
Carnegie Mellon University
Lecture #22
ADVANCED DATABASE SYSTEMS
Vectorized Execution (Part II)
@Andy_Pavlo // 15-721 // Spring 2018

TODAY'S AGENDA

Bit-Slicing

Bit-Weaving

Relaxed Operator Fusion (Prashanth)

BITMAP ENCODING

Original Data

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

BITMAP ENCODING

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 INDEX: ENCODING

Approach #1: Equality Encoding
→ Basic scheme with one Bitmap per unique value.

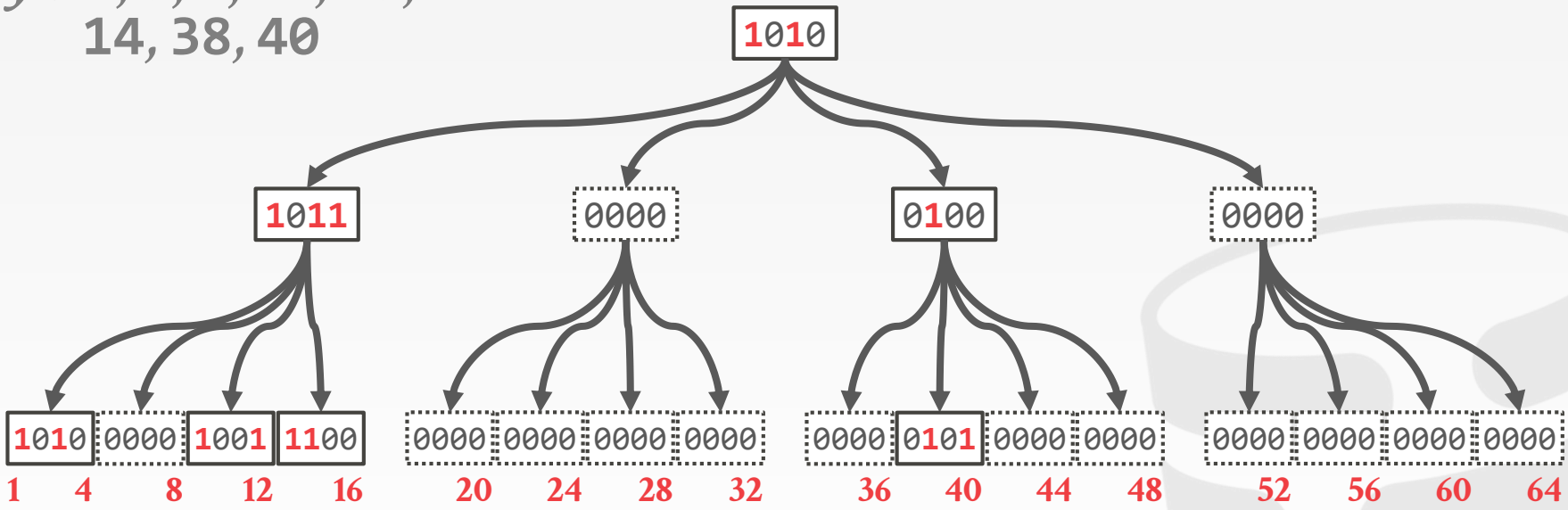
Approach #2: Range Encoding
→ Use one Bitmap per interval instead of one per value.

Approach #3: Hierarchical Encoding
→ Use a tree to identify empty key ranges.

Approach #4: Bit-sliced Encoding
→ Use a Bitmap per bit location across all values.

HIERARCHICAL ENCODING

Keys: 1, 3, 9, 12, 13, 14, 38, 40

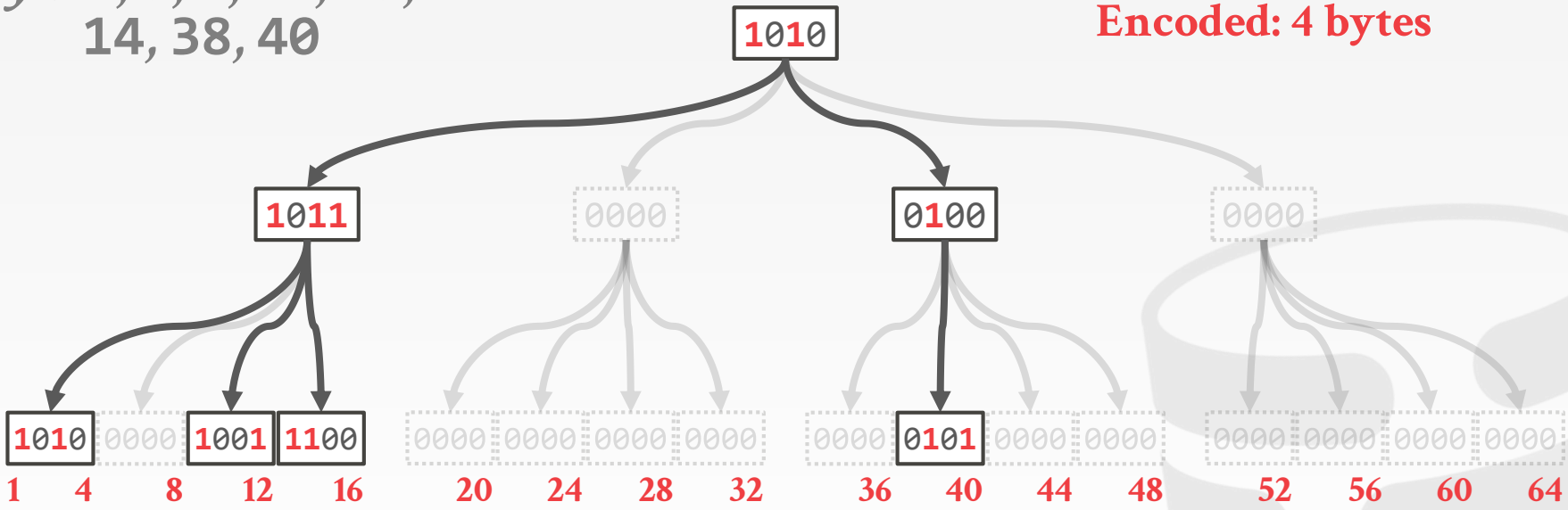


HIERARCHICAL BITMAP INDEX: AN EFFICIENT AND SCALABLE INDEXING TECHNIQUE FOR SET-VALUED ATTRIBUTES
Advances in Databases and Information Systems 2003

HIERARCHICAL ENCODING

Keys: 1, 3, 9, 12, 13, 14, 38, 40

Original: 8 bytes
Encoded: 4 bytes



HIERARCHICAL BITMAP INDEX: AN EFFICIENT AND SCALABLE INDEXING TECHNIQUE FOR SET-VALUED ATTRIBUTES
Advances in Databases and Information Systems 2003

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

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

bin(21042)→ 0010100100011010

Source: Jignesh Patel

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0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	1	0

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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
```

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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

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Walk each slice and construct a result bitmap.

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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)

BIT-SLICED ENCODING

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

Example: `SUM(attr)`

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

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

→ Repeat for the rest of slices…

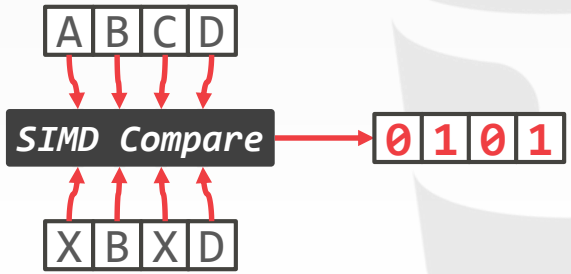
Intel added **POPCNT** SIMD instruction in 2008.

OBSERVATION

The bit width of compressed data does not always fit naturally into SIMD register lanes.

→ This means that the DBMS has to do extra work to transform data into the proper format.

Just because the **lanes** are fully utilized does not mean the **bits** are fully utilized…



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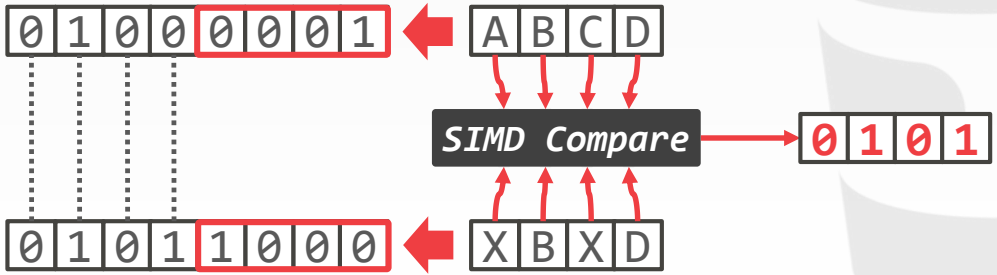

BITWEAVING

Alternative storage layout for columnar databases that is designed for efficient predicate evaluation on compressed data using SIMD.

→ Order-preserving dictionary encoding.
→ Bit-level parallelization.
→ Only require common instructions (no scatter/gather)

Implemented in Wisconsin's QuickStep engine.
Became an Apache Incubator project in 2016.

BITWEAVING: FAST SCANS FOR MAIN MEMORY DATA PROCESSING
SIGMOD 2013

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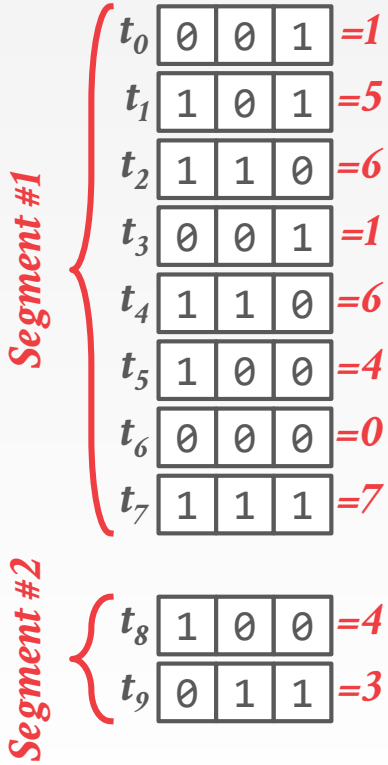
BITWEAVING: FAST SCANS FOR MAIN MEMORY DATA PROCESSING
SIGMOD 2013

BITWEAVING – STORAGE LAYOUTS

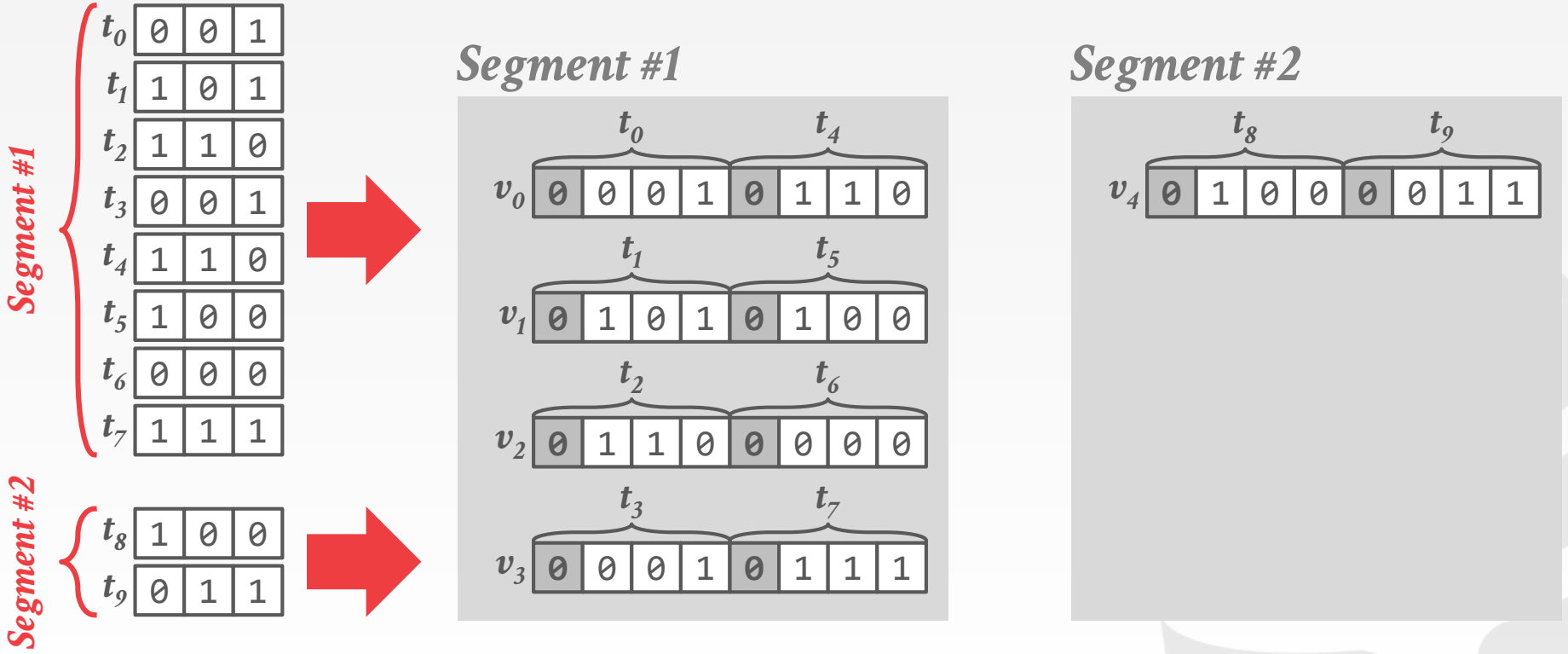
Approach #1: Horizontal
→ Row-oriented storage at the bit-level

Approach #2: Vertical
→ Column-oriented storage at the bit-level

HORIZONTAL STORAGE



HORIZONTAL STORAGE



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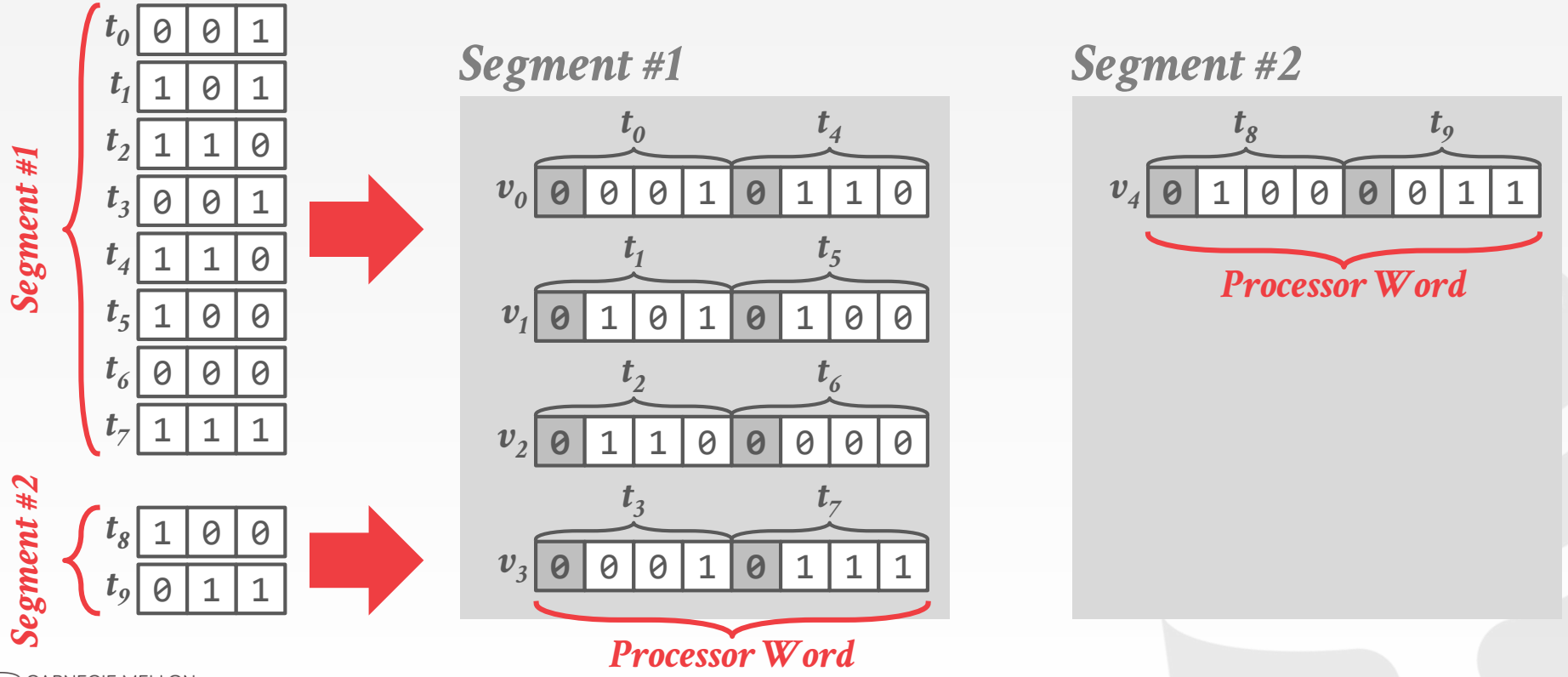
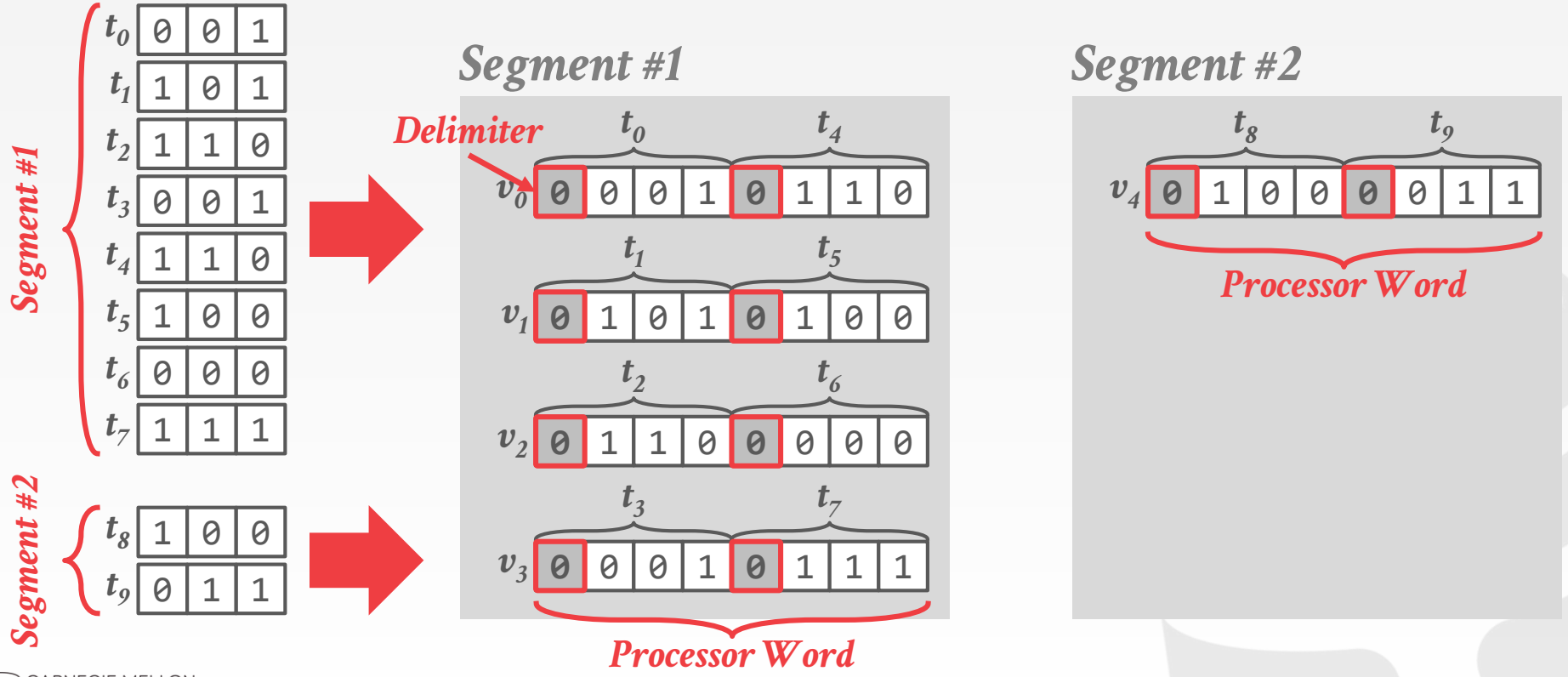
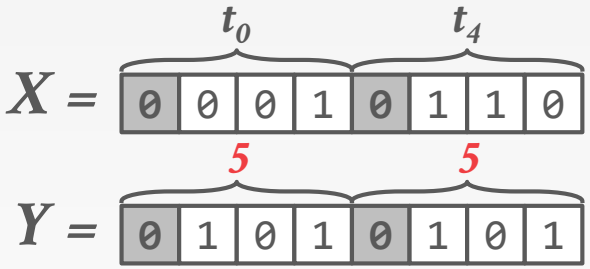


HORIZONTAL STORAGE



BITWEAVING/H – EXAMPLE

```
SELECT * FROM table
 WHERE val < 5
```



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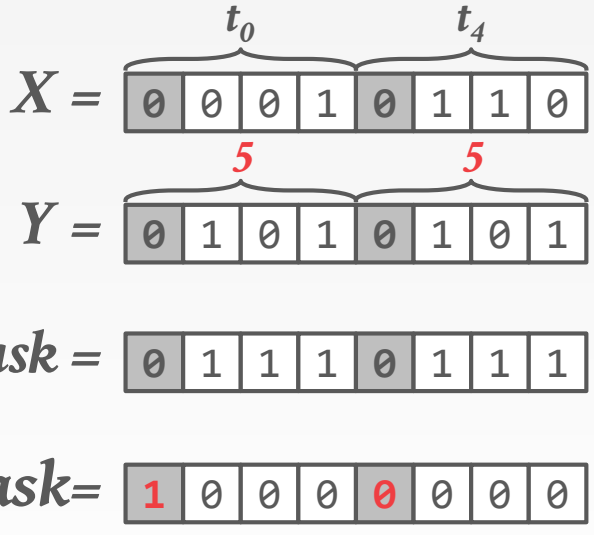

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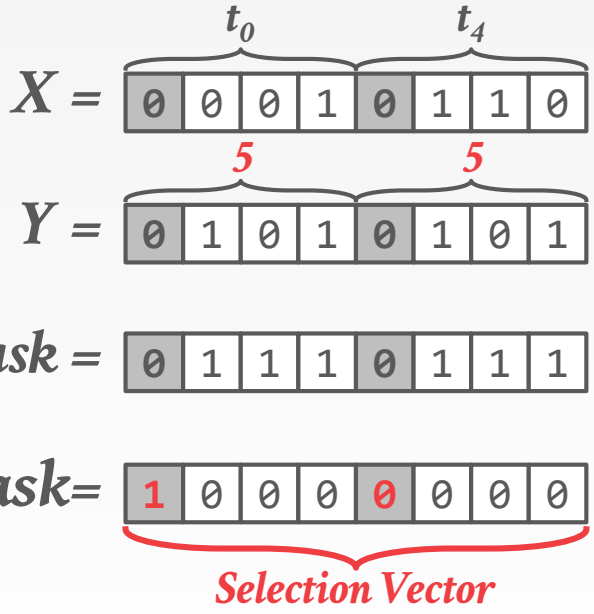

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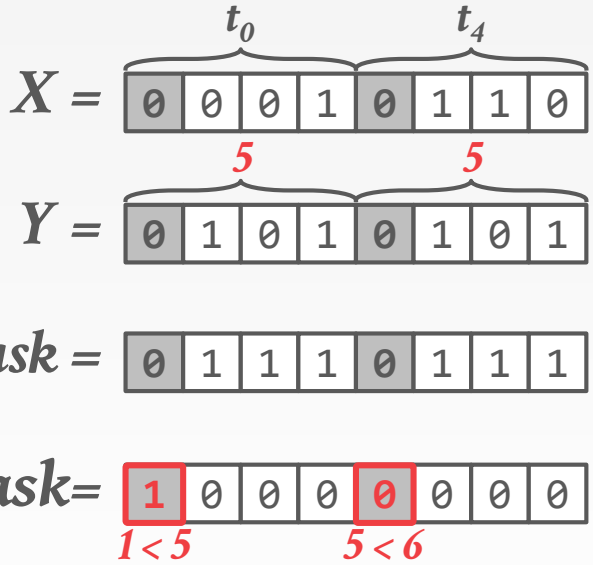

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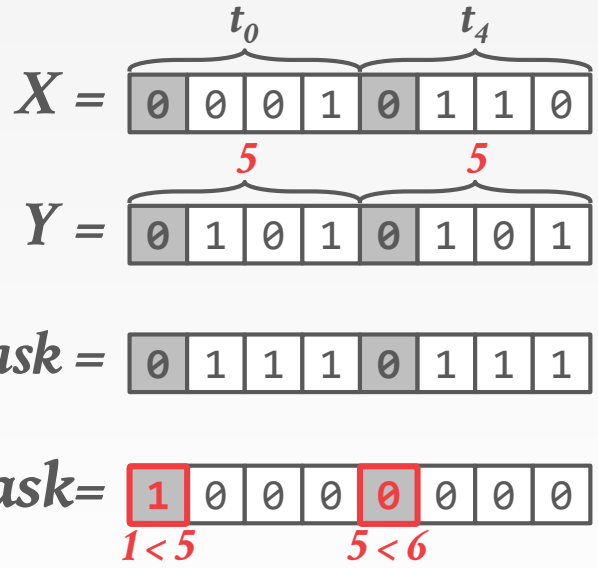

Only requires three instructions to evaluate a single word.

Works on any word size and encoding length.

Paper contains algorithms for other operators.

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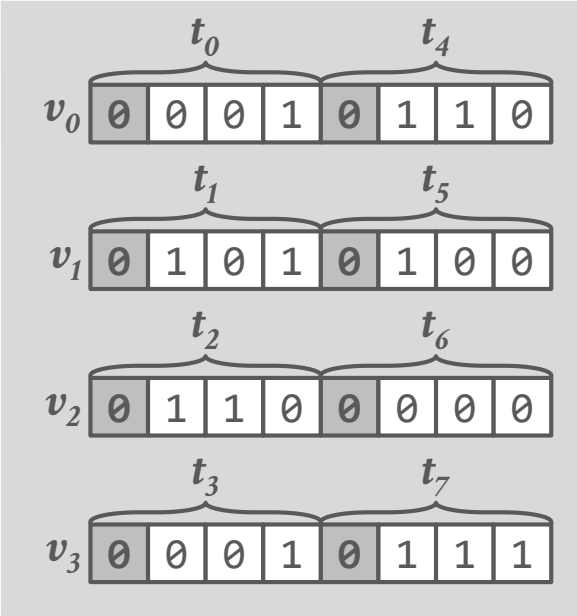

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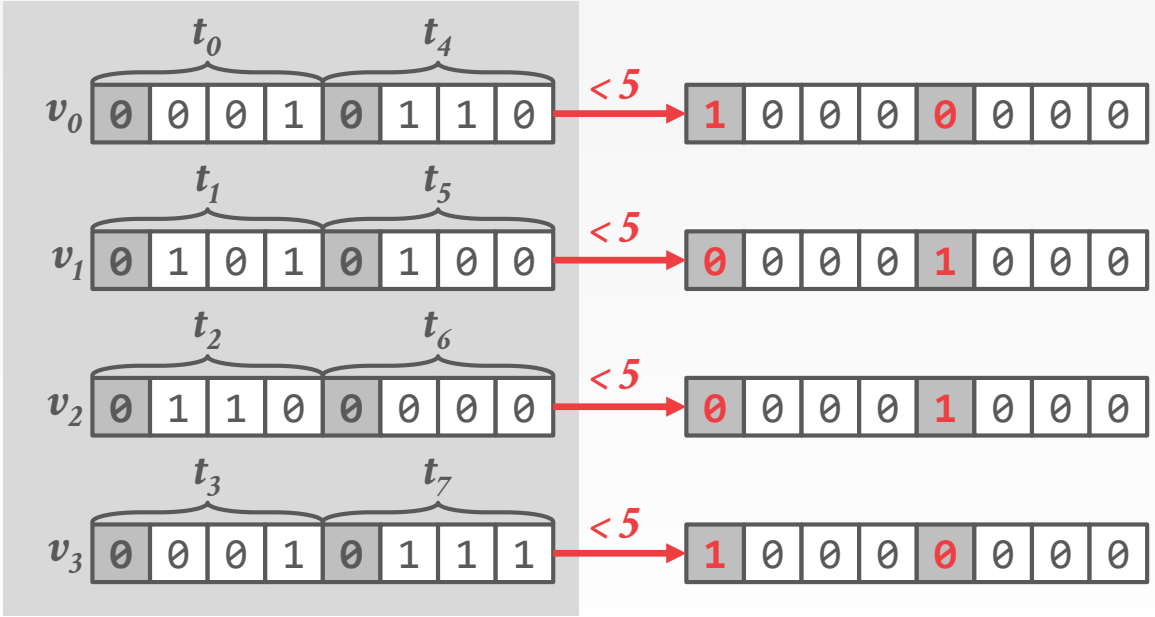

Source: Jignesh Patel

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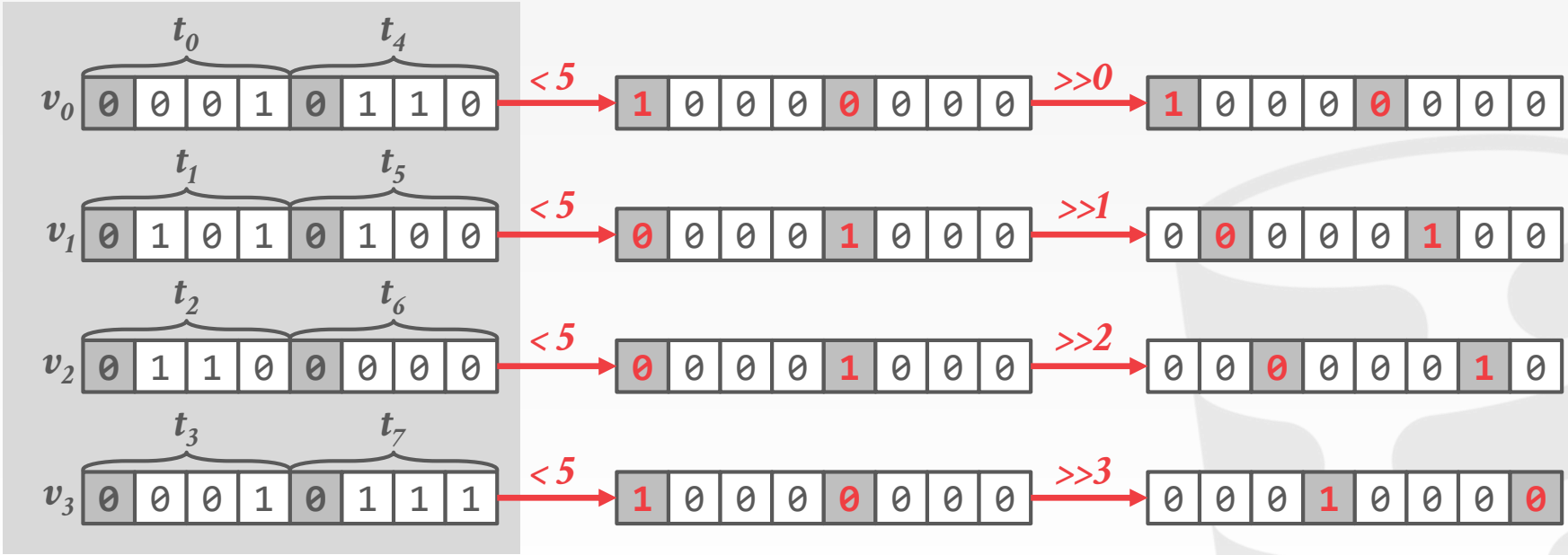

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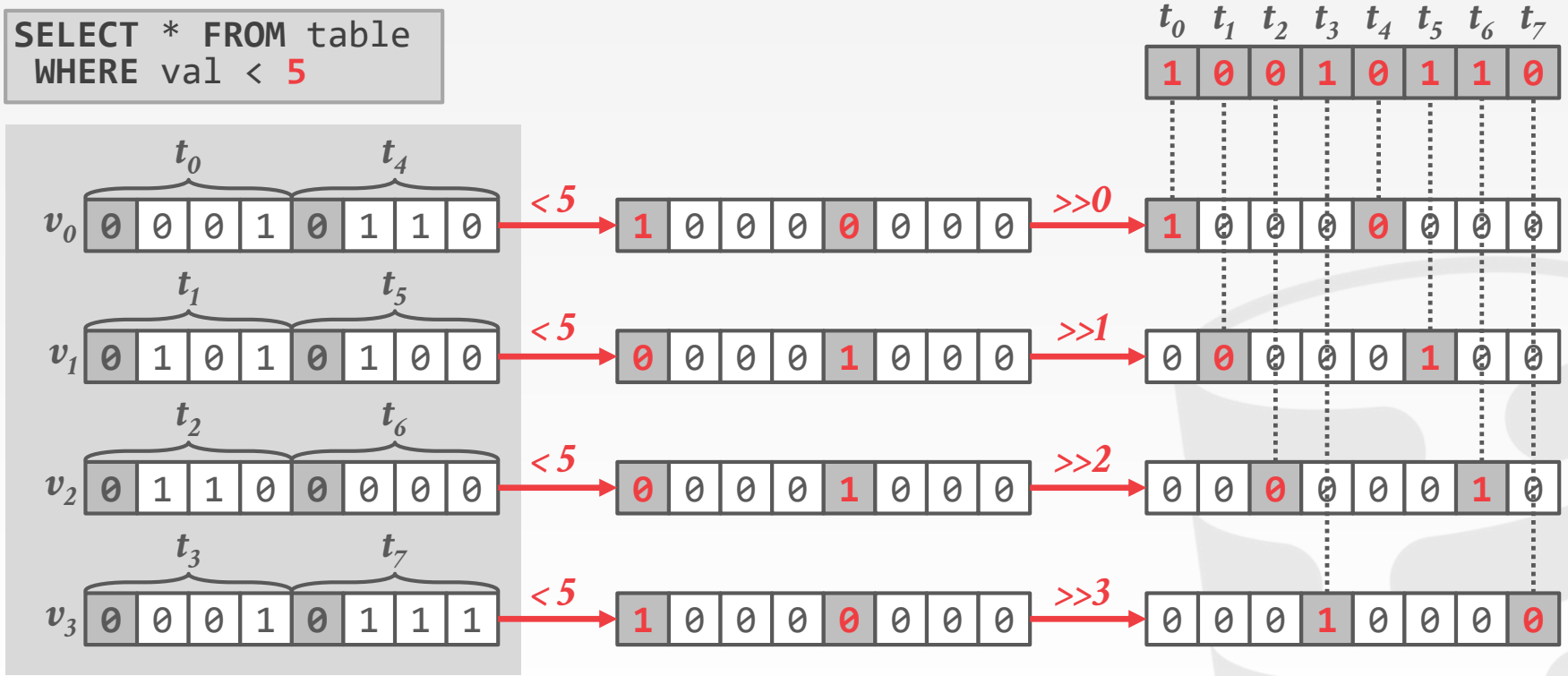

Source: Jignesh Patel

SELECTION VECTOR

SIMD comparison operators produce a bit mask that specifies which tuples satisfy a predicate.

Have to convert it into offsets / positions.

→ Approach #1: Iteration
→ Approach #2: Pre-compute Positions Table

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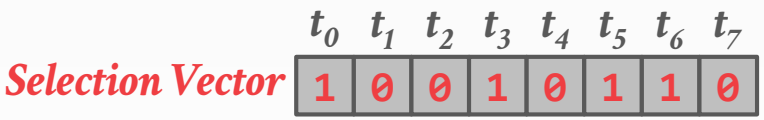

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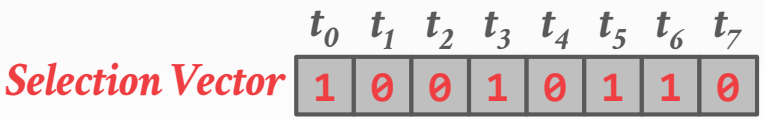


```
tuples = [ ]
for (i=0; i<n; i++) {
  if sv[i] == 1
    tuples.add(i);
}
```

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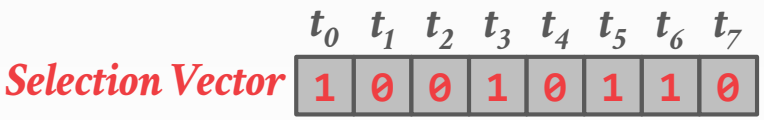

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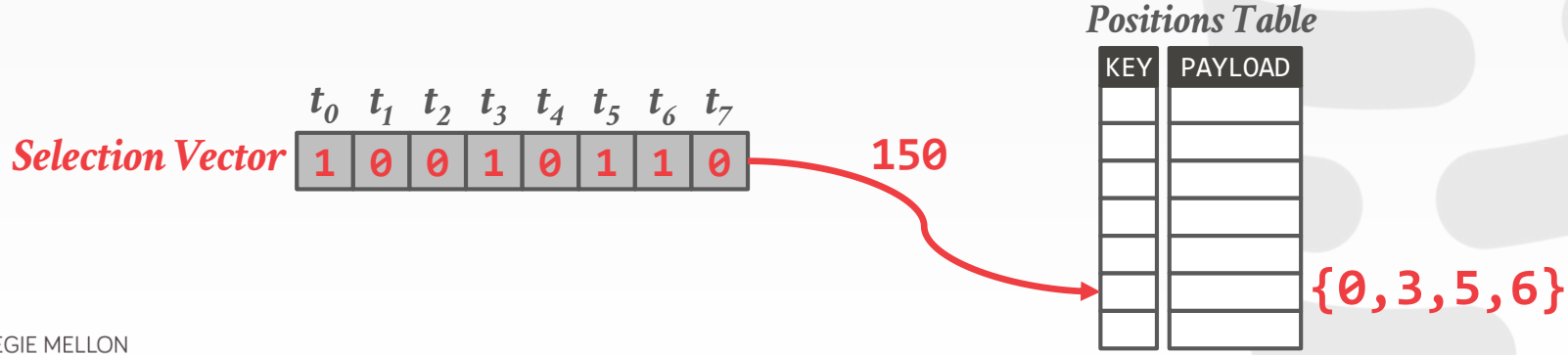
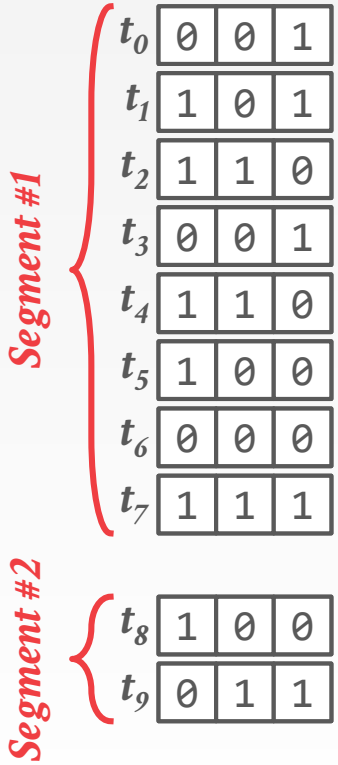


VERTICAL STORAGE



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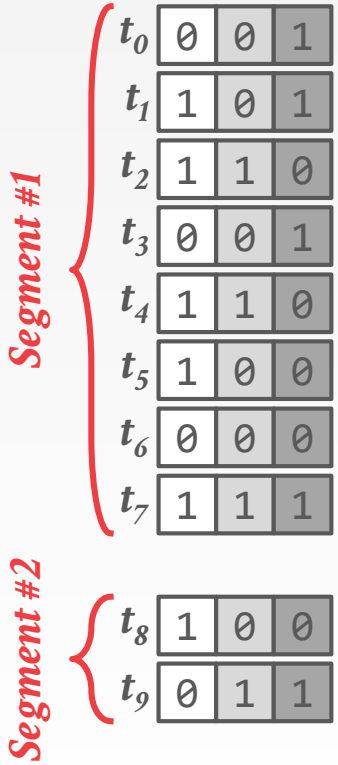

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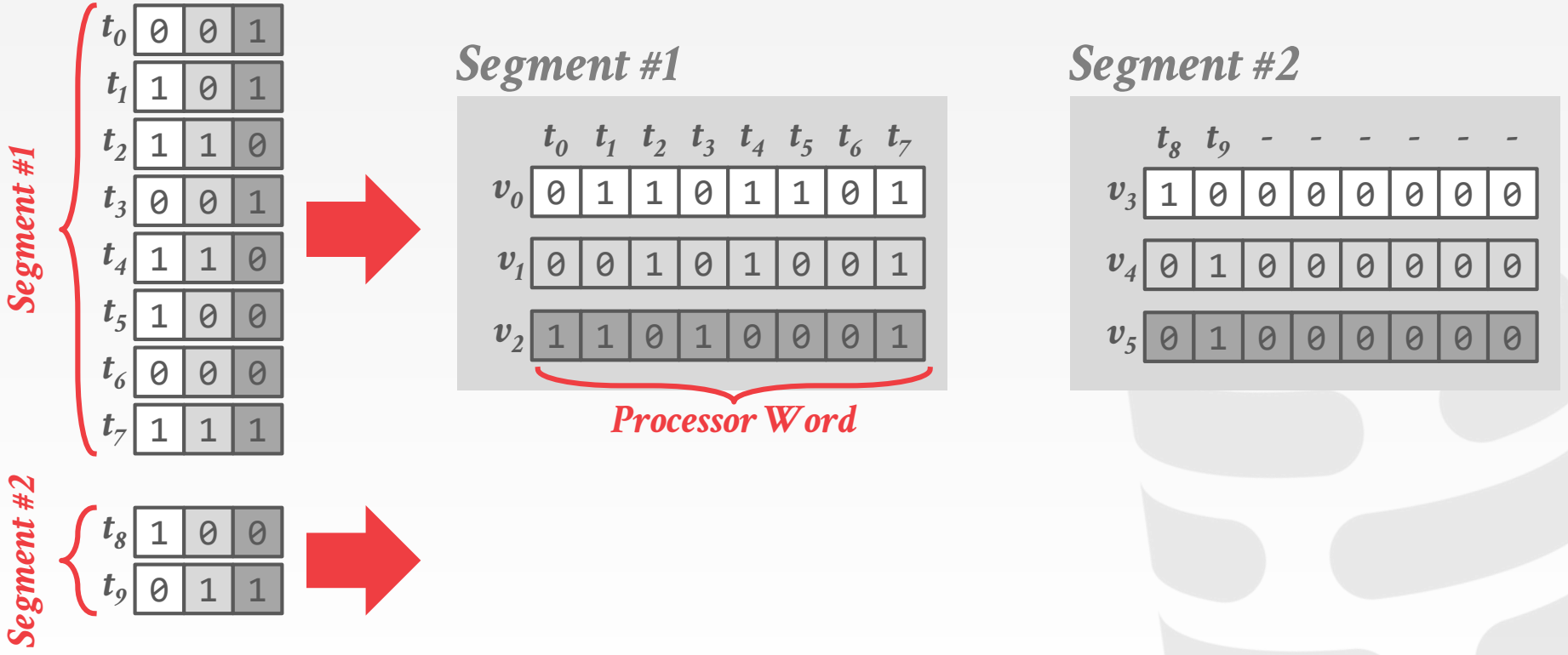
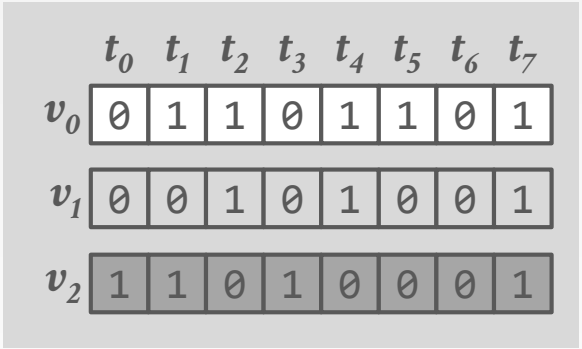


BITWEAVING/V – EXAMPLE

```
SELECT * FROM table
 WHERE key = 2
```

Segment #1



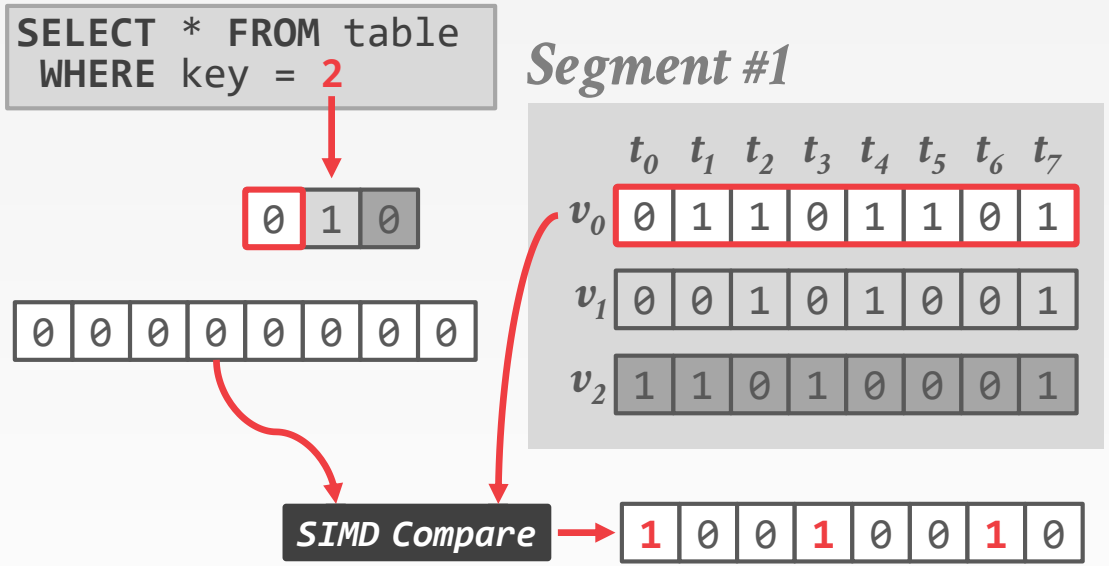
BITWEAVING/V – EXAMPLE

```
SELECT * FROM table
 WHERE key = 2
```

Segment #1

	t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7
v_0	0	1	1	0	1	1	0	1
v_1	0	0	1	0	1	0	0	1
v_2	1	1	0	1	0	0	0	1

BITWEAVING/V – EXAMPLE



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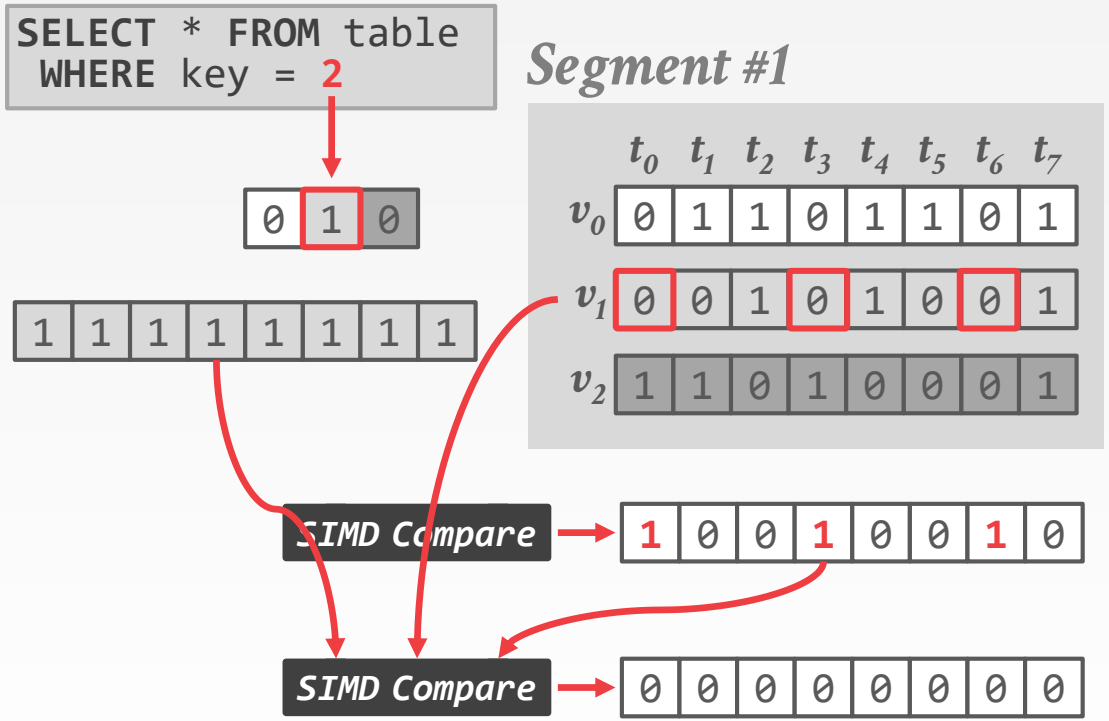


Can perform early pruning just like in BitMap indexes.

The last vector is skipped because all bits in previous comparison are zero.

EVALUATION

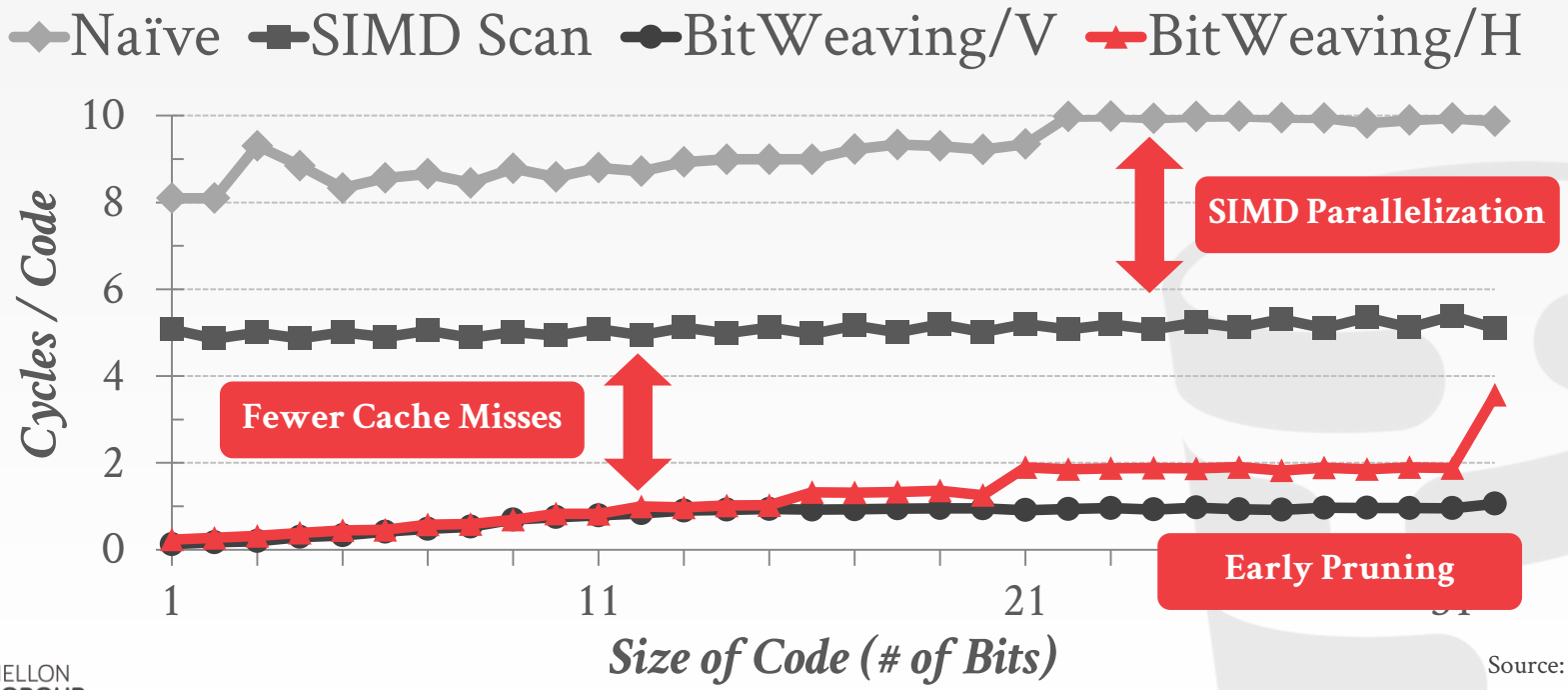
Single-threaded execution of a single query derived from TPC-H benchmark.
→ Selectivity: 10%

```
SELECT COUNT(*)
  FROM R
 WHERE R.a < C
```

10GB TPC-H Database
→ 1 billion tuples
→ Uniform distribution

EVALUATION

TPC-H Aggregation Query
Intel Xeon X5650 @ 2.66 GHz



Source: Jignesh Patel

PARTING THOUGHTS

Just like in query compilation, getting the best performance with vectorization requires the DBMS to store data in a way that is best for the CPU and not the best for humans' understanding.