Project #1 is due Sunday, Sept 26th @11:59pm

Homework #2 is due Sunday, Oct 3rd @11:59pm
Your project implementation must be your own work.
→ You may not copy source code from other groups or the web.
→ Do not publish your implementation on GitHub.

Plagiarism will not be tolerated.
See CMU's Policy on Academic Integrity for additional information.
UPCOMING DATABASE TALKS

Google Napa
→ Today @4:30pm

TileDB
→ Monday, Sept 27th @4:30pm

BodoSQL
→ Monday, Oct 4th @4:30pm
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
→ Trees
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
→ Trees
DATA STRUCTURES

Internal Meta-data
Core Data Storage
Temporary Data Structures
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.
A **hash table** implements an unordered associative array that maps keys to values.

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

Space Complexity: \( O(n) \)

Time Complexity:
- Average: \( O(1) \)
- Worst: \( O(n) \)
A **hash table** implements an unordered associative array that maps keys to values.

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

Space Complexity: $O(n)$

Time Complexity: $\rightarrow$ Need to care about **constants**!
  $\rightarrow$ Average: $O(1)$
  $\rightarrow$ Worst: $O(n)$
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.
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.

\[
\text{hash(key)}
\]

\[
\begin{align*}
0 & \quad \square \\
1 & \quad \square \\
2 & \quad \square \\
\vdots & \quad \square \\
n & \quad \square 
\end{align*}
\]
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.

\[
\begin{array}{c|c}
\text{hash(key)} & \text{abc} \\
0 & \\
1 & \emptyset \\
2 & \text{def} \\
\vdots & \\
n & \text{xyz} \\
\end{array}
\]
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.

Perfect hash function.

→ If key1 ≠ key2, then hash(key1) ≠ hash(key2)
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 find/insert keys.
TODAY'S AGENDA

Hash Functions
Static Hashing Schemes
Dynamic Hashing Schemes
HASH FUNCTIONS

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

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 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.

**Google FarmHash (2014)**
→ Newer version of CityHash with better collision rates.
HASH FUNCTION BENCHMARK

Intel Core i7-8700K @ 3.70GHz

Throughput (MB/sec)

Key Size (bytes)

- crc64
- std::hash
- MurmurHash3
- CityHash
- FarmHash
- XXHash3

Source: Fredrik Widlund
STATIC 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.
→ Must store the key in the index to know when to stop scanning.
→ Insertions and deletions are generalizations of lookups.
LINEAR PROBE HASHING

hash(key)

A
B
C
D
E
F
LINEAR PROBE HASHING

hash(key)

A
B
C
D
E
F

A | val
LINEAR PROBE HASHING

hash(key)

A
B
C
D
E
F

A | val

<key> | <value>
LINEAR PROBE HASHING

\[ \text{hash(key)} \]

- A
- B
- C
- D
- E
- F

<table>
<thead>
<tr>
<th>B</th>
<th>val</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>val</td>
</tr>
</tbody>
</table>

...
LINEAR PROBE HASHING

\[ \text{hash(key)} \]

\[
\begin{array}{c|c}
A & \text{val} \\
B & \text{val} \\
C & A \quad \text{val} \\
D & \\
E & \\
F & \\
\end{array}
\]
LINEAR PROBE HASHING

hash(key)

A
B
C
D
E
F

B | val
A | val
C | val
LINEAR PROBE HASHING

hash(key)

A
B
C
D
E
F

B | val
A | val
C | val
D | val
LINEAR PROBE HASHING

hash(key)

A | val
B | val
C | val
D | val

A | val
B | val
C | val
D | val
E | val
F | val
LINEAR PROBE HASHING

hash(key)

A
B
C
D
E
F

B | val
A | val
C | val
D | val
E | val
# Linear Probe Hashing

The diagram illustrates the process of hash table probing. The hash function `hash(key)` is applied to the keys `A`, `B`, `C`, `D`, `E`, and `F`, resulting in their respective values. The table shows the following entries:

- `B | val`
- `A | val`
- `C | val`
- `D | val`
- `E | val`
- `F | val`

The sequence `A - B - C - D - E - F` suggests a linear probing strategy, where each subsequent probe occurs at the next index in the case of a collision.
### LINEAR PROBE HASHING – DELETES

**hash(key)**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>val</td>
</tr>
<tr>
<td>B</td>
<td>A</td>
<td>val</td>
</tr>
<tr>
<td>C</td>
<td>C</td>
<td>val</td>
</tr>
<tr>
<td>D</td>
<td>D</td>
<td>val</td>
</tr>
<tr>
<td>E</td>
<td>E</td>
<td>val</td>
</tr>
<tr>
<td>F</td>
<td>F</td>
<td>val</td>
</tr>
</tbody>
</table>

- **A** is deleted and moves **B**.
- **B** is deleted and moves **A**.
- **A** is deleted and moves **C**.
- **C** is deleted and moves **D**.
- **D** is deleted and moves **E**.
- **E** is deleted and moves **F**.
LINEAR PROBE HASHING – DELETES

hash(key)

Delete

A
B
C
D
E
F

B | val
A | val
C | val
D | val
E | val
F | val
LINEAR PROBE HASHING – DELETES

hash(key)

Delete

A
B
C
D
E
F

B | val
A | val
C | val
D | val
E | val
F | val
LINEAR PROBE HASHING – DELETES

hash(key)

Delete

A
B
C
D
E
F

B | val
A | val
D | val
E | val
F | val
LINEAR PROBE HASHING – DELETES

hash(key)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>val</td>
<td>A</td>
<td>val</td>
<td>D</td>
<td>val</td>
</tr>
<tr>
<td>E</td>
<td>val</td>
<td>F</td>
<td>val</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Linear Probe Hashing – Deletes

**hash(key)**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
</tr>
</tbody>
</table>

Find →

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>val</td>
</tr>
<tr>
<td>A</td>
<td>val</td>
</tr>
<tr>
<td>D</td>
<td>val</td>
</tr>
<tr>
<td>E</td>
<td>val</td>
</tr>
<tr>
<td>F</td>
<td>val</td>
</tr>
</tbody>
</table>
**LINEAR PROBE HASHING – DELETES**

<table>
<thead>
<tr>
<th>hash(key)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
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<tr>
<td>D</td>
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<tr>
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<p>| | |</p>
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<td>val</td>
</tr>
<tr>
<td></td>
<td>val</td>
</tr>
<tr>
<td>D</td>
<td>val</td>
</tr>
<tr>
<td>E</td>
<td>val</td>
</tr>
<tr>
<td>F</td>
<td>val</td>
</tr>
</tbody>
</table>
LINEAR PROBE HASHING – DELETES

hash(key)

A
B
C
D
E
F

Find

B | val
A | val
D | val
E | val
F | val
**LINEAR PROBE HASHING – DELETES**

**Approach #1: Tombstone**

```
hash(key)

A | val
B | val
C
D | val
E | val
F | val

Find
```

A
B
C
D
E
F
LINEAR PROBE HASHING – DELETES

Approach #1: Tombstone

hash(key)

A
B
C
D
E
F

Find

B | val
A | val
D | val
E | val
F | val
Approach #1: Tombstone

**hash(key)**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Find

```
hash(key)   
A   B   C   D   E   F
val

Approach #1: Tombstone
```
**LINEAR PROBE HASHING – DELETES**

### Approach #1: Tombstone
- A
- B
- C
- D
- E
- F

### Approach #2: Movement
- B `|` val
- A `|` val
- D `|` val
- E `|` val
- F `|` val

*hash(key)*
LINEAR PROBE HASHING – DELETES

Approach #1: Tombstone

Approach #2: Movement

hash(key)

A
B
C
D
E
F

B | val
A | val
D | val
E | val
F | val

Find
LINEAR PROBE HASHING – DELETES

hash(key)

A
B
C
D
E
F

Approach #1: Tombstone

Approach #2: Movement

Find
LINEAR PROBE HASHING – DELETES

Approach #1: Tombstone

Approach #2: Movement

hash(key)

A
B
C
D
E
F

A | val
D | val
E | val
F | val
LINEAR PROBE HASHING – DELETES

hash(key)

A
B
C
D
E
F

Approach #1: Tombstone

Approach #2: Movement
# Linear Probe Hashing – Deletes

<table>
<thead>
<tr>
<th>hash(key)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>C</td>
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<tr>
<td>D</td>
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<td></td>
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<tr>
<td>E</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Approach #1: Tombstone**

**Approach #2: Movement**
LINEAR PROBE HASHING – DELETES

hash(key)
A
B
C
D
E
F

Approach #1: Tombstone

Approach #2: Movement

Find
A | val
D | val
E | val
F | val
LINEAR PROBE HASHING – DELETES

Approach #1: Tombstone

Approach #2: Movement

hash(key)

Find

A
B
C
D
E
F

B | val

A | val

D | val

E | val

F | val
LINEAR PROBE HASHING – DELETES

Approach #1: Tombstone
Approach #2: Movement

hash(key)

A
B
C
D
E
F

Find

B \mid val

A \mid val

D \mid val

E \mid val

F \mid val
Non-Unique Keys

Choice #1: Separate Linked List

→ Store values in separate storage area for each key.
Choice #1: Separate Linked List
→ Store values in separate storage area for each key.
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.
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

hash(key)

A
B
C
D
E
F
ROBIN HOOD HASHING

hash(key)

A
B
C
D
E
F

A | val [0]
ROBIN HOOD HASHING

hash(key)

A
B
C
D
E
F

# of "Jumps" From First Position
ROBIN HOOD HASHING

hash(key)

A
B
C
D
E
F

A | val [0]
ROBIN HOOD HASHING

hash(key)

A
B
C
D
E
F

B | val [0]

A | val [0]
ROBIN HOOD HASHING

hash(key)

A
B
C
D
E
F

B | val [0]

A | val [0]

A[0] == C[0]
ROBIN HOOD HASHING

hash(key)

A
B
C
D
E
F

B | val [0]
A | val [0]
C | val [1]

A[0] == C[0]
ROBIN HOOD HASHING

hash(key)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>A</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>val[0]</td>
<td>val[0]</td>
<td>val[1]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C[1] > D[0]
ROBIN HOOD HASHING

```plaintext
hash(key)

<table>
<thead>
<tr>
<th></th>
<th>val</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>val[0]</td>
</tr>
<tr>
<td>A</td>
<td>val[0]</td>
</tr>
<tr>
<td>C</td>
<td>val[1]</td>
</tr>
<tr>
<td>D</td>
<td>val[1]</td>
</tr>
<tr>
<td>E</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
</tr>
</tbody>
</table>

C[1] > D[0]
ROBIN HOOD HASHING

\[ \text{hash(key)} \]

<table>
<thead>
<tr>
<th></th>
<th>( B \mid \text{val [0]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( A \mid \text{val [0]} )</td>
</tr>
<tr>
<td>B</td>
<td>( C \mid \text{val [1]} )</td>
</tr>
<tr>
<td>C</td>
<td>( D \mid \text{val [1]} )</td>
</tr>
<tr>
<td>D</td>
<td>F</td>
</tr>
<tr>
<td>E</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
</tr>
</tbody>
</table>
ROBIN HOOD HASHING

hash(key)

A
B
C
D
E
F

B | val [0]

A | val [0]

C | val [1]

D | val [1]

A[0] == E[0]
ROBIN HOOD HASHING

hash(key)

A
B
C
D
E
F

B | val [0]
A | val [0]
C | val [1]
D | val [1]

A[0] == E[0]
C[1] == E[1]
ROBIN HOOD HASHING

hash(key)

A
B
C
D
E
F

\[ A[0] == E[0] \]
\[ C[1] == E[1] \]
### ROBIN HOOD HASHING

**hash(key)**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td></td>
<td>A</td>
<td></td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>B</td>
<td></td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
<td>D</td>
<td></td>
<td>E</td>
<td></td>
</tr>
</tbody>
</table>

- A[0] == E[0]
- C[1] == E[1]
ROBIN HOOD HASHING

hash(key)

A | val [0]
B | val [0]
C | val [1]
E | val [1]
D | val [2]

A[0] == E[0]
C[1] == E[1]
ROBIN HOOD HASHING

hash(key)

A
B
C
D
E
F

<table>
<thead>
<tr>
<th>B</th>
<th>val [0]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>val [0]</td>
</tr>
<tr>
<td>C</td>
<td>val [1]</td>
</tr>
<tr>
<td>E</td>
<td>val [2]</td>
</tr>
<tr>
<td>D</td>
<td>val [2]</td>
</tr>
<tr>
<td>F</td>
<td>val [1]</td>
</tr>
</tbody>
</table>

D[2] > F[0]
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.

Best open-source implementation is from CMU.
CUCKOO HASHING

Hash Table #1

Hash Table #2
Cuckoo Hashing

Hash Table #1

Insert A

Hash Table #2
Hash Table #1

Hash Table #2

Insert A

\[ \text{hash}_1(A) \quad \text{hash}_2(A) \]
Cuckoo Hashing

Hash Table #1

Insert A

\[ \text{hash}_1(A) \]

\[ \text{hash}_2(A) \]

Hash Table #2
Cuckoo Hashing

Insert A

Hash Table #1

A | val

Hash Table #2

\[ \text{hash}_1(A) \quad \text{hash}_2(A) \]
CUCKOO HASHING

Hash Table #1

Insert A
hash_1(A)  hash_2(A)

Insert B
hash_1(B)  hash_2(B)

Hash Table #2

A | val
Hash Table #1

Insert A
hash₁(A) hash₂(A)

Insert B
hash₁(B) hash₂(B)

Hash Table #2
Cuckoo Hashing

Hash Table #1

A | val

Hash Table #2

B | val

Insert A
hash₁(A) hash₂(A)

Insert B
hash₁(B) hash₂(B)
CUCKOO HASHING

Hash Table #1

Insert A
\( \text{hash}_1(A) \quad \text{hash}_2(A) \)

Insert B
\( \text{hash}_1(B) \quad \text{hash}_2(B) \)

Insert C
\( \text{hash}_1(C) \quad \text{hash}_2(C) \)

Hash Table #2

B | val

A | val
Hash Table #1

Insert A
\[ \text{hash}_1(A) \text{ hash}_2(A) \]

Insert B
\[ \text{hash}_1(B) \text{ hash}_2(B) \]

Insert C
\[ \text{hash}_1(C) \text{ hash}_2(C) \]

Hash Table #2

\[ A | \text{val} \]
\[ B | \text{val} \]
CUCKOO HASHING

Hash Table #1

A | val

Insert A
hash₁(A)  hash₂(A)

Insert B
hash₁(B)  hash₂(B)

Insert C
hash₁(C)  hash₂(C)

Hash Table #2

B | val
CUCKOO HASHING

Hash Table #1

Insert A
\[\text{hash}_1(A) \quad \text{hash}_2(A)\]

A | val

Insert B
\[\text{hash}_1(B) \quad \text{hash}_2(B)\]

Insert C
\[\text{hash}_1(C) \quad \text{hash}_2(C)\]

Hash Table #2

C | val
Cuckoo Hashing

Hash Table #1

Insert A
\[ \text{hash}_1(A) \quad \text{hash}_2(A) \]

A | val

Insert B
\[ \text{hash}_1(B) \quad \text{hash}_2(B) \]

Insert C
\[ \text{hash}_1(C) \quad \text{hash}_2(C) \]
\[ \text{hash}_1(B) \]

Hash Table #2

C | val
Hash Table #1

Hash Table #2

Insert A
\[ \text{hash}_1(A) \quad \text{hash}_2(A) \]

Insert B
\[ \text{hash}_1(B) \quad \text{hash}_2(B) \]

Insert C
\[ \text{hash}_1(C) \quad \text{hash}_2(C) \quad \text{hash}_1(B) \]

A | val

C | val
**Cuckoo Hashing**

**Hash Table #1**
- Insert A
  - $\text{hash}_1(A)$
  - $\text{hash}_2(A)$
- Insert B
  - $\text{hash}_1(B)$
  - $\text{hash}_2(B)$
- Insert C
  - $\text{hash}_1(C)$
  - $\text{hash}_2(C)$

**Hash Table #2**
- C
  - val
Cuckoo Hashing

Hash Table #1

Insert A
\[ \text{hash}_1(A) \quad \text{hash}_2(A) \]

Insert B
\[ \text{hash}_1(B) \quad \text{hash}_2(B) \]

Insert C
\[ \text{hash}_1(C) \quad \text{hash}_2(C) \]
\[ \text{hash}_1(B) \quad \text{hash}_2(A) \]

Hash Table #2

...
Cuckoo Hashing

**Hash Table #1**

- Insert A
  - $\text{hash}_1(A)$
  - $\text{hash}_2(A)$

**Hash Table #2**

- Insert B
  - $\text{hash}_1(B)$
  - $\text{hash}_2(B)$
- Insert C
  - $\text{hash}_1(C)$
  - $\text{hash}_2(C)$
  - $\text{hash}_1(B)$
  - $\text{hash}_2(A)$
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.
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 resize themselves on demand.
→ Chained Hashing
→ Extendible Hashing
→ Linear 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

hash(key)

A
B
C
D
E
F
CHAINED HASHING

hash(key)

A
B
C
D
E
F

Bucket Pointers

Buckets
CHAINED HASHING

hash(key)

Bucket Pointers

A
B
C
D
E
F

A | val

Buckets
CHAINED HASHING

hash(key)

A
B
C
D
E
F

Bucket Pointers

B | val

A | val

Buckets
CHAINED HASHING

hash(key)

A
B
C
D
E
F

Bucket Pointers

B | val

A | val

C | val

Buckets
CHAINED HASHING

hash(key)

A
B
C
D
E
F

Bucket Pointers

B | val

A | val

C | val

Buckets
CHAINING HASHING

\[ \text{hash(key)} \]

\[ \begin{array}{c}
A \\
B \\
C \\
D \\
E \\
F \\
\end{array} \]

\[ \text{Bucket Pointers} \]

\[ \begin{array}{c}
B | \text{val} \\
\text{null} \\
\text{null} \\
\text{null} \\
\text{null} \\
\text{null} \\
\end{array} \]

\[ \begin{array}{c}
A | \text{val} \\
\text{null} \\
C | \text{val} \\
\text{null} \\
\text{null} \\
\text{null} \\
\end{array} \]

\[ \begin{array}{c}
D | \text{val} \\
\text{null} \\
\text{null} \\
\text{null} \\
\text{null} \\
\text{null} \\
\end{array} \]
CHAINED HASHING

hash(key)

A
B
C
D
E
F

Bucket Pointers

B | val

A | val

C | val

D | val

E | val
CHAINED HASHING

hash(key)

A
B
C
D
E
F

Bucket Pointers

B | val
A | val
C | val
D | val
E | val
F | val
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.

Reshuffle bucket entries on split and increase the number of bits to examine.
→ Data movement is localized to just the split chain.
EXTENDIBLE HASHING

2

0 0...
0 1...
1 0...
1 1...

0010...
0110...
10101...
10011...
11010...
EXTENDIBLE HASHING

global

0 0 ...
0 1 ...
1 0 ...
1 1 ...

0010...
0110...
10101...
10011...
11010...

1
2
2
EXTENDIBLE HASHING

global 2

0 0...
0 1...
1 0...
1 1...

local

00010...
01110...

1...

local

10101...
10011...

2

local

11010...
11010...
EXTENDIBLE HASHING

- **global**
  - 2
- **local**
  - 1
  - 0010...
  - 01110...
  - 2
  - 10101...
  - 10011...
  - 2
  - 11010...
EXTENDIBLE HASHING

Find A
\[ \text{hash}(A) = 01110... \]
EXTENDIBLE HASHING

Find A
hash(A) = 01110...

global

local

00...
01...
10...
11...

1 0010...
0 0110...
1 1010...
1 10011...

1
2
3

11010...
10101...
10011...

EXTENDIBLE HASHING

Find A
\[ \text{hash}(A) = 01110... \]
**EXTENDIBLE HASHING**

Find A
\[ \text{hash}(A) = 01110... \]

Insert B
\[ \text{hash}(B) = 10111... \]
EXTENDIBLE HASHING

Find A
\[ \text{hash}(A) = 01110... \]

Insert B
\[ \text{hash}(B) = 10111... \]
**EXTENDIBLE HASHING**

Find A
\[hash(A) = 01110\ldots\]

Insert B
\[hash(B) = 10111\ldots\]

Insert C
\[hash(C) = 10100\ldots\]
EXTENDIBLE HASHING

Find A
\[
\text{hash}(A) = 01110... 
\]

Insert B
\[
\text{hash}(B) = 10111... 
\]

Insert C
\[
\text{hash}(C) = 10100... 
\]
EXTENDIBLE HASHING

Find A
\[ \text{hash}(A) = 01110... \]

Insert B
\[ \text{hash}(B) = 10111... \]

Insert C
\[ \text{hash}(C) = 10100... \]
EXTENDIBLE HASHING

Find A  
\[ \text{hash}(A) = 01110... \]

Insert B  
\[ \text{hash}(B) = 10111... \]

Insert C  
\[ \text{hash}(C) = 10100... \]
EXTENDIBLE HASHING

Find A
$hash(A) = 01110\ldots$

Insert B
$hash(B) = 10111\ldots$

Insert C
$hash(C) = 10100\ldots$
### EXTENDIBLE HASHING

- **Find A**
  \[
  \text{hash}(A) = 01110... 
  \]

- **Insert B**
  \[
  \text{hash}(B) = 10111... 
  \]

- **Insert C**
  \[
  \text{hash}(C) = 10100... 
  \]
EXTENDIBLE HASHING

Find A
\[ \text{hash}(A) = 01110... \]

Insert B
\[ \text{hash}(B) = 10111... \]

Insert C
\[ \text{hash}(C) = 10100... \]
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

0  1  2  3

- 8  20
- 5  9  13
- 6
- 7  11
LINEAR HASHING

Split Pointer

0
1
2
3

8
20

5
9
13

6

7
11
**LINEAR HASHING**

\[ \text{hash}_1(\text{key}) = \text{key} \mod n \]
**LINEAR HASHING**

- **Split Pointer**

- **Find 6**
  
  \[ \text{hash}_1(6) = 6 \mod 4 = 2 \]

- **hash\_1(key) = key \mod n**

Diagram showing the linear hashing process with keys: 6, 8, 20, 5, 9, 13, 6, 7, 11.
**LINEAR HASHING**

Split Pointer

Find 6
\[ \text{hash}_1(6) = 6 \mod 4 = 2 \]

Insert 17
\[ \text{hash}_1(17) = 17 \mod 4 = 1 \]

\[ \text{hash}_1(key) = \text{key} \mod n \]
**Linear Hashing**

\[ \text{hash}_1(key) = key \mod n \]

Find 6
\[ \text{hash}_1(6) = 6 \mod 4 = 2 \]

Insert 17
\[ \text{hash}_1(17) = 17 \mod 4 = 1 \]

Overflow!
LINEAR HASHING

\[ \text{hash}_1(\text{key}) = \text{key} \mod n \]

Find 6
\[ \text{hash}_1(6) = 6 \mod 4 = 2 \]

Insert 17
\[ \text{hash}_1(17) = 17 \mod 4 = 1 \]

Overflow!
LINEAR HASHING

hash₁(key) = key % n
hash₂(key) = key % 2n

Split Pointer

Find 6
hash₁(6) = 6 % 4 = 2

Insert 17
hash₁(17) = 17 % 4 = 1

Overflow!
**Split Pointer**

Find 6

$\text{hash}_1(6) = 6 \mod 4 = 2$

Insert 17

$\text{hash}_1(17) = 17 \mod 4 = 1$

$\text{hash}_1(key) = key \mod n$

$\text{hash}_2(key) = key \mod 2n$
**LINEAR HASHING**

Find 6
\[ \text{hash}_1(6) = 6 \mod 4 = 2 \]

Insert 17
\[ \text{hash}_1(17) = 17 \mod 4 = 1 \]

\[ \text{hash}_1(\text{key}) = \text{key} \mod n \]
\[ \text{hash}_2(\text{key}) = \text{key} \mod 2n \]
LINEAR HASHING

Split Pointer

Find 6
\[ hash_1(6) = 6 \mod 4 = 2 \]

Insert 17
\[ hash_1(17) = 17 \mod 4 = 1 \]

Find 20
\[ hash_1(20) = 20 \mod 4 = 0 \]

Split Pointer

\[ hash_1(key) = key \mod n \]
\[ hash_2(key) = key \mod 2n \]
LINEAR HASHING

$hash_1(key) = key \% n$

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

Split Pointer

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

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

Find 20
$hash_1(20) = 20 \% 4 = 0$
LINEAR HASHING

Split Pointer

\[
\text{hash}_1(\text{key}) = \text{key} \mod n
\]

\[
\text{hash}_2(\text{key}) = \text{key} \mod 2n
\]

Find 6
\[
\text{hash}_1(6) = 6 \mod 4 = 2
\]

Insert 17
\[
\text{hash}_1(17) = 17 \mod 4 = 1
\]

Find 20
\[
\text{hash}_1(20) = 20 \mod 4 = 0
\]
\[
\text{hash}_2(20) = 20 \mod 8 = 4
\]
**LINEAR HASHING**

*Split Pointer*

\[
\text{hash}_1(key) = key \mod n
\]

\[
\text{hash}_2(key) = key \mod 2n
\]

---

Find 6
\[\text{hash}_1(6) = 6 \mod 4 = 2\]

Insert 17
\[\text{hash}_1(17) = 17 \mod 4 = 1\]

Find 20
\[\text{hash}_1(20) = 20 \mod 4 = 0\]
\[\text{hash}_2(20) = 20 \mod 8 = 4\]

Find 9
\[\text{hash}_1(9) = 9 \mod 4 = 1\]
**LINEAR HASHING**

- **Hash function 1**:
  \[ \text{hash}_1(key) = key \% n \]

- **Hash function 2**:
  \[ \text{hash}_2(key) = key \% 2n \]

- **Example**:
  - **Find 6**
    \[ \text{hash}_1(6) = 6 \% 4 = 2 \]
  - **Insert 17**
    \[ \text{hash}_1(17) = 17 \% 4 = 1 \]
  - **Find 20**
    \[ \text{hash}_1(20) = 20 \% 4 = 0 \]
    \[ \text{hash}_2(20) = 20 \% 8 = 4 \]
  - **Find 9**
    \[ \text{hash}_1(9) = 9 \% 4 = 1 \]
LINEAR HASHING

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.
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...
**NEXT CLASS**

**B+Trees**

→ aka "The Greatest Data Structure of All Time"