HORTON TABLES: FAST HASH TABLES FOR IN-MEMORY DATA-INTENSIVE COMPUTING

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NUWAN JAYASENA, AND DEAN M. TULLSEN

6/23/2016

THE ROLE OF HASH TABLES

IN IN-MEMORY DATA-INTENSIVE COMPUTING

- Data stores and caches
  - Key-value stores (e.g., Memcached, Redis, MongoDB)
  - Relational databases (e.g., MonetDB, HyPer, IBM DB2 with BLU)
    - Hash indexes
    - Join implementation: hash join and variants
    - Grouping: grouping hash table
    - Dictionary encoding

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  - Accelerate computations by computing on hash tables that store sparse images, textures, or surfaces

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- General data compression schemes used in common compression utilities

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- Graphics
  - Accelerate computations by computing on hash tables that store sparse images, textures, or surfaces

- General data compression schemes used in common compression utilities

- **In each of these fields, having a fast hash table is important**

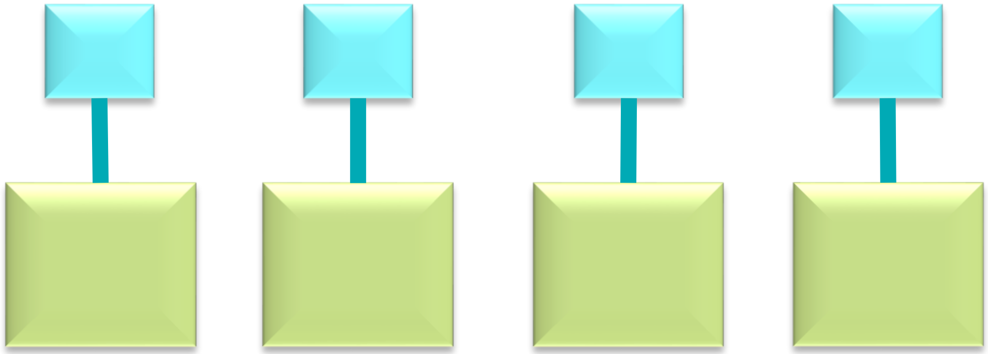
FOCUS OF THIS TALK

OPTIMIZING MEMORY ACCESSES IN FAST IN-MEMORY HASH TABLES

COMPUTE ELEMENTS

FOCUS OF THIS TALK

OPTIMIZING MEMORY ACCESSES IN FAST IN-MEMORY HASH TABLES



COMPUTE ELEMENTS

PRIVATE CACHES

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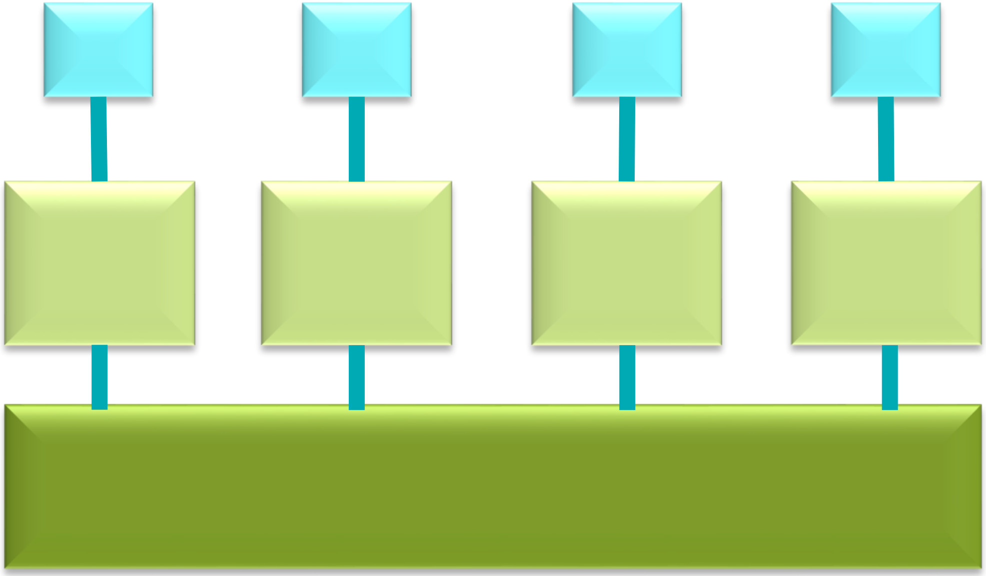

COMPUTE ELEMENTS

PRIVATE CACHES

SHARED LLCs

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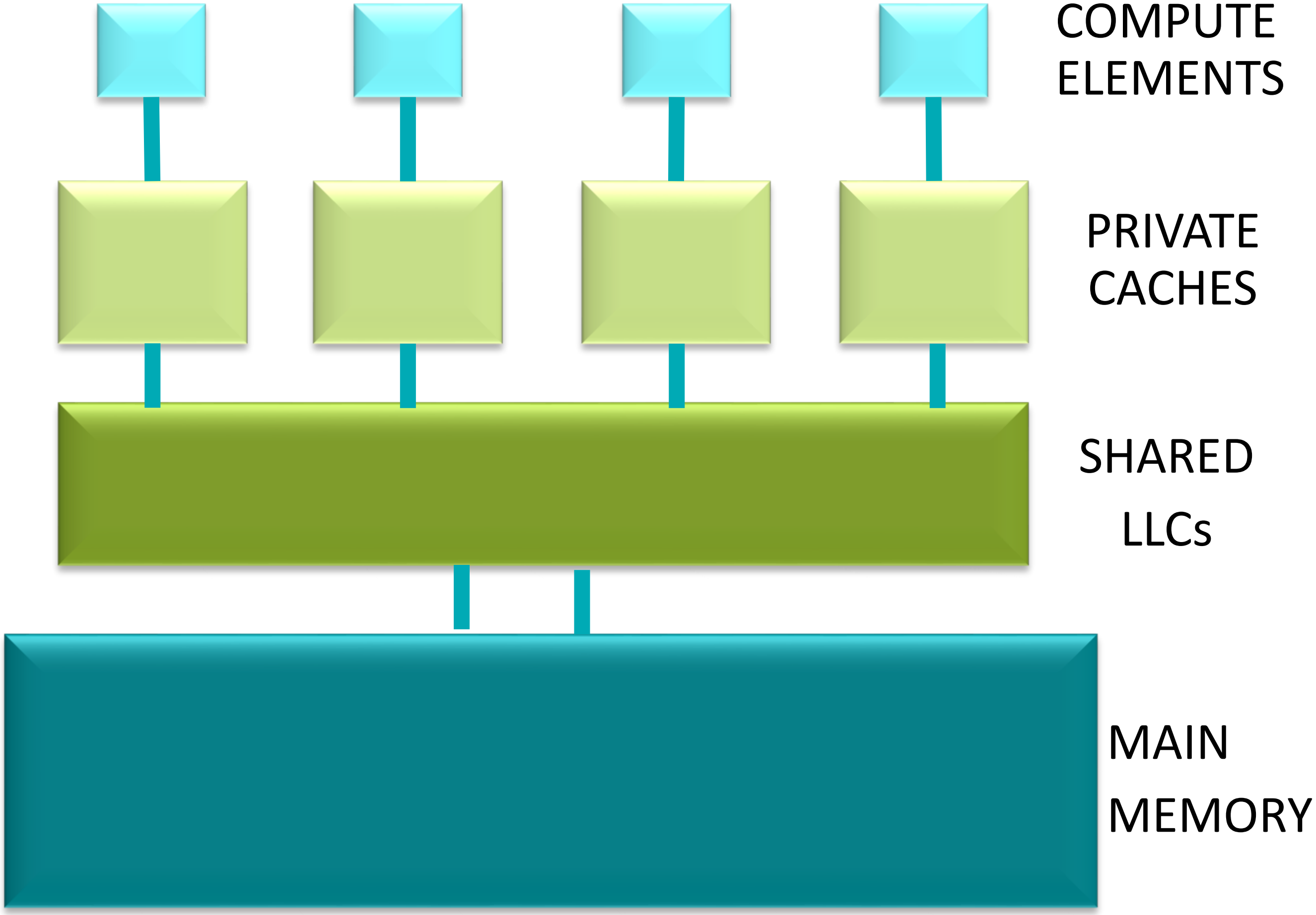

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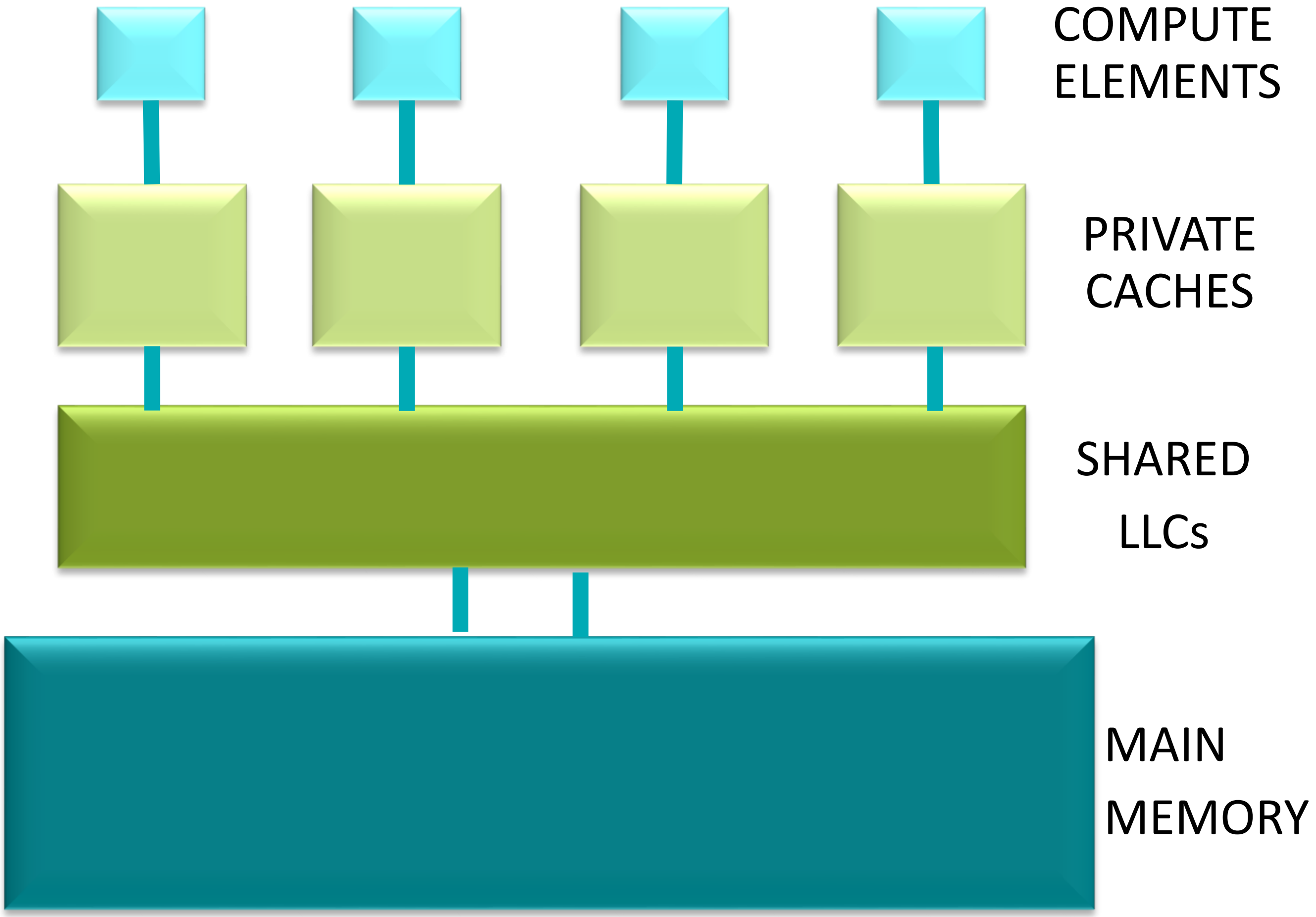

- Hash tables have poor temporal and spatial locality.

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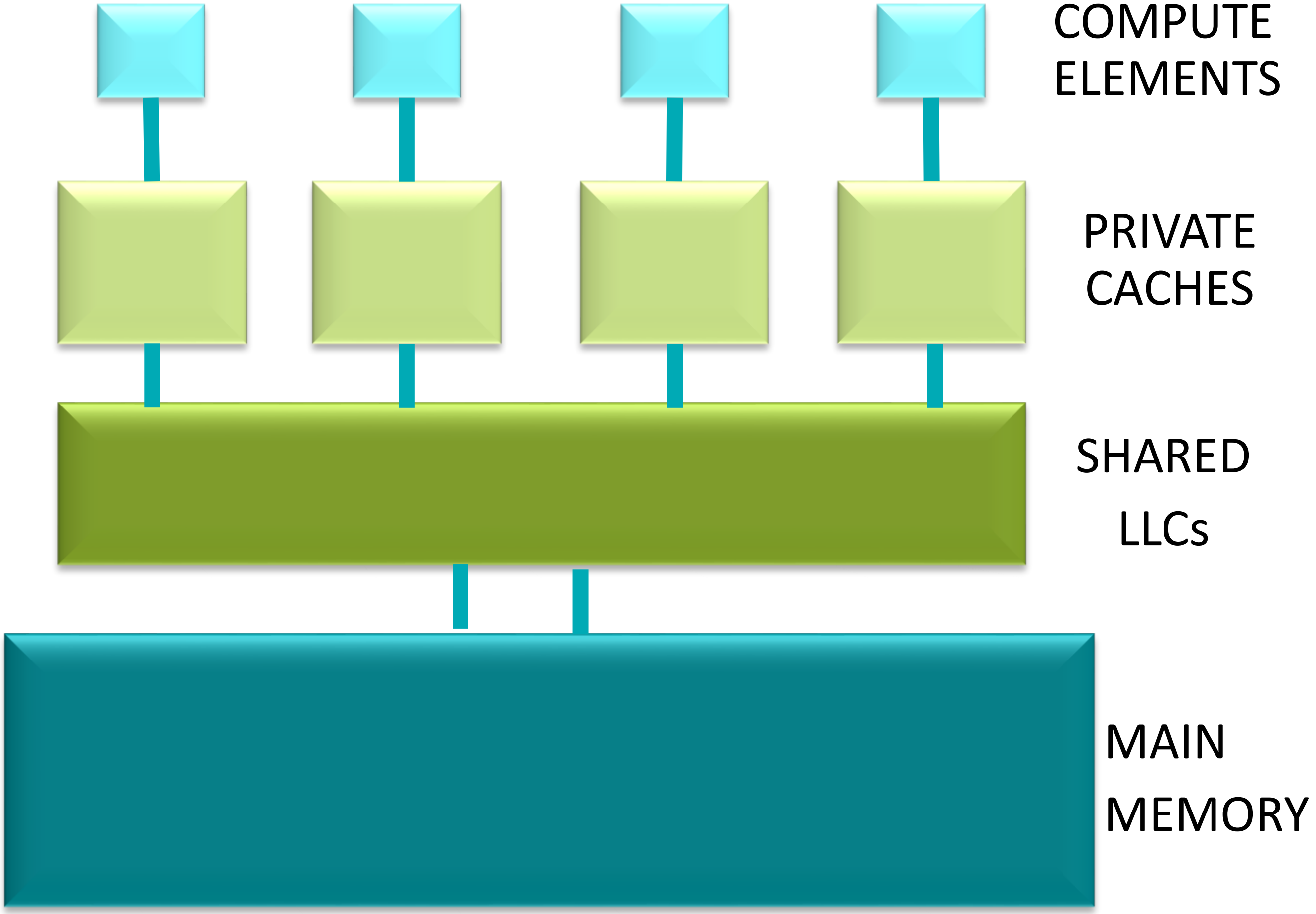

- Hash tables have poor temporal and spatial locality.
- In-memory hash tables often have hot working sets that are bigger than LLCs.

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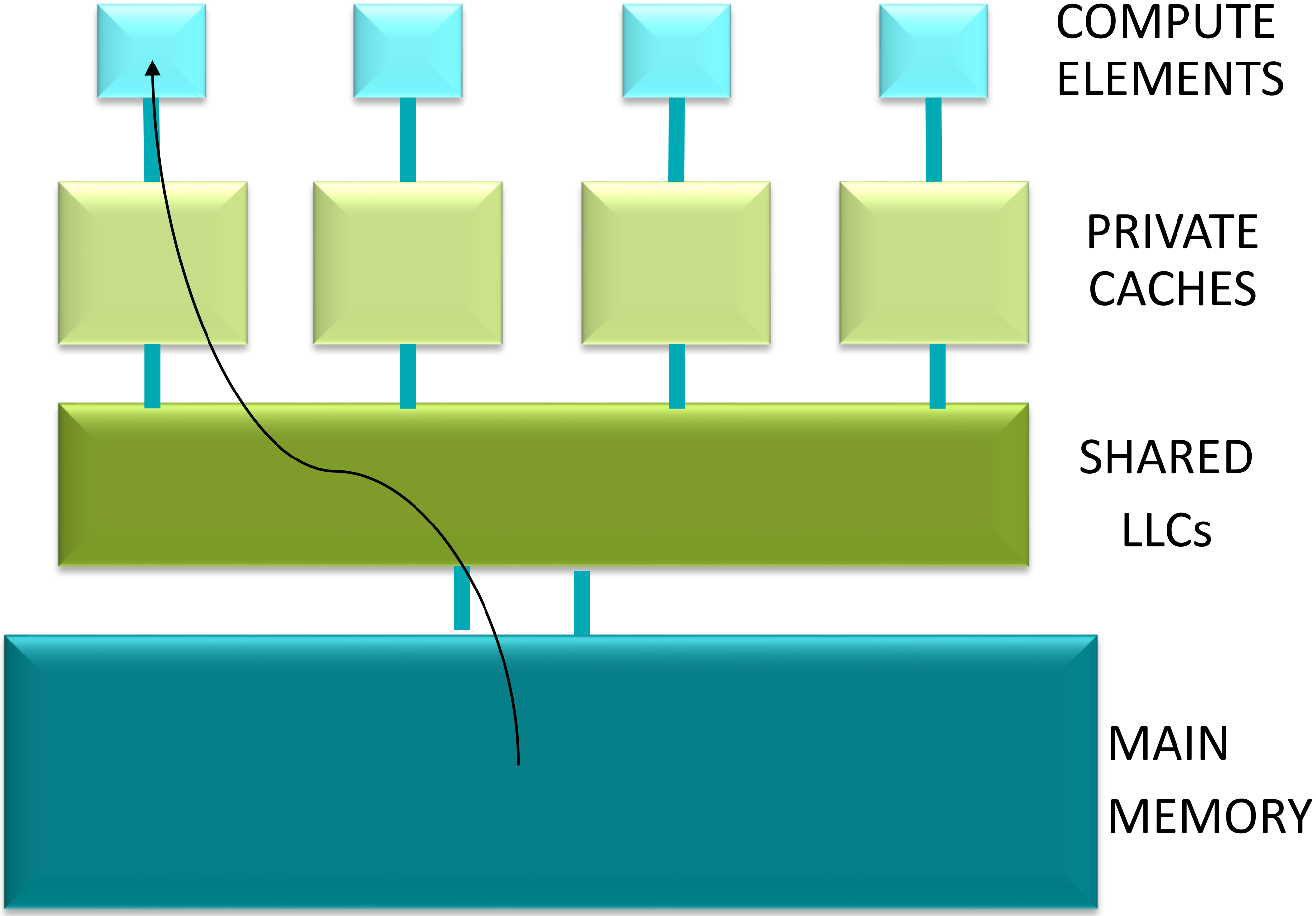

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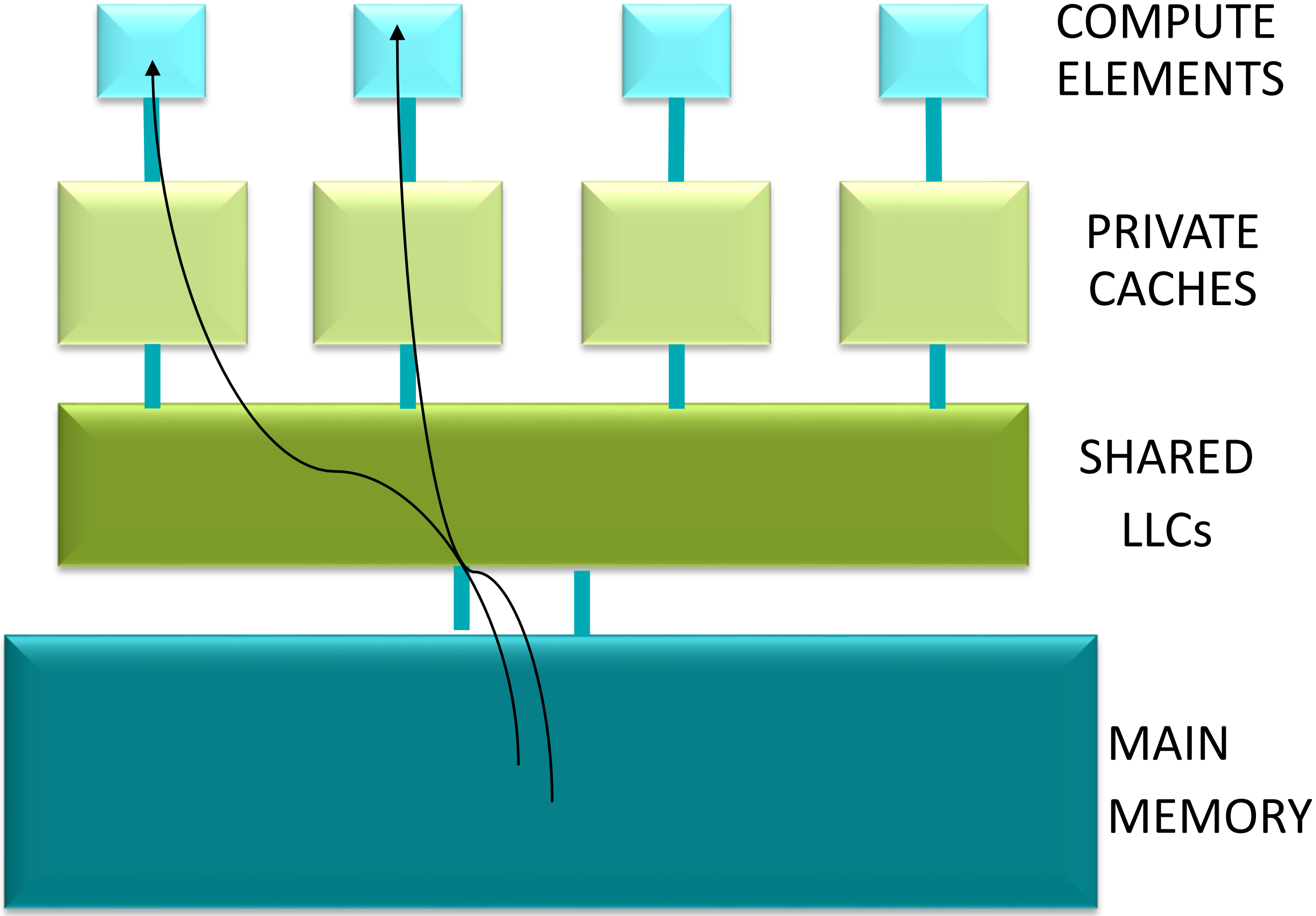

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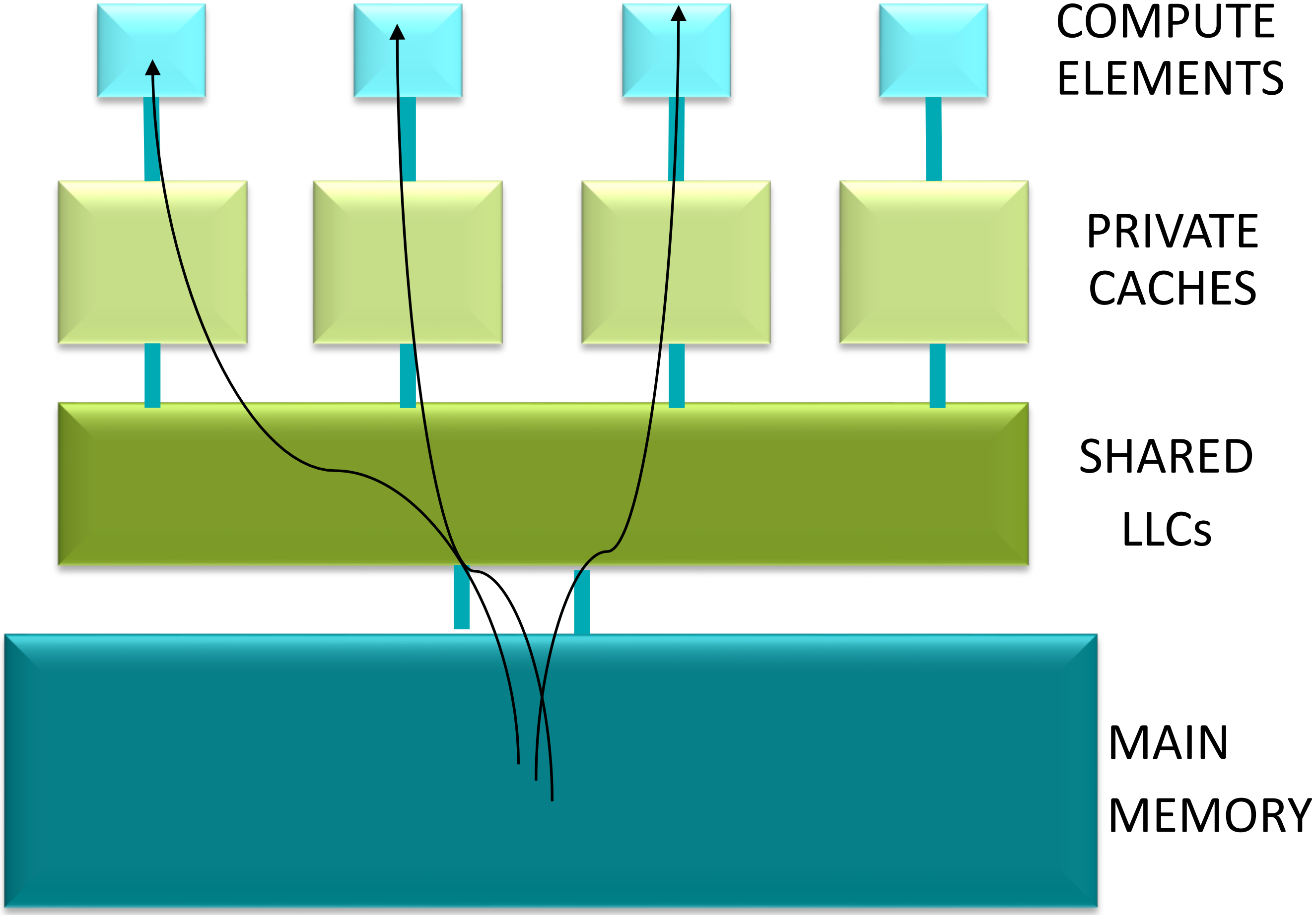

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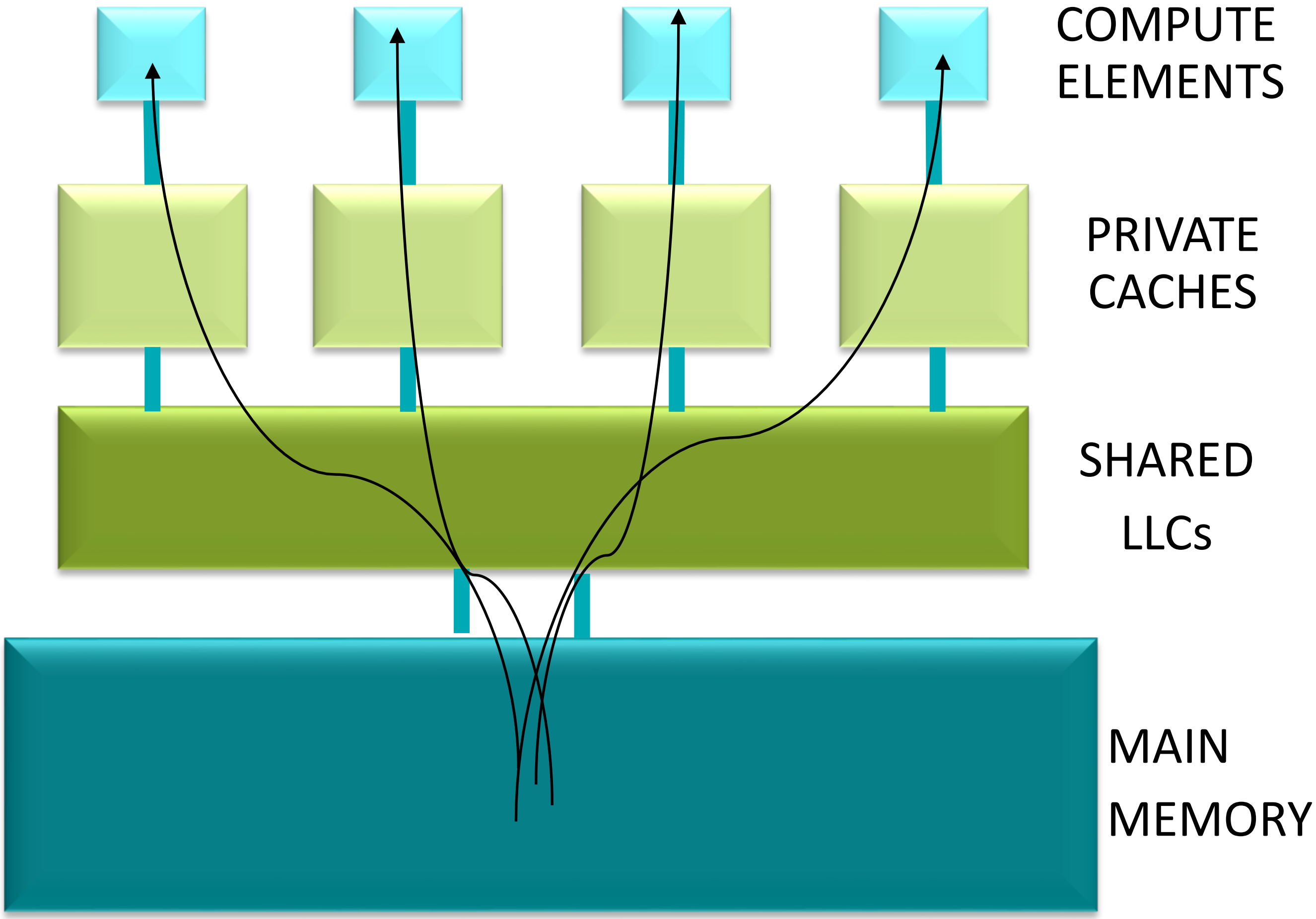

COMPUTE ELEMENTS

PRIVATE CACHES

SHARED LLCs

MAIN MEMORY

- Hash tables have poor temporal and spatial locality.
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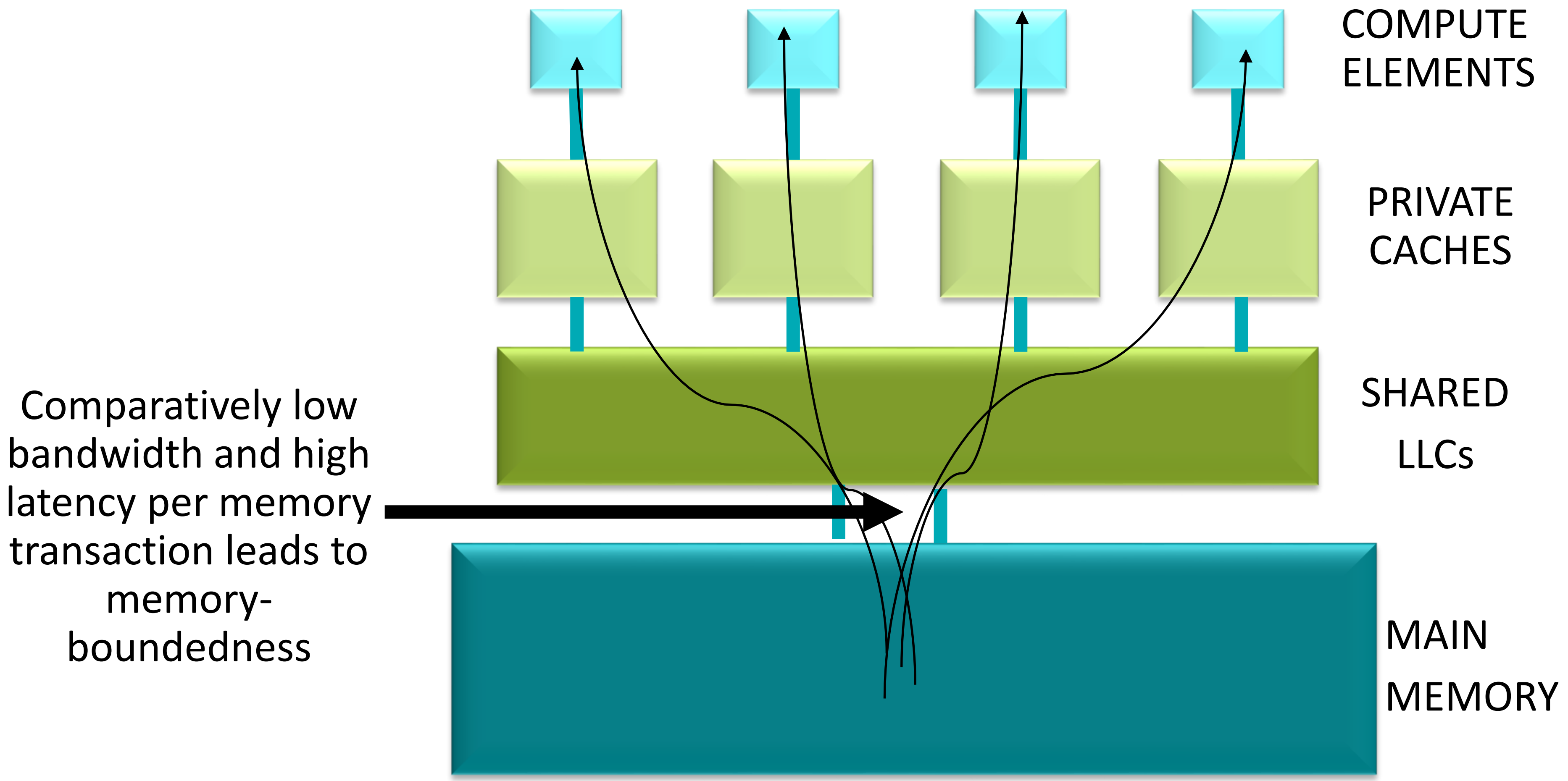

Comparatively low bandwidth and high latency per memory transaction leads to memory-boundedness

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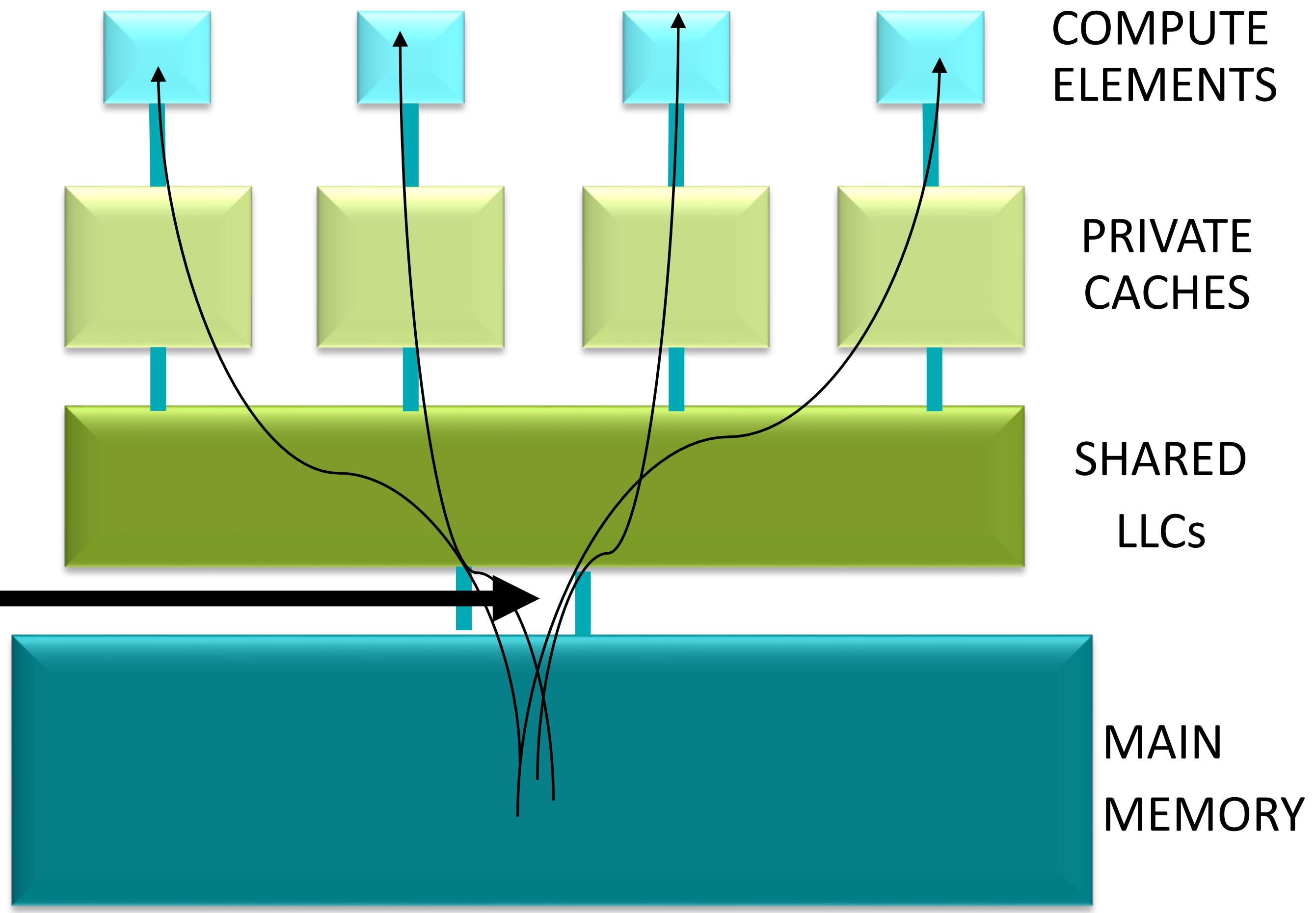
FOCUS OF THIS TALK

OPTIMIZING MEMORY ACCESSES IN FAST IN-MEMORY HASH TABLES

We need to aggressively optimize hash tables to be cognizant of this limitation

Comparatively low bandwidth and high latency per memory transaction leads to memory-boundedness

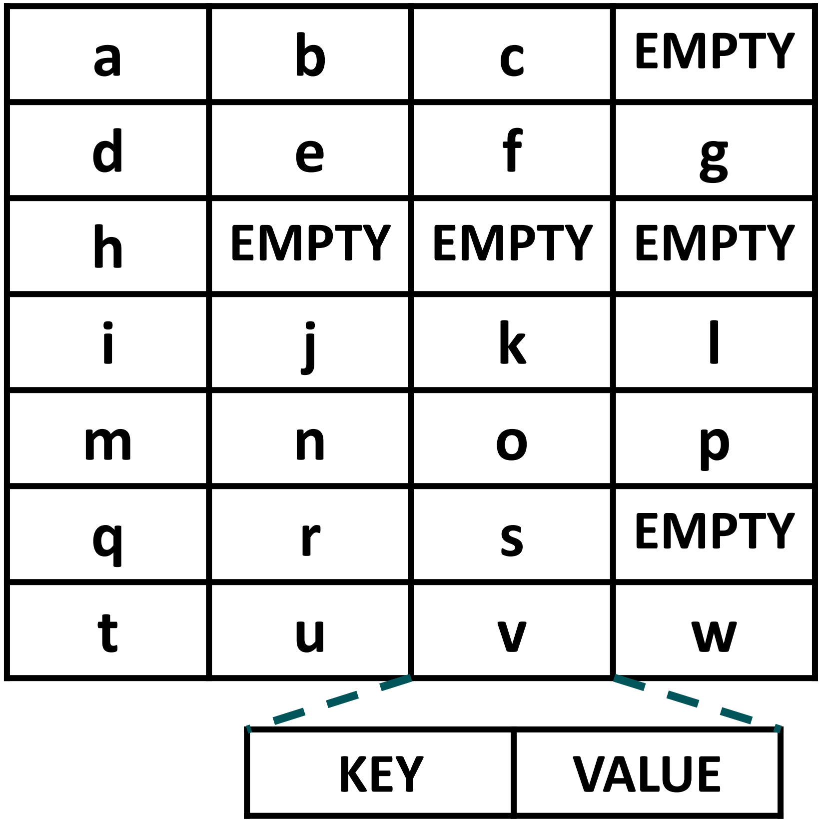


- Hash tables have poor temporal and spatial locality.
- In-memory hash tables often have hot working sets that are bigger than LLCs.

BUCKETIZED CUCKOO HASH TABLES

a	b	c	EMPTY
d	e	f	g
h	EMPTY	EMPTY	EMPTY
i	j	k	l
m	n	o	p
q	r	s	EMPTY
t	u	v	w

BUCKETIZED CUCKOO HASH TABLES



a	b	c	EMPTY
d	e	f	g
h	EMPTY	EMPTY	EMPTY
i	j	k	l
m	n	o	p
q	r	s	EMPTY
t	u	v	w

KEY	VALUE

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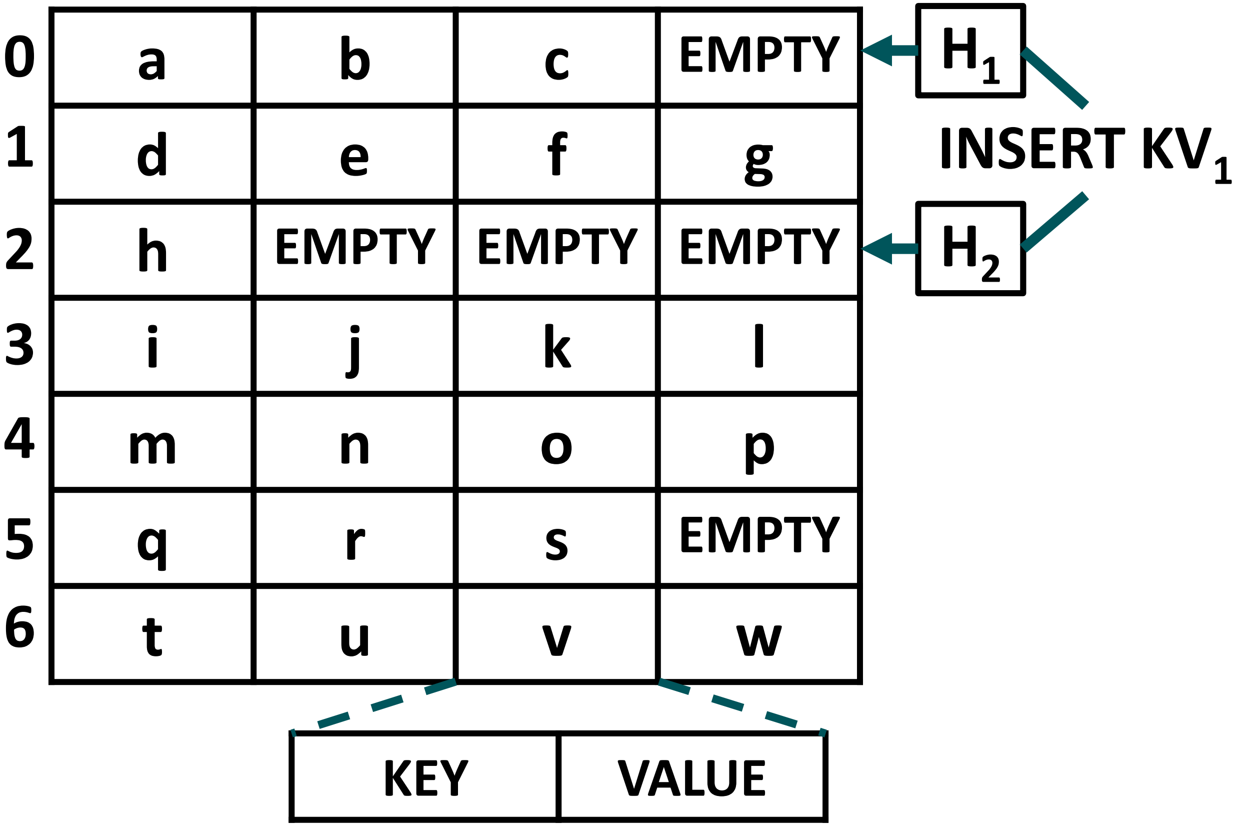

0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

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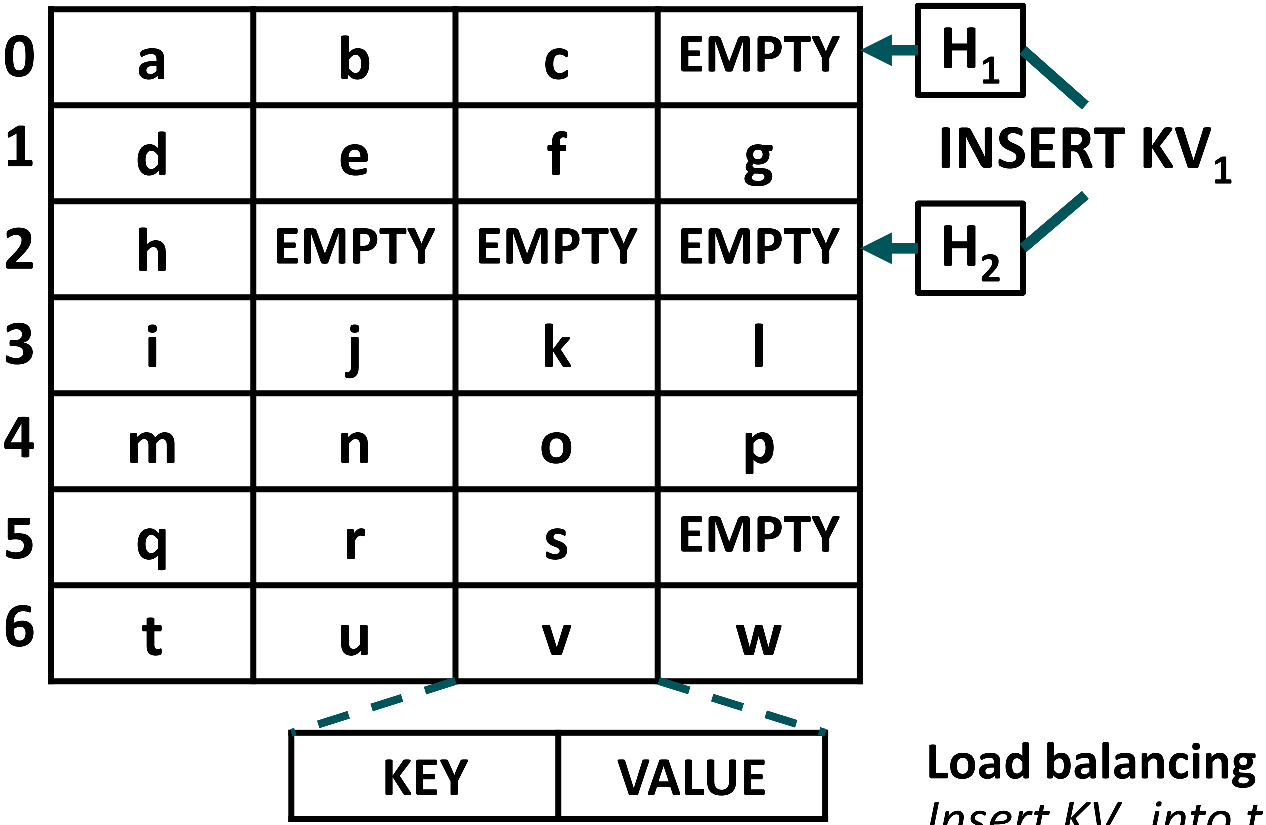

0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

Load balancing

Insert KV_1 into the least full candidate bucket

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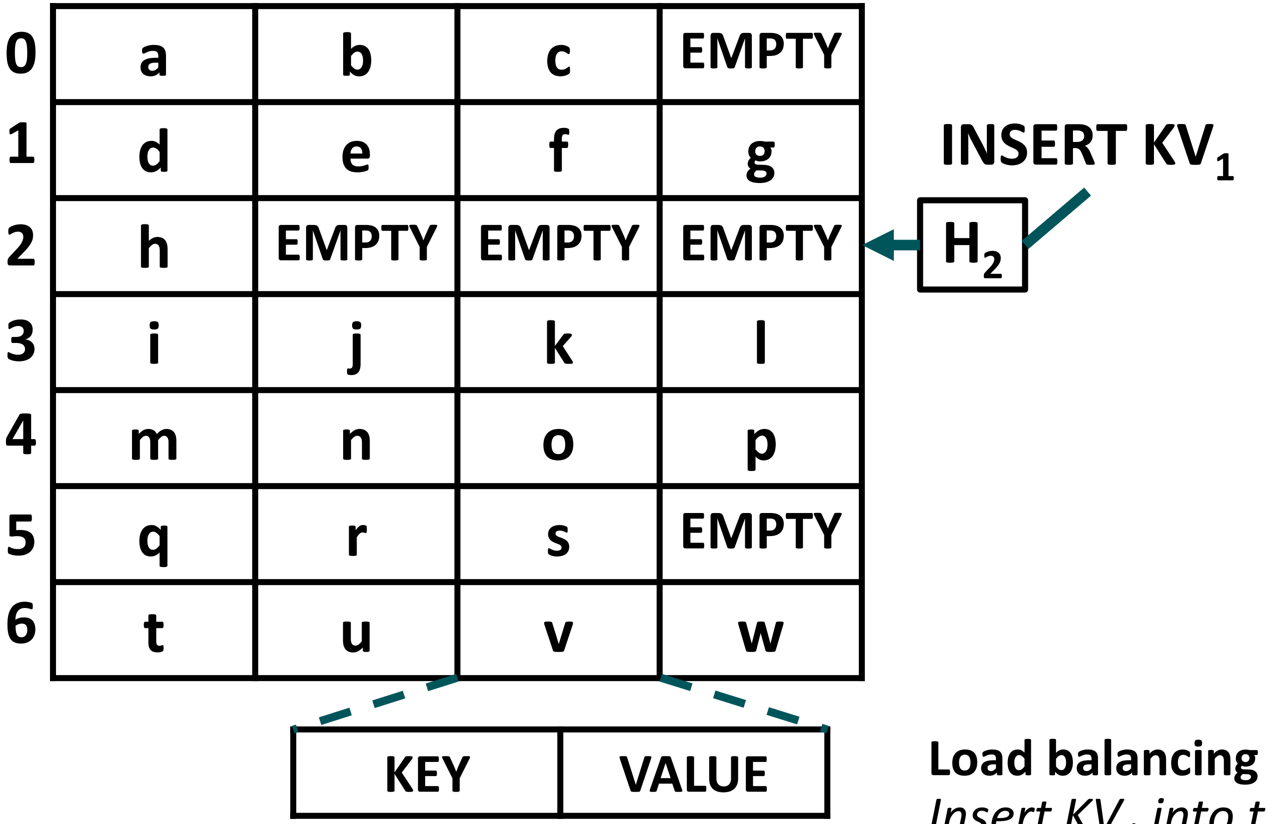

0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

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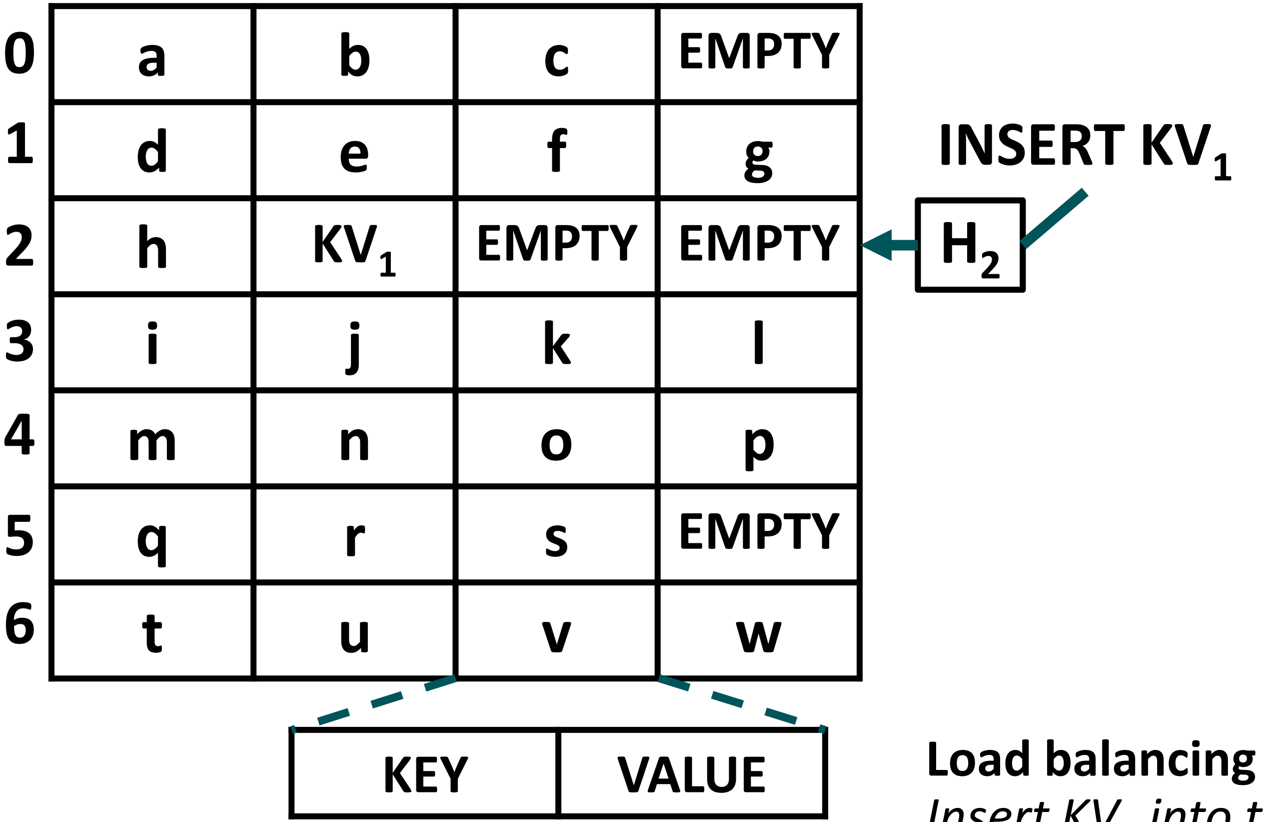

0	a	b	c	EMPTY
1	d	e	f	g
2	h	KV_1	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

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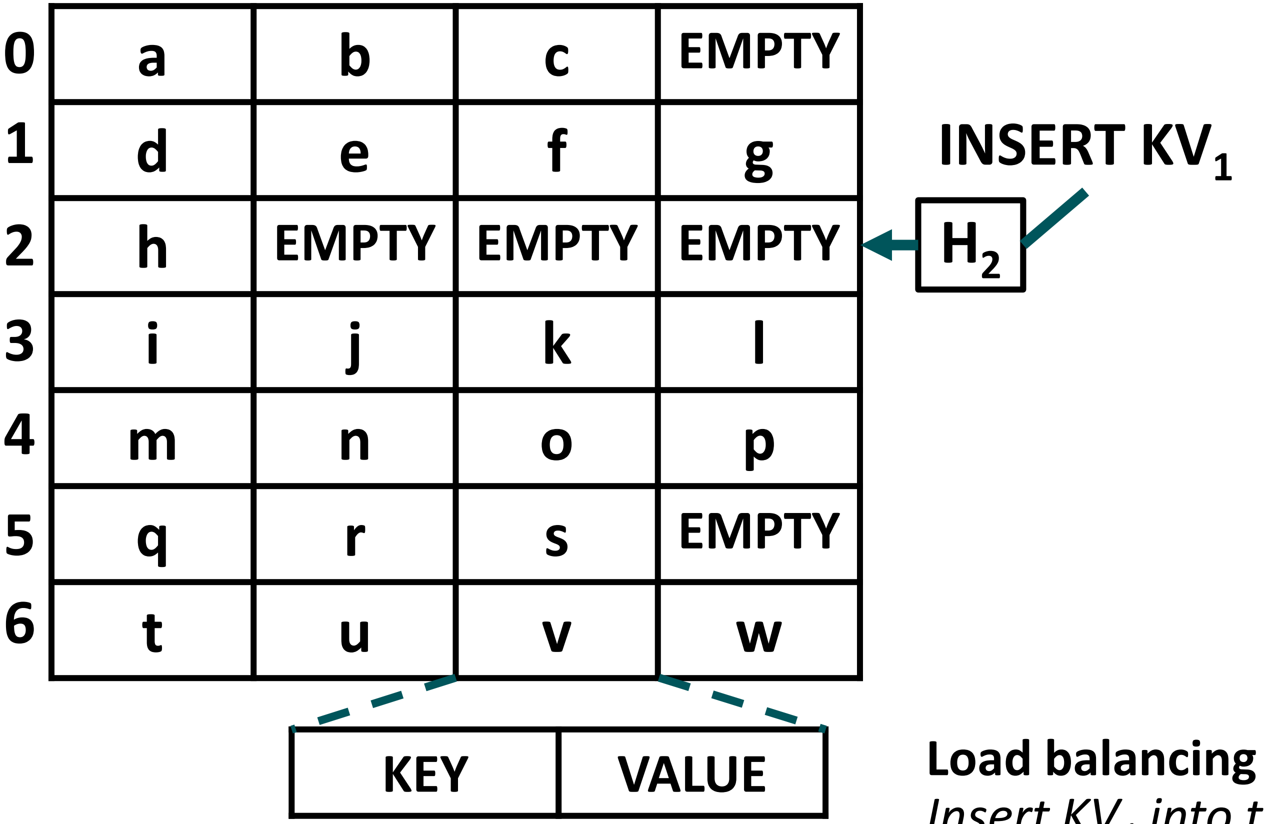

0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

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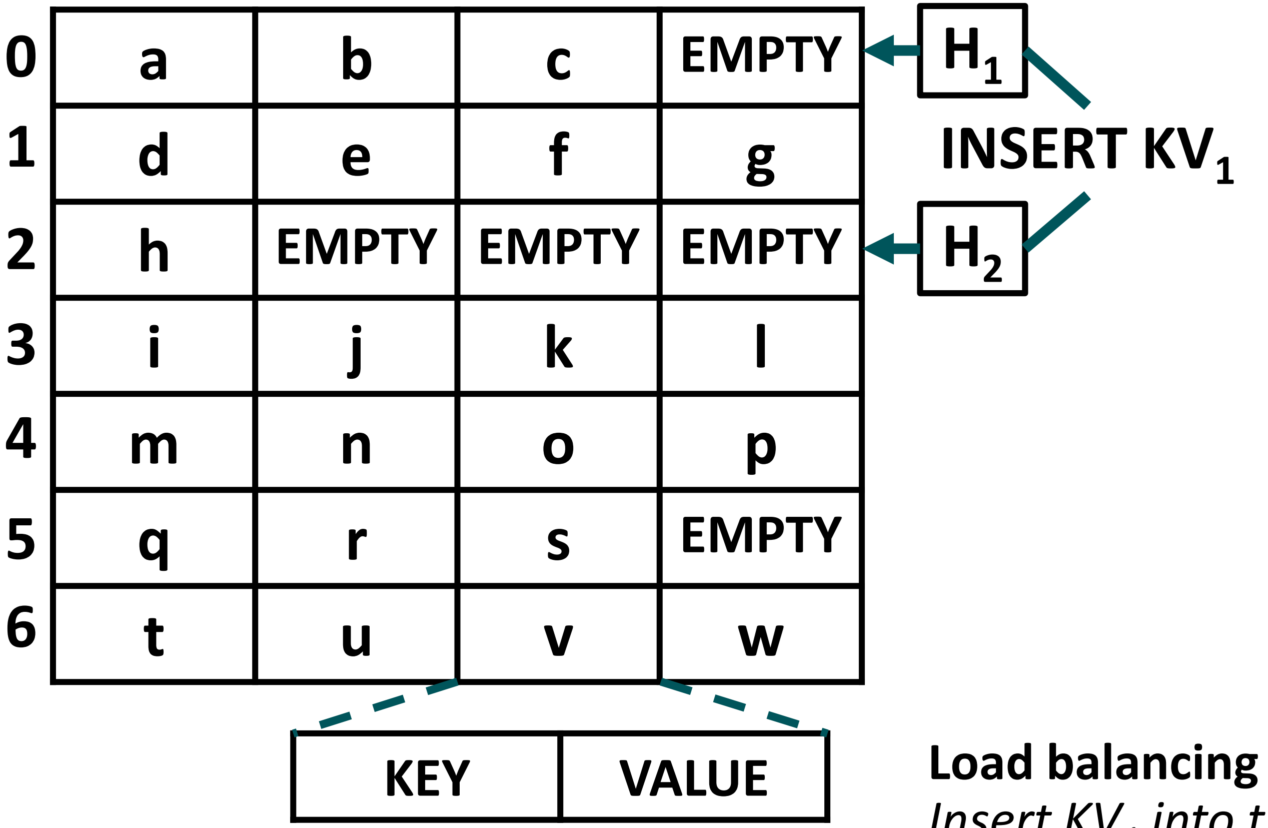

0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

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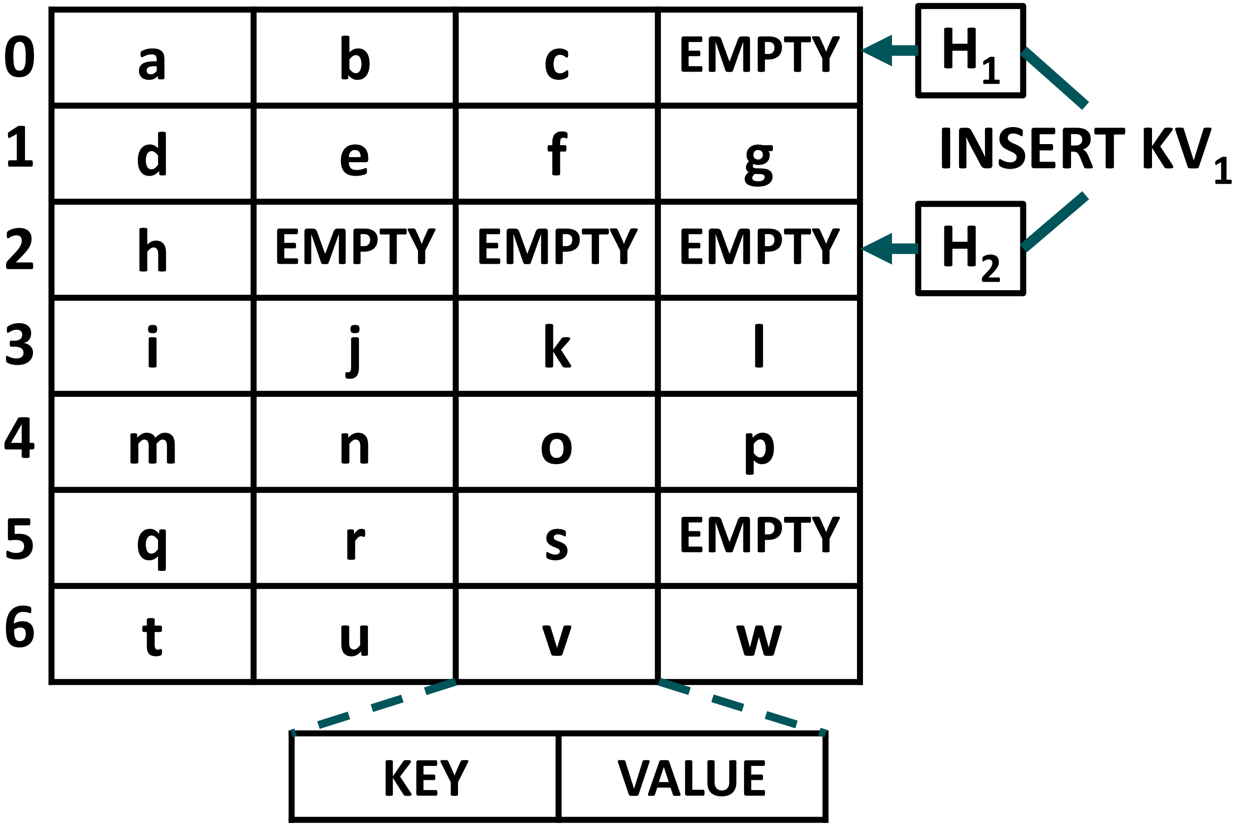

0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

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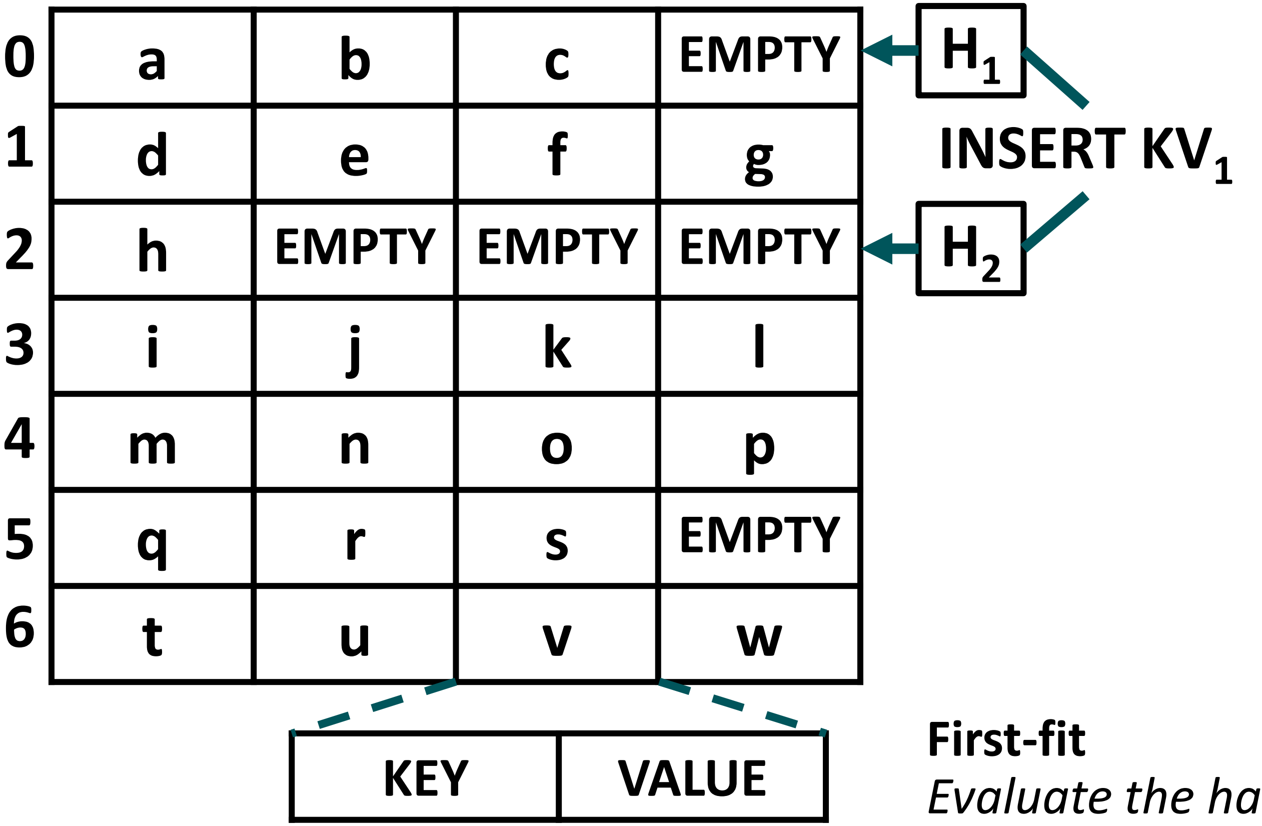

0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

First-fit

Evaluate the hash functions in numerical order and insert KV_1 into the first candidate bucket with a free slot

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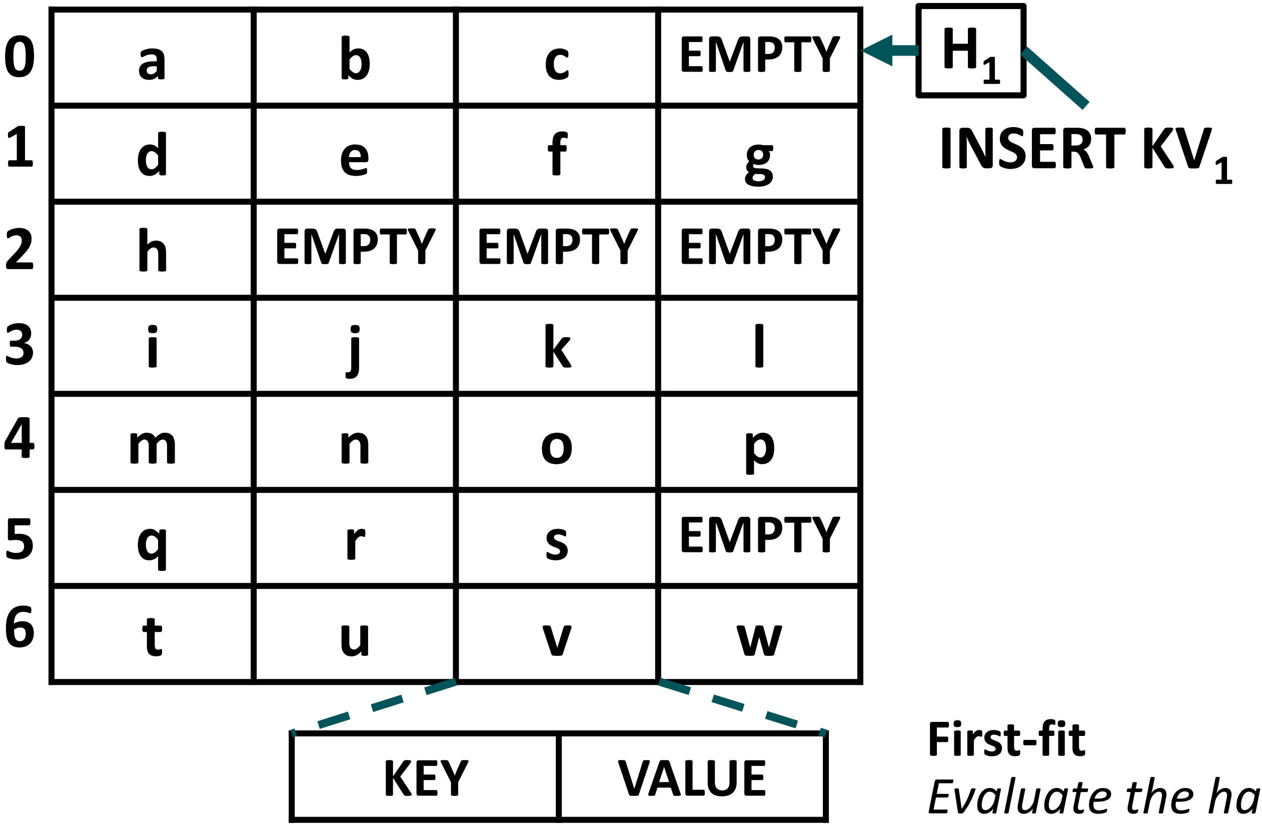


0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

KEY	VALUE

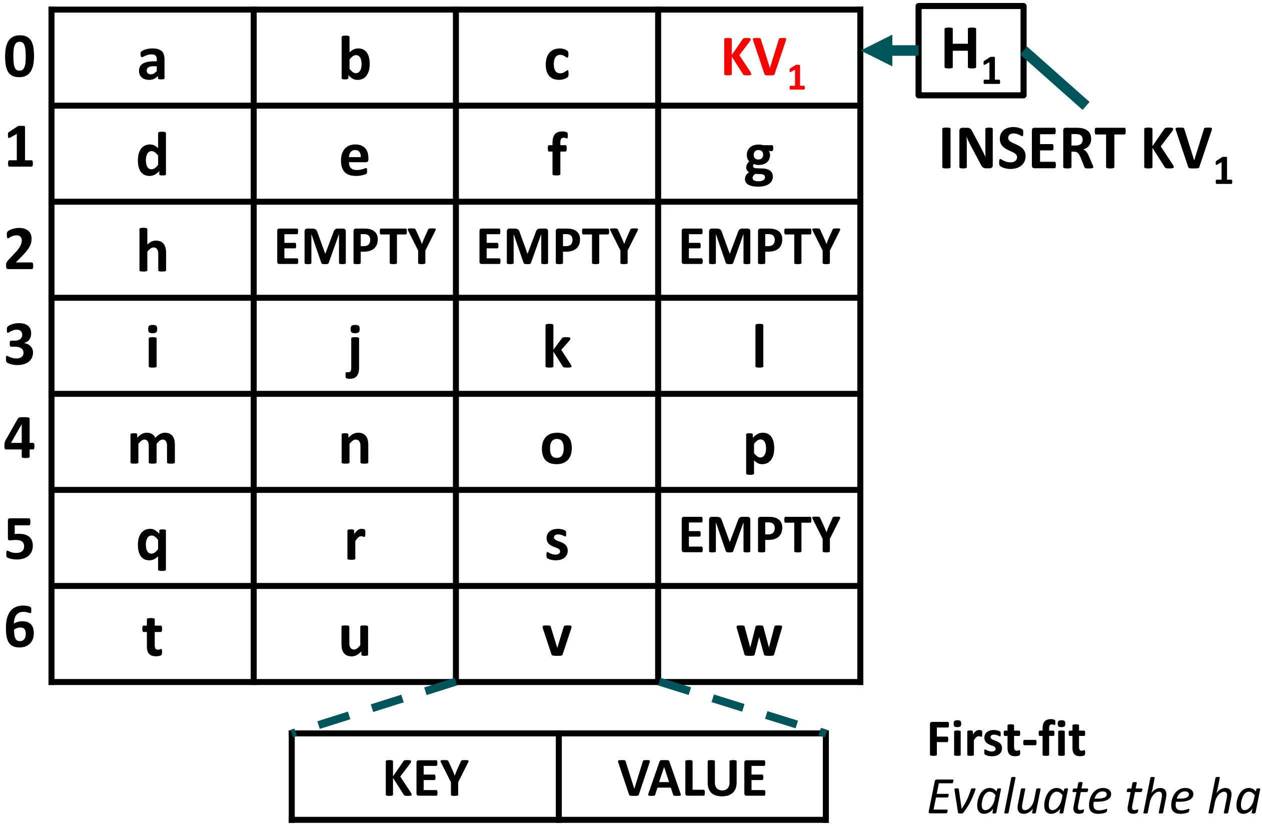
H_1

INSERT KV_1

First-fit

Evaluate the hash functions in numerical order and insert KV_1 into the first candidate bucket with a free slot

BUCKETIZED CUCKOO HASH TABLES



0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

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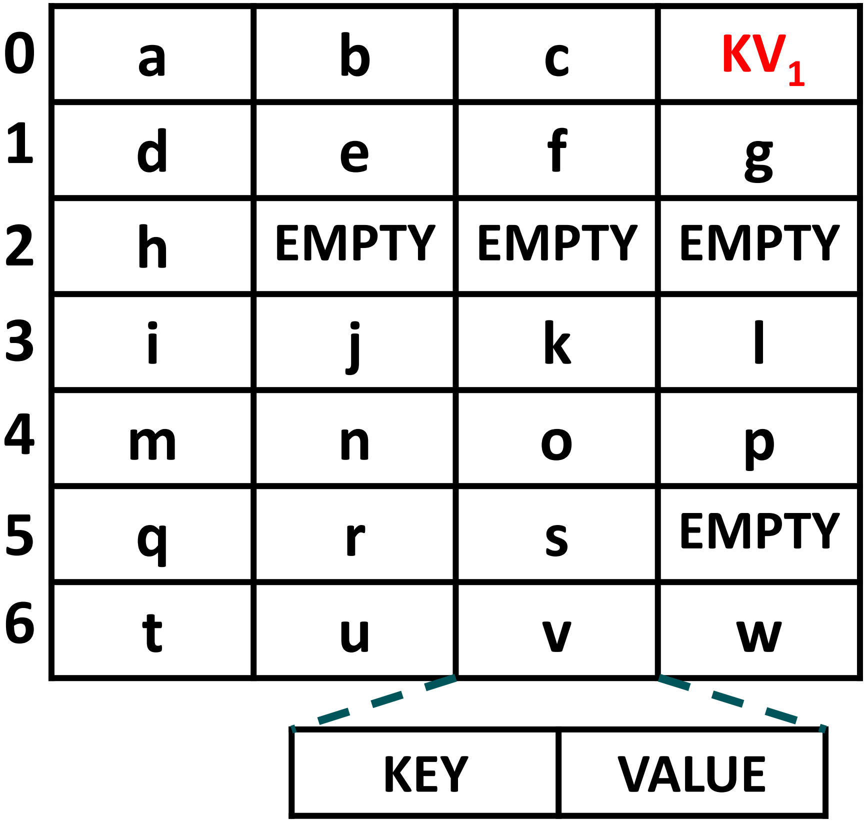

0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

KEY	VALUE

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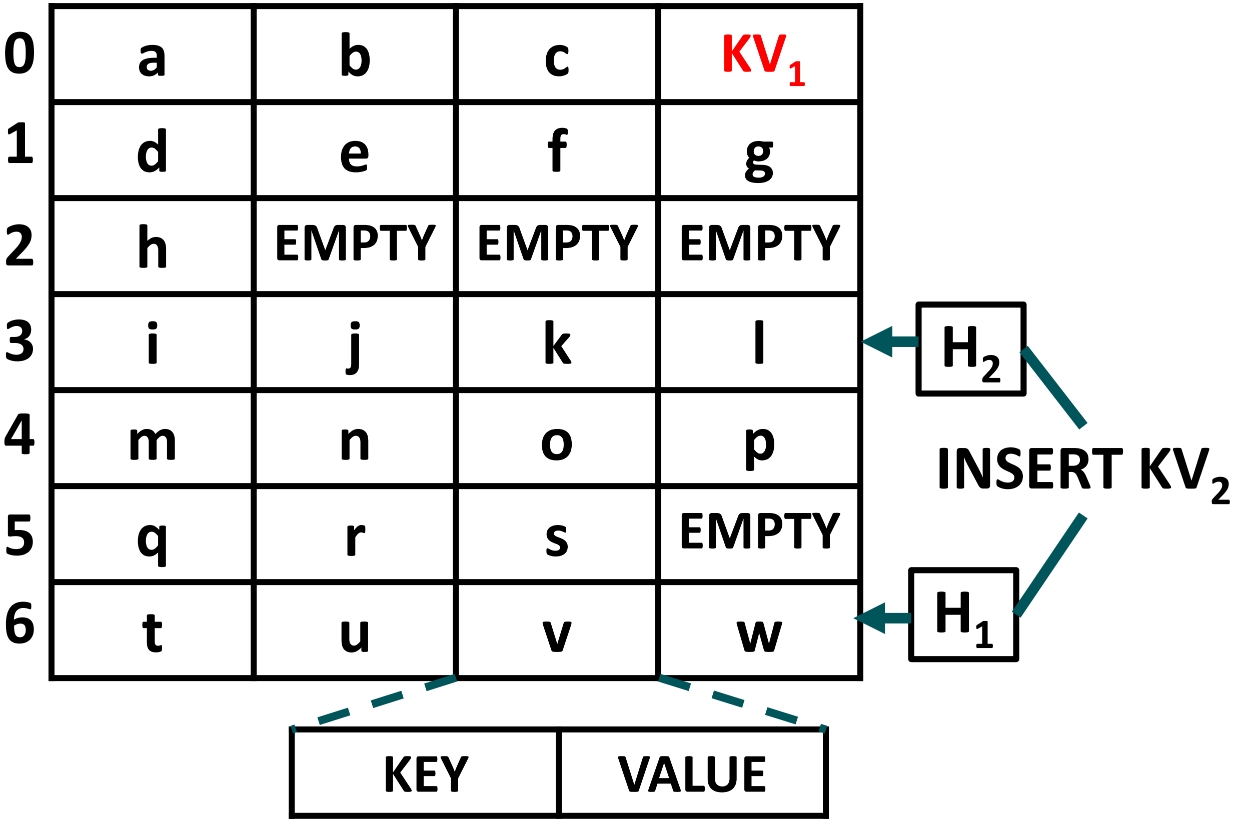

0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

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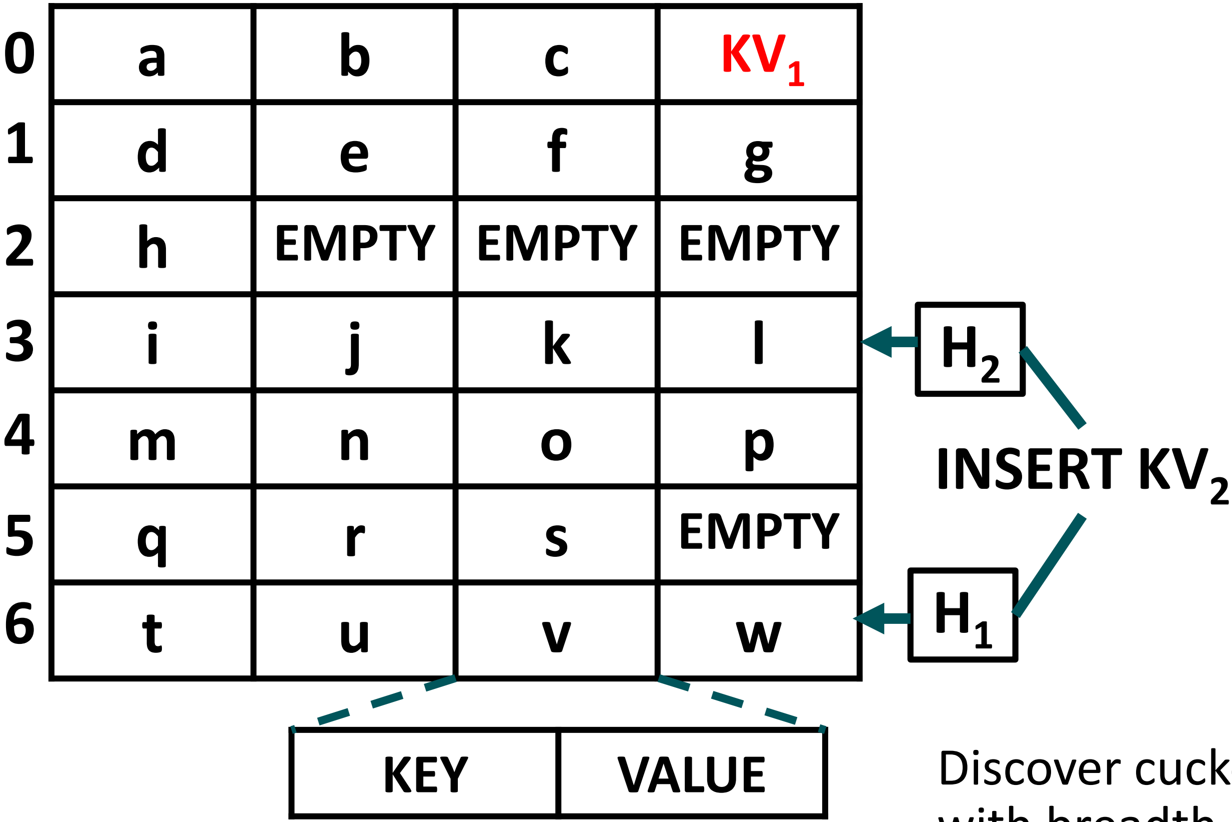
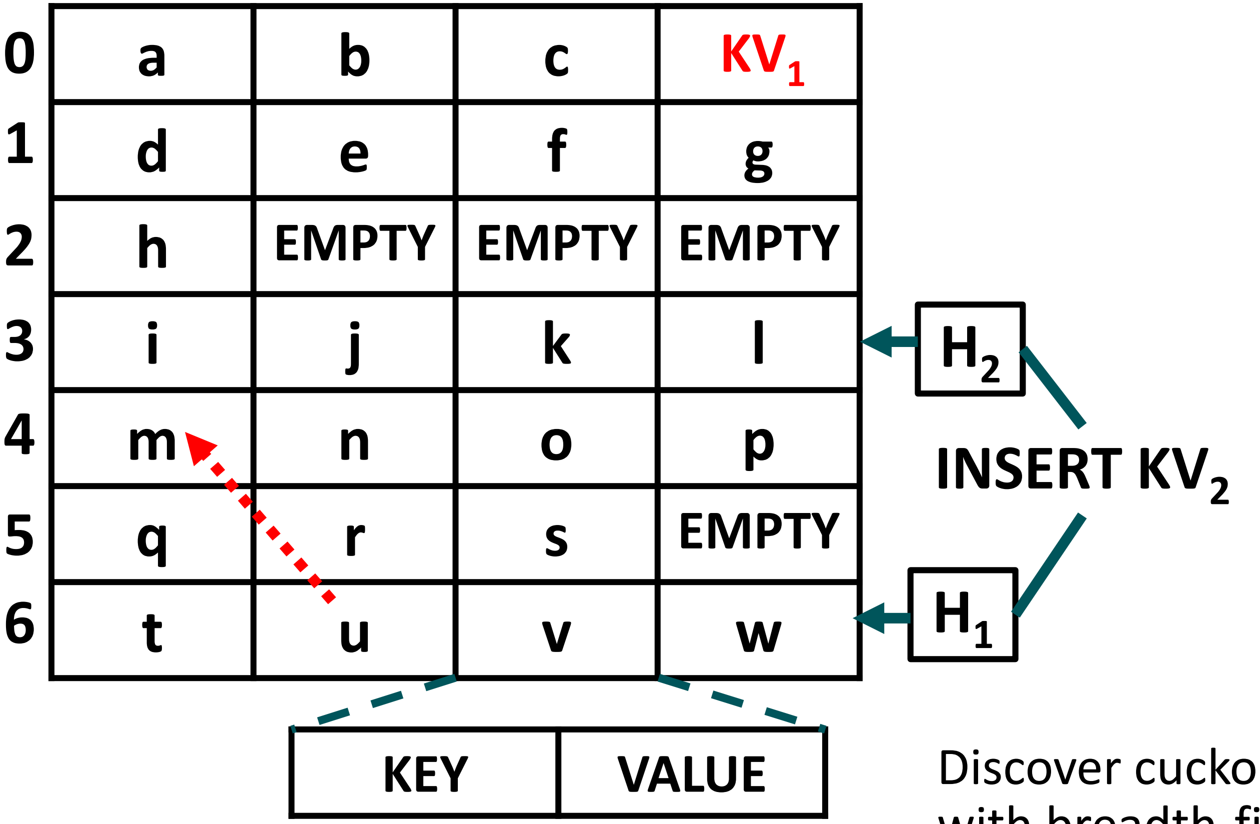


0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

KEY	VALUE

Discover cuckoo chain
with breadth-first search

BUCKETIZED CUCKOO HASH TABLES



0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

KEY	VALUE

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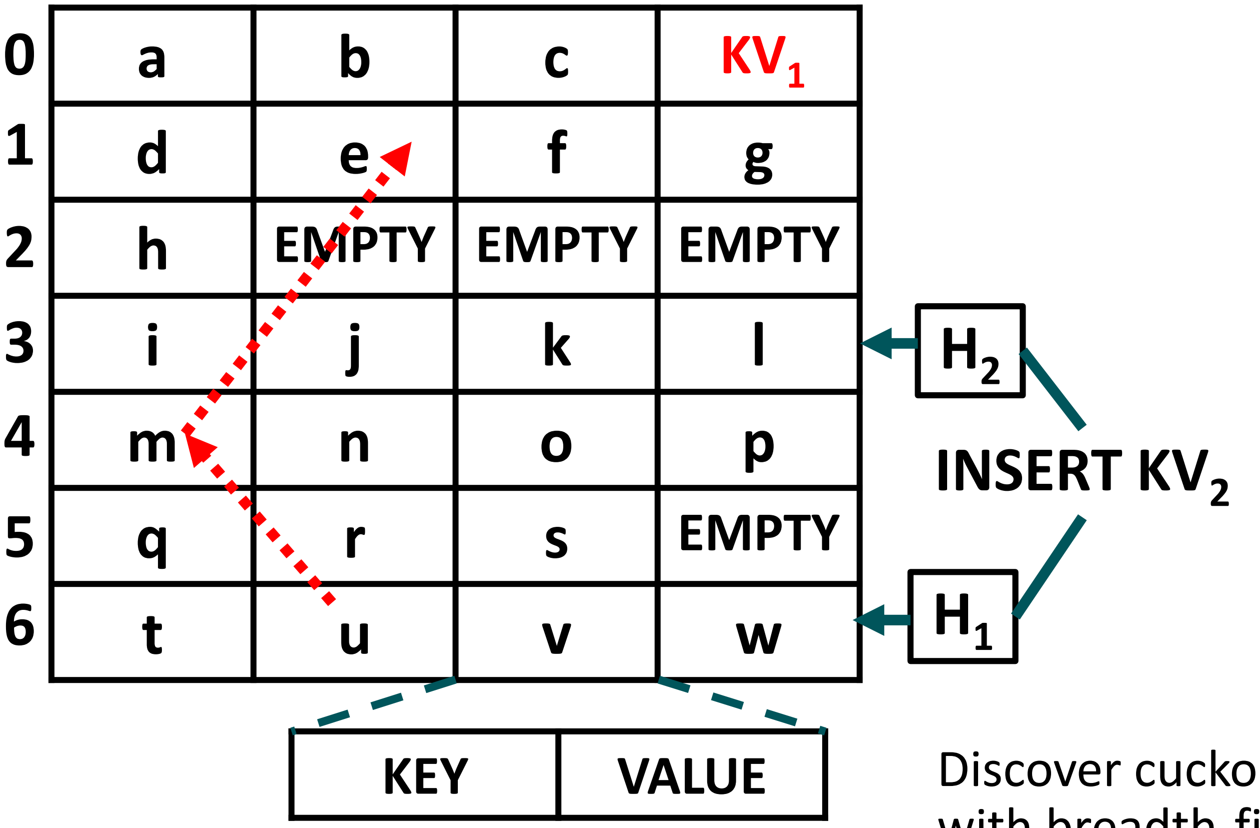

0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

KEY	VALUE

Discover cuckoo chain
with breadth-first search

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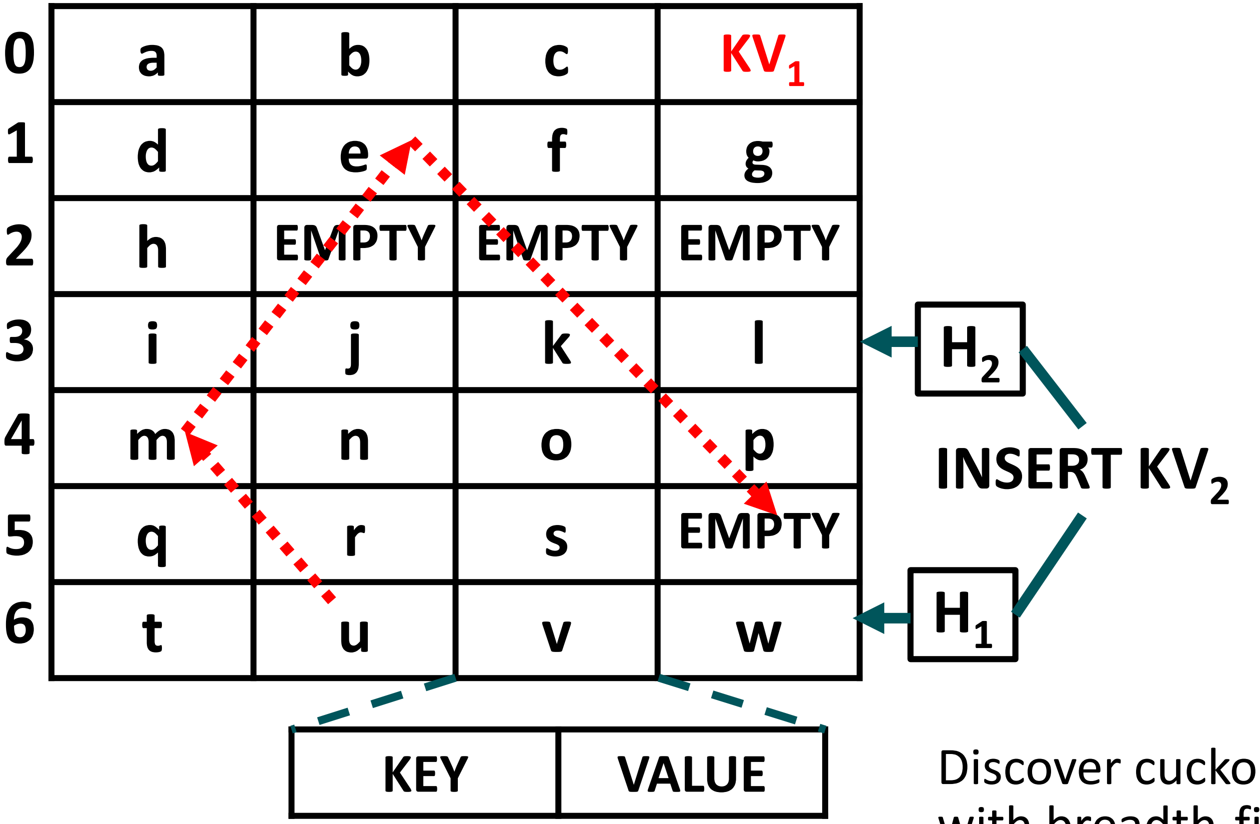

0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

Discover cuckoo chain with breadth-first search

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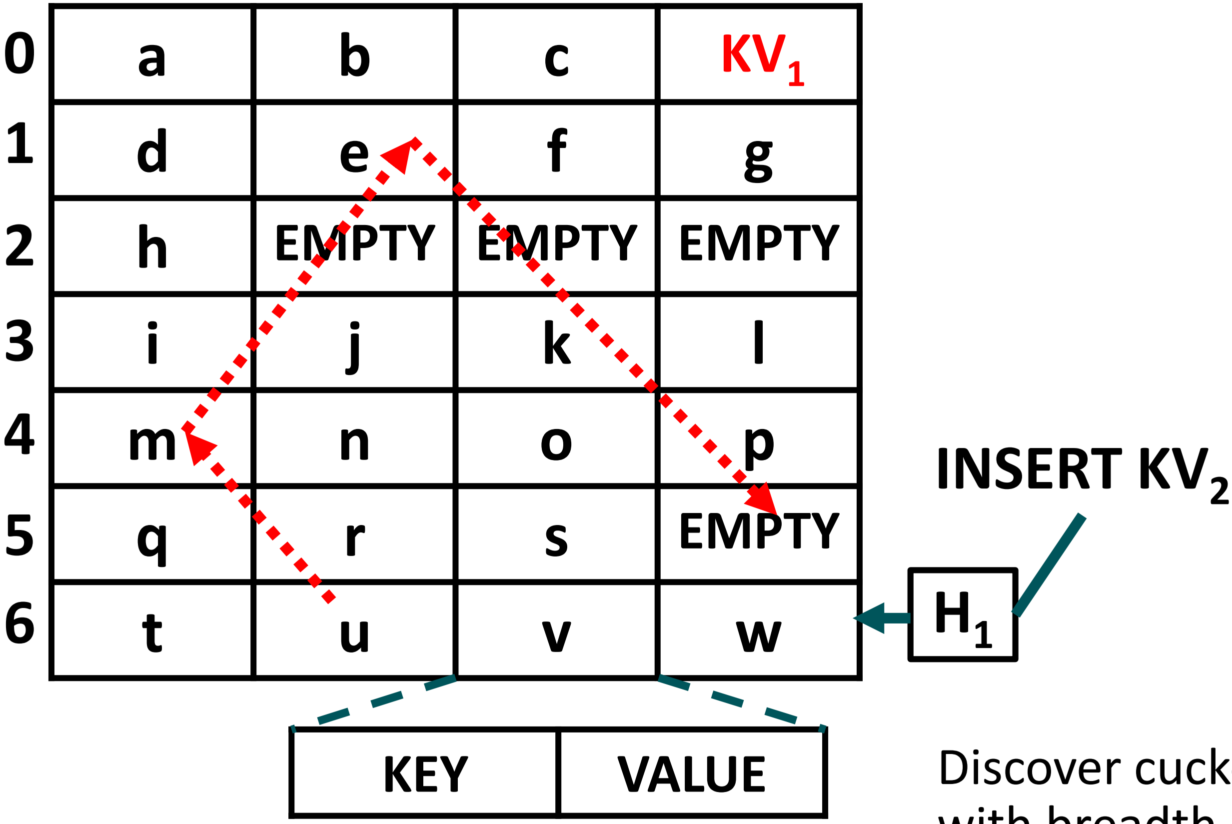


0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

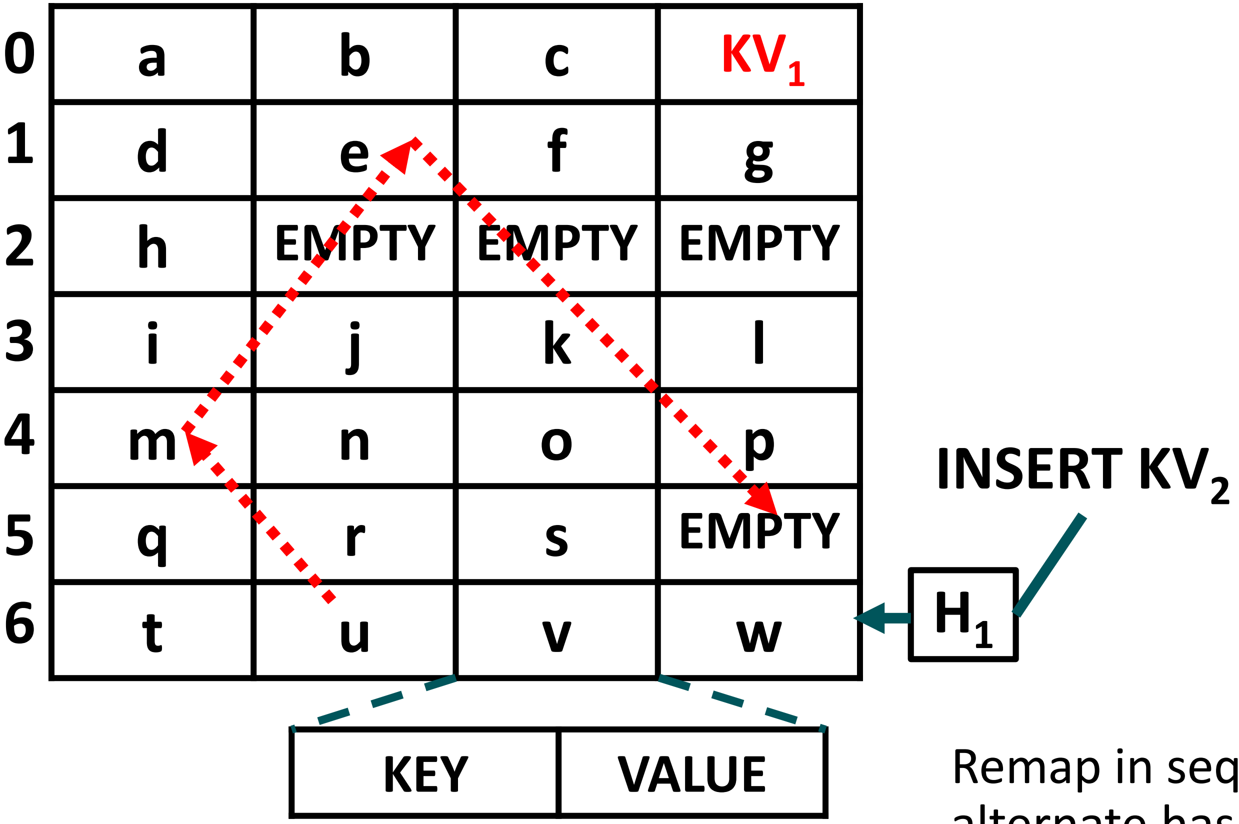
INSERT KV_2

H_1

KEY	VALUE

Discover cuckoo chain with breadth-first search

BUCKETIZED CUCKOO HASH TABLES



0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

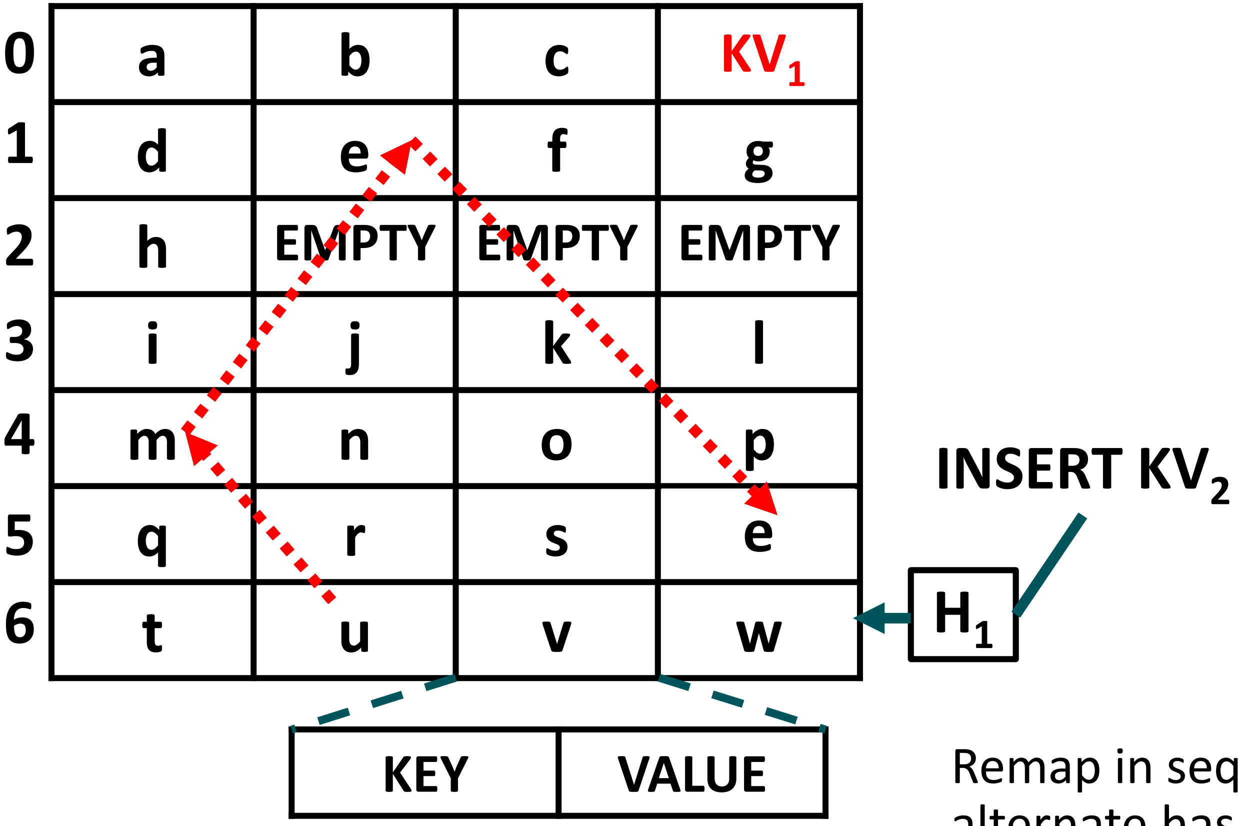
KEY	VALUE

INSERT KV_2

H_1

Remap in sequence with alternate hash function

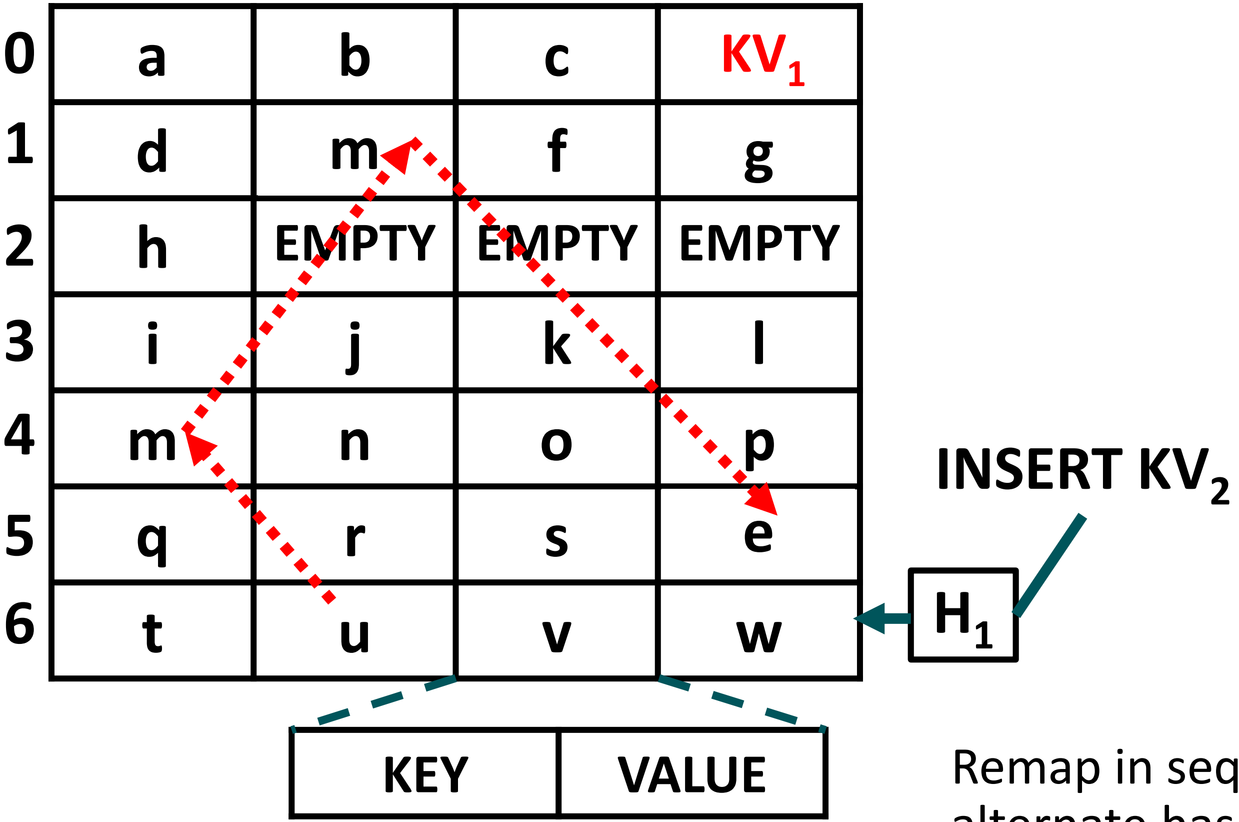
BUCKETIZED CUCKOO HASH TABLES



0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	e
6	t	u	v	w

Remap in sequence with alternate hash function

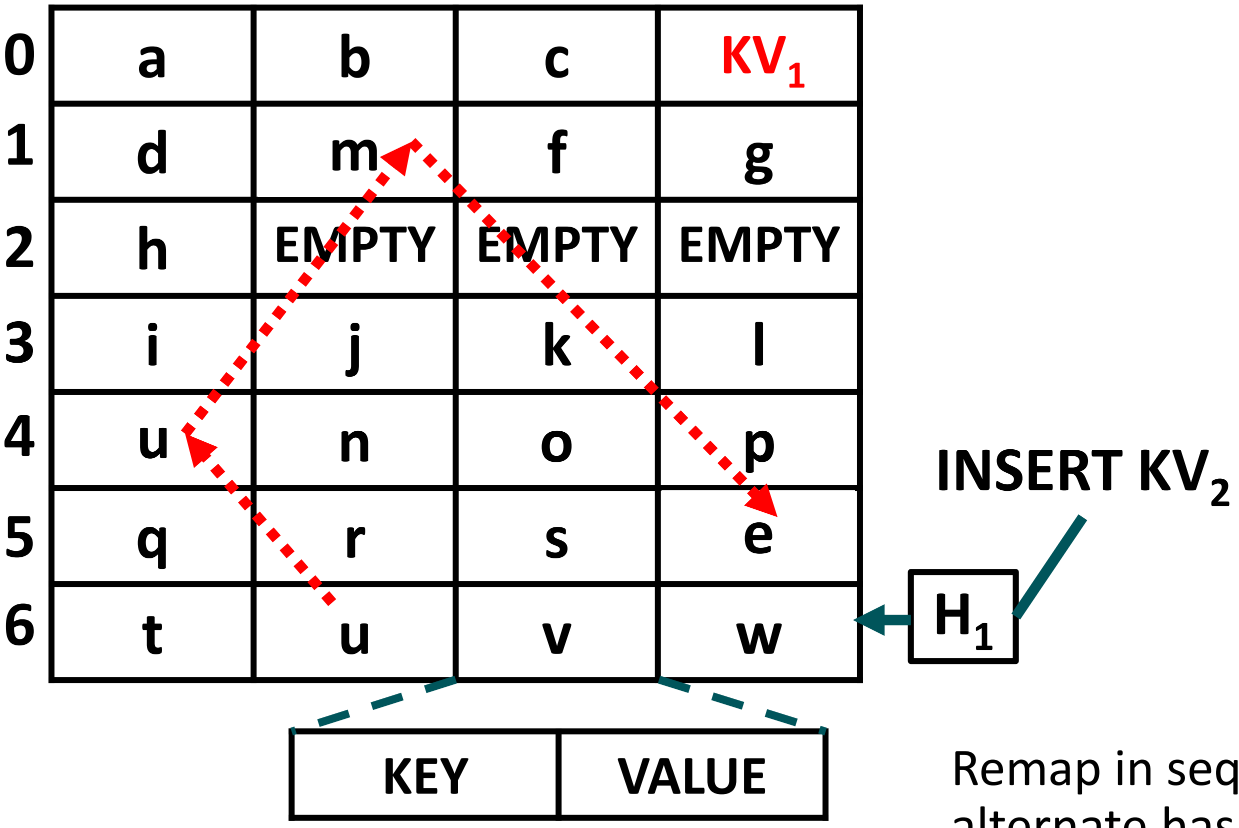
BUCKETIZED CUCKOO HASH TABLES



0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	e
6	t	u	v	w

Remap in sequence with alternate hash function

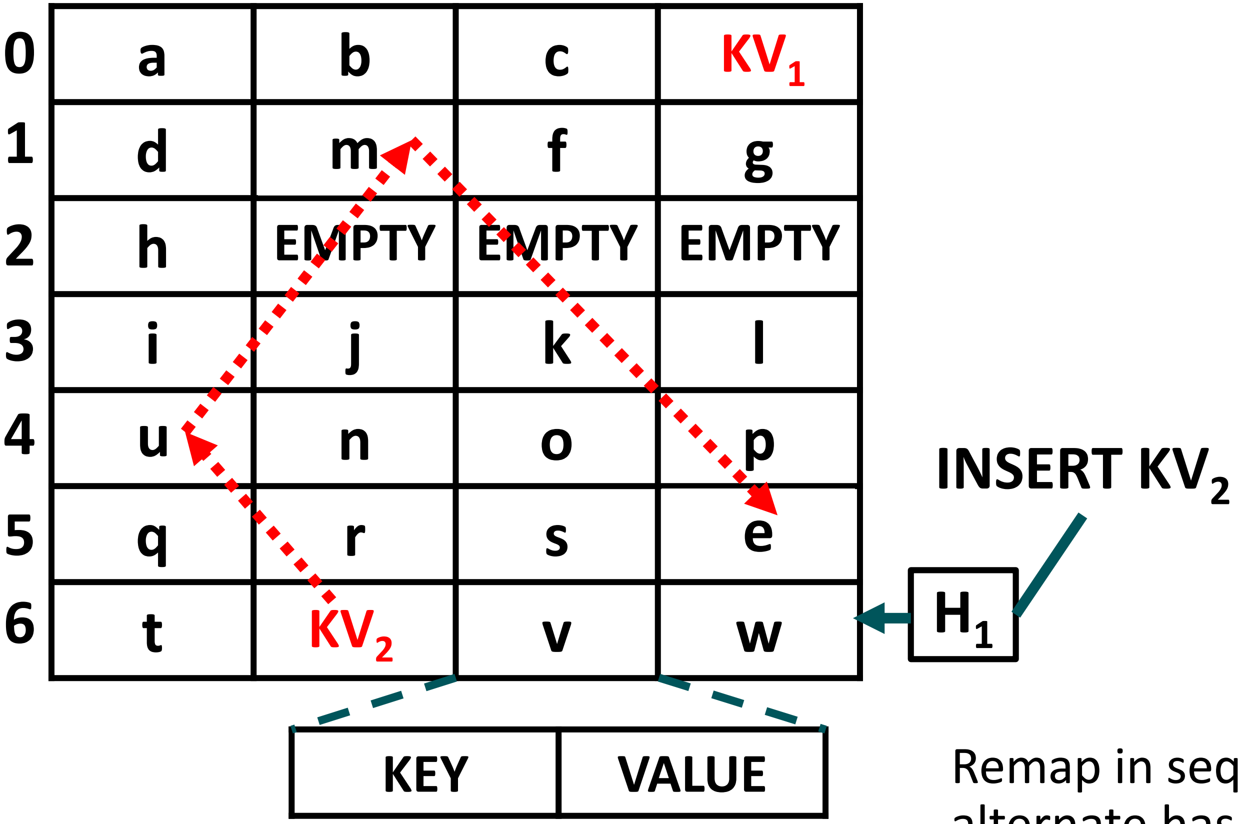
BUCKETIZED CUCKOO HASH TABLES



0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	u	v	w

Remap in sequence with alternate hash function

BUCKETIZED CUCKOO HASH TABLES



0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

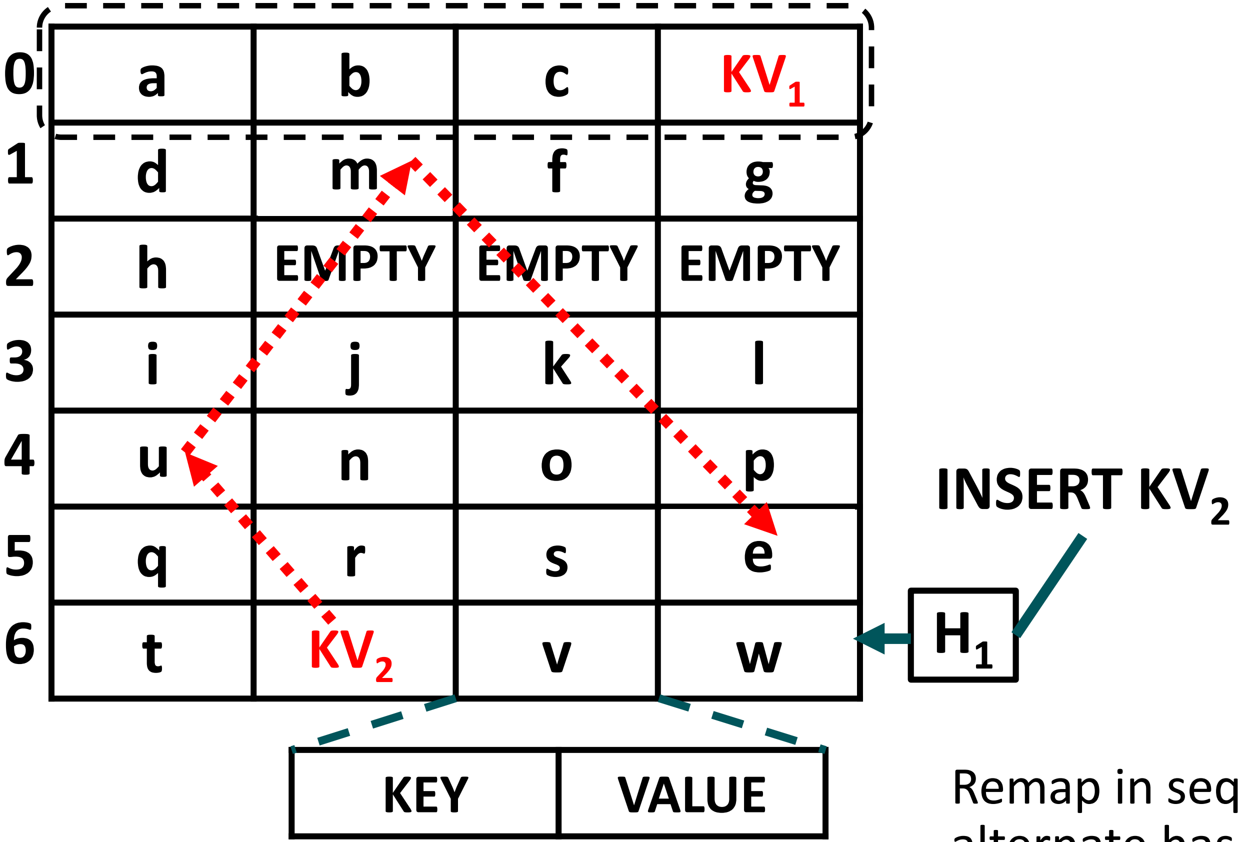
INSERT KV_2

H_1

KEY	VALUE

Remap in sequence with alternate hash function

BUCKETIZED CUCKOO HASH TABLES



0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

KEY	VALUE

INSERT KV_2

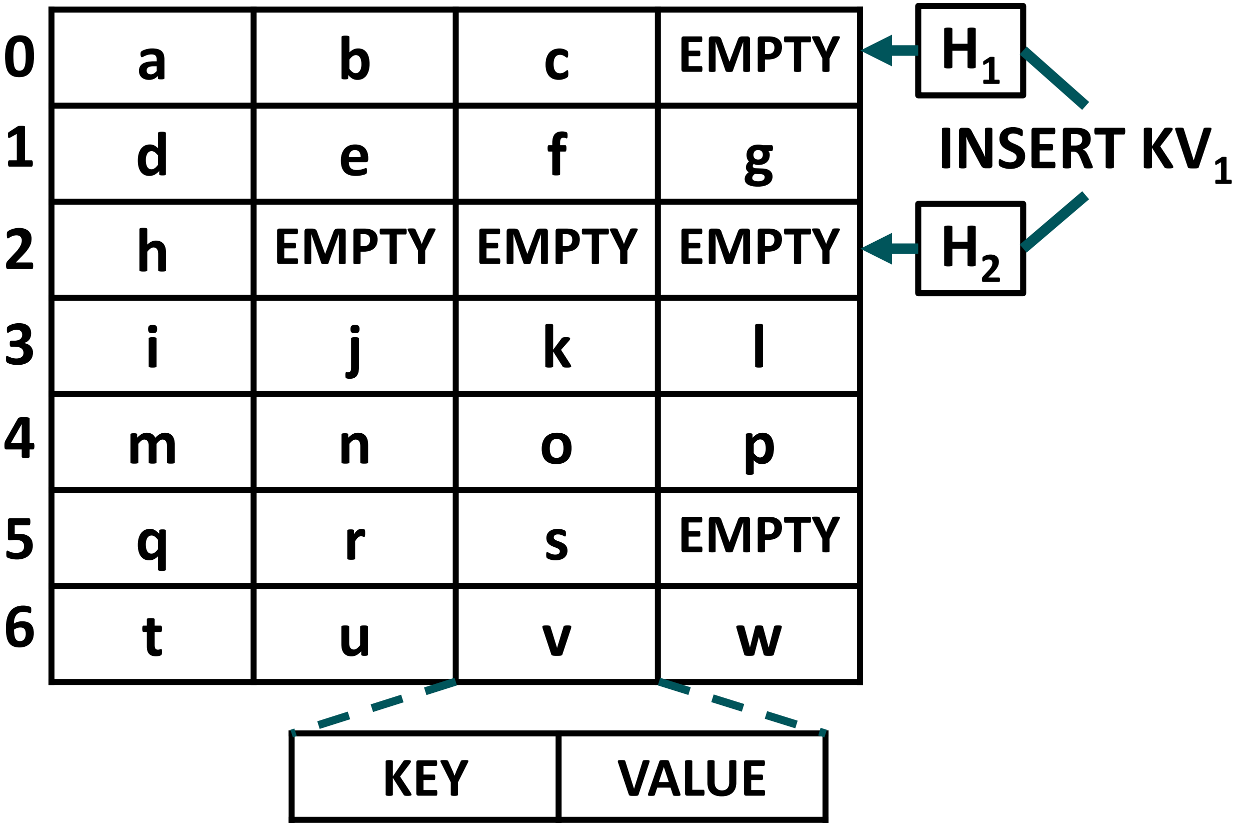
H_1

Remap in sequence with alternate hash function

- Each bucket is typically sized to one hardware cache line or less.
- Overwhelmingly, accesses to the bucket’s cache line hit in the hardware caches during accesses to consecutive cells.

BUCKETIZED CUCKOO HASH TABLES

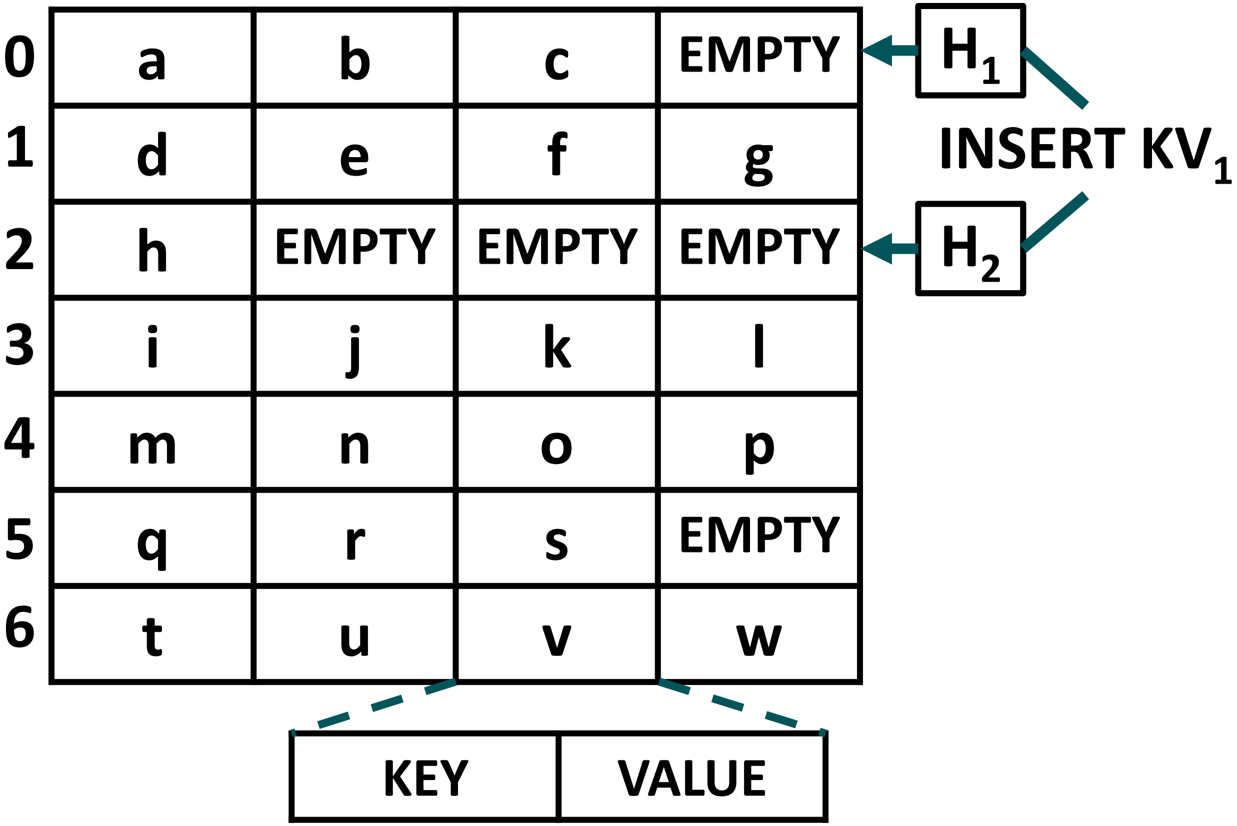
LOOKUPS AND LOAD BALANCING HEURISTIC



0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND LOAD BALANCING HEURISTIC

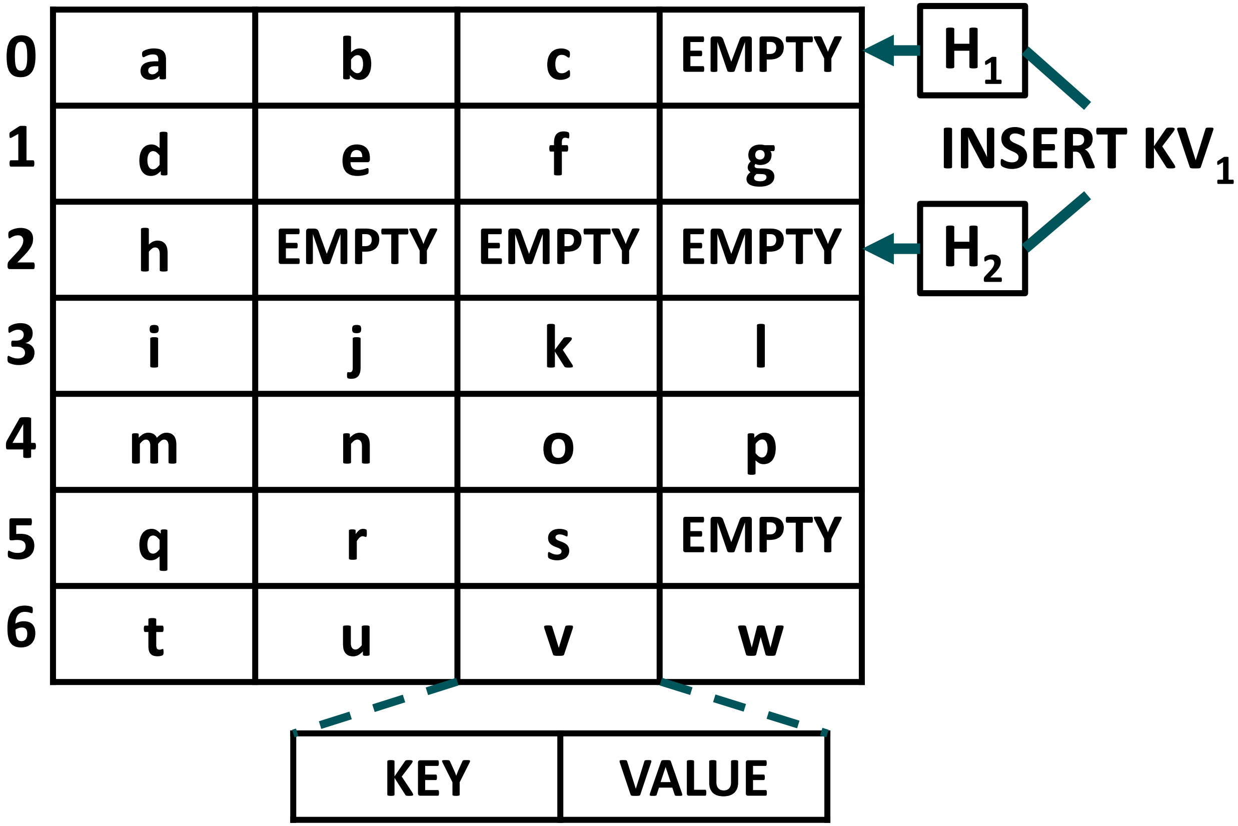


0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

- Expected Positive Lookup Cost Per Item in Buckets:
  (Fraction of Items Hashed by H_1) + 2 * (Fraction of Items Hashed by H_2)

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND LOAD BALANCING HEURISTIC



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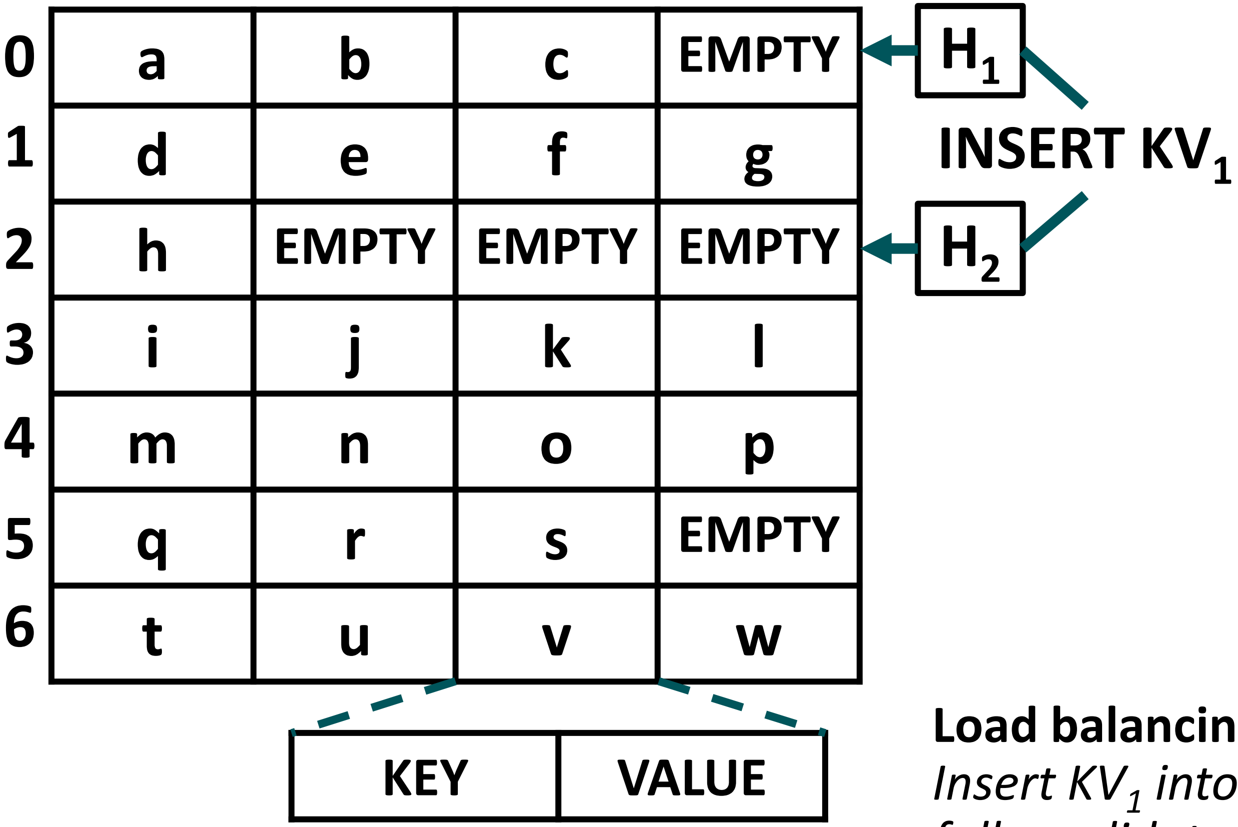
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

- Expected Positive Lookup Cost Per Item in Buckets:
  (Fraction of Items Hashed by H_1) + 2 * (Fraction of Items Hashed by H_2)
- Expected Negative Lookup Cost per Item in Buckets:
  2 (also worst-case)

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND LOAD BALANCING HEURISTIC



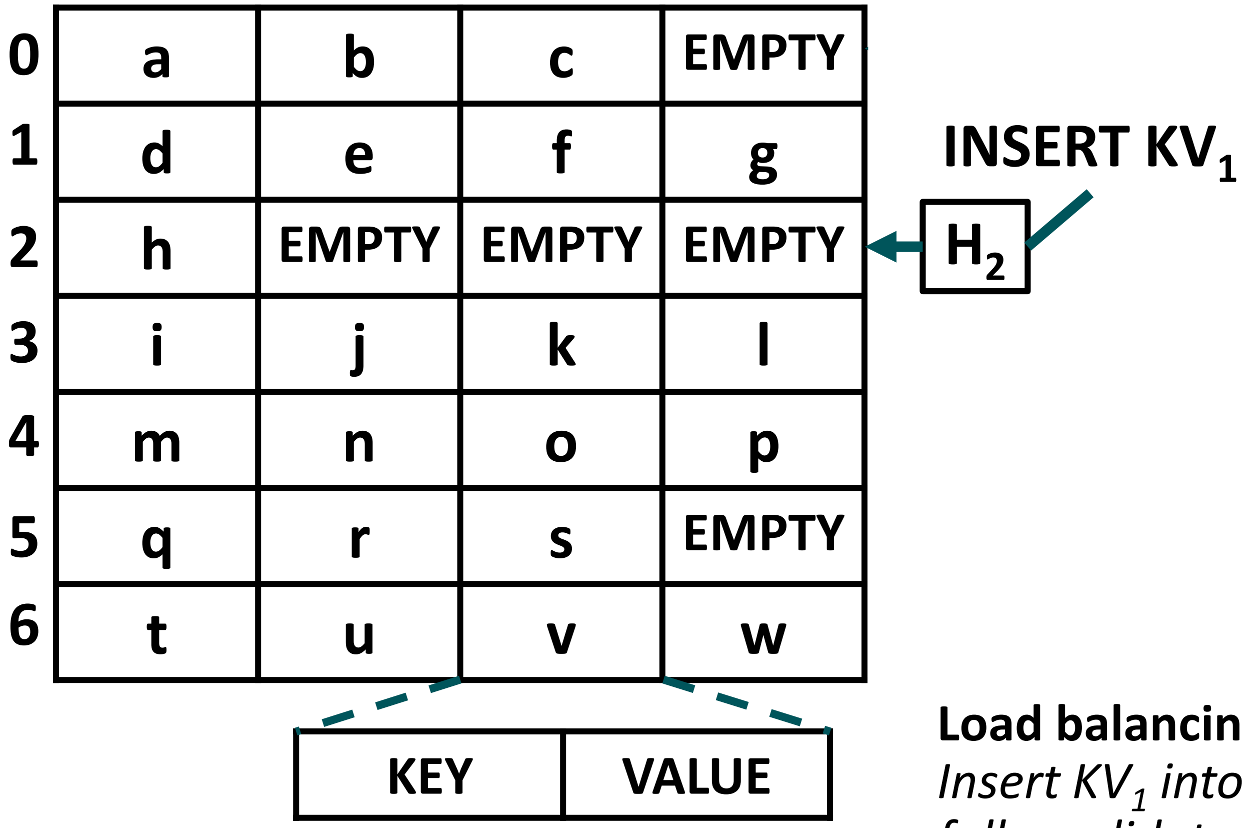
0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

Load balancing
Insert KV_1 into the least full candidate bucket

- Expected Positive Lookup Cost Per Item in Buckets:
  (Fraction of Items Hashed by H_1) + 2 * (Fraction of Items Hashed by H_2)
- Expected Negative Lookup Cost per Item in Buckets:
  2 (also worst-case)

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND LOAD BALANCING HEURISTIC



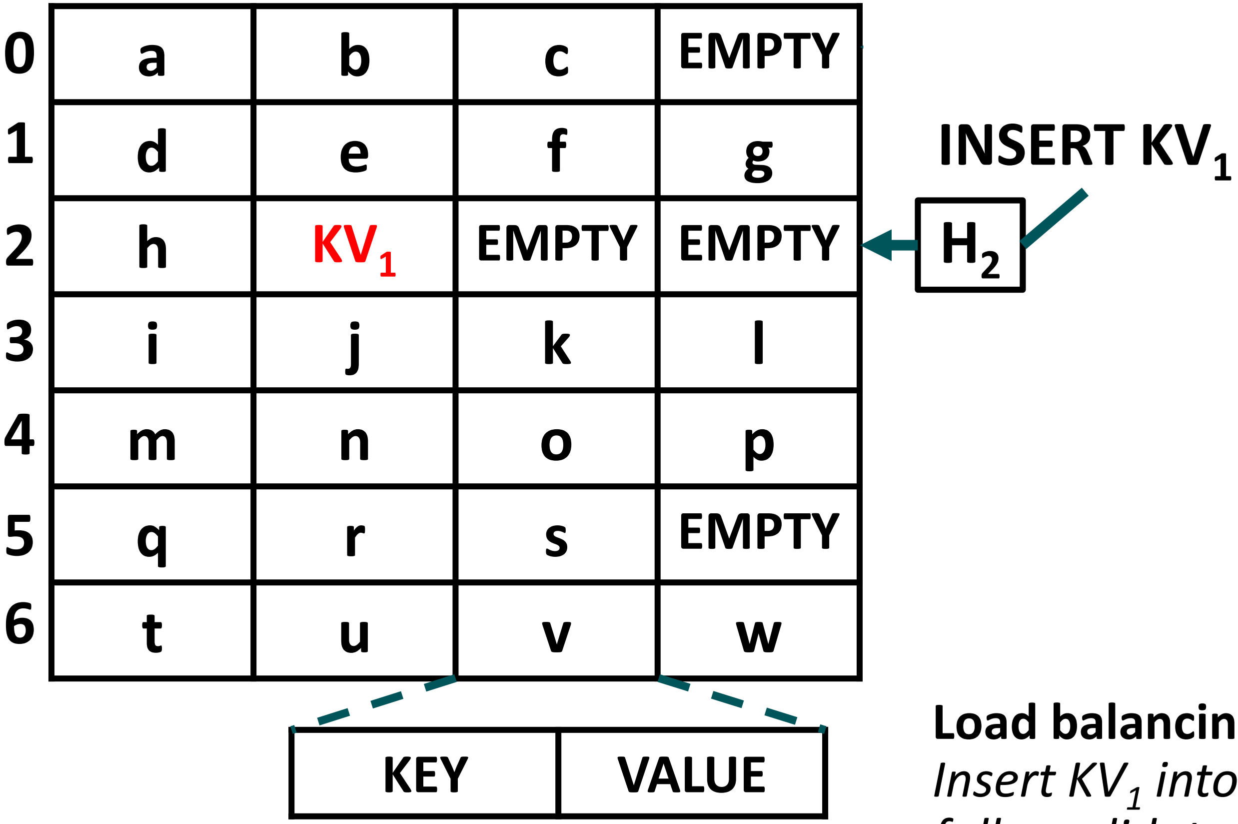
0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

Load balancing
Insert KV_1 into the least full candidate bucket

- Expected Positive Lookup Cost Per Item in Buckets:
  (Fraction of Items Hashed by H_1) + 2 * (Fraction of Items Hashed by H_2)
- Expected Negative Lookup Cost per Item in Buckets:
  2 (also worst-case)

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND LOAD BALANCING HEURISTIC



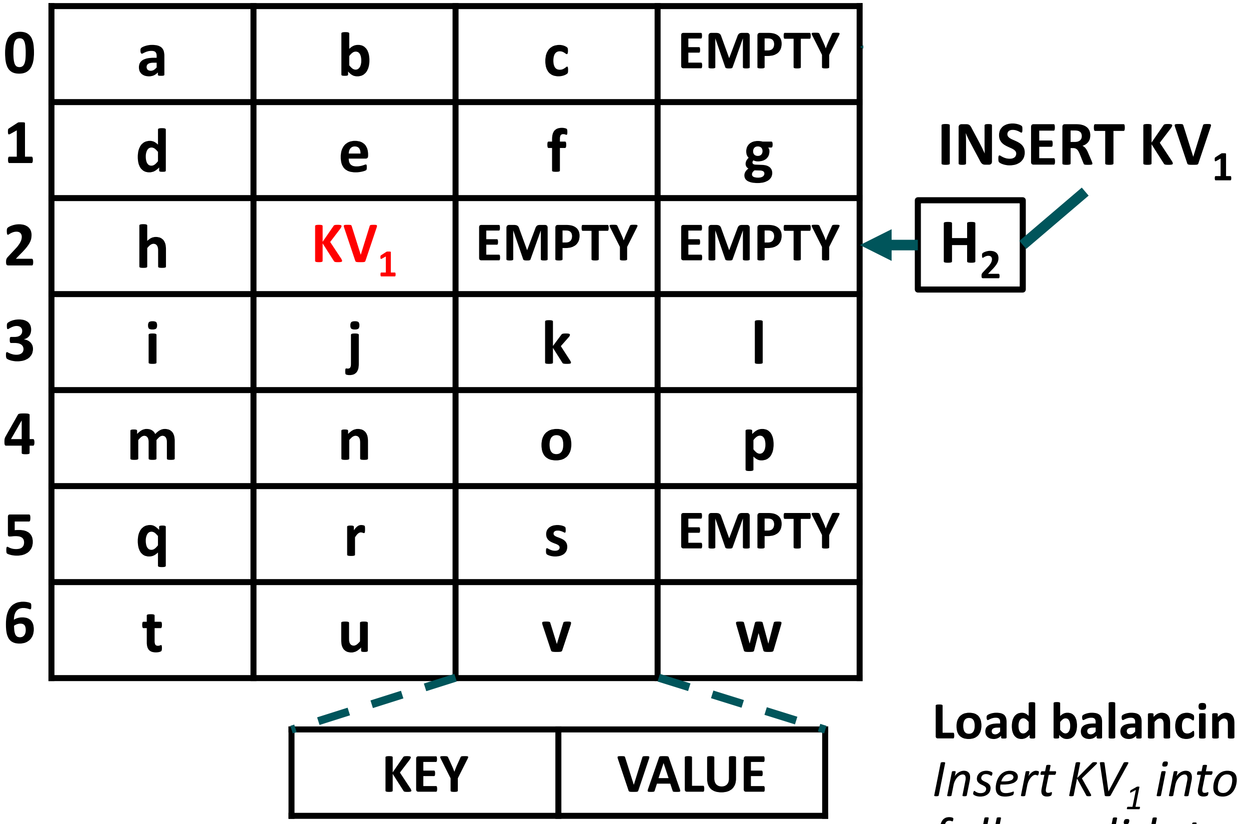
0	a	b	c	EMPTY
1	d	e	f	g
2	h	KV_1	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

Load balancing
Insert KV_1 into the least full candidate bucket

- Expected Positive Lookup Cost Per Item in Buckets:
  (Fraction of Items Hashed by H_1) + 2 * (Fraction of Items Hashed by H_2)
- Expected Negative Lookup Cost per Item in Buckets:
  2 (also worst-case)

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND LOAD BALANCING HEURISTIC

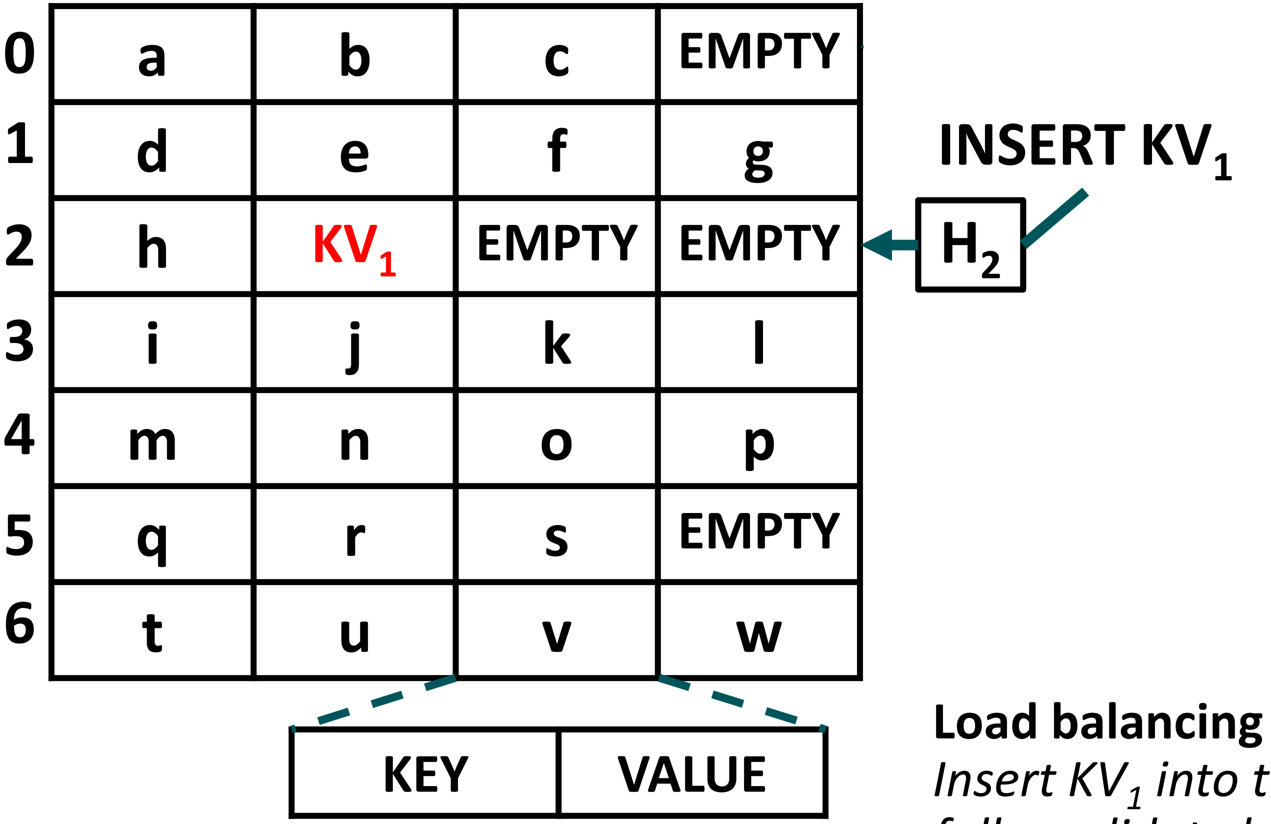


0	a	b	c	EMPTY
1	d	e	f	g
2	h	KV_1	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

Load balancing

Insert KV_1 into the least full candidate bucket

BUCKETIZED CUCKOO HASH TABLES
LOOKUPS AND LOAD BALANCING HEURISTIC



0	a	b	c	EMPTY
1	d	e	f	g
2	h	KV_1	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

KEY	VALUE

INSERT KV_1

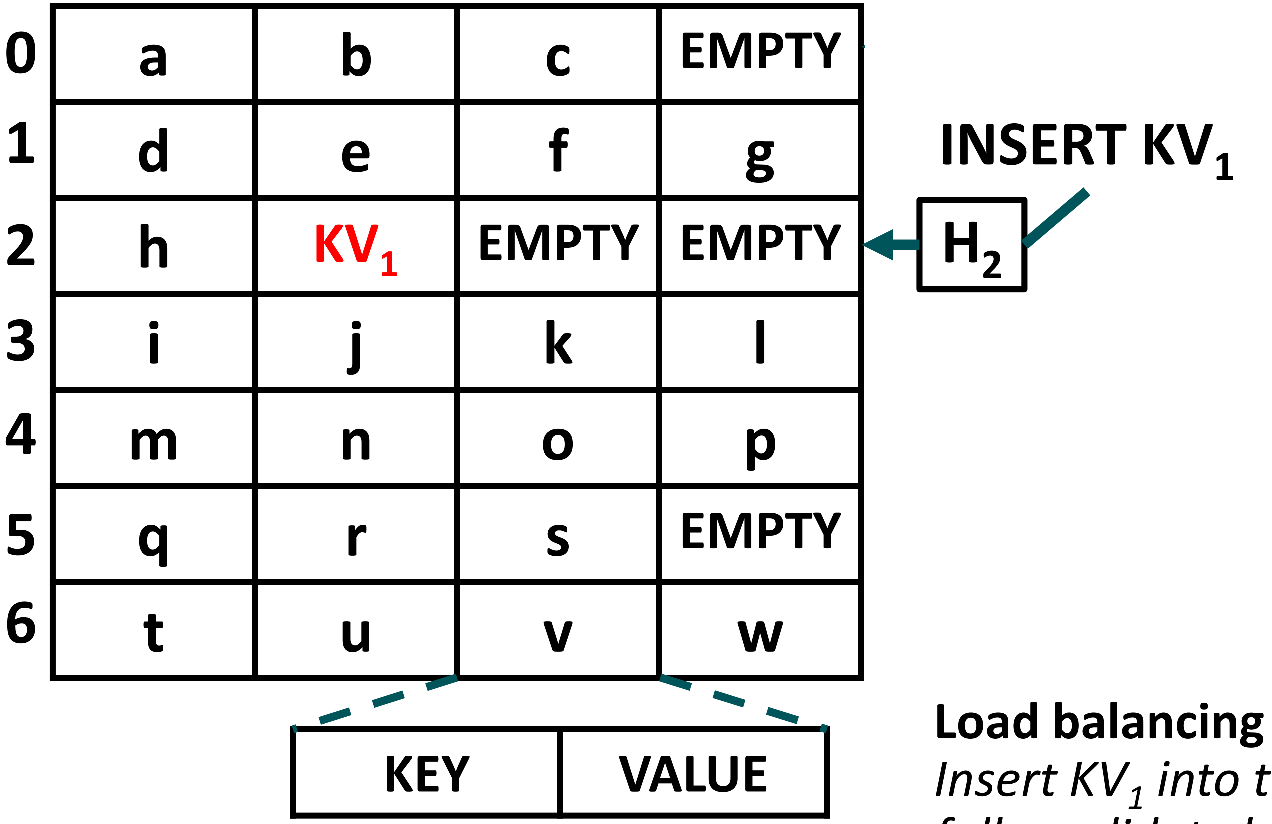
H_2

Load balancing
Insert KV_1 into the least full candidate bucket

- Expected Positive Lookup Cost Per Item in Buckets: 1.5 = (0.5 Hashed by H_1) + 2 * (0.5 Hashed by H_2)

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND LOAD BALANCING HEURISTIC



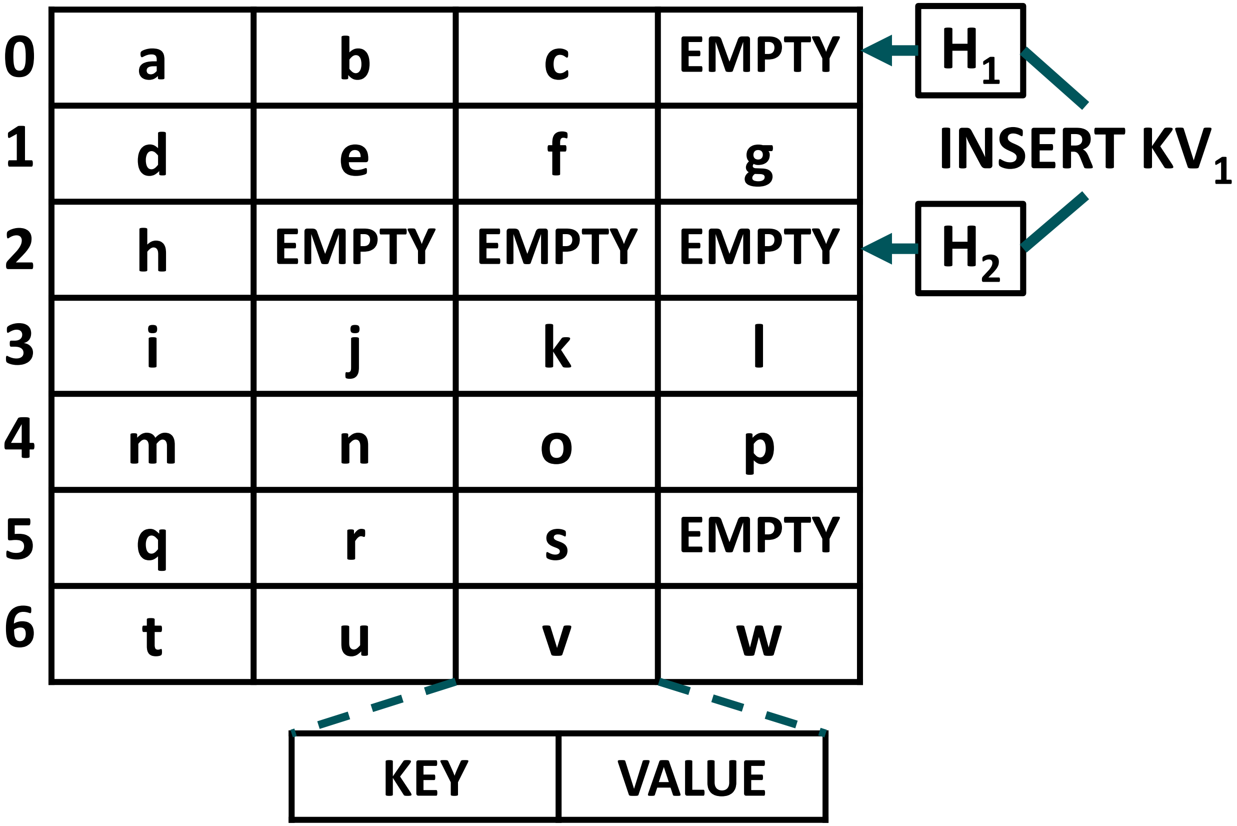
0	a	b	c	EMPTY
1	d	e	f	g
2	h	KV_1	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

Load balancing
Insert KV_1 into the least full candidate bucket

- Expected Positive Lookup Cost Per Item in Buckets: 1.5 = (0.5 Hashed by H_1) + 2 * (0.5 Hashed by H_2)
- Expected Negative Lookup Cost per Item in Buckets: 2 (also worst-case)

BUCKETIZED CUCKOO HASH TABLES

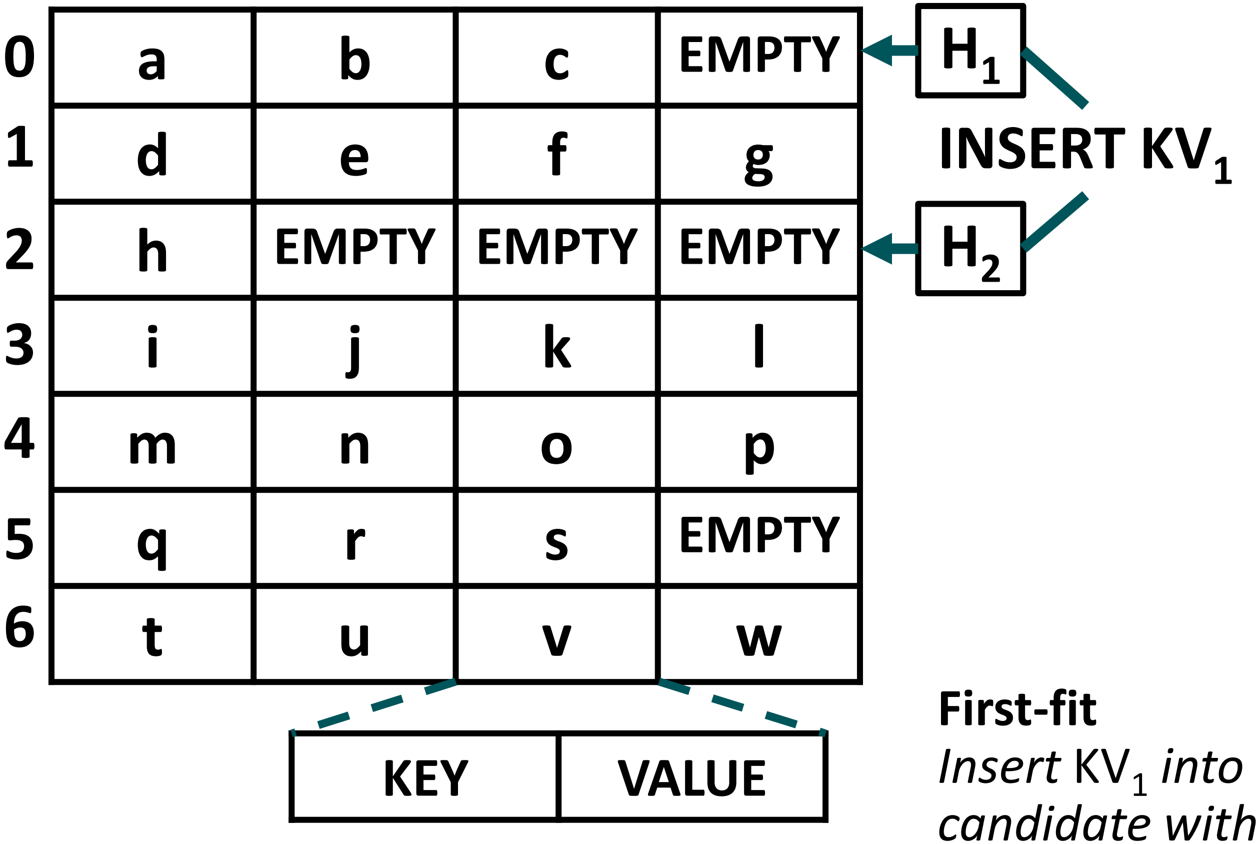
LOOKUPS AND FIRST-FIT INSERTION HEURISTIC



0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND FIRST-FIT INSERTION HEURISTIC



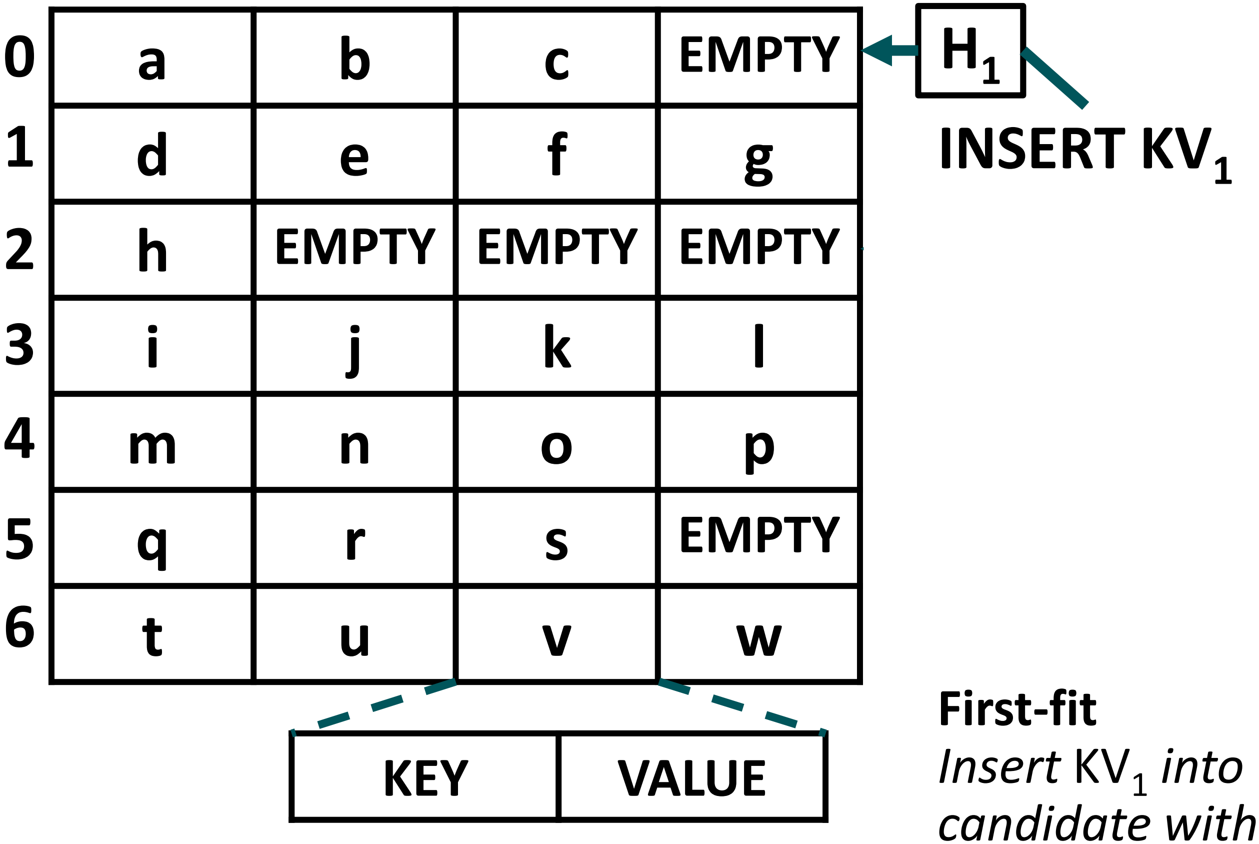
0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

First-fit

Insert KV_1 *into the first candidate with a free slot*

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND FIRST-FIT INSERTION HEURISTIC



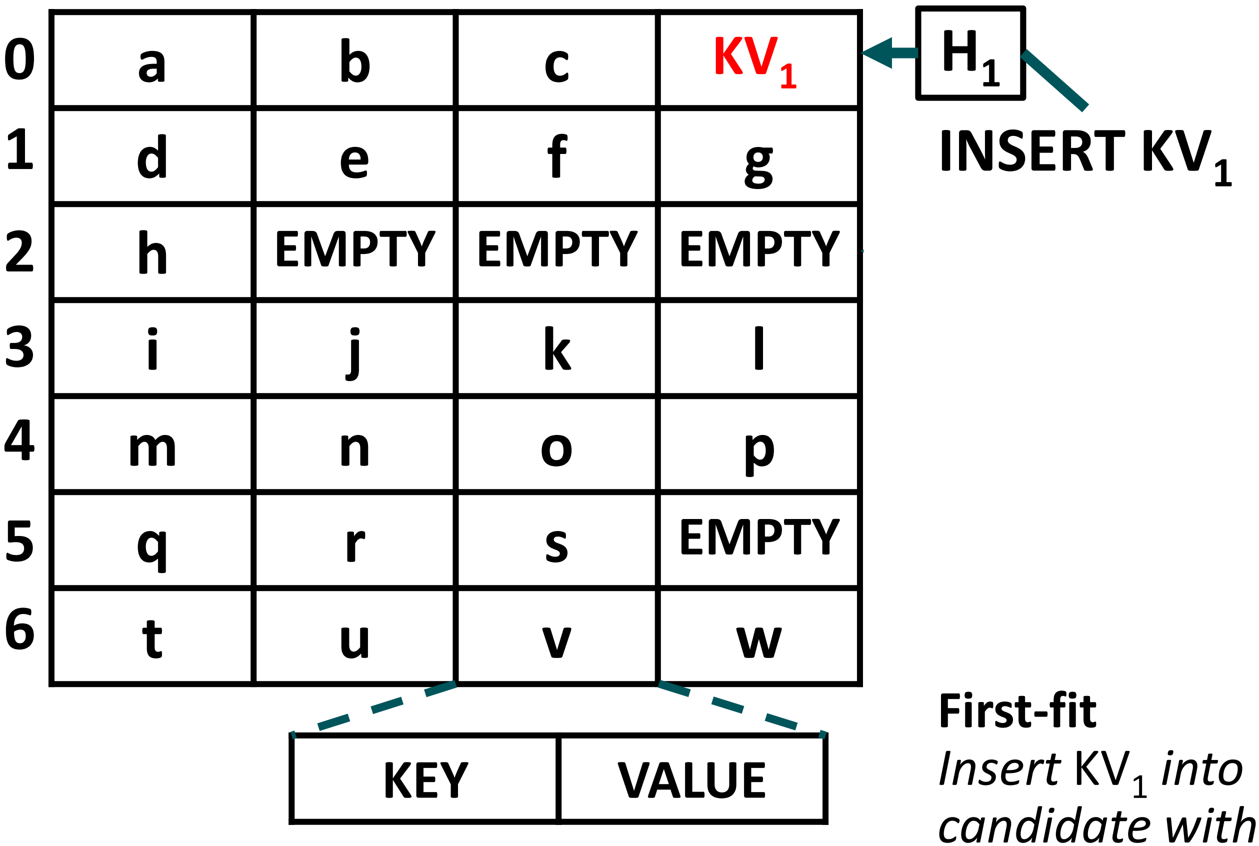
0	a	b	c	EMPTY
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

First-fit

Insert KV_1 *into the first candidate with a free slot*

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND FIRST-FIT INSERTION HEURISTIC



0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

H_1

INSERT KV_1

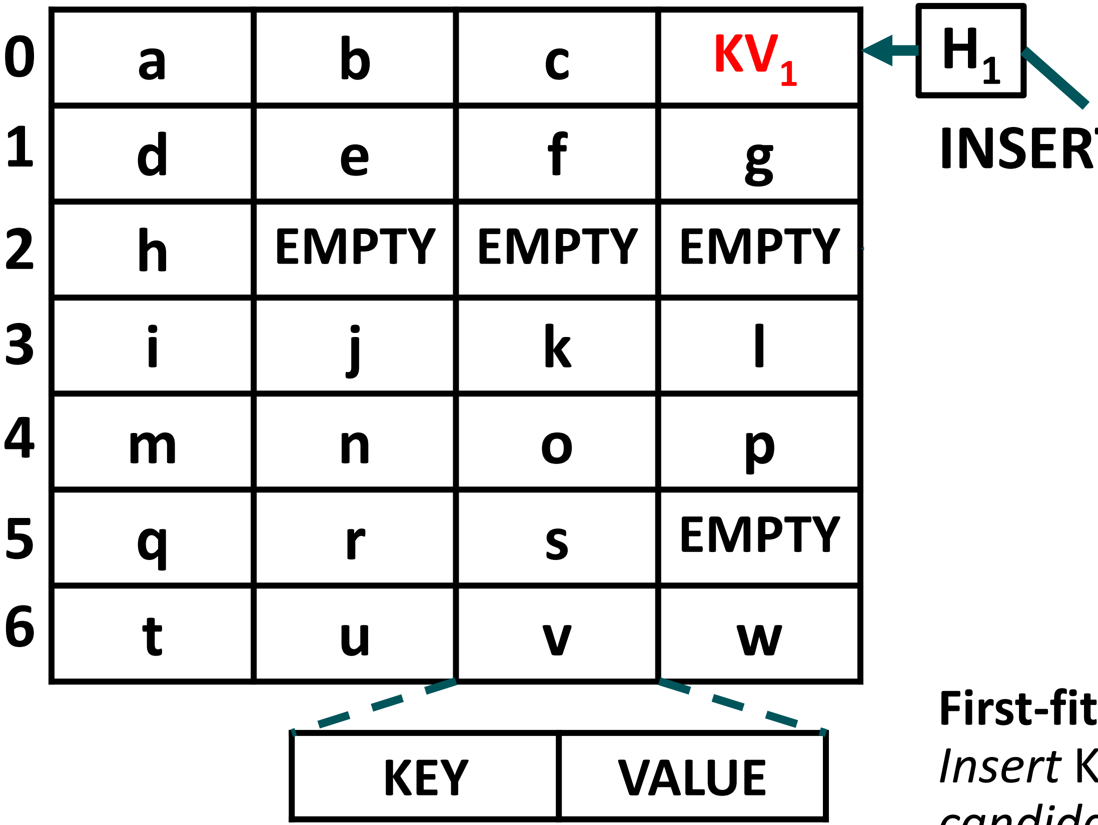
KEY	VALUE

First-fit

Insert KV_1 *into the first candidate with a free slot*

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND FIRST-FIT INSERTION HEURISTIC



0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

INSERT KV_1

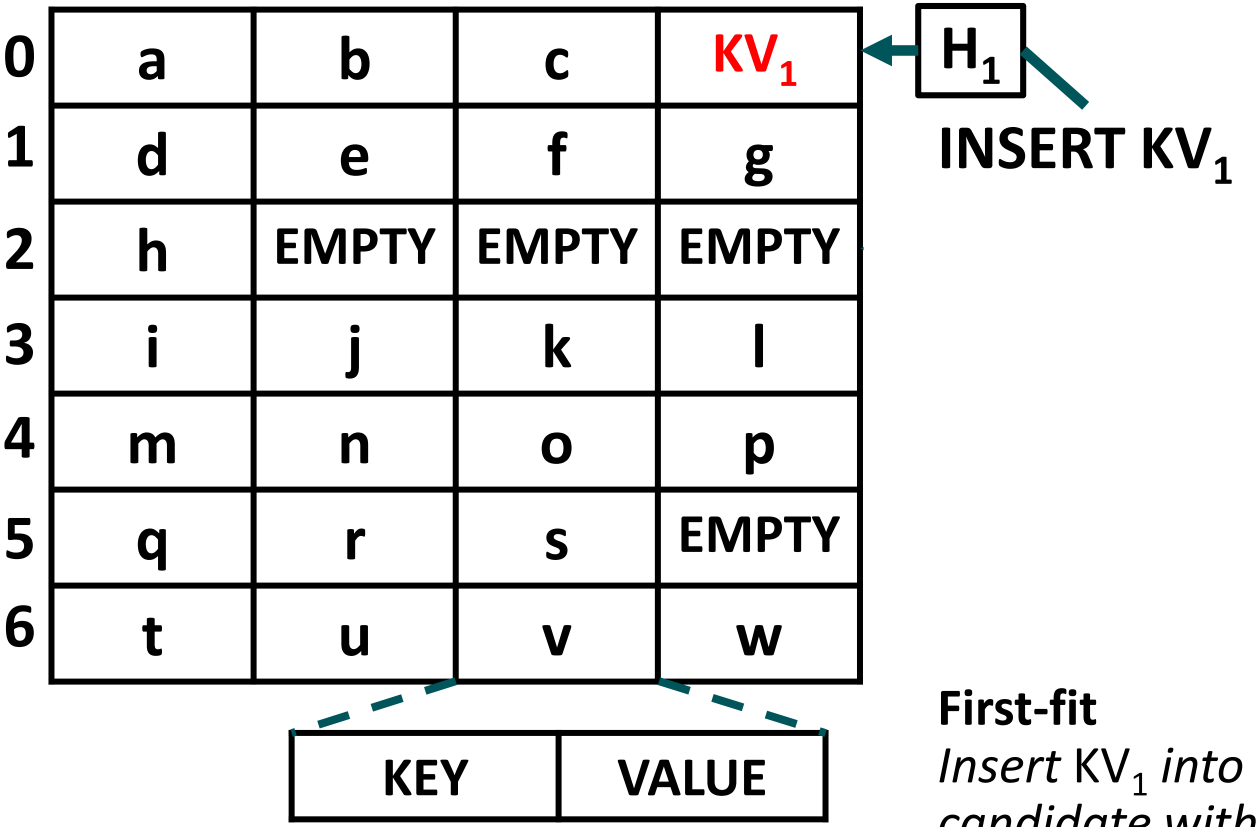
First-fit

Insert KV_1 *into the first candidate with a free slot*

- Expected Positive Lookup Cost Per Item in Buckets:
  1 to 1.3ish depending on the table load factor and the slots per bucket

BUCKETIZED CUCKOO HASH TABLES

LOOKUPS AND FIRST-FIT INSERTION HEURISTIC



0	a	b	c	KV_1
1	d	e	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	m	n	o	p
5	q	r	s	EMPTY
6	t	u	v	w

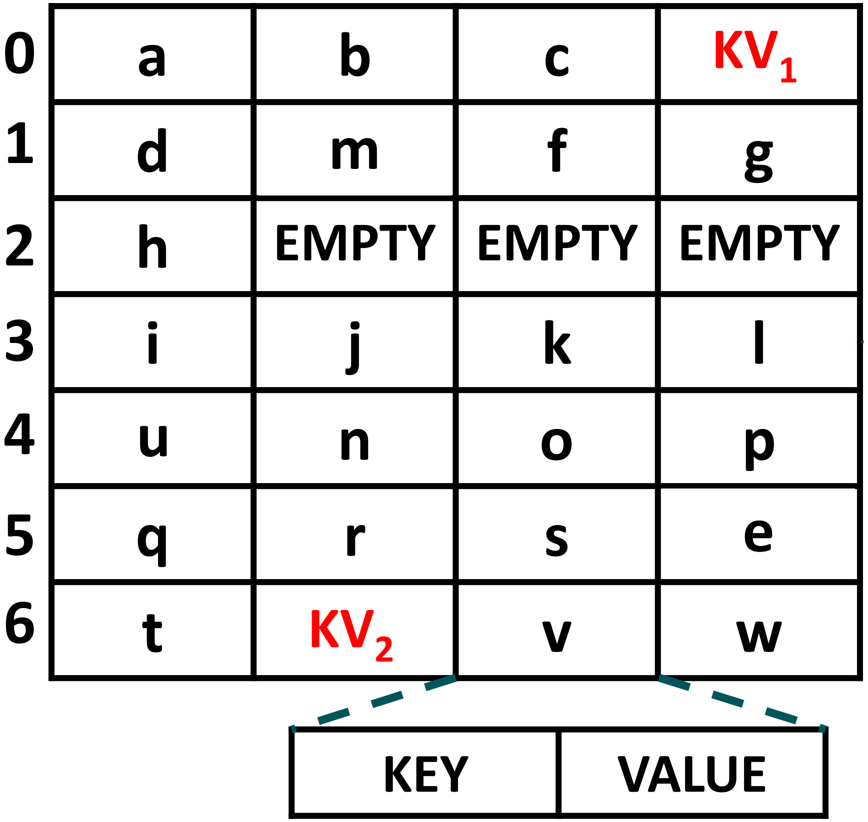
First-fit

Insert KV_1 *into the first candidate with a free slot*

- Expected Positive Lookup Cost Per Item in Buckets:
  1 to 1.3ish depending on the table load factor and the slots per bucket
- Expected Negative Lookup Cost per Item in Buckets:
  2 (also worst-case)

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT

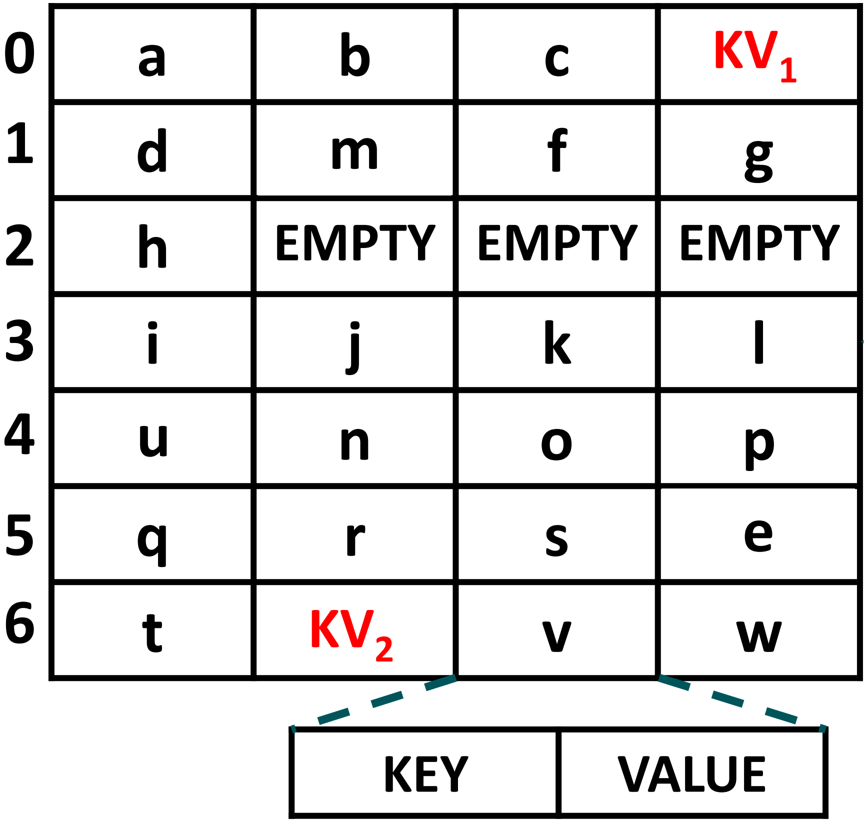


0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

KEY	VALUE

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT



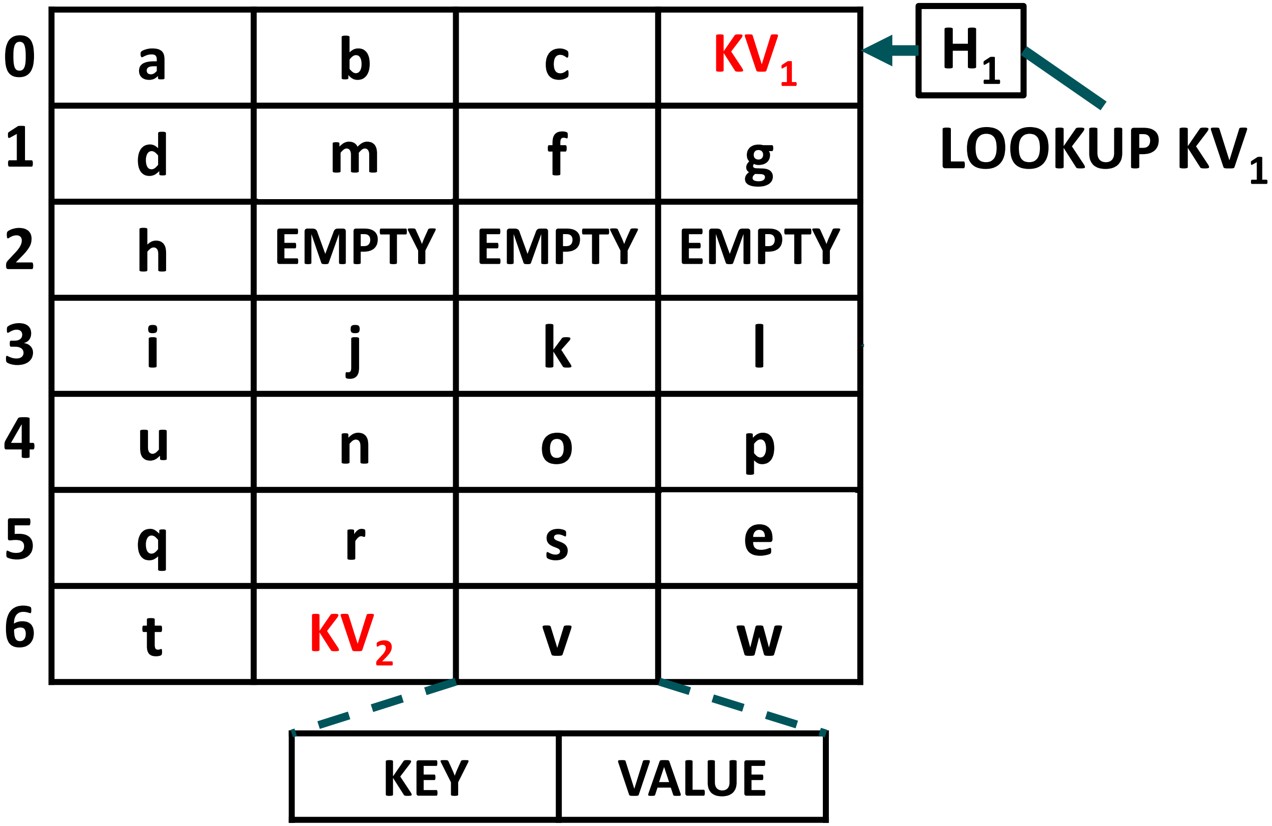
0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

KEY	VALUE

LOOKUP KV_1

BUCKETIZED CUCKOO HASH TABLES

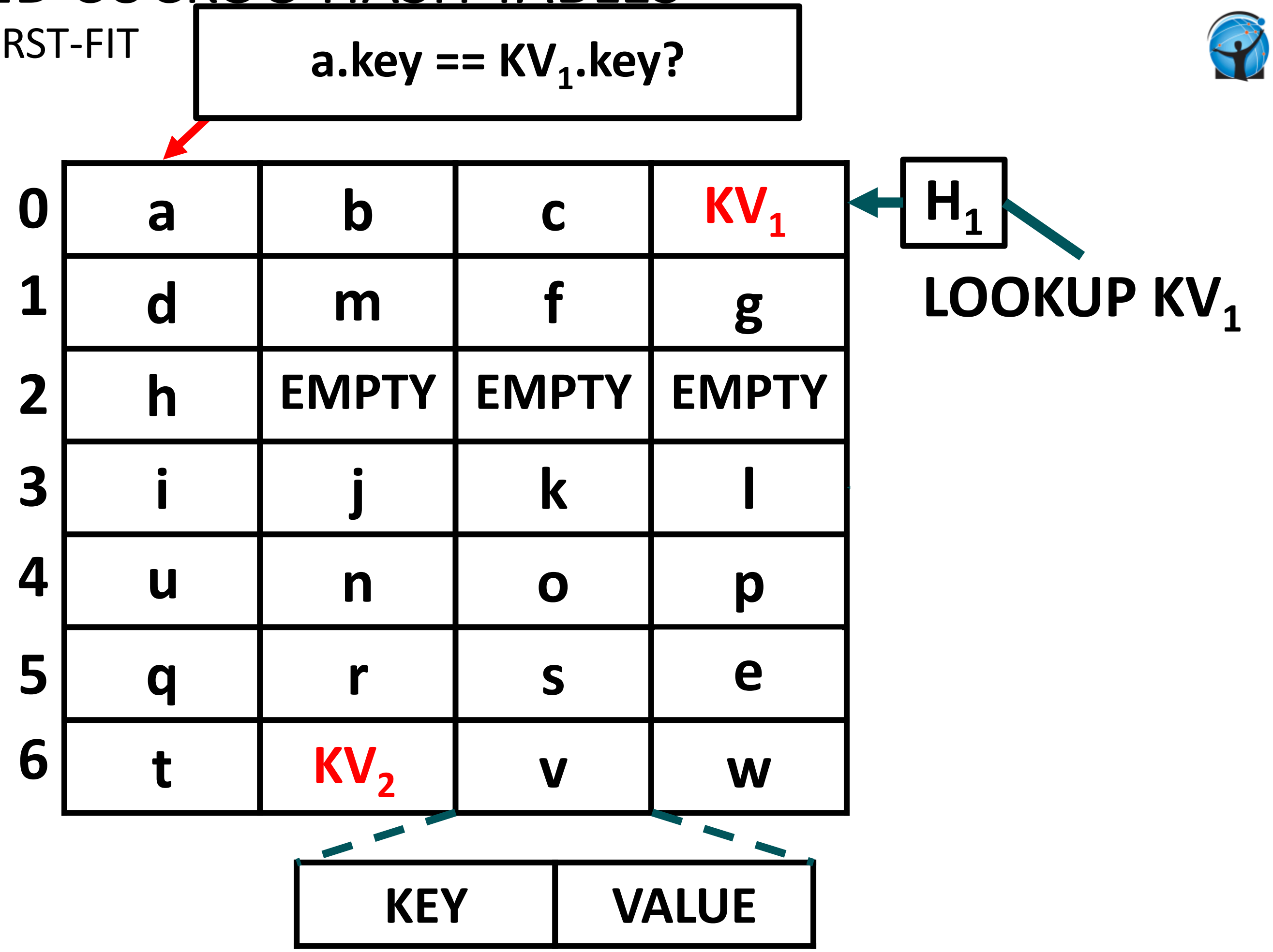
BENEFITS OF FIRST-FIT



0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT



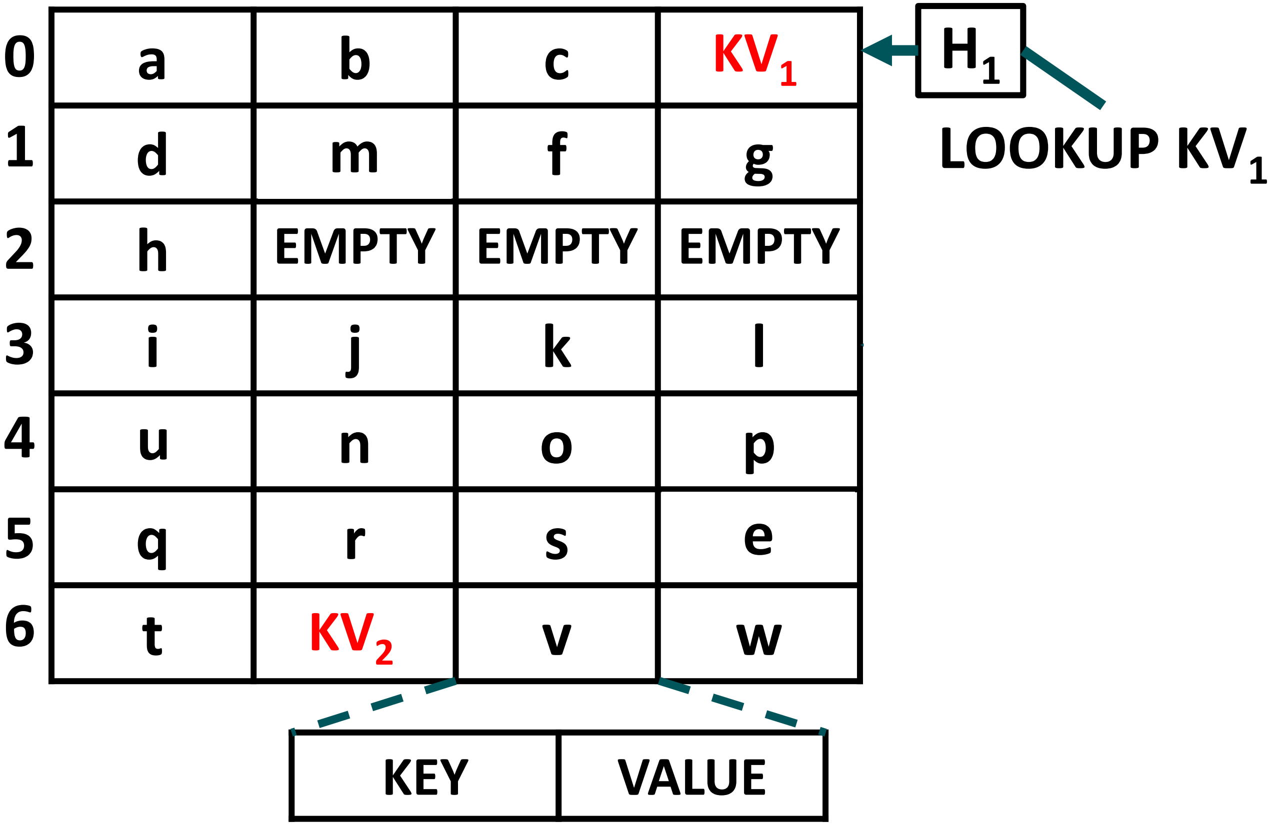
a.key == KV_1.key?

0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT

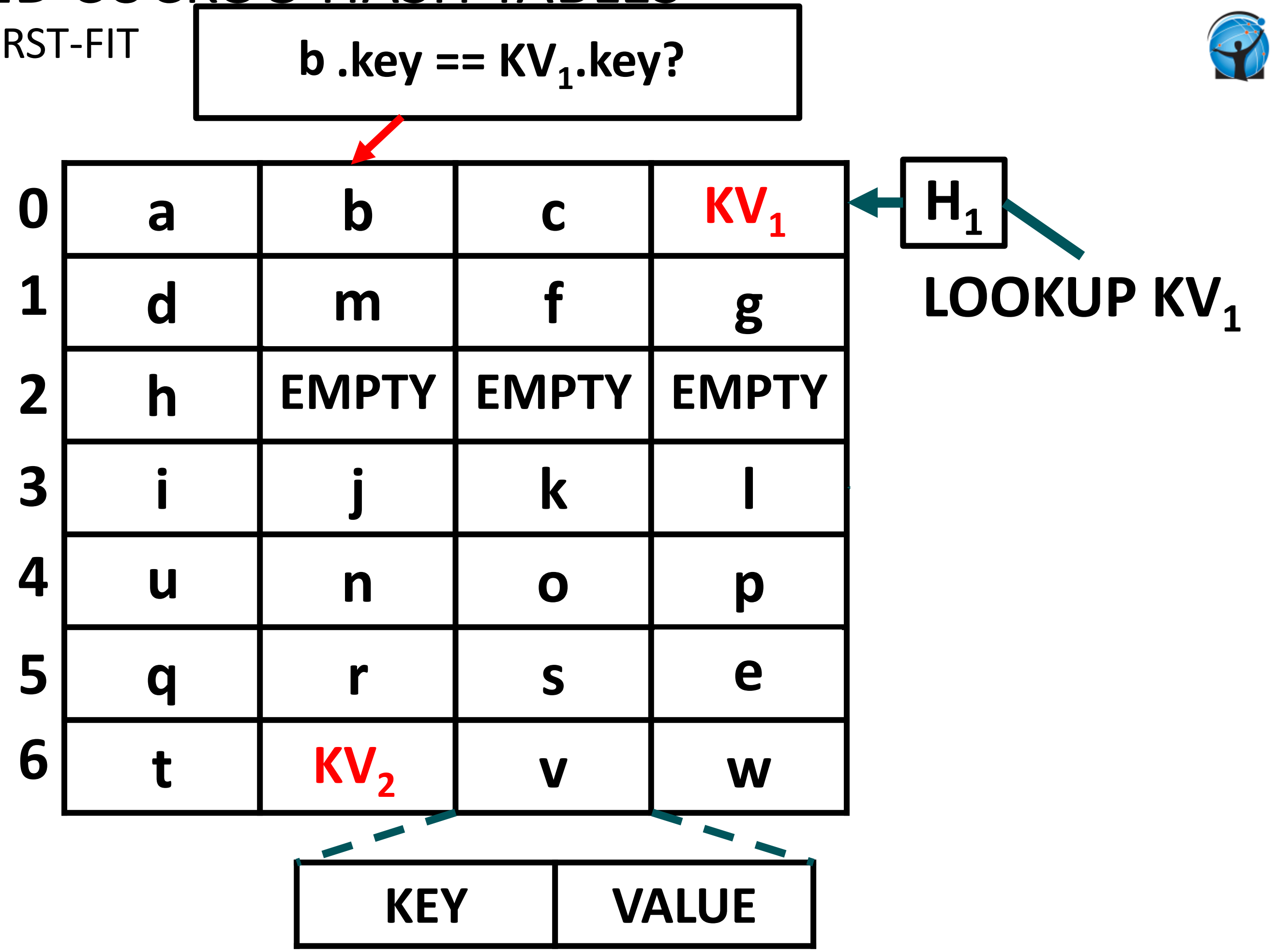
a.key == KV_1.key?



0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT



b .key == KV_1.key?

0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

H_1

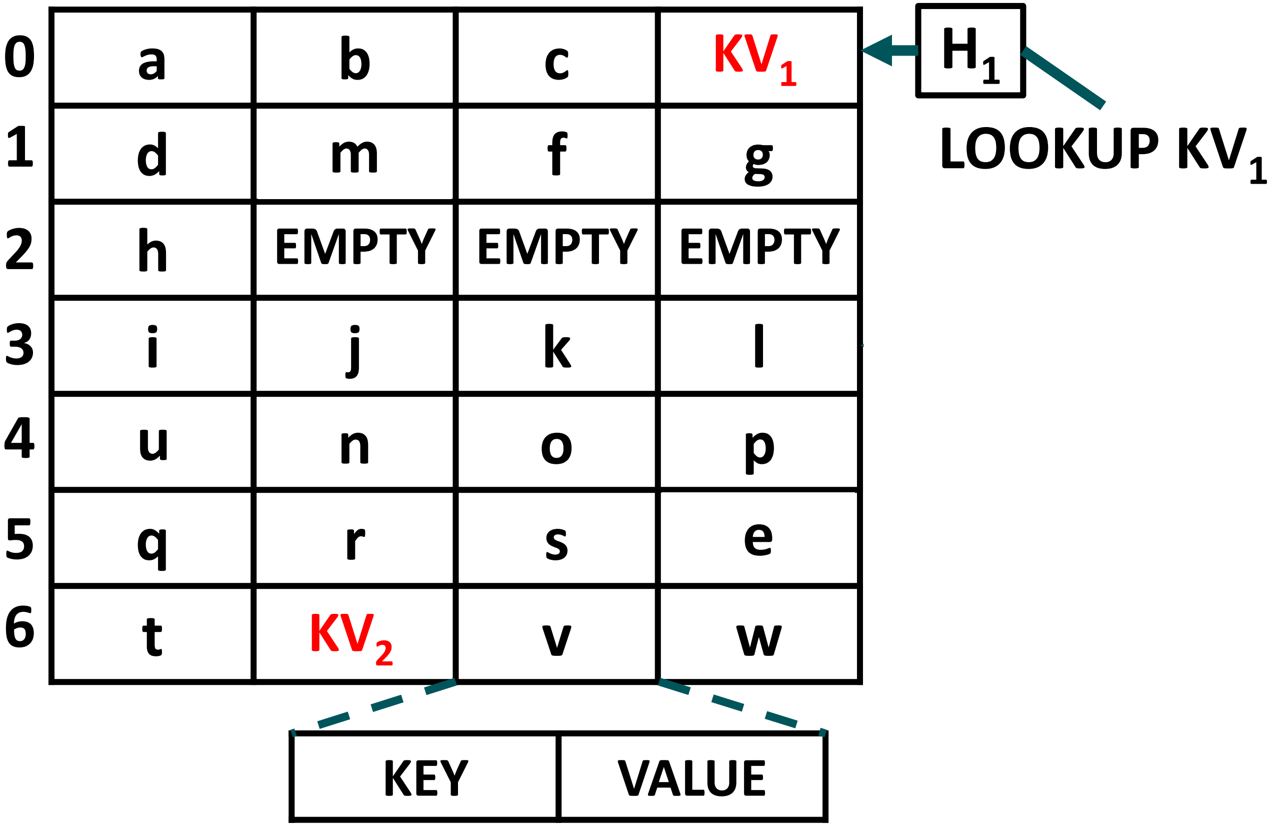
LOOKUP KV_1

KEY	VALUE

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT

b .key == KV_1.key?



0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

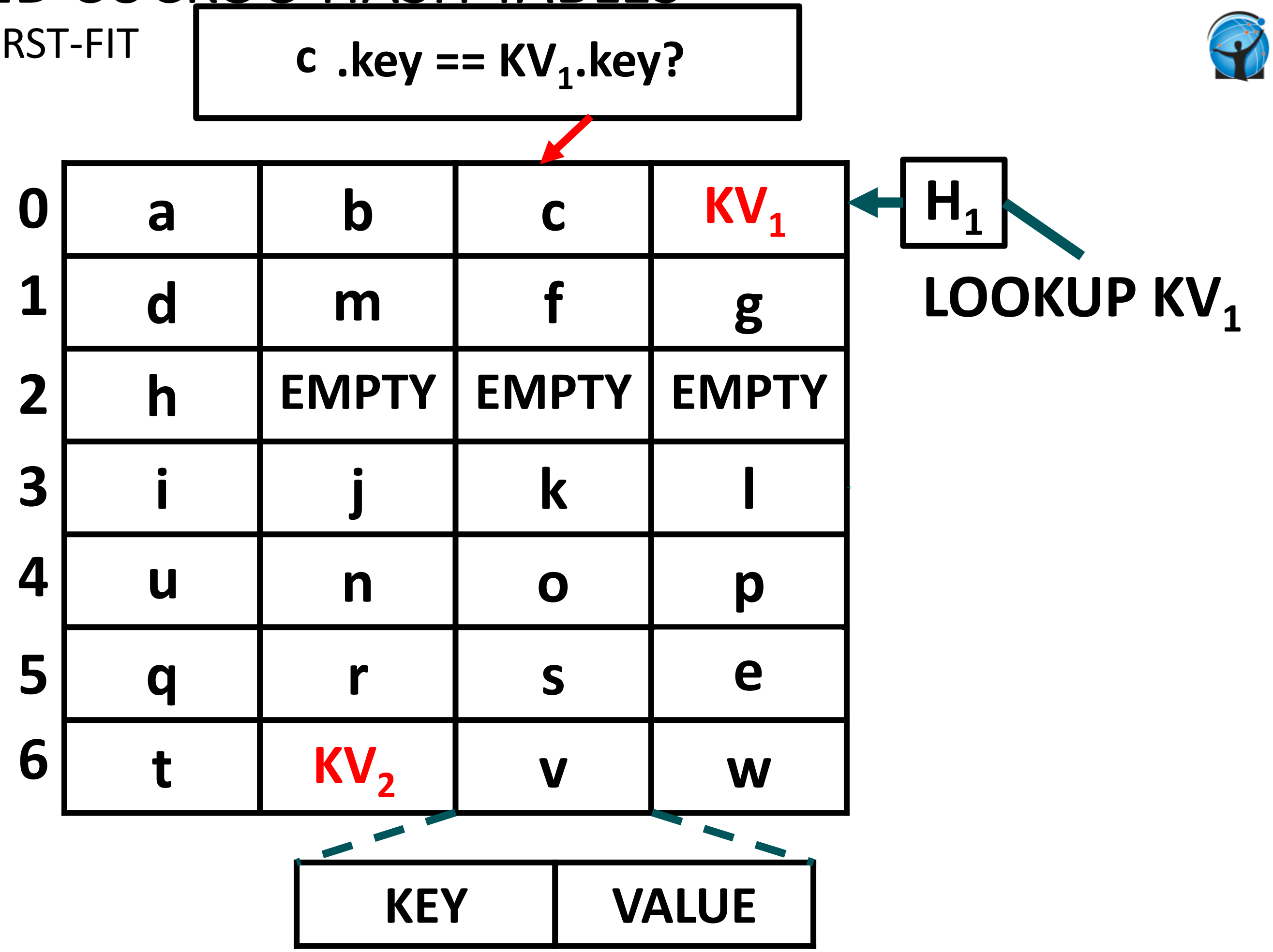
H_1

LOOKUP KV_1

KEY	VALUE

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT



c .key == KV_1.key?

0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

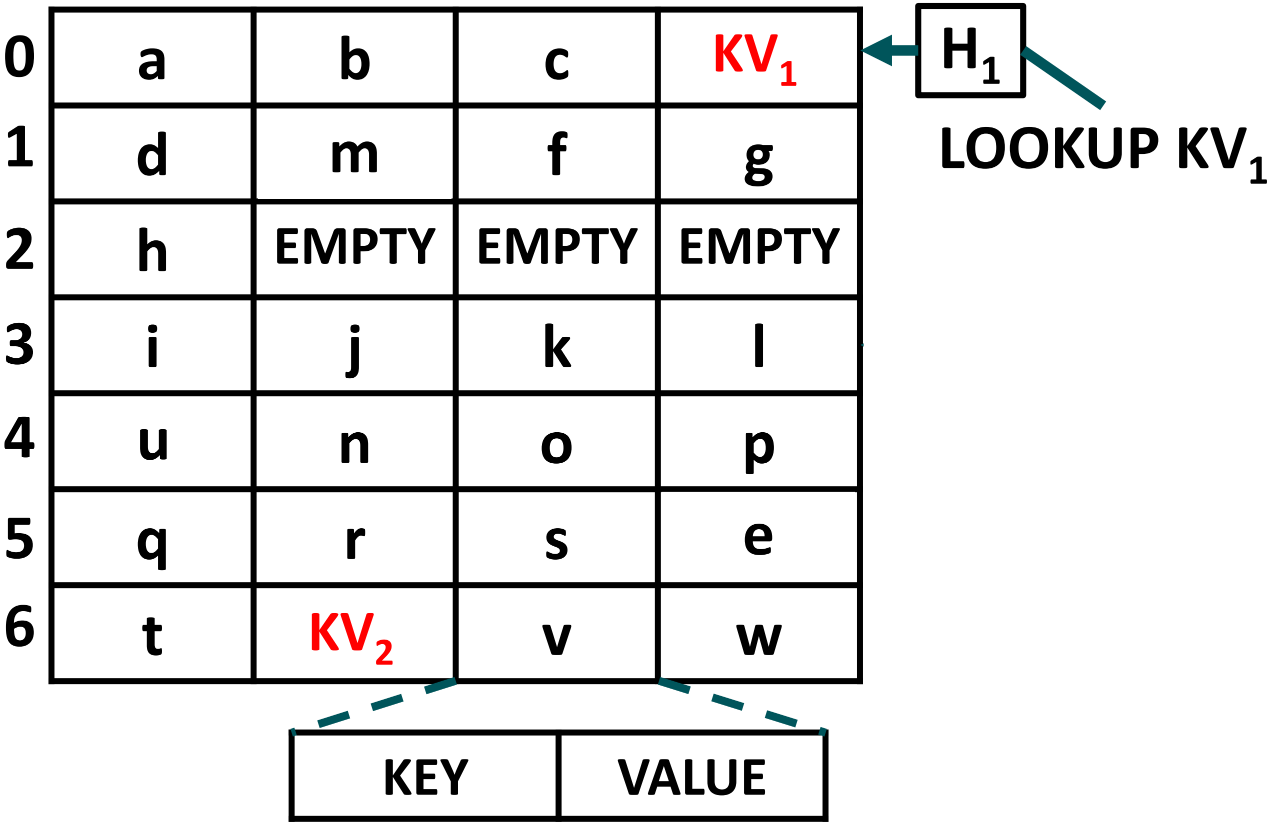
KEY	VALUE

LOOKUP KV_1

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT

c .key == KV_1.key?



0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

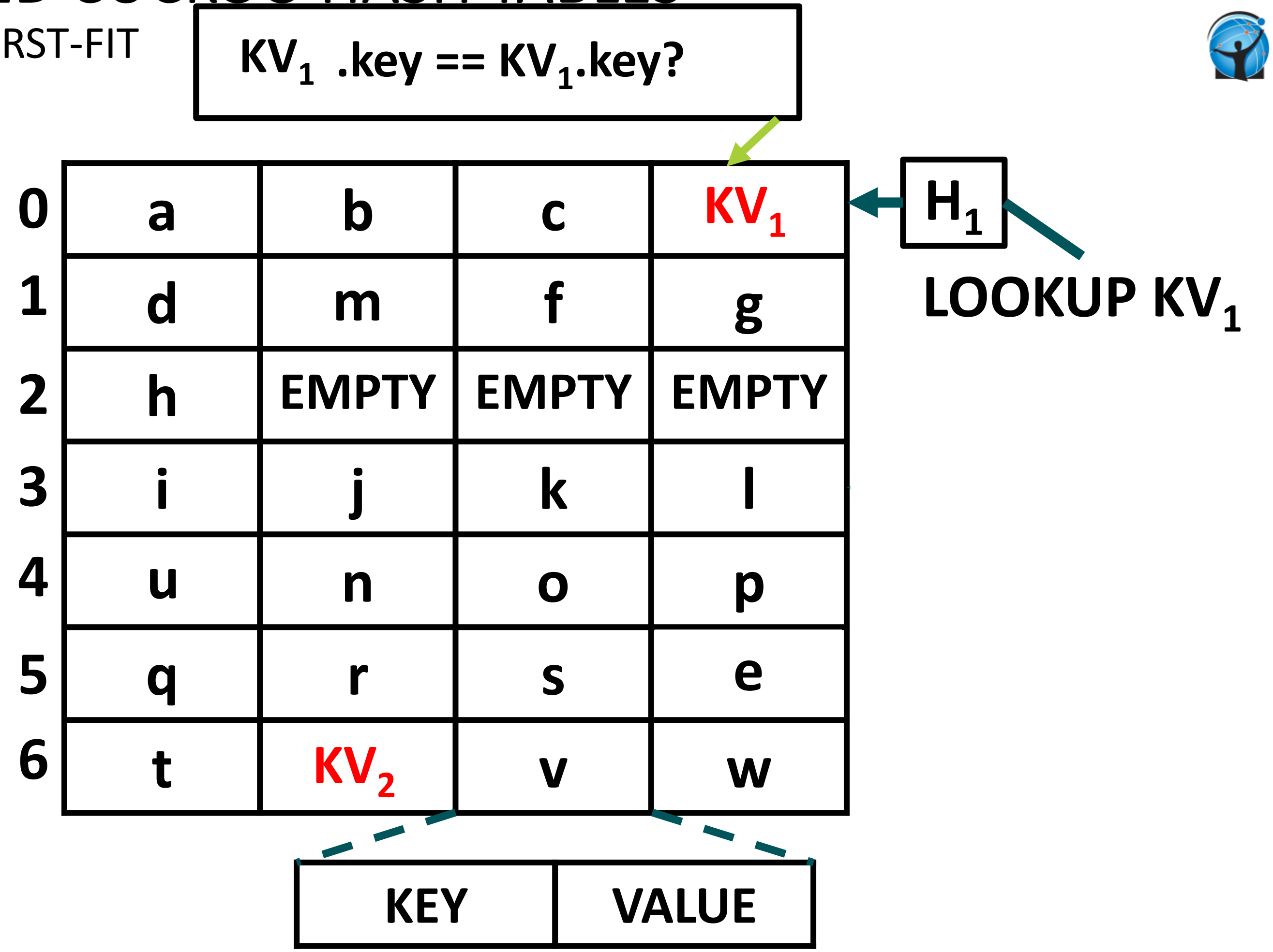
H_1

LOOKUP KV_1

KEY	VALUE

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT



KV_1 .key == KV_1.key?

0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

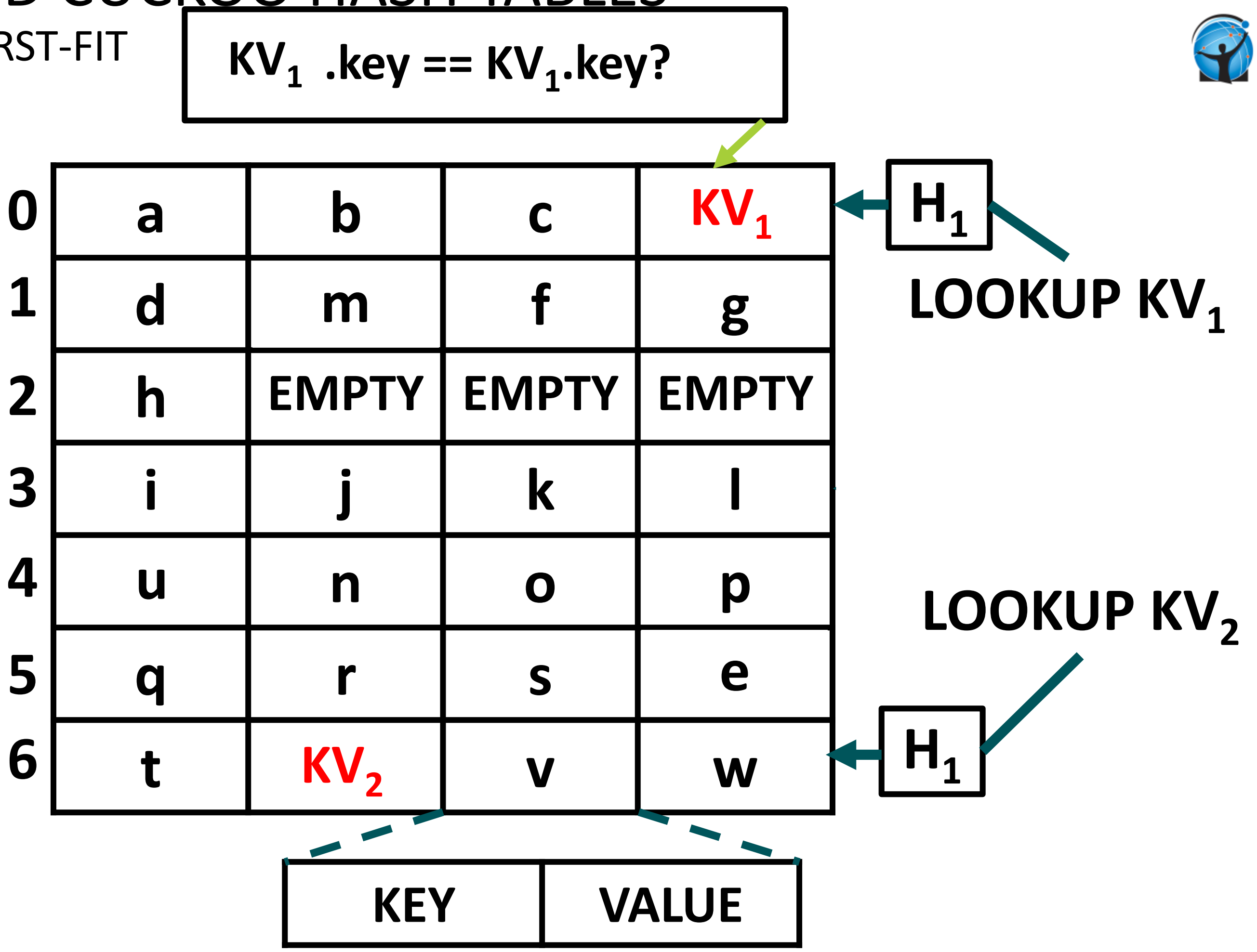
KEY	VALUE

H_1

LOOKUP KV_1

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT



KV_1 .key == KV_1.key?

0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

KEY	VALUE

H_1

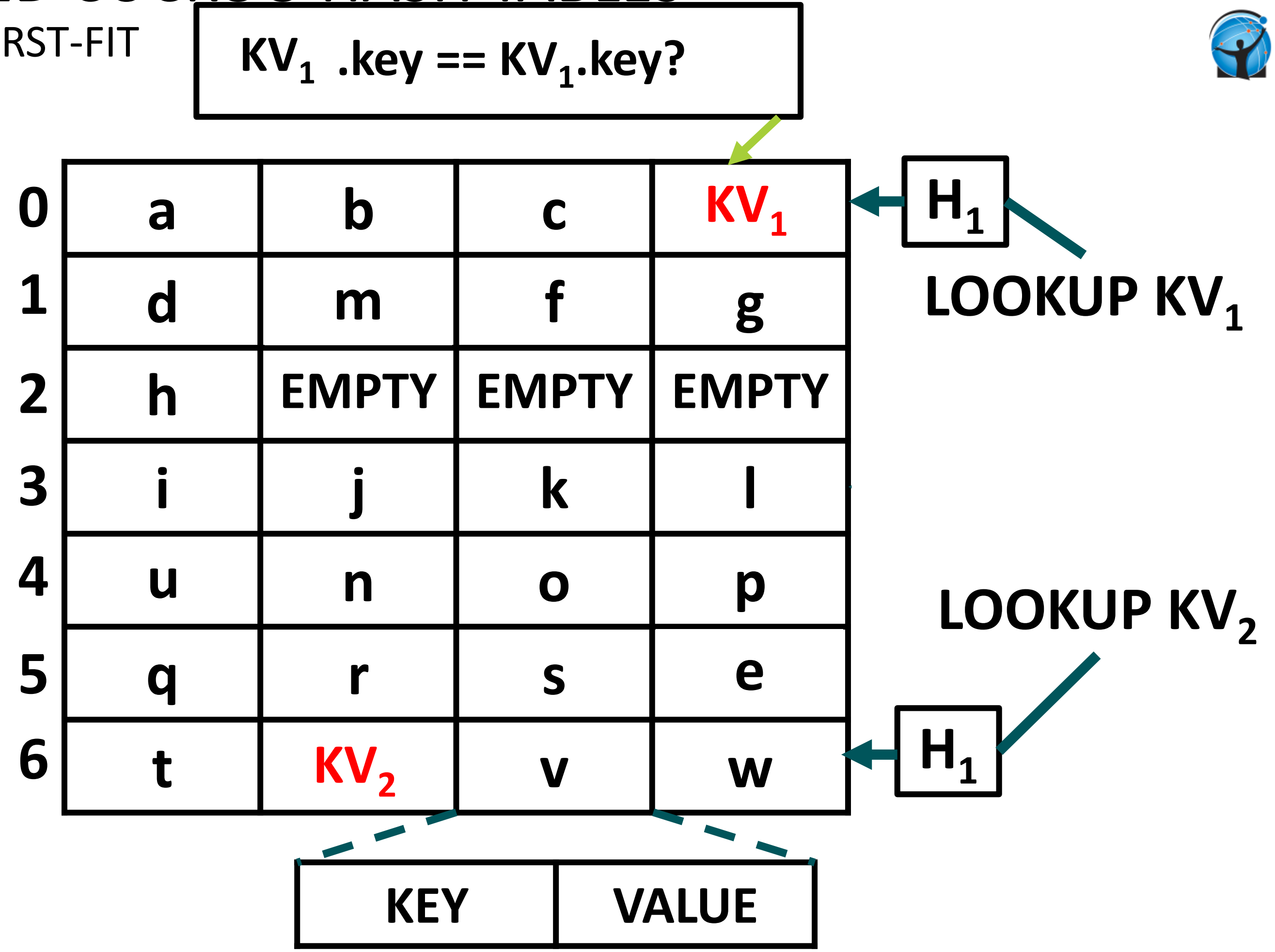
LOOKUP KV_1

LOOKUP KV_2

H_1

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT



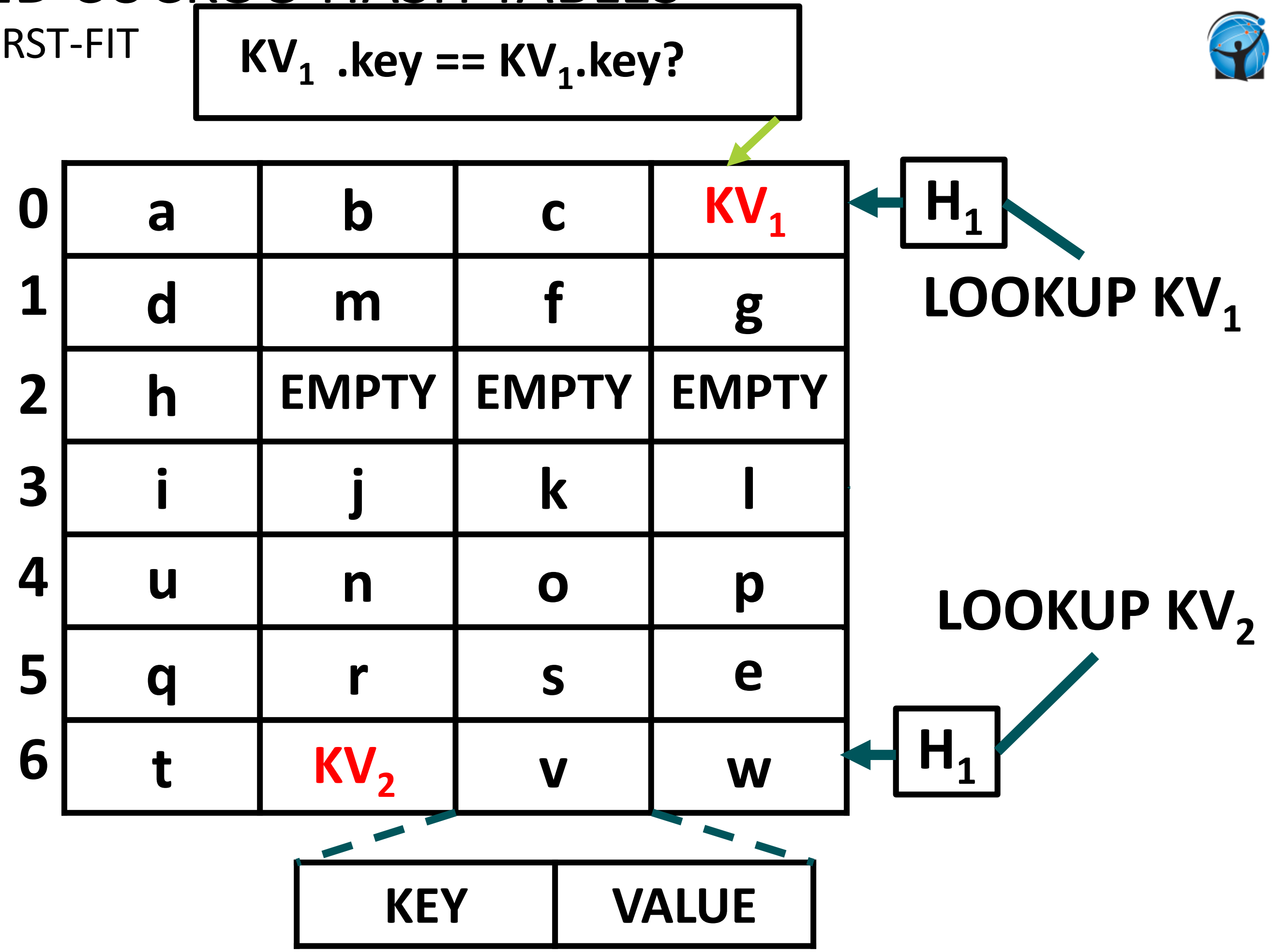
KV_1 .key == KV_1.key?

0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

- Positive Lookups:
  - First-fit gets us most of the way to 1.0 on positive lookups because most elements are hashed with H_1

BUCKETIZED CUCKOO HASH TABLES

BENEFITS OF FIRST-FIT



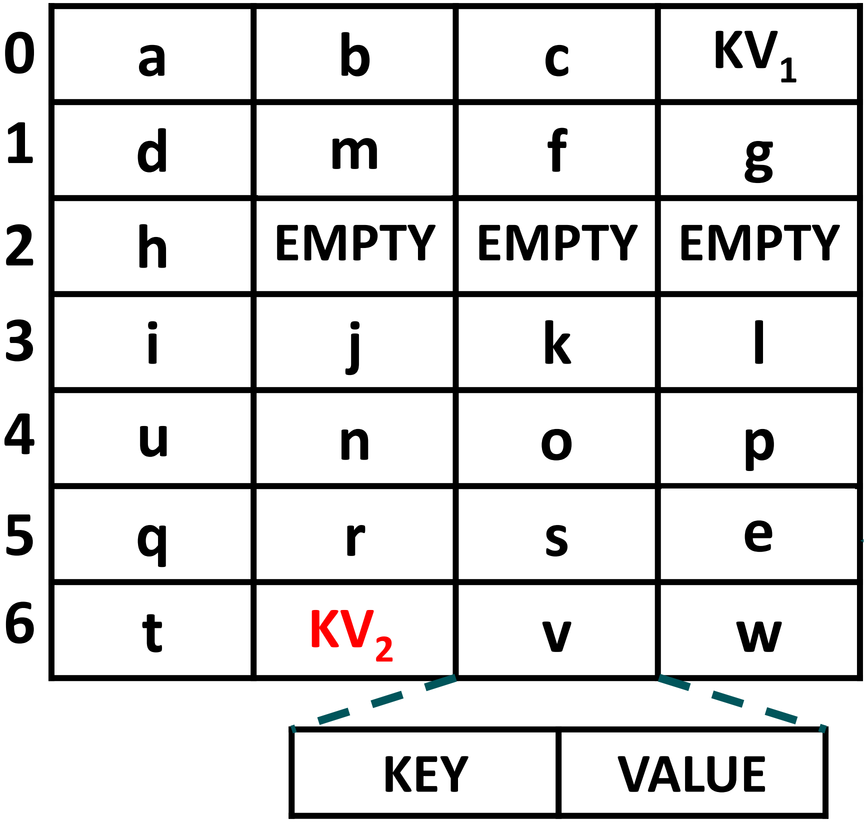
KV_1 .key == KV_1.key?

0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

- Positive Lookups:
  - First-fit gets us most of the way to 1.0 on positive lookups because most elements are hashed with H_1
- But…

BUCKETIZED CUCKOO HASH TABLES

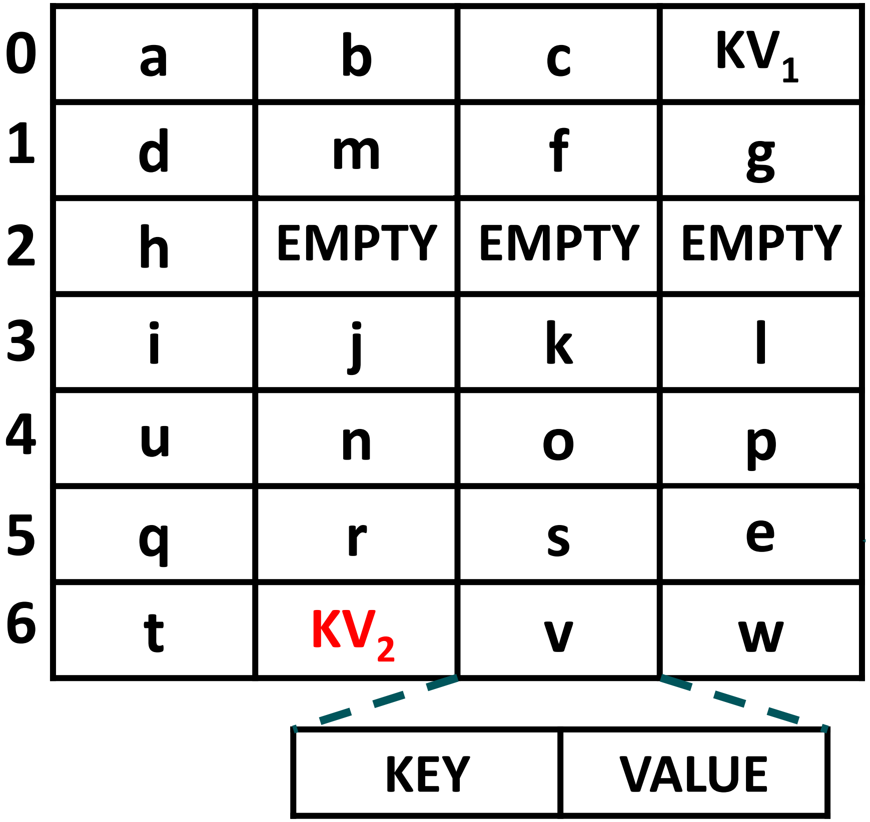
LIMITATIONS OF FIRST-FIT



0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

BUCKETIZED CUCKOO HASH TABLES

LIMITATIONS OF FIRST-FIT



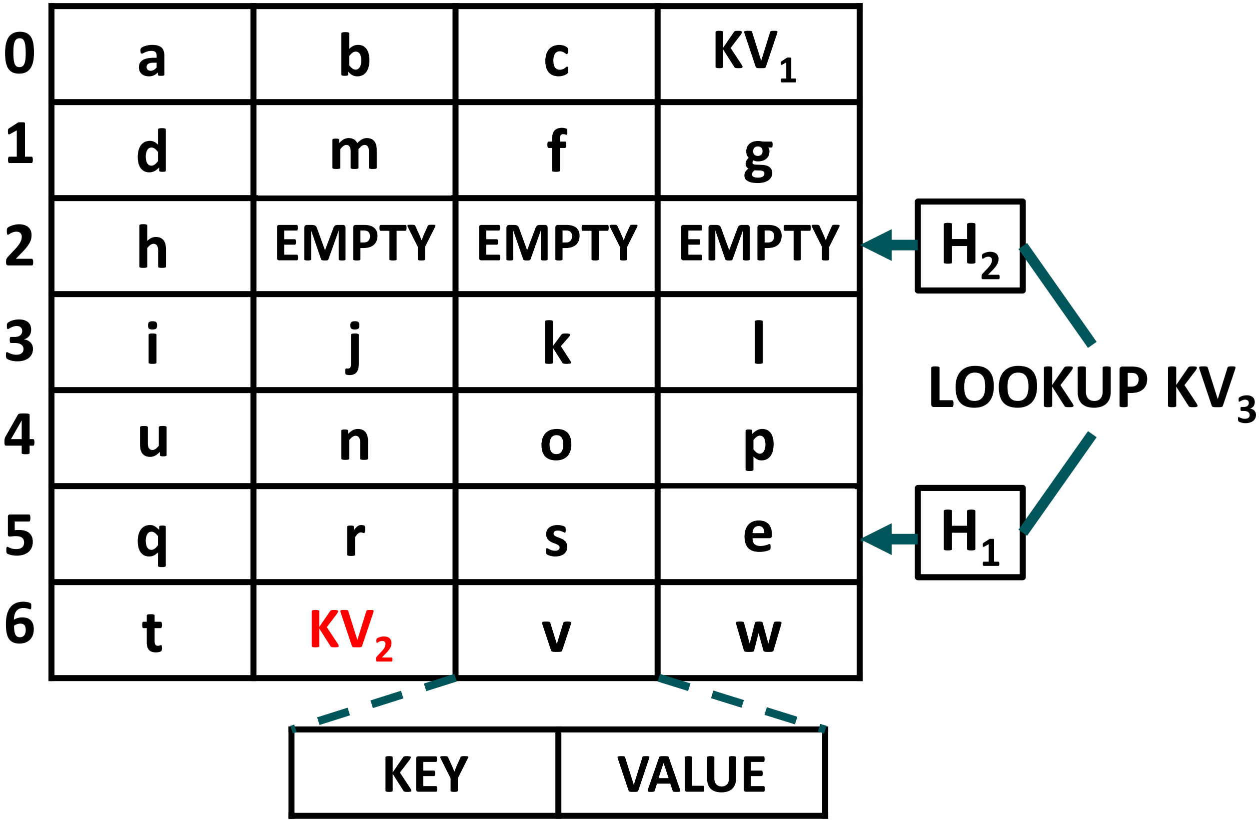
0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

KEY	VALUE

- Expected Negative Lookup Cost per Item in Buckets:
  - First-fit doesn't address the comparatively expensive negative lookup cost. We still need to check all candidate buckets.

BUCKETIZED CUCKOO HASH TABLES

LIMITATIONS OF FIRST-FIT



0	a	b	c	KV_1
1	d	m	f	g
2	h	EMPTY	EMPTY	EMPTY
3	i	j	k	l
4	u	n	o	p
5	q	r	s	e
6	t	KV_2	v	w

H_2

LOOKUP KV_3

H_1

KEY	VALUE

- Expected Negative Lookup Cost per Item in Buckets:
  - First-fit doesn't address the comparatively expensive negative lookup cost. We still need to check all candidate buckets.

HORTON TABLES

DESIGN GOALS

- Positive lookups that typically require accessing only 1 bucket per query
  - If buckets are at most a cache line in size, then only 1 cache line is accessed as well.

HORTON TABLES

DESIGN GOALS

- Positive lookups that typically require accessing only 1 bucket per query
  - If buckets are at most a cache line in size, then only 1 cache line is accessed as well.

- Negative lookups that typically require accessing only 1 bucket per query
  - If buckets are at most a cache line in size, then only 1 cache line is accessed as well.

HORTON TABLES

DESIGN GOALS

- Positive lookups that typically require accessing only 1 bucket per query
  - If buckets are at most a cache line in size, then only 1 cache line is accessed as well.
- Negative lookups that typically require accessing only 1 bucket per query
  - If buckets are at most a cache line in size, then only 1 cache line is accessed as well.
- Retain a worst-case lookup cost of 2 buckets (i.e., often 2 hardware cache lines)

HORTON TABLES

DESIGN GOALS

- Positive lookups that typically require accessing only 1 bucket per query
  - If buckets are at most a cache line in size, then only 1 cache line is accessed as well.

- Negative lookups that typically require accessing only 1 bucket per query
  - If buckets are at most a cache line in size, then only 1 cache line is accessed as well.

- Retain a worst-case lookup cost of 2 buckets (i.e., often 2 hardware cache lines)

- Achieve a load factor exceeding 0.95 (akin to a bucketized cuckoo hash table that uses 2 hash functions and 4-cell buckets)

HORTON TABLES

PRIMARY INSERTIONS AND LOOKUPS

0	8	5	EMPTY	EMPTY
1	33	EMPTY	15	2
2	35	18	22	EMPTY
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

HORTON TABLES

PRIMARY INSERTIONS AND LOOKUPS

0	8	5	EMPTY	EMPTY
1	33	EMPTY	15	2
2	35	18	22	EMPTY
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

- Horton tables start off as standard bucketized cuckoo hash tables

HORTON TABLES

PRIMARY INSERTIONS AND LOOKUPS

0	**8**	**5**	**EMPTY**	**EMPTY**
1	**33**	**EMPTY**	**15**	**2**
2	**35**	**18**	**22**	**EMPTY**
3	**EMPTY**	**EMPTY**	**EMPTY**	**37**
4	**17**	**6**	**21**	**EMPTY**
5	**9**	**24**	**EMPTY**	**EMPTY**

- Horton tables start off as standard bucketized cuckoo hash tables
- Like first-fit, they strongly bias inserts by using a *primary hash function* called H_{primary}

HORTON TABLES

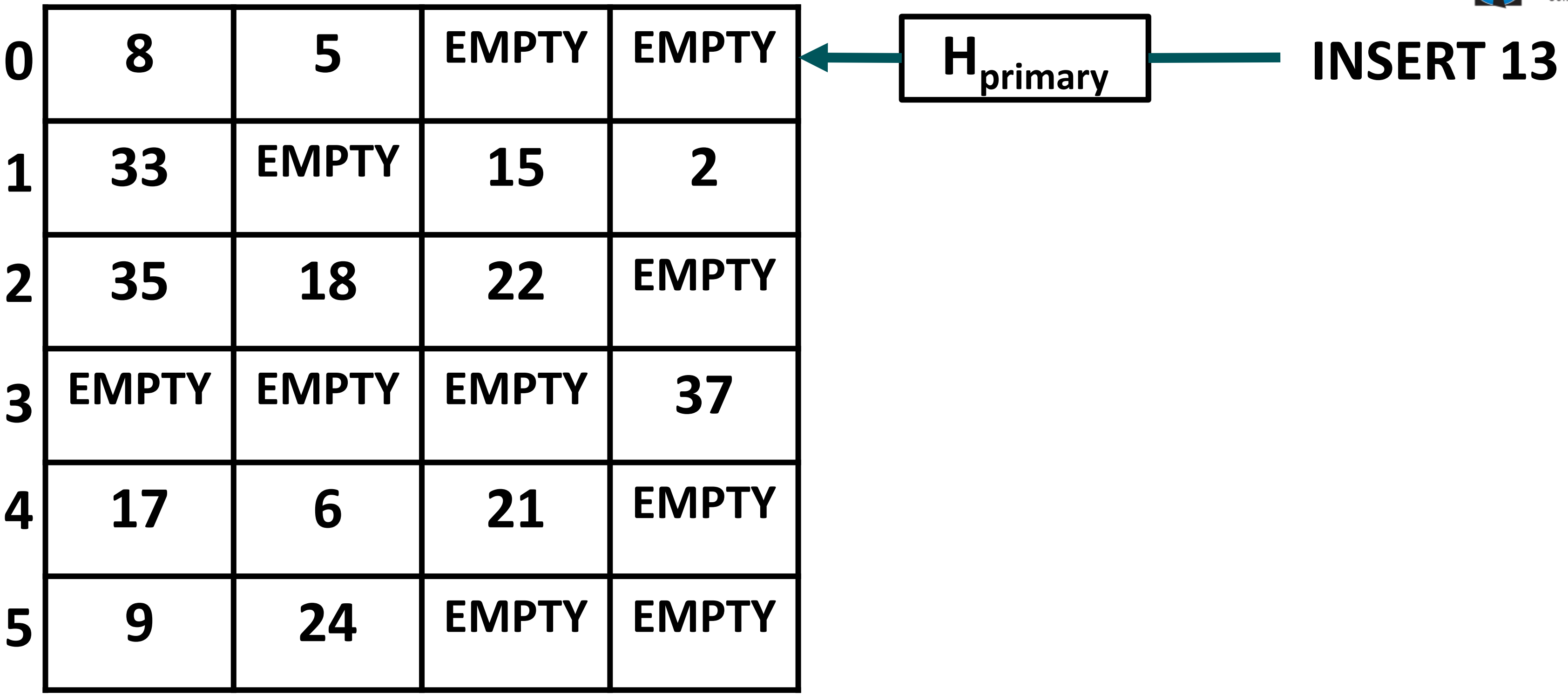
PRIMARY INSERTIONS AND LOOKUPS

0	8	5	EMPTY	EMPTY
1	33	EMPTY	15	2
2	35	18	22	EMPTY
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

- Horton tables start off as standard bucketized cuckoo hash tables
- Like first-fit, they strongly bias inserts by using a *primary hash function* called $H_{primary}$
- Most positive lookups therefore only require accessing a single cache line

HORTON TABLES

PRIMARY INSERTIONS AND LOOKUPS



0	8	5	EMPTY	EMPTY
1	33	EMPTY	15	2
2	35	18	22	EMPTY
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

- Horton tables start off as standard bucketized cuckoo hash tables
- Like first-fit, they strongly bias inserts by using a *primary hash function* called $H_{primary}$
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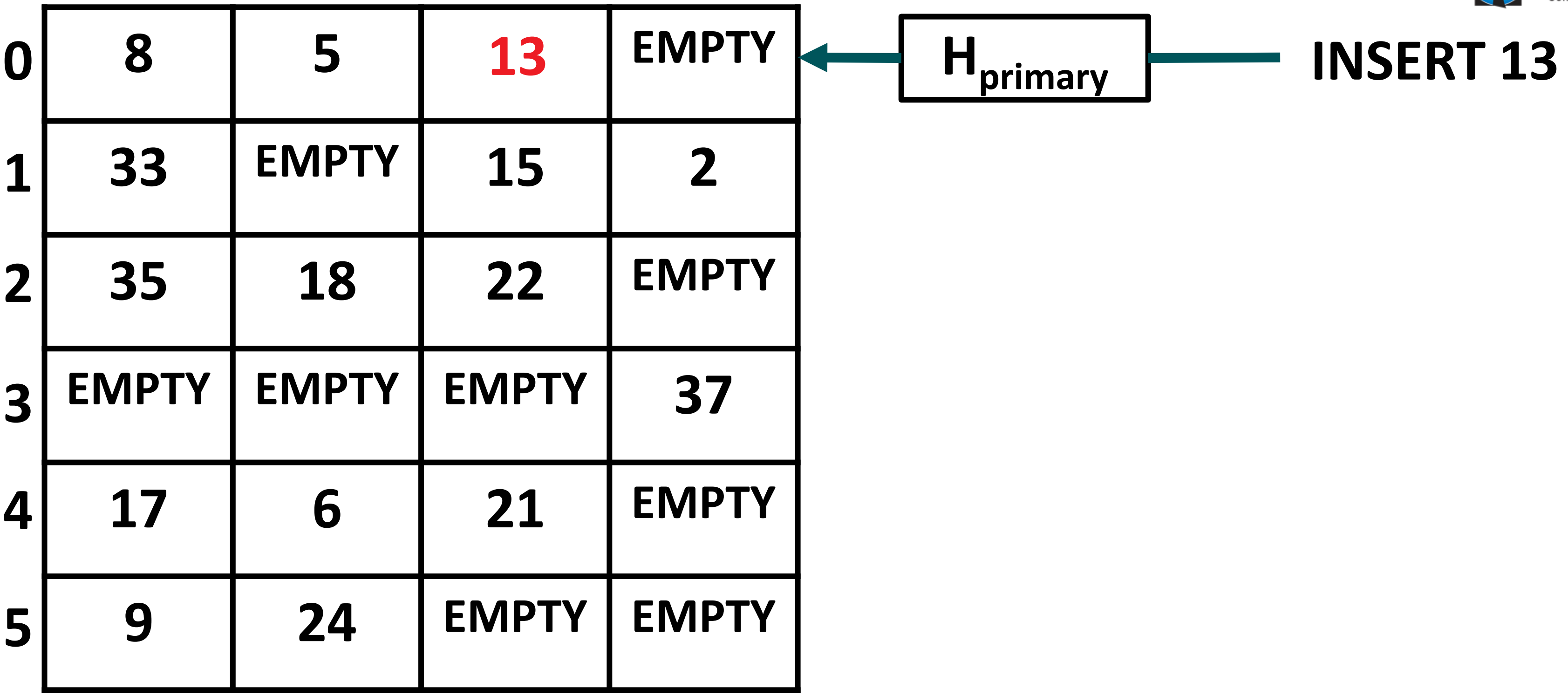
HORTON TABLES

PRIMARY INSERTIONS AND LOOKUPS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	EMPTY
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

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HORTON TABLES

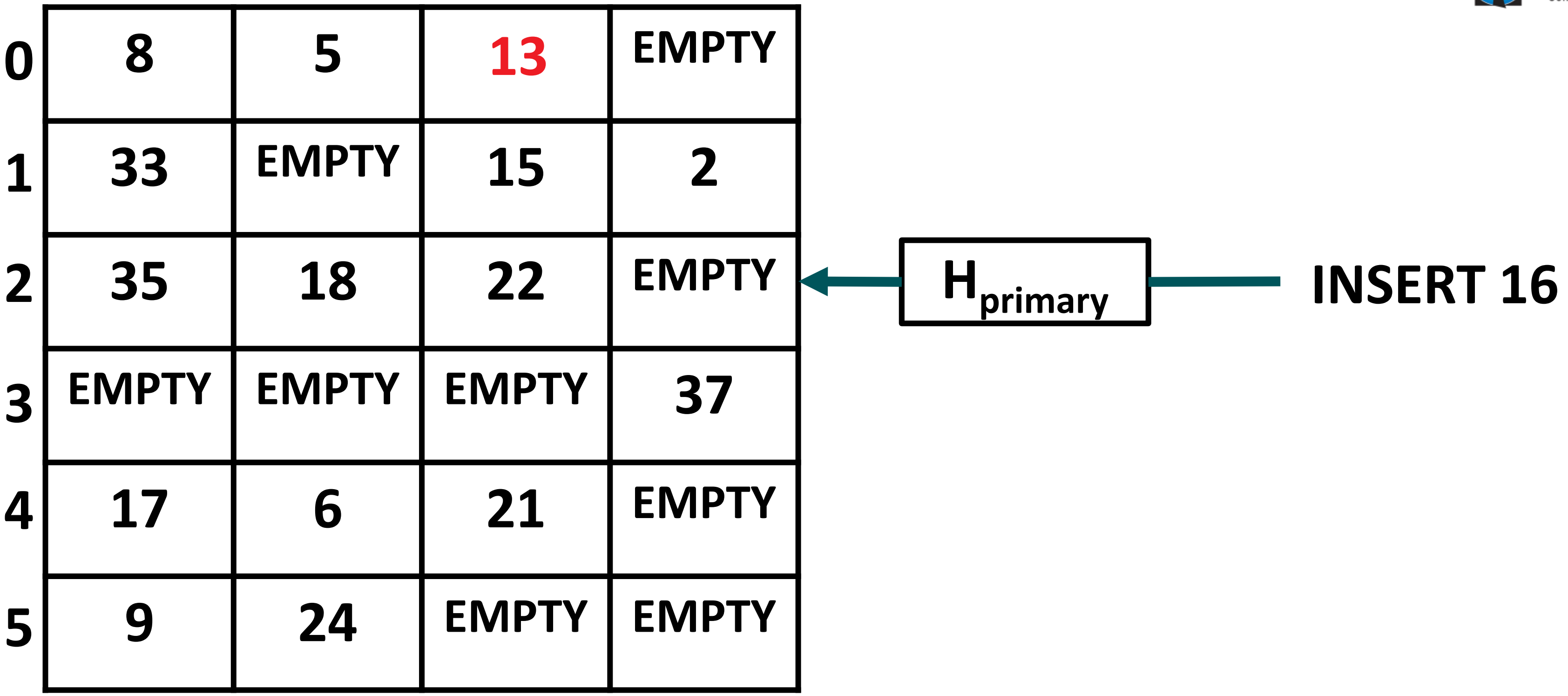
PRIMARY INSERTIONS AND LOOKUPS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	EMPTY
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

- Horton tables start off as standard bucketized cuckoo hash tables
- Like first-fit, they strongly bias inserts by using a *primary hash function* called $H_{primary}$
- Most positive lookups therefore only require accessing a single cache line

HORTON TABLES

PRIMARY INSERTIONS AND LOOKUPS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	EMPTY
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

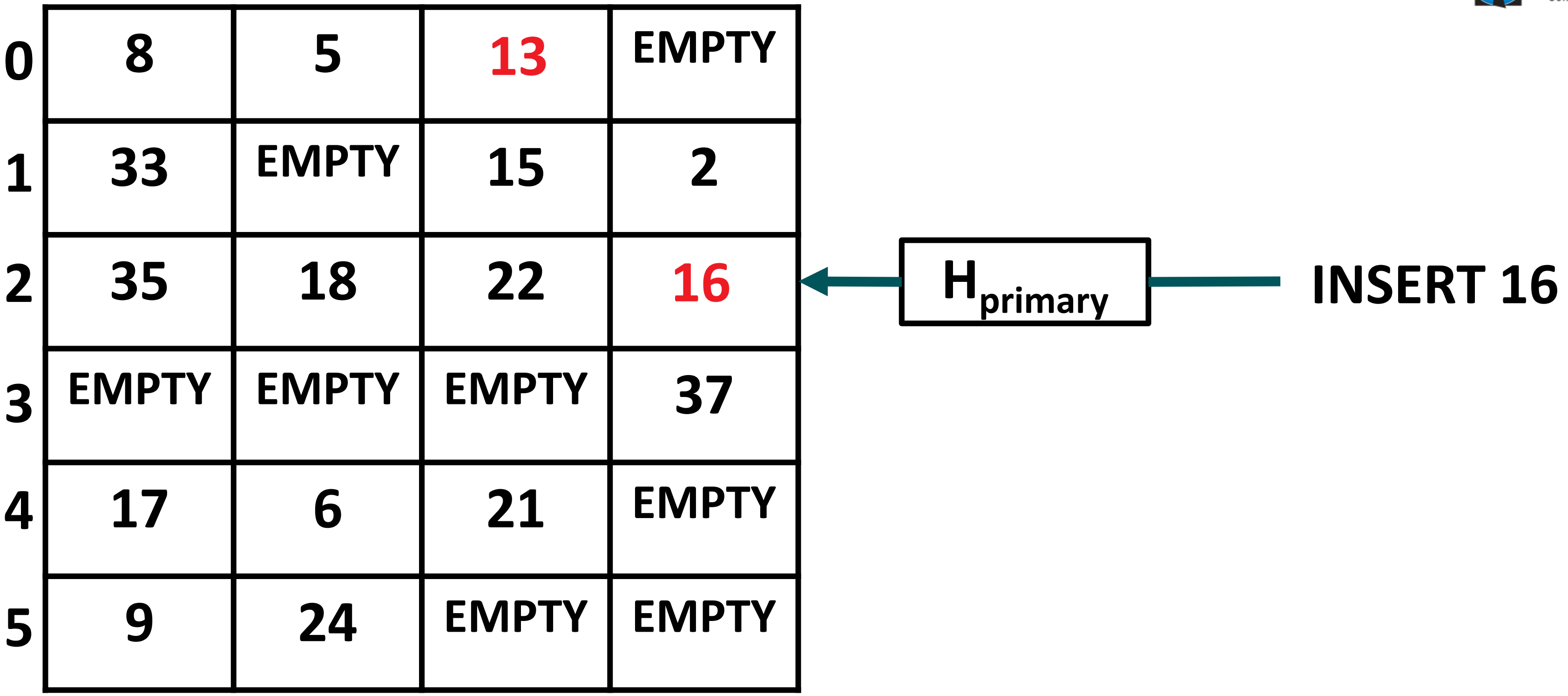
$H_{primary}$

INSERT 16

- Horton tables start off as standard bucketized cuckoo hash tables
- Like first-fit, they strongly bias inserts by using a *primary hash function* called $H_{primary}$
- Most positive lookups therefore only require accessing a single cache line

HORTON TABLES

PRIMARY INSERTIONS AND LOOKUPS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	16
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

$H_{primary}$

INSERT 16

- Horton tables start off as standard bucketized cuckoo hash tables
- Like first-fit, they strongly bias inserts by using a *primary hash function* called $H_{primary}$
- Most positive lookups therefore only require accessing a single cache line

HORTON TABLES

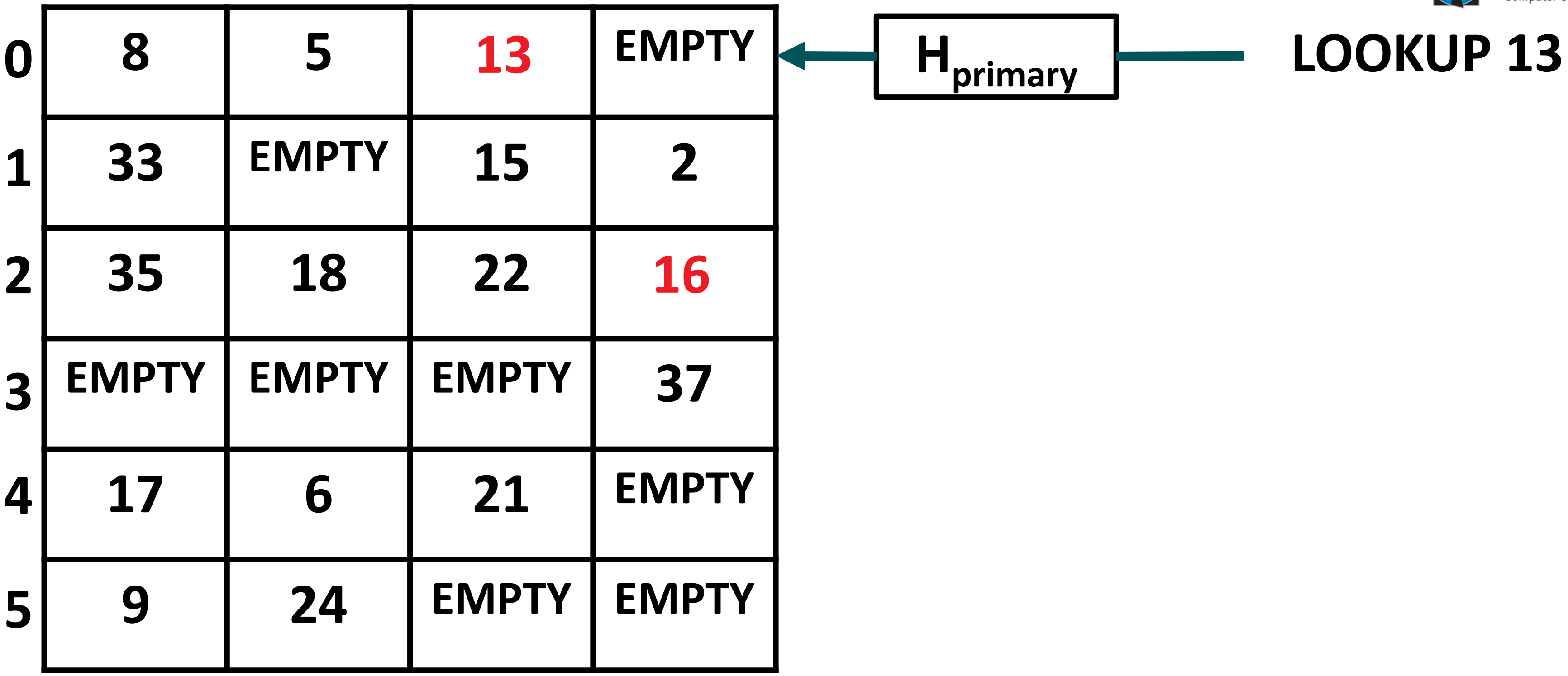
PRIMARY INSERTIONS AND LOOKUPS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	16
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

- Horton tables start off as standard bucketized cuckoo hash tables
- Like first-fit, they strongly bias inserts by using a *primary hash function* called $H_{primary}$
- Most positive lookups therefore only require accessing a single cache line

HORTON TABLES

PRIMARY INSERTIONS AND LOOKUPS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	16
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

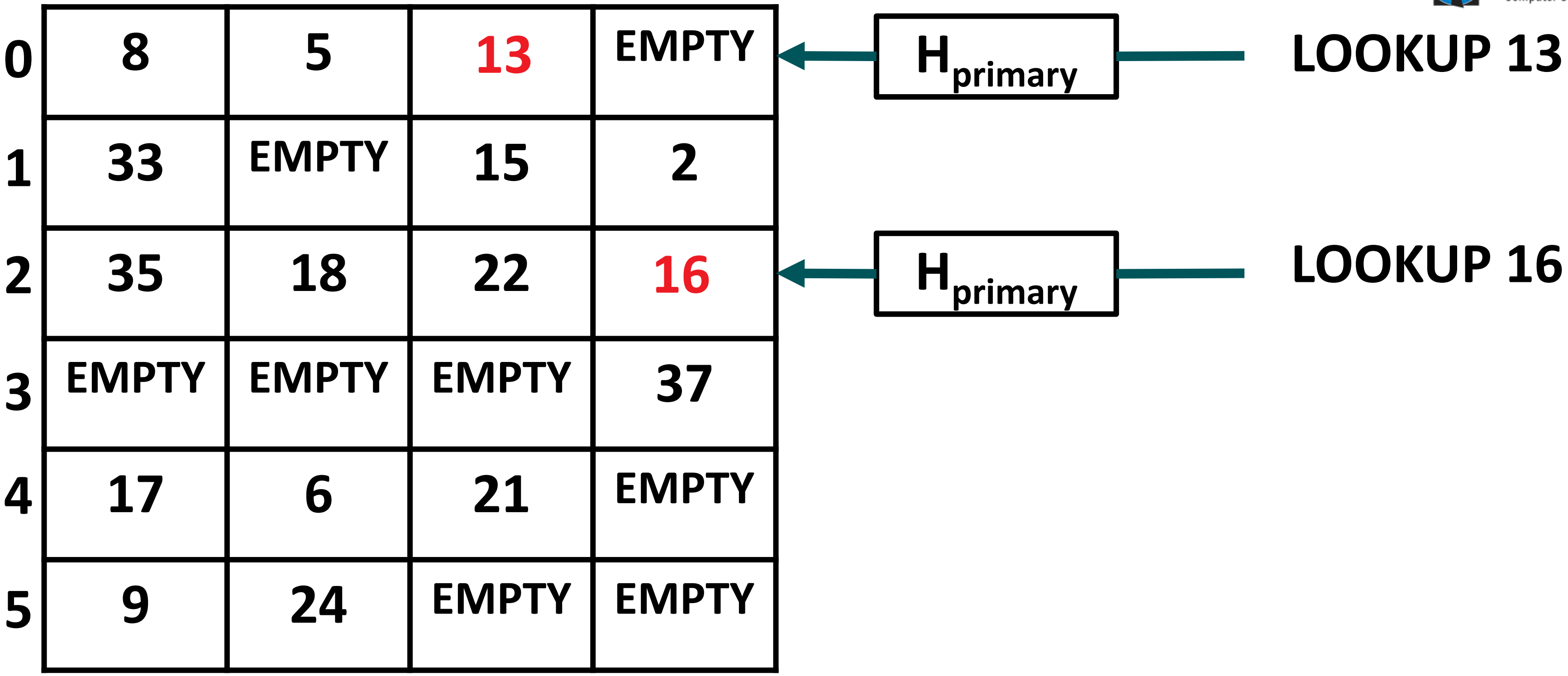
$H_{primary}$

LOOKUP 13

- Horton tables start off as standard bucketized cuckoo hash tables
- Like first-fit, they strongly bias inserts by using a *primary hash function* called $H_{primary}$
- Most positive lookups therefore only require accessing a single cache line

HORTON TABLES

PRIMARY INSERTIONS AND LOOKUPS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	16
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

- Horton tables start off as standard bucketized cuckoo hash tables
- Like first-fit, they strongly bias inserts by using a *primary hash function* called $H_{primary}$
- Most positive lookups therefore only require accessing a single cache line

HORTON TABLES

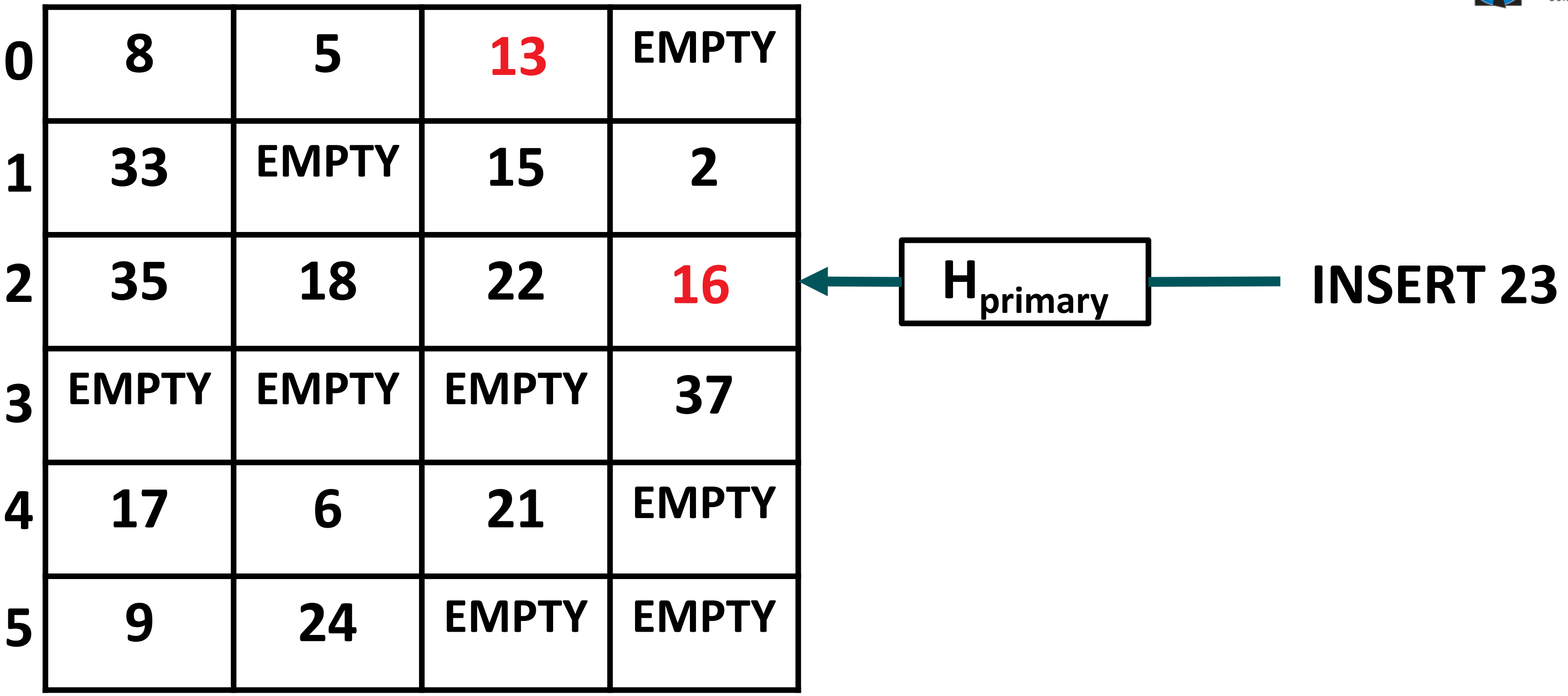
INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	16
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY

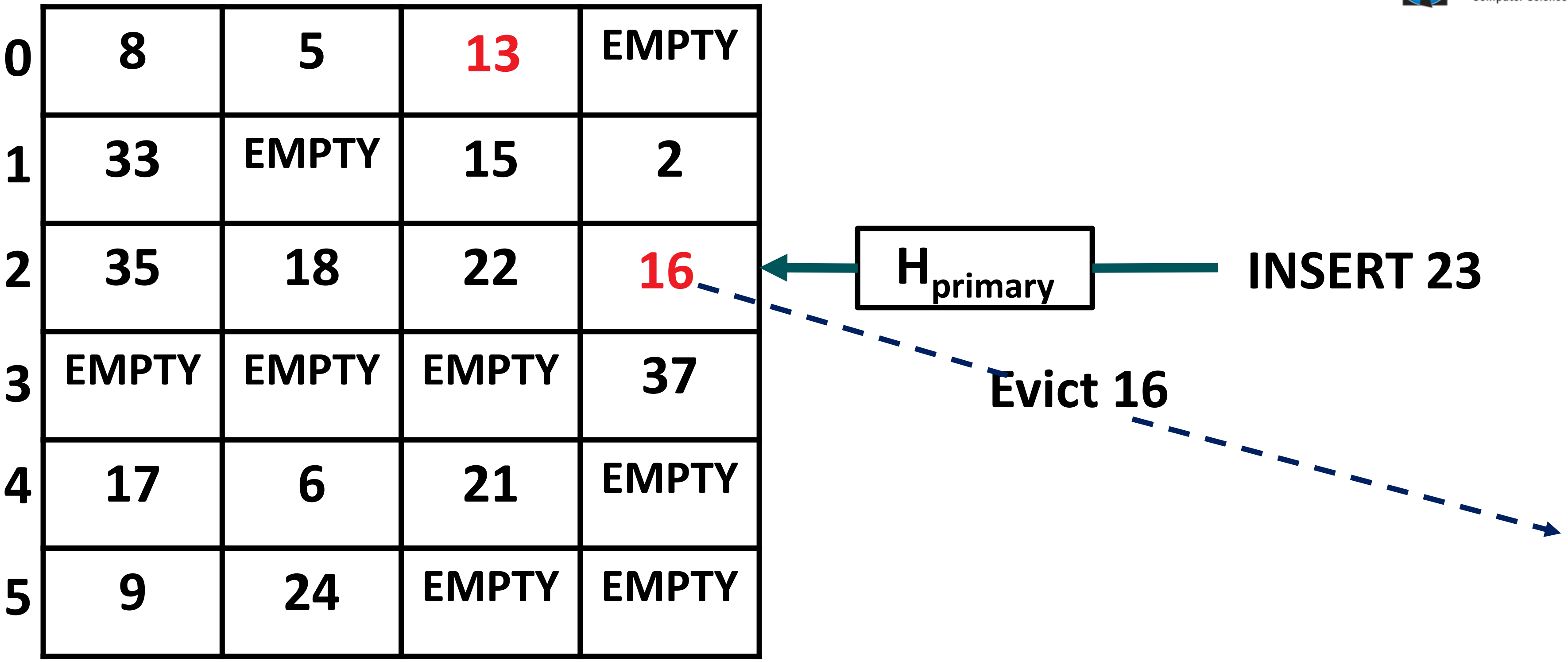


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	16
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	16
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

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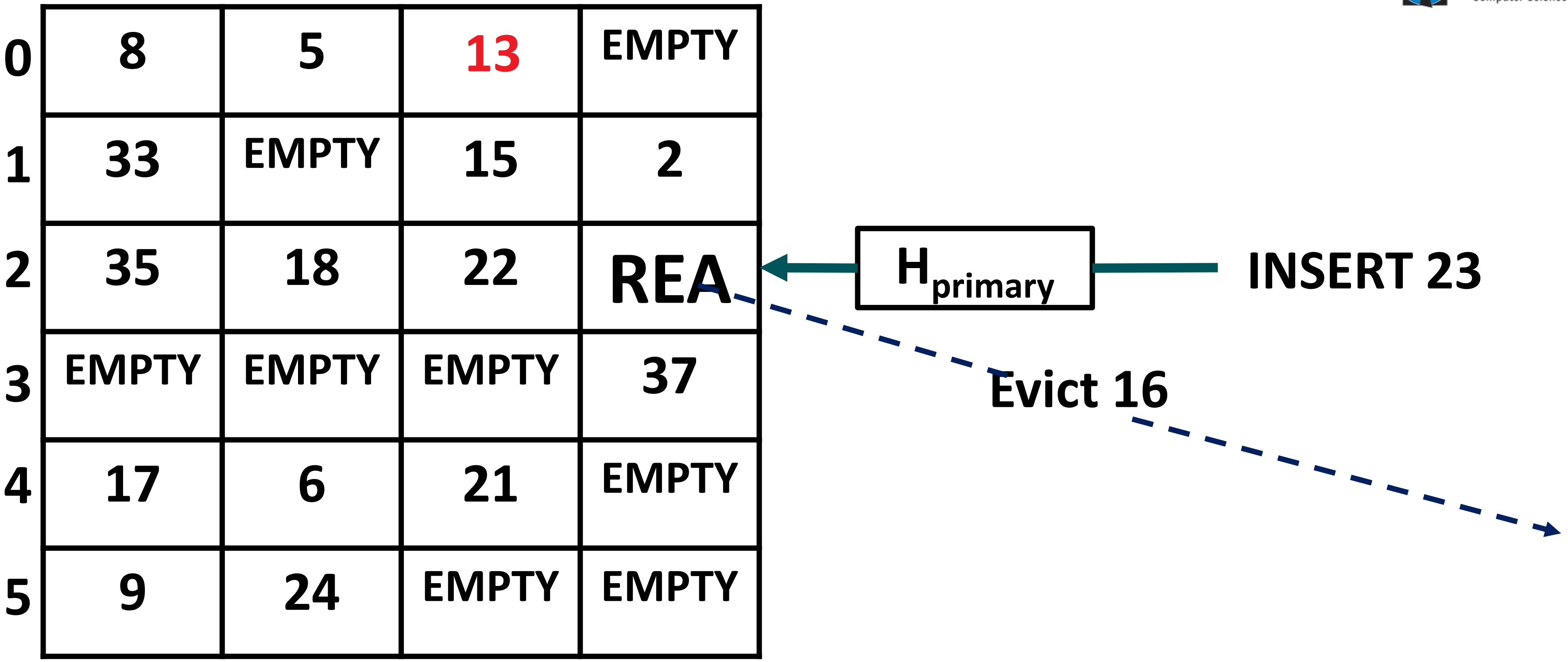
HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

$H_{primary}$

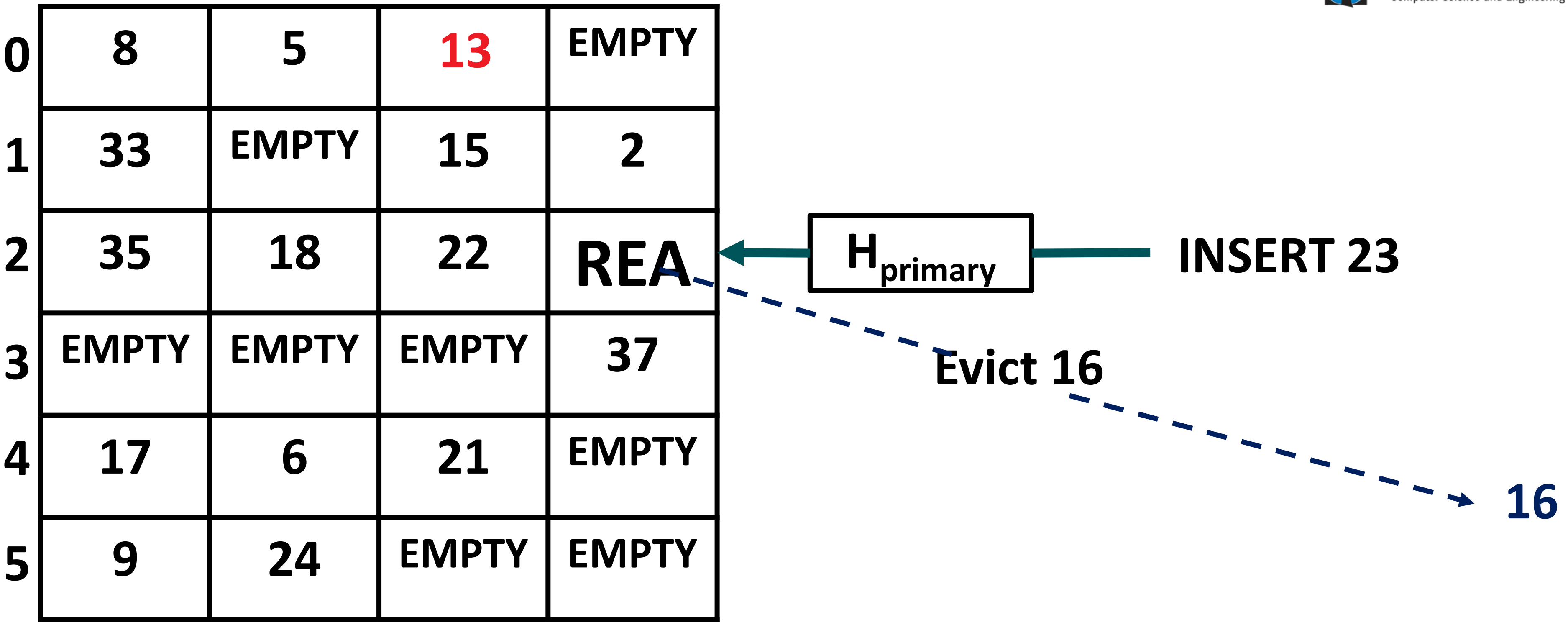
INSERT 23

Evict 16

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



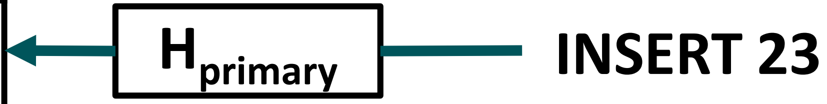
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY



$H_{primary}$

INSERT 23

16

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY

0	**8**	**5**	**13**	**EMPTY**
1	**33**	**EMPTY**	**15**	**2**
2	**35**	**18**	**22**	**REA**
3	**EMPTY**	**EMPTY**	**EMPTY**	**37**
4	**17**	**6**	**21**	**EMPTY**
5	**9**	**24**	**EMPTY**	**EMPTY**

INSERT 23

16

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

16

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

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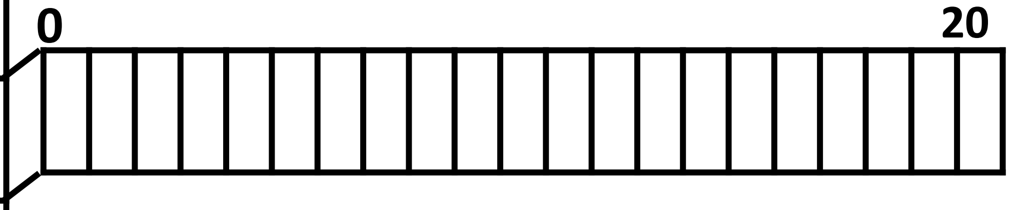
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

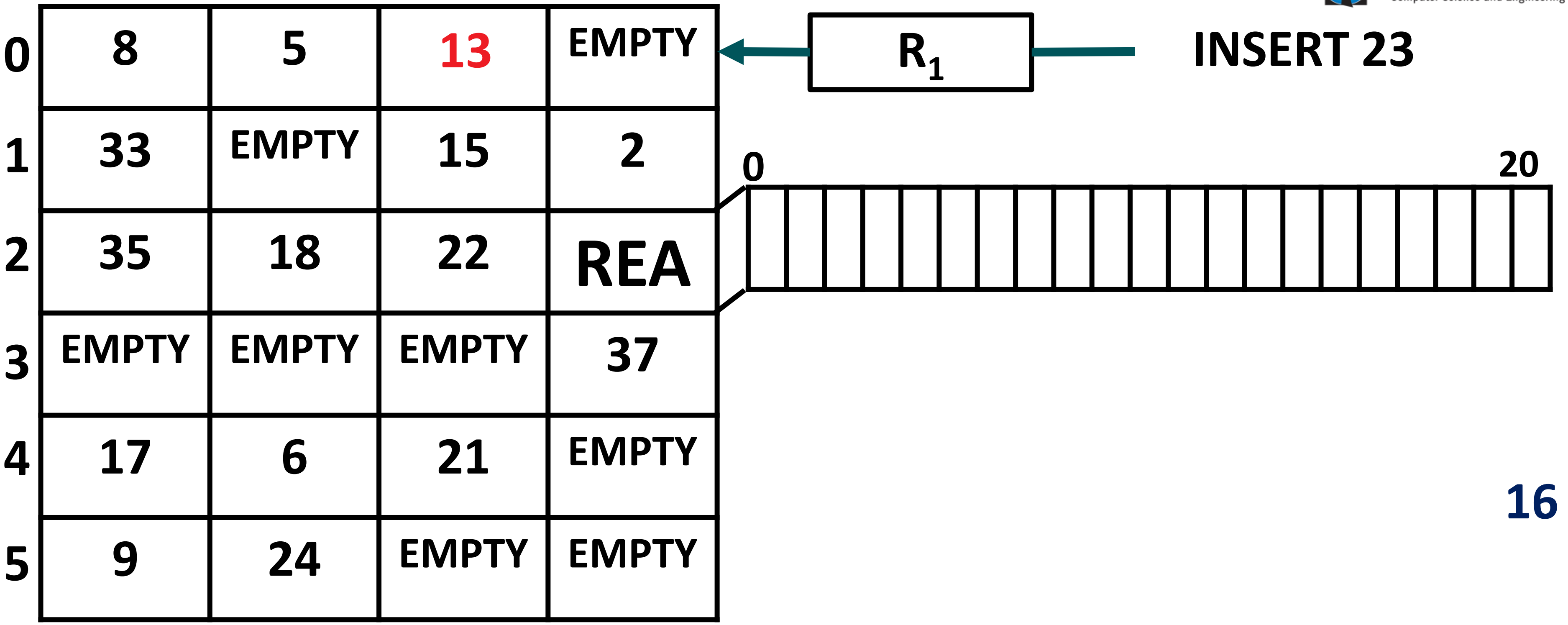


16

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

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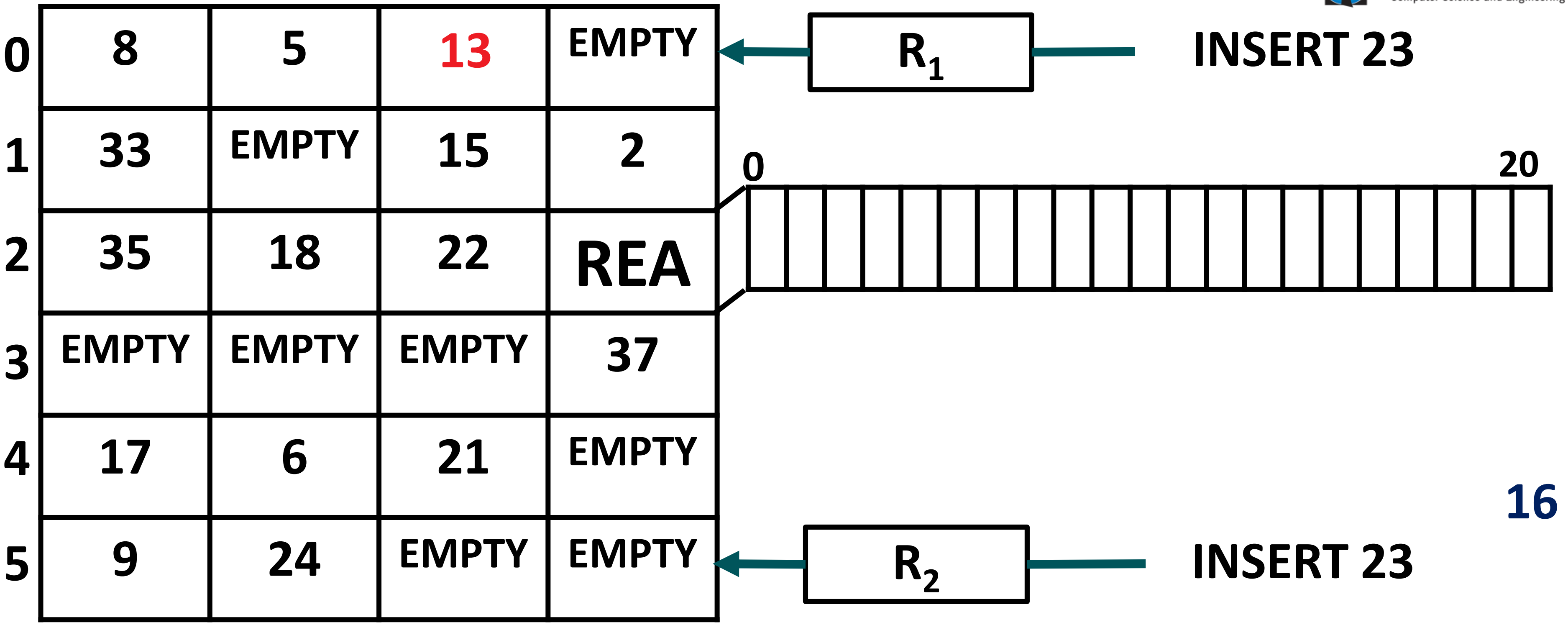
HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

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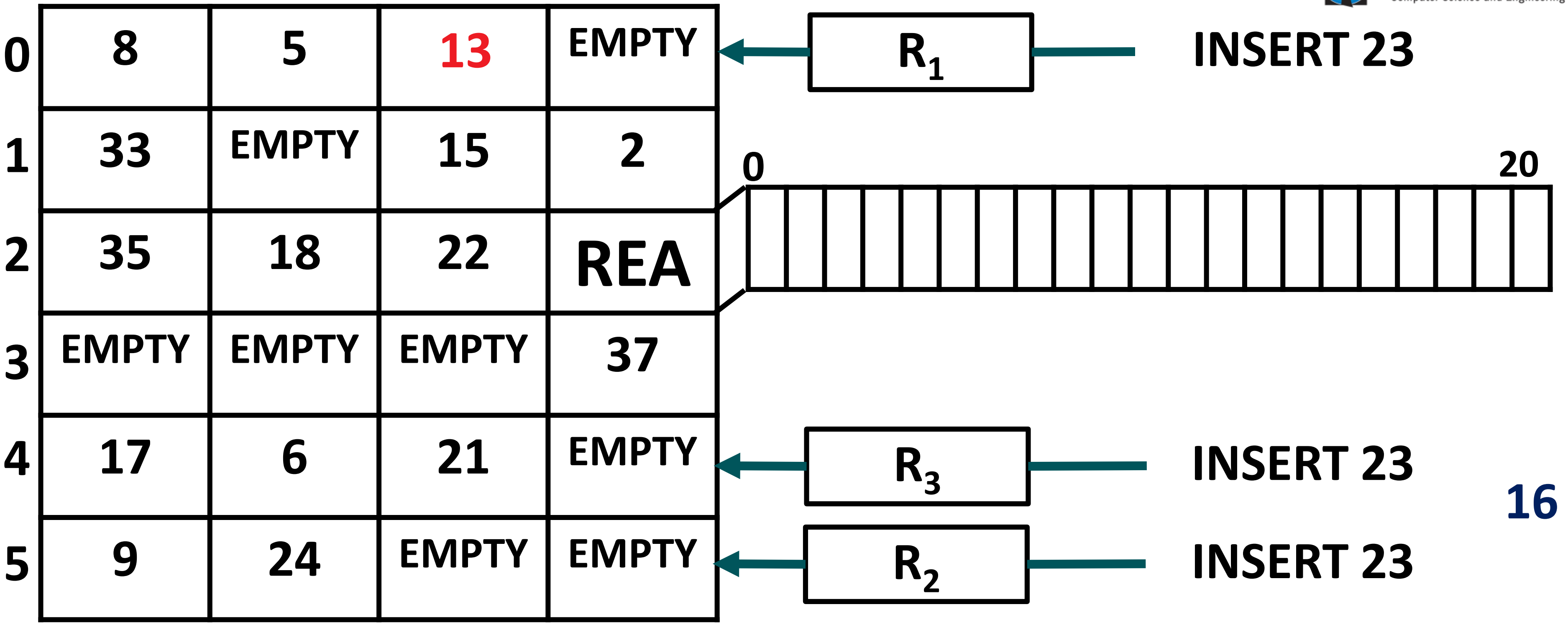
HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

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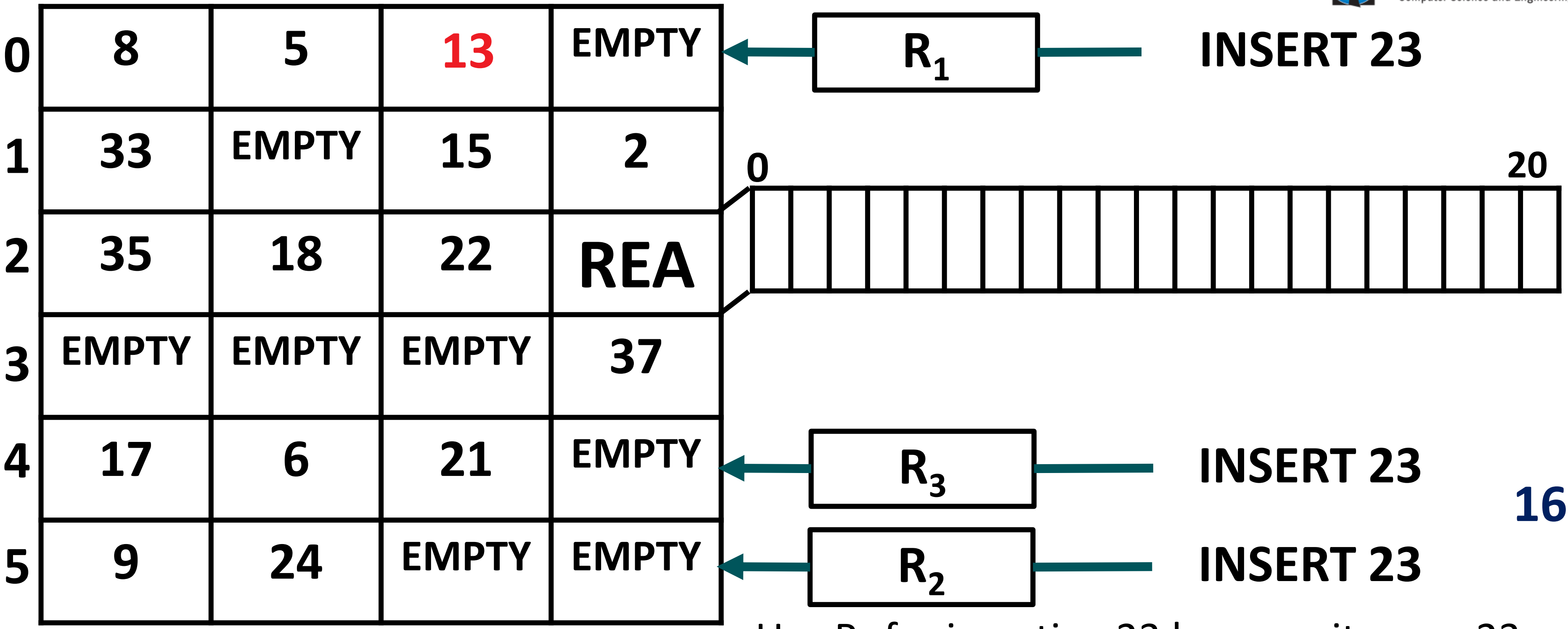
HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



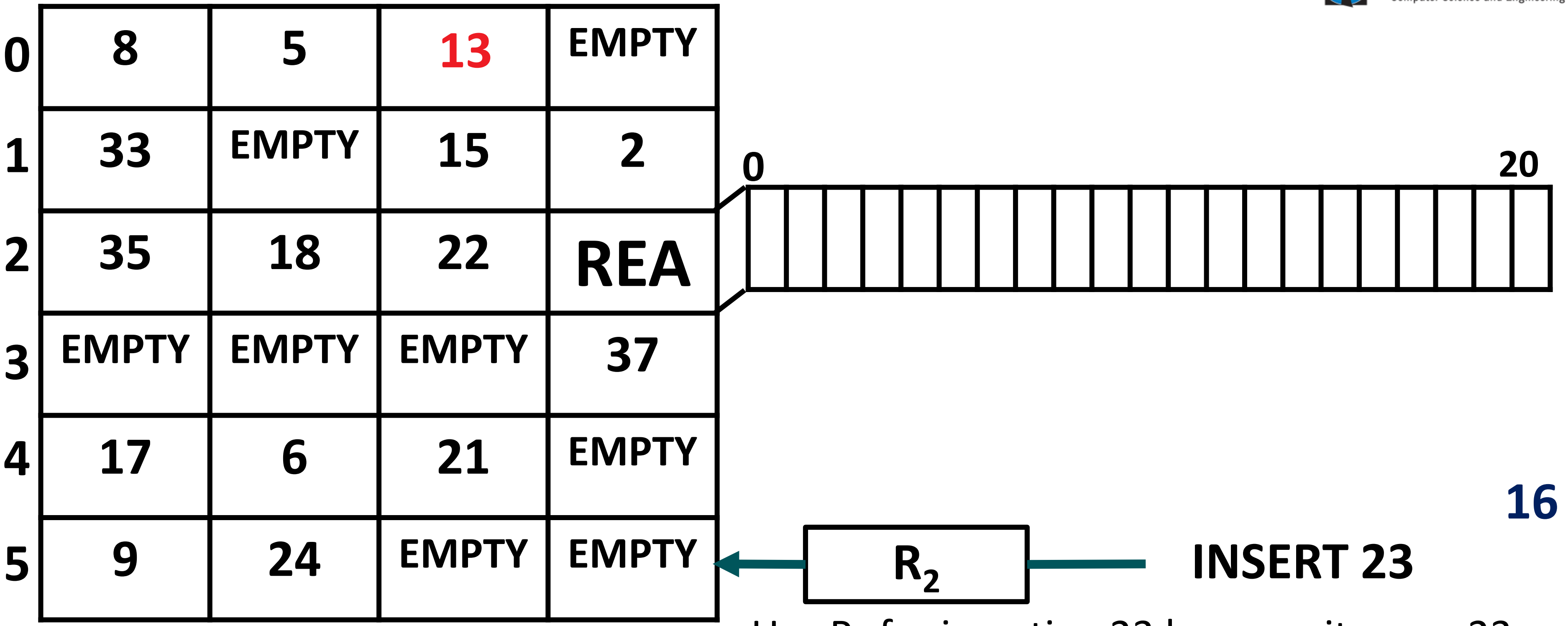
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

Use R_2 for inserting 23 because it maps 23 to least full secondary bucket candidate.

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



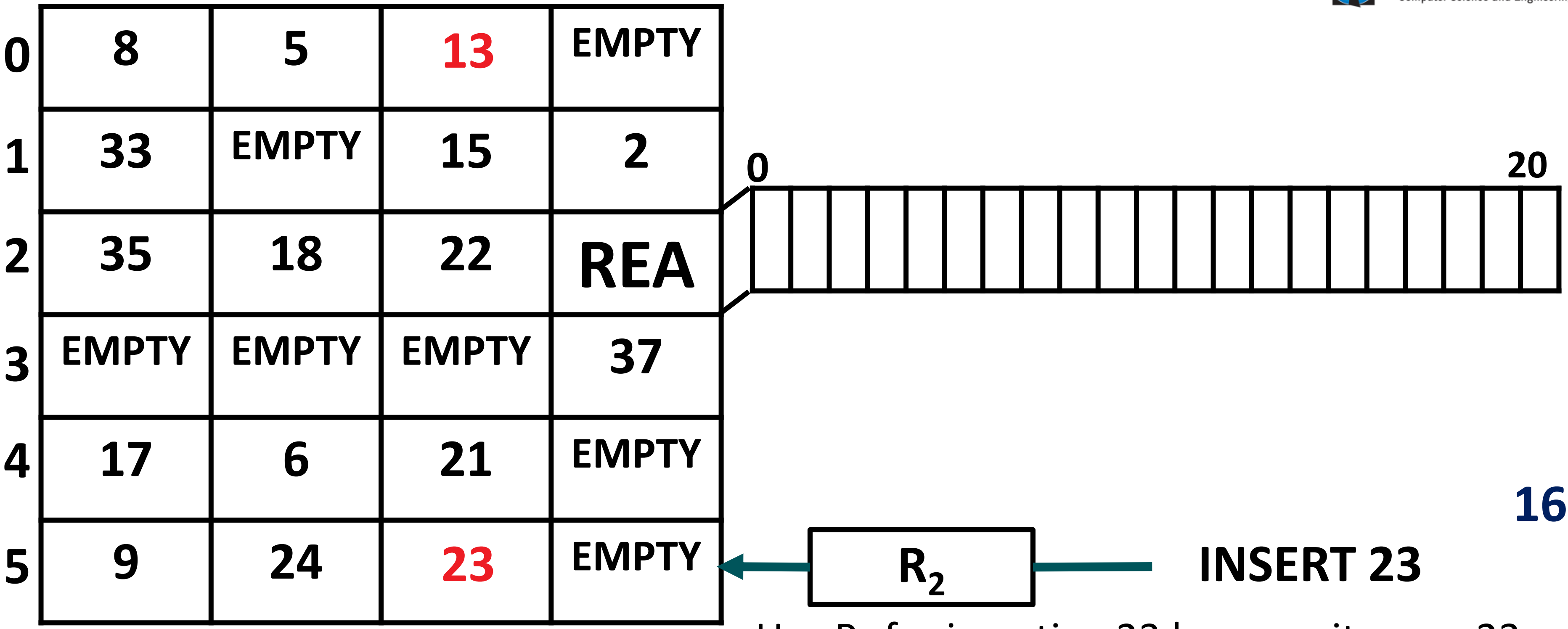
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	EMPTY	EMPTY

Use R_2 for inserting 23 because it maps 23 to least full secondary bucket candidate.

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



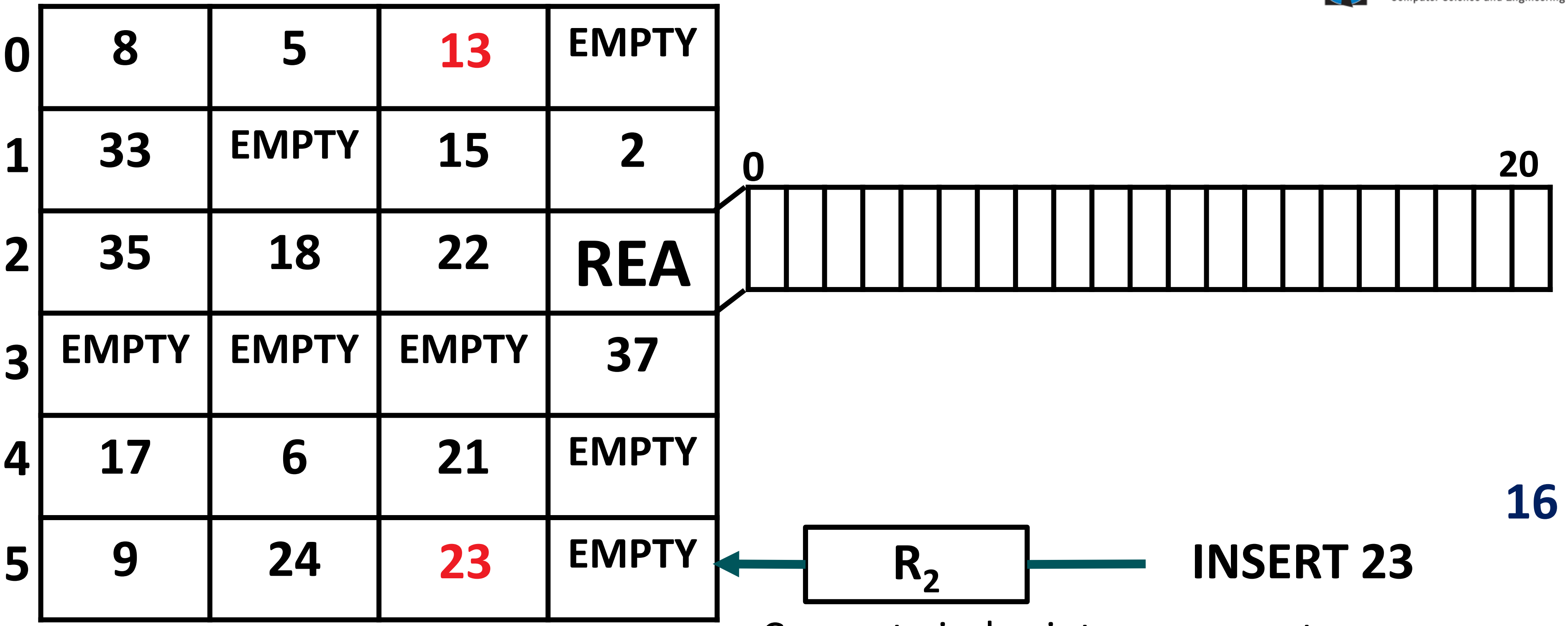
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Use R_2 for inserting 23 because it maps 23 to least full secondary bucket candidate.

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



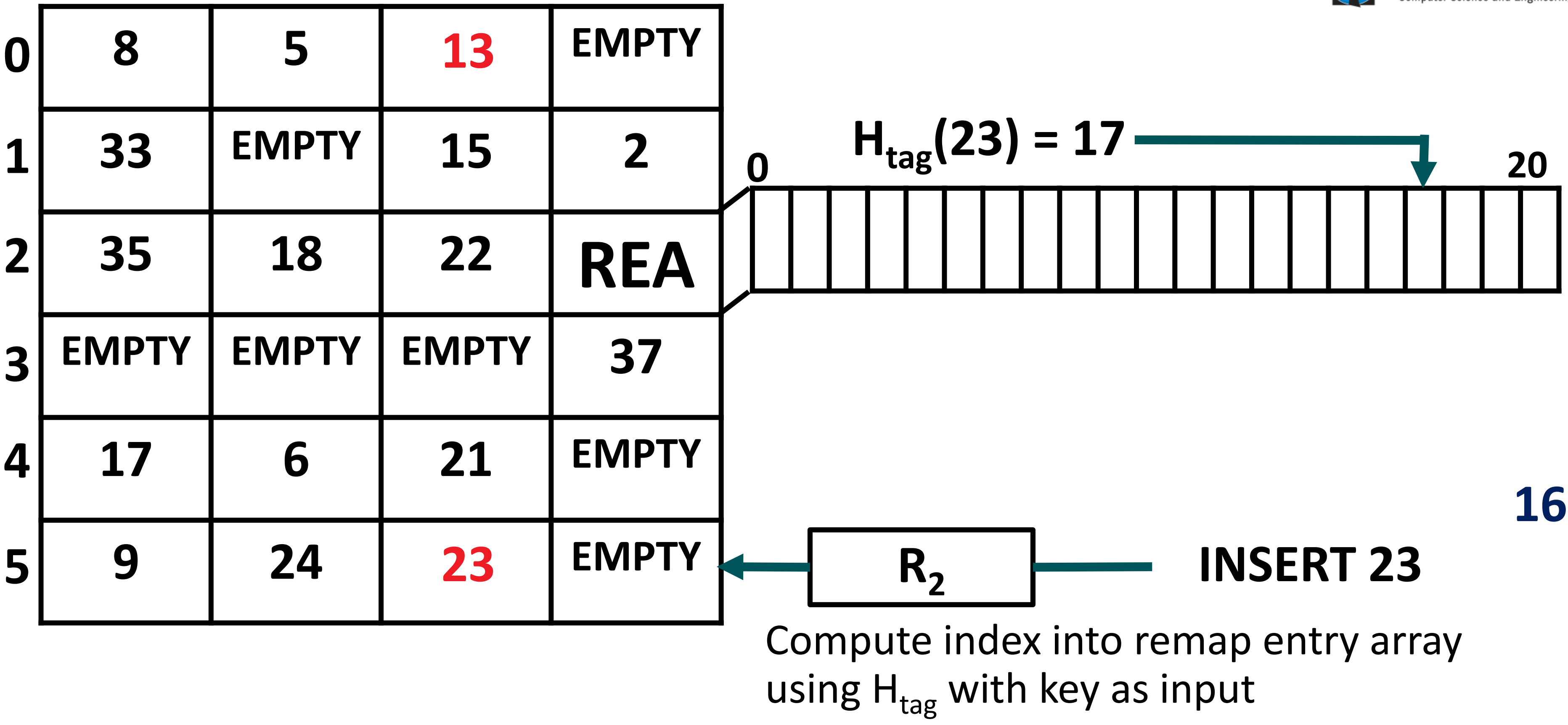
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Compute index into remap entry array using H_{tag} with key as input

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

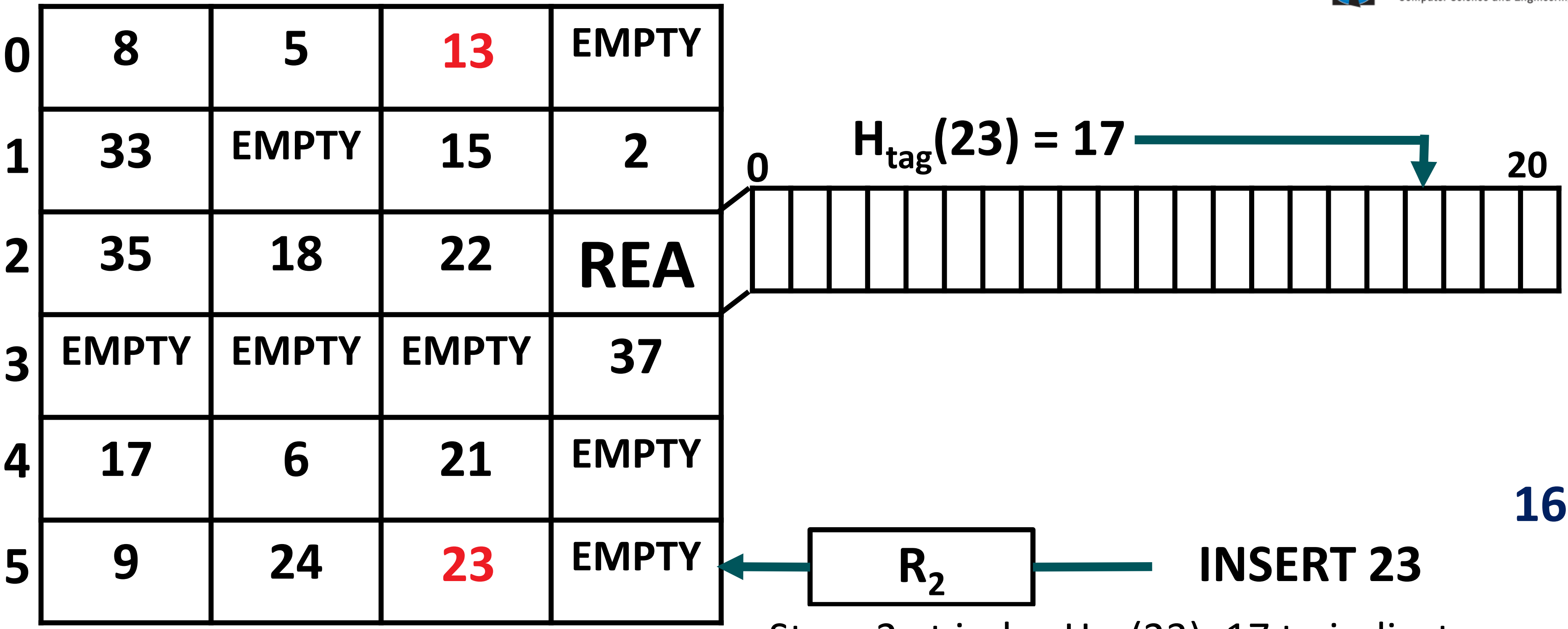
16

Compute index into remap entry array using H_{tag} with key as input

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



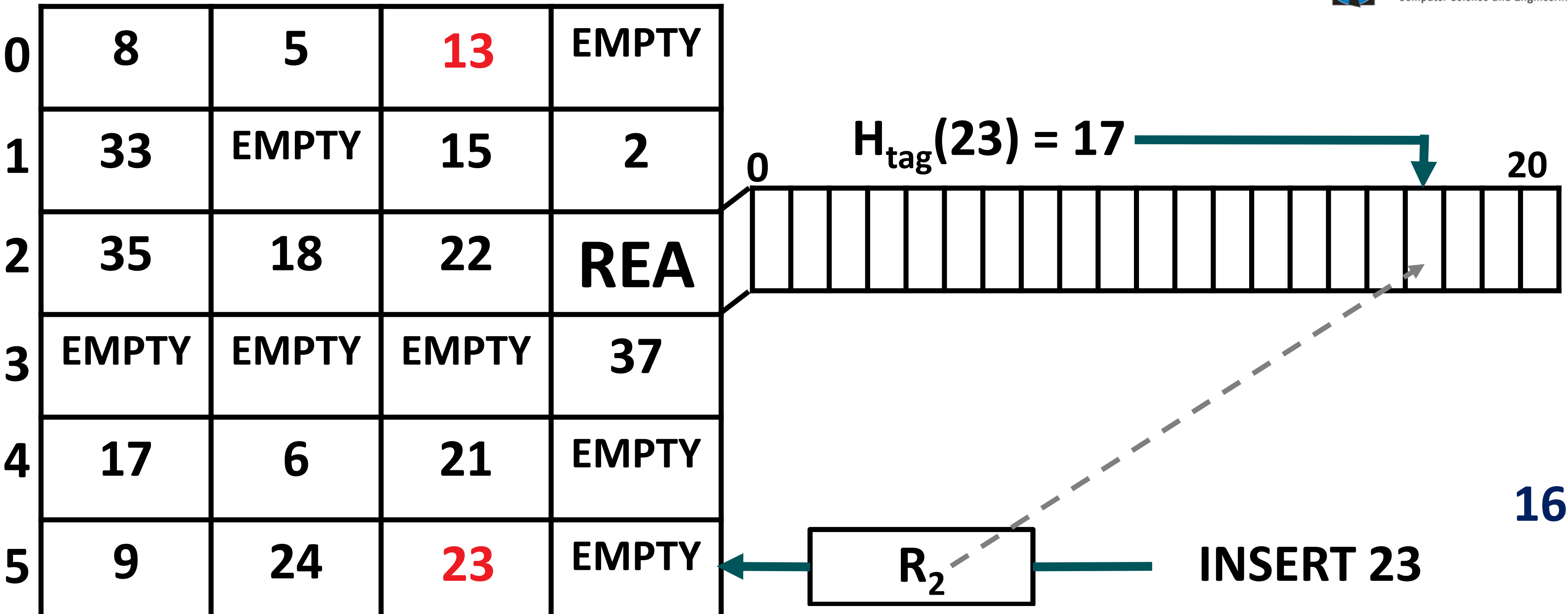
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Store 2 at index $H_{tag}(23)=17$ to indicate that R_2 was used to remap 23

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



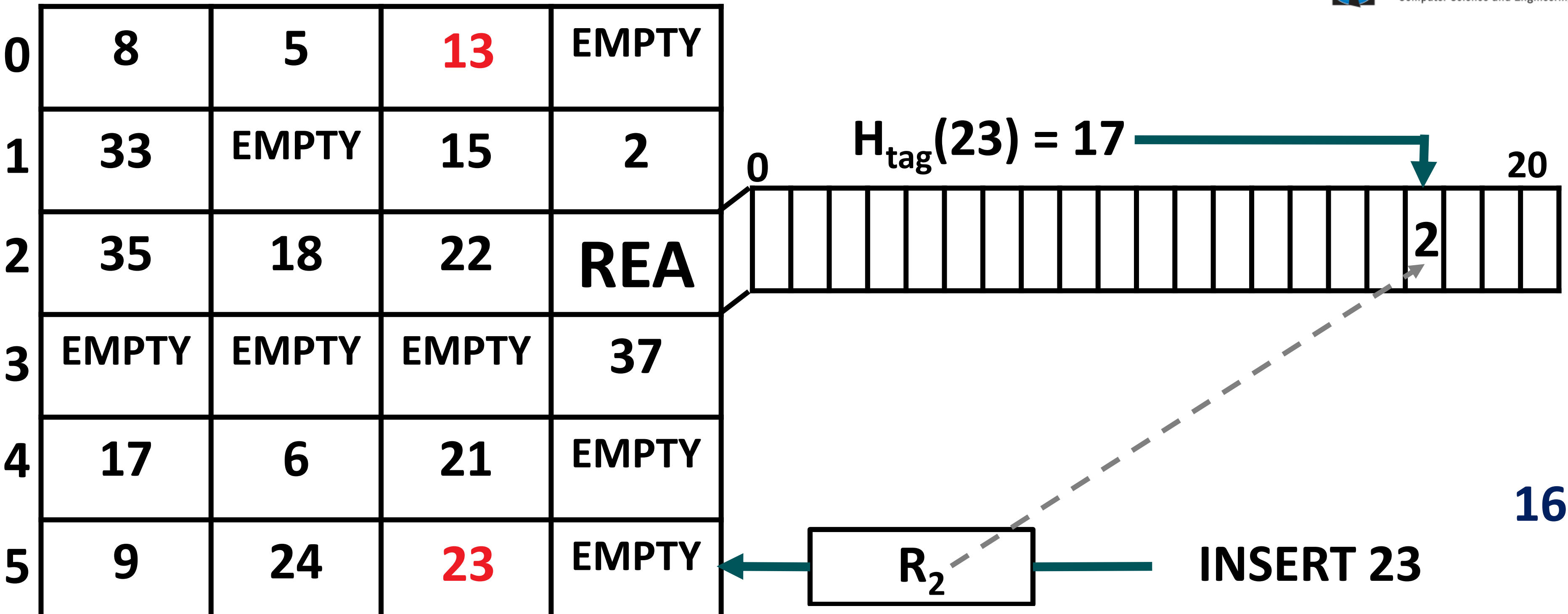
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Store 2 at index $H_{tag}(23)=17$ to indicate that R_2 was used to remap 23

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



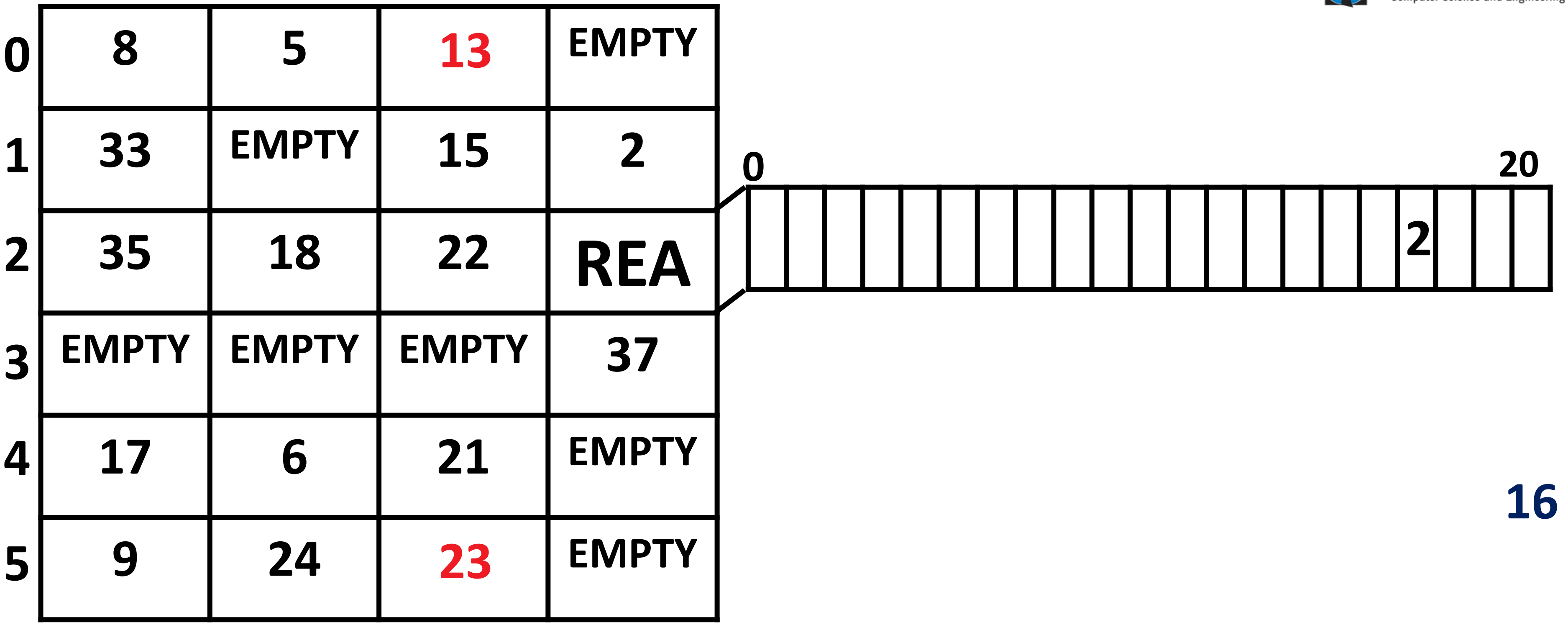
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Store 2 at index $H_{tag}(23)=17$ to indicate that R_2 was used to remap 23

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY

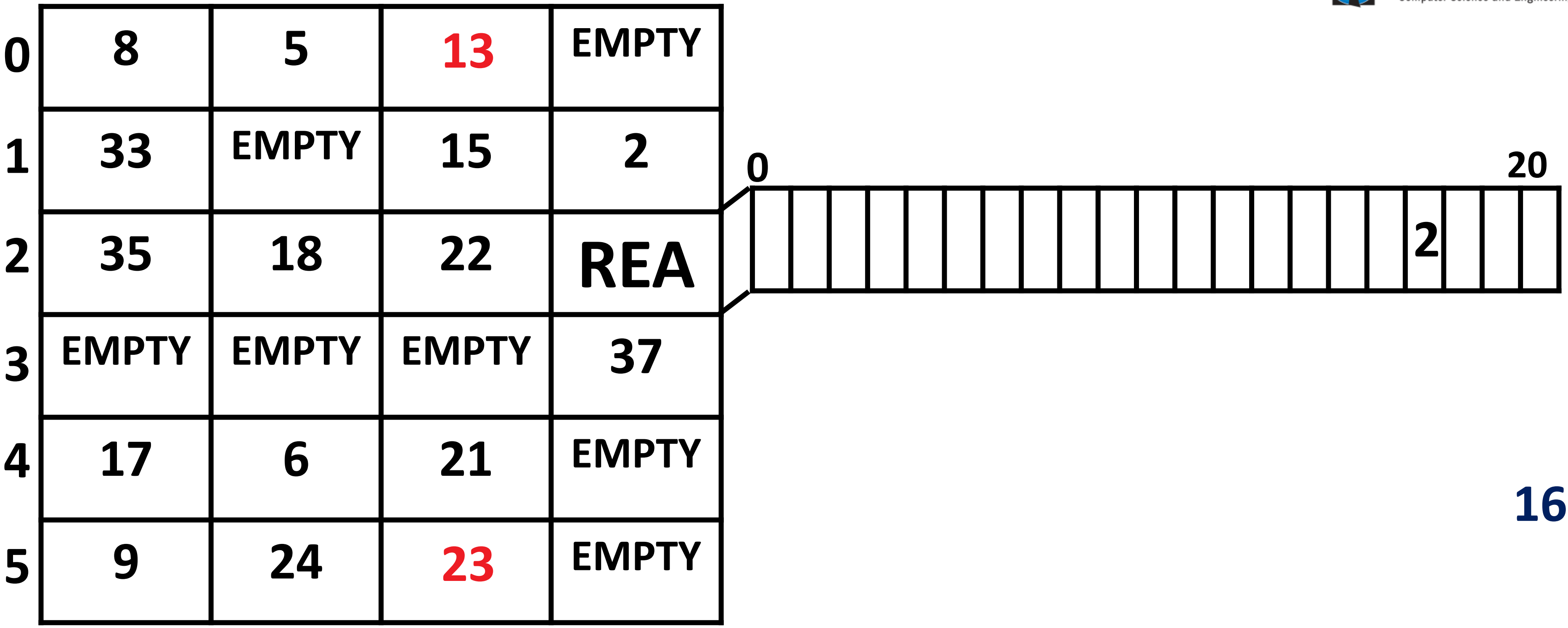


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

16 now also needs to be remapped to a secondary bucket.

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

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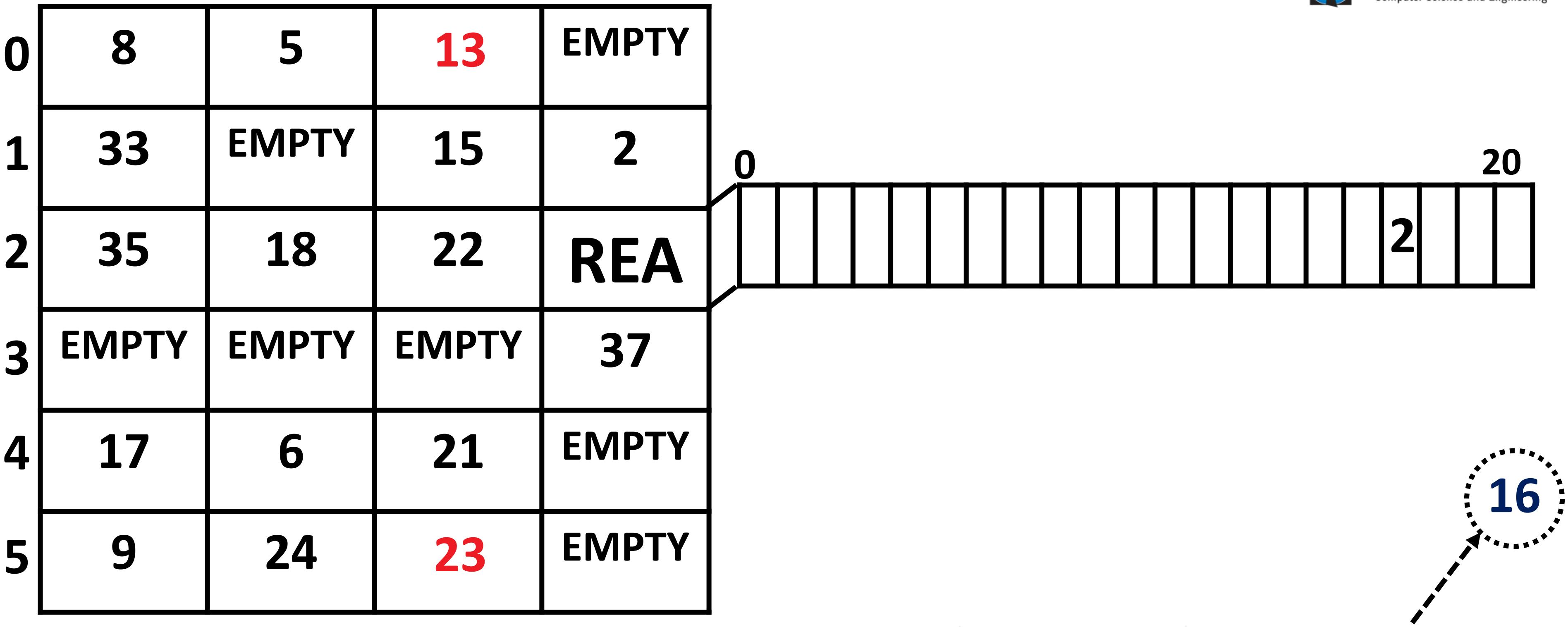

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

16 now also needs to be remapped to a secondary bucket.

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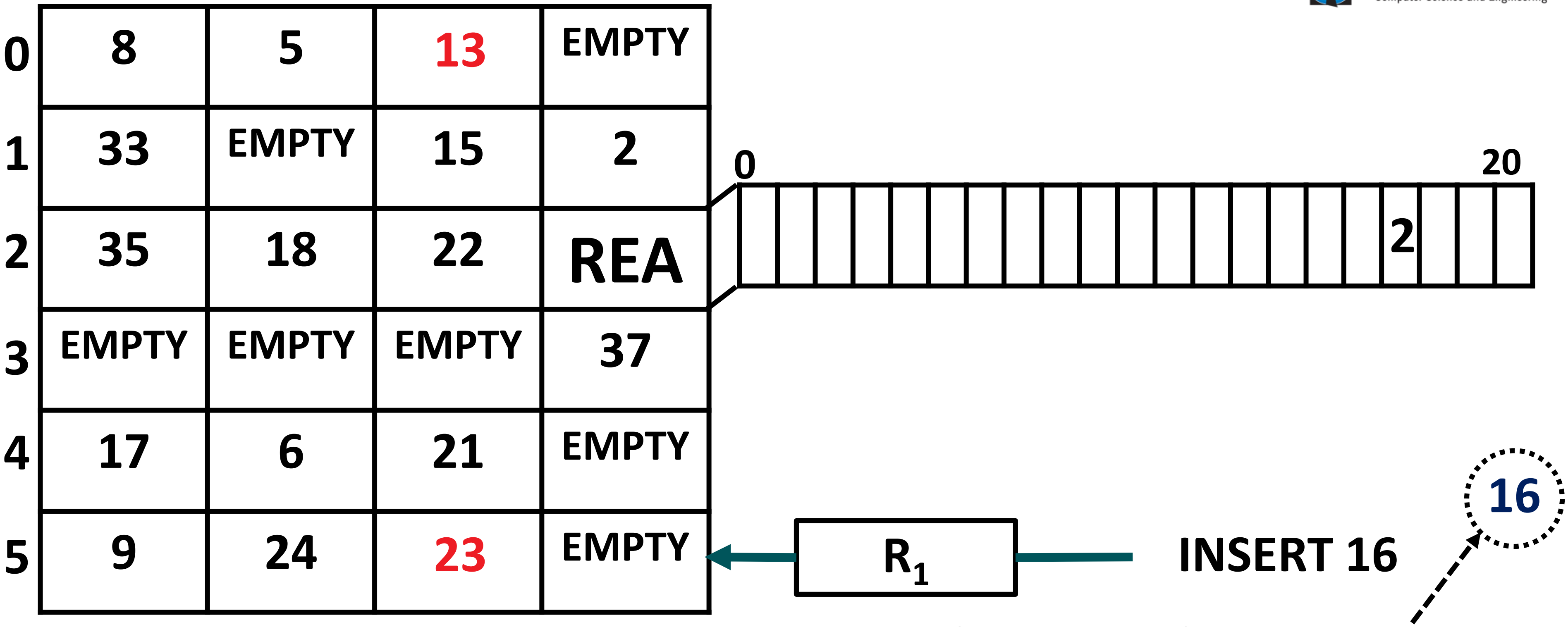
HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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HORTON TABLES

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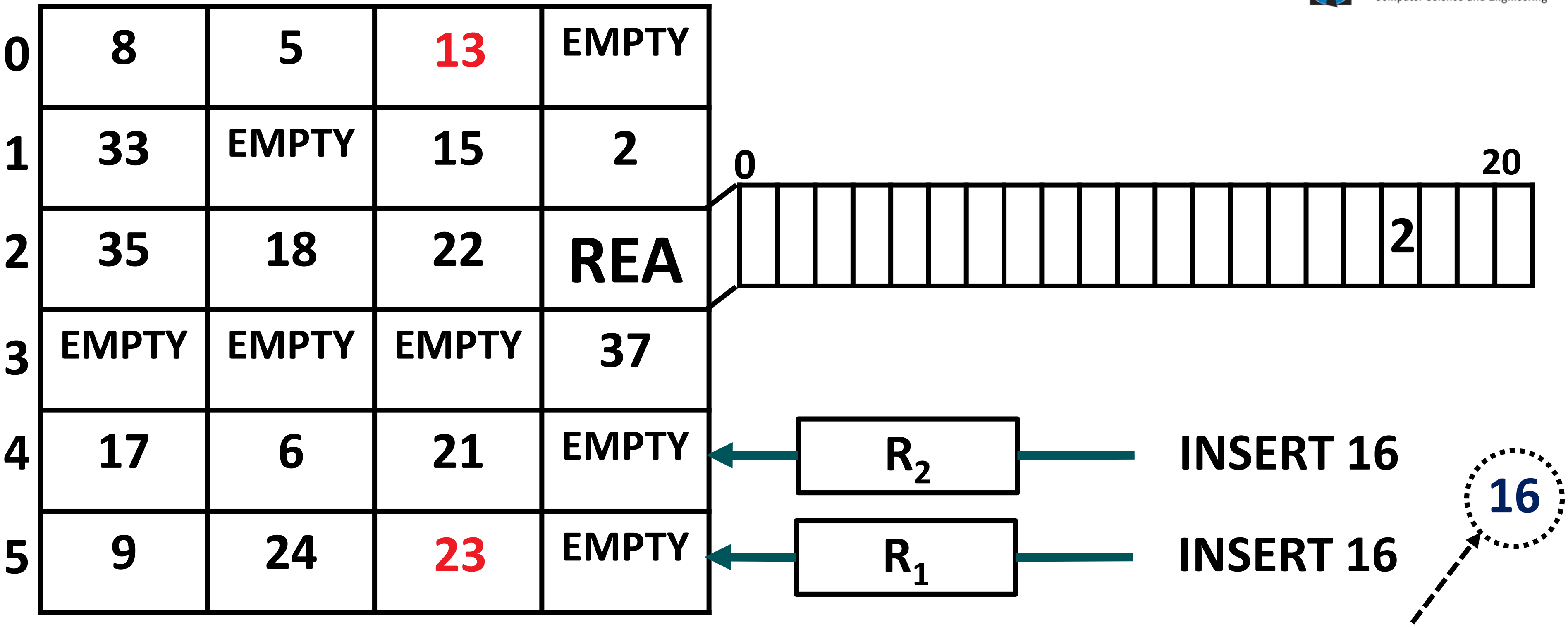

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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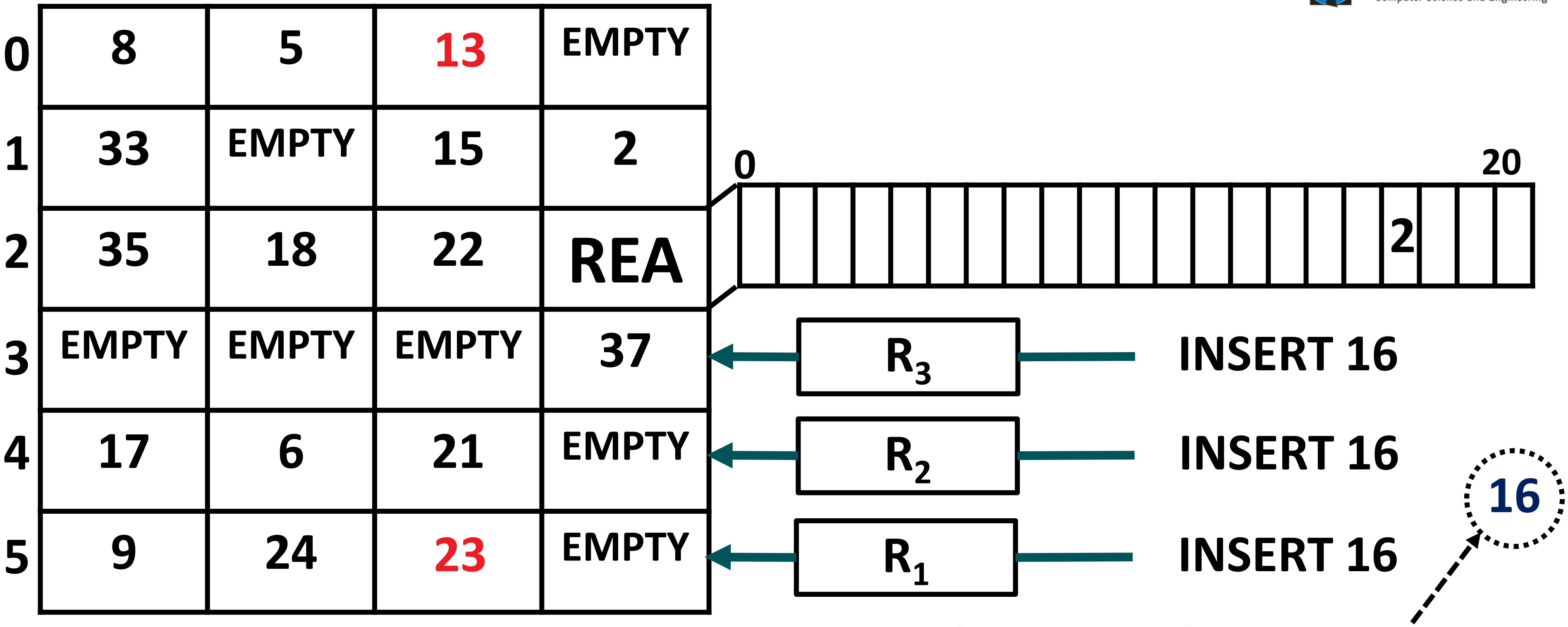
HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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HORTON TABLES

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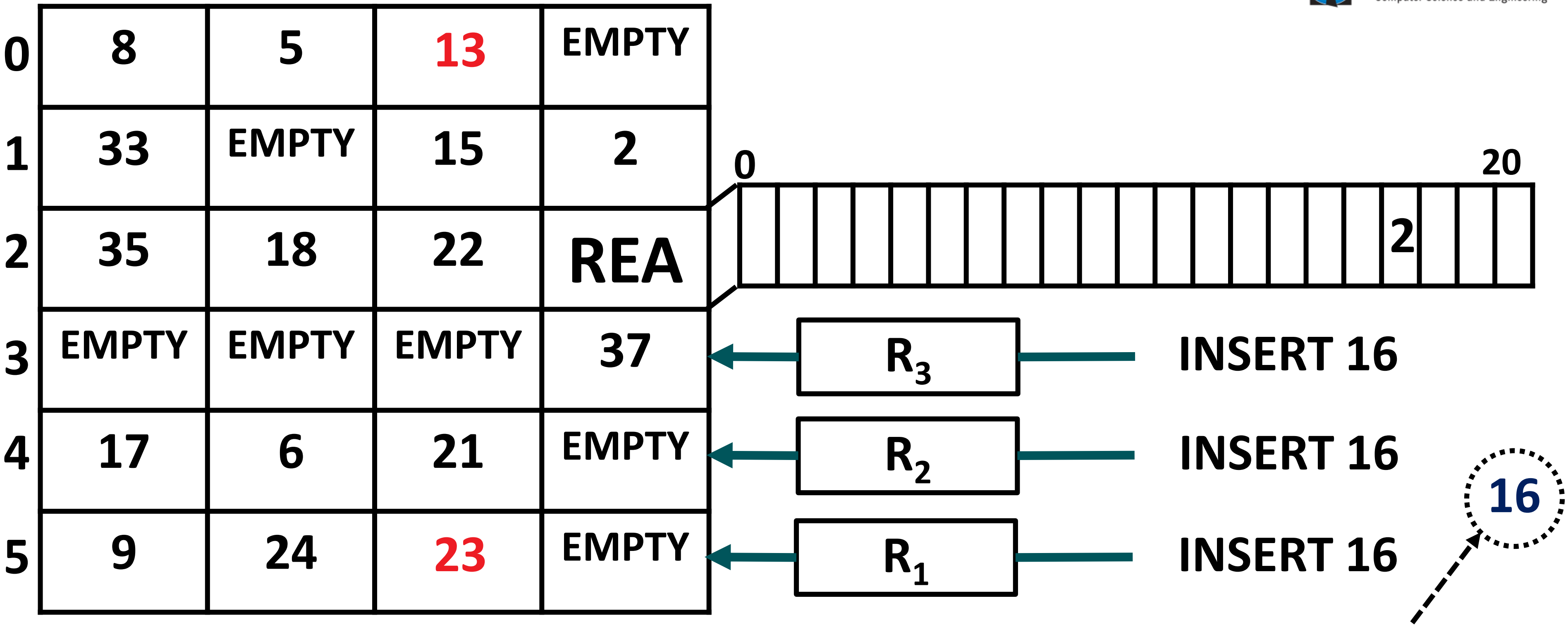


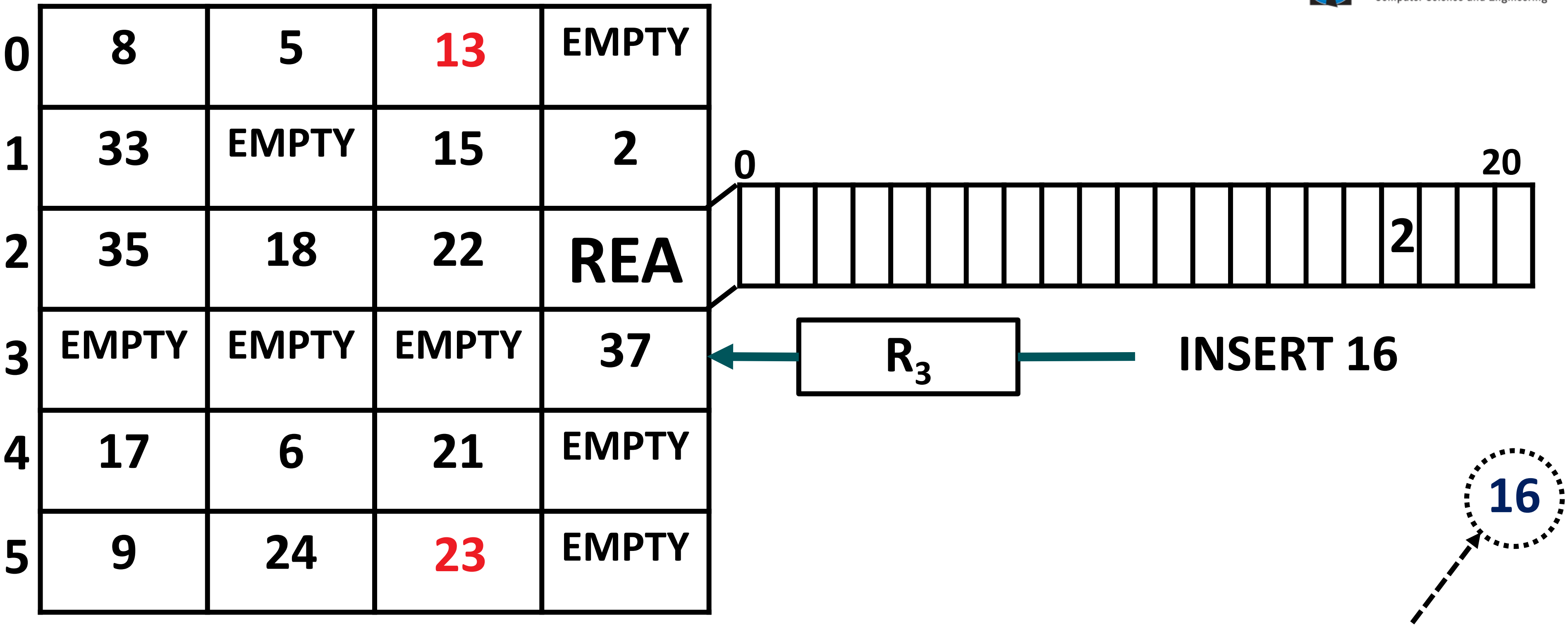
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Use R_3 for inserting 16 because it maps 16 to least full secondary bucket candidate.

- For buckets that overflow, we remap surplus elements using one of many secondary hash functions and register its numerical identifier (e.g., R_2, R_5, R_7) as an element in a *remap entry array* (REA), a sparse, in-bucket array that tracks remapped elements.

HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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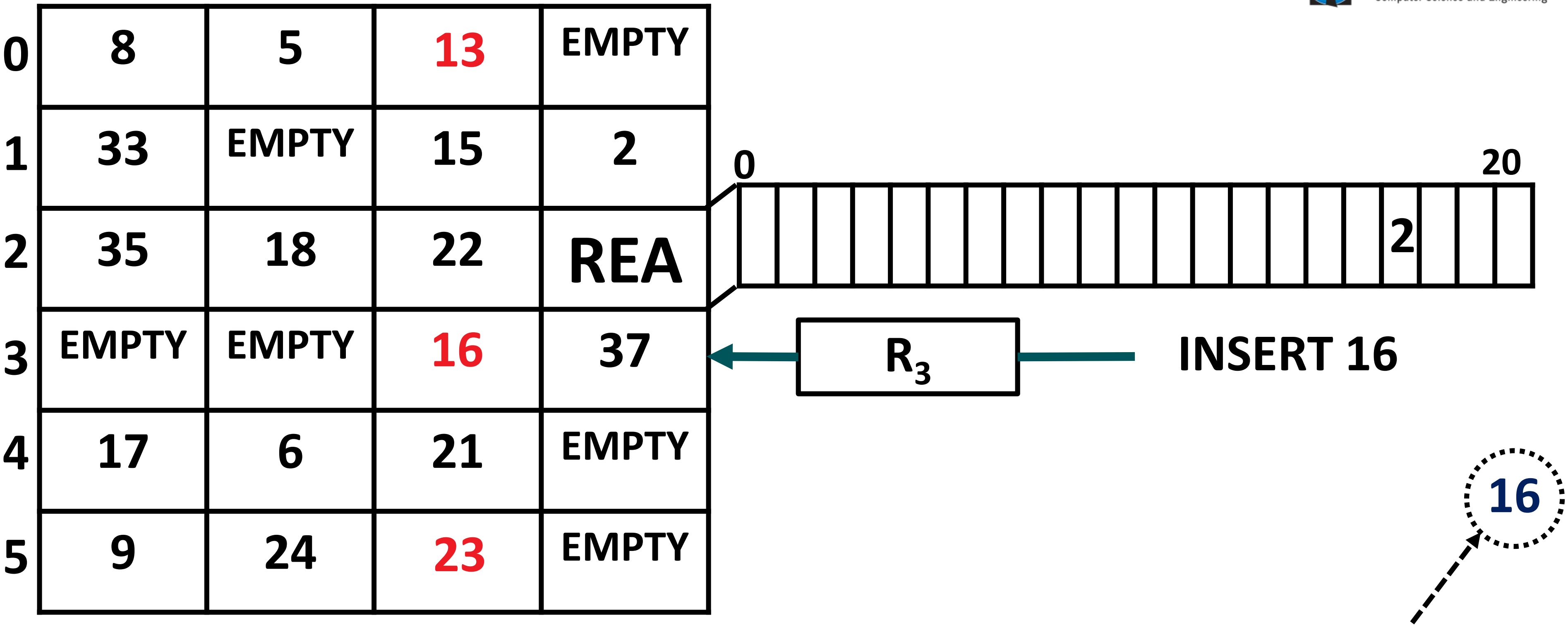
HORTON TABLES

INSERTS THAT TRIGGER CREATION OF REMAP ENTRY ARRAY



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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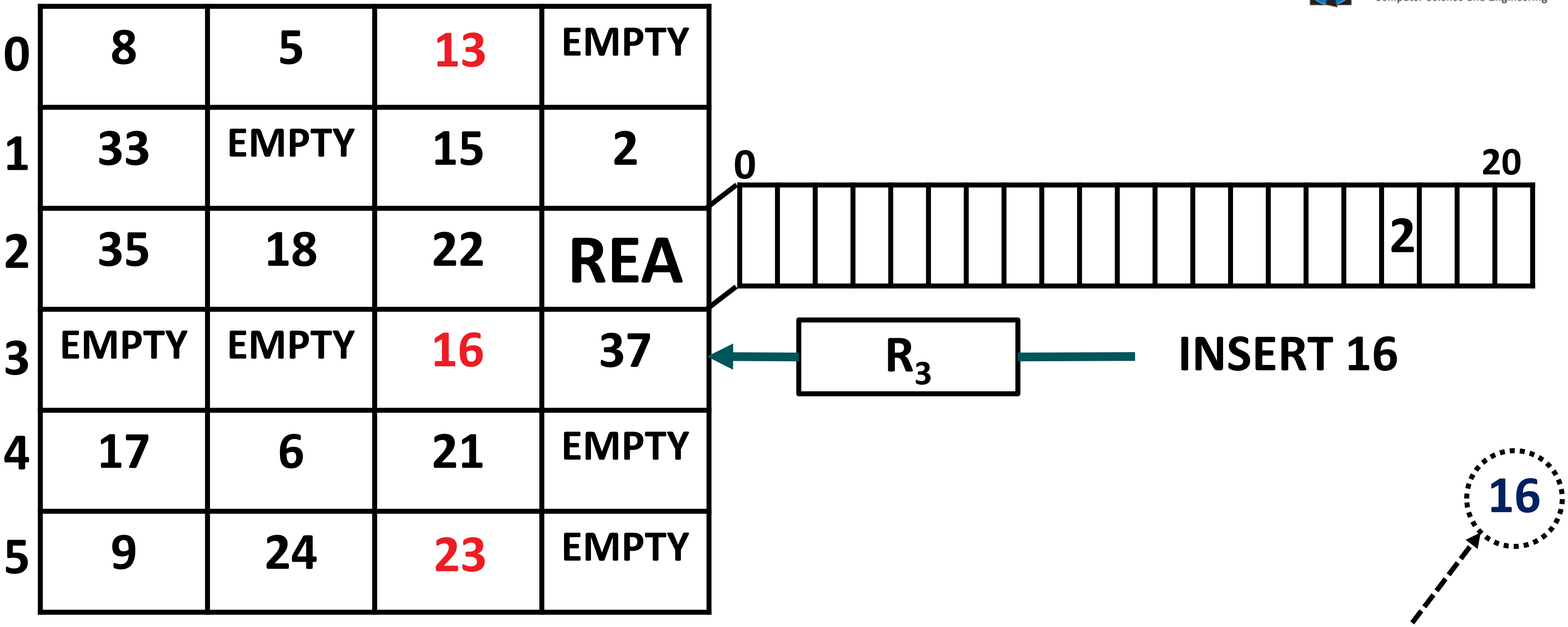

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Compute index into remap entry array using H_{tag} with key as input

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HORTON TABLES

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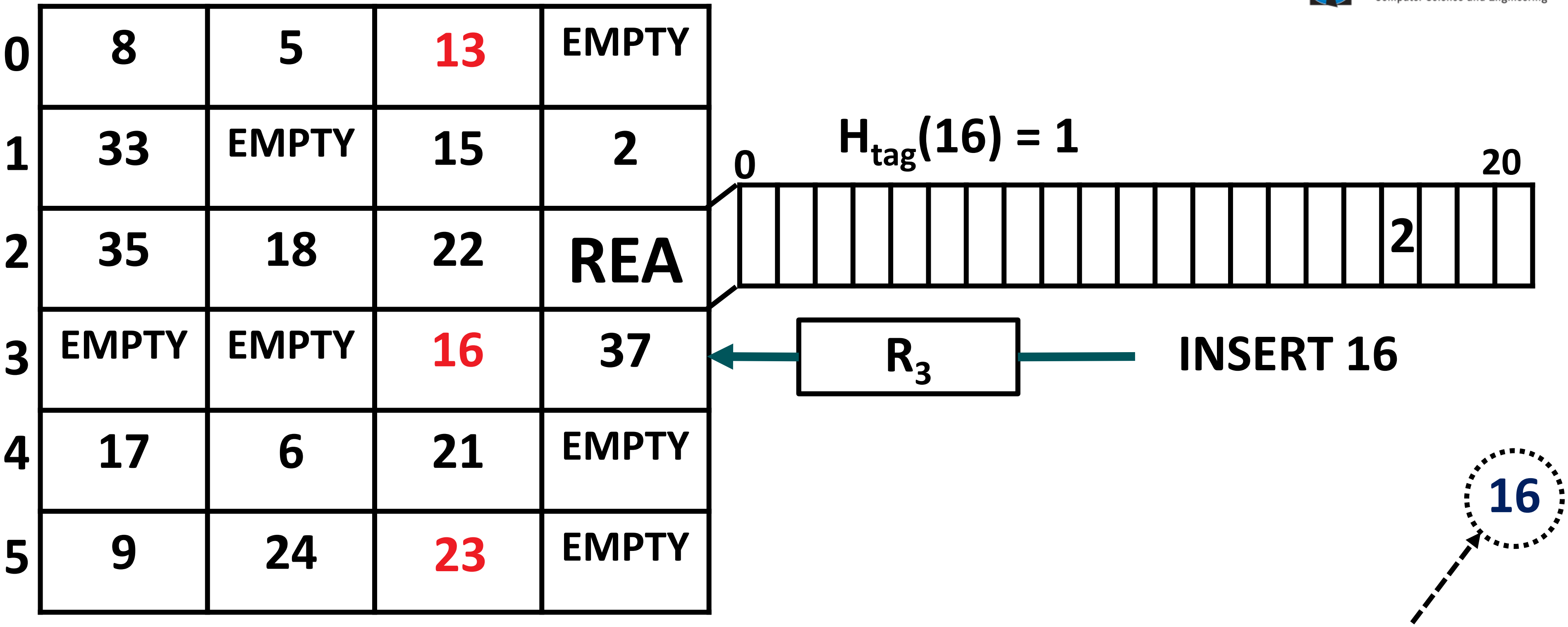

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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HORTON TABLES

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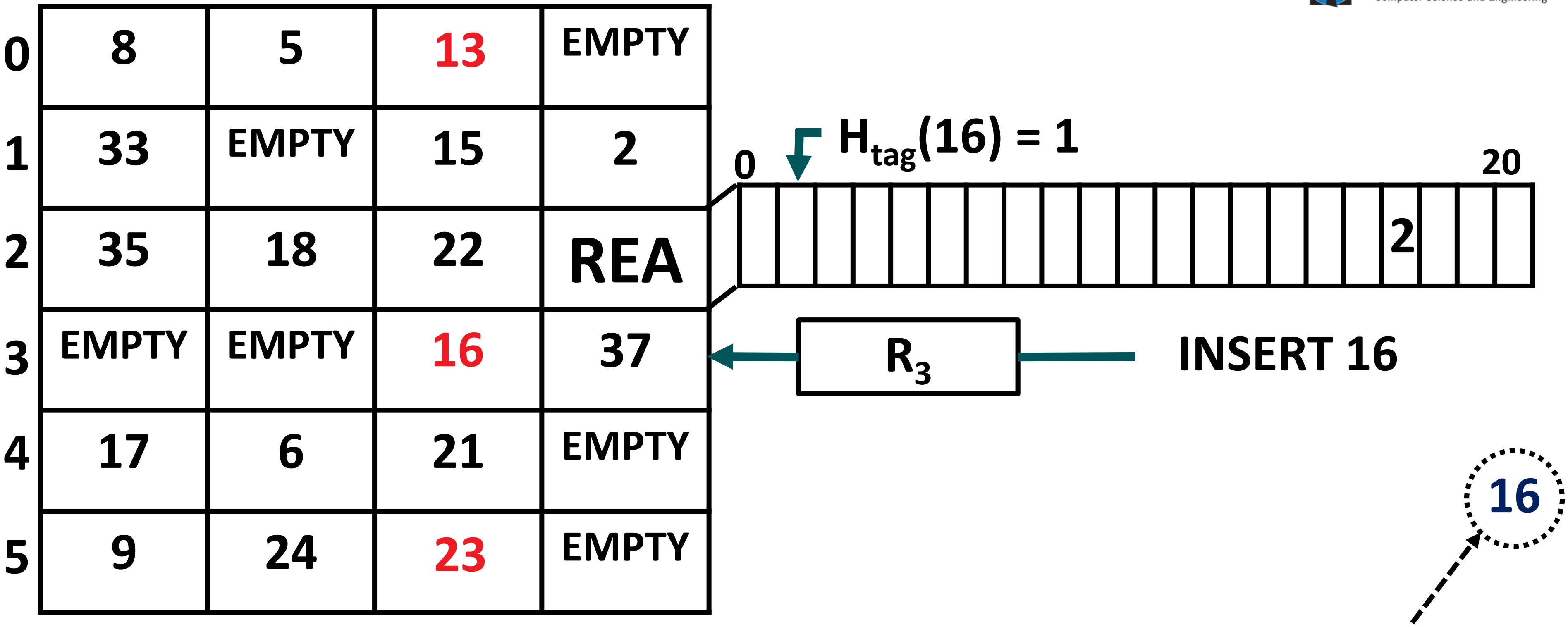

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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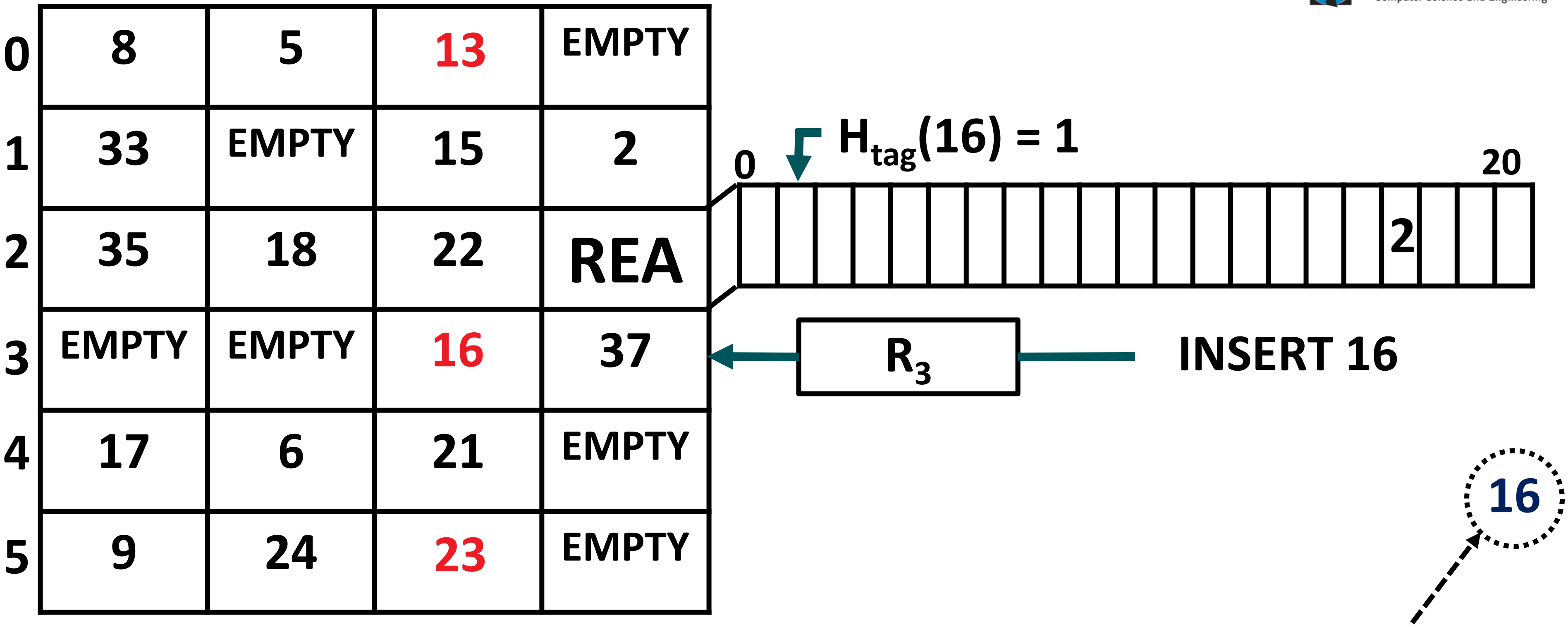

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Store 3 at index $H_{tag}(16)=1$ to indicate that R_3 was used to remap 16

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HORTON TABLES

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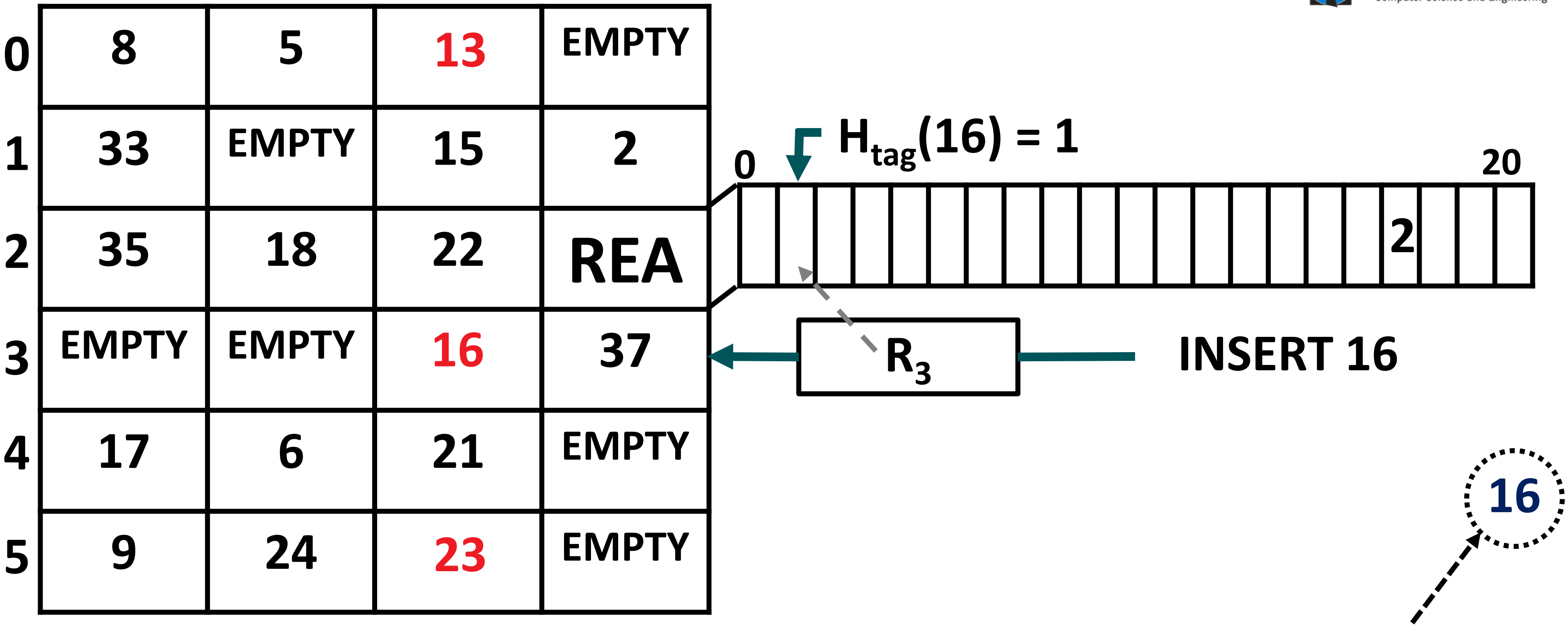

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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HORTON TABLES

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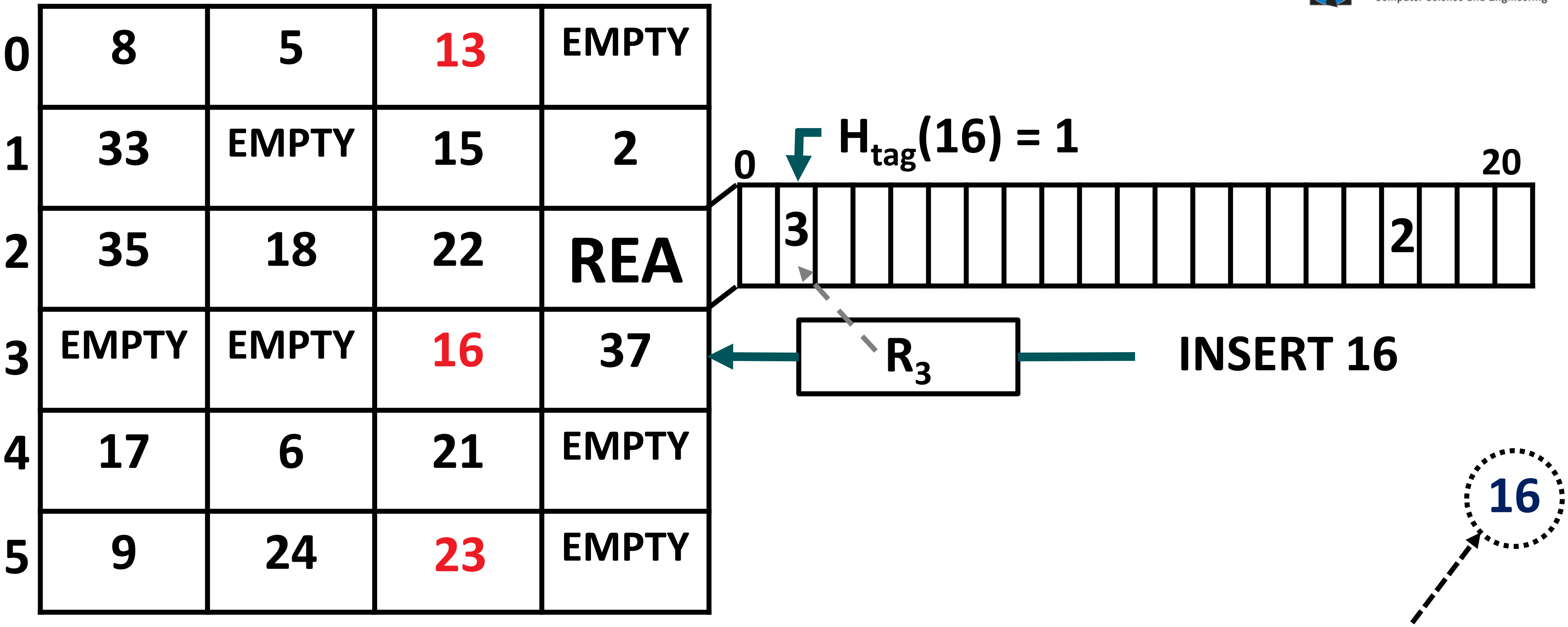

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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HORTON TABLES

RETRIEVING REMAPPED ITEMS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

- Remapped items can always be retrieved by accessing 2 buckets, even when many secondary hash functions are used
- e.g., when retrieving 16, we only access buckets 2 (primary bucket) and 3 (secondary bucket). We skip buckets 4 and 5 even though they were previously candidates.

HORTON TABLES

RETRIEVING REMAPPED ITEMS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Compute primary hash function and examine primary bucket (bucket 2)

- Remapped items can always be retrieved by accessing 2 buckets, even when many secondary hash functions are used
- e.g., when retrieving 16, we only access buckets 2 (primary bucket) and 3 (secondary bucket). We skip buckets 4 and 5 even though they were previously candidates.

HORTON TABLES

RETRIEVING REMAPPED ITEMS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

$H_{primary}$

LOOKUP 16

Compute primary hash function and examine primary bucket (bucket 2)

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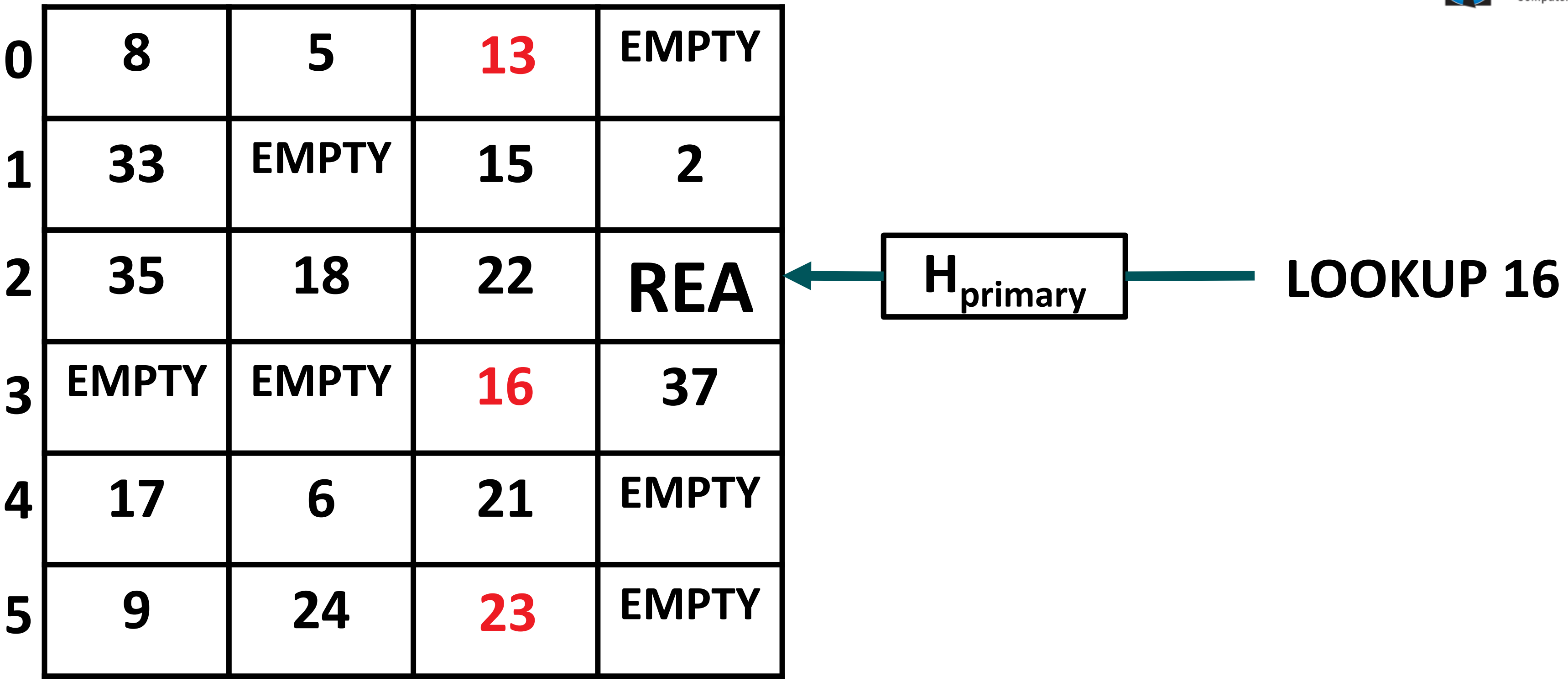
HORTON TABLES

RETRIEVING REMAPPED ITEMS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Determine 16 is not stored in its primary bucket and proceed to examine REA

- Remapped items can always be retrieved by accessing 2 buckets, even when many secondary hash functions are used
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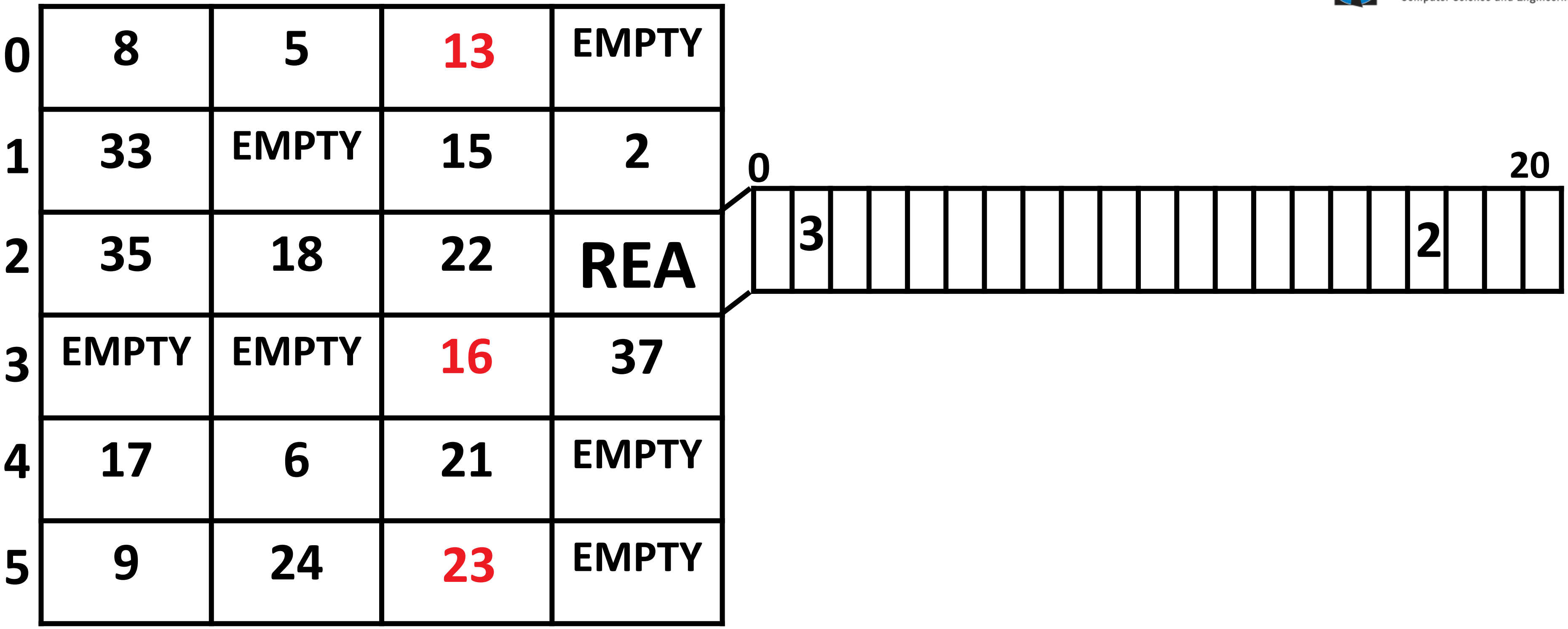
HORTON TABLES

RETRIEVING REMAPPED ITEMS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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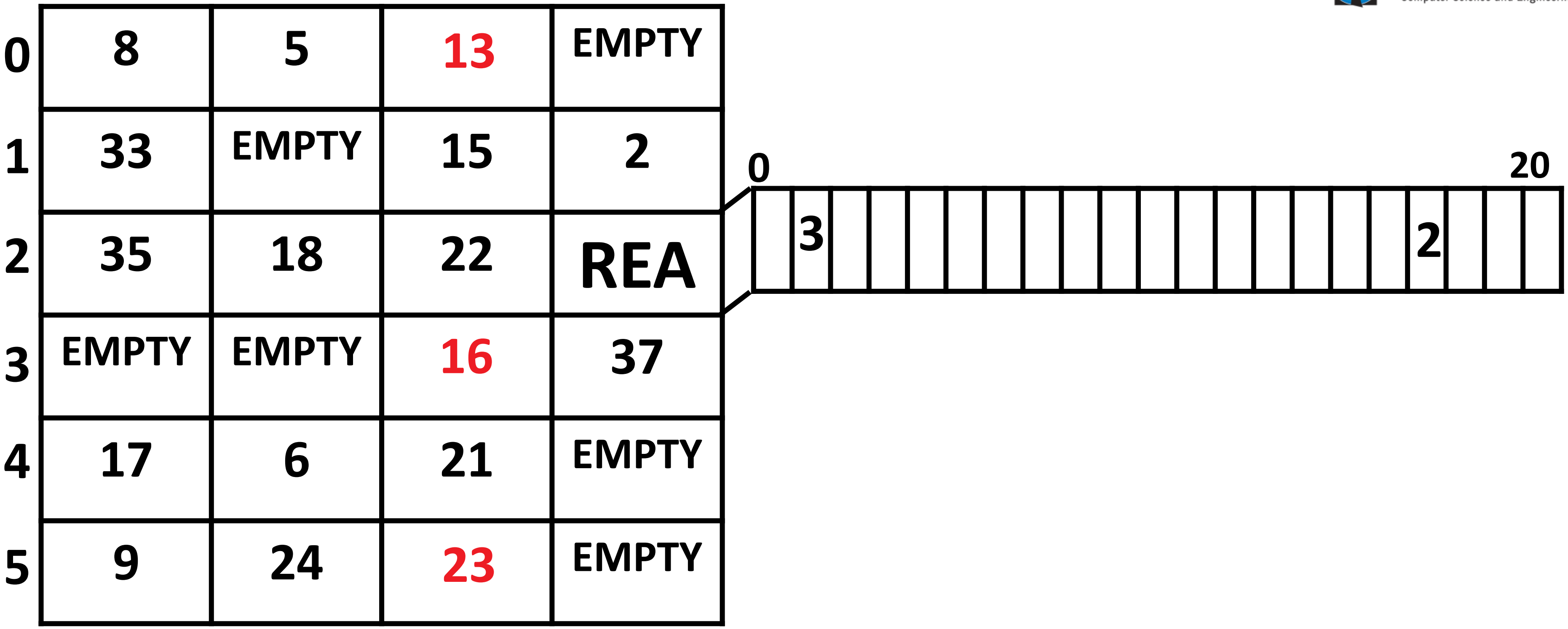
HORTON TABLES

RETRIEVING REMAPPED ITEMS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Compute index into remap entry array using H_{tag} with key as input

- Remapped items can always be retrieved by accessing 2 buckets, even when many secondary hash functions are used
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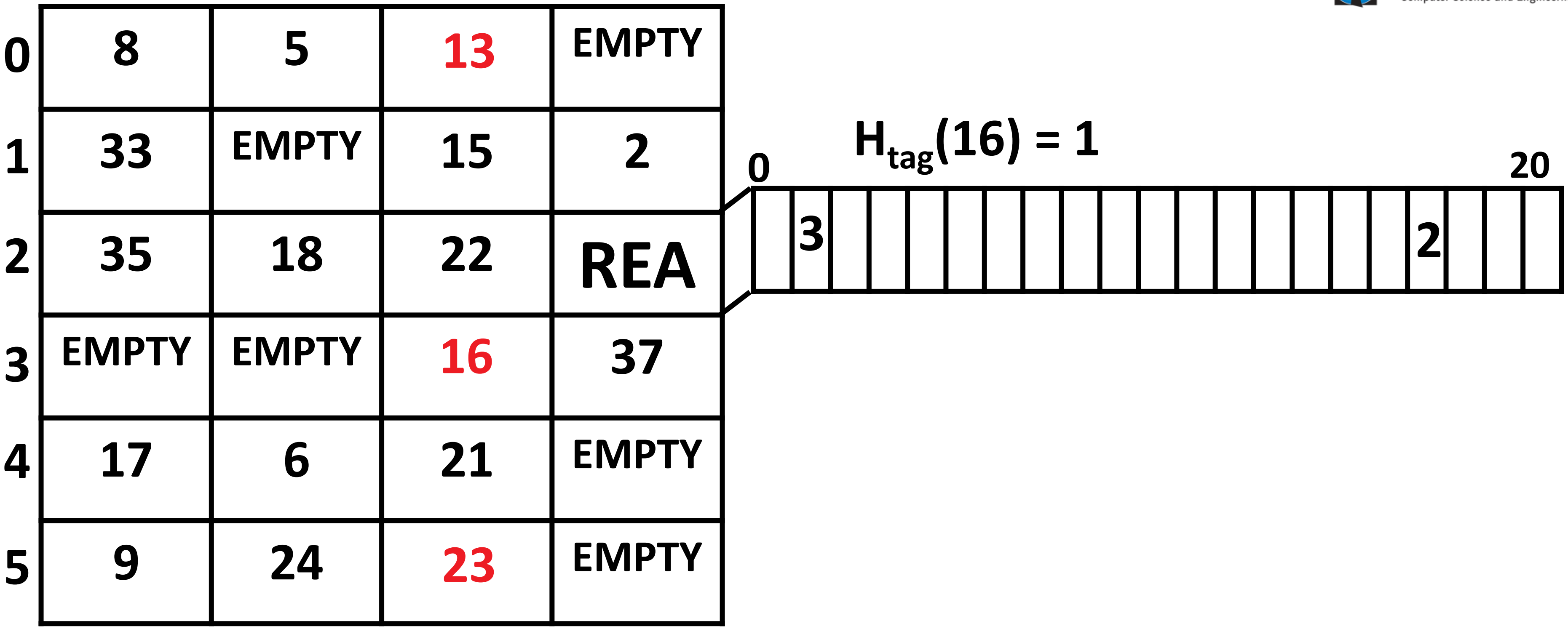
HORTON TABLES

RETRIEVING REMAPPED ITEMS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
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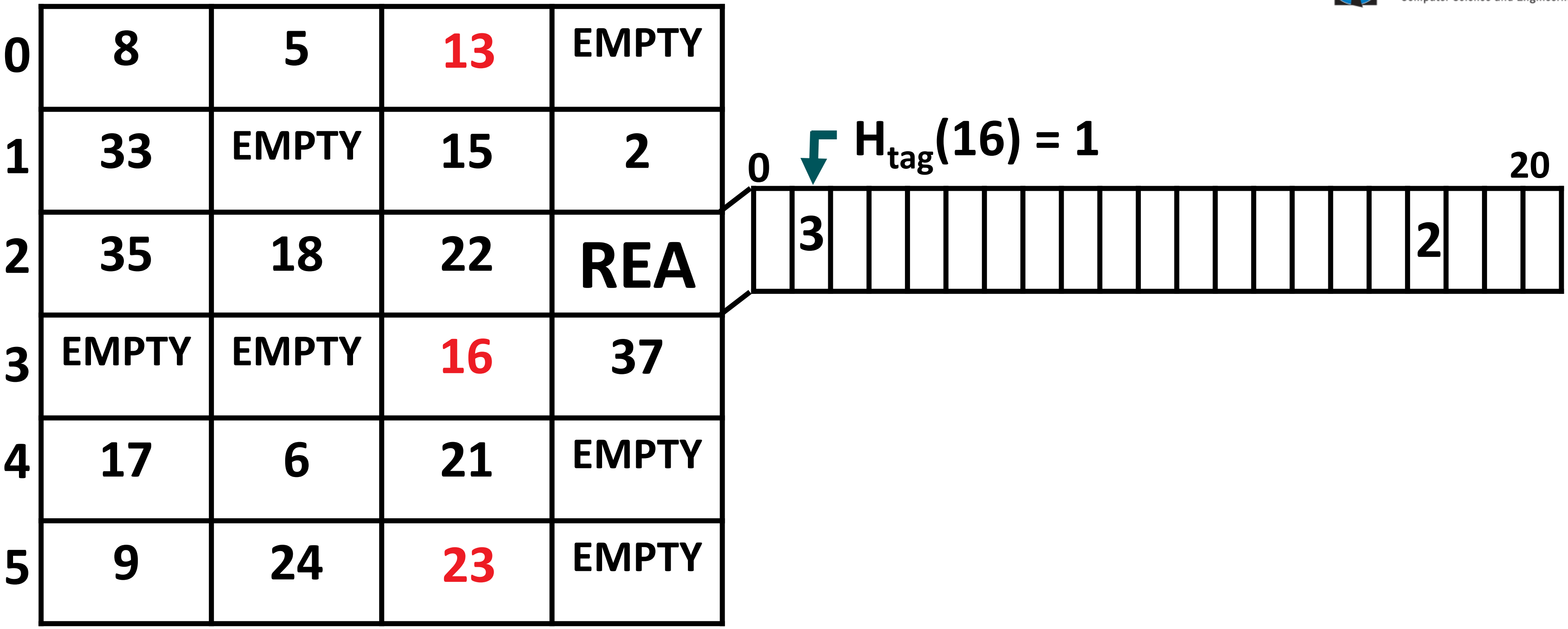
HORTON TABLES

RETRIEVING REMAPPED ITEMS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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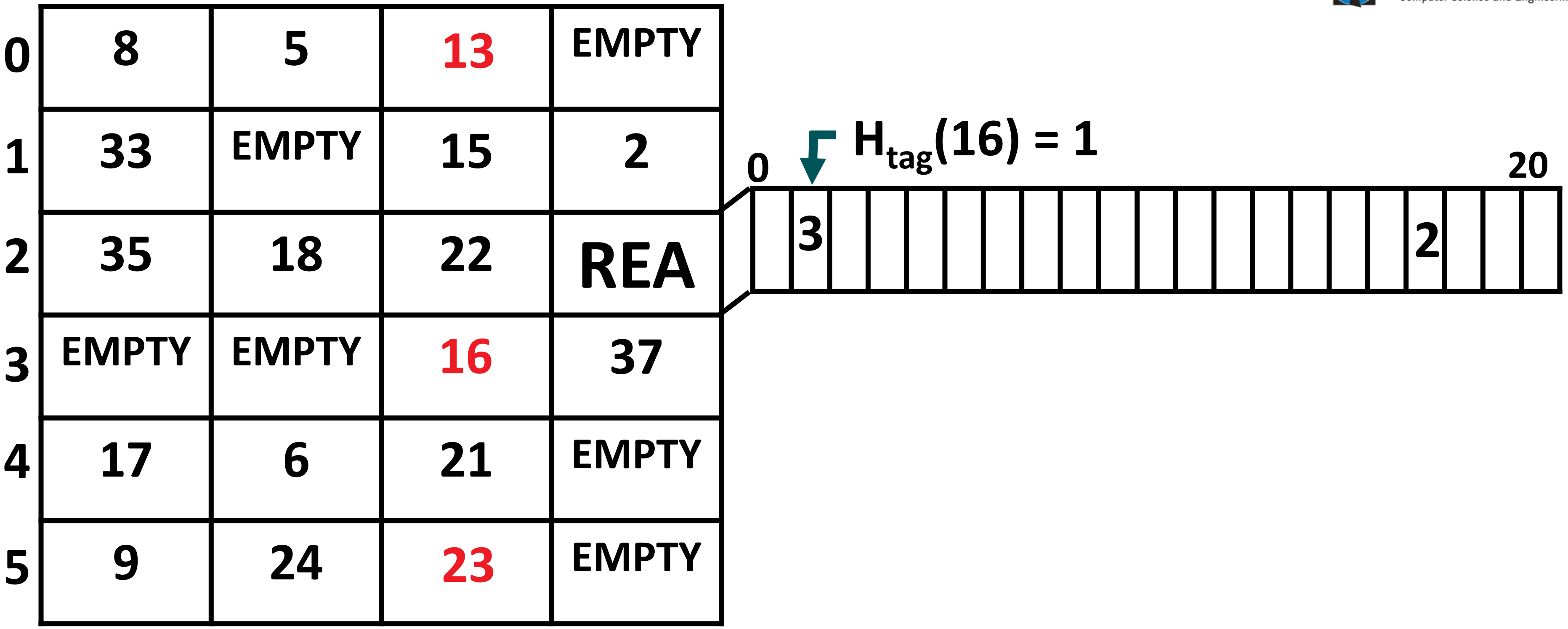
HORTON TABLES

RETRIEVING REMAPPED ITEMS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

The remap entry shows R_3 was used to remap 16, so compute $R_3(16)$.

- Remapped items can always be retrieved by accessing 2 buckets, even when many secondary hash functions are used
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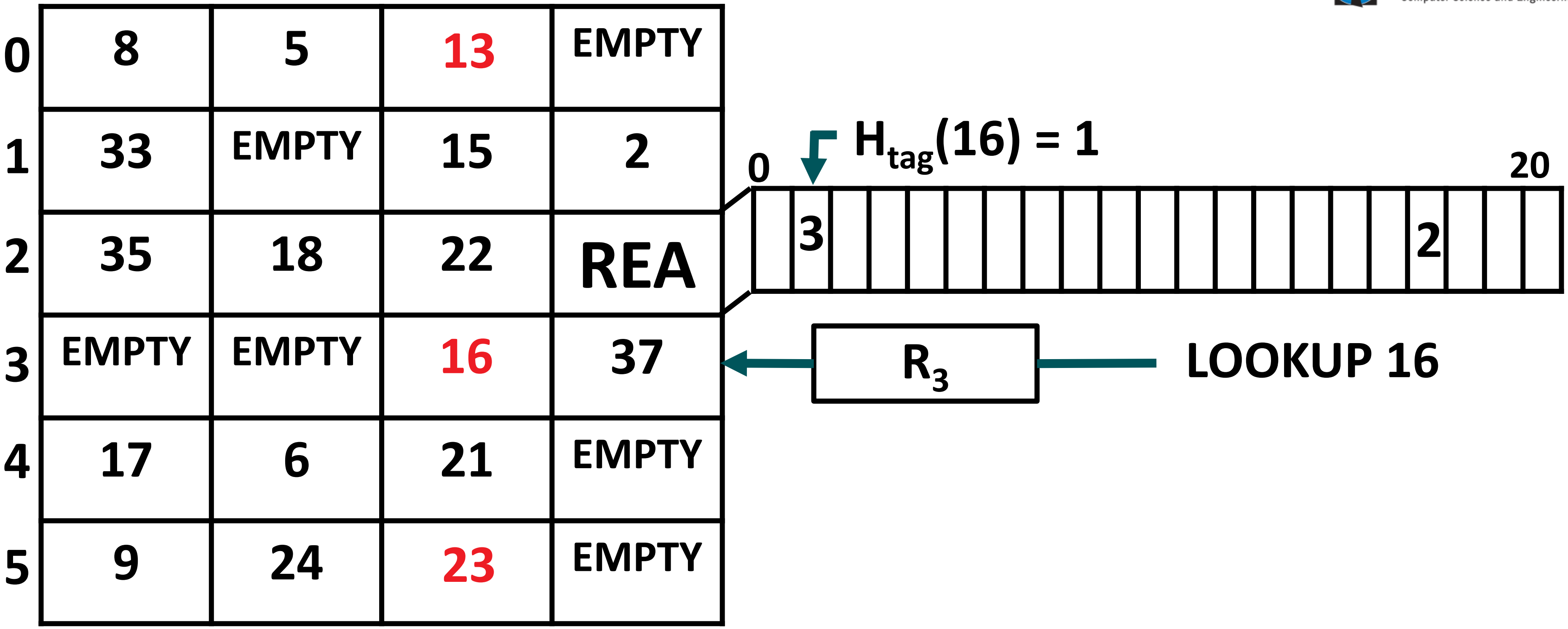
HORTON TABLES

RETRIEVING REMAPPED ITEMS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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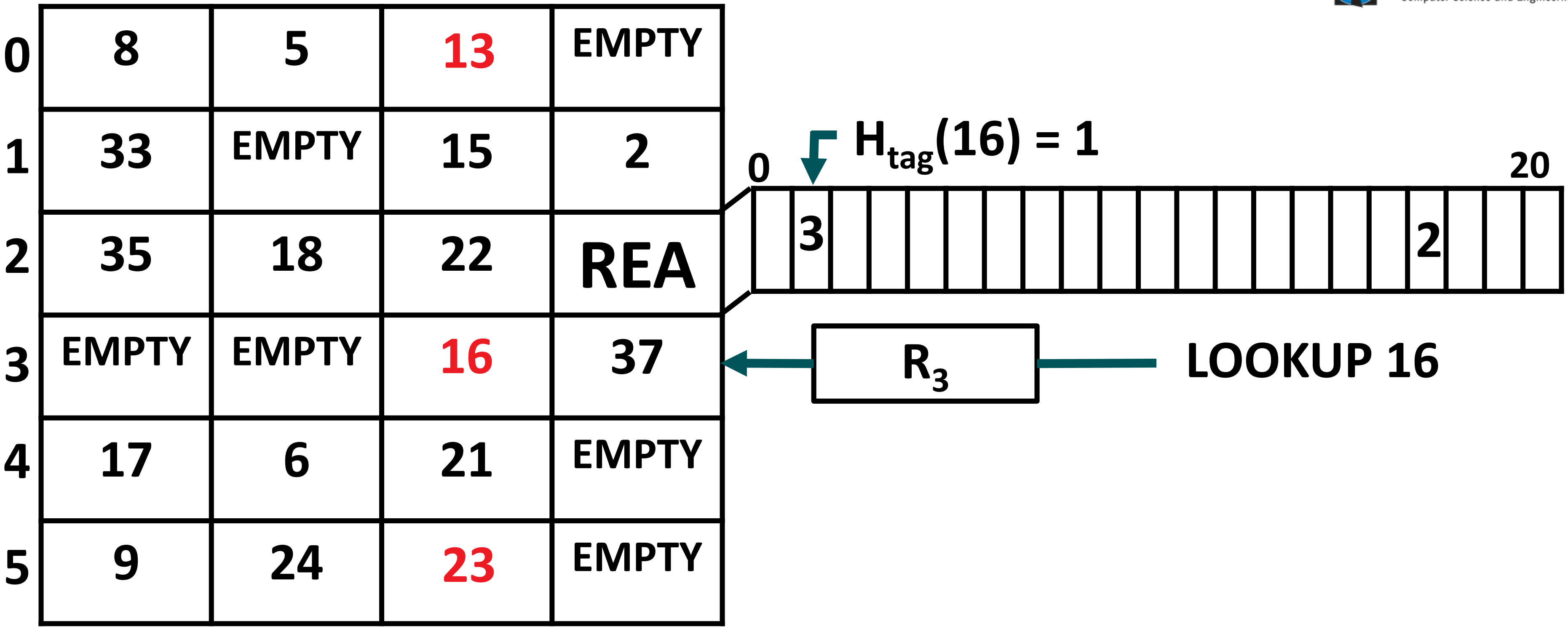
HORTON TABLES

RETRIEVING REMAPPED ITEMS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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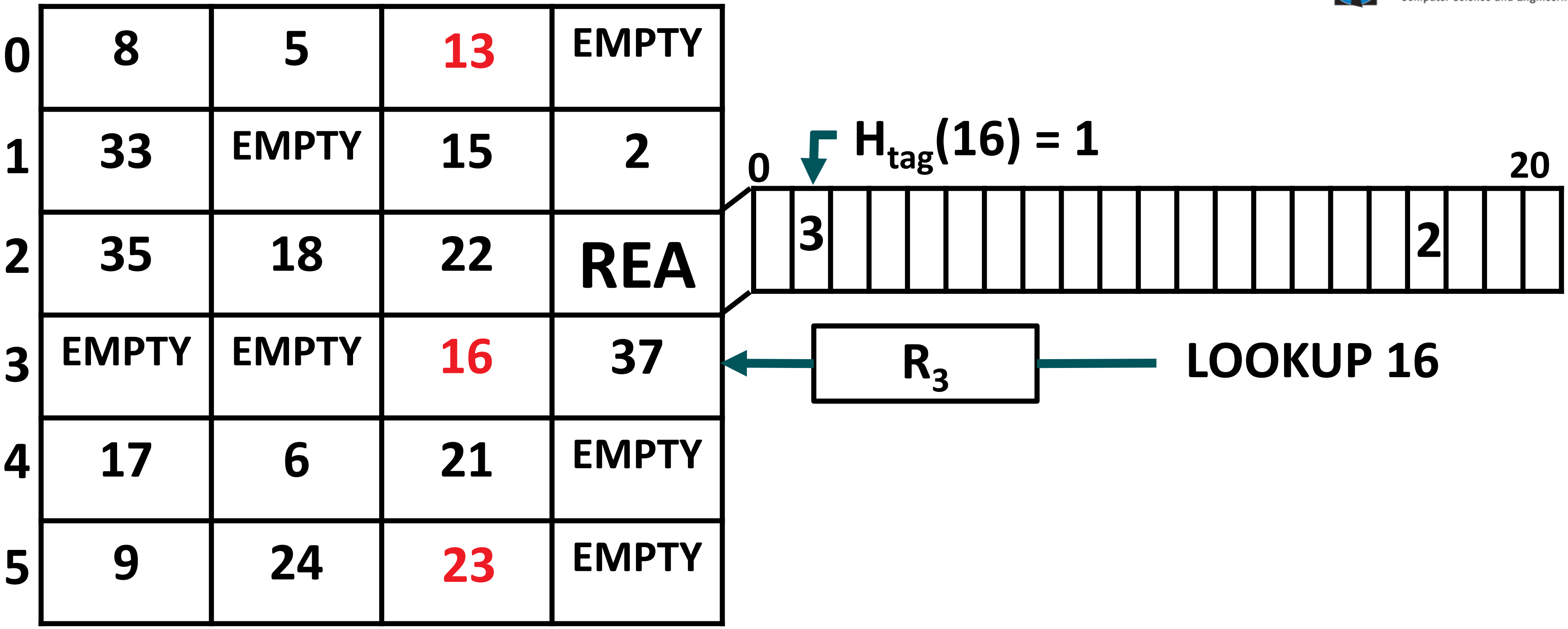
HORTON TABLES

RETRIEVING REMAPPED ITEMS



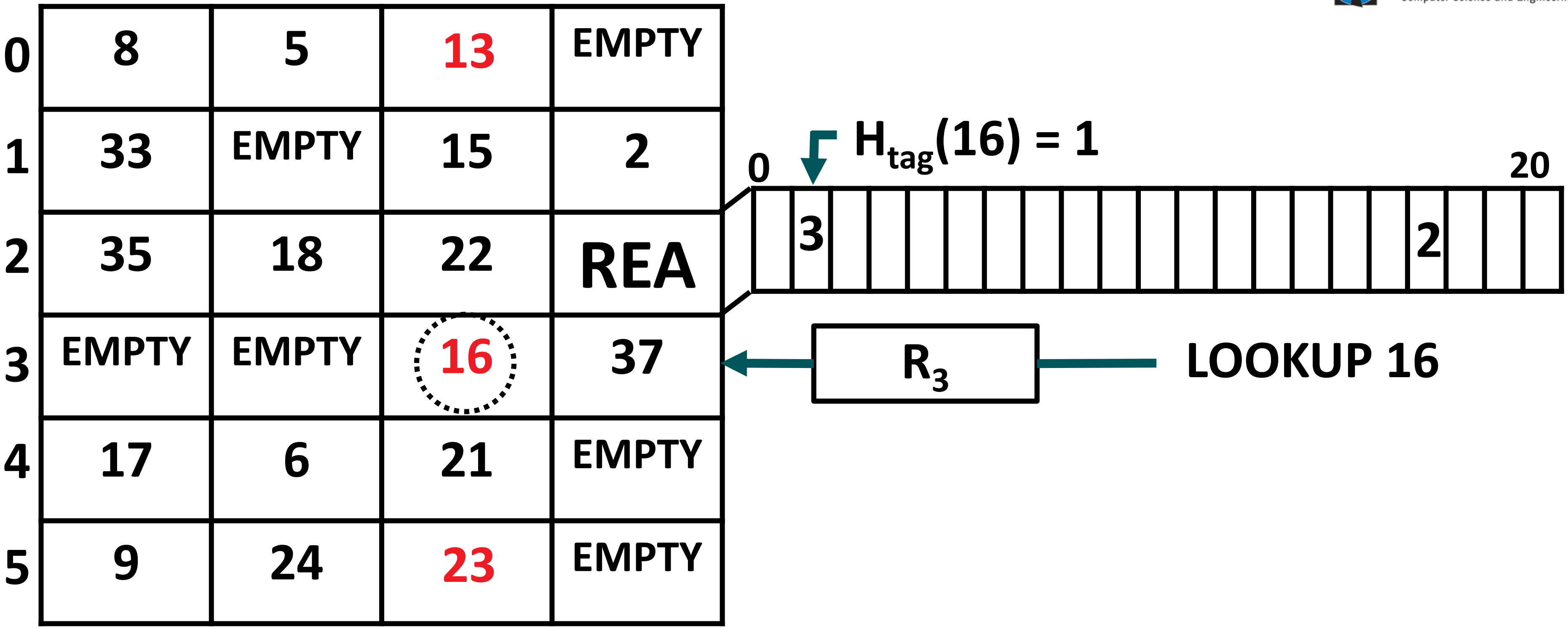
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Retrieve 16 from bucket 3

- Remapped items can always be retrieved by accessing 2 buckets, even when many secondary hash functions are used
- e.g., when retrieving 16, we only access buckets 2 (primary bucket) and 3 (secondary bucket). We skip buckets 4 and 5 even though they were previously candidates.

HORTON TABLES

RETRIEVING REMAPPED ITEMS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

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- Remapped items can always be retrieved by accessing 2 buckets, even when many secondary hash functions are used
- e.g., when retrieving 16, we only access buckets 2 (primary bucket) and 3 (secondary bucket). We skip buckets 4 and 5 even though they were previously candidates.

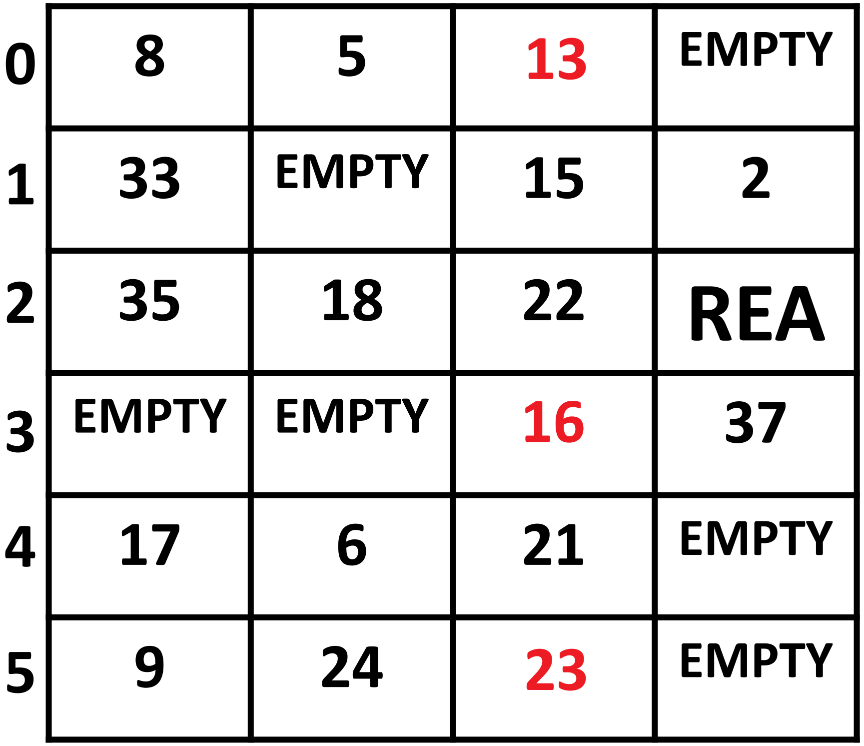
HORTON TABLES

NEGATIVE LOOKUPS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

HORTON TABLES

NEGATIVE LOOKUPS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Most negative lookups only require accessing a single bucket

HORTON TABLES

NEGATIVE LOOKUPS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

LOOKUP 25

Most negative lookups only require accessing a single bucket

HORTON TABLES

NEGATIVE LOOKUPS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

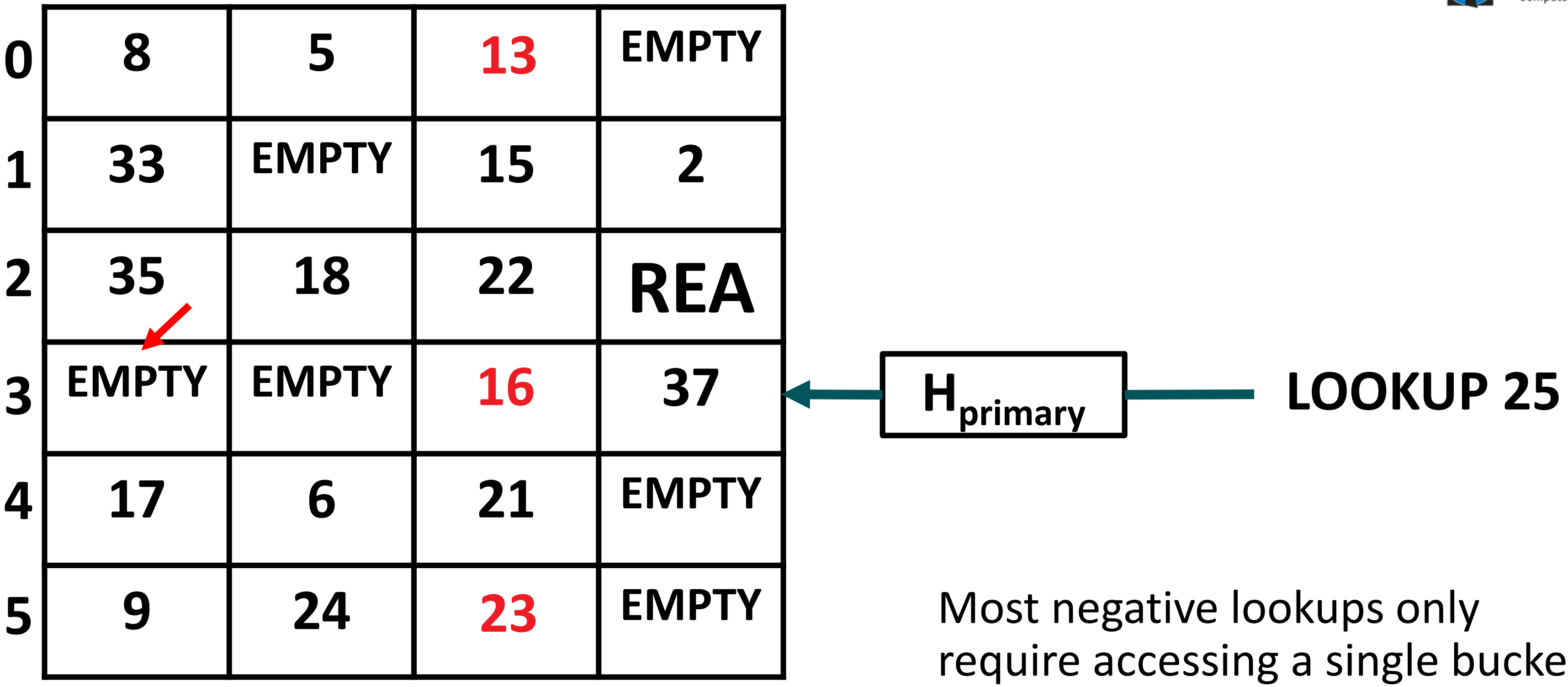
$H_{primary}$

LOOKUP 25

Most negative lookups only require accessing a single bucket

HORTON TABLES

NEGATIVE LOOKUPS

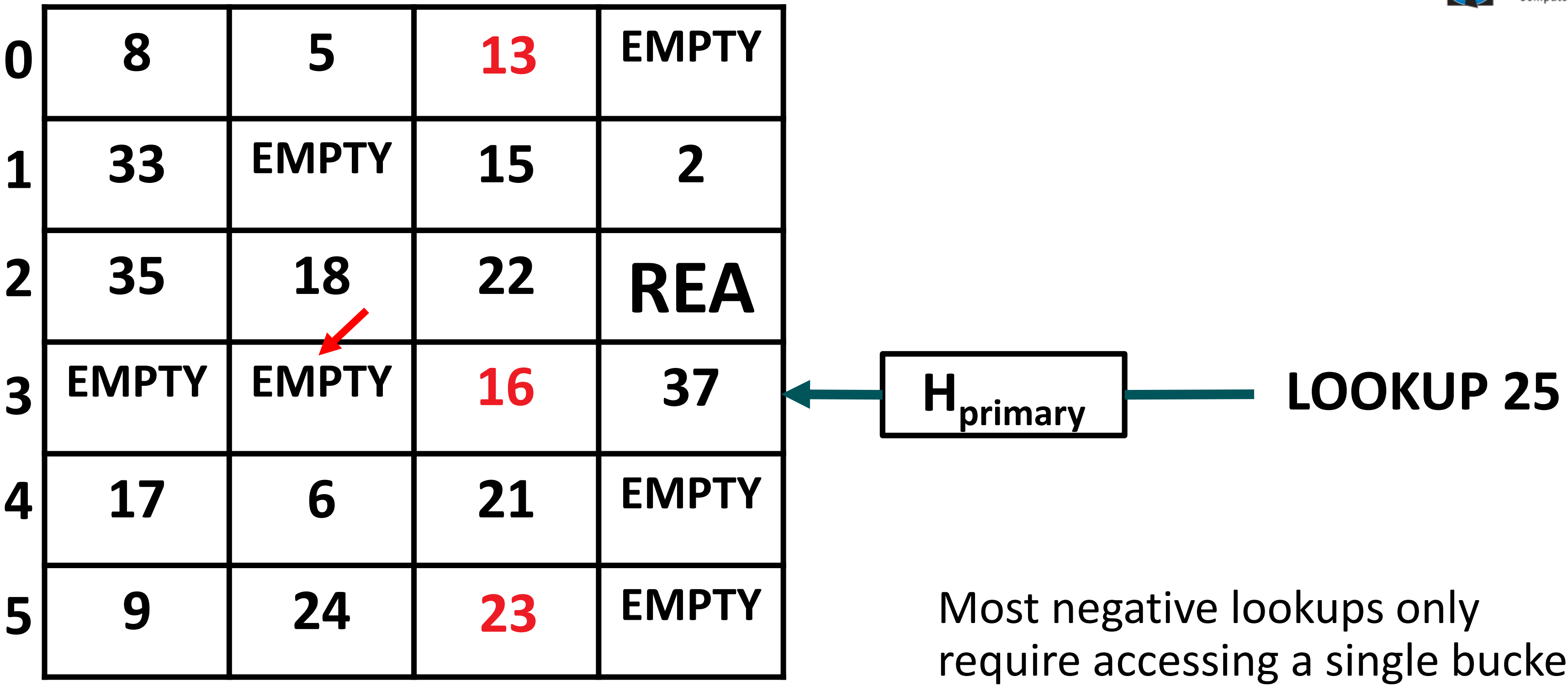


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Most negative lookups only require accessing a single bucket

HORTON TABLES

NEGATIVE LOOKUPS

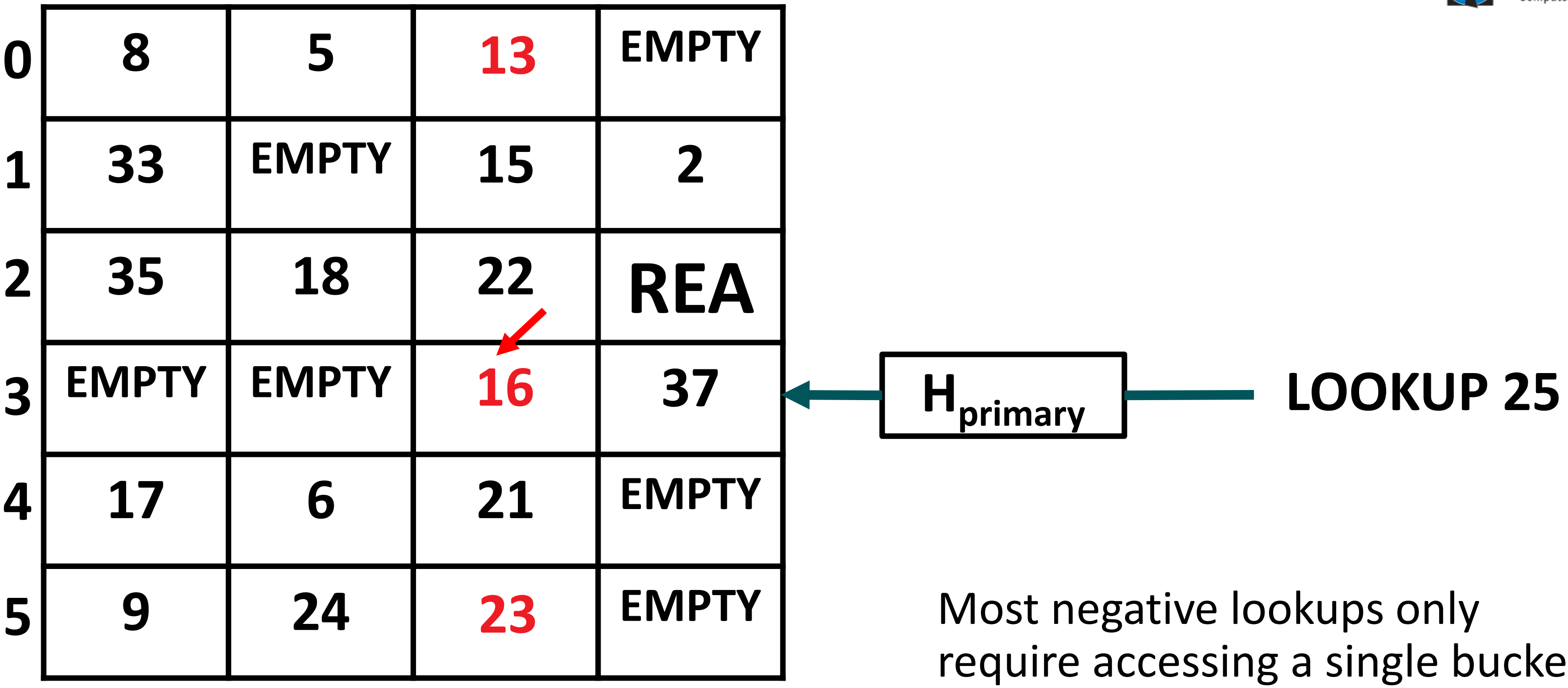


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Most negative lookups only require accessing a single bucket

HORTON TABLES

NEGATIVE LOOKUPS

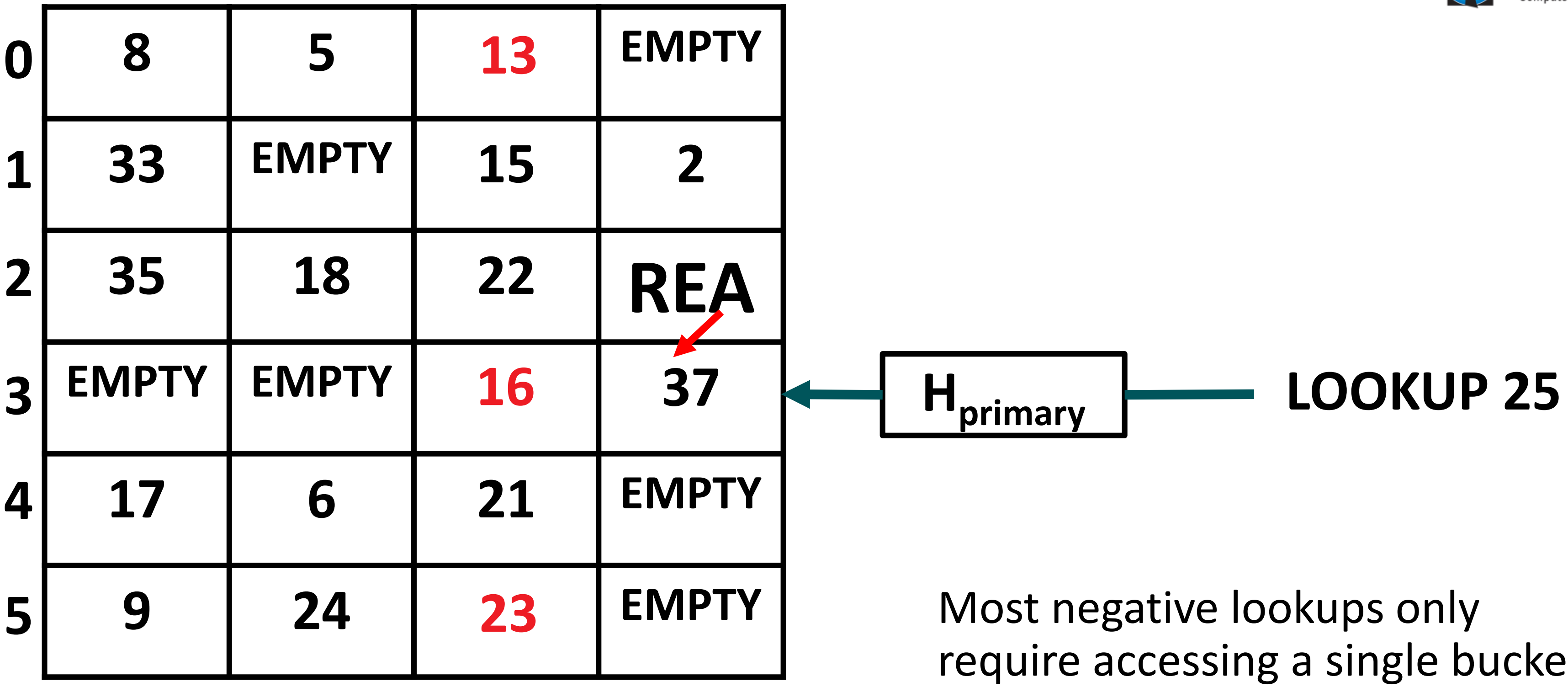


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Most negative lookups only require accessing a single bucket

HORTON TABLES

NEGATIVE LOOKUPS

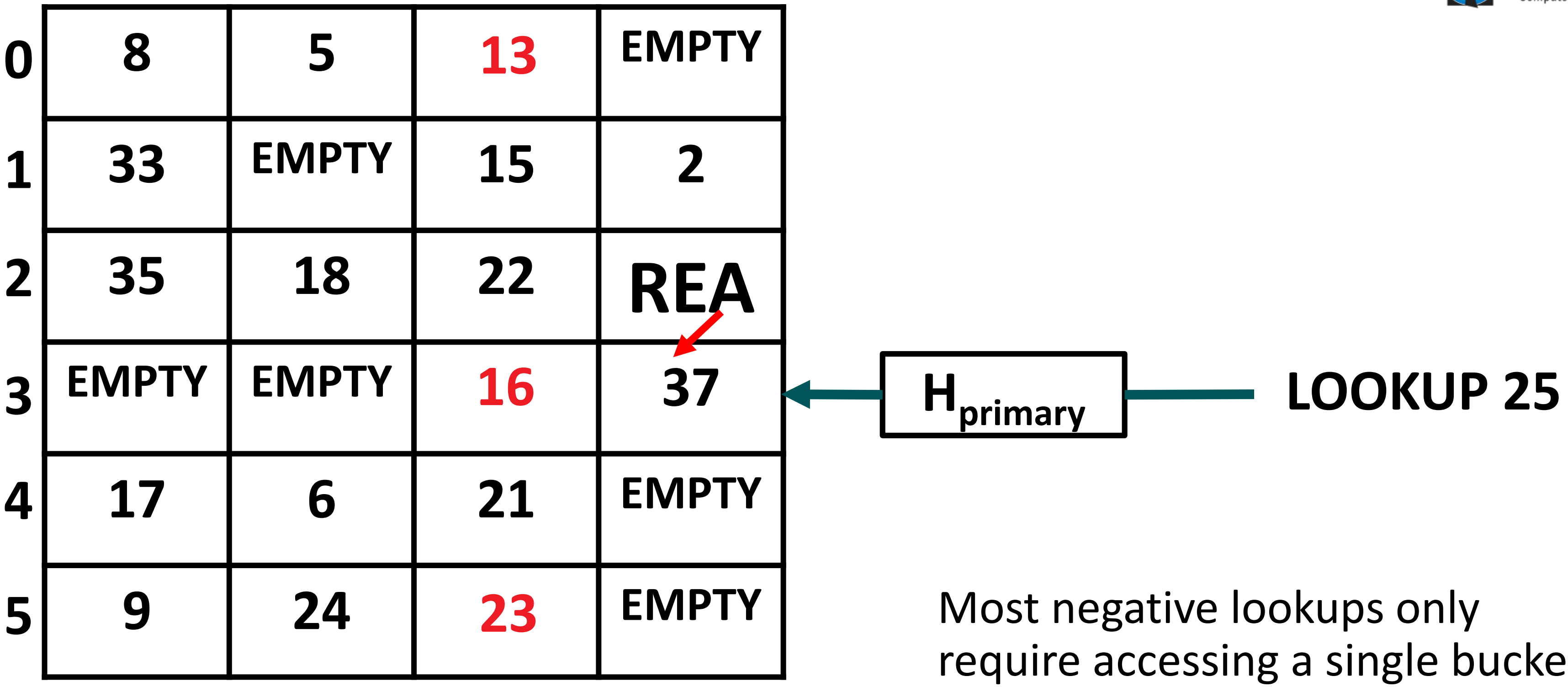


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Most negative lookups only require accessing a single bucket

HORTON TABLES

NEGATIVE LOOKUPS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

$H_{primary}$

LOOKUP 25

Most negative lookups only require accessing a single bucket

- Lookups where the primary bucket is *Type A*, a conventional BCHT bucket without remap entries, only ever require examining 1 bucket and thus 1 cache line for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Most negative lookups only require accessing a single bucket

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

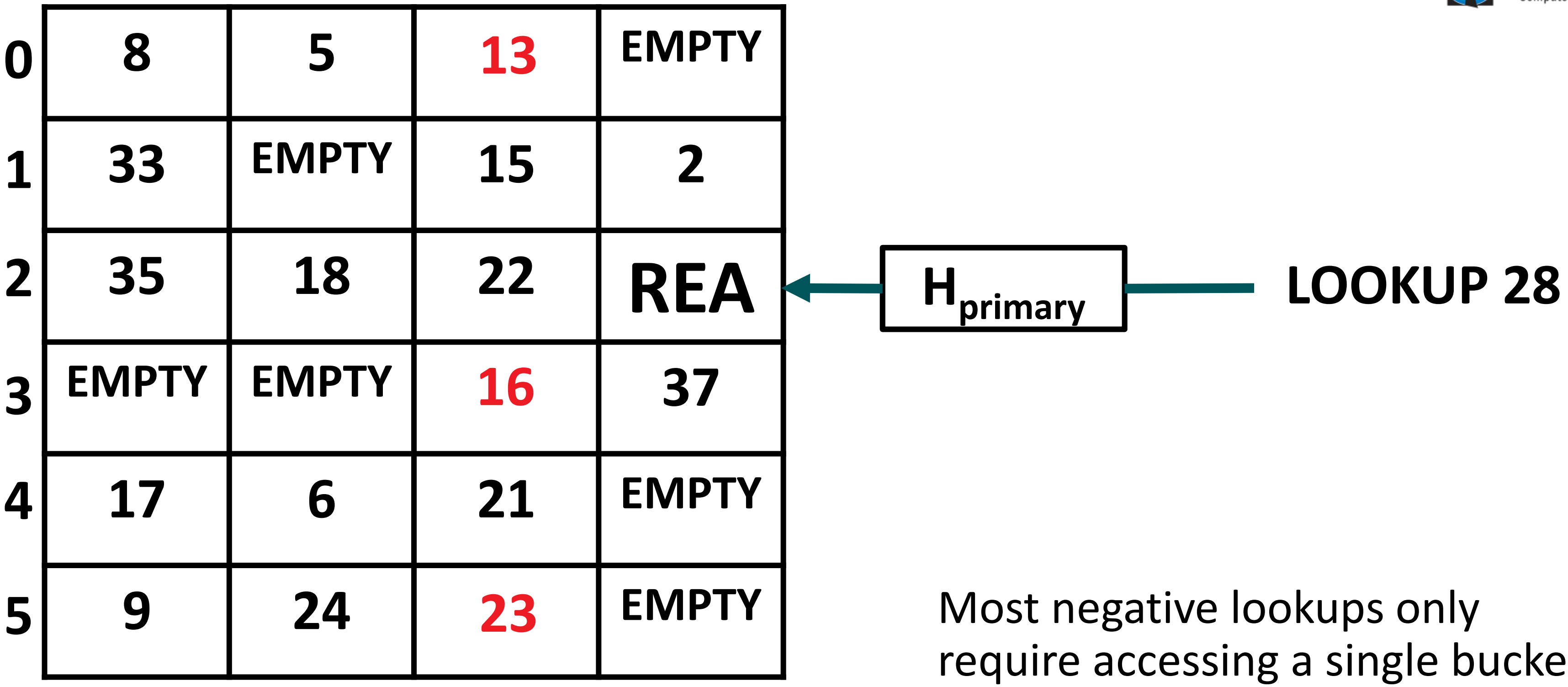
LOOKUP 28

Most negative lookups only require accessing a single bucket

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS



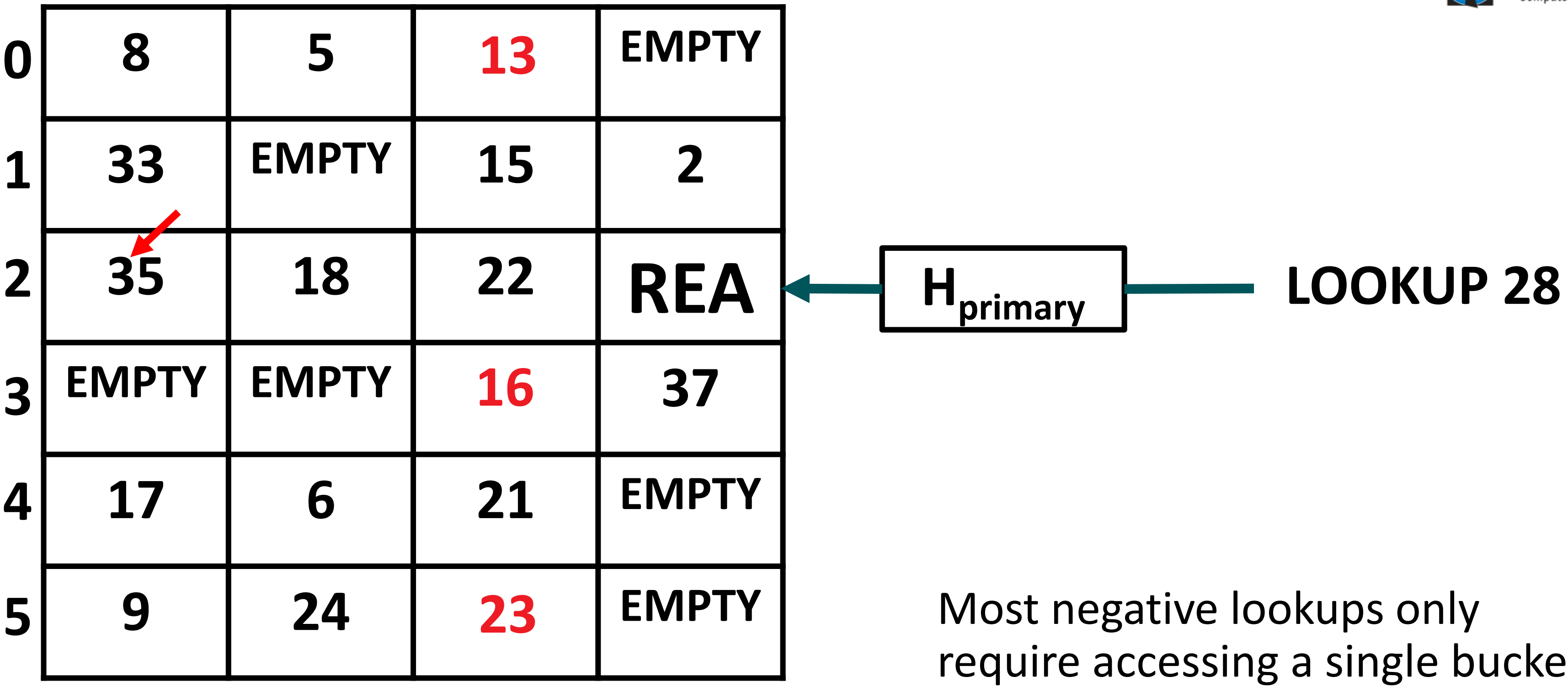
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Most negative lookups only require accessing a single bucket

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS



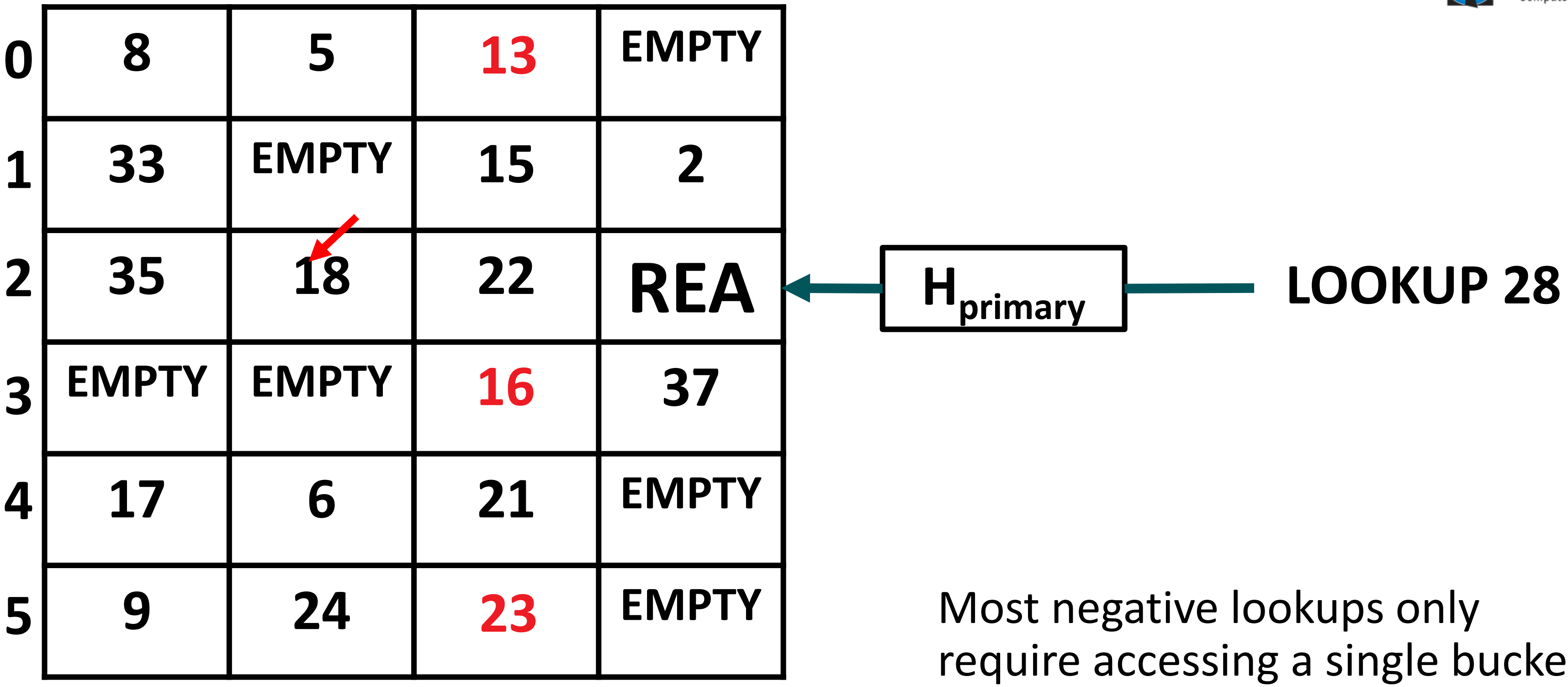
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Most negative lookups only require accessing a single bucket

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS



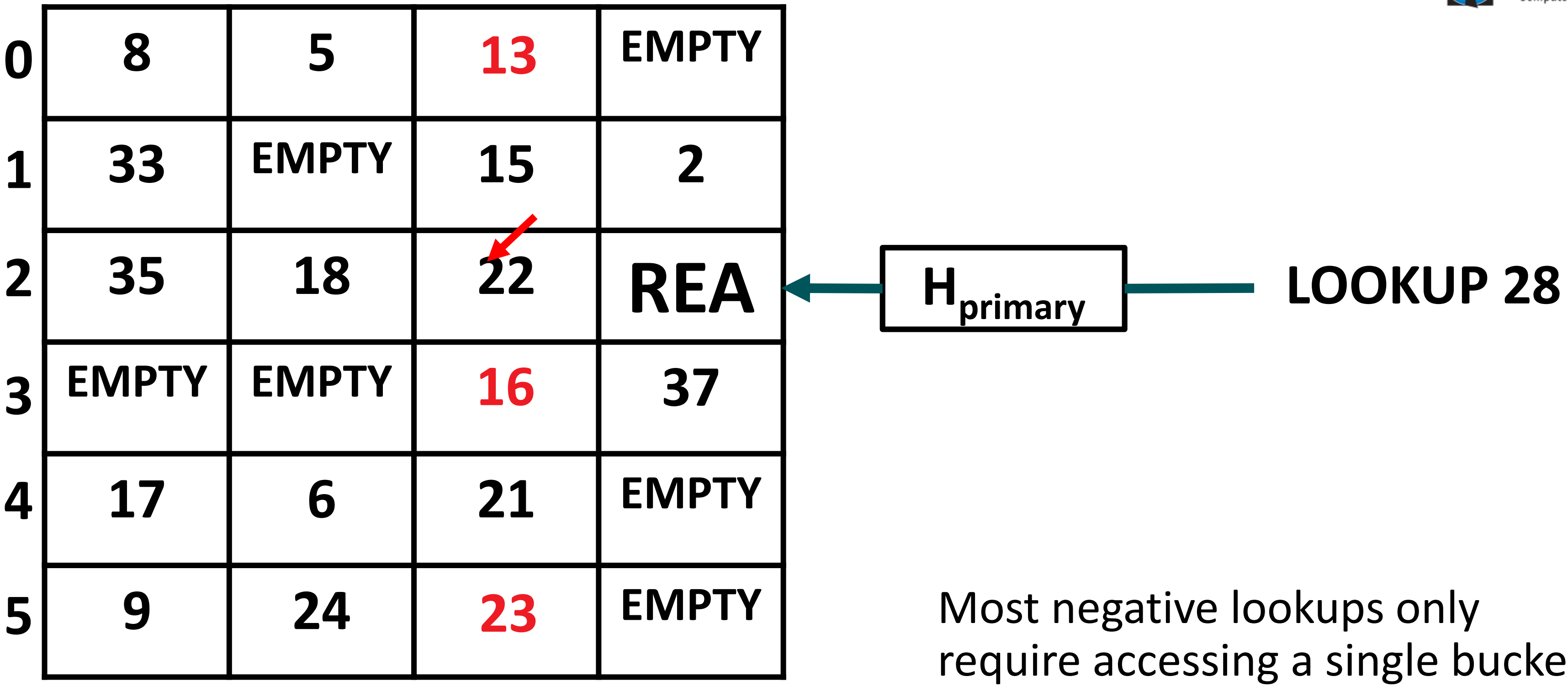
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Most negative lookups only require accessing a single bucket

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS



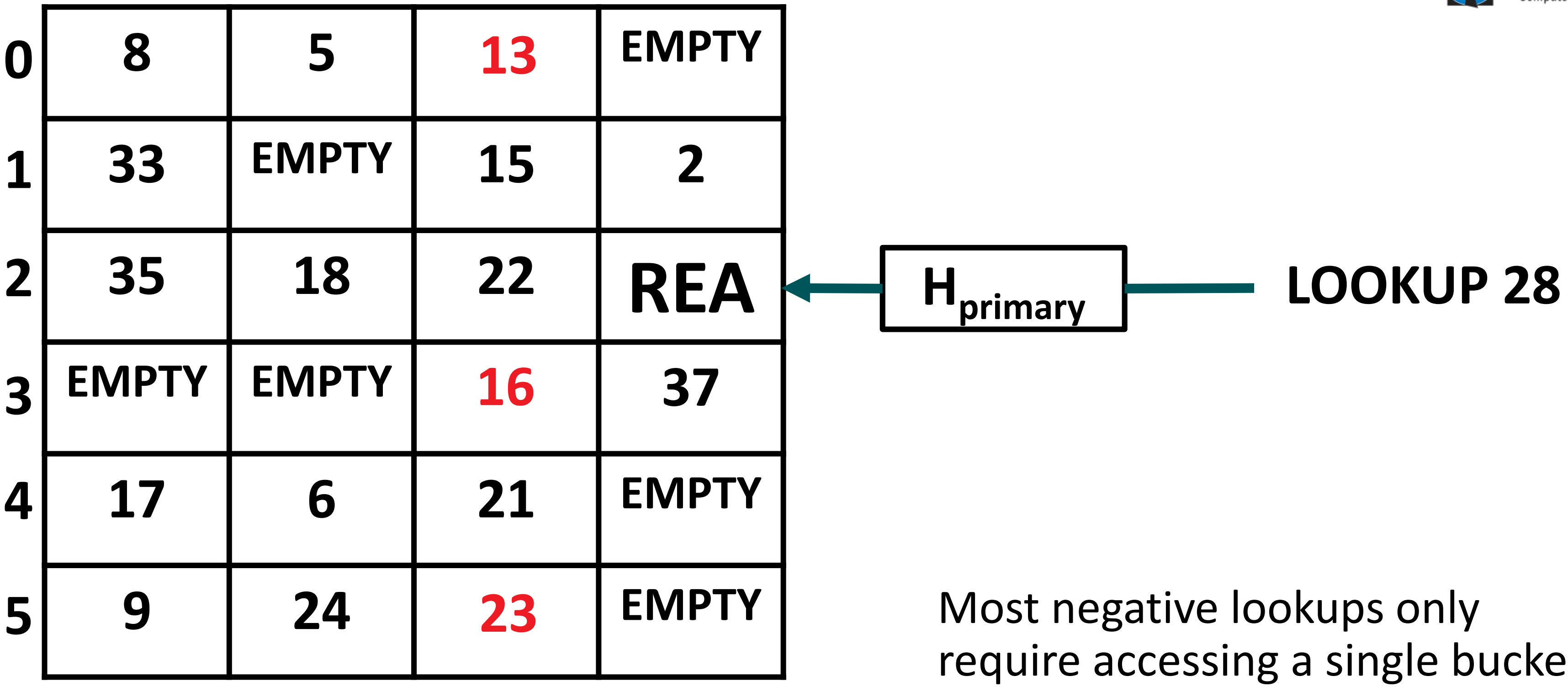
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Most negative lookups only require accessing a single bucket

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

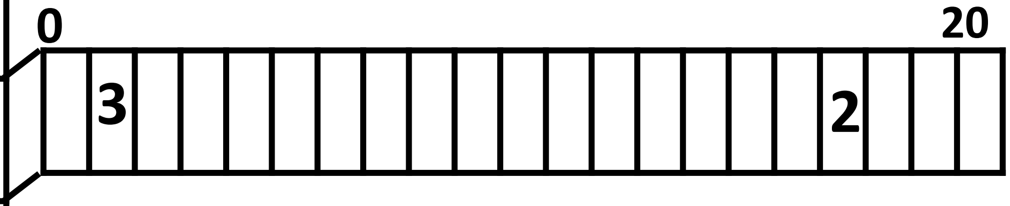
Most negative lookups only require accessing a single bucket

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

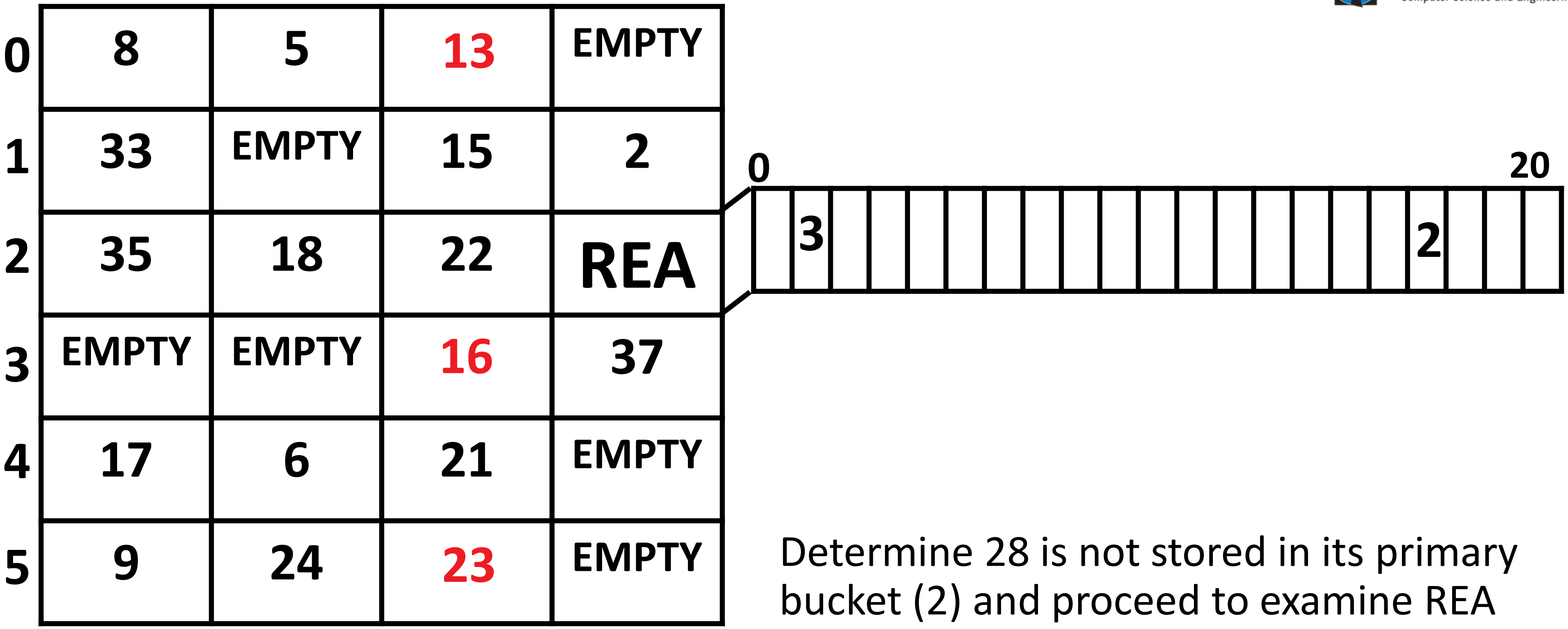


Most negative lookups only require accessing a single bucket

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS



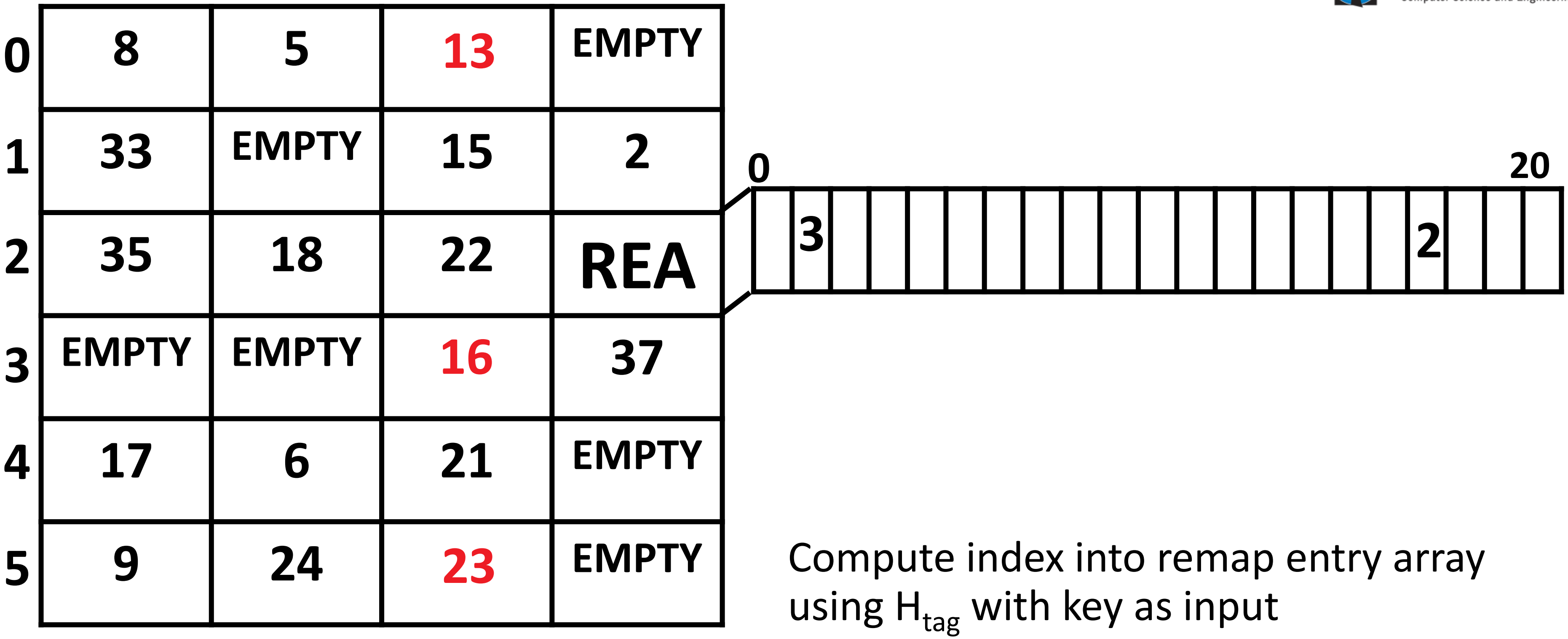
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Determine 28 is not stored in its primary bucket (2) and proceed to examine REA

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS



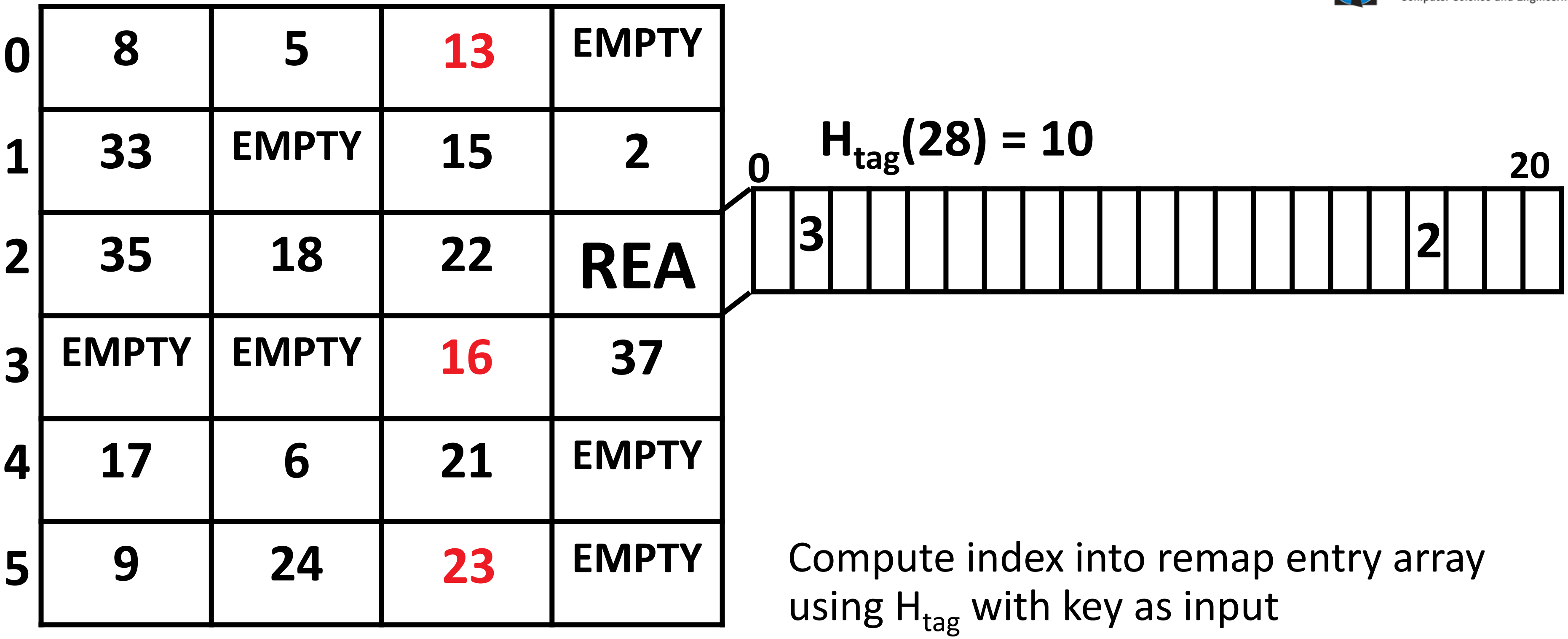
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Compute index into remap entry array using H_{tag} with key as input

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

$H_{tag}(28) = 10$

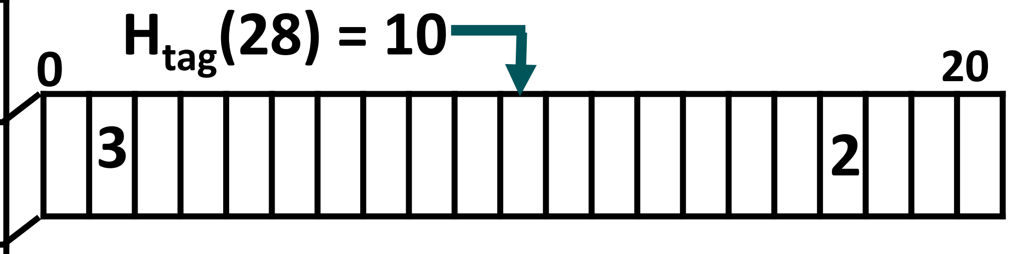
Compute index into remap entry array using H_{tag} with key as input

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY



Examine 10th slot of remap entry array and see it is empty. The search can stop.

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Negative lookups only require accessing 2 buckets on a *tag alias*

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

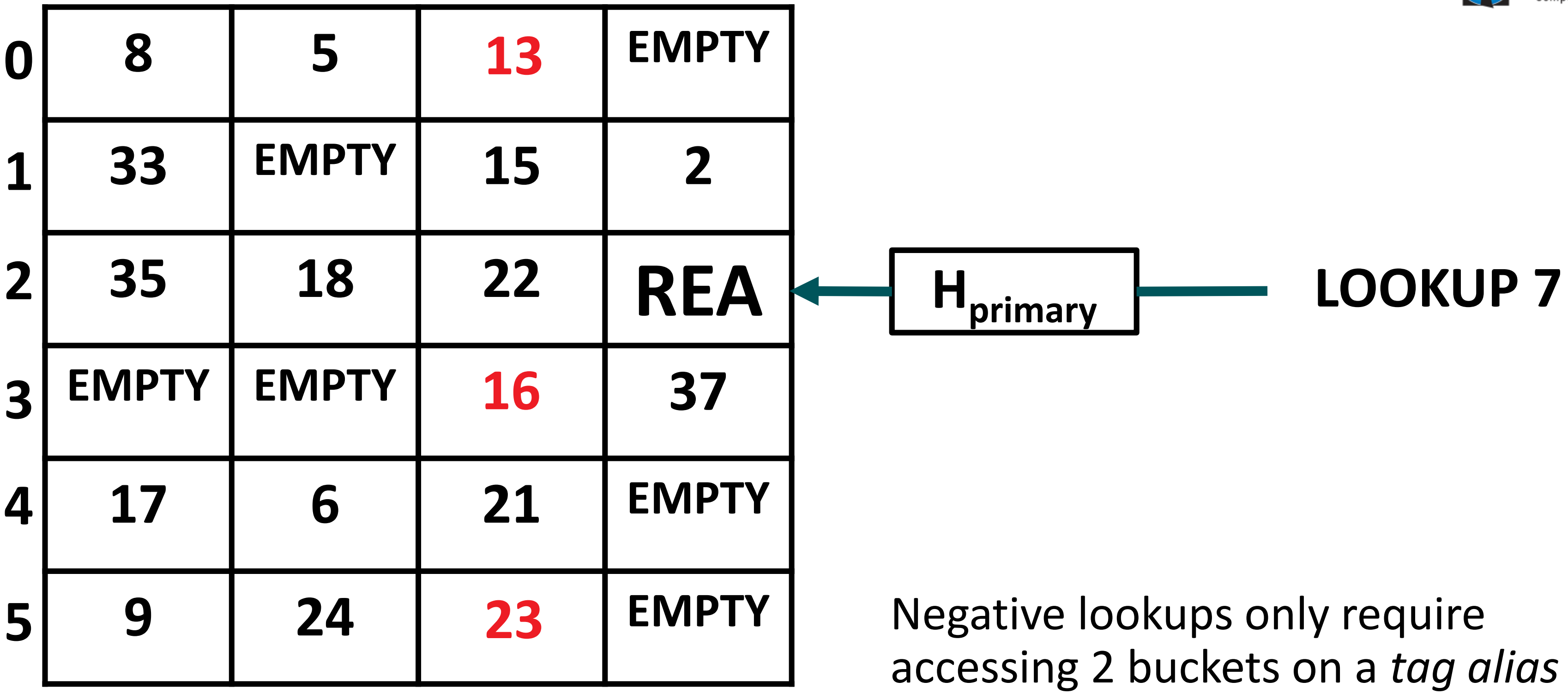
LOOKUP 7

Negative lookups only require accessing 2 buckets on a *tag alias*

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

$H_{primary}$

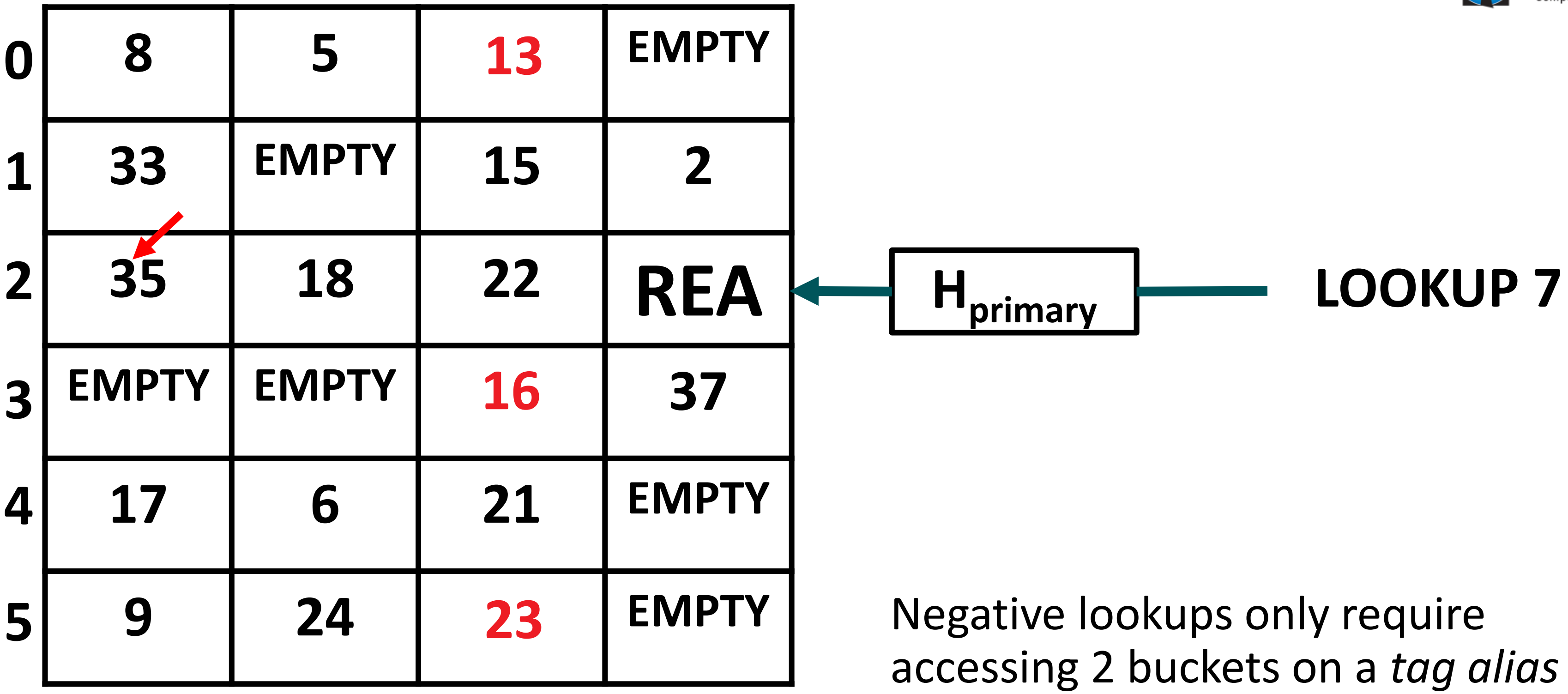
LOOKUP 7

Negative lookups only require accessing 2 buckets on a *tag alias*

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS



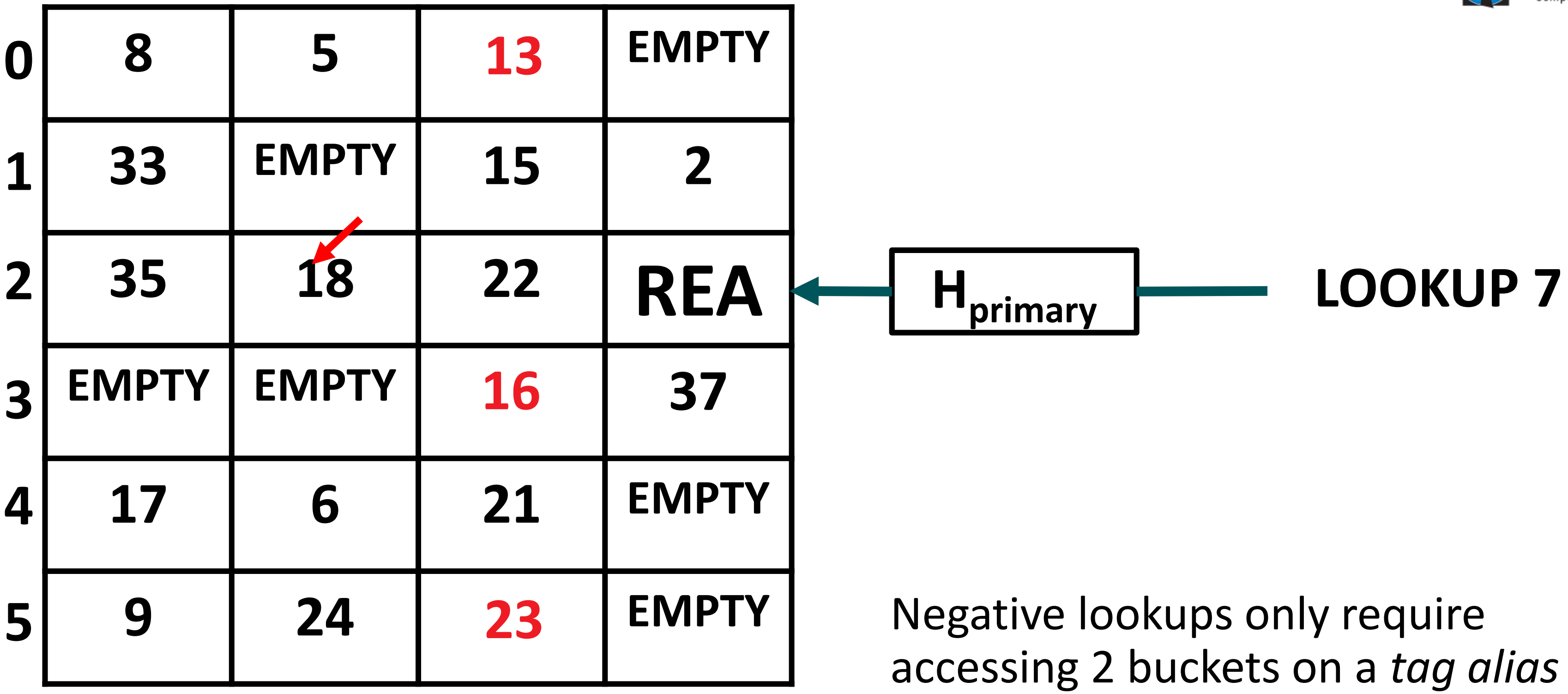
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Negative lookups only require accessing 2 buckets on a *tag alias*

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Negative lookups only require accessing 2 buckets on a *tag alias*

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

$H_{primary}$

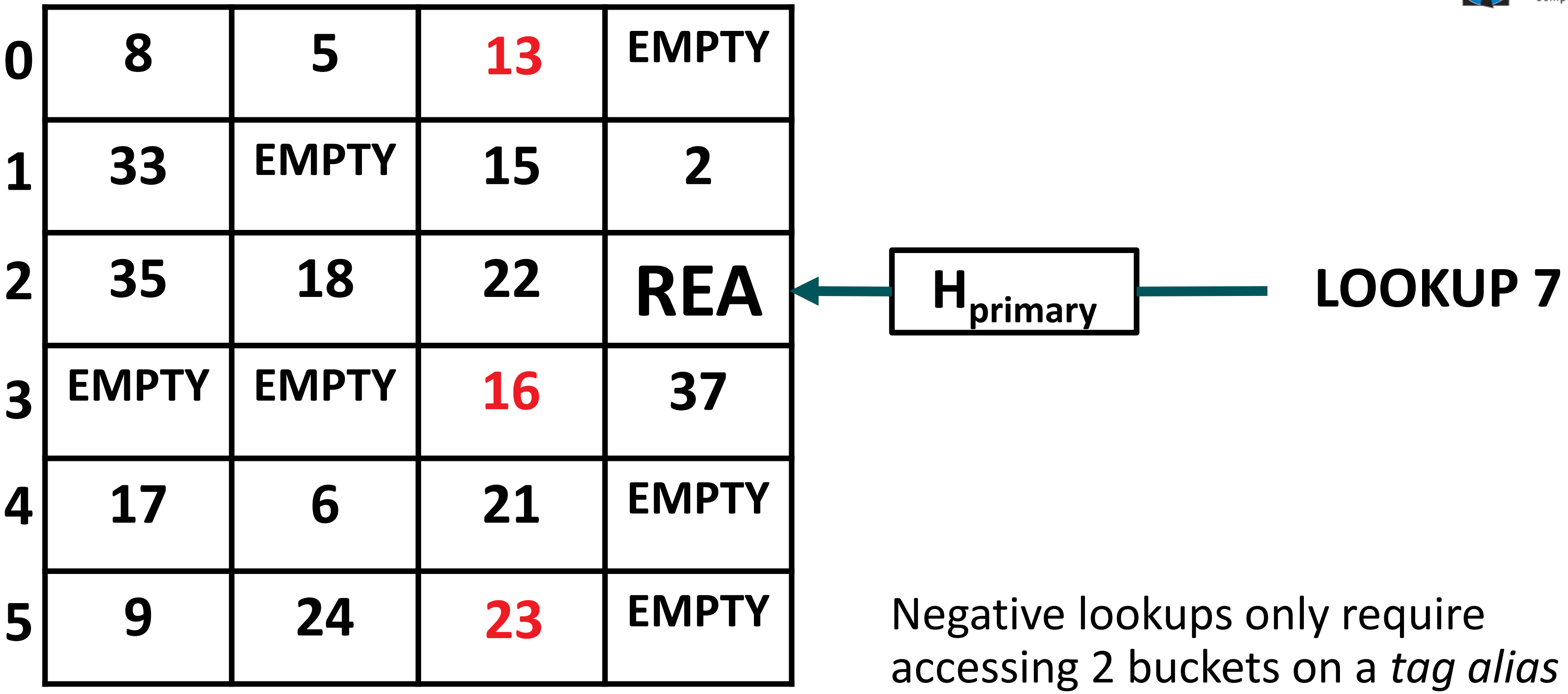
LOOKUP 7

Negative lookups only require accessing 2 buckets on a *tag alias*

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS



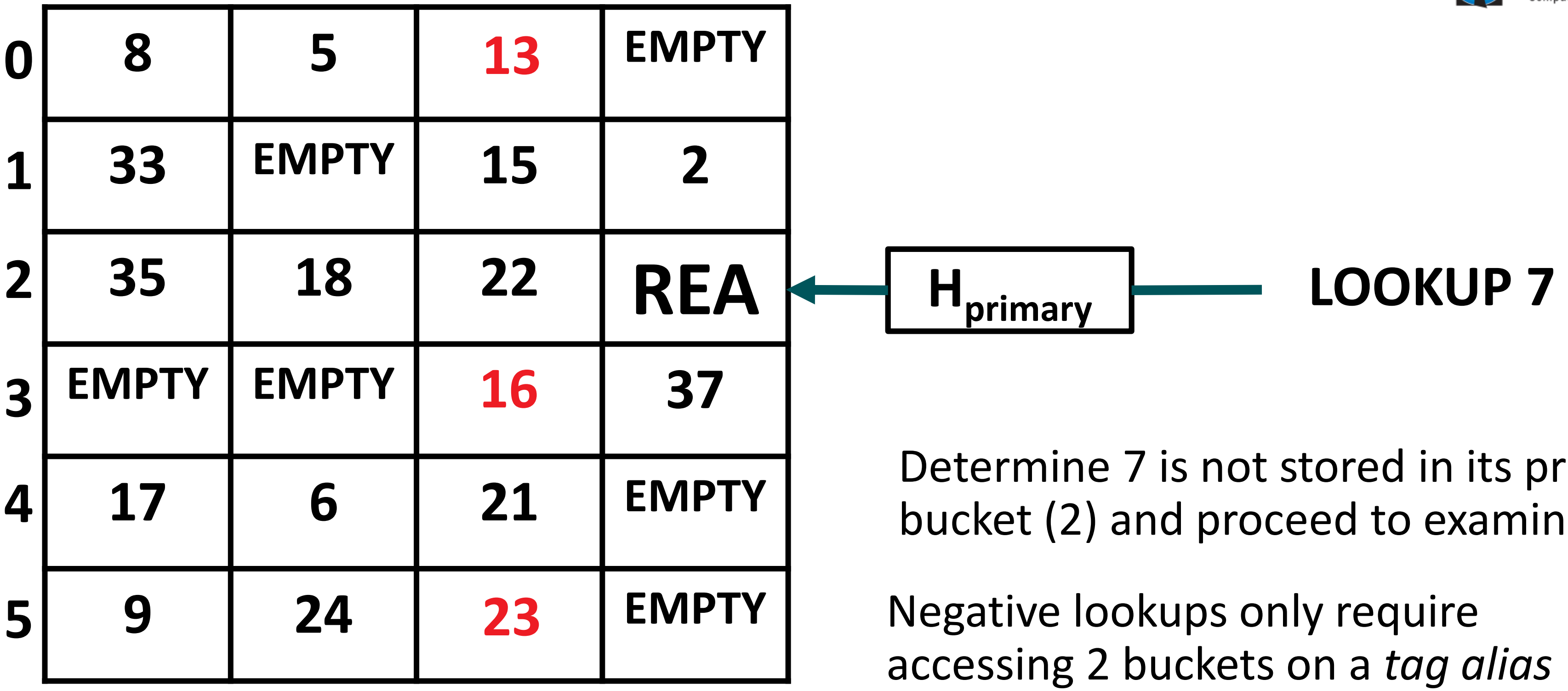
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Negative lookups only require accessing 2 buckets on a *tag alias*

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

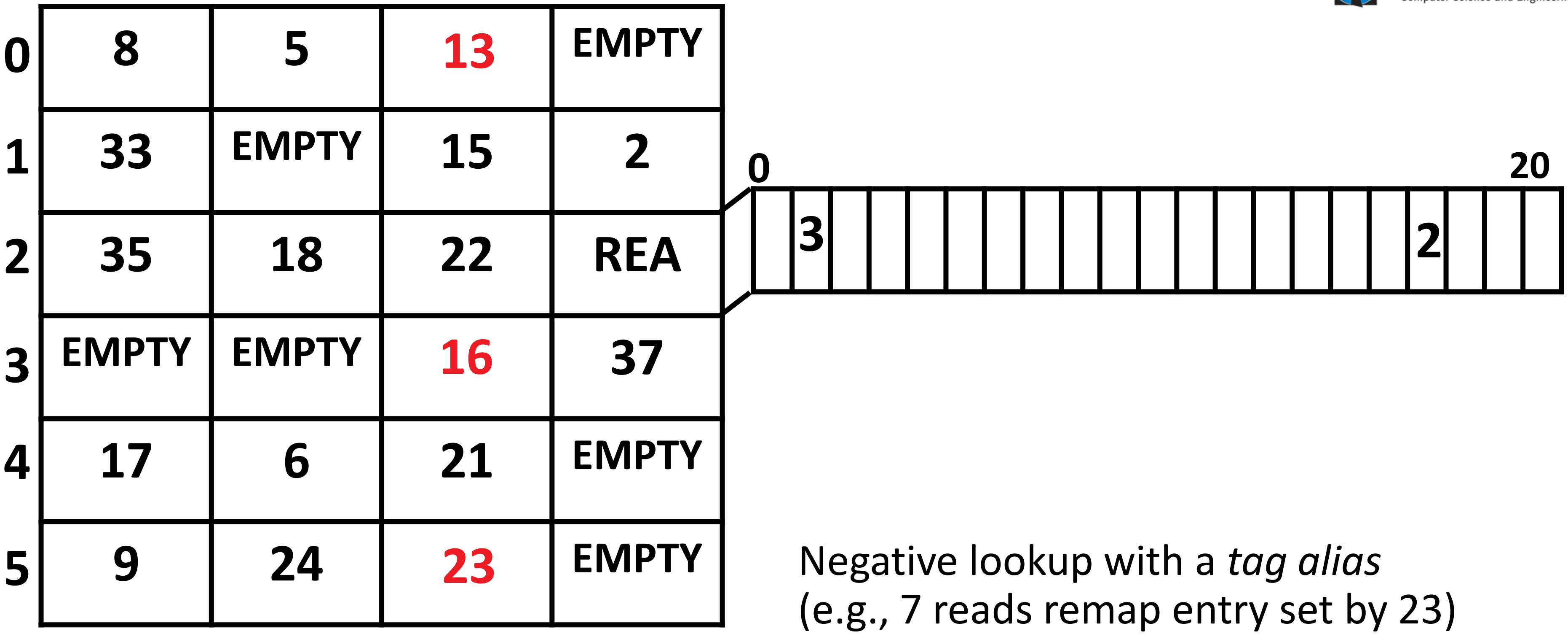
Determine 7 is not stored in its primary bucket (2) and proceed to examine REA

Negative lookups only require accessing 2 buckets on a *tag alias*

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS



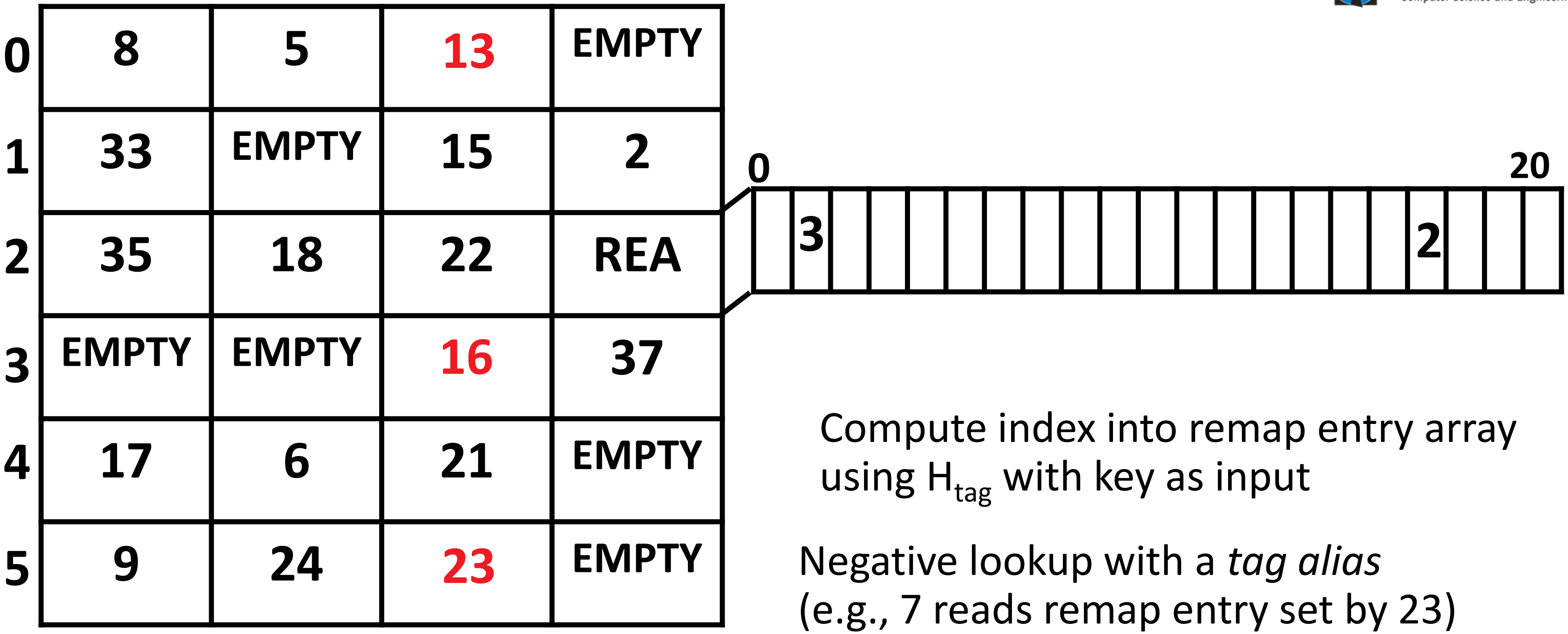
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Negative lookup with a *tag alias*
(e.g., 7 reads remap entry set by 23)

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Compute index into remap entry array using H_{tag} with key as input

Negative lookup with a *tag alias* (e.g., 7 reads remap entry set by 23)

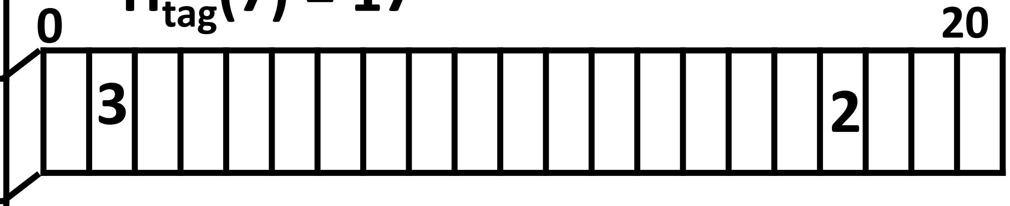
- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

$H_{tag}(7) = 17$



Compute index into remap entry array using H_{tag} with key as input

Negative lookup with a *tag alias* (e.g., 7 reads remap entry set by 23)

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Examine 18th slot of remap entry array and see that R_2 was likely used to remap 7.

Negative lookup with a *tag alias* (e.g., 7 reads remap entry set by 23)

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

LOOKUP 7

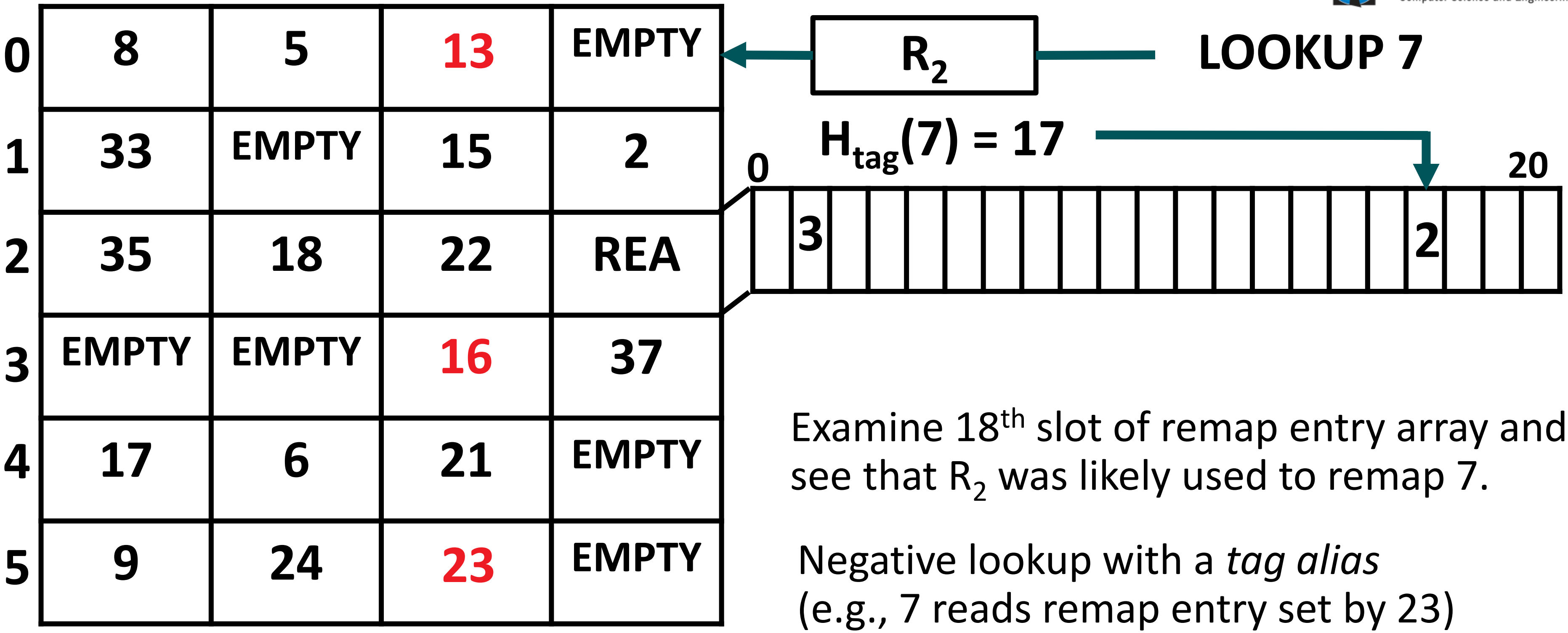
Examine 18th slot of remap entry array and see that R_2 was likely used to remap 7.

Negative lookup with a *tag alias* (e.g., 7 reads remap entry set by 23)

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

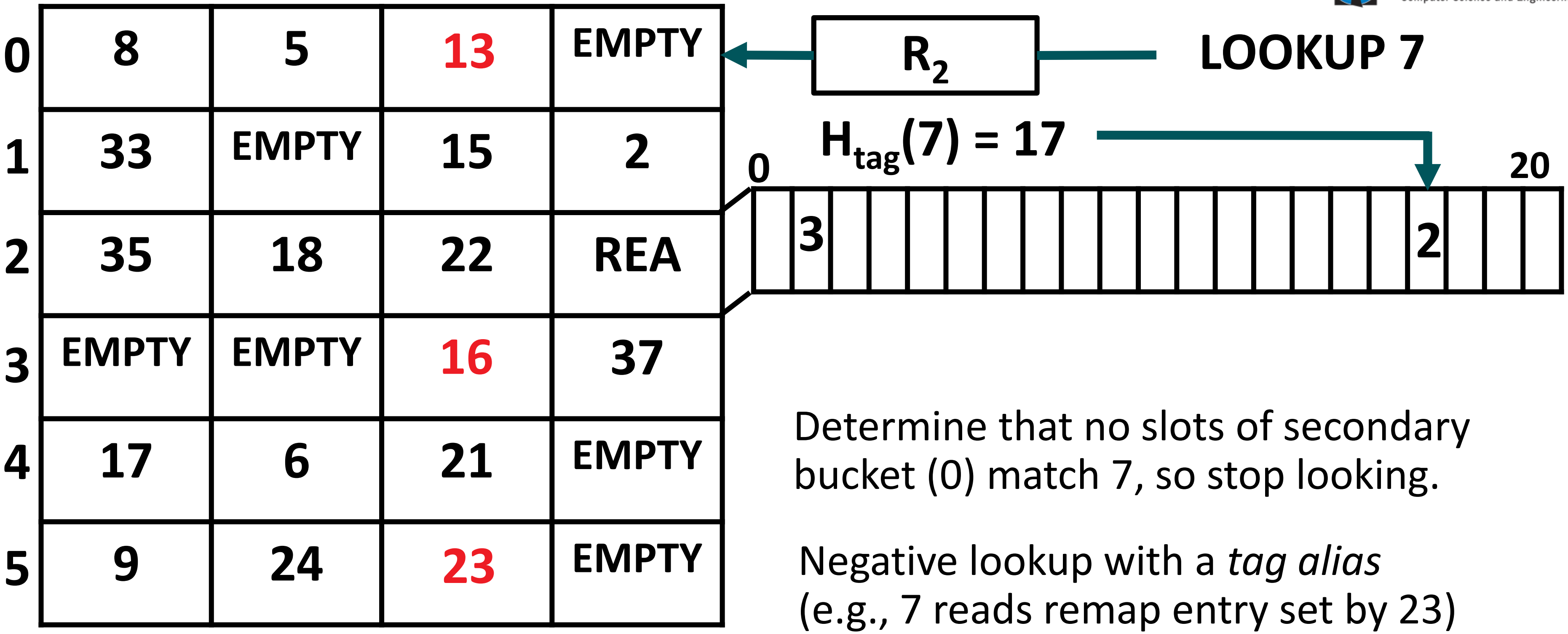
Examine 18th slot of remap entry array and see that R_2 was likely used to remap 7.

Negative lookup with a *tag alias* (e.g., 7 reads remap entry set by 23)

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

HORTON TABLES

NEGATIVE LOOKUPS WITH TAG ALIAS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Determine that no slots of secondary bucket (0) match 7, so stop looking.

Negative lookup with a *tag alias* (e.g., 7 reads remap entry set by 23)

- Lookups where the primary bucket is *Type B*, buckets where the final slot is converted into an REA, often only require accessing 1 bucket and at most 2 for positive and negative queries alike

ADDITIONAL CONTENT IN THE PAPER

- Sharing of remap entries among multiple remapped elements while still permitting their deletion

- Further optimizations for improving lookup throughput

- Analytical models for lookups, insertions and deletions

- More in-depth discussion of prior work and how Horton tables improves over first-fit for positive lookups

EXPERIMENTAL METHODOLOGY

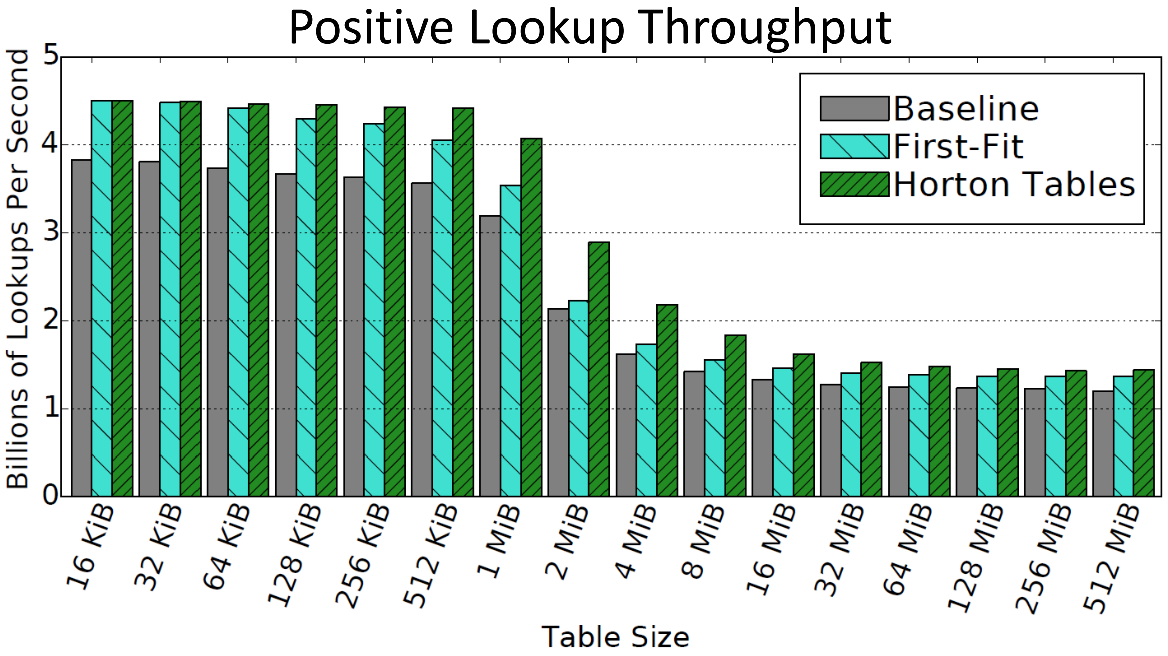
- Conducted a series of analytical studies to determine 8-slots per bucket was a good design point (**more details in paper**)
  - Fills a 64-byte cache line with 8-byte entries
  - High load factors (>95% table can be filled with key-value pairs)
  - Positive lookups that typically access less than 1.18 buckets per query
  - Negative lookups that typically access less than 1.06 buckets per query

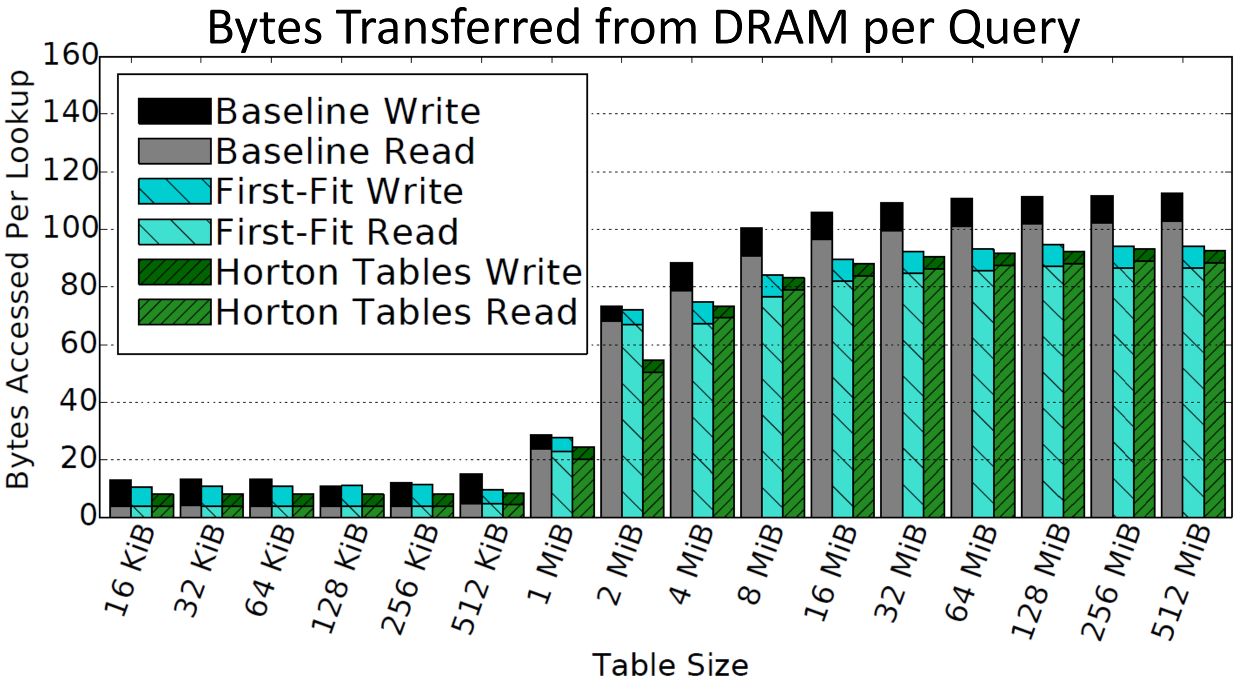
- Further analytical studies demonstrated that 21 entries per REA and 7 secondary functions is often more than sufficient for 8-slot buckets (**more details in paper**)

- Experimental studies conducted on an AMD Radeon^{TM} R9 290X GPU

RESULTS

POSITIVE LOOKUPS

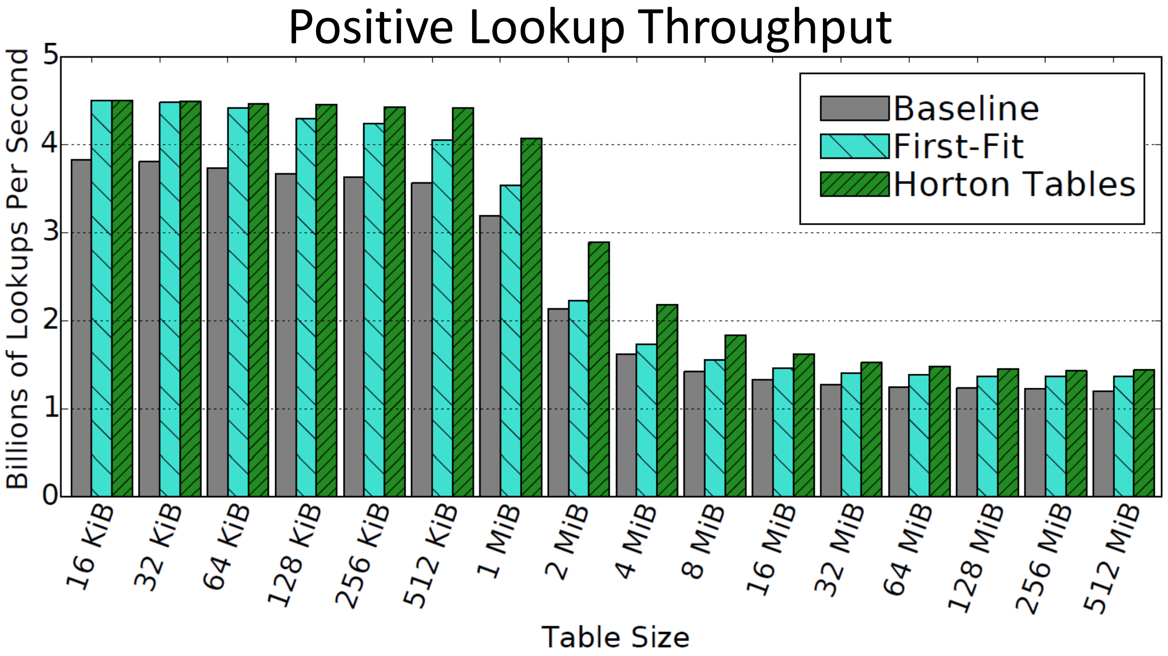


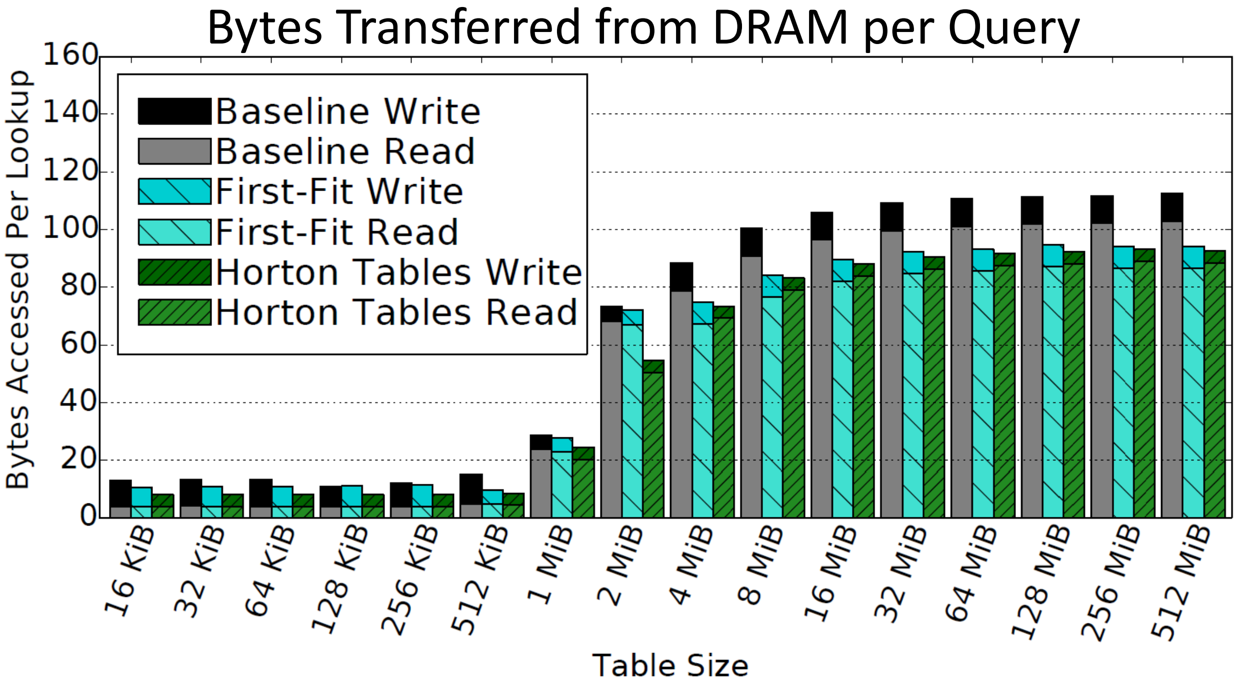


RESULTS

POSITIVE LOOKUPS

HIGHER IS BETTER

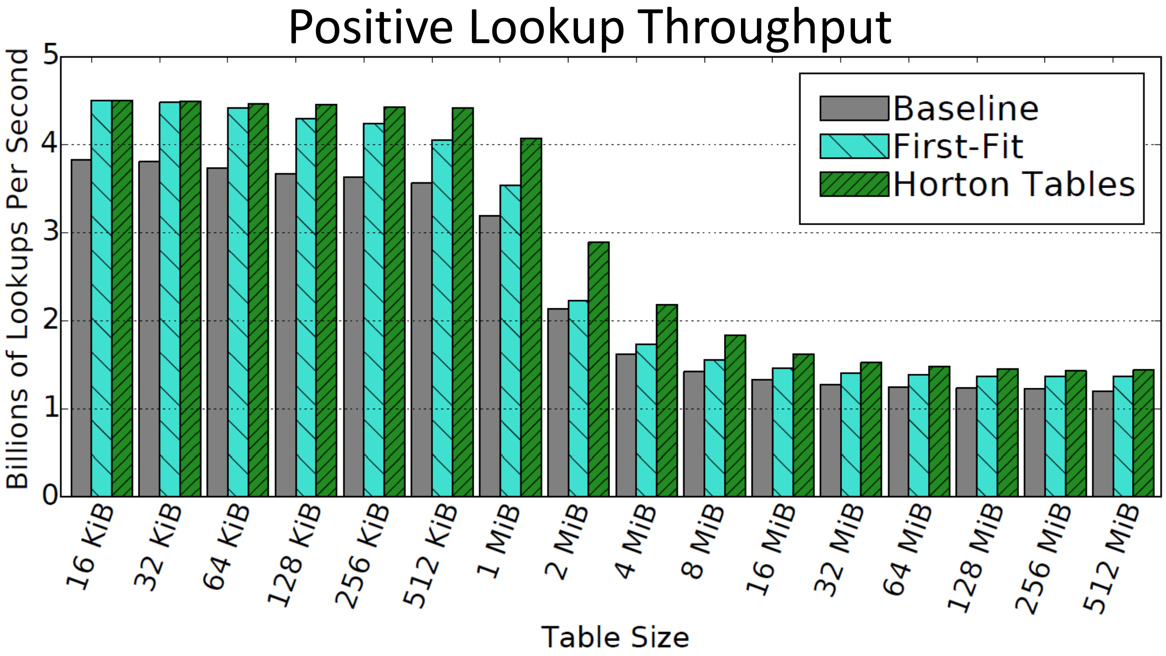




RESULTS

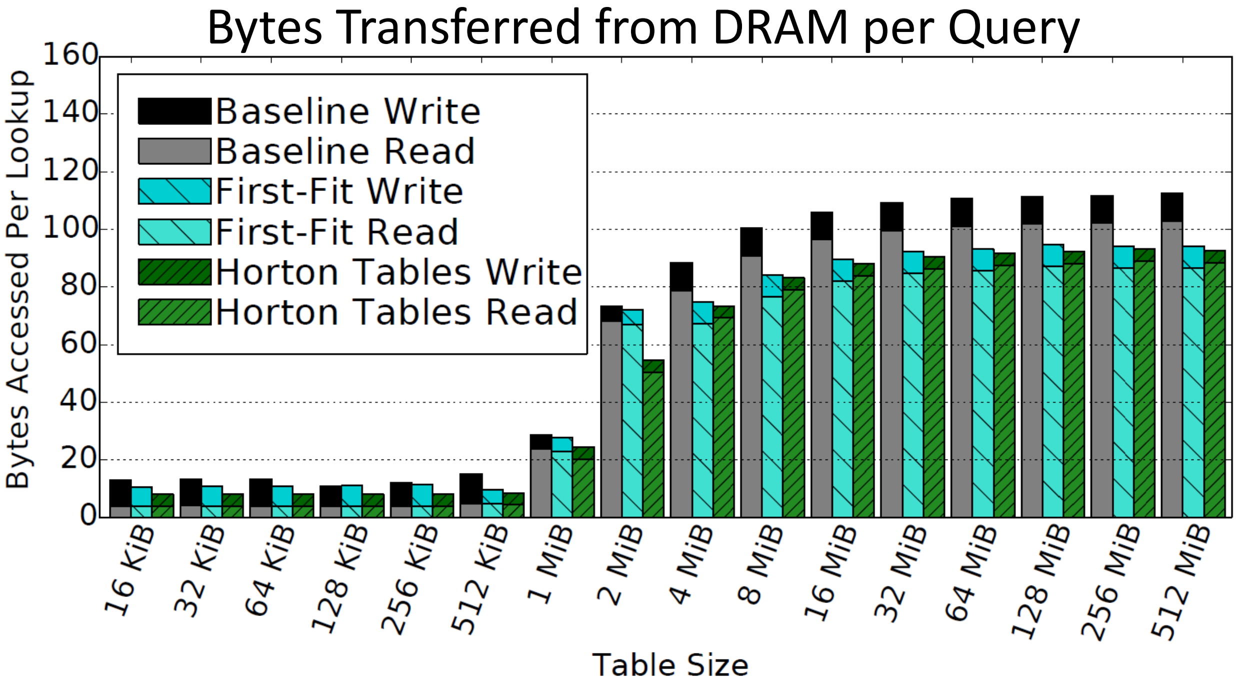
POSITIVE LOOKUPS

HIGHER IS BETTER



Positive Lookup Throughput

LOWER IS BETTER

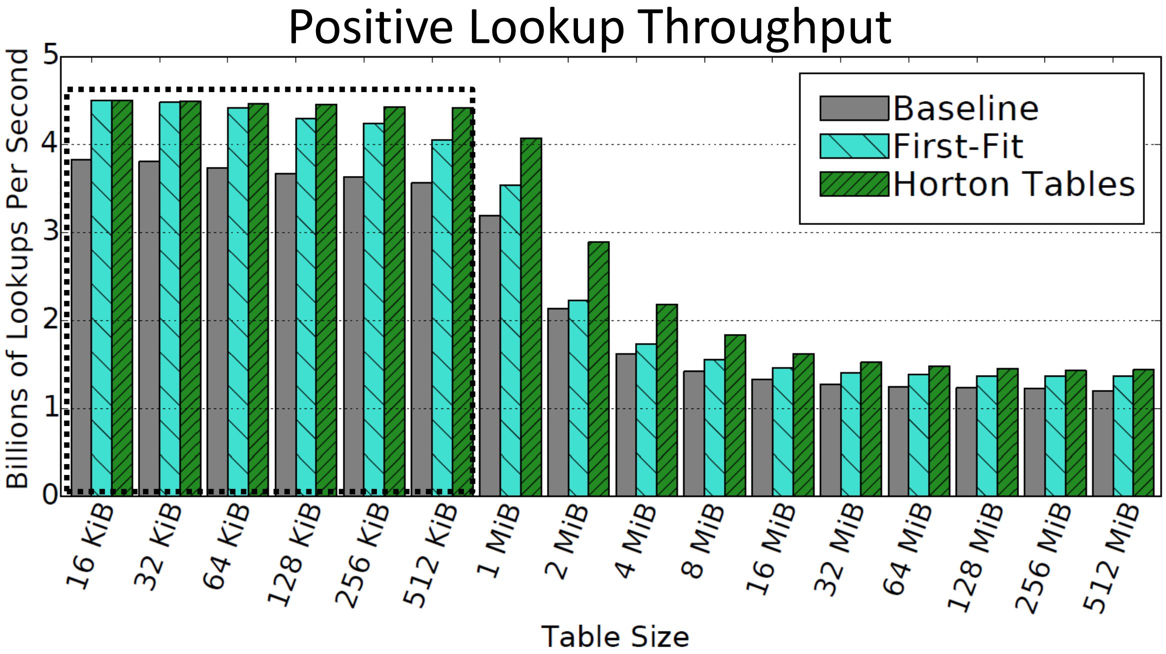


Bytes Transferred from DRAM per Query

RESULTS

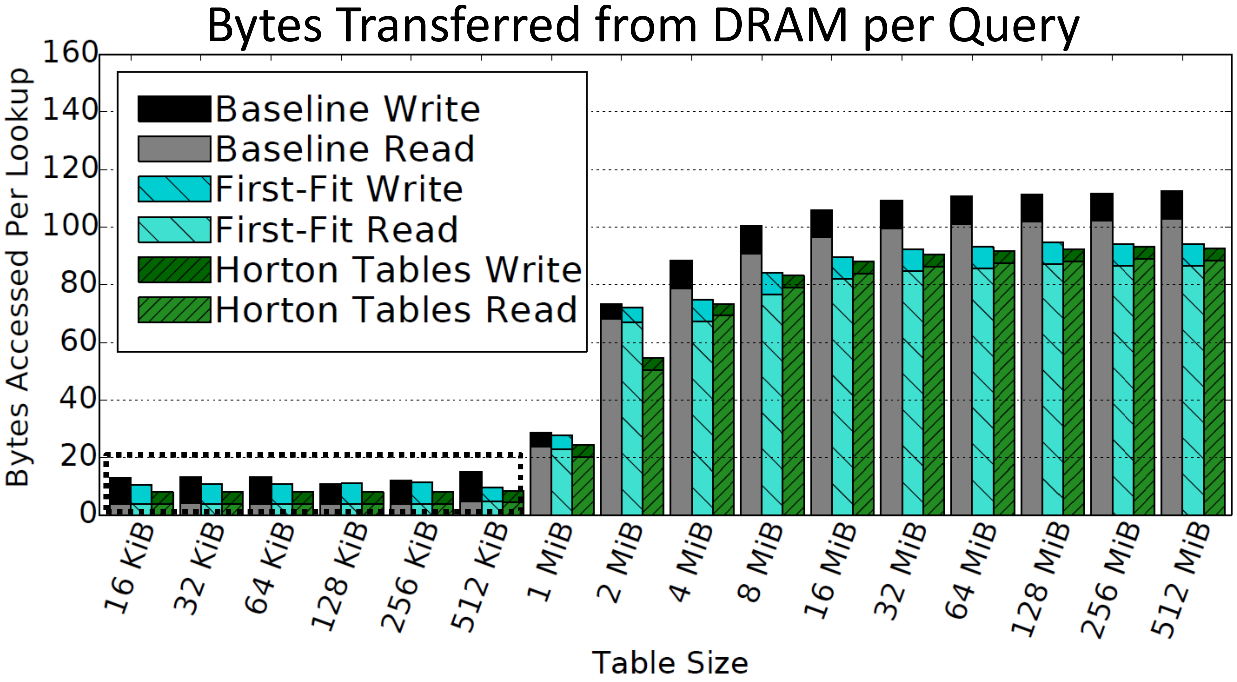
POSITIVE LOOKUPS

HIGHER IS BETTER



Positive Lookup Throughput

LOWER IS BETTER

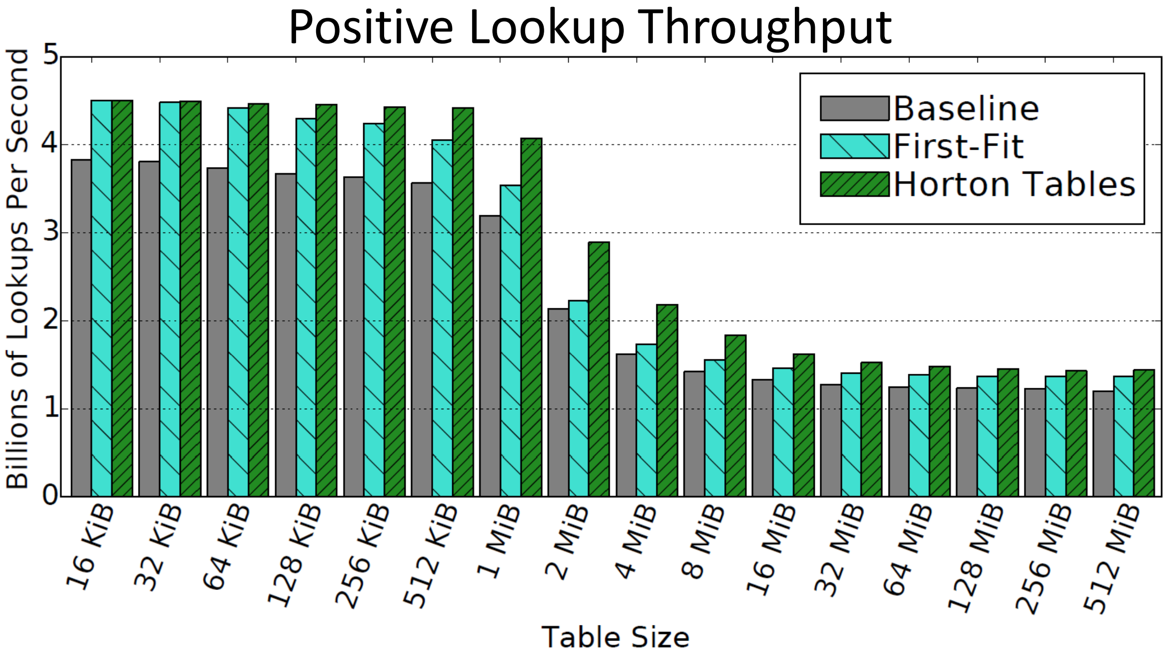


Bytes Transferred from DRAM per Query

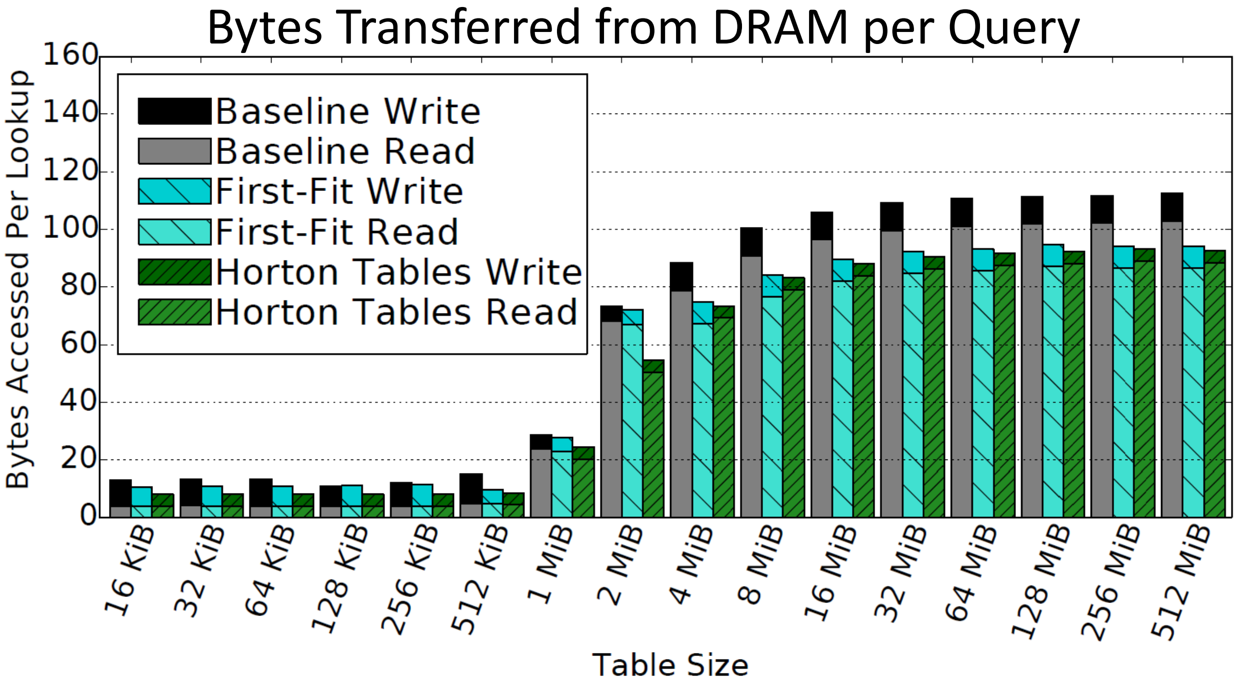
RESULTS

POSITIVE LOOKUPS

HIGHER IS BETTER


Positive Lookup Throughput

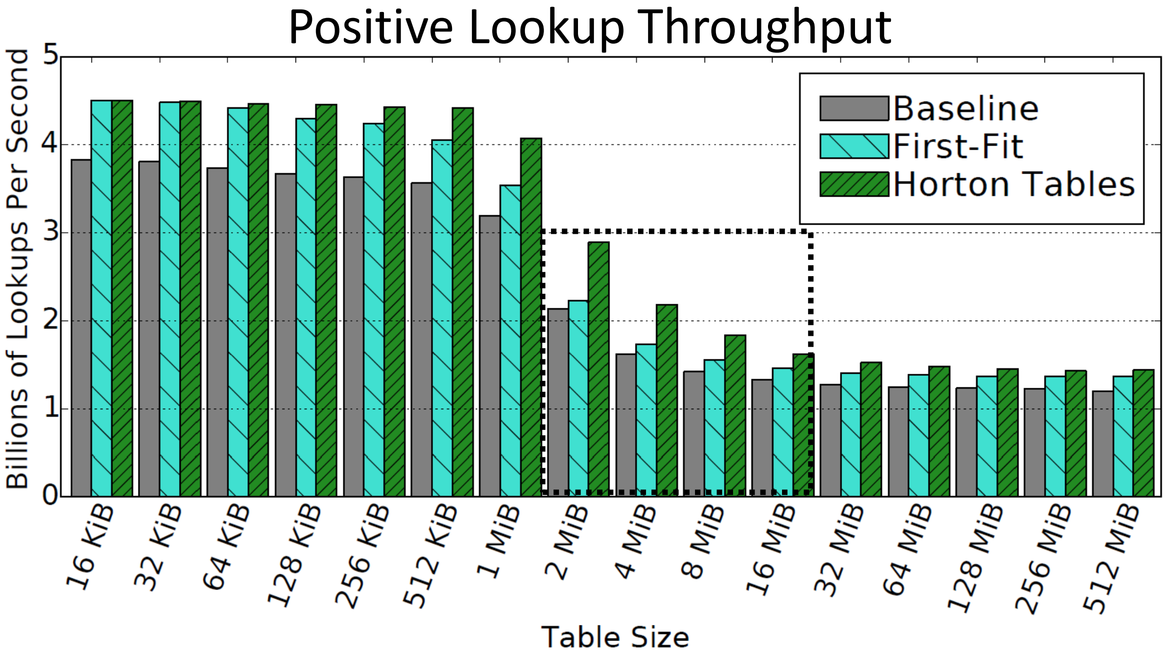
LOWER IS BETTER


Bytes Transferred from DRAM per Query

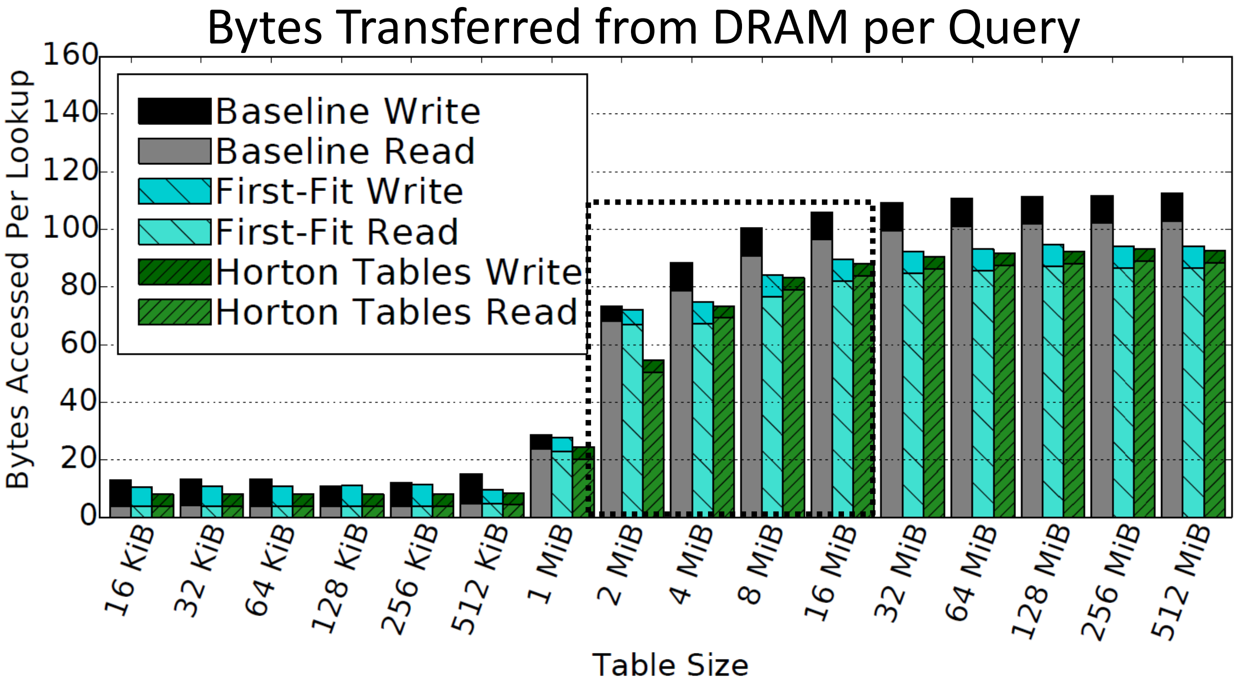
RESULTS

POSITIVE LOOKUPS

HIGHER IS BETTER



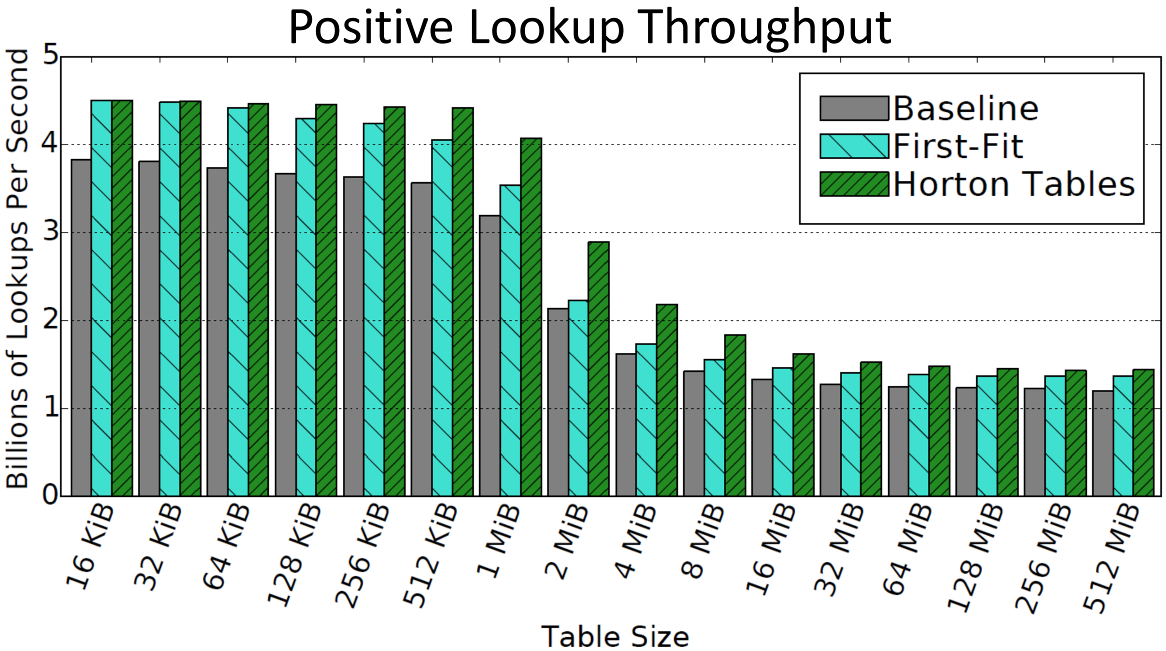
LOWER IS BETTER



RESULTS

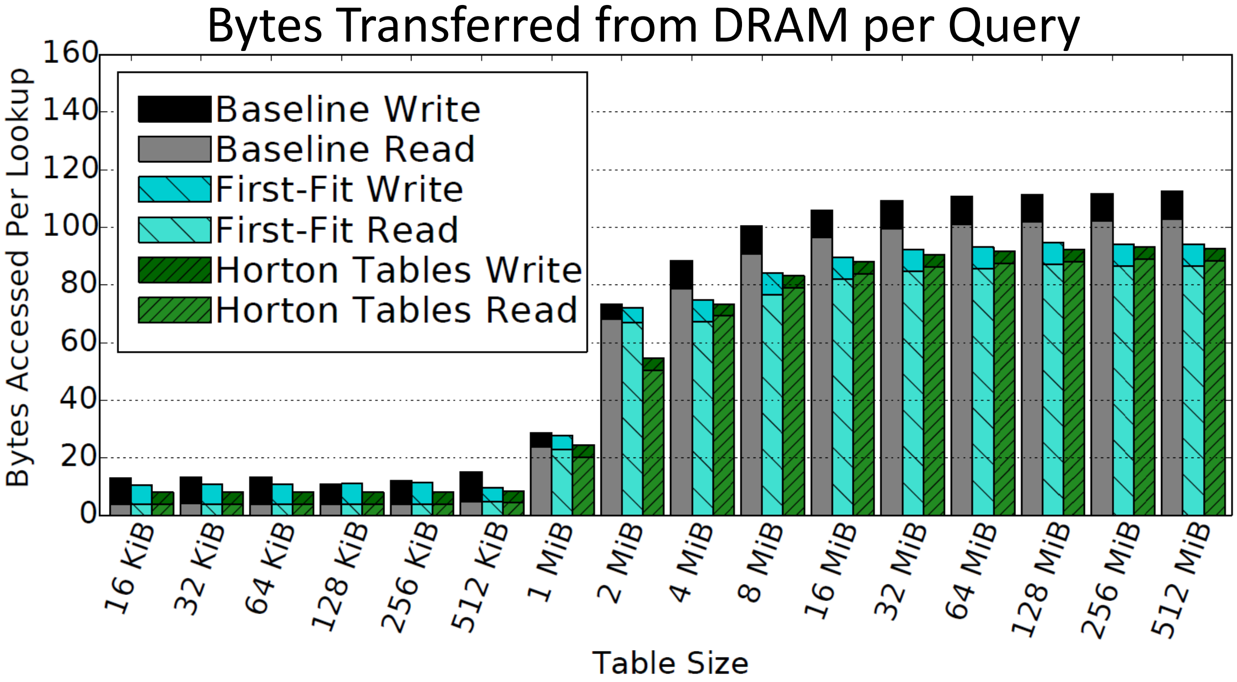
POSITIVE LOOKUPS

HIGHER IS BETTER



Positive Lookup Throughput

LOWER IS BETTER

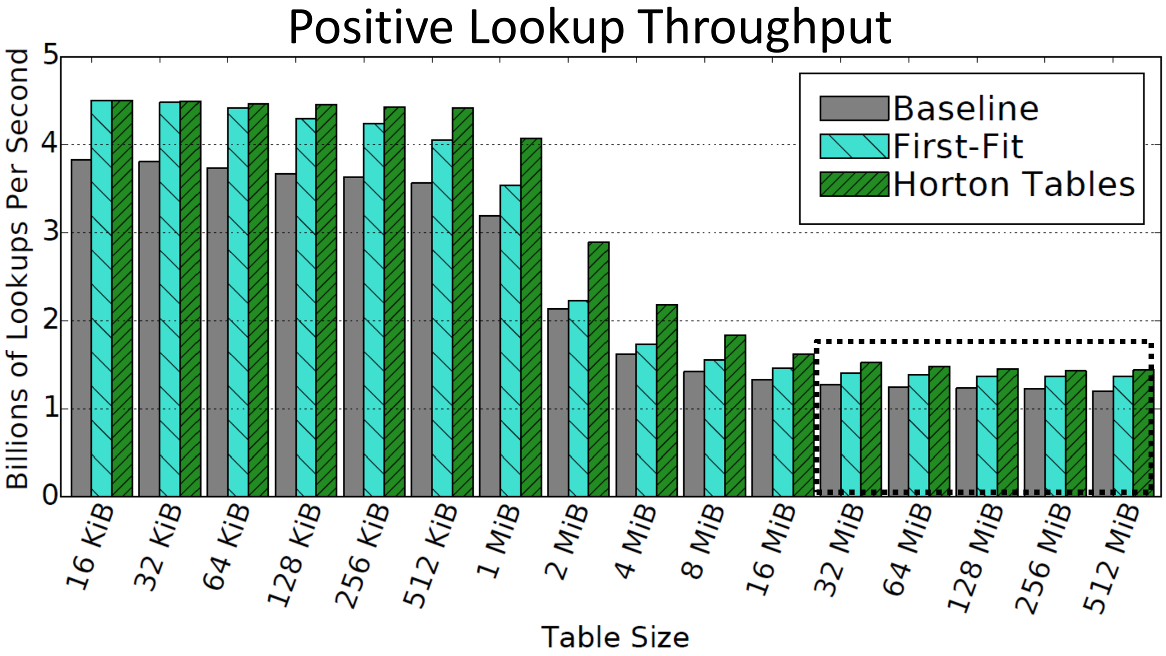


Bytes Transferred from DRAM per Query

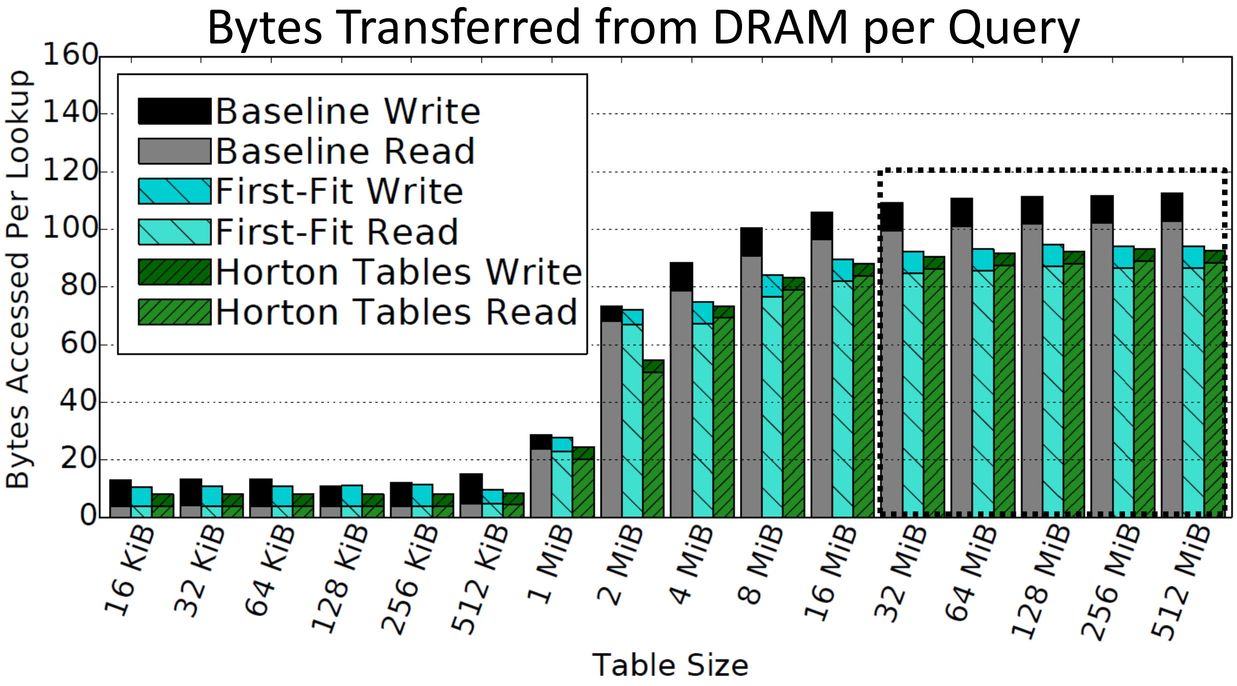
RESULTS

POSITIVE LOOKUPS

HIGHER IS BETTER



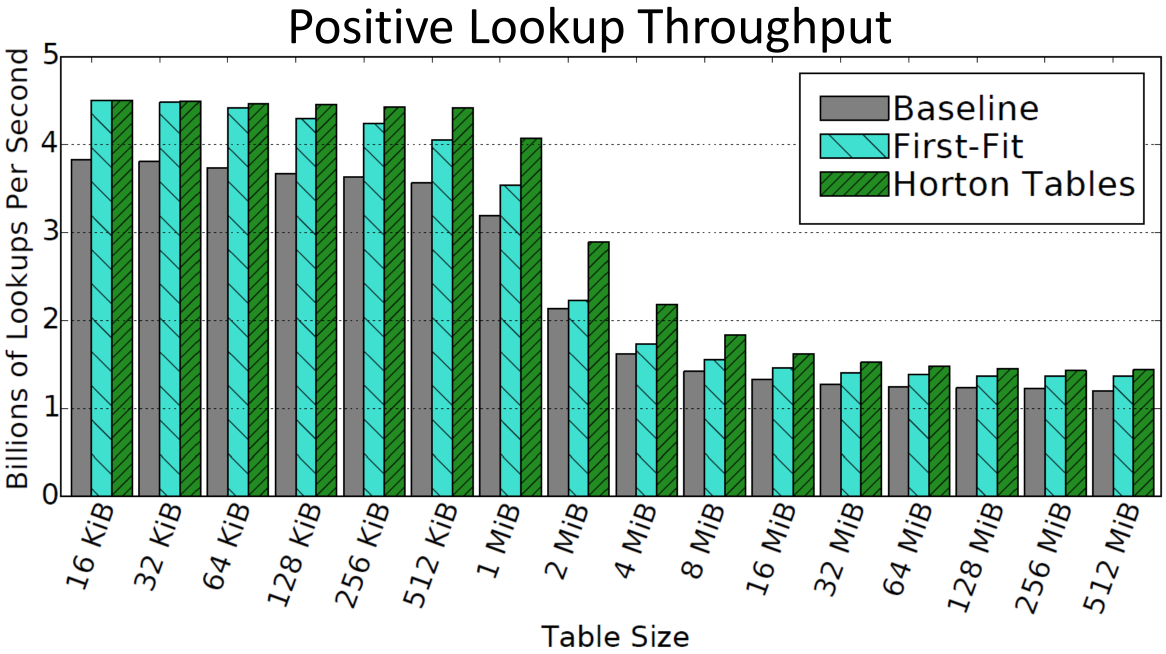
LOWER IS BETTER



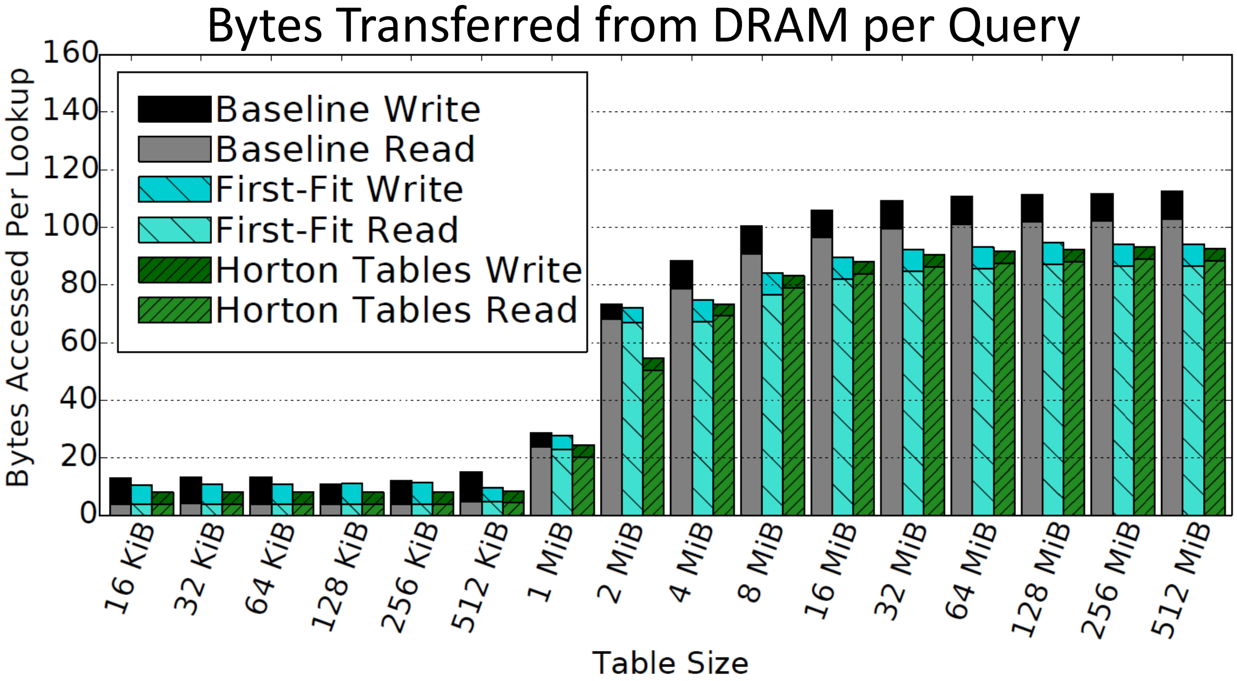
RESULTS

POSITIVE LOOKUPS

HIGHER IS BETTER

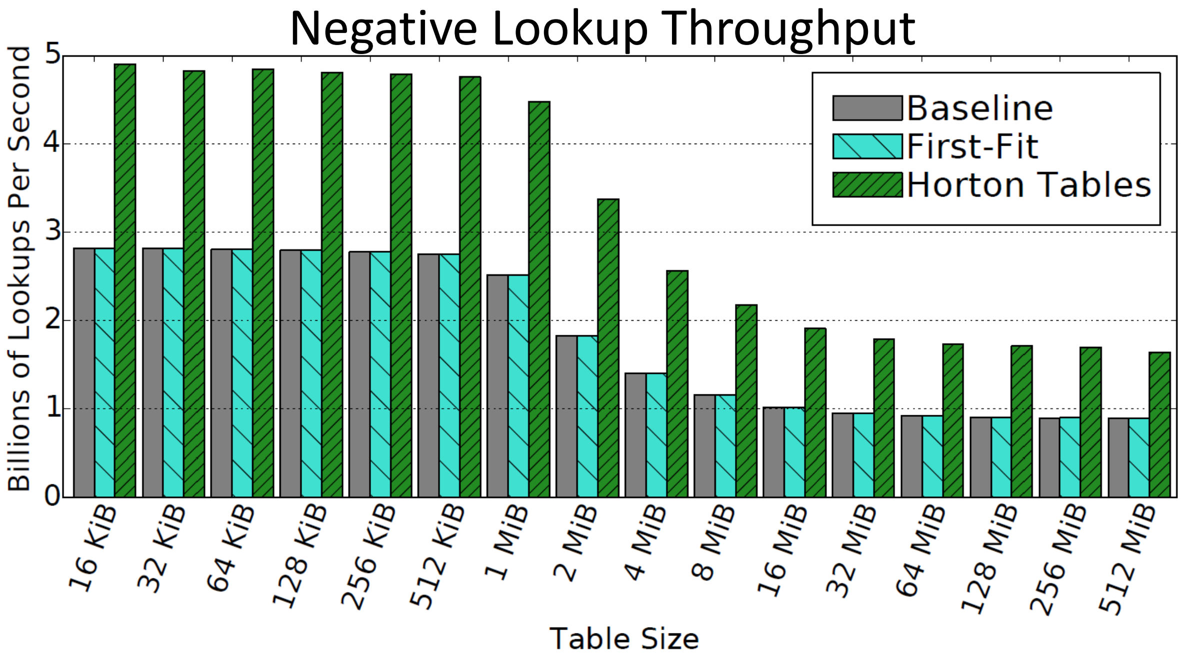

Positive Lookup Throughput

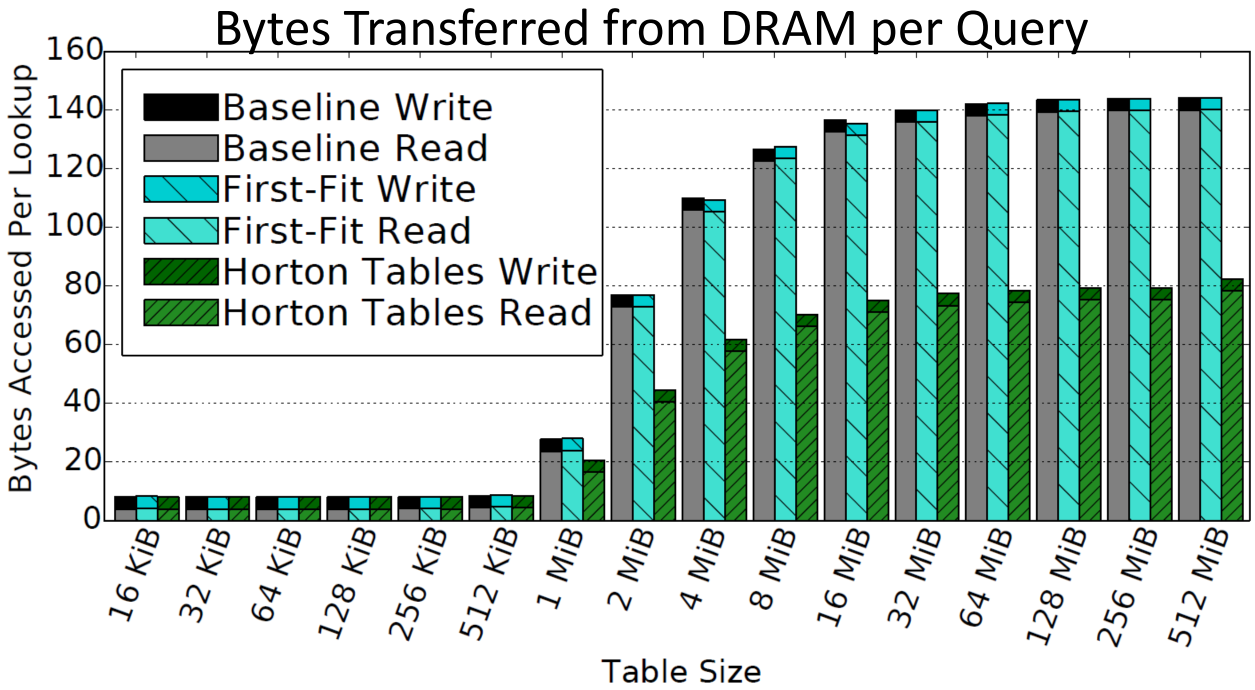
LOWER IS BETTER


Bytes Transferred from DRAM per Query

RESULTS

NEGATIVE LOOKUPS





RESULTS
NEGATIVE LOOKUPS

HIGHER IS BETTER

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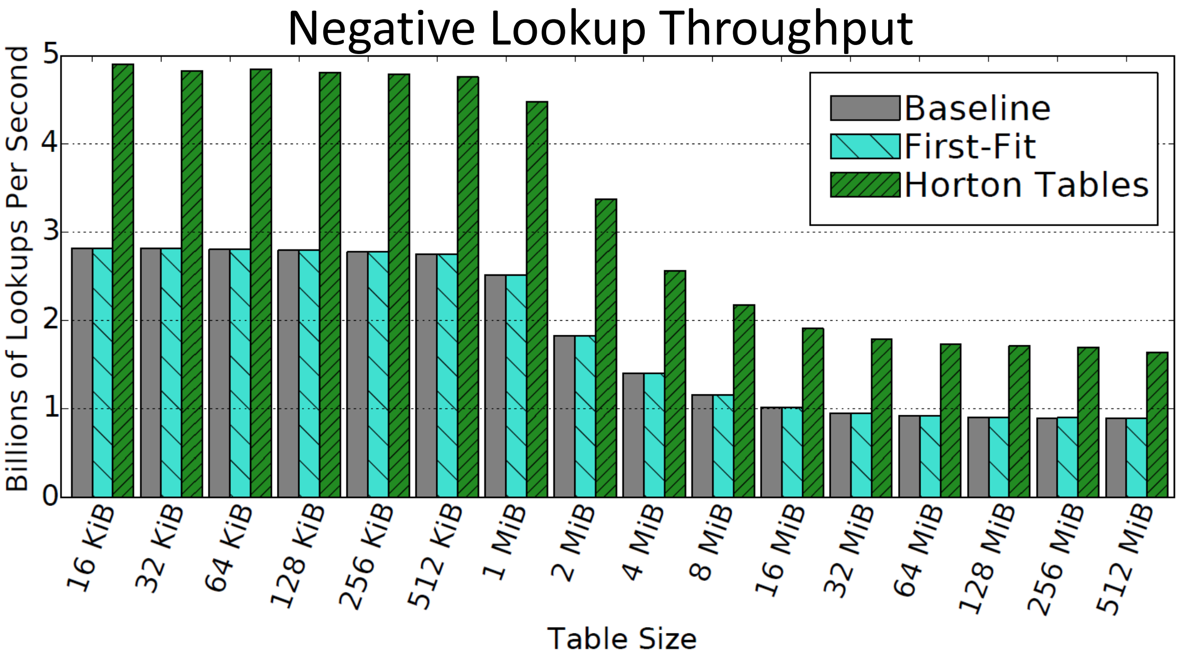
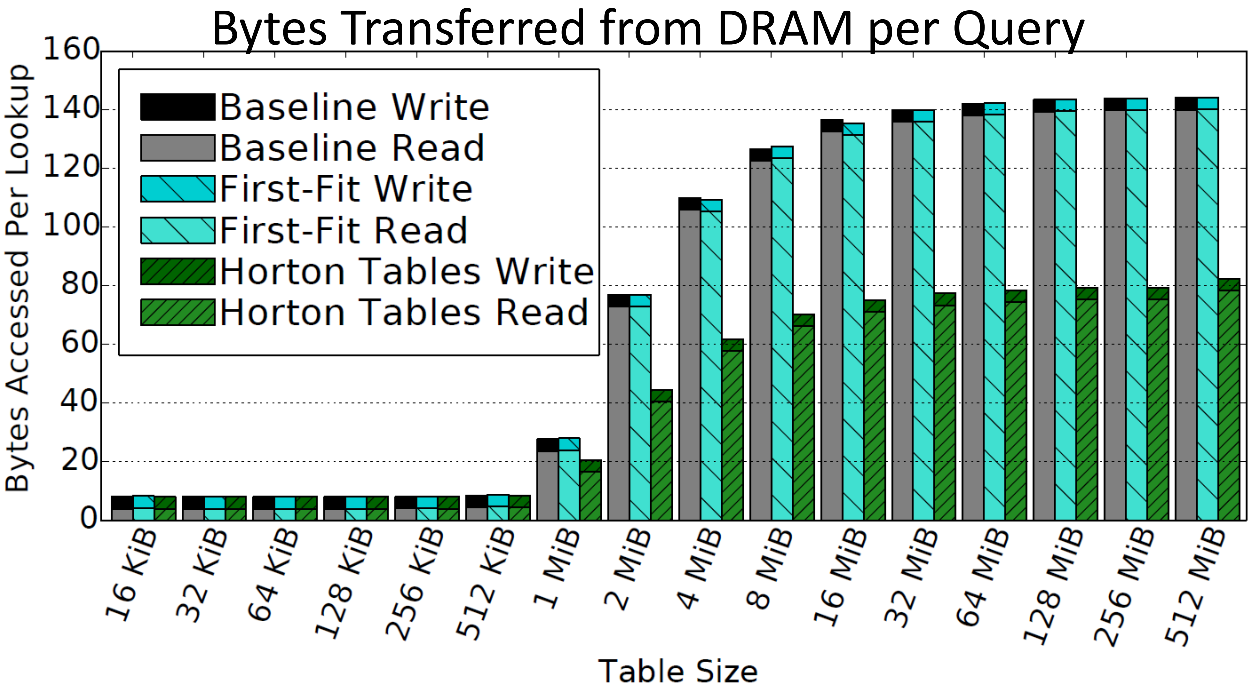
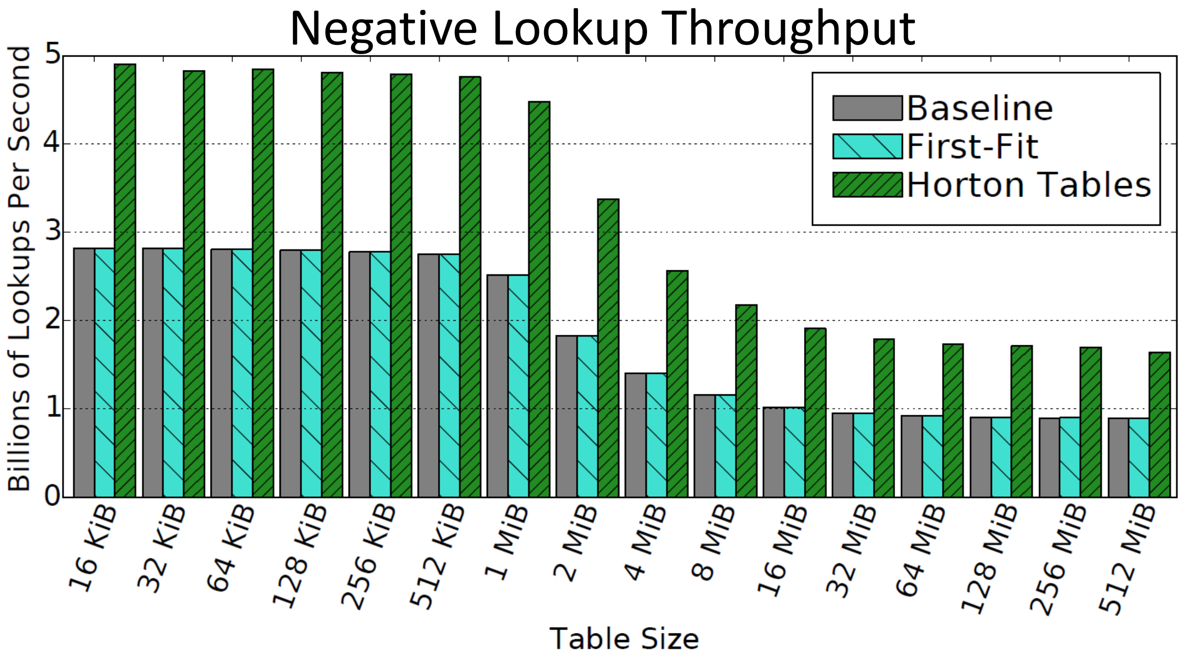

Negative Lookup Throughput


Bytes Transferred from DRAM per Query

RESULTS

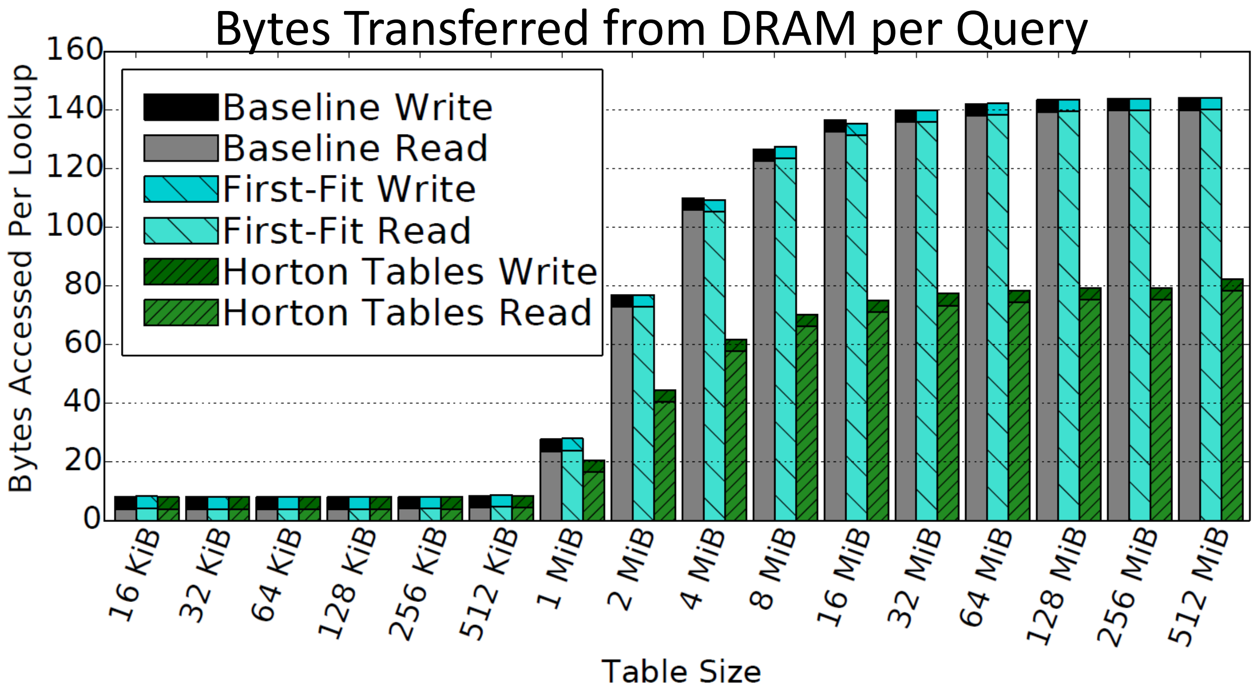
NEGATIVE LOOKUPS

HIGHER IS BETTER



Negative Lookup Throughput

LOWER IS BETTER



Bytes Transferred from DRAM per Query

RESULTS

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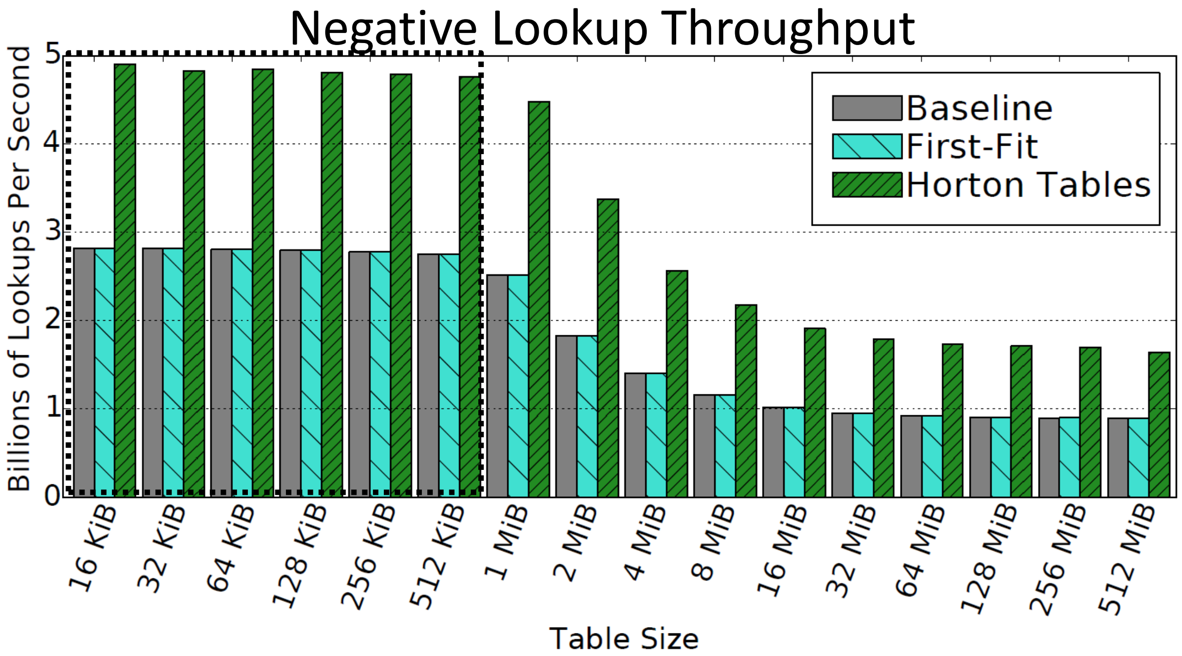
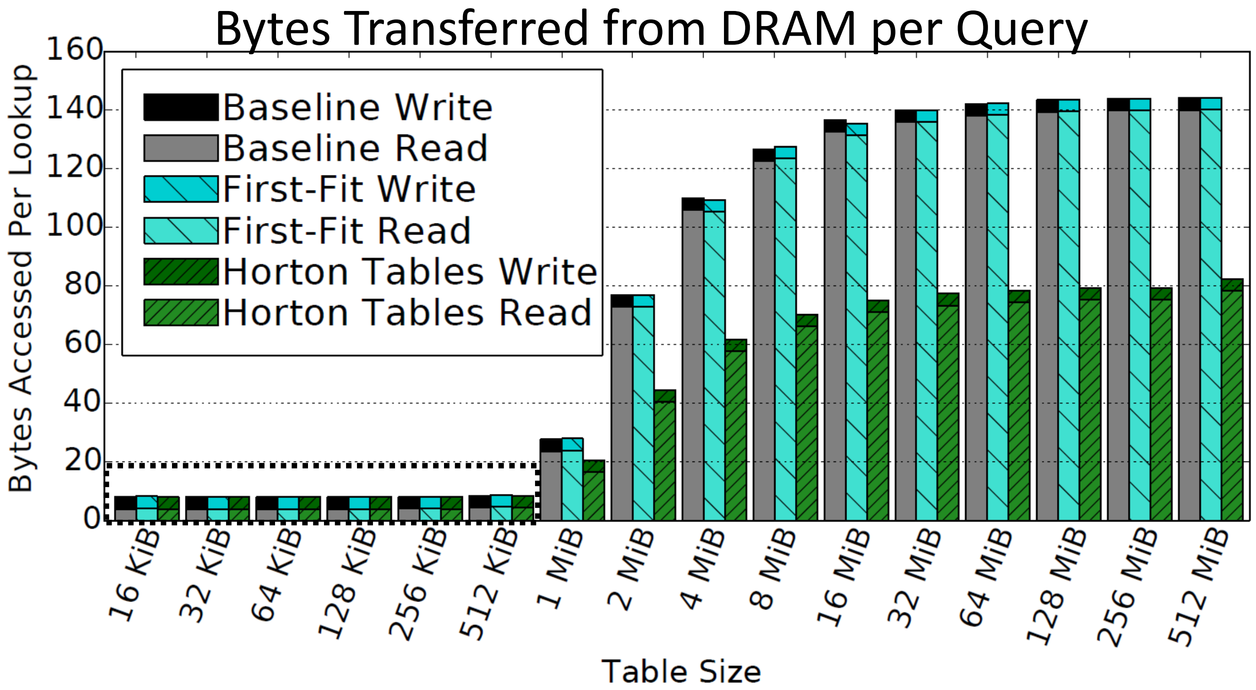


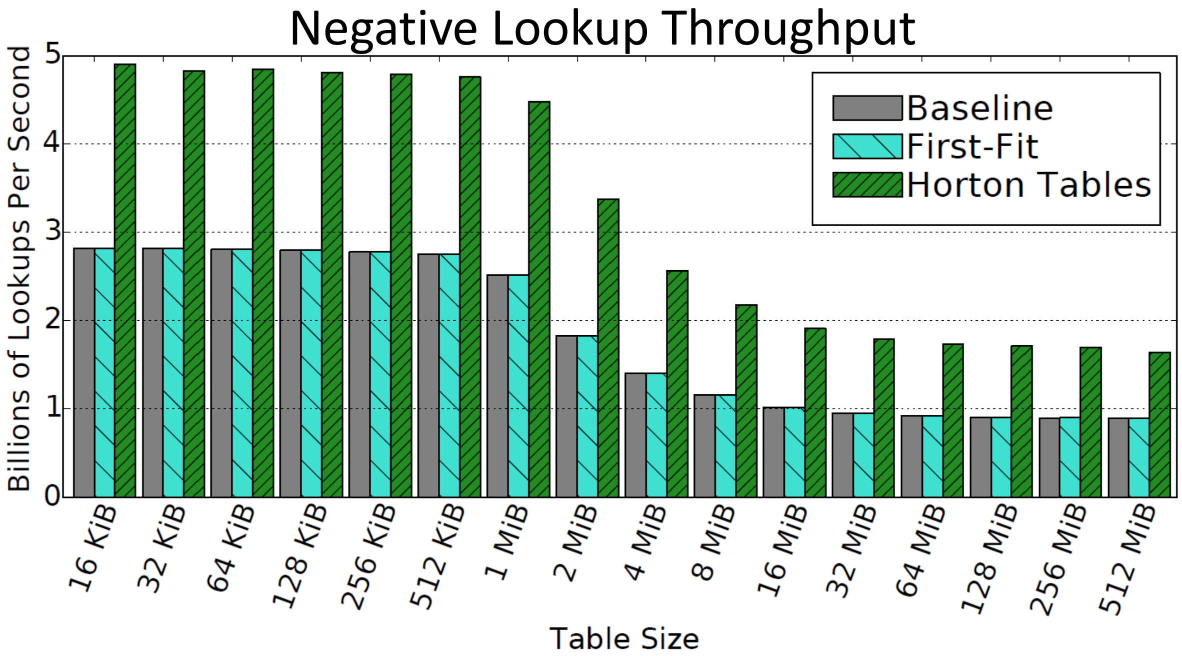
LOWER IS BETTER



RESULTS

NEGATIVE LOOKUPS

HIGHER IS BETTER



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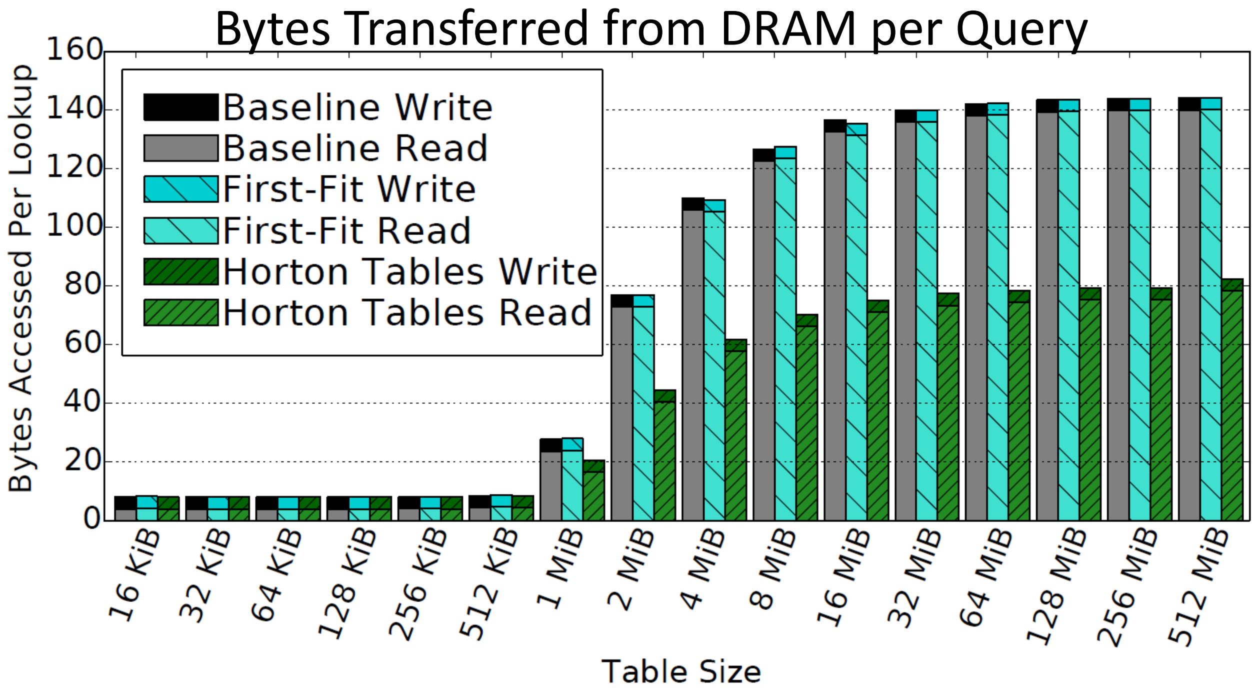

RESULTS

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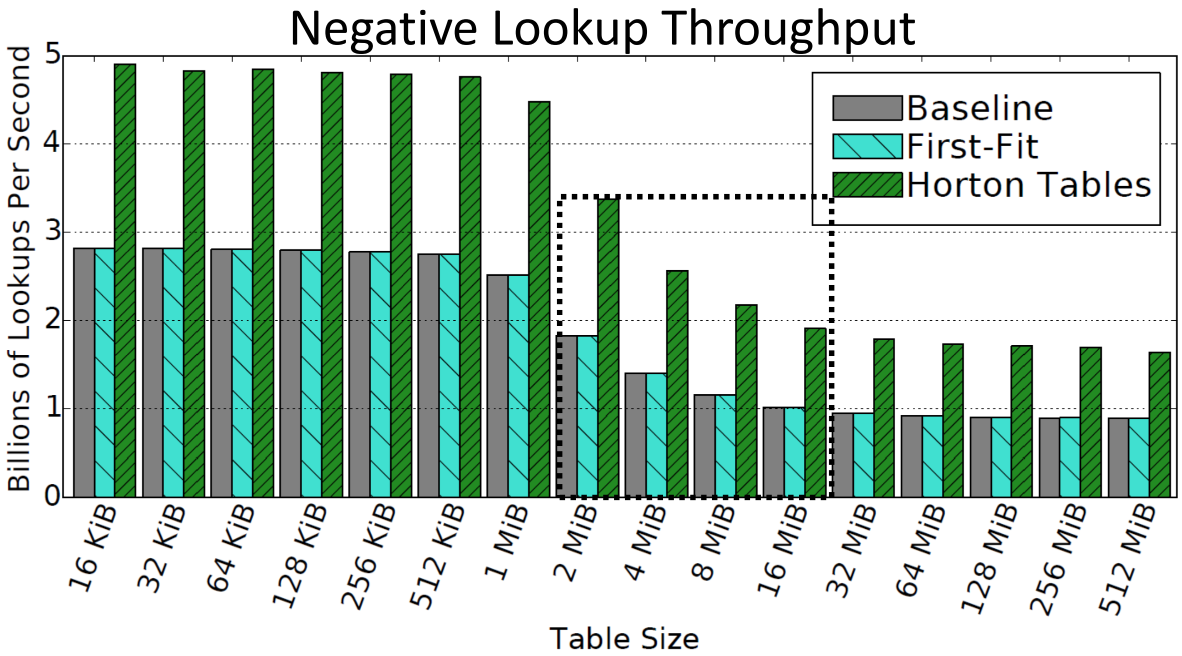

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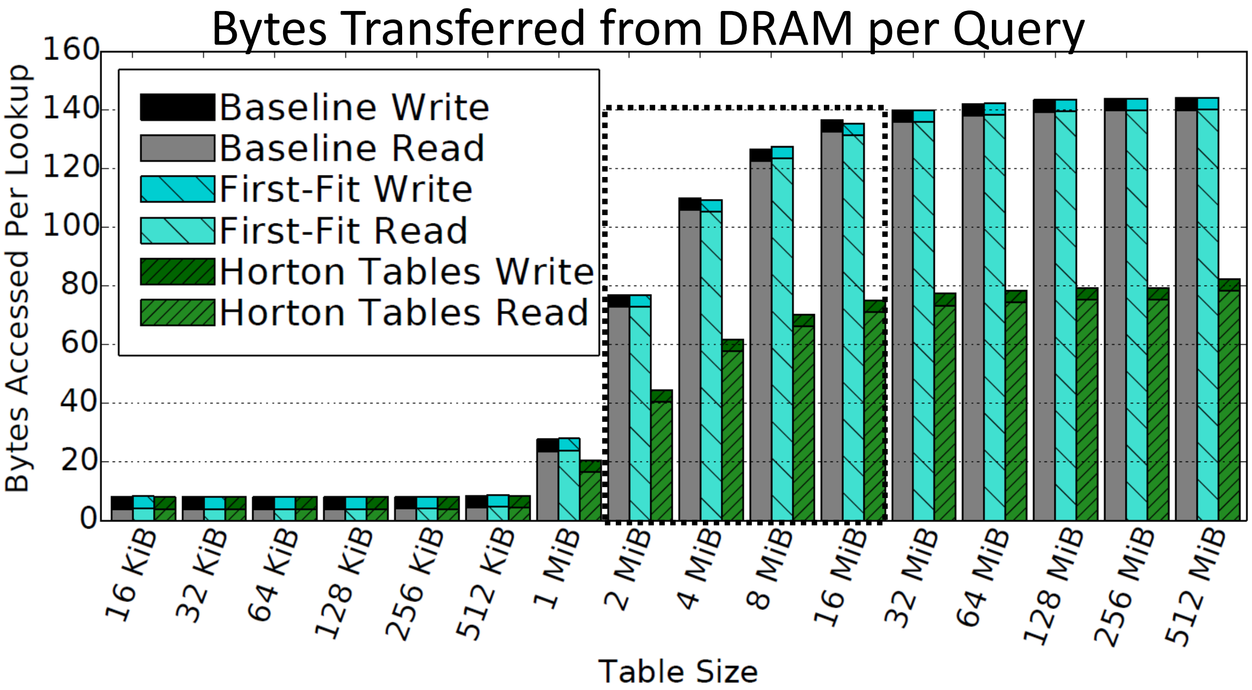

RESULTS

NEGATIVE LOOKUPS

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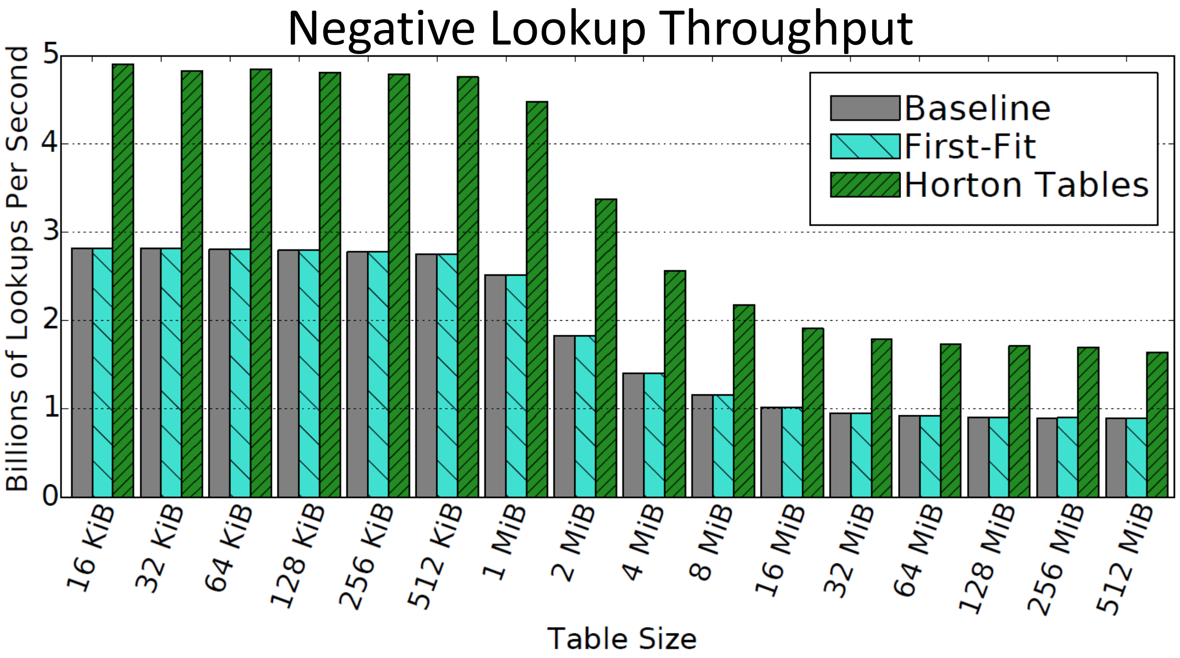
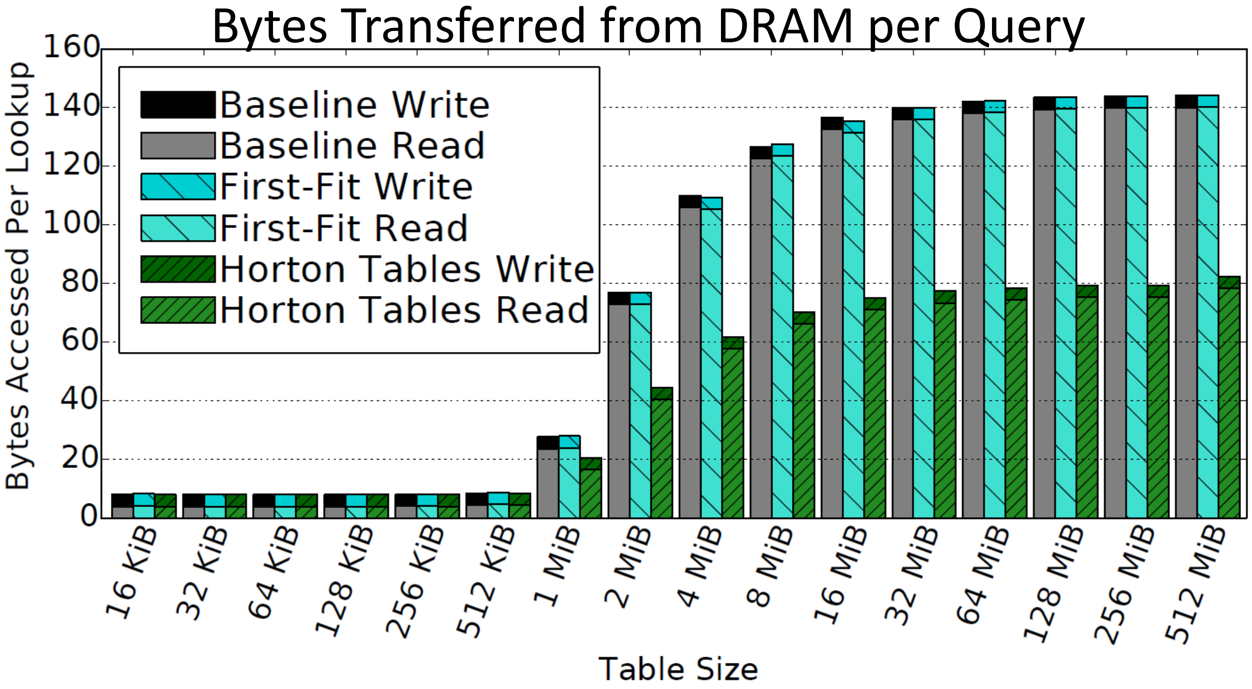


Negative Lookup Throughput

LOWER IS BETTER



Bytes Transferred from DRAM per Query

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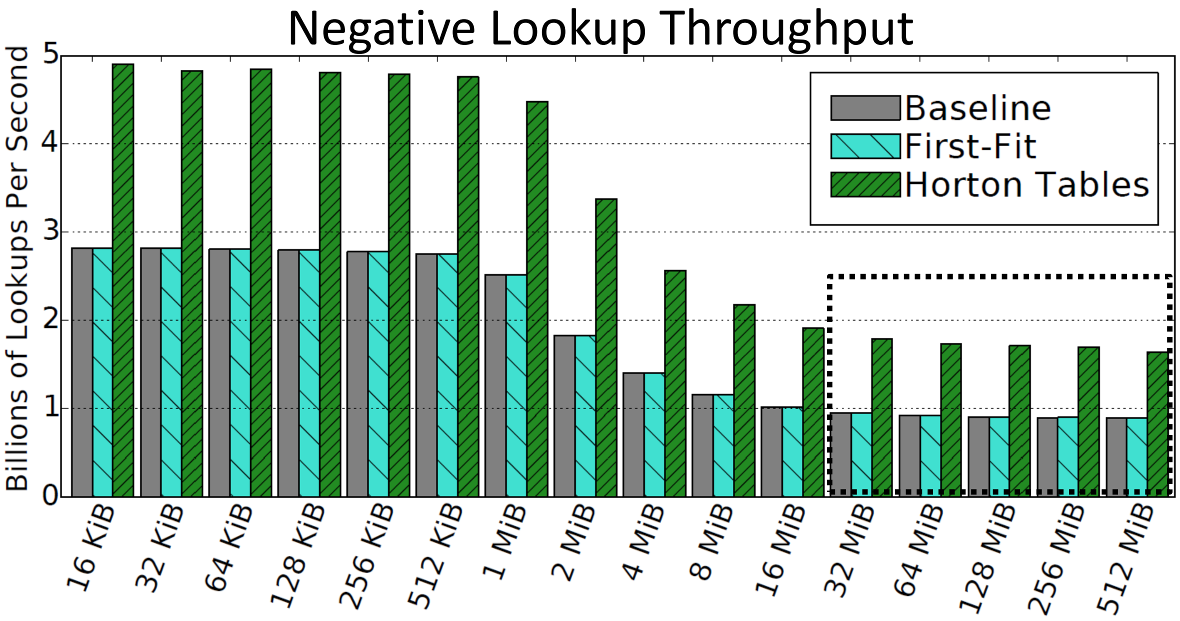
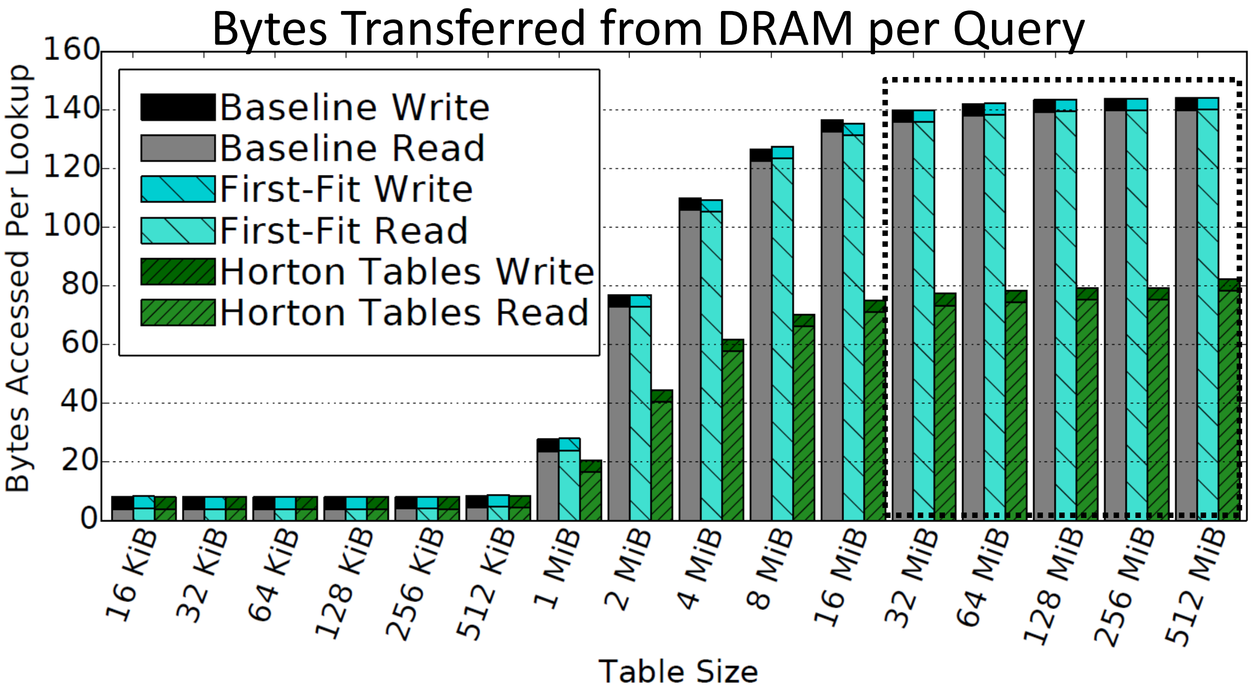
RESULTS

NEGATIVE LOOKUPS

HIGHER IS BETTER

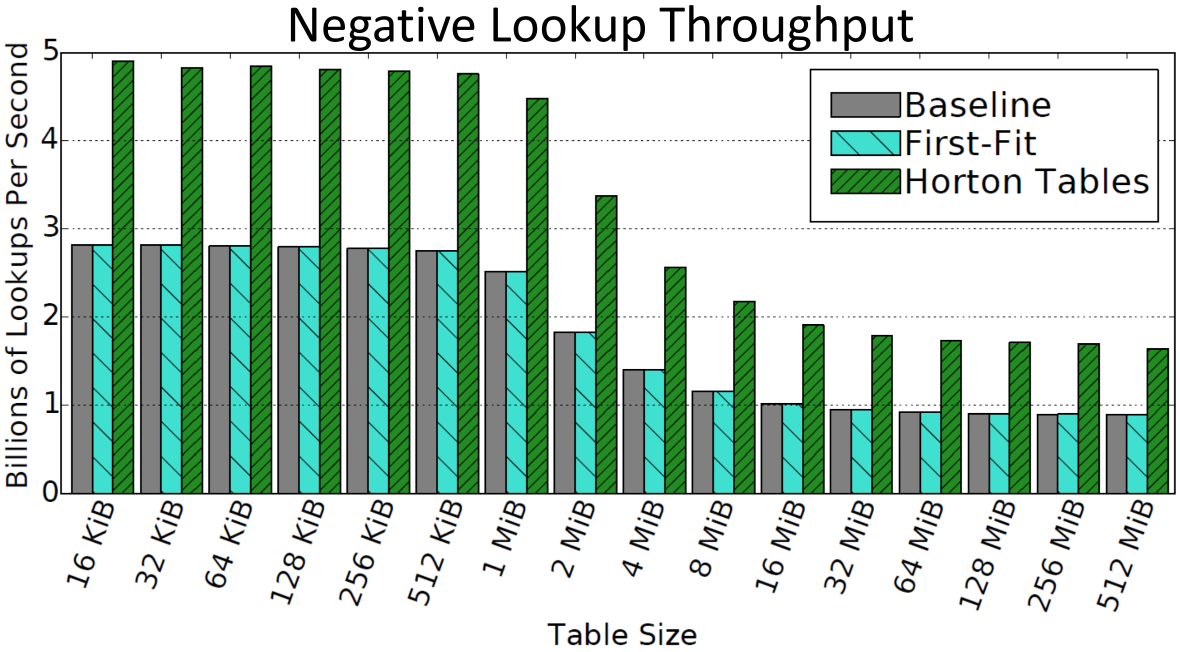


LOWER IS BETTER

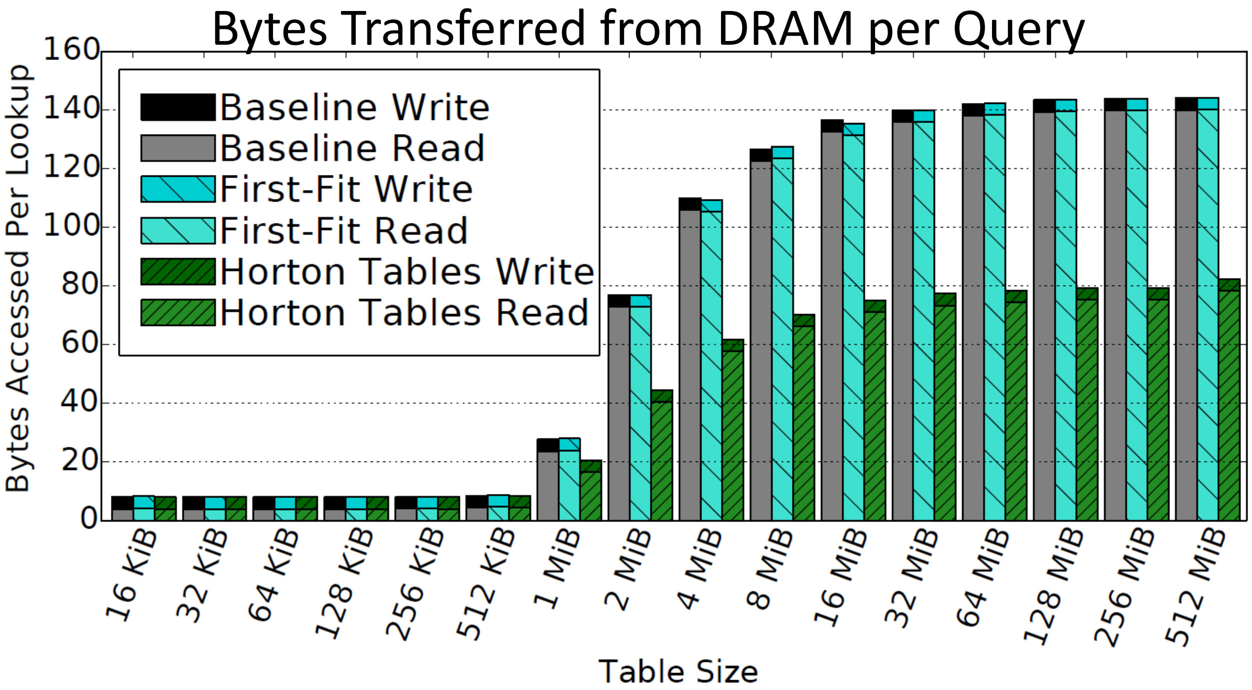


RESULTS
NEGATIVE LOOKUPS

HIGHER IS BETTER


Negative Lookup Throughput

LOWER IS BETTER


Bytes Transferred from DRAM per Query

CONCLUSIONS FROM HORTON TABLES

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- Optimizing hash table algorithms is important because of their wide use throughout all segments of computing
  - e.g., scientific computing and databases, data compression, computer graphics and data visualization

FUTURE WORK

- Evaluation of insertions and deletions and their optimization
  - Write- and update-heavy workloads should also benefit from Horton tables approach.
- Application of Horton tables to data warehousing and analysis applications
  - Database operators’ implementations (e.g., hash joins and grouping hash tables)
  - Key-value stores
- Additional indices for speeding up lookups, insertions, and deletions
- Evaluation of Horton tables on new and emerging memory subsystems as well as tailoring the technique for persistent storage technologies such as SSDs

QUESTIONS?

Thanks for your attention.

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BACKUP SLIDES

HORTON TABLES

SHARING OF REMAP ENTRIES

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

- We permit a single remap entry to reference multiple remapped elements.
- Deleting remap entries is possible by having elements that share remap entries map to the same secondary bucket (see our paper for details).

HORTON TABLES

SHARING OF REMAP ENTRIES

0	**8**	**5**	**13**	**EMPTY**
1	**33**	**EMPTY**	**15**	**2**
2	**35**	**18**	**22**	**REA**
3	**EMPTY**	**EMPTY**	**16**	**37**
4	**17**	**6**	**21**	**EMPTY**
5	**9**	**24**	**23**	**EMPTY**

INSERT 27

- We permit a single remap entry to reference multiple remapped elements.
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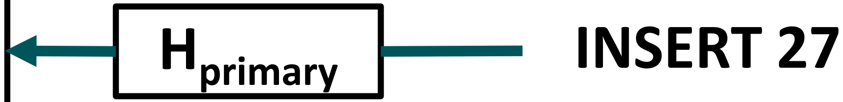
HORTON TABLES

SHARING OF REMAP ENTRIES

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY



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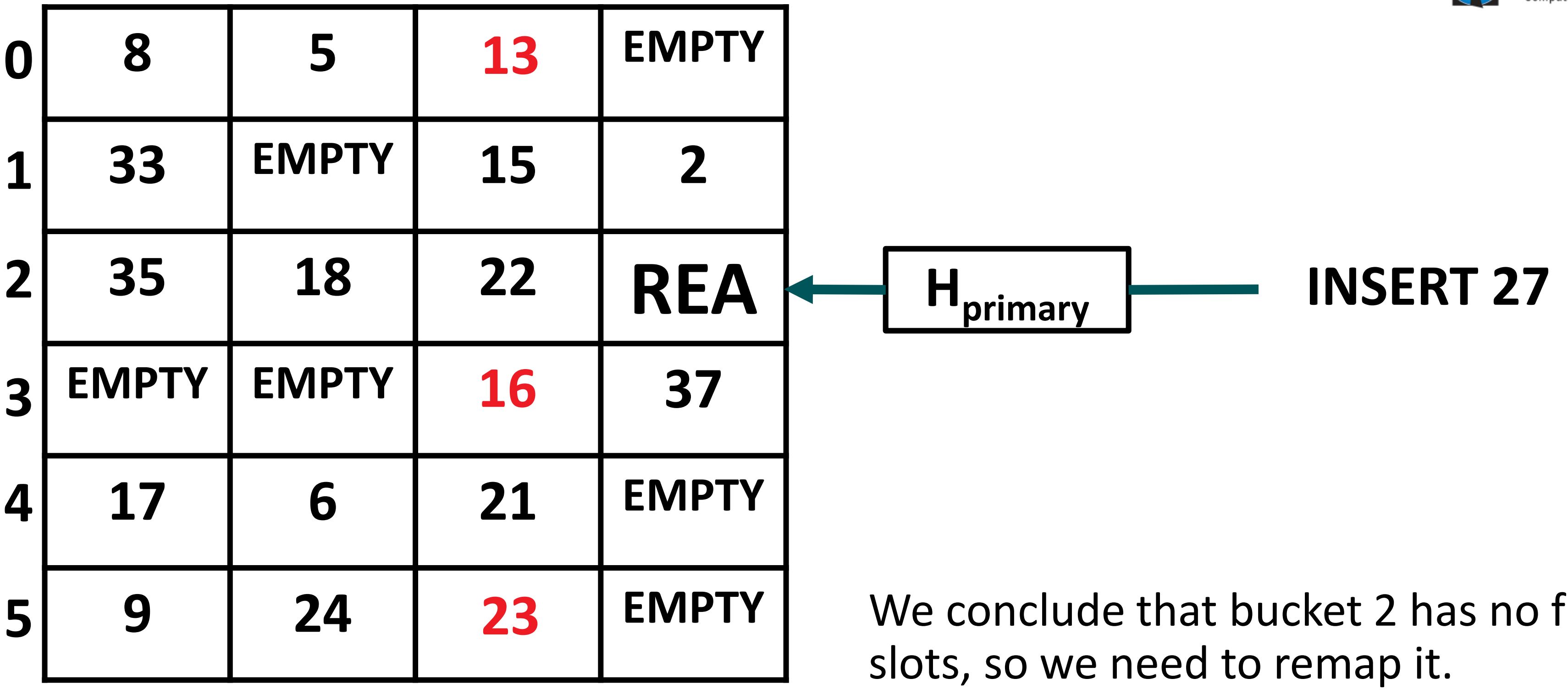
HORTON TABLES

SHARING OF REMAP ENTRIES



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

We conclude that bucket 2 has no free slots, so we need to remap it.

- We permit a single remap entry to reference multiple remapped elements.
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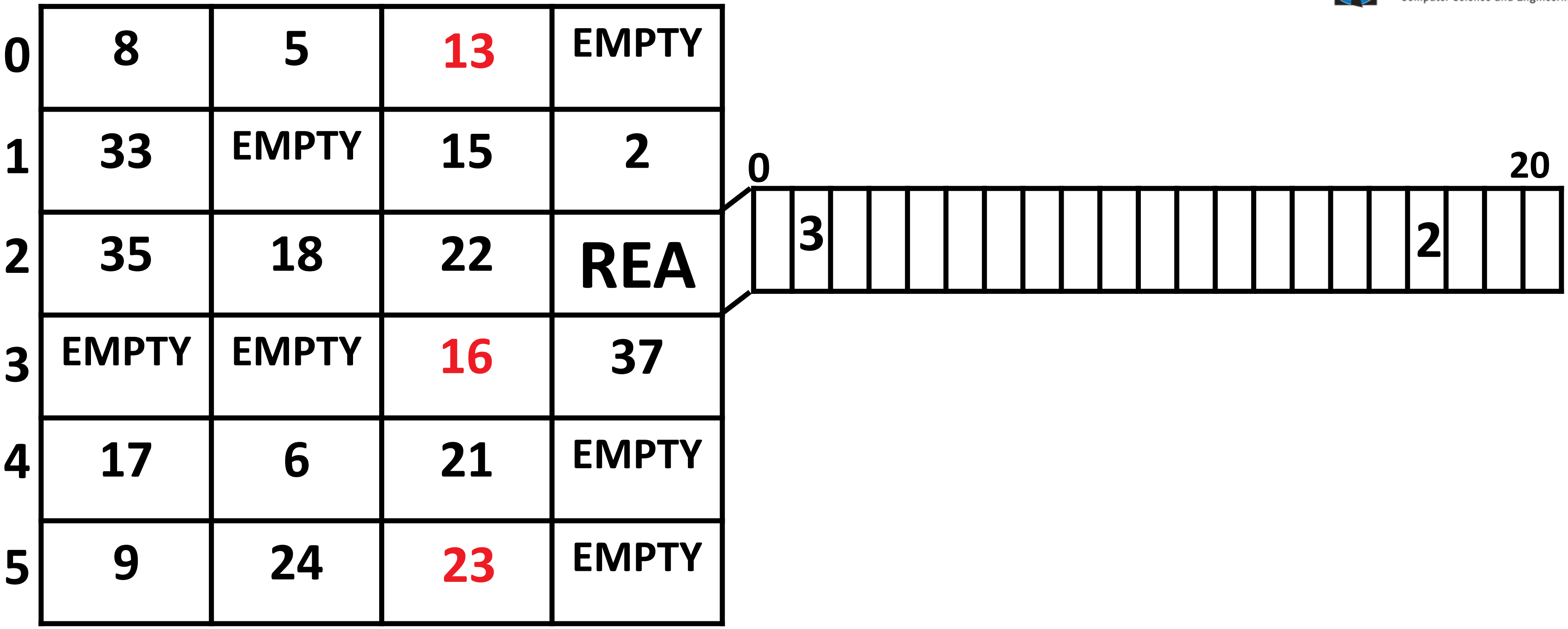
HORTON TABLES

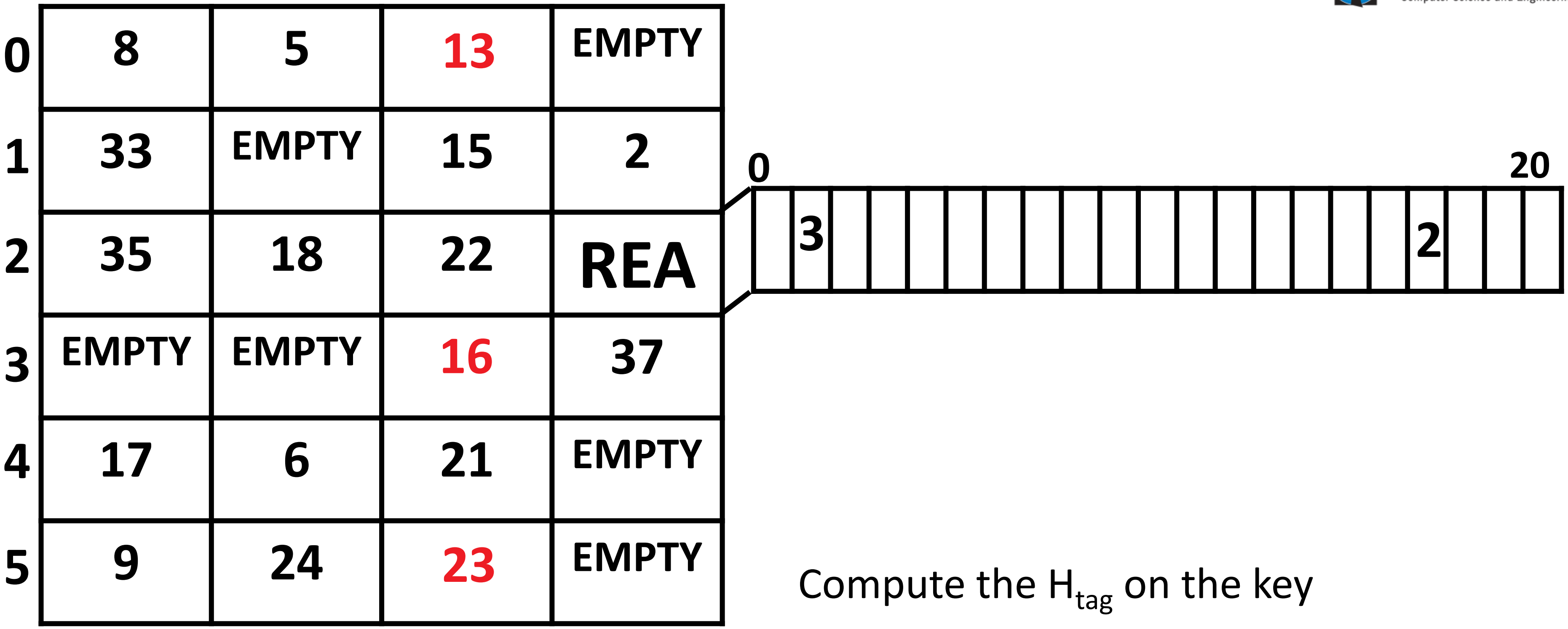
SHARING OF REMAP ENTRIES



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

HORTON TABLES

SHARING OF REMAP ENTRIES



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

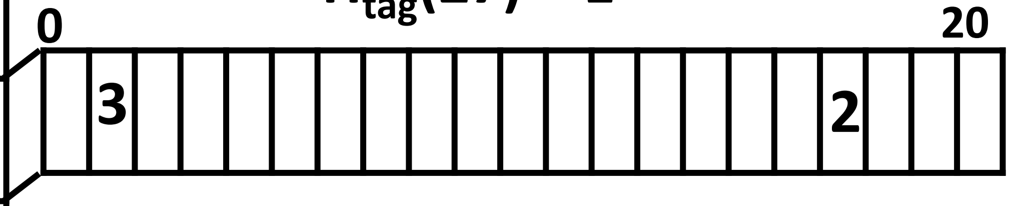
Compute the H_{tag} on the key

HORTON TABLES

SHARING OF REMAP ENTRIES

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

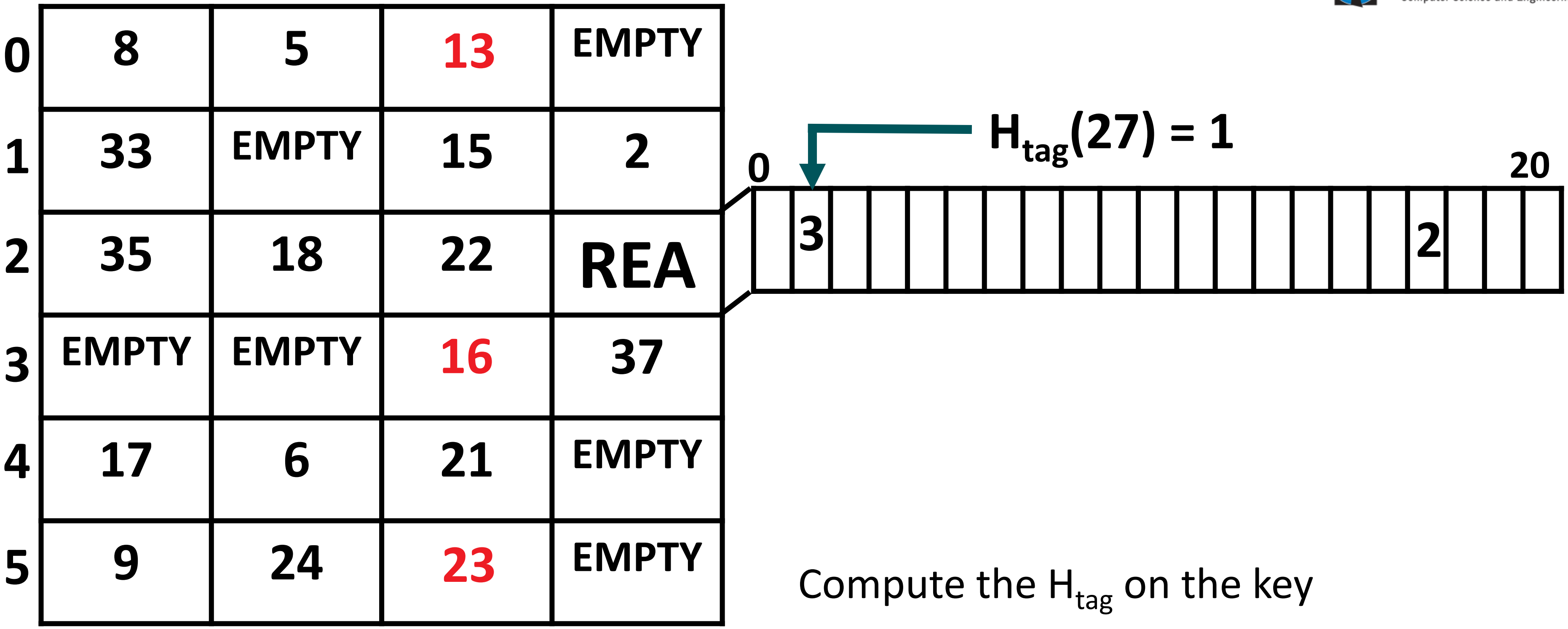
$H_{tag}(27) = 1$



Compute the H_{tag} on the key

HORTON TABLES

SHARING OF REMAP ENTRIES

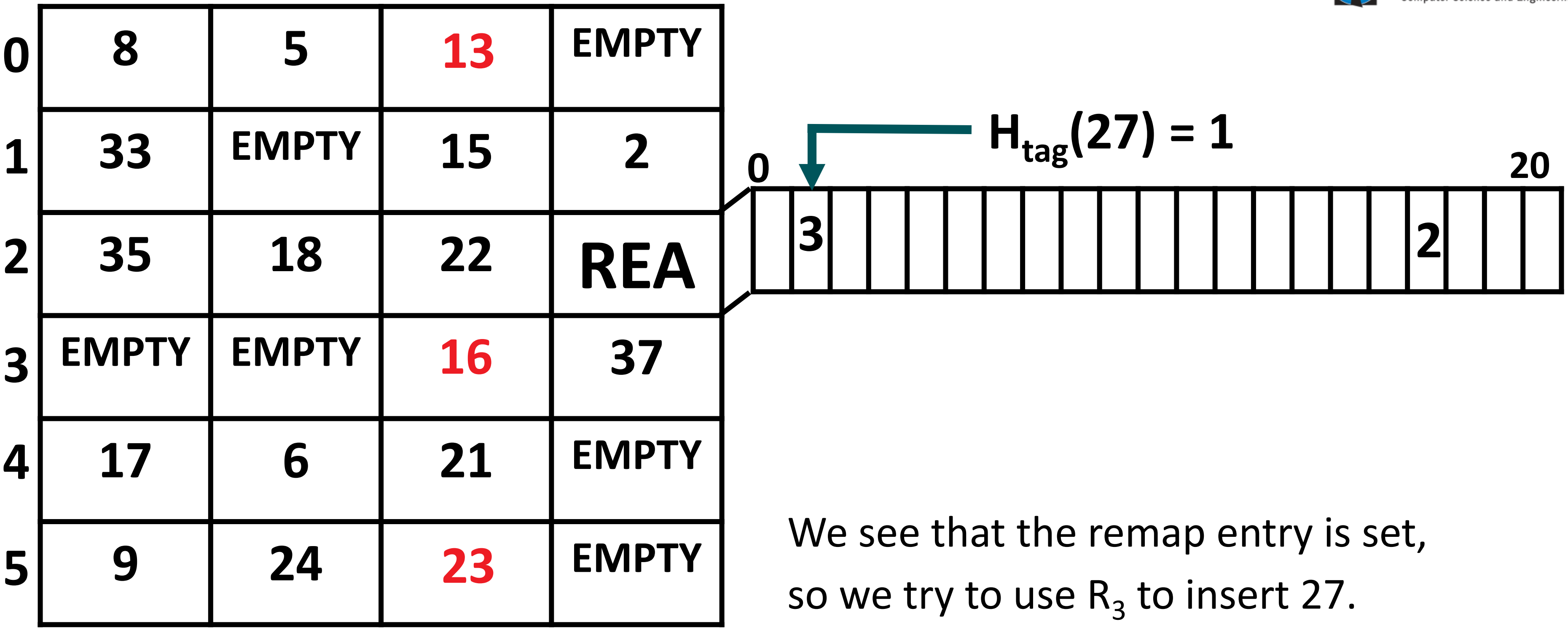


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Compute the H_{tag} on the key

HORTON TABLES

SHARING OF REMAP ENTRIES

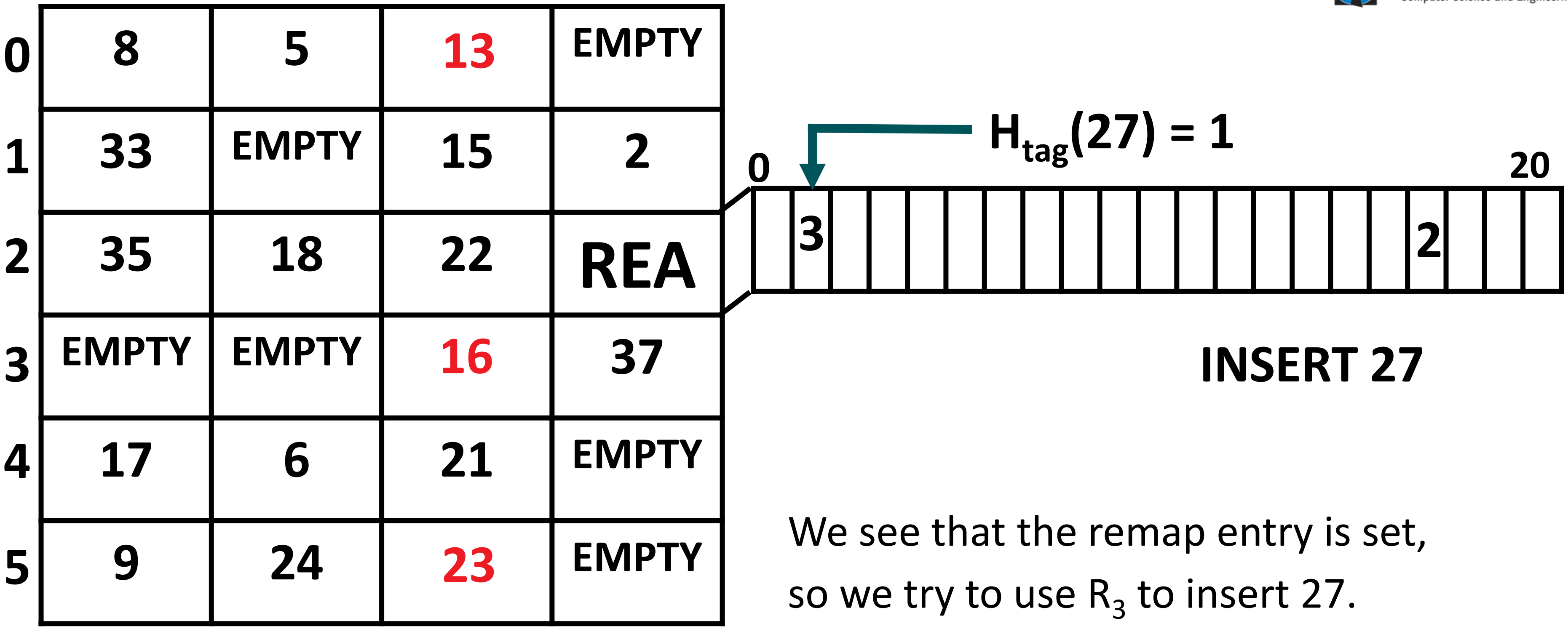


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

We see that the remap entry is set, so we try to use R_3 to insert 27.

HORTON TABLES

SHARING OF REMAP ENTRIES



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

INSERT 27

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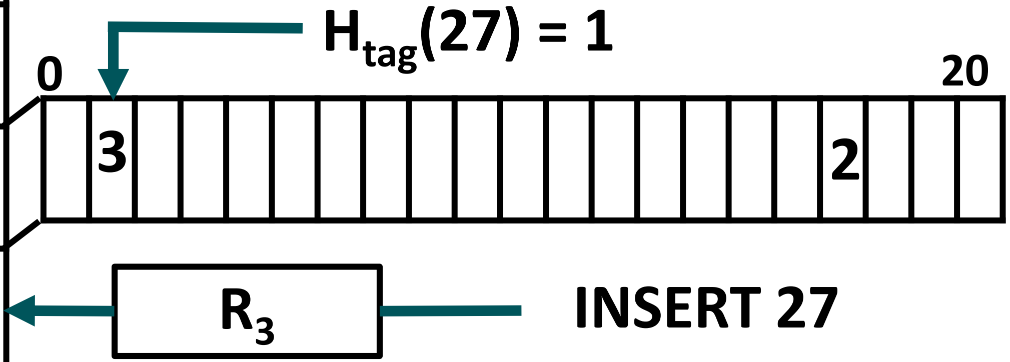
HORTON TABLES

SHARING OF REMAP ENTRIES

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY



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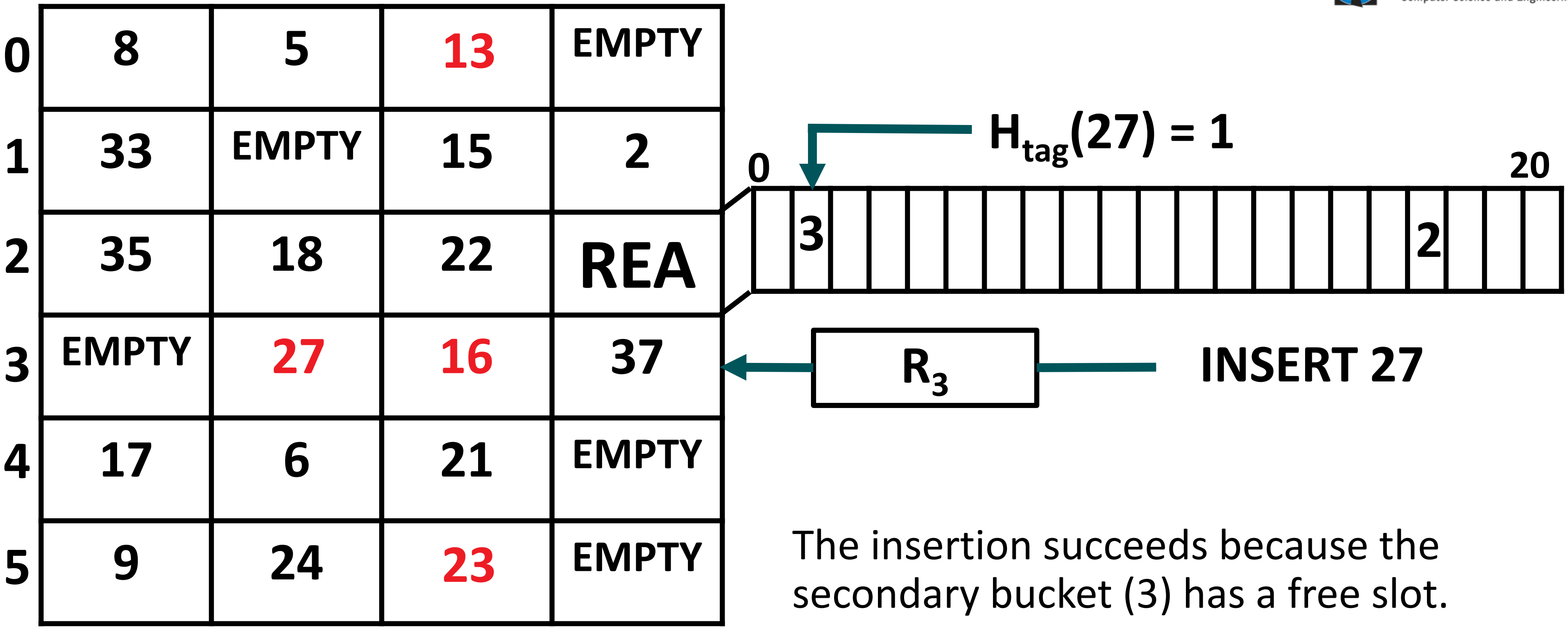
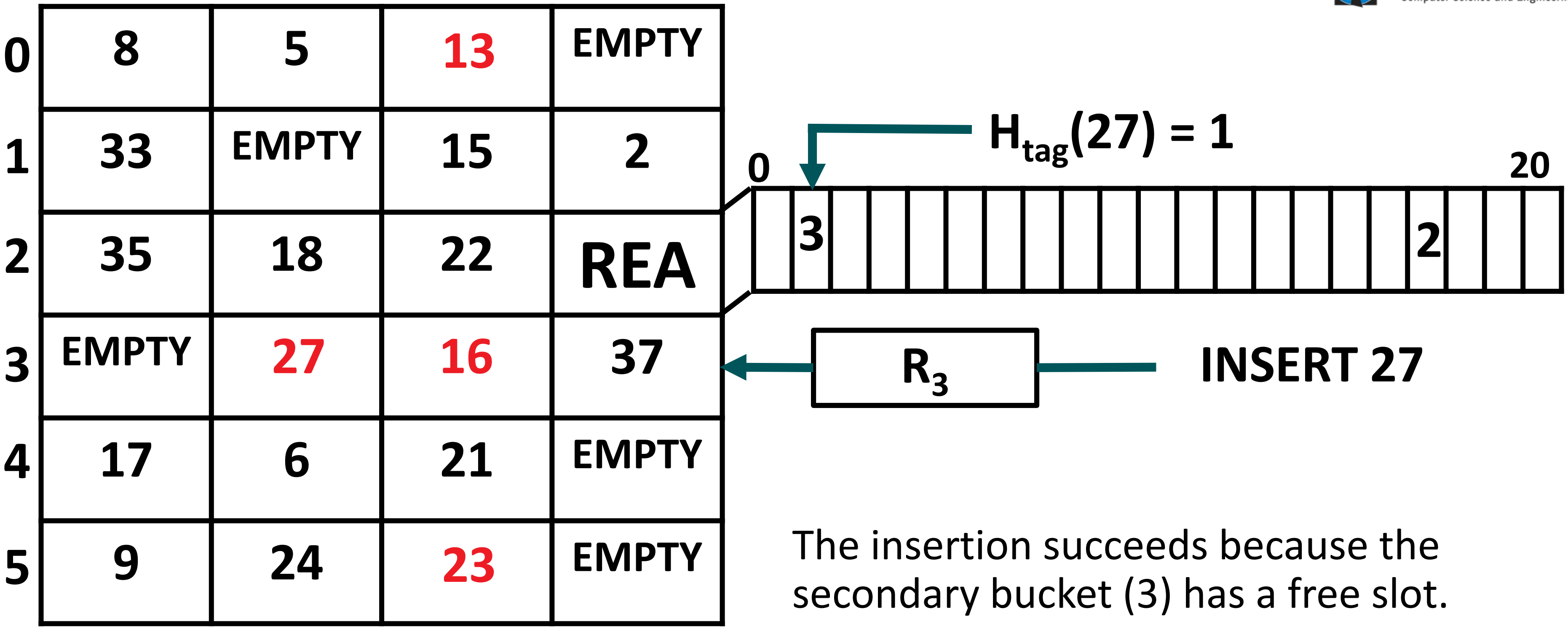


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

The insertion succeeds because the secondary bucket (3) has a free slot.

HORTON TABLES

SHARING OF REMAP ENTRIES



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

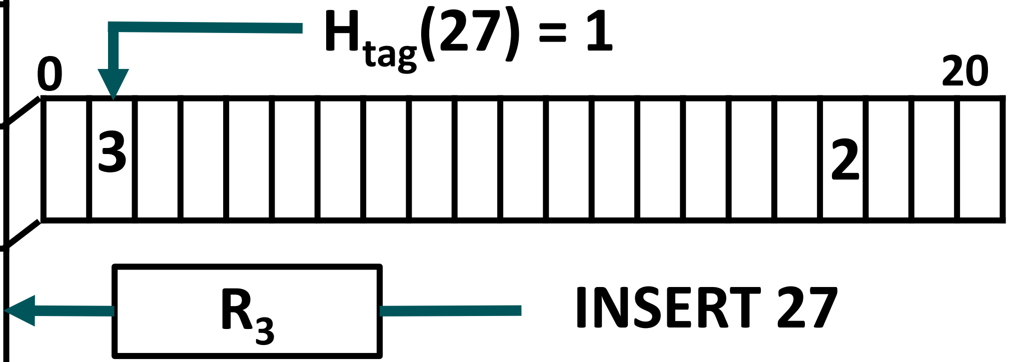
The insertion succeeds because the secondary bucket (3) has a free slot.

- If bucket 3 had been full, we could have swapped 27 with another item from 27’s primary bucket (2) (e.g., 35) and remapped that item instead.

HORTON TABLES

SHARING OF REMAP ENTRIES

0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

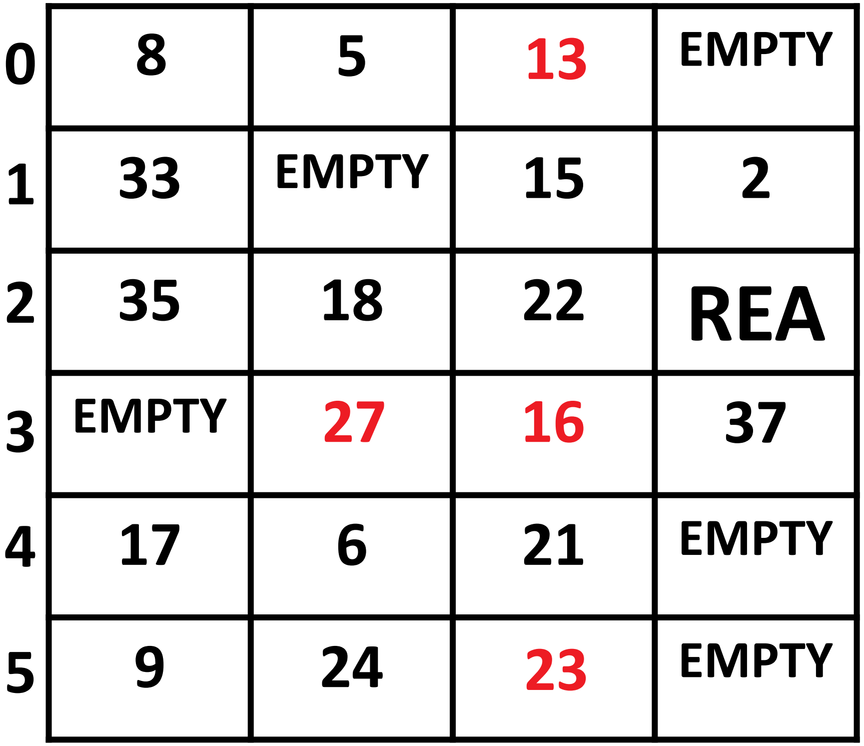


The insertion succeeds because the secondary bucket (3) has a free slot.

- If bucket 3 had been full, we could have swapped 27 with another item from 27’s primary bucket (2) (e.g., 35) and remapped that item instead.
- Alternatively, we could try to remap both 27 and 16 to another shared bucket with a different secondary hash function, but this is more likely to fail.

HORTON TABLES

DELETING ELEMENTS



0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS

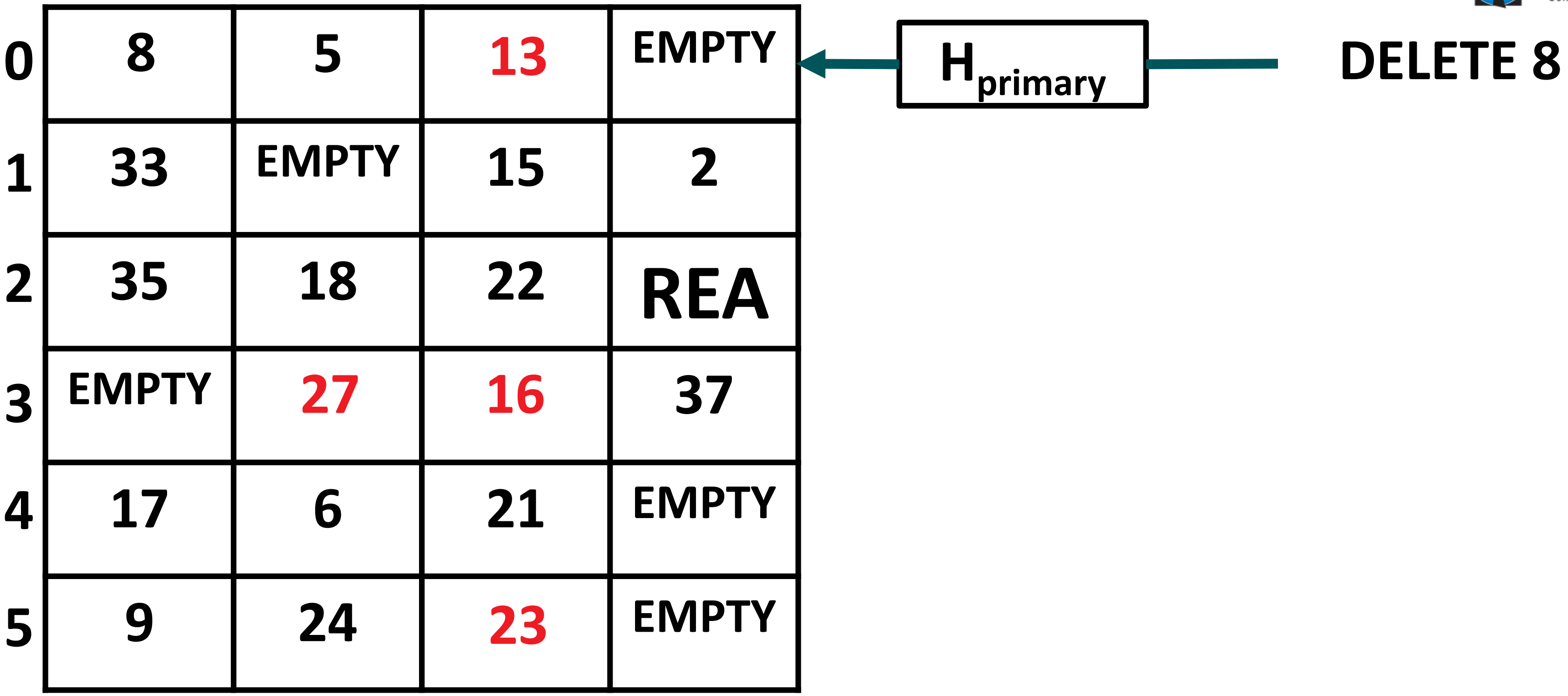
0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

DELETE 8

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS

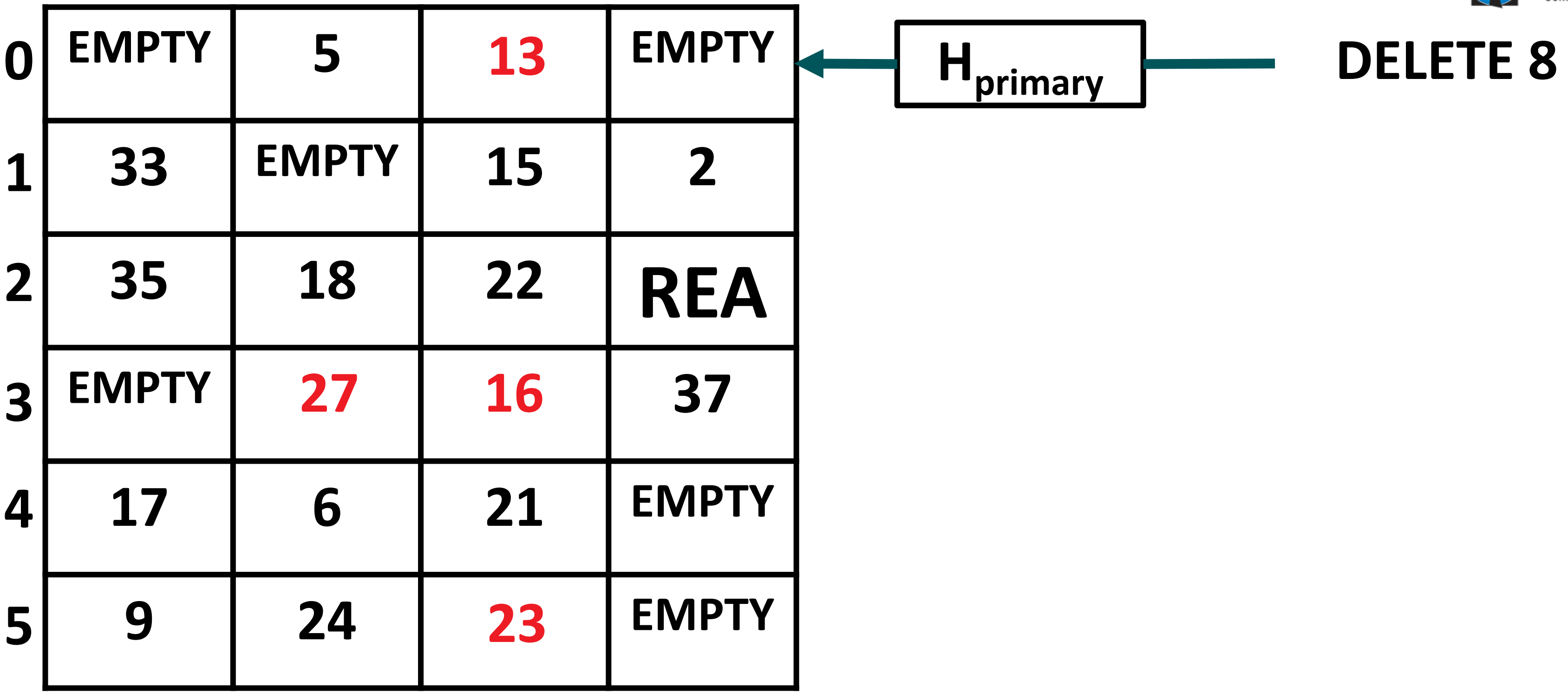


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

$H_{primary}$

DELETE 8

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

AMD

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Computer Science and Engineering

HORTON TABLES

DELETING ELEMENTS

0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS

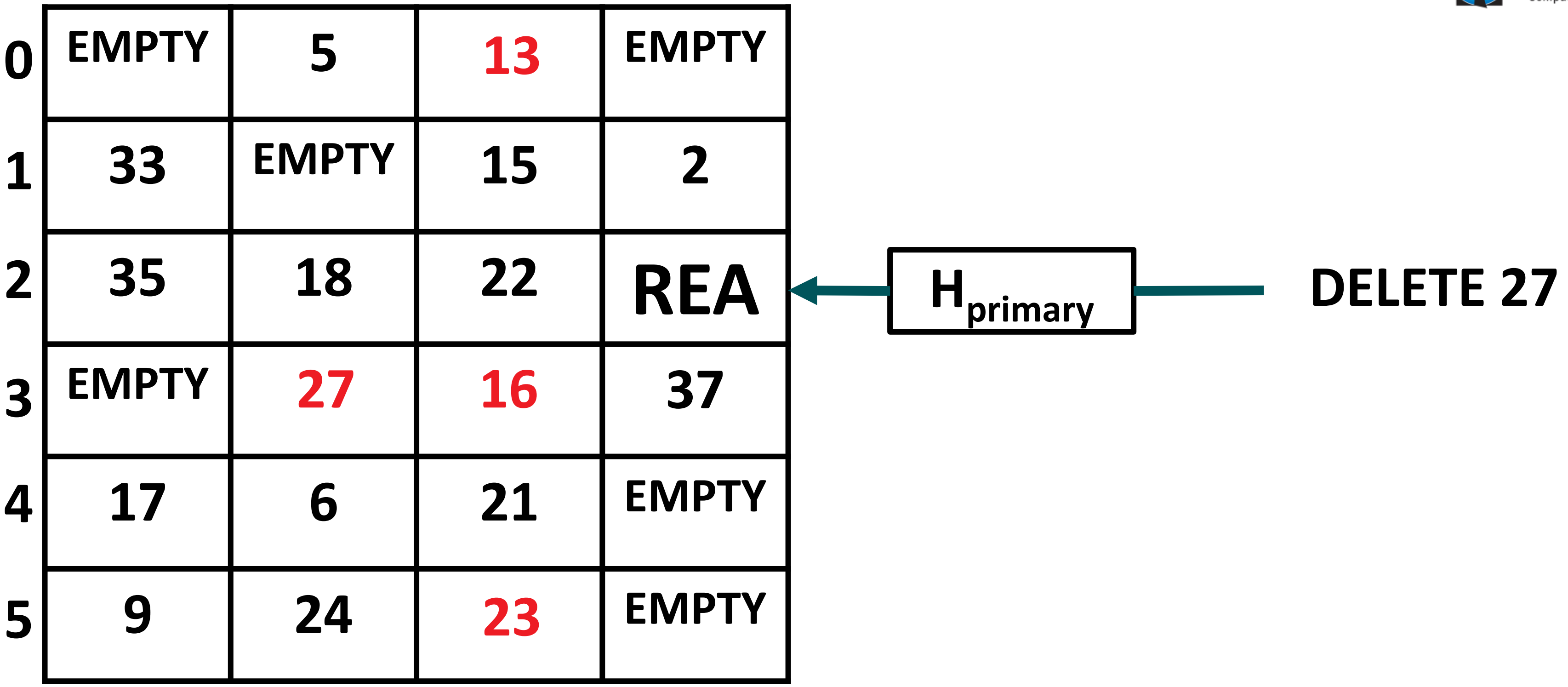
0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

DELETE 27

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

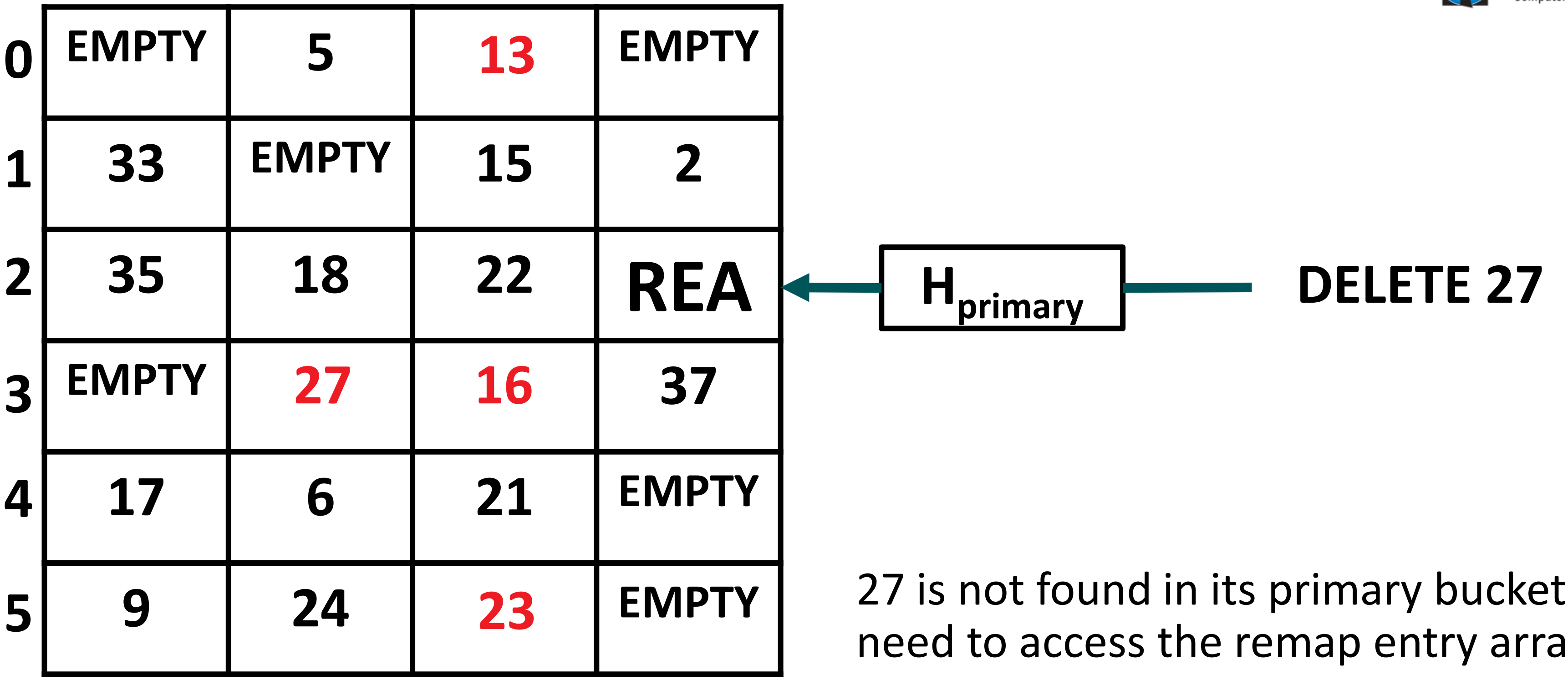
$H_{primary}$

DELETE 27

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



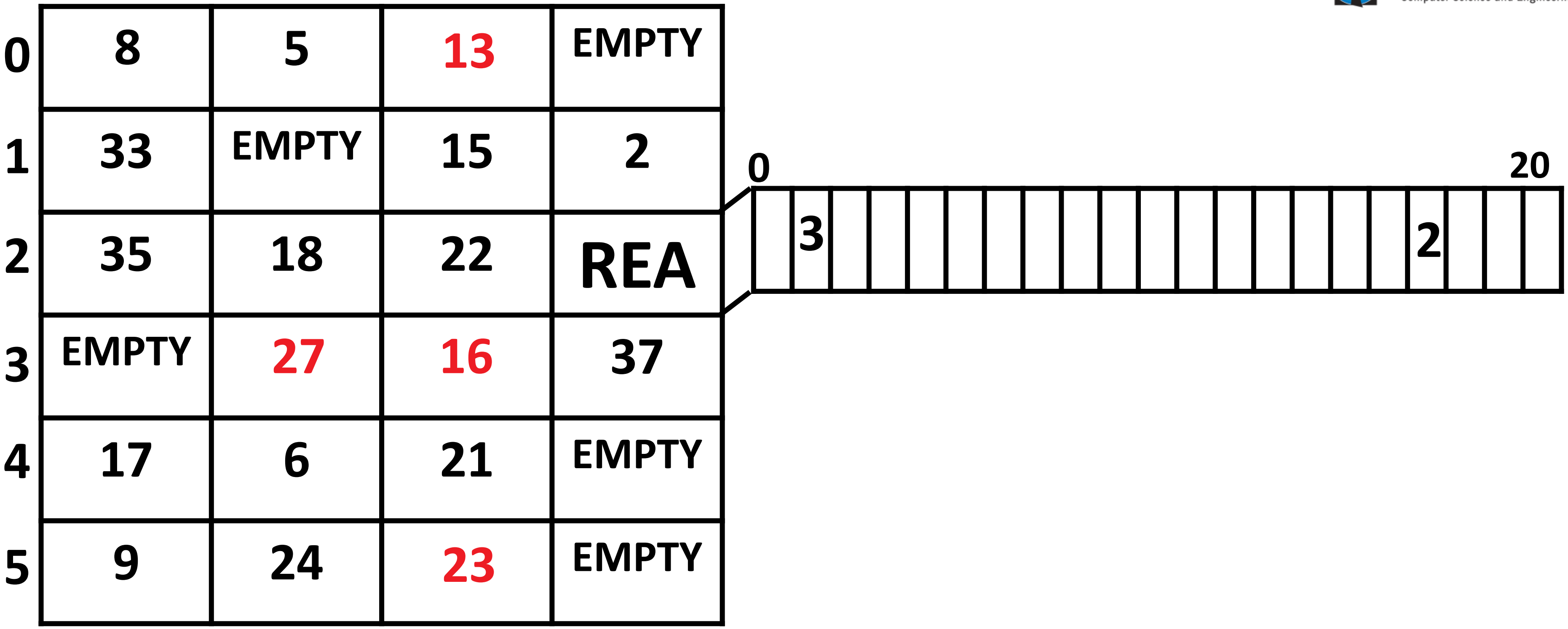
0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

27 is not found in its primary bucket; we need to access the remap entry array.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS

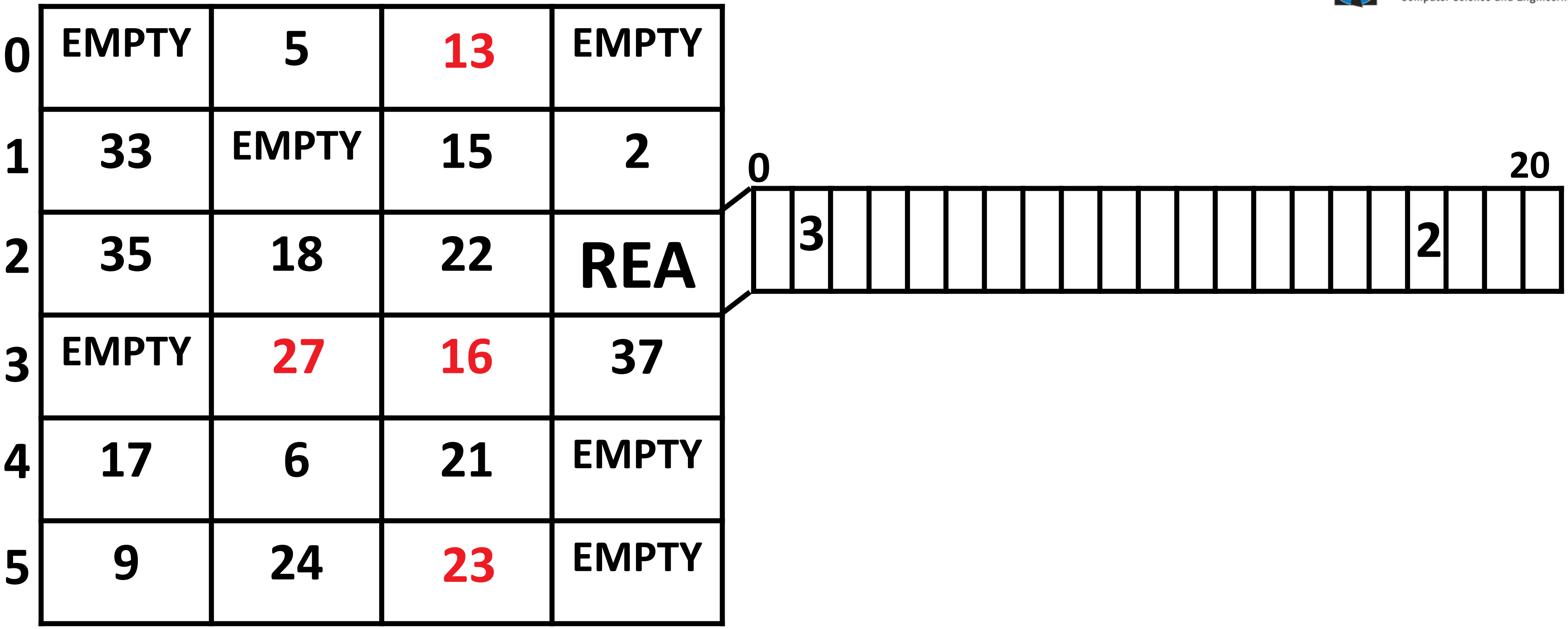


0	8	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS

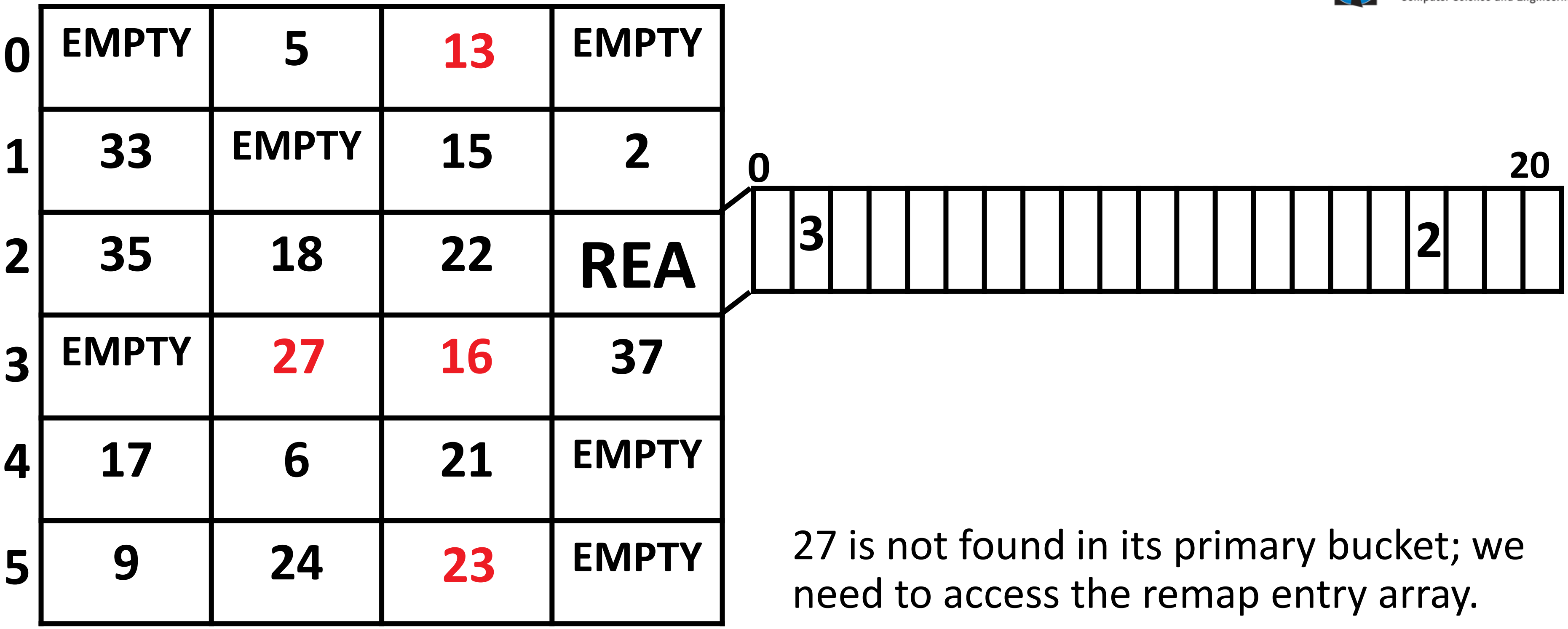


0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

27 is not found in its primary bucket; we need to access the remap entry array.

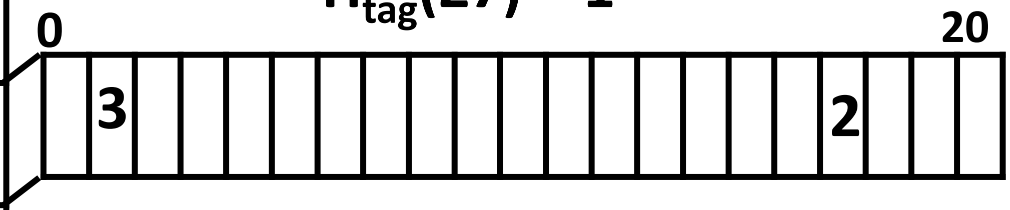
- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS

0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

$H_{tag}(27) = 1$

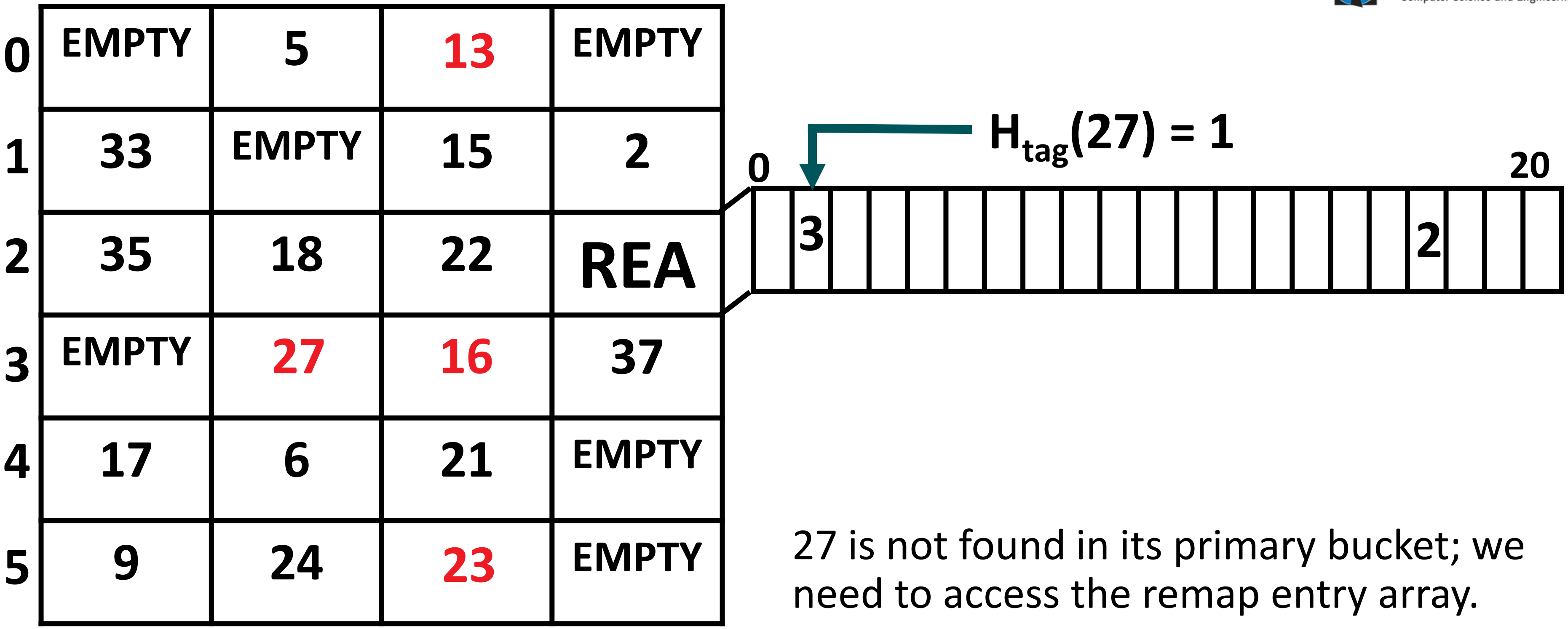


27 is not found in its primary bucket; we need to access the remap entry array.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



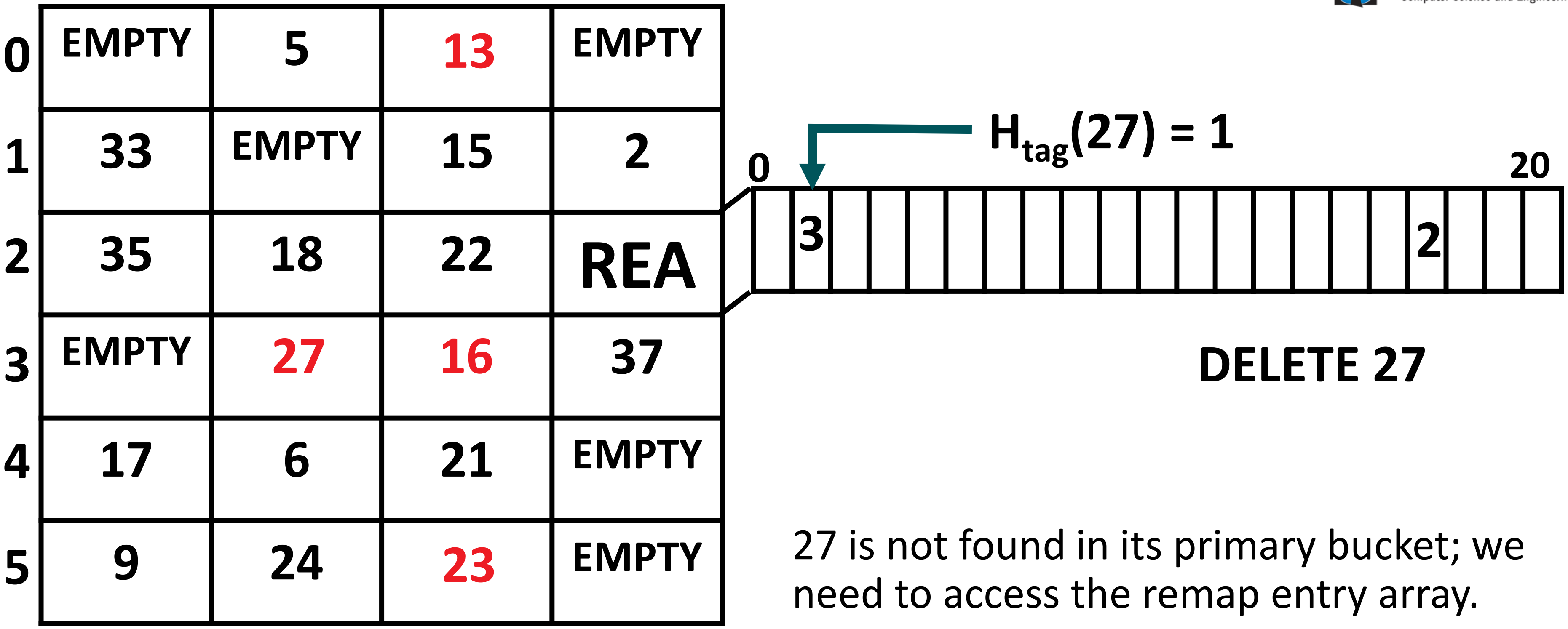
0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

27 is not found in its primary bucket; we need to access the remap entry array.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

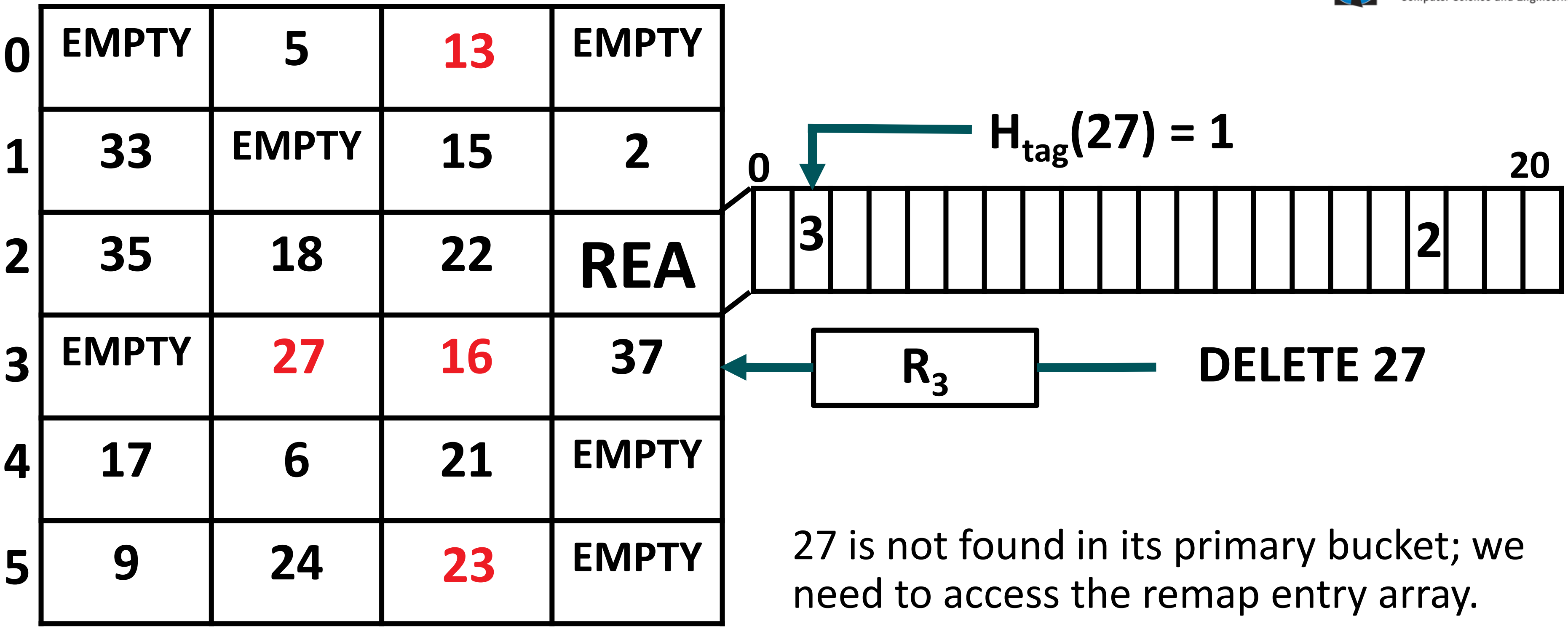
DELETE 27

27 is not found in its primary bucket; we need to access the remap entry array.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



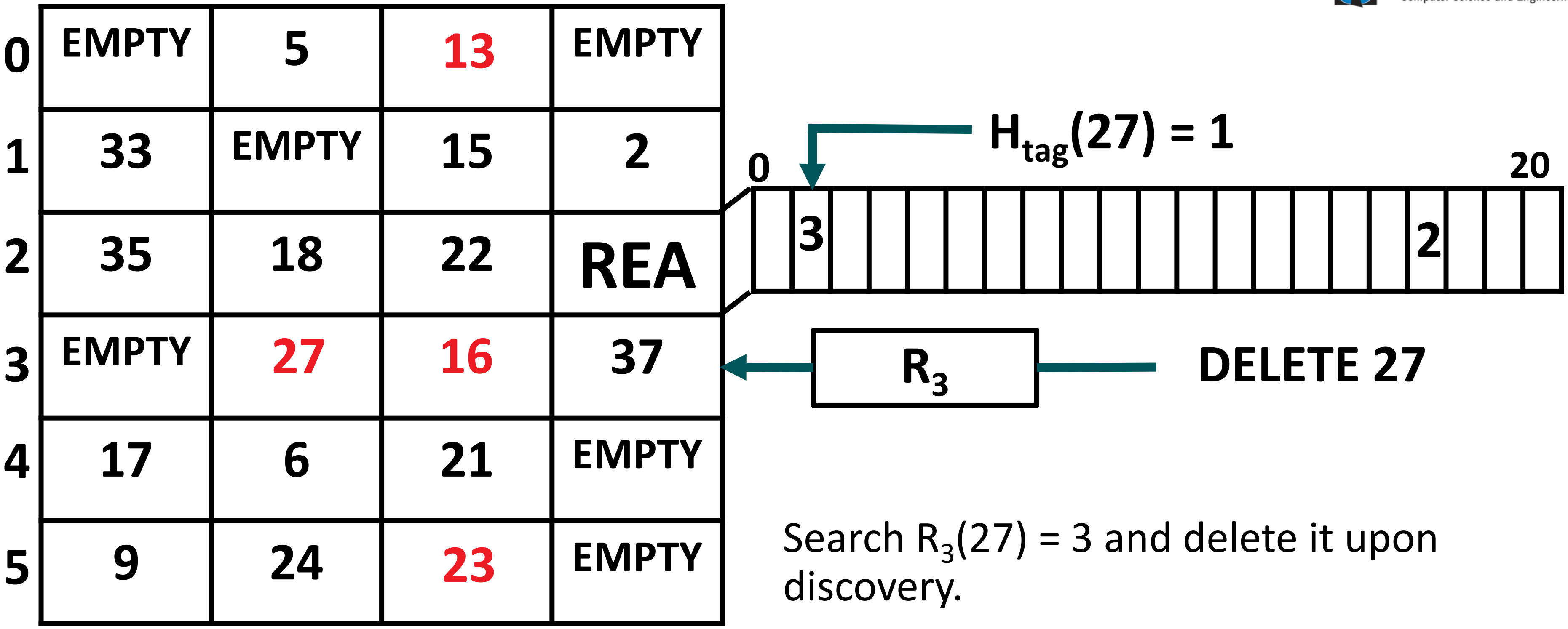
0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

27 is not found in its primary bucket; we need to access the remap entry array.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



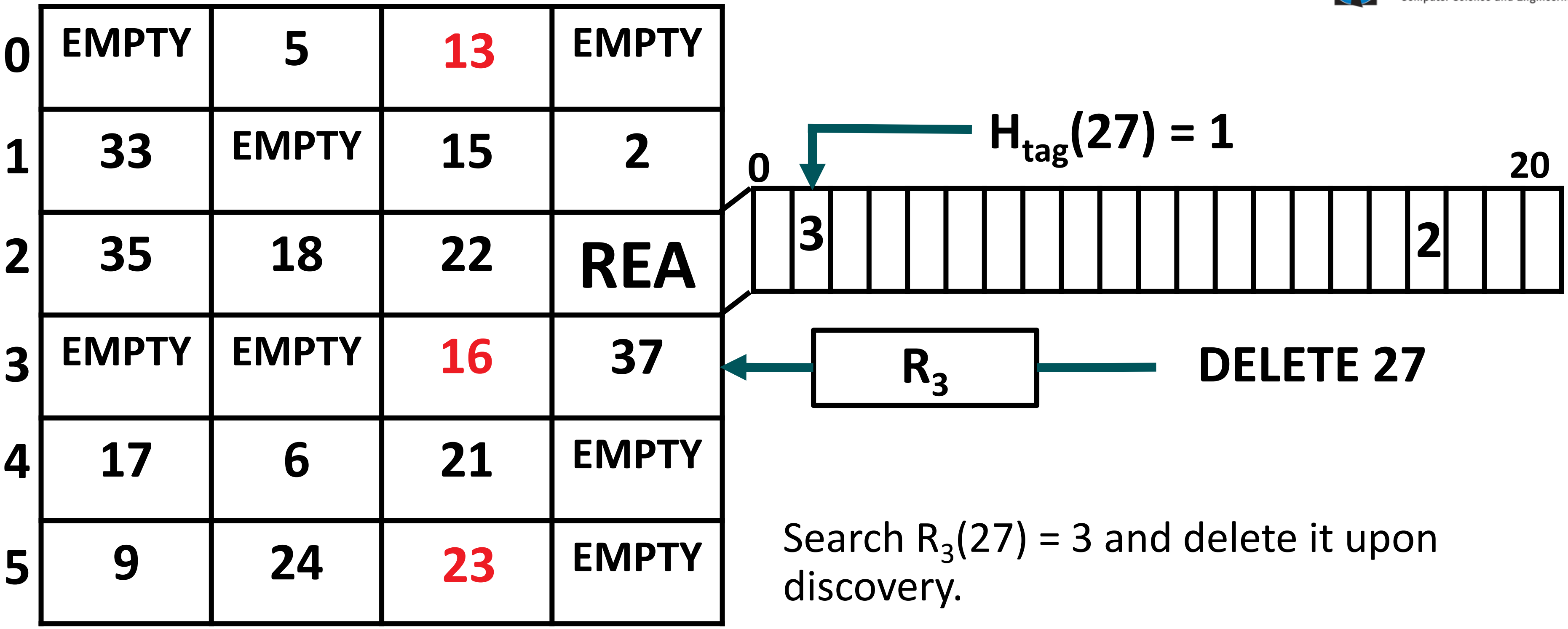
0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	27	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Search $R_3(27) = 3$ and delete it upon discovery.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



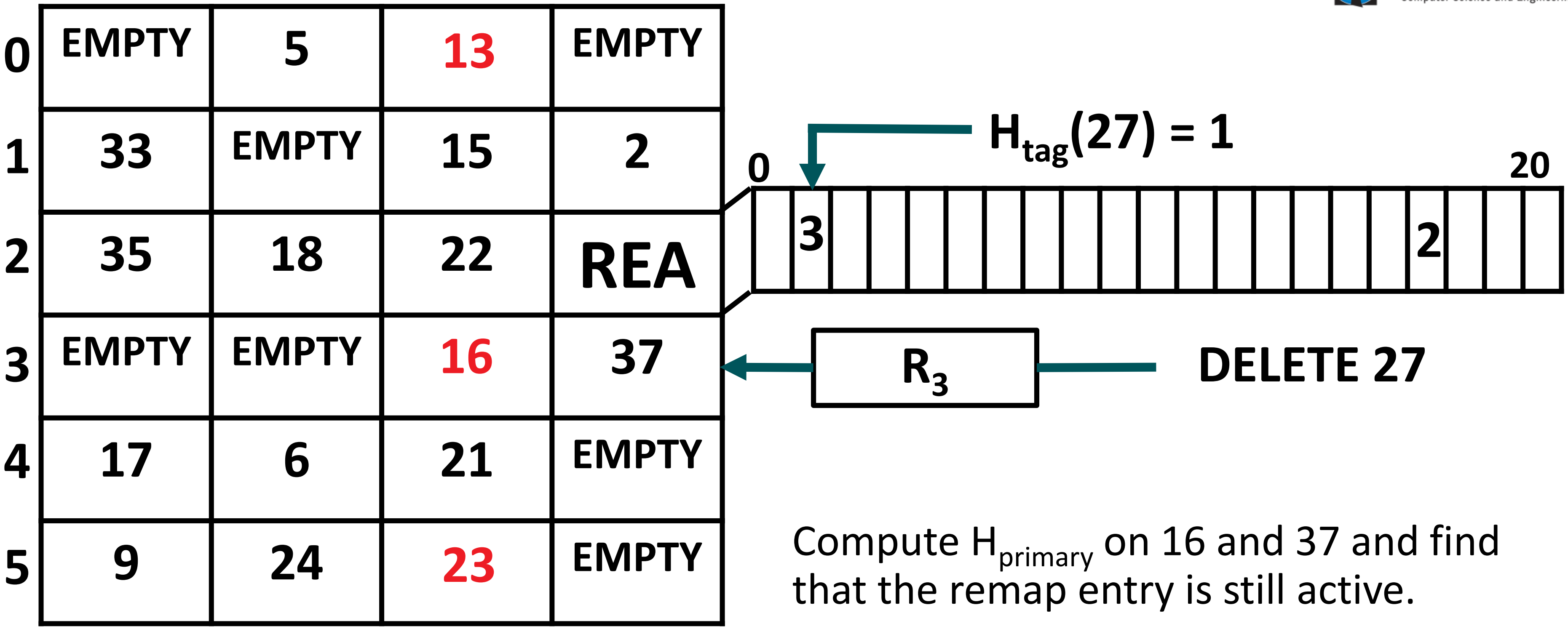
0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Search $R_3(27) = 3$ and delete it upon discovery.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



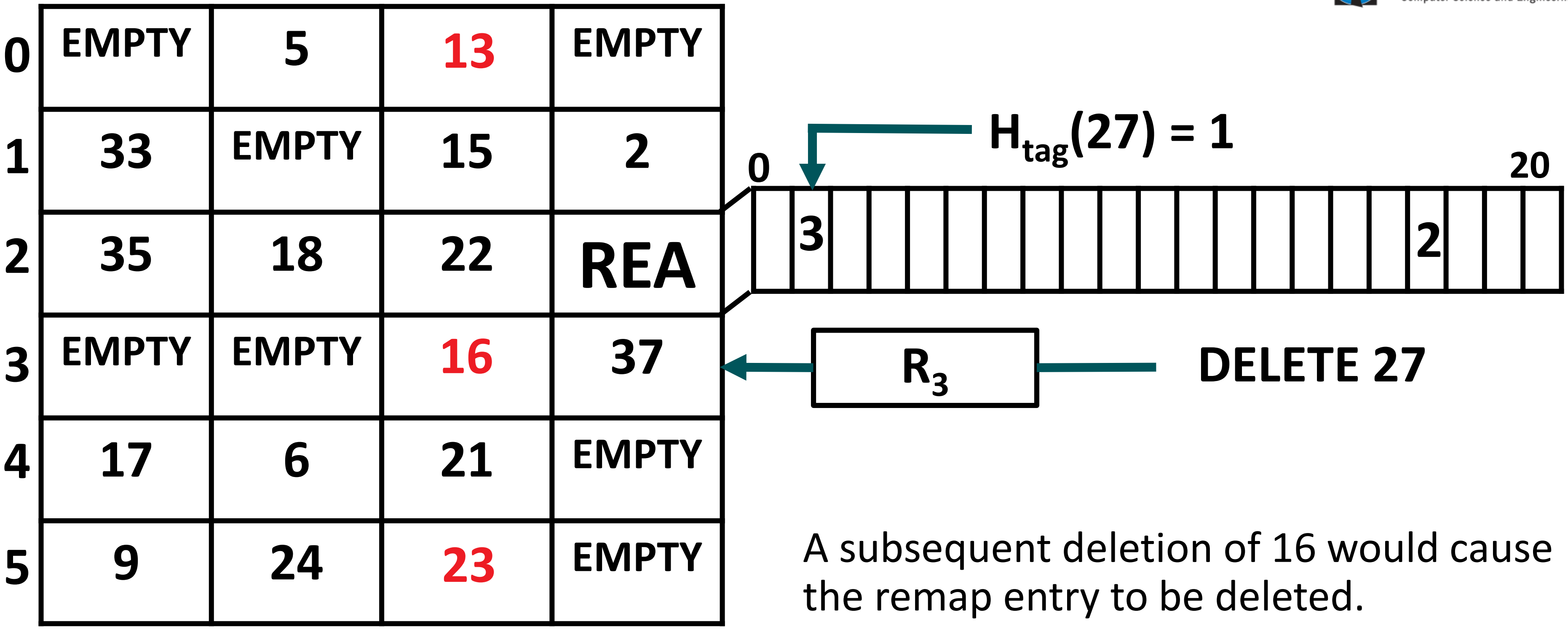
0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

Compute $H_{primary}$ on 16 and 37 and find that the remap entry is still active.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



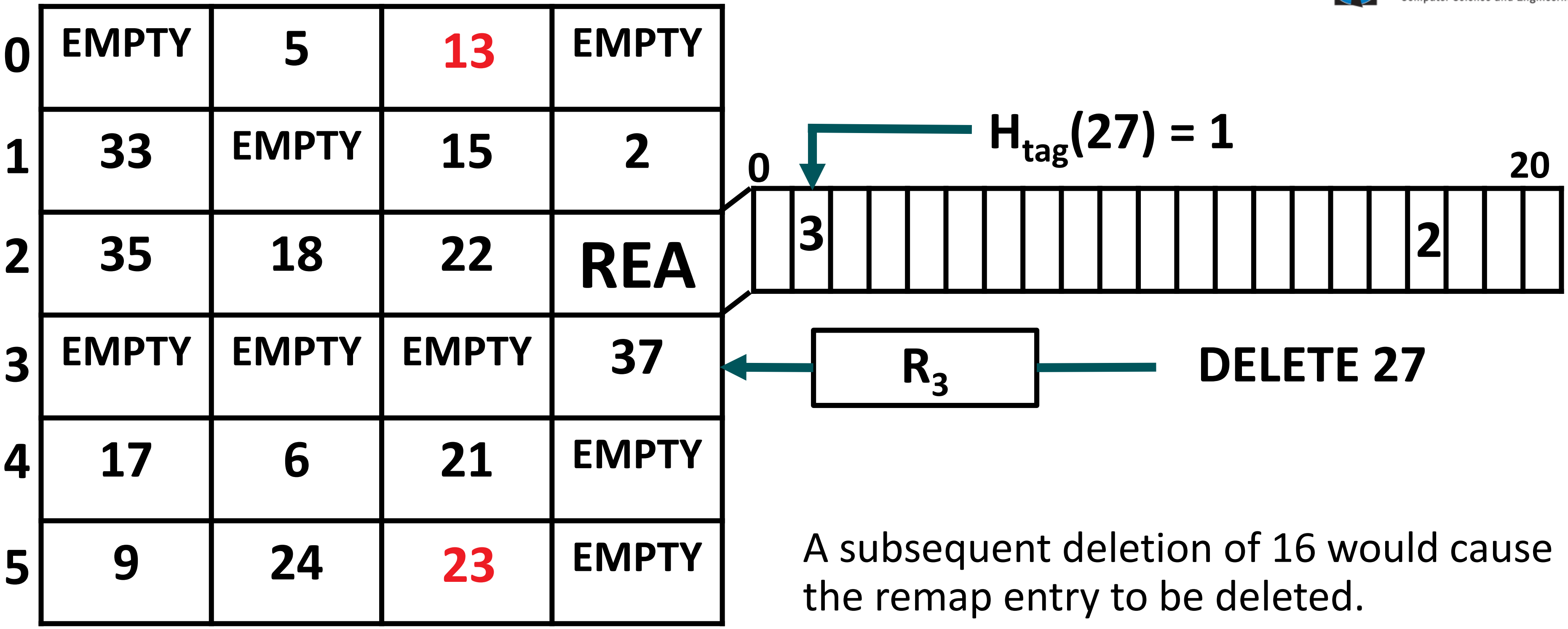
0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	16	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

A subsequent deletion of 16 would cause the remap entry to be deleted.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



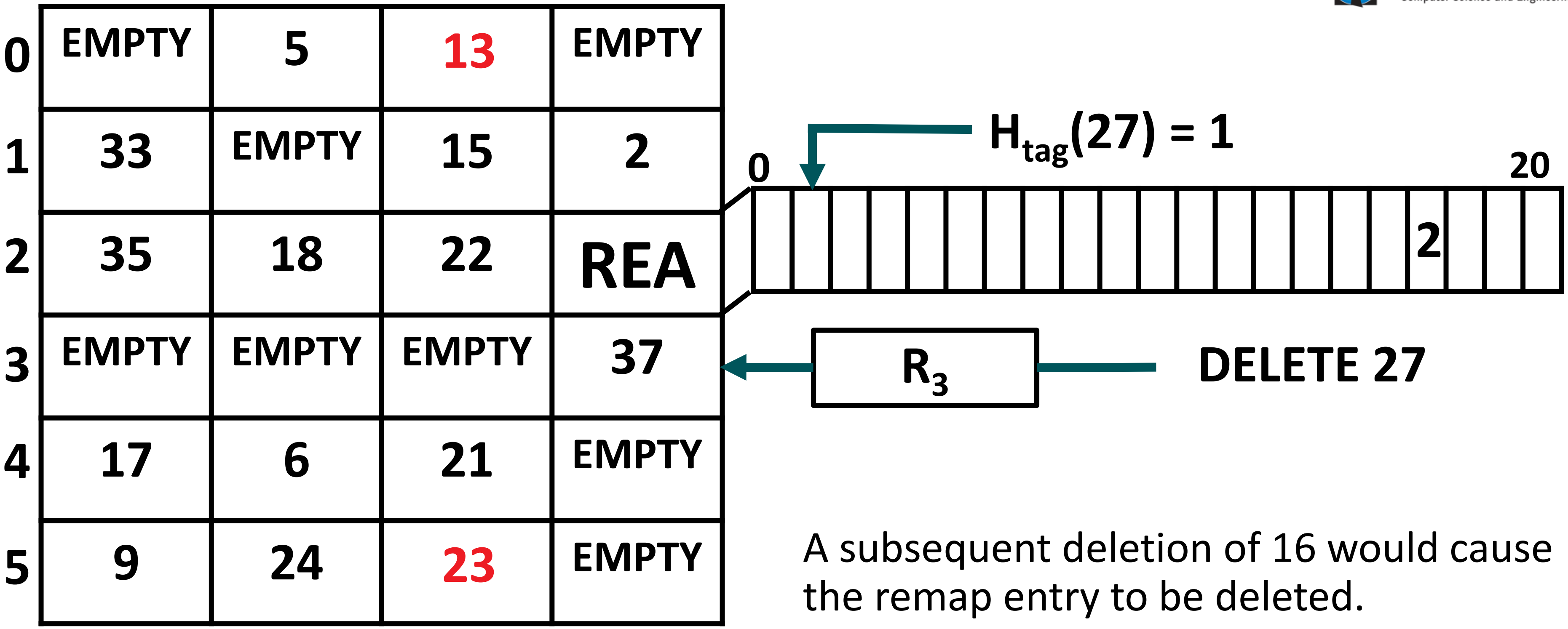
0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

A subsequent deletion of 16 would cause the remap entry to be deleted.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

HORTON TABLES

DELETING ELEMENTS



0	EMPTY	5	13	EMPTY
1	33	EMPTY	15	2
2	35	18	22	REA
3	EMPTY	EMPTY	EMPTY	37
4	17	6	21	EMPTY
5	9	24	23	EMPTY

A subsequent deletion of 16 would cause the remap entry to be deleted.

- Deleting elements that are found in their primary bucket only requires accessing a single bucket
- A remapped element can be deleted by performing a secondary lookup followed by a deletion

END OF BACKUP SLIDES