Georgia Tech

Lecture 13: Hash Tables

CREATING THE NEXT®

Administrivia

- Assignment 3 released
- Ten students will present their project in class.

Today's Agenda

Recap

Hash Tables

Hash Functions

Static Hashing Schemes

Dynamic Hashing Schemes

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?

Hash Tables

Hash Tables

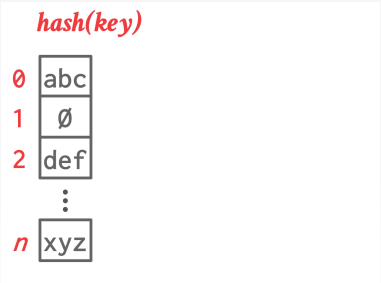
- A hash table implements an **unordered associative array** that maps keys to values.
  - mymap.insert('a', 50);
  - mymap['b']=100;
  - mymap.find('a')
  - mymap['a']
- It uses a **hash function** to compute an offset into the array for a given key, from which the desired value can be found.

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.

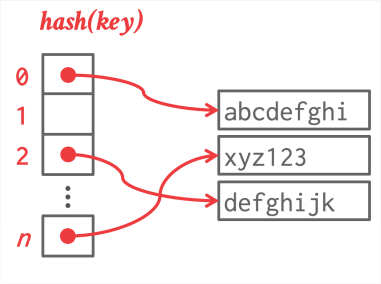
Naïve Hash Table

- 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.



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.



Assumptions

- You know the number of elements ahead of time.
- Each key is unique (*e.g.*, SSN ID ⟶ 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

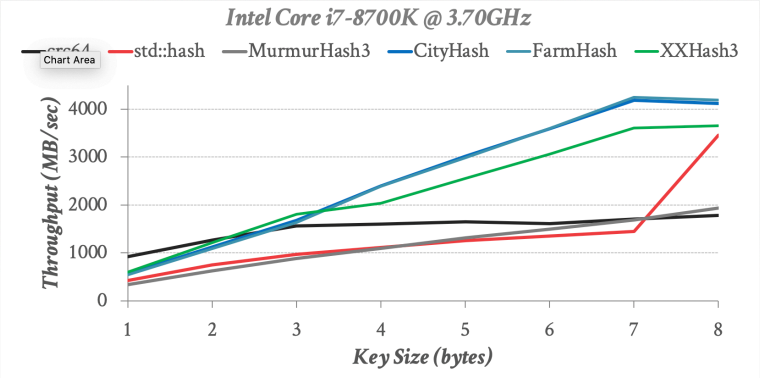
Hash Functions

- 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

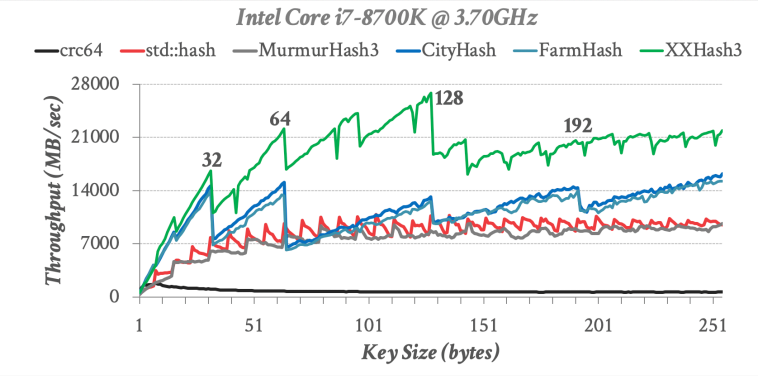
- CRC-64 (1975)
  - Used in networking for error detection.
- MurmurHash (2008)
  - Designed to be a fast, general purpose hash function.
- Google CityHash (2011)
  - Designed to be faster for short keys (<64 bytes).
  - New assembly instructions have been added recently to accelerate hashing
- Facebook 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
- Intel Core i7-8700K @ 3.70GHz

Static Hashing Schemes

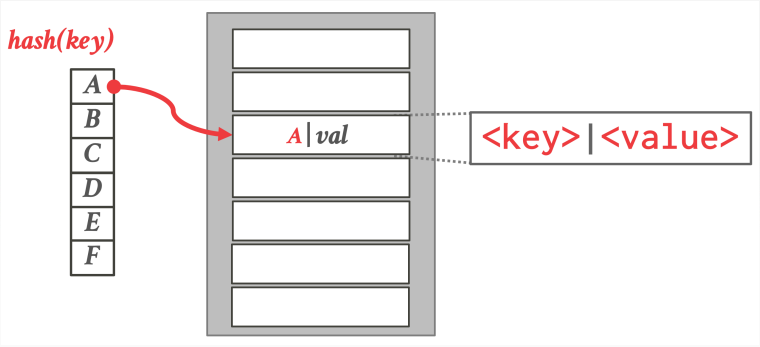
Static Hashing Schemes

- 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

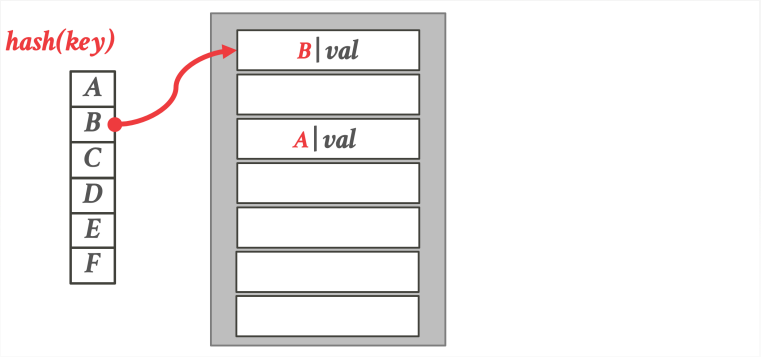
Linear Probe Hashing

- 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.

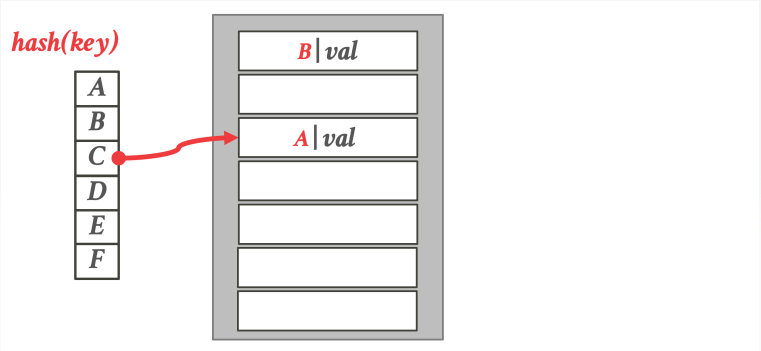
Linear Probe Hashing



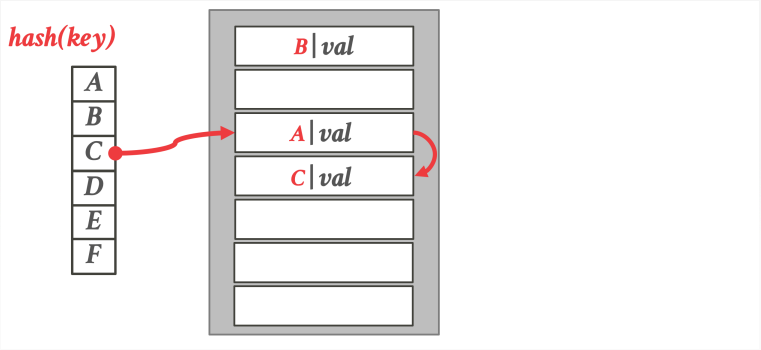
Linear Probe Hashing



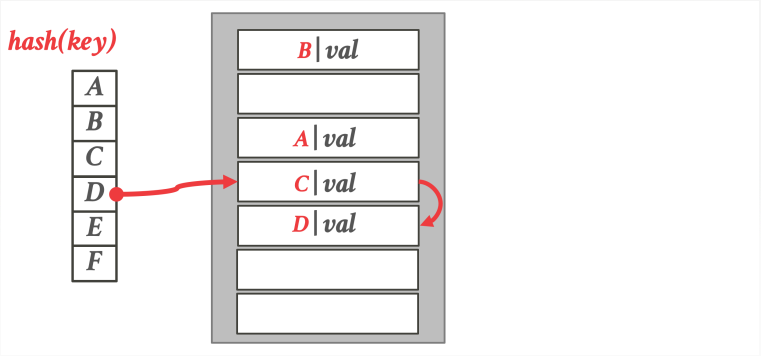
Linear Probe Hashing



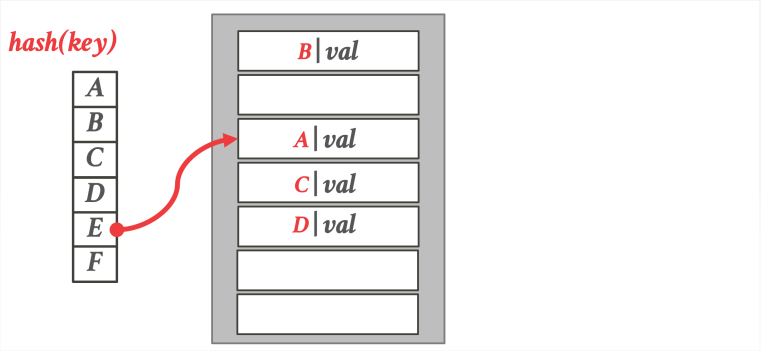
Linear Probe Hashing



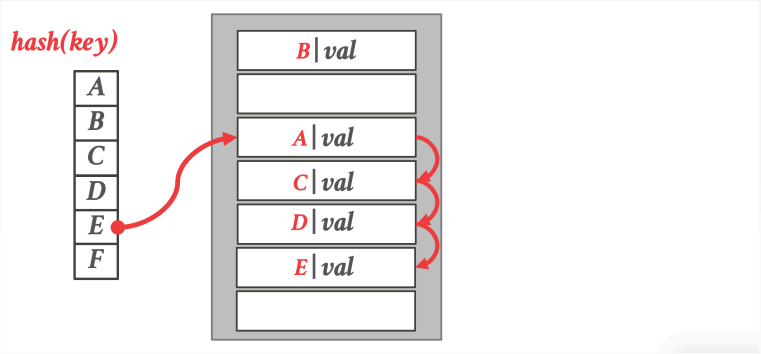
Linear Probe Hashing



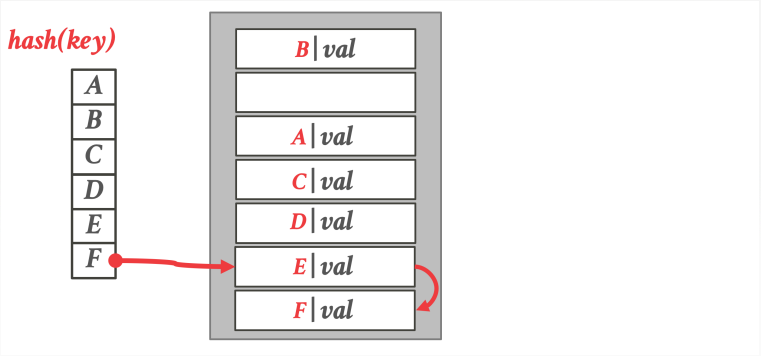
Linear Probe Hashing



Linear Probe Hashing



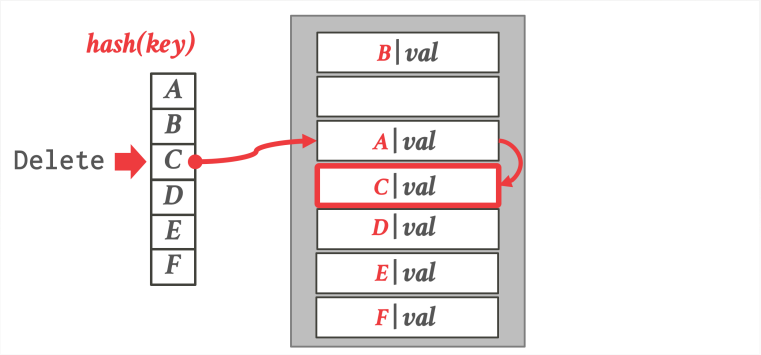
Linear Probe Hashing



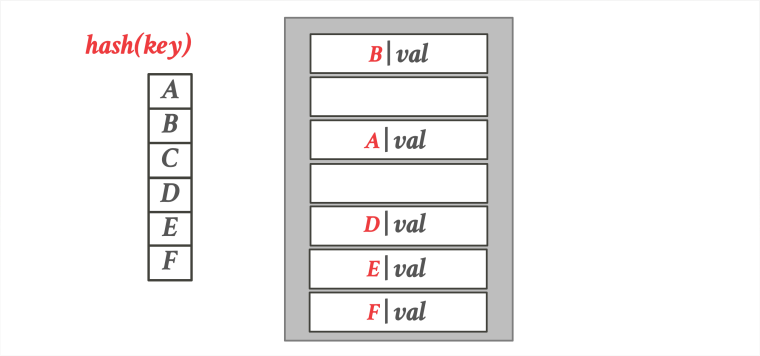
Linear Probe Hashing – Delete

- 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

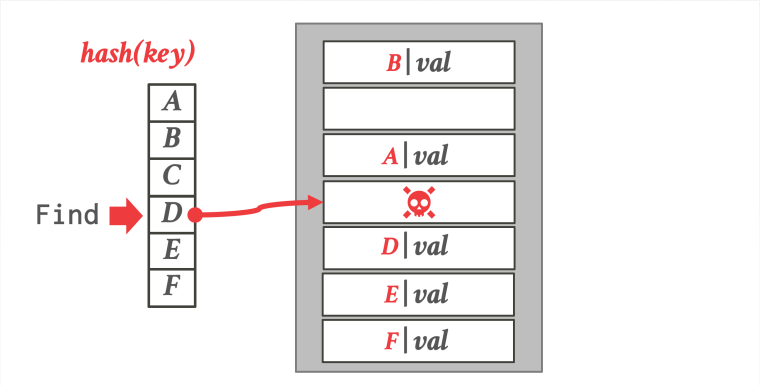
Linear Probe Hashing – Delete



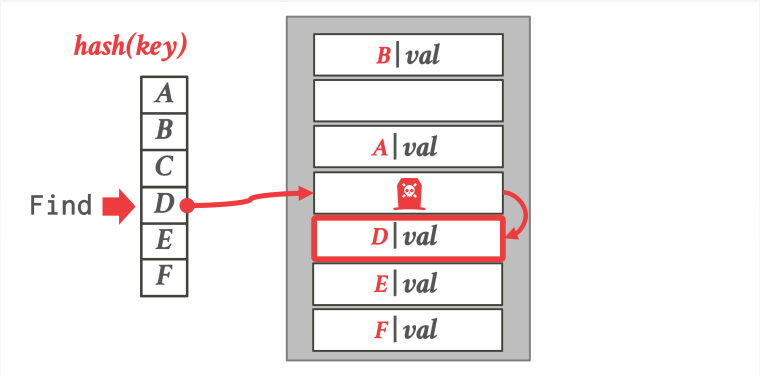
Linear Probe Hashing – Delete



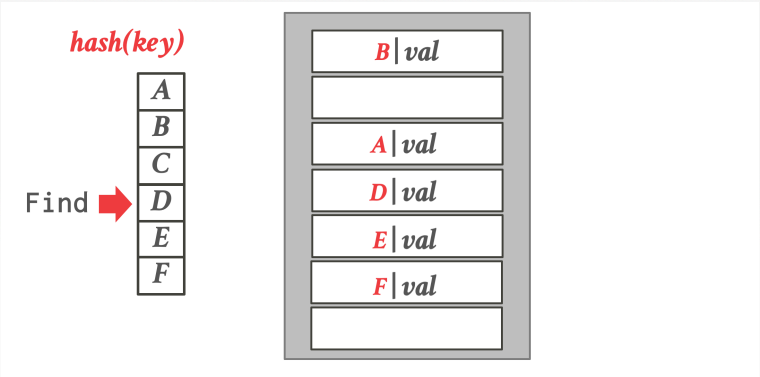
Linear Probe Hashing – Delete



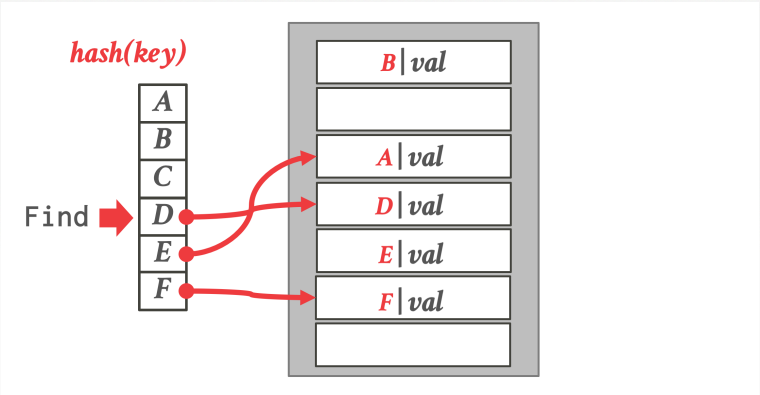
Linear Probe Hashing – Delete



Linear Probe Hashing – Delete

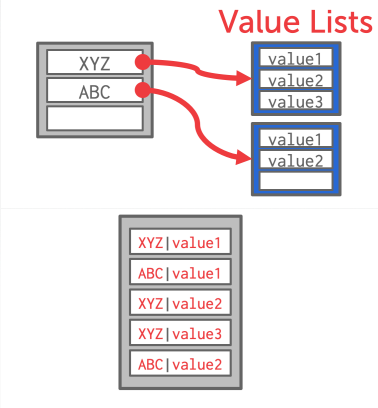


Linear Probe Hashing – Delete



Non-Unique Keys

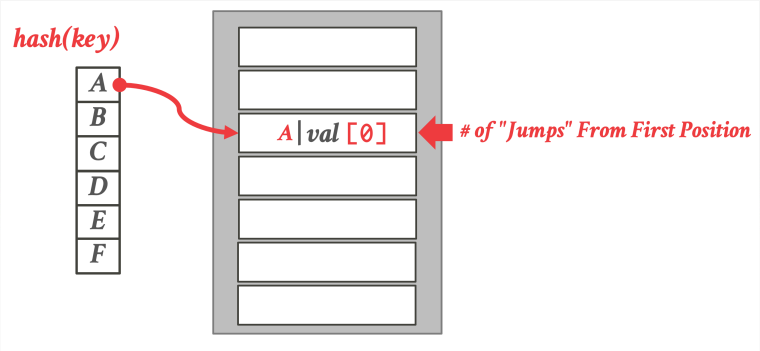
- Choice 1: **Separate Linked List**
  - Store values in separate storage area for each key.
- Choice 2: **Redundant Keys**
  - Store duplicate keys entries together in the hash table.



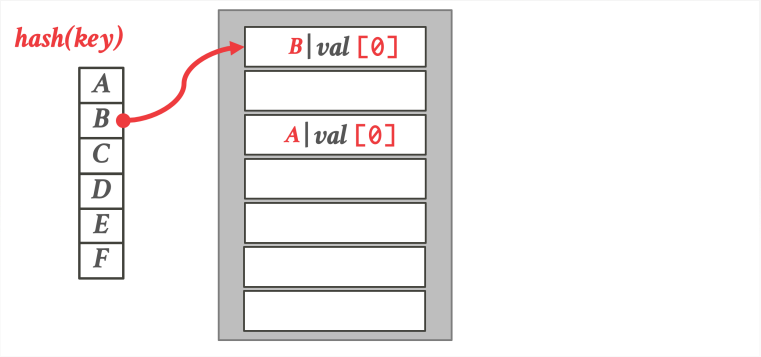
Robin Hood Hashing

- 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.

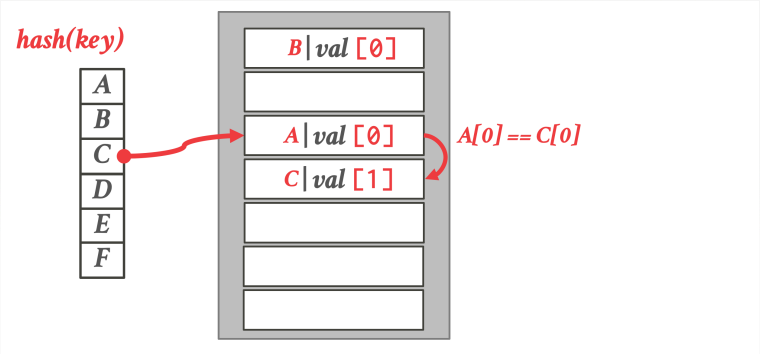
Robin Hood Hashing



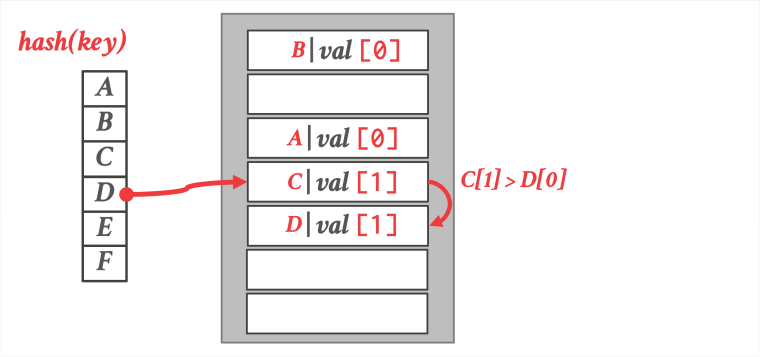
Robin Hood Hashing



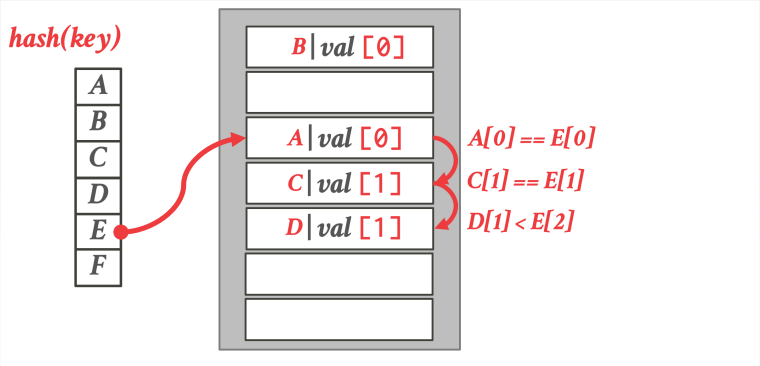
Robin Hood Hashing



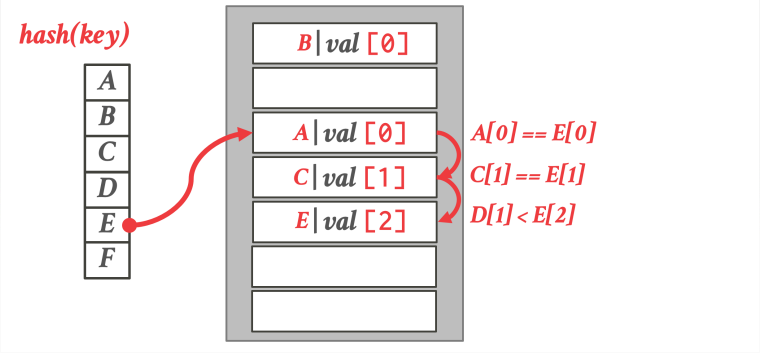
Robin Hood Hashing



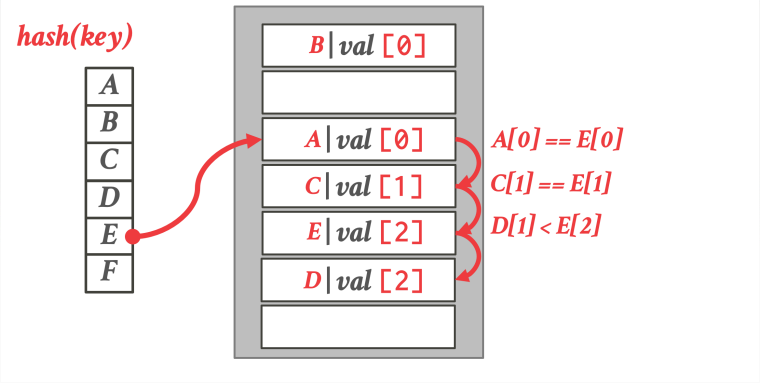
Robin Hood Hashing



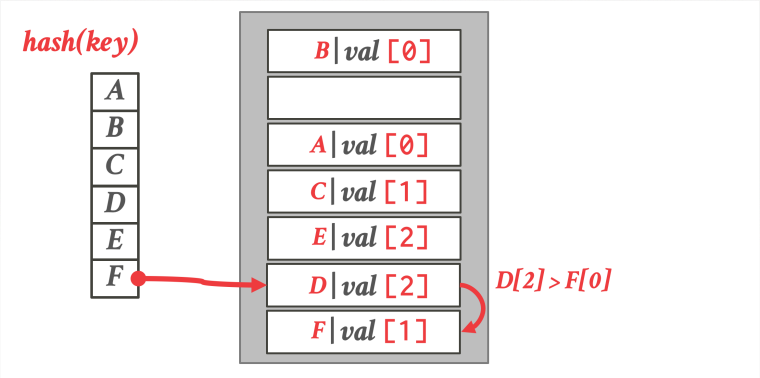
Robin Hood Hashing



Robin Hood Hashing



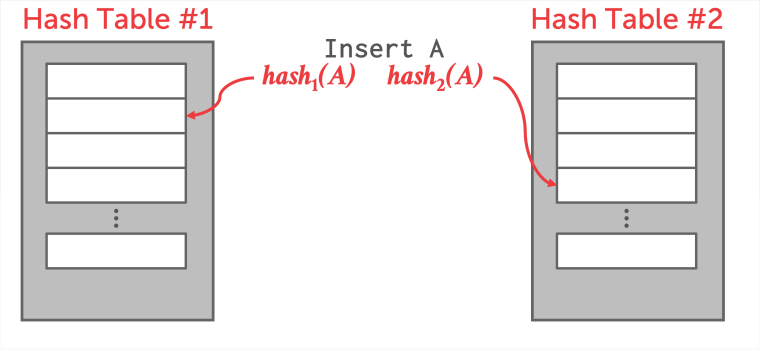
Robin Hood Hashing



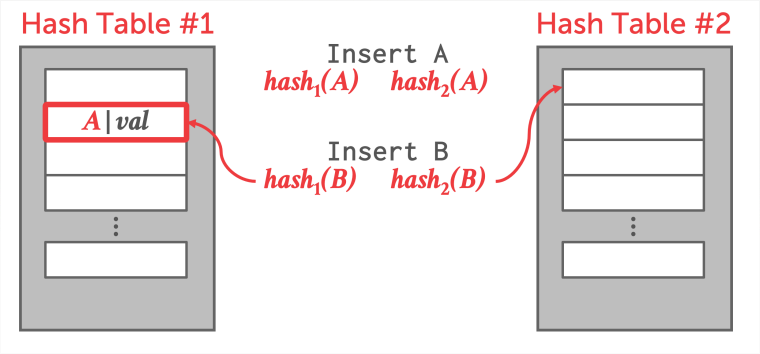
Cuckoo Hashing

- 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.

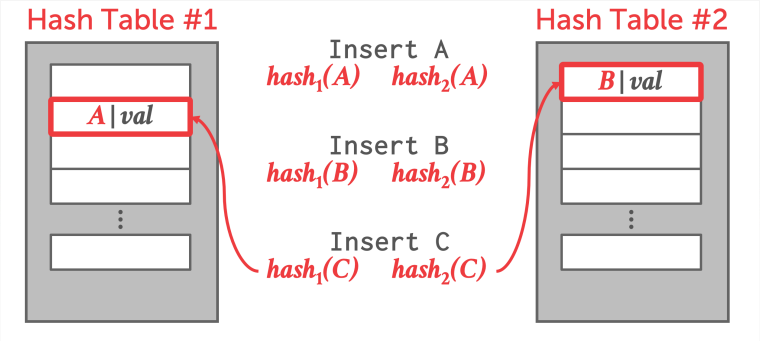
Cuckoo Hashing



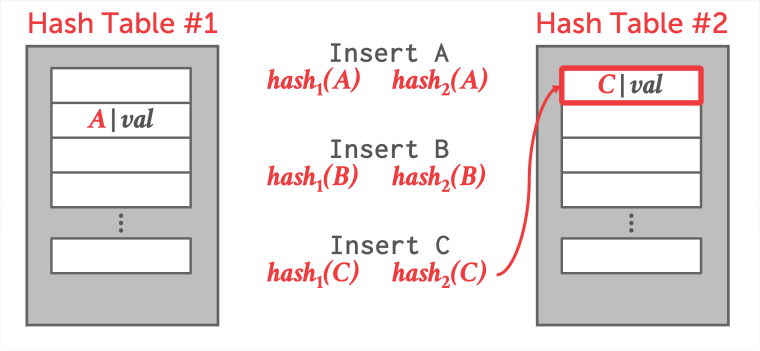
Cuckoo Hashing



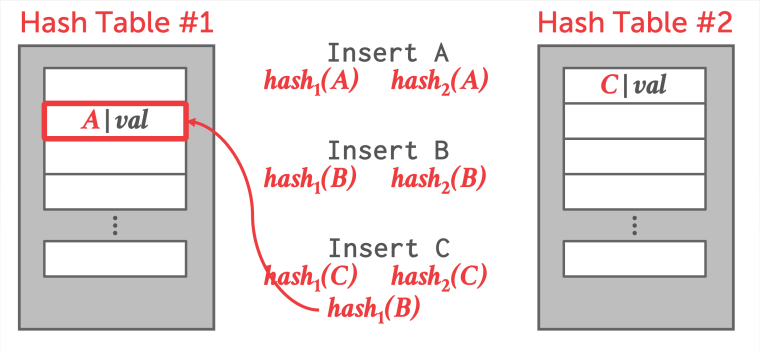
Cuckoo Hashing



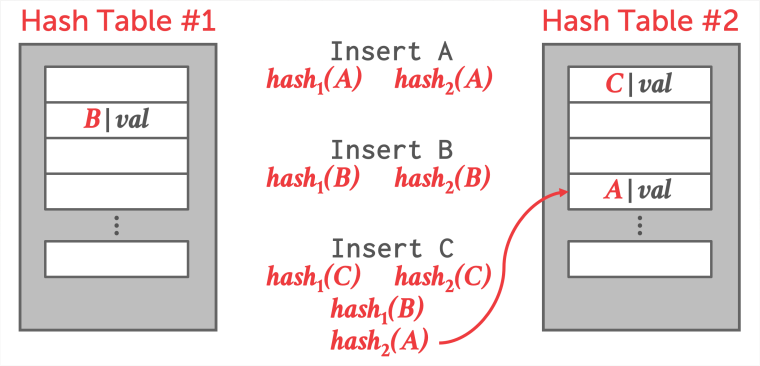
Cuckoo Hashing



Cuckoo Hashing



Cuckoo Hashing



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

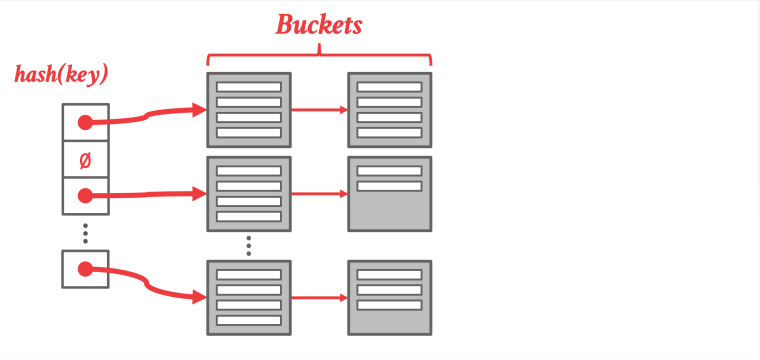
Chained Hashing

- 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.

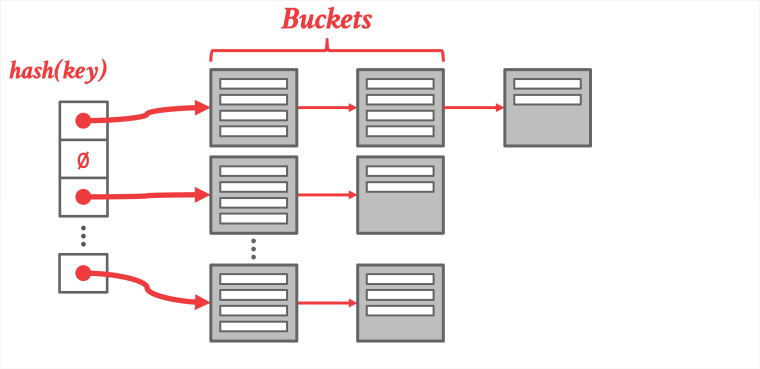
Chained Hashing

- 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

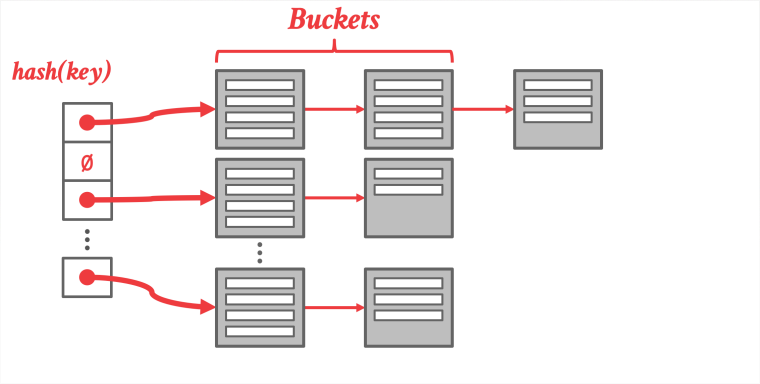
Chained Hashing



Chained Hashing



Chained Hashing



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.

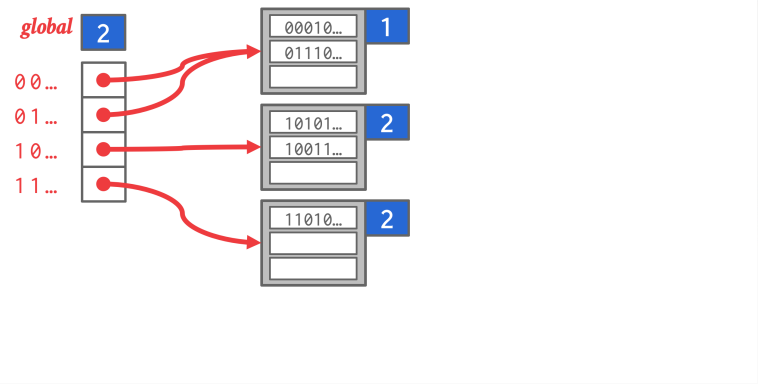
Extendible Hashing

- 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.

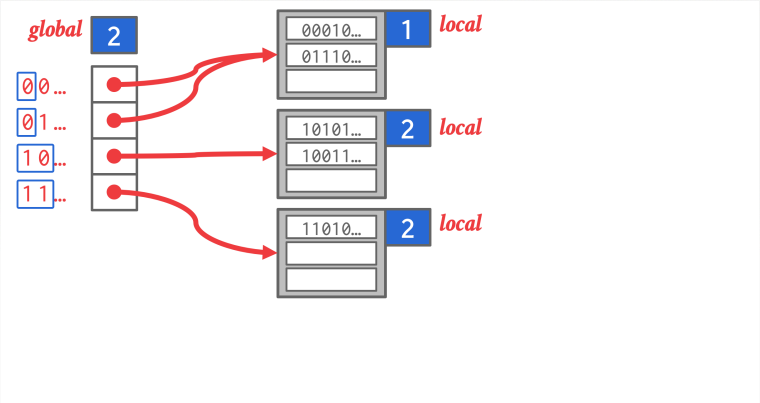
Extendible Hashing

- 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.

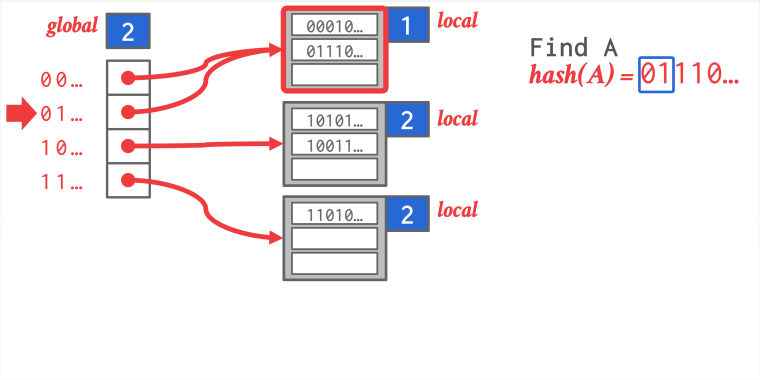
Extendible Hashing



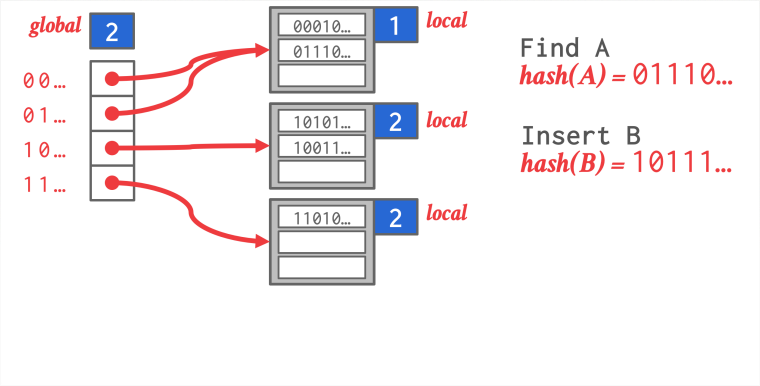
Extendible Hashing



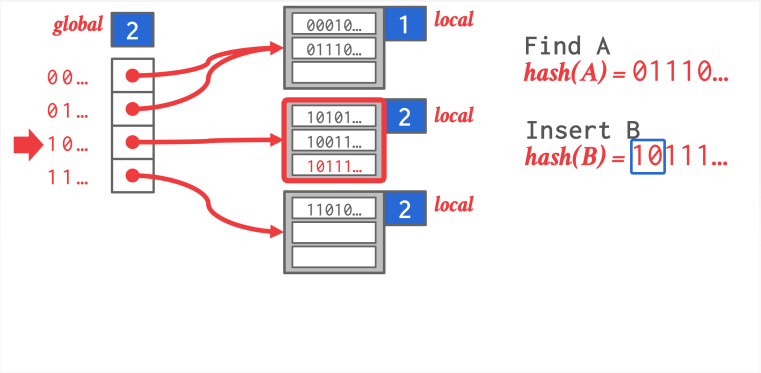
Extendible Hashing



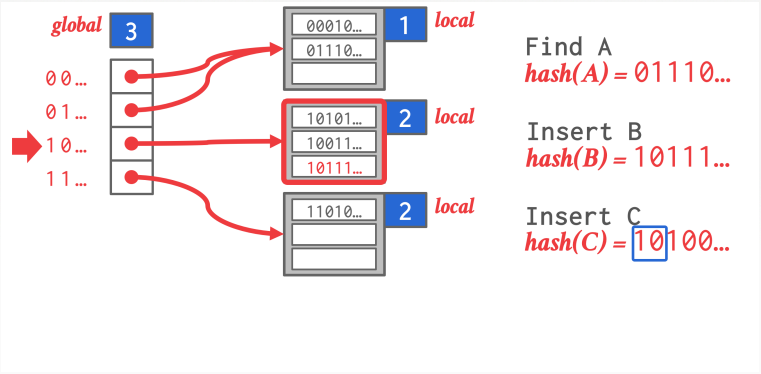
Extendible Hashing



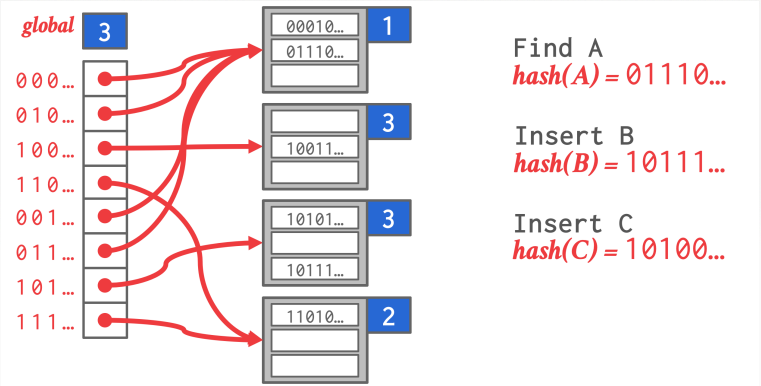
Extendible Hashing



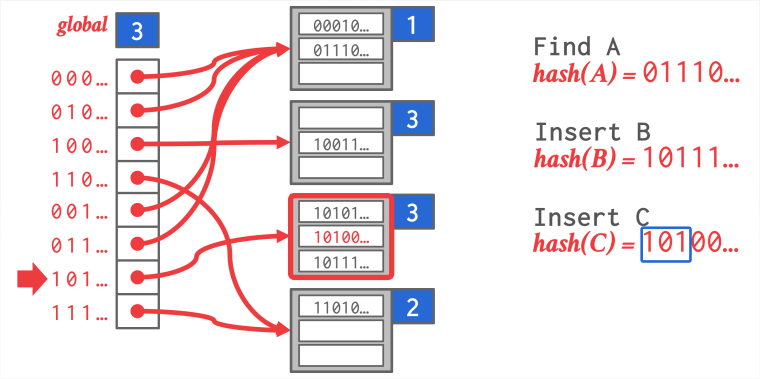
Extendible Hashing



Extendible Hashing



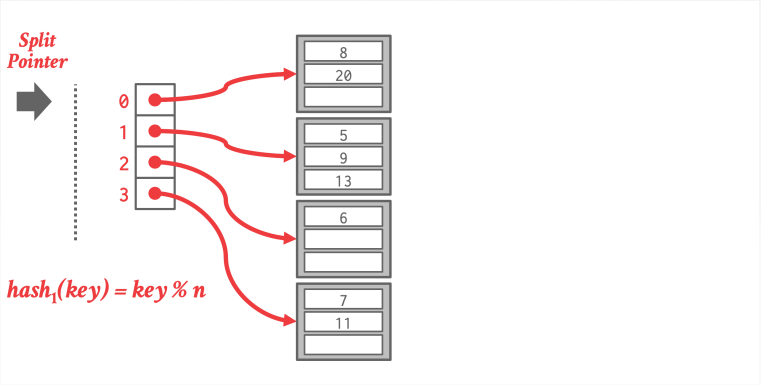
Extendible Hashing



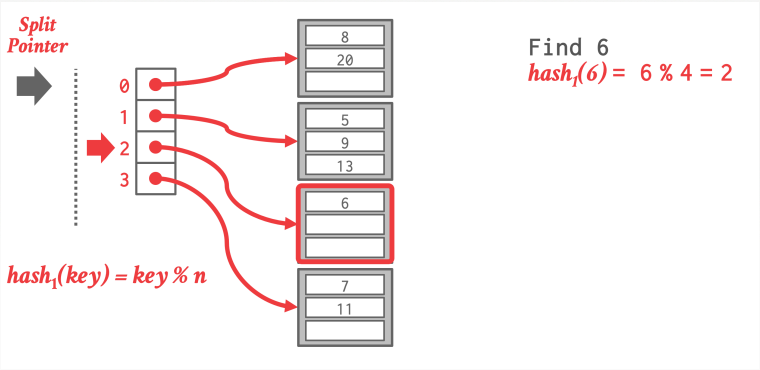
Linear Hashing

- 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

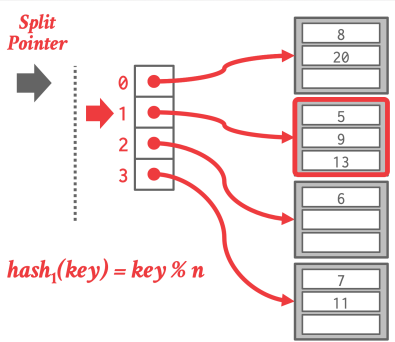
Linear Hashing



Linear Hashing



Linear Hashing



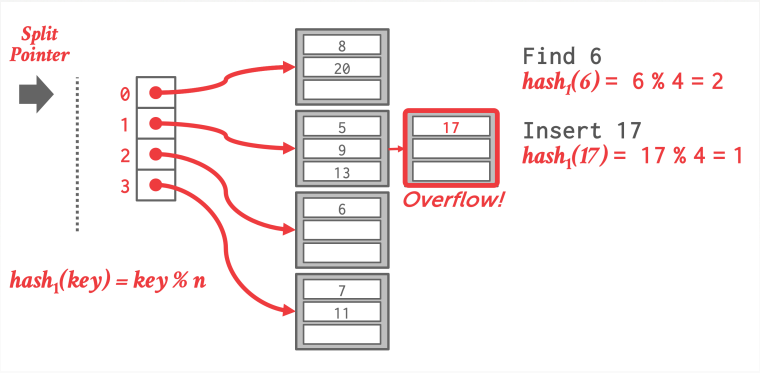
Find 6

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

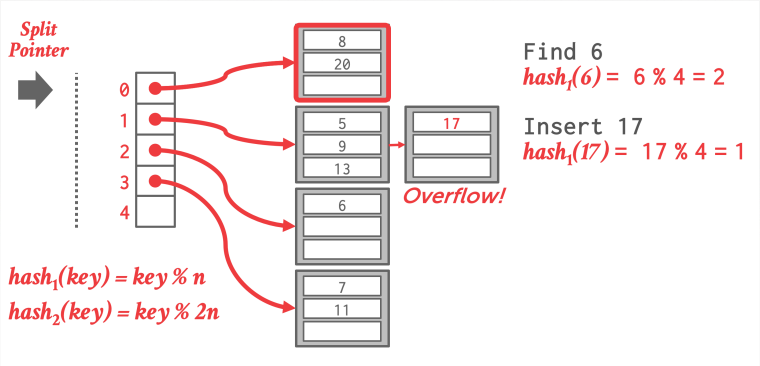
Insert 17

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

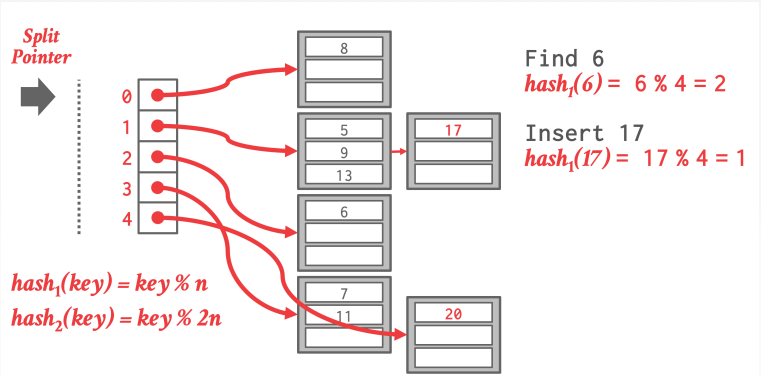
Linear Hashing



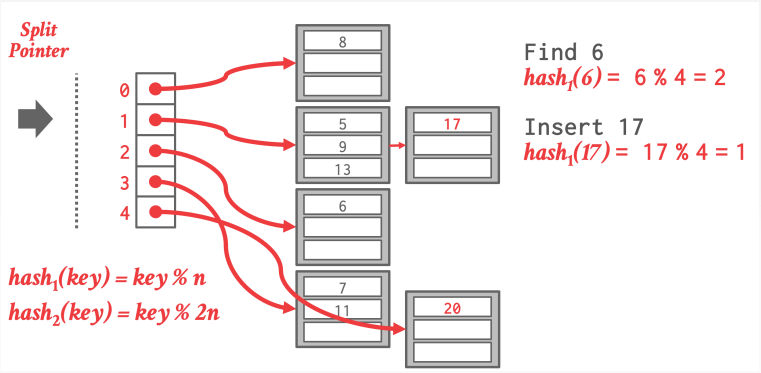
Linear Hashing



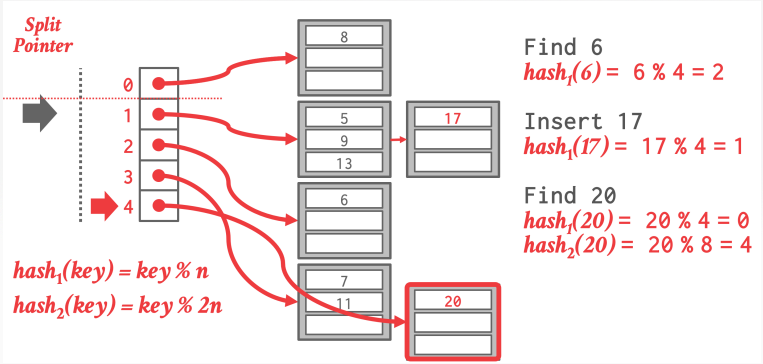
Linear Hashing



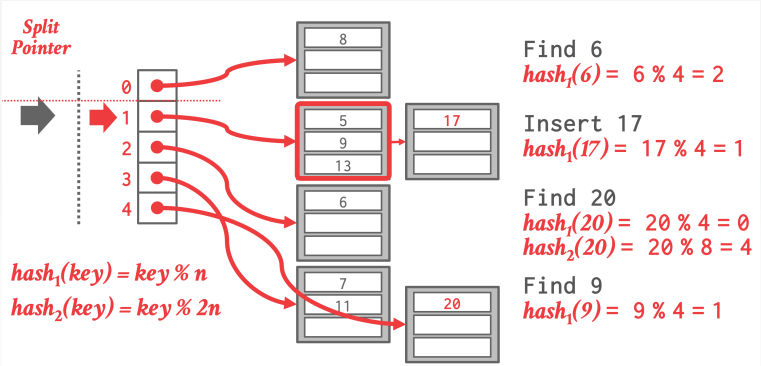
Linear Hashing



Linear Hashing



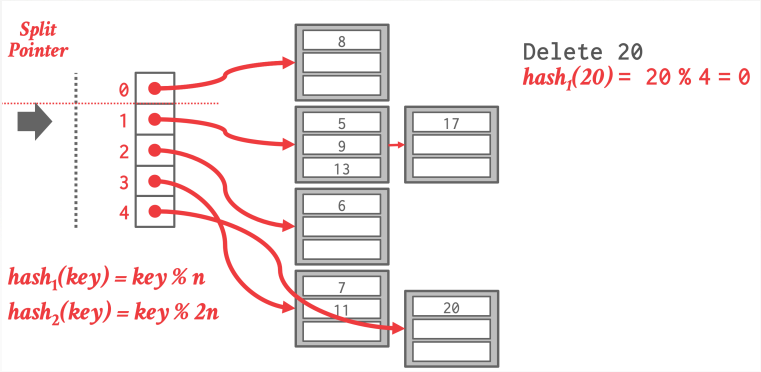
Linear Hashing



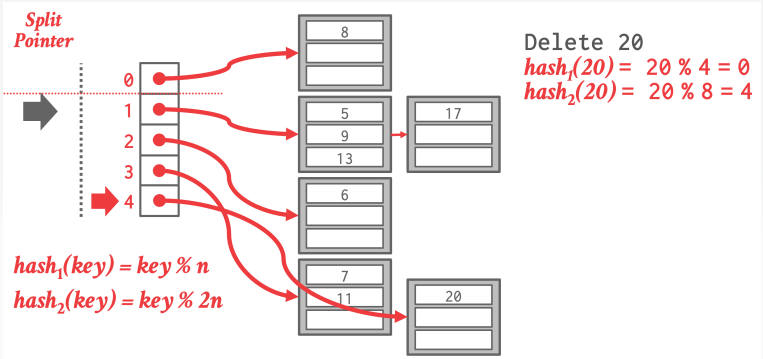
Linear Hashing - Delete

- 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.

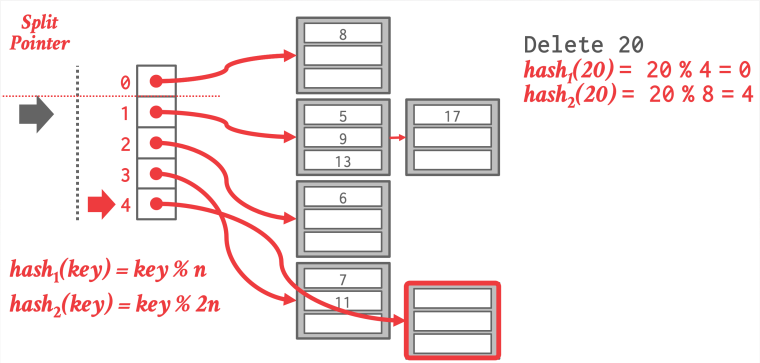
Linear Hashing – Delete



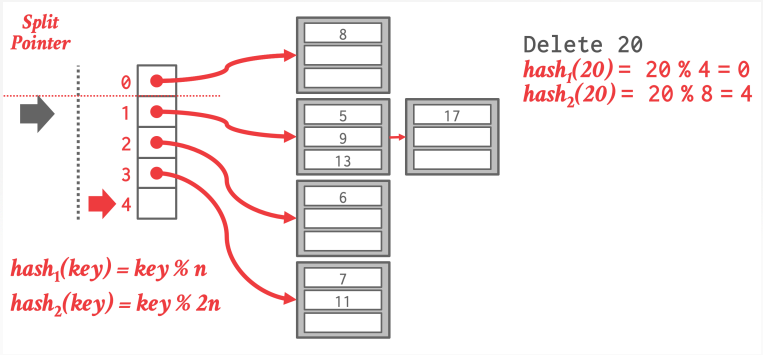
Linear Hashing – Delete



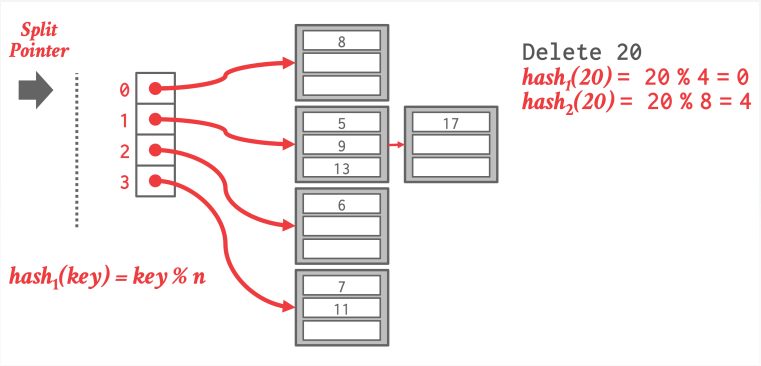
Linear Hashing – Delete



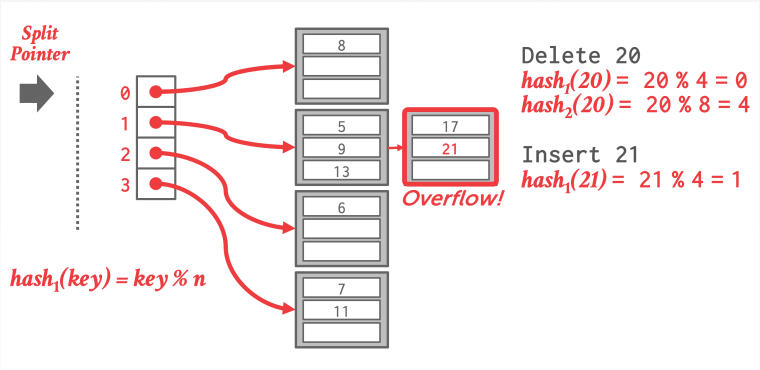
Linear Hashing – Delete



Linear Hashing – Delete



Linear Hashing – Delete



Linear Hashing vs. Extendible Hashing

- Moving from $hash_i$ to $hash_{i+1}$ 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 ⟶ 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!"