Physical Data Organization

Introduction to Database Management

CS348 Fall 2022

Announcements (Thu, Oct 27)

- Milestone 1
  - Feedback on Nov 2
- Midterm Exam
  - Fri, Nov 4, 4:30-6:00pm
  - **Cover Lectures 1-6** [instead of Lectures 1-10]
- Assignment 2
  - Due date [Thur, Oct 27, 11:59pm → Mon, Oct 31, 11:59pm]
  - Grade won't be released before midterm exam, but we will cover solutions related to Lectures 1-6 on the midterm review lecture on Thur, Nov 3.
- Final Exam
  - Tue, Dec 13, 7:30pm – 10:00pm

Where are we?

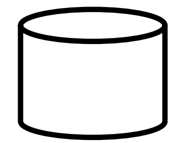
- Relational model (lecture 2)
- SQL (lectures 3-6)
- Database design (lectures 7-10)

Conceptual/Logical level

This lecture

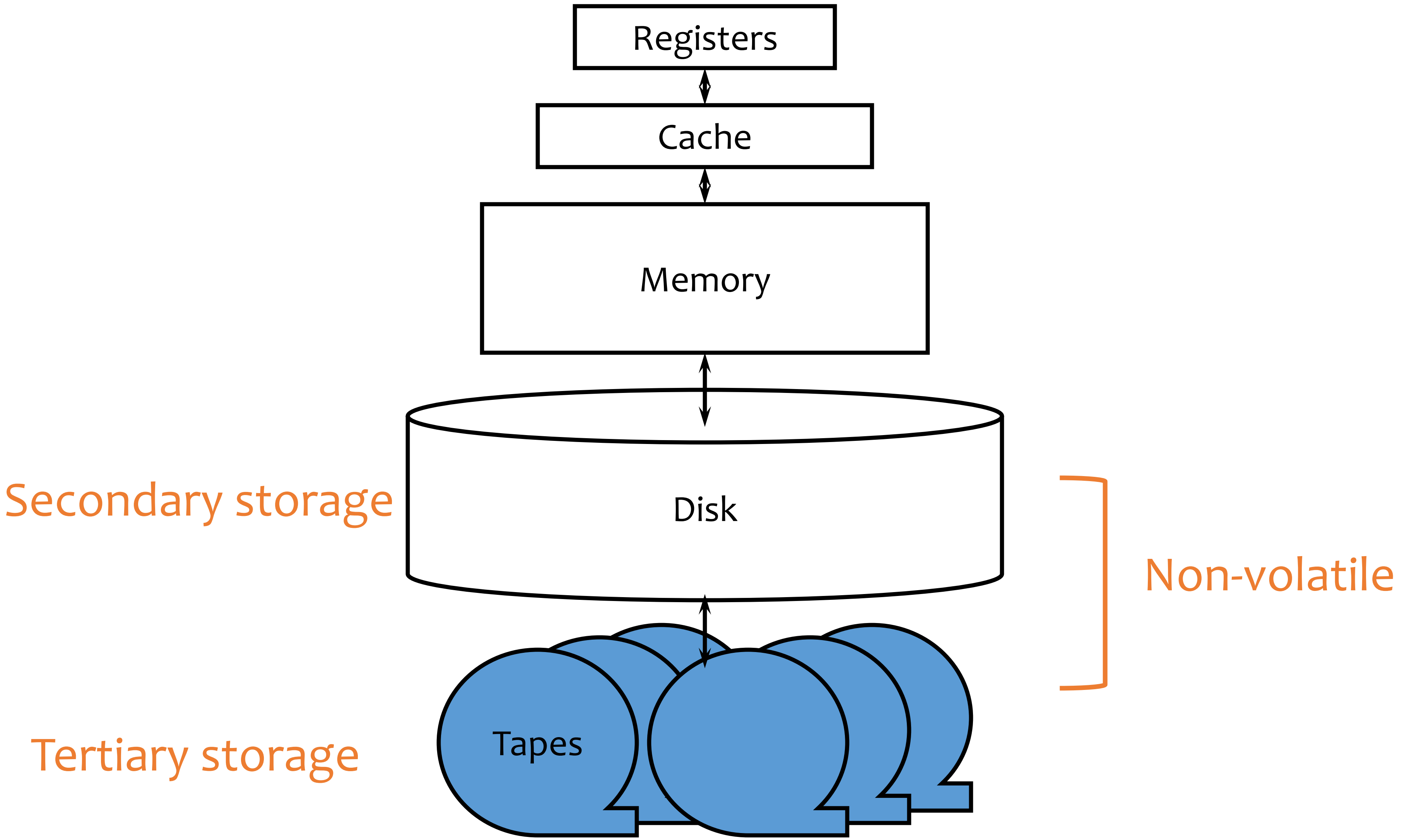
- Storage management & indexing (lectures 11-12)
- Query processing & optimizations (lectures 13-14)
- Transaction management (lectures 15-16)

Physical Data Organization

- 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



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.
Waterloo campus	10 min.
Toronto	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

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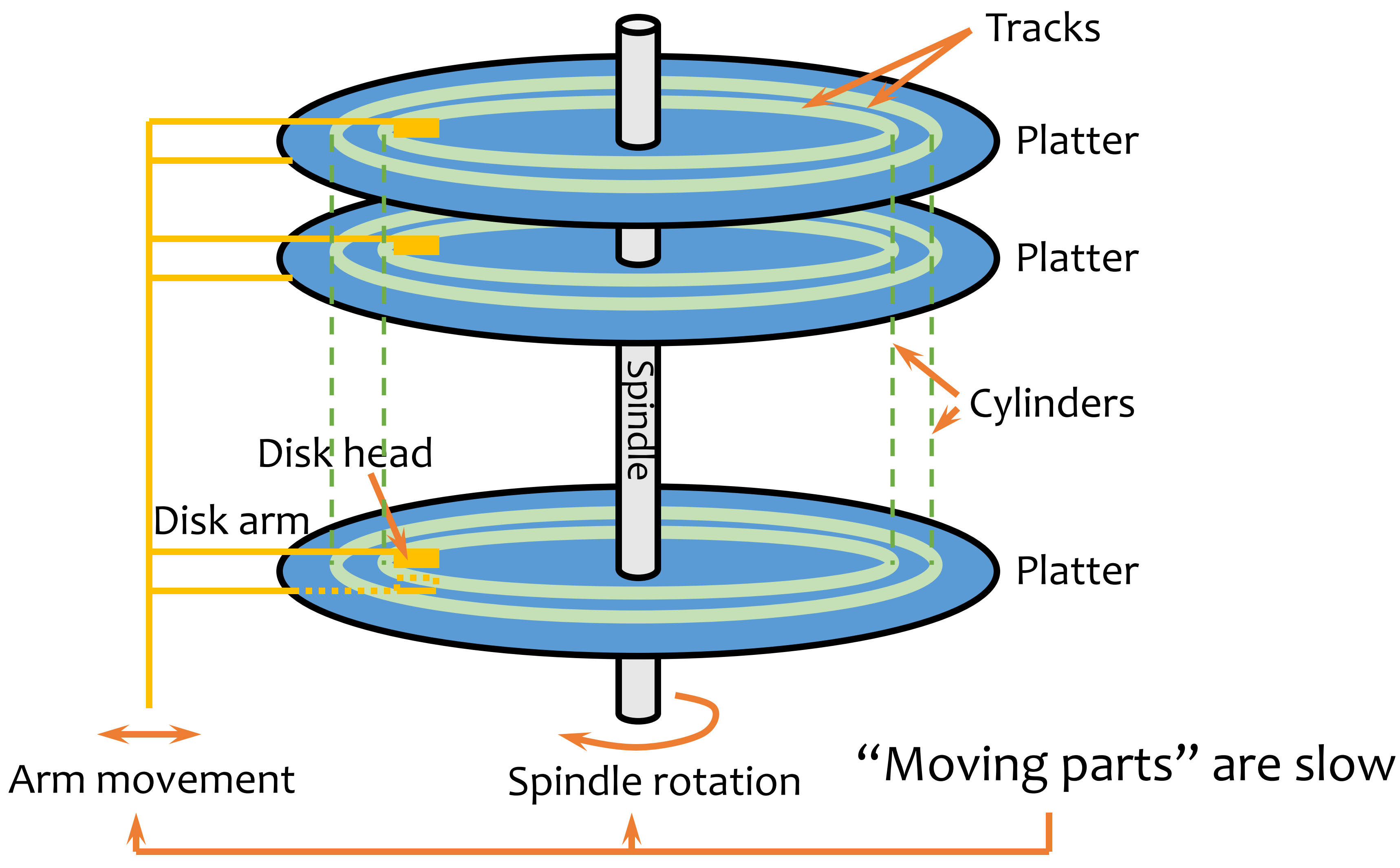
A typical hard drive

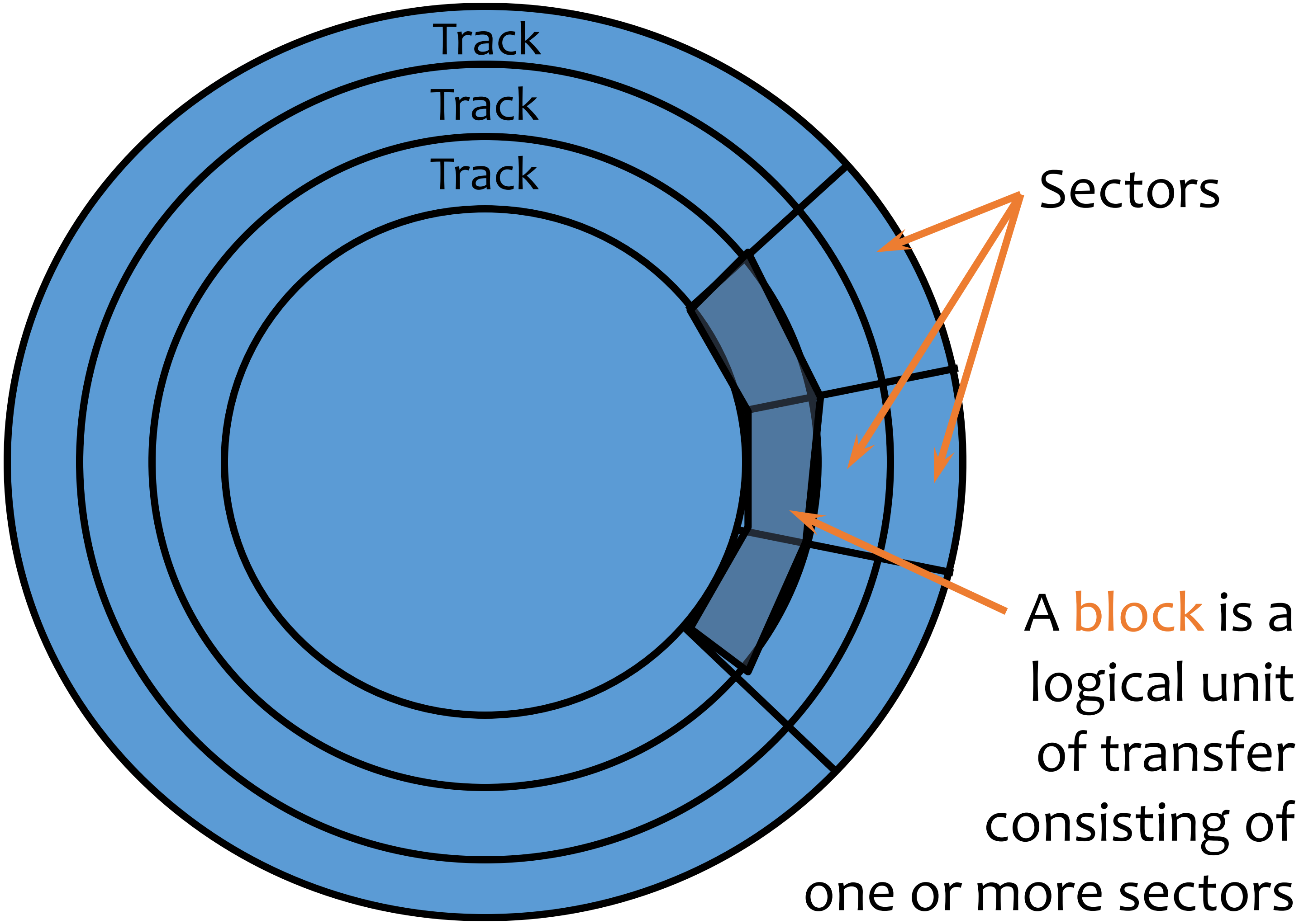
http://upload.wikimedia.org/wikipedia/commons/f/f8/Laptop-hard-drive-exposed.jpg

A typical hard drive



Top view

"Zoning": more sectors/data on outer tracks



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

$$\sum_{s=1}^{n}\sum_{e=1}^{n}|e-s|/n^2 \approx \mathrm{n}/3$$

$$\sum_{s=1}^{n}\sum_{e=s+1}^{s+n}|e-s|/n^2 \approx \mathrm{n}/2$$

- 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)?

No mechanical parts (flash-based)

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

What about SSD (solid-state drives)?

- 1-2 orders of magnitude faster random access than hard drives (under 0.1ms vs. several ms)
- 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 close
- Prefetching
- Parallel I/O: multiple disk heads
- Disk scheduling: e.g. “elevator” algorithm
- Track buffer: read/write one entire track at a time

Where are we?

- Storage hierarchy: I/O cost
- Disk: Sequential versus random accesses
- Record layout

Record layout

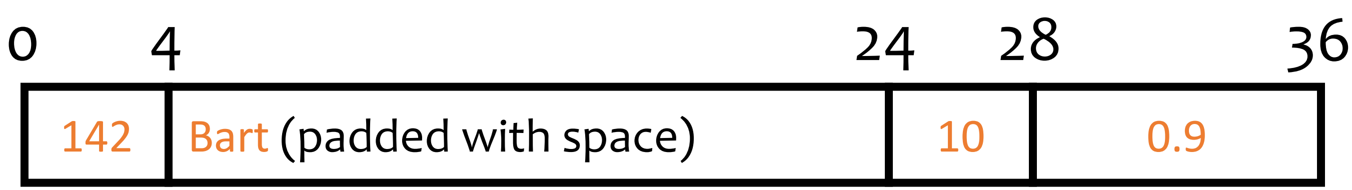
Record = row in a table

- 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

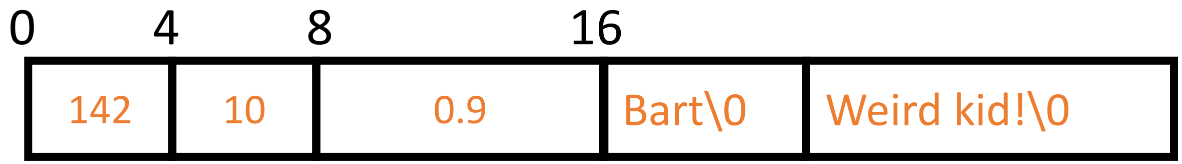
- Example: CREATE TABLE User(uid INT, name CHAR(20), age INT, pop FLOAT);



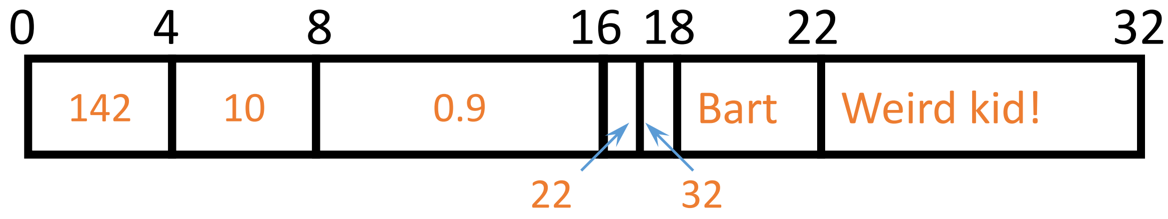
- What about NULL?
    - Add a bitmap at the beginning of the record

Variable-length records

- Example: CREATE TABLE User(uid INT,
  name VARCHAR(20), age INT, pop FLOAT,
  comment VARCHAR(100));
- Put all variable-length fields at the end (why?)
- Approach 1: use field delimiters (‘\0’ okay?)



- Approach 2: use an offset array



- 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));

- User 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*)

Where are we?

- Storage hierarchy: I/O cost
- Disk: Sequential versus random accesses
- Record layout: fixed length v.s. variable length
- Block layout

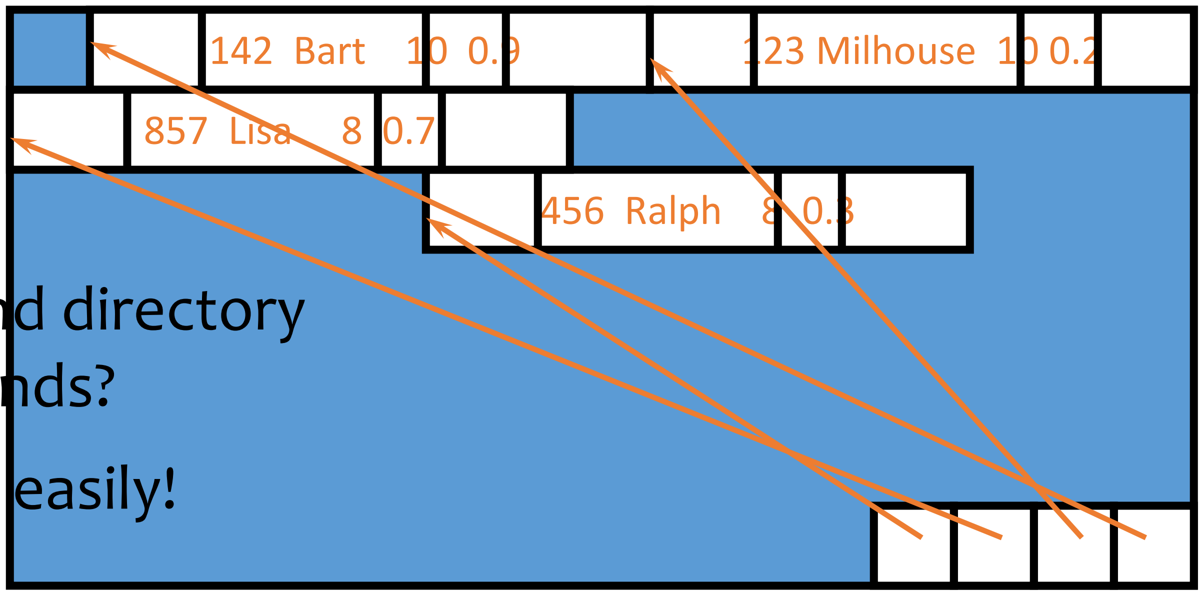
Block layout

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!

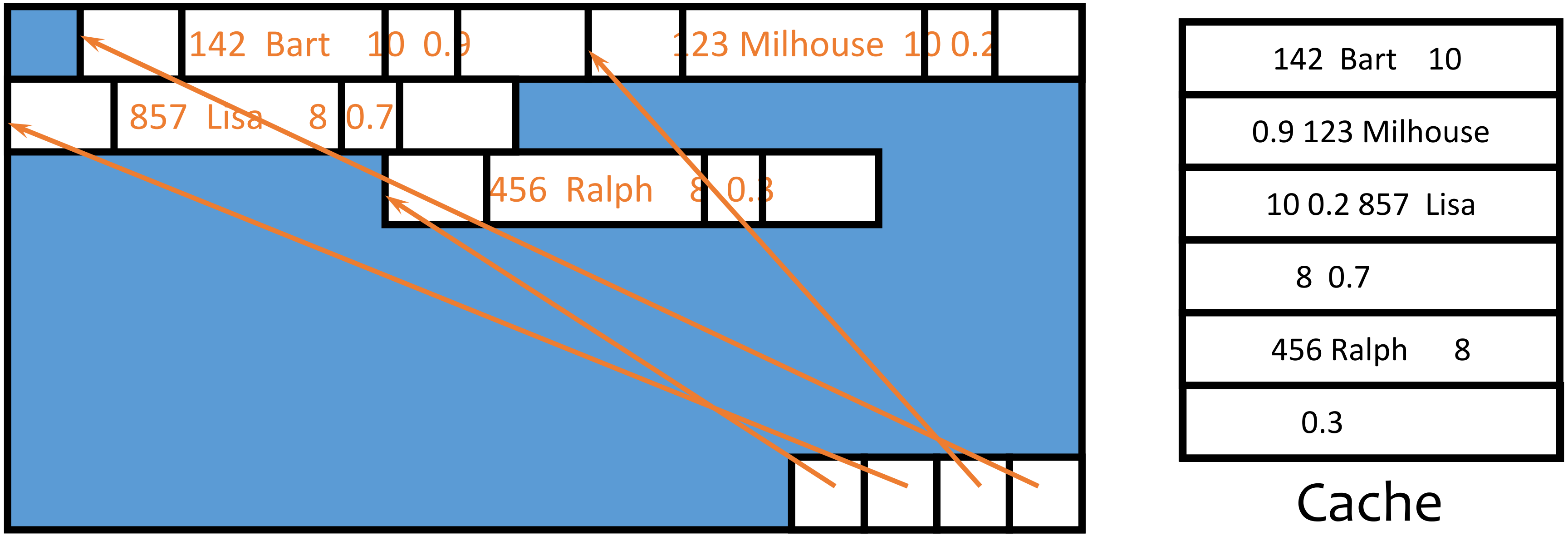
Options

- 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

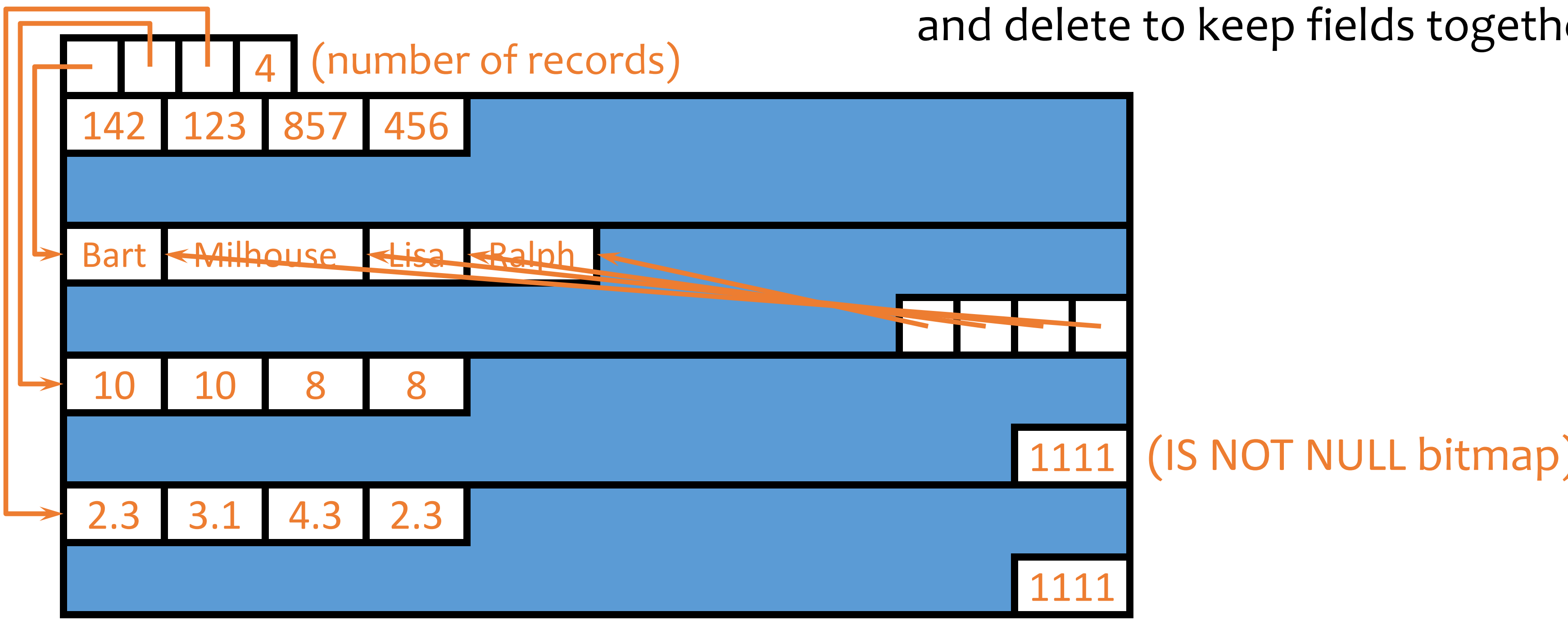
- Query: SELECT uid FROM User WHERE pop > 0.8;
- Assumptions: no index, and cache line size < record size
- Lots of cache misses



PAX

- Most queries only access a few columns
- Cluster values of the same columns in each block

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



Beyond block layout: column stores

- Store tables by columns instead of rows
  - Better cache performance
  - 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
- 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: I/O cost
- Disk: Sequential versus random accesses
- Record layout: fixed length v.s. variable length
- Block layout: NSM v.s. PAX
- Column stores: NSM transposed, beyond blocks