CS525: Advanced Database Organization

Notes 3: Database Storage
Part II

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Slides: adapted from courses taught by Andy Pavlo, Carnegie Mellon University, Hector Garcia-Molina, Stanford, & Shun Yan Cheung, Emory University

Reading

- Database Systems: The Complete Book, 2nd Edition,
  - *Chapter 2: Data Storage*
- Database System Concepts (6th/7th Edition)
  - *Chapter 10 (6th)/ Chapter 13 (7th)*

Database Storage

- `Problem#1`: How the DBMS represents the database in files on disk
    - i.e., how to lay out data on disk.
- `Problem#2`: How the DBMS manages its memory and move data back-and-forth from disk.

Today's Agenda

- Data Representation
  - *How the system stores the actual binary data for individual attributes (columns) within the database.*
- System Catalogs
  - *Internal metadata is maintained by the database to understand both the data that is actually stored and how to interpret the bytes within the tuples*
- Storage Models
  - *How data is organized and stored within the database system.*
- Modification of Tuples

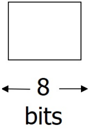
Tuple Storage

- A tuple is essentially a sequence of bytes (byte arrays).
- It is up to the DBMS to know how to interpret those bytes to derive the values for attributes.
- The DBMS's catalogs contain the schema information about tables that the system uses to figure out the tuple's layout.

What are the data items we want to store?

- a salary
- a name
- a date
- a picture

⇒ What we have available: Bytes



Data Representation

- How a DBMS stores the bytes for a value?
  - *How the DBMS stores the binary data for different types of values or attributes?*
- There are five high level data types that can be stored in tuples:
  - integers,
  - variable precision numbers,
  - fixed point precision numbers,
  - variable length values, and
  - dates/times.

IEEE-754 Standard[1]

- This is a specific standard that defines the binary representation of floating-point numbers (like float and double) and their arithmetic operations in computing.
- Ensures consistency in how floating-point numbers are stored and manipulated across different computer architectures and programming languages.
- It specifies the format for representing real numbers, including the sign bit, exponent, and mantissa (fractional part).
- Example: 32 bit in Standard IEEE 754:

To be represented in this format, a number should be in the following normalized form.

(+ or -) 1.(mantissa) x 2^(exponent)

[1] *https://en.wikipedia.org/wiki/IEEE_754*

Data Representation

How a DBMS stores the bytes for a value

- `INTEGER/BIGINT/SMALLINT/TINYINT`
  - `C/C++` Representation
    - All integers are stored in their "native" `C/C++` types[1] within the database.
- `FLOAT/REAL` vs. `NUMERIC/DECIMAL`
  - IEEE-754 Standard/Fixed-point Decimals
- `VARCHAR/VARBINARY/TEXT/BLOB`
  - Header with length, followed by data bytes.
- `TIME/DATE/TIMESTAMP`
  - 32/64-bit integer of (micro)seconds since Unix epoch

[1] *refer to the fundamental data types that are supported directly by the C/C++ programming languages without any additional libraries or custom data types. These native data types are typically used for storing and manipulating data efficiently in these languages.*

Data Representation: Integers

- `C/C++` Representation
  - Most DBMSs store integers using their "native" `C/C++` types as specified by the IEEE-754 standard.
- These values are fixed length.
- Examples: `INTEGER/BIGINT/SMALLINT/TINYINT`

Variable Precision Numbers

- These are inexact[1], variable-precision numeric types that uses the "native" `C/C++` types.
- Store directly as specified by IEEE-754 standard.
- These values are also fixed length.
- Typically faster than arbitrary precision numbers because the CPU can execute instructions on them directly.
  - Example: `FLOAT, REAL/DOUBLE`
- but can have rounding errors[2] when performing computations due to the fact that some numbers cannot be represented precisely in binary floating-point format.
- As a result, calculations may yield slightly inaccurate results.
  - To avoid this issue, we use Fixed-Point Precision Numbers.

[1] *Inexact means that some values cannot be converted exactly to the internal format and are stored as approximations, so that storing and retrieving a value might show slight discrepancies.*

[2] *rounding error, is the difference between the result produced by a given algorithm using exact arithmetic and the result produced by the same algorithm using finite-precision, rounded arithmetic.*

Variable Precision Numbers

- Rounding Example

```c
#include <stdio.h>

int main(int argc, char* argv[]) {
   float x = 0.1;
   float y = 0.2;
   printf("x+y = %f\n", x+y);
   printf("0.3 = %f\n", 0.3);
}
```

```
Output
x+y = 0.300000
0.3 = 0.300000
```

Variable Precision Numbers

- Rounding Example

```
#include <stdio.h>

int main(int argc, char* argv[]) {
    float x = 0.1;
    float y = 0.2;
    printf("x+y = %.20f\n", x+y);
    printf("0.3 = %.20f\n", 0.3);
}
```

```
Output
x+y = 0.30000001192092895508
0.3 = 0.29999999999999998890
```

Variable Precision Numbers

- Rounding Example

```
public class RoundingError {
 public static void main(String[] args) {
   float x = 1.0f;
   for (int i = 0; i < 10; i++) {
         x -= 0.1f;
   }
   System.out.printf("Result w precision: %.1f\n", x);
   System.out.printf("Result w precision 10: %.10f\n",x);
 }
}
```

```
Output
Result w precision 1 : -0.0
Result w precision 10: -0.0000000745
```

Data Representation: Fixed Point Precision Numbers

- Numeric data types with arbitrary precision and scale.
- Used when round errors are unacceptable.
  - Example: `NUMERIC, DECIMAL`
- Typically stored in an exact, variable-length binary representation with additional meta-data that specifies the length of the data and the position of the decimal point.
  - Like a `VARCHAR` but not stored as a string
- but the DBMS pays a performance penalty to get this accuracy.
  - *Calculations involving fixed-point precision numbers may be slower compared to operations with native numeric types like FLOAT or DOUBLE, which use hardware-based floating-point arithmetic.*

PostgreSQL: NUMERIC

of Digits

Weight of 1st Digit

Scale Factor

Positive/Negative/NaN

Digit Storage

```c
typedef unsigned char NumericDigit;
typedef struct {
  int ndigits;
  int weight;
  int scale;
  int sign;
  NumericDigit *digits;
} numeric;
```

```c
/*
 * add_var() -
 *
 *  Full version of add functionality on variable level (handling signs).
 *  result might point to one of the operands too without danger.
 */
static void
add_var(const NumericVar *var1, const NumericVar *var2, NumericVar *result)
{
    /*
     * Decide on the signs of the two variables what to do
     */
    if (var1->sign == NUMERIC_POS)
    {
        if (var2->sign == NUMERIC_POS)
        {
            /*
             * Both are positive result = +(ABS(var1) + ABS(var2))
             */
            add_abs(var1, var2, result);
            result->sign = NUMERIC_POS;
        }
        else
        {
            /*
             * var1 is positive, var2 is negative Must compare absolute values
             */
            switch (cmp_abs(var1, var2))
            {
                case 0:
                    /* ----------
                     * ABS(var1) == ABS(var2)
                     * result = ZERO
                     * ----------
                     */
                    zero_var(result);
                    result->dscale = Max(var1->dscale, var2->dscale);
                    break;

                case 1:
                    /* ----------
                     * ABS(var1) > ABS(var2)
                     * result = +(ABS(var1) - ABS(var2))
                     * ----------
                     */
                    sub_abs(var1, var2, result);
                    result->sign = NUMERIC_POS;
                    break;

                case -1:
                    /* ----------
                     * ABS(var1) < ABS(var2)
                     * result = -(ABS(var2) - ABS(var1))
                     * ----------
                     */
                    sub_abs(var2, var1, result);
                    result->sign = NUMERIC_NEG;
                    break;
            }
        }
    }
    else
    {
        if (var2->sign == NUMERIC_POS)
        {
            /* ----------
             * var1 is negative, var2 is positive
             * Must compare absolute values
             * ----------
             */
            switch (cmp_abs(var1, var2))
            {
                case 0:
                    /* ----------
                     * ABS(var1) == ABS(var2)
                     * result = ZERO
                     * ----------
                     */
                    zero_var(result);
                    result->dscale = Max(var1->dscale, var2->dscale);
                    break;
```

PostgreSQL Source Code, numeric.c

Data Representation: Variable Length Data

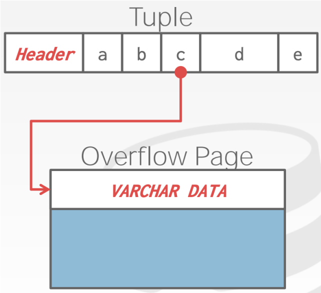
- These represent data types of arbitrary length.
  - An array of bytes of arbitrary length.
- Has a header that keeps track of the length of the string to make it easy to jump to the next value. It may also contain a checksum for the data.
- Example: `VARCHAR, VARBINARY, TEXT, BLOB`.

Large Values

- Most DBMSs don't allow a tuple to exceed the size of a single page.
- Handling tuples that exceed the size of a single page in a DBMS is a common challenge.
- DBMSs typically have strategies to deal with this situation to ensure data integrity and efficient storage.
- Two common approaches to handle such cases are:
  - overflow page
  - external storage

Large Values: Overflow Page

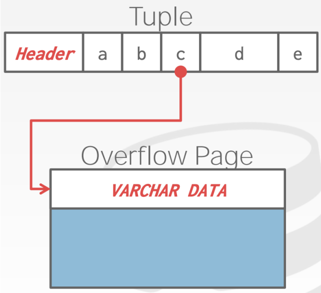
- To store values that are larger than a page, the DBMS uses separate overflow storage pages and have the tuple contain a reference to that page.
  - The main part of the tuple, which can fit within a single page, is stored in the primary page, while the overflowed part is stored in one or more additional overflow pages.
  - Overflow pages are linked to the primary page, forming a chain of pages that together represent the complete tuple.
  - When querying the data, the DBMS follows these chains of pages to reconstruct the complete tuple.



- These overflow pages can contain pointers to additional overflow pages until all the data can be stored.

Large Values: Overflow Page

- To store values that are larger than a page, the DBMS uses separate overflow storage pages and have the tuple contain a reference to that page.
- Different DBMSs have different name/specification/requirements when they do that:
  - `Postgres: TOAST (The Oversized-Attribute Storage Technique) (>2KB)`
  - `MySQL: Overflow (>` $\frac{1}{2}$ `size of page)`
  - `SQL Server: Overflow (> size of page)`



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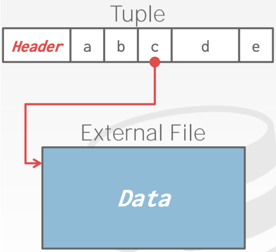
External Value Storage

- Some systems allow to store large data values, such as files or binary objects, in an external file rather than directly within the database, and then the tuple will contain a pointer to that file.
- Example:
  - if the database is storing photo information, the DBMS can store the photos in the external files rather than having them take up large amounts of space in the DBMS.

- Treated as a `BLOB` type
  - `Oracle: BFILE data type`
    - Contains a locator pointing to a large binary file stored outside the database.
  - `Microsoft: FILESTREAM data type`
- The DBMS **cannot** manipulate the contents of an external file.



- Reading: A paper explains the trade-offs between these two options:
  - To BLOB or Not To BLOB: Large Object Storage in a Database or a Filesystem

Data Representation: Dates and Times

- Varies widely across different database systems?
- However, a common approach is to represent dates and times as the number of (micro/milli)seconds since the Unix epoch[1].
- Example: `TIME, DATE, TIMESTAMP`.

[1] *The Unix epoch is a reference point in time, representing January 1, 1970, at 00:00:00 UTC (Coordinated Universal Time). It is widely used as a starting point for measuring time intervals.*

System Catalog

- In order for the DBMS to be able to decipher the contents of tuples, it maintains an internal catalog to tell it meta-data about the databases
  - A DBMS stores meta-data about databases in its internal catalogs.
- The meta-data will contain what tables and columns the databases have along with their types and the orderings of the values.
  - Tables, columns, indexes, views
  - Users, permissions
  - Internal statistics
- Almost every DBMS stores their a database's catalog in itself in the format that they use for their tables
  - They use special code to bootstrap[1] these catalog tables (wrap low-level access methods to access the catalog)

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[1] *Bootstrapping is the process of initializing a DBMS's catalog during system setup or database creation. During this phase, the DBMS uses low-level access methods or internal mechanisms to create the catalog tables and populate them with initial data*

System Catalog

- You can query the DBMS's internal `INFORMATION_SCHEMA` catalog to get info about the database.
  - ANSI standard set of read-only views that provide info about all of the tables, views, columns, and procedures in a database.
- DBMSs also have non-standard shortcuts to retrieve this information.

Accessing Table Schema

- List all of the tables in the current database:

```
-- SQL-92
SELECT *
FROM INFORMATION_SCHEMA.TABLES
WHERE table_catalog = '<db name>';
```

```
\d;          -- Postgres
SHOW TABLES; -- MySQL
.tables;     -- SQLite
```

Accessing Table Schema

- List all of the columns in the *student* table:

```
-- SQL-92
SELECT *
FROM INFORMATION_SCHEMA.TABLES
WHERE table_name = 'student'
```

```
\d student;          -- Postgres
DESCRIBE student;    -- MySQL
.schema student;     -- SQLite
```

Today's Agenda

- Data Representation
- System Catalogs
- Storage Models
  - Ways to store tuples in pages

Observation

- The relational model does **not** specify that we have to store all of a tuple's attributes together in a single page.
- This may not actually be the best layout for some workloads
- There are many different workloads for database systems.
- By workload[1], we are referring to the general nature of requests a system will have to handle.
- Different workloads have different requirements for data storage and access patterns.

[1] *refers to the types of queries, transactions, and operations the system is expected to handle.*

Wikipedia Example

```sql
CREATE TABLE useracct (
  userID INT PRIMARY KEY,
  userName VARCHAR UNIQUE,
  ⋮
);
```

```sql
CREATE TABLE pages (
  pageID INT PRIMARY KEY,
  title VARCHAR UNIQUE,
  latest INT
  REFERENCES revisions (revID),
);
```

```sql
CREATE TABLE revisions (
  revID INT PRIMARY KEY,
  userID INT REFERENCES useracct (userID),
  pageID INT REFERENCES pages (pageID),
  content TEXT,
  updated DATETIME
);
```

OLTP

- On-line Transaction Processing:
  - Simple queries that read/update a small amount of data that is related to a single entity in the database.
- This is usually the kind of application that people build first.

```sql
SELECT P.*, R.*
FROM pages AS P
   INNER JOIN revisions AS R
      ON P.latest = R.revID
WHERE P.pageID = ?
```

```sql
UPDATE useracct
SET lastLogin = NOW(),
   hostname = ?
WHERE userID = ?
```

```sql
INSERT INTO revisions
VALUES (?,?...,?)
```

OLTP: On-line Transaction Processing

- Fast, short running operations
- Simple queries that operate on single entity at a time
- Typically handle more writes than reads
- Repetitive operations
- Usually the kind of application that people build first
- Example
  - User invocations of Amazon (Amazon storefront).
    - Users can add things to their cart,
    - they can make purchases,
    - but the actions only affect their accounts.

OLAP

- On-line Analytical Processing:
  - Complex queries that read large portions of the database spanning multiple entities.
- You execute these workloads on the data you have collected from your OLTP application(s).

```
SELECT COUNT(U.lastLogin),
   EXTRACT(month FROM
      U.lastLogin) AS month
FROM useracct AS U
WHERE U.hostname LIKE '%.gov'
GROUP BY
   EXTRACT(month FROM U.
    lastLogin)
```

OLAP: On-line Analytical Processing

- Long running, more complex queries
- Reads large portions of the database
- Analyzing and deriving new data from existing data collected on the OLTP side
- Example
  - Amazon computing the five most bought items over a one month period for these geographical locations.

HTAP: Hybrid Transaction + Analytical Processing

- A new type of workload which has become popular recently is HTAP, which is like a combination which tries to do `OLTP` and `OLAP` together on the same database.
- Watch HTAP Databases: What is New and What is Next - SIGMOD22-HTAP-Tutorial- June 2022

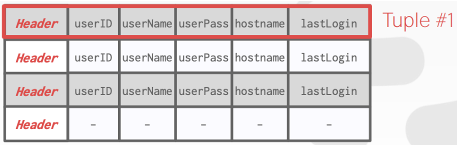
Data Storage Model

- There are different ways to store tuples in pages.
- The DBMS can store tuples in different ways that are better for either OLTP or OLAP workloads
- We have been assuming the n`-ary storage model` (aka "row storage") so far this semester.

N-ARY Storage Model (NSM)

- The DBMS stores all attributes for a single tuple contiguously in a single page.
- Ideal for OLTP workloads where requests are insert-heavy and transactions tend to operate only an individual entity
  - it takes only one fetch to be able to get all of the attributes for a single tuple.

- The DBMS stores all attributes for a single tuple contiguously in a single page.



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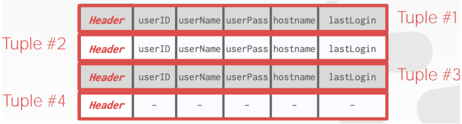

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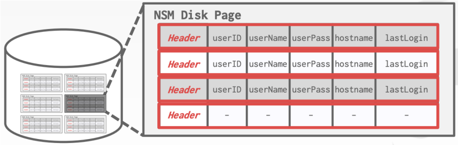
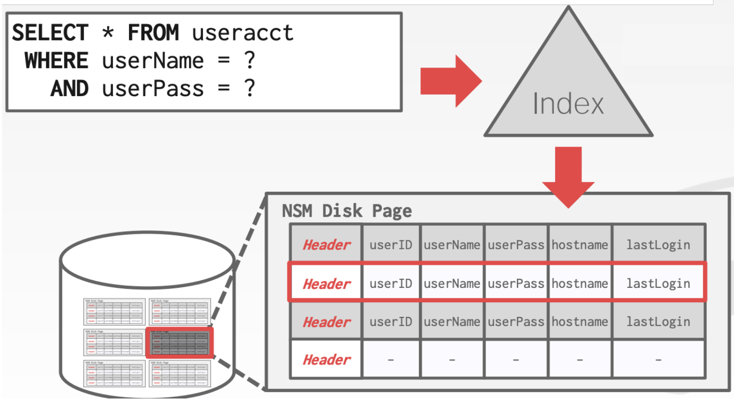


N-ARY Storage Model (NSM)

```sql
SELECT * FROM useracct
WHERE userName = ? AND userPass = ?
```

```sql
INSERT INTO useracct
VALUES (?,?,..,?)
```

N-ARY Storage Model (NSM)



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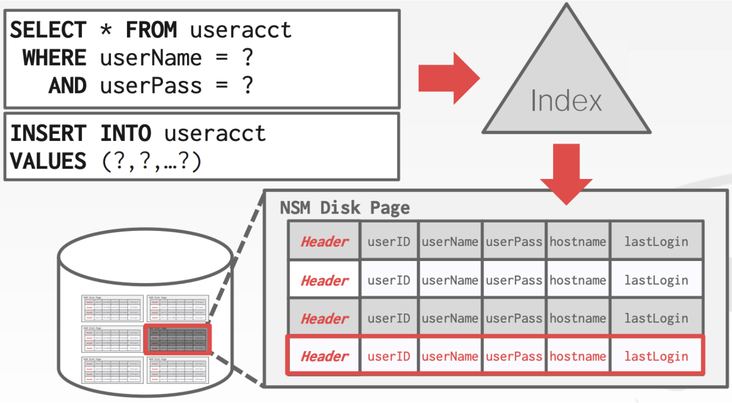

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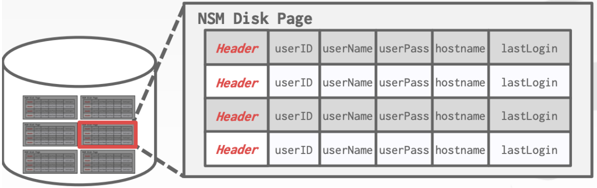

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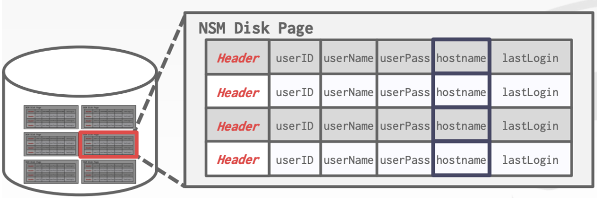

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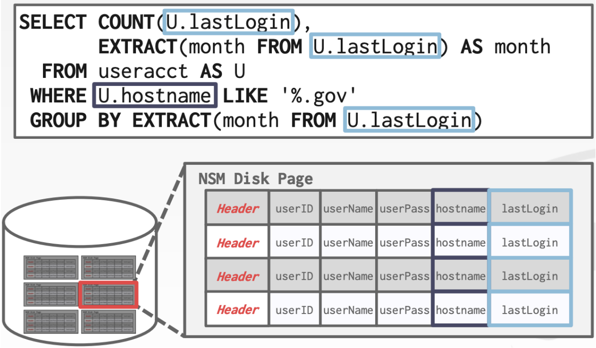

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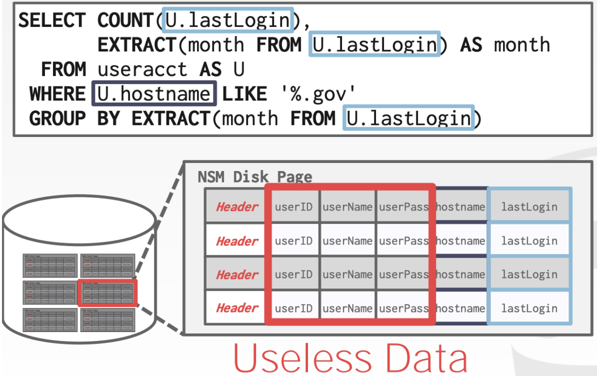


N-ARY Storage Model (NSM)

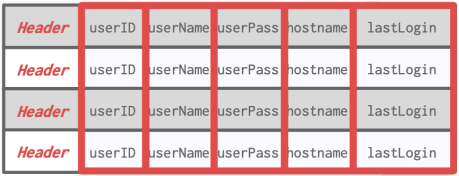
- Advantages
  - Fast inserts, updates, and deletes.
  - Good for queries that need the entire tuple.
- Disadvantages
  - Not good for scanning large portions of the table and/or a subset of the attributes.
  - This is because it pollutes the buffer pool by fetching data that is not needed for processing the query.

Decomposition Storage Model (DSM)

- The DBMS stores the values of a single attribute (column) for all tuples contiguously in a block of data.
  - *Vertically partition a database into a collection of individual columns that are stored separately*
  - Also known as a "column store".
- Ideal for OLAP workloads where read-only queries perform large scans over a subset of the table's attributes.

Decomposition Storage Model (DSM)

- The DBMS stores the values of a single attribute for all tuples contiguously in a page.
  - Also known as a “column store”.



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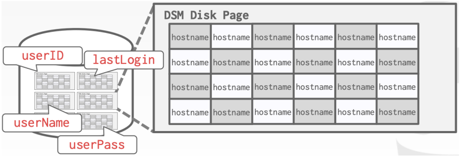

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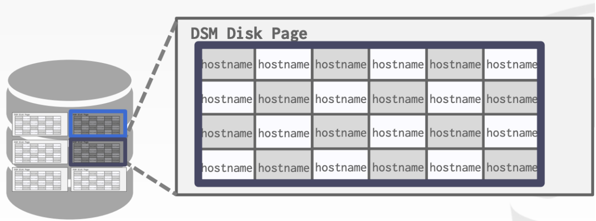


- *If there is a match on one page, how can we figure out a match on another page?*

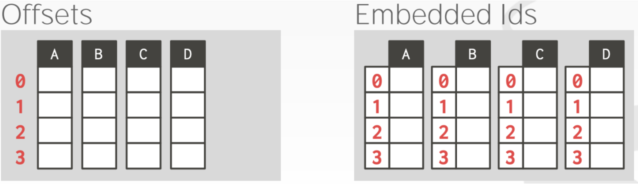
Decomposition Storage Model: Tuple Identification

- To put the tuples back together when we are using a column store, we can use:
  - Choice #1: Fixed-length Offsets (most commonly used approach)
  - Choice #2: Embedded Tuple Ids (less common approach)

- *When decomposing a relational database into a column store model, it's essential to have a mechanism to identify and reconstruct the original tuples when needed.*

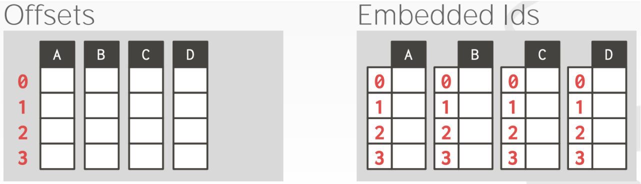
Choice #1: Fixed-length Offsets

- Each column of the table is stored separately, and for each column, a fixed-length offset is used to locate the position of each tuple within that column.
  - Assuming the attributes are all fixed-length, the DBMS can compute the offset of the attribute for each tuple.
- When the system wants the attribute for a specific tuple, it knows how to jump to that spot in the file from the offset.
- To accommodate the variable-length fields, the system can either pad fields so that they are all the same length or use a dictionary that takes a fixed-size integer and maps the integer to the value.



Choice #2: Embedded Tuple Ids

- A less common approach
- Each column is still stored separately, but instead of using fixed-length offsets, each column contains embedded tuple IDs or pointers that indicate the position or identity of the tuple to which each value belongs.
- These embedded IDs link the values across columns, allowing the DBMS to reconstruct tuples by following the tuple IDs across columns.
- Note that this method has a large storage overhead because it needs to store a tuple id for every attribute entry.



Decomposition Storage Model (DSM)

- Advantages
  - Reduces the amount wasted I/O because the DBMS only reads the data that it needs.
  - Enable better query processing and data compression.
    - because all of the values for the same attribute are stored contiguously
- Disadvantages
  - Slow for point queries, inserts, updates, and deletes because of tuple splitting/stitching.

Modification of Tuples

How to handle the following operations on the tuple level?

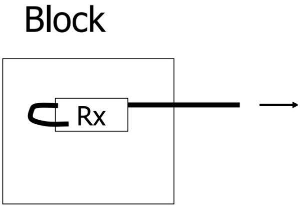
1. Insertion
2. Deletion
3. Update

1) Insertion

- **Easy case** Tuples with Fixed Length and not in Sequence (Unordered)
  - Insert new tuple at end of file
  - or, in deleted slot if one is available.
  - Deleted slots can be used to reuse space efficiently.
- **A little harder**: Tuples with Variable Size
  - If records are variable size, insertion becomes more complex.
  - Reusing space may not always be possible, leading to fragmentation where empty spaces are scattered throughout the storage.
  - This can impact storage efficiency over time.
- **A Difficult case**: Tuples in Sequence (Ordered)
  - Inserting tuples into a sequence can be challenging
  - Find position and slide following tuples to make room
  - If tuples are sequenced by linking, insert overflow blocks (there isn't enough space in the current block or node)

- *Overflow blocks are essentially additional blocks or nodes that are linked to the main sequence. They hold excess data when the main sequence's blocks are full.*

2) Deletion



Options

(a) Deleted and immediately reclaim space by shifting other tuples or removing overflows
(b) Mark deleted and list as free for re-use
    - May need chain of deleted tuples (for re-use)
    - Need a way to mark

Trade-offs

- How expensive is immediate reclaim?
    - How expensive is to move valid tuple to free space for immediate reclaim?
- How much space is wasted?
    - e.g., deleted tuples, delete fields, ...

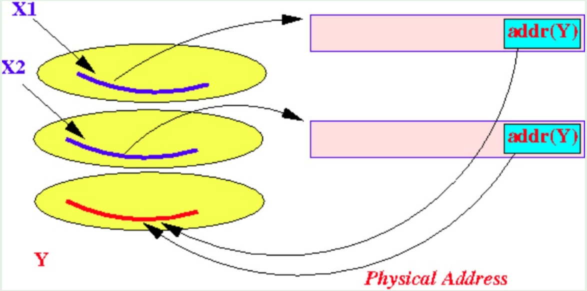
- *Space Efficiency vs. Performance: Immediate reclamation is more space-efficient but can be performance-intensive. Marking as deleted is less performance-intensive but can lead to space wastage.*

Concern with deletions

A caveat when using physical addresses to reference a block/record

Example

- Record Y can be referenced by other tuples (e.g., tuples $X1$ & $X2$)

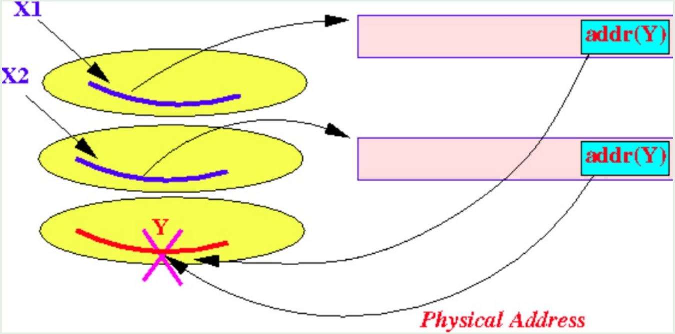


Concern with deletions

A caveat when using physical addresses to reference a block/record

Example

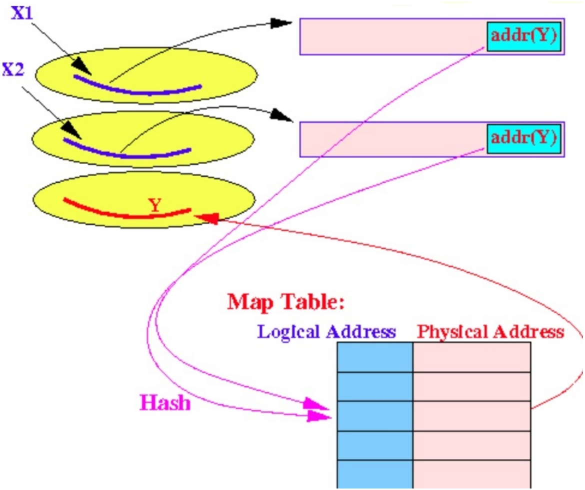
- When the tuple Y is deleted



- the physical addresses will reference an incorrect tuple

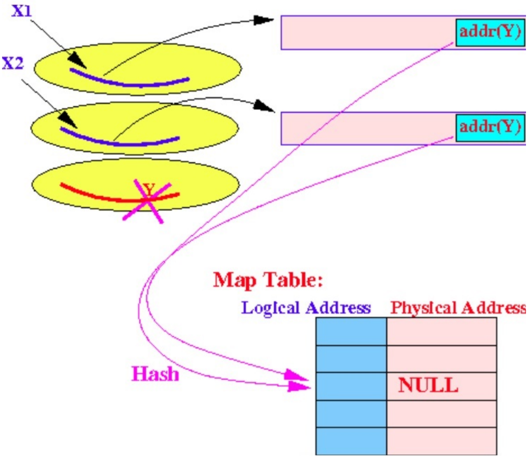
Techniques to handle tuple deletion

- Using logical addresses is easy
- Before deleting tuple Y that is referenced by tuples $X1$ and $X2$



Techniques to handle tuple deletion

- Using logical addresses is easy
- After deleting tuple Y



- Deleted tuple is identified by a NULL physical address in the Map table

Very important

- The logical address used by tuple Y must remain in the map table
- Furthermore:
  - The logical address used by tuple Y cannot be re-used

Techniques to handle tuple deletion

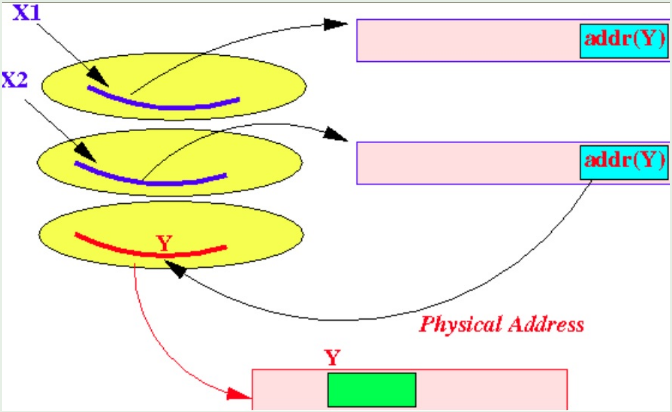
- Deleting a tuple using physical address: use a tombstone record
- Tombstone record
  - A tombstone record is a special-purpose tuple that is very small in size and serves as a marker to indicate that a tuple has been deleted.
- When a tuple is deleted, it is replaced by the tombstone record
  - Instead of physically removing the tuple from the database or shifting other records, you replace the target tuple with a tombstone record
  - This tombstone record essentially **marks** the tuple as deleted without removing it entirely.
- This tombstone is permanent, it must exist until the entire database is reconstructed

- *A map table or mapping structure is used to keep track of the relationships between logical or physical addresses and the actual data. When a tuple is deleted, the tombstone record can be represented in the map table, often as a null pointer or a specific value indicating deletion, in place of the physical address.*

Tombstones

Example

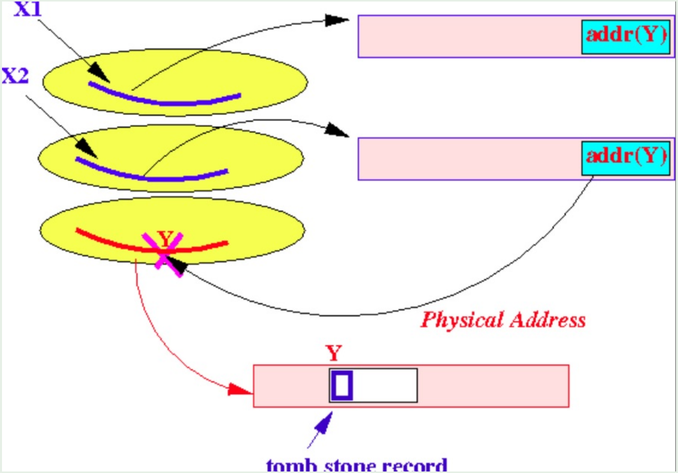
- Before deleting tuple Y



Tombstones

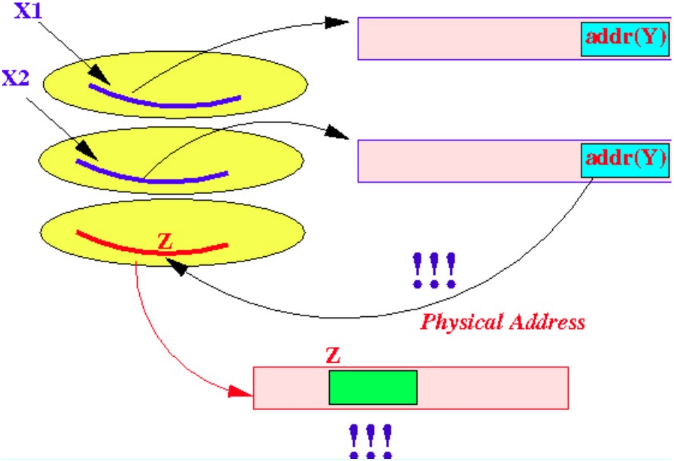
Example

- After deleting tuple Y



Tombstones

- When you insert a new tuple, you cannot use the space of a tombstone tuple (tombstone tuple must be preserved)
- Because: Existing tuple references to the deleted tuple will then references to the newly inserted tuple:



Update

- If new tuple is shorter than previous, easy
- If it is longer, need to shift tuples, create overflow blocks
- Note: We will never create a tombstone tuple in an update operation

Conclusion

- The storage manager is not entirely independent from the rest of the DBMS.
- A DBMS encodes and decodes the tuple's bytes into a set of attributes based on its schema.
- It is important to choose the right storage model for the target workload:
  - OLTP = Row Store
  - OLAP = Column Store

Database Storage: Next

- `Problem#1`: How the DBMS represents the database in files on disk
  - i.e., how to lay out data on disk.
- `Problem#2`: How the DBMS manages its memory and move data back-and-forth from disk.