Physical Data Organization

Introduction to Databases

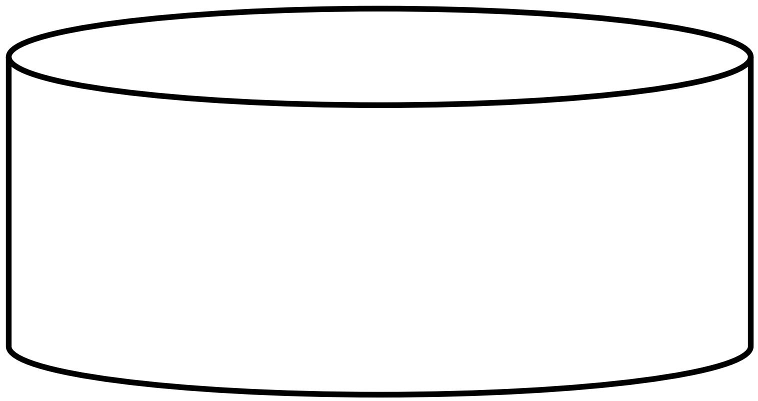
CompSci 316 Spring 2020

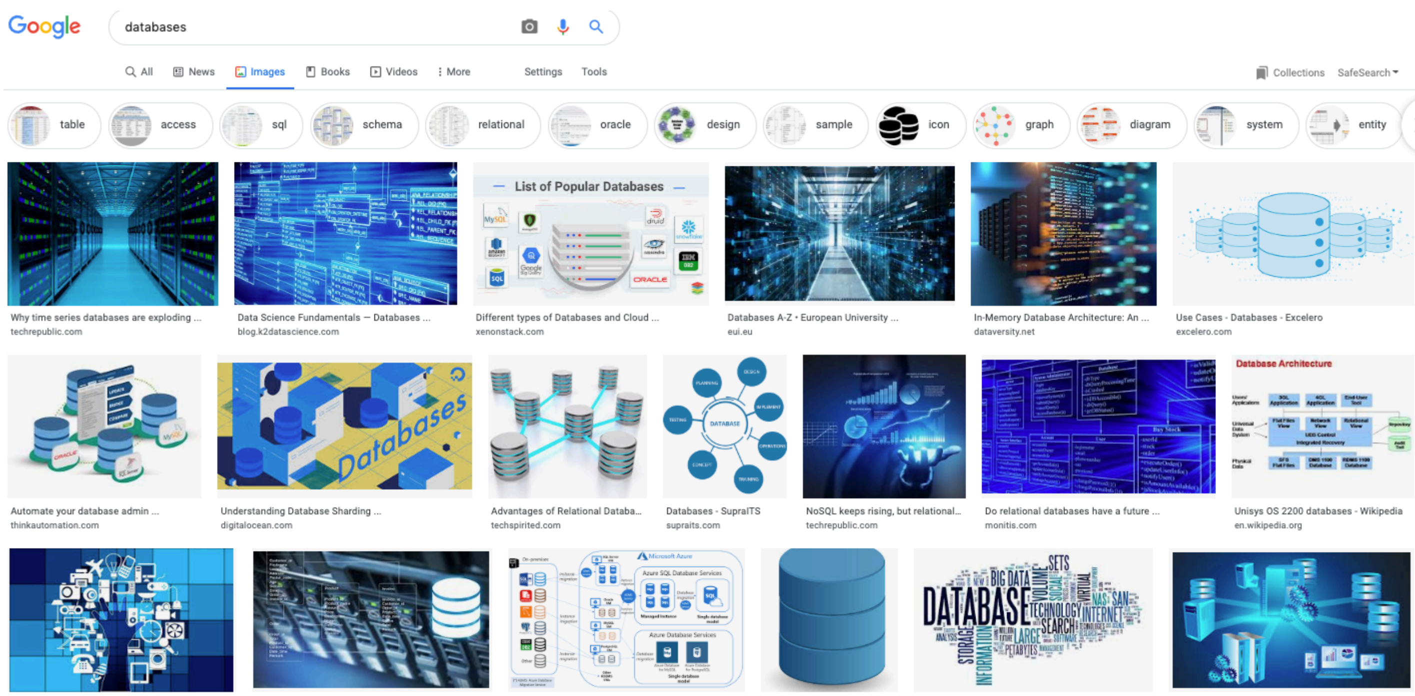
DUKE
COMPUTER SCIENCE

Announcements (Tue. Feb. 25)

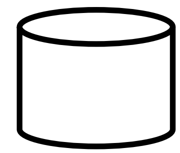
- HW4: A group homework on creating a basic flask-based website will be published today – due next Tuesday 02/03
  - Each project group will work on this homework together
  - Everyone in a team will get the same grade
  - You should divide the task or work on the same task as works for you
  - It should provide the basic infrastructure for your website or app
- Midterm scores and statistics published
  - You can submit regrade requests on gradescope by next Tuesday 02/03.

Why do we draw databases like this?

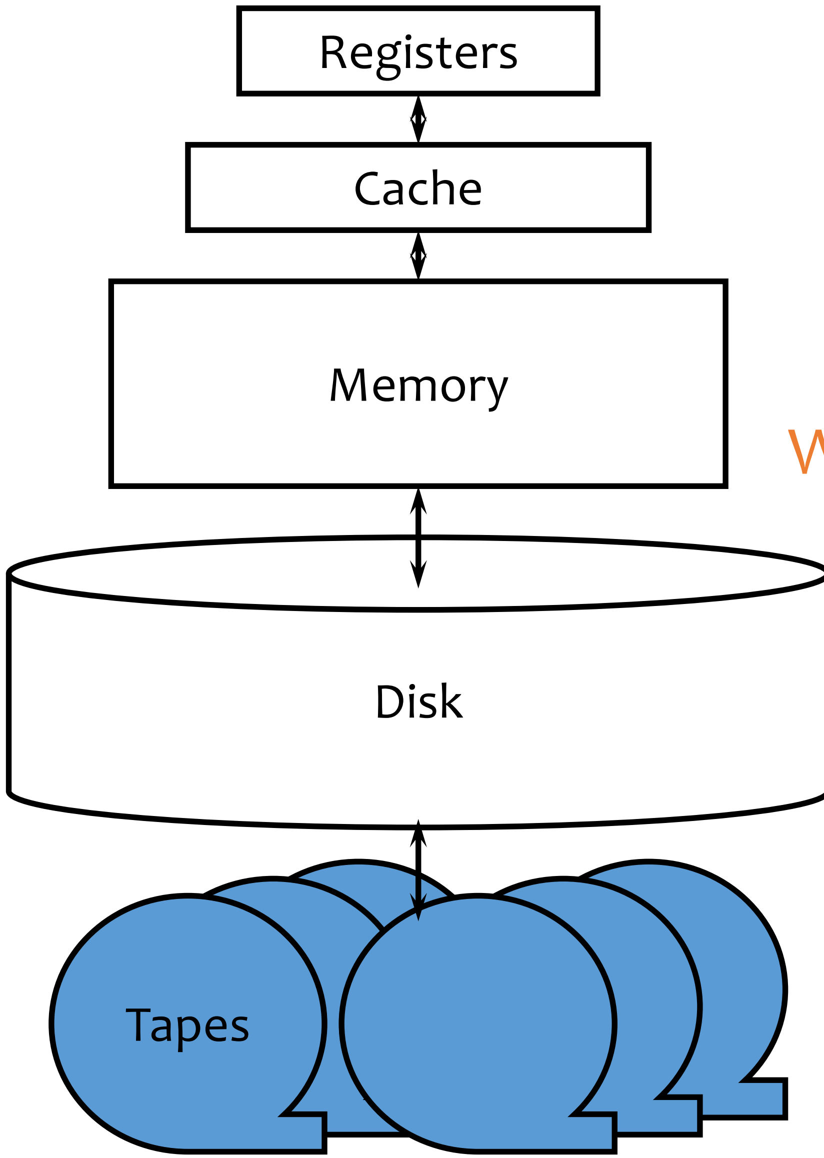




Outline

- It's all about disks!
  - That's why we always draw databases as 
  - And why the single most important metric in database processing is (oftentimes) the number of disk I/O's performed
- Storing data on a disk
  - Record layout
  - Block layout
  - Column stores

Storage hierarchy



Why a hierarchy?

How far away is data?

Location	Cycles
Registers	1
On-chip cache	2
On-board cache	10
Memory	100
Disk	10^6
Tape	10^9

Location	Time
My head	1 min.
This room	2 min.
Duke campus	10 min.
Washington D.C.	1.5 hr.
Pluto	2 yr.
Andromeda	2000 yr.

(Source: AlphaSort paper, 1995)
The gap has been widening!

☞ I/O dominates—design your algorithms to reduce I/O!

Latency Numbers Every Programmer Should Know

Take a look yourself!

```
Latency Comparison Numbers
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L1 cache reference                           0.5 ns
Branch mispredict                            5   ns
L2 cache reference                           7   ns                      14x L1 cache
Mutex lock/unlock                           25   ns
Main memory reference                      100   ns                      20x L2 cache, 200x L1 cache
Compress 1K bytes with Zippy             3,000   ns        3 us
Send 1K bytes over 1 Gbps network       10,000   ns       10 us
Read 4K randomly from SSD*             150,000   ns      150 us          ~1GB/sec SSD
Read 1 MB sequentially from memory     250,000   ns      250 us
Round trip within same datacenter      500,000   ns      500 us
Read 1 MB sequentially from SSD*     1,000,000   ns    1,000 us    1 ms  ~1GB/sec SSD, 4X memory
Disk seek                           10,000,000   ns   10,000 us   10 ms  20x datacenter roundtrip
Read 1 MB sequentially from disk    20,000,000   ns   20,000 us   20 ms  80x memory, 20X SSD
Send packet CA->Netherlands->CA    150,000,000   ns  150,000 us  150 ms

Notes
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1 ns = 10^-9 seconds
1 us = 10^-6 seconds = 1,000 ns
1 ms = 10^-3 seconds = 1,000 us = 1,000,000 ns

Credit
------
By Jeff Dean:               http://research.google.com/people/jeff/
Originally by Peter Norvig: http://norvig.com/21-days.html#answers
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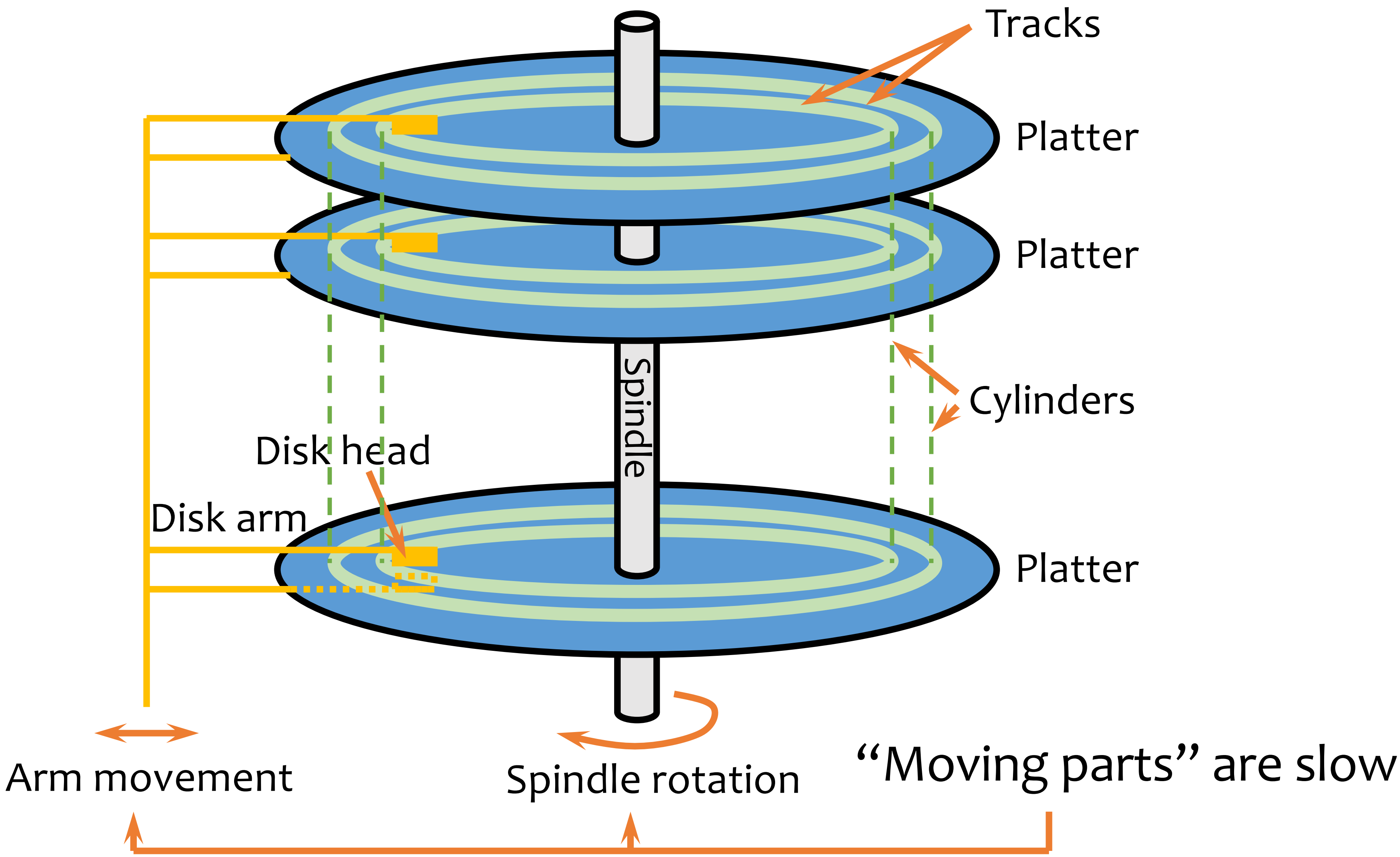
A typical hard drive

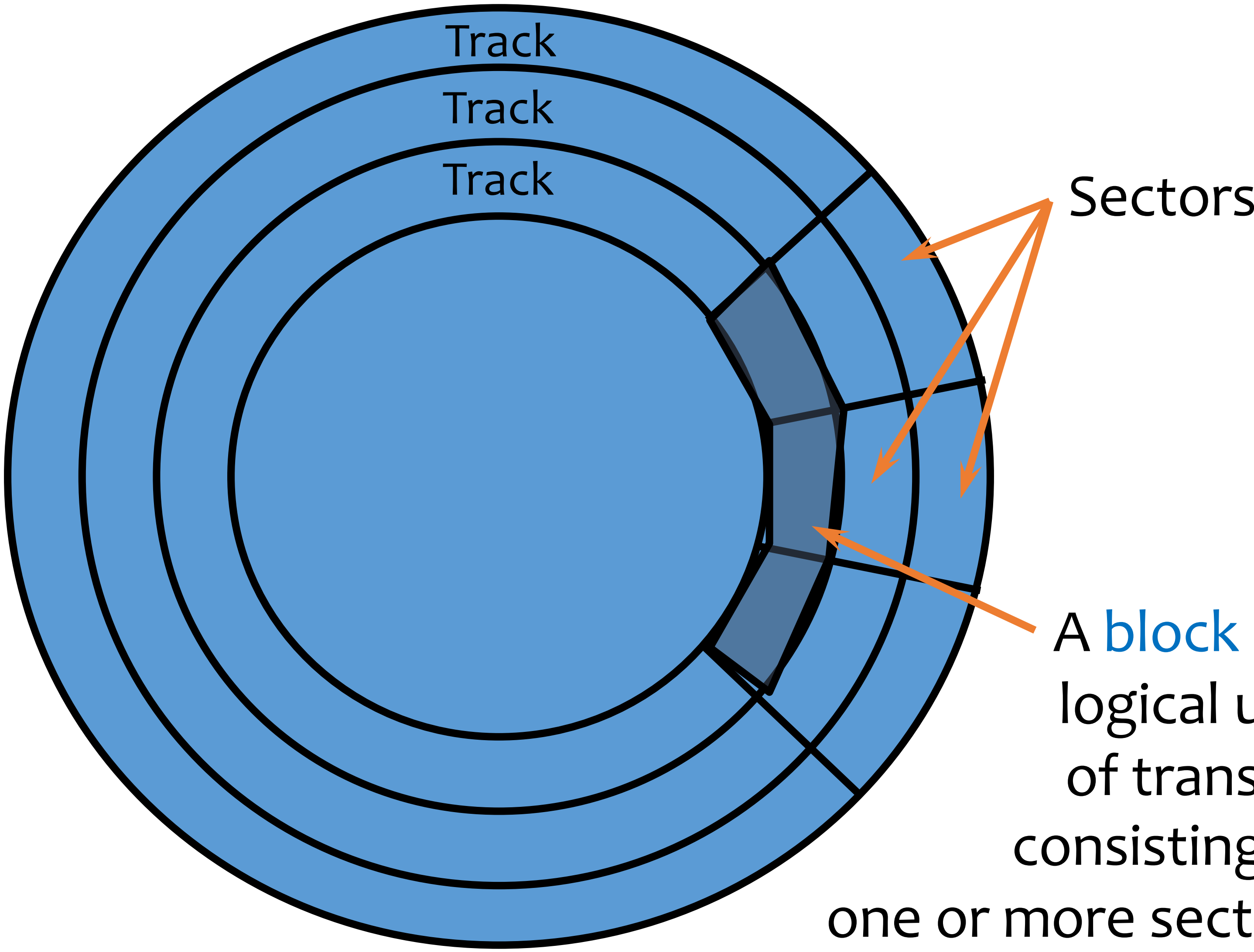
http://upload.wikimedia.org/wikipedia/commons/f/f8/Laptop-hard-drive-exposed.jpg

A typical hard drive



Top view

"Zoning": more sectors/data on outer tracks



A block is a logical unit of transfer consisting of one or more sectors

Disk access time

Sum of:

- Seek time: time for disk heads to move to the correct cylinder
- Rotational delay: time for the desired block to rotate under the disk head
- Transfer time: time to read/write data in the block (= time for disk to rotate over the block)

Any guess of their relative values of random and sequential access?

Random disk access

Seek time + rotational delay + transfer time

- Average seek time
  - "Typical" value: 5 ms

- Average rotational delay
  - Time for a half rotation (a function of RPM)
  - "Typical" value: 4.2 ms (7200 RPM)

Sequential disk access

Seek time + rotational delay + transfer time

- Seek time
  - 0 (assuming data is on the same track)
- Rotational delay
  - 0 (assuming data is in the next block on the track)
- Easily an order of magnitude faster than random disk access!

What about SSD (solid-state drives)?

- 1-2 orders of magnitude faster random access than hard drives (under 0.1ms vs. several ms)
  - But still much slower than memory (~0.1μs)
- Little difference between random vs. sequential read performance
- Random writes still hurt
  - In-place update would require erasing the whole “erasure block” and rewriting it!

http://www.techgoondu.com/wp-content/uploads/2012/12/SSD-6-25-121.jpg

Important consequences

- It's all about reducing I/O's!
- Cache blocks from stable storage in memory
  - DBMS maintains a memory buffer pool of blocks
  - Reads/writes operate on these memory blocks
  - Dirty (updated) memory blocks are "flushed" back to stable storage
- Sequential I/O is much faster than random I/O

Picture on board that we will use again and again!

Performance tricks

- Disk layout strategy
  - Keep related things (what are they?) close together: same sector/block → same track → same cylinder → adjacent cylinder
- Prefetching
  - While processing the current block in memory, fetch the next block from disk (overlap I/O with processing)
- Parallel I/O
  - More disk heads working at the same time
- Disk scheduling algorithm
  - Example: “elevator” algorithm
- Track buffer
  - Read/write one entire track at a time

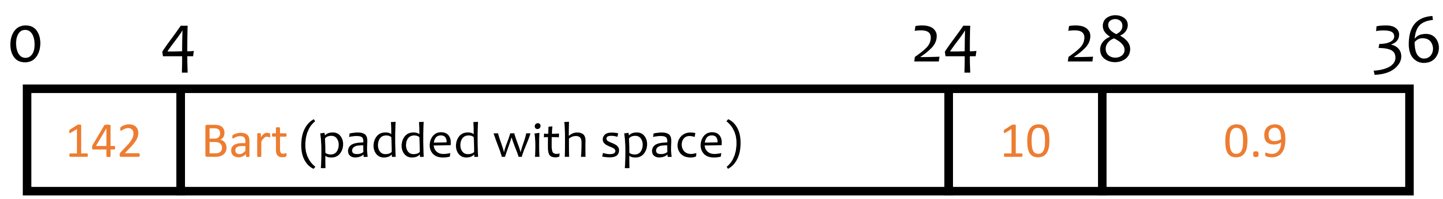
Record layout

Record = row in a table

- Variable-format records
  - Rare in DBMS—table schema dictates the format
  - Relevant for semi-structured data such as XML
- Focus on fixed-format records
  - With fixed-length fields only, or
  - With possible variable-length fields

Fixed-length fields

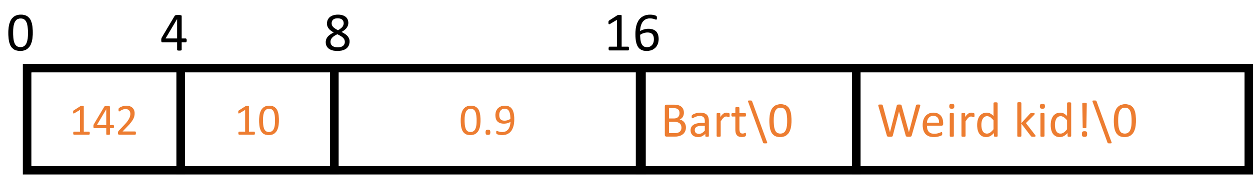
- All field lengths and offsets are constant
  - Computed from schema, stored in the system catalog
- Example: CREATE TABLE User(uid INT, name CHAR(20), age INT, pop FLOAT);



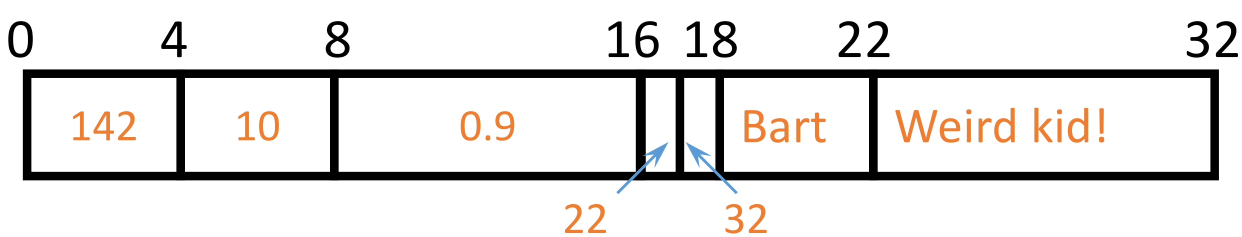
- Watch out for alignment
  - May need to pad; reorder columns if that helps
- What about NULL?
  - Add a bitmap at the beginning of the record

Variable-length records

- Example: CREATE TABLE User(uid INT,
  name VARCHAR(20), age INT, pop FLOAT,
  comment VARCHAR(100));
- Approach 1: use field delimiters ('\0' okay?)



- Approach 2: use an offset array



- Put all variable-length fields at the end (why?)
- Update is messy if it changes the length of a field

LOB fields

- Example: CREATE TABLE User(uid INT,
  name CHAR(20), age INT,
  pop FLOAT, picture BLOB(32000));
- Student records get "de-clustered"
  - Bad because most queries do not involve picture
- Decomposition (automatically and internally done by DBMS without affecting the user)
  - (*uid*, *name*, *age*, *pop*)
  - (*uid*, *picture*)

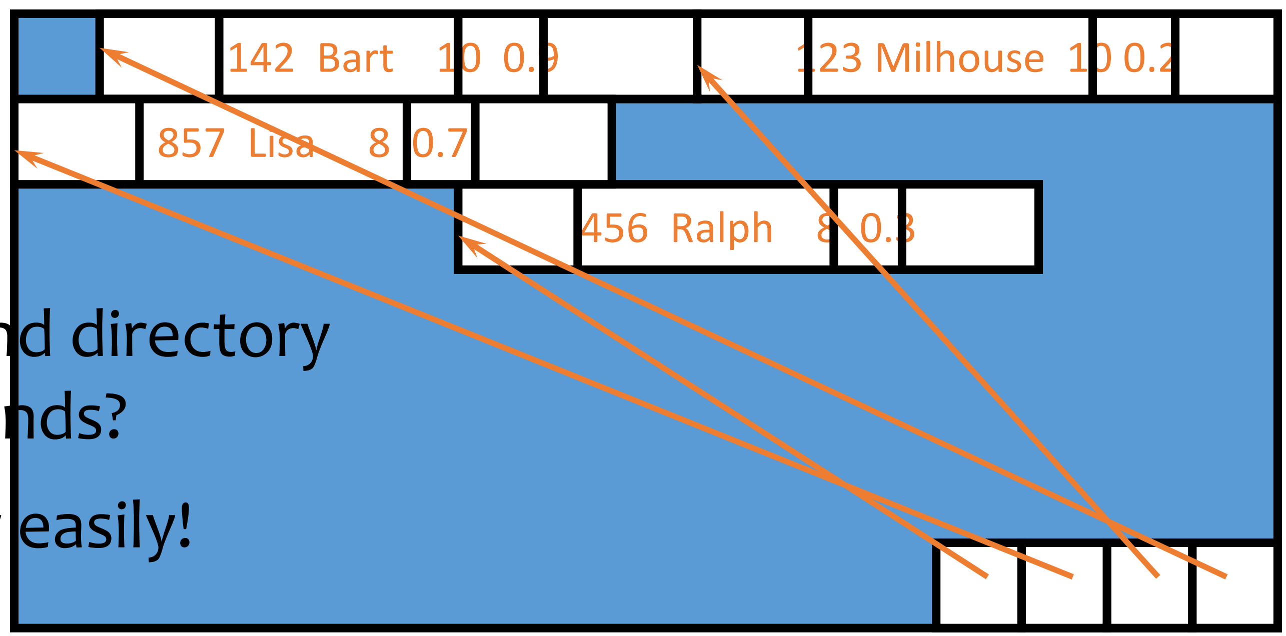
Block layout

How do you organize records in a block?

- NSM (N-ary Storage Model)
  - Most commercial DBMS
- PAX (Partition Attributes Across)
  - Ailamaki et al., *VLDB* 2001

NSM

- Store records from the beginning of each block
- Use a directory at the end of each block
  - To locate records and manage free space
  - Necessary for variable-length records



Why store data and directory at two different ends?

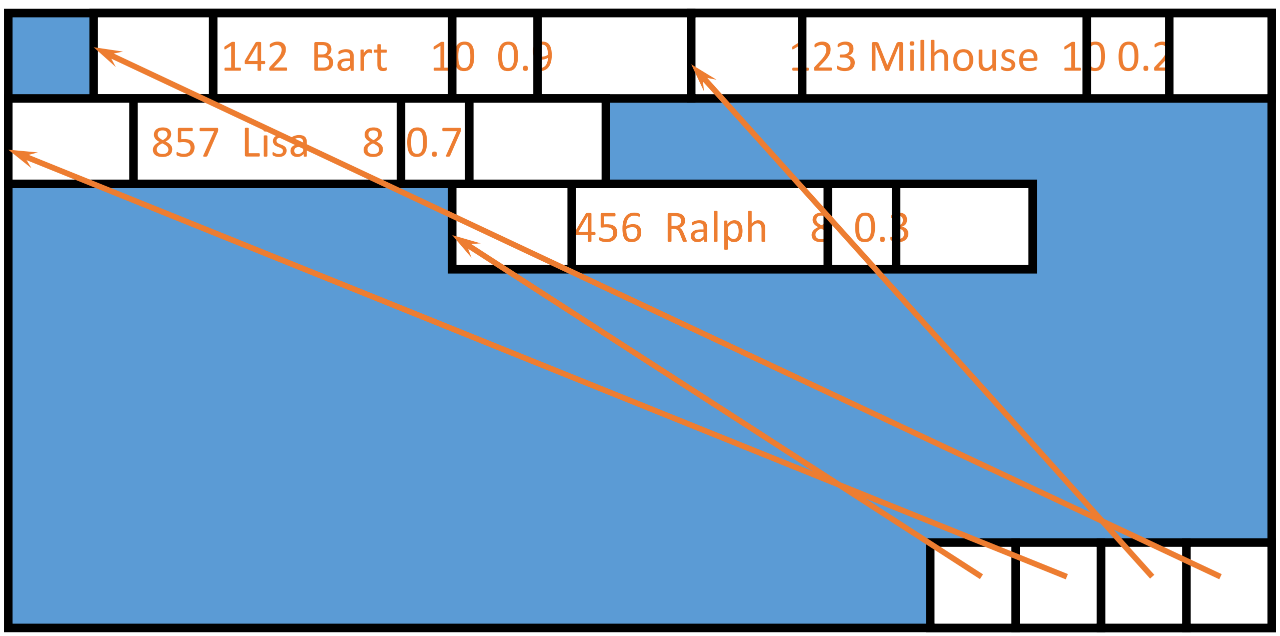
So both can grow easily!

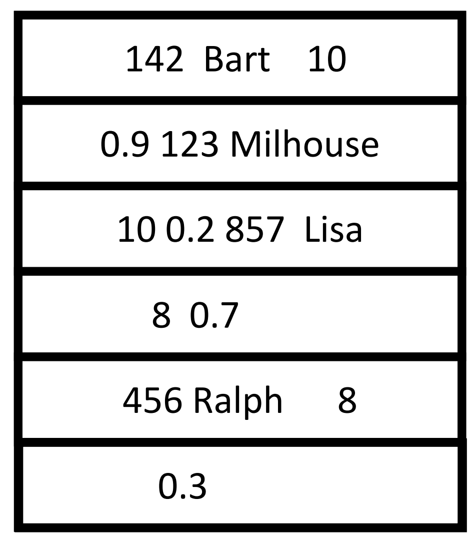
Options

- Reorganize after every update/delete to avoid fragmentation (gaps between records)
  - Need to rewrite half of the block on average
- A special case: What if records are fixed-length?
  - Option 1: reorganize after delete
    - Only need to move one record
    - Need a pointer to the beginning of free space
  - Option 2: do not reorganize after update
    - Need a bitmap indicating which slots are in use

Cache behavior of NSM

- Query: SELECT uid FROM User WHERE pop > 0.8;
- Assumptions: no index, and cache line size < record size
- Lots of cache misses
  - uid and pop are not close enough by memory standards

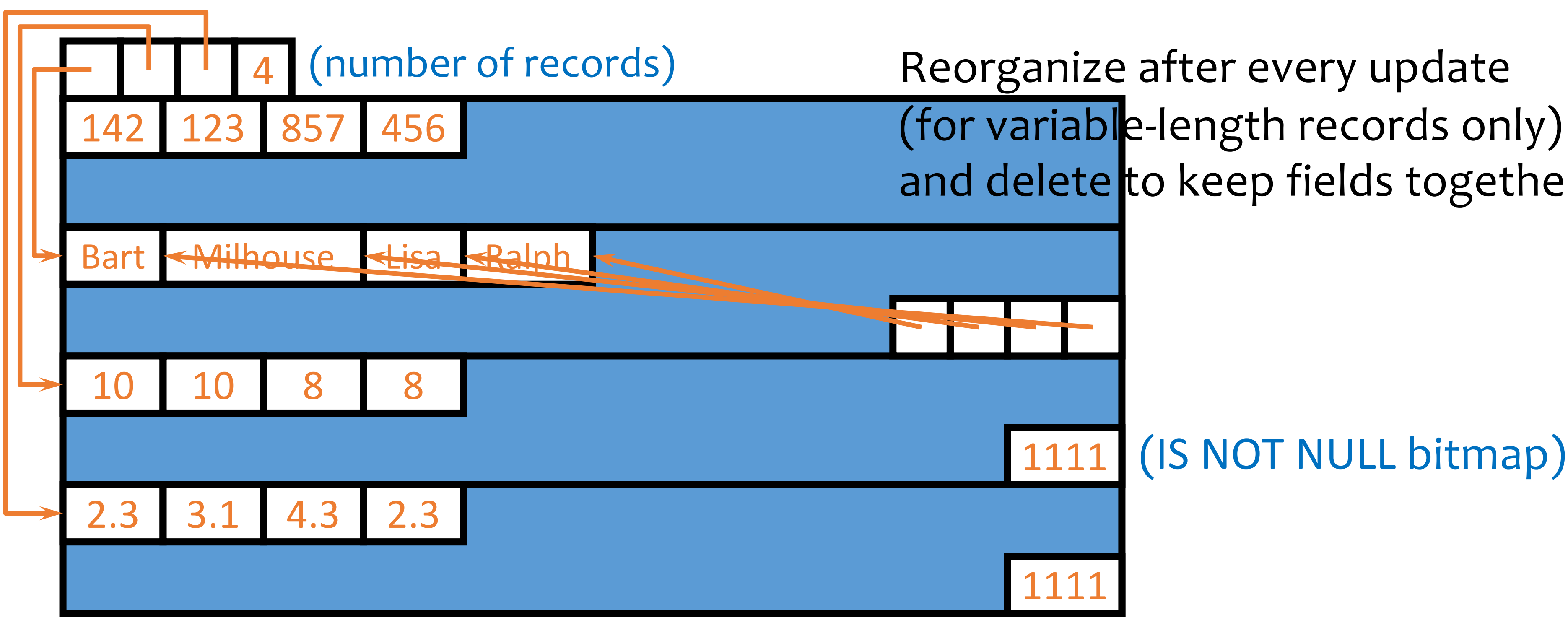




Cache

PAX

- Most queries only access a few columns
- Cluster values of the same columns in each block
  - When a particular column of a row is brought into the cache, the same column of the next row is brought in together



Reorganize after every update (for variable-length records only) and delete to keep fields together

Beyond block layout: column stores

- The other extreme: store tables by columns instead of rows
- Advantages (and disadvantages) of PAX are magnified
    - Not only better cache performance, but also fewer I/O's for queries involving many rows but few columns
    - Aggressive compression to further reduce I/O's
- More disruptive changes to the DBMS architecture are required than PAX
    - Not only storage, but also query execution and optimization
- Example: Apache Parquet

Summary

- Storage hierarchy
  - Why I/O's dominate the cost of database operations
- Disk
  - Steps in completing a disk access
  - Sequential versus random accesses
- Record layout
  - Handling variable-length fields
  - Handling NULL
  - Handling modifications
- Block layout
  - NSM: the traditional layout
  - PAX: a layout that tries to improve cache performance
- Column stores: NSM transposed, beyond blocks