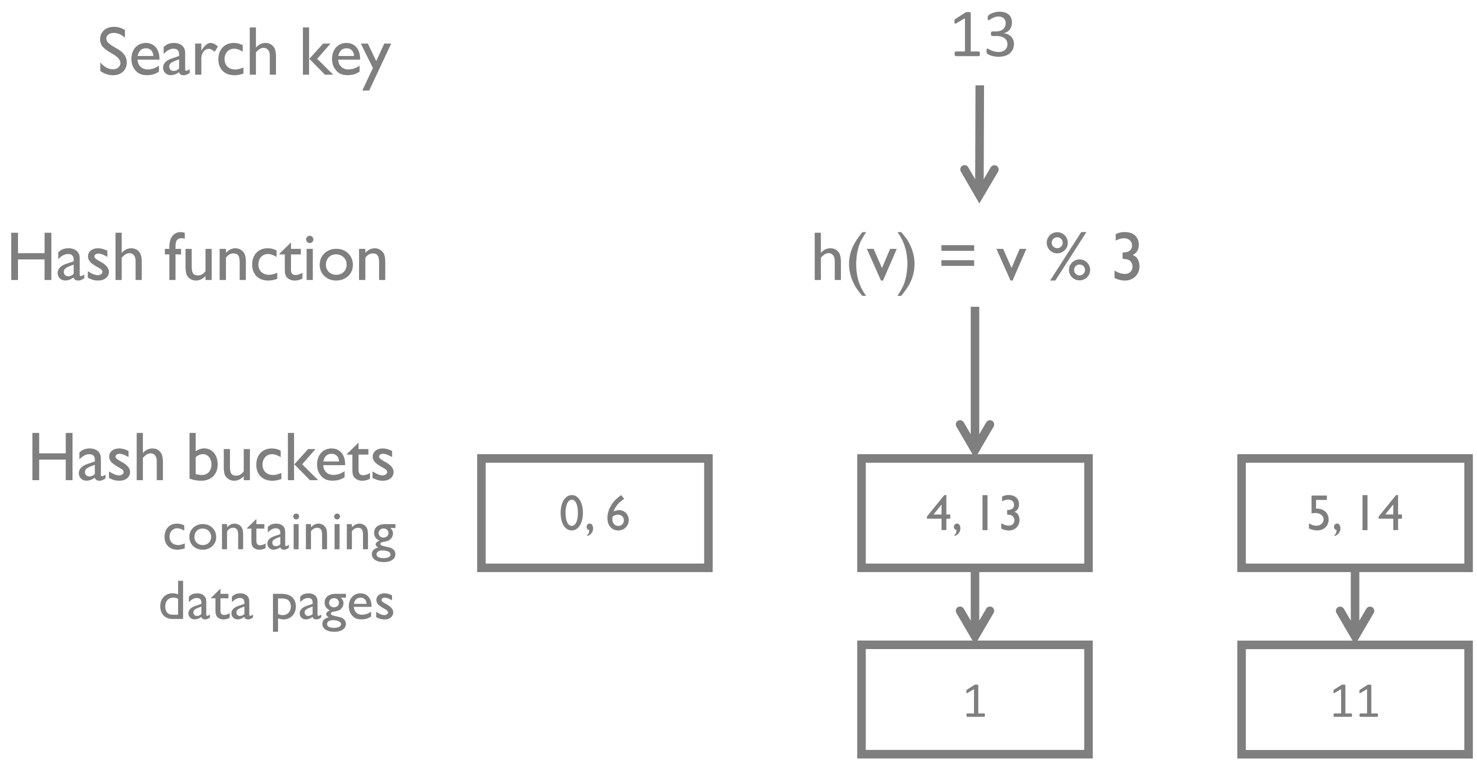
Hash buckets containing data pages



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
- Indexes can be primary or secondary

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 tuple	
Delete tuple	DELETE WHERE …

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

The above table's calculations will be based on assumptions about the fill factors, directory and data entry sizes, page sizes, etc. They estimate the cost in expectation.

The assumptions may vary depending on the system and configuration.

- 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

assume: directory pages are in memory

equality on a key. How many results?

Sorted File

assume: 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

assume: directory pages are in memory

equality on a key. How many results?

Sorted File

assume: files compacted after deletion

B+ Tree

100 entries/directory page

80% fill factor (B is the # of data pages if fill factor were 100%)

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

assume: directory pages are in memory

equality on a key. How many results?

Sorted File

assume: files compacted after deletion

B+ Tree

100 entries/directory page

80% fill factor (B is the # of data pages if fill factor were 100%)

Hash index

80% fill factor when computing scans

assumes no overflow when computing equality/insert/delete.

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

Page Size	$p = 100$	records/page	$p / r = 10$
Record Size	$r = 10$	direntries/page	$p / d = 20$
Dir entry Size	$d = 5$	fanout:	20
Fill Factor	$f = 100\%$	# data pages	$n/(p/r) = 800$
# Records	$n = 8000$	height	$\log_{20} 800 = 3$

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

Secondary B+ Index

Page Size	$p = 100$	records/page	$p / r = 10$
Record Size	$r = 10$	direntries/page	$p / d = 20$
Dir entry Size	$d = 5$	fanout:	20
Fill Factor	$f = 100\%$	# data pages	$n/(p/d) = 400$
# Records	$n = 8000$	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 or tree 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 & differences between RAM, SSD, Hard drives

What files, pages, and records are, and how different than UNIX model

Heap File data structure

B+ tree and Hash indexes

Performance characteristics of different file organizations

Given statistics, figure out directory size, index height, access cost