

Lecture 6: Data Representation

CREATING THE NEXT®

Administrivia

- Assignment 1 is due on September 17th @ 11:59pm
- Start thinking about project topics

Today's Agenda

Data Representation

- 1.1 Recap
- 1.2 Data Representation
- 1.3 Storage Models

Recap

Memory Mapping Files

`mmap()` is used to manage the virtual address space of a process.

- One use case for `mmap()` is to map the contents of a file into the virtual memory.
- `mmap()` can also be used to allocate memory by not associating it with a file.
- With `mmap()`, data migration is automatically done by the OS (not by the DBMS).
- The key limitation of `mmap()` is that it does not provide fine-grained control over when and which pages are moved from DRAM to SSD.
- We will learn about how to design a buffer manager that allows us to gain this control in a DBMS.

Disk Block Mapping

The units of database space allocation are disk blocks, extents, and segments.

- A disk block is the smallest unit of data used by a database.
- An extent is a logical unit of database storage space allocation made up of a number of contiguous disk blocks.
- A segment is made up of one or more extents (and is hence not always contiguous on disk).

System Catalog

- A DBMS stores meta-data about databases in its internal catalog.
- List of tables, columns, indexes, views
- Almost every DBMS stores their catalog as a private database.
- Specialized code for “bootstrapping” catalog tables.

Today's Agenda

- Data Representation
- Storage Models

Data Representation

Data Representation

- A catalog table contain the schema information about the user tables
- The DBMS uses this schema information to figure out the tuple's data representation.
- In this way, it interprets the tuple's bytes into a set of attributes (types and values).

Data Representation

- **INTEGER/BIGINT/SMALLINT/TINYINT**
 - ▶ C/C++ Representation
- **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

Variable Precision Numbers

- Inexact, variable-precision numeric type that uses the "native" C/C++ types.
 - ▶ Examples: FLOAT, REAL/DOUBLE
- Store directly as specified by **IEEE-754**.
- Typically faster than arbitrary precision numbers but can have rounding errors. . .

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 = %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 = 0.300000001192092895508  
0.3 = 0.29999999999999998890
```

Fixed Precision Numbers

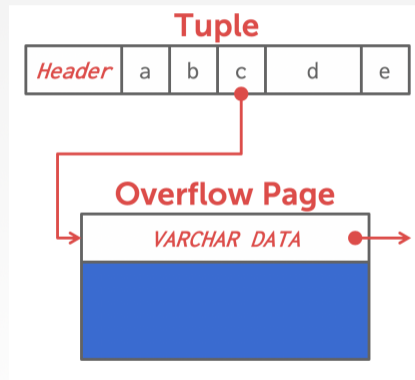
- Numeric data types with arbitrary precision and scale.
- Used when rounding errors are unacceptable.
 - ▶ Example: NUMERIC, DECIMAL
- Typically stored in a exact, variable-length binary representation with additional meta-data.
 - ▶ Like a VARCHAR but not stored as a string

Postgres: Numeric

```
typedef unsigned char NumericDigit;
typedef struct {
int ndigits;           // number of digits
int weight;           // weight of 1st Digit
int scale;            // scale factor
int sign;             // positive/negative/NaN
NumericDigit *digits; // digit storage
} numeric;
```

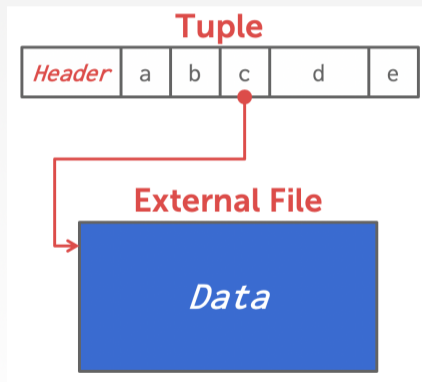

Large Values

- Most DBMSs don't allow a tuple to exceed the size of a single page.
- To store values that are larger than a page, the DBMS uses separate **overflow** storage pages.
 - ▶ Postgres: TOAST (>2KB)
 - ▶ MySQL: Overflow (>½ size of page)
 - ▶ SQL Server: Overflow (>size of page)



External Value Storage

- Some systems allow you to store a really large value in an external file. Treated as a BLOB type.
 - ▶ Oracle: BFILE data type
 - ▶ Microsoft: FILESTREAM data type
- The DBMS **cannot** manipulate the contents of an external file.
 - ▶ No durability guarantees.
 - ▶ No transaction protections.
- Objects < 256 KB are best stored in a database
- Objects > 1 MB are best stored in the filesystem
- Reference: **To BLOB or Not To BLOB: Large Object Storage in a Database or a Filesystem?**



Schema Changes: Index

- CREATE INDEX:
 - ▶ Scan the entire table and populate the index (*e.g.*, hash table: tuple id \rightarrow tuple pointer).
 - ▶ Have to record changes made by txns that modified the table while another txn was building the index.
 - ▶ When the scan completes, lock the table and resolve changes that were missed after the scan started.
- DROP INDEX:
 - ▶ Just drop the index logically from the catalog.
 - ▶ It only becomes "invisible" when the txn that dropped it **commits**.
 - ▶ All ongoing txns will still have to update it.

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 **storage layout** for some workloads. . .

Storage Models

Wikipedia Example

```
CREATE TABLE pages (  
  userID INT PRIMARY KEY,  
  userName VARCHAR UNIQUE,  
);
```

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

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

OLTP Workload

On-line Transaction Processing (OLTP)

- 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.

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

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

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

OLTP Workload

On-line Transaction Processing (OLTP)

- 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.

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


OLAP Workload

On-line Analytical Processing (OLAP)

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

Workload Characterization

Workload	Operation Complexity	Workload Focus
OLTP	Simple	Writes
OLAP	Complex	Reads
HTAP	Medium	Mixture

Source

Workload Types

- OLTP: On-line Transaction Processing; Simple + Write-intensive
- OLAP: On-line Analytical Processing; Complex + Read-intensive
- HTAP: Hybrid Transaction/Analytical Processing; Medium + Mixed

Data Storage Models

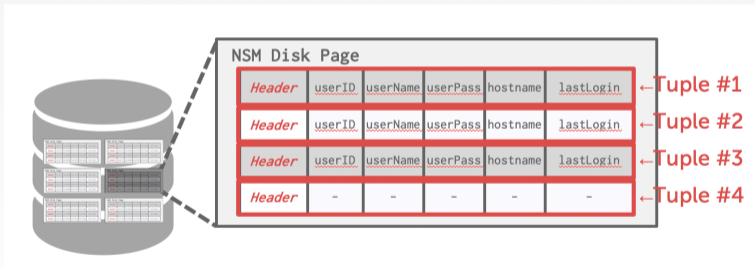
- The DBMS can store tuples in different ways that are better for either OLTP or OLAP workloads.
- We have been assuming the n-ary storage model (NSM) (*a.k.a.*, row storage) so far this semester.

N-ary Storage Model (NSM)

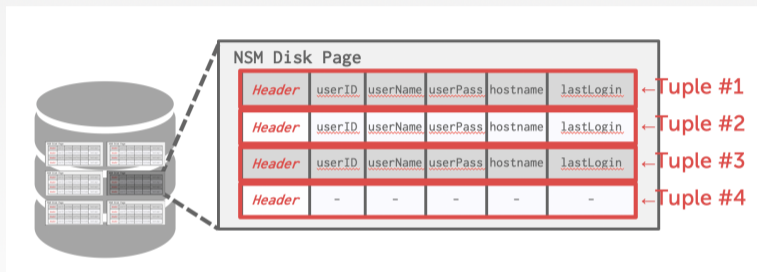
- The DBMS stores all attributes for a single tuple contiguously in a page.
- Ideal for OLTP workloads where queries tend to operate only on an individual entity and insert-heavy workloads.

N-ary Storage Model (NSM)

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



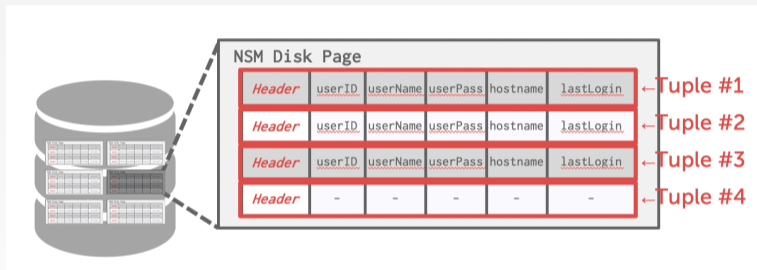
N-ary Storage Model (NSM)



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

Use index to access the particular user's tuple.

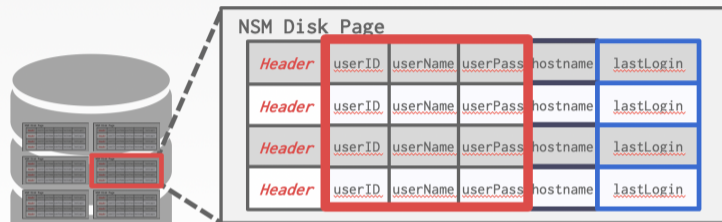
N-ary Storage Model (NSM)



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

Add the user's tuple using `std::memcpy`.

N-ary Storage Model (NSM)



Useless Data

```
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)
```

Useless data accessed for this query.

N-ary Storage Model (NSM)

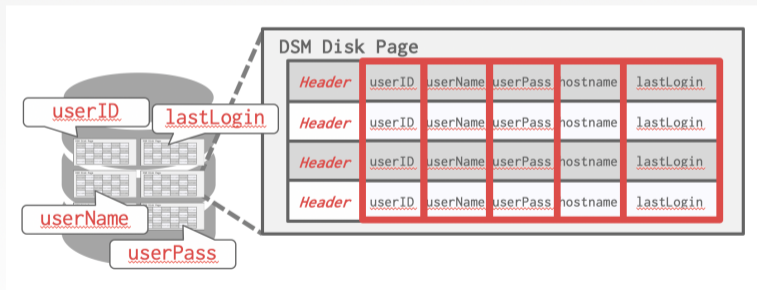
- Advantages
 - ▶ Fast inserts, updates, and deletes.
 - ▶ Good for queries that need the entire tuple.
- Disadvantages
 - ▶ Not good for scanning large portions of the table and/or a subset of the attributes.

Decomposition Storage Model (DSM)

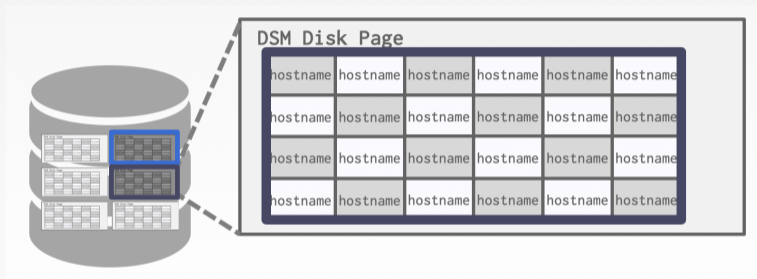
- The DBMS stores the values of a single attribute for all tuples contiguously in a page.
 - ▶ Also known as a "column store".
- Ideal for OLAP workloads where read-only queries perform large scans over a subset of the table's attributes.

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".



Decomposition Storage Model (DSM)



```
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)
```

Tuple Identification

- Choice 1: Fixed-length Offsets
 - ▶ Each value is the same length for an attribute.
- Choice 2: Embedded Tuple Ids
 - ▶ Each value is stored with its tuple id in a column.

Offsets

	A	B	C	D
0				
1				
2				
3				

Embedded Ids

	A	B	C	D
0		0		0
1		1		1
2		2		2
3		3		3

Decomposition Storage Model (DSM)

- Advantages
 - ▶ Reduces the amount wasted I/O because the DBMS only reads the data that it needs.
 - ▶ Better query processing and data compression (more on this later).
- Disadvantages
 - ▶ Slow for point queries, inserts, updates, and deletes because of tuple splitting/stitching.

DSM History

- 1970s: Cantor DBMS
- 1980s: **DSM Proposal**
- 1990s: SybaseIQ (in-memory only)
- 2000s: Vertica, VectorWise, MonetDB
- 2010s: Everyone

Schema Changes: Columns

- ADD COLUMN:
 - ▶ NSM: Copy tuples into new region in memory.
 - ▶ DSM: Just create the new column segment on disk.
- DROP COLUMN:
 - ▶ NSM-1: Copy tuples into new region of memory.
 - ▶ NSM-2: Mark column as "deprecated", clean up later.
 - ▶ DSM: Just drop the column and free memory.
- CHANGE COLUMN:
 - ▶ Check whether the conversion is allowed to happen. Depends on default values.

Conclusion

- 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 \rightarrow Row-Store
 - ▶ OLAP \rightarrow Column-Store