Hash Tables

Administrivia

- Assignment 2 has been released.
- We will be having a couple of guest lectures later in the semester.

Recap

Access Methods

Access methods are alternative **ways for retrieving specific tuples** from a relation.

- Typically, there is more than one way to retrieve tuples.
- Depends on the availability of **indexes** and the conditions specified in the query for selecting the tuples
- Includes **sequential scan** method of **unordered table heap**
- Includes **index scan** of different types of **index structures**

Index Structures: Design Decisions

- **Meta-Data Organization**
  - How to organize meta-data on disk or in memory to support efficient access to specific tuples?
- **Concurrency**
  - How to allow multiple threads to access the derived data structure at the same time without causing problems?

Today's Agenda

- Hash Tables
- Hash Functions
- Static Hashing Schemes
- Dynamic Hashing Schemes

Hash Tables

Hash Tables

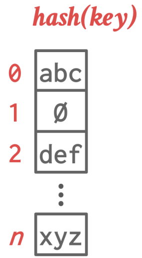
- A hash table implements an **unordered associative array** that maps keys to values.
  - mymap.insert('a', 50);
  - mymap['b']=100;
  - mymap.find('a')
  - mymap['a']
- It uses a **hash function** to compute an offset into the array for a given key, from which the desired value can be found.

Hash Tables

- Operation Complexity:
  - Average: O(1)
  - Worst: O(n)
- Space Complexity: O(n)
- Constants matter in practice.
- **Reminder:** In theory, there is no difference between theory and practice. But in practice, there is.

Naïve 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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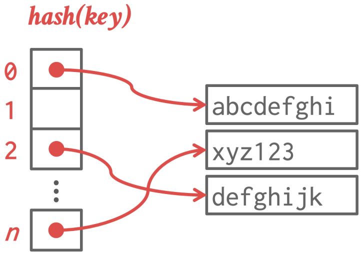


Assumptions

- You know the number of elements ahead of time.
- Each key is unique (*e.g.*, SSN ID $\longrightarrow$ Name).
- Perfect hash function (no **collision**).
  - If key1 != key2, then hash(key1) != hash(key2)

Hash Table: Design Decisions

- Design Decision 1: **Hash Function**
  - How to map a large key space into a smaller domain of array offsets.
  - 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 steps to find/insert keys.

Hash Functions

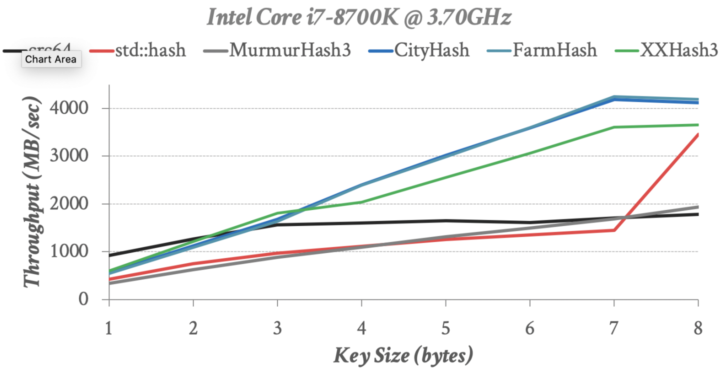
Hash Functions

- For any input key, return an integer representation of that key.
- We want to map the key space to a smaller domain of array offsets.
- We do **not** want to use a cryptographic hash function for DBMS hash tables.
- We want something that is fast and has a low collision rate.

Hash Functions

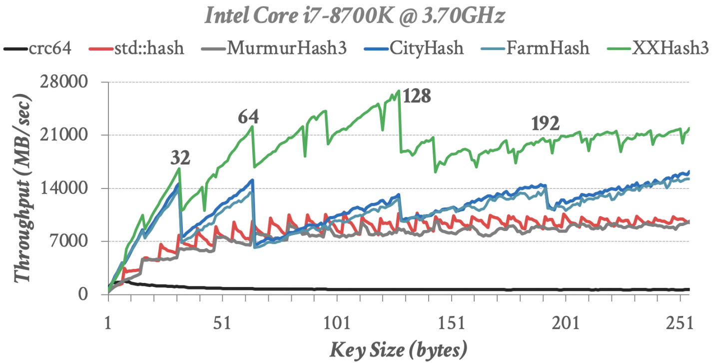
- CRC-64 (1975)
  - Used in networking for error detection.
- MurmurHash (2008)
  - Designed to a fast, general purpose hash function.
- Google CityHash (2011)
  - Designed to be faster for short keys (<64 bytes).
  - New assembly instructions have been added recently to accelerate hashing
- Facebook XXHash (2012)
  - From the creator of zstd compression.
- Google FarmHash (2014)
  - Newer version of CityHash with better collision rates.

Hash Function Benchmark



- Source
- Intel Core i7-8700K @ 3.70GHz

Hash Function Benchmark



- Source
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Static Hashing Schemes

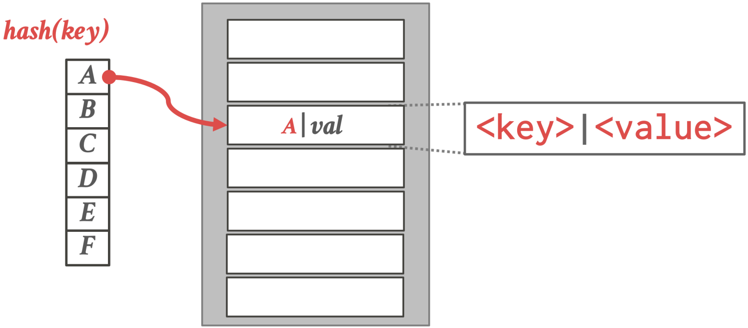
Static Hashing Schemes

- These schemes are typically used when you have an **upper bound** on the number of keys that you want to store in the hash table.
- These are often used during query execution because they are **faster than dynamic hashing schemes**.
  - Approach 1: Linear Probe Hashing
  - Approach 2: Robin Hood Hashing
  - Approach 3: Cuckoo Hashing

Linear Probe Hashing

- Single giant table of 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 index and scan for it.
  - Have to store the key in the index to know when to stop scanning.
  - Insertions and deletions are generalizations of lookups.

Linear Probe Hashing



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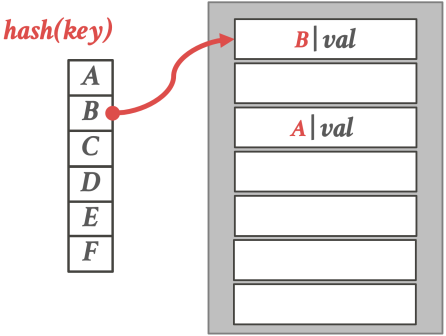

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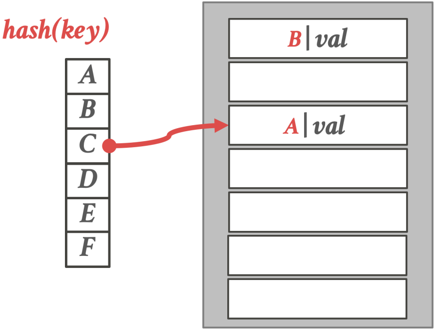

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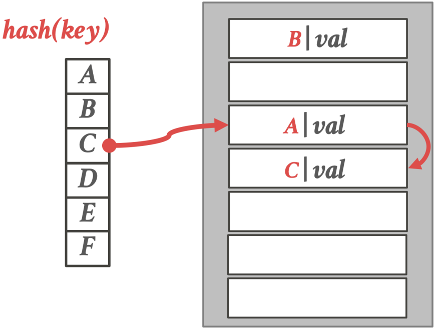

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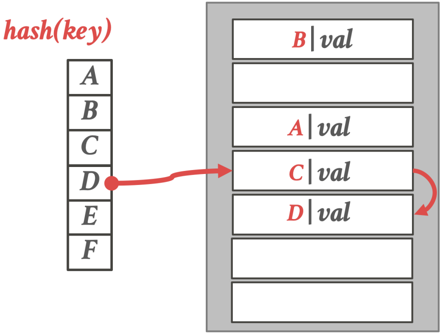

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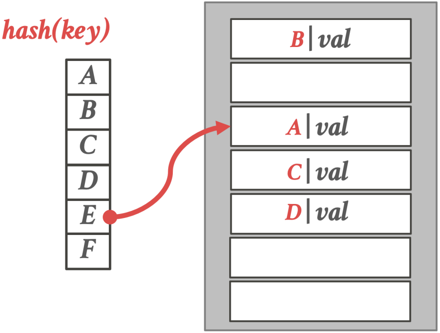

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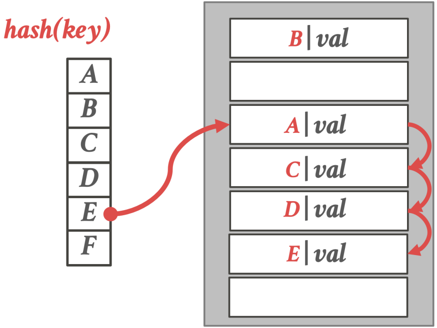

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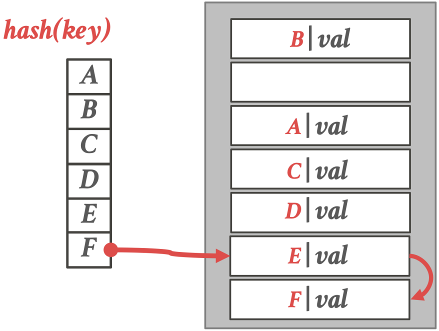
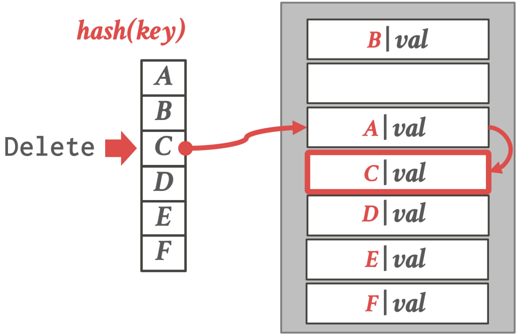


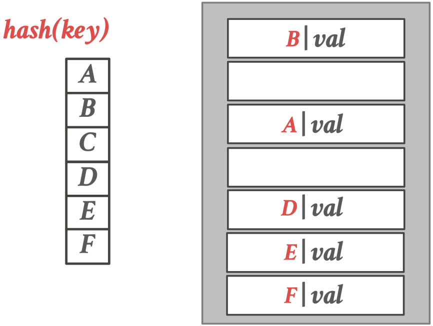
Linear Probe Hashing – Delete

- It is **not sufficient** to simply delete the key.
- This would affect searches for other keys that have a hash value earlier than the emptied cell, but that are stored in a position later than the emptied cell.
- Solutions:
  - Approach 1: Tombstone
  - Approach 2: Movement

Linear Probe Hashing – Delete



Linear Probe Hashing – Delete



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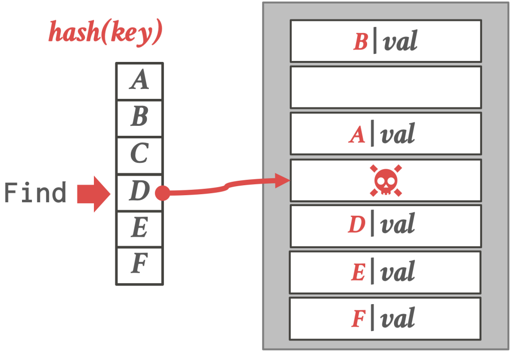

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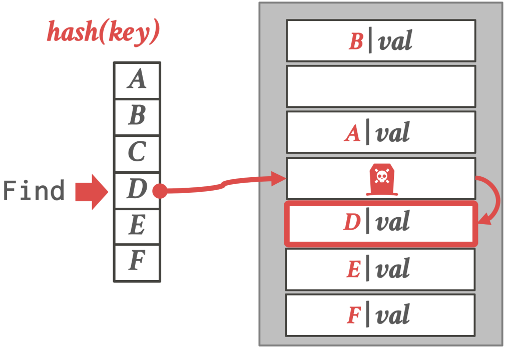

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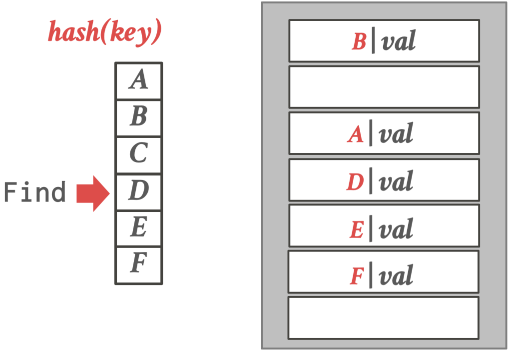

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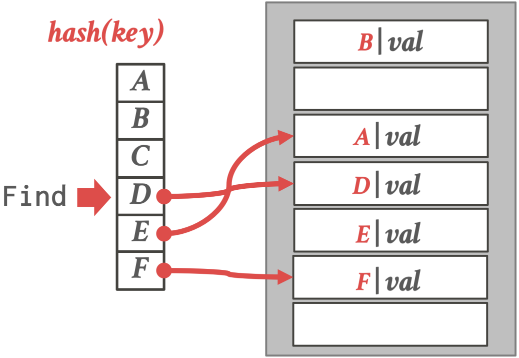
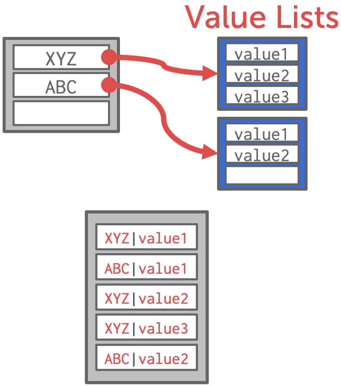


Non-Unique Keys

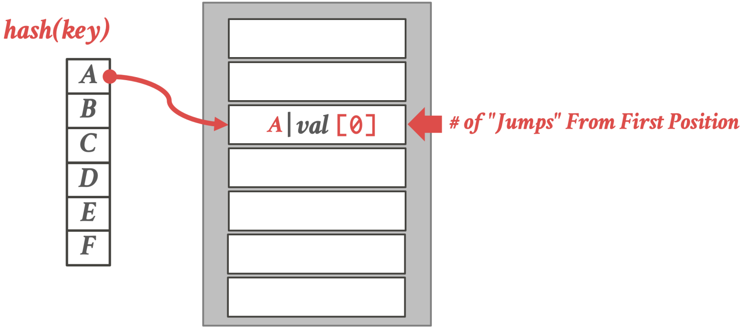
- Choice 1: **Separate Linked List**
  - Store values in separate storage area for each key.
- Choice 2: **Redundant Keys**
  - Store duplicate keys entries together in the hash table.



Robin Hood Hashing

- Variant of linear probe hashing that steals slots from **rich** keys and give them to **poor** keys.
  - Each key tracks the **number of positions** they are from where its optimal position in the table.
  - On insert, a key takes the slot of another key if the first key is farther away from its optimal position than the second key.

Robin Hood Hashing



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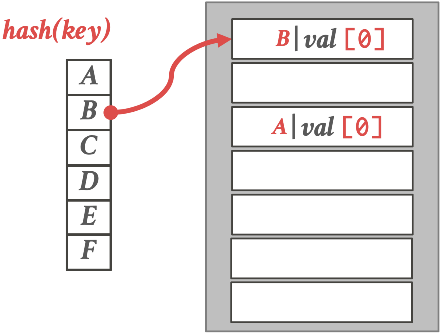

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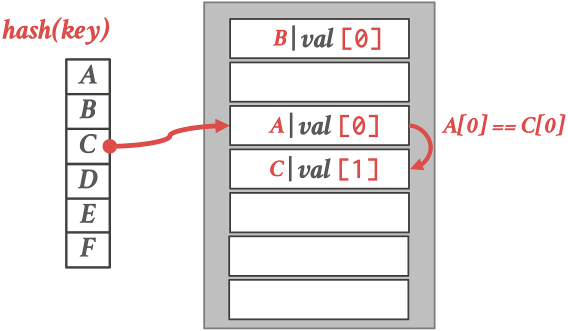

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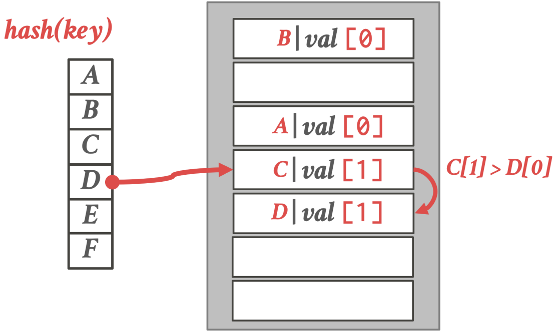

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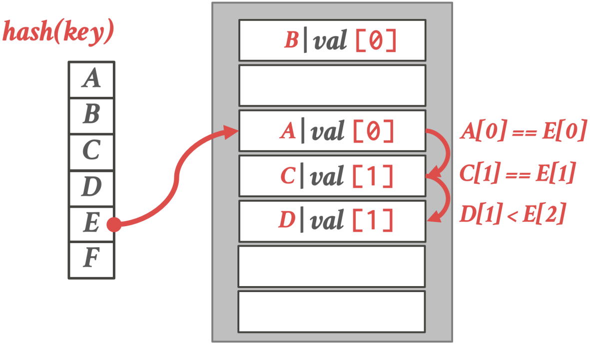

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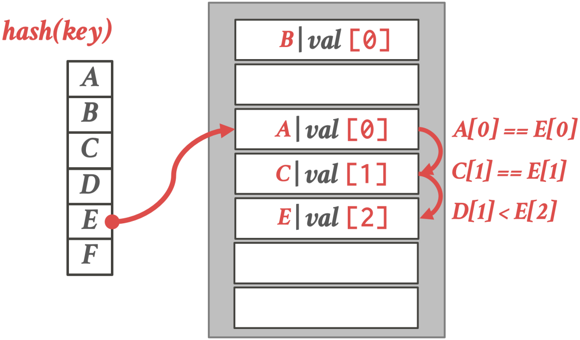

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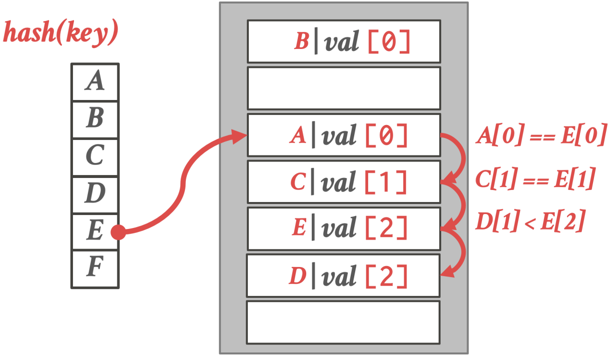

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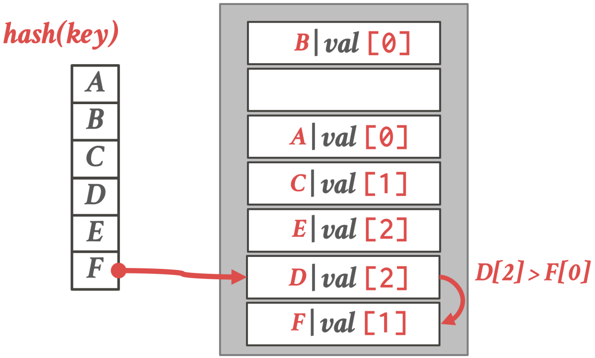
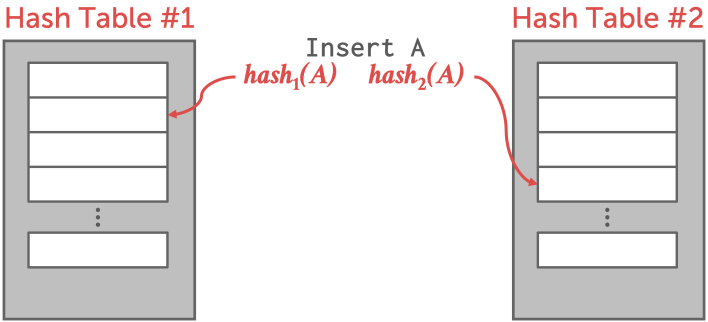


Cuckoo Hashing

- Use **multiple hash tables** with different hash function seeds.
  - On insert, check every table and pick anyone that has a free slot.
  - If no table has a free slot, 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.

Cuckoo Hashing



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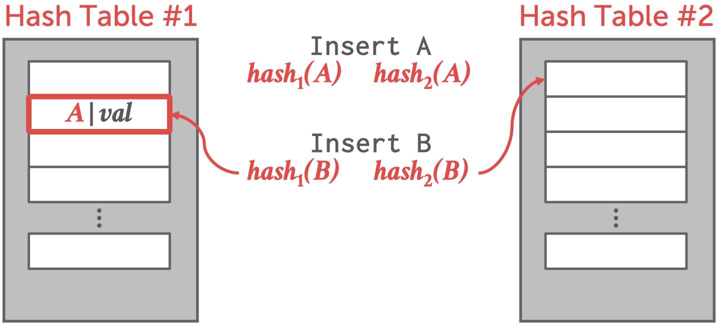

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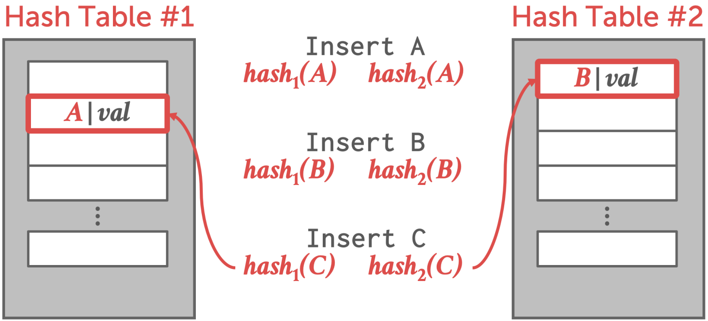

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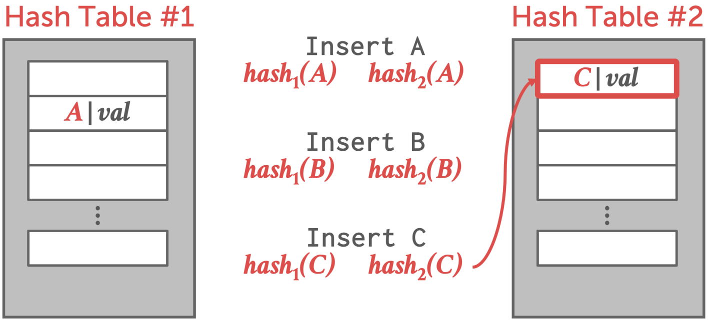

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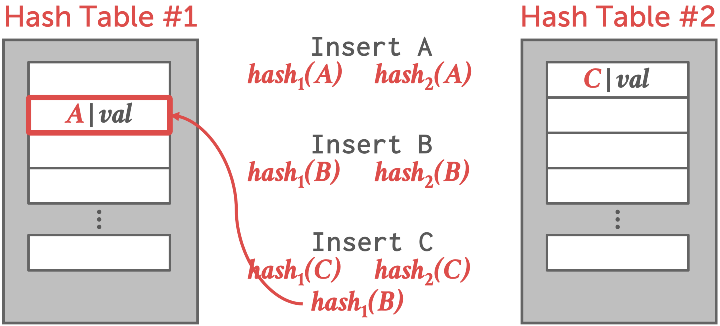

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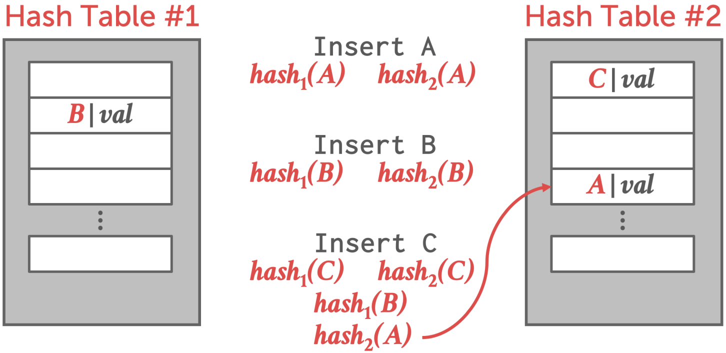


Observation

- Static hashing schemes require the DBMS to know the number of keys to be stored.
  - Otherwise it has to rebuild the table if it needs to grow/shrink the table in size. Why?
  - You would have to take a latch on the entire hash table to prevent threads from adding new entries.
- Dynamic hashing schemes resize themselves on demand.
  - Approach 1: Chained Hashing
  - Approach 2: Extendible Hashing
  - Approach 3: Linear Hashing

Dynamic Hashing Schemes

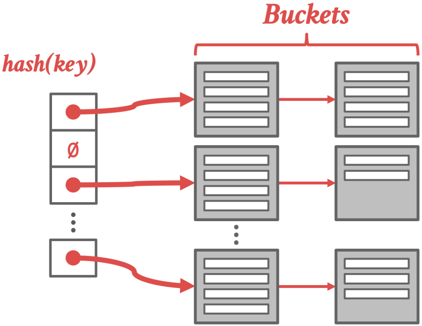
Chained Hashing

- Maintain a linked list of **buckets for each slot** in the hash table.
- Resolve collisions by placing all keys with the same hash value 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

- Unlike static hashing schemes, two different keys may hash to the same offset
- If you want to enforce **unique keys**, then you have perform an additional comparison of each key to determine whether they exactly match
- So, unlike static hashing schemes, need to retain the original key in the table

Chained Hashing



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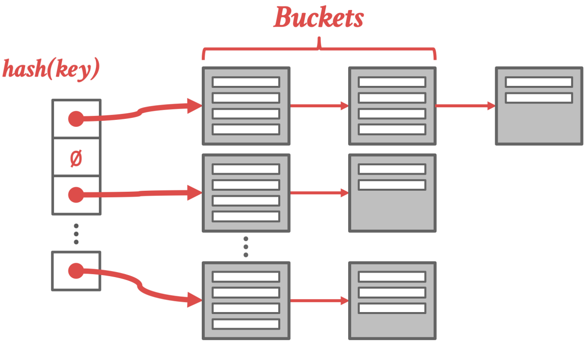

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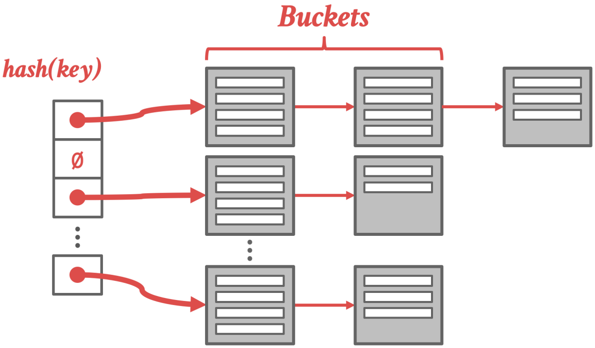


Chained Hashing

- The hash table can grow infinitely because you just keep adding new buckets to the linked list.
- You only need to take a latch on the bucket to store a new entry or extend the linked list.

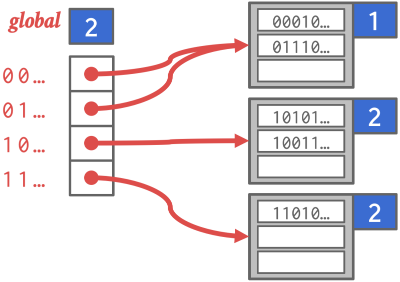
Extendible Hashing

- Chained-hashing approach where we **split buckets** instead of letting the linked list grow forever.
- Multiple slot locations can point to the same bucket chain.
- Reshuffling bucket entries on split and increase the number of bits to examine.
  - Data movement is **localized** to just the split chain.

Extendible Hashing

- The slot array maps hashes to buckets.
- A hash value may occupy an arbitrary number of bits.
- With extendible hashing, the **number of bits** that the hash table uses to map hashes to buckets **changes over time**.
  - **Global counter** keeps track of the number of bits that the the hash table uses.
  - **Local counter** in each bucket tracks the number of hash bits used by that bucket.

Extendible Hashing



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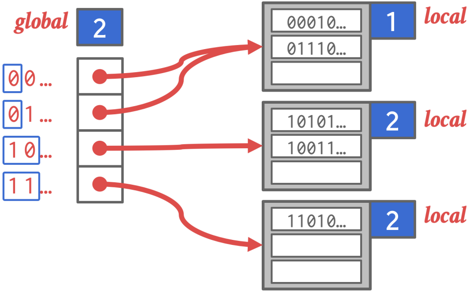

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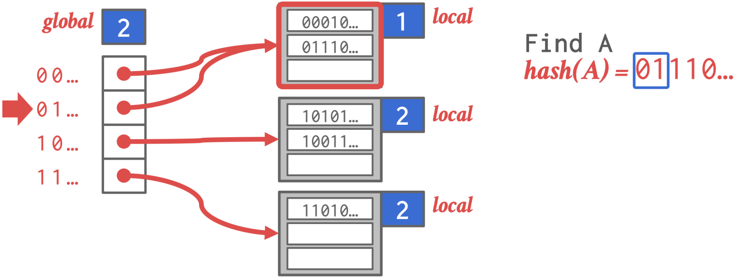

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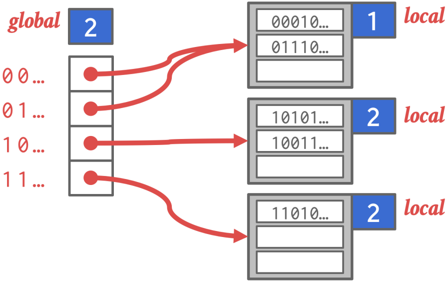
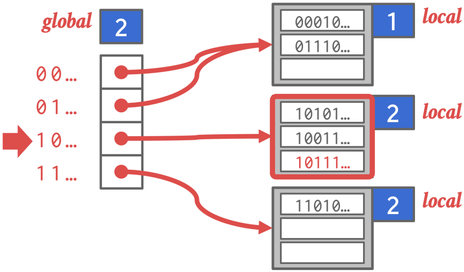


Find A
hash(A) = 01110…

Insert B
hash(B) = 10111…

Extendible Hashing



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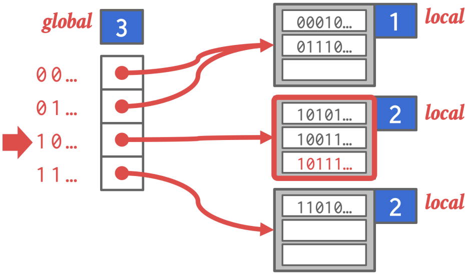
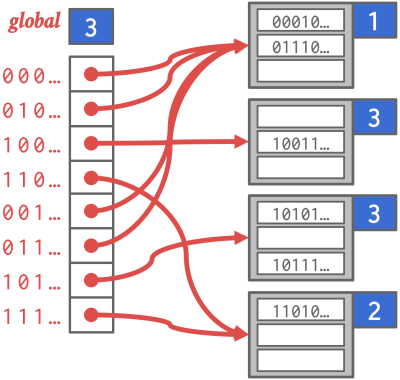


Find A
hash(A) = 01110...

Insert B
hash(B) = 10111...

Insert C
hash(C) = 10100...

Extendible Hashing



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Insert C
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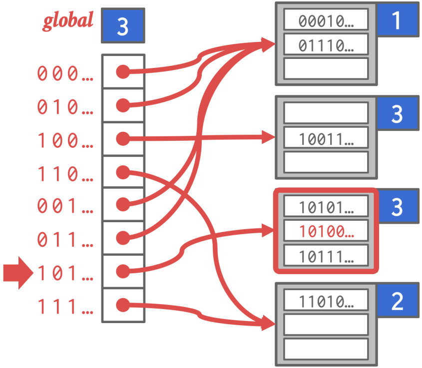
Extendible Hashing



Find A
hash(A) = 01110…

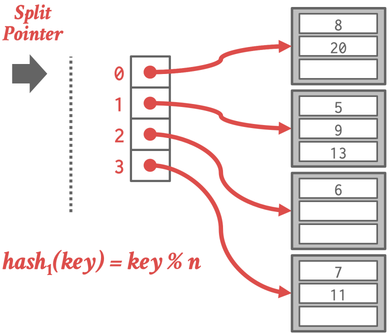
Insert B
hash(B) = 10111…

Insert C
hash(C) = 10100…

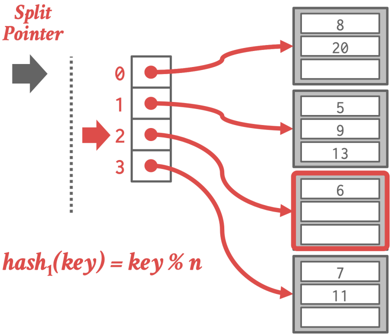
Linear Hashing

- 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

Linear Hashing



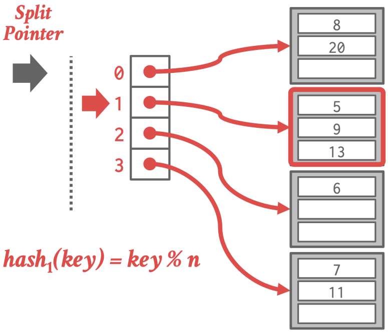
Linear Hashing



Find 6

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

Linear Hashing



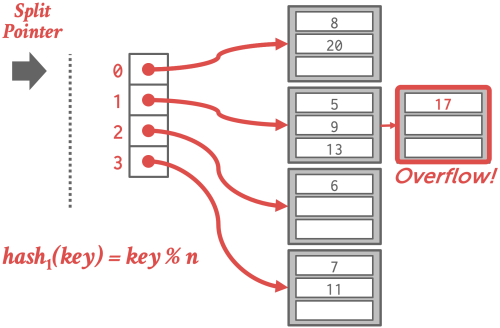
Find 6

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

Insert 17

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

Linear Hashing



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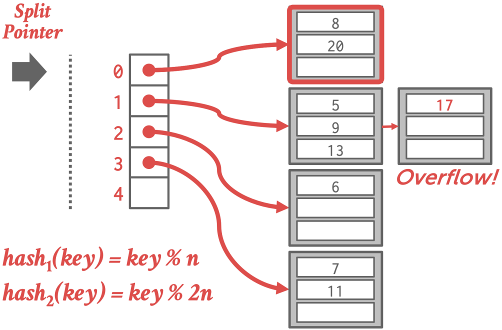
Linear Hashing



$hash_1(key) = key \% n$

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

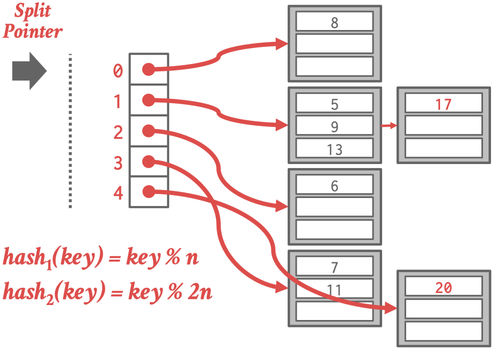
Find 6

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

Insert 17

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

Linear Hashing



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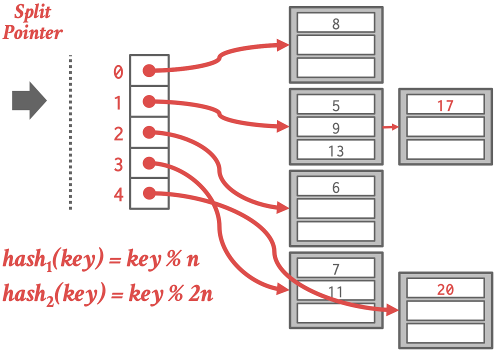


$hash_1(key) = key \% n$

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

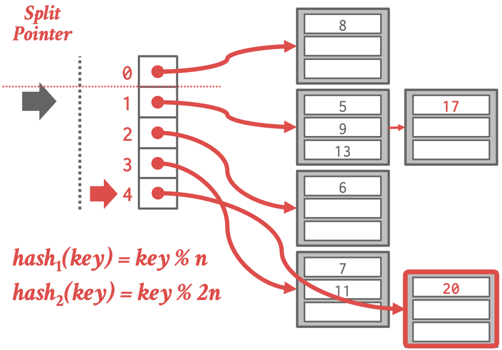
Find 6

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

Insert 17

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

Linear Hashing



$hash_1(key) = key \% n$

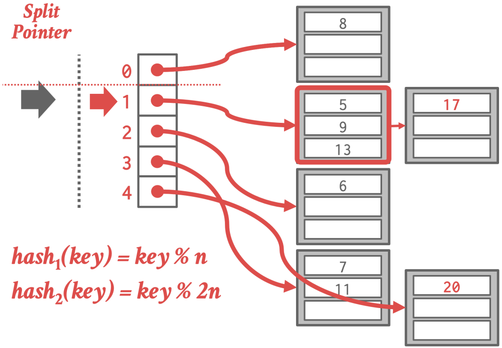
$hash_2(key) = key \% 2n$

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

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

Find 20
$hash_1(20) = 20 \% 4 = 0$
$hash_2(20) = 20 \% 8 = 4$

Linear Hashing



Find 6

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

Insert 17

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

Find 20

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

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

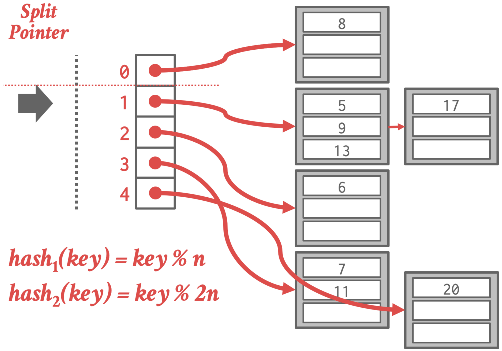
Find 9

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

Linear Hashing - Delete

- Splitting buckets based on the split pointer will eventually get to all overflowed buckets.
  - When the pointer reaches the last slot, delete the first hash function and move back to beginning.
- The pointer can also **move backwards** when buckets are empty.

Linear Hashing – Delete



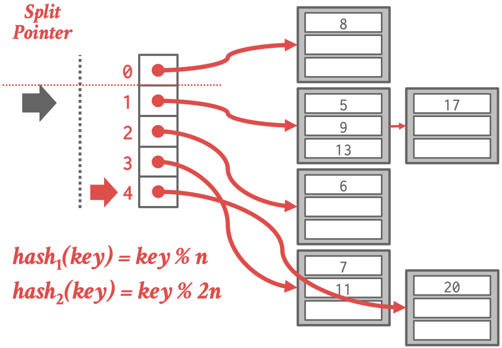
hash$_1$*(key) = key % n*

hash$_2$*(key) = key % 2n*

Delete 20

hash$_1$*(20)* = 20 % 4 = 0

Linear Hashing – Delete



$hash_1(key) = key \% n$

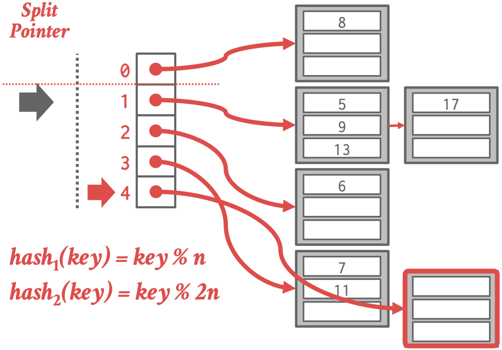
$hash_2(key) = key \% 2n$

Delete 20

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

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

Linear Hashing – Delete



$hash_1(key) = key \% n$

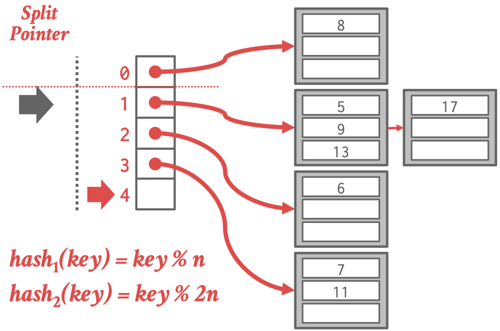
$hash_2(key) = key \% 2n$

Delete 20

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

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

Linear Hashing – Delete

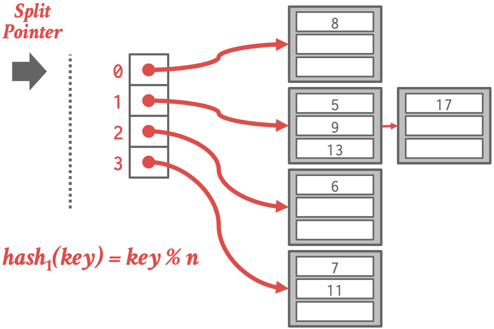


Delete 20

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

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

Linear Hashing – Delete

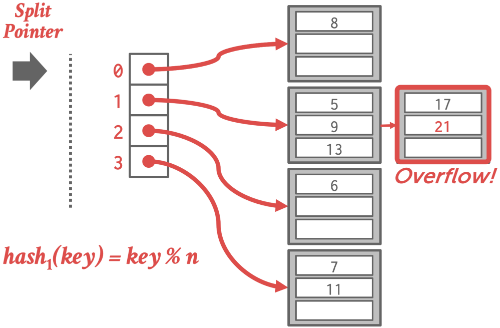


Delete 20

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

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

Linear Hashing – Delete



Delete 20
$hash_1(20) =$ 20 % 4 = 0
$hash_2(20) =$ 20 % 8 = 4

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

Linear Hashing vs. Extendible Hashing

- Moving from $\mathtt{hash}_i$ to $\mathtt{hash}_{i+1}$ in Linear Hashing corresponds to
- Bumping up the global counter in Extendible Hashing
- Linear Hashing
  - Directory is gradually doubled over the course of a round
  - A directory can be avoided by a clever choice of the buckets to split
  - More flexibility: need not always split the appropriate dense bucket

Conclusion

- Hash tables are fast data structures that support O(1) look-ups
- Used all throughout the DBMS internals.
  - Examples: Page Table (Buffer Manager), Lock Table (Lock Manager)
- Trade-off between speed and flexibility.

Conclusion

- Hash tables are usually **not** what you want to use for a indexing tables
  - Lack of ordering in widely-used hashing schemes
  - Lack of locality of reference $\longrightarrow$ more disk seeks
  - Persistent data structures are much more complex (logging and recovery)
  - Reference
- We will cover B+Trees in the next lecture
  - *a.k.a.*, "The Greatest Data Structure of All Time!"