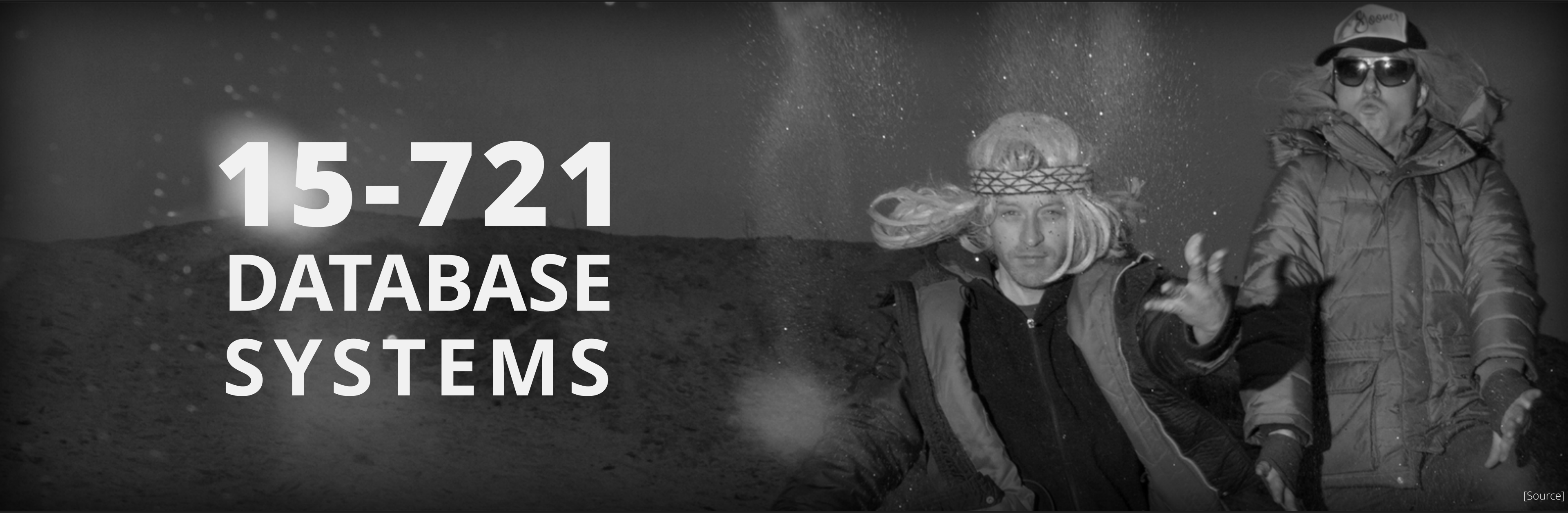


Lecture #08 – Indexing (OLAP)

Andy Pavlo // Carnegie Mellon University // Spring 2016

TODAY'S AGENDA

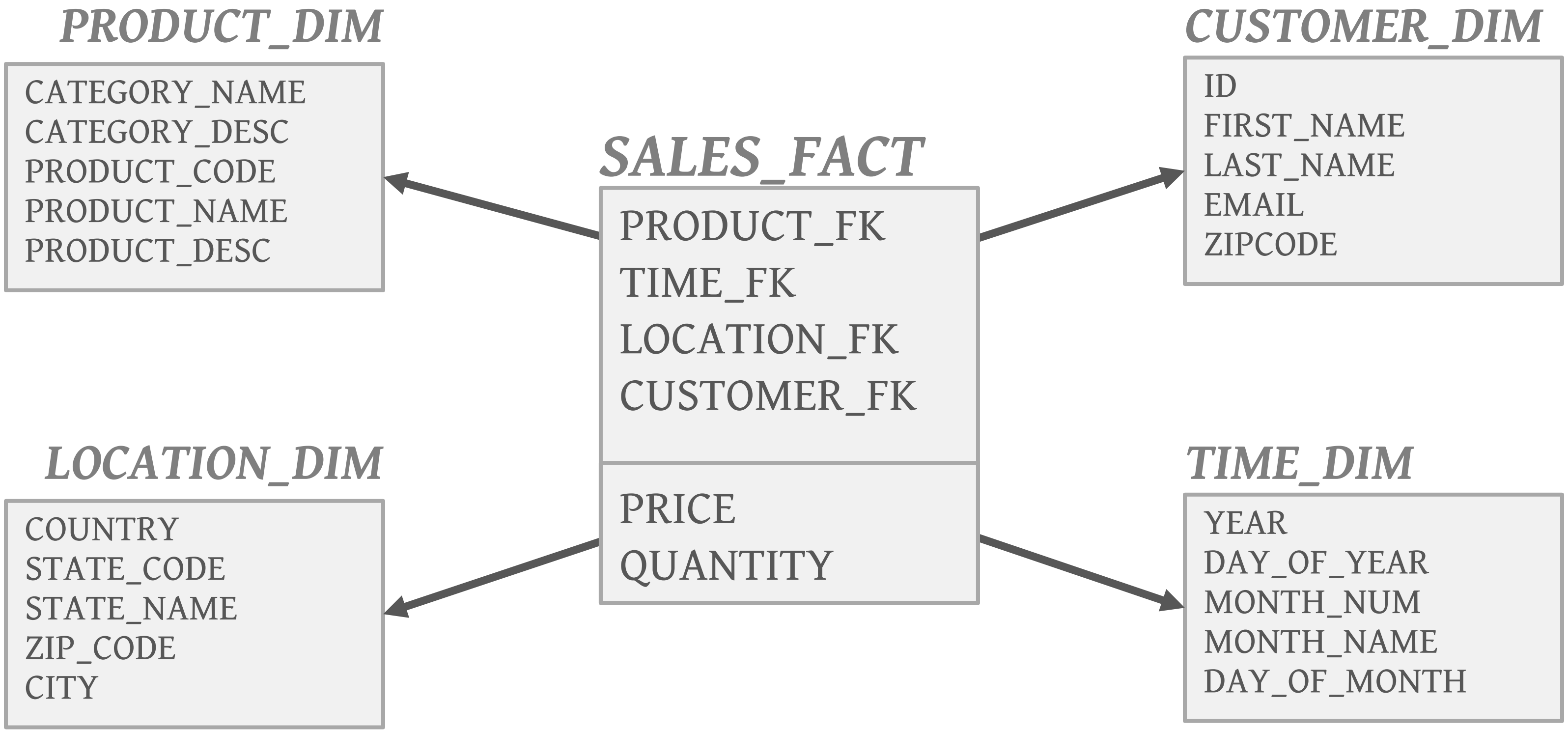
Background
Projection/Columnar Indexes (MSSQL)
Bitmap Indexes
Project #2

DECISION SUPPORT SYSTEMS

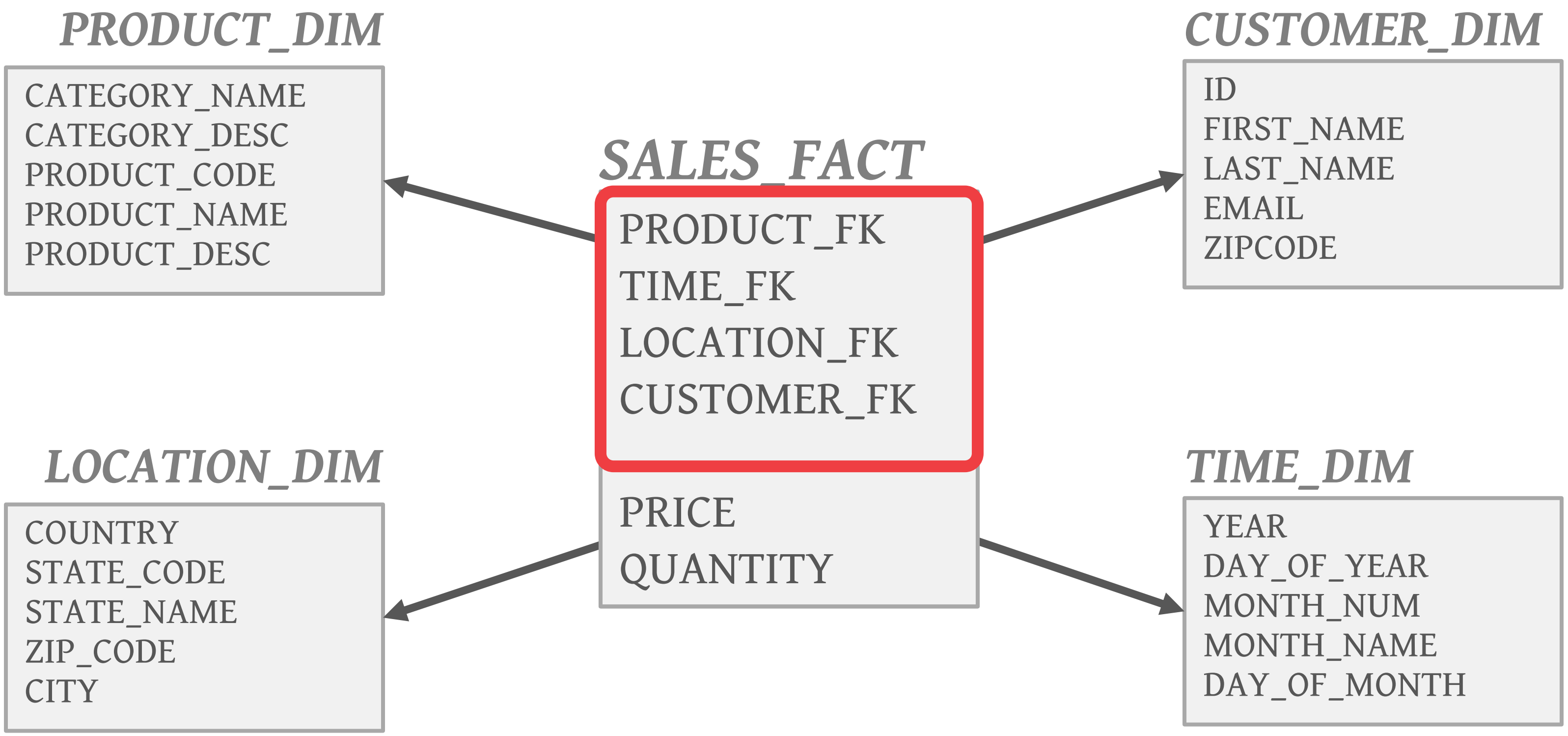
Applications that serve the management, operations, and planning levels of an organization to help people make decisions about future issues and problems by analyzing historical data.

Star Schema vs. Snowflake Schema

STAR SCHEMA


PRODUCT_DIM
CATEGORY_NAME
CATEGORY_DESC
PRODUCT_CODE
PRODUCT_NAME
PRODUCT_DESC
CUSTOMER_DIM
ID
FIRST_NAME
LAST_NAME
EMAIL
ZIPCODE
SALES_FACT
PRODUCT_FK
TIME_FK
LOCATION_FK
CUSTOMER_FK
PRICE
QUANTITY
LOCATION_DIM
COUNTRY
STATE_CODE
STATE_NAME
ZIP_CODE
CITY
TIME_DIM
YEAR
DAY_OF_YEAR
MONTH_NUM
MONTH_NAME
DAY_OF_MONTH

STAR SCHEMA


PRODUCT_DIM
CATEGORY_NAME
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PRODUCT_CODE
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ID
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LAST_NAME
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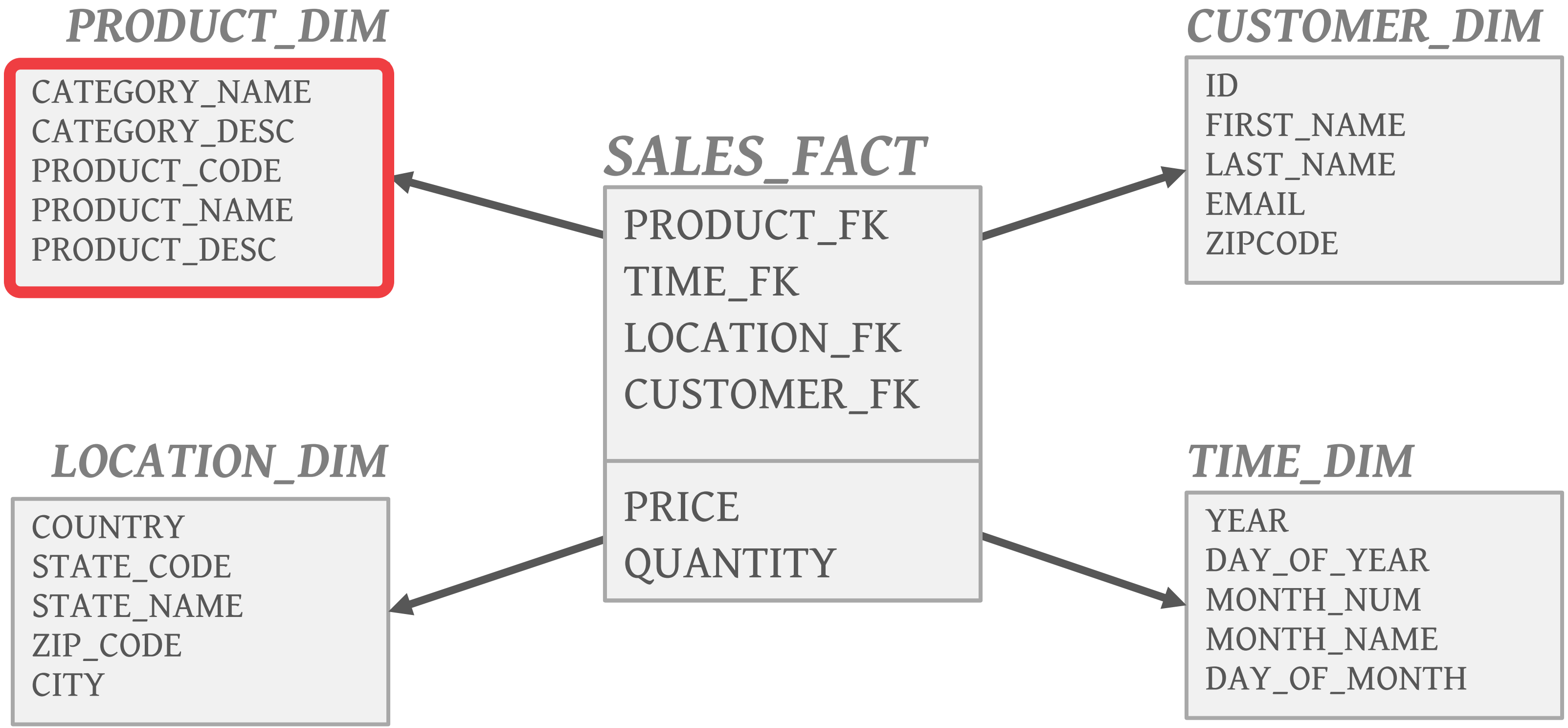
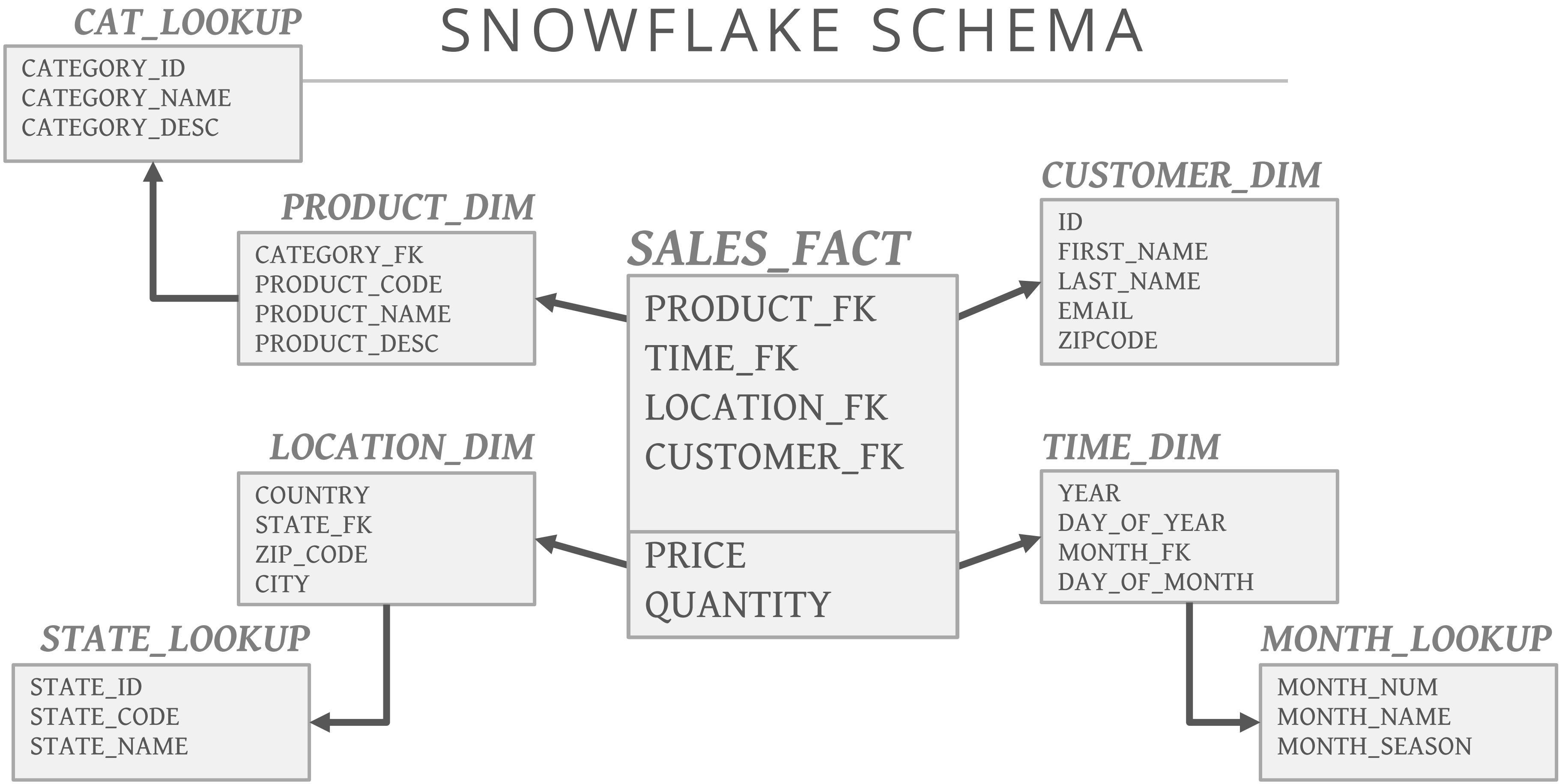
TIME_FK
LOCATION_FK
CUSTOMER_FK
PRICE
QUANTITY
LOCATION_DIM
COUNTRY
STATE_CODE
STATE_NAME
ZIP_CODE
CITY
TIME_DIM
YEAR
DAY_OF_YEAR
MONTH_NUM
MONTH_NAME
DAY_OF_MONTH

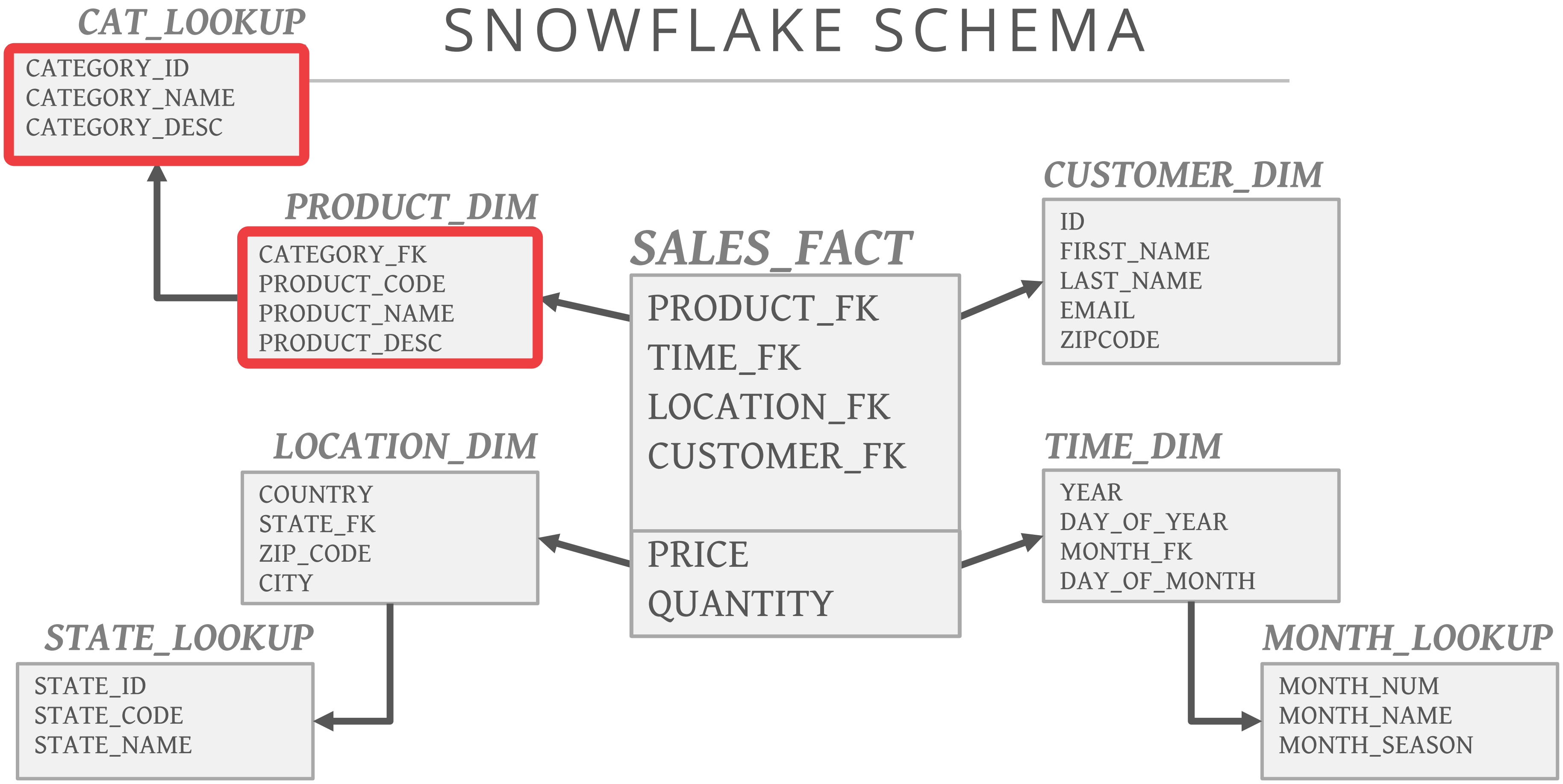
STAR SCHEMA


PRODUCT_DIM
CATEGORY_NAME
CATEGORY_DESC
PRODUCT_CODE
PRODUCT_NAME
PRODUCT_DESC
SALES_FACT
PRODUCT_FK
TIME_FK
LOCATION_FK
CUSTOMER_FK
PRICE
QUANTITY
CUSTOMER_DIM
ID
FIRST_NAME
LAST_NAME
EMAIL
ZIPCODE
LOCATION_DIM
COUNTRY
STATE_CODE
STATE_NAME
ZIP_CODE
CITY
TIME_DIM
YEAR
DAY_OF_YEAR
MONTH_NUM
MONTH_NAME
DAY_OF_MONTH

SNOWFLAKE SCHEMA



SNOWFLAKE SCHEMA



OBSERVATION

Using a B+tree index on a large table results in a lot of wasted storage if the values are repetitive and the cardinality is low.

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Using a B+tree index on a large table results in a lot of wasted storage if the values are repetitive and the cardinality is low.

```
CREATE TABLE sales_fact (
  id INT PRIMARY KEY,
  ⋮
  customer_fk INT
   REFERENCES customer_dim (id)
);
```

```
CREATE TABLE customer_dim (
  id INT PRIMARY KEY,
  ⋮
  zipcode INT
);
```

```
SELECT COUNT(*)
  FROM sales_fact AS S
  JOIN customer_dim AS C
    ON S.customer_fk = C.id
 WHERE C.zipcode = 15217
```

MSSQL: COLUMNAR INDEXES

Decompose rows into compressed column segments for single attributes.
→ Original data still remains in row store.
→ No way to map an entry in the column index back to its corresponding entry in row store.

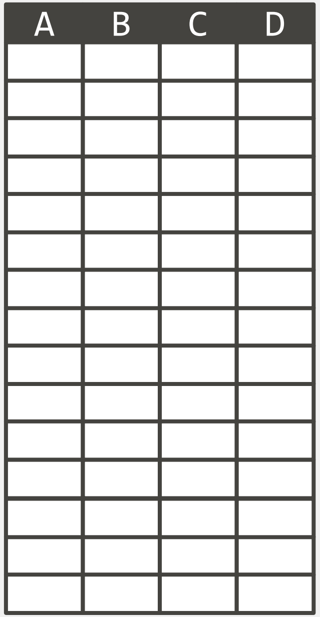
Use as many existing components in MSSQL.

Original implementation in 2012 would force a table to become read-only.

SQL SERVER COLUMN STORE INDEXES
SIGMOD 2010

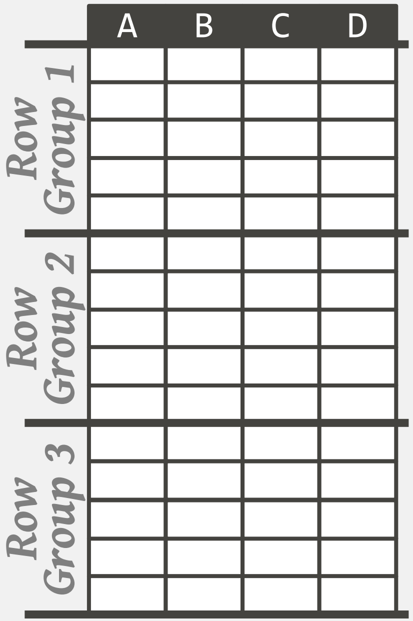
MSSQL: COLUMNAR INDEXES

Data Table



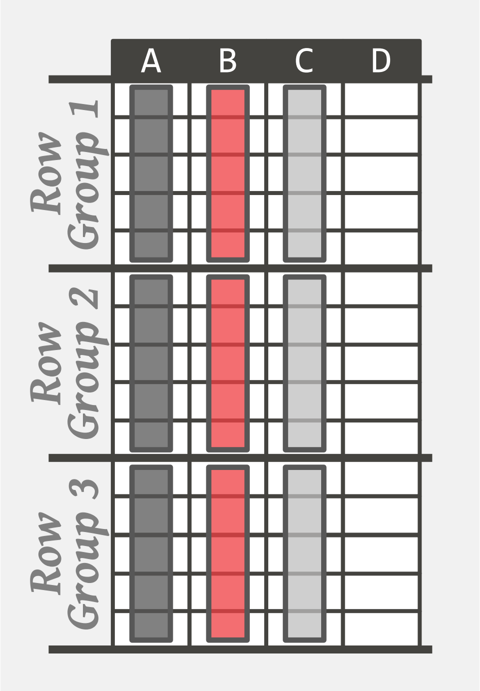
MSSQL: COLUMNAR INDEXES

Data Table



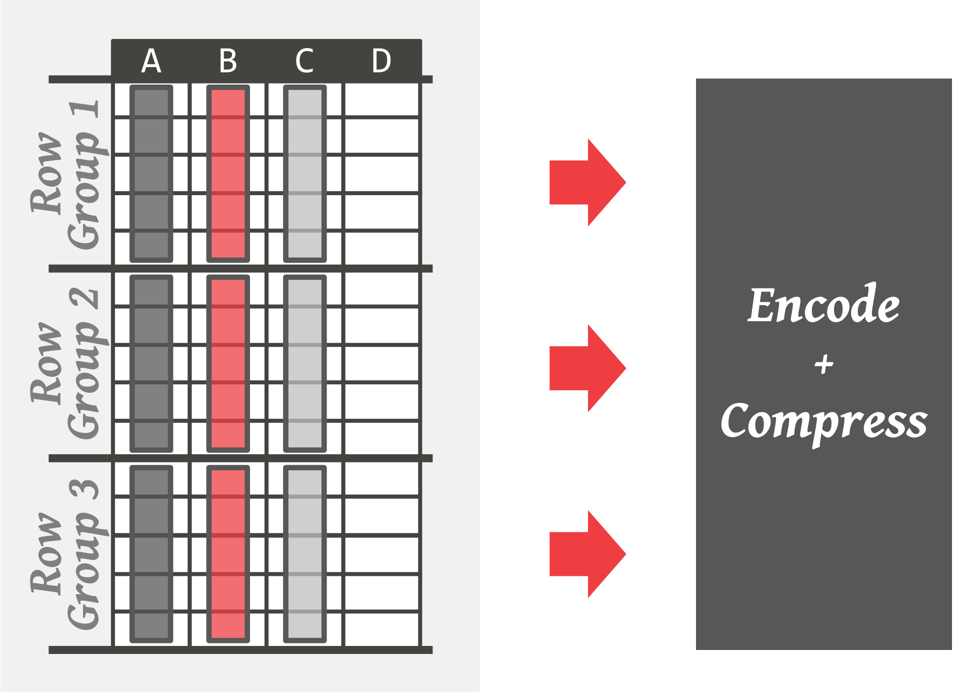
MSSQL: COLUMNAR INDEXES

Data Table

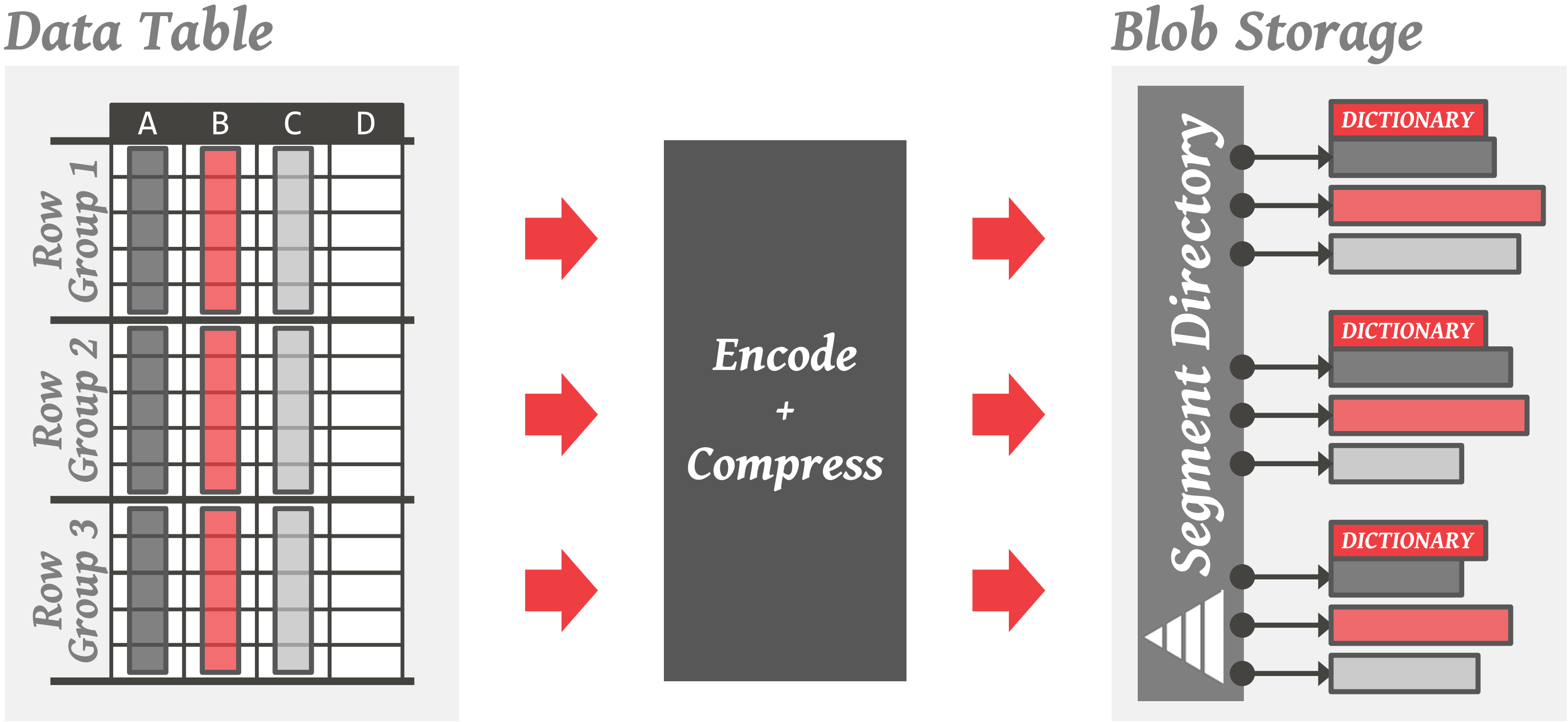


MSSQL: COLUMNAR INDEXES

Data Table



MSSQL: COLUMNAR INDEXES



MSSQL: INTERNAL CATALOG

Segment Directory: Keeps track of statistics for each column segments per row group.

→ Size
→ # of Rows
→ Min and Max key values
→ Encoding Meta-data

Data Dictionary: Maps dictionary ids to their original values.

MSSQL: DICTIONARY ENCODING

Construct a separate table of the unique values for an attribute sorted by frequency.

For each tuple, store the 32-bit position of its value in the dictionary instead of the real value.

MSSQL: DICTIONARY ENCODING

Original Data

id	city
1	New York
2	Chicago
3	New York
4	New York
6	Pittsburgh
7	Chicago
8	New York
9	New York

MSSQL: DICTIONARY ENCODING

Original Data

id	city
1	New York
2	Chicago
3	New York
4	New York
6	Pittsburgh
7	Chicago
8	New York
9	New York

MSSQL: DICTIONARY ENCODING

Original Data

id	city
1	New York
2	Chicago
3	New York
4	New York
6	Pittsburgh
7	Chicago
8	New York
9	New York

Compressed Data

id	city
1	0
2	1
3	0
4	0
6	2
7	1
8	0
9	0

DICTIONARY
0→(New York,5)
1→(Chicago,2)
2→(Pittsburgh,1)

MSSQL: DICTIONARY ENCODING

Original Data

id	city
1	New York
2	Chicago
3	New York
4	New York
6	Pittsburgh
7	Chicago
8	New York
9	New York

Compressed Data

id	city
1	0
2	1
3	0
4	0
6	2
7	1
8	0
9	0

DICTIONARY
0→(New York,5)
1→(Chicago,2)
2→(Pittsburgh,1)

MSSQL: VALUE ENCODING

Transform the domain of a numeric column segment into a set of distinct values in a smaller domain of integers.

Allows the DBMS to use smaller data types to store larger values.

Also sometimes called **delta encoding**.

VALUE ENCODING: DECIMALS

Values: `0.5, 10.77, 1.33`

VALUE ENCODING: DECIMALS

Values: `0.5, 10.77, 1.33`

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

VALUE ENCODING: DECIMALS

Values: `0.5, 10.77, 1.33`

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

Initial Encoding: $0.5\ 10^3 \rightarrow \mathbf{500}$
$10.77\ 10^3 \rightarrow \mathbf{10770}$
$1.33\ 10^3 \rightarrow \mathbf{1333}$

VALUE ENCODING: DECIMALS

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 → **`1333`**

Base: `500`

VALUE ENCODING: DECIMALS

Values: `0.5, 10.77, 1.33`

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

Initial Encoding: $\boxed{0.5\ 10^3 \rightarrow \mathbf{500}}$
$10.77\ 10^3 \rightarrow \mathbf{10770}$
$1.33\ 10^3 \rightarrow \mathbf{1333}$

Base: 500

VALUE ENCODING: DECIMALS

Values: `0.5, 10.77, 1.33`

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

Initial Encoding: $\boxed{0.5\ 10^3 \rightarrow \mathbf{500}}$
$10.77\ 10^3 \rightarrow \mathbf{10770}$
$1.33\ 10^3 \rightarrow \mathbf{1333}$

Base: 500

Final Encoding: $(0.5\ 10^3)-500 \rightarrow \mathbf{0}$
$(10.77\ 10^3)-500 \rightarrow \mathbf{10270}$
$(1.33\ 10^3)-500 \rightarrow \mathbf{833}$

VALUE ENCODING: INTEGERS

Values: `500, 1700, 1333000`

VALUE ENCODING: INTEGERS

Values: `500, 1700, 1333000`

Exponent: -2 (i.e., 10^{-2})

VALUE ENCODING: INTEGERS

Values: `500, 1700, 1333000`

Exponent: -2 (i.e., 10^{-2})

Initial Encoding: 500 10^{-2}→**5**
1700 10^{-2}→**17**
1333000 10^{-2}→**13330**

VALUE ENCODING: INTEGERS

Values: `500, 1700, 1333000`

Exponent: -2 (i.e., 10^{-2})

Initial Encoding: $\boxed{500 \cdot 10^{-2} \rightarrow \mathbf{5}}$
$1700 \cdot 10^{-2} \rightarrow \mathbf{17}$
$1333000 \cdot 10^{-2} \rightarrow \mathbf{13330}$

Base: 5

VALUE ENCODING: INTEGERS

Values: 500, 1700, 1333000

Exponent: -2 (i.e., 10^{-2})

Initial Encoding: $\boxed{500\ 10^{-2} \rightarrow \mathbf{5}}$

$1700\ 10^{-2} \rightarrow \mathbf{17}$

$1333000\ 10^{-2} \rightarrow \mathbf{13330}$

Base: 5

Final Encoding: $(500\ 10^{-2})-5 \rightarrow \mathbf{0}$

$(1700\ 10^{-2})-5 \rightarrow \mathbf{12}$

$(1333000\ 10^{-2})-5 \rightarrow \mathbf{13325}$

MSSQL: RUN-LENGTH ENCODING

Compress runs of the same value in a single column into triplets:

→ The value of the attribute.
→ The start position in the column segment.
→ The # of elements in the run.

Requires the columns to be sorted intelligently to maximize compression opportunities.

MSSQL: RUN-LENGTH ENCODING

Original Data

id	sex
1	M
2	M
3	M
4	F
6	M
7	F
8	M
9	M

MSSQL: RUN-LENGTH ENCODING

Original Data

id	sex
1	M
2	M
3	M
4	F
6	M
7	F
8	M
9	M

MSSQL: RUN-LENGTH ENCODING

Original Data

id	sex
1	M
2	M
3	M
4	F
6	M
7	F
8	M
9	M

Compressed Data

id
1
2
3
4
6
7
8
9

sex
(M,0,3)
(F,3,1)
(M,4,1)
(F,5,1)
(M,6,2)

MSSQL: RUN-LENGTH ENCODING

Original Data

id	sex
1	M
2	M
3	M
4	F
6	M
7	F
8	M
9	M

Compressed Data

id
1
2
3
4
6
7
8
9

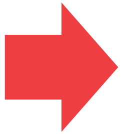
sex
(M,0,3)
(F,3,1)
(M,4,1)
(F,5,1)
(M,6,2)

RLE Triplet
- ***Value***
- ***Offset***
- ***Length***

MSSQL: RUN-LENGTH ENCODING

Original Data

id	sex
1	M
2	M
3	M
4	F
6	M
7	F
8	M
9	M



Compressed Data

id	sex
1	(M,0,3)
2	(F,3,1)
3	(M,4,1)
4	(F,5,1)
6	(M,6,2)
7	
8	
9	

RLE Triplet
- *Value*
- *Offset*
- *Length*

MSSQL: RUN-LENGTH ENCODING

Sorted Data

id	sex
1	M
2	M
3	M
6	M
8	M
9	M
4	F
7	F

Compressed Data

RLE Triplet
- *Value*
- *Offset*
- *Length*

MSSQL: RUN-LENGTH ENCODING

Sorted Data

id	sex
1	M
2	M
3	M
6	M
8	M
9	M
4	F
7	F

Compressed Data

id	sex
1	(M,0,6)
2	(F,7,2)
3	
6	
7	
9	
4	
7	

RLE Triplet
- *Value*
- *Offset*
- *Length*

MSSQL: QUERY PROCESSING

Modify the query planner and optimizer to be aware of the columnar indexes.

Add new vector-at-a-time operators that can operate directly on columnar indexes.

Compute joins using Bitmaps built on-the-fly.

MSSQL: UPDATES SINCE 2012

Clustered column indexes.

More data types.

Support for **INSERT**, **UPDATE**, and **DELETE**:

→ Use a **delta store** for modifications and updates. The DBMS seamlessly combines results from both the columnar indexes and the delta store.

→ Deleted tuples are marked in a bitmap.

ENHANCEMENTS TO SQL SERVER COLUMN STORES
SIGMOD 2013

BITMAP INDEXES

Store a separate Bitmap for each unique value for a particular attribute where an offset in the vector corresponds to a tuple.

→ The ith position in the Bitmap corresponds to the ith tuple in the table.

Typically segmented into chunks to avoid allocating large blocks of contiguous memory.

MODEL 204 ARCHITECTURE AND PERFORMANCE
High Performance Transaction Systems 1987

BITMAP INDEXES

Original Data

id	sex
1	M
2	M
3	M
4	F
6	M
7	F
8	M
9	M

BITMAP INDEXES

Original Data

id	sex
1	M
2	M
3	M
4	F
6	M
7	F
8	M
9	M

BITMAP INDEXES

Original Data

id	sex
1	M
2	M
3	M
4	F
6	M
7	F
8	M
9	M

Compressed Data

	sex	
id	M	F
1	1	0
2	1	0
3	1	0
4	0	1
6	1	0
7	0	1
8	1	0
9	1	0

BITMAP INDEXES

Original Data

id	sex
1	M
2	M
3	M
4	F
6	M
7	F
8	M
9	M

Compressed Data

	sex	
id	M	F
1	1	0
2	1	0
3	1	0
4	0	1
6	1	0
7	0	1
8	1	0
9	1	0

BITMAP INDEXES: EXAMPLE

```
CREATE TABLE customer_dim (
  id INT PRIMARY KEY,
  name VARCHAR(32),
  email VARCHAR(64),
  address VARCHAR(64),
  zipcode INT
);
```

BITMAP INDEXES: EXAMPLE

```
CREATE TABLE customer_dim (
  id INT PRIMARY KEY,
  name VARCHAR(32),
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BITMAP INDEXES: EXAMPLE

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  zipcode INT
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```

Assume we have 10 million tuples.
43,000 zip codes in the US.
→ 10000000   43000 = **53.75 GB**

BITMAP INDEXES: EXAMPLE

```
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  email VARCHAR(64),
  address VARCHAR(64),
  zipcode INT
);
```

Assume we have 10 million tuples.
43,000 zip codes in the US.
→ 10000000   43000 = **53.75 GB**

Every time a txn inserts a new tuple, we have to extend 43,000 different bitmaps.

BITMAP INDEX: DESIGN CHOICES

Encoding Scheme

Compression

BITMAP INDEX: ENCODING

Choice #1: Equality Encoding

→ Basic scheme with one Bitmap per unique value.

Choice #2: Range Encoding

→ Use one Bitmap per interval instead of one per value.

Choice #3: Bit-sliced Encoding

→ Use a Bitmap per bit location across all values.

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

Source: Jignesh Patel

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

Source: Jignesh Patel

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

bin(21042)→ 00101001000110010

Source: Jignesh Patel

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

N?	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

bin(21042)→ 00101001000110010

Source: Jignesh Patel

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
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Bit-Slices

N?	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0																	

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0																	

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Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

N?	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	1	0

bin(21042)→ 00101001000110010

Source: Jignesh Patel

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

N?	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	1	0

Source: Jignesh Patel

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

N?	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	1	0
0	0	0	0	1	1	1	0	1	1	0	1	1	1	0	0	0	1
0	0	0	0	0	0	1	0	1	1	0	1	0	1	0	1	1	1
0	1	0	1	1	0	0	0	0	0	0	1	1	0	1	1	0	0
0	0	0	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1
0	0	1	1	0	1	0	0	0	1	1	1	0	0	0	1	1	1

Source: Jignesh Patel

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

N?	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	1	0
0	0	0	0	1	1	1	0	1	1	0	1	1	1	0	0	0	1
0	0	0	0	0	0	1	0	1	1	0	1	0	1	0	1	1	1
0	1	0	1	1	0	0	0	0	0	0	1	1	0	1	1	0	0
0	0	0	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1
0	0	1	1	0	1	0	0	0	1	1	1	0	0	0	1	1	1

```
SELECT * FROM customer_dim
 WHERE zipcode < 15217
```

Source: Jignesh Patel

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

N?	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	1	0
0	0	0	0	1	1	1	0	1	1	0	1	1	1	0	0	0	1
0	0	0	0	0	0	1	0	1	1	0	1	0	1	0	1	1	1
0	1	0	1	1	0	0	0	0	0	0	1	1	0	1	1	0	0
0	0	0	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1
0	0	1	1	0	1	0	0	0	1	1	1	0	0	0	1	1	1

```
SELECT * FROM customer_dim
 WHERE zipcode < 15217
```

Walk each slice and construct a result bitmap.

Source: Jignesh Patel

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

N?	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	1	0
0	0	0	0	1	1	1	0	1	1	0	1	1	1	0	0	0	1
0	0	0	0	0	0	1	0	1	1	0	1	0	1	0	1	1	1
0	1	0	1	1	0	0	0	0	0	0	1	1	0	1	1	0	0
0	0	0	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1
0	0	1	1	0	1	0	0	0	1	1	1	0	0	0	1	1	1

```
SELECT * FROM customer_dim
 WHERE zipcode < 15217
```

Walk each slice and construct a result bitmap.

Source: Jignesh Patel

BIT-SLICED ENCODING

Original Data

id	zipcode
1	21042
2	15217
3	02903
4	90220
6	14623
7	53703

Bit-Slices

N?	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	1	0
0	0	0	0	1	1	1	0	1	1	0	1	1	1	0	0	0	1
0	0	0	0	0	0	1	0	1	1	0	1	0	1	0	1	1	1
0	1	0	1	1	0	0	0	0	0	0	1	1	0	1	1	0	0
0	0	0	0	1	1	1	0	0	1	0	0	0	1	1	1	1	1
0	0	1	1	0	1	0	0	0	1	1	1	0	0	0	1	1	1

```
SELECT * FROM customer_dim
 WHERE zipcode < 15217
```

Walk each slice and construct a result bitmap.

Skip entries that have **1** in first 3 slices (16, 15, 14)

Source: Jignesh Patel

BIT-SLICED ENCODING

Bit-slices can also be used for efficient aggregate computations.

Example: `SUM(attr)`

→ First, count the number of 1s in $\textbf{slice}_{17}$ and multiply the count by 2^{17}

→ Then, count the number of 1s in $\textbf{slice}_{16}$ and multiply the count by 2^{16}

→ Repeat for the rest of slices...

BITMAP INDEX: COMPRESSION

Choice #1: General Purpose Compression

→ Use standard compression algorithms (e.g., LZ4, Snappy).
→ Have to decompress before you can use it to process a query. Not useful for in-memory DBMSs.

Choice #2: Byte-aligned Bitmap Codes (BBC)

→ Structured run-length encoding compression.

Choice #3: Roaring Bitmaps

→ Modern hybrid of run-length encoding and value lists.

BYTE-ALIGNED BITMAP CODES

Divide Bitmap into chunks that contain different categories of bytes:

→ **Gap Byte**: All the bits are **`0`**s.
→ **Tail Byte:** Some bits are **`1`**s.

Encode each **<u>chunk</u>** that consists of some **Gap Bytes** followed by some **Tail Bytes.**

→ Gap Bytes are compressed with RLE.
→ Tail Bytes are stored uncompressed unless it consists of only 1 byte or has only 1 non-zero bit.

BYTE-ALIGNED BITMAP COMPRESSION
Data Compression Conference 1995

BYTE-ALIGNED BITMAP CODES

Bitmap

```
00000000 00000000 00010000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

Source: Brian Babcock

BYTE-ALIGNED BITMAP CODES

Bitmap

```
00000000 00000000 00010000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

Source: Brian Babcock

BYTE-ALIGNED BITMAP CODES

Bitmap

```
00000000 00000000 00010000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

#1

Compressed Bitmap

Source: Brian Babcock

BYTE-ALIGNED BITMAP CODES

Bitmap

Gap Bytes *Tail Bytes*

```
00000000 00000000 00010000 #1
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

Source: Brian Babcock

BYTE-ALIGNED BITMAP CODES

Bitmap

Gap Bytes *Tail Bytes*

```
00000000 00000000 00010000  #1
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000  #2
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

Source: Brian Babcock

BYTE-ALIGNED BITMAP CODES

Bitmap

```
00000000 00000000 00010000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

Chunk #1 (Bytes 1-3)

Header Byte:

→ Number of Gap Bytes (Bits 1-3)
→ Is the tail special? (Bit 4)
→ Number of verbatim bytes (if Bit 4=0)
→ Index of **1** bit in tail byte (if Bit 4=1)

No gap length bytes since gap length < 7

No verbatim bytes since tail is special

Source: Brian Babcock

BYTE-ALIGNED BITMAP CODES

Bitmap

```
00000000 00000000 00010000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

#1 (010)(1)(0100)

Chunk #1 (Bytes 1-3)

Header Byte:

→ Number of Gap Bytes (Bits 1-3)
→ Is the tail special? (Bit 4)
→ Number of verbatim bytes (if Bit 4=0)
→ Index of **1** bit in tail byte (if Bit 4=1)

No gap length bytes since gap length < 7

No verbatim bytes since tail is special

Source: Brian Babcock

BYTE-ALIGNED BITMAP CODES

Bitmap

```
00000000 00000000 00010000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

```
#1 (010)(1)(0100)
```

Chunk #2 (Bytes 4-18)

Header Byte:

→ 13 gap bytes, two tail bytes

→ # of gaps is > 7, so have to use extra byte

One gap length byte gives gap length = 13

Two verbatim bytes for tail.

Source: Brian Babcock

BYTE-ALIGNED BITMAP CODES

Bitmap

```
00000000 00000000 00010000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

```
#1 (010)(1)(0100)

#2 (111)(0)(0010) 00001101
   01000000 00100010
```

Chunk #2 (Bytes 4-18)

Header Byte:

→ 13 gap bytes, two tail bytes

→ # of gaps is > 7, so have to use extra byte

One gap length byte gives gap length = 13

Two verbatim bytes for tail.

Source: Brian Babcock

BYTE-ALIGNED BITMAP CODES

Bitmap

```
00000000 00000000 00010000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

#1 (010)(1)(0100)

Gap Length

#2 (111)(0)(0010) $\boxed{00001101}$
01000000 00100010

Chunk #2 (Bytes 4-18)

Header Byte:

→ 13 gap bytes, two tail bytes
→ # of gaps is > 7, so have to use extra byte

One gap length byte gives gap length = 13

Two verbatim bytes for tail.

Source: Brian Babcock

BYTE-ALIGNED BITMAP CODES

Bitmap

```
00000000 00000000 00010000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

```
#1 (010)(1)(0100)

#2 (111)(0)(0010) 00001101
    01000000 00100010
```

Verbatim Tail Bytes

Chunk #2 (Bytes 4-18)

Header Byte:
→ 13 gap bytes, two tail bytes
→ # of gaps is > 7, so have to use extra byte

One gap length byte gives gap length = 13

Two verbatim bytes for tail.

BYTE-ALIGNED BITMAP CODES

Bitmap

```
00000000 00000000 00010000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000 00000000
00000000 01000000 00100010
```

Compressed Bitmap

```
#1 (010)(1)(0100)

#2 (111)(0)(0010) 00001101
   01000000 00100010
```

Verbatim Tail Bytes

Chunk #2 (Bytes 4-18)

Header Byte:

→ 13 gap bytes, two tail bytes

→ # of gaps is > 7, so have to use extra byte

One gap length byte gives gap length = 13

Two verbatim bytes for tail.

Original: 18 bytes

BBC Compressed: 5 bytes.

Source: Brian Babcock

OBSERVATION

Oracle's BBC is an obsolete format

→ Although it provides good compression, it is likely much slower than more recent alternatives due to excessive branching.

→ Word-Aligned Hybrid (WAH) is a patented variation on BBC that provides better performance.

None of these support random access.

→ If you want to check whether a given value is present, you have to start from the beginning and uncompress the whole thing.

ROARING BITMAPS

Store 32-bit integers in a compact two-level indexing data structure.

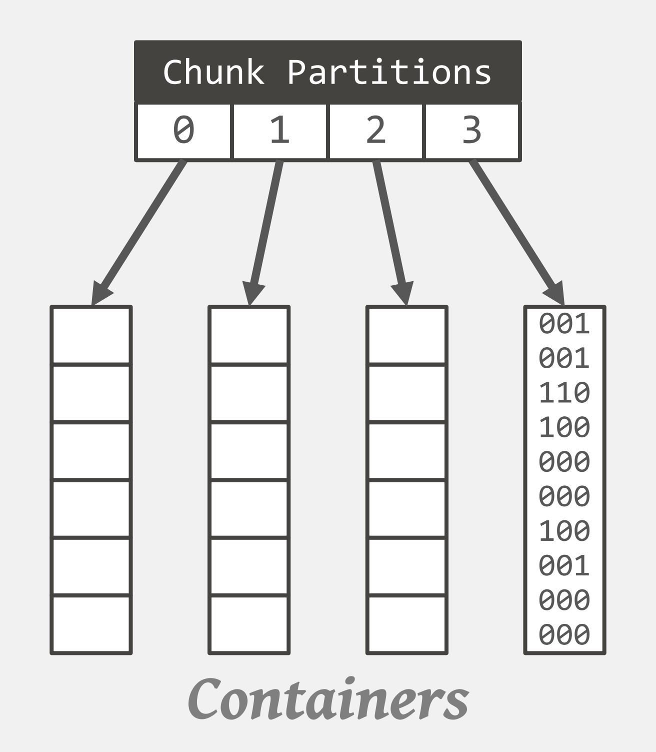
→ Dense chunks are stored using bitmaps

→ Sparse chunks use packed arrays of 16-bit integers.

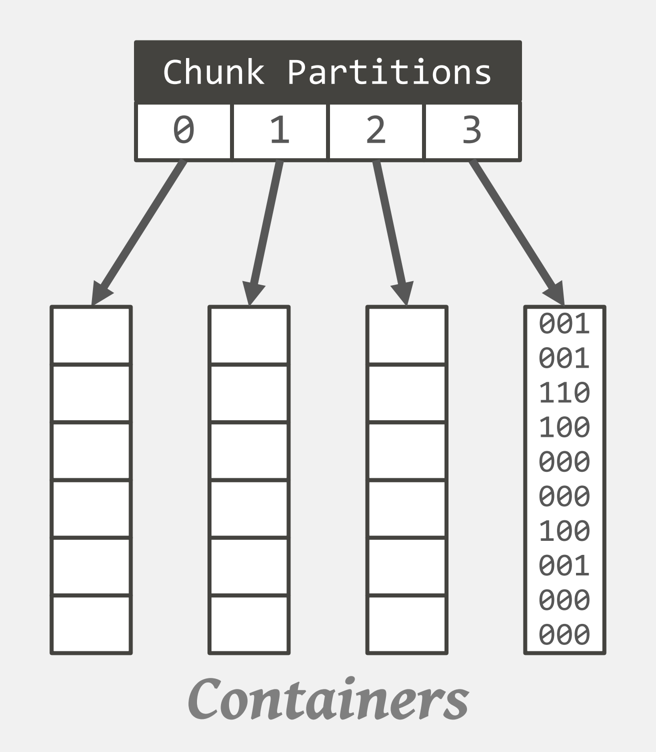
Now used in Lucene, Hive, Spark.

BETTER BITMAP PERFORMANCE WITH ROARING BITMAPS
Software: Practice and Experience 2015

ROARING BITMAPS

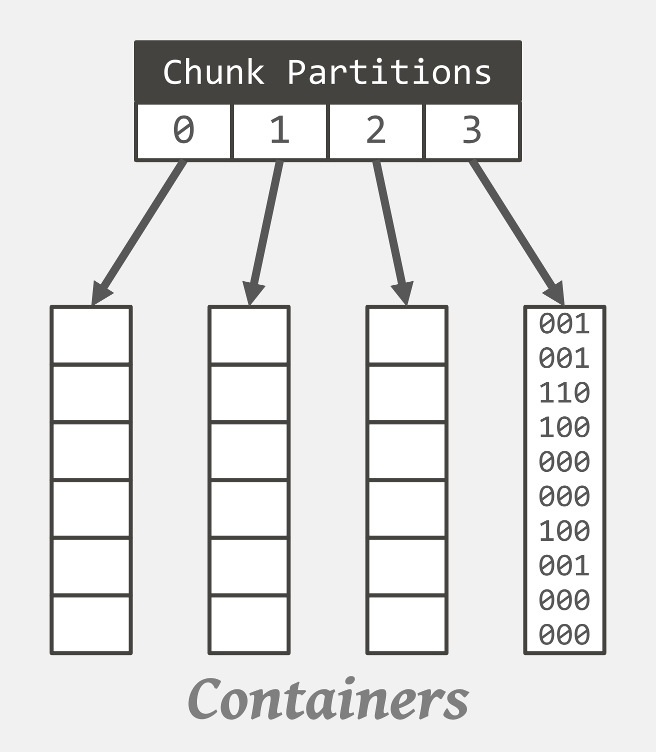


ROARING BITMAPS



For each value **N**, assign it to a chunk based on $\mathbf{N/2^{16}}$.

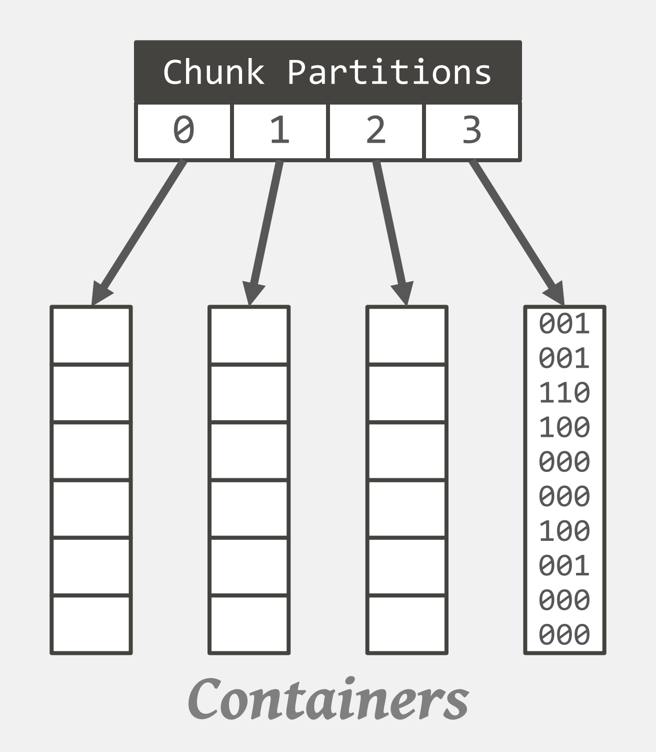
ROARING BITMAPS



For each value **N**, assign it to a chunk based on $\mathbf{N/2^{16}}$.

Only store $\mathbf{N\%2^{16}}$ in container.

ROARING BITMAPS

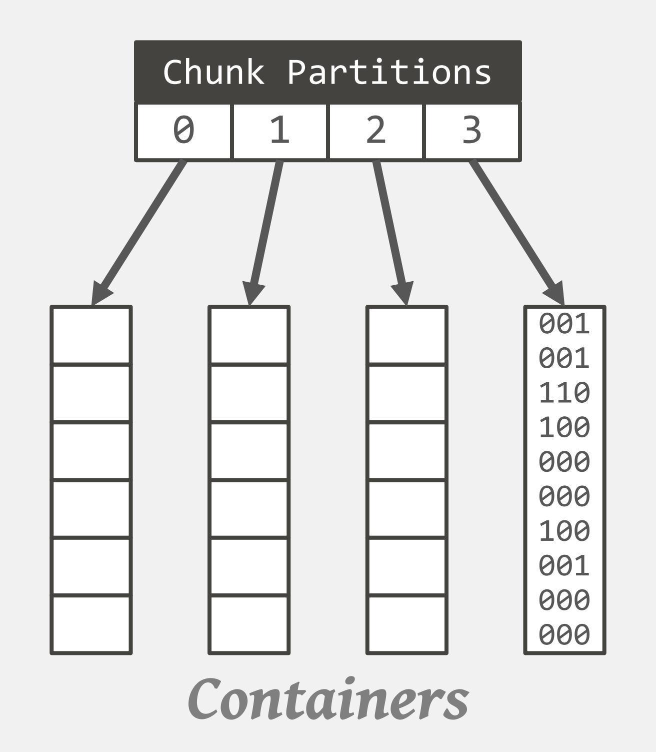


For each value **N**, assign it to a chunk based on $\mathbf{N/2^{16}}$.

Only store $\mathbf{N\%2^{16}}$ in container.

If # of values in container is less than 4096, store as array. Otherwise, store as Bitmap.

ROARING BITMAPS



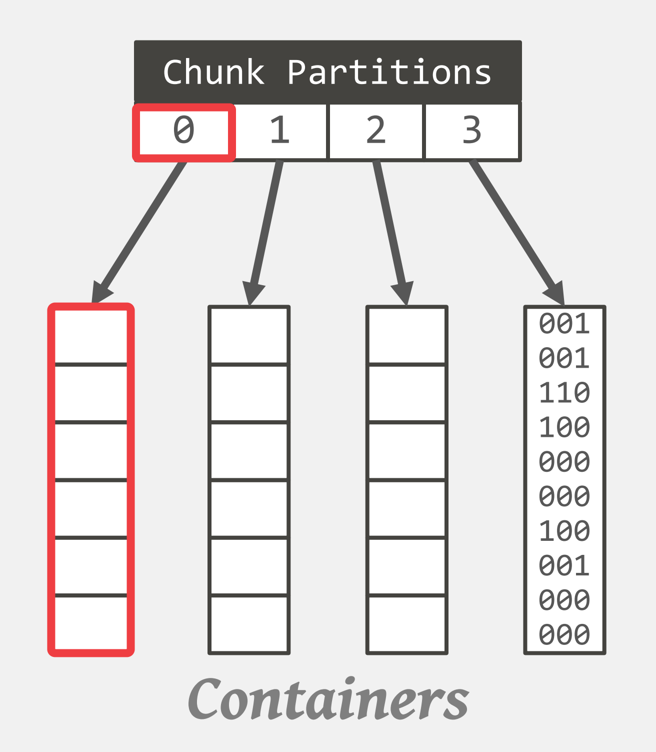
For each value **N**, assign it to a chunk based on $\mathbf{N/2^{16}}$.

Only store $\mathbf{N\%2^{16}}$ in container.

If # of values in container is less than 4096, store as array. Otherwise, store as Bitmap.

N=1000

ROARING BITMAPS



For each value **N**, assign it to a chunk based on $\mathbf{N/2^{16}}$.

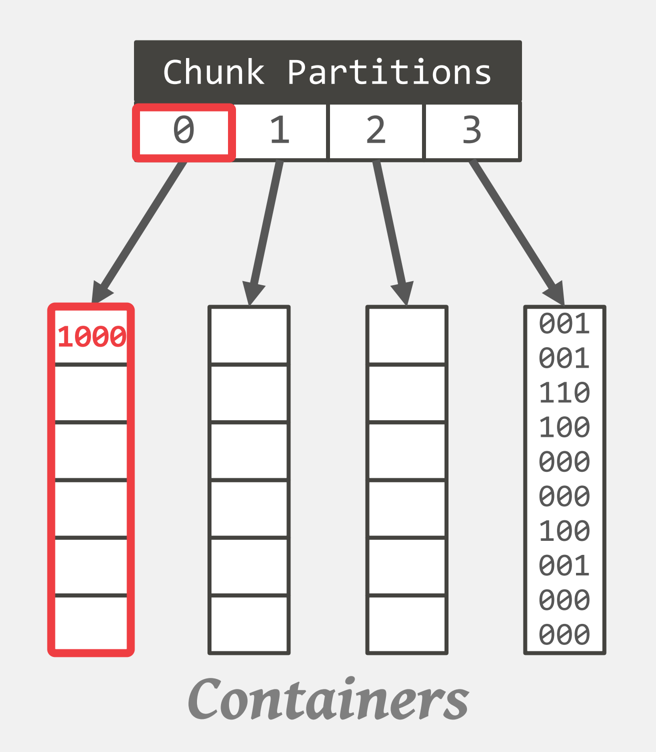
Only store $\mathbf{N\%2^{16}}$ in container.

If # of values in container is less than 4096, store as array. Otherwise, store as Bitmap.

N=1000

$1000/2^{16}=0$

ROARING BITMAPS



For each value **N**, assign it to a chunk based on $\mathbf{N/2^{16}}$.

Only store $\mathbf{N\%2^{16}}$ in container.

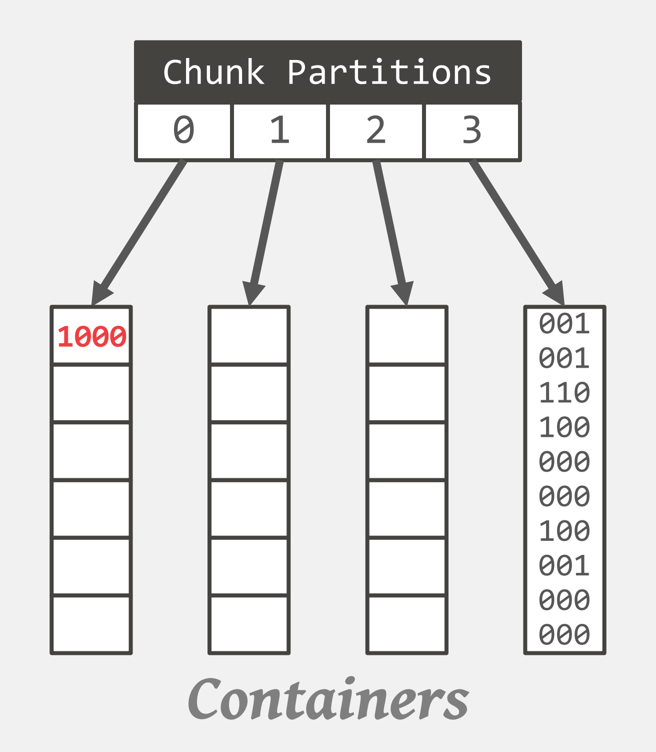
If # of values in container is less than 4096, store as array. Otherwise, store as Bitmap.

N=1000

$\mathbf{1000/2^{16}=0}$

$\mathbf{1000\%2^{16}=1000}$

ROARING BITMAPS



For each value **N**, assign it to a chunk based on **N/2^{16}**.

Only store **N%2^{16}** in container.

If # of values in container is less than 4096, store as array. Otherwise, store as Bitmap.

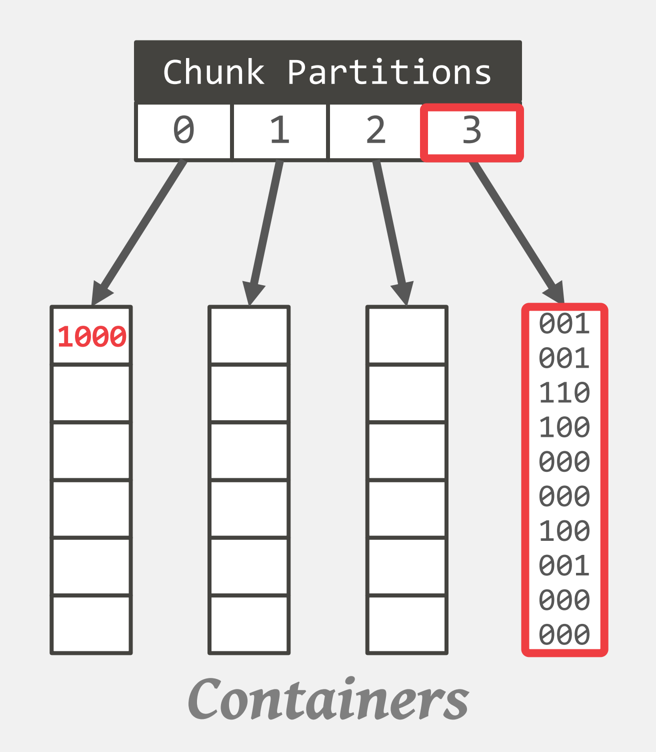
N=1000

$1000/2^{16}=0$

$1000\%2^{16}=1000$

N=199658

ROARING BITMAPS



For each value **N**, assign it to a chunk based on $\mathbf{N/2^{16}}$.

Only store $\mathbf{N\%2^{16}}$ in container.

If # of values in container is less than 4096, store as array. Otherwise, store as Bitmap.

N=1000

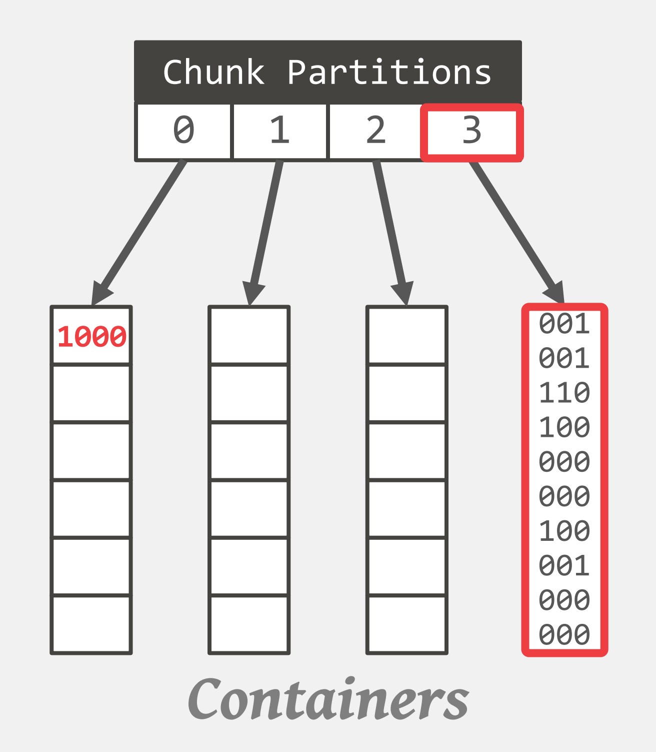
$1000/2^{16}=0$

$1000\%2^{16}=1000$

N=199658

$199658/2^{16}=3$

ROARING BITMAPS



For each value **N**, assign it to a chunk based on **N/2¹⁶**.

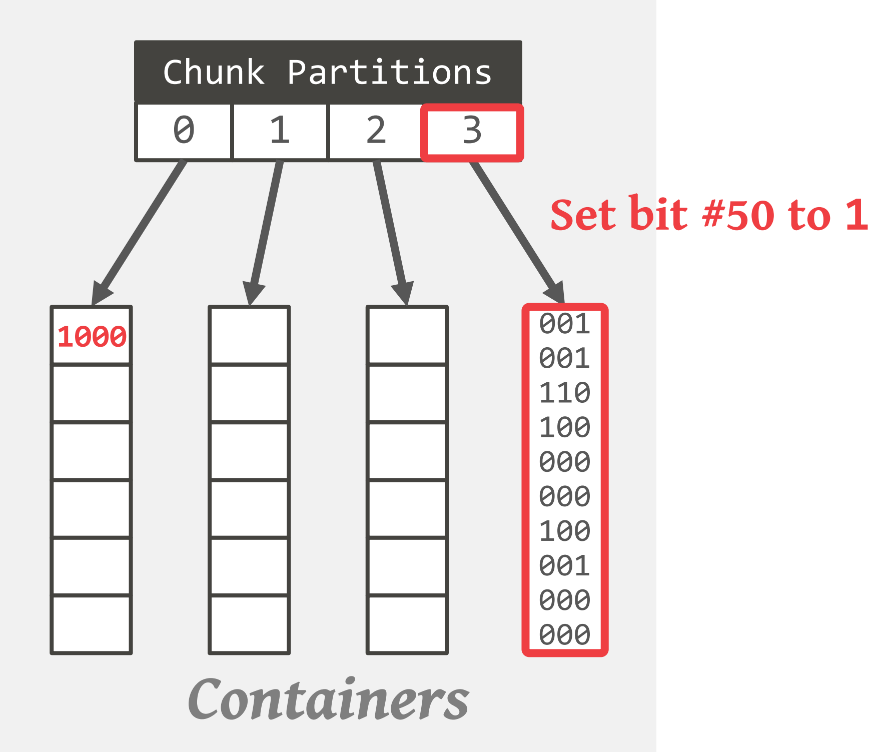
Only store **N%2¹⁶** in container.

If # of values in container is less than 4096, store as array. Otherwise, store as Bitmap.

N=1000
$1000/2^{16}=0$
$1000\%2^{16}=1000$

N=199658
$199658/2^{16}=3$
$199658\%2^{16}=50$

ROARING BITMAPS



For each value **N**, assign it to a chunk based on **$N/2^{16}$**.

Only store **$N\%2^{16}$** in container.

If # of values in container is less than 4096, store as array. Otherwise, store as Bitmap.

N=1000	N=199658
$1000/2^{16}=0$	$199658/2^{16}=3$
$1000\%2^{16}=1000$	$199658\%2^{16}=50$

PARTING THOUGHTS

These require that the position in the Bitmap corresponds to the tuple's position in the table.

→ This is not possible in a MVCC DBMS using the **Insert Method** unless there is a look-up table.

Maintaining a Bitmap Index is wasteful if there are a large number of unique values for a column and if those values are ephemeral.

We're ignoring multi-dimensional indexes…

PROJECT #2

Implement a latch-free Bw-Tree in Peloton.
→ CAS Mapping Table
→ Delta Chains
→ Split / Merge / Consolidation
→ Cooperative Garbage Collection

Must be able to support both unique and non-unique keys.

PROJECT #2 – DESIGN

We will provide you with a header file with the index API that you have to implement.

→ Data serialization and predicate evaluation will be taken care of for you.

There are several design decisions that you are going to have to make.

→ There is no right answer.

→ Do not expect us to guide you at every step of the development process.

PROJECT #2 – TESTING

We are providing you with C++ unit tests for you to check your implementation.

We also have a B+Tree implementation using `stx::btree` with a coarse-grained lock.

We **strongly** encourage you to do your own additional testing.

PROJECT #2 – DOCUMENTATION

You must write sufficient documentation and comments in your code to explain what you are doing in all different parts.

We will inspect the submissions manually.

PROJECT #2 – GRADING

We will run additional tests beyond what we provided you for grading.

→ Bonus points will be given to the student with the fastest implementation.

→ We will use Valgrind when testing your code.

All source code must pass ClangFormat syntax formatting checker.

→ See Peloton documentation for formatting guidelines.

PROJECT #2 – GROUPS

We have exactly 10 groups of 3 people each.

Everyone should contribute equally.

This isn’t a game. This is real life.

Protect your neck.

PROJECT #2

Due Date: March 2^{nd}, 2016 @ 11:59pm
Projects will be turned in using Autolab.

Full description and instructions:
http://15721.courses.cs.cmu.edu/spring2016/project2.html

NEXT CLASS

Storage Models

Performance Profiling for Project #2