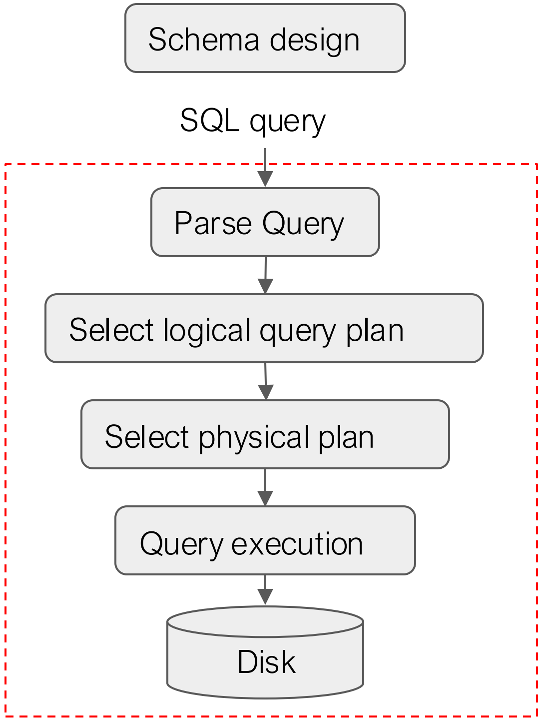
CS 6400 A

# Database Systems Concepts and Design

Lecture 7
09/11/24

# Next Part: Database System Internals

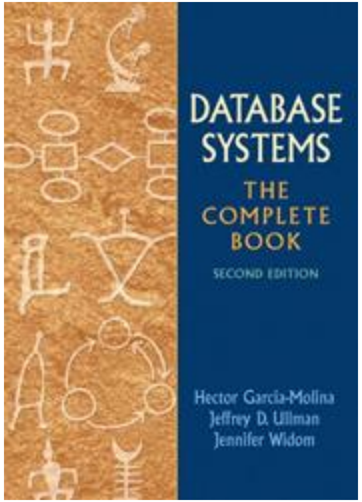
- Hardware and file system structure
- Indexing and hashing
- Query optimization
- Transactions
- Crash recovery
- Concurrency control



# Reading Materials

Database Systems: The Complete Book (2nd edition)

- Chapter 13: Secondary Storage Management



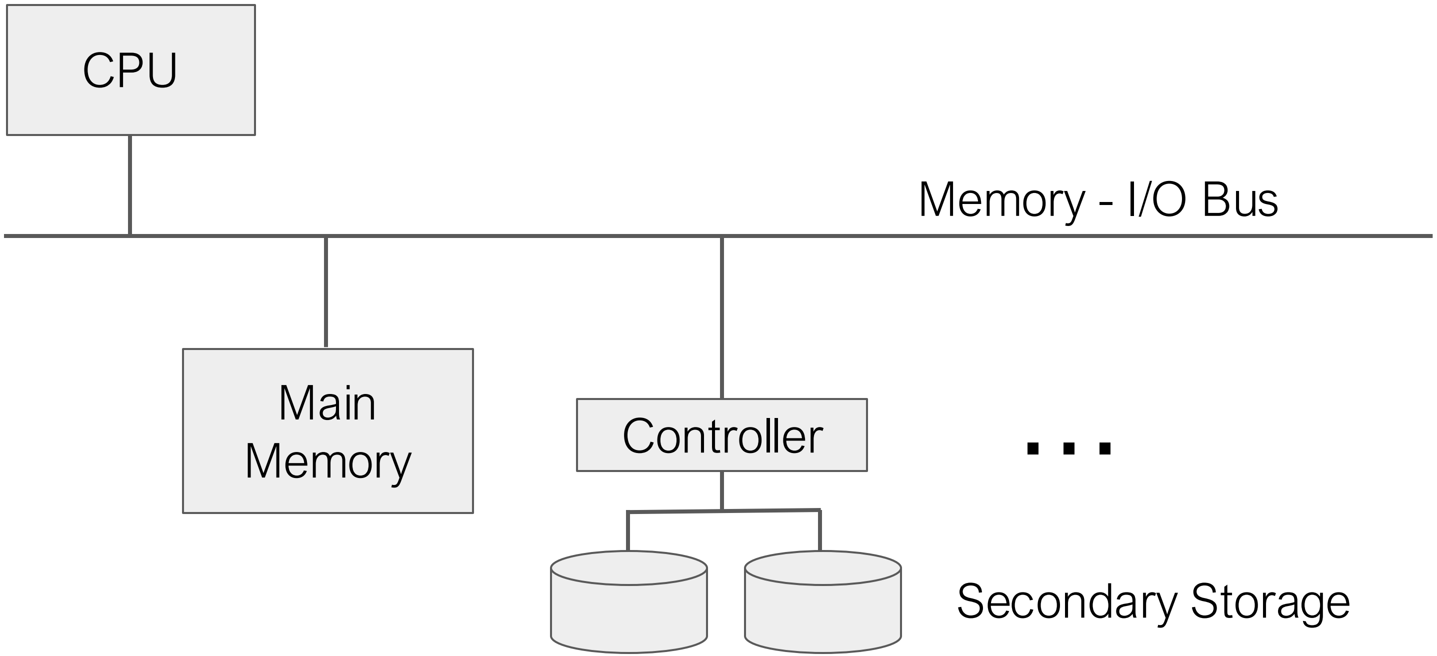

Acknowledgement: The following slides have been adapted from EE477 (Database and Big Data Systems) taught by Steven Whang and CS245 (Principles of Data-Intensive Systems) taught by Matei Zaharia.

# Agenda

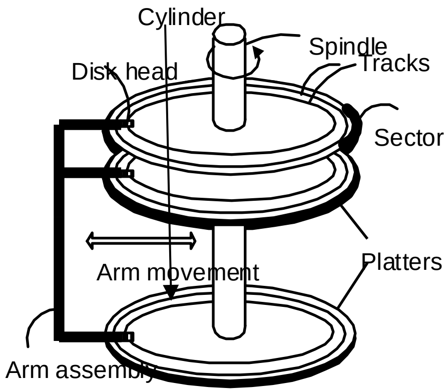
1. Storage hardware
2. Record encoding
3. Collection Storage

# 1. Storage Hardware

# Typical computer system (Von Neumann architecture)



# High-level: Disk vs. Main Memory




**Disk:**

- ***Fast:*** sequential block access
  - Read a blocks (not byte) at a time, so sequential access is cheaper than random
  - Disk read / writes are expensive
- ***Durable:*** We will assume that once on disk, data is safe!
- ***Cheap***

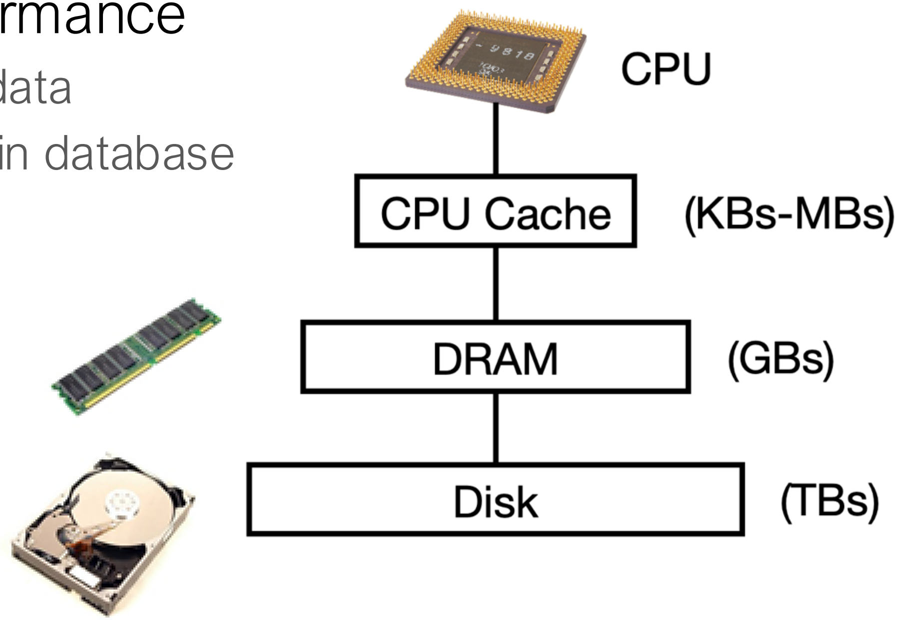
**Random Access Memory (RAM) or Main Memory:**

- ***Fast:*** Random access, byte addressable
  - ~10x faster for sequential access
  - ~100,000x faster for random access!
- ***Volatile:*** Data can be lost if e.g. crash occurs, power goes out, etc!
- ***Expensive:*** For $100, get 16GB of RAM vs. 2TB of disk!

# Storage Hierarchies

Typically **cache** frequently accessed data on faster storage to improve performance

- Main memory stores current data
- Secondary storage stores main database



# Numbers everyone should know

"Numbers Everyone Should Know" from Jeff Dean. Slides #1, Slides #2 (

| | | |
|---|---|---|
| L1 cache reference | 0.5 ns | |
| Branch mispredict | 5 ns | |
| L2 cache reference | 7 ns | |
| Mutex lock/unlock | 100 ns | |
| Main memory reference | 100 ns | |
| Compress 1K bytes with Zippy | 10,000 ns | 0.01 ms |
| Send 1K bytes over 1 Gbps network | 10,000 ns | 0.01 ms |
| Read 1 MB sequentially from memory | 250,000 ns | 0.25 ms |
| Round trip within same datacenter | 500,000 ns | 0.5 ms |
| Disk seek | 10,000,000 ns | 10 ms |
| Read 1 MB sequentially from network | 10,000,000 ns | 10 ms |
| Read 1 MB sequentially from disk | 30,000,000 ns | 30 ms |
| Send packet CA->Netherlands->CA | 150,000,000 ns | 150 ms |

Where

- 1 ns = $10^{-9}$ seconds
- 1 ms = $10^{-3}$ seconds

by Jeff Dean

# Jim Gray’s storage latency analogy: how far is the data?

Turing Award, 1998

| | | | |
|---|---|---|---|
| $10^9$ | Tape | Andromeda | 2,000 years |
| $10^6$ | Disk | Pluto | 2 years |
| 100 | Memory | Columbus, GA | 1.5 hours |
| 10 | On board cache | This building | 10 min |
| 2 | On chip cache | This room | |
| 1 | Registers | My head | 1 min |

# Sizing Storage Tiers

When should we cache data in DRAM vs storing it on disks?

Can determine based on workload & cost

"The 5 Minute Rule for Trading Memory Accesses for Disc Accesses"
Jim Gray & Franco Putzolu
May 1985

# The five minute rule

"Pages referenced every 5 minutes should be memory resident (1987)"

$$BreakEvenReferenceInterval\ (seconds) = \frac{PagesPerMBofRAM}{AccessPerSecondPerDisk} \times \frac{PricePerDiskDrive}{PricePerMBofRAM}$$

Technology ratio

Economic ratio

# The five minute rule

"Pages referenced every 5 minutes should be memory resident (1987)"

$$\mathit{BreakEvenReferenceInterval\ (seconds)} = \frac{\mathit{PagesPerMBofRAM}}{\mathit{AccessPerSecondPerDisk}} \times \frac{\mathit{PricePerDiskDrive}}{\mathit{PricePerMBofRAM}}$$

| Tier | 1987 | 1997 | 2007 | 2017 |
|---|---|---|---|---|
| DRAM–HDD | 5m | 5m | 1.5h | 4h |
| DRAM–SSD | - | - | 15m | 7m (r) / 24m (w) |
| SSD–HDD | - | - | 2.25h | 1d |

Source: The Five-minute Rule Thirty Years Later and its Impact on the Storage Hierarchy

# Most Common Permanent Storage: Hard Disks

- We will focus on the typical magnetic disk
- One or more circular platters rotate around a spindle
- Tracks of the same radius form a cylinder

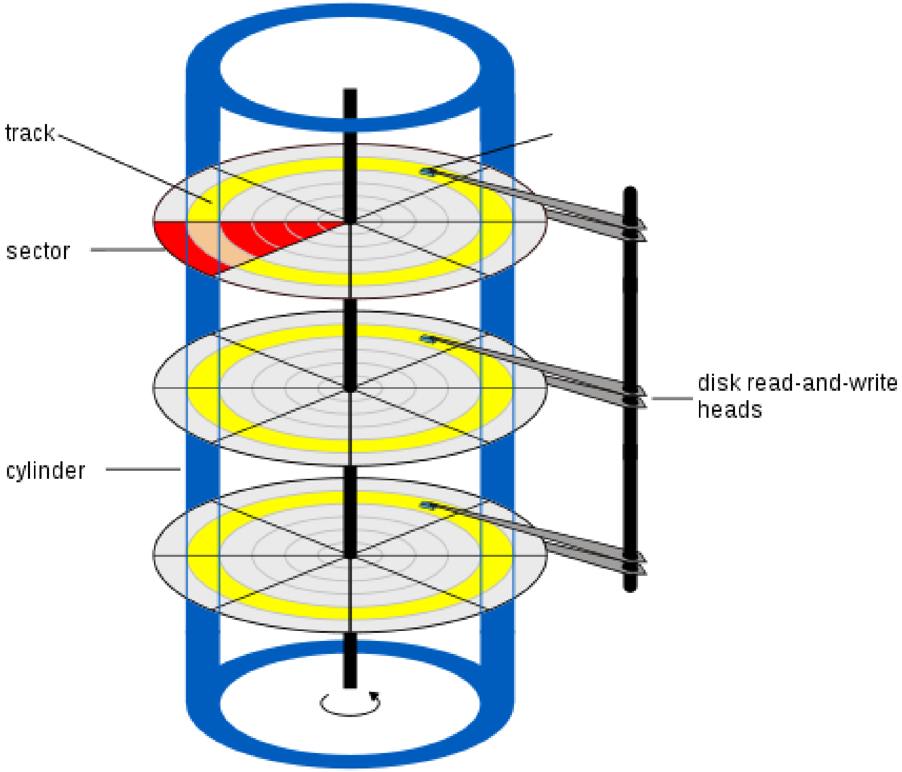
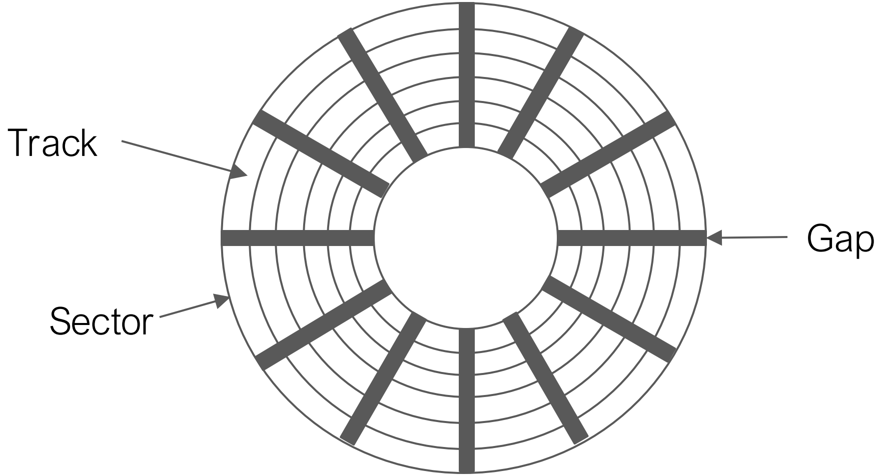



Image source: https://en.wikipedia.org/wiki/Cylinder-head-sector

# Top view of disk surface

- The disk is organized into tracks
- Tracks are organized into sectors, which are indivisible units
- Blocks (unit of transfer to memory) consist of one or more sectors
- Gaps are used to identify the beginnings of sectors



# Disk access time

Latency = seek time + rotational delay + transfer time + other

- Transfer time: time to read/write data in sectors

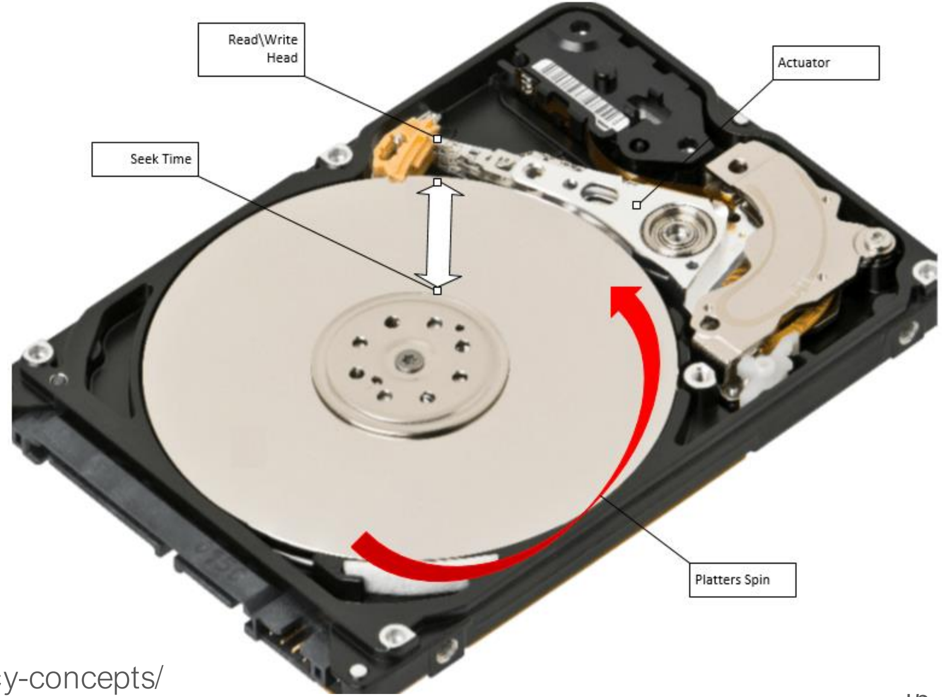
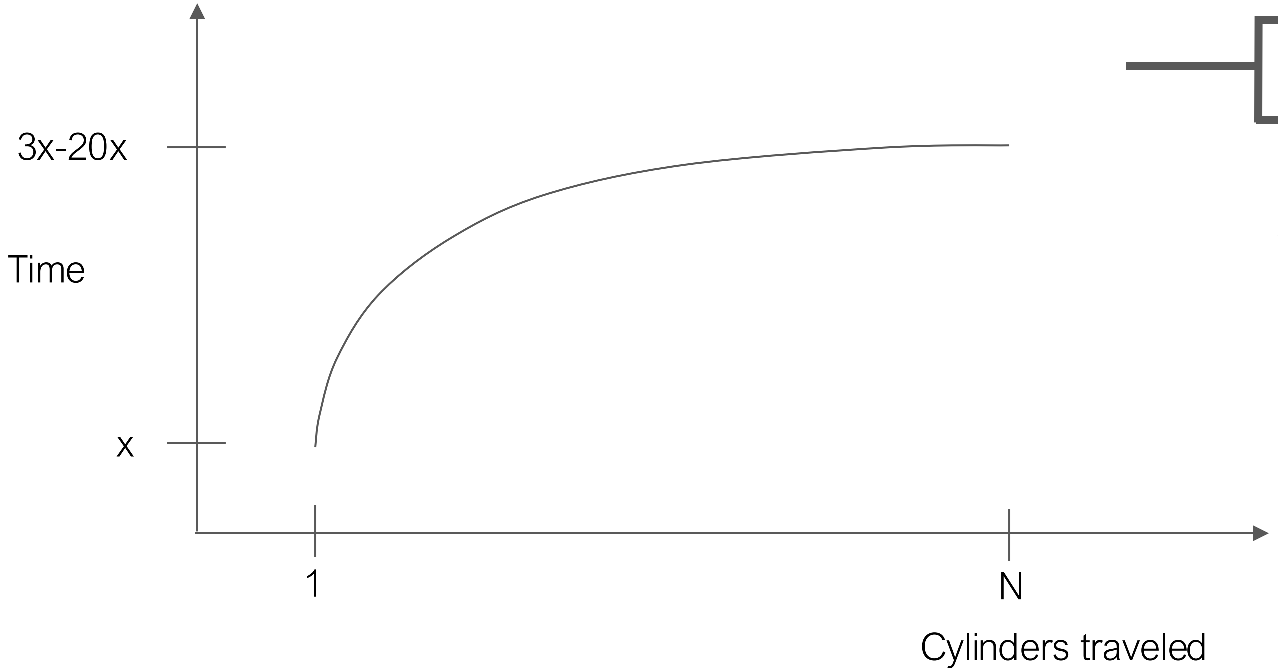
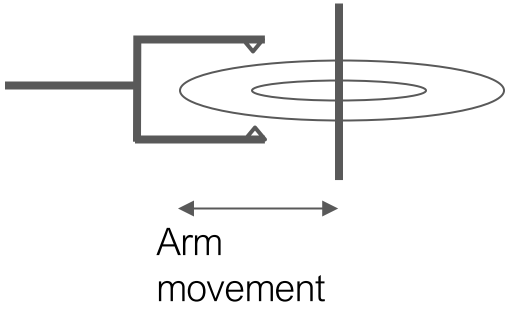



Image source: https://theithollow.com/2013/11/18/disk-latency-concepts/

# Seek time

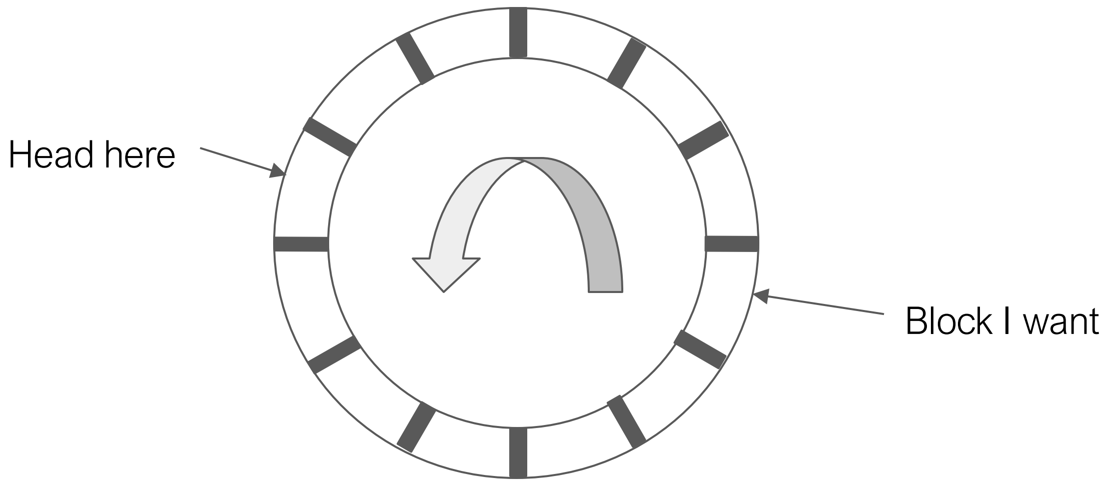
- The seek time depends on the distance the head has to travel to the desired cylinder



# Rotational delay

- The time can range from 0 to the time to rotate the disk once

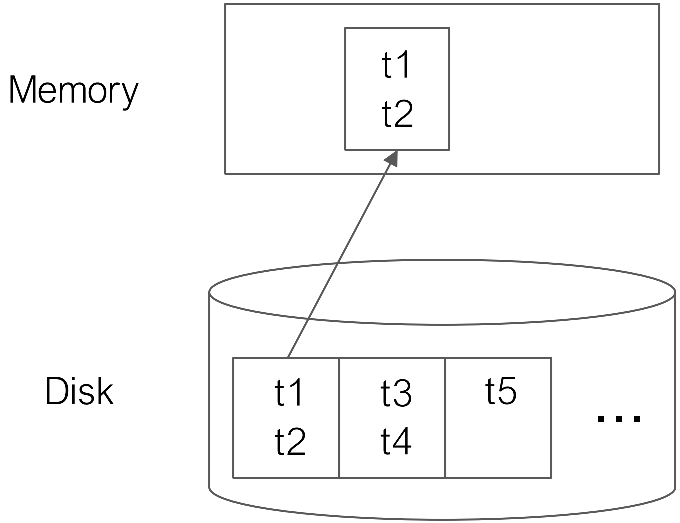


# Relative times

- Seek time
  - Disk: 1~15ms
  - Solid-state drive (SSD): 0.08~0.16ms
- Rotational delay
  - Disk: 0~10ms (on average, 1/2 rotation)
  - SSD: 0ms
- Transfer time
  - Disk: < 1ms for 4KB block
  - SSD: several times faster than disk
- Other delays
  - CPU time, contention for controller/bus/memory
  - Typically 0

# I/O model of computation

- Time to read a block from disk >> time to search a record within that block
- Algorithm time ≈ Number of disk I/Os



# Exercise #1

- Consider a 500GB hard disk with the following performance characteristics
  - 5000 revolution-per-minute (RPM) rotation rate
  - 200 cylinders
  - Takes 1 + (t / 20) milliseconds to move heads t cylinders
  - 100MB/s transfer rate

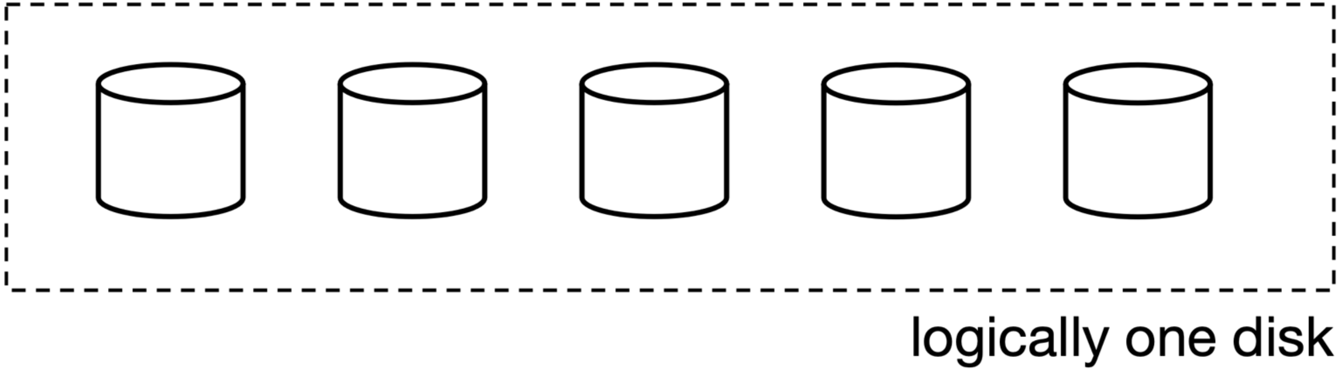
- What is the average time to read a 1MB block from the hard disk?
  - Assumes that the head travels 100 cylinders on average
  - On average the disk rotates half a circle

# Speeding up disk access

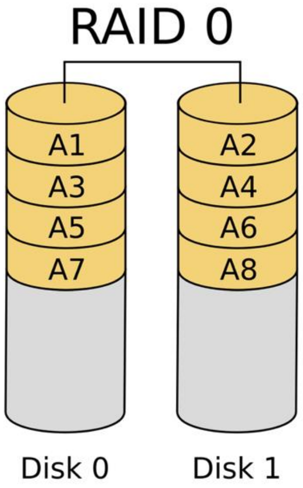
- The previous analysis was on random accesses
- In general, sequential access is much faster than random accesses
- There are several techniques for decreasing average disk access time

# RAID: Combining storage devices

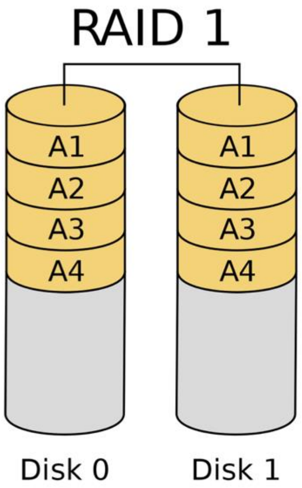
- RAID: redundant array of inexpensive disks
- Many flavors of “RAID”: striping, mirroring, etc to increase performance and reliabilitv



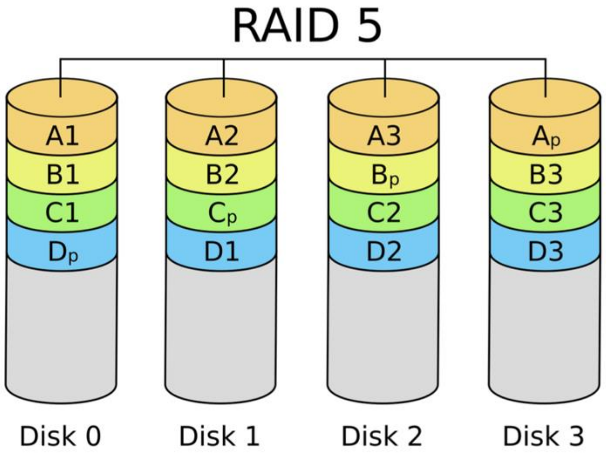
# Common RAID Levels




Striping across 2 disks: adds performance but not reliability




Mirroring across 2 disks: adds reliability but not performance (except for reads)

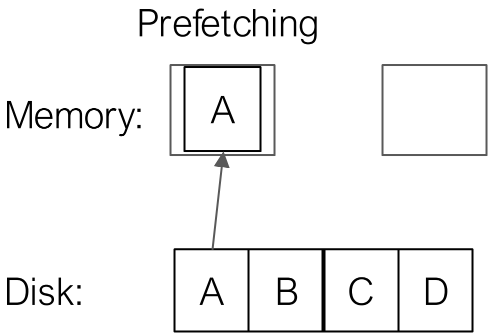



Striping + 1 parity disk: adds performance and reliability at lower storage cost

Image source: Wikipedia

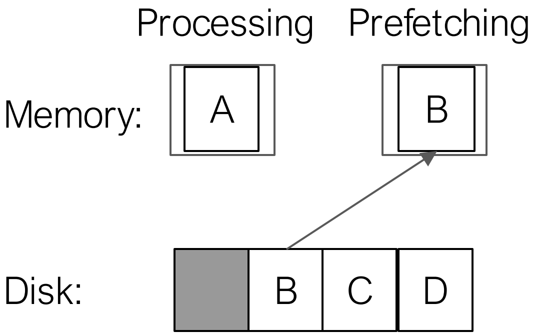
# Prefetching/Double buffering

- Predict block request order and load into memory before needed
- Reduces average block access time



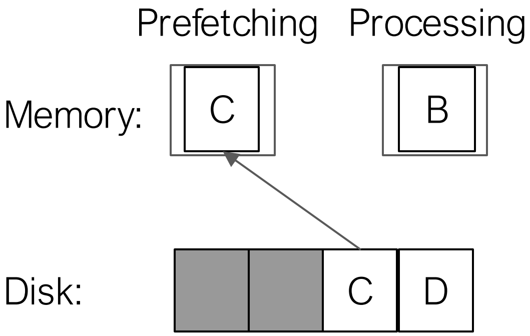
# Prefetching/Double buffering

- Predict block request order and load into memory before needed
- Reduces average block access time



# Prefetching/Double buffering

- Predict block request order and load into memory before needed
- Reduces average block access time



# Exercise #2

- Suppose
  - P = processing time / block
  - R = I/O time / block
  - N = number of blocks
- If P ≥ R, what is the processing time of
  - Single buffering
  - Double buffering

# 2. Record Encoding

# File system structure

- Now let's look at how disks are used to store databases

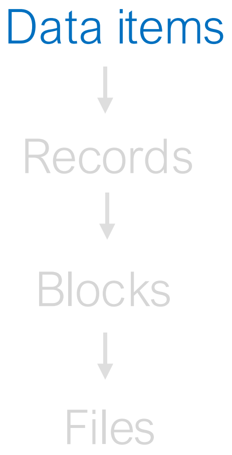
- A tuple is represented by a record,
  which consists of consecutive bytes in a disk block

Data items
↓
Records
↓
Blocks
↓
Files

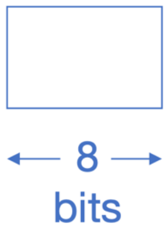
# Physical Representation of Data Items

Example data items that we want to store:

- Date
- Salary
- Name
- Picture




What we have available: bytes



# Fixed length items

Integer: fixed # of bytes (e.g., 2 bytes)

e.g., 35 is 00000000 00100011

Floating-point: n-bit mantissa, m-bit exponent

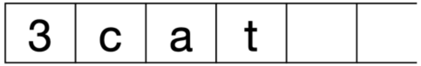
Character: encode as integer (e.g. ASCII)

# Variable length items

String of characters:

- Null-terminated


- Length + data




- Fixed-length

Bag of bits:

# Storing Records

- Record (tuple): consecutive bytes in disk blocks
  - e.g. employee record:
    - name field
    - salary field
    - date-of-hire field
- Fixed vs variable **length**
- Fixed vs variable **format**

Data items
↓
Records
↓
Blocks
↓
Files

# Fixed-format records

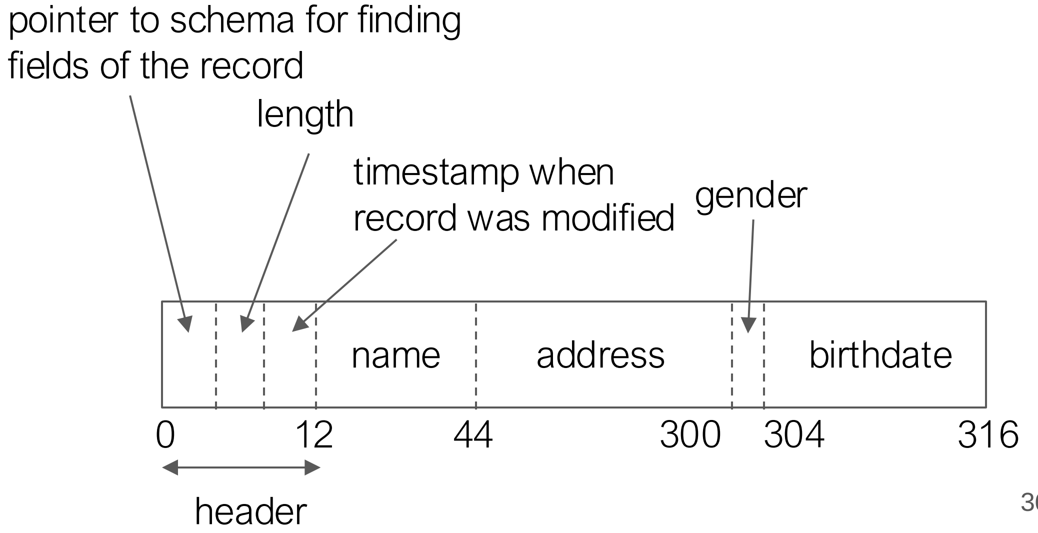
A schema for all records in table specifies:

- # of fields
- type of each field
- order in record
- meaning of each field

# Fixed-length records

- header + fixed-length region of record's information
- It is common for field addresses to be multiples of 4 or 8 to align data for efficient reading/writing of main memory (a CPU accesses memory one word at a time)

```
CREATE TABLE MovieStar (
  name              CHAR(30),
  address           CHAR(255),
  gender            CHAR(1),
  birthdate   DATE
);
```



# Variable-length records

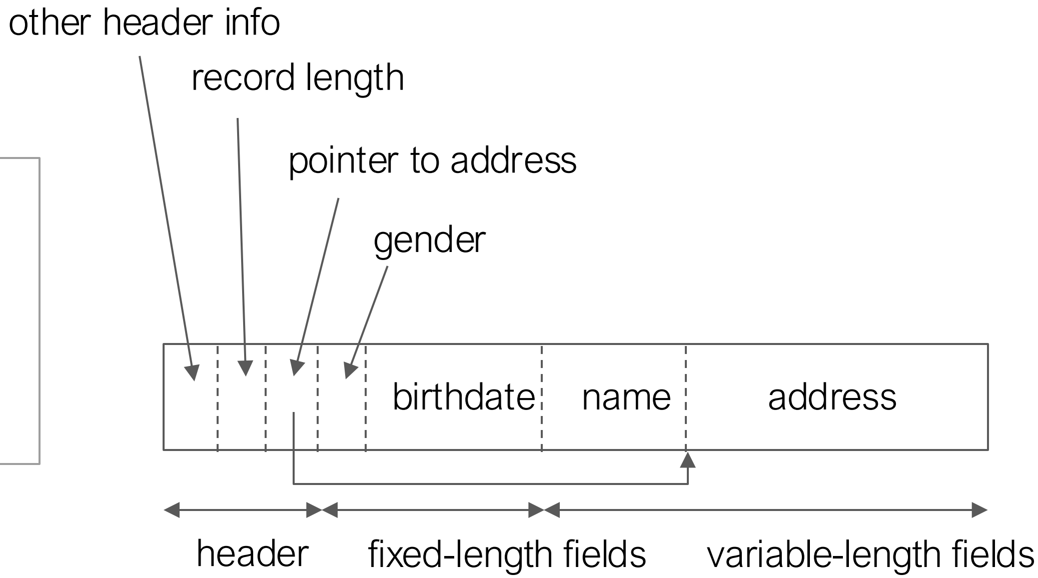
Some records may not have a fixed schema with a list of fixed-length fields

- e.g., VARCHAR
- other data models (e.g., semi-structured)

# Records with variable-length fields

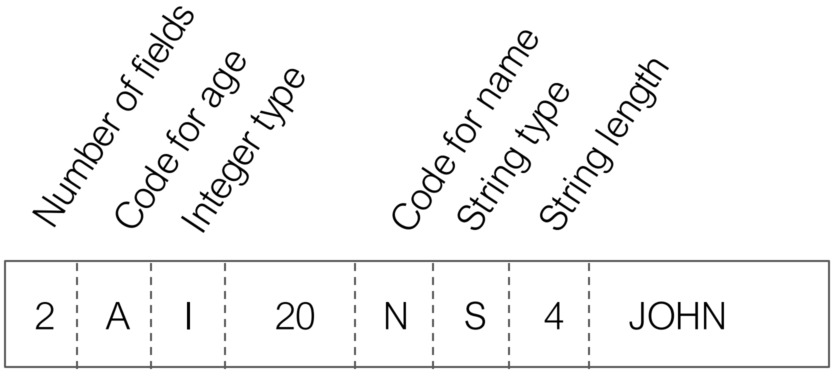
- Put all fixed-length fields ahead of the variable-length fields

```
CREATE TABLE MovieStar (
  name          VARCHAR(30),
  address       VARCHAR(100),
  gender        CHAR(1),
  birthdate     DATE
);
```



# Variable-format records

- Records may not have a fixed schema (e.g., JSON)
- Use tagged fields to make record “self-describing”



# Variable format useful for

"Sparse" records

Repeating fields

Evolving formats

But many waste space…

# 3. Collection Storage

# Collection Storage Questions

How do we place data items and records for efficient access?

- Locality
- Searchability

How do we physical encode records in blocks and files?

Data items
↓
Records
↓
Blocks
↓
Files



Adapted from Stanford CS245 from Matei Zaharia

# Place Data for Efficient Access

Locality: which items are accessed together

- When you read one field of a record, you're likely to read other fields of the same record
- When you read one field of record 1, you're likely to read the same field of record 2

Searchability: quickly find relevant records

- E.g. sorting the file lets you do binary search

# Locality Example: Row Stores vs Column Stores

**Row Store**

| name | age | state |
|---|---|---|
| Alex | 20 | CA |
| Bob | 30 | CA |
| Carol | 42 | NY |
| David | 21 | MA |
| Eve | 26 | CA |
| Frances | 56 | NY |
| Gia | 19 | MA |
| Harold | 28 | AK |
| Ivan | 41 | CA |

Fields stored contiguously in one file

**Column Store**

| name |
|---|
| Alex |
| Bob |
| Carol |
| David |
| Eve |
| Frances |
| Gia |
| Harold |
| Ivan |

| age |
|---|
| 20 |
| 30 |
| 42 |
| 21 |
| 26 |
| 56 |
| 19 |
| 28 |
| 41 |

| state |
|---|
| CA |
| CA |
| NY |
| MA |
| CA |
| NY |
| MA |
| AK |
| CA |

Each column in a different file

Adapted from Stanford CS245 from Matei Zaharia

# Locality Example: Row Stores vs Column Stores

## Row Store

| name | age | state |
|---|---|---|
| Alex | 20 | CA |
| Bob | 30 | CA |
| Carol | 42 | NY |
| David | 21 | MA |
| Eve | 26 | CA |
| Frances | 56 | NY |
| Gia | 19 | MA |
| Harold | 28 | AK |
| Ivan | 41 | CA |

Fields stored contiguously in one file

## Column Store

| name |
|---|
| Alex |
| Bob |
| Carol |
| David |
| Eve |
| Frances |
| Gia |
| Harold |
| Ivan |

| age |
|---|
| 20 |
| 30 |
| 42 |
| 21 |
| 26 |
| 56 |
| 19 |
| 28 |
| 41 |

| state |
|---|
| CA |
| CA |
| NY |
| MA |
| CA |
| NY |
| MA |
| AK |
| CA |

Each column in a different file

Accessing all fields of one record: 1 random I/O for row, 3 for column



Adapted from Stanford CS245 from Matei Zaharia

# Locality Example: Row Stores vs Column Stores

## Row Store

| name | age | state |
|---|---|---|
| Alex | 20 | CA |
| Bob | 30 | CA |
| Carol | 42 | NY |
| David | 21 | MA |
| Eve | 26 | CA |
| Frances | 56 | NY |
| Gia | 19 | MA |
| Harold | 28 | AK |
| Ivan | 41 | CA |

Fields stored contiguously in one file

## Column Store

| name |
|---|
| Alex |
| Bob |
| Carol |
| David |
| Eve |
| Frances |
| Gia |
| Harold |
| Ivan |

| age |
|---|
| 20 |
| 30 |
| 42 |
| 21 |
| 26 |
| 56 |
| 19 |
| 28 |
| 41 |

| state |
|---|
| CA |
| CA |
| NY |
| MA |
| CA |
| NY |
| MA |
| AK |
| CA |

Each column in a different file

Accessing one field of all records: 3x less I/O for column store

Adapted from Stanford CS245 from Matei Zaharia

# Can We Have Hybrids Between Row & Column?

Yes! For example, colocated **column groups**:

| name |
| --- |
| Alex |
| Bob |
| Carol |
| David |
| Eve |
| Frances |
| Gia |
| Harold |
| Ivan |

File 1

| age | state |
| --- | --- |
| 20 | CA |
| 30 | CA |
| 42 | NY |
| 21 | MA |
| 26 | CA |
| 56 | NY |
| 19 | MA |
| 28 | AK |
| 41 | CA |

File 2: age & state

Helpful if age & state are frequently co-accessed

# Improving Searchability: Ordering

**Ordering** the data by a field will give:

- Smaller I/Os if queries tend to read data with nearby values of the field (e.g. time ranges)
- Option to accelerate search via an ordered index (e.g. B-tree), binary search, etc

Q: What's the downside of having an ordering?

# Improving Searchability: Partitions

Just place data into buckets based on a field
(but not necessarily fine-grained order)

E.g. Hive table storage over a filesystem:

```
/my_table/date=20190101/file1.parquet
                       /file2.parquet
         /date=20190102/file1.parquet
                       /file2.parquet
         /date=20190103/file1.parquet
                         ...
```

Easy to add, remove, list any files in a directory

# Can We Have Searchability on Multiple Fields at Once?

Yes! Many possible ways:

1) Multiple partition or sort keys (e.g., partition by date, then sort by userID)

2) Interleaved orderings such as Z-ordering

# Z-Ordering

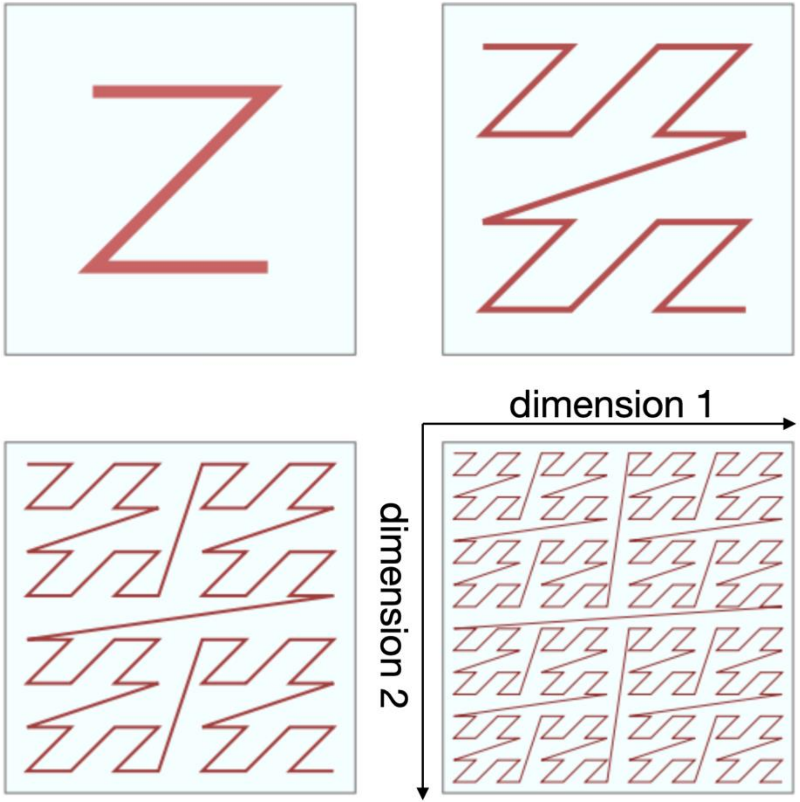
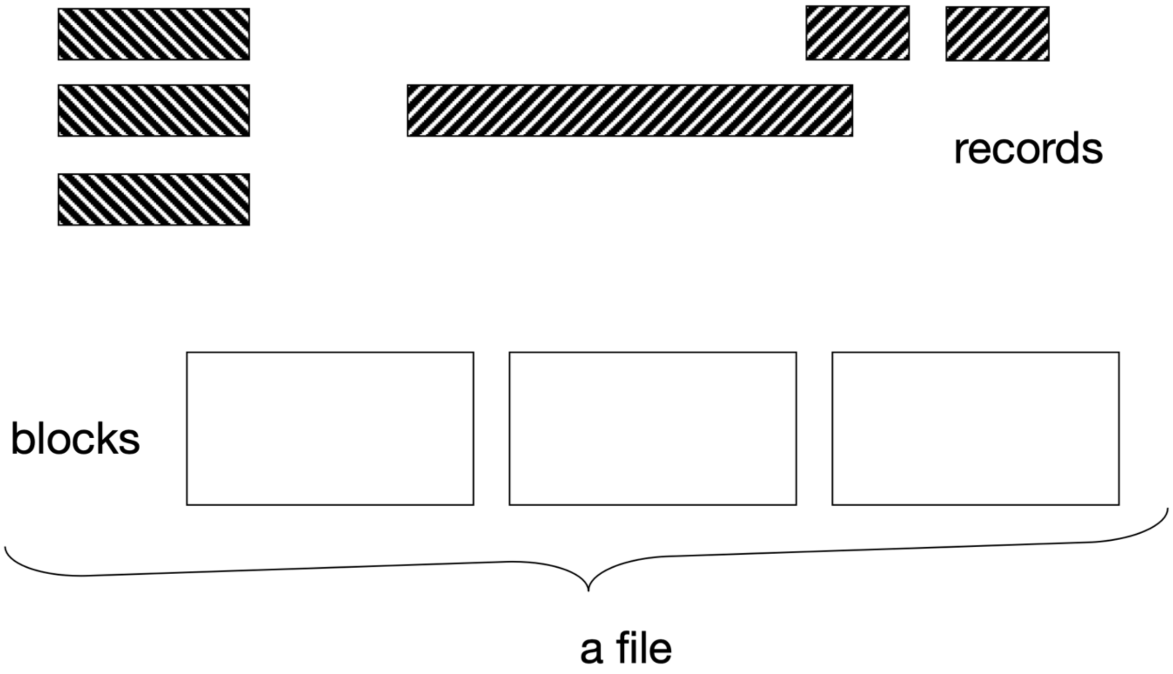



Image source: wikipedia

# How Do We Encode Records into Blocks & Files?




Data items

Records

Blocks

Files



Adapted from Stanford CS245 from Matei Zaharia

# Storing records into blocks

Records are stored in blocks, which are moved into main memory.

Several options:

(1) separating records

(2) spanned vs. unspanned

(3) indirection

# (1) Separating Records

(a) no need to separate - fixed size recs.

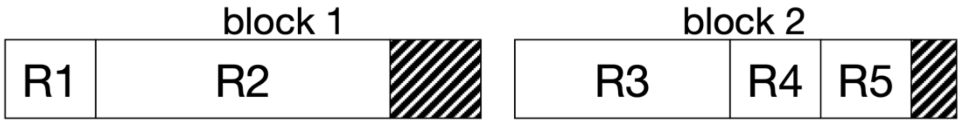
(b) special marker

(c) give record lengths (or offsets)

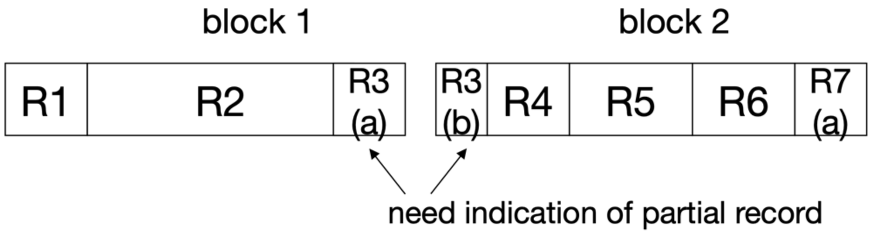
- within each record
- in block header

# (2) Spanned vs Unspanned

Unspanned: records must be within one block




Spanned:



# (3) Indirection

How does one refer to other records?


Many options: physical vs indirect

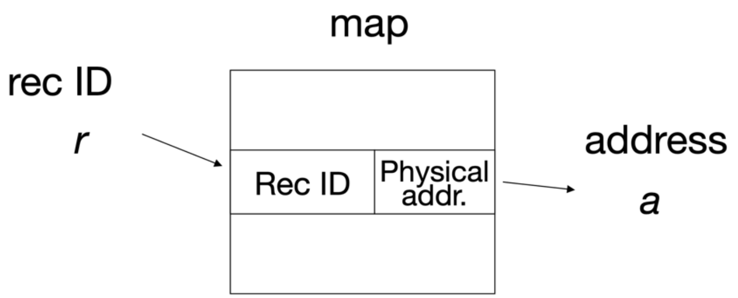
# (3) Indirection

## Purely Physical

E.g., Record Address or ID = { Device ID, Cylinder #, Track #, Block # (Block ID), Offset in block }

## Fully Indirect

E.g., Record ID is arbitrary bit string




**Tradeoff:**
Flexibility to move records <> cost of indirection

# Inserting Records

Easy case: records not ordered

- Insert record at end of file or in a free space
- Harder if records are variable-length

Hard case: records are ordered

- If free space close by, not too bad...
- Otherwise, use an overflow area and reorganize the file periodically

# Deleting Records

Immediately reclaim space

OR

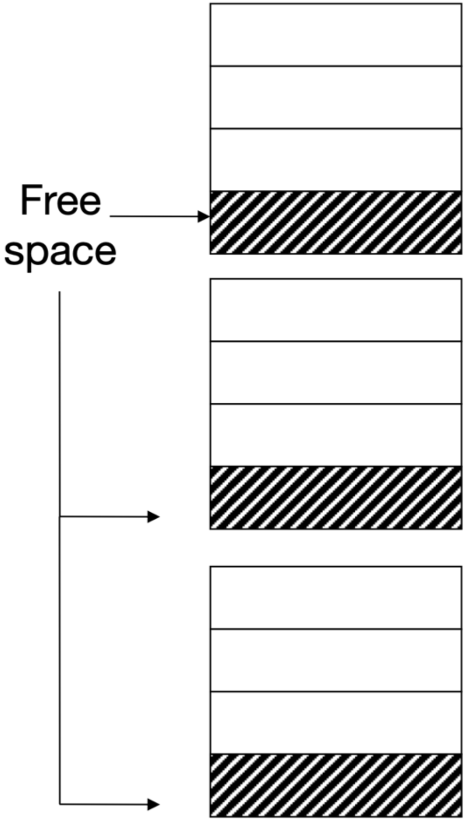
Mark deleted

- And keep track of freed spaces for later use

# Interesting Problems

How much free space to leave in each block, track, cylinder, etc?

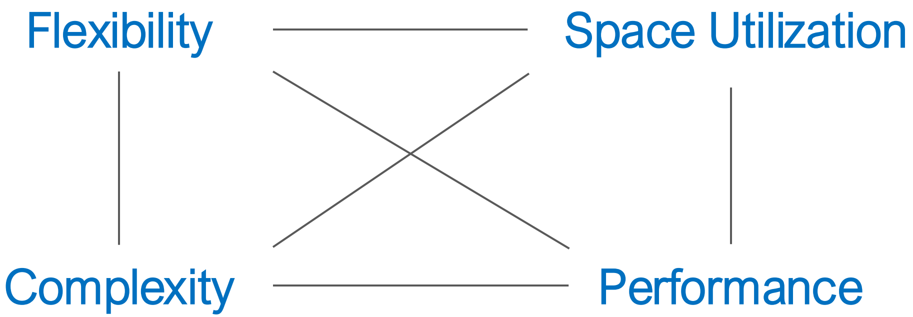
How often to reorganize file + merge overflow?



# Summary

Many ways to store data on disk!

Key tradeoffs:



# To Evaluate a Strategy, Compare:

Space used for expected data

Expected time to

- fetch record given key
- read whole file
- insert record
- delete record
- update record
- reorganize file
- ...