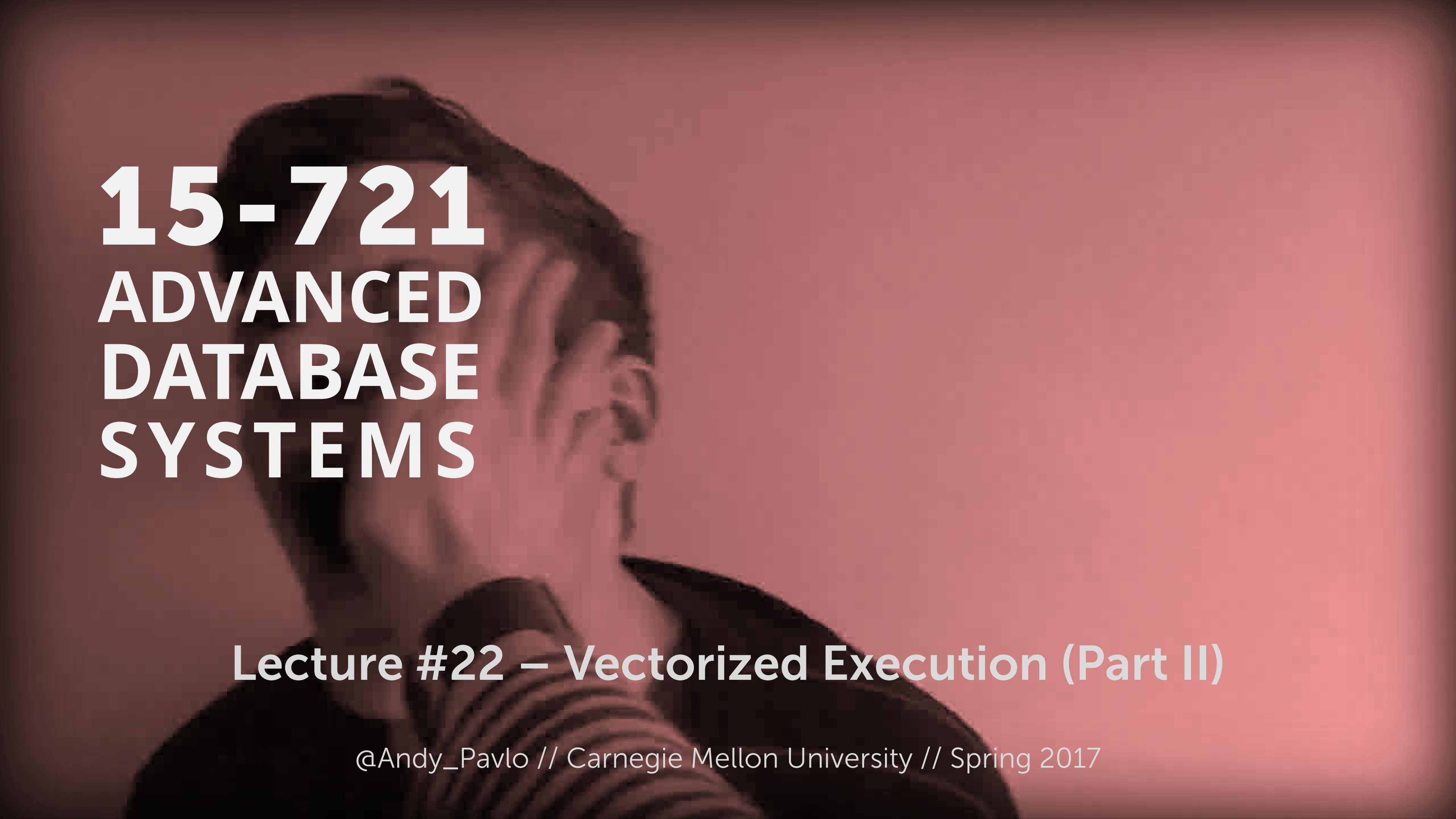


15-721 ADVANCED DATABASE SYSTEMS

Lecture #22 – Vectorized Execution (Part II)

@Andy_Pavlo // Carnegie Mellon University // Spring 2017

CORRECTION

Original Xeon Phi (***Knights Corner***) uses in-order execution CPUs with a ring-based bus.

2016 Xeon Phi CPUs (***Knights Landing***) support out-of-order execution with tile architecture.

Three versions / form factors:

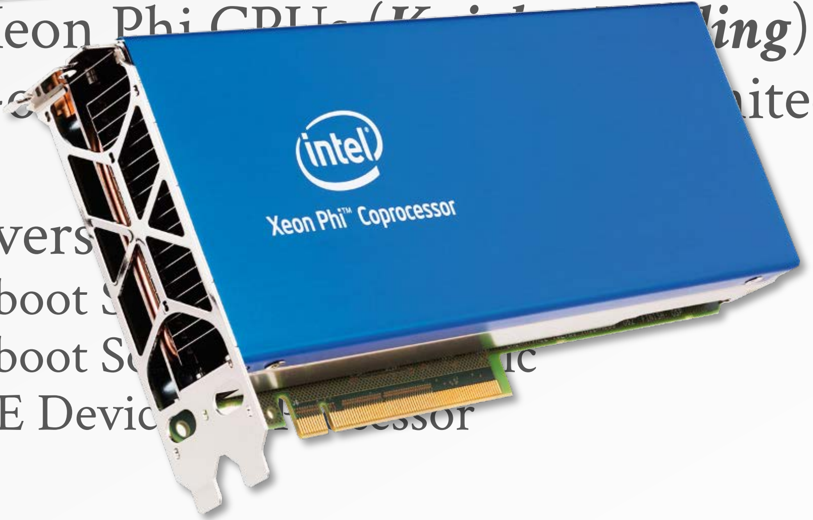
→ Self-boot Socket CPU
→ Self-boot Socket CPU + Fabric
→ PCI-E Device Co-Processor

Source: Avinash Sodani

CORRECTIO

Phi (*Knights*
Us with a ring-bas

2016 Xeon Phi CPUs (*K* *ling*) support
out-of-o itecture.



Three vers

→ Self-boot S

→ Self-boot S ic

→ PCI-E Devic essor

Source: Avinash Sodani

TODAY'S AGENDA

Quickstep Bitweaving

HyPer Data Blocks

Project #3 Code Review Guidelines

OBSERVATION

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

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

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

BITWEAVING – STORAGE LAYOUTS

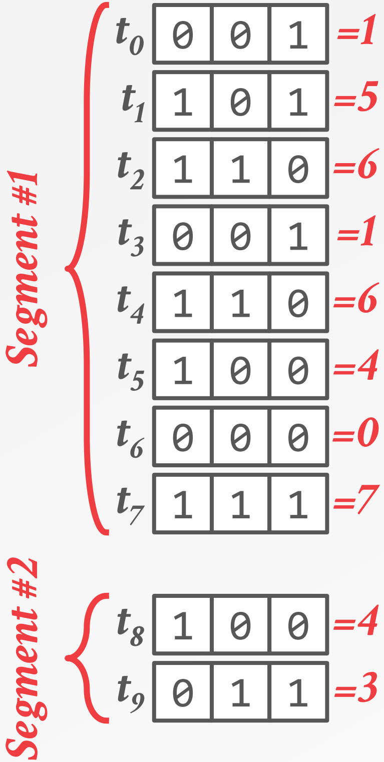
Approach #1: Horizontal

→ Row-oriented storage at the bit-level

Approach #2: Vertical

→ Column-oriented storage at the bit-level

HORIZONTAL STORAGE



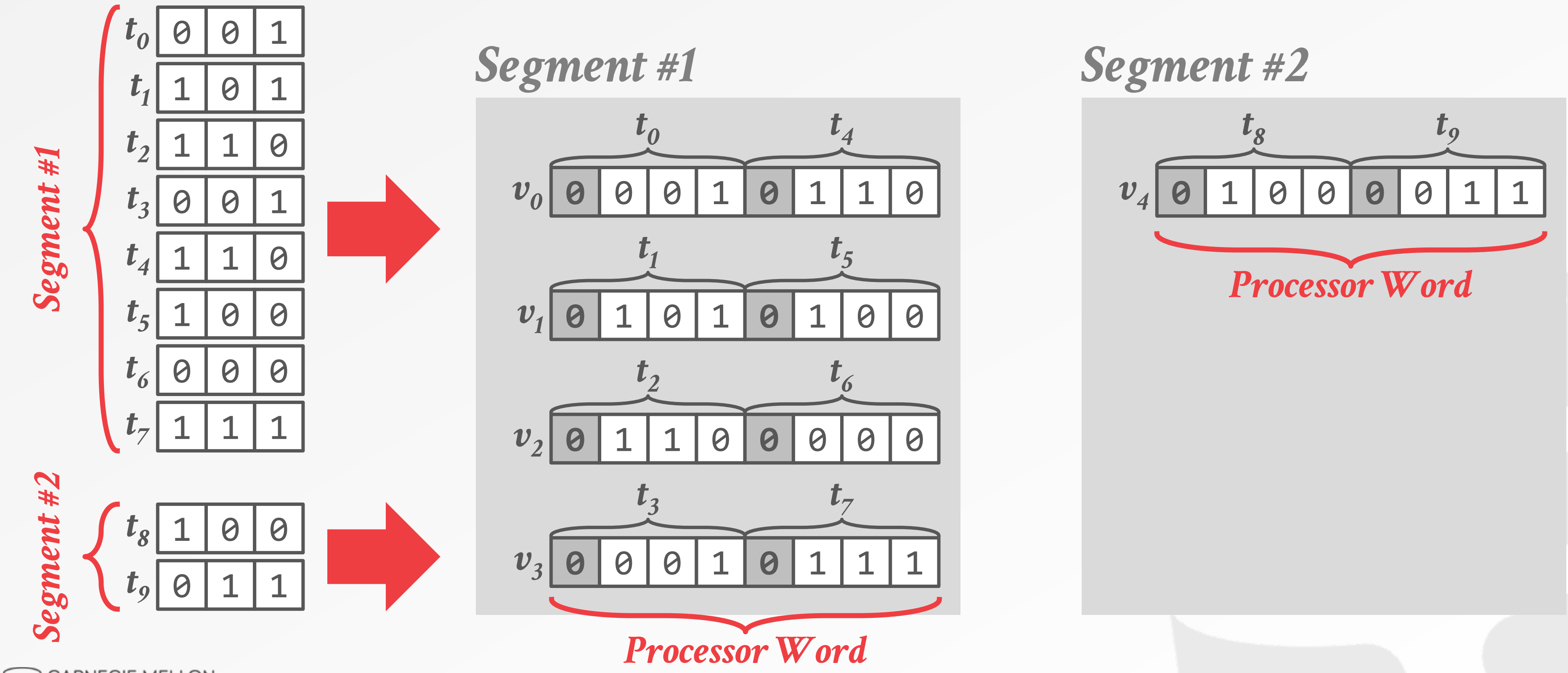
Segment #1

t_0	0	0	1	=1
t_1	1	0	1	=5
t_2	1	1	0	=6
t_3	0	0	1	=1
t_4	1	1	0	=6
t_5	1	0	0	=4
t_6	0	0	0	=0
t_7	1	1	1	=7

Segment #2

t_8	1	0	0	=4
t_9	0	1	1	=3

HORIZONTAL STORAGE



t_0	0	0	1
t_1	1	0	1
t_2	1	1	0
t_3	0	0	1
t_4	1	1	0
t_5	1	0	0
t_6	0	0	0
t_7	1	1	1
t_8	1	0	0
t_9	0	1	1

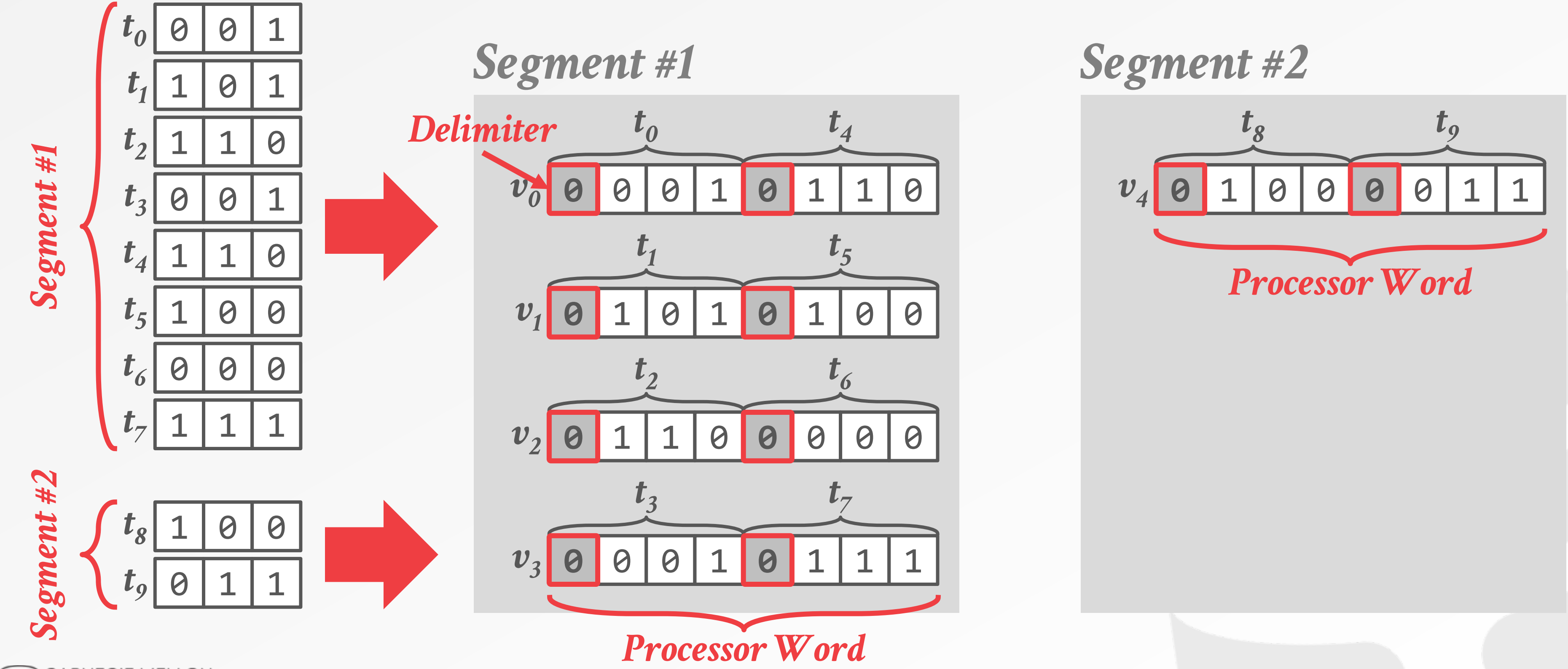
Segment #1

	t_0 / t_1 / t_2 / t_3				t_4 / t_5 / t_6 / t_7			
v_0	0	0	0	1	0	1	1	0
v_1	0	1	0	1	0	1	0	0
v_2	0	1	1	0	0	0	0	0
v_3	0	0	0	1	0	1	1	1

Segment #2

	t_8				t_9			
v_4	0	1	0	0	0	0	1	1

HORIZONTAL STORAGE



Segment #1

t_0	0	0	1
t_1	1	0	1
t_2	1	1	0
t_3	0	0	1
t_4	1	1	0
t_5	1	0	0
t_6	0	0	0
t_7	1	1	1

Segment #2

t_8	1	0	0
t_9	0	1	1

Segment #1

Delimiter

	t_0				t_4			
v_0	0	0	0	1	0	1	1	0

	t_1				t_5			
v_1	0	1	0	1	0	1	0	0

	t_2				t_6			
v_2	0	1	1	0	0	0	0	0

	t_3				t_7			
v_3	0	0	0	1	0	1	1	1

Processor Word

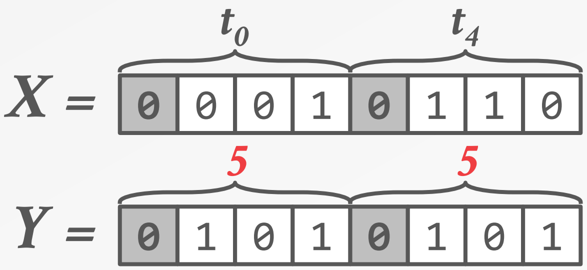
Segment #2

	t_8				t_9			
v_4	0	1	0	0	0	0	1	1

Processor Word

BITWEAVING/H – EXAMPLE

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



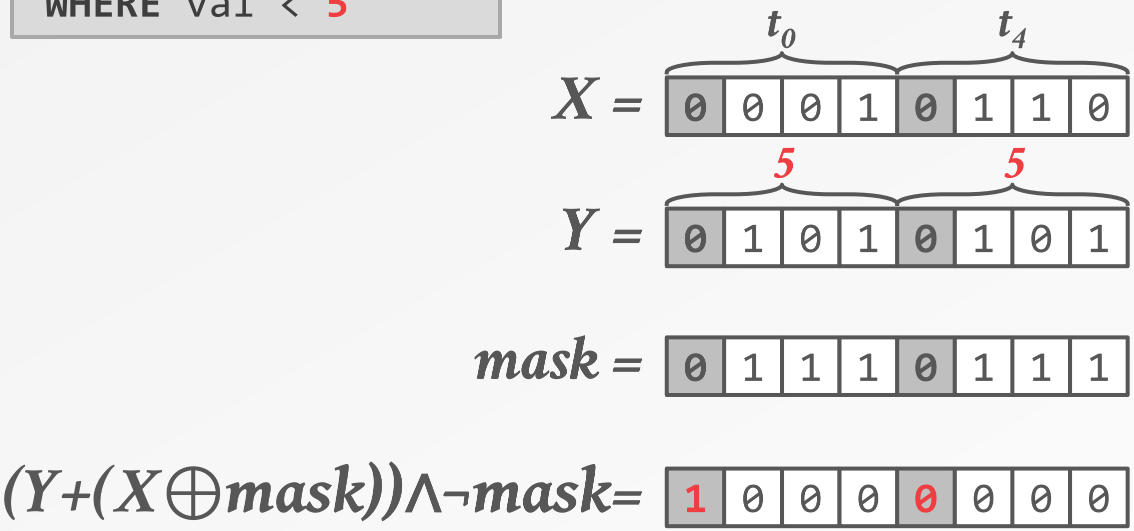
$$X = \overbrace{0\;0\;0\;1}^{t_0}\;\overbrace{0\;1\;1\;0}^{t_4}$$

$$Y = \overbrace{0\;1\;0\;1}^{5}\;\overbrace{0\;1\;0\;1}^{5}$$

Source: Jignesh Patel

BITWEAVING/H – EXAMPLE

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



$X =$ 0 0 0 1 0 1 1 0

$Y =$ 0 1 0 1 0 1 0 1

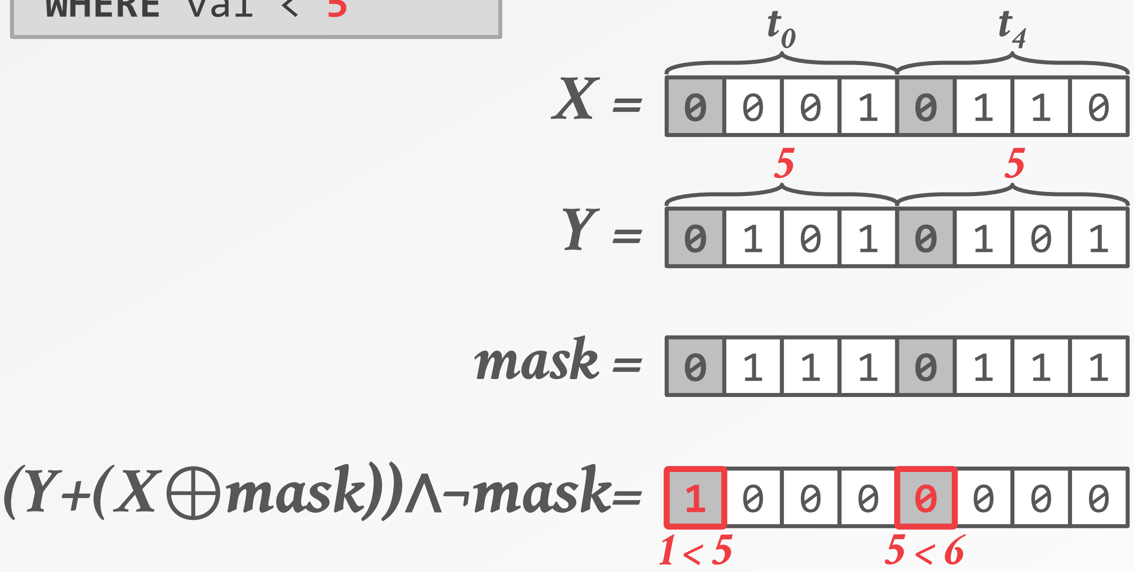
$mask =$ 0 1 1 1 0 1 1 1

$(Y+(X\oplus mask))\wedge\neg mask=$ 1 0 0 0 0 0 0 0

Source: Jignesh Patel

BITWEAVING/H – EXAMPLE

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



t_0 t_4

$X =$ 0 0 0 1 0 1 1 0

5 5

$Y =$ 0 1 0 1 0 1 0 1

$mask =$ 0 1 1 1 0 1 1 1

$(Y+(X\oplus mask))\wedge\neg mask =$ 1 0 0 0 0 0 0 0

$1 < 5$ $5 < 6$

Only requires three instructions to evaluate a single word.

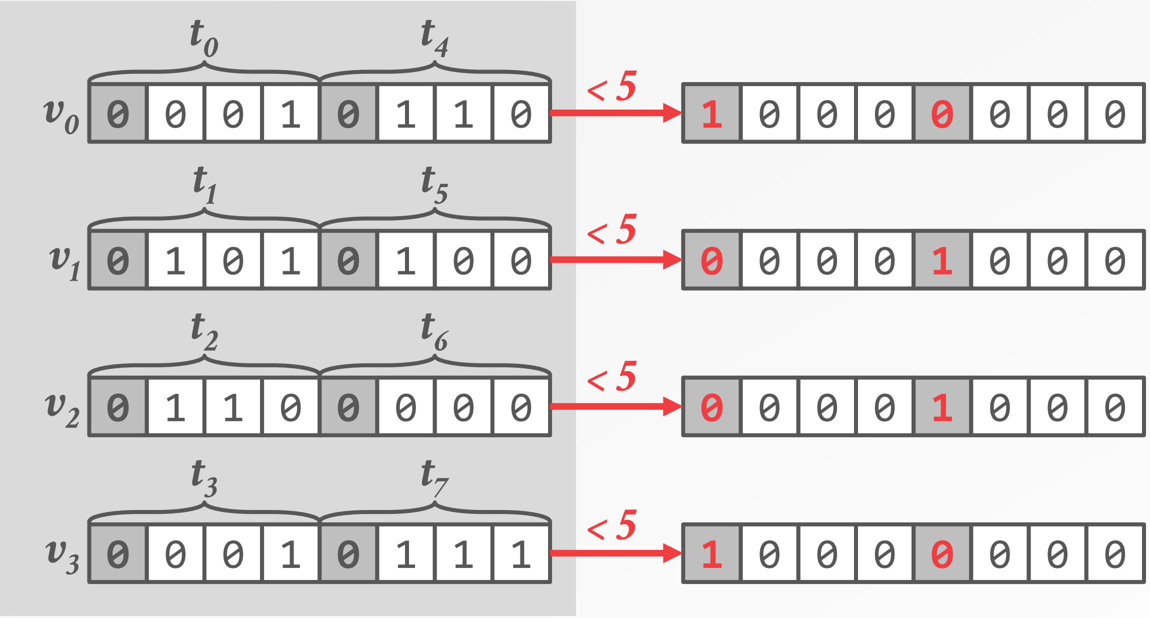
Works on any word size and encoding length.

Paper contains algorithms for other operators.

Source: Jignesh Patel

BITWEAVING/H – EXAMPLE

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



t_0 t_4

v_0: 0 0 0 1 0 1 1 0 $\xrightarrow{<5}$ 1 0 0 0 0 0 0 0

t_1 t_5

v_1: 0 1 0 1 0 1 0 0 $\xrightarrow{<5}$ 0 0 0 0 1 0 0 0

t_2 t_6

v_2: 0 1 1 0 0 0 0 0 $\xrightarrow{<5}$ 0 0 0 0 1 0 0 0

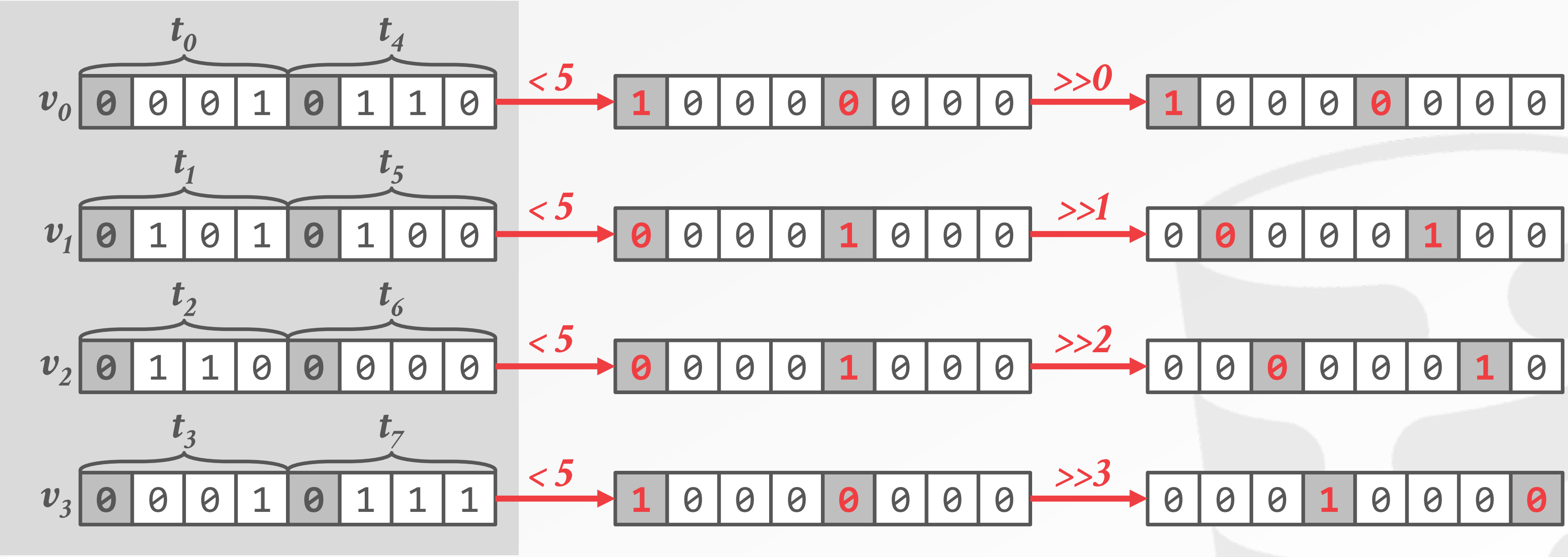
t_3 t_7

v_3: 0 0 0 1 0 1 1 1 $\xrightarrow{<5}$ 1 0 0 0 0 0 0 0

Source: Jignesh Patel

BITWEAVING/H – EXAMPLE

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



v_0 0 0 0 1 0 1 1 0 → <5 → 1 0 0 0 0 0 0 0 → $>>0$ → 1 0 0 0 0 0 0 0

v_1 0 1 0 1 0 1 0 0 → <5 → 0 0 0 0 1 0 0 0 → $>>1$ → 0 0 0 0 0 1 0 0

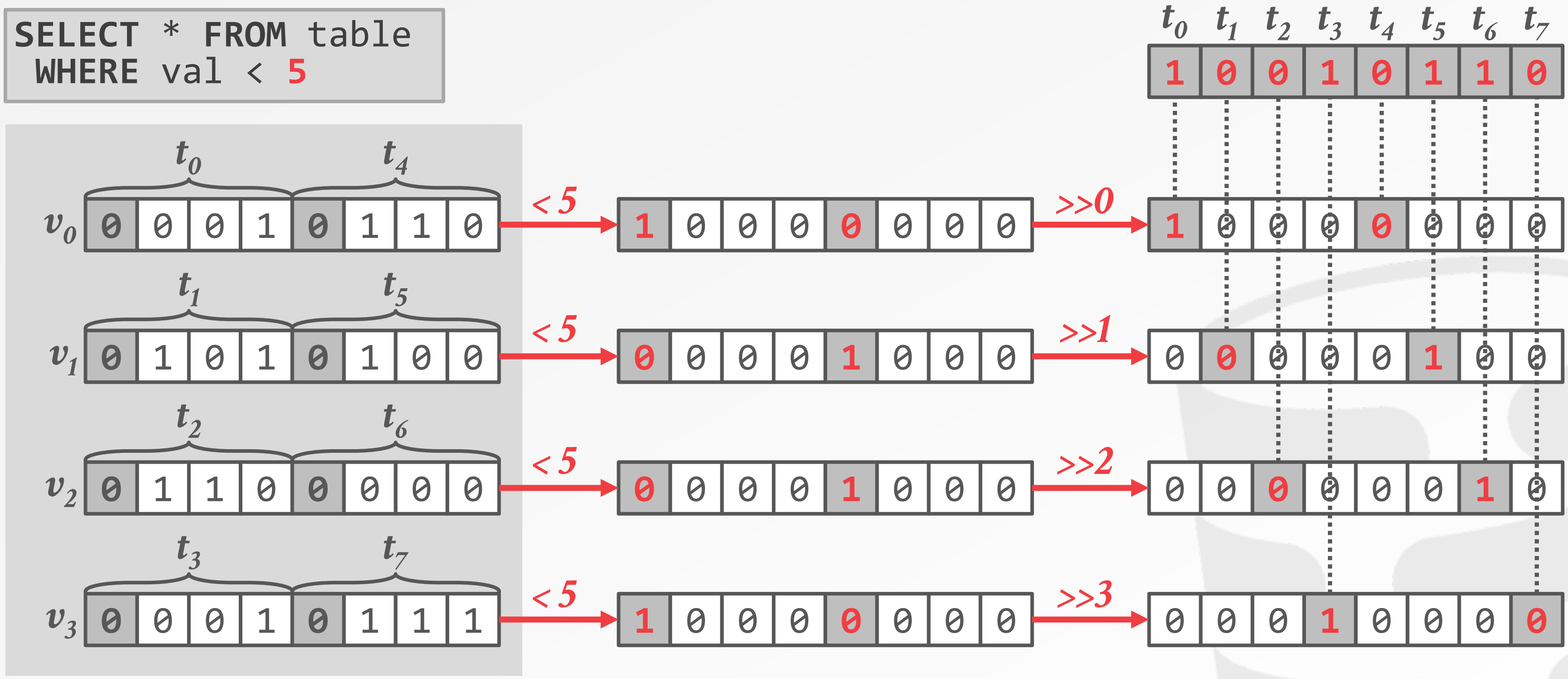
v_2 0 1 1 0 0 0 0 0 → <5 → 0 0 0 0 1 0 0 0 → $>>2$ → 0 0 0 0 0 0 1 0

v_3 0 0 0 1 0 1 1 1 → <5 → 1 0 0 0 0 0 0 0 → $>>3$ → 0 0 0 1 0 0 0 0

Source: Jignesh Patel

BITWEAVING/H – EXAMPLE

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



	t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7
	1	0	0	1	0	1	1	0

	t_0 / t_1 / t_2 / t_3	t_4 / t_5 / t_6 / t_7				
v_0	0 0 0 1	0 1 1 0	< 5	1 0 0 0 0 0 0 0	>>0	1 0 0 0 0 0 0 0
v_1	0 1 0 1	0 1 0 0	< 5	0 0 0 0 1 0 0 0	>>1	0 0 0 0 0 1 0 0
v_2	0 1 1 0	0 0 0 0	< 5	0 0 0 0 1 0 0 0	>>2	0 0 0 0 0 0 1 0
v_3	0 0 0 1	0 1 1 1	< 5	1 0 0 0 0 0 0 0	>>3	0 0 0 1 0 0 0 0

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

	t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7
Selection Vector	1	0	0	1	0	1	1	0

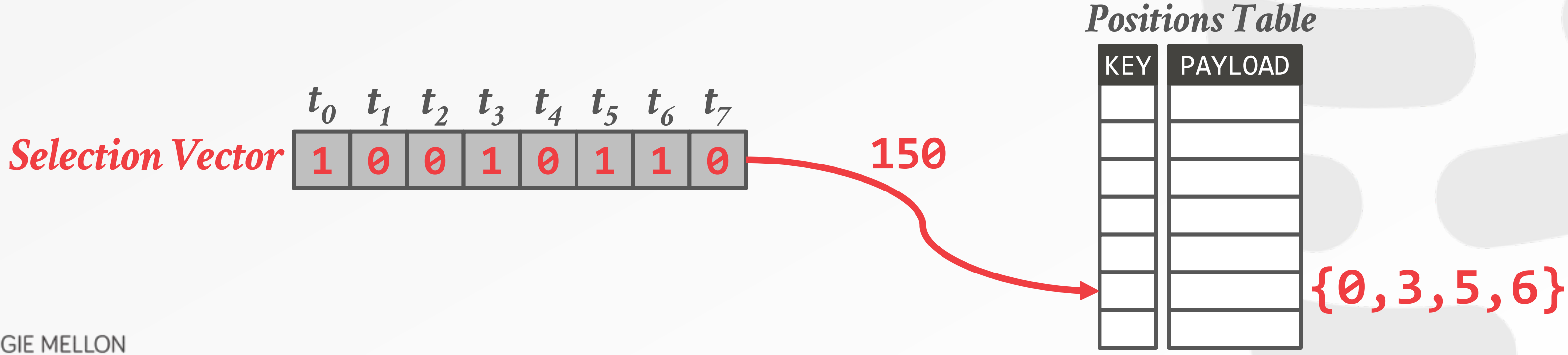
```
tuples = [ ]
for (i=0; i<n; i++) {
  if sv[i] == 1
    tuples.add(i);
}
```

SELECTION VECTOR

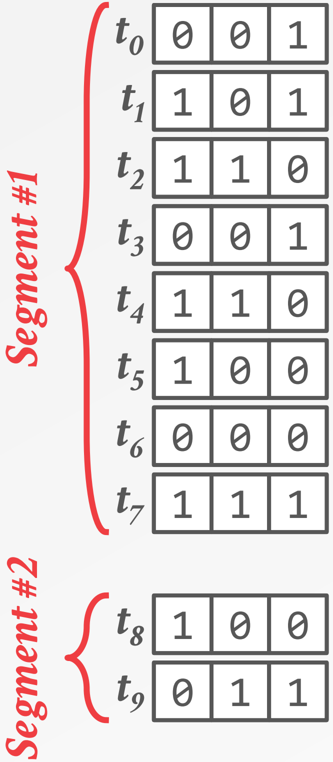
SIMD comparison operators produce a bit mask that specifies which tuples satisfy a predicate.

Have to convert it into offsets / positions.

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



VERTICAL STORAGE



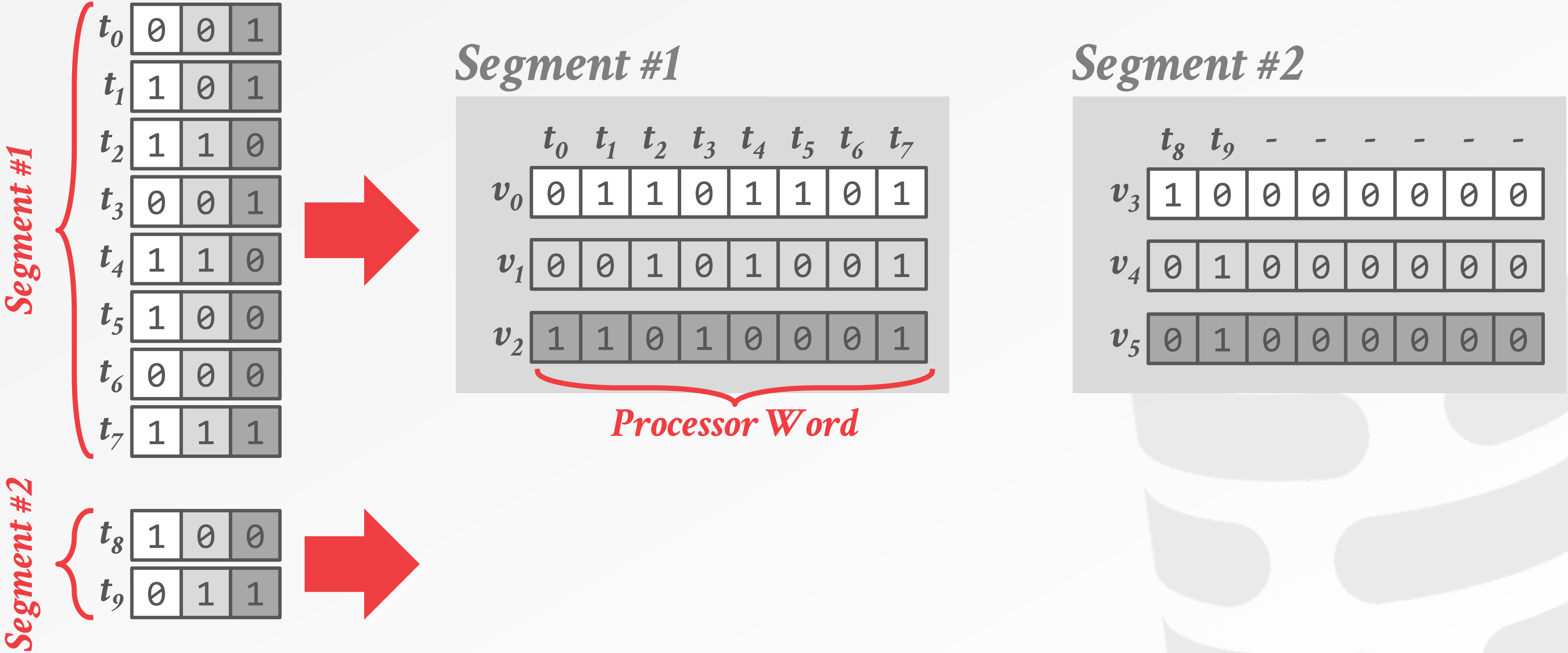
Segment #1

t_0	0	0	1
t_1	1	0	1
t_2	1	1	0
t_3	0	0	1
t_4	1	1	0
t_5	1	0	0
t_6	0	0	0
t_7	1	1	1

Segment #2

t_8	1	0	0
t_9	0	1	1

VERTICAL STORAGE



Segment #1

t_0	0	0	1
t_1	1	0	1
t_2	1	1	0
t_3	0	0	1
t_4	1	1	0
t_5	1	0	0
t_6	0	0	0
t_7	1	1	1

Segment #2

t_8	1	0	0
t_9	0	1	1

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

Processor Word

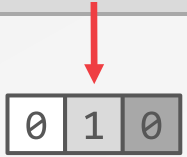
Segment #2

	t_8	t_9	-	-	-	-	-	-
v_3	1	0	0	0	0	0	0	0
v_4	0	1	0	0	0	0	0	0
v_5	0	1	0	0	0	0	0	0

CARNEGIE MELLON
DATABASE GROUP

BITWEAVING/V – EXAMPLE

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



0	1	0

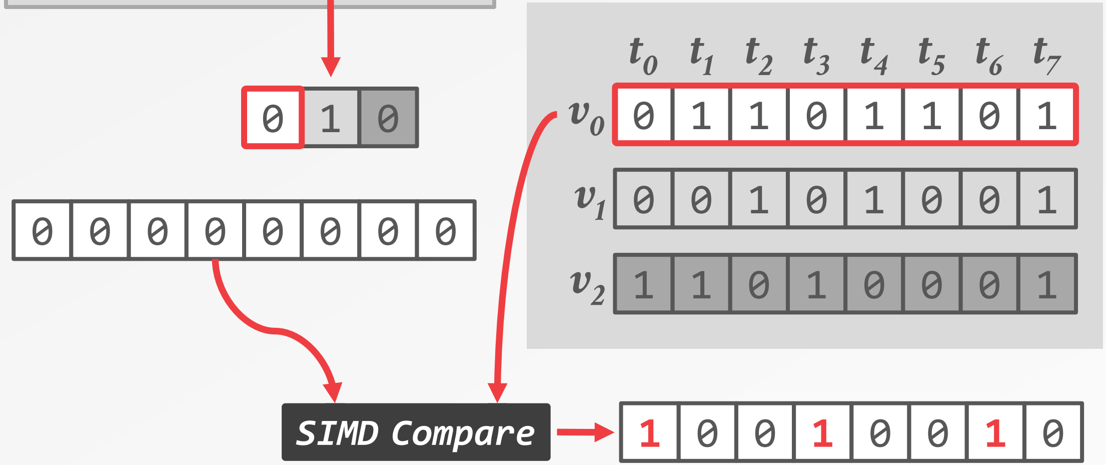
Segment #1

	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

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

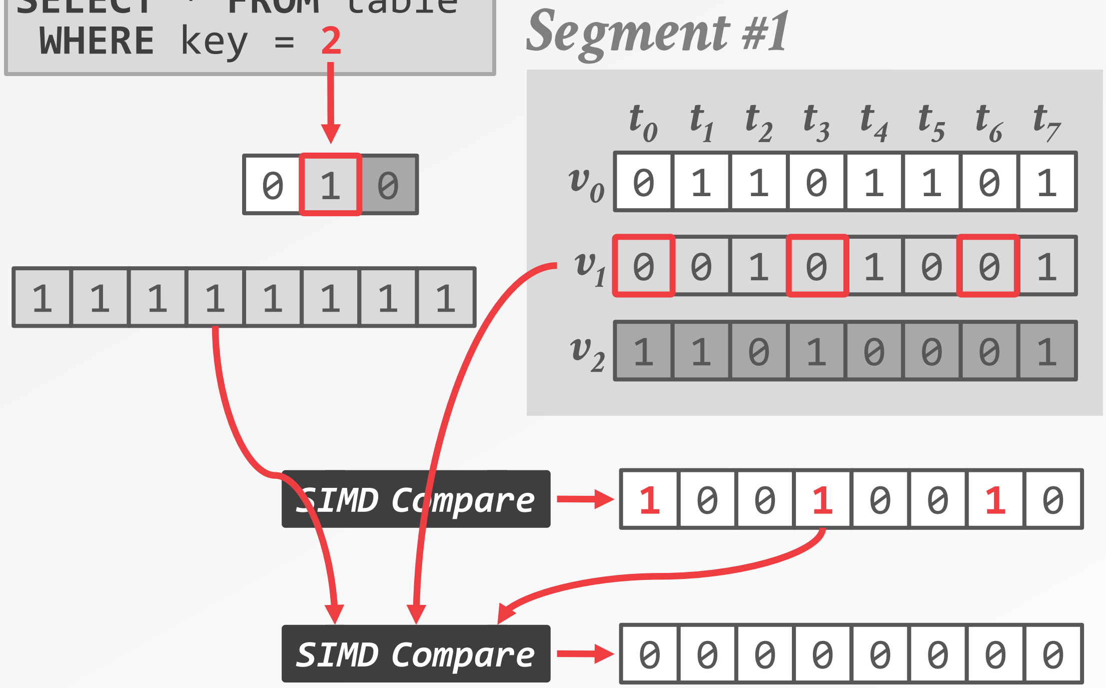
Segment #1



	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

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



0 1 0

1 1 1 1 1 1 1 1

Segment #1

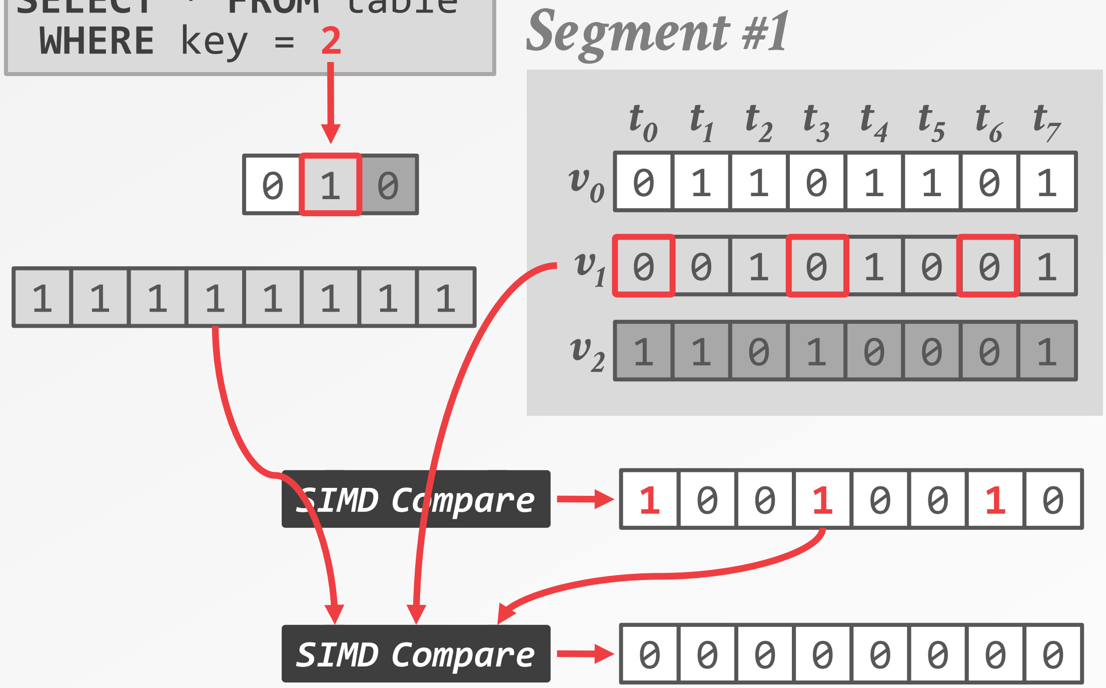
	t_0	t_1	t_2	t_3	t_4	t_5	t_6	t_7
v_0	0	1	1	0	1	1	0	1
v_1	0	0	1	0	1	0	0	1
v_2	1	1	0	1	0	0	0	1

SIMD Compare → 1 0 0 1 0 0 1 0

SIMD Compare → 0 0 0 0 0 0 0 0

BITWEAVING/V – EXAMPLE

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



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

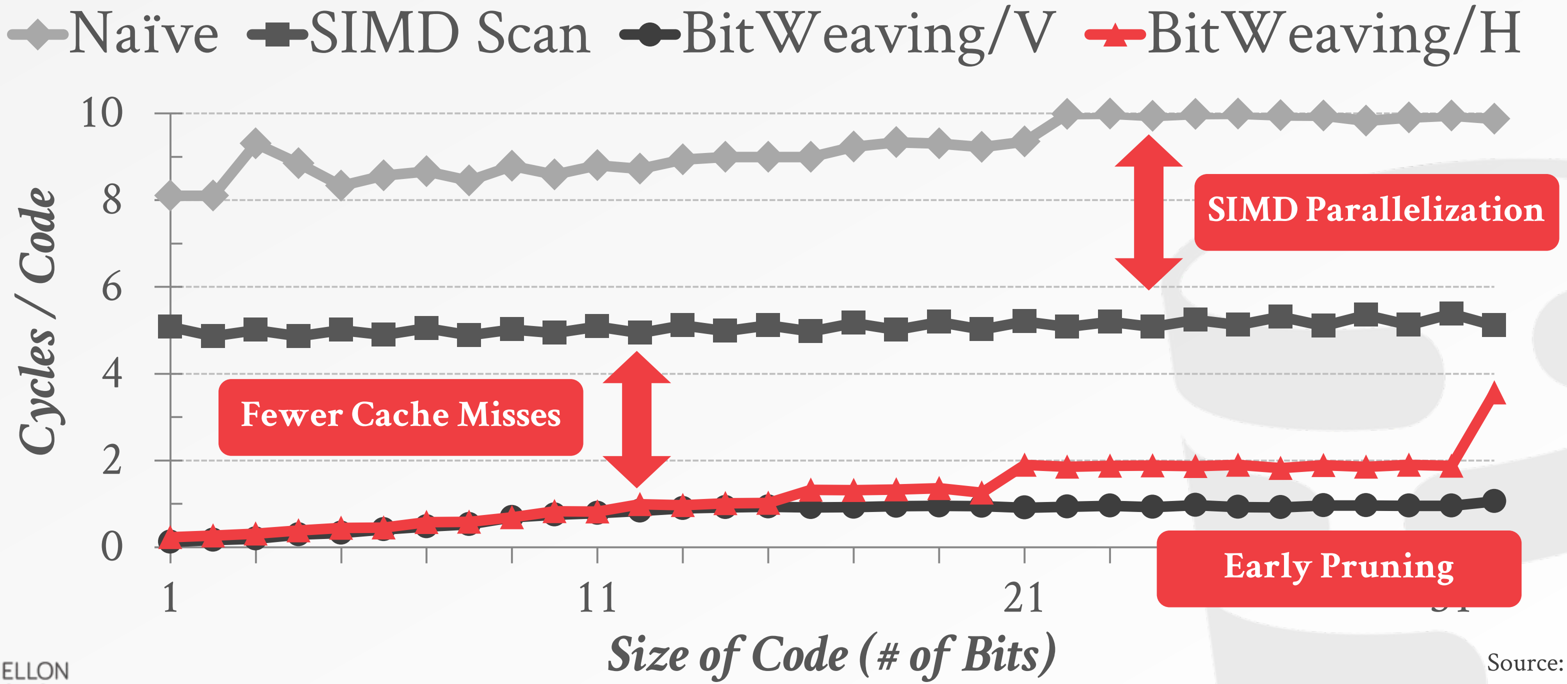
→ 1 billion tuples

→ Uniform distribution

Source: Jignesh Patel

EVALUATION

TPC-H Aggregation Query
Intel Xeon X5650 @ 2.66 GHz



SIMD Parallelization

Fewer Cache Misses

Early Pruning

Source: Jignesh Patel

OBSERVATION

At a high-level, BitWeaving is essentially a bitmap index. This is great for OLAP, bad for OLTP.

How can compress data in such a way that still allow for efficient point queries?

HYPER – DATA BLOCKS

Individually determine the best suitable compression scheme per block.

→ Hot tuples are stored uncompressed (OLTP)

→ Cold tuples are stored in compressed **Data Blocks** (OLAP)

Each Data Block is compressed using the best scheme for its tuples.

DATA BLOCKS: HYBRID OLTP AND OLAP ON COMPRESSED STORAGE USING BOTH VECTORIZATION AND COMPILATION
SIGMOD 2016

OBSERVATION

Multiple storage layouts and compression schemes mean the DBMS has to generate multiple code paths per query plan.

This increases the compilation time per query and the total size of the query plan cache.

HYPER – SPLIT EXECUTION MODELS

Compressed Data: Vectorized Execution

→ Use the pre-compiled primitives from Vectorwise.

Uncompressed Data: LLVM Compilation

→ Data is always stored in the same format so there is only ever one code path to compile.

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.

ADMINISTRIVIA

Code Review #1 Submission: April 11th

Project Status Meetings: April 13th

Project Status Updates: April 18th

Code Review #1 Completion: April 18th

CODE REVIEWS

Each group will send a pull request to the CMU-DB master branch.

- → This will automatically run tests + coverage calculation.
- → PR must be able to merge cleanly into master branch.
- → Reviewing group will write comments on that request.
- → Add the URL to the Google spreadsheet and notify the reviewing team that it is ready.

Please be helpful and courteous.

GENERAL TIPS

The dev team should provide you with a summary of what files/functions the reviewing team should look at.

Review fewer than 400 lines of code at a time and only for at most 60 minutes.

Use a **checklist** to outline what kind of problems you are looking for.

Source: SmartBear

CHECKLIST – GENERAL

Does the code work?

Is all the code easily understood?

Is there any redundant or duplicate code?

Is the code as modular as possible?

Can any global variables be replaced?

Is there any commented out code?

Is it using proper debug log functions?

Source: Gareth Wilson

CHECKLIST – DOCUMENTATION

Do comments describe the intent of the code?

Are all functions commented?

Is any unusual behavior described?

Is the use of 3rd-party libraries documented?

Is there any incomplete code?

Source: Gareth Wilson

CHECKLIST – TESTING

Do tests exist and are they comprehensive?

Are the tests actually testing the feature?

Are they relying on hardcoded answers?

What is the code coverage?

Source: Gareth Wilson

PROJECT #3 – STATUS UPDATE

I will meet with groups individually on Thursday.

Next Tuesday each group will give a **five** minute presentation to update the class about the current status of your project.

Each presentation should include:

→ Current development status.
→ Whether anything in your plan has changed.
→ Any thing that surprised you.