Department of Computer Science
University of Cyprus


## EPL646 – Advanced Topics in Databases

# Lecture 2

# Storage I: Storage and Indexing

## Chap. 8.1-8.5: Ramakr. & Gehrke

*** exclude 8.4.5-8.4.6**


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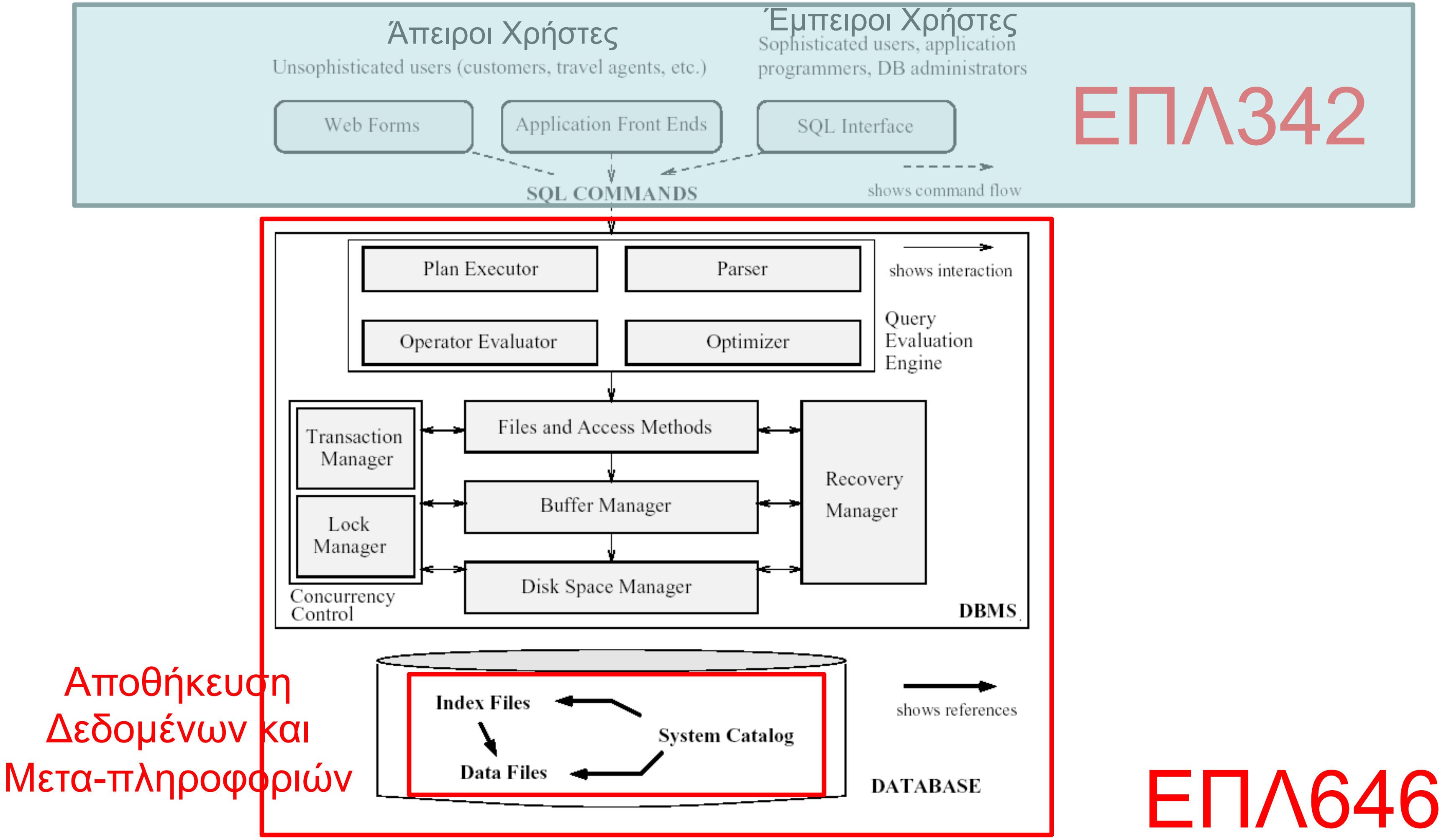
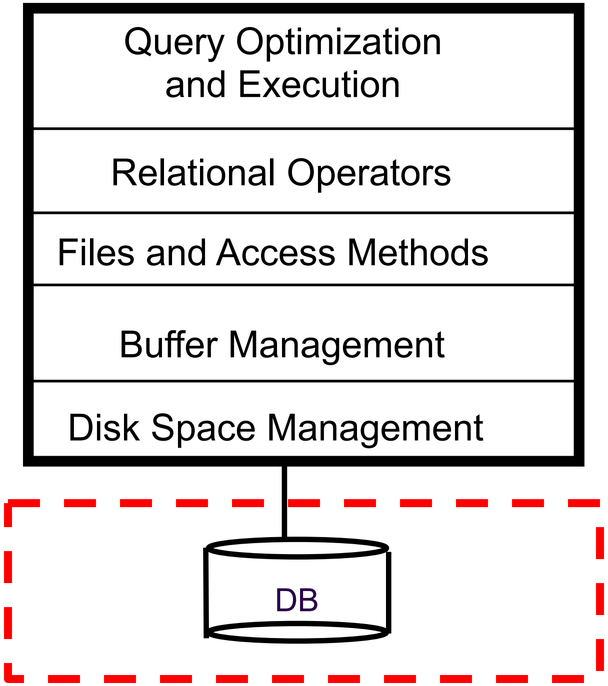
http://www.cs.ucy.ac.cy/~dzeina/courses/epl646

# ΕΠΛ646: Ενότητα Α
# Εσωτερική Λειτουργία ενός RDBMS



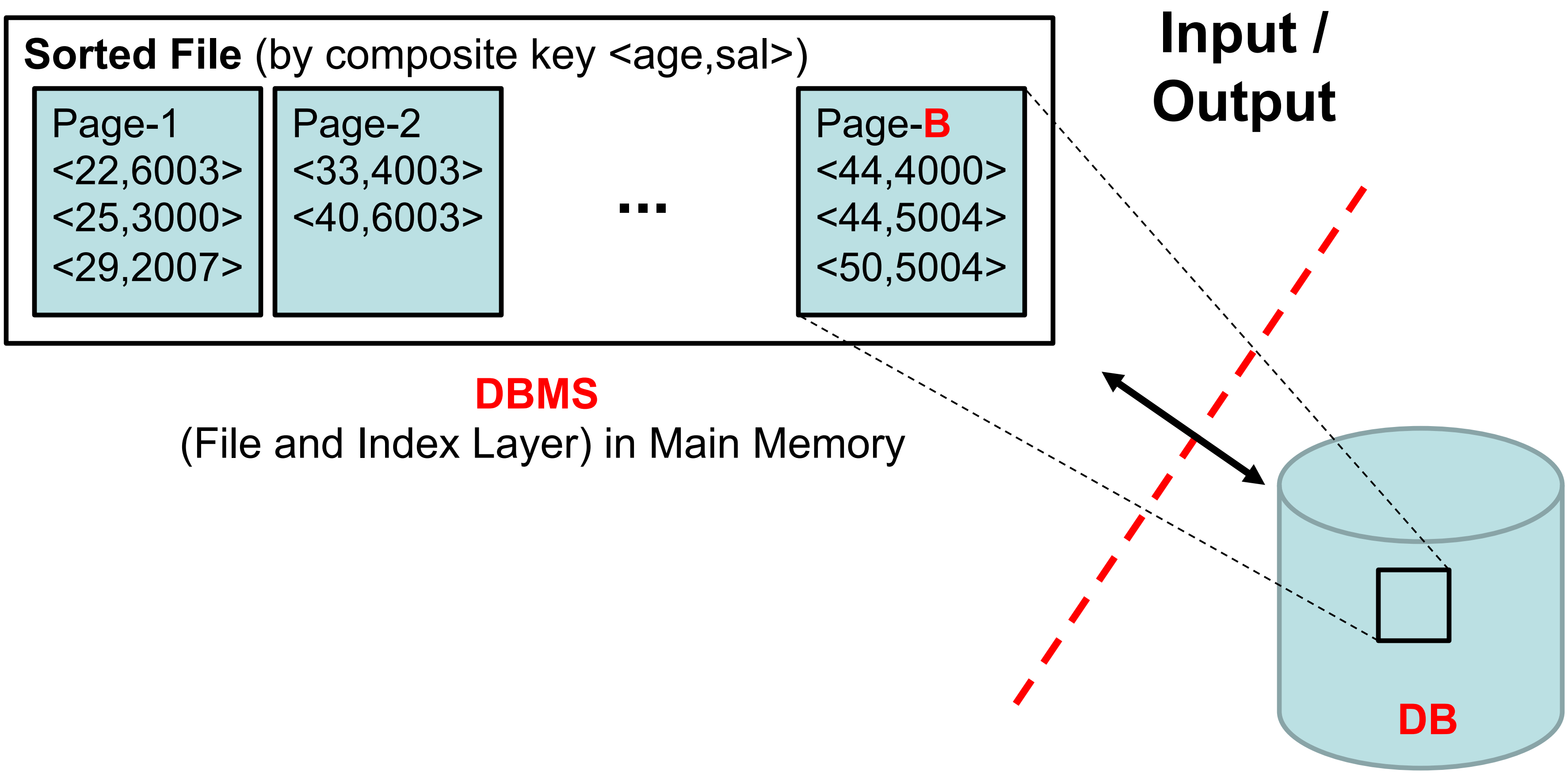
# Context of next slides



# Data on External Storage (Δεδομένα στη Δευτερεύουσα Μνήμη)

- A DBMS stores **vast amounts** of data and the data has to **persists** across program executions.
- Therefore, data is stored on **external storage** and **fetched** into **main memory** as needed for processing.
- The unit of information that is read and written to a disk is called **Page (Σελίδα)**, e.g., 4KB ή 8KB
- Higher layers of the DBMS view these pages as unified **Files (Αρχείο)** and can read/write **Records (Εγγραφές, Πλειάδες)** to these files.
  - Consider a data record (id:4B, name:28B) and a 4096B (4KB) page size. That would yield ~128 records / page (some bytes go to headers and other auxiliary structures).
- **What is the basic performance cost in a DBMS?**
  - **I/O (Input/Output): # pages read/write** for a given operation.
  - **Complexity** of algorithms in DBMSs is expressed in I/Os

# Data on External Storage (Δεδομένα στη Δευτερεύουσα Μνήμη)



# Storage Mediums (Μέσα Αποθήκευσης)

- Disks: Can retrieve a **random** page at a **fixed cost**
  - But reading several **consecutive pages** is much cheaper than reading them in **random order**

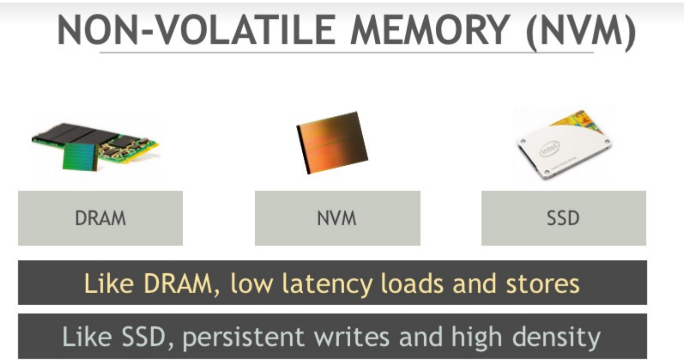
Main focus of DBMSs

- Tapes: Can only read pages **in sequence**
  - **Cheaper** than disks; used for **archiving** (αρχειοθέτηση)
- Flash Memory (Solid State Disks): Reading data at the speed of main memory, writing is slower.
  - More **expensive** than disks; used for applications with read workloads that require **fast random** accesses.

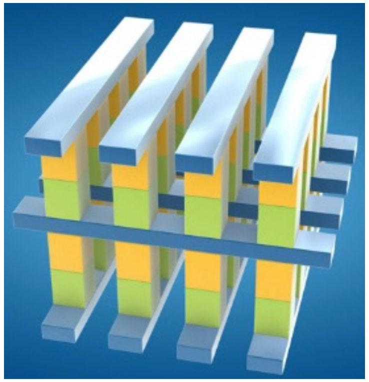

# Short-term Future of Storage (NVM/NVRAM/NVDIMMs)

**Hardware Slot: non-volatile dual in-line memory module (NVDIMM)**
**Memory Type: Non-volatile random-access memory (NVRAM) or Non-volatile memory (NVM) or non-volatile storage (NVS)**

- NVM PROPERTIES – see video: https://goo.gl/f2LbKv
  - **Byte addressable –** Loads and stores unlike SSD/HDD
  - **High random write throughput –** Orders of magnitude higher than SSD/HDD – Smaller gap between sequential & random write throughput
  - **Read-write asymmetry & wear-leveling –** Writes might take longer to complete compared to reads – Excessive writes to a single NVM cell can destroy it (similar to SSD – can be handled by controller)







: e.g., Intel Optane 3D XPoint

- **ACM SIGMOD 2017 Tutorial:** https://www.cc.gatech.edu/~jarulraj/talks/2017.nvm.sigmod.pdf
- **Non-Volatile Memory Database Management Systems,** *Joy Arulraj, Georgia Institute of Technology, Andrew Pavlo, Carnegie Mellon University*
  **ISBN:** 9781681734842 | **PDF ISBN:** 9781681734859, **Hardcover ISBN:** 9781681734866, **Copyright** © 2019 | 191 Pages

# Computational Storage Drive (CSD)

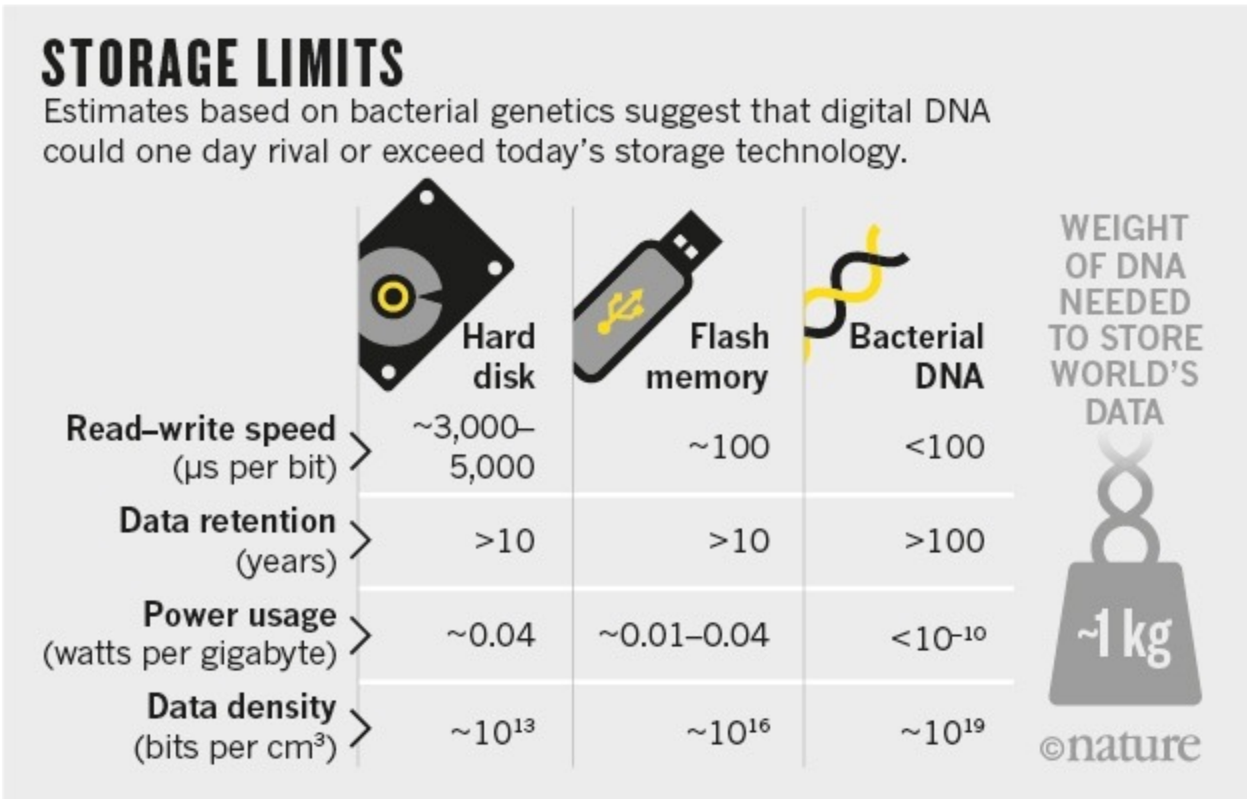
- Dramatically accelerates data-intensive applications by 10X or more by pushing compute to where the data lives.
- Examples:
  - The Samsung SmartSSD® computational storage drive (CSD)- powered by the AMD Adaptive Platform-

# Cloud Storage (AWS Case Study – 2019)

- **Amazon Elastic Block Store (EBS) [ OLTP & OLAP ]**
  - persistent local storage for Amazon EC2, for relational and NoSQL databases, data warehousing, enterprise applications, Big Data processing, or backup and recovery
- **Amazon Elastic File System (EFS) [ Filesystem ]**
  - A simple, scalable, **elastic file system** for **Linux-based workloads** for use with AWS Cloud services and on-premises resources. It is built to scale on demand to petabytes without disrupting applications, growing and shrinking automatically as you add and remove files, so your applications have the storage they need – when they need it.
- **Amazon FSx (EFS) [ Maching Learning ]**
  - A fully managed file system that is optimized for compute-intensive workloads, such as high **performance computing, machine learning**, and m**edia data processing workflow**s, and is seamlessly integrated with Amazon S3
- **Amazon S3 [ Storage]**
  - A scalable, durable platform to make data accessible from any Internet location, for user-generated content, active archive, serverless computing, **Big Data storage or backup and recovery**
- **Amazon Glacier [ Deep Storage – Tertiary ]**
  - Highly affordable long-term storage that can **replace tape** for **archive** and regulatory compliance
- **Amazon Backup**
  - A fully managed backup service that makes it easy to centralize and automate the back up of data across AWS services in the cloud as well as on premises using the AWS Storage Gateway.

# The Future of Storage

http://www.nature.com/news/how-dna-could-store-all-the-world-s-data-1.20496



**STORAGE LIMITS**

Estimates based on bacterial genetics suggest that digital DNA could one day rival or exceed today's storage technology.

| | Hard disk | Flash memory | Bacterial DNA |
|---|---|---|---|
| Read–write speed (µs per bit) | ~3,000–5,000 | ~100 | <100 |
| Data retention (years) | >10 | >10 | >100 |
| Power usage (watts per gigabyte) | ~0.04 | ~0.01–0.04 | $<10^{-10}$ |
| Data density (bits per cm³) | $\sim 10^{13}$ | $\sim 10^{16}$ | $\sim 10^{19}$ |



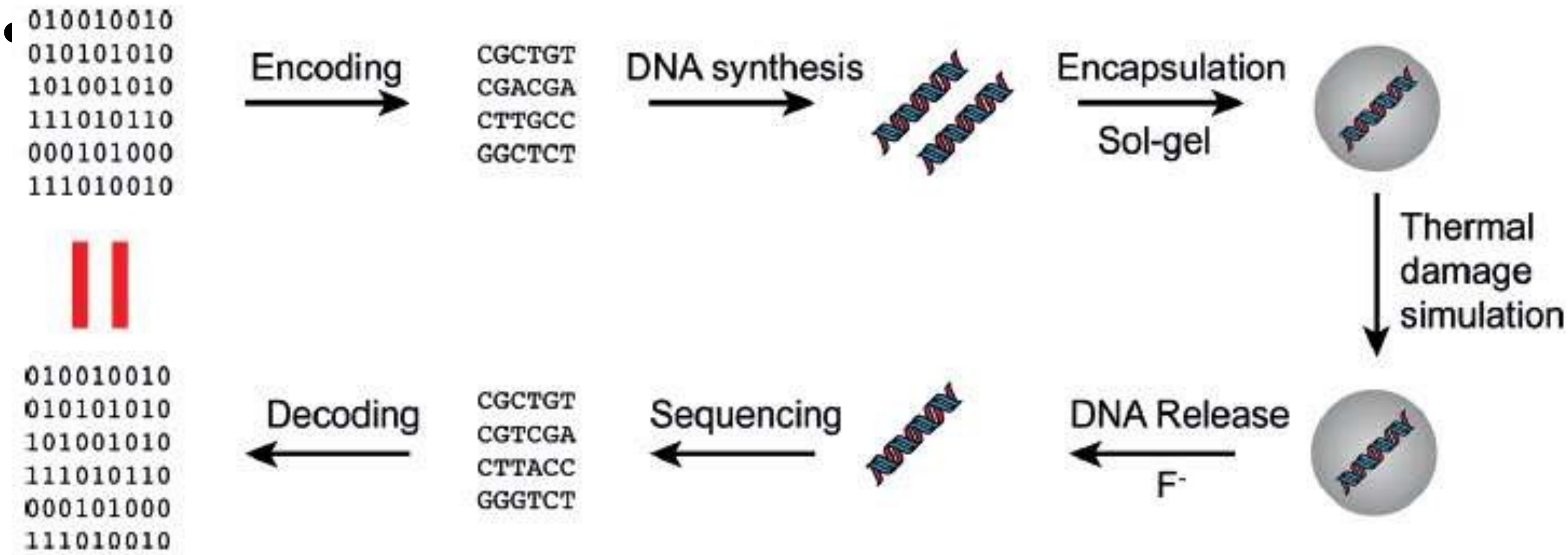
1gr DNA = 230-730PB of data ☺

1 MB of DNA = 3,500 $ ☹

Might one day create "global seed vault" (i.e., offer tertiary storage alternatives for archiving – not replace HDD/SSD)

# The Future of Storage

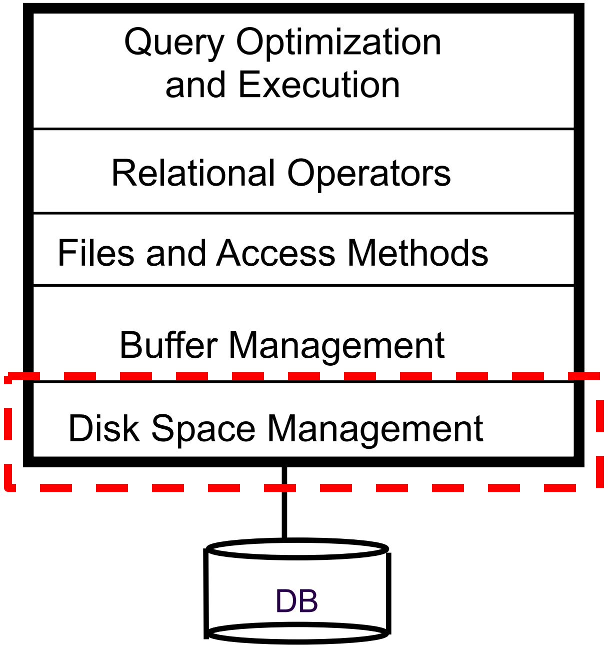
How does DNA Sequencing Works ? – **Youtube Video**




Credits: https://goo.gl/vsJggQ

Microsoft/Univ. of Washington (2016): stored 100 literary documents of size 220MB | https://goo.gl/1GyiyZ

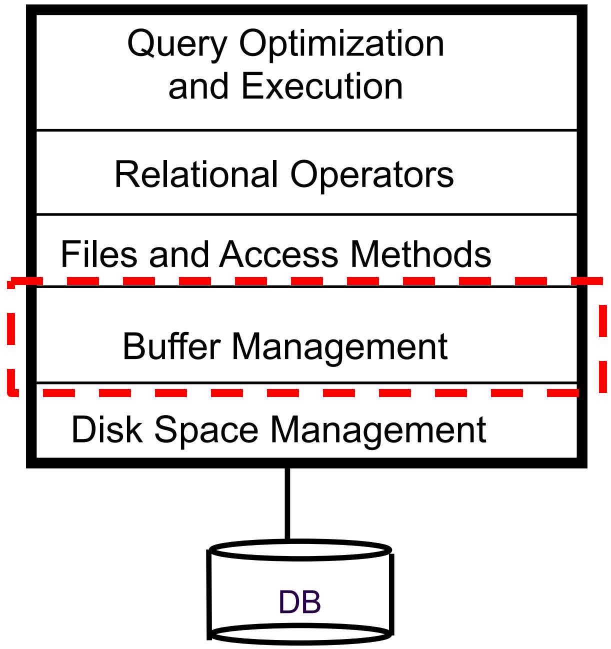
# Context of next slides



# Disk Space Manager (DSM)
## (Διαχειριστής Χώρου Δίσκου)

- **DSM:** Supports the concept of a **page** as a unit of data and provides commands to **allocate/deallocate**, **read/write** a page to external storage.
  - Size of Page == Size of Disk Block, in order to support read/write operations in one I/O operation.
  - The higher layers in the DB architecture (i.e., the **Buffer Manager**) interact directly with the DSM.
- Other Duties: **Keep track of Free Blocks**.
  - Initially a DB is stored on consecutive **disk blocks** (when it acts in its own partition) or inside a **file** (when it is stored inside an Operation System file).
  - Subsequent **deletions** might easily create **"holes"** in that sequence (either file or disk), thus the DSM needs to track the free pages.

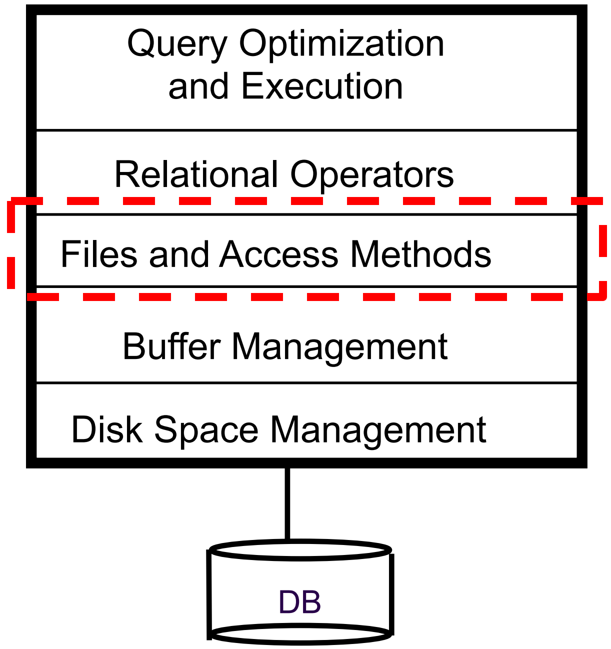
# Context of next slides



# Buffer Manager (BM)
## (Διαχειριστής Κρυφής Μνήμης)

- **BM:** Subsystem that is responsible for **loading** pages from **external storage** to the main memory **buffer pool**
  - File & Index layers make calls to the buffer manager.
  - **Idea:** Keep as many blocks (pages) in memory as possible to reduce disk accesses.
- **Replacement Policies**
  - **e.g., LRU** (Least-Recently-Used pages … are discarded => the oldest are discarded first), **MRU** (Most-Recently-Used, the newest are discarded first), **LFU** (Least-Frequently-Used)
- **Prefetching or Double Buffering**
  - **Idea:** speed-up access by pre-loading "future"-needed data
  - **Cons:** requires extra main memory; no help if requests are random

# Context of next slides



# Alternative File Organizations (Εναλλακτική Οργάνωση Αρχείων)

- **File organization (Οργάνωση Αρχείου):** Method for **arranging** a collection of records and supporting the concept of a **file.**
- In all file organizations the records are accessed by their respective **RecordID**
  - Note that a **Record ID (RID)** usually has the following structure **(PageID, SlotID)**, where **SlotID** defines the offset : i) inside **PageID** at which RID begins; or ii) inside the Slot Directory that resides within page PageID (explained in next lectures)

*Page i*


- **Basic Questions**
  - How to store data inside **data records** (fixed-length records vs. variable-length records)?
  - How to store data-records **inside a file** (heap file, sorted file, indexed file)?
  - How to make a certain File Organization more powerful by complementing them with an Index?

# File Organization Types (Τύποι Οργάνωσης Αρχείων)

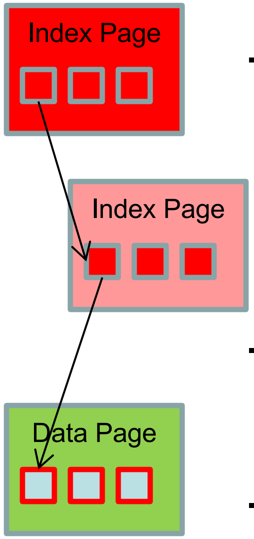
- Heap files (Αρχεία Σωρού): Suitable when typical access is a **file scan (σάρωση αρχείου)** retrieving **ALL** records
  - Suitable for queries like "SELECT * FROM Employees;"

- Sorted Files (Ταξινομημένα Αρχεία): Best if records must be retrieved in some order, or only a **`range' (διάστημα)** of records is needed.
  - Suitable for queries like "SELECT * FROM Employees WHERE 20<age and age<30;"
- **Each file organization makes certain operations efficient, but we are interested in supporting more than one operation!**
- To deal with such situations the DBMS builds one or more **indexes**.
- An **index** on a file is designed to speed up operations that are **not efficiently** supported by the basic organization of that file.

# Indexes (Access Methods) (Ευρετήρια Δευτερεύουσας Μνήμης)

- An *index* is a data structure that has **index records** which **point to** certain **data records**.
- An index can **optimize** certain kinds of retrieval operations (depending on the index).

- **Definitions**

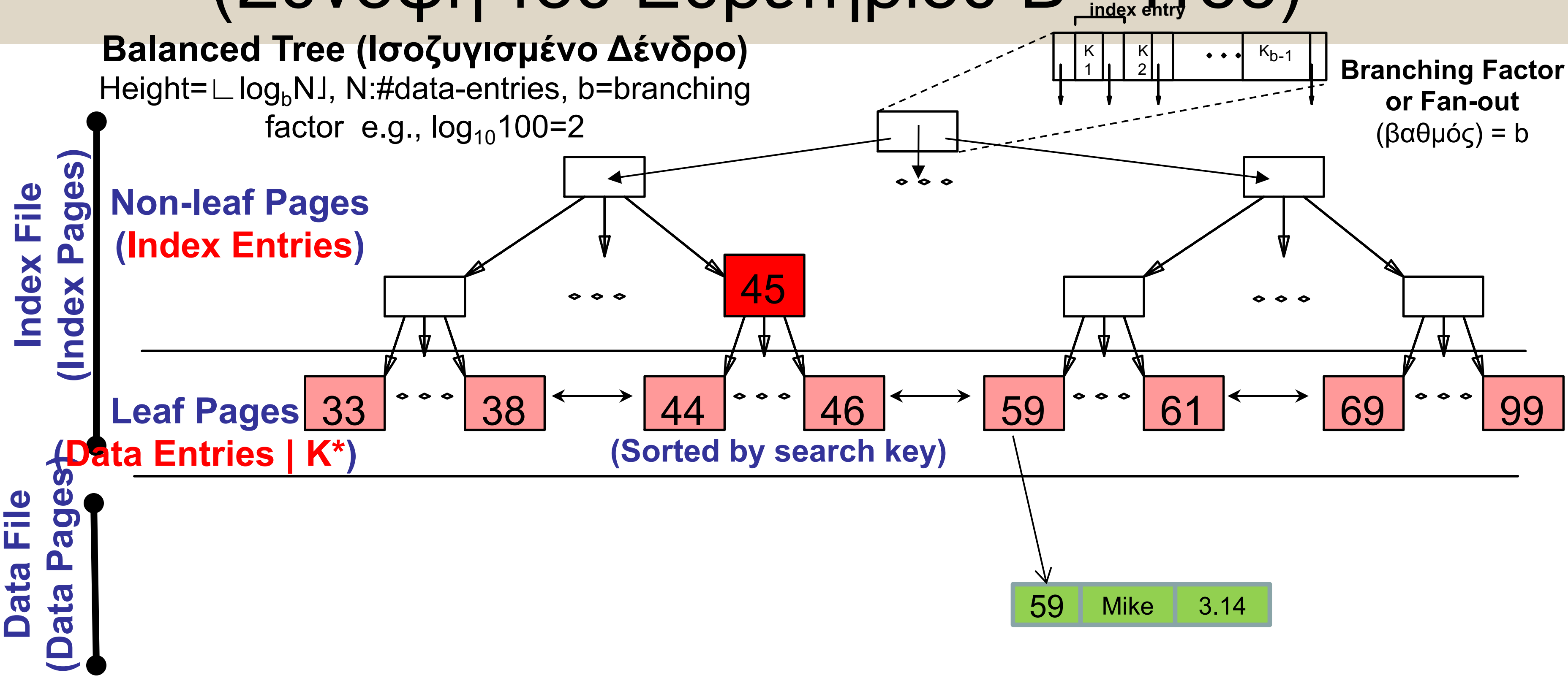



  - **Index Page (Σελίδες Ευρετηρίου) vs. Data Pages (Σελίδες Δεδομένων):** Index Pages store index records to data records. Both reside on disk because we might have many of these pages!
  - **Data Record (Εγγραφή Δεδομένων):** Stores the actual data e.g., (59,Mike,3.14) .
  - **Index Record (Εγγραφή Ευρετηρίου):** Stores the RID of another index record or a data record.

# B+ Tree Index Overview (Σύνοψη του Ευρετηρίου B+ Tree)

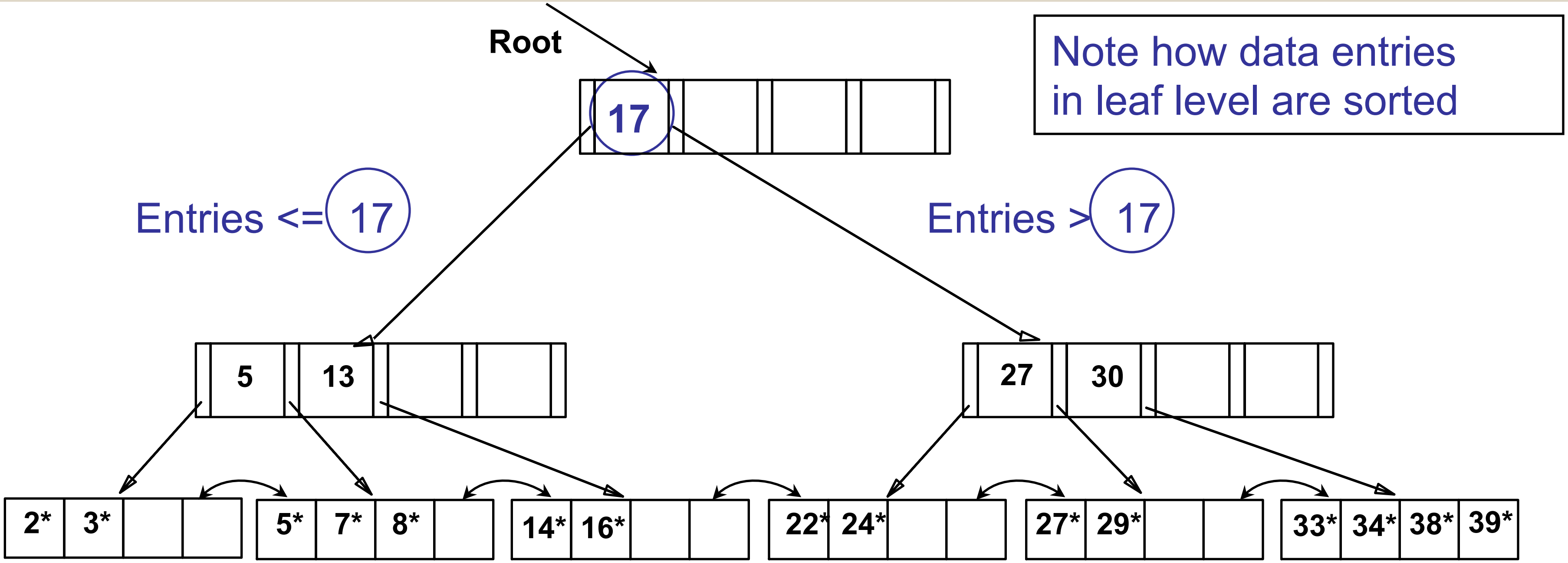
**Balanced Tree (Ισοζυγισμένο Δένδρο)**

Height=$\lfloor \log_b N \rfloor$, N:#data-entries, b=branching factor e.g., $\log_{10}100=2$




- Non-leaf pages have *index entries;* only used to direct searches.
- Leaf pages contain *data entries K**, and are chained (prev&next)
- The data records e.g., (59,Mike,3.14) could have been stored inside he respective data entry. Then the index file would be the same with the data file. ➔ **Index File Organization.**

# Example B+ Tree (Παράδειγμα Χρήσης B+ Tree)




- Find 28*? 29*? All > 15* and < 30*
- Insert/delete: Find data entry in leaf, then change it. Need to adjust parent sometimes.
  - And change sometimes bubbles up the tree

# Structure of Data Entry k* (Δομή της Καταχώρησης K*)

- In a **data entry k*** we can store:
  - **Alternative 1: <k>** (Key Value), or
  - **Alternative 2: <k, RID>**(Key Value, Data record with key value k)>, or
  - **Alternative 3: <k, [$RID_1$, $RID_2$, …, $RID_n$]>,** where ***$RID_i$*** is a data record with key value k.
- *Choice of alternative for data entries* is **orthogonal** to the indexing technique used to locate data entries with a given key value k.
  - **In particular, ANY of the above alternatives might be used with ANY index (hash or tree)**

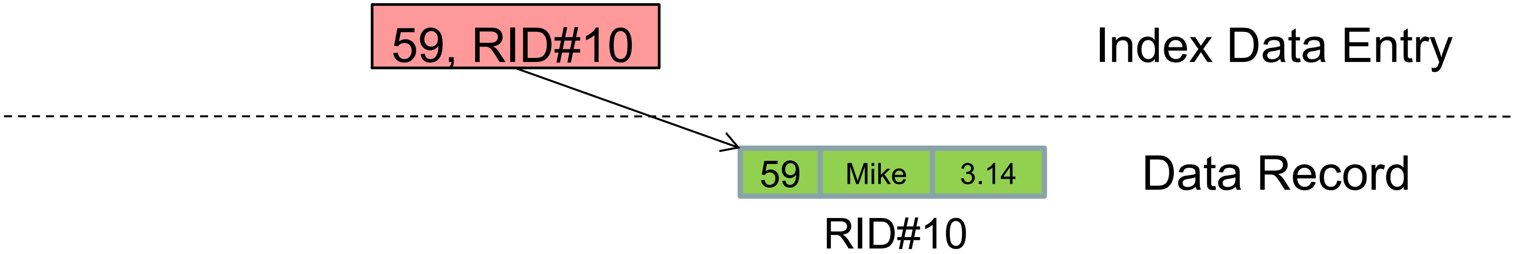
# Data Entry **k*** Examples (Παραδείγματα Καταχώρησης **k***)

- **Alternative 1: <k>**

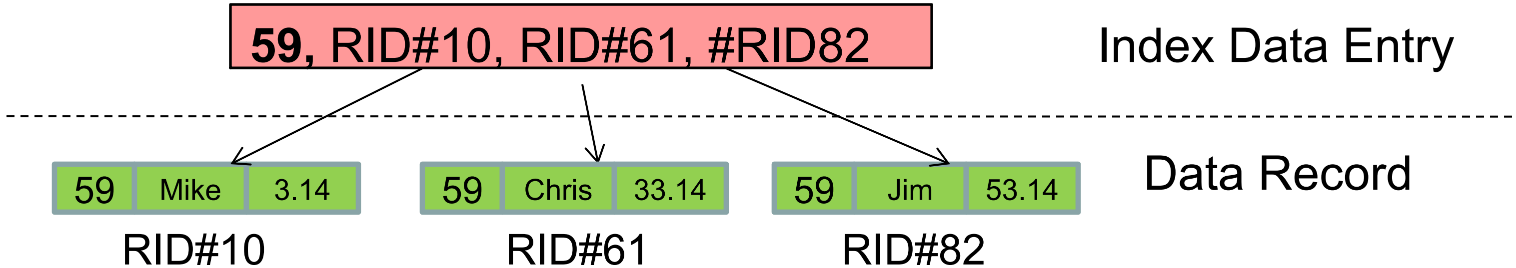
Results in a
Index File Organization!

59, Mike, 3.14 — Index Data Entry

- **Alternative 2: <k, RID>**

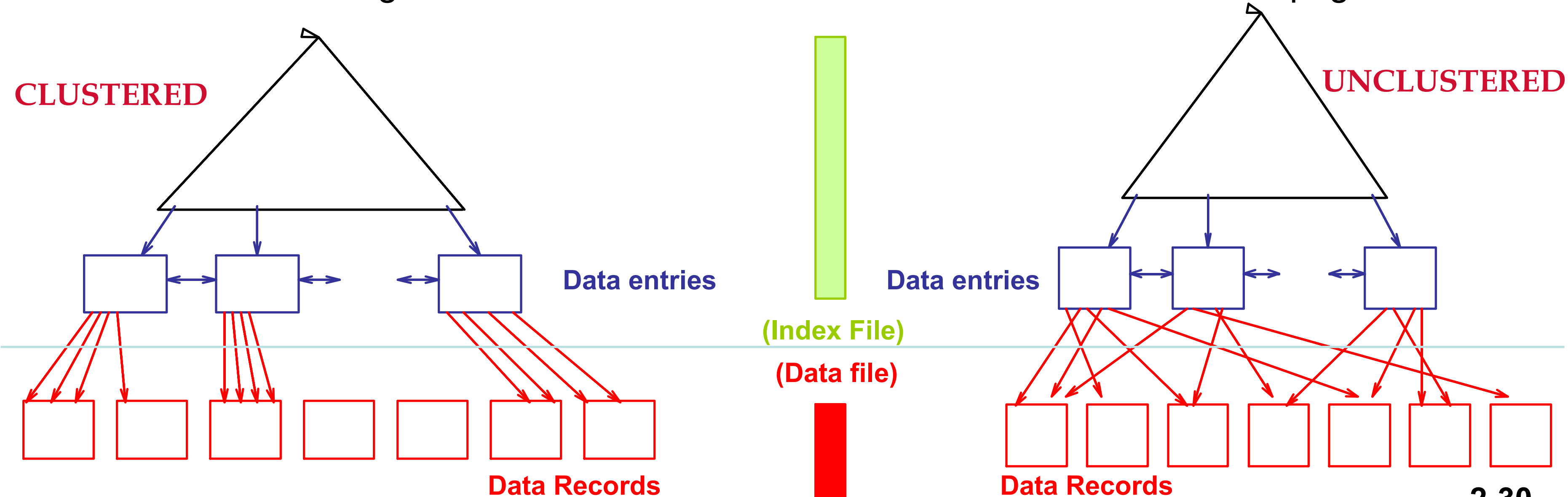



- **Alternative 3: <k, [RID,…,RID]>**



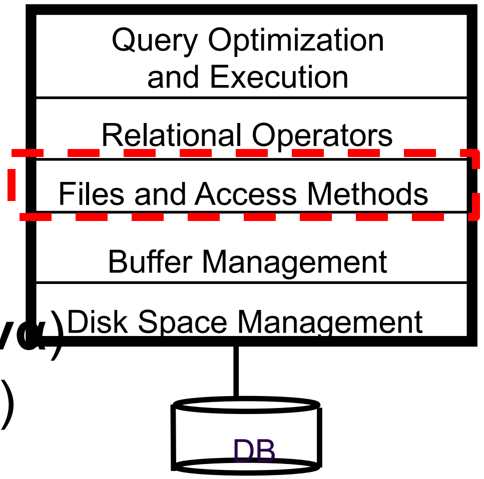
# Clustered vs. Unclustered Indexes
## (Ομαδοποιημένα vs. Μη-Ομαδοποιημένα Ευρετήρια)

- *Clustered* Index (Ομαδοποιημένο Ευρετήριο): If **order (διάταξη)** of **data records** is the same as, or `close to', order of **data entries,** else called unclustered index.
- **Alternative 1** implies **clustered** (since datarec same as dateentry)
  - Faster Range Queries: Consecutive data records reside on the same page.
- **Alternatives 2,3** are usually **unclustered**.
  - Slower Range Queries: Consecutive data records reside on different pages



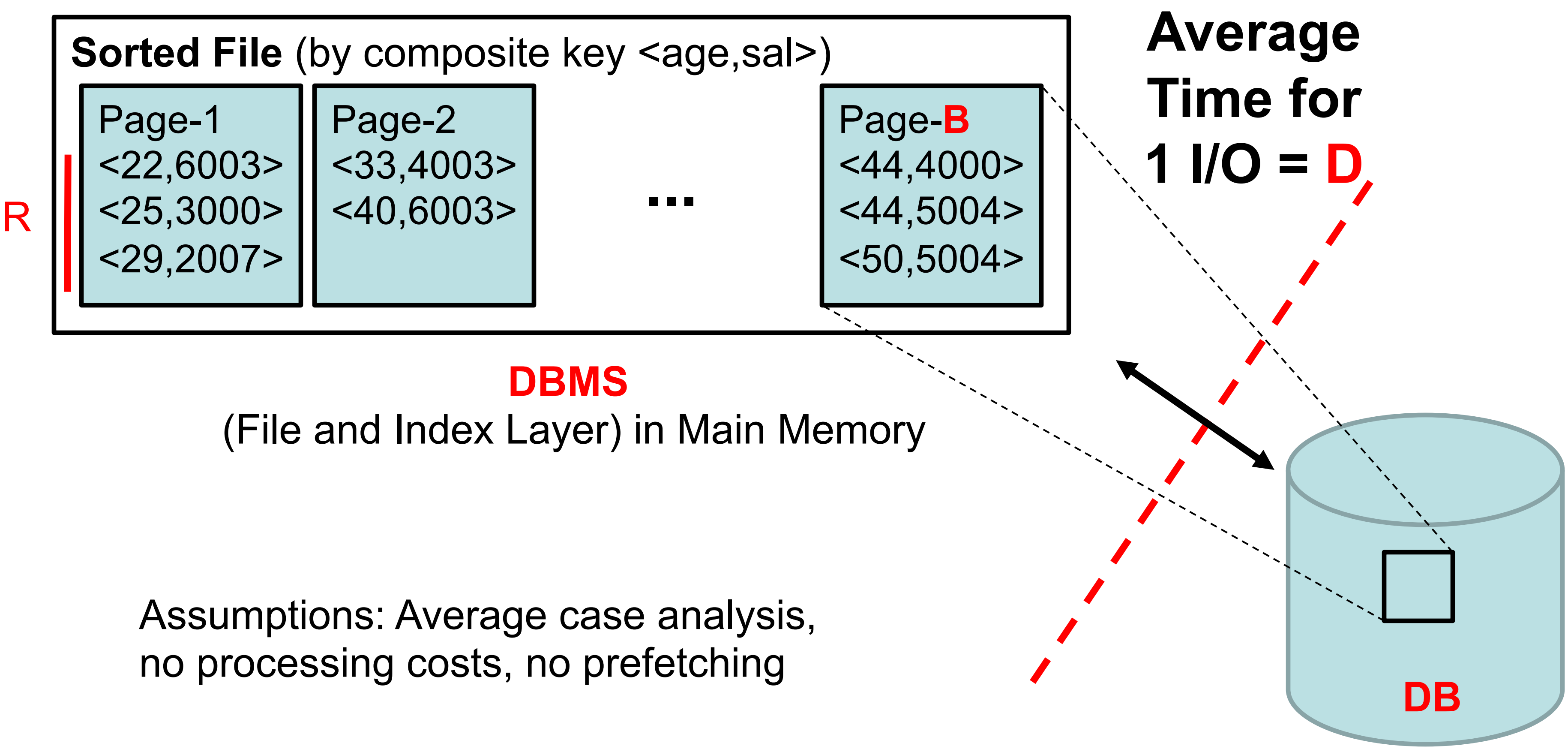
# Lecture Outline
## Overview of Storage and Indexing

- **Note:** The subsequent slides aim to ***qualitatively compare (ποιοτική σύγκριση)*** the file organization and indexes alternatives we introduced previously.
- 8.4) Comparison of File Organization
  - System and Cost Model (Μοντέλο Κόστους)
  - **Heap** Files, **Sorted** Files and **Clustered** Files (Αρχεία: **Σωρού**, **Ταξινομημένα**, **Ομαδοποιημένα**)
  - Comparison on I/O Costs (Σύγκριση Κόστους I/O)




- 8.5) Indexes and **Performance Tuning** (Ρύθμιση Επίδοσης)
  - Understanding the **Workload** (Εκτιμώντας τον Φόρτο Εργασίας)
  - Index **Specification** in SQL (Δήλωση Ευρετηρίων στην SQL)
  - **Index-Only Plans** (Πλάνα με Μόνο το Ευρετήριο)
  - Index Selection **Guidelines** (Οδηγίες Επιλογής Ευρετηρίων)

# System Model
## (Μοντέλο Συστήματος)




Assumptions: Average case analysis, no processing costs, no prefetching

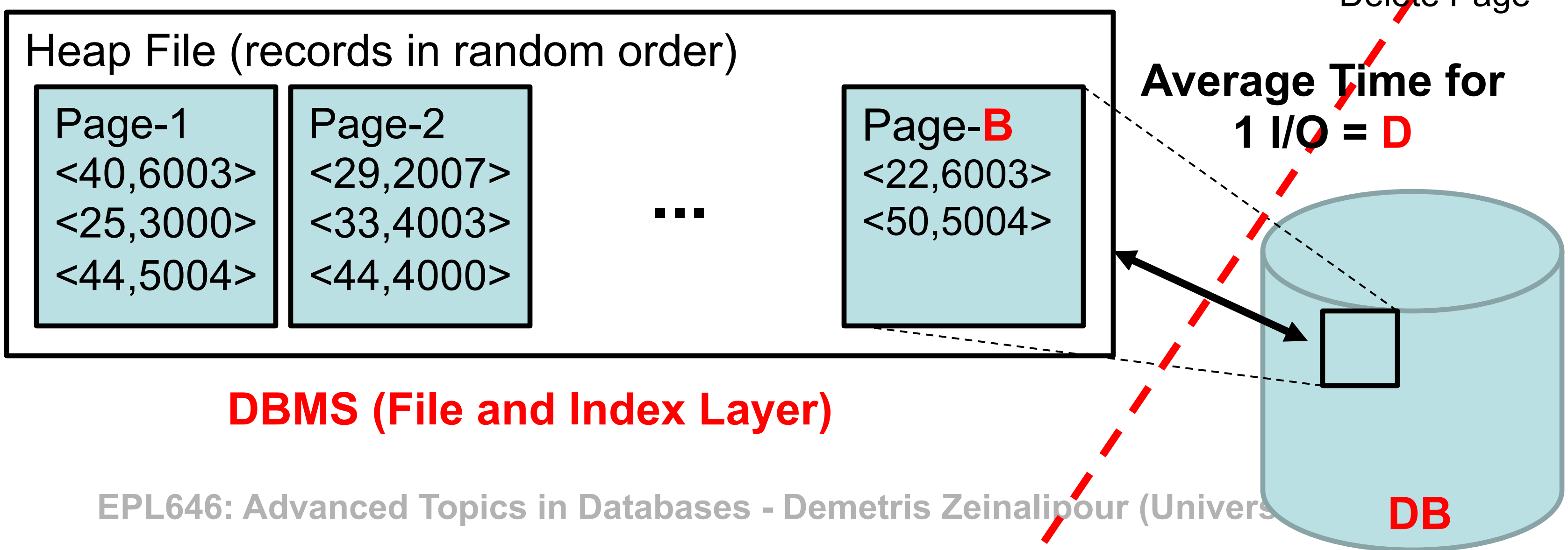
# Operations to Compare
## (Πράξεις που θα Συγκριθούν)

- **Scan (Σάρωση):** Fetch all records from disk
  - e.g., SELECT * FROM Employees;
- **Equality Selection (Επιλογή Ισότητας)**
  - e.g., SELECT * FROM Employees WHERE **age=33 AND sal=4003**;
- **Range selection (Επιλογή Διαστήματος)**
  - e.g., SELECT * FROM Employees WHERE **age BETWEEN 35 AND 45;**
  - e.g., SELECT * FROM Employees WHERE **35<age AND sal<=4000;**
  - ***But NOT:*** *SELECT * FROM Employees WHERE* ***sal>40;*** *(tree index is on age ☹)*
- **Insert a record (Εισαγωγή Εγγραφής)**
  - e.g., INSERT INTO Employees (age, sal) VALUES (45, 3000);
- **Delete a record (Διαγραφή Εγγραφής)**
  - e.g., DELETE FROM Employees WHERE age=45;

# **Heap** File Analysis
# (Ανάλυση Αρχείου Σωρού)

- **Heap File Assumptions**
  - Equality Selection on key <age,sal>
  - Equality Selection produces exactly 1 match.

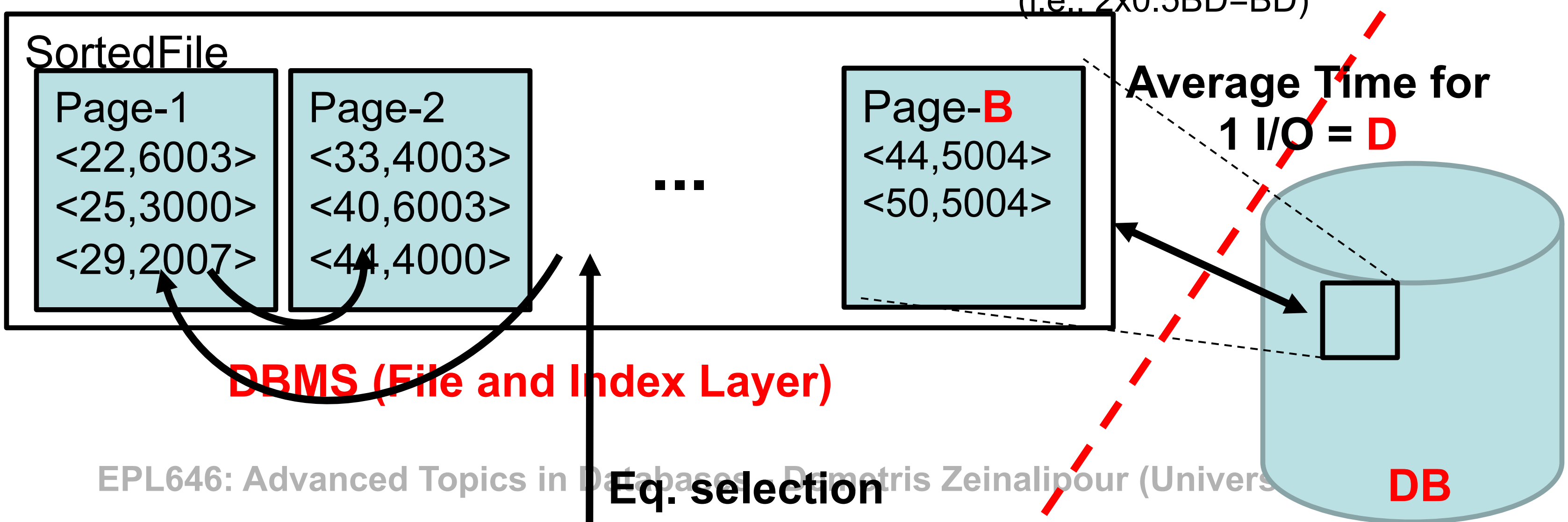
| ScanAll | Eq. Selection | Range Selection | Insert | Delete |
|---|---|---|---|---|
| BD | 0.5BD | BD | 2D | 0.5BD+ D |
| All records | On average we traverse ½ records | Traverse all to find pages in range | Read (last) PageB + Write PageB | Find Page + Delete Page |



# **Sorted** File Analysis (Ανάλυση Ταξινομημένου Αρχείου)

- **Sorted File Assumptions**
  - Files compacted after deletions (no holes in pages)

| ScanAll | Eq. Selection | Range Selection | Insert | Delete |
|---|---|---|---|---|
| BD | $D\log_2 B$ | $D(\log_2 B$ + #matches) | $D\log_2 B + BD$ | $D\log_2 B + BD$ |
| All records | Binary Search over B pages. Each I/O costs D | Binary Search for 1 tuple, then transfer rest qualifying pages | Binary Search for Correct Position + Shift (Read/Write) ½ subsequent pages (i.e., 2x0.5BD=BD) | Same as Insert but ½ pages are shifted back in order to compact the file |



# Understanding the Workload (Εκτιμώντας τον Φόρτο Εργασίας)

- **Workload (Φόρτος Εργασίας):** The typical mix of **i) Query (Select)** and ii) **Update (Insert/Delete/Update)** operations in a DBMS system.
- i) For each **query/update** in the **workload** :
  - Which types are involved (Select,Insert,Delete,Update)
  - Which **relations**/attributes**(σχέσεις, χαρακτηριστικά)** does it **access**?
  - Which **attributes** are involved in **selection/join** (επιλογή/ συνένωση) conditions? How **selective** are these conditions likely to be?
- **Selectivity (Επιλεκτικότητα της Συνθήκης):** The fraction of tuples selected by a selection condition is referred to as the selectivity of the condition.

E.g., $\sigma_{age>40}$**(EMPLOYEE)** returns 10 out of 1000 tuples. **Selectivity=1%**

# Index Specification in SQL
# Δήλωση Ευρετηρίου στη SQL

- The **SQL standard (up until SQL 2008)** does not include any statement for **creating/dropping** indexes.
- **However**, in practice **every major DBMS supports** such **indexes (access methods)** such as **Btrees, Hash, Rtrees, GIST.**

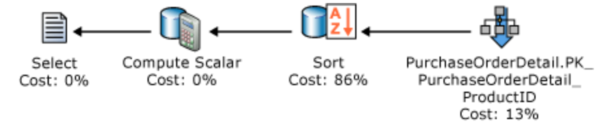
***Example from the PostgreSQL DBMS***

```
CREATE INDEX AgeSalIndex
    ON Employees (age, sal)
    USING BTREE
    WHERE sal > 3000
```

# Choice of Indexes
## (Επιλογή των Ευρετηρίων)

- The DBA is usually confronted with several questions in regards to indexes:
  - **Which relations** should have indexes?
  - What **type** of index should we use? Clustered? Hash? Btree?
  - What **attribute(s)** should be the search key?
  - Should we build **several indexes**?

SQL Server 2014 Index Guidelines: https://docs.microsoft.com/en-us/sql/2014-toc/sql-server-index-design-guide?view=sql-server-2014



# Index Selection Guidelines
# (Οδηγίες Επιλογής των Ευρετηρίων)

- **Tip 1:** Consider the **queries executed most of the time** (most important ones), e.g., for Oracle :
  - SELECT executions, sql_text FROM v$sqlarea ORDER BY executions desc;
  - V$ => Oracle's Dynamic Performance Views
- **Tip 2:** Try to choose indexes that **benefit as many queries as possible**
- **Tip 3:** Attributes in **WHERE** clause are candidates for index keys.
- **Tip 4:** **Hash** vs. **Tree**
  - **Exact match** condition suggests **Hash index**.
  - **Range query** suggests **tree index**.

# Index Selection Guidelines
## (Οδηγίες Επιλογής των Ευρετηρίων)

- **Tip 5:** Consider the best plan using the **current indexes**, and see if a better plan is possible with an additional index. If so, create it!
- **Tip 6:** Since only one index can be **clustered** per relation, choose it based on important queries that would benefit the most from clustering.
- **Tip 7:** **Multi-attribute <a,b,c> search keys** should be considered when a WHERE clause contains several conditions (e.g., a=3 and b>3 and c>3).
- **Tip 8:** Indexes can make **queries go** faster but **updates** become **slower**. Indexes also require additional disk space, choose them wisely!