Physical Data Organization

CS348 Spring 2023

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Sections: **002 & 004 only**

Announcements

- Assignment 2
  - Due today!

- Milestone 1
  - Due Thursday, June 22nd

- Midterm Exam
  - Monday, June 26th, 7-8:50 PM
  - **Covers lectures 1-10** (except lecture 6)

Where are we?

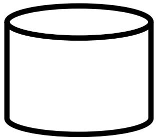
- Relational model (lecture 2)
- SQL (lectures 3-6)
- Database design (lectures 7-10)

Conceptual/Logical level

This lecture

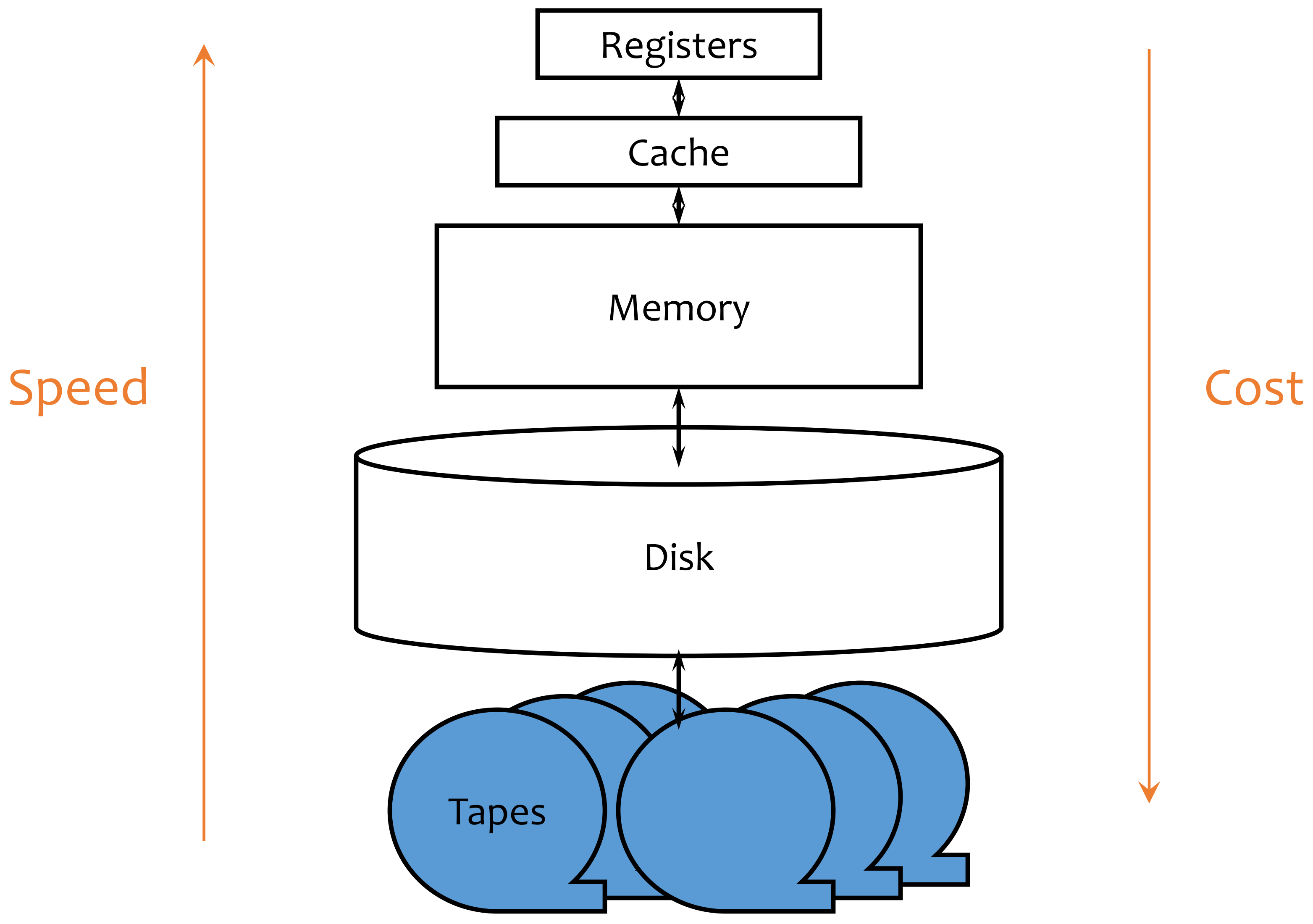
- Storage management & indexing (lectures 11-12)
- Query processing & optimizations (lectures 13-14)
- Transaction management (lectures 15-17)

Physical Data Organization

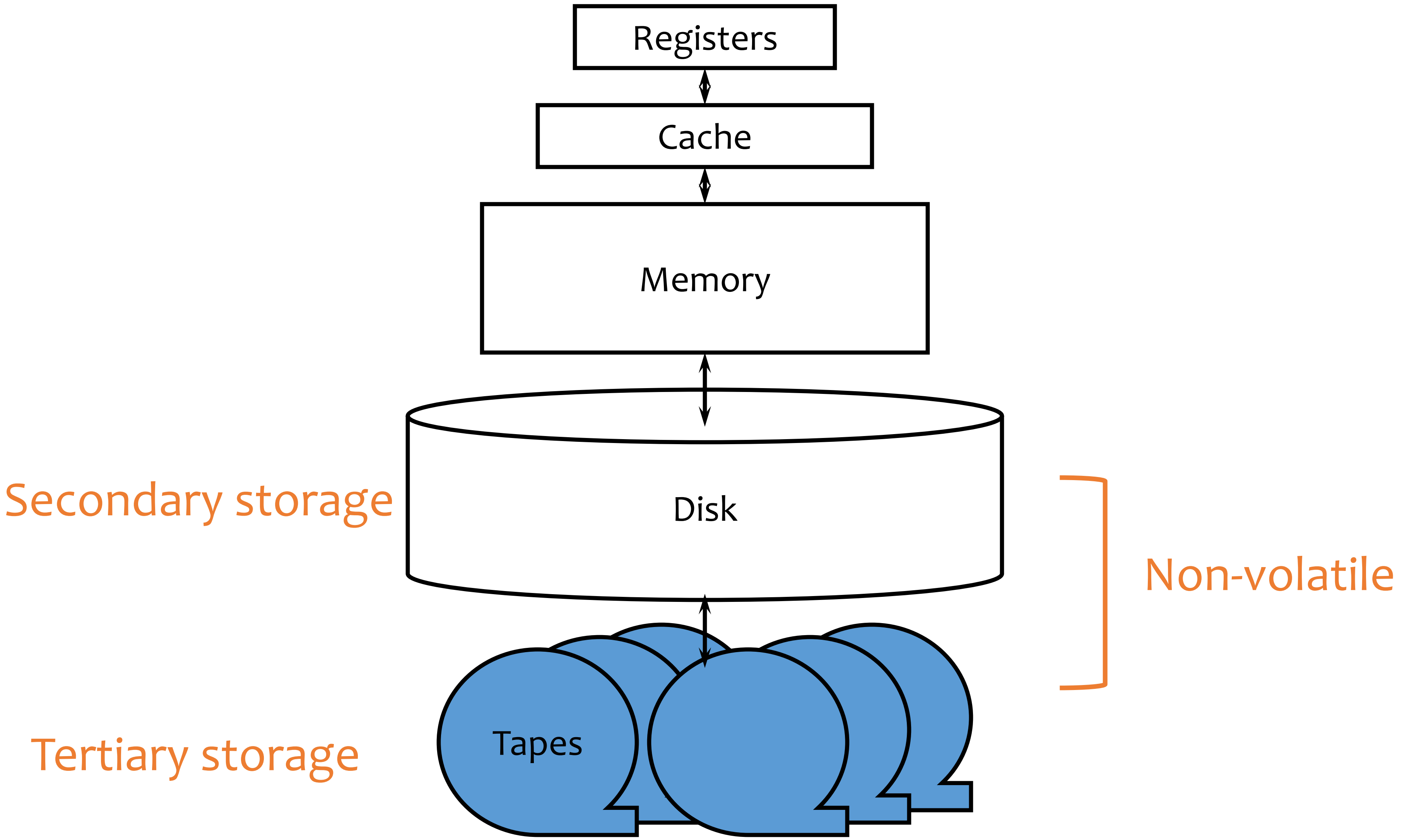
- It's all about disks!
  - That's why we always draw databases as 
  - And why one of the most important metric in database processing is the number of disk I/O's performed

- Storing data on a disk
  - Record layout
  - Block layout
  - Column stores

Storage hierarchy



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
This room	1-2 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
--------------------------
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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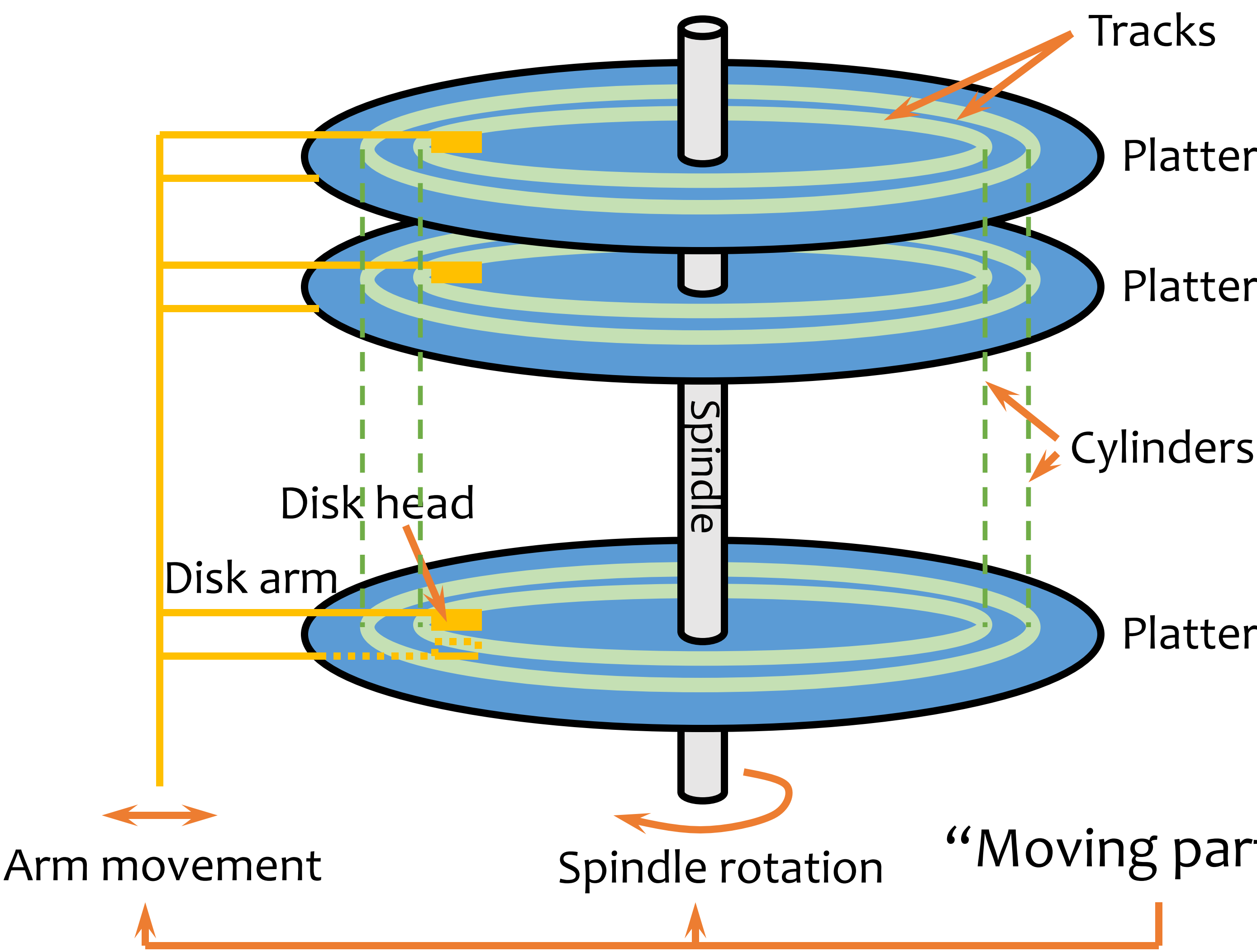
A typical hard drive

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

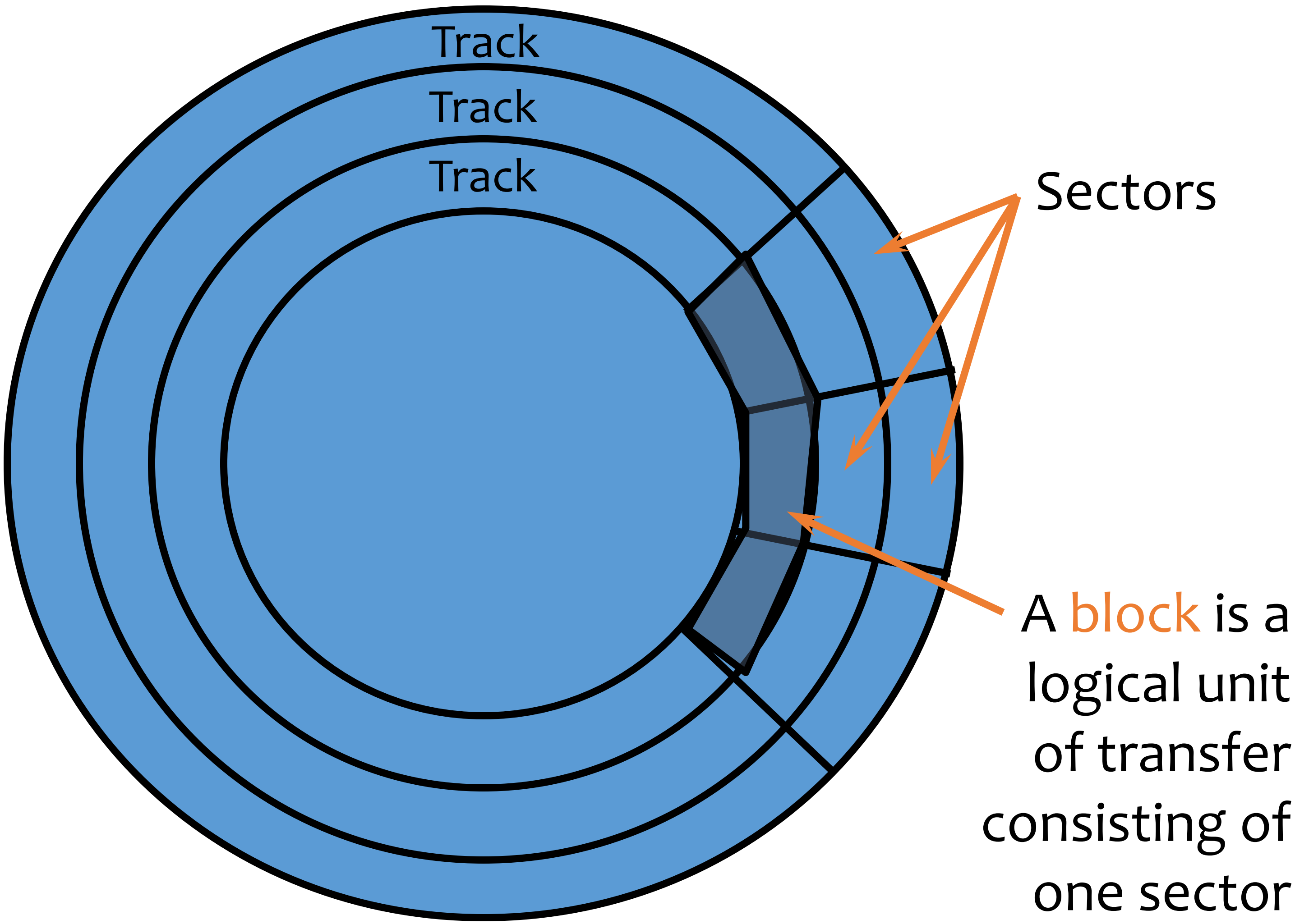
A typical hard drive



"Moving parts" are slow

Top view

"Zoning": more sectors/data on outer tracks



Disk access time

Disk access time: time from when a read or write request is issued to when data transfer begins

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)

- Total data access time = seek time + rotational delay + transfer time

Random disk access

→ Successive requests are for blocks that are randomly located on disk

Delay = Seek time + rotational delay + transfer time

- Average seek time
  - Seek the right cylinder for each access
  - “Typical” value: 5 ms

- Average rotational delay
  - Rotate for the right block for each access
  - “Typical” value: 4.2 ms (7200 RPM)

Sequential disk access

→ Successive requests are for successive block numbers, which are on the same track, or on adjacent tracks

Delay = Seek time + rotational delay + transfer time

- Seek time
  - 1 time delay: seek the right cylinder once
- Rotational delay
  - 1 time delay: rotate to the right block once
- 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

- 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

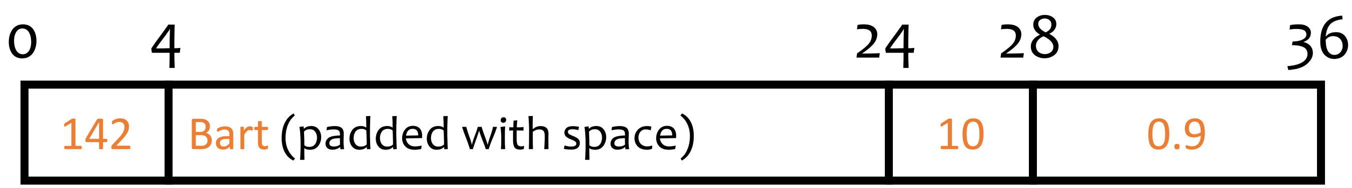
Record layout

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

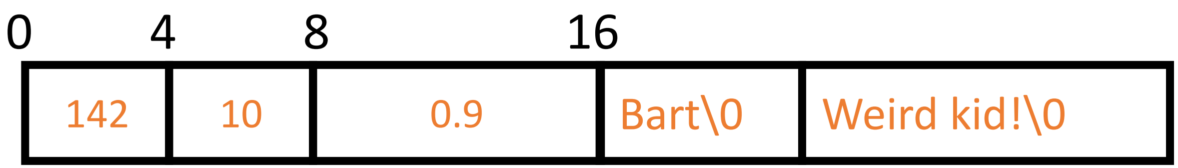
- All field lengths and offsets are constant
  - Computed from schema, stored in the system catalog
- Example: CREATE TABLE User(uid INT, name CHAR(20), age INT, pop FLOAT);



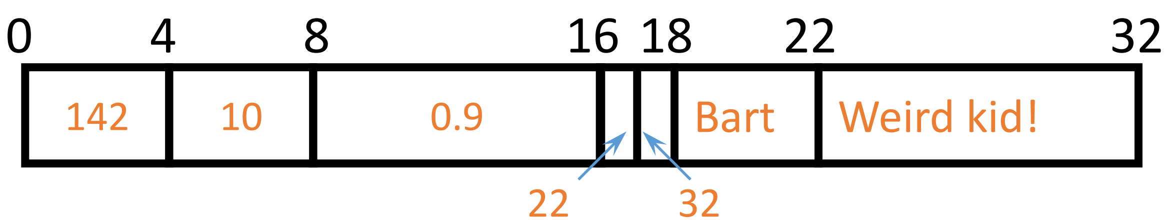
- If block size != 36, one row maybe split across multiple blocks or move to next block & leave the remaining space empty
- What about NULL?
  - Add a bitmap at the beginning of the record

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
- Approach 1: use field delimiters (‘\0’ okay?)



- Approach 2: use an offset array



- Scheme update is messy if it changes the length of a field

BLOB 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)
  - (*<u>uid</u>*, *name*, *age*, *pop*)
  - (*<u>uid</u>*, *picture*)

Where are we?

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

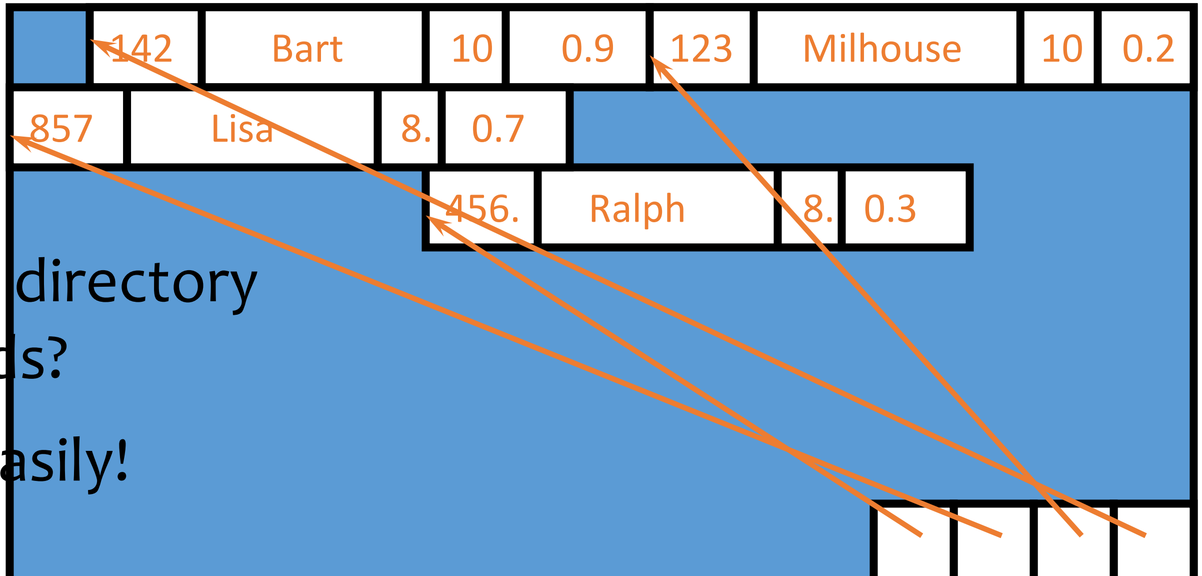
Block layout

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!

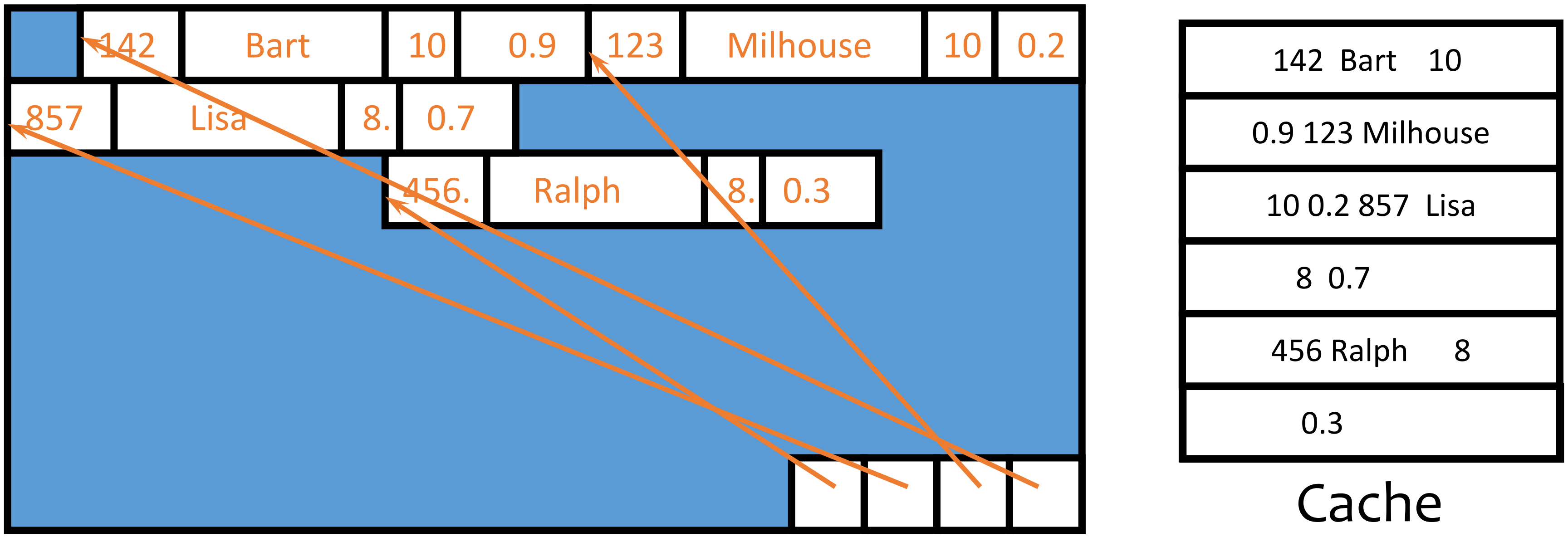
Options

- 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

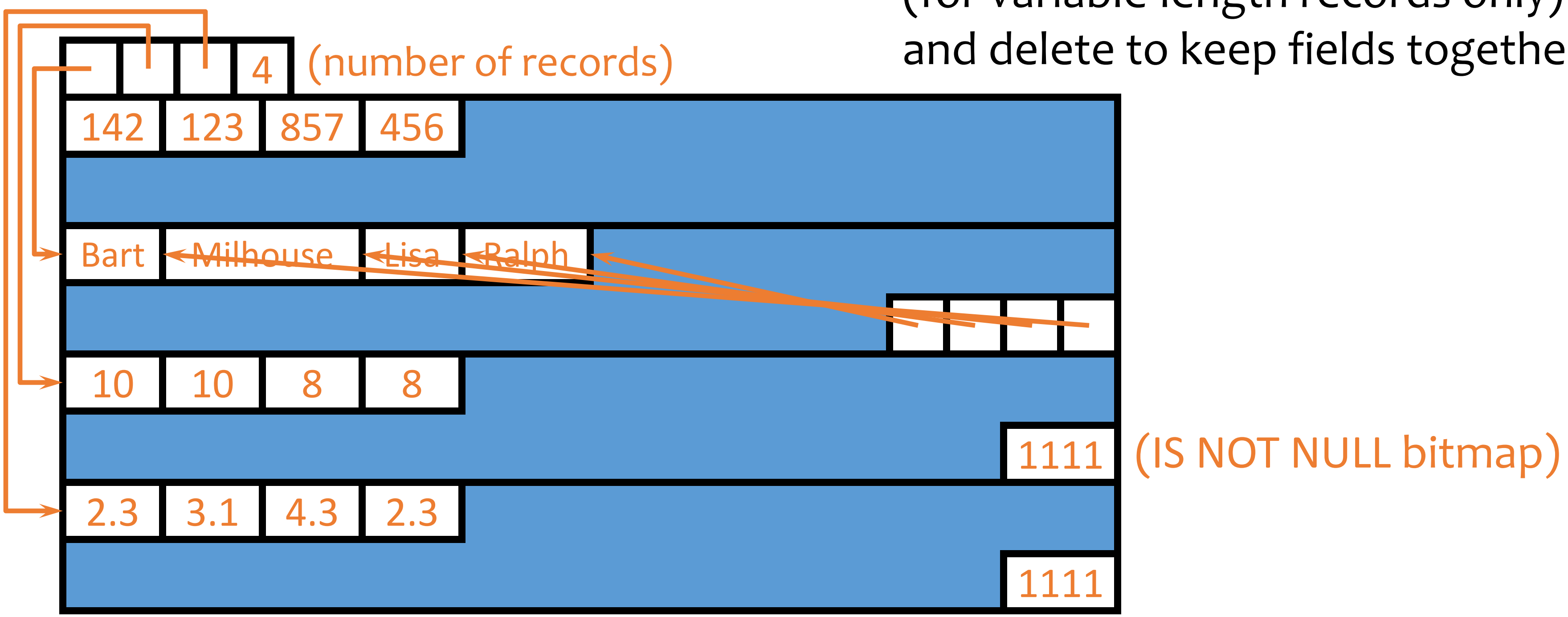
- Query: SELECT uid FROM User WHERE pop > 0.8;
- Assumptions: no index, and cache line size < record size
- Lots of cache misses



PAX

- Most queries only access a few columns
- Cluster values of the same columns in each block
- Better sequential reads for queries that read a single column

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

Column vs. row oriented db

User:

uid	name	pop	age
1	Bart	.6	12
2	Lisa	.9	10
3	Abe	.3	65

Row oriented

1	Bart	.6	12
2	Lisa	.9	10
3	Abe	.3	65

Column oriented

1	2	3
Bart	Lisa	Abe
.6	.9	.3
12	10	65

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