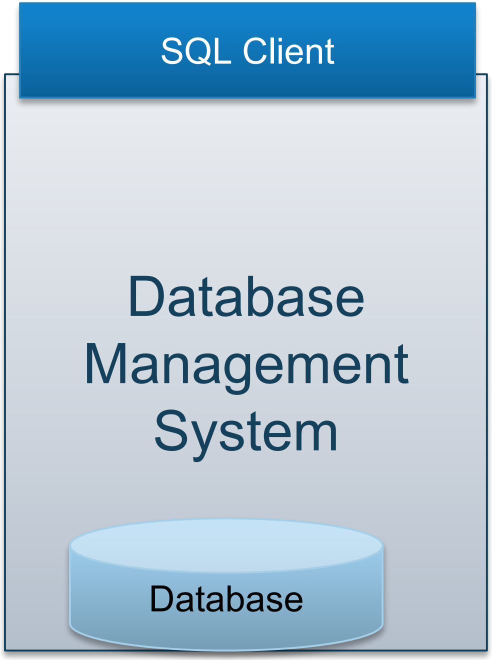
Storing Data:
Disks and Buffers

Berkeley
cs186

BIG PICTURE:
ARCHITECTURE OF A DBMS

Architecture of a DBMS: SQL Client

- Last few lectures: SQL
- Next:
  - How is a SQL query executed?



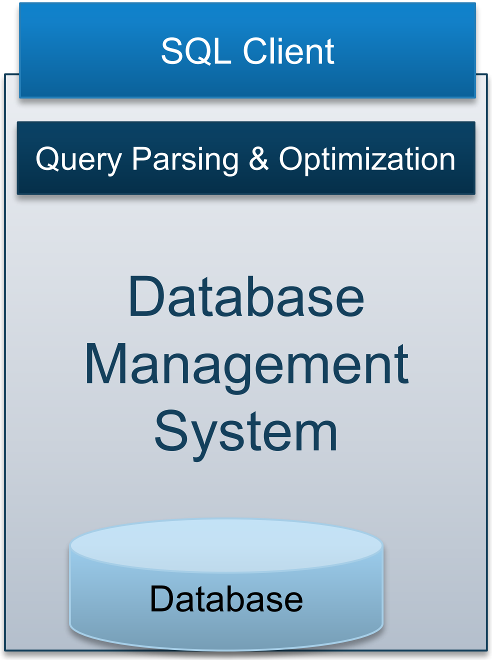
DBMS: Parsing & Optimization

Purpose:

Parse, check, and verify the SQL

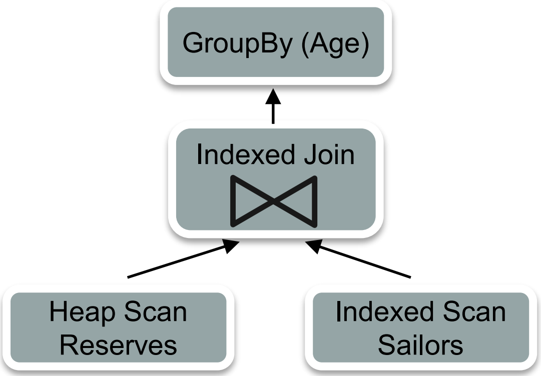
```
SELECT S.sid, S.sname, R.bid
FROM Sailors R, Reserves R
WHERE S.sid = R.sid and S.age > 30
GROUP BY age
```

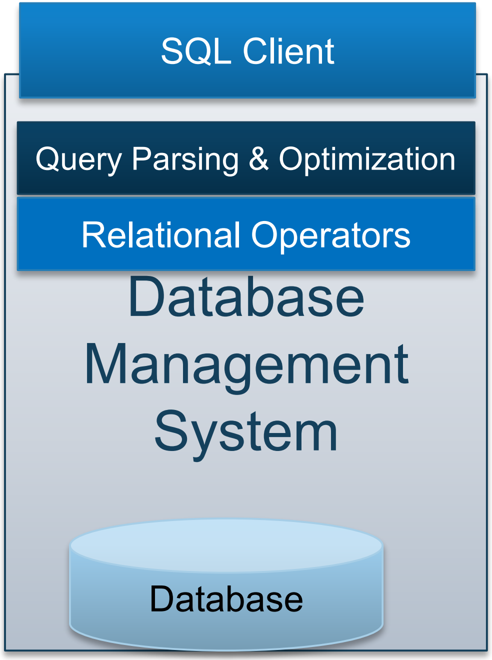
And translate into an efficient relational query plan



DBMS: Relational Operators

Purpose: Execute a dataflow by operating on **records** and **files**

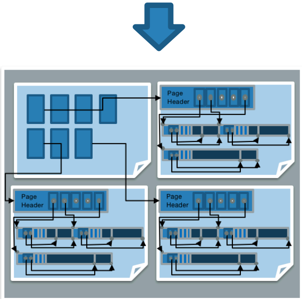


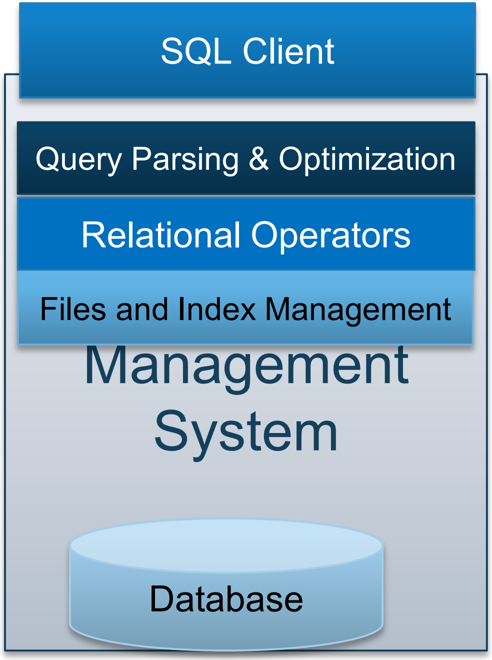


DBMS: Files and Index Management

Purpose: Organize tables and Records as groups of pages in a logical file

SSN	Last Name	First Name	Age	Salary
123	Adams	Elmo	31	$400
443	Grouch	Oscar	32	$300
244	Oz	Bert	55	$140
134	Sanders	Ernie	55	$400




SQL Client

Query Parsing & Optimization

Relational Operators

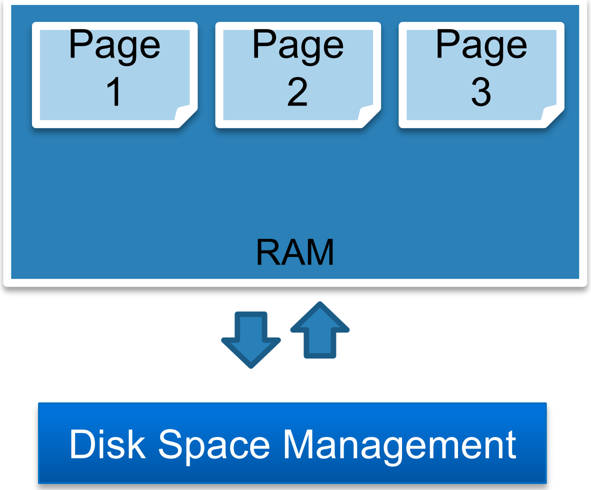
Files and Index Management

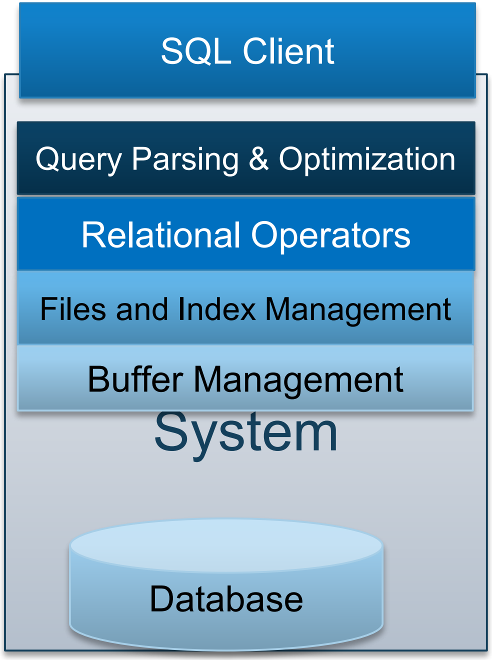
Management System

Database

DBMS: Buffer Management

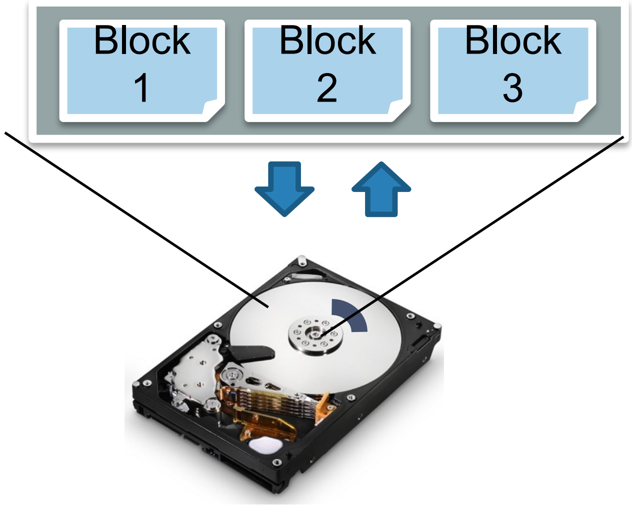
Purpose:
Provide the illusion of operating in memory





DBMS: Disk Space Management

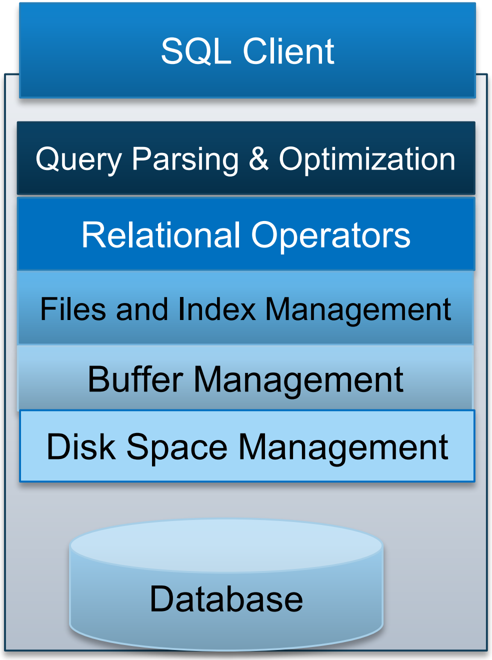
Purpose: Translate page requests into physical bytes on one or more device(s)



Block 1

Block 2

Block 3



SQL Client

Query Parsing & Optimization

Relational Operators

Files and Index Management

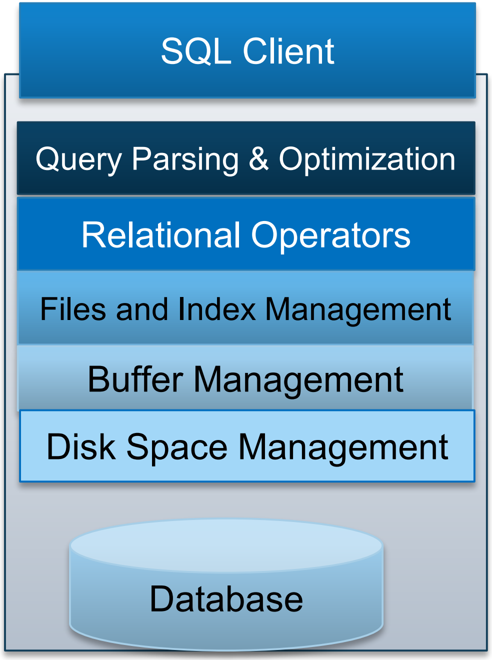
Buffer Management

Disk Space Management

Database

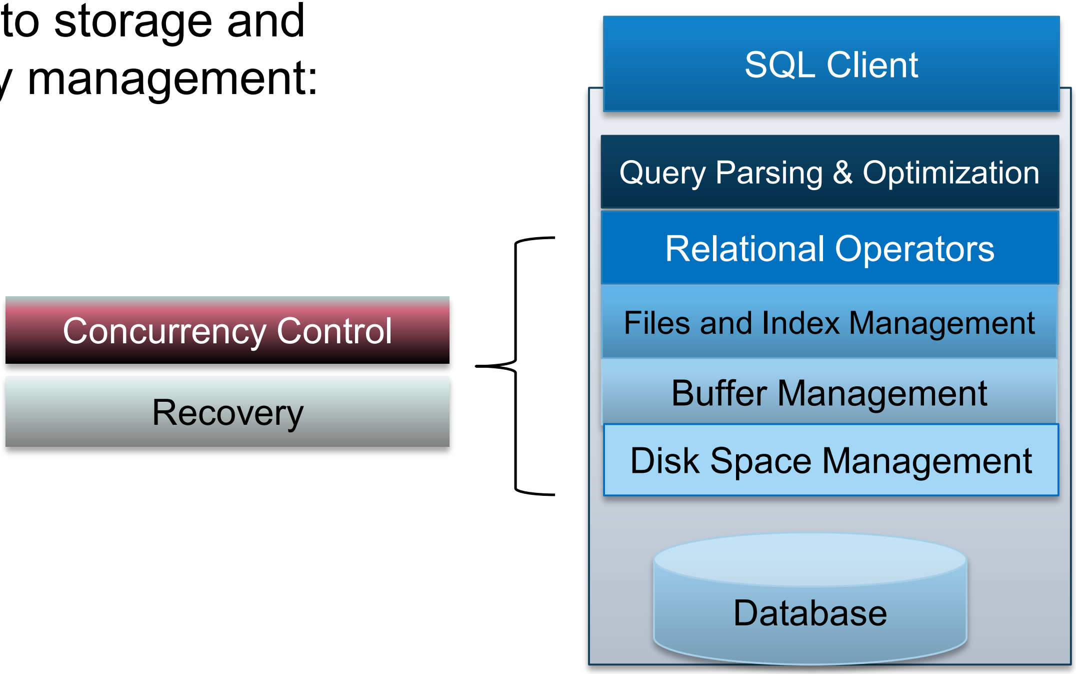
Architecture of a DBMS

- Organized in layers
- Each layer abstracts the layer below
    - Manage complexity
    - Performance assumptions
- Example of good systems design

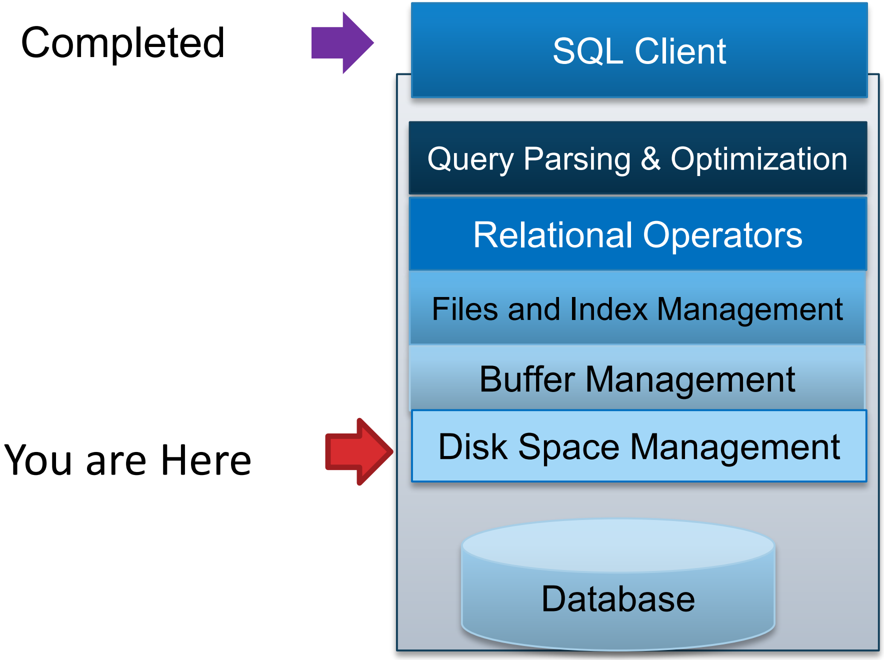


DBMS: Concurrency & Recovery

Two cross-cutting issues related to storage and memory management:



Context



Completed

You are Here

SQL Client

Query Parsing & Optimization

Relational Operators

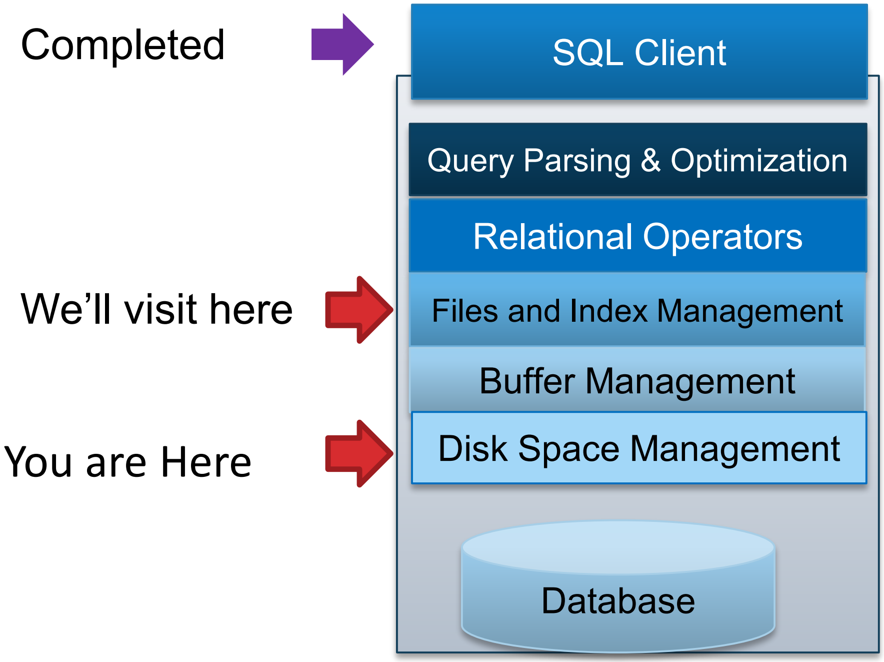
Files and Index Management

Buffer Management

Disk Space Management

Database

Context, cont.



BEFORE WE BEGIN: STORAGE MEDIA

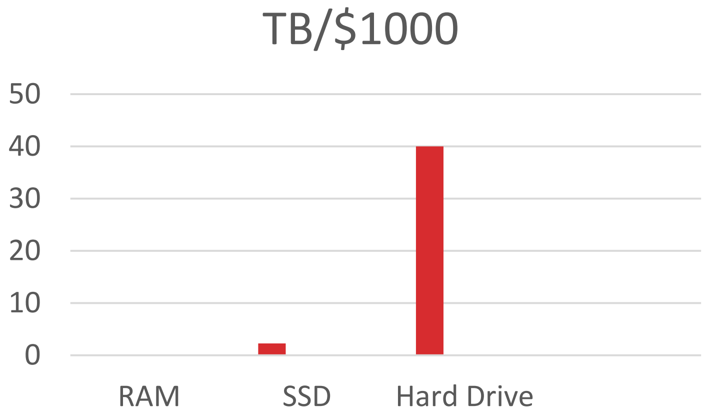
Disks

- Most database systems were originally designed for magnetic disks
  - Disk are a mechanical anachronism!
  - Instilled design ideas that apply to using solid state disks as well

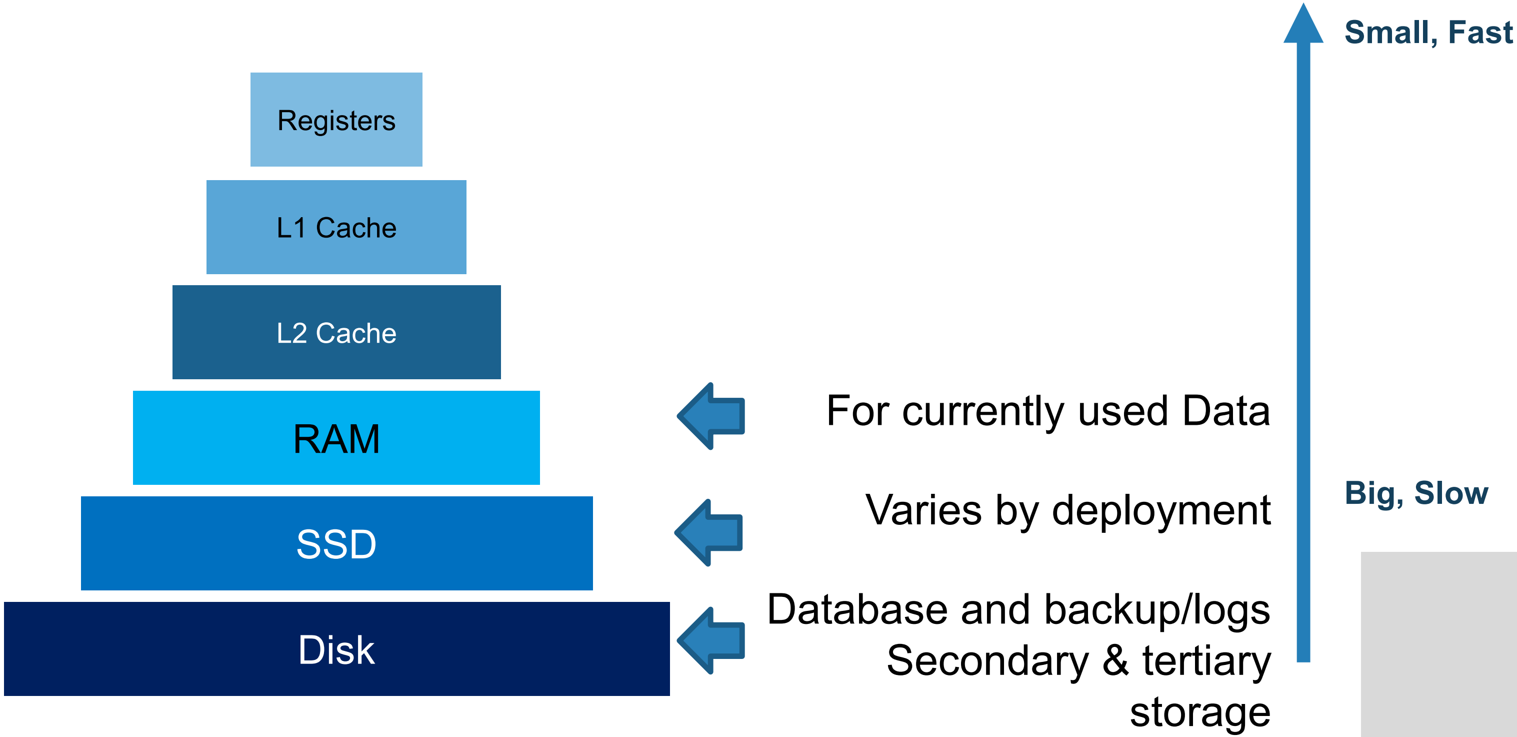
- Major implications!
  - **No “pointer derefs**”. Instead, an API:
    - READ: transfer “page” of data from disk to RAM.
    - WRITE: transfer “page” of data from RAM to disk.
  - Both API calls are very**, very slow!**
    - Plan carefully!
  - An explicit API can be a good thing
    - **Minimizes the kind of pointer errors** you see in C

Economics

- $1000 at NewEgg 2018:
  - Mag Disk: ~40TB for $1000
  - SSD: ~2.3TB for $1000
  - RAM: 80GB for $1000



Storage Hierarchy



Registers

L1 Cache

L2 Cache

RAM

SSD

Disk

For currently used Data

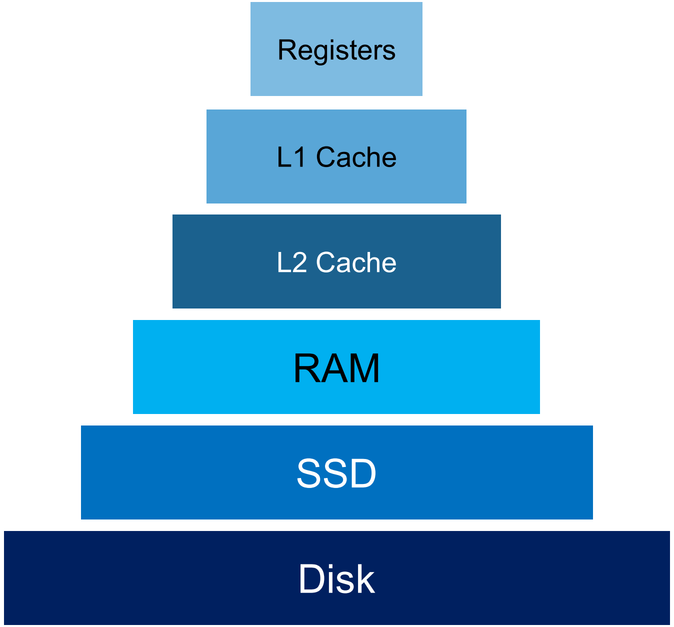
Varies by deployment

Database and backup/logs
Secondary & tertiary
storage

Small, Fast

Big, Slow

Hierarchy - Storage Latencies



Registers

L1 Cache

L2 Cache

RAM

SSD

Disk

.5 ns – L1 cache reference

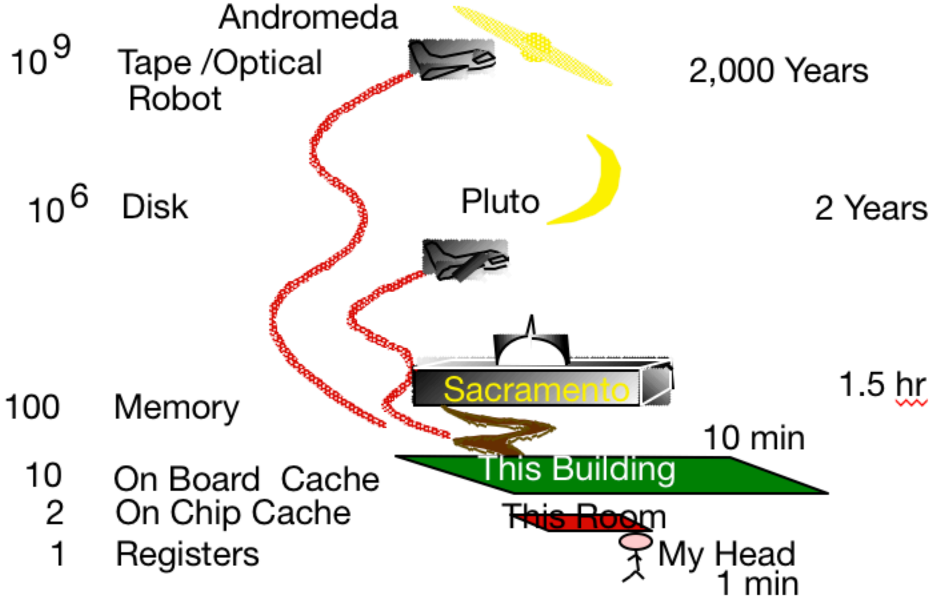
7.0 ns – L2 cache reference

100.0 ns – main memory reference

1,000,000.0 ns – to read 1MB sequentially

20,000,000.0 ns to read 1MB sequentially

How Far Away is the Data?



Andromeda

10^9 Tape /Optical Robot

2,000 Years

10^6 Disk

Pluto

2 Years

Sacramento

1.5 hr

100 Memory

10 min

This Building

10 On Board Cache

2 On Chip Cache

This Room

1 Registers

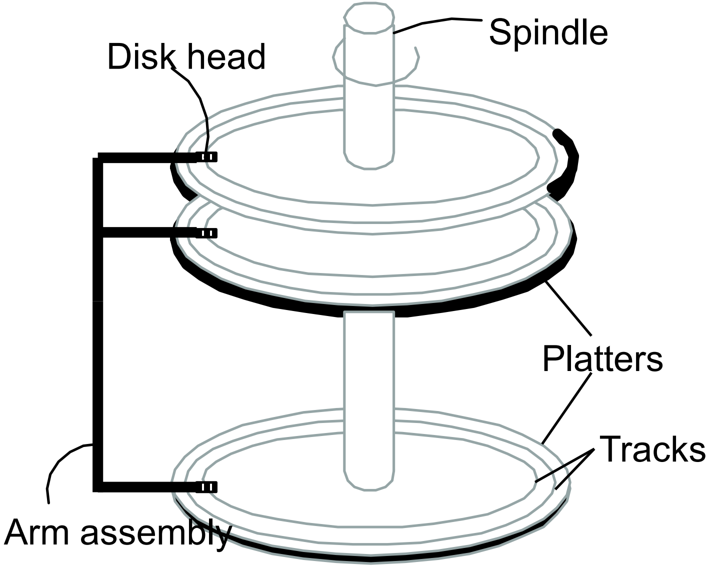
My Head

1 min

Note: From Turing Award Winner Jim Gray

Components of a Disk, Pt. 1

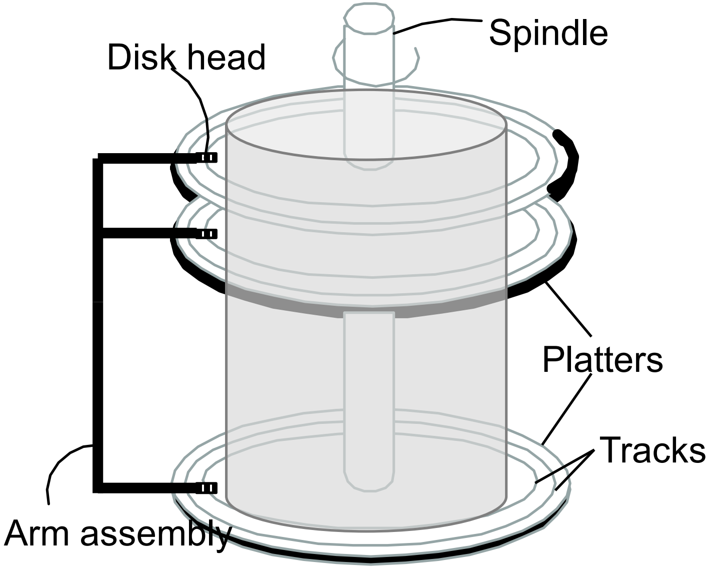
- **Platters** spin (say 15000 rpm)
- **Arm assembly** moved in or out to position a **head** on a desired **track**
  - Tracks under heads make a “cylinder”



Disk Platters

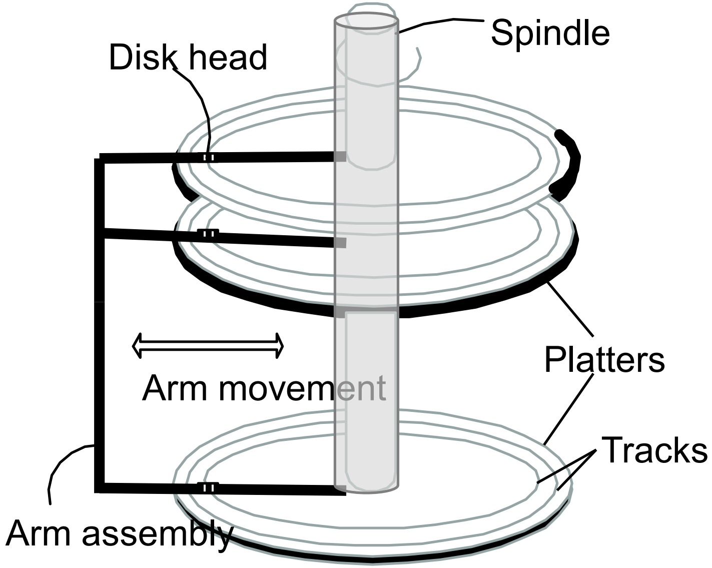
Components of a Disk, Pt. 2

- **Platters** spin (say 15000 rpm)
- **Arm assembly** moved in or out to position a **head** on a desired **track**
  - Tracks under heads make a “cylinder”



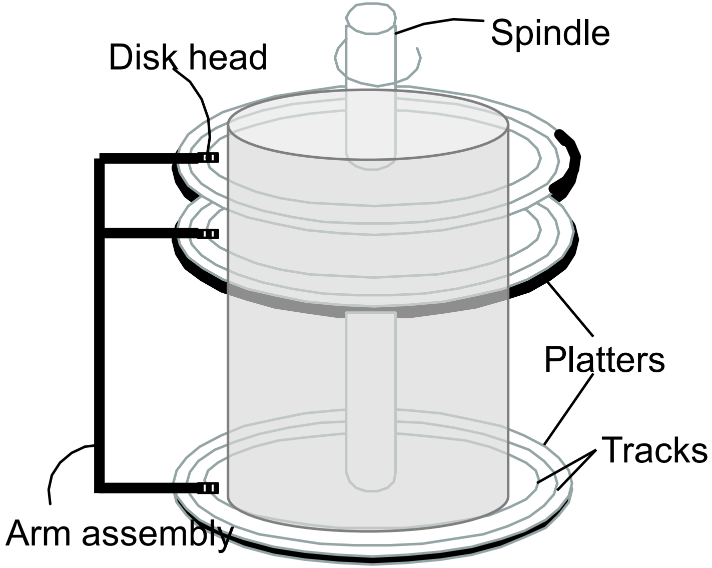
Components of a Disk, Pt. 3

- **Platters** spin (say 15000 rpm)
- **Arm assembly** moved in or out to position a **head** on a desired **track**
  - Tracks under heads make a “cylinder”



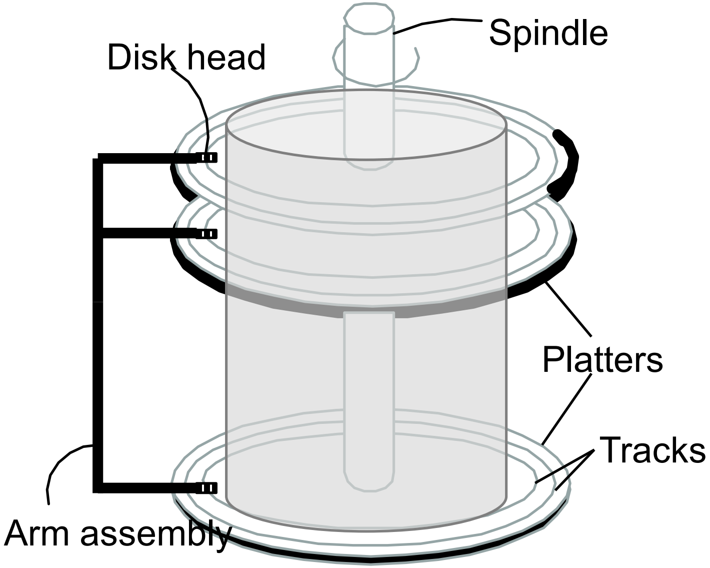
Components of a Disk, Pt. 4

- **Platters** spin (say 15000 rpm)
- **Arm assembly** moved in or out to position a **head** on a desired **track**
  - Tracks under heads make a “cylinder”



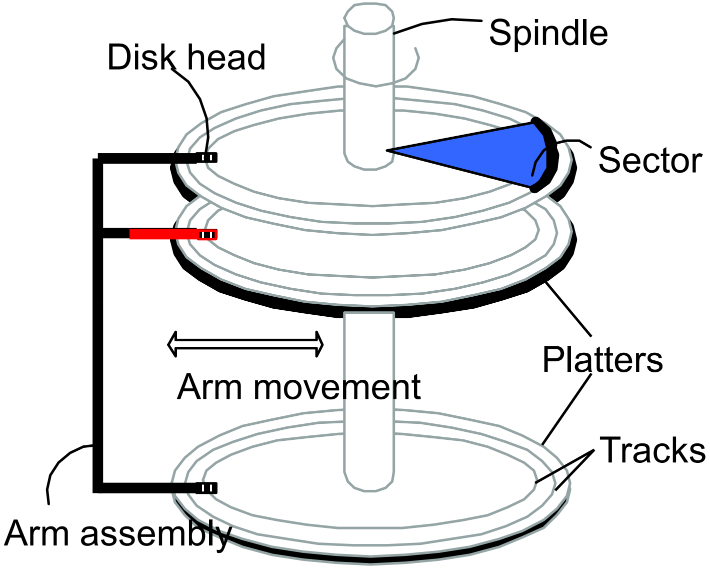
Components of a Disk, Pt. 5

- **Platters** spin (say 15000 rpm)
- **Arm assembly** moved in or out to position a **head** on a desired **track**
  - Tracks under heads make a “cylinder”
- Only one head reads/writes at any one time



Components of a Disk, Pt. 6

- **Platters** spin (say 15000 rpm)
- **Arm assembly** moved in or out to position a **head** on a desired **track**
  - Tracks under heads make a "cylinder"
- Only one head reads/writes at any one time
- Block/page size is a multiple of (fixed) **sector** size



Accessing a Disk page

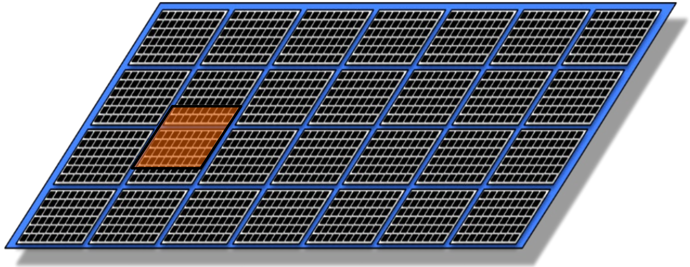
- Time to access (read/write) a disk block:
  - **seek time** (moving arms to position disk head on track)
    - ~2-3 ms on average
  - **rotational delay** (waiting for block to rotate under head)
    - ~0-4 ms (15000 RPM)
  - **transfer time** (actually moving data to/from disk surface)
    - ~0.25 ms per 64KB page

- Key to lower I/O cost: reduce seek/rotational delays

Content Break

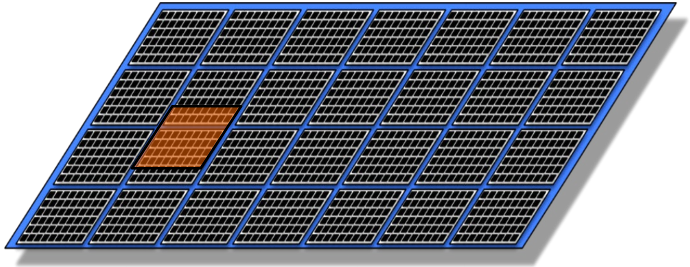
Notes on Flash (SSD)

- Issues in current generation (NAND)
  - Fine-grain reads (4-8K reads), coarse-grain writes (1-2 MB writes)
  - Only 2k-3k erasures before failure, so keep moving hot write units around ("wear leveling")
  - Write amplification: big units, need to reorg for wear & garbage collection



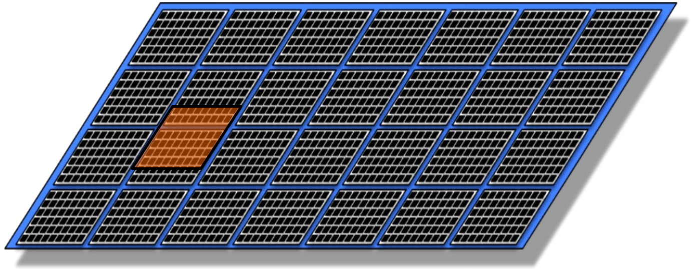
Notes on Flash (SSD), Pt. 2

- So… read is fast and predictable
  - Single read access time: 0.03 ms
  - 4KB random reads: ~500MB/sec
  - Sequential reads: ~525MB/sec
  - 64K: 0.48 ms



Notes on Flash (SSD), cont

- But... write is not! Slower for random
  - Single write access time: 0.03 ms
  - 4KB random writes: ~120 MB/sec
  - Sequential writes: ~480 MB/sec



Is Flash Faster than Disk?

- Why of course it is…it’s called “flash”!
  - Can be 1-10x the bandwidth (bytes/sec) of ideal HDD #s
    - Note: Ideal HDD #s hard to achieve.
    - Expect 10-100x bandwidth for non-sequential read.

Created by Dima Sho
from Noun Project

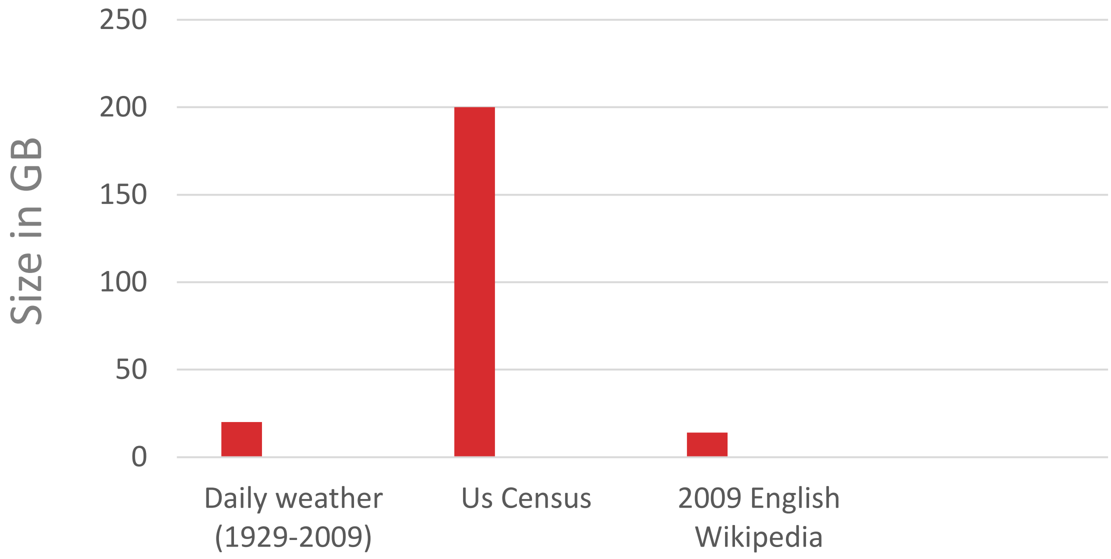
Image

Is Flash Faster Than Disk Pt 2.

- Locality” matters for both
  - Reading/writing to “far away” blocks on disk requires slow seek/rotation delay
  - Writing 2 “far away” blocks on SSD can require writing multiple much larger units
  - High-end flash drives are getting much better at this
- And don’t forget:
  - Disk offers about 10x the capacity per $

Storage Pragmatics & Trends

- Many significant DBs are not big.



Storage Trends Pt. 2

- But data sizes grow faster than Moore’s Law
  - “Big Data” is real
    - Boeing 787 generates ½ TB of data per flight
    - Walmart handles 1M transactions/hour,
      - maintains 2.5 PetaByte data warehouse

Created by Ralf Schmitzer
from Noun Project

Created by Adrien Coquet
from Noun Project

- So…what is the role of disk, flash, RAM
  - The subject of some debate!

Airplane Cash Register

Bottom Line (last few years)

- Very large DBs: relatively traditional
  - Disk still the best cost/MB by a lot
  - SSDs improve performance and performance variance
- Smaller DB story is changing quickly
  - Entry cost for disk is not cheap, so flash wins at the low end
  - Many interesting databases fit in RAM

Bottom Line Pt. 2

- Change brewing on the HW storage tech side
- Mixed answers on the SW/usage side
  - Big Data: Can generate and archive data cheaply and easily
  - Small Data: Many rich data sets have (small) fixed size
- People will continue to worry about magnetic disk for some time yet, typically at large scale

Content Break 2

DISK SPACE MANAGEMENT

Disks and Files

- Recall, most DBMSs stores information on **Disks** and **SSDs**.
  - Disk are a mechanical anachronism (slow!)
  - SSDs faster, **slow relative to memory**, costly writes

Disk Platters

Block Level Storage

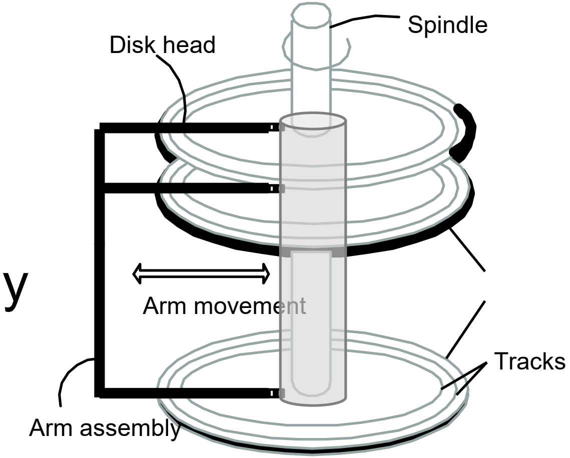
- Read and Write **large chunks of sequential bytes**
- *Sequentially*: “Next” disk block is fastest
- Maximize usage of data per Read/Write
    - “Amortize” seek delays (HDDs) and writes (SSDs):
      if you’re going all the way to Pluto, pack the spaceship full!
- Predict future behavior
    - Cache popular blocks
    - Pre-fetch likely-to-be-accessed blocks
    - Buffer writes to sequential blocks
    - More on these as we go

A Note on Terminology

- **Block = Unit of transfer for disk read/write**
  - 64KB – 128KB is a good number today
  - Book says 4KB
- **Page: a common synonym for “block”**
  - In some texts, “page” = a block-sized chunk of RAM

- We’ll treat “block” and “page” as synonyms

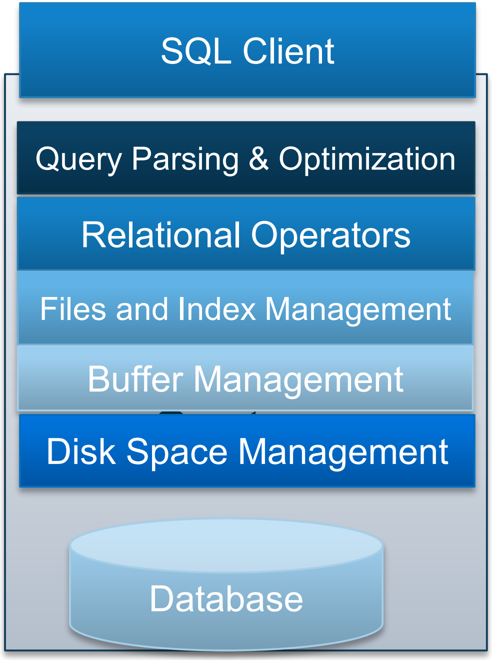
Arranging Blocks on Disk



- **'Next'** block concept:
  - sequential blocks on same track, followed by
  - blocks on same cylinder, followed by
  - blocks on adjacent cylinder
- Arrange file pages sequentially by 'next' on disk
  - minimize seek and rotational delay.
- For a **sequential scan**, *pre-fetch*
  - several blocks at a time!
- **Read large consecutive blocks**

Disk Space Management, cont

- **Lowest layer of DBMS, manages space on disk**
- **Purpose:**
  - Map pages to locations on disk
  - Load pages from disk to memory
  - Save pages back to disk & ensuring writes
- Higher levels call upon this layer to:
  - Read/write a page
  - Allocate/de-allocate logical pages



Disk Space Management: Requesting Pages

- Request for a *sequence* of pages best satisfied by pages stored sequentially on disk
    - Physical details hidden from higher levels of system
    - Higher levels may “safely” assume **Next Page** is fast, so they will simply expect sequential runs of pages to be quick to scan.

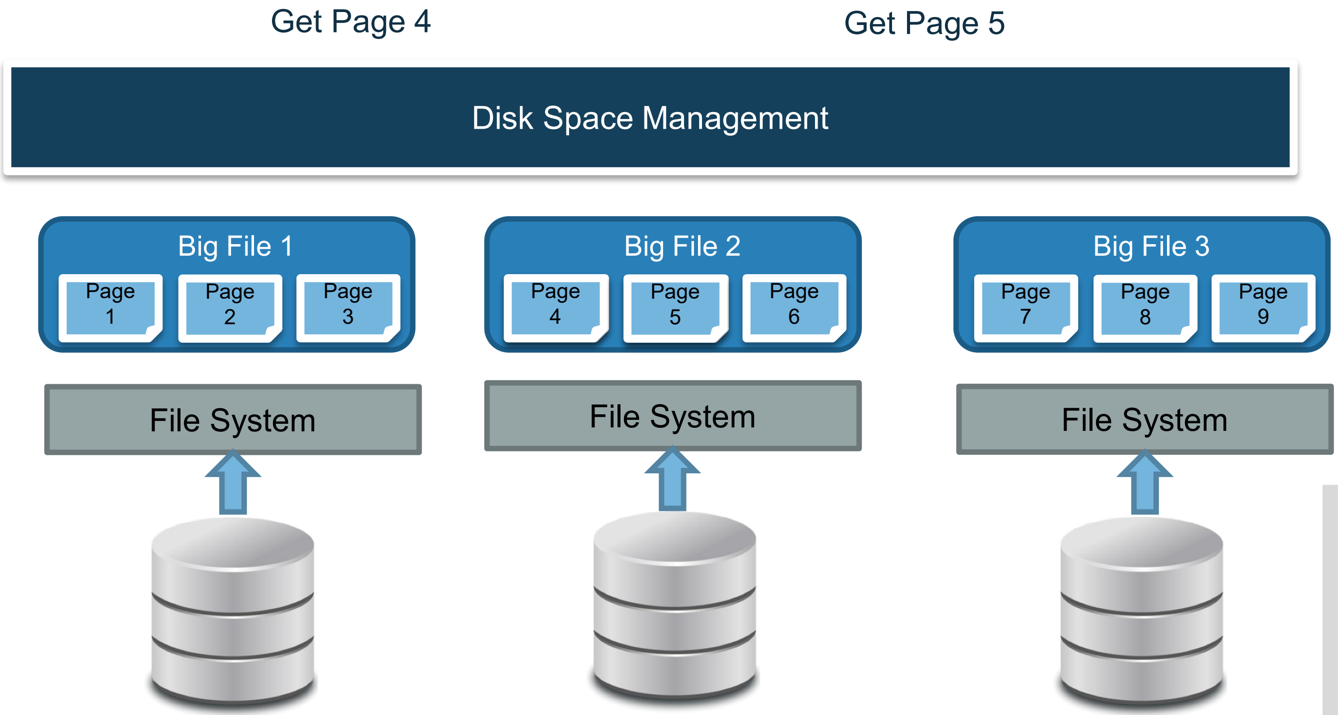
Disk Space Management: Implementation

- **Proposal 1:** Talk to the storage device directly
  - Could be very fast if you knew the device well
  - What happens when devices change?

Disk Space Management: Implementation 2

- **Proposal 2**: Run over filesystem (FS)
  - Allocate single large “contiguous” file on a nice empty disk,
    and assume sequential/nearby byte access are fast
  - Most FS optimize disk layout for sequential access
    - Gives us more or less what we want if we start with an empty disk
  - DBMS “file” may span multiple FS files on multiple disks/machines

Using Local Filesystem



Get Page 4

Get Page 5

Disk Space Management

Big File 1

Page 1

Page 2

Page 3

Big File 2

Page 4

Page 5

Page 6

Big File 3

Page 7

Page 8

Page 9

File System

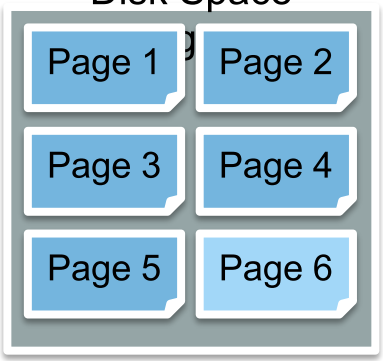
File System

File System

Summary: Disk Space Management

- Provide API to read and write pages to device
- Pages: block level organization of bytes on disk
- Provides “next” locality and abstracts FS/device details

Disk Space



Content Break 3

Disks and Files: Summary

- Magnetic (hard) disks and SSDs
  - Basic HDD mechanics
  - SSD write amplification
  - Concept of “near” pages and how it relates to cost of access
  - Relative cost of
    - Random vs. sequential disk access (10x)
    - Disk (pluto) vs RAM (sacramento) vs. registers (your head)
      - Big, big differences!

Files: Summary Pt 2

- DB File storage
  - Typically over FS file(s)
- Disk space manager loads and stores pages
  - Block level reasoning
  - Abstracts device and file system; provides fast “next”