Database Systems

Storage Engine, Buffer, and Files

Based on slides by Feifei Li, University of Utah

Now Something Different

What is “Systems”?

A: Not Programming
Not programming big things..

Systems = Efficient and safe use of limited resources (e.g., disks)

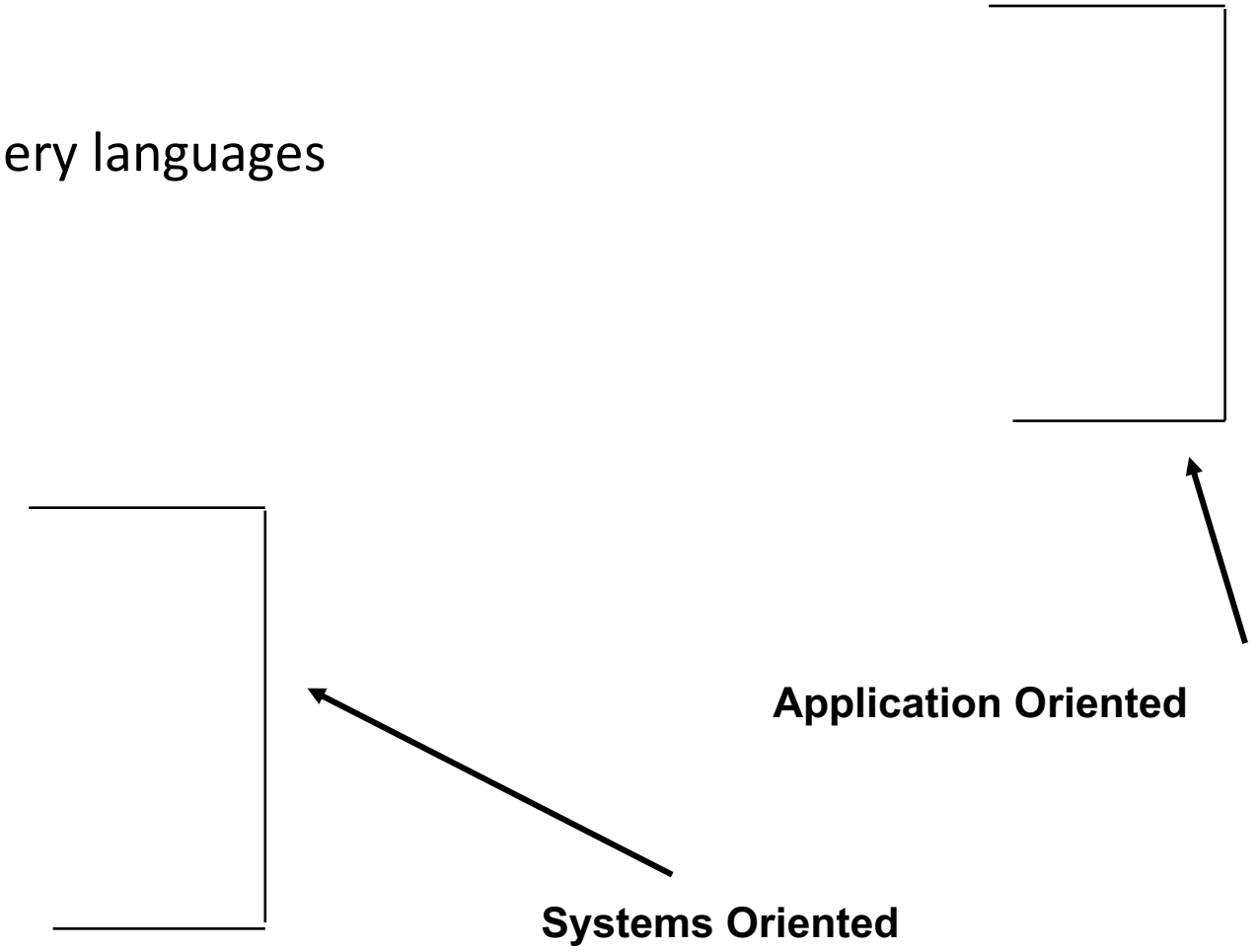
Efficient: resources should be shared, utilized as much as possible

Safe: sharing should not corrupt work of individual jobs

General Overview

- Relational model - SQL
  - Formal & commercial query languages
- Functional Dependencies
- Normalization

- Physical Design
- Indexing
- Query evaluation
- Query optimization
- ….



Data Organization

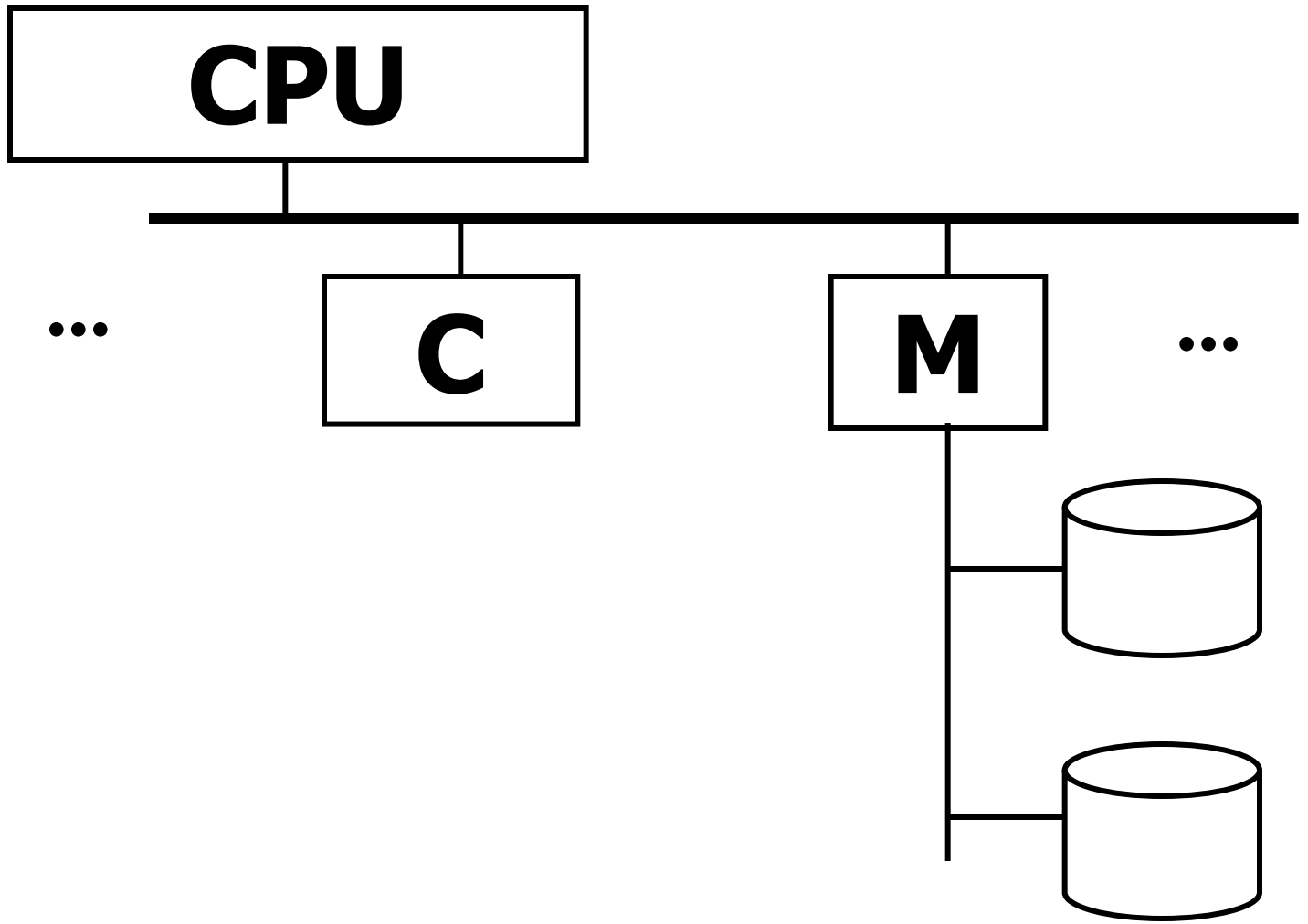
Storage Media

- Memory hierarchy
- Efficient/reliable transfer of data between disks and main memory
  - Hardware techniques (RAID disks)
  - Software techniques (Buffer management)

Storage strategies for relation-file organization

- Representation of tuples on disks
- Storage of tuples in pages, clustering.

Memory Hierarchy



Typical Computer

Secondary Storage

Storage Media: Players

- Cache – fastest and most costly form of storage; volatile; managed by the computer system hardware.
- Main memory:
  - fast access (10s to 100s of nanoseconds; 1 nanosecond = 10^{-9} seconds)
  - generally not big enough (or too expensive) to store the entire database
  - **Volatile** — contents of main memory are usually lost if a power failure or system crash occurs.
  - But… CPU operates only on data in main memory

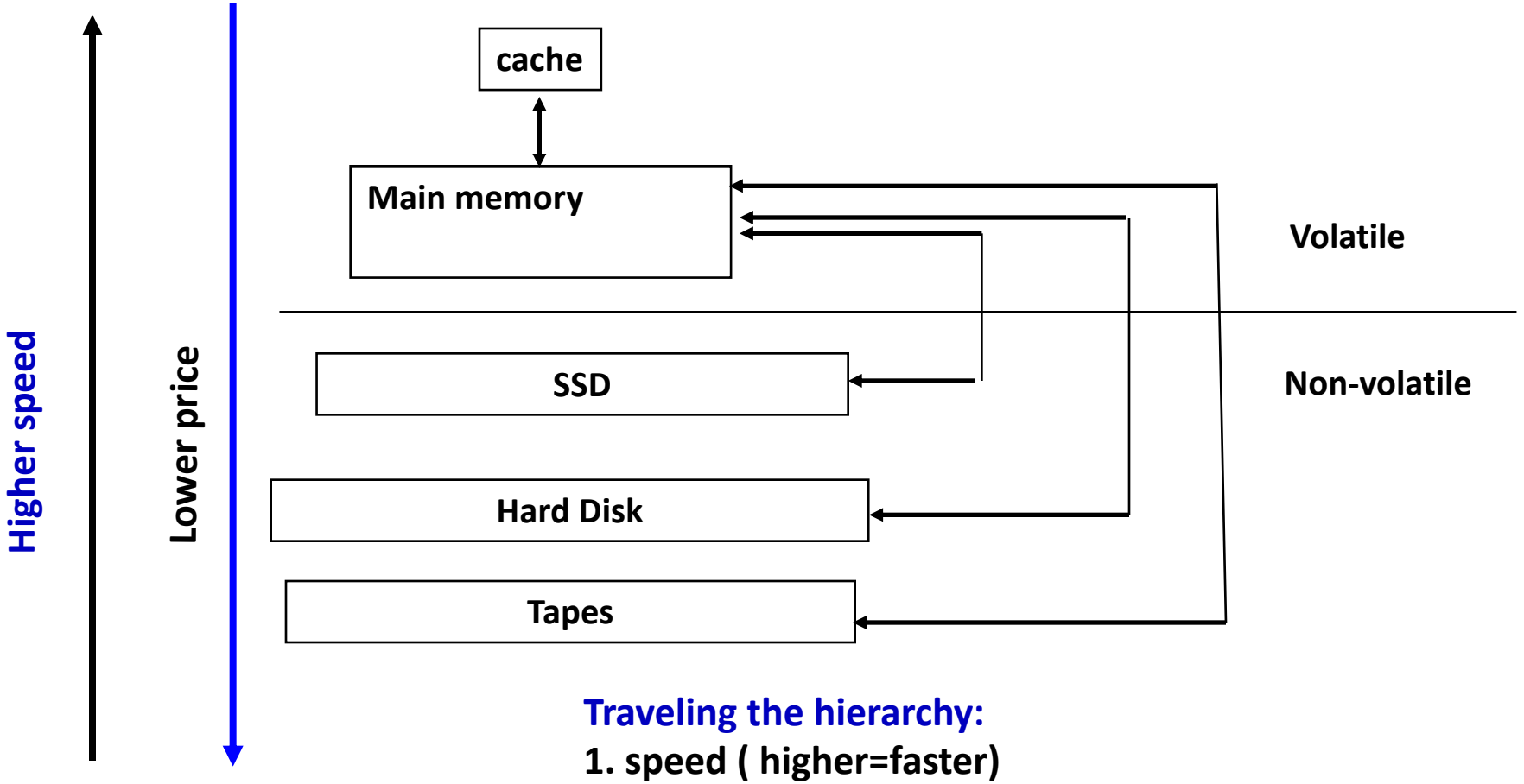
Storage Media: Players

- Disk
  - Primary medium for the long-term storage of data; typically stores entire database.
  - random-access – possible to read data on disk in any order, unlike magnetic tape
  - Non-volatile: data survive a power failure or a system crash, disk failure less likely than them
  - Sequential access vs. Random access (more on this later)

Storage Media: Players

- Solid State Drive (aka flash disk)
  - non-volatile
  - Writes are expensive (Erasure block)
  - Random reads are almost as efficient as sequential reads
  - More expensive than disks ($/byte)
- Tapes
  - Sequential access (very slow)
  - Cheap, high capacity

Memory Hierarchy



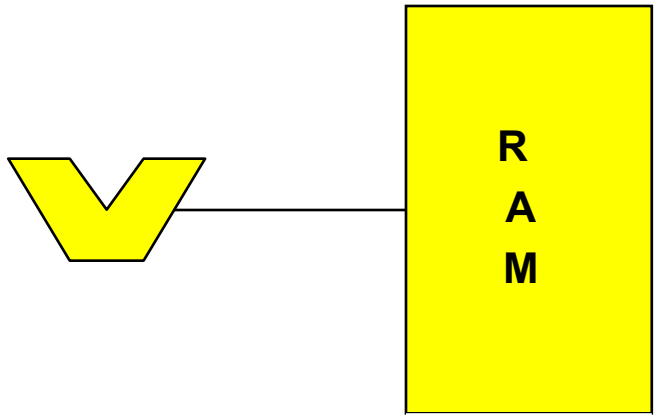
Traveling the hierarchy:

1. speed (higher=faster)
2. cost (lower=cheaper)
3. volatility (between MM and Disk)
4. Data transfer (Main memory the “hub”)
5. Storage classes (P=primary, S=secondary, T=tertiary)

Memory Hierarchy

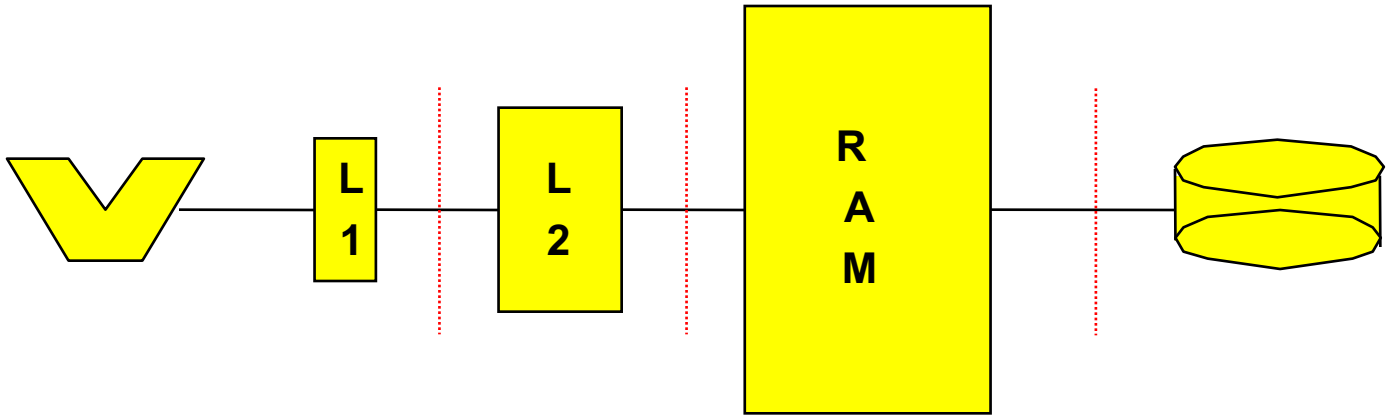
- Data transfers
  - cache – mm : OS/hardware controlled (main memory DBMS starts controlling this as well)
  - mm – disk : <- reads, -> writes controlled by DBMS
  - mm – SSD
  - disk – SSD
  - disk – Tapes

Random Access Machine Model



- Constant-cost for accessing a memory address anywhere from the memory
- Standard theoretical model of computation:
  - Infinite memory
  - Uniform access cost
- Simple model crucial for success of computer industry

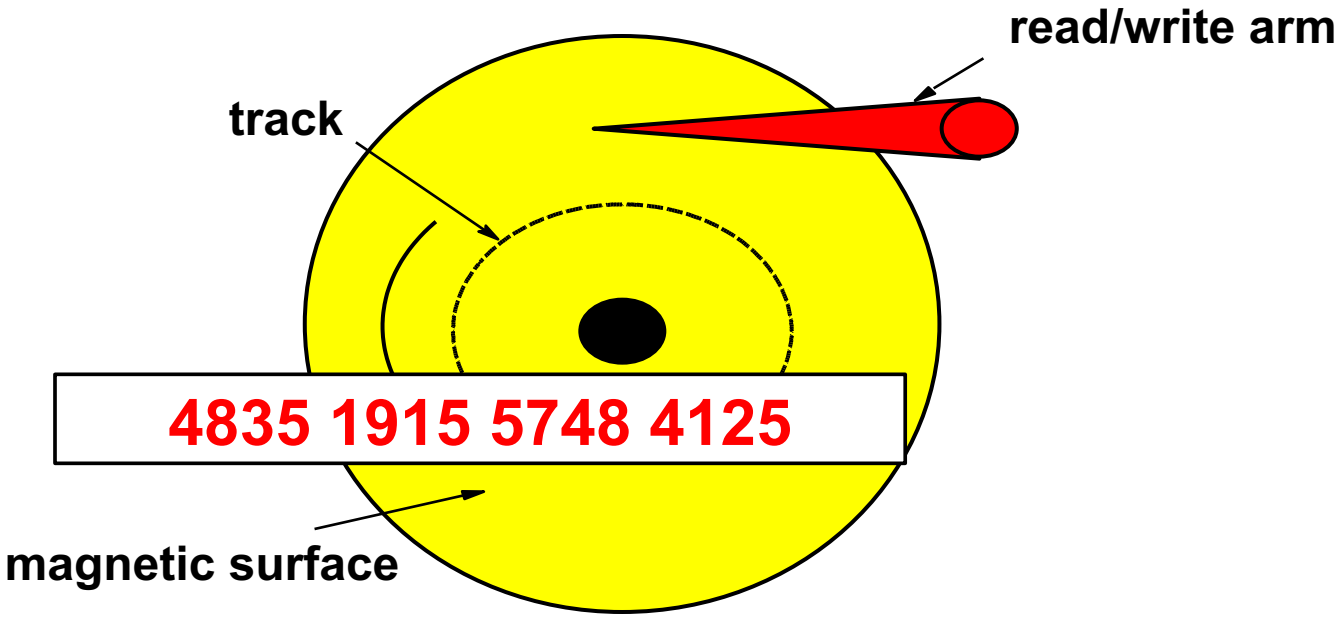
Hierarchical Memory



- Modern machines have complicated memory hierarchy
  - Levels get larger and slower further away from CPU
  - Data moved between levels using large blocks

Slow I/O (Input/Output)

- **Disk access is 10^6 times slower than main memory access**



  - Disk systems try to amortize large access time transferring large contiguous blocks of data (8-16Kbytes)
  - Important to store/access data to take advantage of blocks (locality)

Main memory -- Disk Data Transfers

- Concerns:
  - Efficiency (speed)

    can be improved by...

    a. improving raw data transfer speed

    b. avoiding untimely data transfer

    c. avoiding unnecessary data transfer
- Safety (reliability, availability)

  can be improved by...

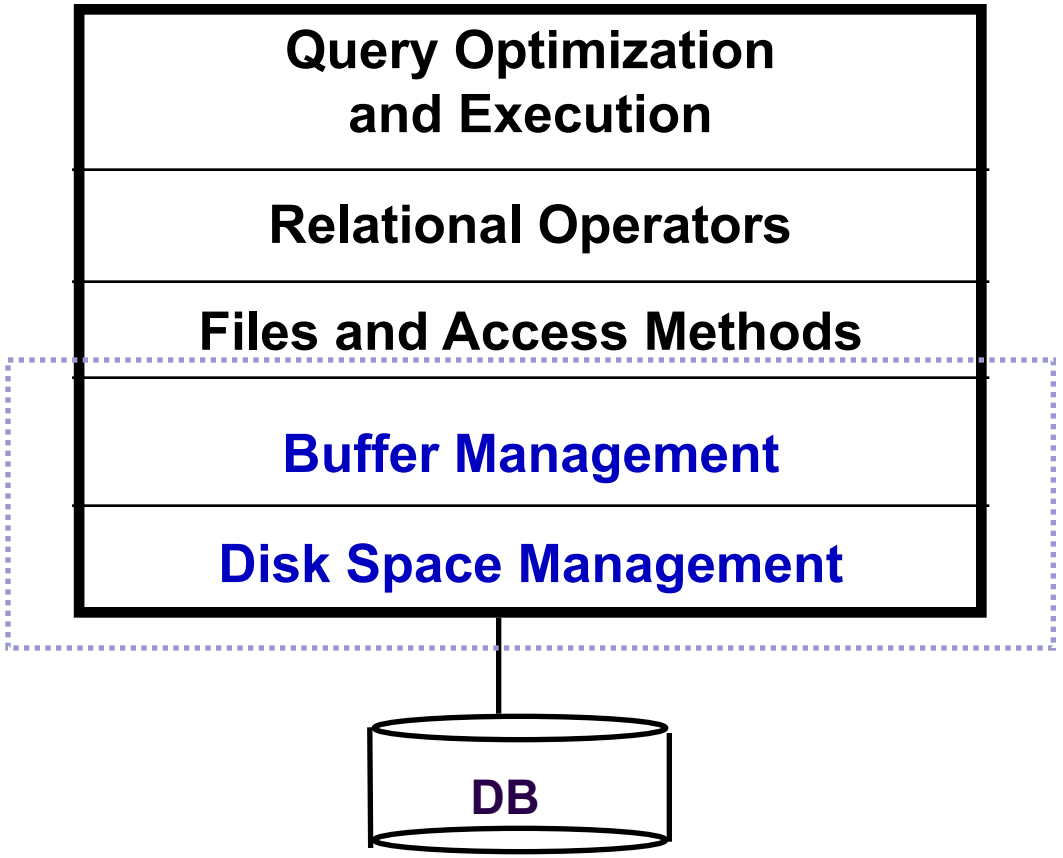
  a. storing data redundantly

Main memory -- Disk Data Transfers

- Achieving efficiency:
  - Improve Raw data Transfer speed
    - Faster Disks
    - Parallelization (RAID)
  - Avoiding untimely data Transfers
    - Disk scheduling
    - Batching
  - Avoiding unnecessary data xfers
    - Buffer Management
    - Good file organization

Disks, Memory, and Files

The BIG picture…



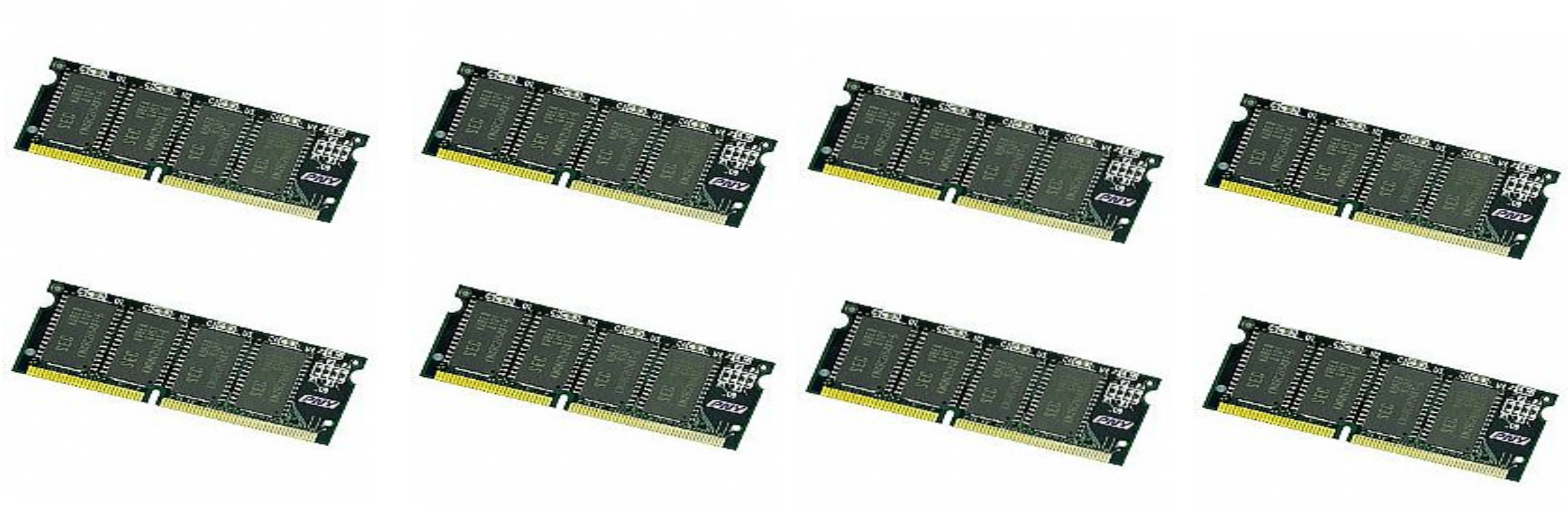
Disks and Files

- DBMS stores information on disks.
  - In an electronic world, disks are a mechanical anachronism!
- This has major implications for DBMS design!
  - READ: transfer data from disk to main memory (RAM).
  - WRITE: transfer data from RAM to disk.
  - Both are high-cost operations, relative to in-memory operations, so must be planned carefully!

Why Not Store Everything in Main Memory?

- *Costs too much…*
- *Main memory is volatile*. We want data to be saved between runs. (Obviously!)
- Typical storage hierarchy:
  - Main memory (RAM) for currently used data.
  - Disk for the main database (secondary storage).
  - Tapes for archiving older versions of the data (tertiary storage)

Solution 1: Buy More Memory

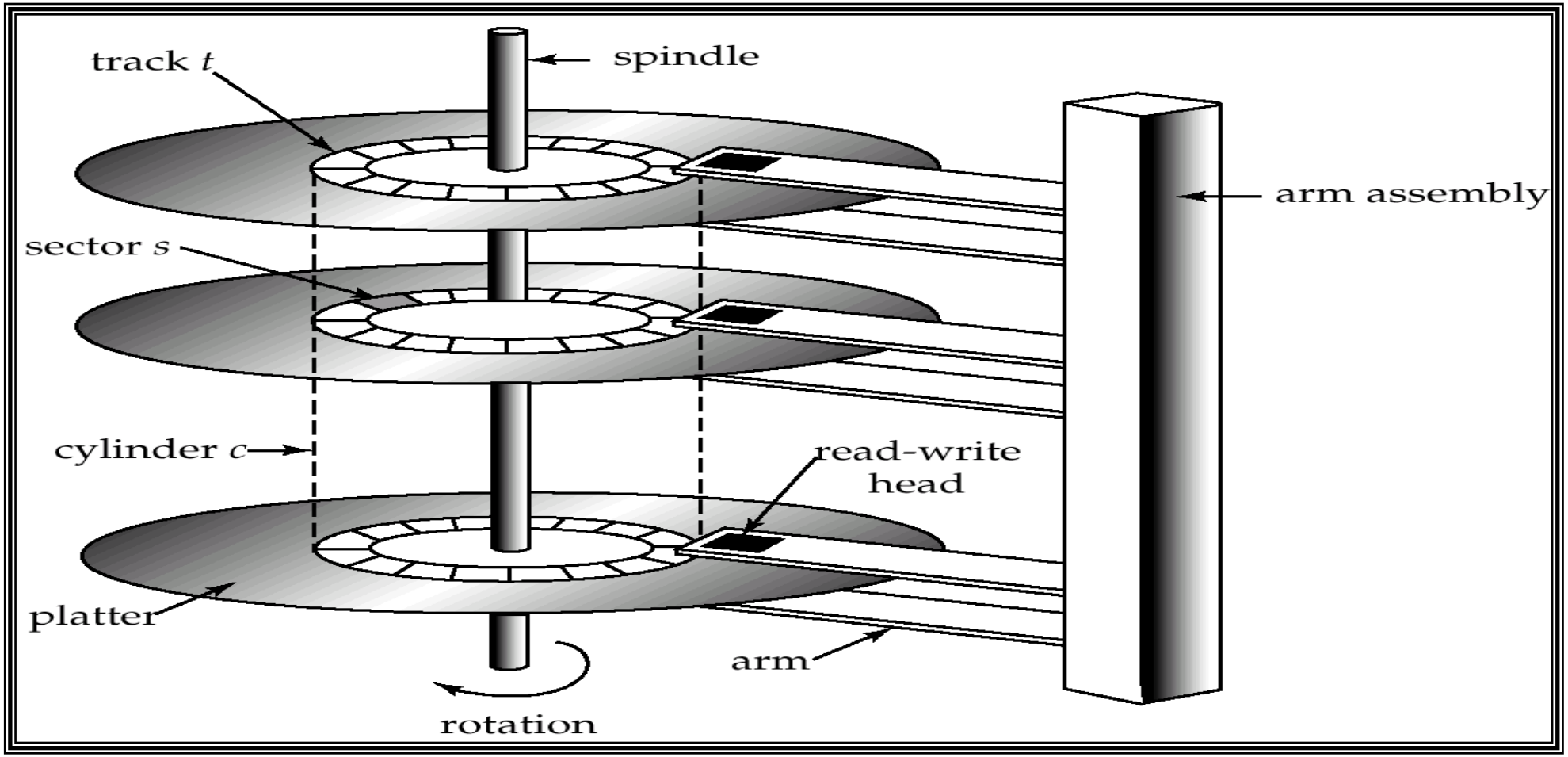


- Expensive
- (Probably) not scalable
  - Growth rate of data is higher than the growth of memory

Disks

- Secondary storage device of choice.
- Main advantage over tapes: *random access* vs. *sequential*.
- Data is stored and retrieved in units called *disk blocks* or *pages*.
- Unlike RAM, time to retrieve a disk block varies depending upon location on disk.
  - Therefore, relative placement of blocks on disk has major impact on DBMS performance!

Hard Disk Mechanism



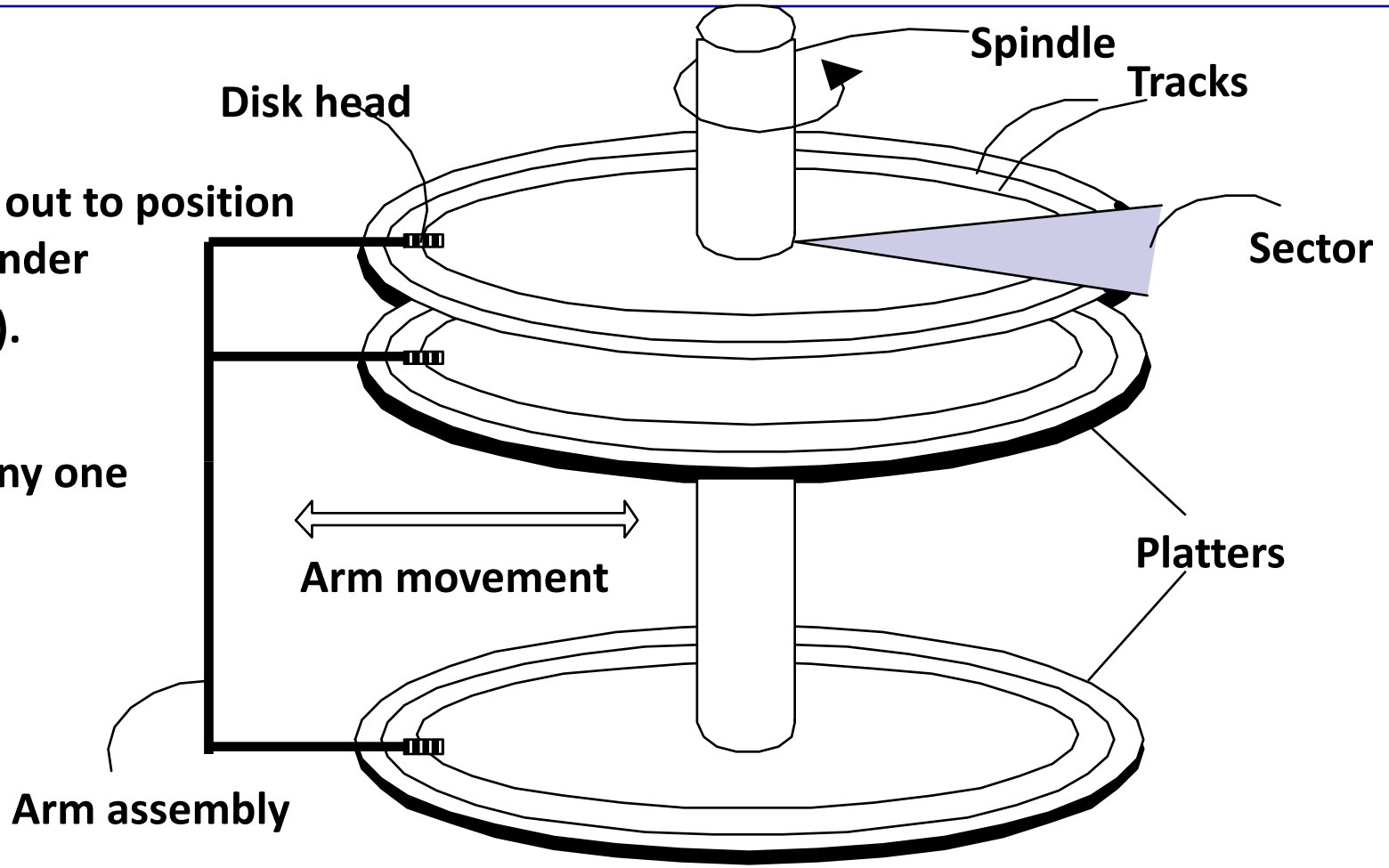
Components of a Disk

- The platters spin (say, 120 rps).

- The arm assembly is moved in or out to position a head on a desired track. Tracks under heads make a *cylinder* (imaginary!).

- Only one head reads/writes at any one time.

  - *Block size* is a multiple of *sector size* (which is fixed).



Components of a Disk

- Read-write head
  - Positioned very close to the platter surface (almost touching it)
- Surface of platter divided into circular tracks
- Each track is divided into sectors.
  - A sector is the smallest unit of data that can be read or written.
- To read/write a sector
  - disk arm swings to position head on right track
  - platter spins continually; data is read/written as sector passes under head
- Block: a sequence of sectors
- Cylinder *i* consists of i^{th} track of all the platters

Components of a Disk

"Typical" Values

Diameter:	1 inch → 15 inches
Cylinders:	100 → 2000
Surfaces:	1 or 2
(Tracks/cyl):	a few → 30
Sector Size:	512B → 50K
Capacity:	100s GB → a few TB

Accessing a Disk Page

- Time to access (read/write) a disk block:
  - *seek time* (moving arms to position disk head on track)
  - *rotational delay* (waiting for block to rotate under head)
  - *transfer time* (actually moving data to/from disk surface)
- Seek time and rotational delay dominate.
  - Seek time varies between about 0.3 and 10msec
  - Rotational delay varies from 0 to 6msec
  - Transfer rate around .008msec per 8K block
- Key to lower I/O cost:
  - reduce seek/rotation delays! Hardware vs. software solutions?

Example

ST3120022A : Barracuda 7200.7

Capacity:120 GB

Interface: Ultra ATA/100

RPM: 7200 RPM (Rotation per Minute)

Seek time: 8.5 ms avg

Latency time?:

7200/60 = 120 rotations/sec

1 rotation in 8.3 ms => So, Av. Latency = 4.16 ms

Arranging Pages on Disk

- `*Next*' block concept:
  - blocks on same track, followed by
  - blocks on same cylinder, followed by
  - blocks on adjacent cylinder
- Blocks in a file should be arranged sequentially on disk (by `next'), to minimize seek and rotational delay.
- For a sequential scan, *pre-fetching* several pages at a time is a big win!

Random vs sequential i/o

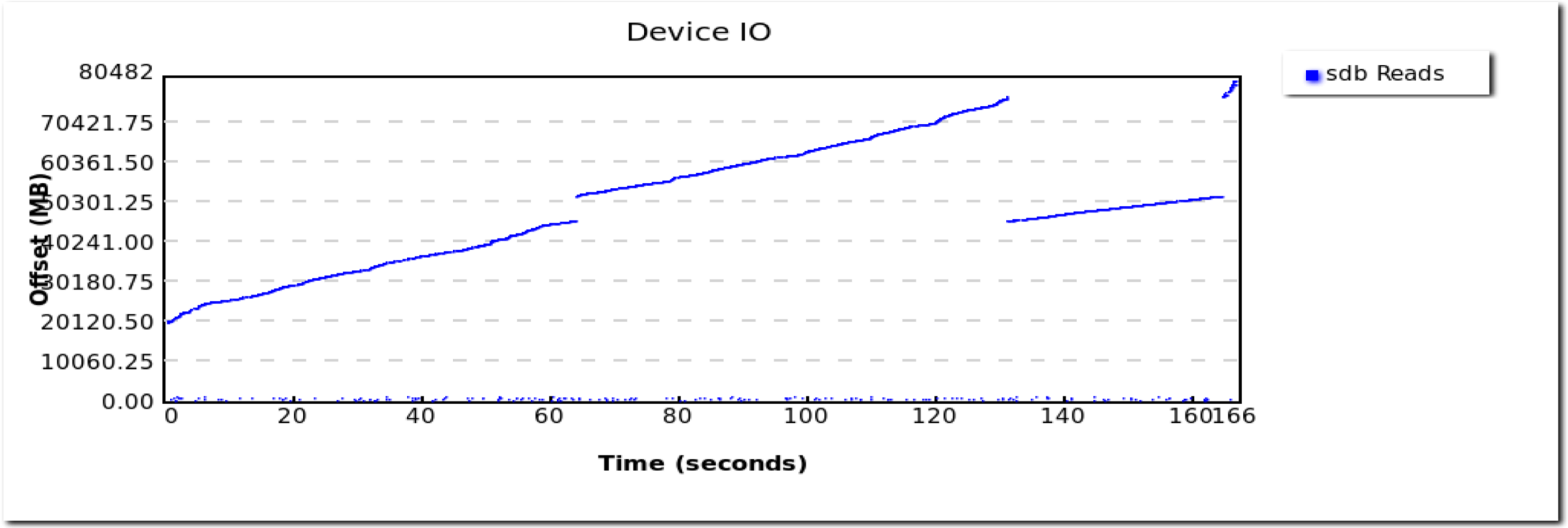
- Ex: 1 KB Block
  - Random I/O: ~ 15 ms.
  - Sequential I/O: ~ 1 ms.

Rule of Thumb

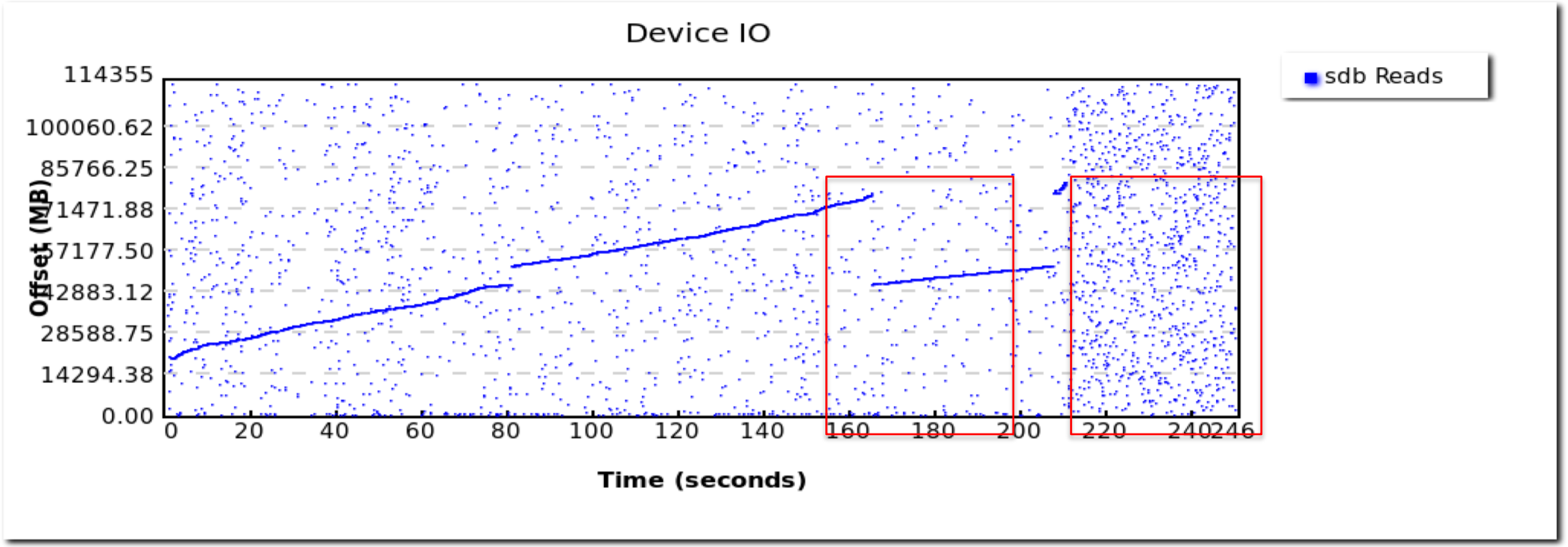
Random I/O: Expensive

Sequential I/O: Much less ~10-20 times

iotrace of sdb for dd-alone (dd is a sequential workload)

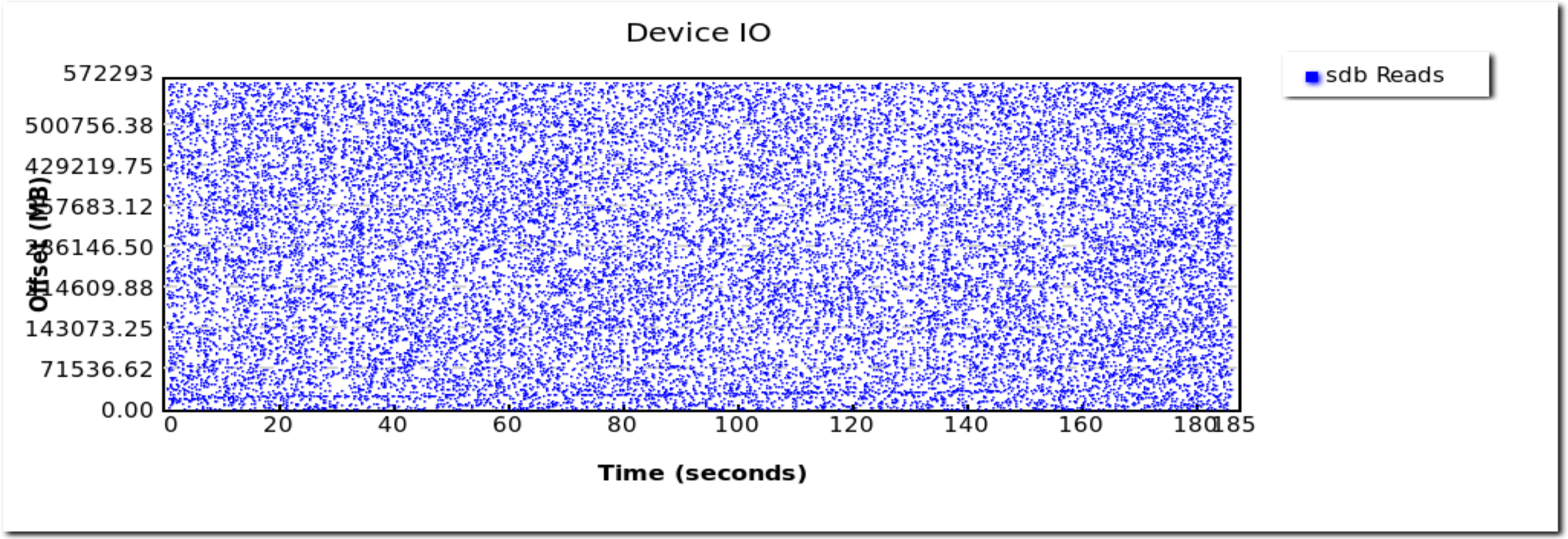


iotrace of sdb for dd-rr (rr is a random read workload)



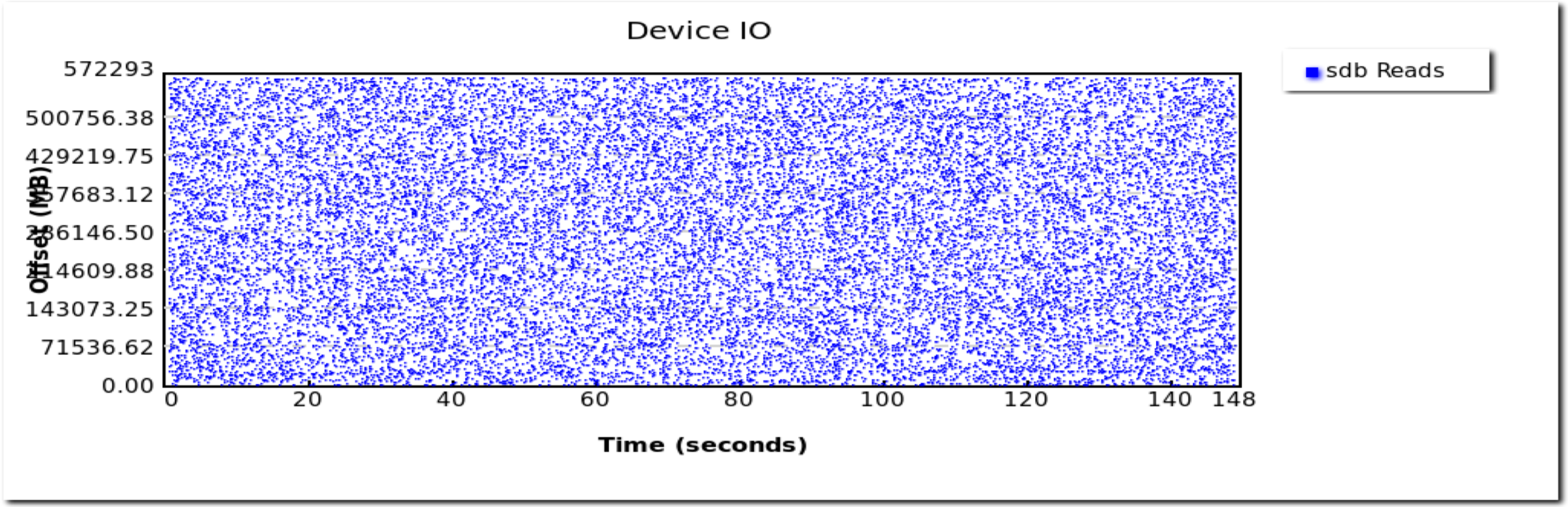
Fewer requests from RR are served when dd was running.

iotrace of sdb for dd-2rr

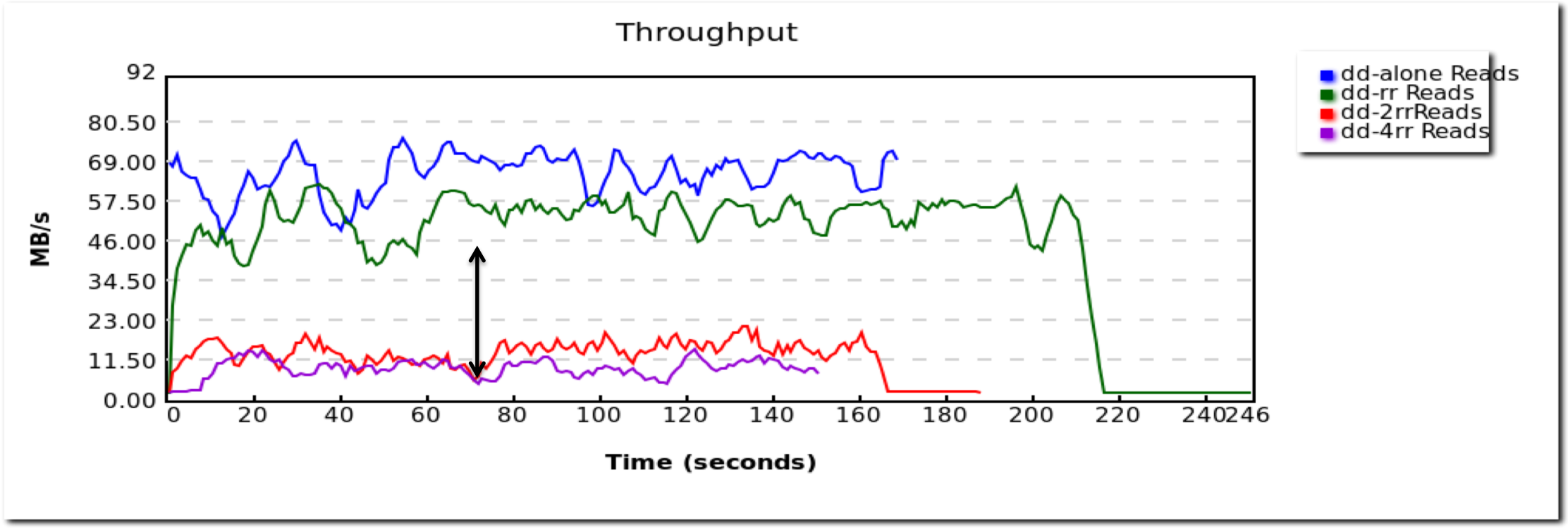


Sequential IOs become almost random!!!

iotrace of sdb for dd-4rr



Bandwidth of sdb



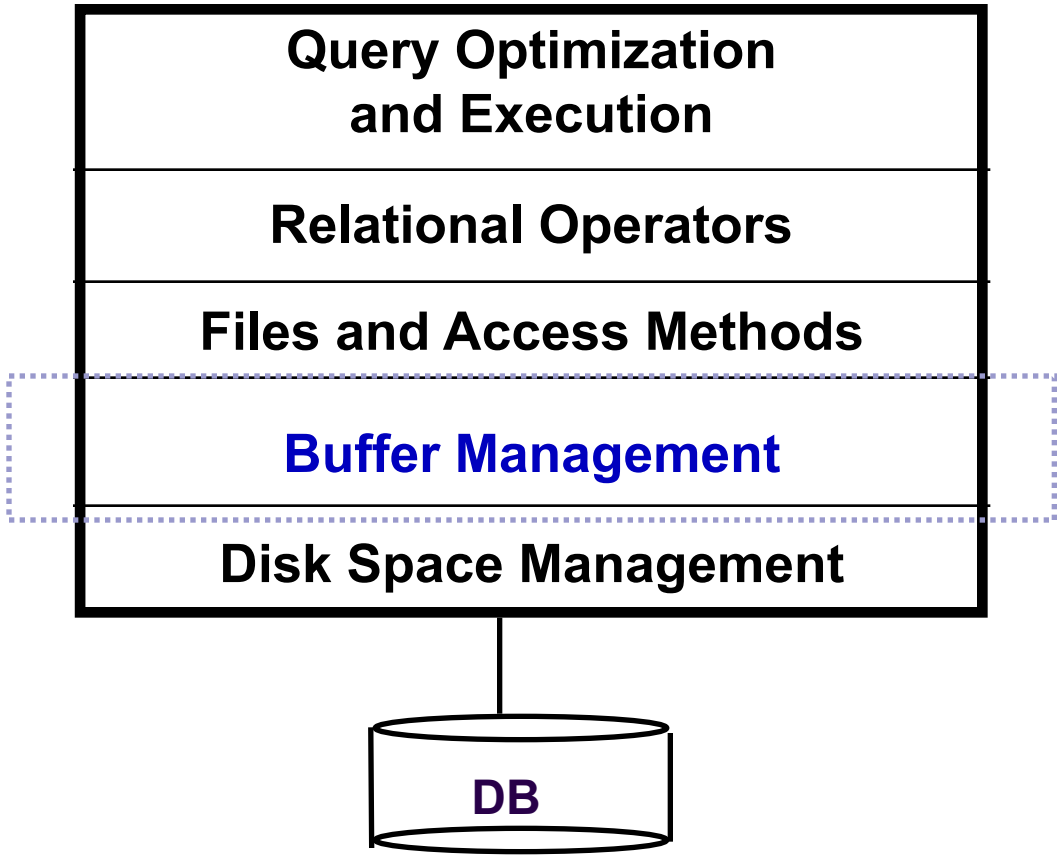
Disk Space Management

- Lowest layer of DBMS software manages space on disk (using OS file system or not?).

- Higher levels call upon this layer to:
  - allocate/de-allocate a page
  - read/write a page

- Best if a request for a *sequence* of pages is satisfied by pages stored sequentially on disk!
  - Responsibility of disk space manager.
  - Higher levels don't know how this is done, or how free space is managed.
  - Though they may assume sequential access for files!
    - Hence disk space manager should do a decent job.

Context


Query Optimization
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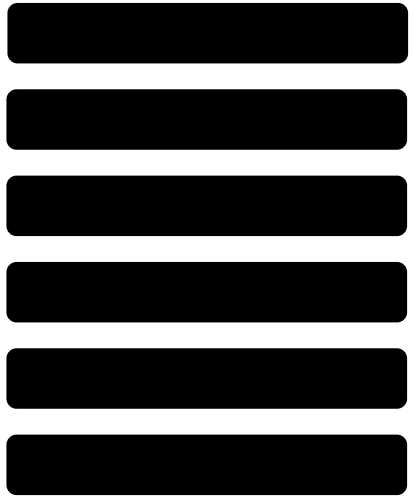
Before we go there:… How do you store a table?

one row at a time



how to efficiently access data?

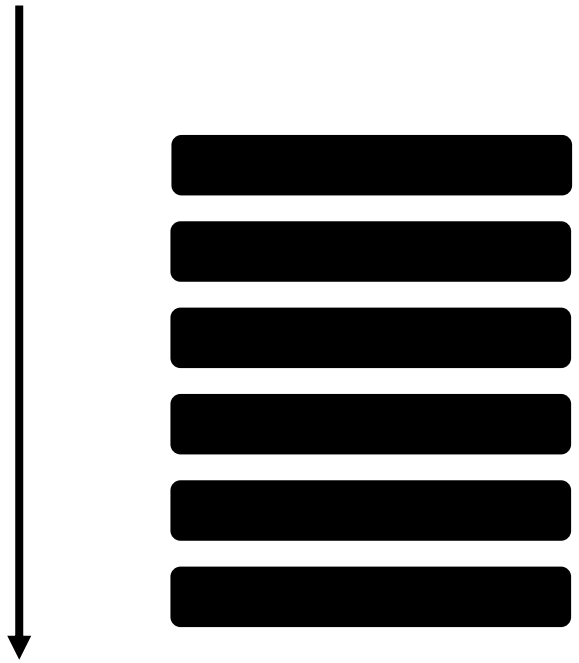
how to retrieve rows:

if I am interested in the average GPA of all students?

if I am interested in the GPA of student A?

how to efficiently access data?

Scan the whole table



if I am interested in most of the data

how to efficiently access data?

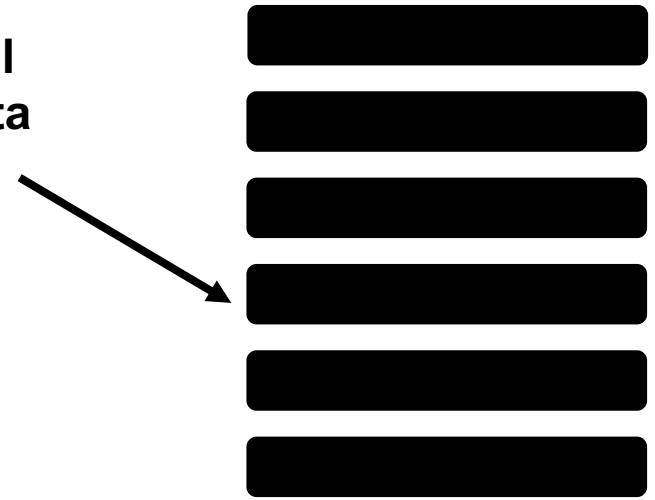
how to retrieve rows:

if I am interested in the average GPA of all students?

if I am interested in the GPA of student A?

how to efficiently access data?

Ask an ***oracle*** to tell
me where is my data



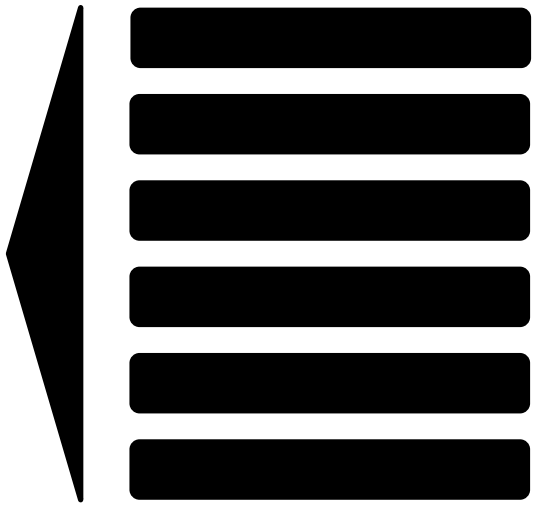
if I am interested in a single row

how to efficiently access data?

what is an ***oracle*** or ***index***?

a data structure that given a value (e.g., student id)
returns location (e.g., row id or a pointer)
with less than O(n) cost

ideally O(1)!

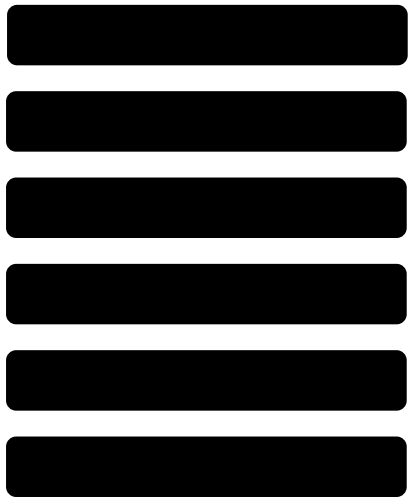


e.g., B Tree, bitmap, hash index

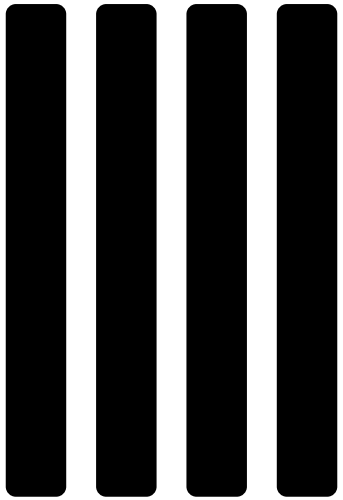
how to physically store data?

is there another way?

one row at a time

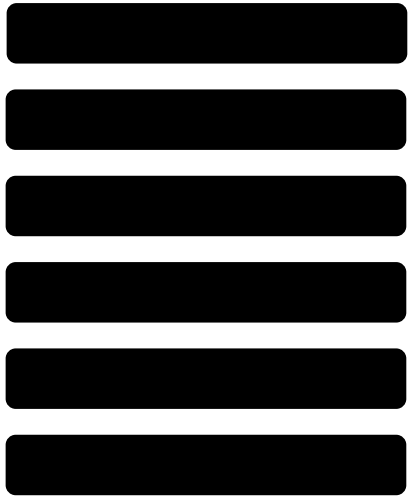


columns first

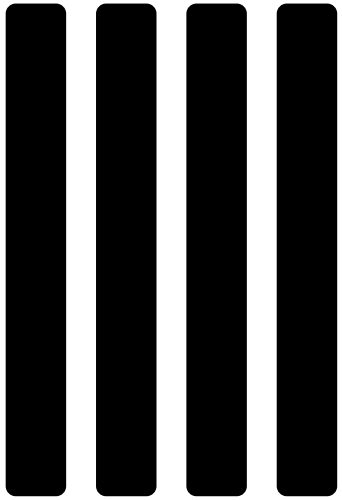


how to efficiently access data?

rows first



columns first



if I want to read an entire single row?

if I want to find the name of the younger student?

if I want to calculate the average GPA?

if I want the average GPA of all students with CS Major?

does that affect the way we *evaluate* queries?

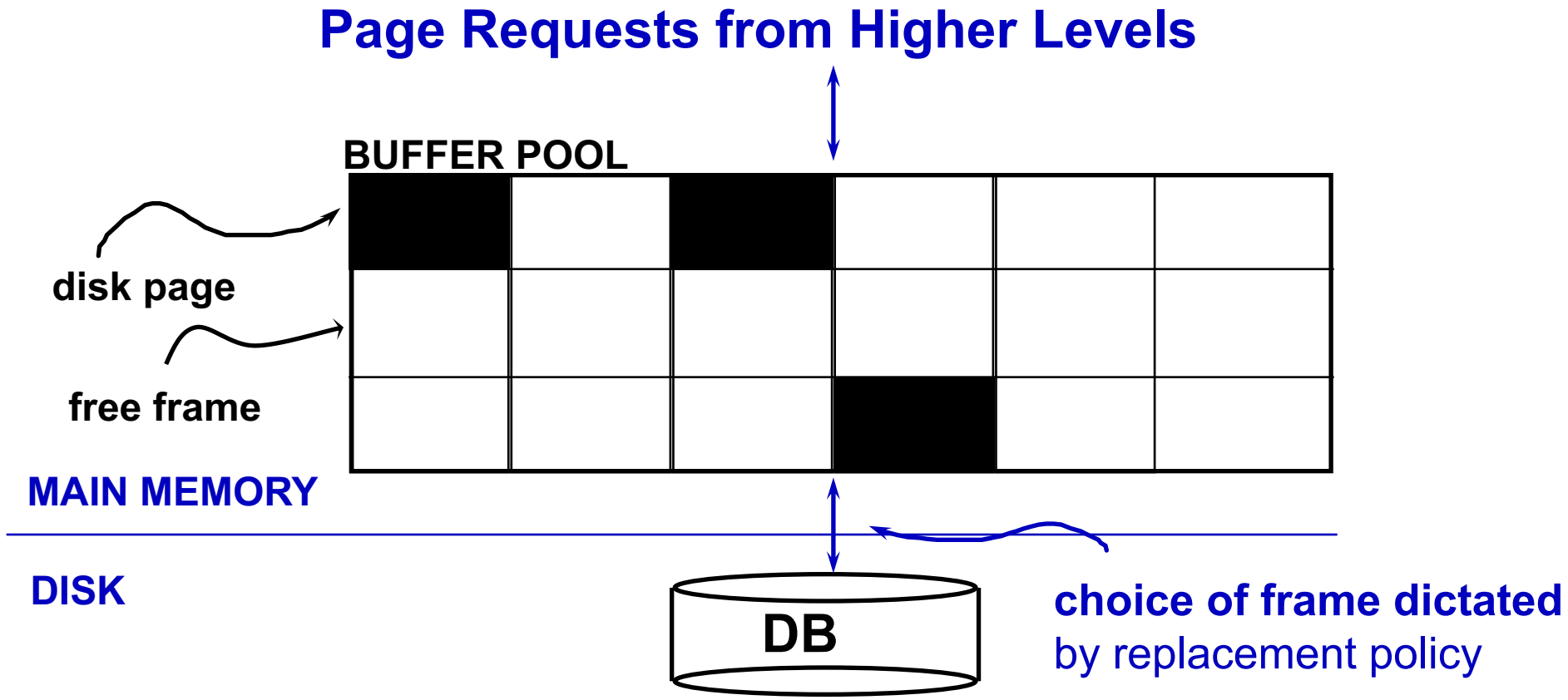
Query Engine *is* different

row-oriented systems (”row-stores”)
move around rows

column-oriented systems (”column-stores”)
move around columns

Here we concentrate on Row-stores (row-wise storage) (for now..)

Buffer Management in a DBMS



- *Data must be in RAM for DBMS to operate on it!*
- *Buffer Mgr hides the fact that not all data is in RAM*

When a Page is Requested ...

- Buffer pool information table contains:
  <frame#, pageid, pin_count, dirty>

- If requested page is not in pool:
  - Choose a frame for *replacement.*
    Only "un-pinned" pages are candidates!
  - If frame is "dirty", write it to disk
  - Read requested page into chosen frame
- *Pin* the page and return its address.

☛ ***If requests can be predicted (e.g., sequential scans) pages can be pre-fetched several pages at a time!***

More on Buffer Management

- Requestor of page must eventually unpin it, and indicate whether page has been modified:
  - *dirty* bit is used for this

- Page in pool may be requested many times,
  - a *pin count* is used.
  - To pin a page, pin_count++
  - A page is a candidate for replacement iff *pin count* == 0 (*"unpinned"*)

- CC & recovery may entail additional I/O when a frame is chosen for replacement.
  - *Write-Ahead Log* protocol; more later!

Buffer Replacement Policy

- Frame is chosen for replacement by a *replacement policy*:
  - Least-recently-used (LRU), MRU, Clock, etc.
- Policy can have big impact on # of I/O's; depends on the *access pattern*.

LRU Replacement Policy

- *Least Recently Used (LRU)*
  - for each page in buffer pool, keep track of time when last *unpinned*
  - replace the frame which has the oldest (earliest) time
  - very common policy: intuitive and simple
    - Works well for repeated accesses to popular pages
- Problems?
- *Problem: Sequential flooding*
  - LRU + repeated sequential scans.
  - # buffer frames < # pages in file means each page request causes an I/O.
  - Idea: MRU better in this scenario?

Competitive Ratio for online algorithms

- Measuring how good a buffer replacement policy is
- Comparing an online algorithm with the optimal offline algorithm (on ALL possible instances)
- What will be the optimal offline algorithm for buffer replacement?
- LRU, FIFO are k-competitive; LFU has no bounded competitive ratio.

Competitive analysis

- For any valid input instance I

$$cratio(A) = \max_{I \in \mathcal{I}} \frac{cost(A,I)}{cost(offline,I)} \quad \text{competitive ratio}$$

- Instance optimal:

for a class $\mathcal{A}$ of algorithms, A_I^* is the optimal algorithm on an input I

$$ratio(A,I) = \frac{cost(A,I)}{cost(A_I^*,I)}$$

$$ratio(A) = \max_{I \in \mathcal{I}} ratio(A,I)$$

Example, LRU

Theorem: Suppose that, for a certain sequence of requests, the optimal sequence of choices for a size-h cache causes m misses. Then, for the same sequence of requests, LRU for a size-k cache causes at most

$$\frac{k}{k-h+1} \cdot m$$

misses.

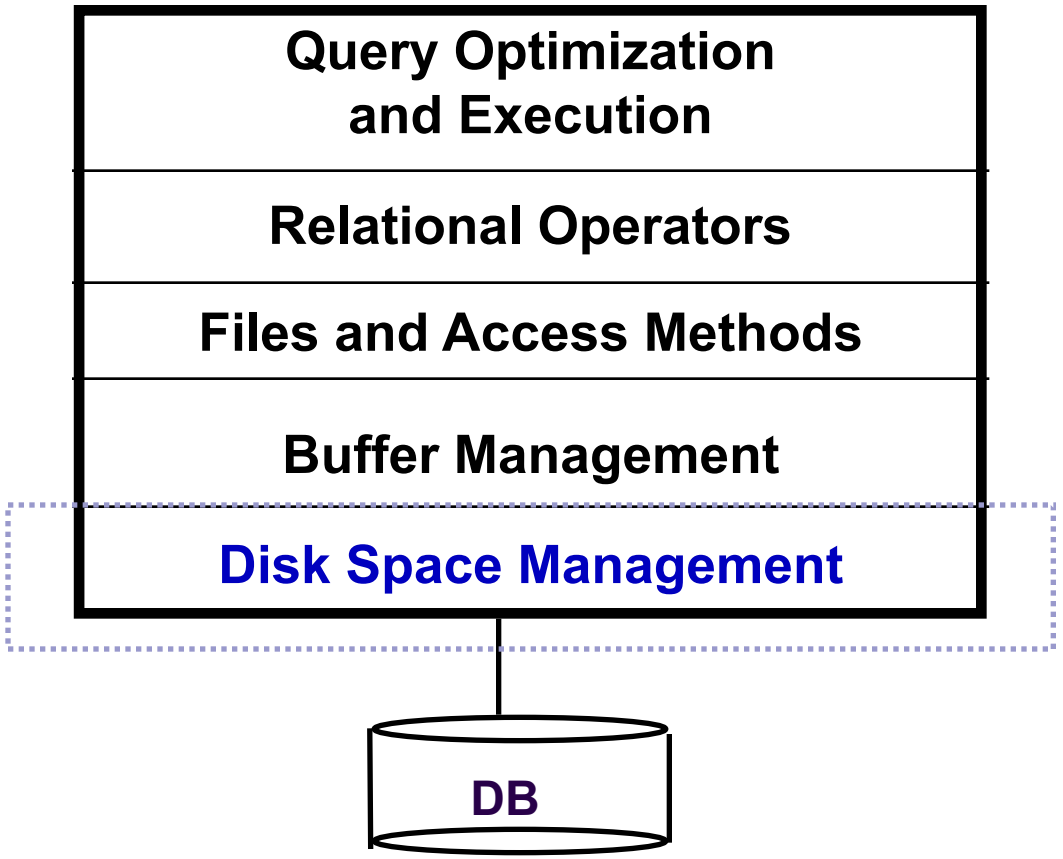
Proof?

DBMS vs. OS File System

OS does disk space & buffer management: why not let OS manage these tasks?

- Some limitations, e.g., files can't span disks.
- Buffer management in DBMS requires ability to:
  - pin a page in buffer pool, force a page to disk & order writes (important for implementing CC, concurrency control, & recovery)
  - adjust *replacement policy,* and pre-fetch pages based on access patterns in typical DB operations.

Context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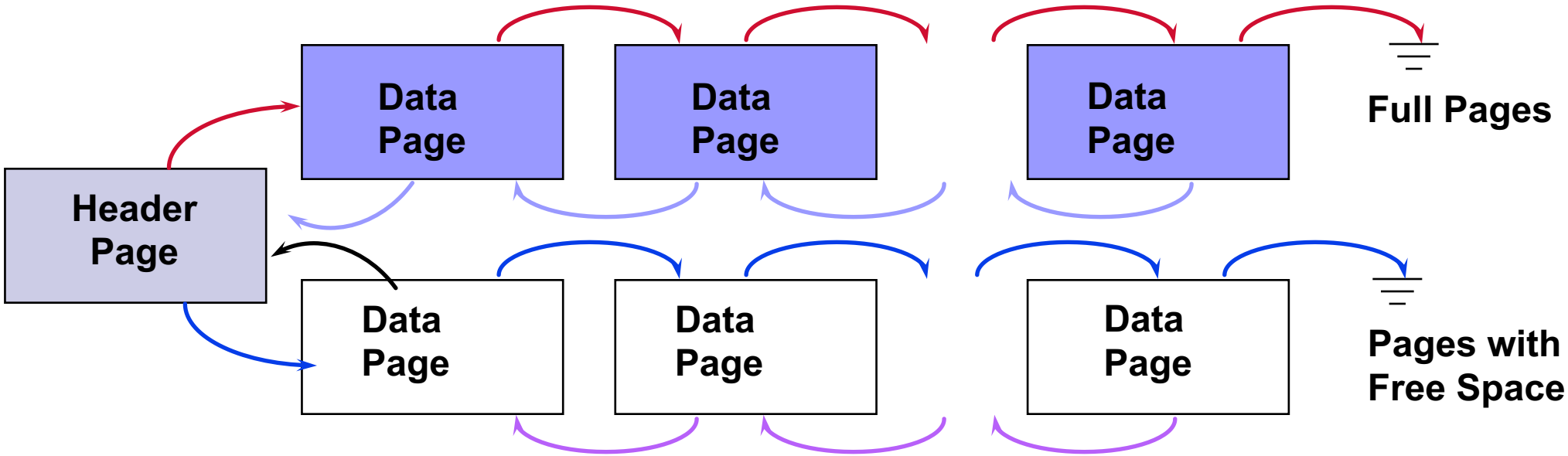
Files of Records

- Blocks interface for I/O, but…
- Higher levels of DBMS operate on *records*, and *files of records*.
- FILE: A collection of pages, each containing a collection of records. Must support:
  - insert/delete/modify record
  - fetch a particular record (specified using *record id*)
  - scan all records (possibly with some conditions on the records to be retrieved)

Unordered (Heap) Files

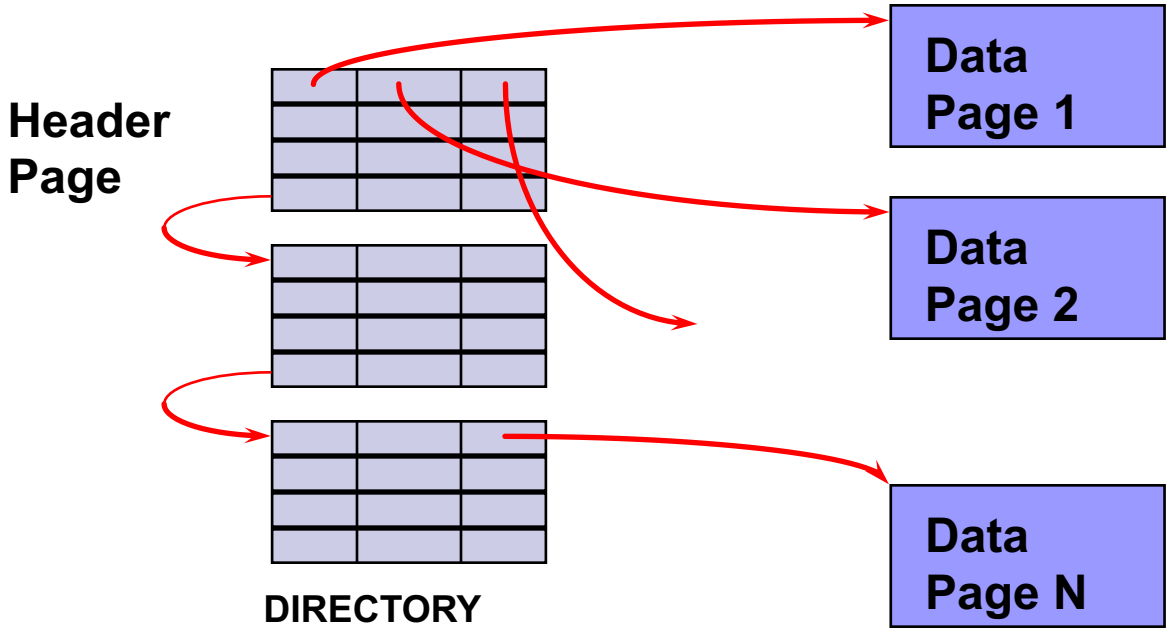
- Simplest file structure contains records in no particular order.
- As file grows and shrinks, disk pages are allocated and de-allocated.
- To support record level operations, we must:
  - keep track of the *pages* in a file
  - keep track of *free space* on pages
  - keep track of the *records* on a page
- There are many alternatives for keeping track of this.
  - We'll consider 2

Heap File Implemented as a List



- The header page id and Heap file name must be stored someplace.
  - Database “catalog”
- Each page contains 2 `pointers’ plus data.

Heap File Using a Page Directory

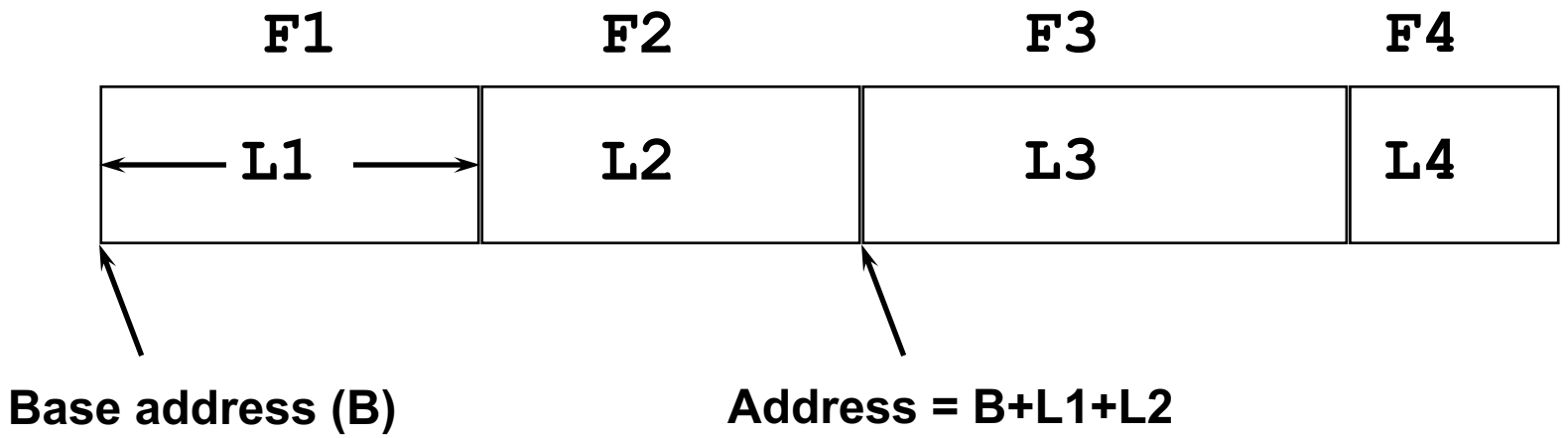


- The entry for a page can include the number of free bytes on the page.
- The directory is a collection of pages; linked list implementation is just one alternative.
  - *Much smaller than linked list of all HF pages*!

Indexes (a sneak preview)

- A Heap file allows us to retrieve records:
  - by specifying the *rid*, or
  - by scanning all records sequentially
- Sometimes, we want to retrieve records by specifying the *values in one or more fields*, e.g.,
  - Find all students in the "CS" department
  - Find all students with a gpa > 3
- Indexes are file structures that enable us to answer such value-based queries efficiently.

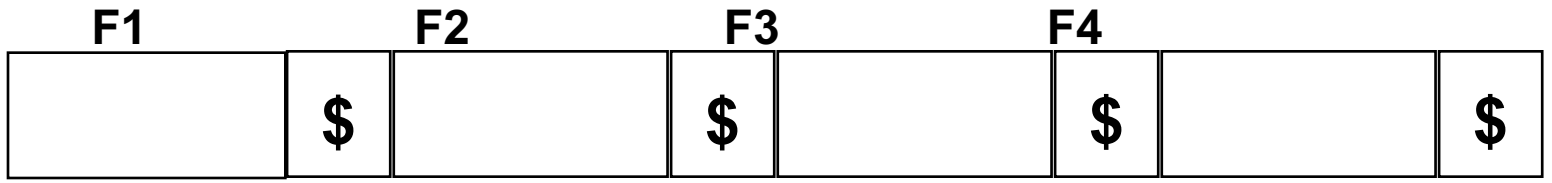
Record Formats: Fixed Length



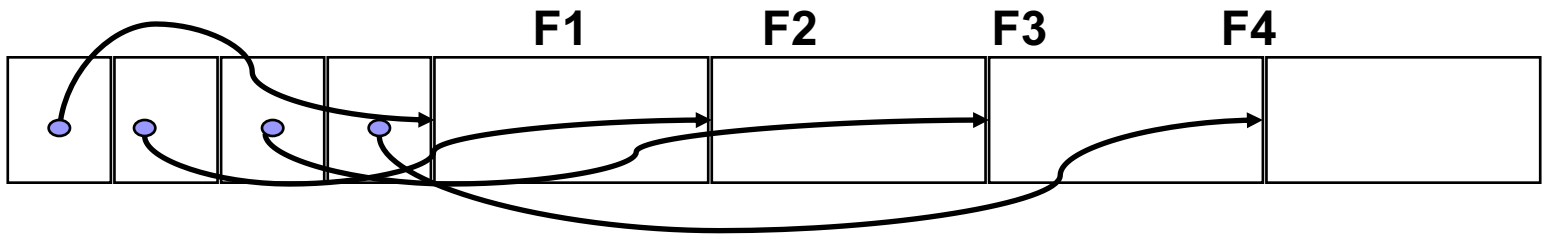
- Information about field types same for all records in a file; stored in *system catalogs.*
- Finding *i'th* field done via arithmetic.

Record Formats: Variable Length

- Two alternative formats (# fields is fixed):



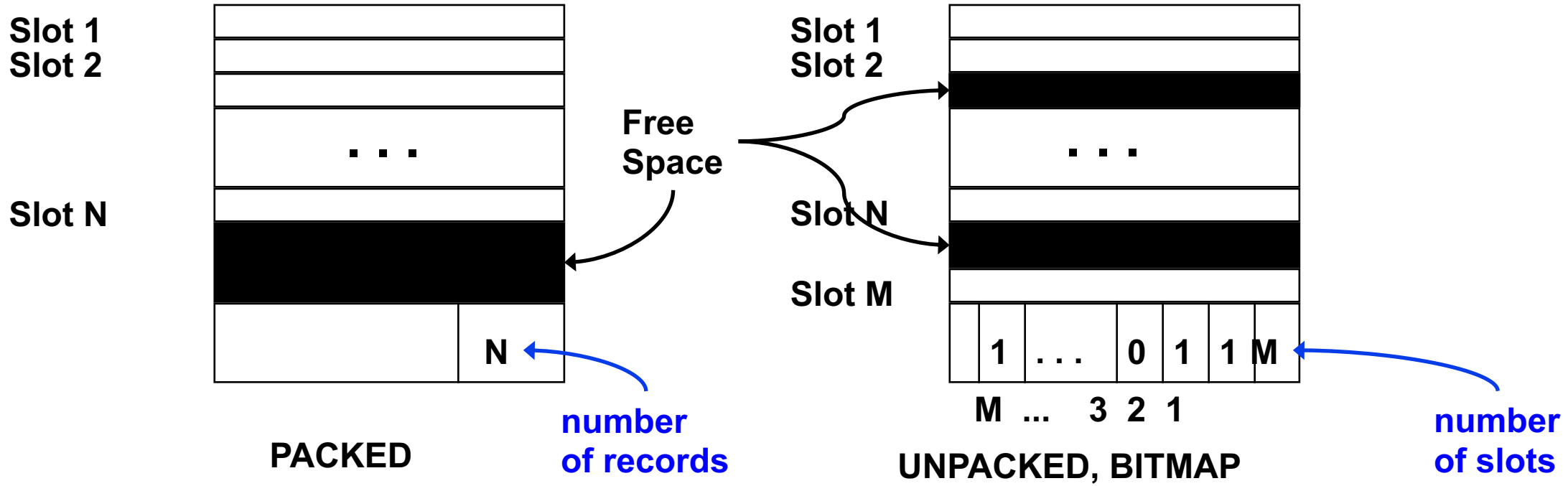
Fields Delimited by Special Symbols



Array of Field Offsets

☛ **Second offers direct access to i'th field, efficient storage of *nulls* (special *don't know* value); small directory overhead.**

Page Formats: Fixed Length Records

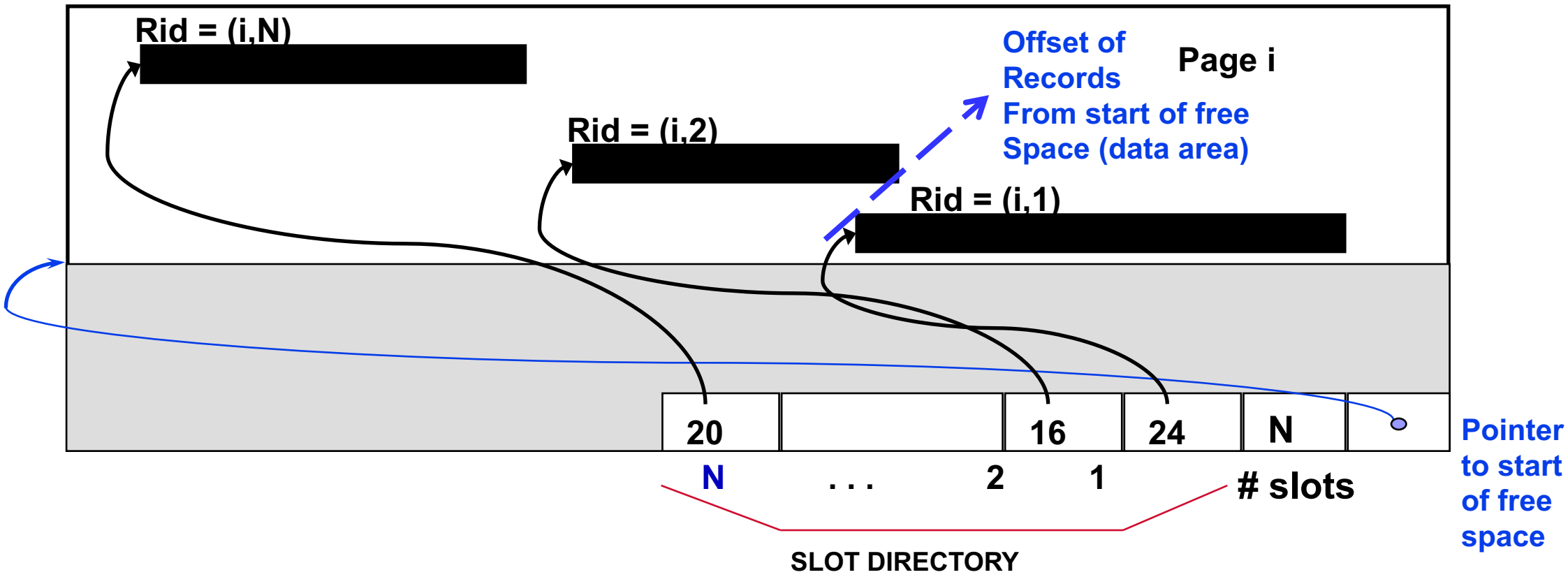


- *Record id = <page id, slot #>. In first alternative, moving records for free space management changes rid; may not be acceptable.*

Variable Length Records

- Find an empty slot of the just right length
- Ensure that all the free space on the page is contiguous
- Idea:
  - Dictionary of slots with format as <record offset, record length)
  - Record offset is the offset in bytes from the start of the data area on the page to the start of the record.
  - Deletion is achieved by setting record offset to -1.

Page Formats: Variable Length Records

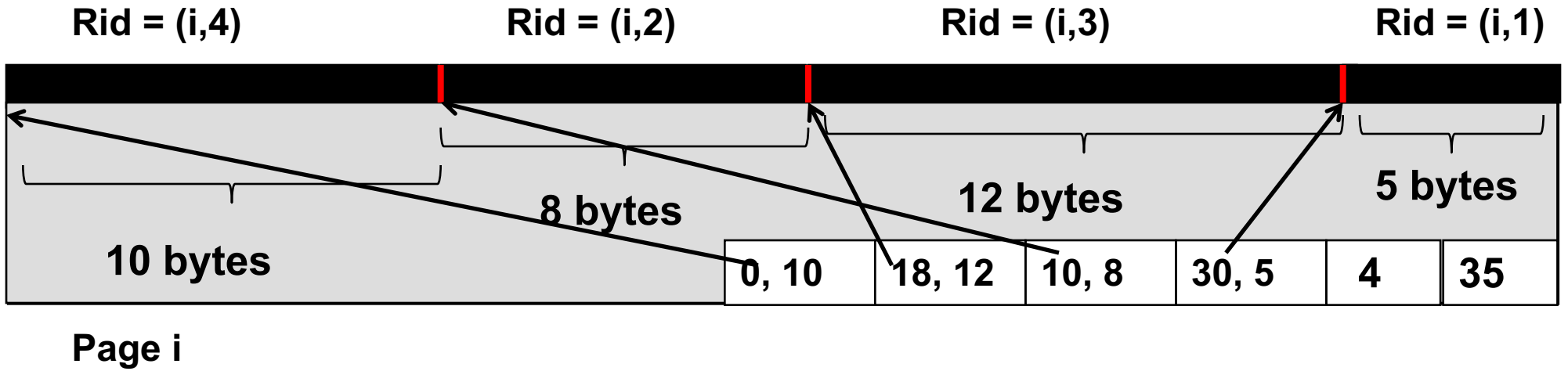


- *Can move records on page without changing rid; so, attractive for fixed-length records too.*

Any other possible variation? **Store the record length at the beginning of the record**

Variable Length Records: Dynamic Update

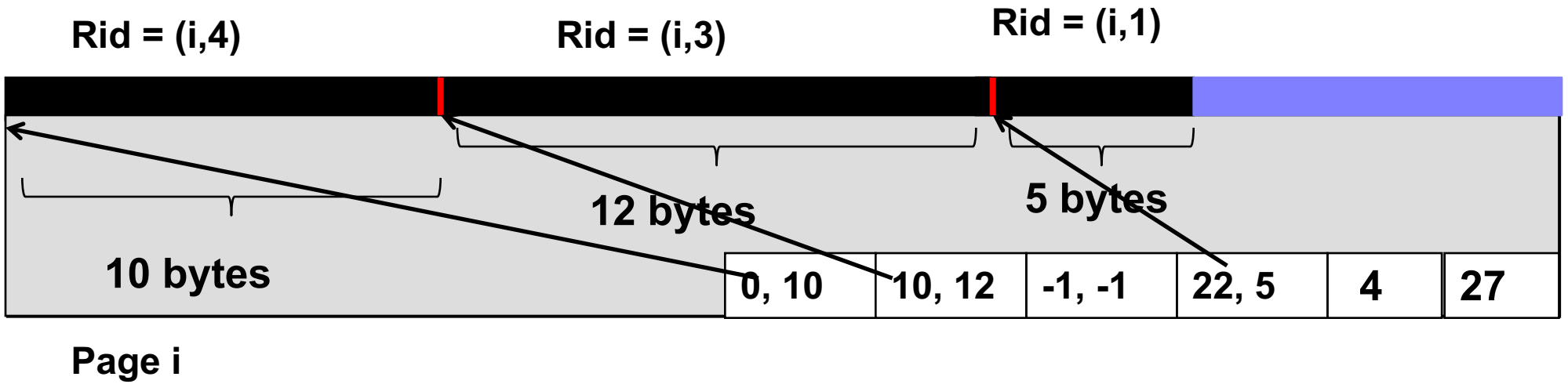
Initial Page:



Page i

Variable Length Records: Deletion

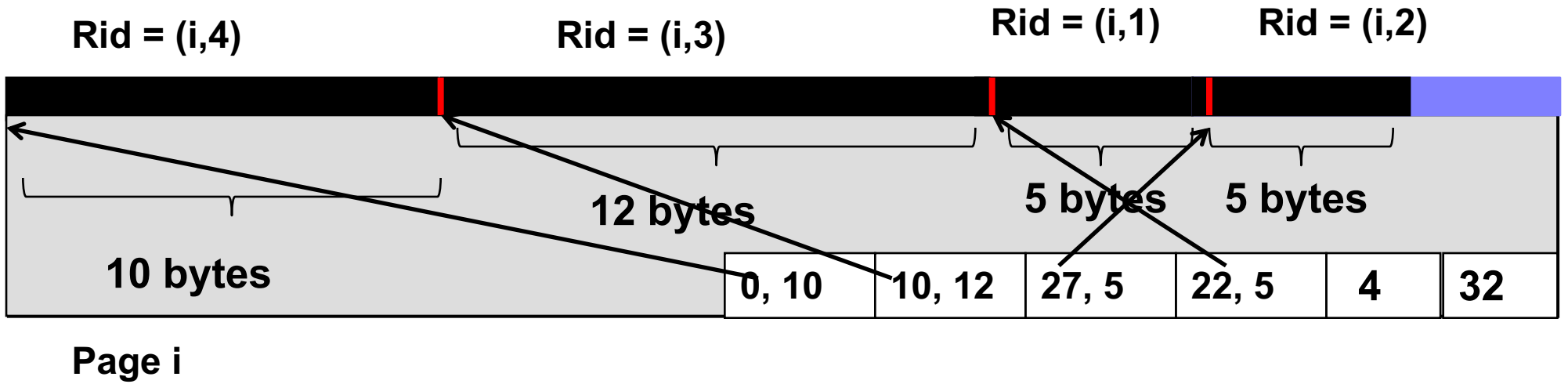
After the deletion of Rid=(i,2):



Page i

Variable Length Records: Insertion

After the insertion of a new record of 5 bytes:



Page i

Deletion

- Leave the slot and don’t remove the slot
  - Why? As doing so will change the rids of the records pointed to by the subsequent slots
  - The only way to remove a slot from the slot directory is to remove the last slot if the corresponding record is deleted
  - Insertion does not have to create a new slot in the slot dictionary: scan for a “free” slot
  - In cases where we don’t care about rid, we can compact the slot dictionary after the delete, e.g., B+ tree with pointers in the leaf entry

System Catalogs

- For each relation:
  - name, file location, file structure (e.g., Heap file)
  - attribute name and type, for each attribute
  - index name, for each index
  - integrity constraints
- For each index:
  - structure (e.g., B+ tree) and search key fields
- For each view:
  - view name and definition
- Plus statistics, authorization, buffer pool size, etc.

☛ ***Catalogs are themselves stored as relations/tables!***

Attr_Cat(attr_name, rel_name, type, position)

attr_name	rel_name	type	position
attr_name	Attribute_Cat	string	1
rel_name	Attribute_Cat	string	2
type	Attribute_Cat	string	3
position	Attribute_Cat	integer	4
sid	Students	string	1
name	Students	string	2
login	Students	string	3
age	Students	integer	4
gpa	Students	real	5
fid	Faculty	string	1
fname	Faculty	string	2
sal	Faculty	real	3

PostgreSQL as an example

- Each database has three “schema” types: a “schema” is like a namespace.
  - public: user-defined tables, views, indexes, sequences.
    - \dt by default means \dt public.*, \d+ by default means \d+ public.*, etc.
  - pg_catalog: system catalog tables and views.
    - \dt pg_catalog.*, \dv pg_catalog.*
  - information_schema: views defined over system catalog (that confirm to SQL standard and portable to other DB systems), and tables contain SQL language information
    - \dt information_schema.*, \dv information_schema.*
  - \d+ viewname to explain a view.

PostgreSQL as an example

- Now consider pg_catalog schema:
  - pg_class contains metadata about relations (tables) in the current database
    - E.g. select oid, relname from pg_catalog.pg_class;
  - pg_attribute contains metadata about attributes of all relations in the current database;
    - select oid, attname, atttypid, attlen from pg_catalog.pg_attribute A, pg_catalog.pg_class C where A.attrelid=C.oid and C.relname=‘payment’;
    - select attname, atttypid, attlen, typname, typlen from pg_catalog.pg_attribute A, pg_catalog.pg_class C, pg_catalog.pg_type T where A.attrelid=C.oid and C.relname='customer' and A.atttypid=T.oid;
    - select relfilenode, relpages, reltuples, relnatts from pg_class where relname='actor';
  - pg_type contains metadata about attribute types.

Summary

- Disks provide cheap, non-volatile storage.
  - Random access, but cost depends on location of page on disk; important to arrange data sequentially to minimize *seek* and *rotation* delays.
- Buffer manager brings pages into RAM.
  - Page stays in RAM until released by requestor.
  - Written to disk when frame chosen for replacement (which is sometime after requestor releases the page).
  - Choice of frame to replace based on *replacement policy.*
  - Tries to *pre-fetch* several pages at a time.

Summary (Contd.)

- DBMS vs. OS File Support
  - DBMS needs features not found in many OS's, e.g., forcing a page to disk, controlling the order of page writes to disk, files spanning disks, ability to control pre-fetching and page replacement policy based on predictable access patterns, etc.
- Variable length record format with field offset directory offers support for direct access to i'th field and null values.
- Slotted page format supports variable length records and allows records to move on page.

Summary (Contd.)

- File layer keeps track of pages in a file, and supports abstraction of a collection of records.
  - Pages with free space identified using linked list or directory structure (similar to how pages in file are kept track of).
- Indexes support efficient retrieval of records based on the values in some fields.
- Catalog relations store information about relations, indexes and views. (*Information that is common to all records in a given collection.*)