Physical Data Organization

Introduction to Databases

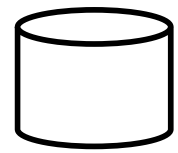
CompSci 316 Fall 2019

DUKE COMPUTER SCIENCE

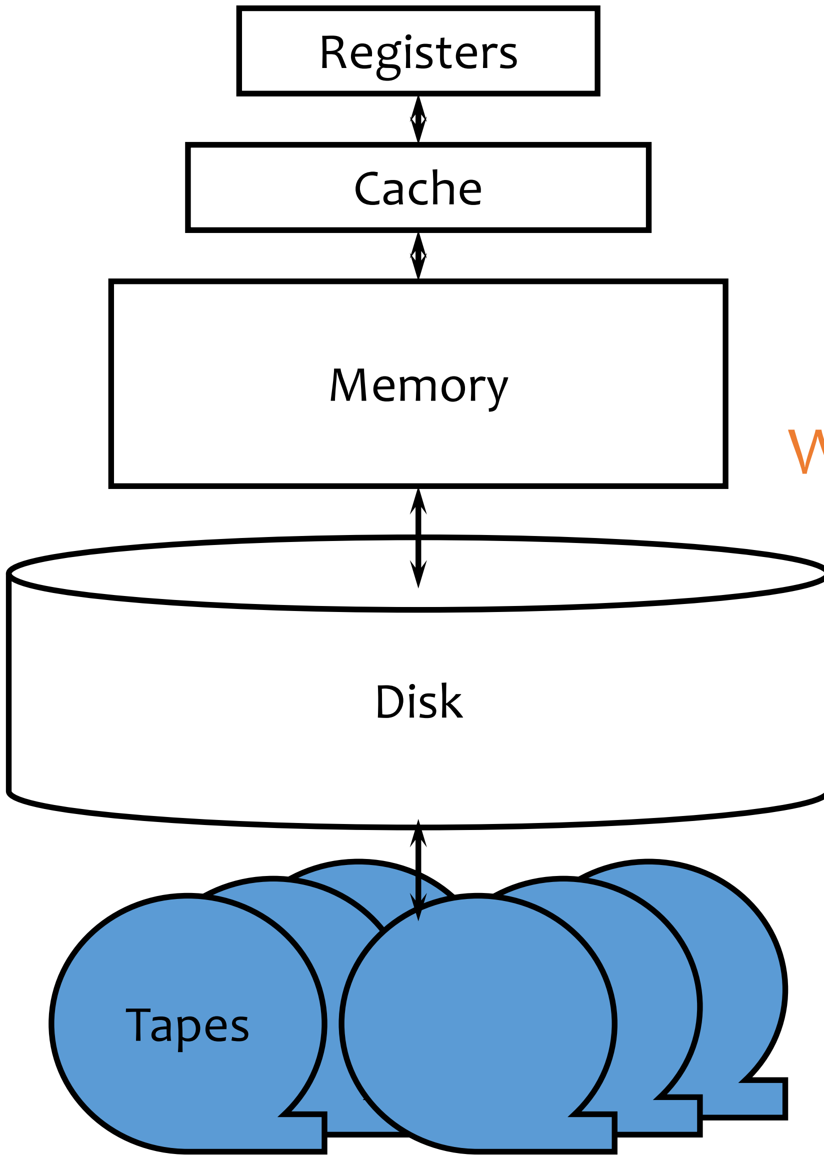
Announcements (Wed., Oct. 30)

- Homework 3 due Monday
- Project milestone 2 due Wednesday
  - Remember the weekly progress update due today
  - No weekly progress update due next week

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

(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

```
Latency Comparison Numbers
--------------------------
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
```
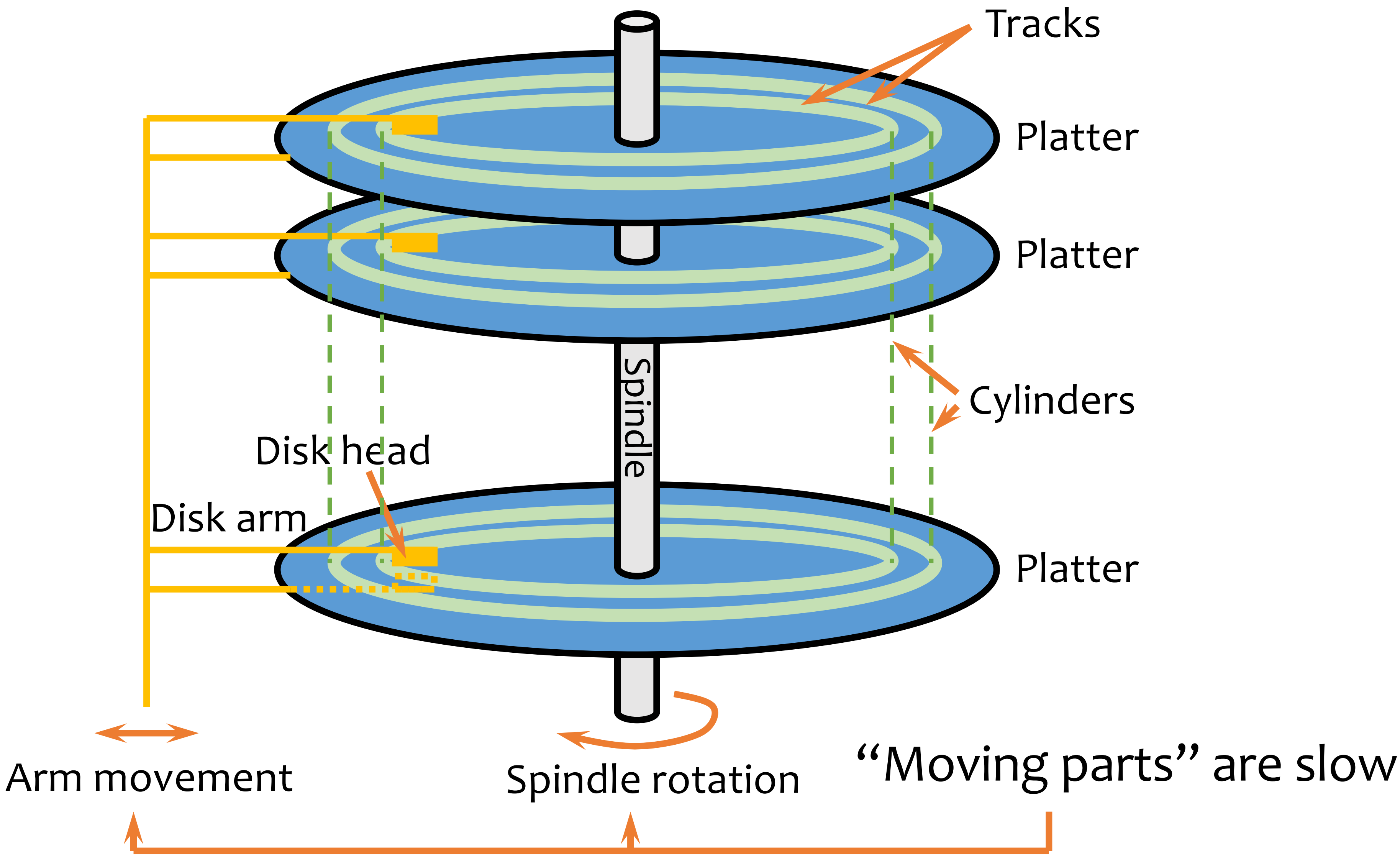

A typical hard drive

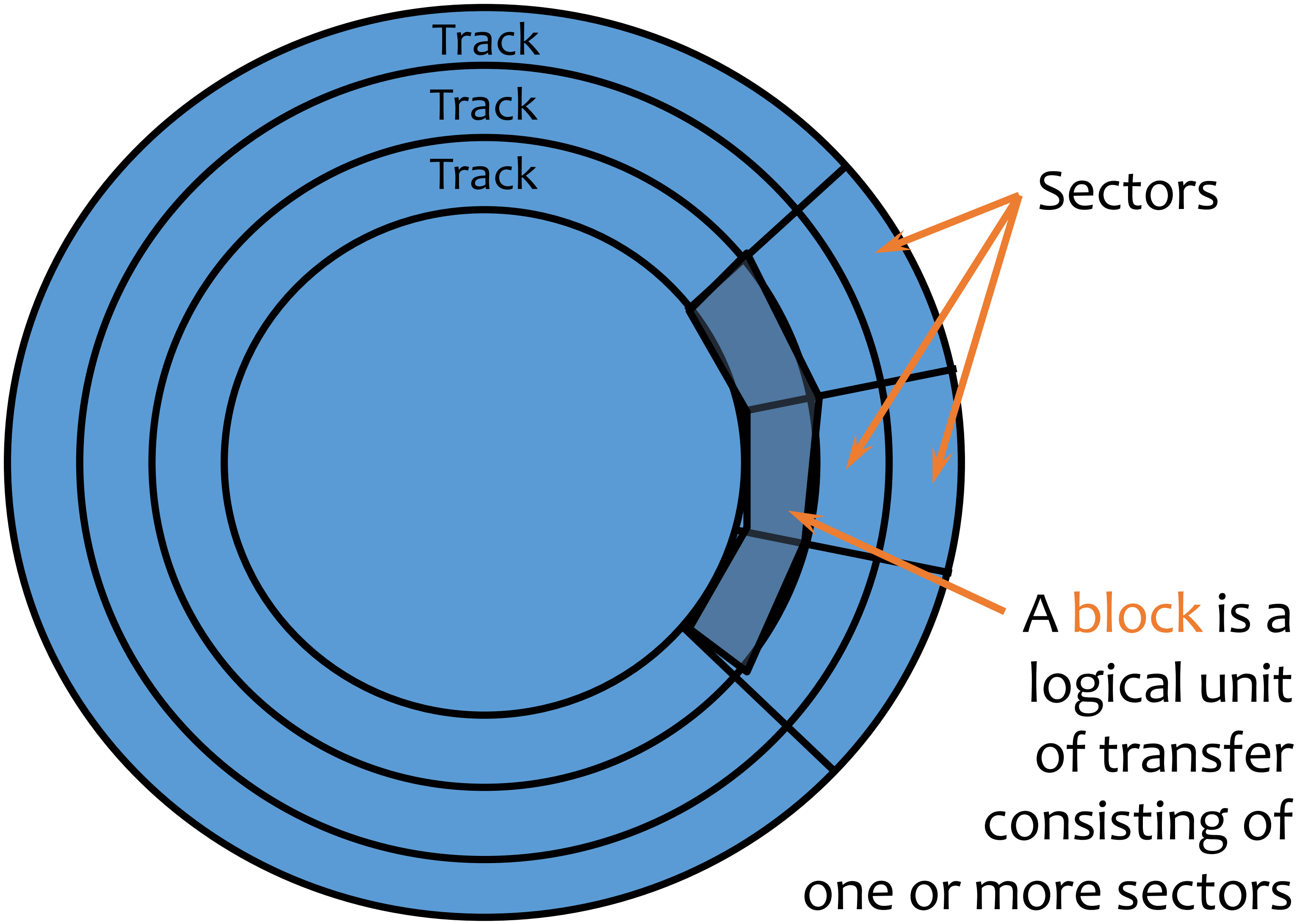
http://upload.wikimedia.org/wikipedia/commons/f/f8/Laptop-hard-drive-exposed.jpg

A typical hard drive



Top view

"Zoning": more sectors/data on outer tracks



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)

Random disk access

Seek time + rotational delay + transfer time

- Average seek time
  - Time to skip one half of the cylinders?
  - Not quite; should be time to skip a third of them (why?)
  - "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)?

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

What about SSD (solid-state drives)?

- No mechanical parts
- Mostly flash-based nowadays
- 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!

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

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

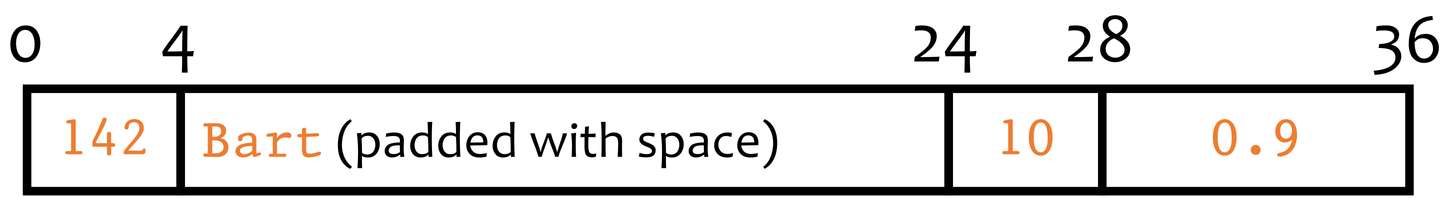
Record layout

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

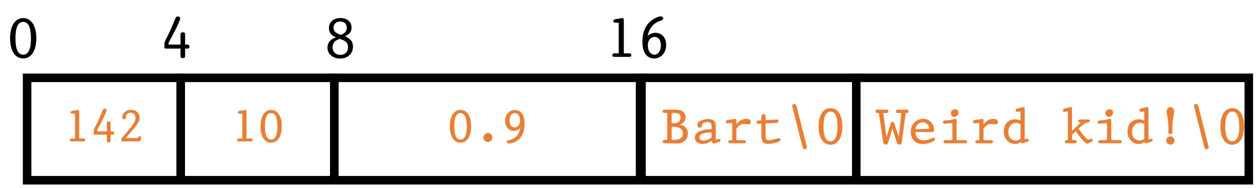
- All field lengths and offsets are constant
  - Computed from schema, stored in the system catalog
- Example: `CREATE TABLE User(uid INT, name CHAR(20), age INT, pop FLOAT);`



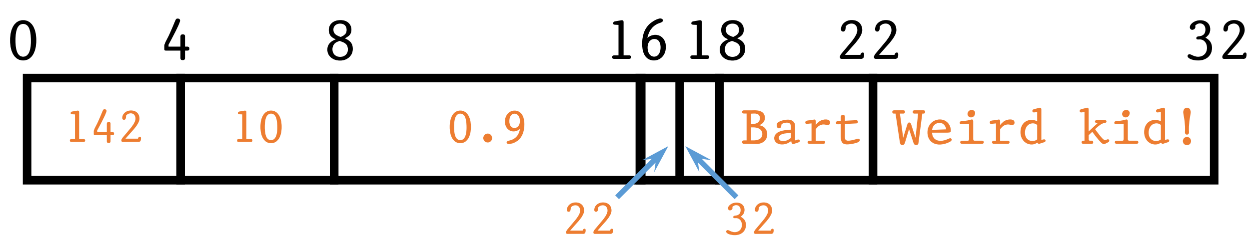
- Watch out for alignment
  - May need to pad; reorder columns if that helps
- What about `NULL`?
  - Add a bitmap at the beginning of the record

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*)

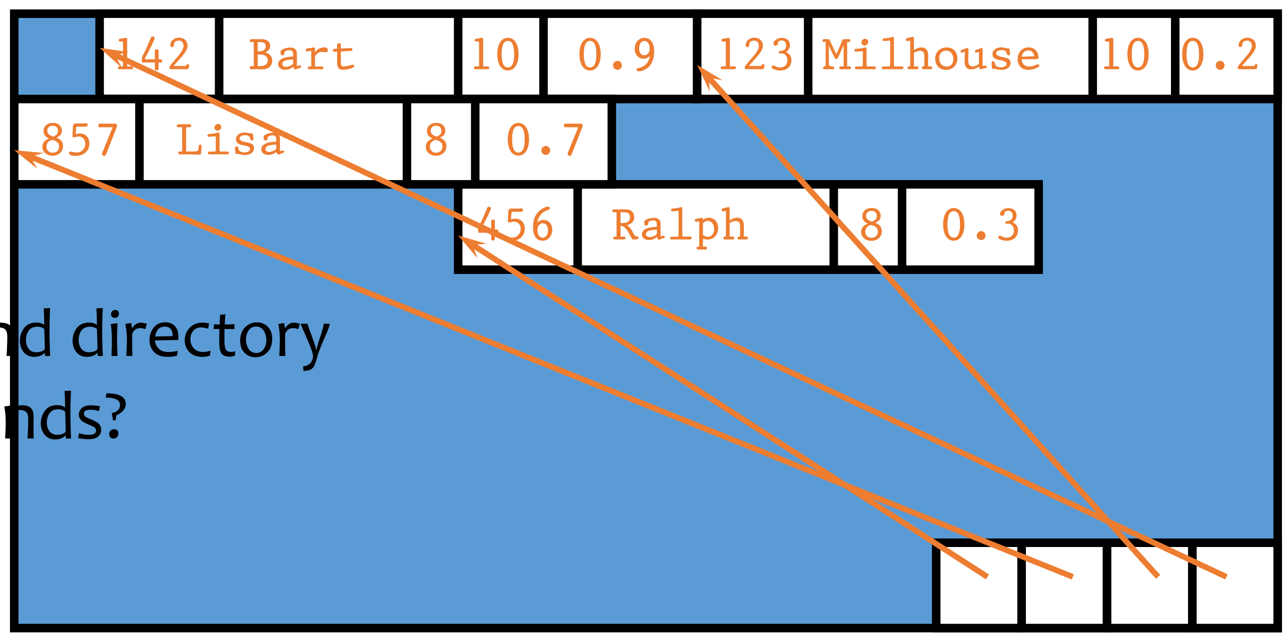
Block layout

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



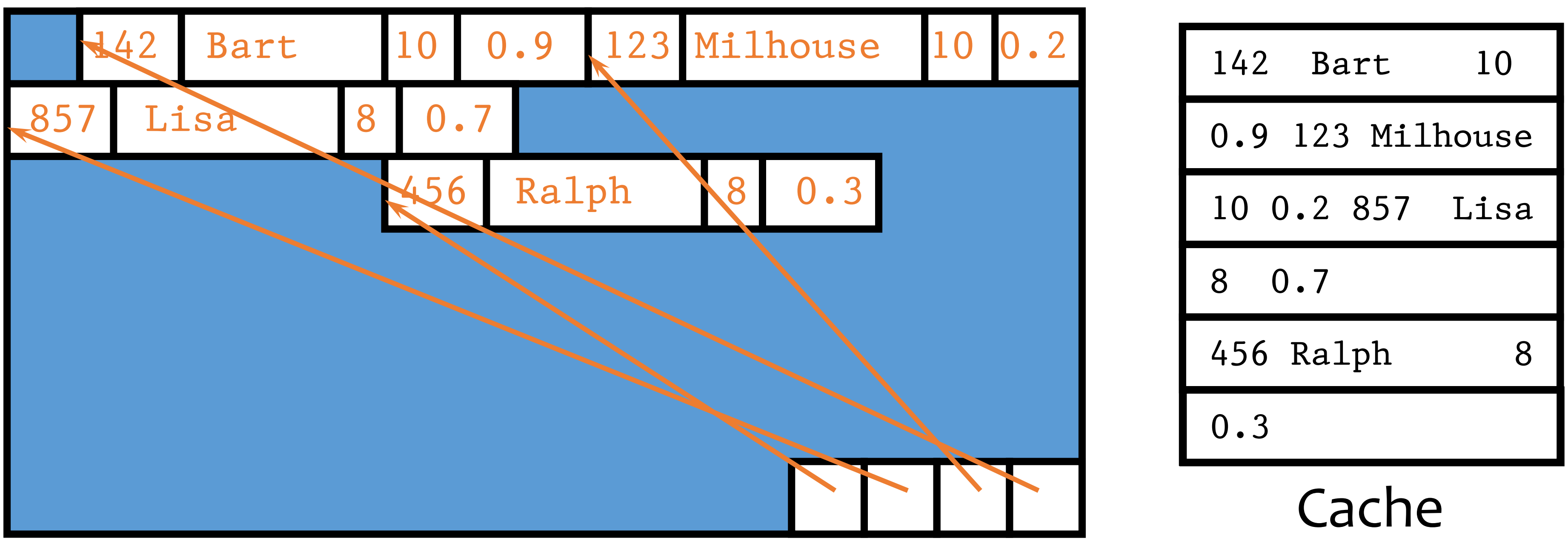
Why store data and directory at two different ends?

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

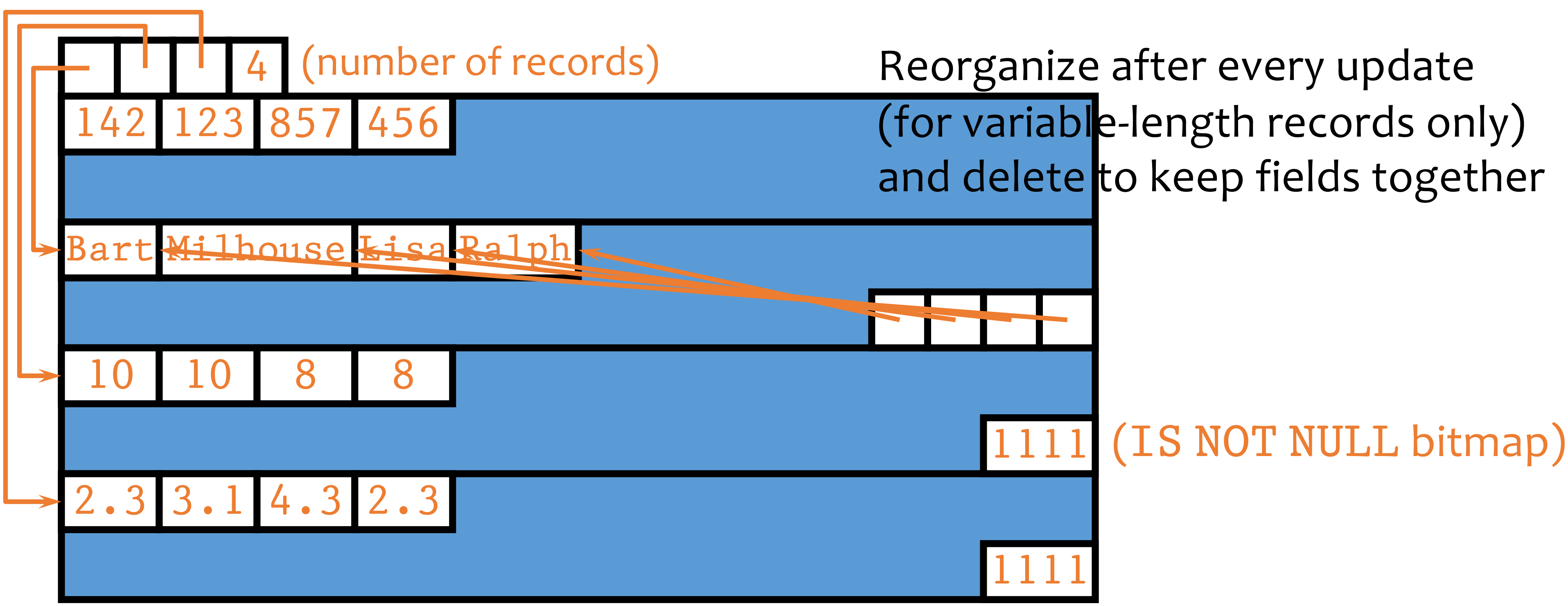
Cache behavior of NSM

- 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



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

- A table is horizontally partitioned into row groups (~512MB-1GB/row group); each group is stored consecutively
  - On a "block" of HDFS (Hadoop Distributed File System)
- A row group is vertically divided into column chunks, one per column
- Each column chunk is stored in pages (~8KB/page); each page can be compressed/encoded independently

☞Not designed for in-place updates though!

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