



Chapter 13: Data Storage Structures

Database System Concepts, 7th Ed.

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File Organization

- The database is stored as a collection of *files*.
 - Each file is a sequence of *records*.
 - A record is a sequence of fields.
- One approach
 - Assume record size is fixed
 - Each file has records of one particular type only
 - Different files are used for different relations
- This case is easiest to implement; will consider variable length records later
- We assume that records are smaller than a disk block



Instructor Record

- Assume that each character occupies 1 byte and that numeric (8,2) occupies 8 bytes.
- Let's assume we allocate the maximum number of bytes that each attribute can hold.
- Then, the *instructor* record is 53 bytes long. A simple approach is to use the first 53 bytes for the first record, the next 53 bytes for the second record, and so on

```
type instructor = record
    ID varchar (5);
    name varchar(20);
    dept_name varchar (20);
    salary numeric (8,2);
end
```



Fixed-Length Records

- Simple approach:
 - Store record i starting from byte $n * (i - 1)$, where n is the size of each record.
 - Record access is simple but records may cross blocks
 - Modification: do not allow records to cross block boundaries

record 0	10101	Srinivasan	Comp. Sci.	65000
record 1	12121	Wu	Finance	90000
record 2	15151	Mozart	Music	40000
record 3	22222	Einstein	Physics	95000
record 4	32343	El Said	History	60000
record 5	33456	Gold	Physics	87000
record 6	45565	Katz	Comp. Sci.	75000
record 7	58583	Califieri	History	62000
record 8	76543	Singh	Finance	80000
record 9	76766	Crick	Biology	72000
record 10	83821	Brandt	Comp. Sci.	92000
record 11	98345	Kim	Elec. Eng.	80000



Fixed-Length Records

- Deletion of record i : alternatives:
 - **move records $i + 1, \dots, n$ to $i, \dots, n - 1$**
 - move record n to i
 - do not move records, but link all free records on a *free list*

Record 3 deleted

record 0	10101	Srinivasan	Comp. Sci.	65000
record 1	12121	Wu	Finance	90000
record 2	15151	Mozart	Music	40000
record 4	32343	El Said	History	60000
record 5	33456	Gold	Physics	87000
record 6	45565	Katz	Comp. Sci.	75000
record 7	58583	Califieri	History	62000
record 8	76543	Singh	Finance	80000
record 9	76766	Crick	Biology	72000
record 10	83821	Brandt	Comp. Sci.	92000
record 11	98345	Kim	Elec. Eng.	80000



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 - move records $i + 1, \dots, n$ to $i, \dots, n - 1$
 - **move record n to i**
 - do not move records, but link all free records on a *free list*

Record 3 deleted and replaced by record 11

record 0	10101	Srinivasan	Comp. Sci.	65000
record 1	12121	Wu	Finance	90000
record 2	15151	Mozart	Music	40000
record 11	98345	Kim	Elec. Eng.	80000
record 4	32343	El Said	History	60000
record 5	33456	Gold	Physics	87000
record 6	45565	Katz	Comp. Sci.	75000
record 7	58583	Califieri	History	62000
record 8	76543	Singh	Finance	80000
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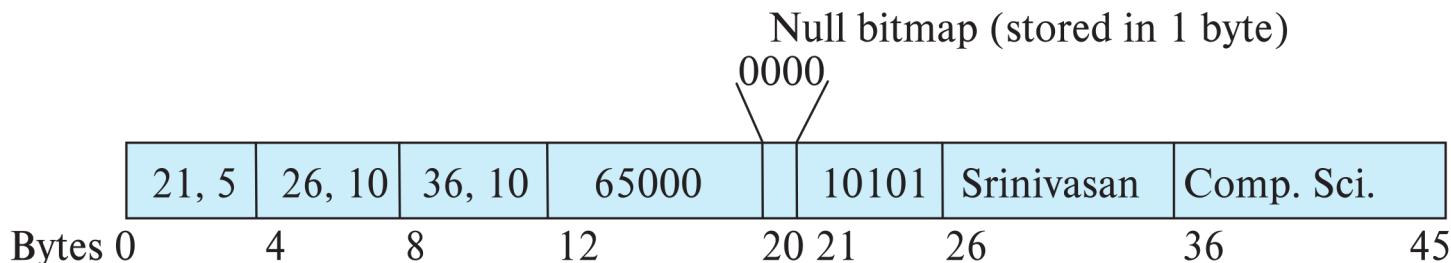
header				
record 0	10101	Srinivasan	Comp. Sci.	65000
record 1				
record 2	15151	Mozart	Music	40000
record 3	22222	Einstein	Physics	95000
record 4				
record 5	33456	Gold	Physics	87000
record 6				
record 7	58583	Califieri	History	62000
record 8	76543	Singh	Finance	80000
record 9	76766	Crick	Biology	72000
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Diagram illustrating the deletion of record 5 (Gold) from the fixed-length record table. Arrows point from the last four records (records 6 through 9) to a horizontal line representing a free list.



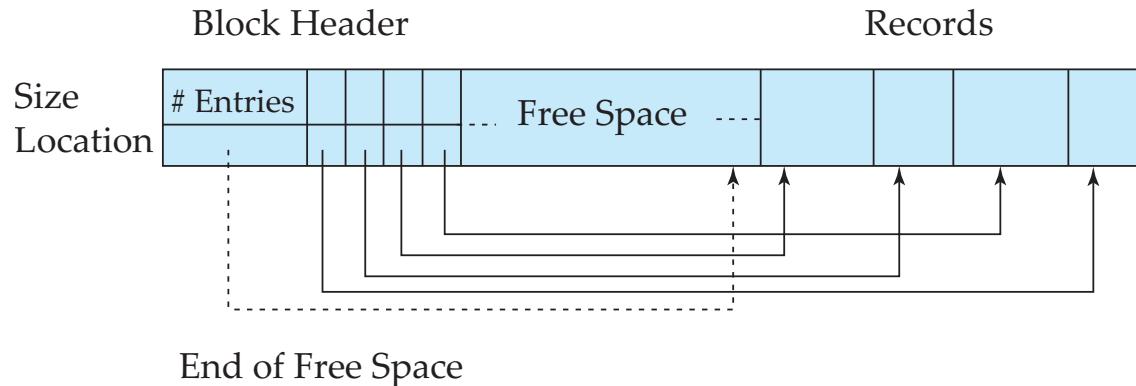
Variable-Length Records

- Variable-length records arise in database systems in several ways:
 - Storage of multiple record types in a file.
 - Record types that allow variable lengths for one or more fields such as strings (**varchar**)
 - Record types that allow repeating fields (used in some older data models).
- Attributes are stored in order
- Variable length attributes represented by fixed size (offset, length), with actual data stored after all fixed length attributes
- Null values represented by null-value bitmap , which indicates which attributes of the record have a null value.





Variable-Length Records: Slotted Page Structure



- **Slotted page** header contains:
 - number of record entries
 - end of free space in the block
 - An array whose entries contain the location and size of each record
- Records can be moved around within a page to keep them contiguous with no empty space between them; entry in the header must be updated.
- Records can be grown or shrunk, as long as there is space in the block.
 - The cost of moving the records is not too high, since the size of a block is limited: typical values are around 4 to 8 kilobytes.



Storing Large Objects

- E.g., blob/clob types
- Records must be smaller than pages
- Alternatives:
 - Store as files in file systems
 - Store as files managed by database
 - Break into pieces and store in multiple tuples in separate relation
 - PostgreSQL TOAST



Organization of Records in Files

- **Heap** – record can be placed anywhere in the file where there is space
- **Sequential** – store records in sequential order, based on the value of the search key of each record
- In a **multitable clustering file organization** records of several different relations can be stored in the same file
 - Motivation: store related records on the same block to minimize I/O
- **B⁺-tree file organization**
 - Ordered storage even with inserts/deletes
- **Hashing** – a hash function computed on search key; the result specifies in which block of the file the record should be placed



Heap File Organization

- Records can be placed anywhere in the file where there is free space
 - Records usually do not move once allocated
 - Important to be able to efficiently find free space within file
 - **Free-space map is** to track which blocks have free space to store records.
 - Array with 1 entry per block. Each entry is a few bits to a byte, and records fraction of block that is free
 - If 3 bits are used to store the occupancy fraction; the value at position i should be divided by 8 to get the free-space fraction for block i .
 - For example, a value of 7 indicates that at least $7/8$ th of the space in the block is free.
- | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 2 | 1 | 4 | 7 | 3 | 6 | 5 | 1 | 2 | 0 | 1 | 1 | 0 | 5 | 6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
- Can have second-level free-space map. In example below, each entry stores maximum from 4 entries of first-level free-space map

4	7	2	6
---	---	---	---

- Free space map written to disk periodically, OK to have wrong (old) values for some entries (will be detected and fixed)



Sequential File Organization

- Suitable for applications that require sequential processing of the entire file
- The records in the file are ordered by a **search-key**

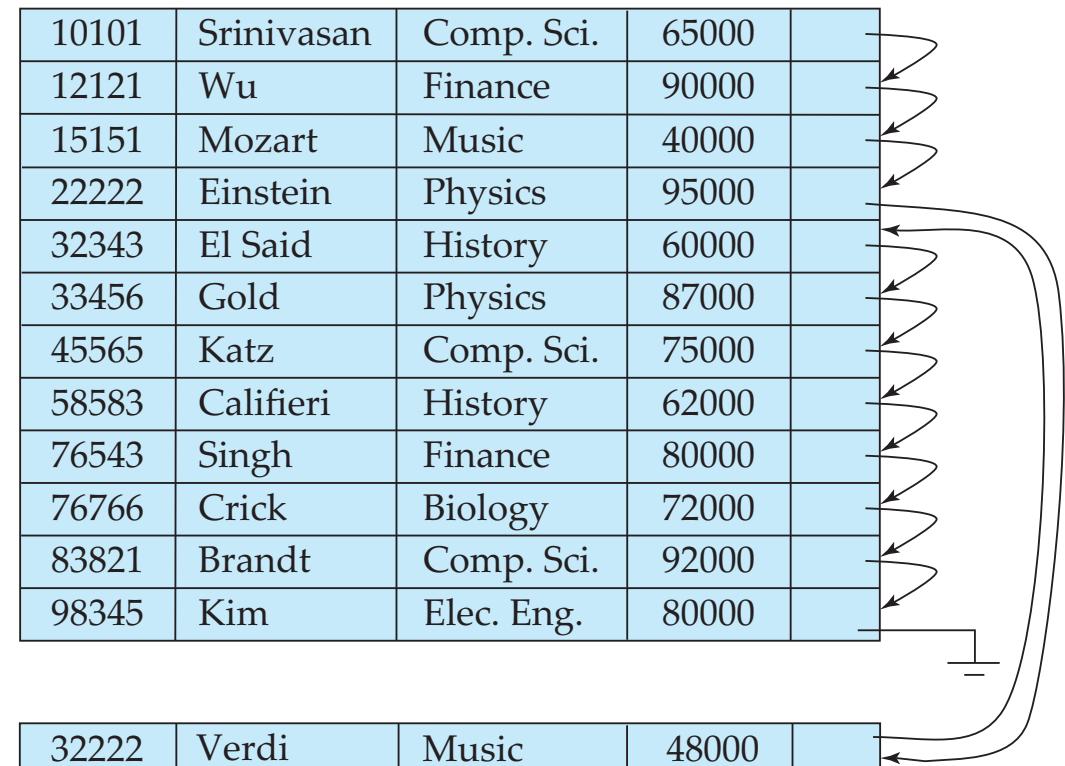
10101	Srinivasan	Comp. Sci.	65000	
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A diagram illustrating a sequential file organization. It consists of a table with 12 rows, each representing a record. The first column contains unique search keys. Vertical arrows point from the right edge of each row to a single vertical line at the bottom, symbolizing the sequential access path through the file.



Sequential File Organization (Cont.)

- Deletion – use pointer chains
- Insertion – locate the position where the record is to be inserted
 - if there is free space insert there
 - if no free space, insert the record in an **overflow block**
 - In either case, pointer chain must be updated
- Need to reorganize the file from time to time to restore sequential order





Multitable Clustering File Organization

Store several relations in one file using a **multitable clustering** file organization

department

<i>dept_name</i>	<i>building</i>	<i>budget</i>
Comp. Sci.	Taylor	100000
Physics	Watson	70000

instructor

<i>ID</i>	<i>name</i>	<i>dept_name</i>	<i>salary</i>
10101	Srinivasan	Comp. Sci.	65000
33456	Gold	Physics	87000
45565	Katz	Comp. Sci.	75000
83821	Brandt	Comp. Sci.	92000

multitable clustering
of *department* and
instructor

Comp. Sci.	Taylor	100000	
10101	Srinivasan	Comp. Sci.	65000
45565	Katz	Comp. Sci.	75000
83821	Brandt	Comp. Sci.	92000
Physics	Watson	70000	
33456	Gold	Physics	87000



Multitable Clustering File Organization (cont.)

- Good for queries involving *department* \bowtie *instructor*, and for queries involving one single department and its instructors
- Bad for queries involving only, for example, *department*
 - Would require more block accesses since each block now contains significantly fewer *department* records.
- Results in variable size records
- Can add pointer chains to link records of a particular relation



Partitioning

- **Table partitioning:** Records in a relation can be partitioned into smaller relations that are stored separately
- E.g., *transaction* relation may be partitioned into *transaction_2018*, *transaction_2019*, etc.
- Queries written on *transaction* must access records in all partitions
 - Unless query has a selection such as *year=2019*, in which case only one partition is needed
- Partitioning
 - Reduces costs of some operations such as free space management
 - Allows different partitions to be stored on different storage devices
 - E.g., *transaction* partition for current year on SSD, for older years on magnetic disk



Data Dictionary Storage

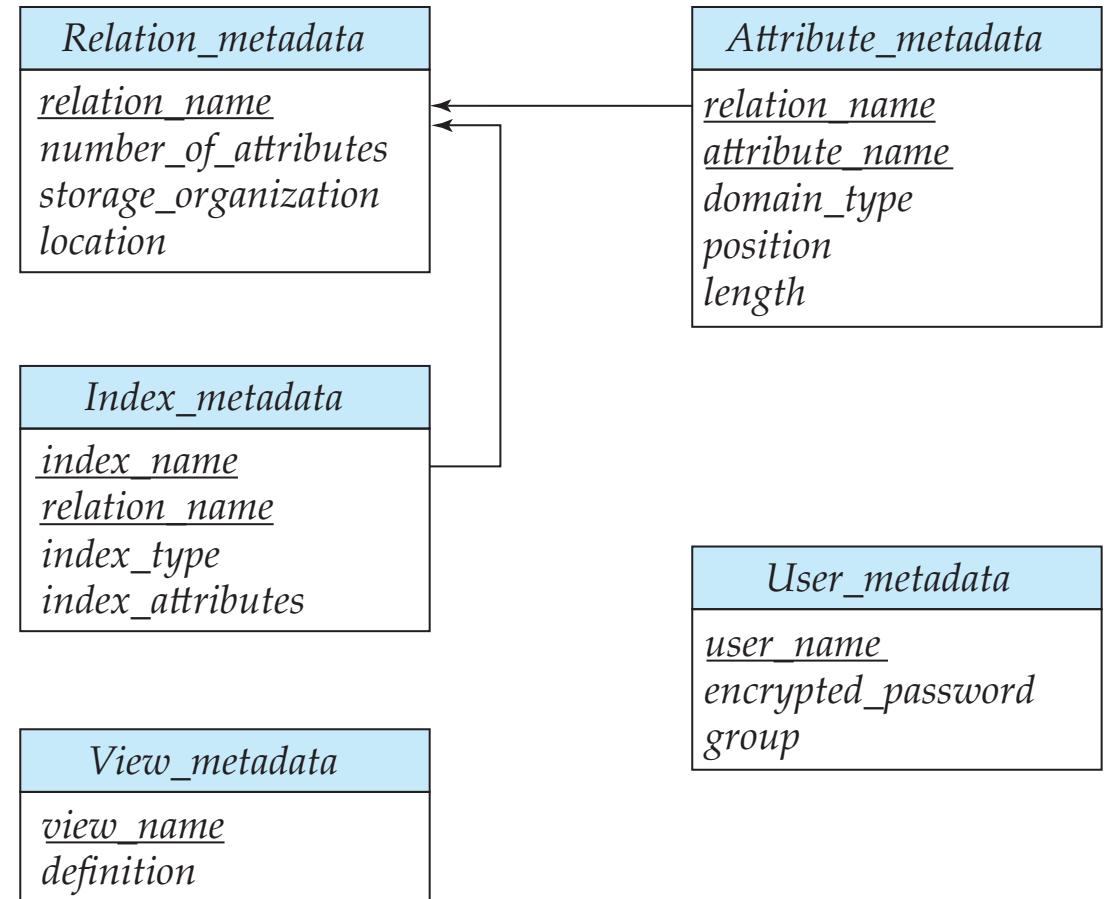
The **Data dictionary** (also called **system catalog**) stores **metadata**; that is, data about data, such as

- Information about relations
 - names of relations
 - names, types and lengths of attributes of each relation
 - names and definitions of views
 - integrity constraints
- User and accounting information, including passwords
- Statistical and descriptive data
 - number of tuples in each relation
- Physical file organization information
 - How relation is stored (sequential/hash/...)
 - Physical location of relation
- Information about indices



Relational Representation of System Metadata

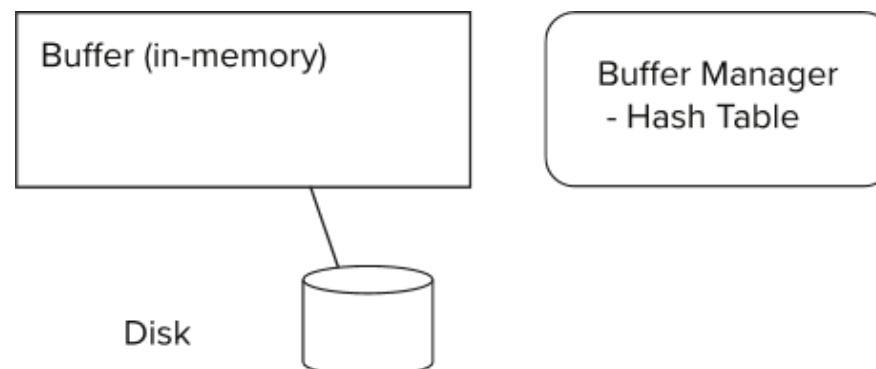
- Relational representation on disk
- Specialized data structures designed for efficient access, in memory





Storage Access

- Blocks are units of both storage allocation and data transfer.
- Database system seeks to minimize the number of block transfers between the disk and memory. We can reduce the number of disk accesses by keeping as many blocks as possible in main memory.
- **Buffer** – portion of main memory available to store copies of disk blocks.
- **Buffer manager** – subsystem responsible for allocating buffer space in main memory.





Buffer Manager

- Programs call on the buffer manager when they need a block from disk.
 - If the block is already in the buffer, buffer manager returns the address of the block in main memory
 - If the block is not in the buffer, the buffer manager
 - Allocates space in the buffer for the block
 - Replacing (throwing out) some other block, if required, to make space for the new block.
 - Replaced block written back to disk only if it was modified since the most recent time that it was written to/fetched from the disk.
 - Reads the block from the disk to the buffer, and returns the address of the block in main memory to requester.



Buffer Manager

- **Buffer replacement strategy** (details coming up!)
- **Pinned block:** memory block that is not allowed to be written back to disk
 - **Pin** done before reading/writing data from a block
 - **Unpin** done when read /write is complete
 - Multiple concurrent pin/unpin operations possible
 - Keep a pin count, buffer block can be evicted only if pin count = 0
- **Shared and exclusive locks on buffer**
 - Needed to prevent concurrent operations from reading page contents as they are moved/reorganized, and to ensure only one move/reorganize at a time
 - Readers get shared lock, updates to a block require exclusive lock
 - **Locking rules:**
 - Only one process can get exclusive lock at a time
 - Shared lock cannot be concurrently with exclusive lock
 - Multiple processes may be given shared lock concurrently



Buffer-Replacement Policies

- Most operating systems replace the block **least recently used** (LRU strategy)
 - Idea behind LRU – use past pattern of block references as a predictor of future references
 - LRU can be bad for some queries
- Queries have well-defined access patterns (such as sequential scans), and a database system can use the information in a user's query to predict future references
- Mixed strategy with hints on replacement strategy provided by the query optimizer is preferable
- Example of bad access pattern for LRU: when computing the join of 2 relations r and s by a nested loops

```
for each tuple  $tr$  of  $r$  do
    for each tuple  $ts$  of  $s$  do
        if the tuples  $tr$  and  $ts$  match ...
```



Buffer-Replacement Policies (Cont.)

- **Toss-immediate** strategy – frees the space occupied by a block as soon as the final tuple of that block has been processed
- **Most recently used (MRU) strategy** – system must pin the block currently being processed. After the final tuple of that block has been processed, the block is unpinned, and it becomes the most recently used block.
- Buffer manager can use statistical information regarding the probability that a request will reference a particular relation
 - E.g., the data dictionary is frequently accessed. Heuristic: keep data-dictionary blocks in main memory buffer
- Operating system or buffer manager may reorder writes
 - Can lead to corruption of data structures on disk
 - E.g., linked list of blocks with missing block on disk
 - File systems perform consistency check to detect such situations
 - Careful ordering of writes can avoid many such problems



Column-Oriented Storage

- Also known as **columnar representation**
- Store each attribute of a relation separately
- Example

10101	Srinivasan	Comp. Sci.	65000
12121	Wu	Finance	90000
15151	Mozart	Music	40000
22222	Einstein	Physics	95000
32343	El Said	History	60000
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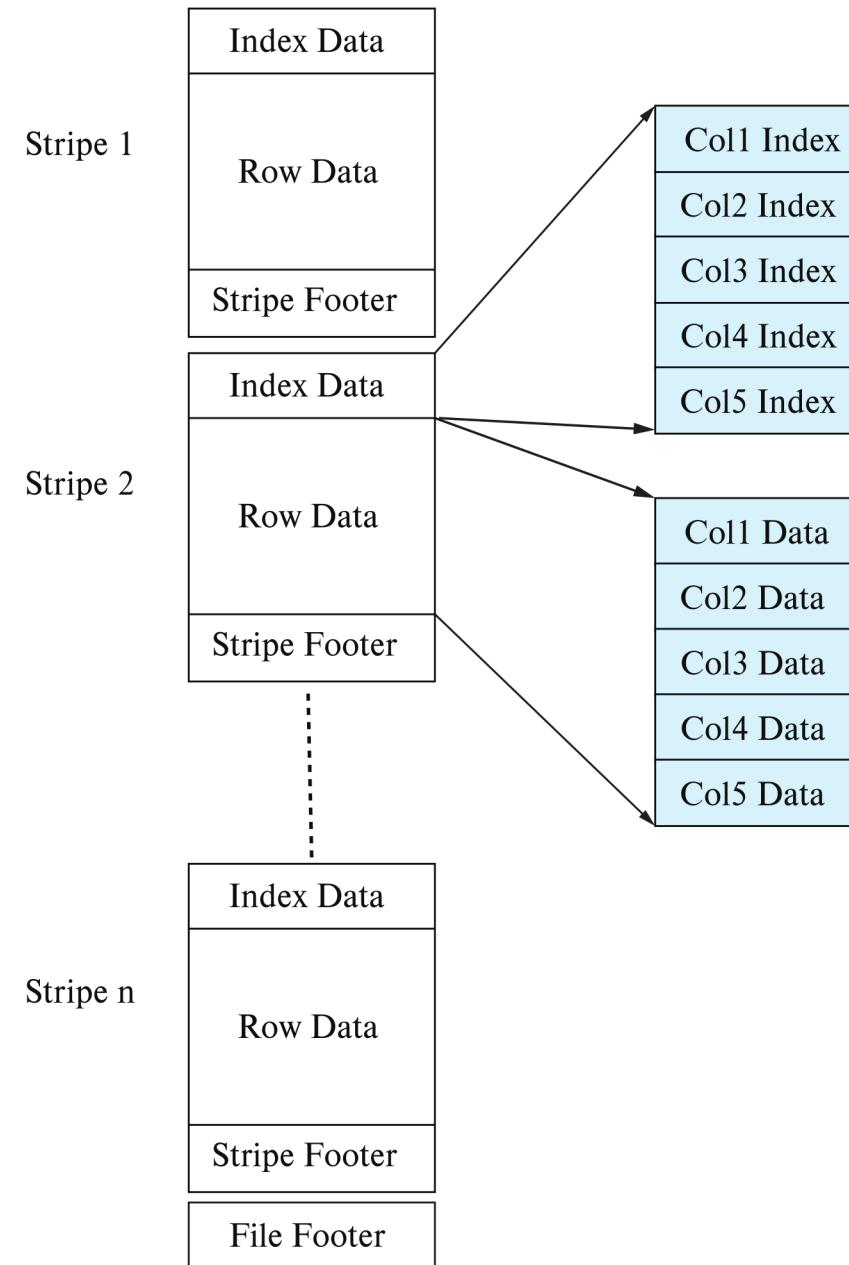
Columnar Representation

- Benefits:
 - Reduced IO if only some attributes are accessed
 - Improved CPU cache performance
 - Improved compression due to having same type of values
 - **Vector processing** on modern CPU architectures allows a CPU operation to be applied in parallel on a number of elements of an array.
- Drawbacks
 - Cost of tuple reconstruction from columnar representation
 - Cost of tuple deletion and update
 - Cost of decompression, i.e., fetching data from a compressed representation requires *decompression*
- Columnar representation found to be more efficient for decision support
- Traditional row-oriented representation preferable for transaction processing
- Some databases support both representations
 - Called **hybrid row/column stores**



Columnar File Representation

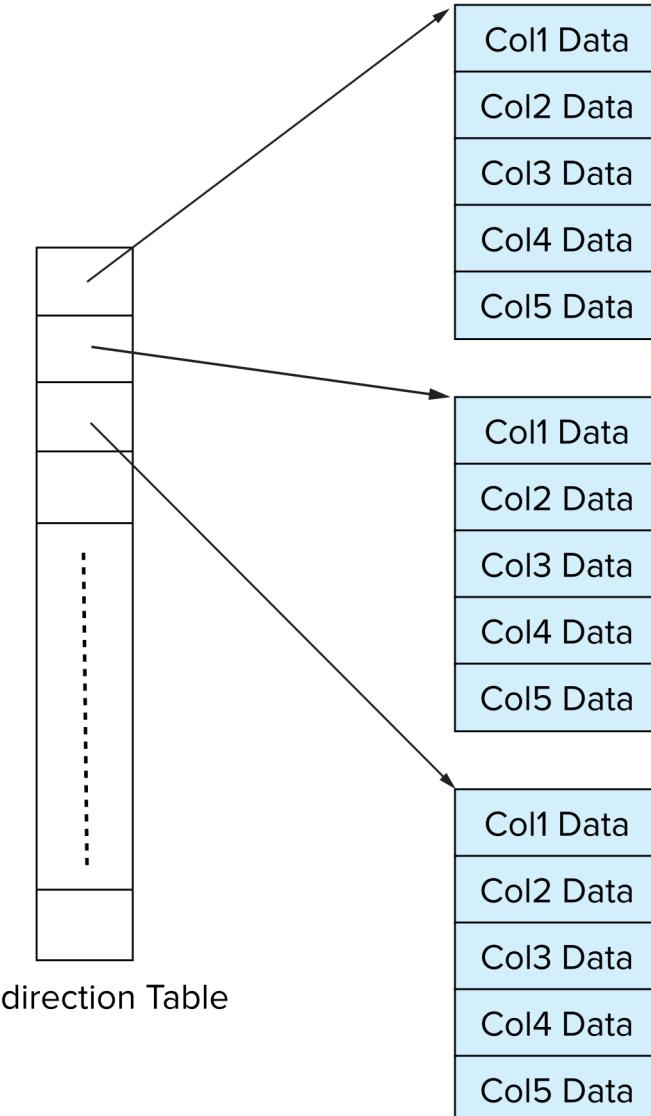
- ORC and Parquet: file formats with columnar storage inside file
- Very popular for big-data applications
- Orc file format shown on right (some other info are ignored to avoid clutter):





Storage Organization in Main-Memory Databases

- A **main-memory database** is a database where all data reside in memory
- Can store records directly in memory without a buffer manager
- Column-oriented storage can be used in-memory for decision support applications
 - Compression reduces memory requirement





End of Chapter 13