Carnegie Mellon University

Database Systems

Hash Tables

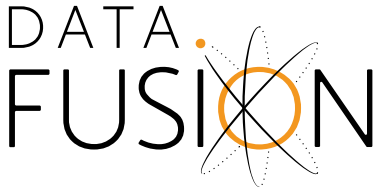
ADMINISTRIVIA

Homework #2 is due Sept 22nd @ 11:59pm

Project #1 is due Sept 29th @ 11:59pm
→ **Recitation on Thursday Sept 19th @ 6:00pm (See @144)**

UPCOMING DATABASE TALKS

DataFusion (DB Seminar)
→ Monday Sept 23rd @ 4:30pm ET
→ Zoom



DataFusion Comet (DB Seminar)
→ Monday Sept 30th @ 4:30pm ET
→ Zoom

Oracle Talk (DB Group)
→ Tuesday Oct 1st @ 12:00pm ET
→ GHC 6501

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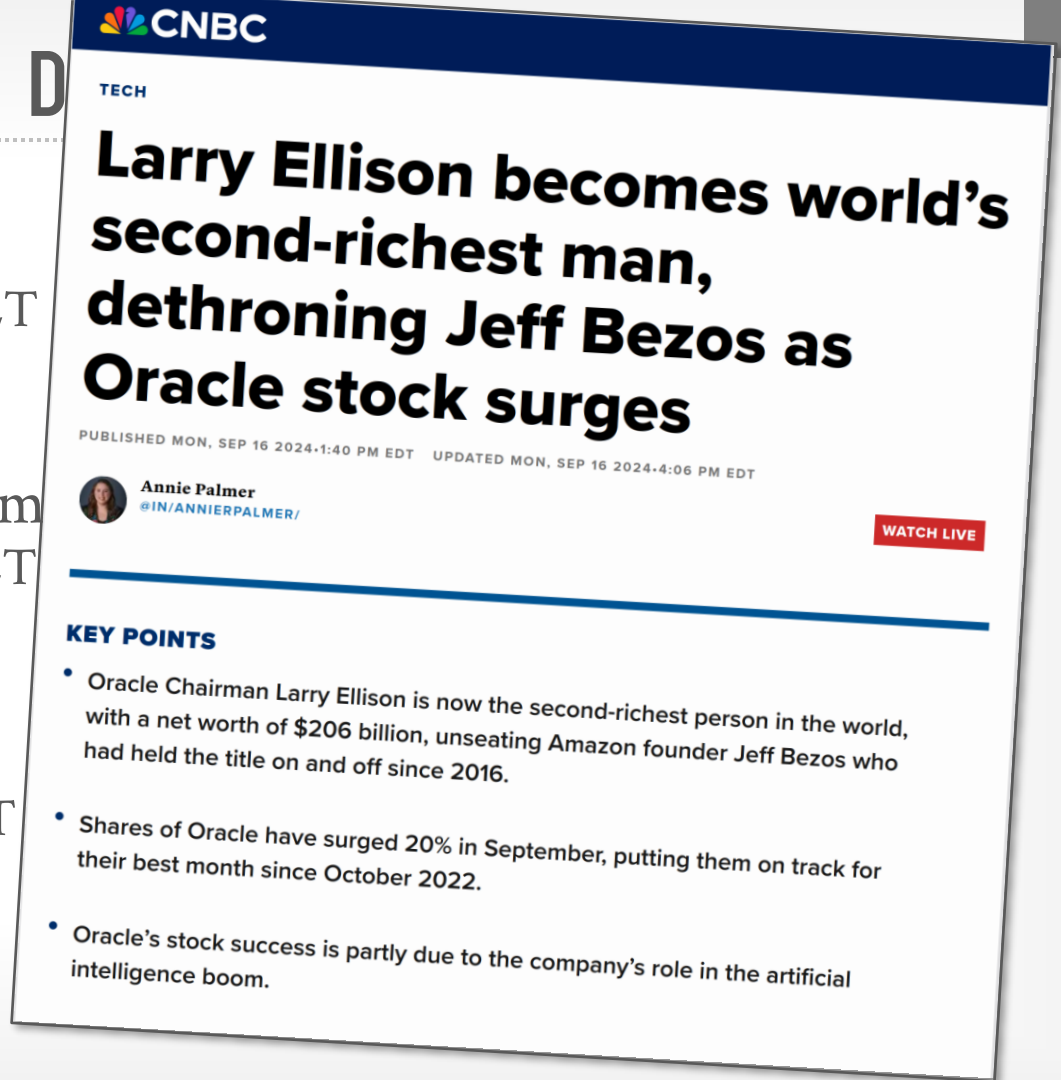


CNBC

TECH

Larry Ellison becomes world's second-richest man, dethroning Jeff Bezos as Oracle stock surges

PUBLISHED MON, SEP 16 2024•1:40 PM EDT UPDATED MON, SEP 16 2024•4:06 PM EDT

Annie Palmer
@IN/ANNIERPALMER/

WATCH LIVE

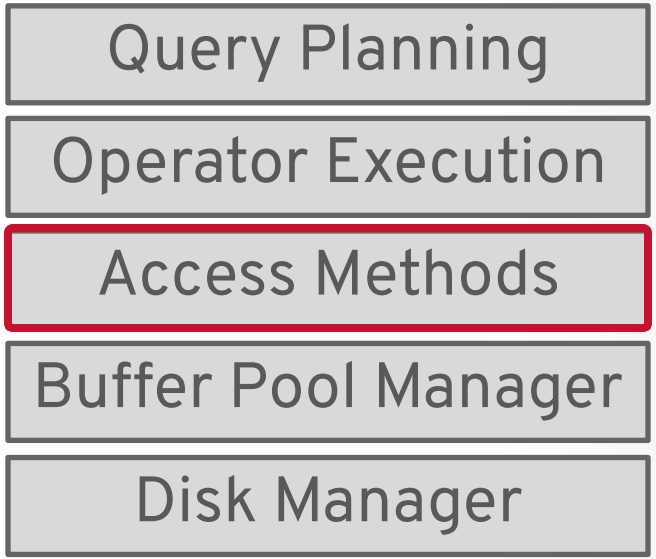
KEY POINTS

- Oracle Chairman Larry Ellison is now the second-richest person in the world, with a net worth of $206 billion, unseating Amazon founder Jeff Bezos who had held the title on and off since 2016.
- Shares of Oracle have surged 20% in September, putting them on track for their best month since October 2022.
- Oracle's stock success is partly due to the company's role in the artificial intelligence boom.

COURSE OUTLINE

We are now going to talk about how to support the DBMS's execution engine to read/write data from pages.

Two types of data structures:
→ Hash Tables (Unordered)
→ Trees (Ordered)



TODAY'S AGENDA

Background

Hash Functions

Static Hashing Schemes 固定数量的键值对元素

Dynamic Hashing Schemes

DB Flash Talk: RelationalAI

DATA STRUCTURES

Internal Meta-data

Core Data Storage

Temporary Data Structures JOIN 算子生成的哈希表

Table Indexes

DESIGN DECISIONS

Data Organization

→ How we layout data structure in memory/pages and what information to store to support efficient access.

Concurrency

→ How to enable multiple threads to access the data structure at the same time without causing problems.

HASH TABLES

A **hash table** implements an unordered associative array that maps keys to values.

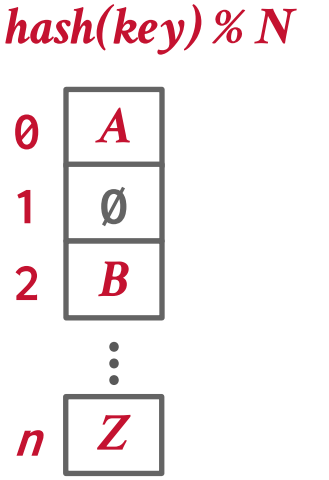
It uses a **hash function** to compute an offset into this array for a given key, from which the desired value can be found.

Space Complexity: **O(n)**
Time Complexity:
→ Average: **O(1)** ⬅ ***Databases care about constants!***
→ Worst: **O(n)**

STATIC HASH TABLE

Allocate a giant array that has one slot for every element you need to store.

To find an entry, mod the key by the number of elements to find the offset in the array.



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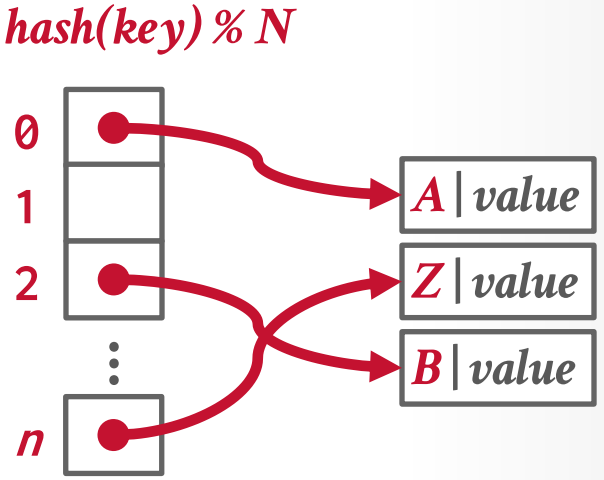


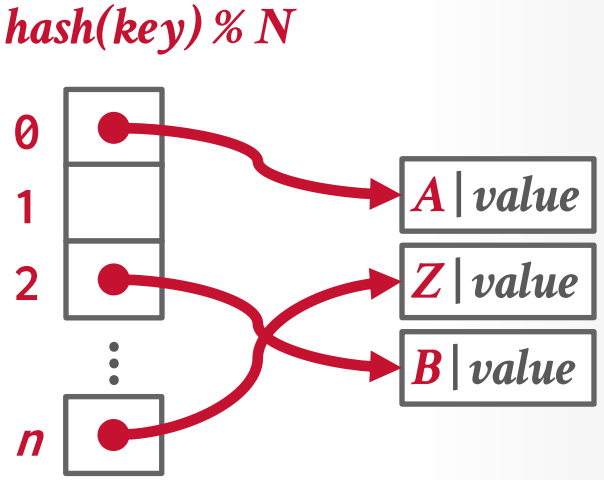
UNREALISTIC ASSUMPTIONS

Assumption #1: Number of elements is known ahead of time and fixed.

Assumption #2: Each key is unique.

Assumption #3: Perfect hash function guarantees no collisions.

→ If **key1≠key2**, then **hash(key1)≠hash(key2)**



HASH TABLE

Design Decision #1: Hash Function

→ How to map a large key space into a smaller domain.
→ Trade-off between being fast vs. collision rate.

Design Decision #2: Hashing Scheme

→ How to handle key collisions after hashing.
→ Trade-off between allocating a large hash table vs. additional instructions to get/put keys.

HASH FUNCTIONS

For any input key, return an integer representation of that key.

→ Converts arbitrary byte array into a fixed-length code.

We want something that is fast and has a low collision rate.

速率与碰撞率之间的权衡.

We do not want to use a cryptographic hash function for DBMS hash tables (e.g., SHA-2).

HASH FUNCTIONS

CRC-64 (1975)
→ Used in networking for error detection.

MurmurHash (2008)
→ Designed as a fast, general-purpose hash function.

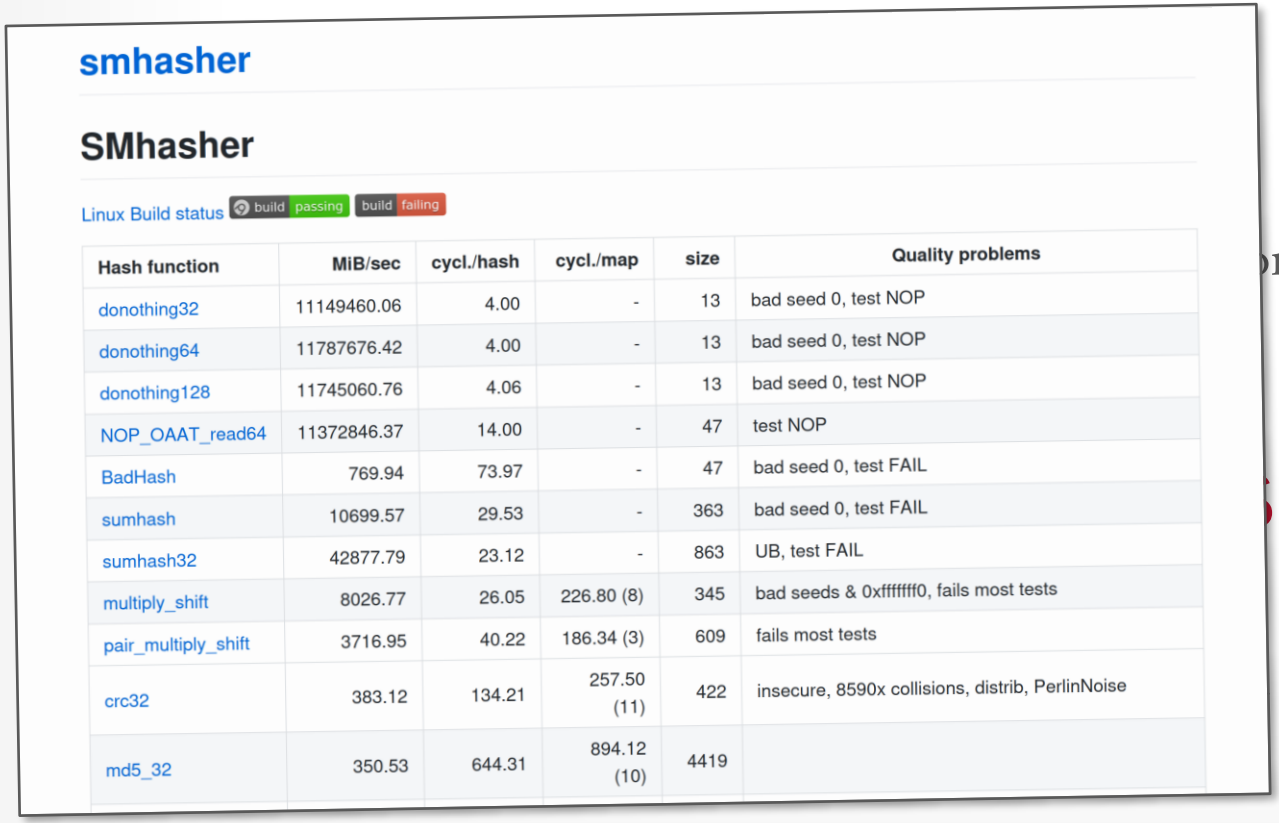
Google CityHash (2011)
→ Designed to be faster for short keys (<64 bytes).

Facebook XXHash (2012)
→ From the creator of zstd compression.

← State-of-the-art

Google FarmHash (2014)
→ Newer version of CityHash with better collision rates.

HASH FUNCTIONS



smhasher

SMhasher

Linux Build status build passing build failing

Hash function	MiB/sec	cycl./hash	cycl./map	size	Quality problems
donothing32	11149460.06	4.00	-	13	bad seed 0, test NOP
donothing64	11787676.42	4.00	-	13	bad seed 0, test NOP
donothing128	11745060.76	4.06	-	13	bad seed 0, test NOP
NOP_OAAT_read64	11372846.37	14.00	-	47	test NOP
BadHash	769.94	73.97	-	47	bad seed 0, test FAIL
sumhash	10699.57	29.53	-	363	bad seed 0, test FAIL
sumhash32	42877.79	23.12	-	863	UB, test FAIL
multiply_shift	8026.77	26.05	226.80 (8)	345	bad seeds & 0xffffffff0, fails most tests
pair_multiply_shift	3716.95	40.22	186.34 (3)	609	fails most tests
crc32	383.12	134.21	257.50 (11)	422	insecure, 8590x collisions, distrib, PerlinNoise
md5_32	350.53	644.31	894.12 (10)	4419	

on.

State-of-the-art

rates.

HASH FUNCTIONS

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BadHash	769.94	73.97	-	4
sumhash	10699.57	29.53	-	36
sumhash32	42877.79	23.12	-	8
multiply_shift	8026.77	26.05	226.80 (8)	3
pair_multiply_shift	3716.95	40.22	186.34 (3)	6
crc32	383.12	134.21	257.50 (11)	
md5_32	350.53	644.31	894.12 (10)	4

Summary

I added some SSE assisted hashes and fast intel/arm CRC32-C, AES and SHA HW variants. See also the old https://github.com/aappleby/smhasher/wiki, the improved, but unmaintained fork https://github.com/demerphq/smhasher, and the new improved version SMHasher3 https://gitlab.com/fwojcik/smhasher3.

So the fastest hash functions on x86_64 without quality problems are:

- rapidhash (an improved wyhash)
- xxh3low
- wyhash
- umash (even universal!)
- ahash64
- t1ha2_atonce
- komihash
- FarmHash (*not portable, too machine specific: 64 vs 32bit, old gcc, ...*)
- halftime_hash128
- Spooky32
- pengyhash
- nmhash32
- mx3
- MUM/mir (*different results on 32/64-bit archs, lots of bad seeds to filter out*)
- fasthash32

STATIC HASHING SCHEMES

Approach #1: Linear Probe Hashing
Approach #2: Cuckoo Hashing

←Open Addressing

相同 key 每次计算出的位置是随机的，不一定是相同的.

There are several other schemes covered in the Advanced DB course:

→ Robin Hood Hashing
→ Hopscotch Hashing
→ Swiss Tables

当哈希冲突发生时，如何处理：移动想要空间里的元素还是寻找其他位置?

LINEAR PROBE HASHING

对于给定 key 经过哈希函数计算后，对槽数组长度取模获得键值对插入的位置： pos = hash(key) % n

Single giant table of fixed-length slots.

Resolve collisions by linearly searching for the next free slot in the table.

→ To determine whether an element is present, hash to a location in the table and scan for it.
→ Store keys in table to know when to stop scanning.
→ Insertions and deletions are generalizations of lookups.

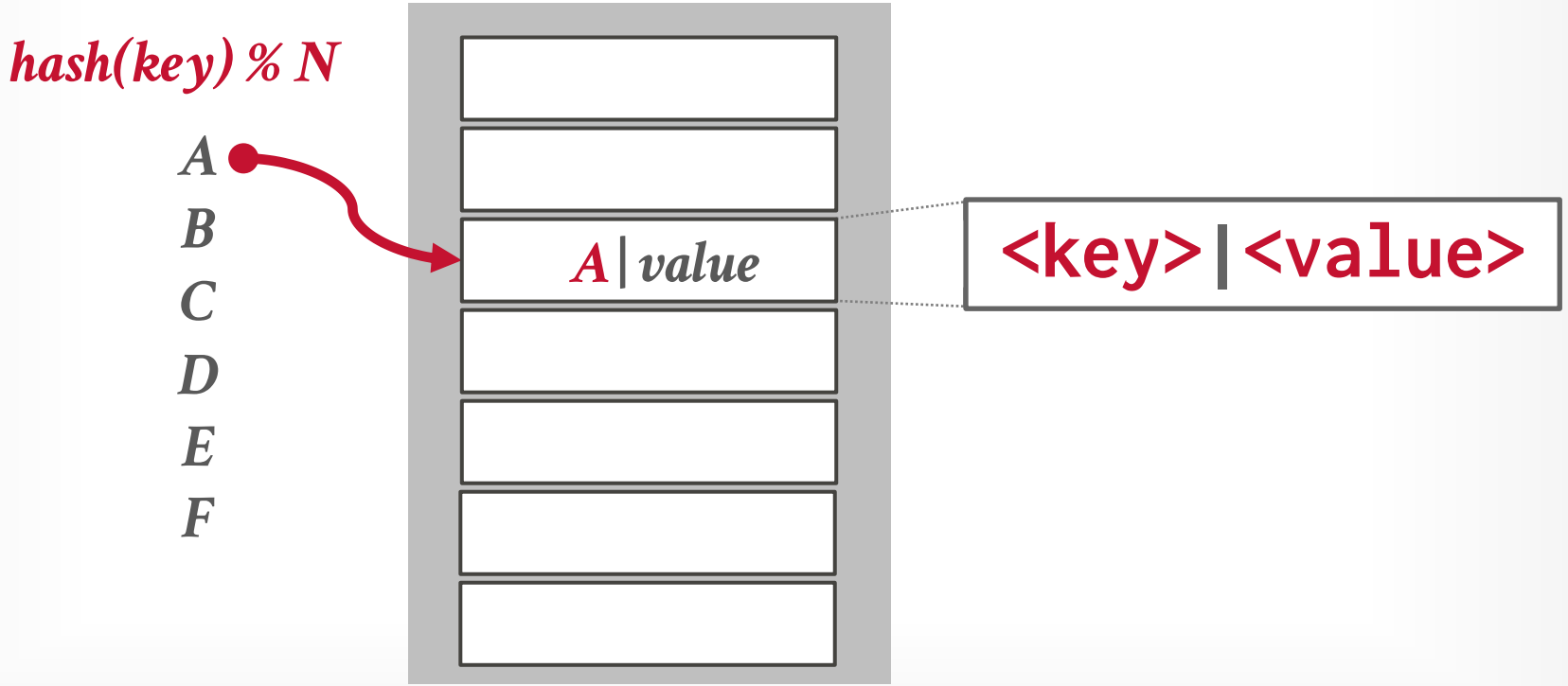
在 hash join 计算时, 通常会使用线性探测法.

The table's **load factor** determines when it is becoming too full and should be resized. 通常设置为 70% 或 80% 的比例.

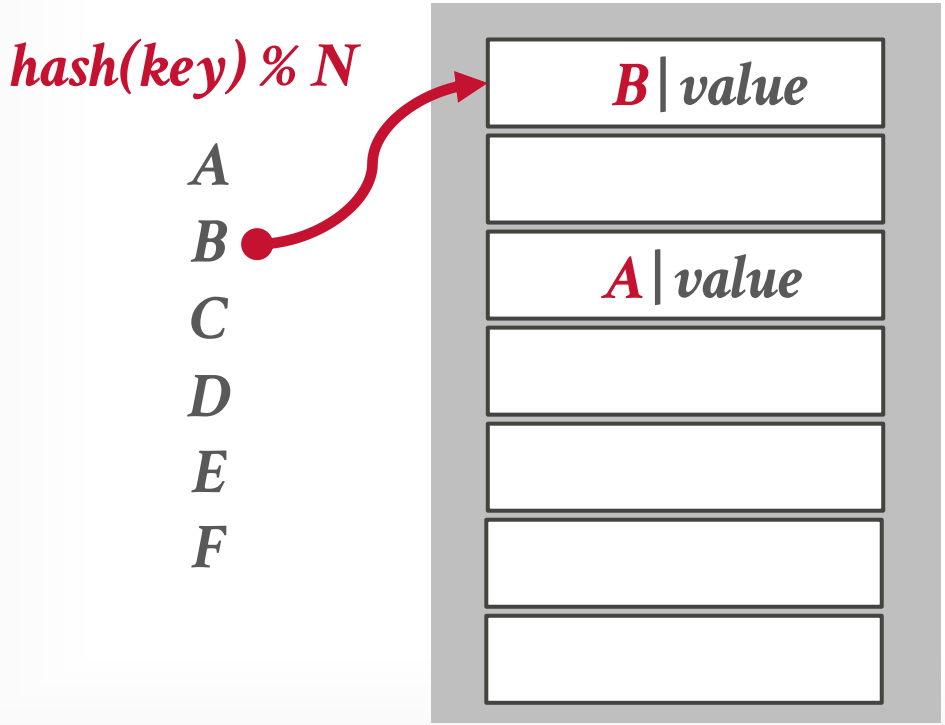
→ Allocate a new table twice as large and rehash entries.

尽量避免哈希表的动态扩容：需要对已有元素进行重新哈希计算.

LINEAR PROBE HASHING



LINEAR PROBE HASHING



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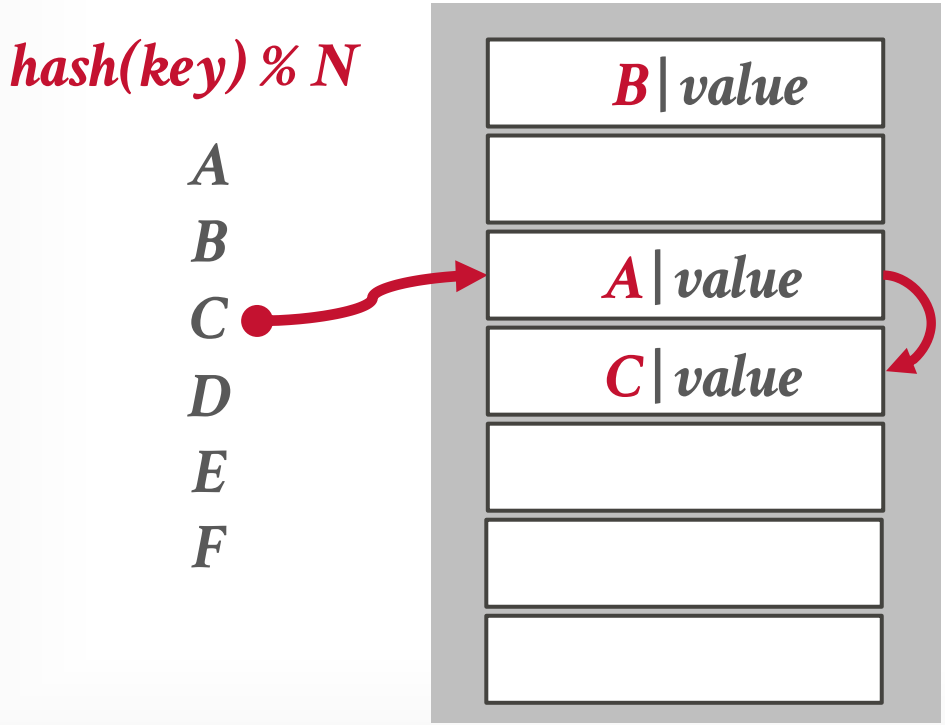

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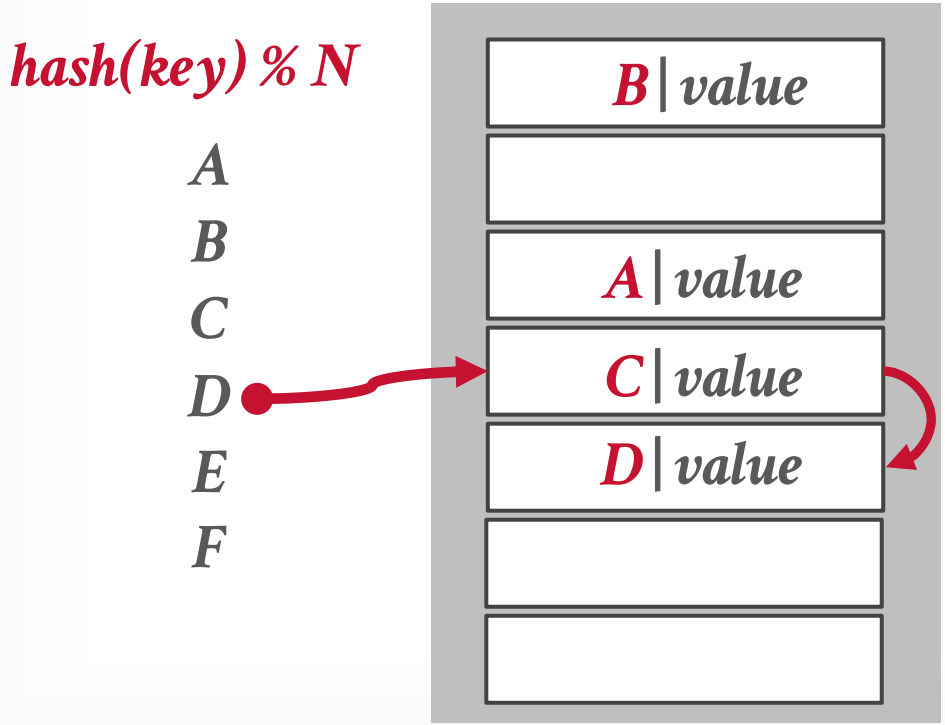

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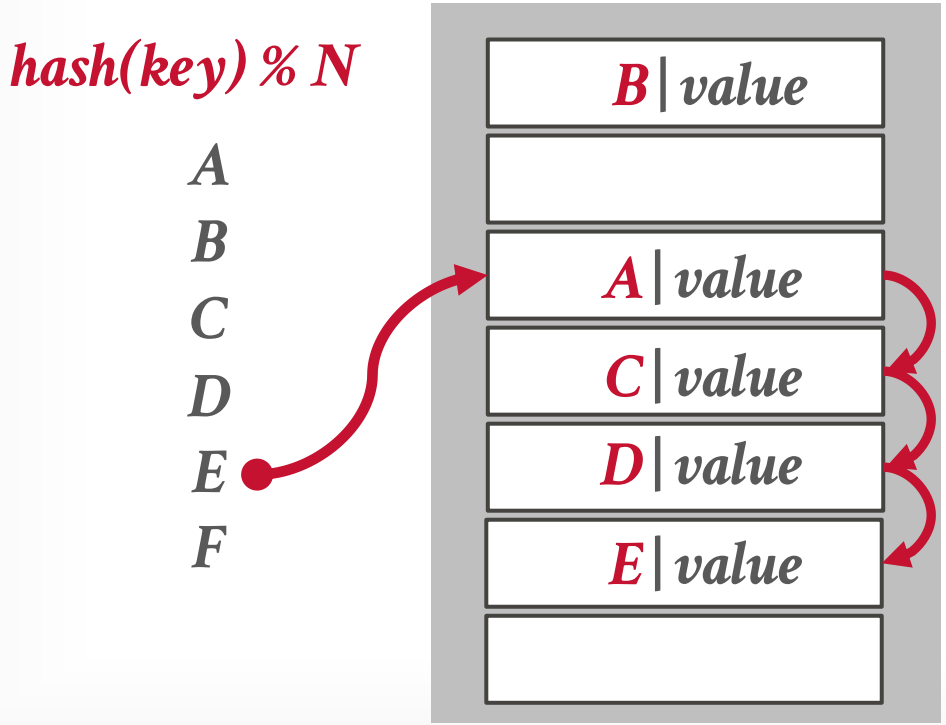
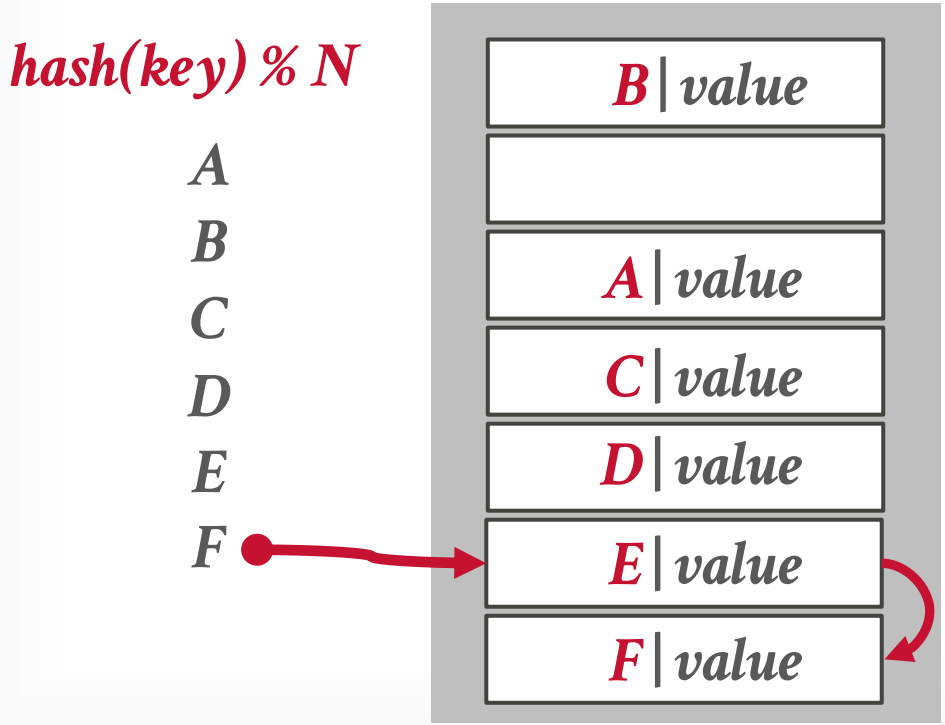


发生哈希冲突时，线性扫描直至获取下一个空闲位置.

LINEAR PROBE HASHING



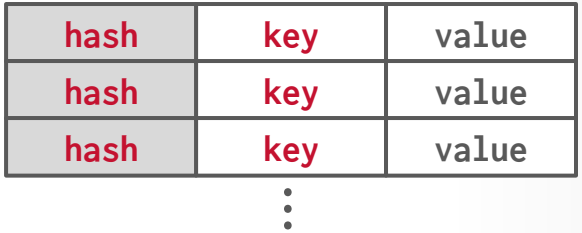
HASH TABLE – KEY/VALUE ENTRIES

Fixed-length Key/Values:

→ Store inline within the hash table pages.

→ Optional: Store the key's hash with the key for faster comparisons.

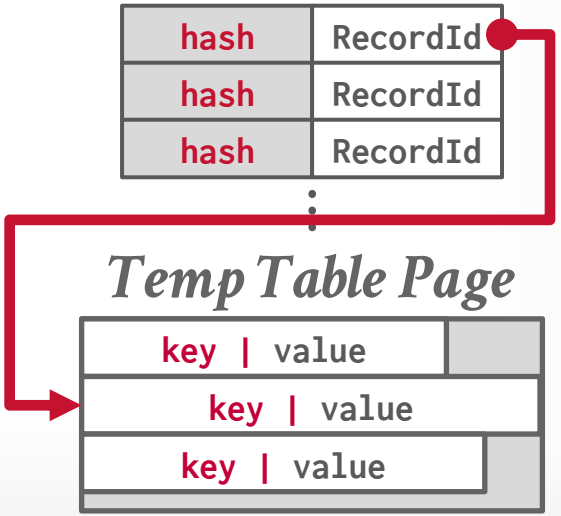
空间换时间：少量的空间存储哈希值, 以加快查找速度.



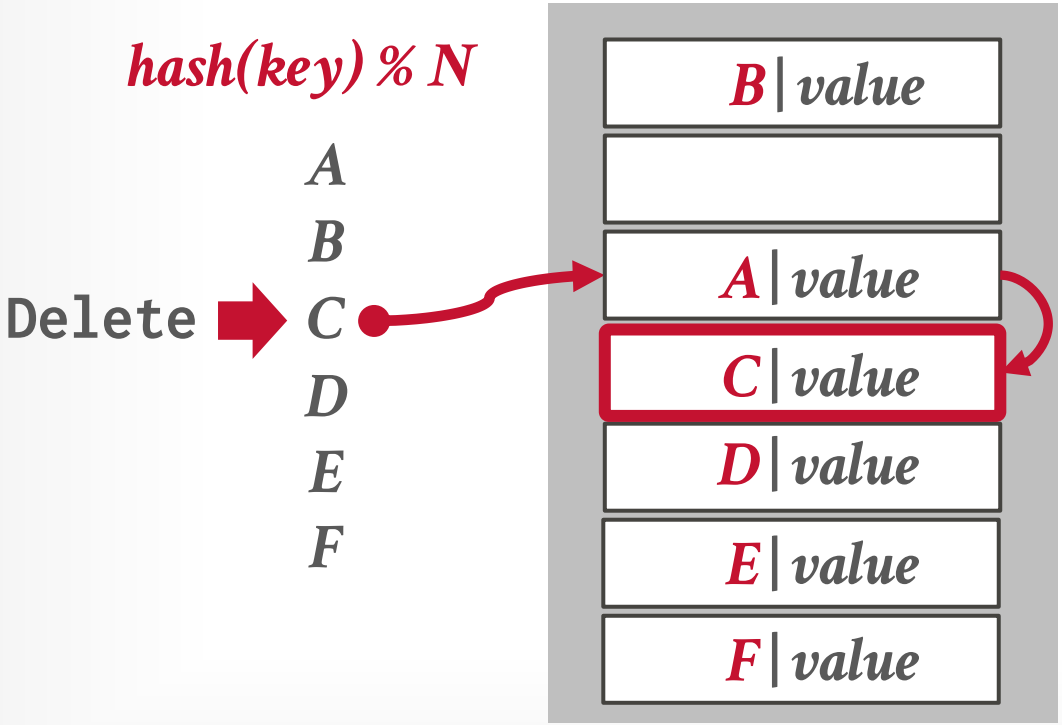
Variable-length Key/Values:

→ Insert key/value data in separate a private temporary table.

→ Store the hash as the key and use the record id pointing to its corresponding entry in the temporary table as the value.



LINEAR PROBE HASHING – DELETES



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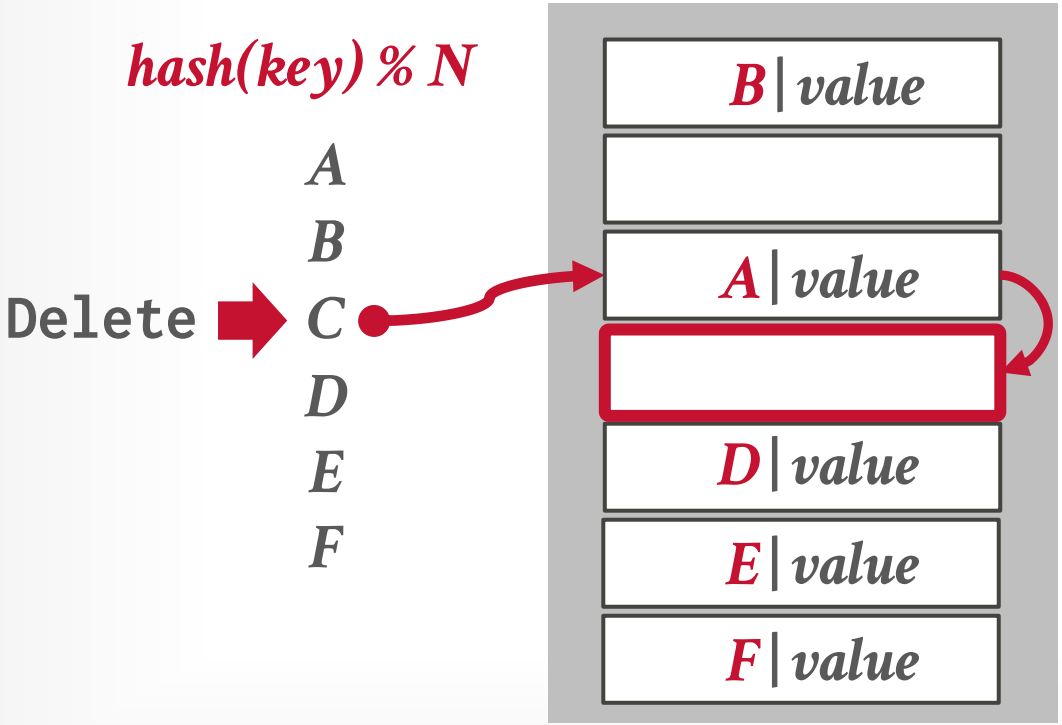

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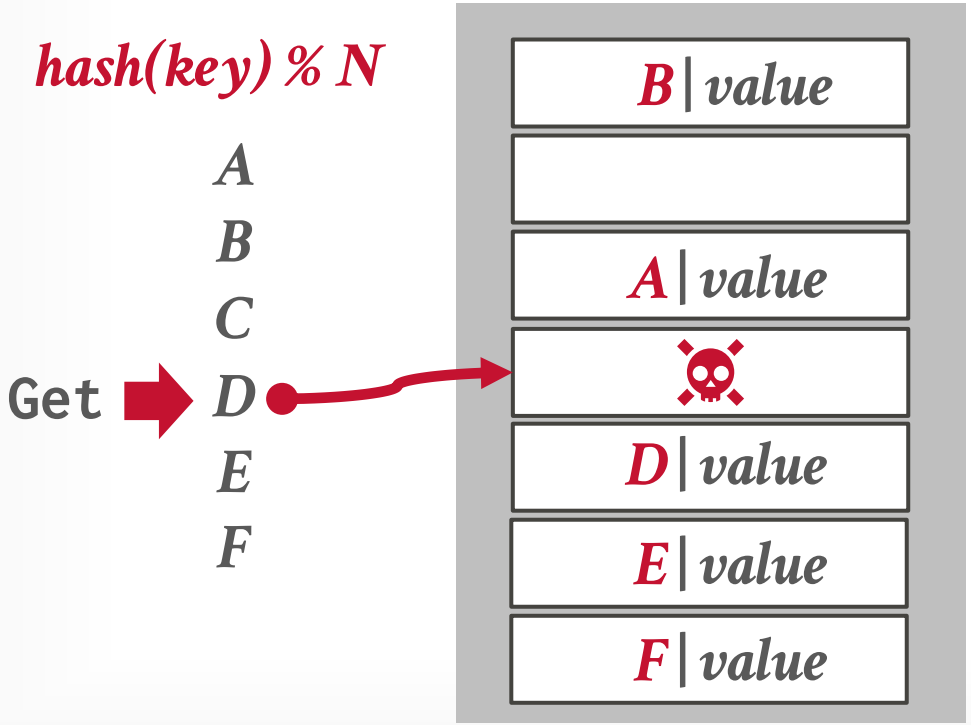


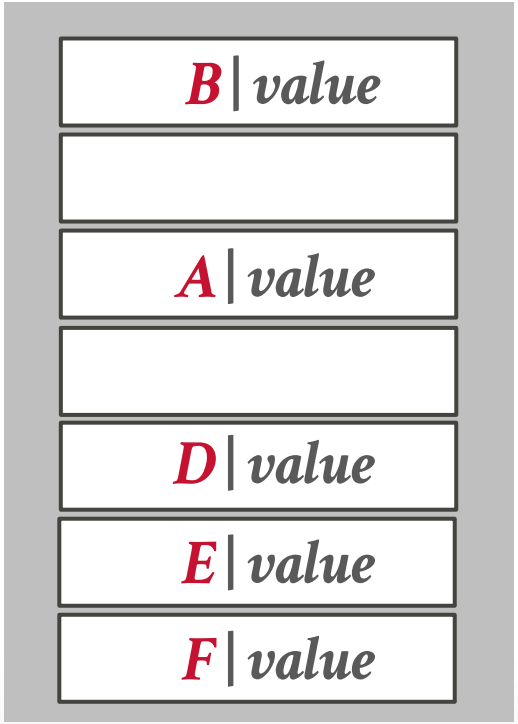
查找元素: 如果发现空槽位, 则结束查找流程, 表示该元素不在哈希表中.

LINEAR PROBE HASHING – DELETES

hash(key) % N

Get → *D*

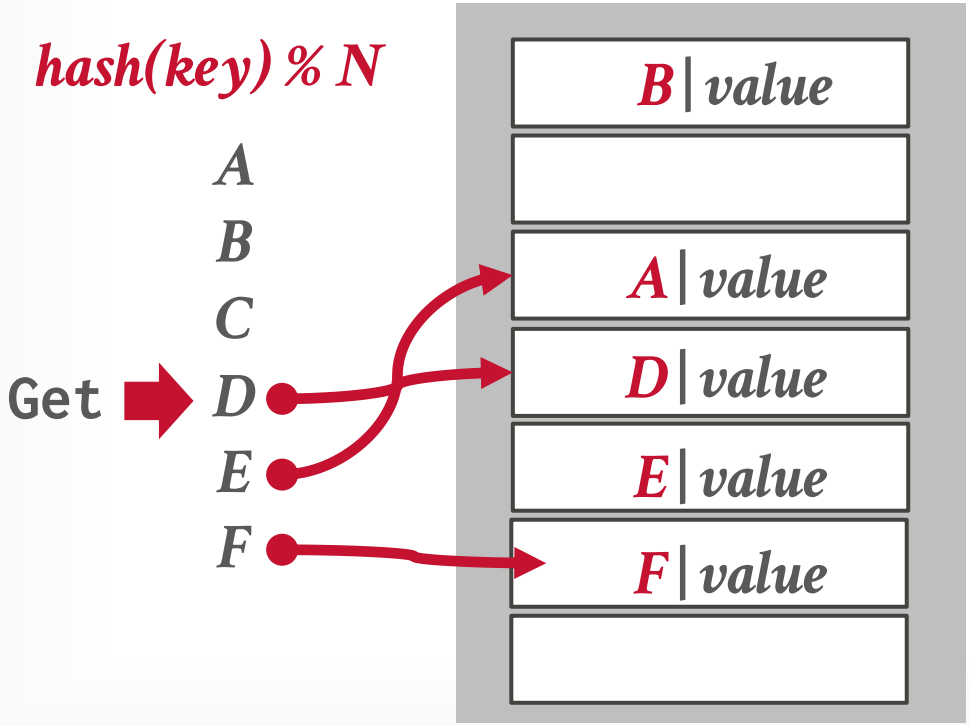
A
B
C
D
E
F



Approach #1: Movement

→ Rehash keys until you find the first empty slot.

LINEAR PROBE HASHING – DELETES



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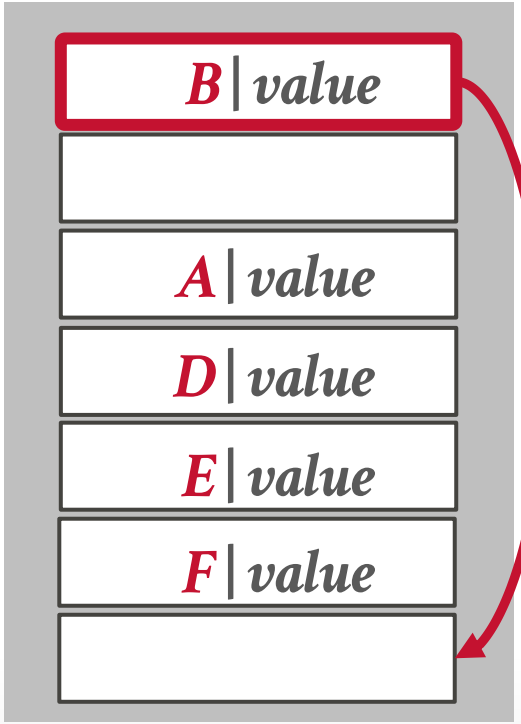

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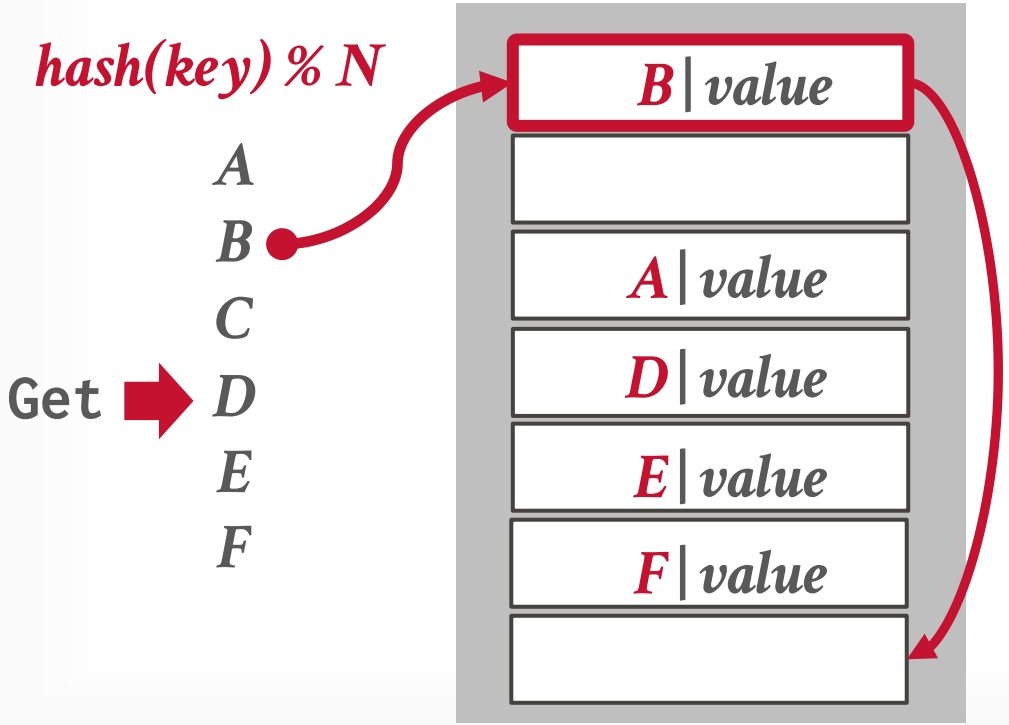


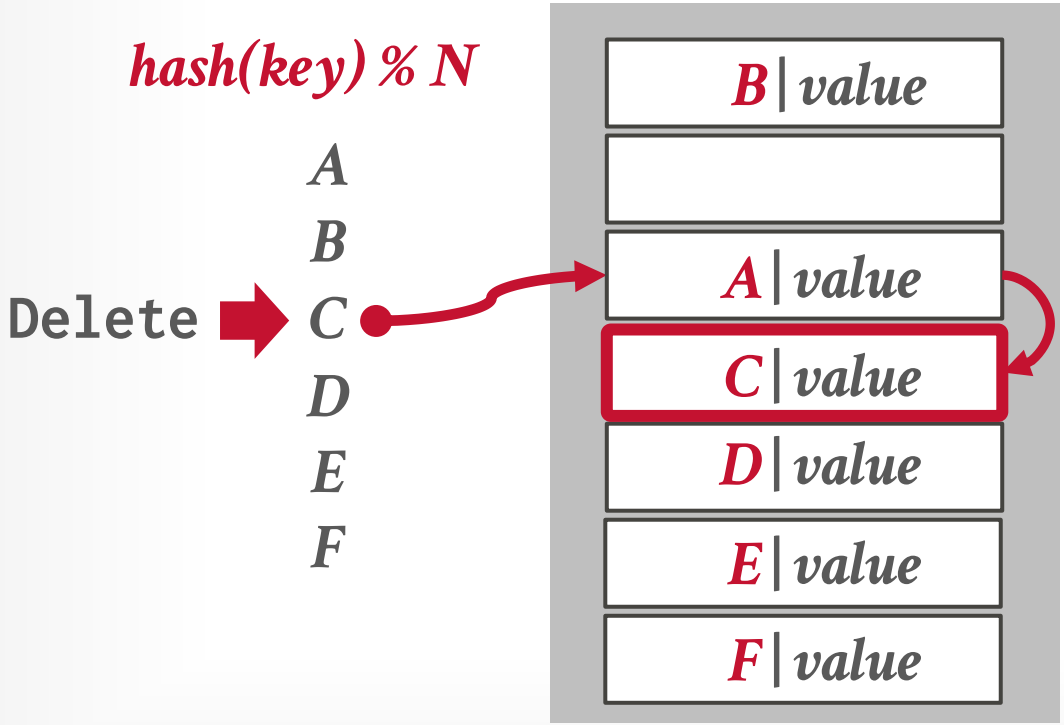
Approach #1: Movement

→ Rehash keys until you find the first empty slot.

→ Expensive! May need to reorganize the entire table.

→ No DBMS does this.

LINEAR PROBE HASHING – DELETES



使用逻辑删除位进行标记删除的元素.

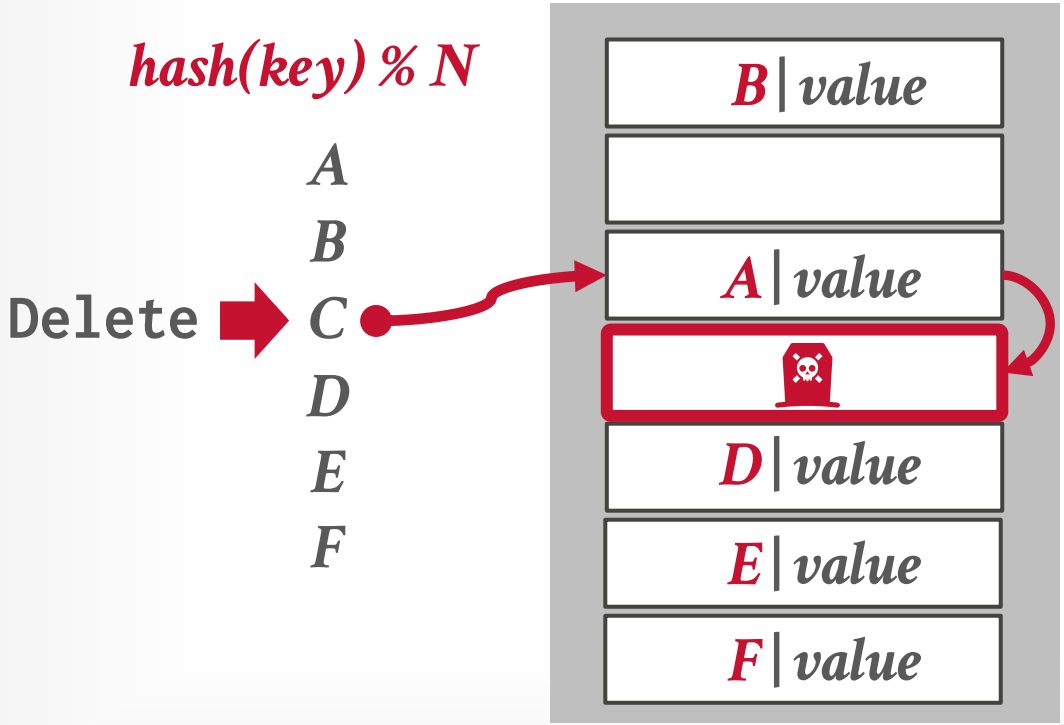
Approach #2: Tombstone

→ Maintain separate bit map to indicate that the entry in the slot is logically deleted.

→ Reuse the slot for new keys.

→ May need periodic garbage collection.

LINEAR PROBE HASHING – DELETES



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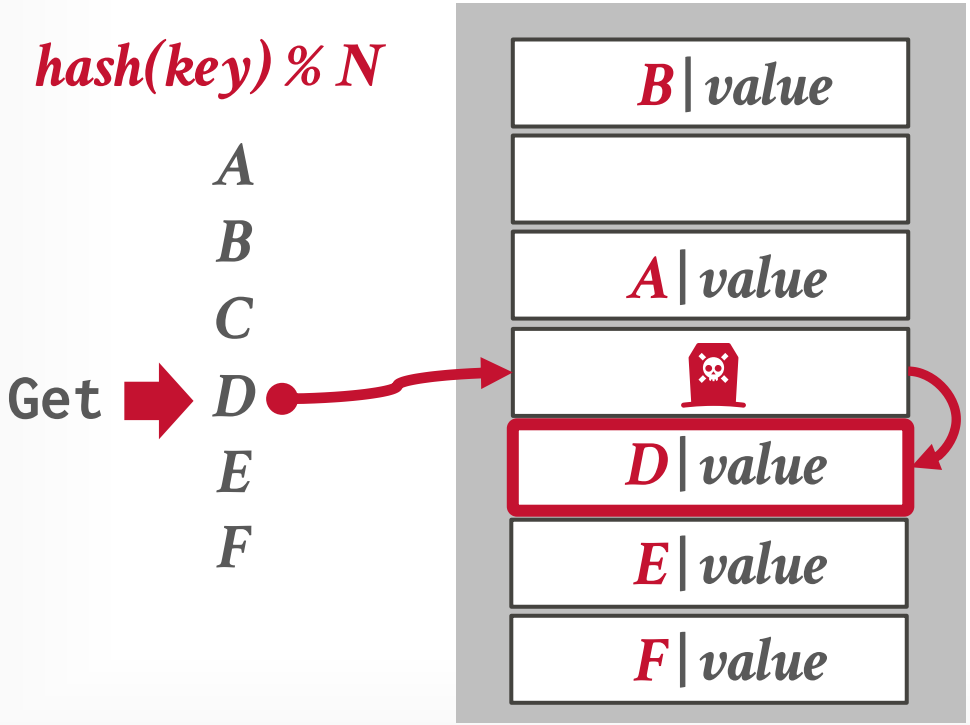

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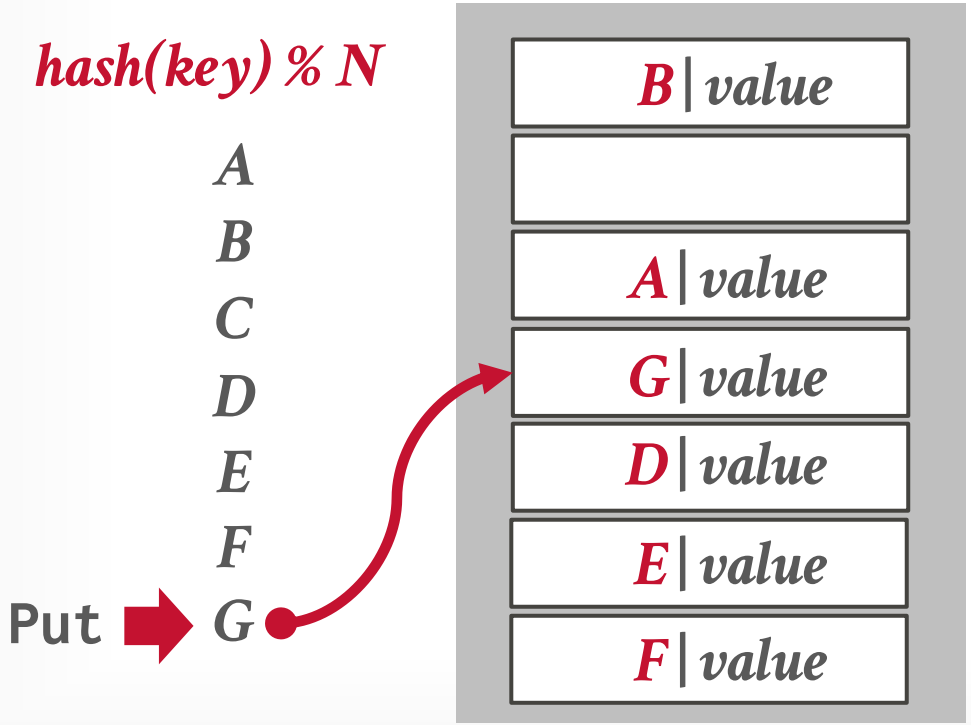

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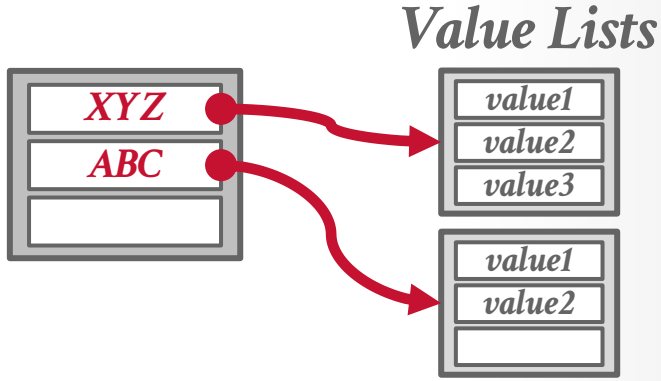
HASH TABLE – NON-UNIQUE KEYS

Choice #1: Separate Linked List

→ Store values in separate storage area for each key.

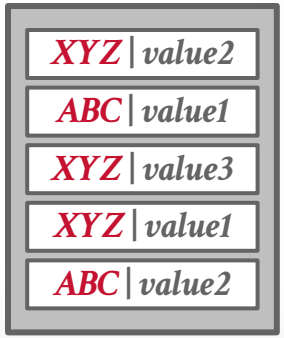
→ Value lists can overflow to multiple pages if the number of duplicates is large.



Choice #2: Redundant Keys

→ Store duplicate keys entries together in the hash table.

→ This is what most systems do.



OPTIMIZATIONS

Specialized hash table implementations based on key type(s) and sizes. clickhouse 提供不同类型的哈希表实现.

→ Example: Maintain multiple hash tables for different string sizes for a set of keys.

Store metadata separate in a separate array.

→ Packed bitmap tracks whether a slot is empty/tombstone.

Use table + slot versioning metadata to quickly invalidate all entries in the hash table.

→ Example: If table version does not match slot version, then treat the slot as empty.

Source: Maksim Kita

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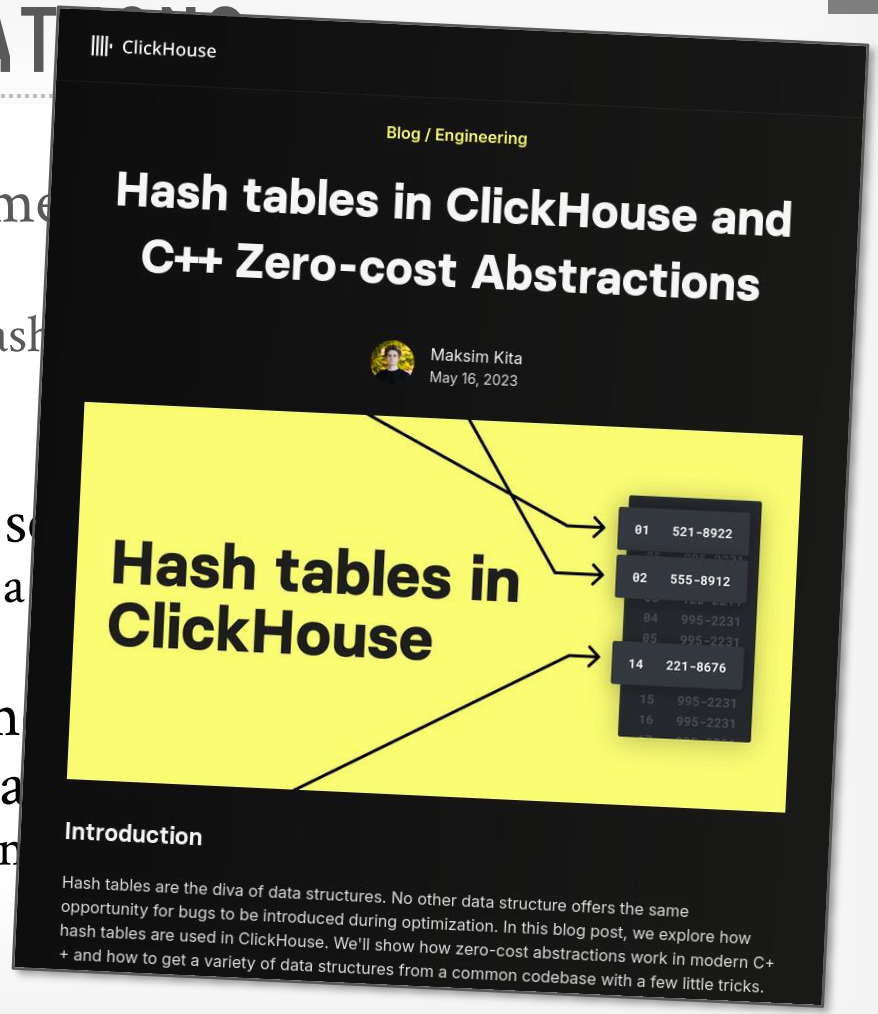


Source: Maksim Kita

CUCKOO HASHING

同时使用多个哈希函数替代顺序扫描来查找一个空闲槽或键.

Use multiple hash functions to find multiple locations in the hash table to insert records.

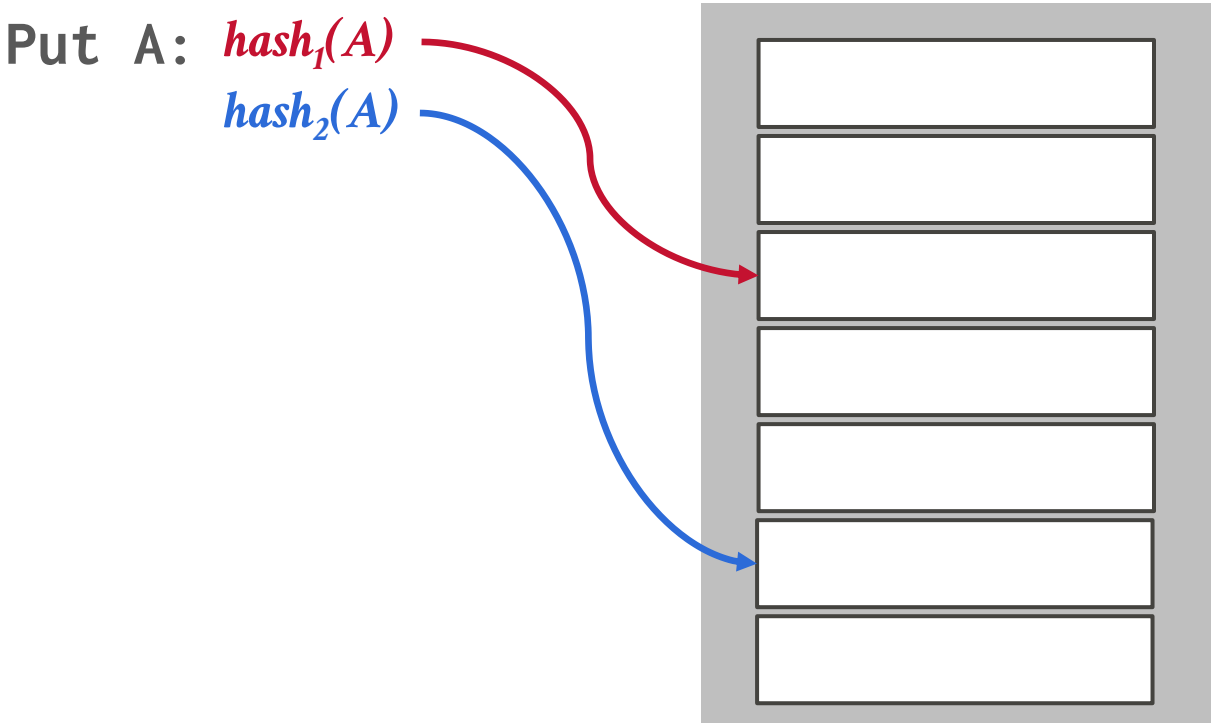
→ On insert, check multiple locations and pick the one that is empty.

→ If no location is available, evict the element from one of them and then re-hash it find a new location.

Look-ups and deletions are always **O(1)** because only one location per hash table is checked.

Best open-source implementation is from CMU.

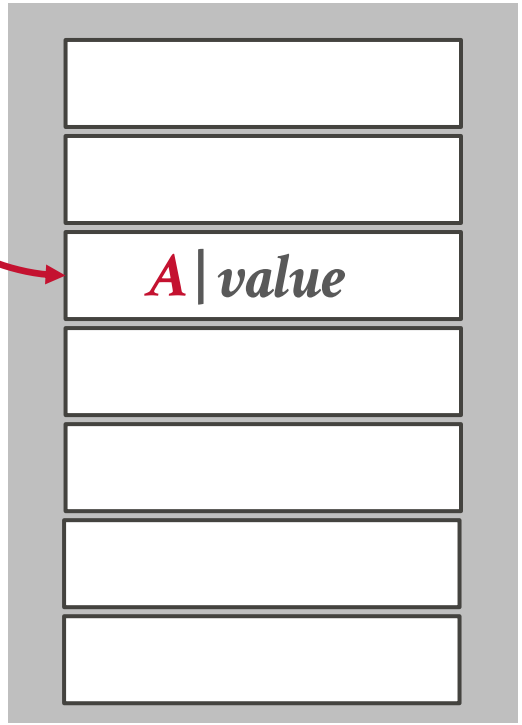
CUCKOO HASHING



CUCKOO HASHING

Put A: $hash_1(A)$

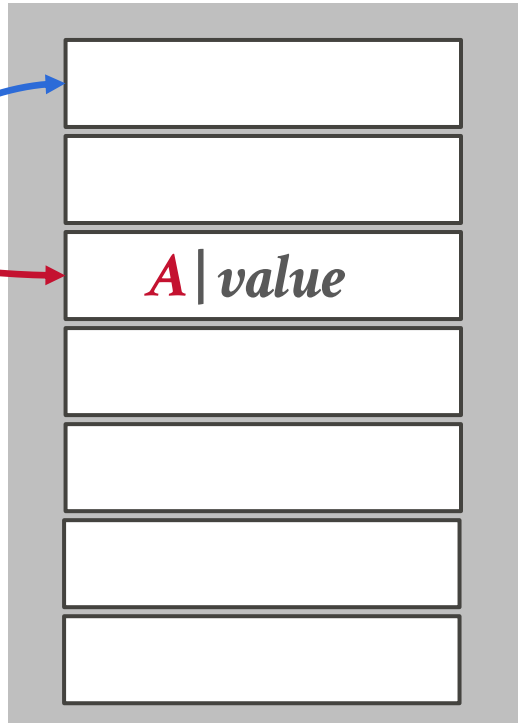
$hash_2(A)$



CUCKOO HASHING

Put A: $hash_1(A)$
$hash_2(A)$

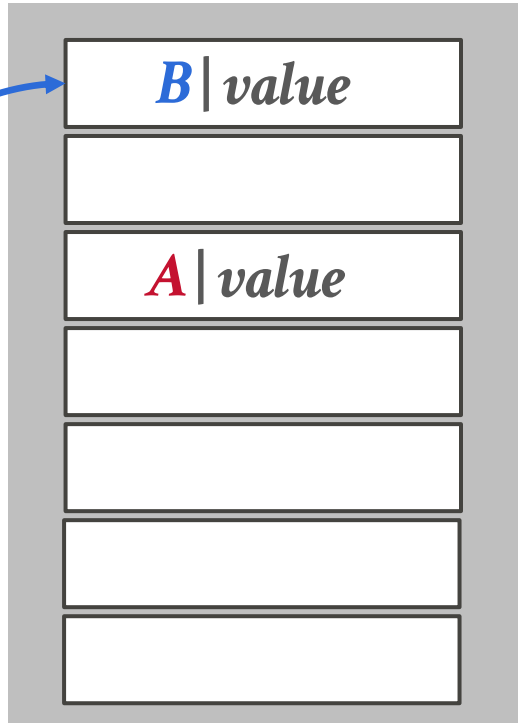
Put B: $hash_1(B)$
$hash_2(B)$



CUCKOO HASHING

Put A: $hash_1(A)$
$hash_2(A)$

Put B: $hash_1(B)$
$hash_2(B)$

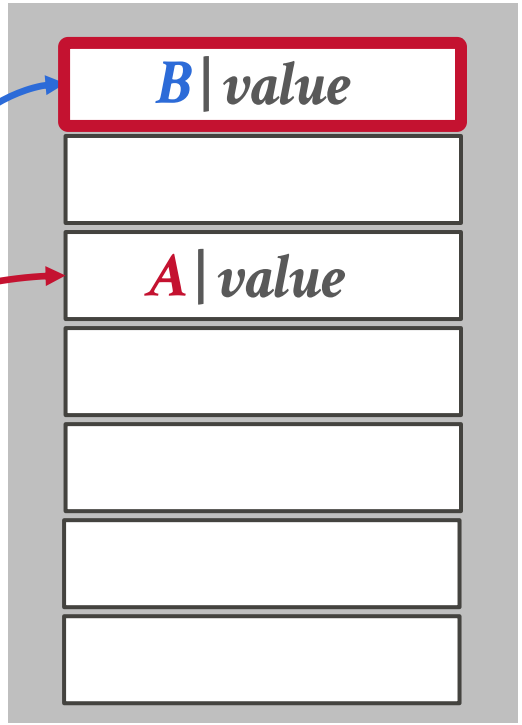


CUCKOO HASHING

Put A: $hash_1(A)$
$hash_2(A)$

Put B: $hash_1(B)$
$hash_2(B)$

Put C: $hash_1(C)$
$hash_2(C)$

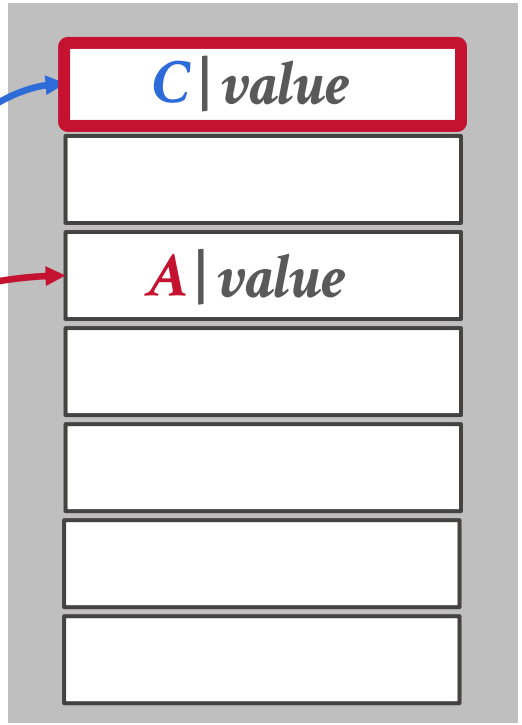


CUCKOO HASHING

Put A: $hash_1(A)$
$hash_2(A)$

Put B: $hash_1(B)$
$hash_2(B)$

Put C: $hash_1(C)$
$hash_2(C)$



CUCKOO HASHING

Put A: $hash_1(A)$

$hash_2(A)$

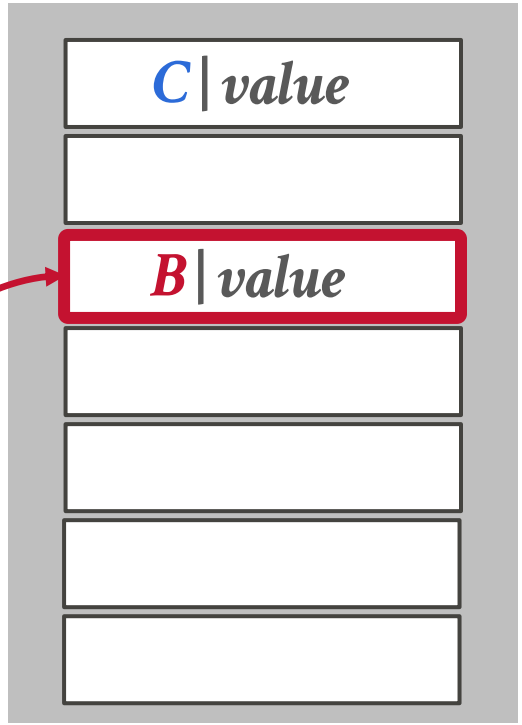
Put B: $hash_1(B)$

$hash_2(B)$

Put C: $hash_1(C)$

$hash_2(C)$

$hash_1(B)$



CUCKOO HASHING

Put A: $hash_1(A)$

$hash_2(A)$

Put B: $hash_1(B)$

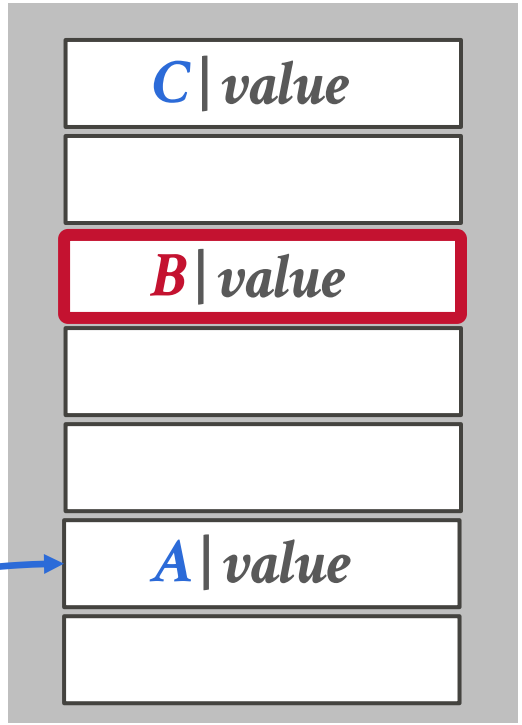
$hash_2(B)$

Put C: $hash_1(C)$

$hash_2(C)$

$hash_1(B)$

$hash_2(A)$



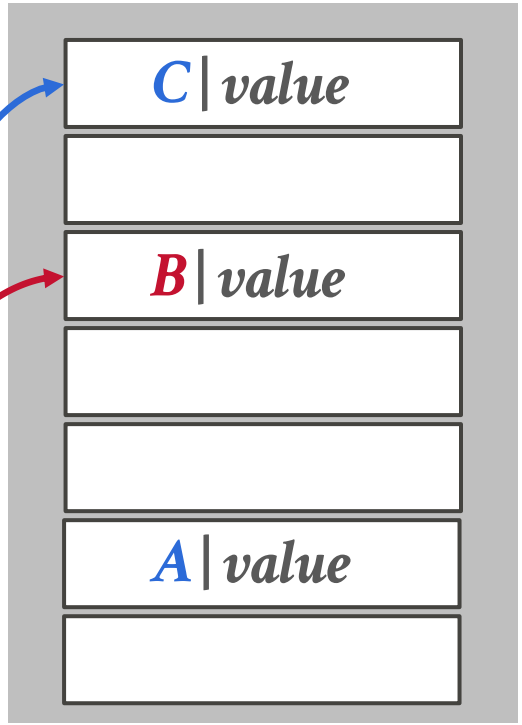
CUCKOO HASHING

Put A: $hash_1(A)$
$hash_2(A)$

Put B: $hash_1(B)$
$hash_2(B)$

Put C: $hash_1(C)$
$hash_2(C)$
$hash_1(B)$
$hash_2(A)$

Get B: $hash_1(B)$
$hash_2(B)$



OBSERVATION

The previous hash tables require the DBMS to know the number of elements it wants to store.

→ Otherwise, it must rebuild the table if it needs to grow/shrink in size.

Dynamic hash tables incrementally resize themselves as needed.

→ Chained Hashing
→ Extendible Hashing
→ Linear Hashing

CHAINED HASHING

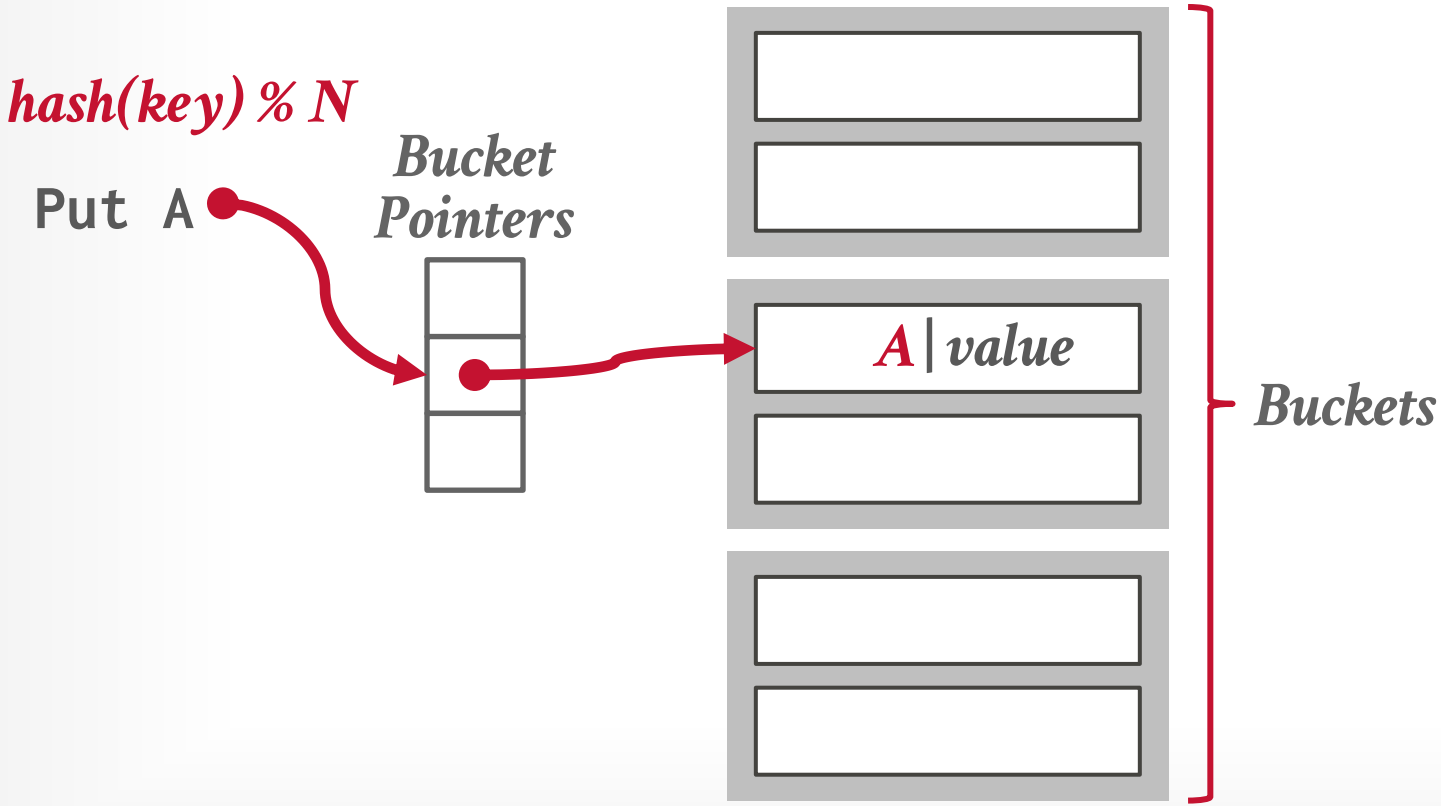
Maintain a linked list of buckets for each slot in the hash table.

Resolve collisions by placing all elements with the same hash key into the same bucket.

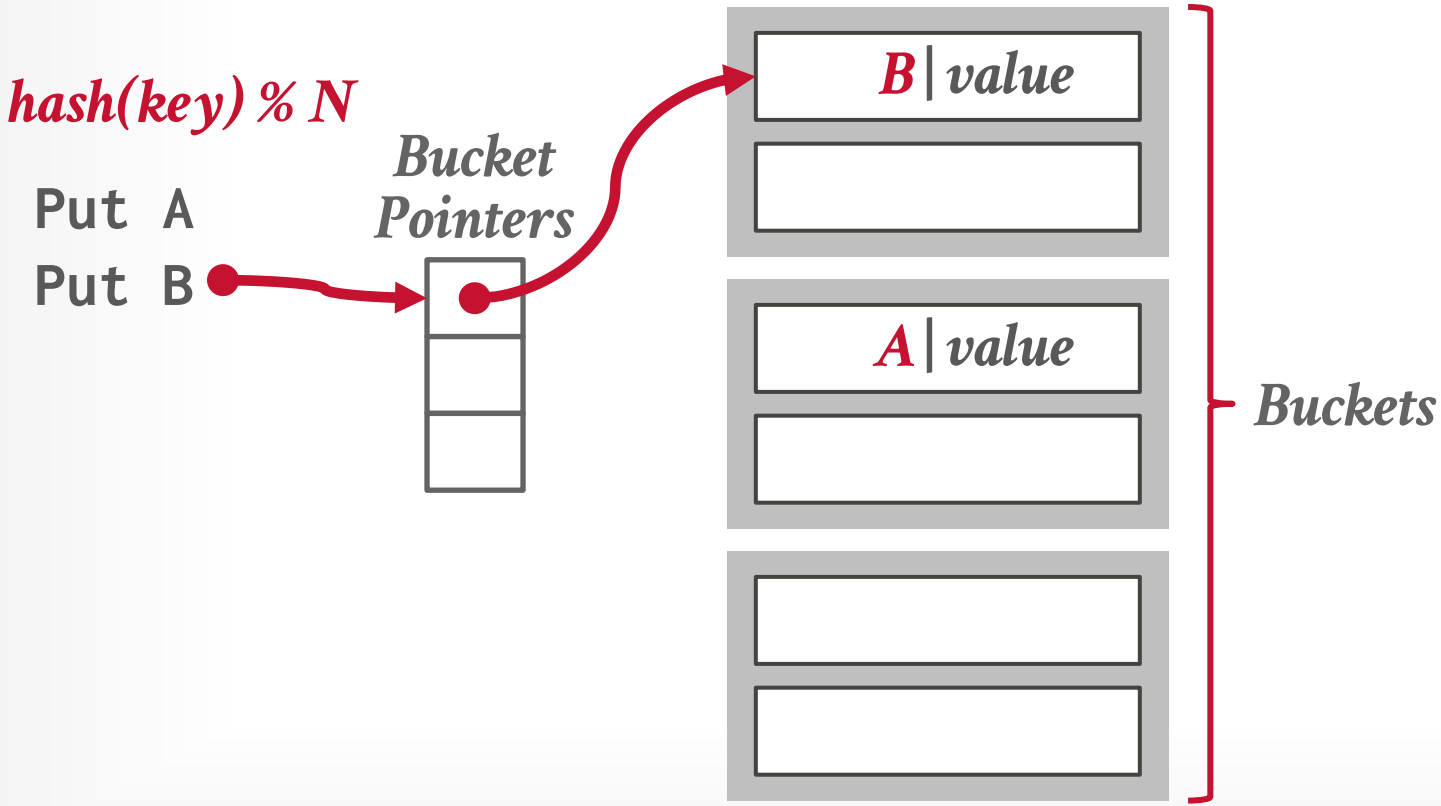
→ To determine whether an element is present, hash to its bucket and scan for it.

→ Insertions and deletions are generalizations of lookups.

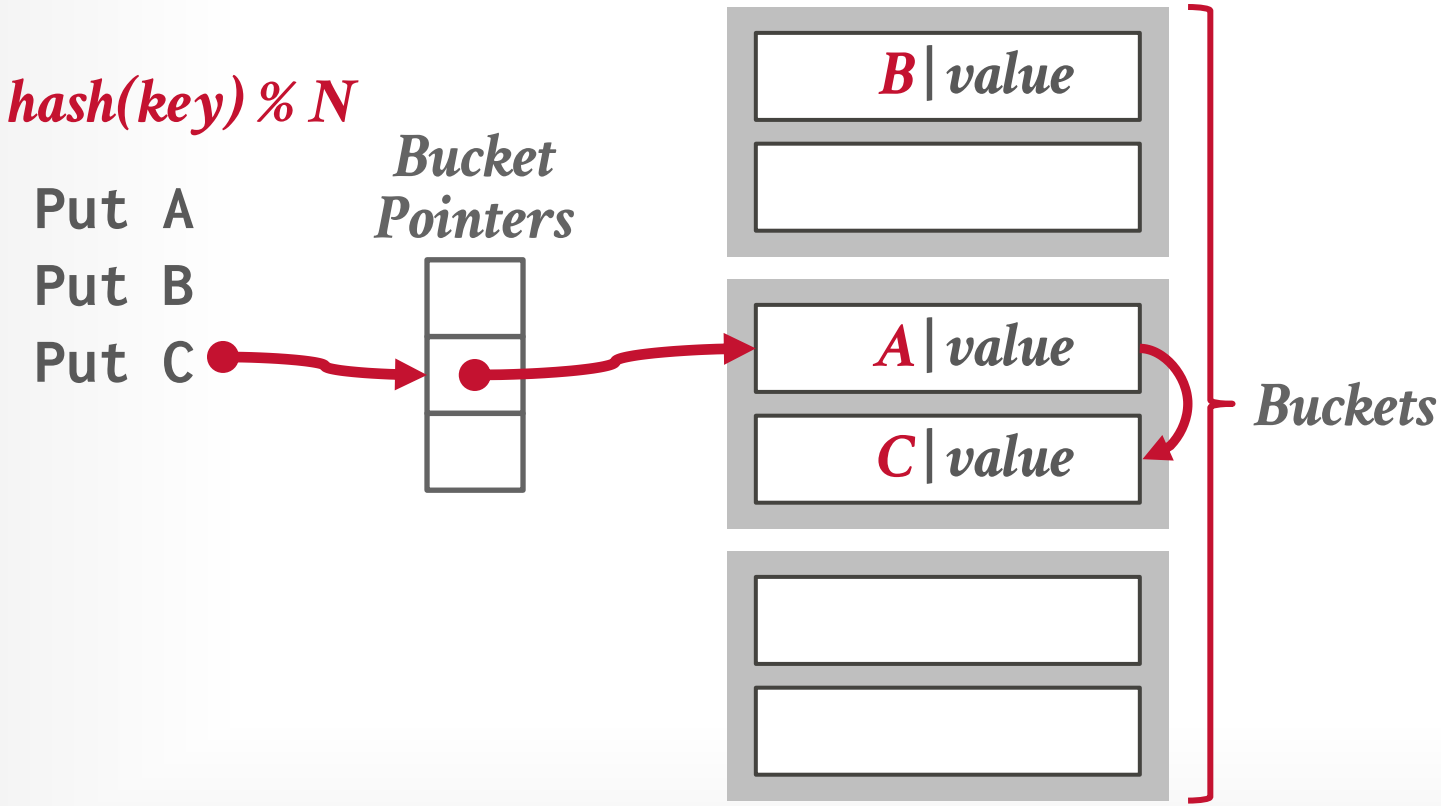
CHAINED HASHING



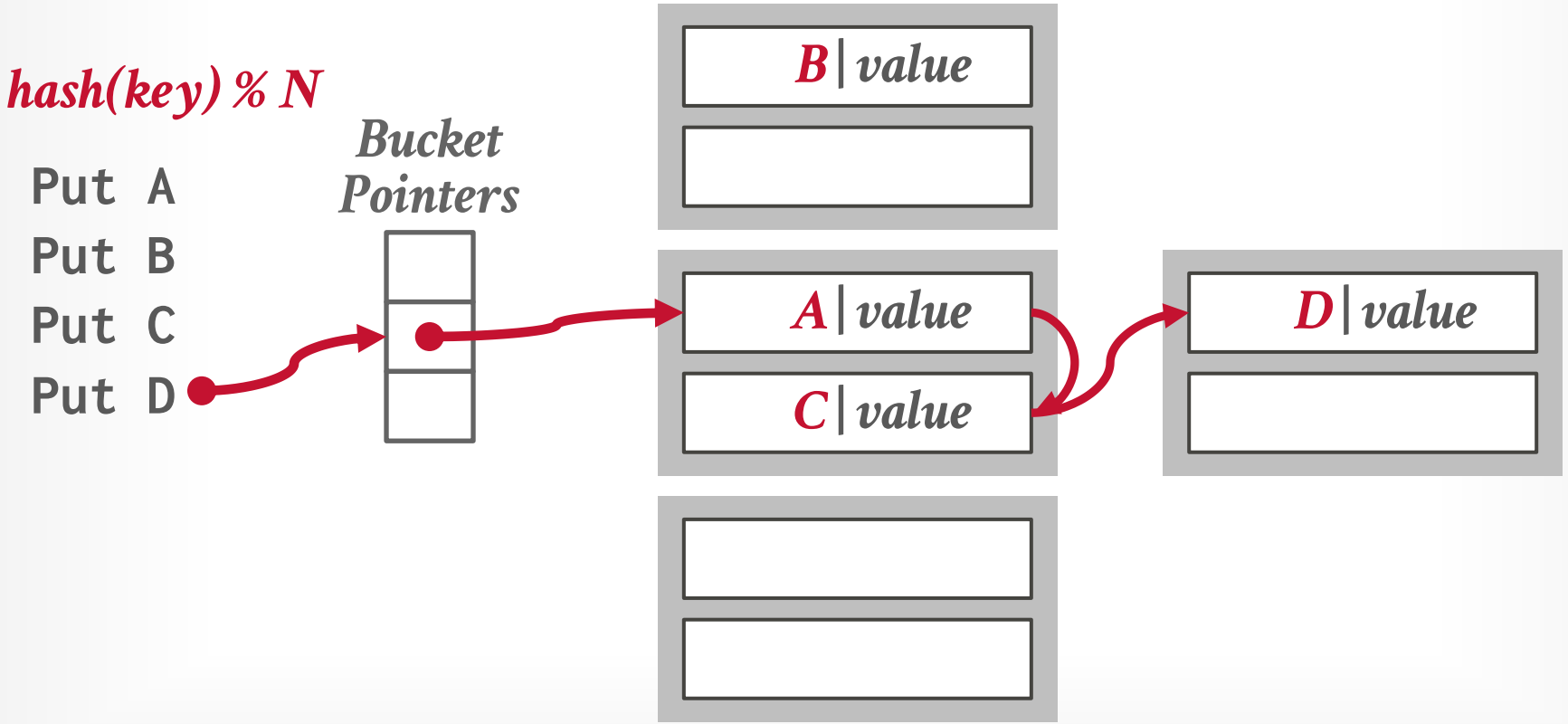
CHAINED HASHING



CHAINED HASHING



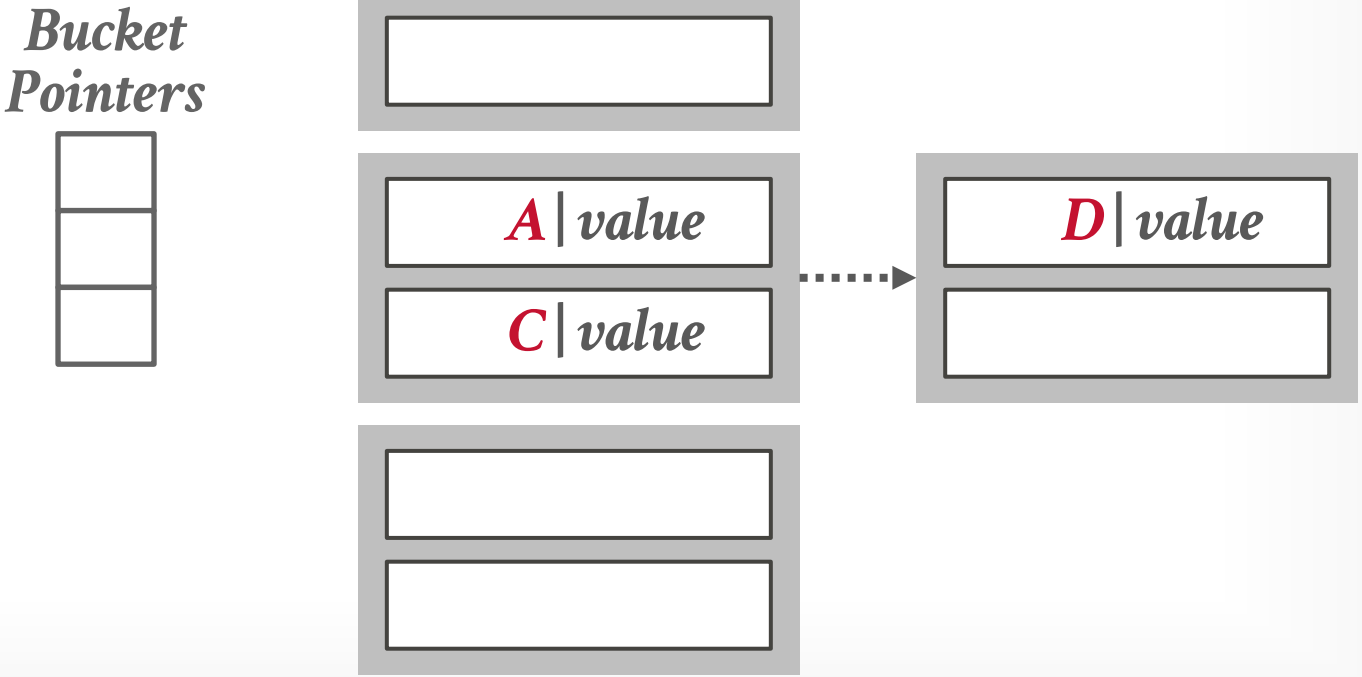
CHAINED HASHING



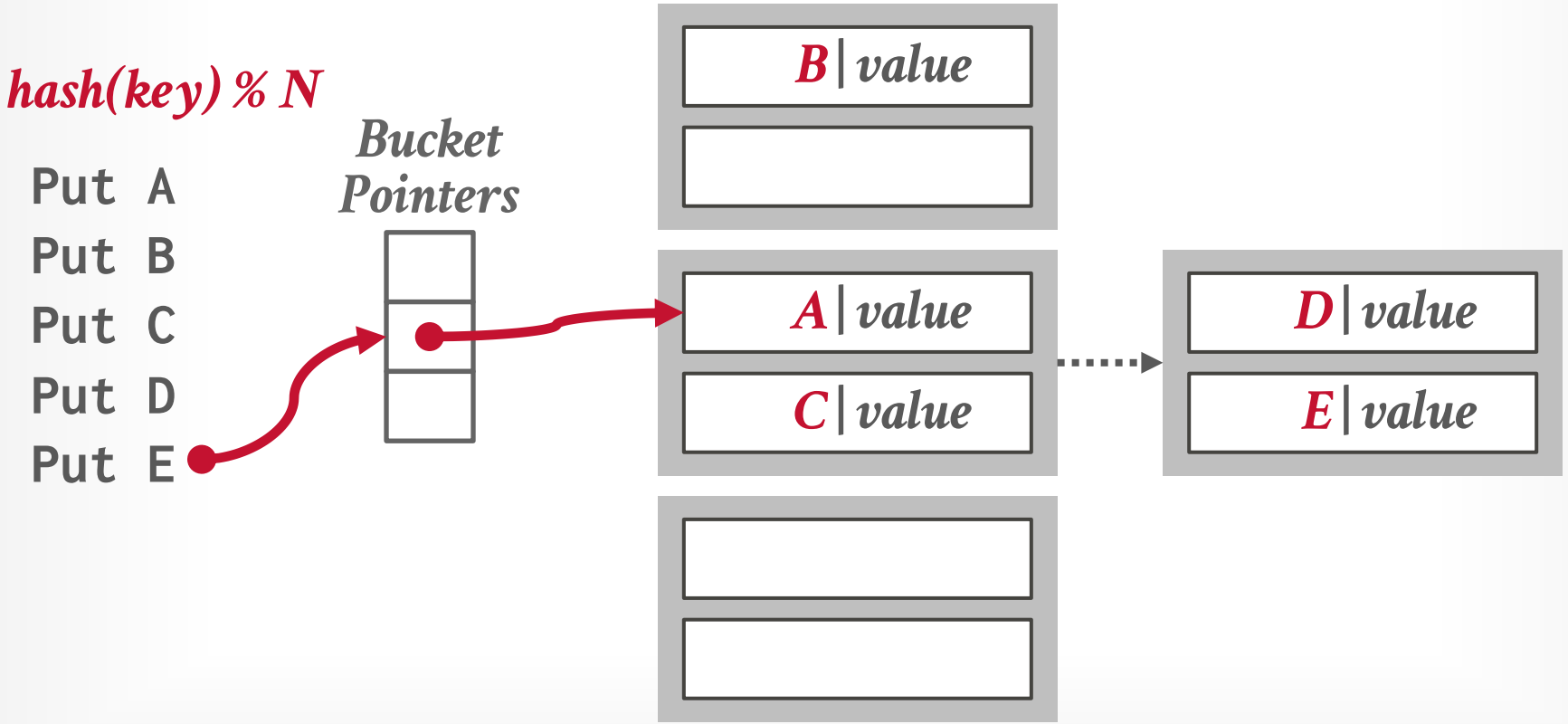
CHAINED HASHING

hash(key) % N

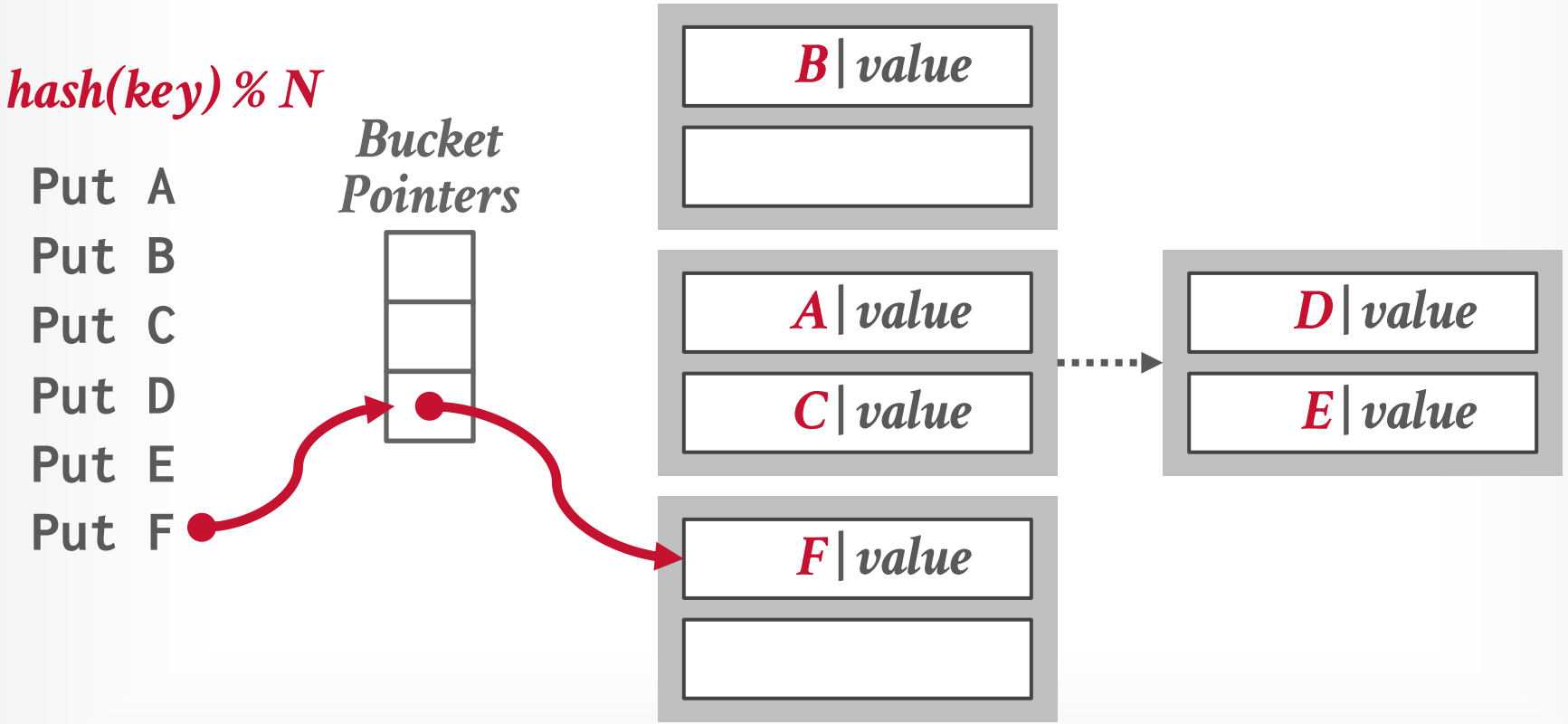
Put A
Put B
Put C
Put D
Put E



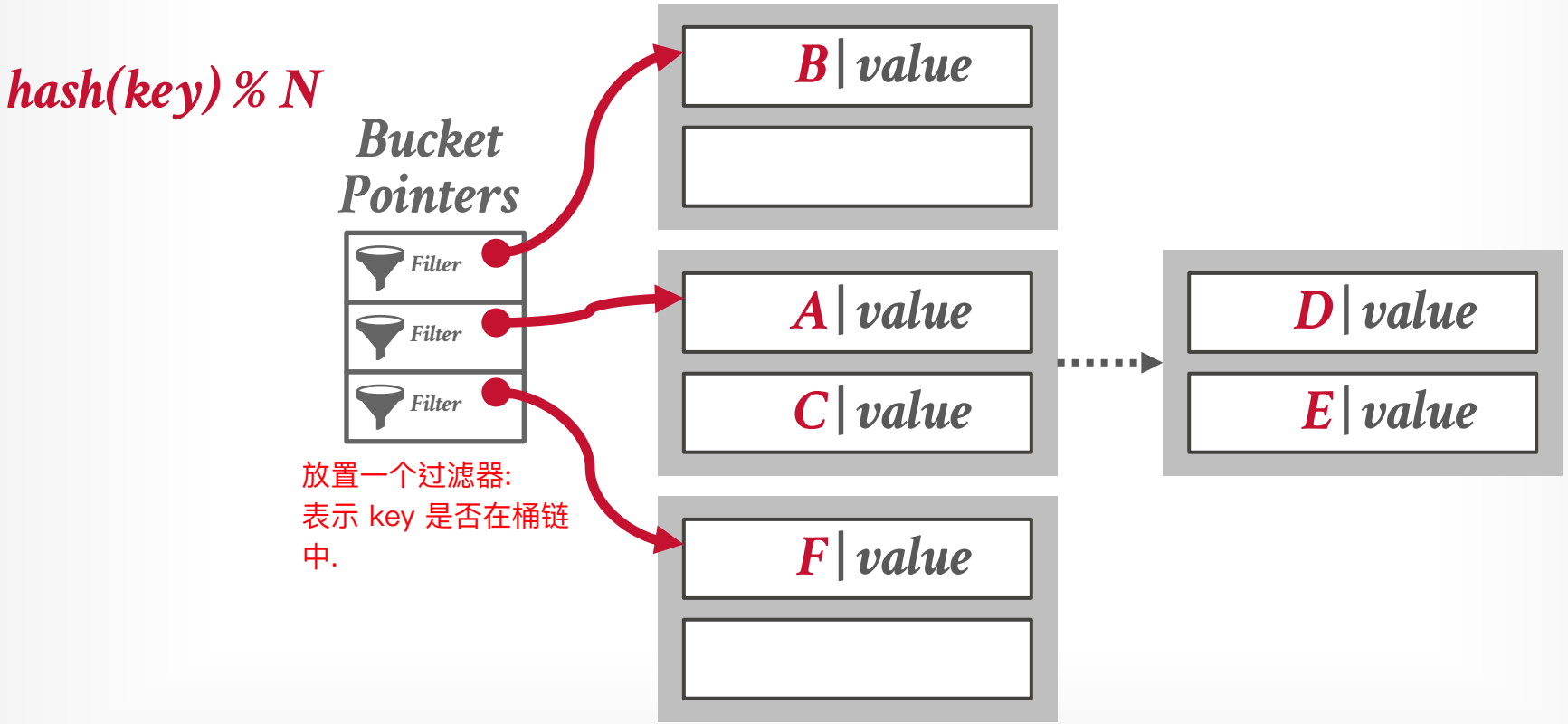
CHAINED HASHING



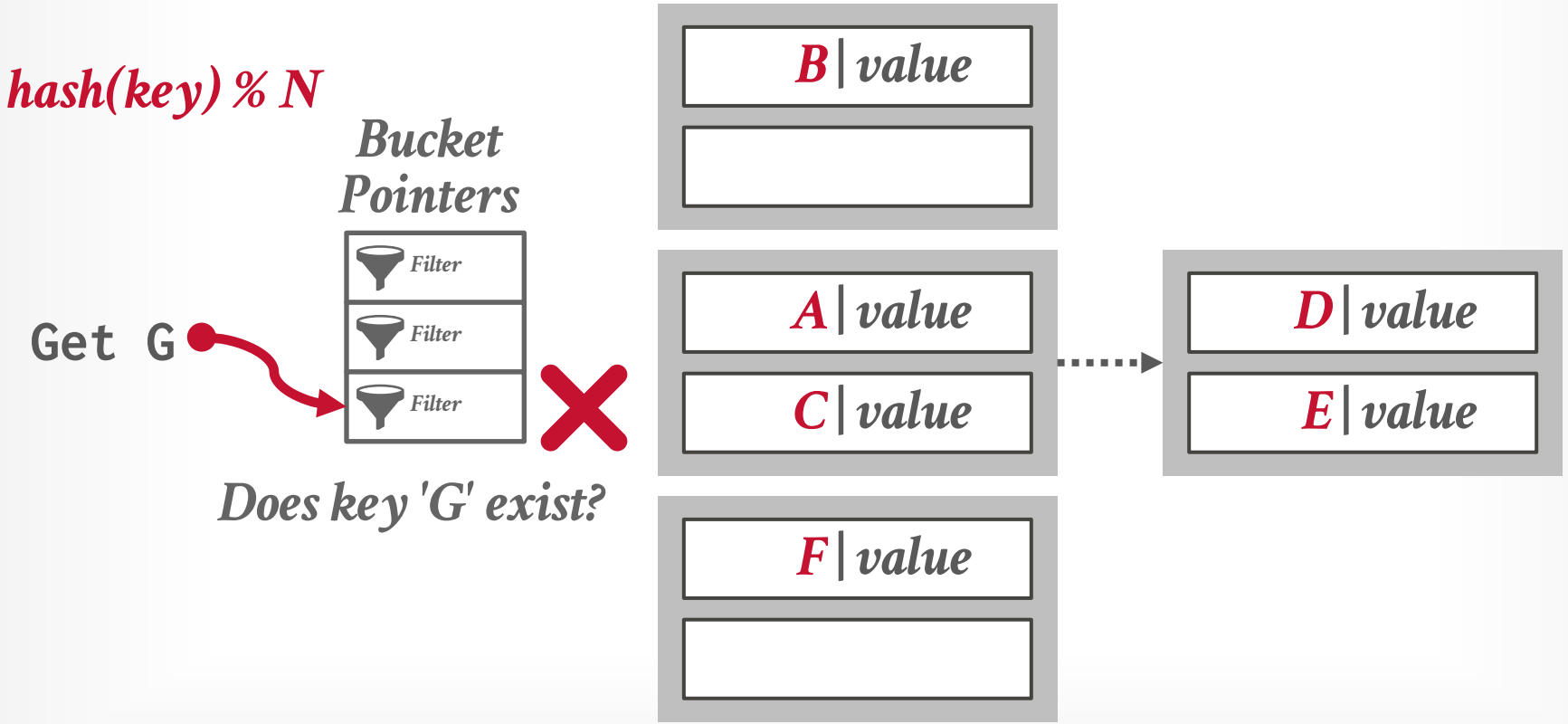
CHAINED HASHING



CHAINED HASHING



CHAINED HASHING



EXTENDIBLE HASHING

链式哈希表可能会无限增长, 存在数据倾斜的问题, 这导致数据插入或查找会退化为线性扫描.

Chained-hashing approach that splits buckets incrementally instead of letting the linked list grow forever.

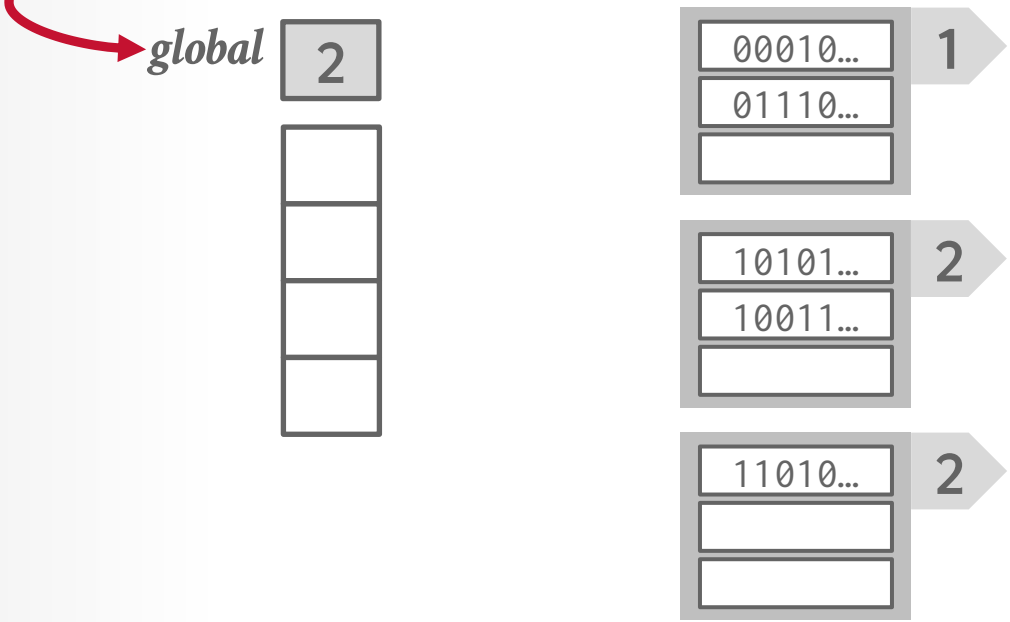
Multiple slot locations can point to the same bucket chain.

Reshuffle bucket entries on split and increase the number of bits to examine. 仅分割溢出的桶链表空间.

→ Data movement is localized to just the split chain.

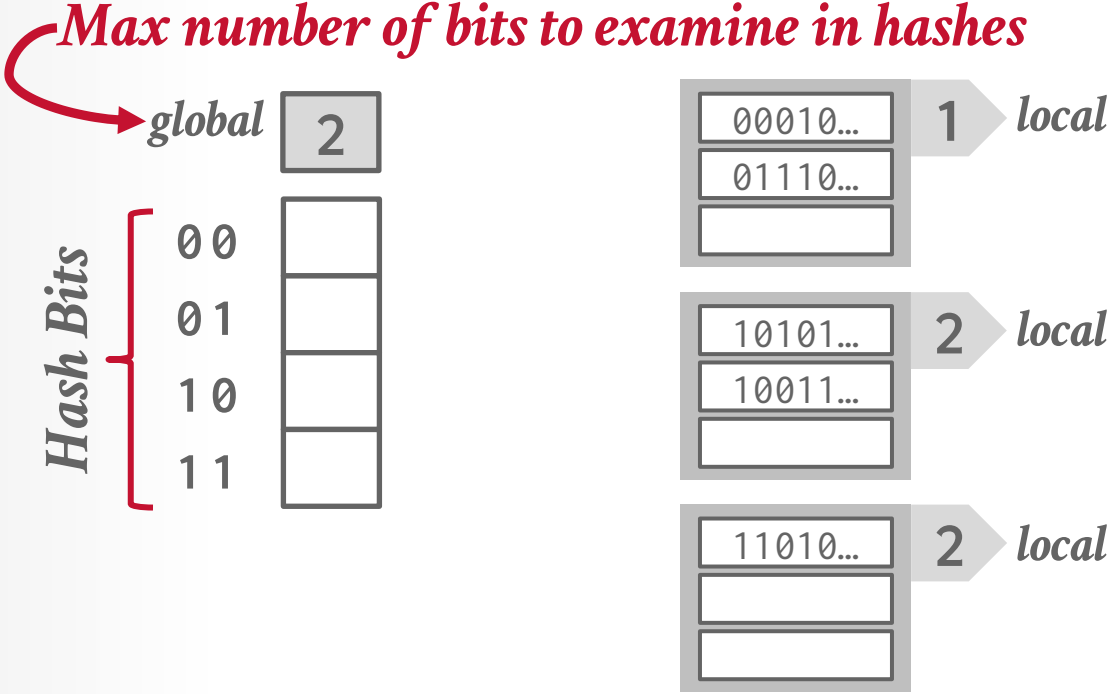
EXTENDIBLE HASHING

Max number of bits to examine in hashes

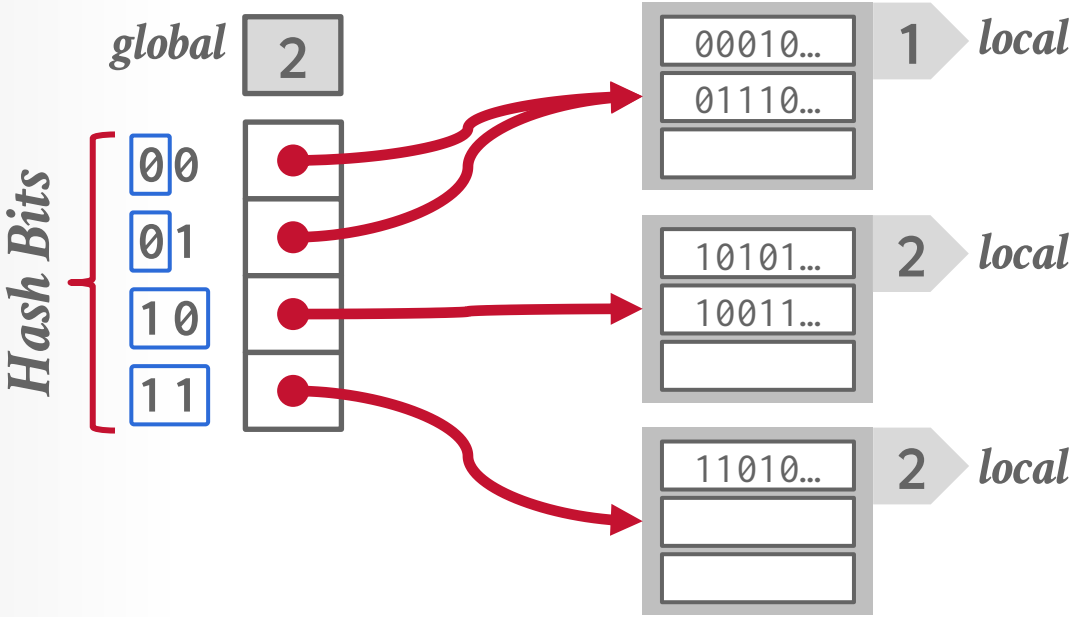


EXTENDIBLE HASHING

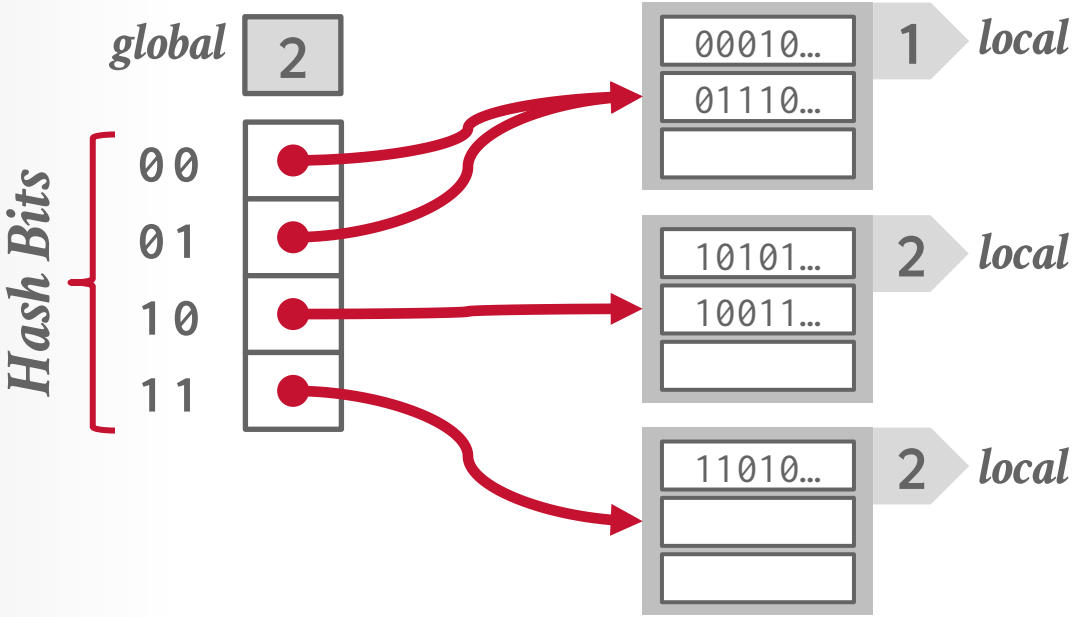
Max number of bits to examine in hashes



EXTENDIBLE HASHING



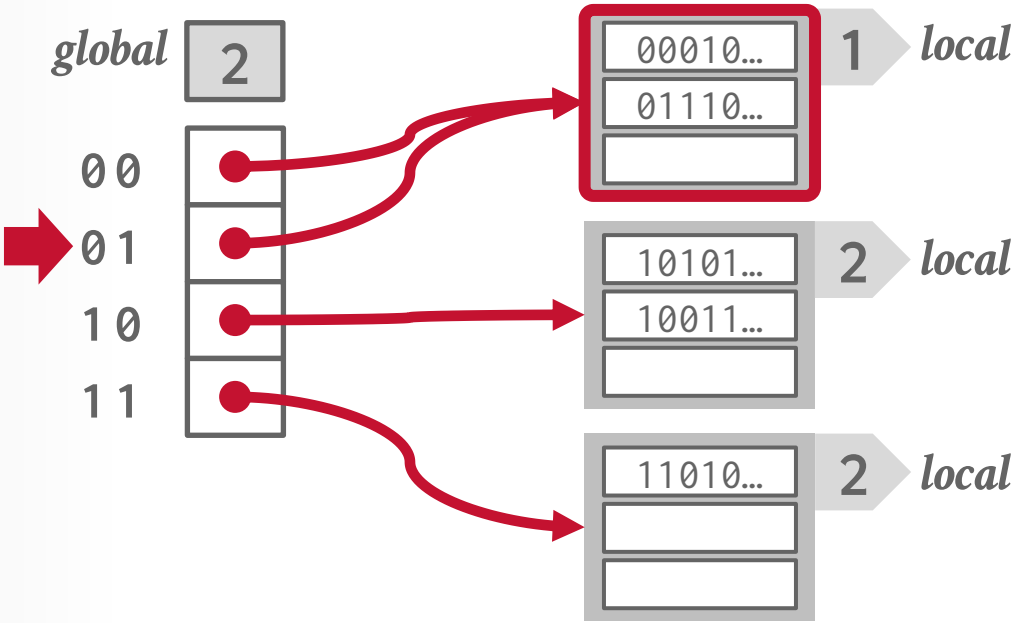
EXTENDIBLE HASHING



Get A

hash(A) = 01110...

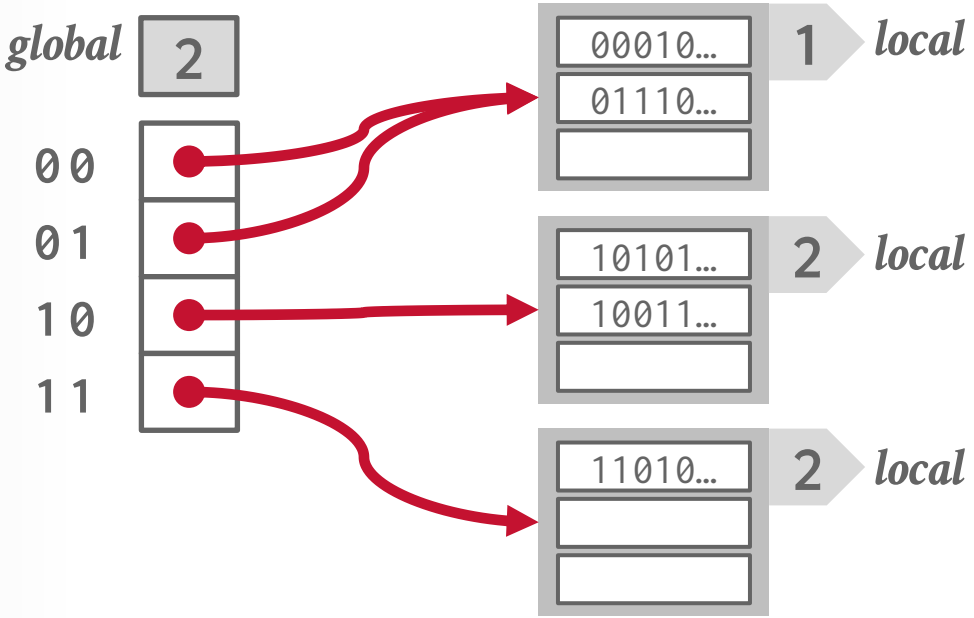
EXTENDIBLE HASHING



Get A

hash(A) = 01110...

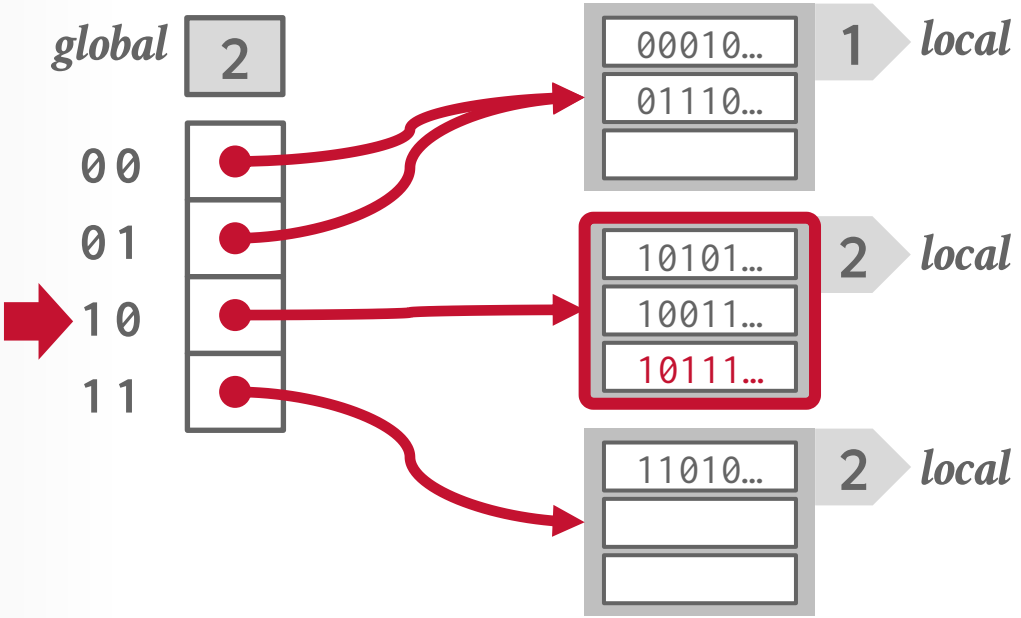
EXTENDIBLE HASHING



Get A
hash(A) = 01110...

Put B
hash(B) = 10111...

EXTENDIBLE HASHING



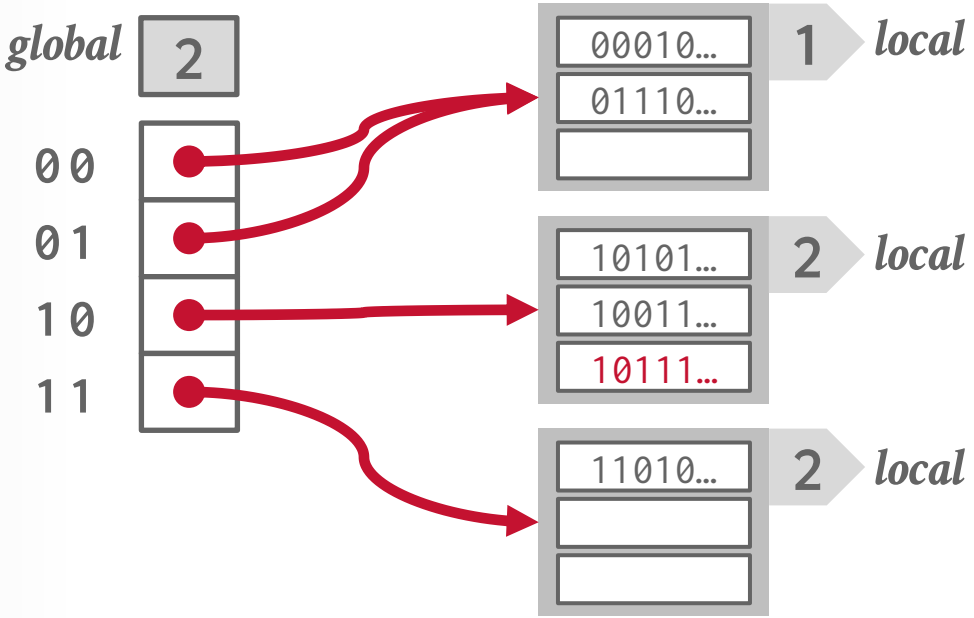
Get A

hash(A) = 01110...

Put B

hash(B) = 10111...

EXTENDIBLE HASHING

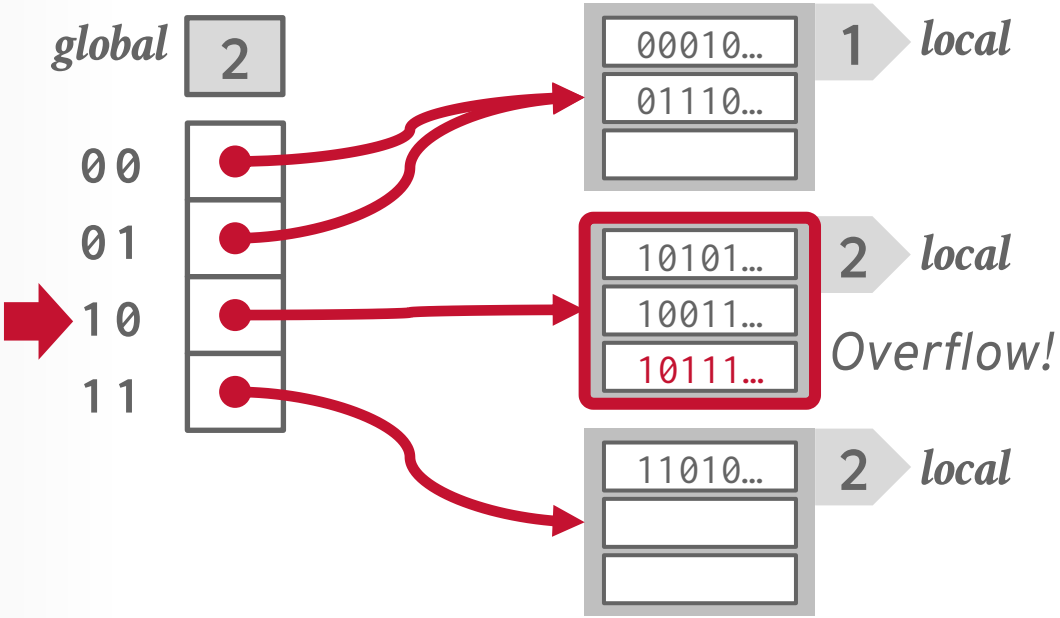


Get A
hash(A) = 01110...

Put B
hash(B) = 10111...

Put C
hash(C) = 10100...

EXTENDIBLE HASHING

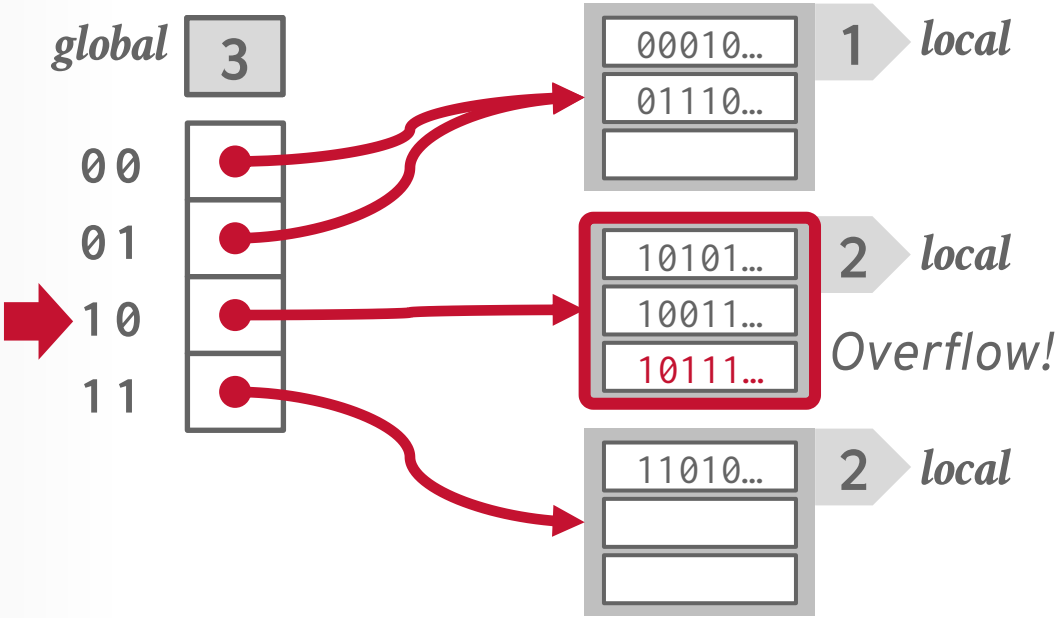


Get A
hash(A) = 01110...

Put B
hash(B) = 10111...

Put C
hash(C) = 10100...

EXTENDIBLE HASHING

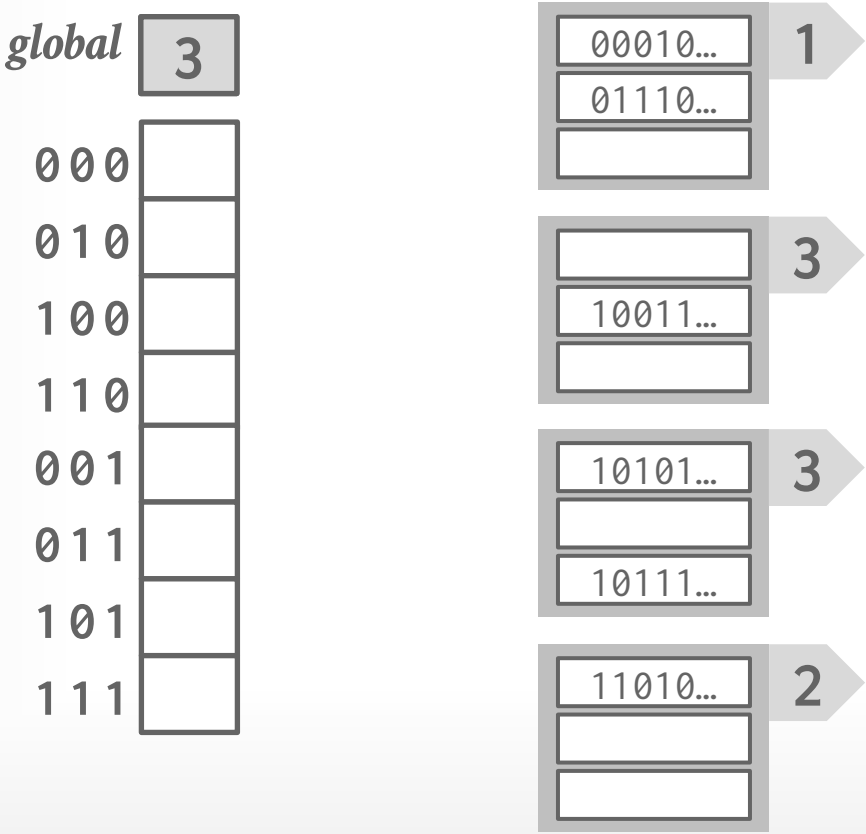


Get A
hash(A) = 01110...

Put B
hash(B) = 10111...

Put C
hash(C) = 10100...

EXTENDIBLE HASHING

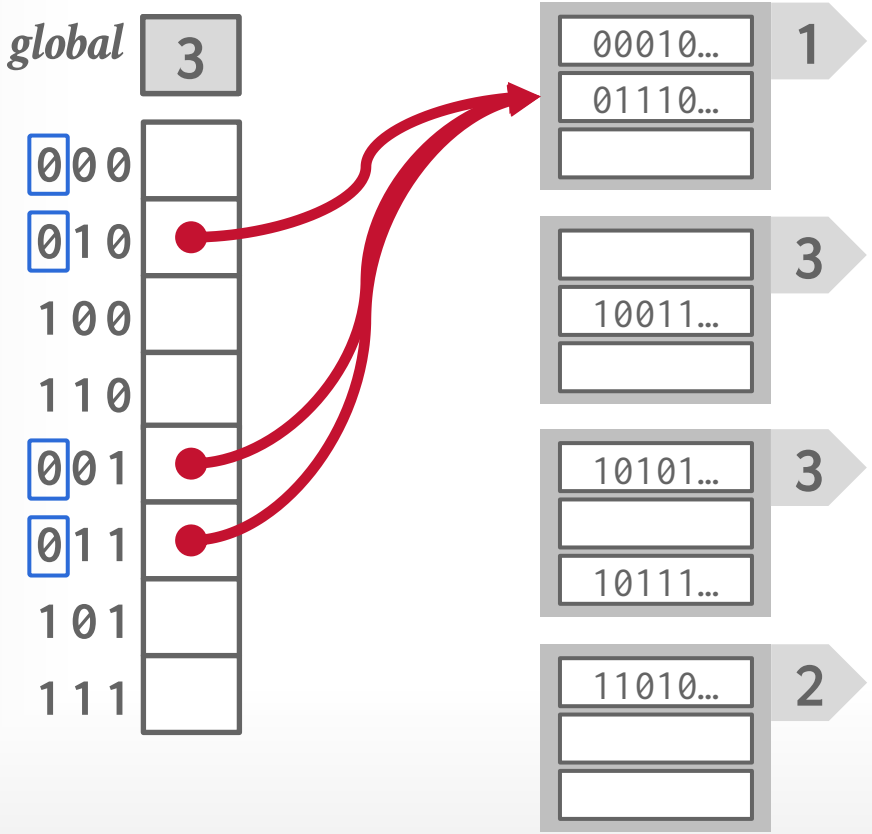


Get A
hash(A) = 01110...

Put B
hash(B) = 10111...

Put C
hash(C) = 10100...

EXTENDIBLE HASHING

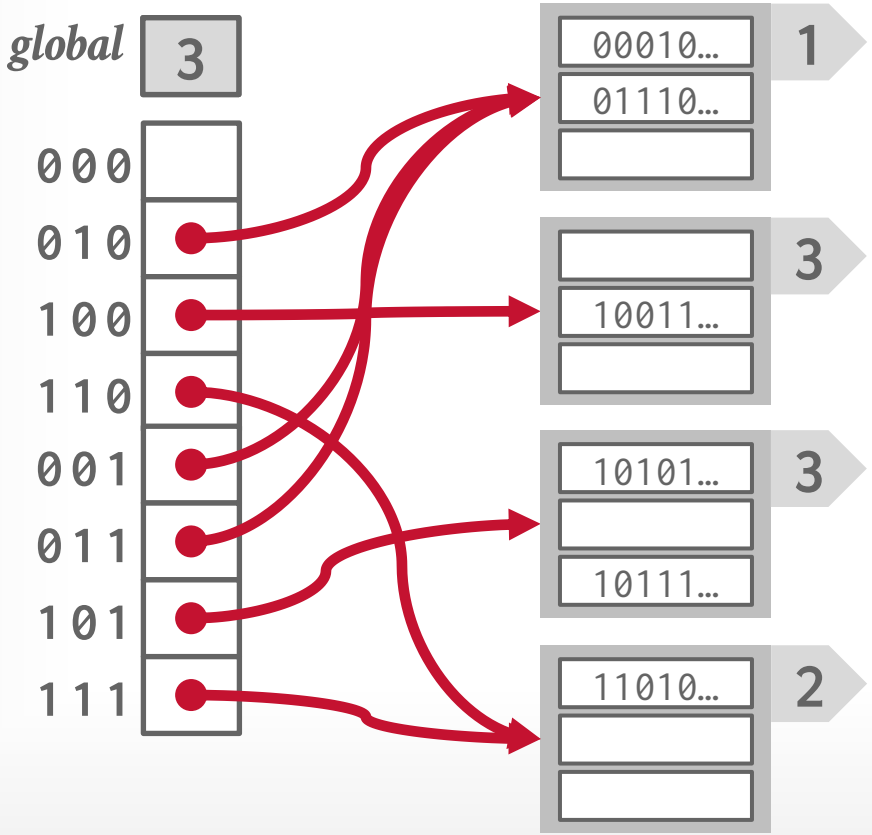


Get A
hash(A) = 01110...

Put B
hash(B) = 10111...

Put C
hash(C) = 10100...

EXTENDIBLE HASHING

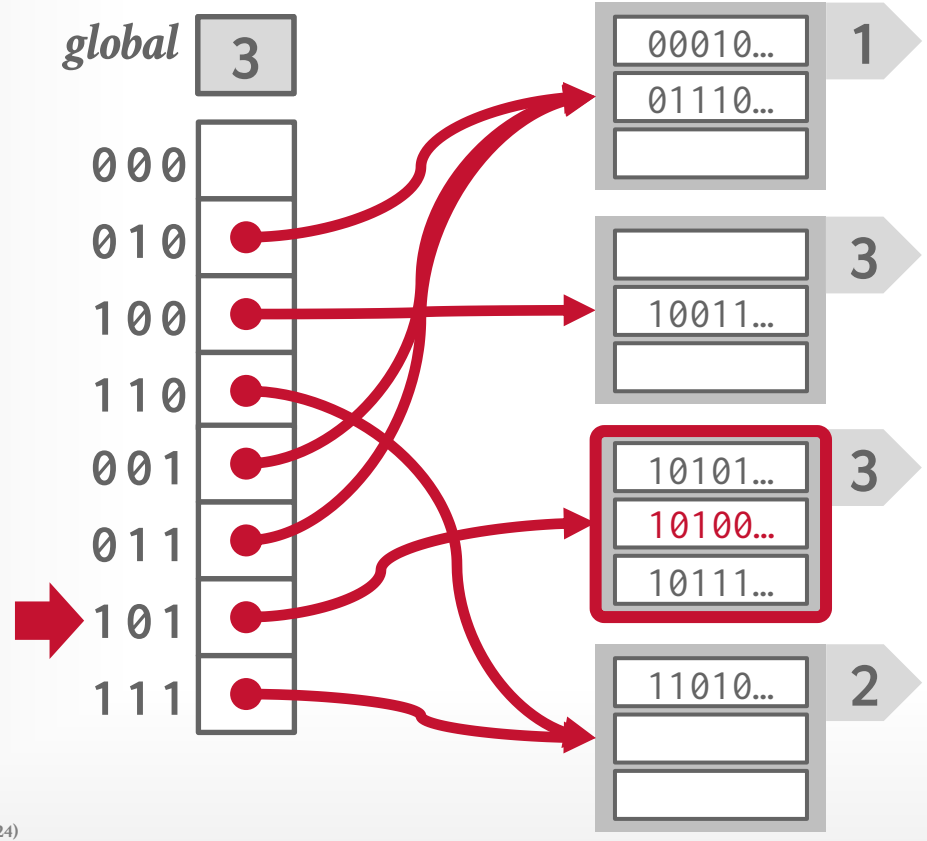


Get A
hash(A) = 01110...

Put B
hash(B) = 10111...

Put C
hash(C) = 10100...

EXTENDIBLE HASHING



Get A
hash(A) = 01110...

Put B
hash(B) = 10111...

Put C
hash(C) = 10100...

LINEAR HASHING

维护一个分割指针: 当某个桶溢出时, 从分割指针当前所指位置开始重新分割所有桶链.

The hash table maintains a pointer that tracks the next bucket to split.

→ When any bucket overflows, split the bucket at the pointer location.

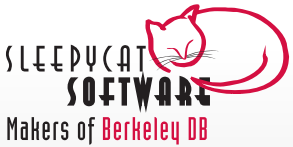
Use multiple hashes to find the right bucket for a given key.

Can use different overflow criterion:

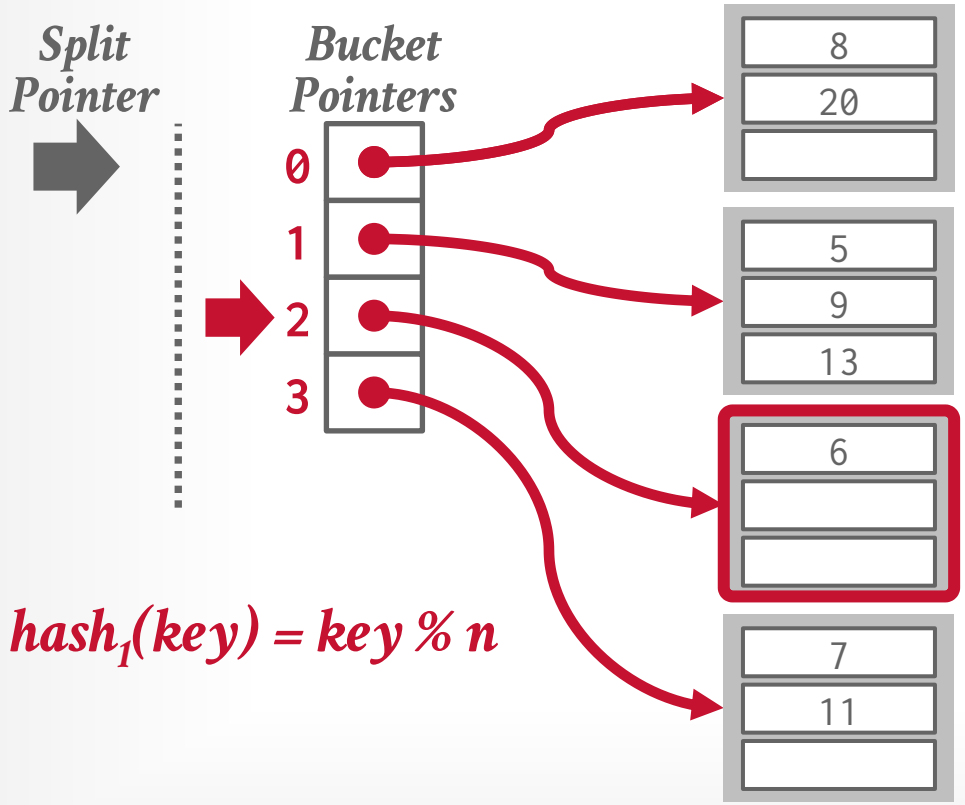
→ Space Utilization

→ Average Length of Overflow Chains

Postgres 在 dynahash.c 文件实现这个方法.



LINEAR HASHING

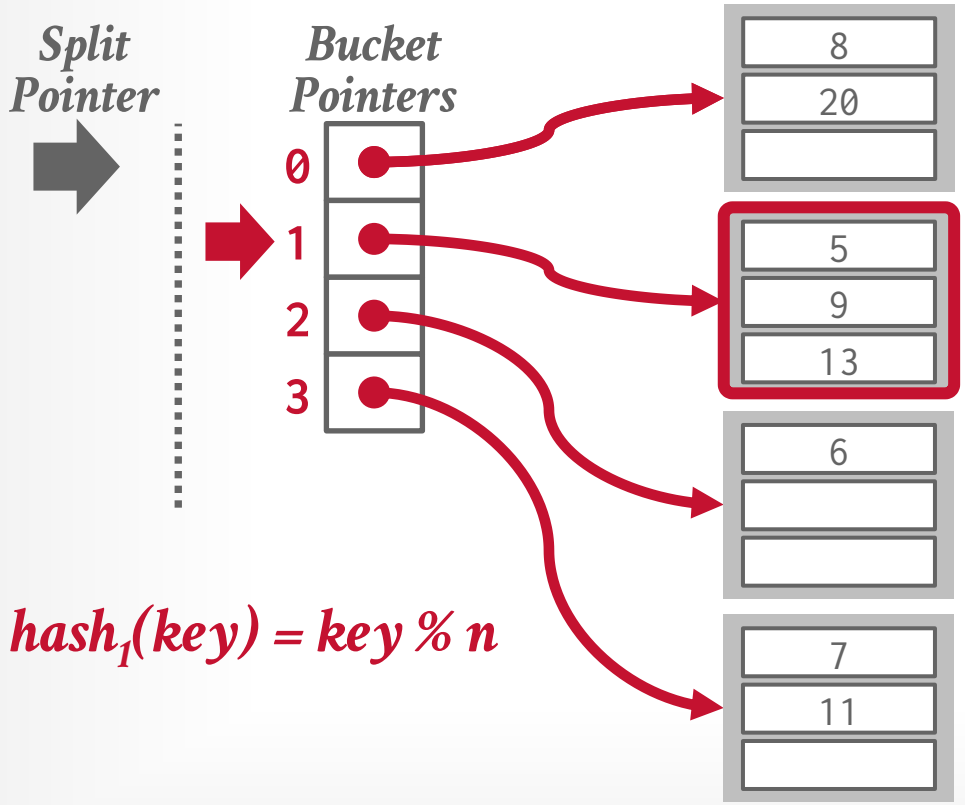


$hash_1(key) = key \% n$

Get 6

$hash_1(6) = 6 \% 4 = 2$

LINEAR HASHING



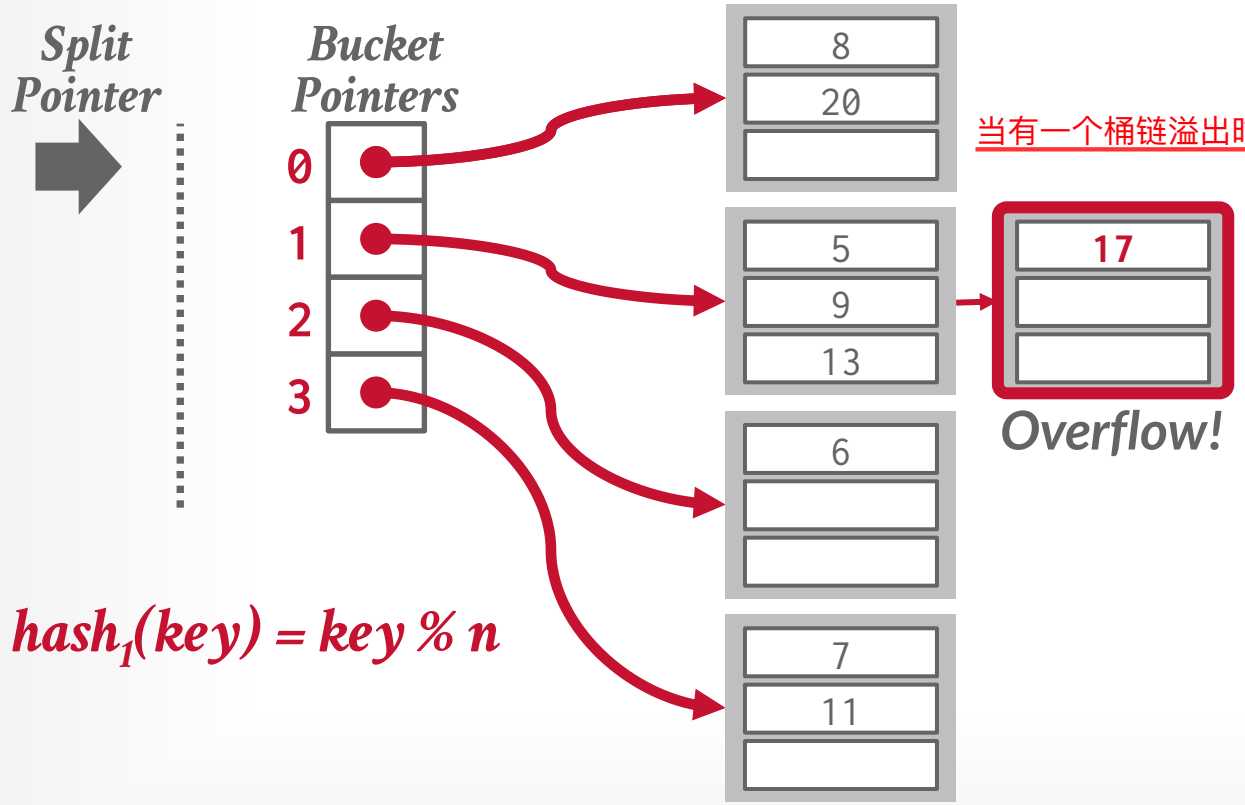
Get 6

$hash_1(6) = 6 \% 4 = 2$

Put 17

$hash_1(17) = 17 \% 4 = 1$

LINEAR HASHING



$hash_1(key) = key \% n$

Get 6

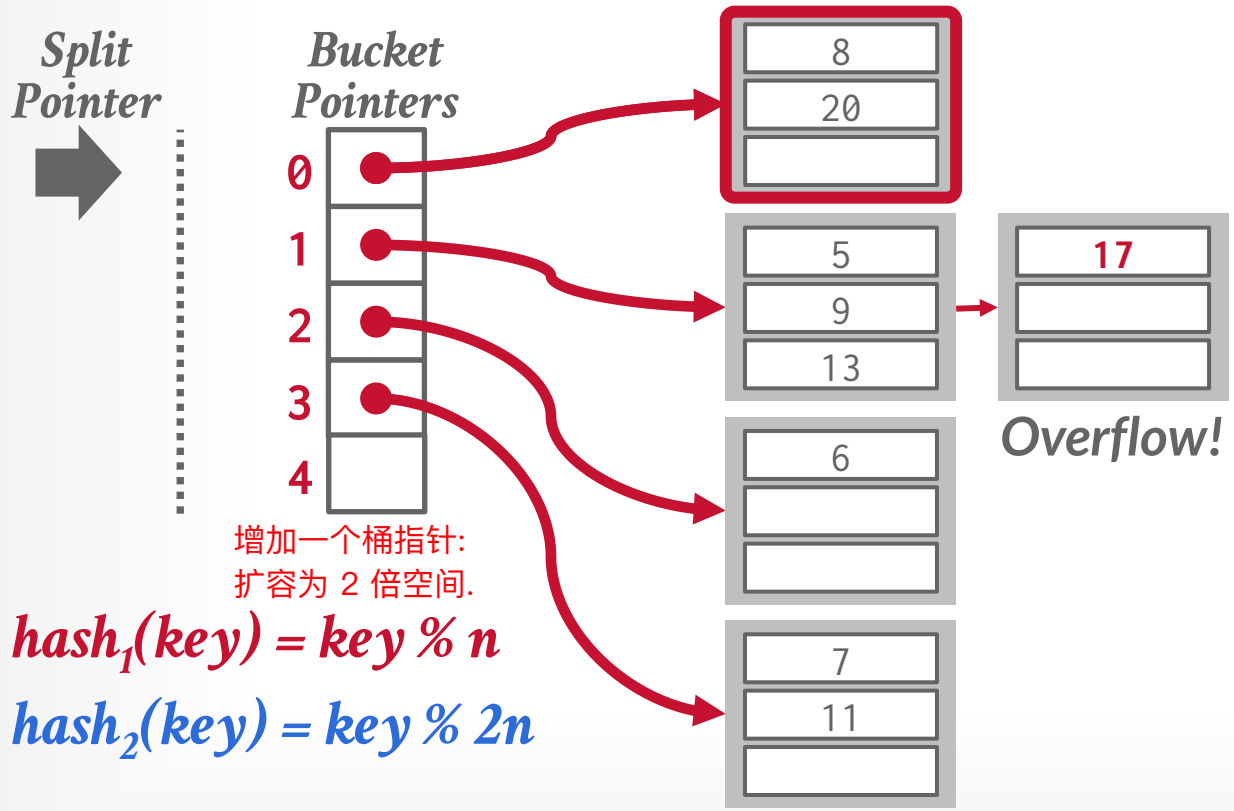
$hash_1(6) = 6 \% 4 = 2$

当有一个桶链溢出时，分割指针开始重新划分桶链.

Put 17

$hash_1(17) = 17 \% 4 = 1$

LINEAR HASHING



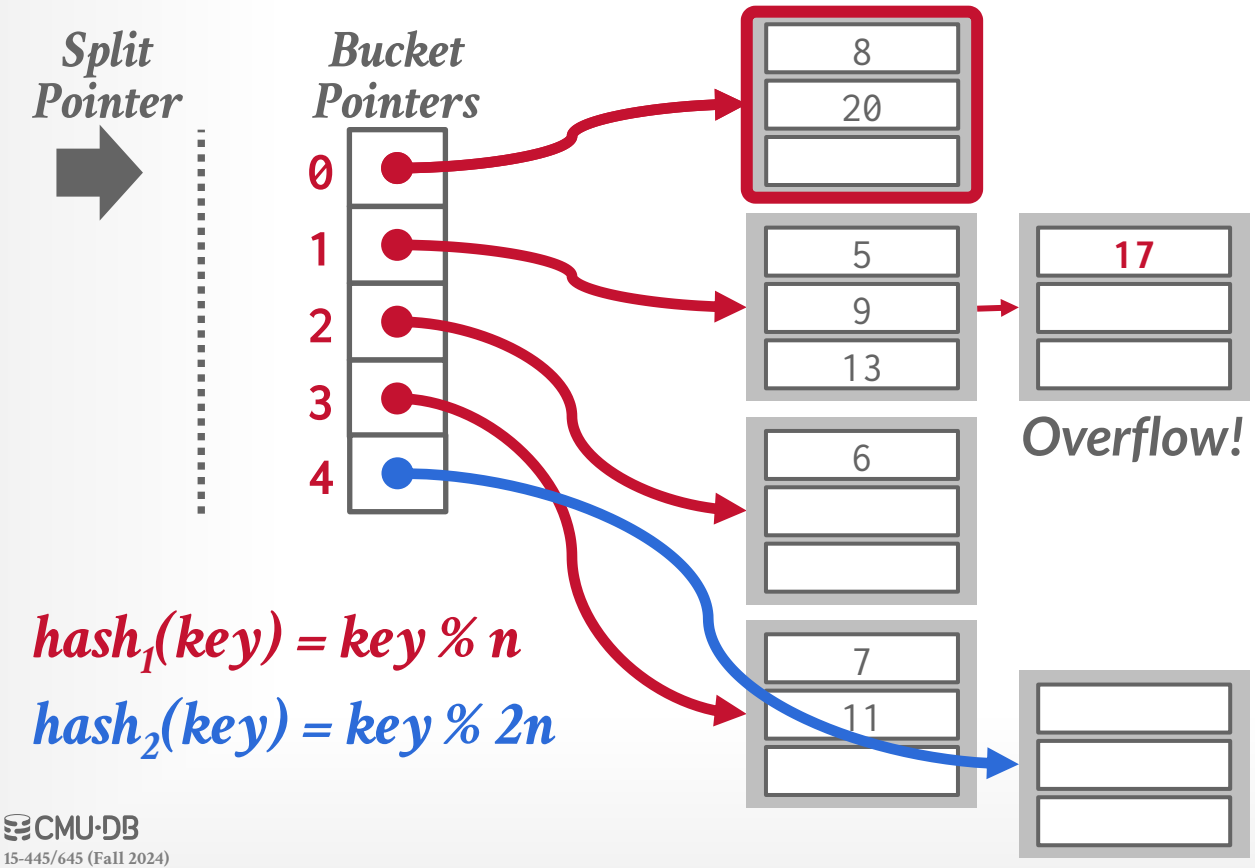
Get 6

$hash_1(6) = 6 \% 4 = 2$

Put 17

$hash_1(17) = 17 \% 4 = 1$

LINEAR HASHING



$hash_1(key) = key \% n$

$hash_2(key) = key \% 2n$

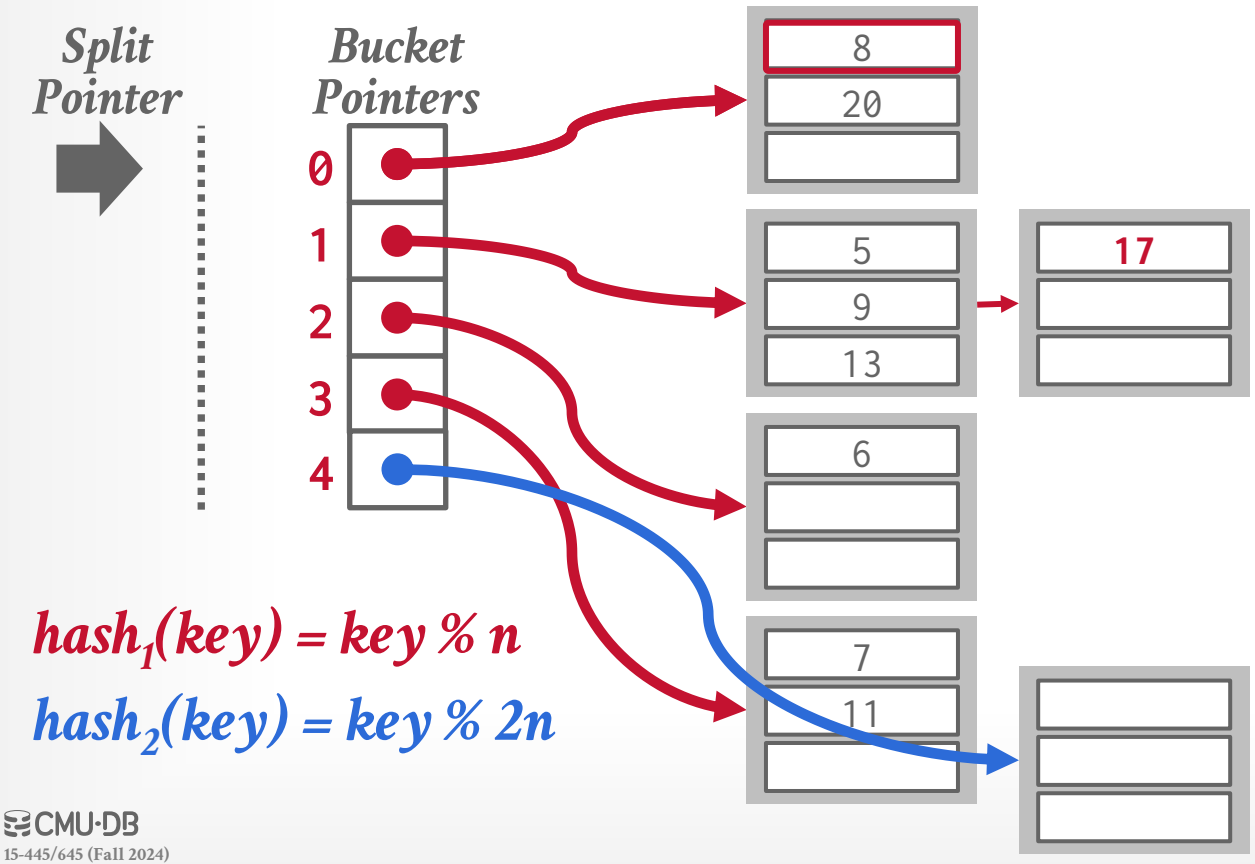
Get 6

$hash_1(6) = 6 \% 4 = 2$

Put 17

$hash_1(17) = 17 \% 4 = 1$

LINEAR HASHING



Get 6

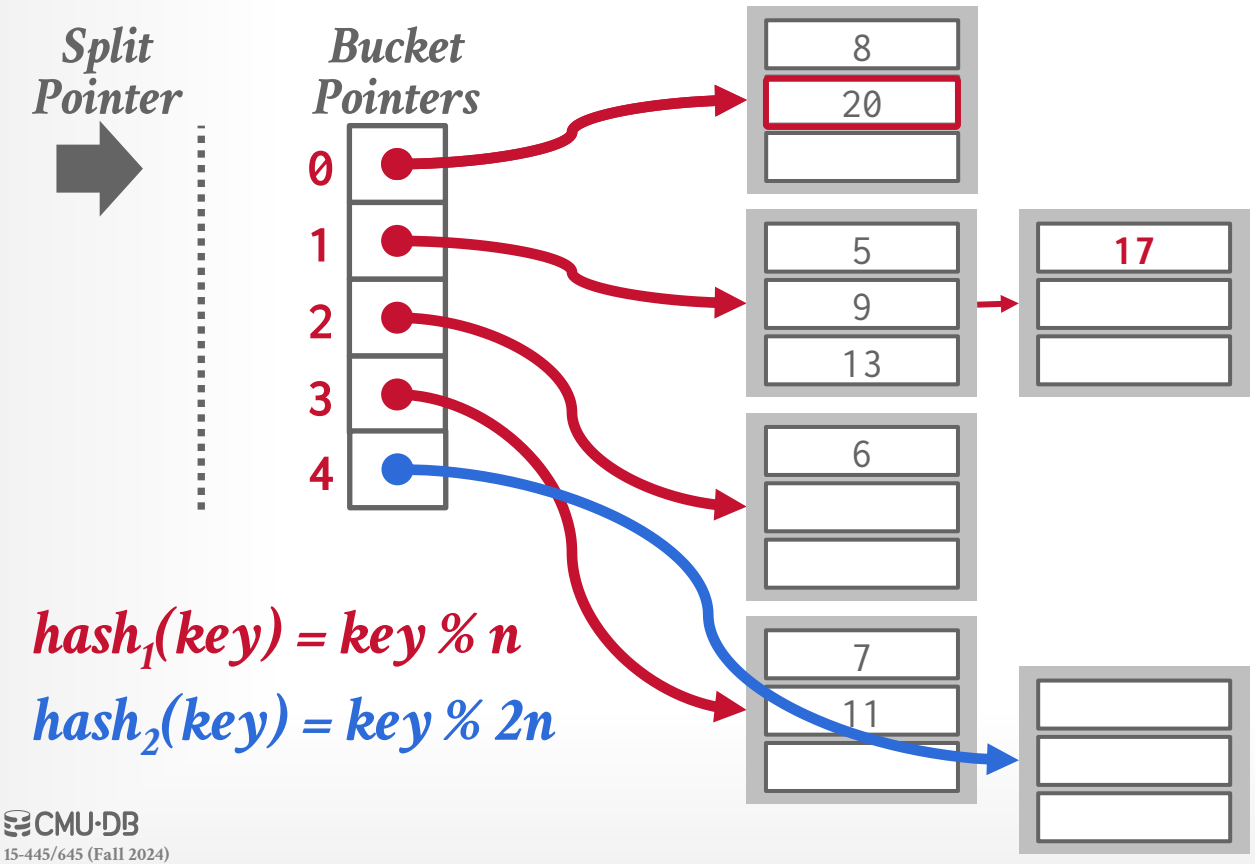
$hash_1(6) = 6 \% 4 = 2$

Put 17

$hash_1(17) = 17 \% 4 = 1$

$hash_2(8) = 8 \% 8 = 0$

LINEAR HASHING



Get 6

$hash_1(6) = 6 \% 4 = 2$

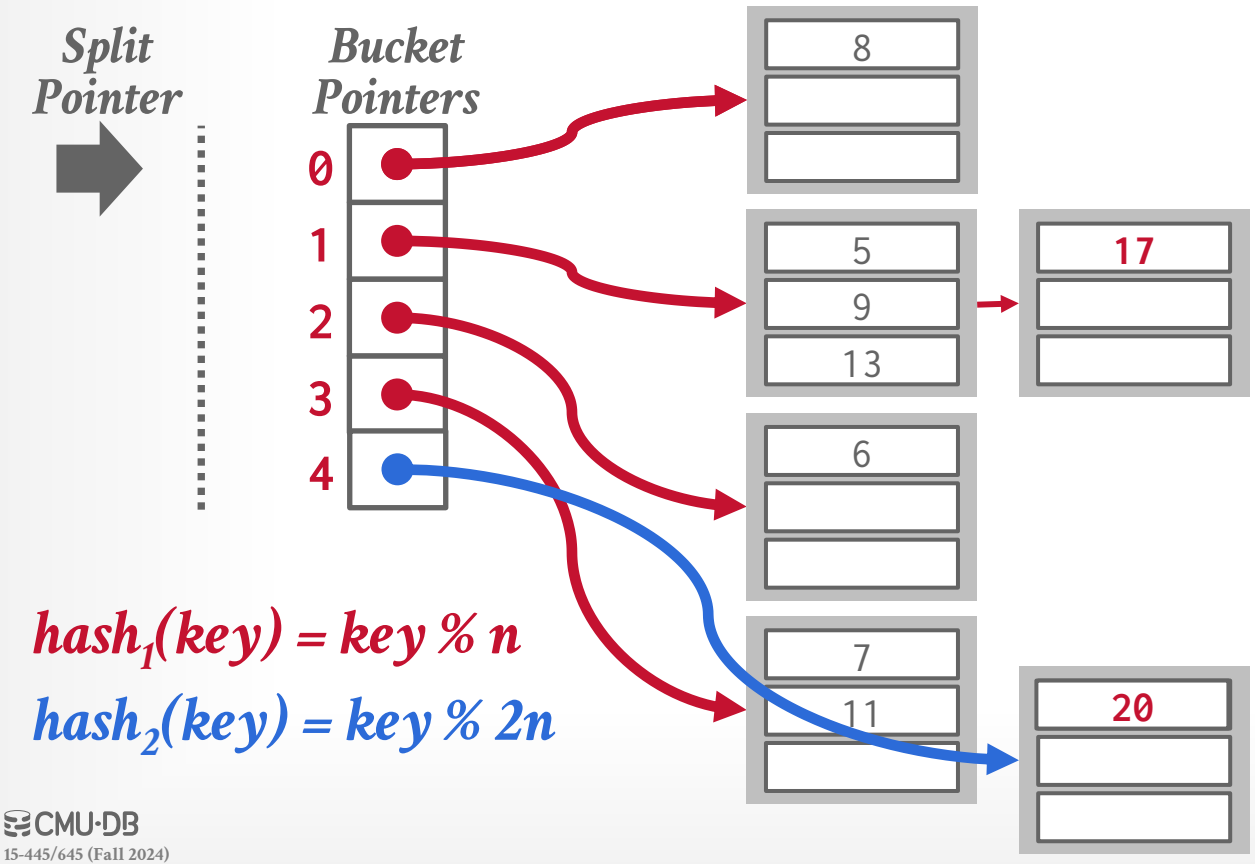
Put 17

$hash_1(17) = 17 \% 4 = 1$

$hash_2(8) = 8 \% 8 = 0$

$hash_2(20) = 20 \% 8 = 4$

LINEAR HASHING



$hash_1(key) = key \% n$

$hash_2(key) = key \% 2n$

Get 6

$hash_1(6) = 6 \% 4 = 2$

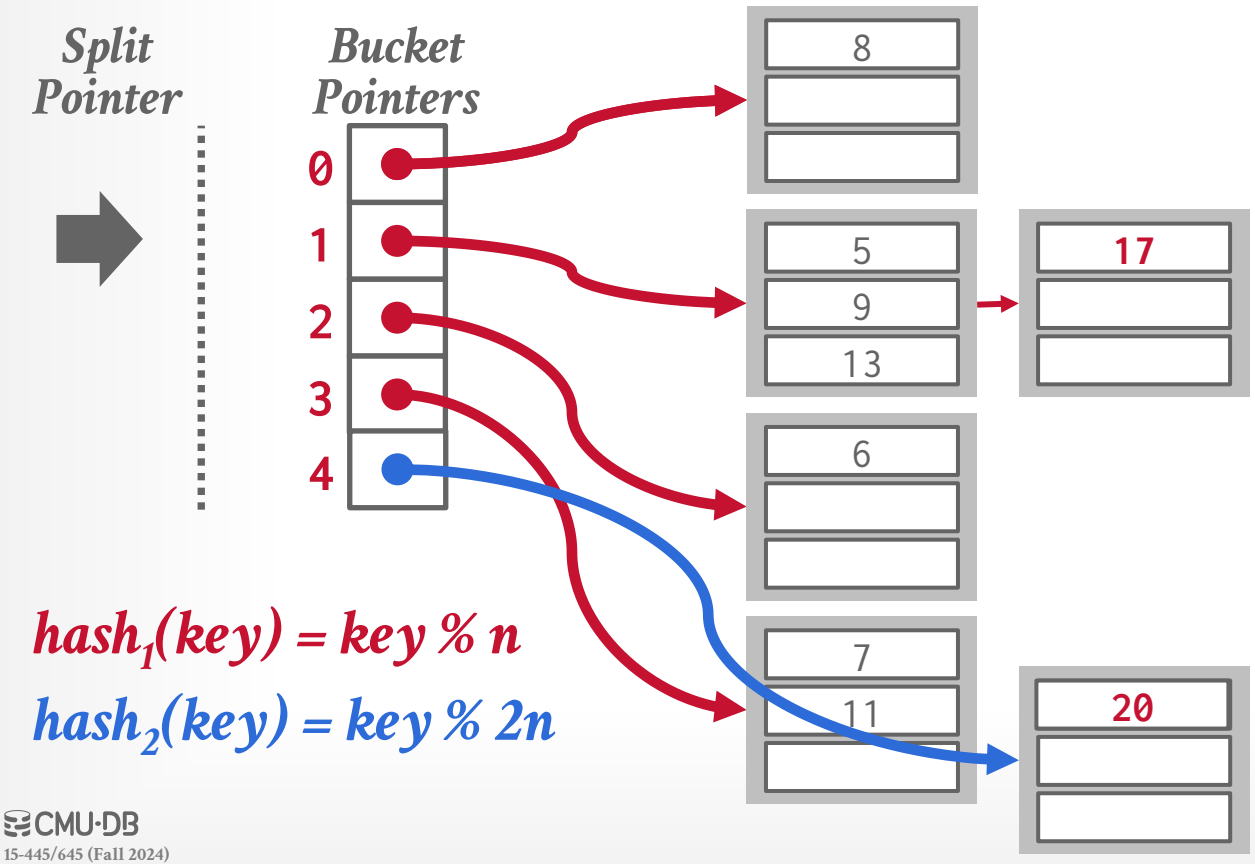
Put 17

$hash_1(17) = 17 \% 4 = 1$

$hash_2(8) = 8 \% 8 = 0$

$hash_2(20) = 20 \% 8 = 4$

LINEAR HASHING



$hash_1(key) = key \% n$

$hash_2(key) = key \% 2n$

Get 6

$hash_1(6) = 6 \% 4 = 2$

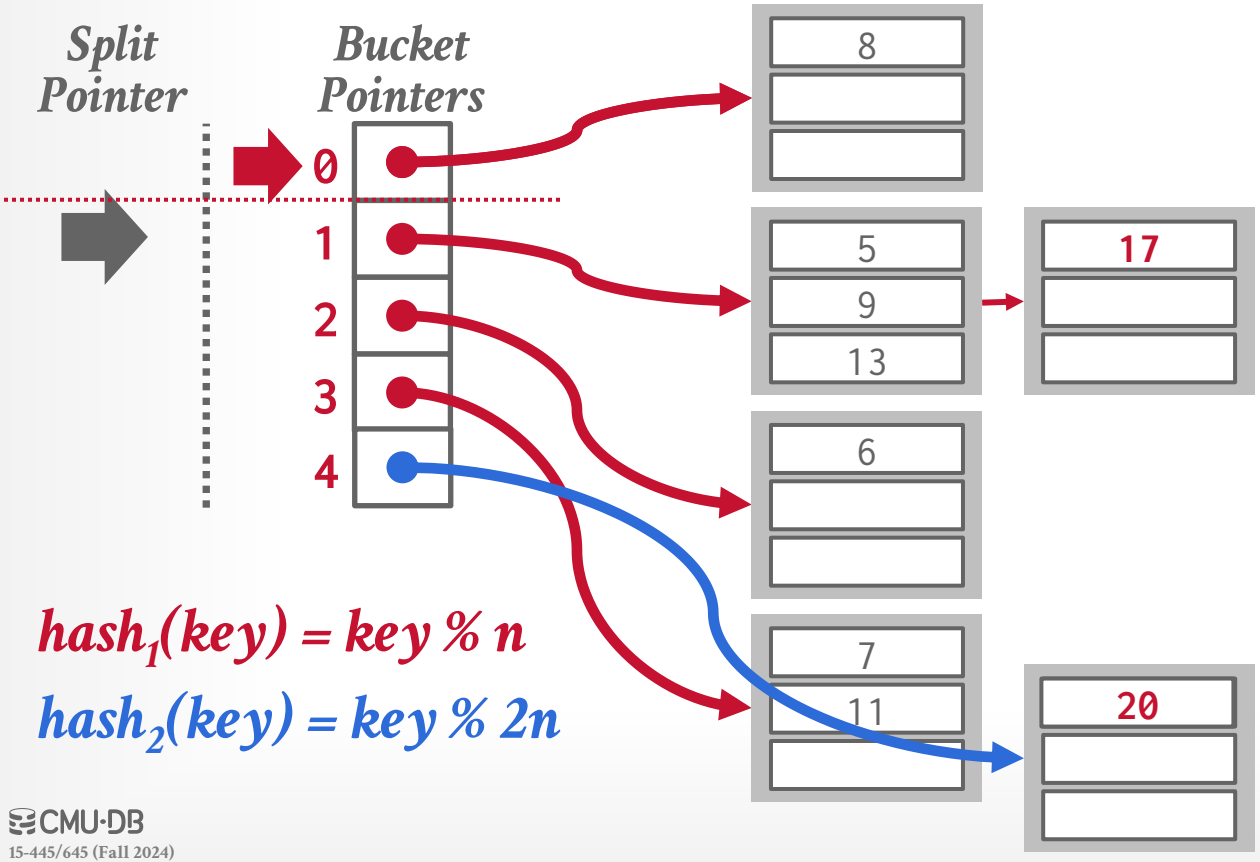
Put 17

$hash_1(17) = 17 \% 4 = 1$

$hash_2(8) = 8 \% 8 = 0$

$hash_2(20) = 20 \% 8 = 4$

LINEAR HASHING



Get 6

$hash_1(6) = 6 \% 4 = 2$

Put 17

$hash_1(17) = 17 \% 4 = 1$

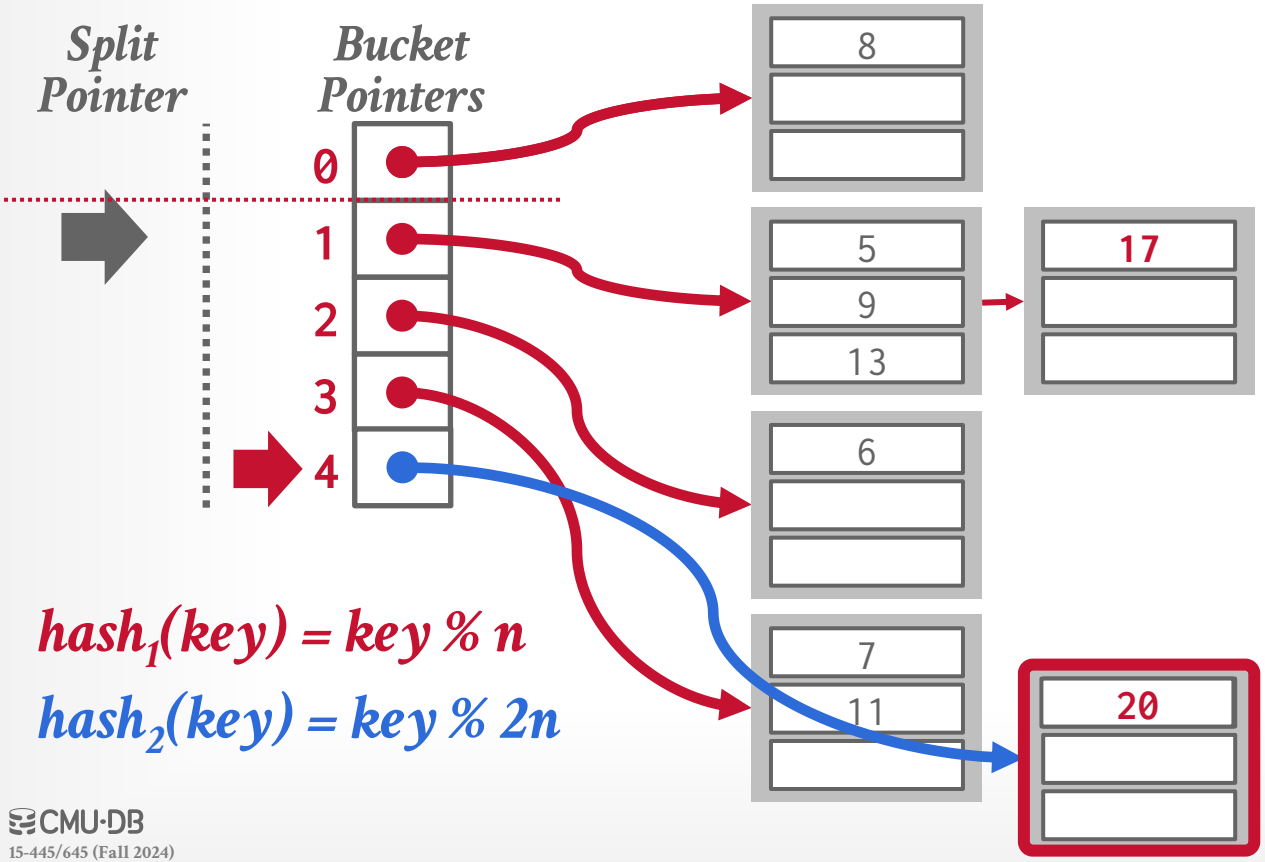
$hash_2(8) = 8 \% 8 = 0$

$hash_2(20) = 20 \% 8 = 4$

Get 20

$hash_1(20) = 20 \% 4 = 0$

LINEAR HASHING



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$hash_1(17) = 17 \% 4 = 1$

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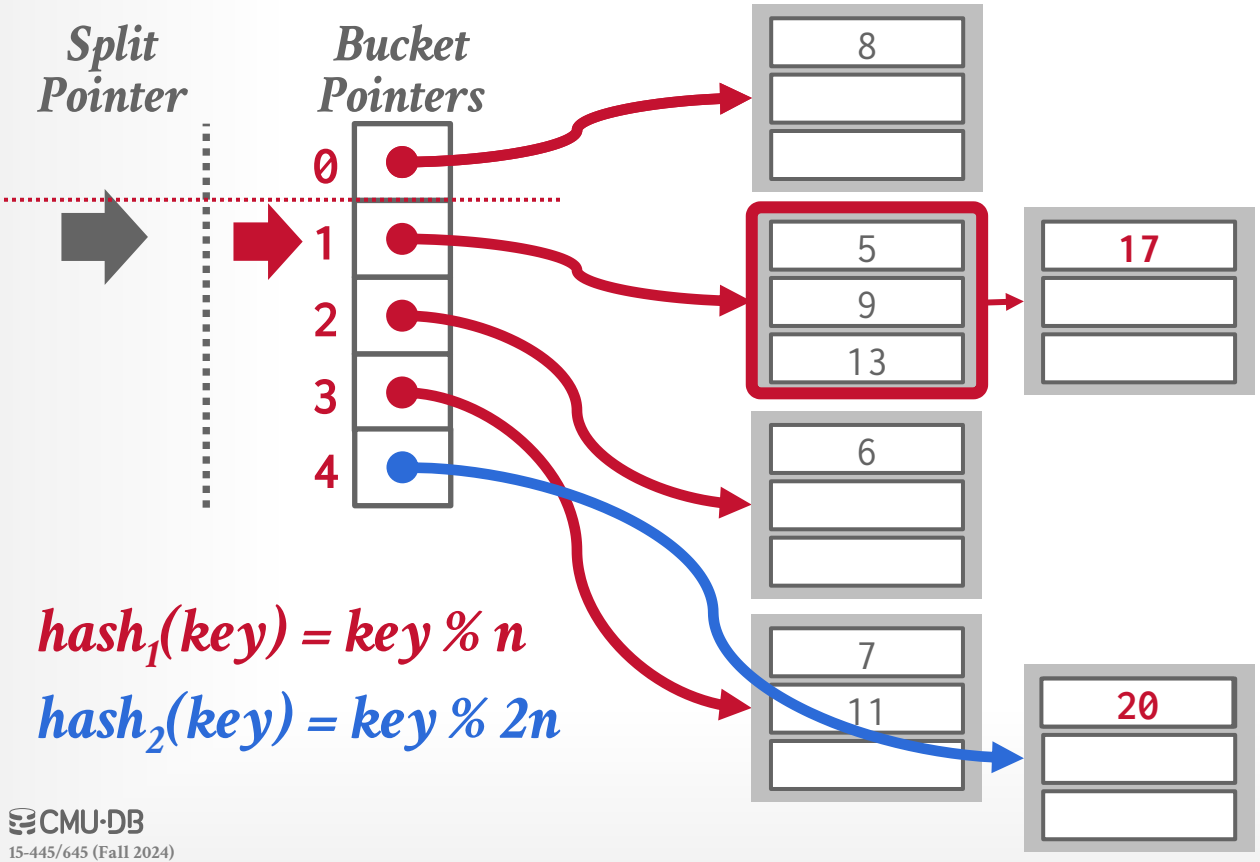
$hash_2(20) = 20 \% 8 = 4$

Get 20

$hash_1(20) = 20 \% 4 = 0$

$hash_2(20) = 20 \% 8 = 4$

LINEAR HASHING



Get 6

$hash_1(6) = 6 \% 4 = 2$

Put 17

$hash_1(17) = 17 \% 4 = 1$

$hash_2(8) = 8 \% 8 = 0$

$hash_2(20) = 20 \% 8 = 4$

Get 20

$hash_1(20) = 20 \% 4 = 0$

$hash_2(20) = 20 \% 8 = 4$

Get 9

$hash_1(9) = 9 \% 4 = 1$

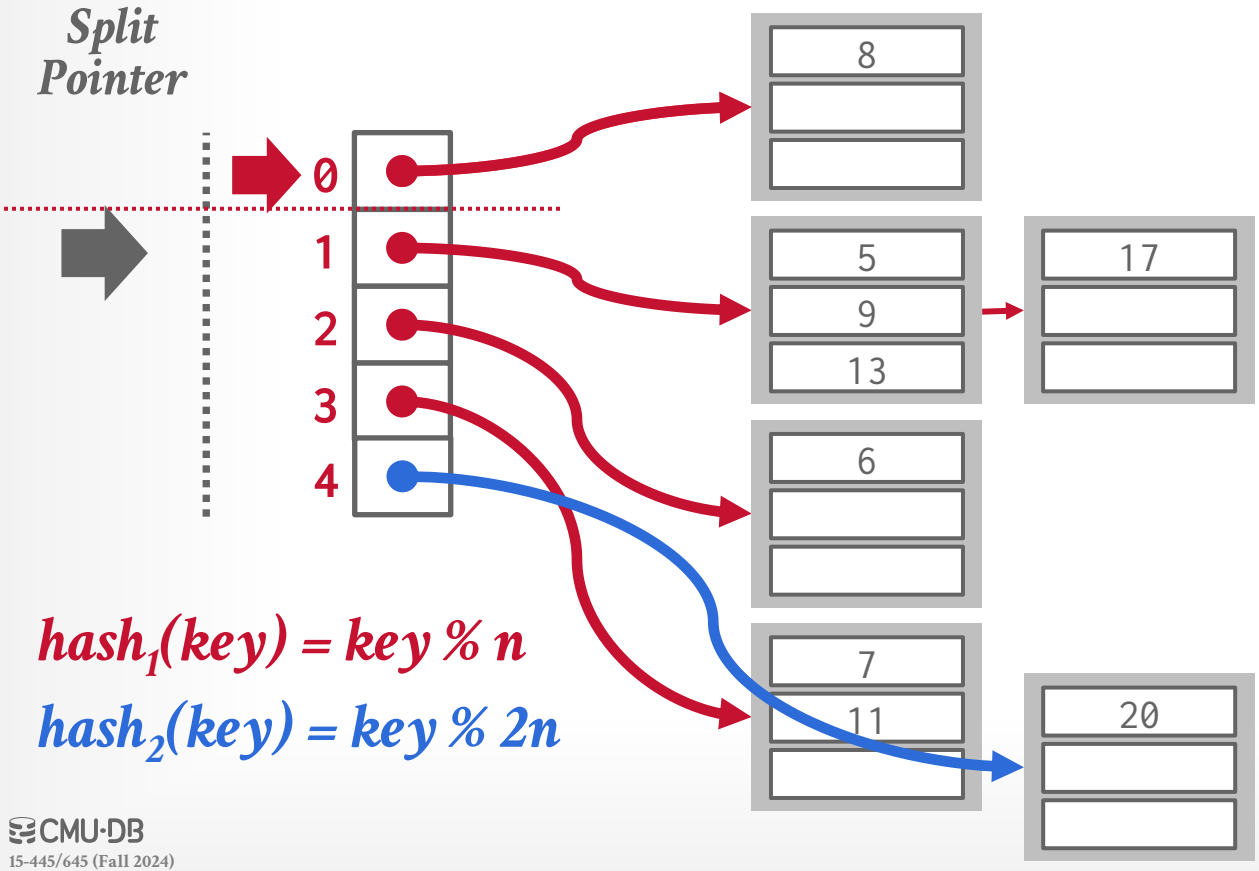
LINEAR HASHING - RESIZING

Splitting buckets based on the split pointer will eventually get to all overflowed buckets.

→ When the pointer reaches the last slot, remove the first hash function and move pointer back to beginning.

If the "highest" bucket below the split pointer is empty, the hash table could remove it and move the splinter pointer in reverse direction.

LINEAR HASHING – DELETES



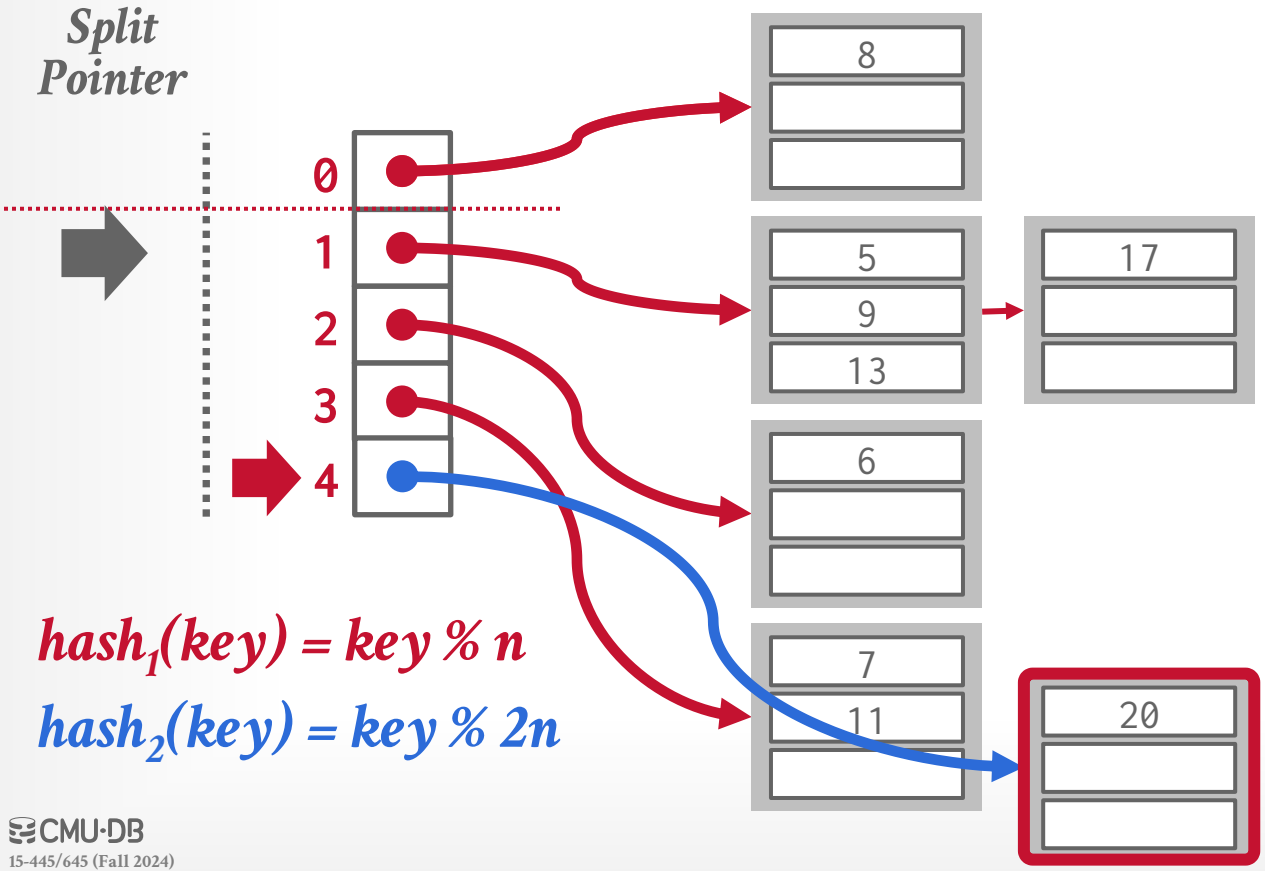
Delete 20

$hash_1(20) = 20 \% 4 = 0$

$hash_1(key) = key \% n$

$hash_2(key) = key \% 2n$

LINEAR HASHING – DELETES



$hash_1(key) = key \% n$

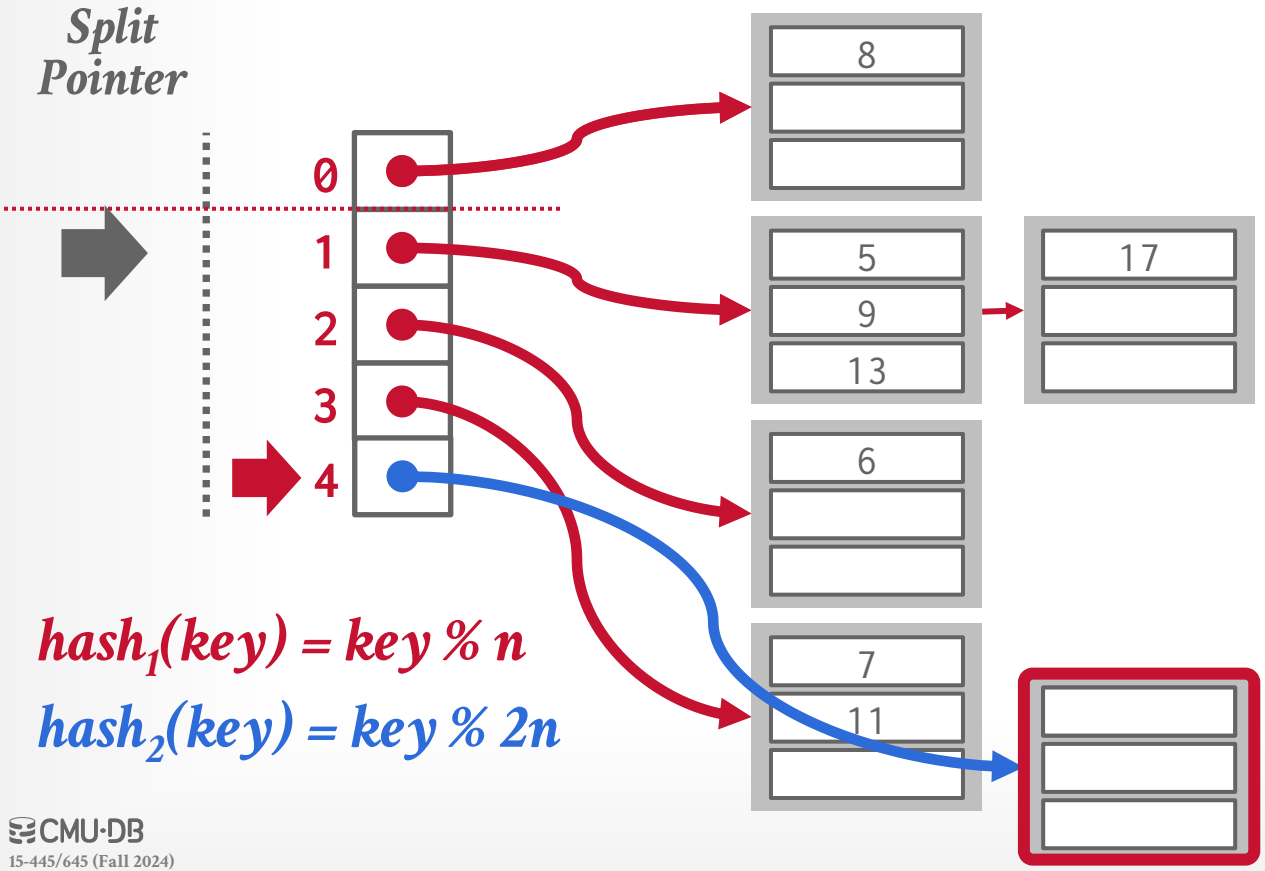
$hash_2(key) = key \% 2n$

Delete 20

$hash_1(20) = 20 \% 4 = 0$

$hash_2(20) = 20 \% 8 = 4$

LINEAR HASHING – DELETES

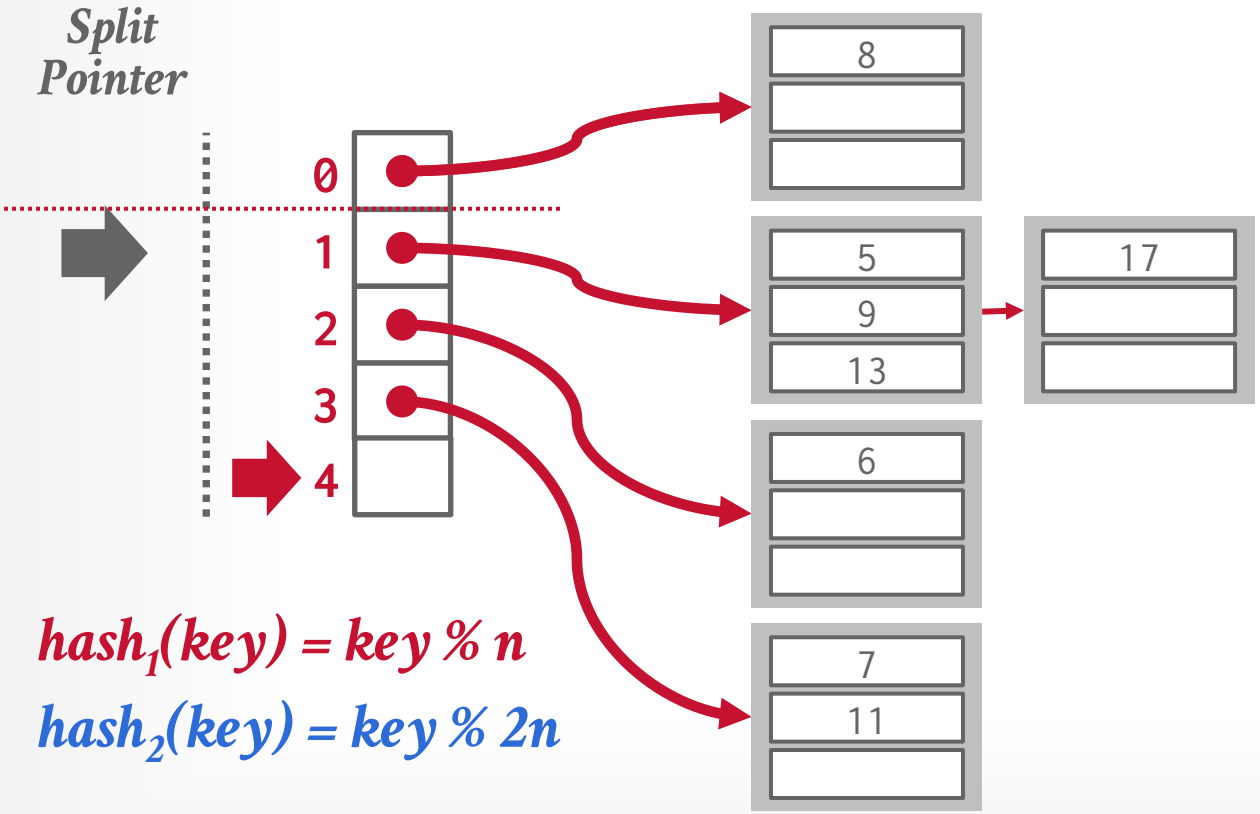


Delete 20

$hash_1(20) = 20 \% 4 = 0$

$hash_2(20) = 20 \% 8 = 4$

LINEAR HASHING – DELETES



$hash_1(key) = key \% n$

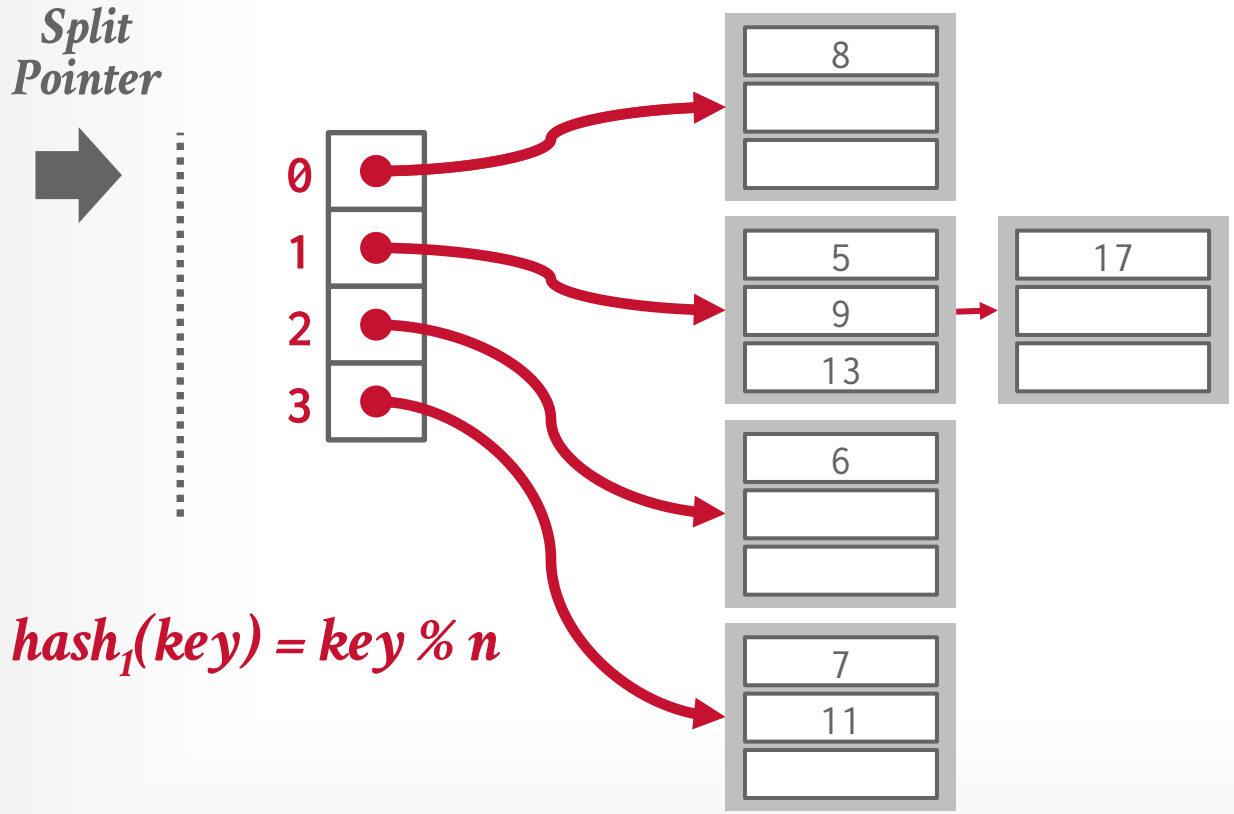
$hash_2(key) = key \% 2n$

Delete 20

$hash_1(20) = 20 \% 4 = 0$

$hash_2(20) = 20 \% 8 = 4$

LINEAR HASHING – DELETES

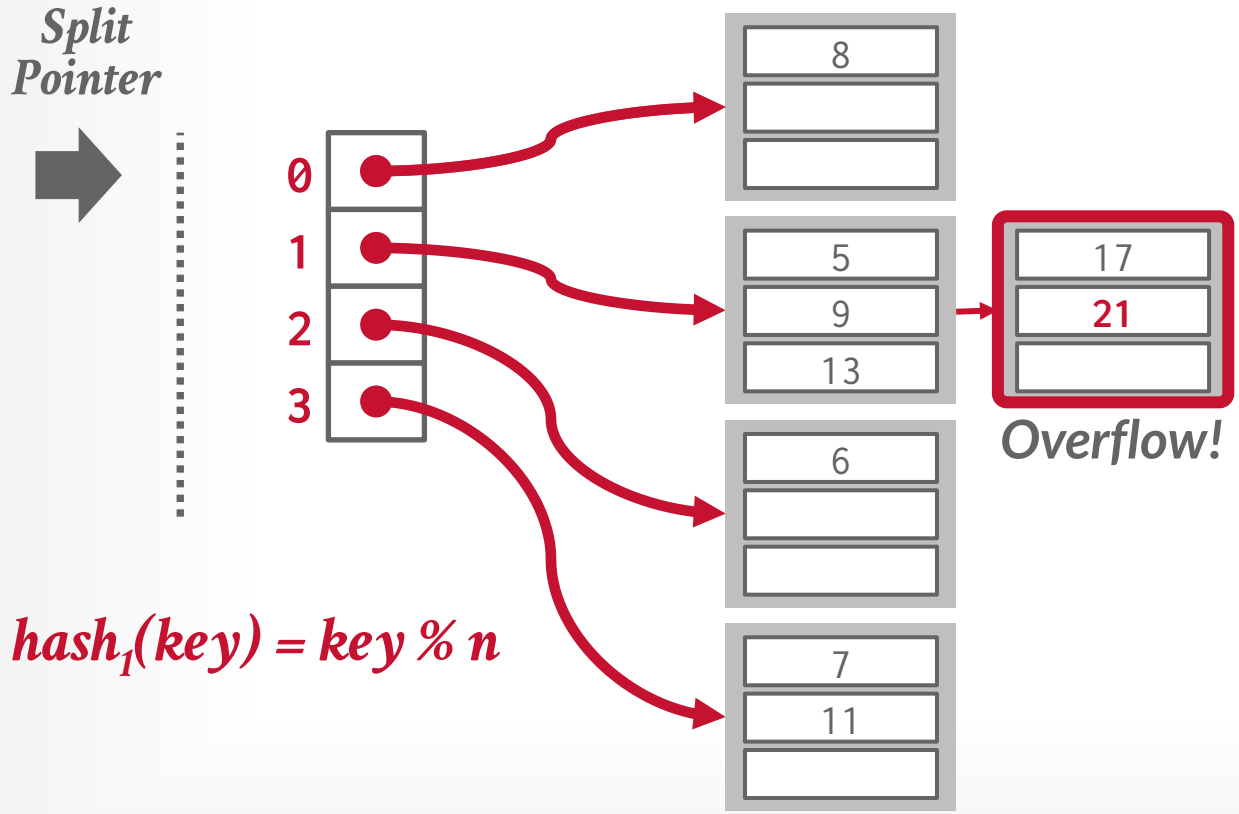


Delete 20

$hash_1(20) = 20 \% 4 = 0$

$hash_2(20) = 20 \% 8 = 4$

LINEAR HASHING – DELETES



$hash_1(key) = key \% n$

Delete 20

$hash_1(20) = 20 \% 4 = 0$

$hash_2(20) = 20 \% 8 = 4$

Put 21

$hash_1(21) = 21 \% 4 = 1$

CONCLUSION

Fast data structures that support **O(1)** look-ups that are used all throughout DBMS internals.
→ Trade-off between speed and flexibility.

Hash tables are usually **not** what you want to use for a table index…

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Fast data structures that support **O(1)** look-ups that are used all throughout DBMS internals.
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PostgreSQL

```
CREATE INDEX ON xxx (val);
CREATE INDEX ON xxx USING BTREE (val);
CREATE INDEX ON xxx USING HASH (val);
```

NEXT CLASS

Order-Preserving Indexes ft. B+Trees

→ aka "The Greatest Data Structure of All Time"