

CS 6530: Advanced Database Systems Fall 2022

Lecture 15

Vectorization

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VECTORIZATION

- The process of converting an algorithm's scalar implementation that processes a single pair of operands at a time, to a vector implementation that processes one operation on multiple pairs of operands at once.

WHY THIS MATTERS

- Say we can parallelize our algorithm over 32 cores.
- Each core has a 4-wide SIMD registers.
- **Potential Speed-up: $32x \times 4x = 128x$**

SINGLE INSTRUCTION, MULTIPLE DATA

- A class of CPU instructions that allow the processor to perform the same operation on multiple data points simultaneously.
- All major ISAs have microarchitecture support SIMD operations.
 - **x86**: MMX, SSE, SSE2, SSE3, SSE4, AVX, AVX2, AVX512
 - **PowerPC**: AltiVec
 - **ARM**: NEON, [SVE](#)

SIMD INSTRUCTIONS (1)

- **Data Movement**

- Moving data in and out of vector registers

- **Arithmetic Operations**

- Apply operation on multiple data items (e.g., 2 doubles, 4 floats, 16 bytes)
- Example: **ADD, SUB, MUL, DIV, SQRT, MAX, MIN**

- **Logical Instructions**

- Logical operations on multiple data items
- Example: **AND, OR, XOR, ANDN, ANDPS, ANDNPS**

SIMD INSTRUCTIONS (2)

- **Comparison Instructions**

- Comparing multiple data items (`==`, `<`, `<=`, `>`, `>=`, `!=`)

- **Shuffle instructions**

- Move data in between SIMD registers

- **Miscellaneous**

- Conversion: Transform data between x86 and SIMD registers.
- Cache Control: Move data directly from SIMD registers to memory (bypassing CPU cache).

INTEL SIMD EXTENSIONS

		<i>Width</i>	<i>Integers</i>	<i>Single-P</i>	<i>Double-P</i>
1997	MMX	64 bits	✓		
1999	SSE	128 bits	✓	✓(×4)	
2001	SSE2	128 bits	✓	✓	✓(×2)
2004	SSE3	128 bits	✓	✓	✓
2006	SSSE 3	128 bits	✓	✓	✓
2006	SSE 4.1	128 bits	✓	✓	✓
2008	SSE 4.2	128 bits	✓	✓	✓
2011	AVX	256 bits	✓	✓(×8)	✓(×4)
2013	AVX2	256 bits	✓	✓	✓
2017	AVX-512	512 bits	✓	✓(×16)	✓(×8)

Source: [James Reinders](#)

SIMD TRADE-OFFS

- **Advantages:**

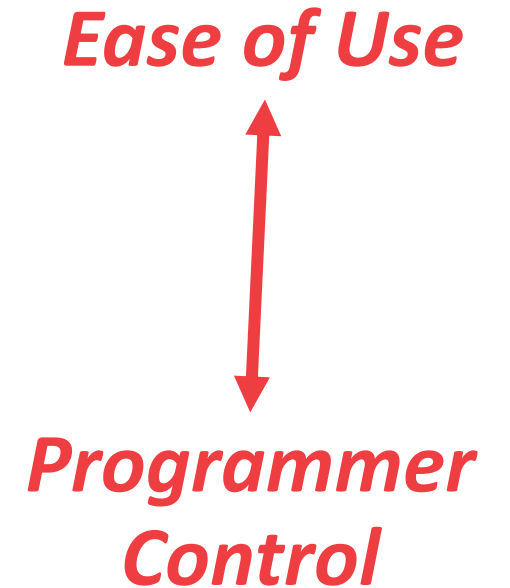
- Significant performance gains and resource utilization if an algorithm can be vectorized.

- **Disadvantages:**

- Implementing an algorithm using SIMD is still mostly a manual process.
- SIMD may have restrictions on data alignment.
- Gathering data into SIMD registers and scattering it to the correct locations is tricky and/or inefficient.

VECTORIZATION

- **Choice #1: Automatic Vectorization**
- **Choice #2: Compiler Hints**
- **Choice #3: Explicit Vectorization**



AUTOMATIC VECTORIZATION

- The compiler can identify when instructions inside of a loop can be rewritten as a vectorized operation.
- Works for simple loops only and is rare in database operators. Requires hardware support for SIMD instructions.

AUTOMATIC VECTORIZATION

```
void add(int *X,  
        int *Y,  
        int *Z) { ← *Z=*X+1  
    for (int i=0; i<MAX; i++) {  
        Z[i] = X[i] + Y[i];  
    }  
}
```

***These might point
to the same
address!***

- This loop is not legal to automatically vectorize.
- The code is written such that the addition is described sequentially.

COMPILER HINTS

- Provide the compiler with additional information about the code to let it know that is safe to vectorize.
- Two approaches:
 - Give explicit information about memory locations.
 - Tell the compiler to ignore vector dependencies.

COMPILER HINTS

```
void add(int *restrict X,  
        int *restrict Y,  
        int *restrict Z) {  
    for (int i=0; i<MAX; i++) {  
        Z[i] = X[i] + Y[i];  
    }  
}
```

- The **restrict** keyword in C++ tells the compiler that the arrays are distinct locations in memory.

COMPILER HINTS

```
void add(int *X,  
        int *Y,  
        int *Z) {  
    #pragma ivdep  
    for (int i=0; i<MAX; i++) {  
        Z[i] = X[i] + Y[i];  
    }  
}
```

- This pragma tells the compiler to ignore loop dependencies for the vectors.
- It's up to you make sure that this is correct.

EXPLICIT VECTORIZATION

- Use CPU intrinsics to manually marshal data between SIMD registers and execute vectorized instructions.
- Potentially not portable.

EXPLICIT VECTORIZATION

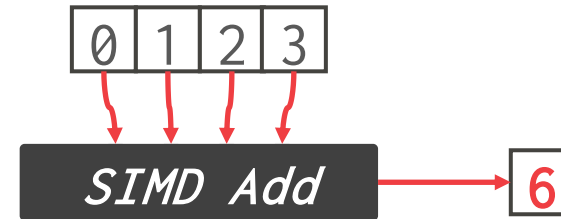
```
void add(int *X,  
        int *Y,  
        int *Z) {  
    __mm128i *vecX = (__m128i*)X;  
    __mm128i *vecY = (__m128i*)Y;  
    __mm128i *vecZ = (__m128i*)Z;  
    for (int i=0; i<MAX/4; i++) {  
        _mm_store_si128(vecZ++,  
            _mm_add_epi32(*vecX++,  
                *vecY++));  
    }  
}
```

- Store the vectors in 128-bit SIMD registers.
- Then invoke the intrinsic to add together the vectors and write them to the output location.

VECTORIZATION DIRECTION

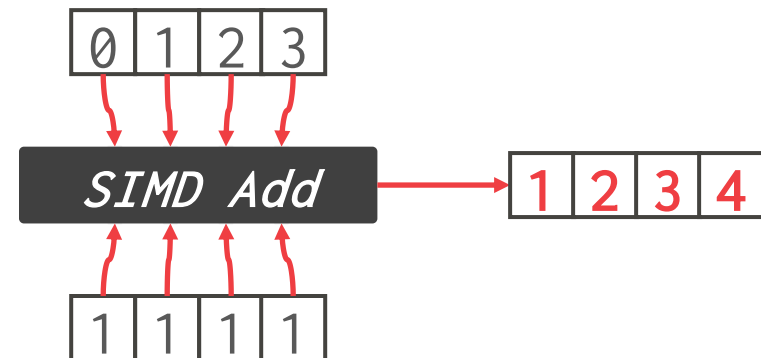
- **Approach #1: Horizontal**

- Perform operation on all elements together within a single vector.



- **Approach #2: Vertical**

- Perform operation in an elementwise manner on elements of each vector.



EXPLICIT VECTORIZATION

- **Linear Access Operators**
 - Predicate evaluation
 - Compression
- **Ad-hoc Vectorization**
 - Sorting
 - Merging
- **Composable Operations**
 - Multi-way trees
 - Bucketized hash tables

Source: [Orestis Polychroniou](#)

VECTORIZED DBMS ALGORITHMS

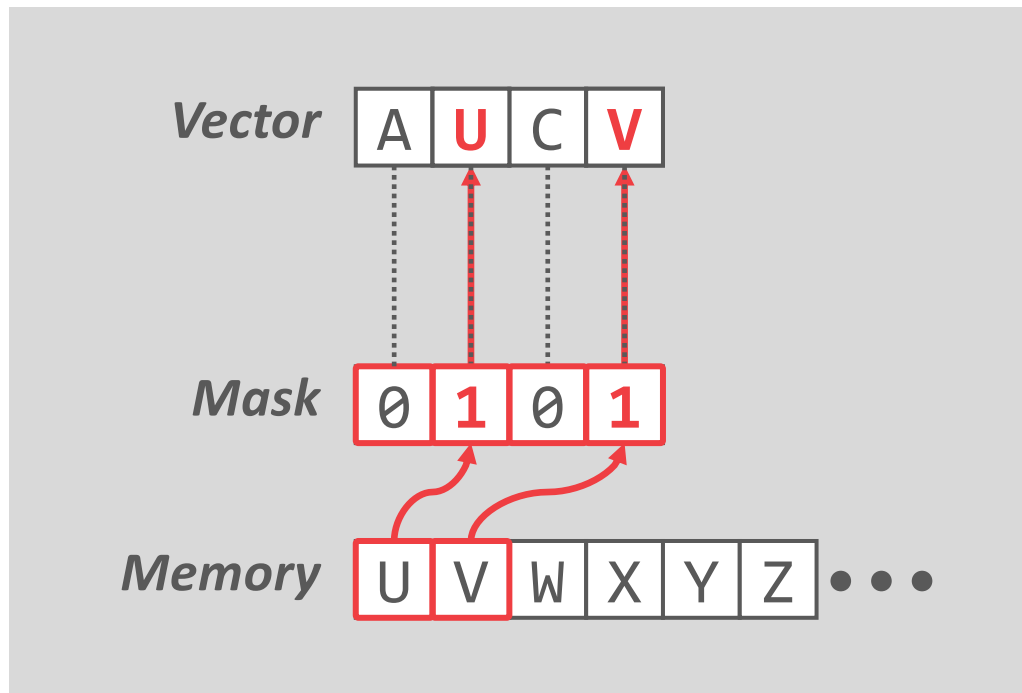
- Principles for efficient vectorization by using fundamental vector operations to construct more advanced functionality.
 - Favor *vertical* vectorization by processing different input data per lane.
 - Maximize lane utilization by executing unique data items per lane subset (i.e., no useless computations).

FUNDAMENTAL OPERATIONS

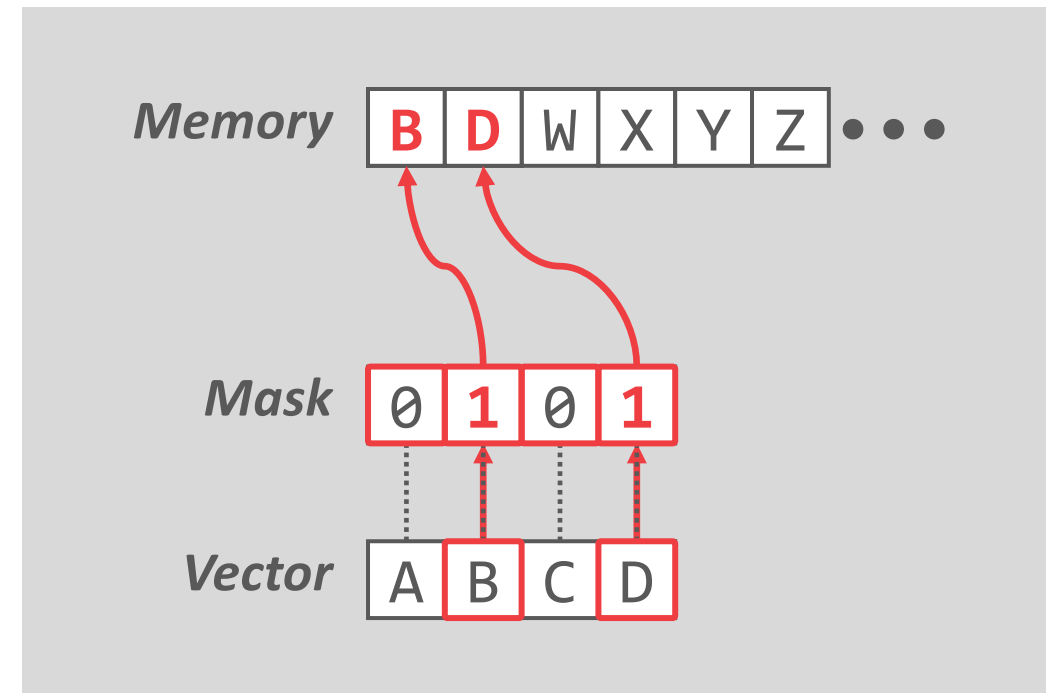
- Selective Load
- Selective Store
- Selective Gather
- Selective Scatter

FUNDAMENTAL VECTOR OPERATIONS

Selective Load

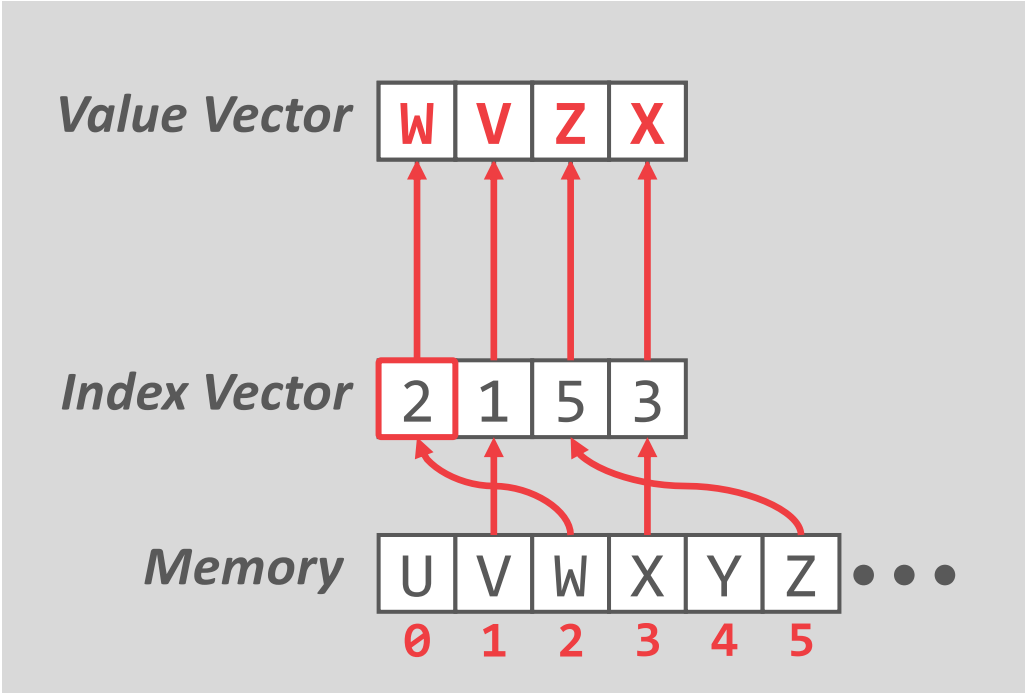


Selective Store

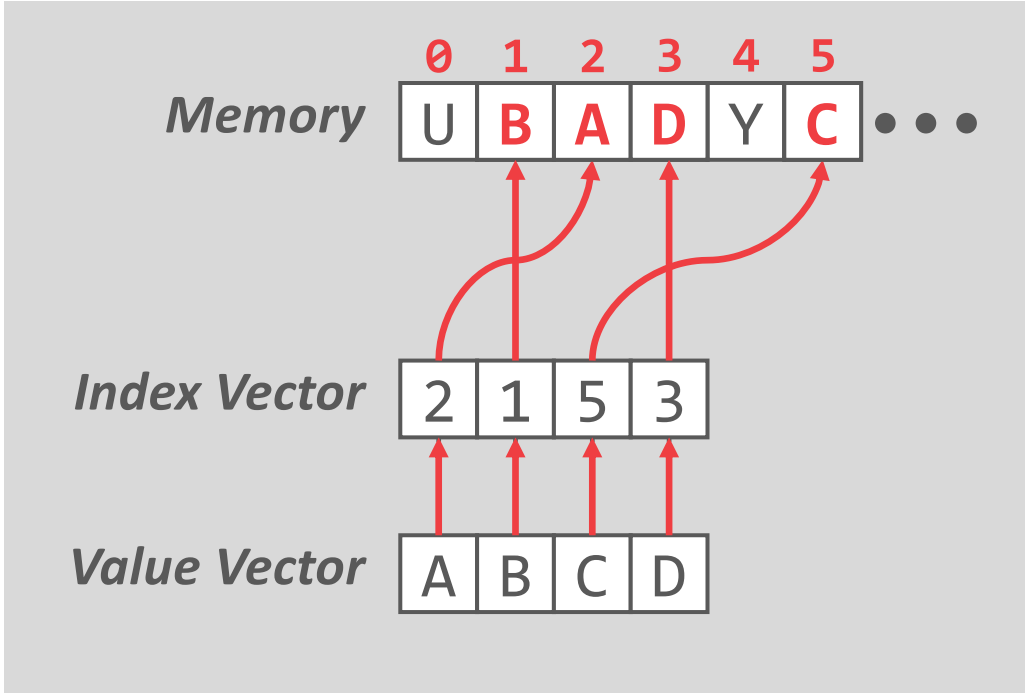


FUNDAMENTAL VECTOR OPERATIONS

Selective Gather



Selective Scatter



ISSUES

- Gathers and scatters are not really executed in parallel because the L1 cache only allows one or two distinct accesses per cycle.
- Gathers are only supported in newer CPUs.
- Selective loads and stores are also implemented in Xeon CPUs using vector permutations.

VECTORIZED OPERATORS

- Selection Scans
- Hash Tables
- Partitioning / Histograms
- Paper provides additional vectorized algorithms:
 - Joins, Sorting, Bloom filters.

SELECTION SCANS

Scalar (Branching)

```
i = 0
for t in table:
    key = t.key
    if (key ≥ low) && (key ≤ high):
        copy(t, output[i])
    i = i + 1
```

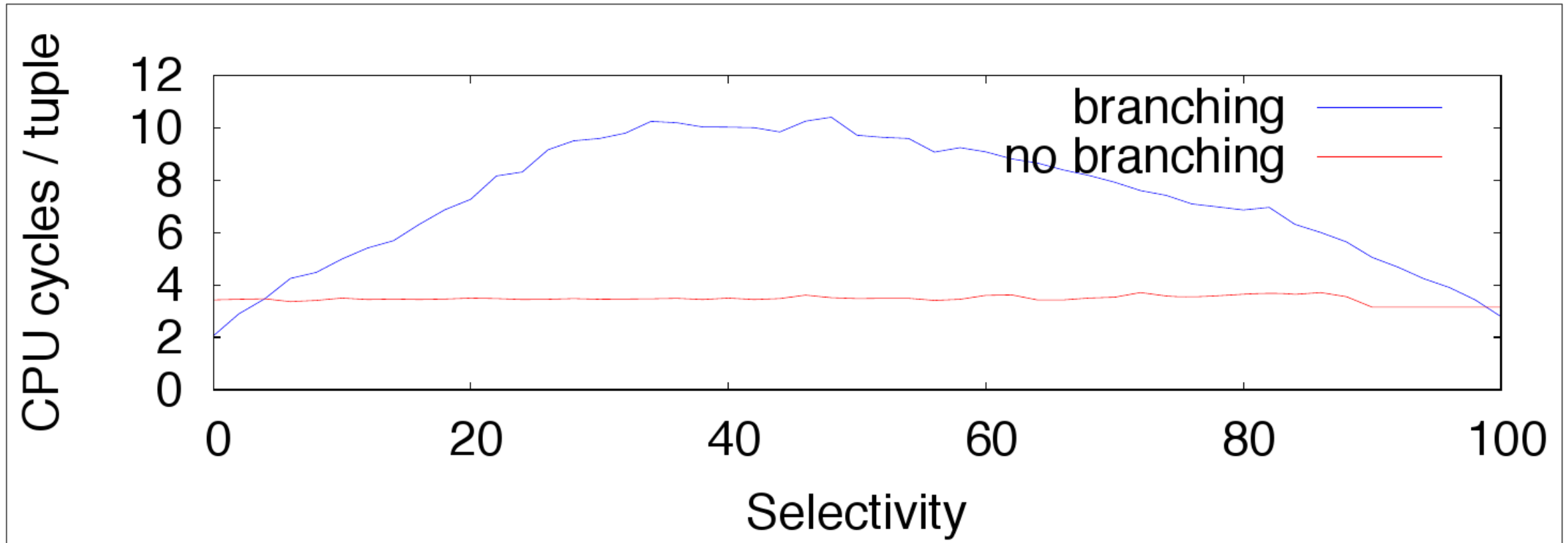
Scalar (Branchless)

```
i = 0
for t in table:
    copy(t, output[i])
    key = t.key
    m = (key ≥ low ? 1 : 0) &
        (key ≤ high ? 1 : 0)
    i = i + m
```

```
SELECT * FROM table
WHERE key ≥ $low AND key ≤
$high
```

Source: [Bogdan Raducanu](#)

SELECTION SCANS



Source: [Bogdan Raducanu](#)

SELECTION SCANS

Vectorized

```

i = 0
for vt in table:
    simdLoad(vt.key, vk)
    vm = (vk ≥ low ? 1 : 0) &
          (vk ≤ high ? 1 : 0)
    simdStore(vt, vm, output[i])
    i = i + |vm ≠ false|
  
```

```

SELECT * FROM table
WHERE key >= "O" AND key <= "U"
  
```

ID	KEY
1	J
2	O
3	Y
4	S
5	U
6	X

Key Vector

J	O	Y	S	U	X
---	---	---	---	---	---

SIMD Compare

Mask

0	1	0	1	1	0
---	---	---	---	---	---

All Offsets

0	1	2	3	4	5
---	---	---	---	---	---

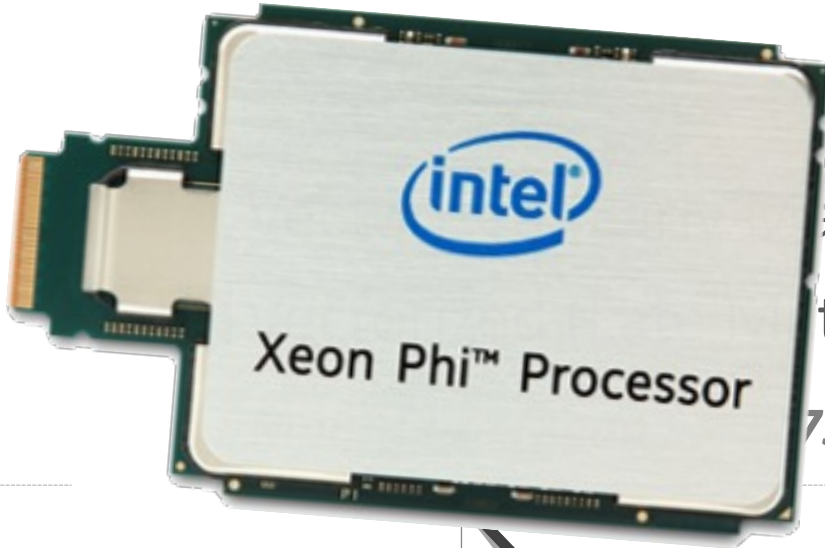
SIMD Store

Matched Offsets

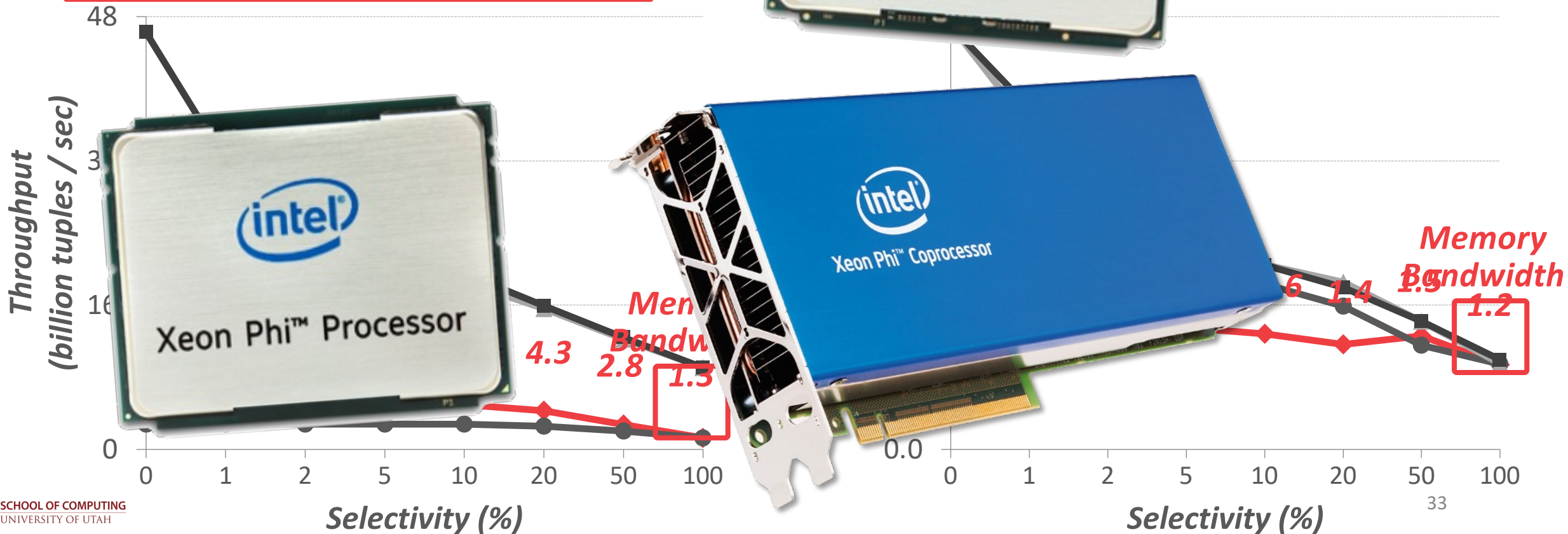
1	3	4			
---	---	---	--	--	--

SELECTION SCANS

- ◆ Scalar (Branching)
- Scalar (Branchless)

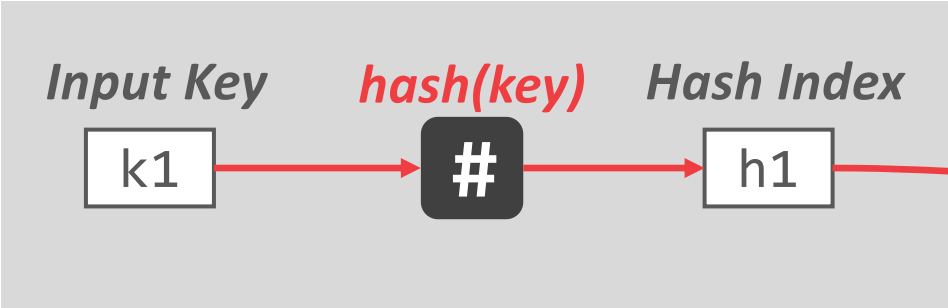


MIC (Xeon Phi 7120P – 61 Cores + 4×HT)

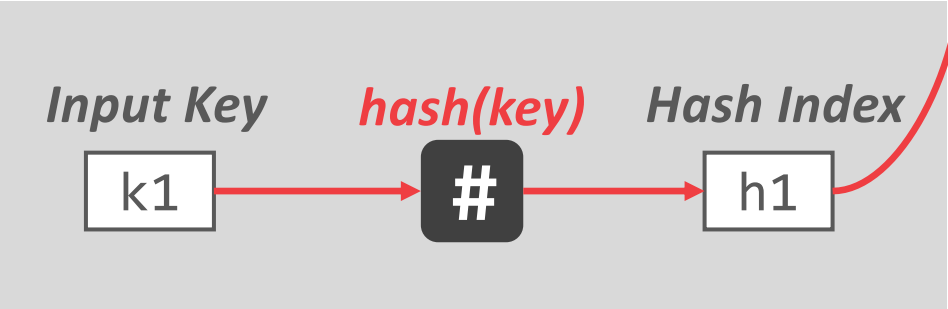


HASH TABLES – PROBING

Scalar

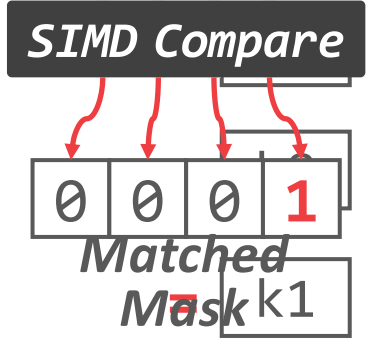


Vectorized (Horizontal)



Linear Probing
Bucketized Table

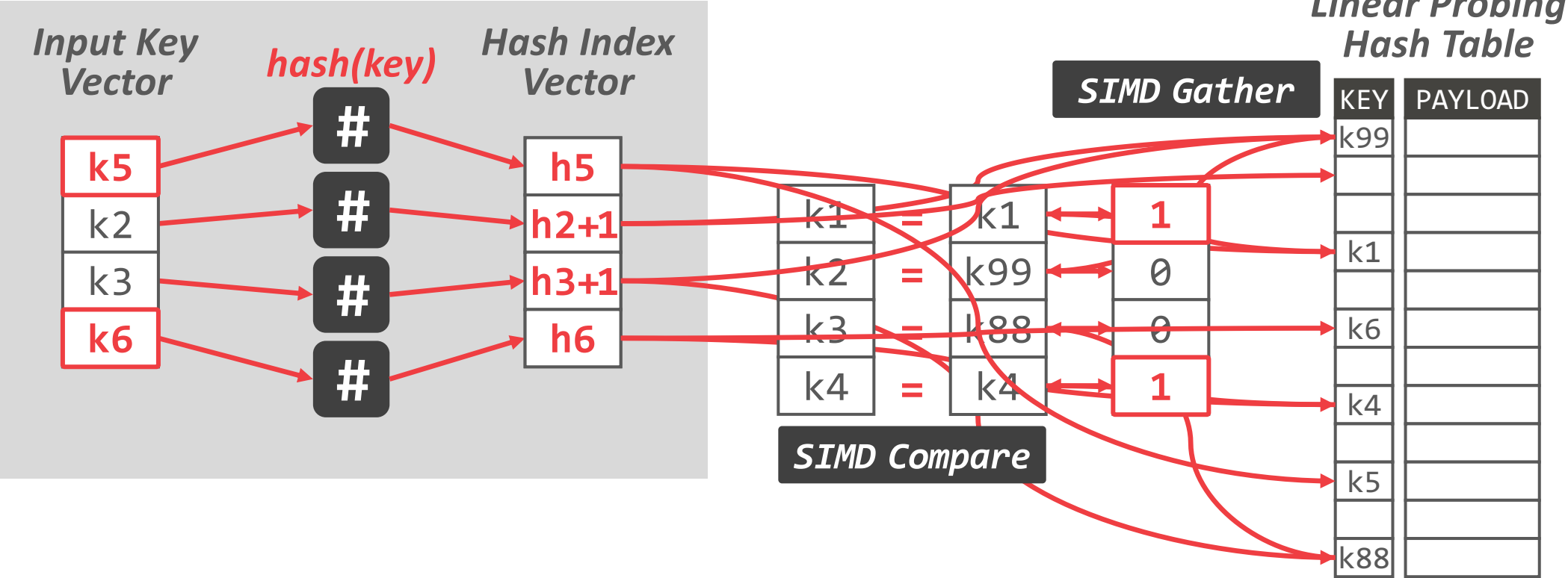
KEYS				PAYLOAD			



Four Keys Four Values

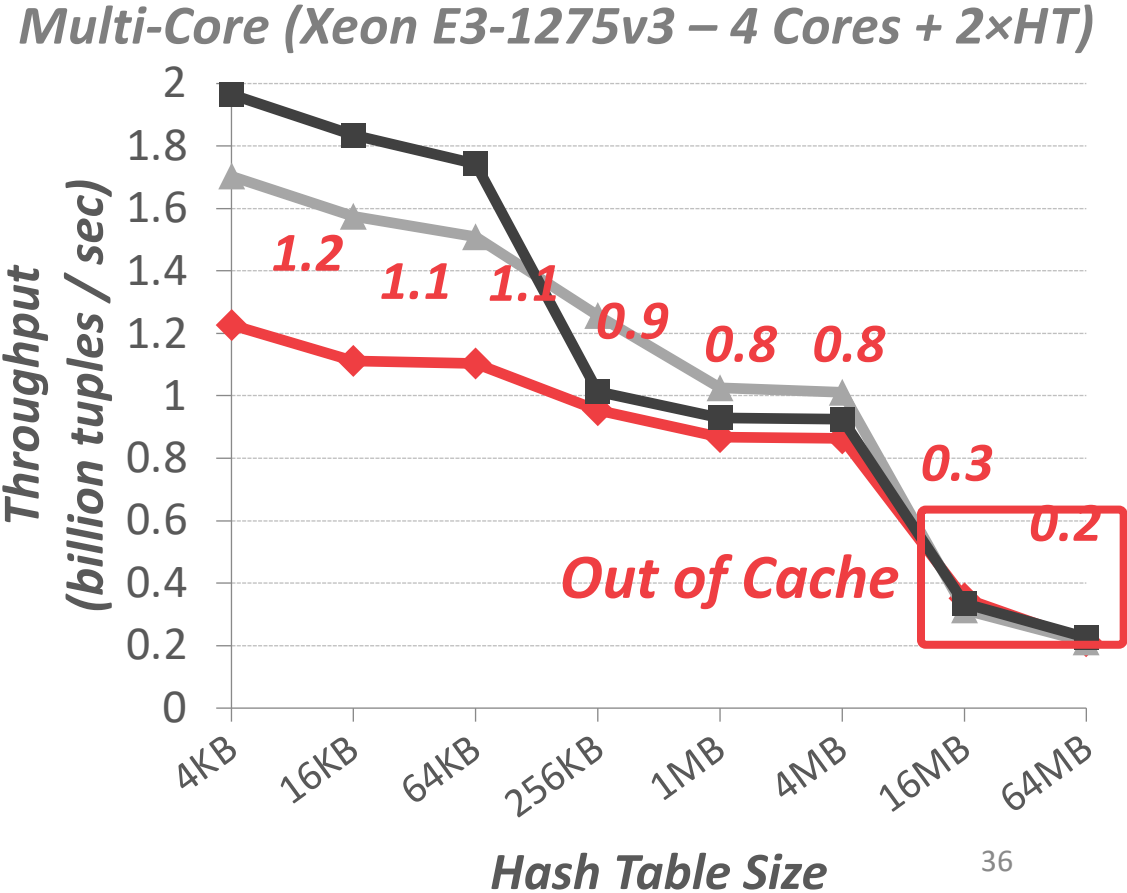
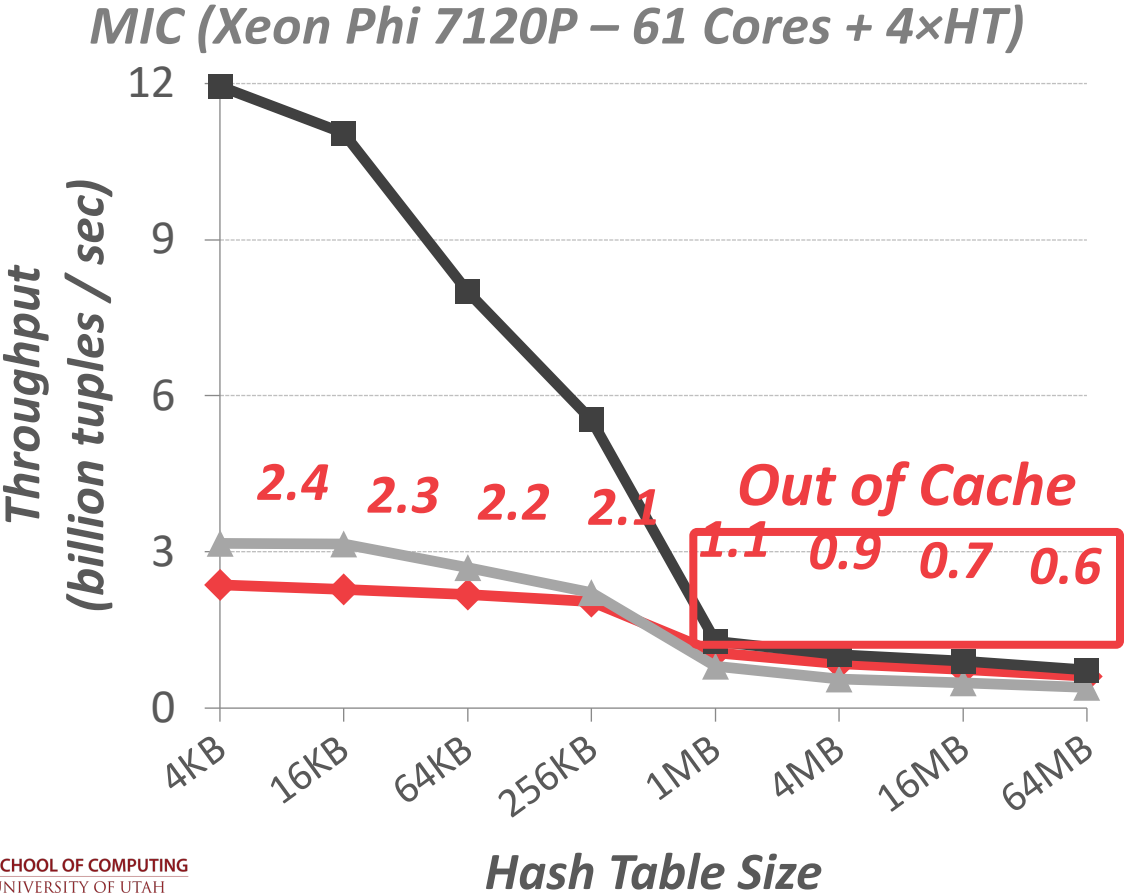
HASH TABLES – PROBING

Vectorized (Vertical)



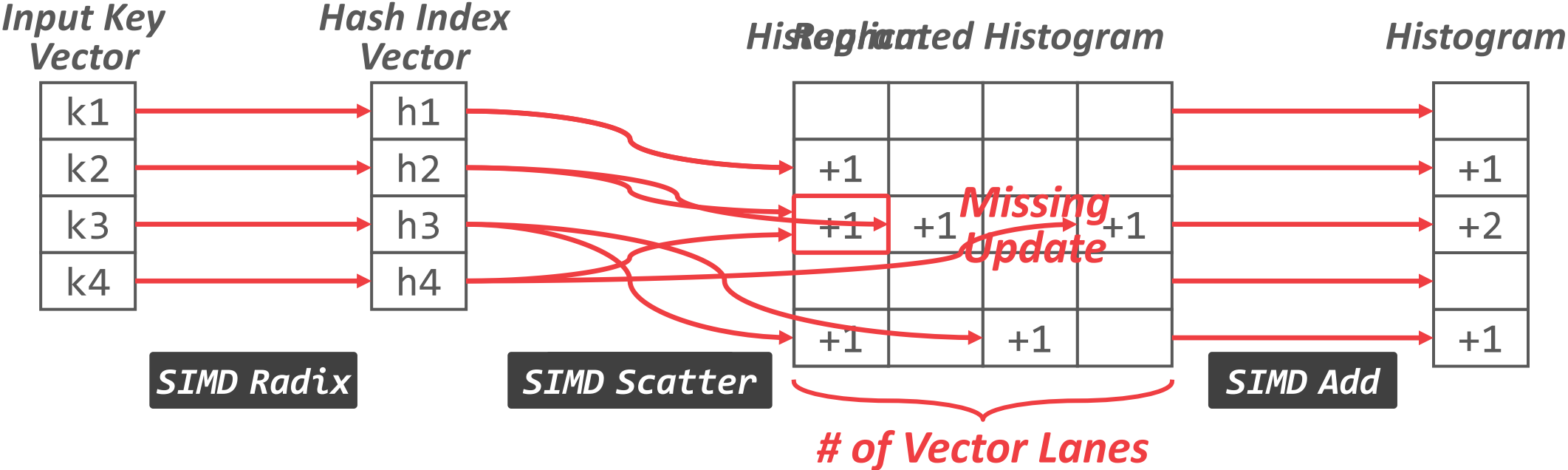
HASH TABLES – PROBING

◆ Scalar
 ▲ Vectorized (Horizontal)
 ■ Vectorized (Vertical)



PARTITIONING – HISTOGRAM

- Use scatter and gathers to increment counts.
- Replicate the histogram to handle collisions.

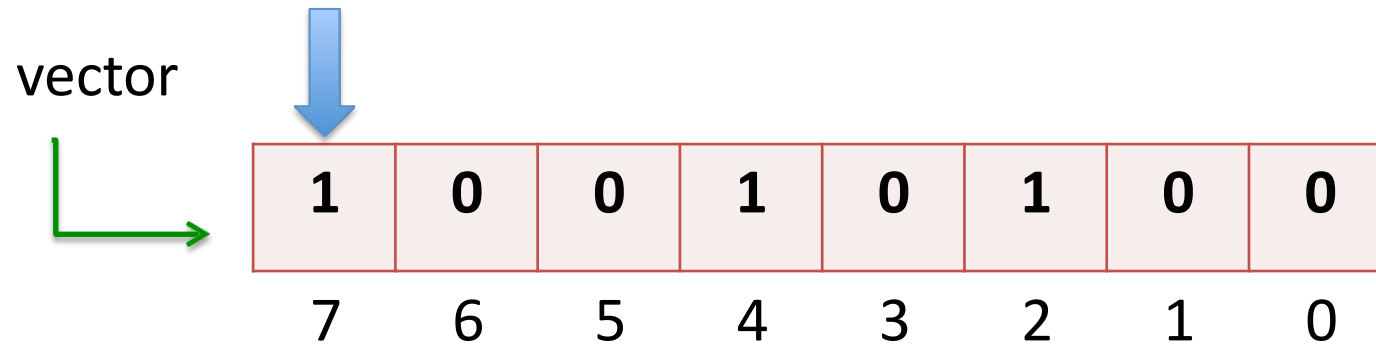


JOINS

- **No Partitioning**
 - Build one shared hash table using atomics
 - Partially vectorized
- **Min Partitioning**
 - Partition building table
 - Build one hash table per thread
 - Fully vectorized
- **Max Partitioning**
 - Partition both tables repeatedly
 - Build and probe cache-resident hash tables
 - Fully vectorized

Rank-Select Primitive

[Jacobson, Guy. "Space-efficient static trees and graphs." 1989]

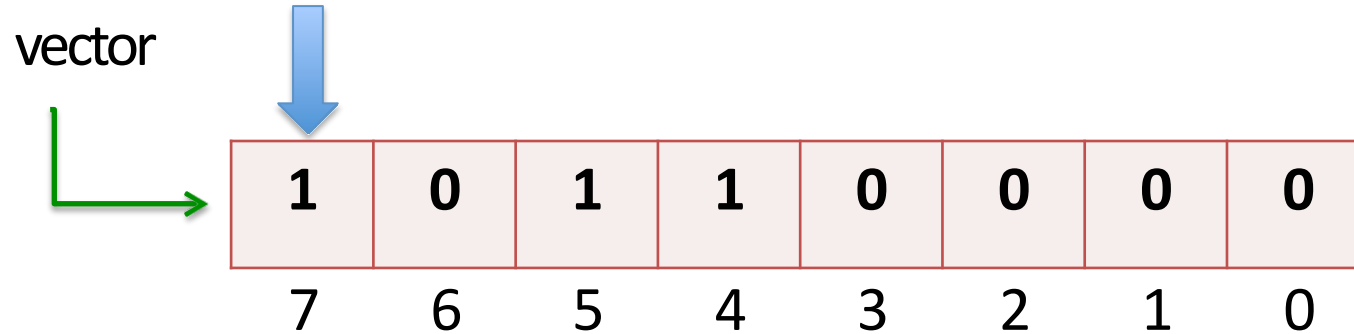


$$\text{Rank}(7) = 3$$

$$\text{popcnt}(\text{vector}) = 3$$

- The operation $\text{rank}(i)$ is defined as the number of set bits in the vector..
- This is a generalization of *popcnt* instruction.
- *popcnt*: Bit set count.

Rank-Select Primitive



$$\text{Select}(3) = 7$$

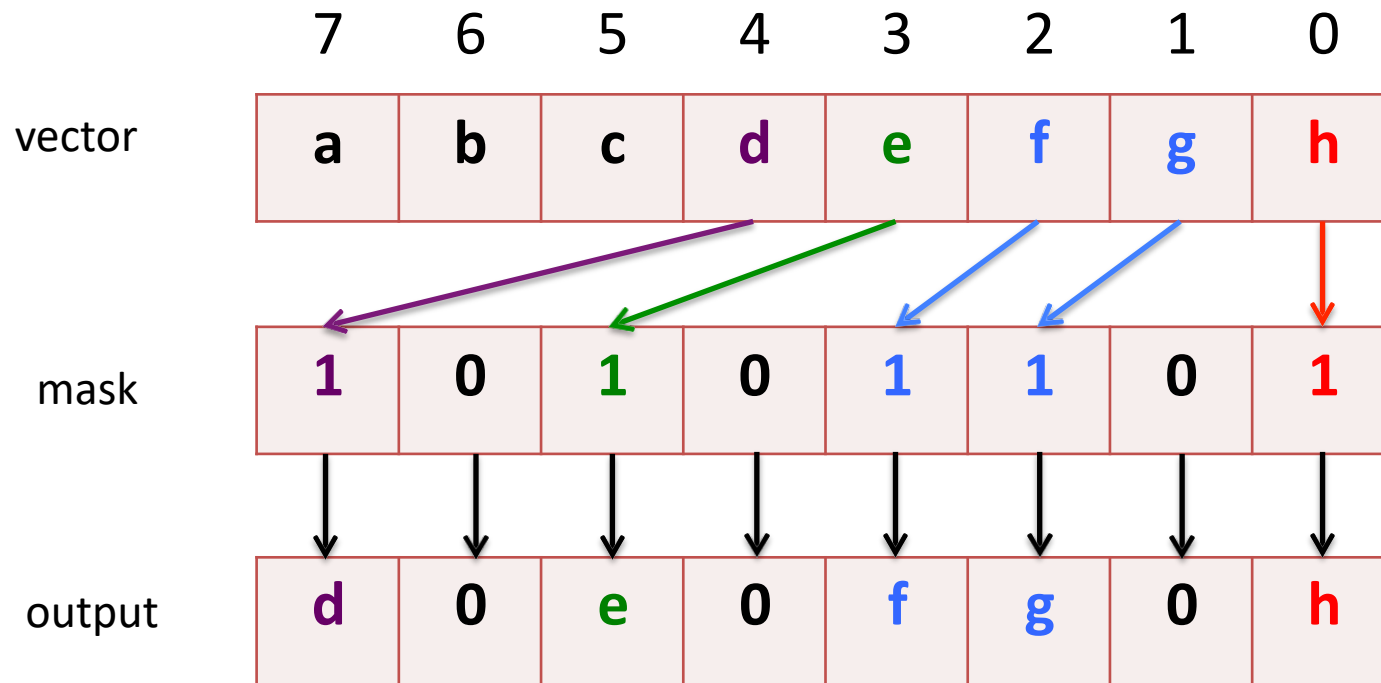
$$pdep(100, 10110000) = 10000000$$

$$tzcnt(10000000) = 7$$

- The operation $\text{select}(i)$ is defined as at which position is the i th set bit.
- We can implement select using $pdep$ and $tzcnt$ instructions.
- $pdep$: parallel bit deposit $tzcnt$: trailing zeros count.

PDEP Instruction

[Hilewitz, Yedidyah, and Ruby B. Lee. "Fast bit compression and expansion with parallel extract and parallel deposit instructions."]



pdep: It copies the contiguous low-order bits to selected bits of the destination; other destination bits are cleared.

