15-721 DATABASE SYSTEMS

Lecture #10 – Storage Models & Data Layout

@Andy_Pavlo // Carnegie Mellon University // Spring 2017

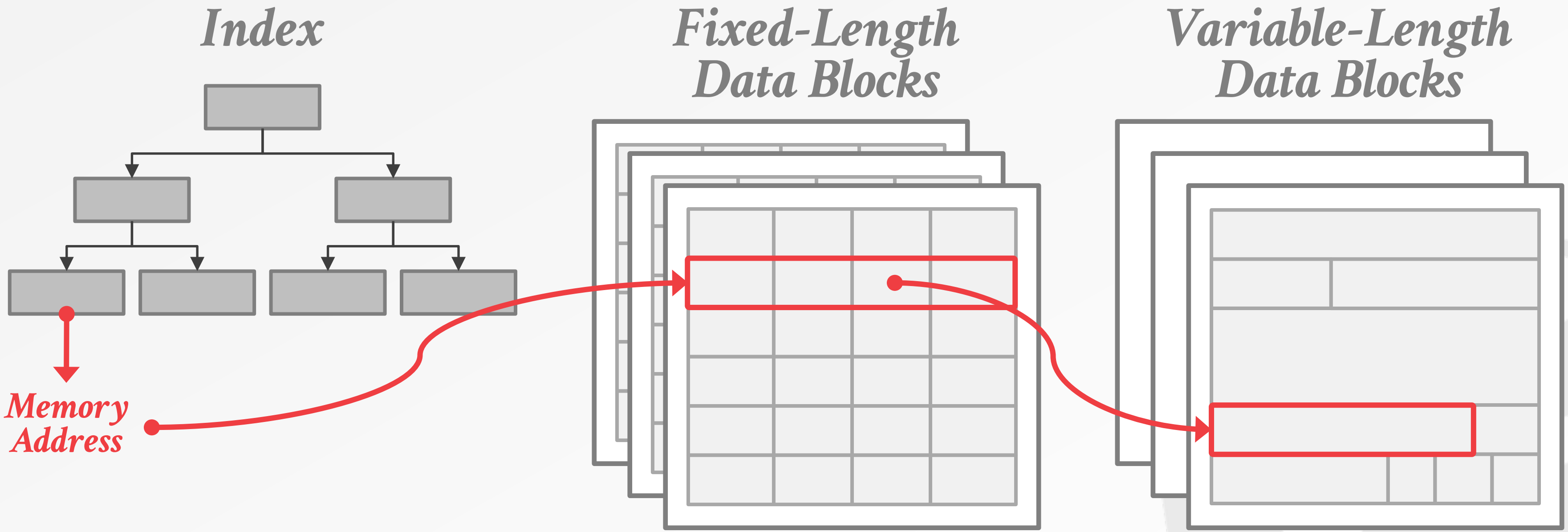
TODAY'S AGENDA

Type Representation

In-Memory Data Layout

Storage Models

DATA ORGANIZATION



DATA ORGANIZATION

One can think of an in-memory database as just a large array of bytes.

→ The schema tells the DBMS how to convert the bytes into the appropriate type.

Each tuple is prefixed with a header that contains its meta-data.

Storing tuples with just their fixed-length data makes it easy to compute the starting point of any tuple.

DATA REPRESENTATION

INTEGER/BIGINT/SMALLINT/TINYINT

→ C/C++ Representation

FLOAT/REAL vs. **NUMERIC/DECIMAL**

→ IEEE-754 Standard / Fixed-point Decimals

VARCHAR/VARBINARY/TEXT/BLOB

→ Pointer to other location if type is ≥64-bits

→ Header with length and address to next location (if segmented), 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.

Store directly as specified by IEEE-754.

Typically faster than arbitrary precision numbers.

→ Example: **FLOAT**, **REAL**/**DOUBLE**

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
```

FIXED PRECISION NUMBERS

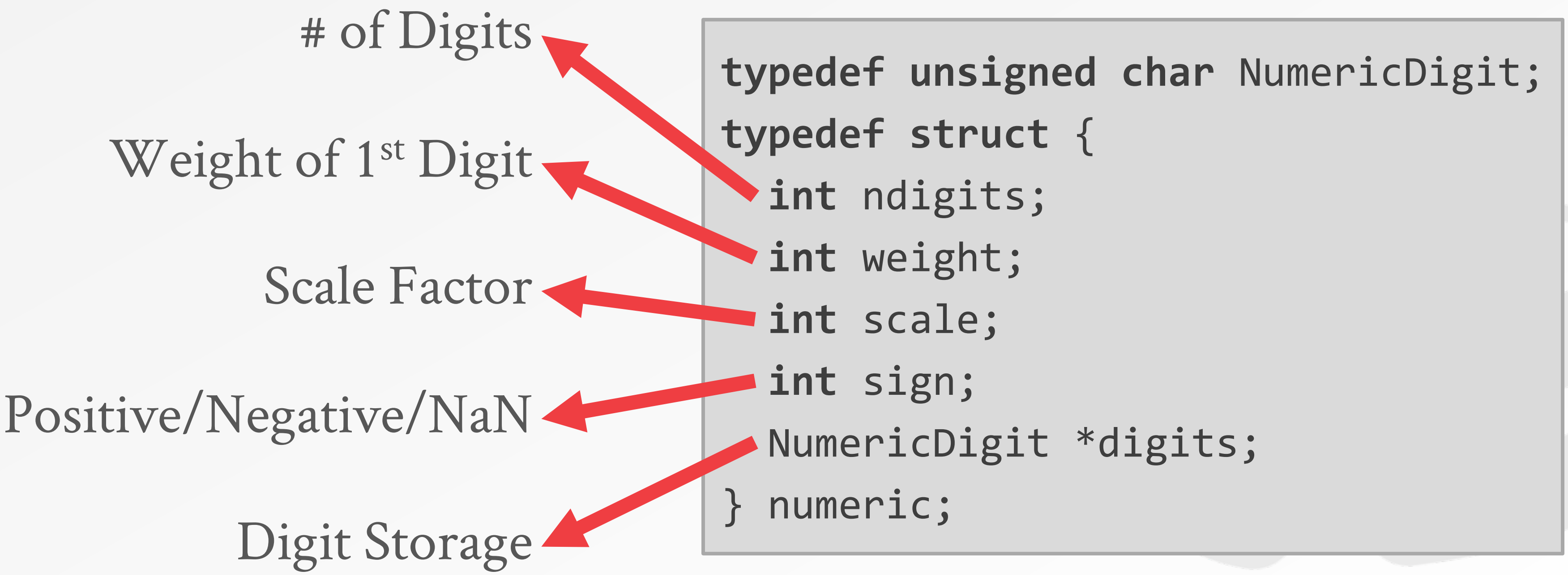
Numeric data types with arbitrary precision and scale. Used when round errors are unacceptable.

→ 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



# of Digits

Weight of 1st Digit

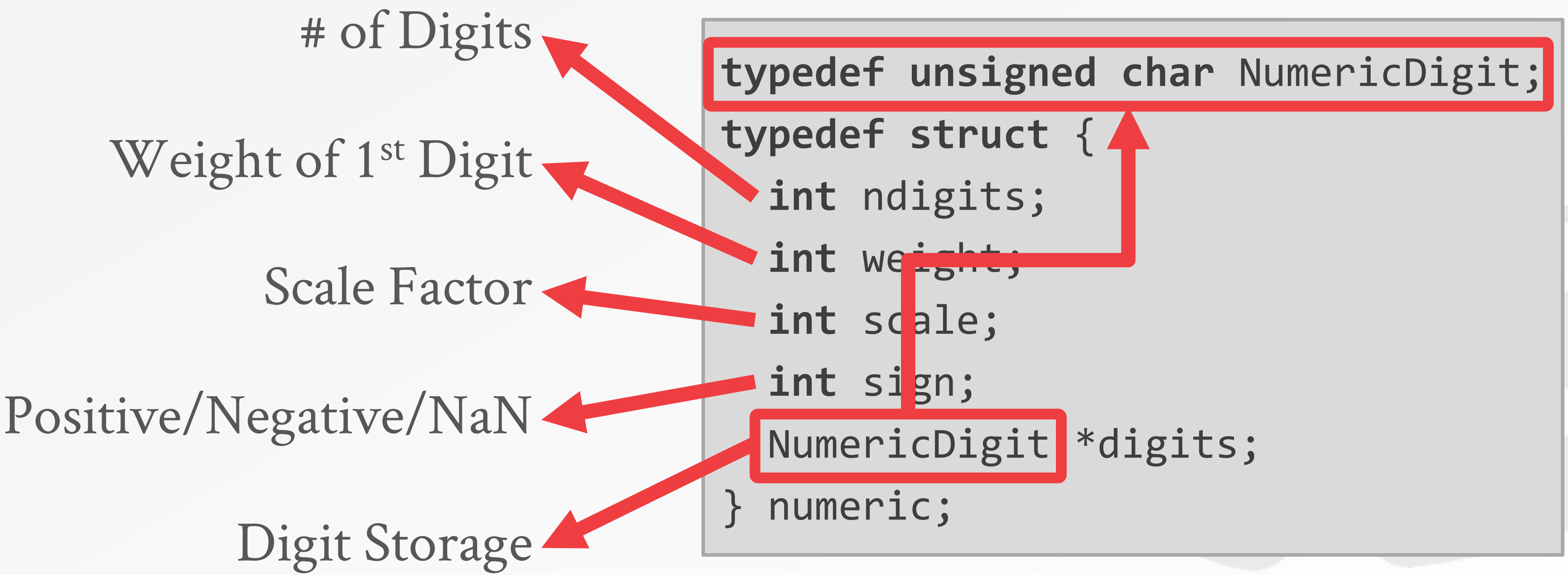
Scale Factor

Positive/Negative/NaN

Digit Storage

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

POSTGRES: NUMERIC



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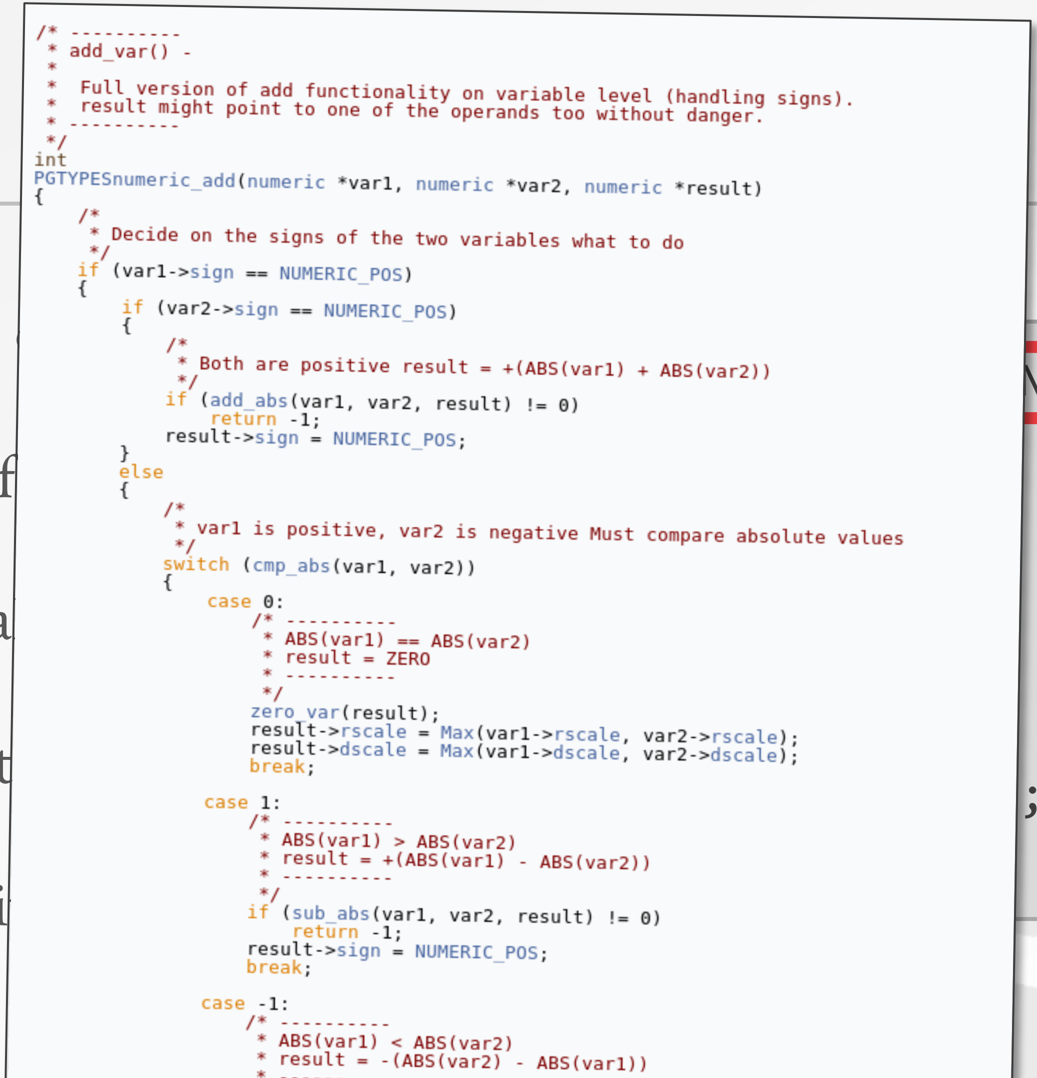

```
/* ----------
 * add_var() -
 *
 *  Full version of add functionality on variable level (handling signs).
 *  result might point to one of the operands too without danger.
 * ----------
 */
int
PGTYPESnumeric_add(numeric *var1, numeric *var2, numeric *result)
{
    /*
     * Decide on the signs of the two variables what to do
     */
    if (var1->sign == NUMERIC_POS)
    {
        if (var2->sign == NUMERIC_POS)
        {
            /*
             * Both are positive result = +(ABS(var1) + ABS(var2))
             */
            if (add_abs(var1, var2, result) != 0)
                return -1;
            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->rscale = Max(var1->rscale, var2->rscale);
                    result->dscale = Max(var1->dscale, var2->dscale);
                    break;

                case 1:
                    /* ----------
                     * ABS(var1) > ABS(var2)
                     * result = +(ABS(var1) - ABS(var2))
                     * ----------
                     */
                    if (sub_abs(var1, var2, result) != 0)
                        return -1;
                    result->sign = NUMERIC_POS;
                    break;

                case -1:
                    /* ----------
                     * ABS(var1) < ABS(var2)
                     * result = -(ABS(var2) - ABS(var1))
```

MSSQL: DECIMAL ENCODING

Values: `0.5, 10.77, 1.33`

Exponent: 3 (i.e., 10^3)

Initial Encoding: 0.5 10^3→**500**
10.77 10^3→**10770**
1.33 10^3→**1330**

SQL SERVER COLUMN STORE INDEXES
SIGMOD 2010

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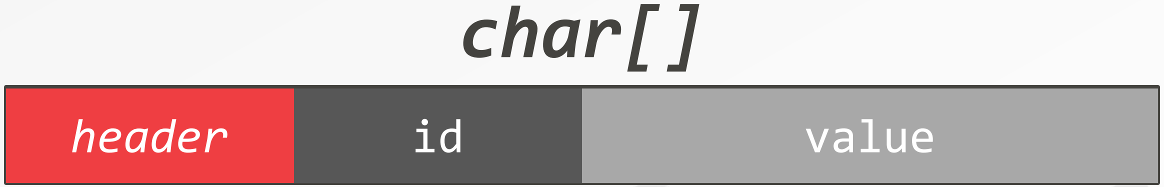
Base: 500

Final Encoding: $(0.5\ 10^3)\text{-}500 \rightarrow \mathbf{0}$
$(10.77\ 10^3)\text{-}500 \rightarrow \mathbf{10270}$
$(1.33\ 10^3)\text{-}500 \rightarrow \mathbf{830}$

SQL SERVER COLUMN STORE INDEXES
SIGMOD 2010

DATA LAYOUT

```
CREATE TABLE AndySux (
  id INT PRIMARY KEY,
  value BIGINT
);
```



char[]

header	id	value

DATA LAYOUT

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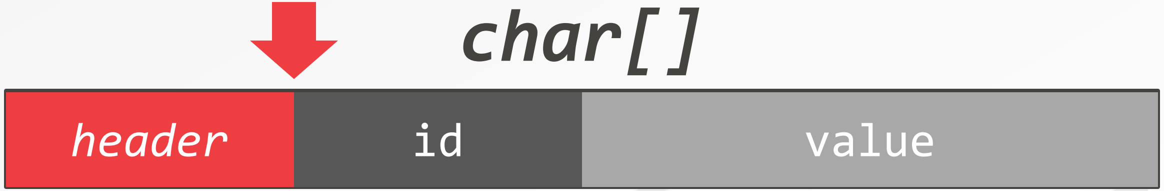


```
reinterpret_cast<int32_t*>(address)
```

NULL DATA TYPES

Choice #1: Special Values

→ Designate a value to represent **NULL** for a particular data type (e.g., `INT32_MIN`).

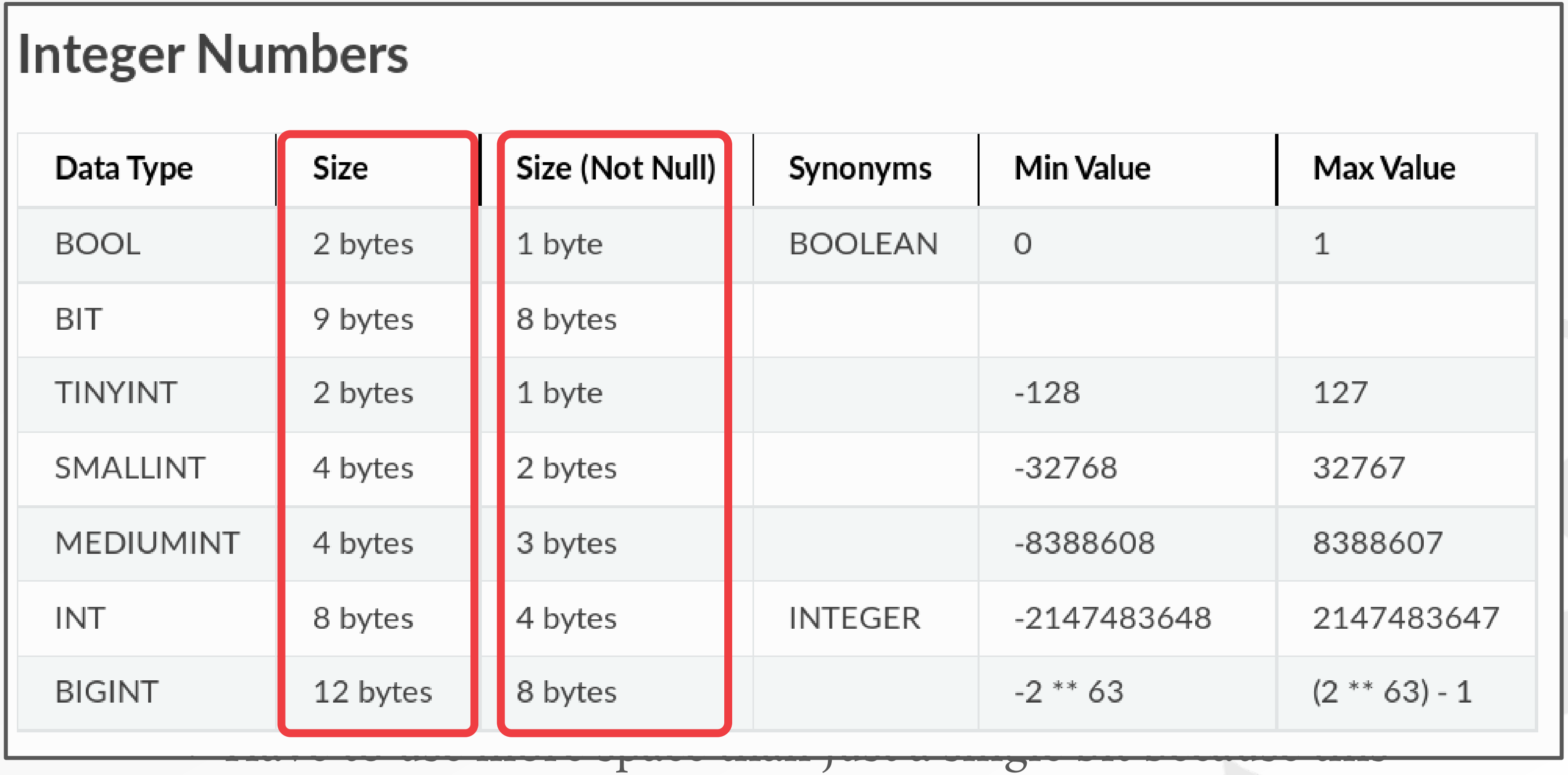
Choice #2: Null Column Bitmap Header

→ Store a bitmap in the tuple header that specifies what attributes are null.

Choice #3: Per Attribute Null Flag

→ Store a flag that marks that a value is null.
→ Have to use more space than just a single bit because this messes up with word alignment.

NULL DATA TYPES



Integer Numbers

Data Type	Size	Size (Not Null)	Synonyms	Min Value	Max Value
BOOL	2 bytes	1 byte	BOOLEAN	0	1
BIT	9 bytes	8 bytes			
TINYINT	2 bytes	1 byte		-128	127
SMALLINT	4 bytes	2 bytes		-32768	32767
MEDIUMINT	4 bytes	3 bytes		-8388608	8388607
INT	8 bytes	4 bytes	INTEGER	-2147483648	2147483647
BIGINT	12 bytes	8 bytes		-2 ** 63	(2 ** 63) - 1

→ have to use more space than just a single bit because this messes up with word alignment.

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NOTICE

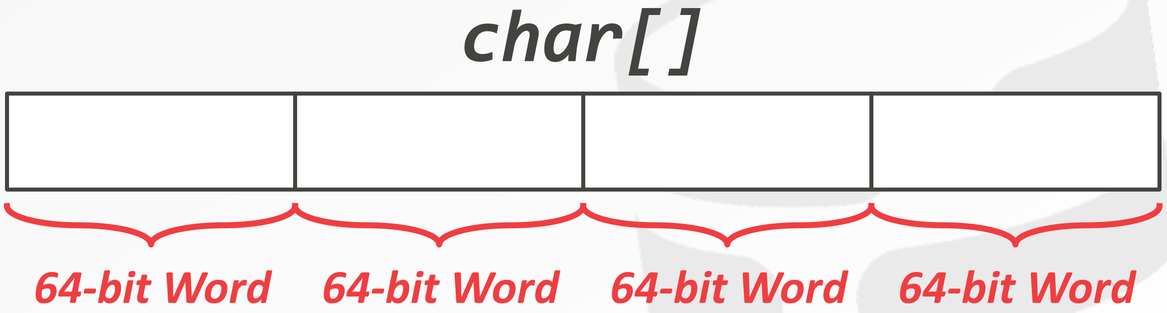
The truth is that you only need to worry about word-alignment for cache lines (e.g., 64 bytes).

I'm going to show you the basic idea using 64-bit words since it's easier to see…

WORD-ALIGNED TUPLES

All attributes in a tuple must be word aligned to enable the CPU to access it without any unexpected behavior or additional work.

```
CREATE TABLE AndySux (
  id INT PRIMARY KEY,
  cdate TIMESTAMP,
  color CHAR(2),
  zipcode INT
);
```



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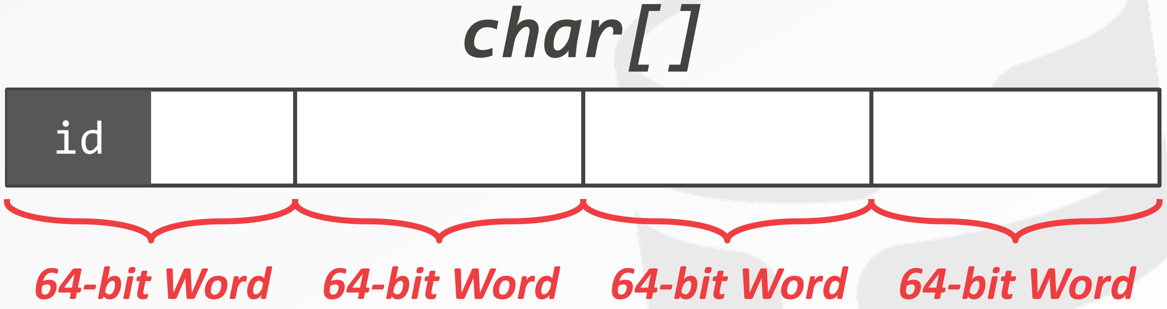
32-bits



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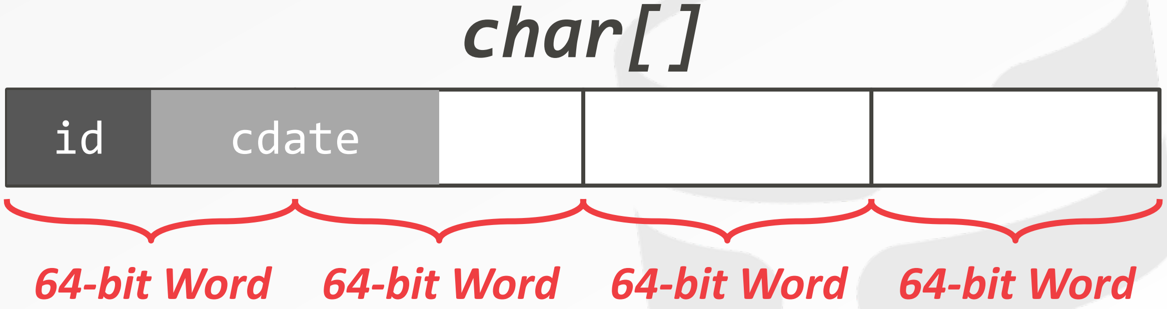
32-bits

64-bits



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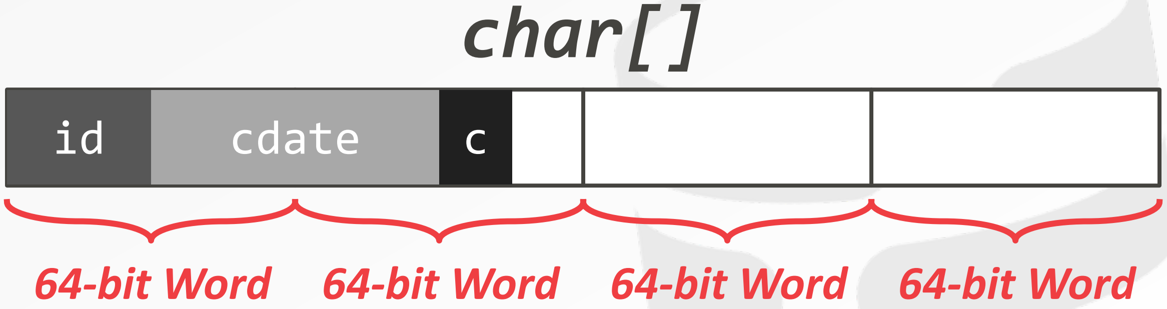
```
        CREATE TABLE AndySux (
32-bits   id INT PRIMARY KEY,
64-bits   cdate TIMESTAMP,
16-bits   color CHAR(2),
          zipcode INT
        );
```



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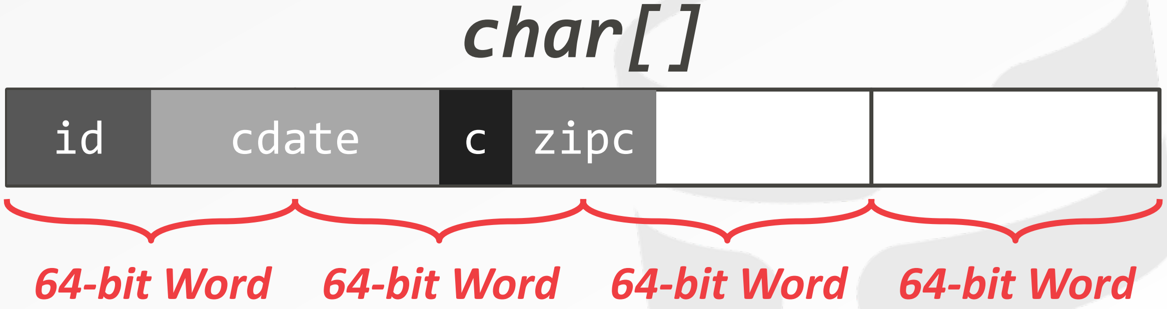

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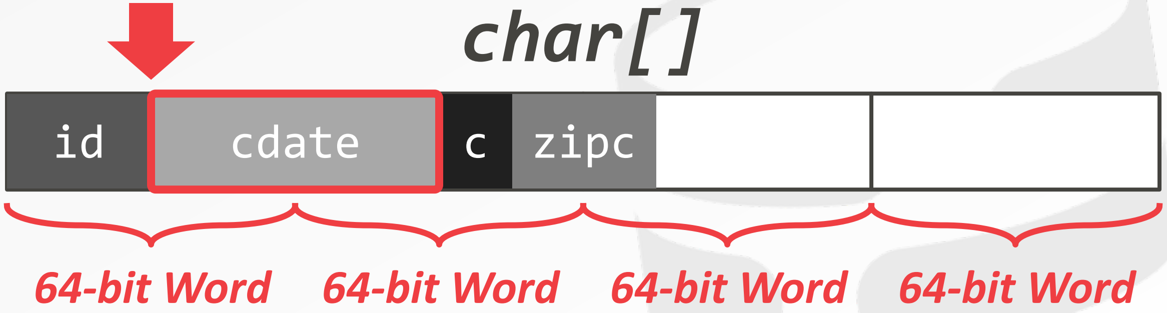

WORD-ALIGNED TUPLES

If the CPU fetches a 64-bit value that is not word-aligned, it has three choices:

→ Execute two reads to load the appropriate parts of the data word and reassemble them.

→ Read some unexpected combination of bytes assembled into a 64-bit word.

→ Throw an exception

WORD-ALIGNED TUPLES

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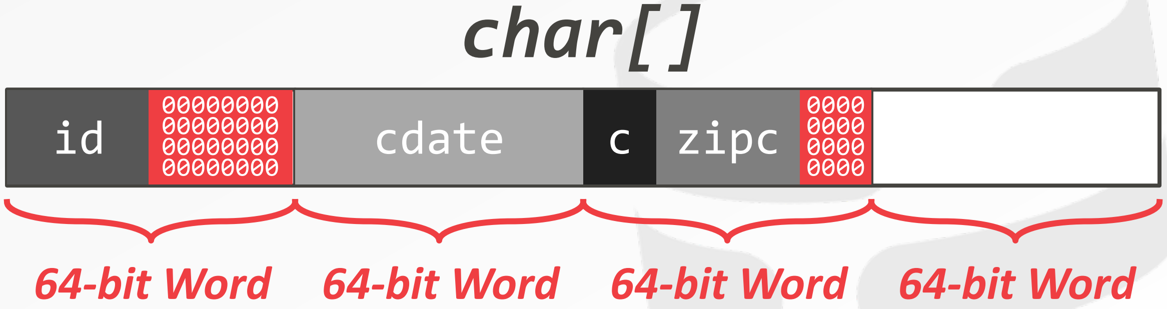


STORAGE MODELS

N-ary Storage Model (NSM)

Decomposition Storage Model (DSM)

Hybrid Storage Model

N-ARY STORAGE MODEL (NSM)

The DBMS stores all of the attributes for a single tuple contiguously.

Ideal for OLTP workloads where txns tend to operate only on an individual entity and insert-heavy workloads.

Use the tuple-at-a-time iterator model.

NSM PHYSICAL STORAGE

Choice #1: Heap-Organized Tables

→ Tuples are stored in blocks called a heap.
→ The heap does not necessarily define an order.

Choice #2: Index-Organized Tables

→ Tuples are stored in the index itself.
→ Not quite the same as a clustered index.

CLUSTERED INDEXES

The table is stored in the sort order specified by the primary key.

→ Can be either heap- or index-organized storage.

Some DBMSs always use a clustered index.

→ If a table doesn't include a pkey, the DBMS will automatically make a hidden row id pkey.

Other DBMSs cannot use them at all.

→ A clustered index is non-practical in a MVCC DBMS using the **Append Storage Method**.

N-ARY STORAGE MODEL (NSM)

Advantages

→ Fast inserts, updates, and deletes.
→ Good for queries that need the entire tuple.
→ Can use index-oriented physical storage.

Disadvantages

→ Not good for scanning large portions of the table and/or a subset of the attributes.

DECOMPOSITION STORAGE MODEL (DSM)

The DBMS stores a single attribute for all tuples contiguously in a block of data.

→ Sometimes also called **vertical partitioning**.

Ideal for OLAP workloads where read-only queries perform large scans over a subset of the table's attributes.

Use the vector-at-a-time iterator model.

DECOMPOSITION STORAGE MODEL (DSM)

1970s: Cantor DBMS

1980s: DSM Proposal

1990s: SybaseIQ (in-memory only)

2000s: Vertica, Vectorwise, MonetDB

2010s: "The Big Three"
Cloudera Impala, Amazon Redshift,
SAP HANA, MemSQL

CLUSTERED INDEXES

Some columnar DBMSs store data in sorted order to maximize compression.

→ Bitmap indexes with RLE from last class

Vertica does not even use indexes because all columns are sorted.

TUPLE IDENTIFICATION

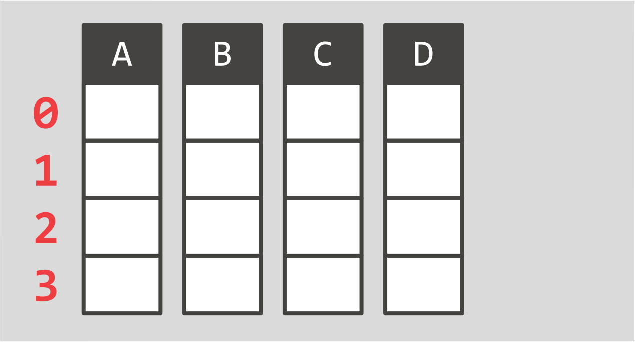
Choice #1: Fixed-length Offsets

→ Each value is the same length for an attribute.

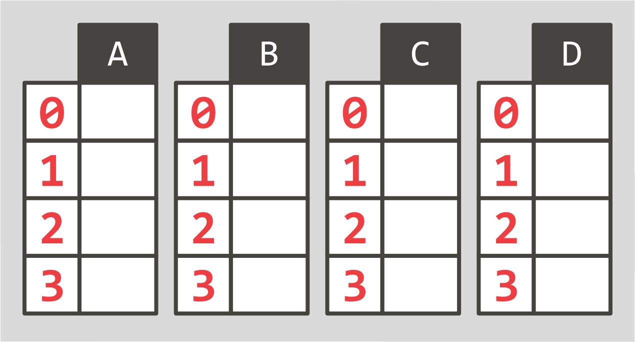
Choice #2: Embedded Tuple Ids

→ Each value is stored with its tuple id in a column.

Offsets



Embedded Ids



DECOMPOSITION STORAGE MODEL (DSM)

Advantages

→ Reduces the amount wasted work because the DBMS only reads the data that it needs.

→ Better compression.

Disadvantages

→ Slow for point queries, inserts, updates, and deletes because of tuple splitting/stitching.

OBSERVATION

Data is "hot" when first entered into database

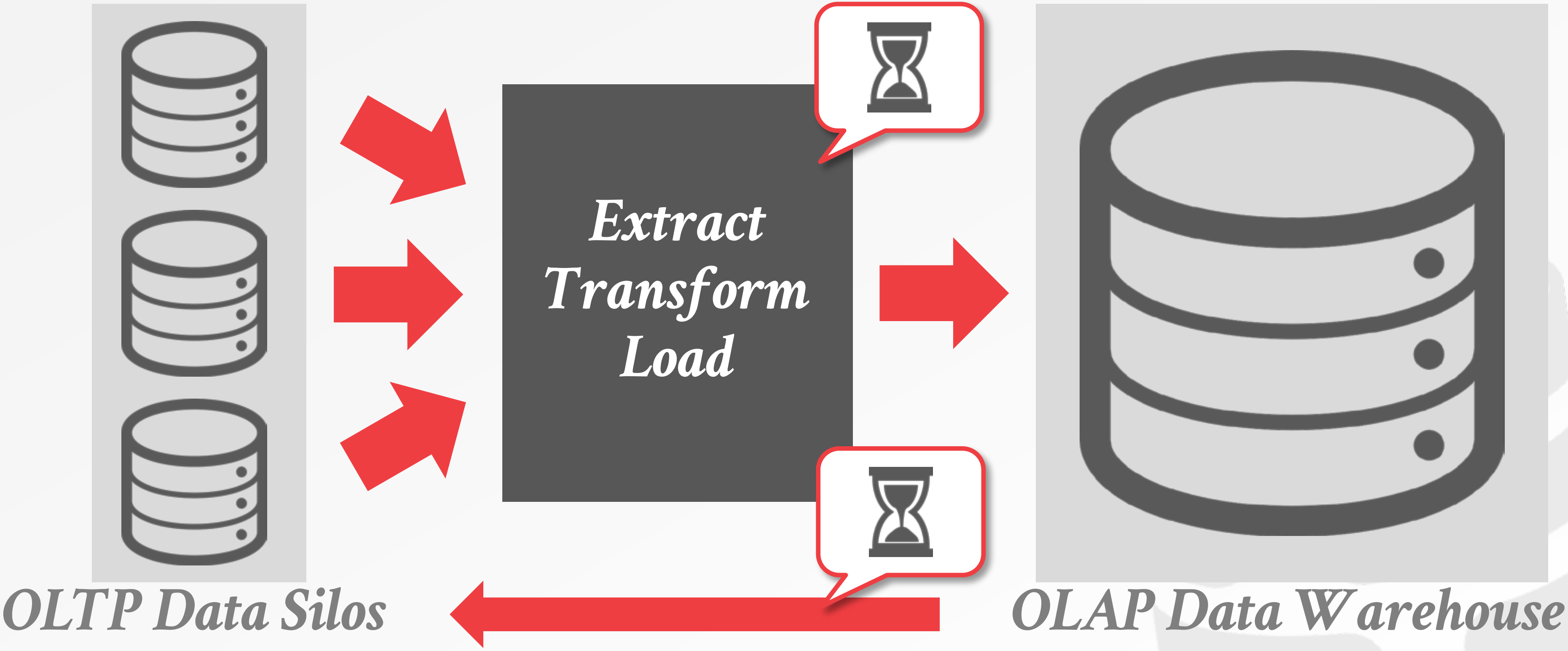
→ A newly inserted tuple is more likely to be updated again the near future.

As a tuple ages, it is updated less frequently.

→ At some point, a tuple is only accessed in read-only queries along with other tuples.

What if we want to use this data to make decisions that affect new txns?

BIFURCATED ENVIRONMENT



Extract
Transform
Load

OLTP Data Silos

OLAP Data Warehouse

HYBRID STORAGE MODEL

Single logical database instance that uses different storage models for hot and cold data.

Store new data in NSM for fast OLTP
Migrate data to DSM for more efficient OLAP

HYBRID STORAGE MODEL

Choice #1: Separate Execution Engines

→ Use separate execution engines that are optimized for either NSM or DSM databases.

Choice #2: Single, Flexible Architecture

→ Use single execution engine that is able to efficiently operate on both NSM and DSM databases.

SEPARATE EXECUTION ENGINES

Run separate "internal" DBMSs that each only operate on DSM or NSM data.

→ Need to combine query results from both engines to appear as a single logical database to the application.
→ Have to use a synchronization method (e.g., 2PC) if a txn spans execution engines.

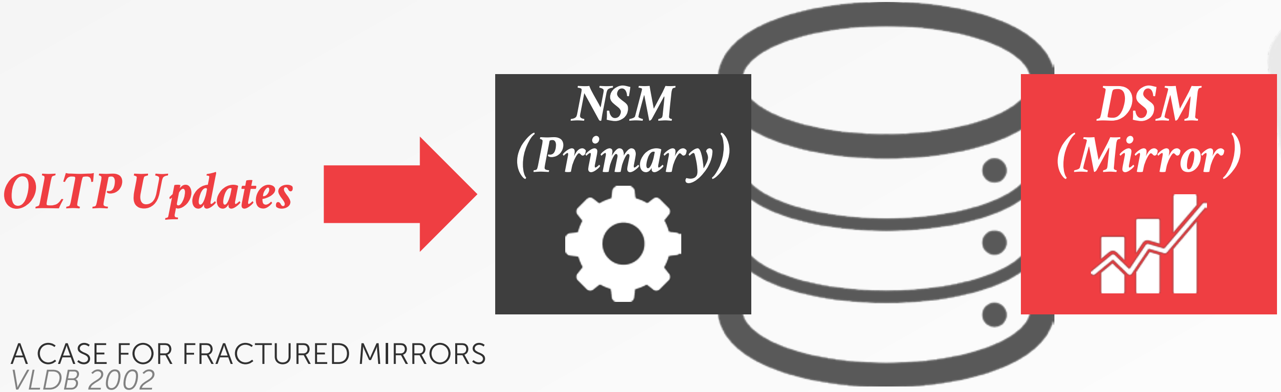
Two approaches to do this:

→ **Fractured Mirrors** (Oracle, IBM)
→ **Delta Store** (SAP HANA)

FRACTURED MIRRORS

Store a second copy of the database in a DSM layout that is automatically updated.

→ All updates are first entered in NSM then eventually copied into DSM mirror.



OLTP Updates

NSM (Primary)

DSM (Mirror)

A CASE FOR FRACTURED MIRRORS
VLDB 2002

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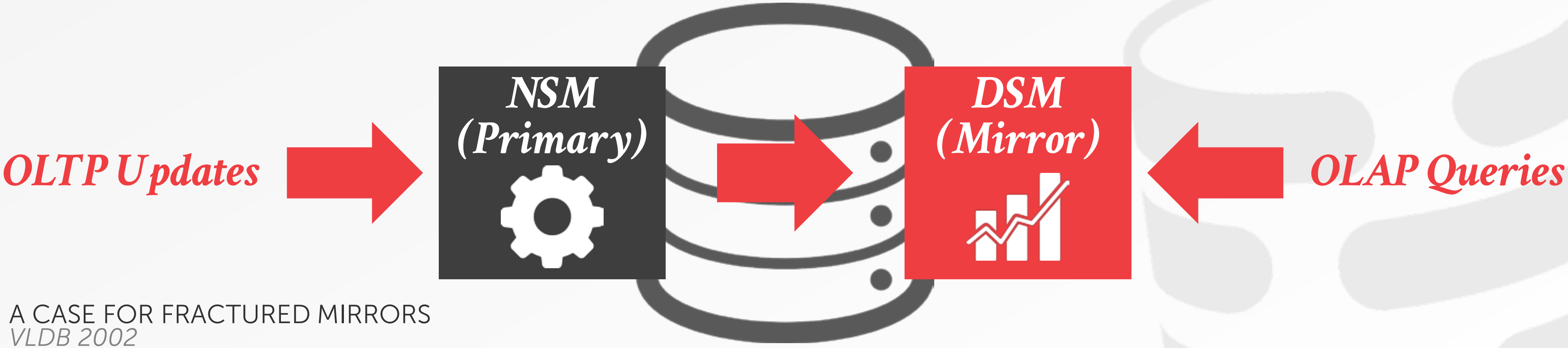
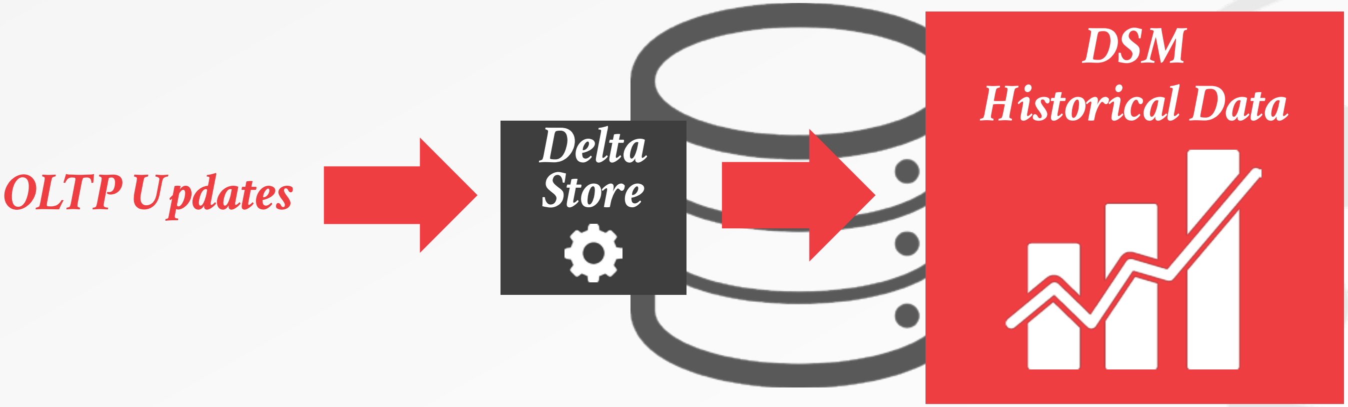


A CASE FOR FRACTURED MIRRORS
VLDB 2002

DELTA STORE

Stage updates to the database in an NSM table.

A background thread migrates updates from delta store and applies them to DSM data.



CATEGORIZING DATA

Choice #1: Manual Approach

→ DBA specifies what tables should be stored as DSM.

Choice #2: Off-line Approach

→ DBMS monitors access logs offline and then makes decision about what data to move to DSM.

Choice #3: On-line Approach

→ DBMS tracks access patterns at runtime and then makes decision about what data to move to DSM.

PELOTON ADAPTIVE STORAGE

Employ a single execution engine architecture that is able to operate on both NSM and DSM data.

→ Don't need to store two copies of the database.

→ Don't need to sync multiple database segments.

Note that a DBMS can still use the delta-store approach with this single-engine architecture.

BRIDGING THE ARCHIPELAGO BETWEEN ROW-STORES AND COLUMN-STORES FOR HYBRID WORKLOADS
SIGMOD 2016

PELOTON ADAPTIVE STORAGE

```
UPDATE AndySux
   SET A = 123,
       B = 456,
       C = 789
 WHERE D = “xxx”
```

```
SELECT AVG(B)
  FROM AndySux
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```

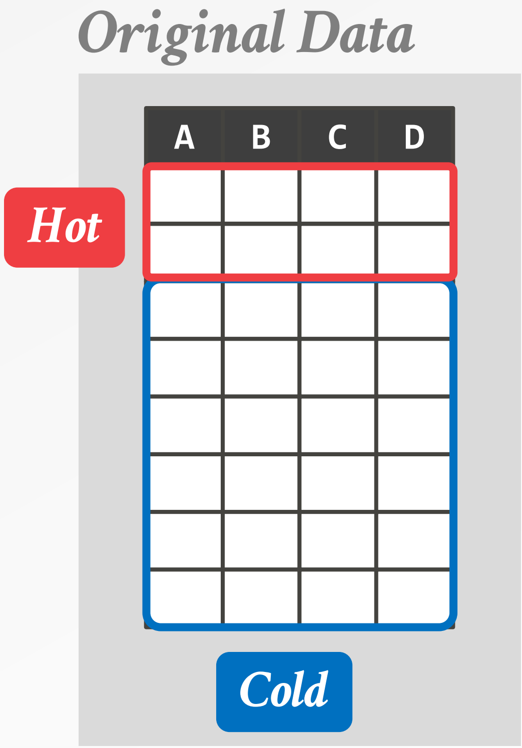

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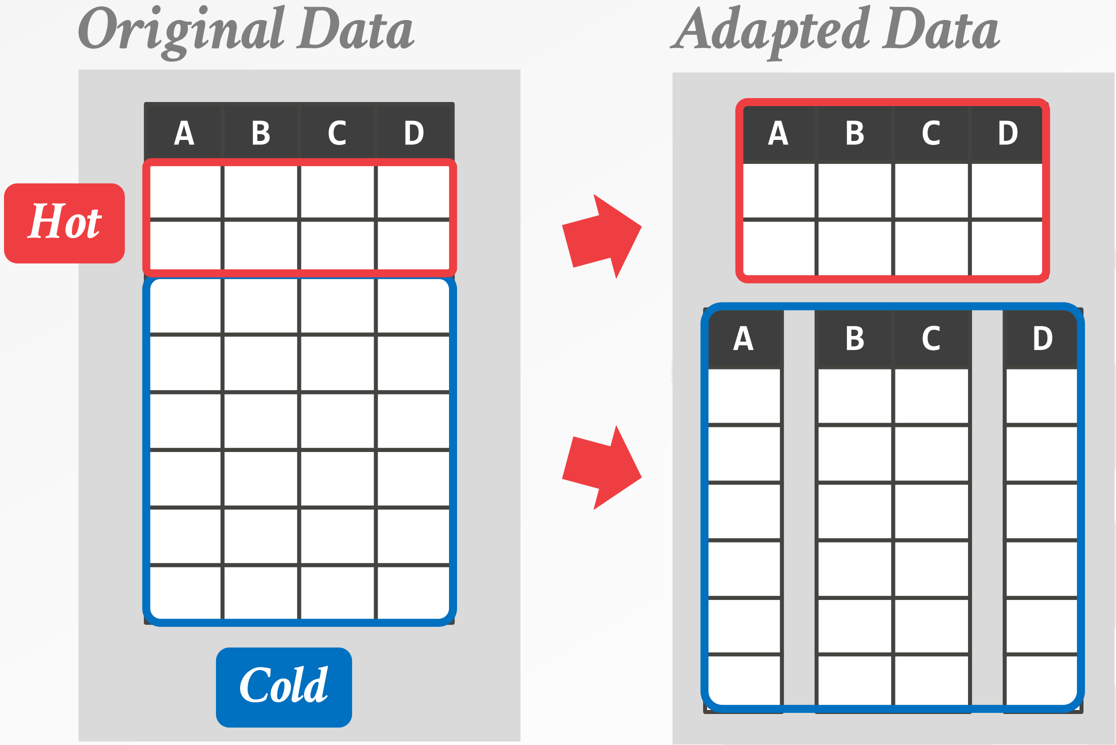
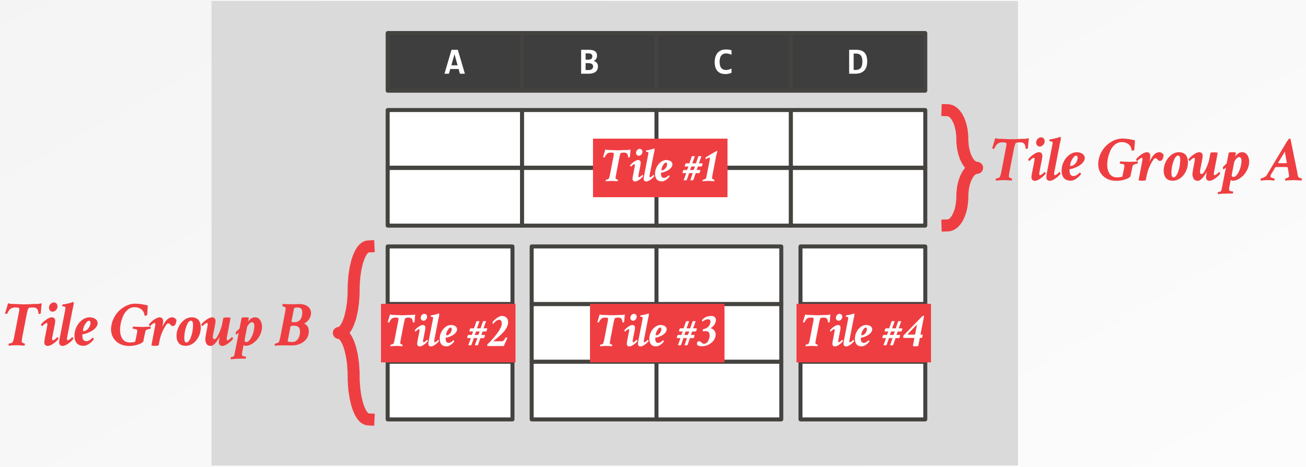


TILE ARCHITECTURE

Introduce an indirection layer that abstracts the true layout of tuples from query operators.



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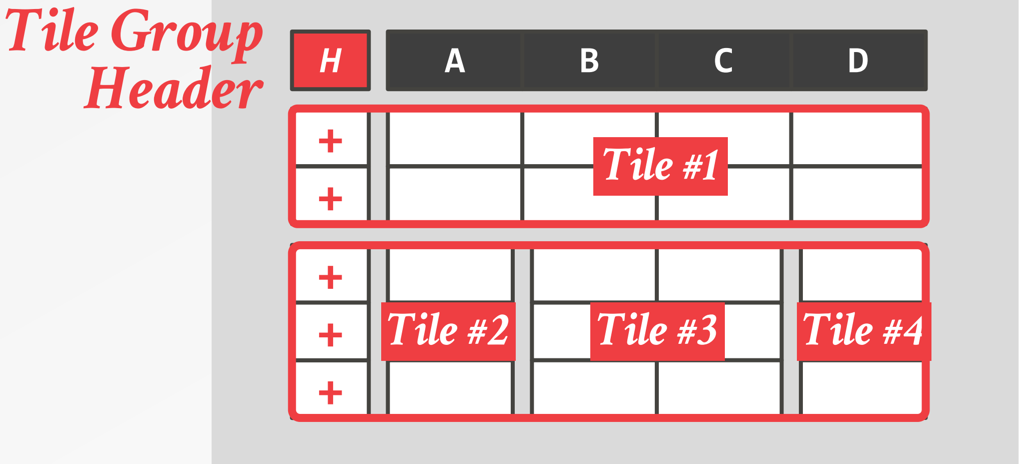

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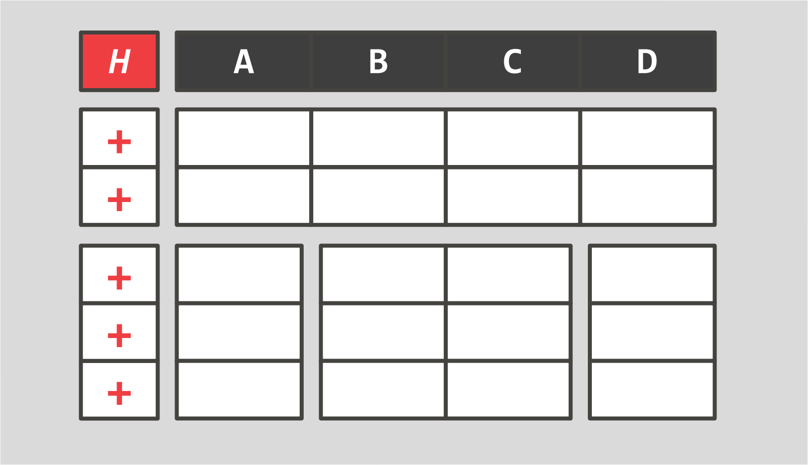

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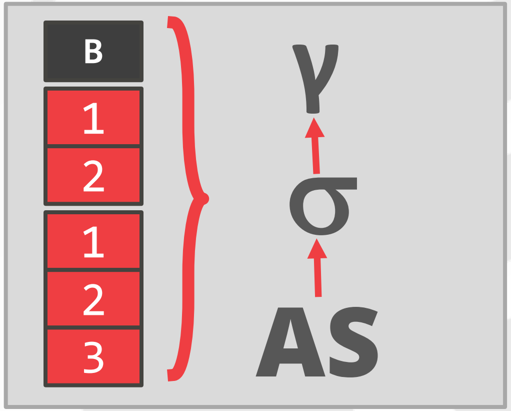

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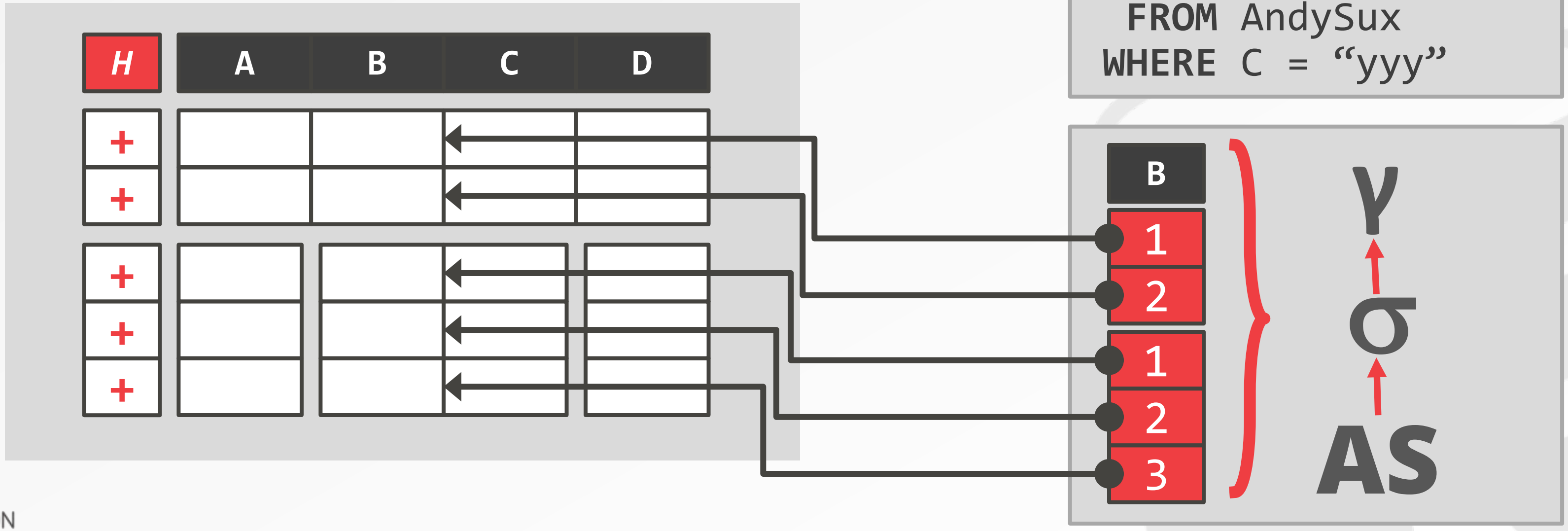
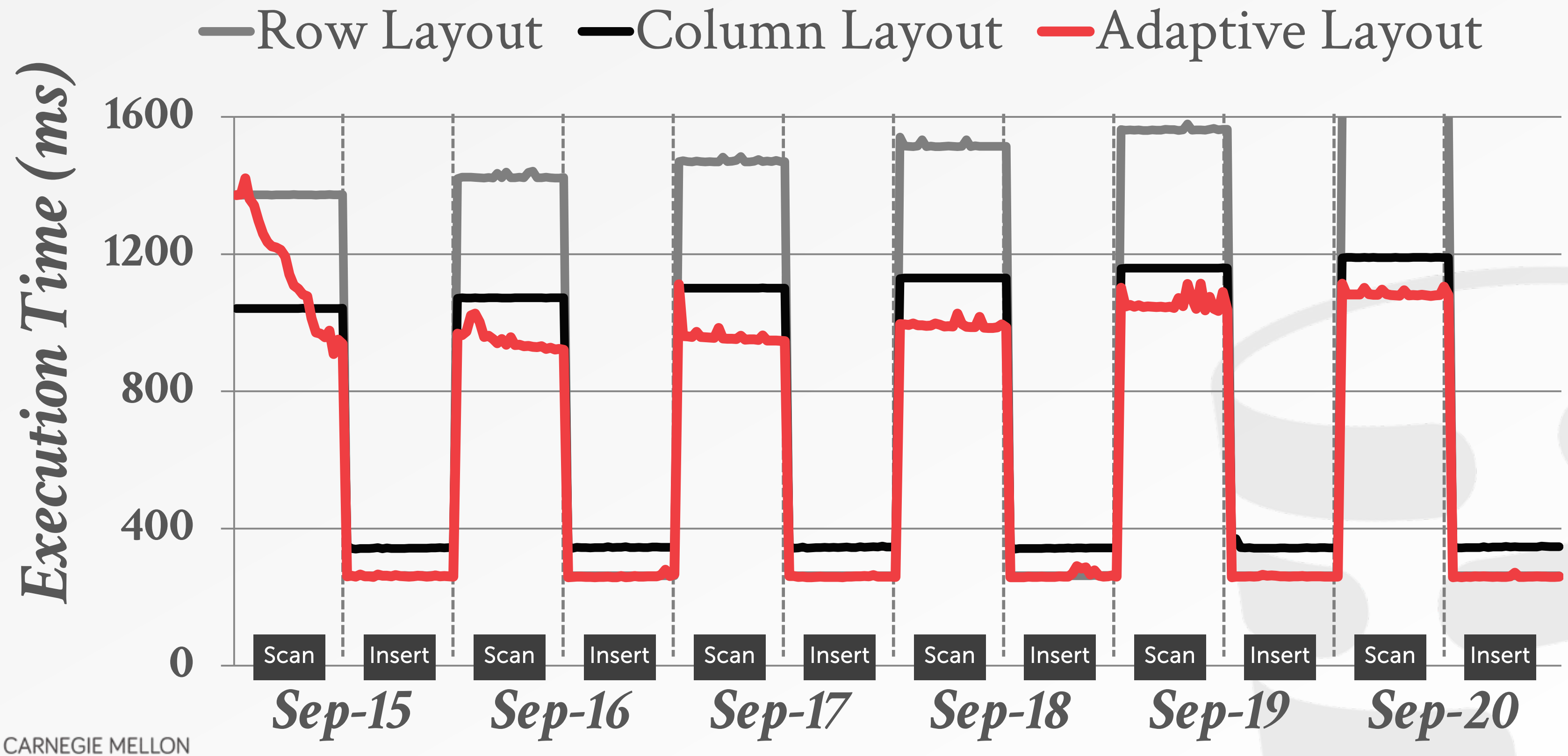


PELOTON ADAPTIVE STORAGE



H_2O ADAPTIVE STORAGE

Examine the access patterns of queries and then dynamically reconfigure the database to optimize decomposition and layout.

Copies columns into a new layout that is optimized for each query.

- → Think of it like a mini fractured mirror.
- → Use query compilation to speed up operations.

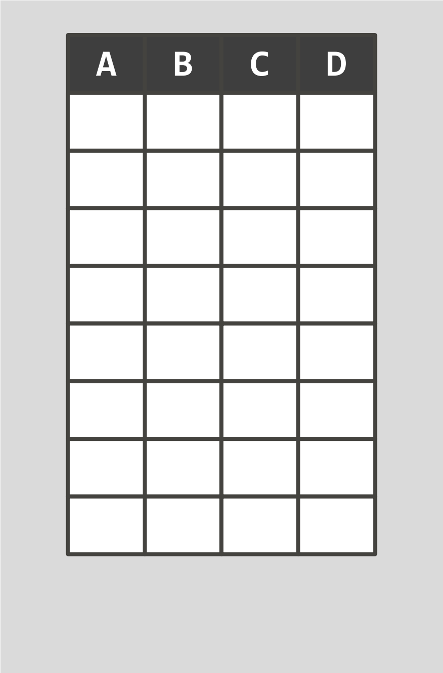
H_2O: A HANDS-FREE ADAPTIVE STORE
SIGMOD 2014

H_2O ADAPTIVE STORAGE

```
UPDATE AndySux
   SET A = 123,
       B = 456,
       C = 789
 WHERE D = “xxx”
```

```
SELECT AVG(B)
  FROM AndySux
 WHERE C = “yyy”
```

Original Data



H_2O ADAPTIVE STORAGE

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UPDATE AndySux
   SET A = 123,
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  FROM AndySux
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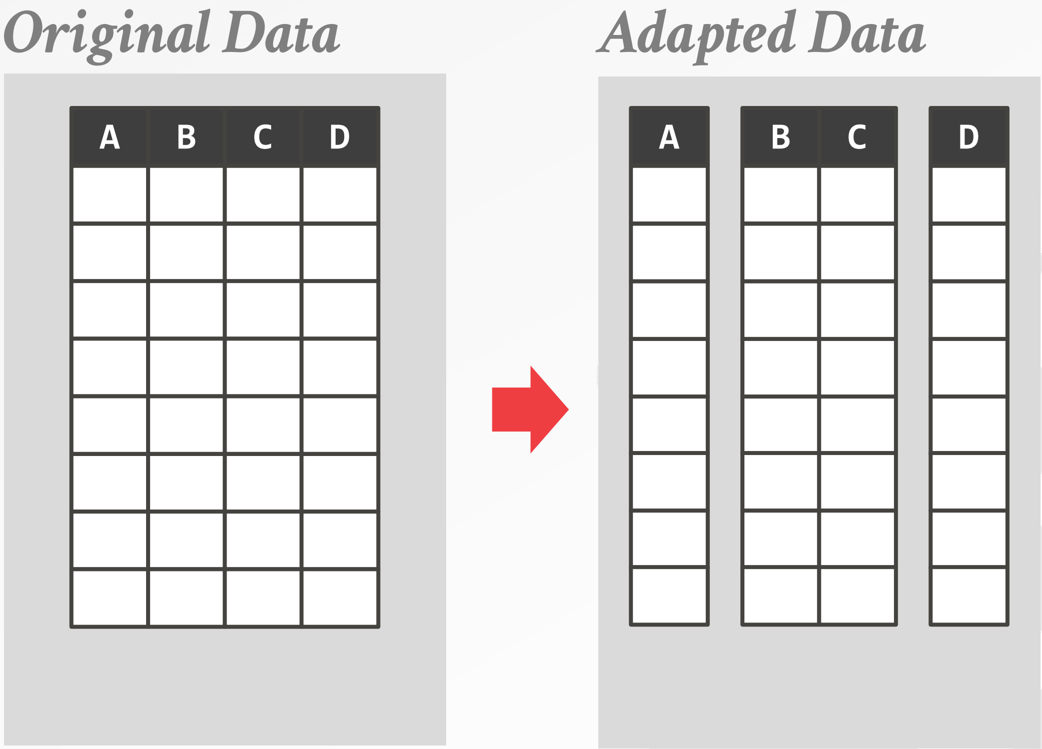

H_2O ADAPTIVE STORAGE

This approach is unable to handle updates to the database.
It also unable to store tuples in the same table in a different layout.

This is because they are missing the ability to categorize whether data is hot or cold…

PARTING THOUGHTS

A flexible architecture that supports a hybrid storage model is the next major trend in DBMSs

This will enable relational DBMSs to support all known database workloads except for matrices in machine learning.