

# VE281

## Data Structures and Algorithms

### **Hashing: Collision Resolution**

#### **Learning Objectives:**

- Understand separate chaining
- Understand the general idea of open addressing
- Know three basic ways of open addressing and their advantages and disadvantages

# Announcement

- No OH tomorrow (9/29)

# Outline

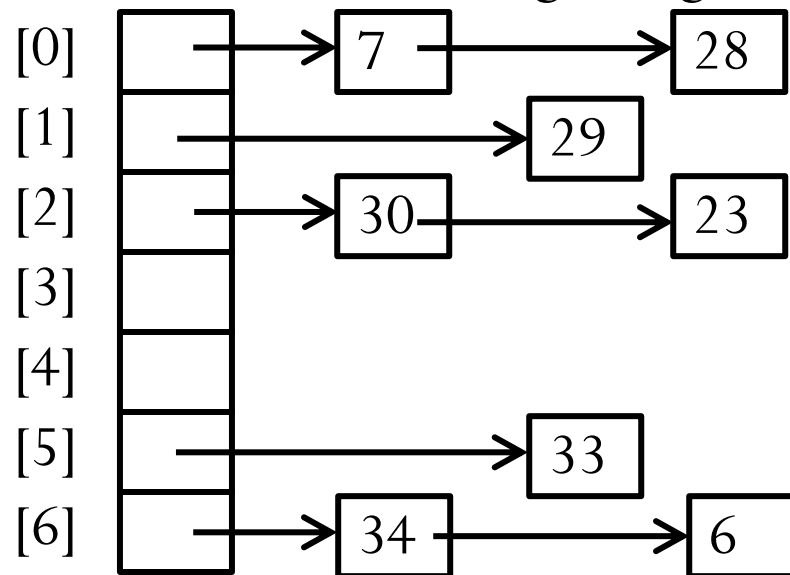
- Collision Resolution: Separate Chaining
- Collision Resolution: Open Addressing
  - Linear Probing
  - Quadratic Probing and Double Hashing
  - Performance of Open Addressing

# Collision Resolution Scheme

- **Collision-resolution scheme**: assigns distinct locations in the hash table to items involved in a collision.
- Two major scheme:
  - Separate chaining
  - Open addressing

# Separate Chaining

- Each bucket keeps a **linked list** of all items whose home buckets are that bucket.
- Example: Put pairs whose keys are 6, 23, 34, 28, 29, 7, 33, 30 into a hash table with  $n = 7$  buckets.
  - **homeBucket = key % 7**
  - Note: we insert object at the beginning of a linked list.



# Separate Chaining

- **Value find(Key key)**
  - Compute  $k = h(key)$
  - Search in the linked list located at the  $k$ -th bucket (e.g., check every entry) with the key.
- **void insert(Key key, Value value)**
  - Compute  $k = h(key)$
  - Search in the linked list located at the  $k$ -th bucket. If found, update its value; otherwise, insert the pair at the beginning of the linked list in  $O(1)$  time.

# Separate Chaining

- **Value remove(Key key)**
  - Compute  $k = h(key)$
  - Search in the linked list located at the  $k$ -th bucket. If found, remove that pair.

# Short Break



# Outline

- Collision Resolution: Separate Chaining
- Collision Resolution: Open Addressing
  - Linear Probing
  - Quadratic Probing and Double Hashing
  - Performance of Open Addressing

# Open Addressing

- Reuse empty space in the hash table to hold colliding items.
- To do so, search the hash table in some systematic way for a bucket that is empty.
  - Idea: we use a sequence of hash functions  $h_0, h_1, h_2, \dots$  to probe the hash table until we find an empty slot.
    - I.e., we **probe** the hash table buckets mapped by  $h_0(\text{key})$ ,  $h_1(\text{key})$ ,  $\dots$ , in sequence, until we find an empty slot.
    - Generally, we could define  $h_i(x) = h(x) + f(i)$

# Open Addressing

- Three methods:

- Linear probing:

$$h_i(x) = (h(x) + i) \% n$$

- Quadratic probing:

$$h_i(x) = (h(x) + i^2) \% n$$

- Double hashing:

$$h_i(x) = (h(x) + i * g(x)) \% n$$

$n$  is the hash table size

# Linear Probing

$$h_i(\text{key}) = (h(\text{key}) + i) \% n$$

- Apply hash function  $h_0, h_1, \dots$ , in sequence until we find an empty slot.
  - This is equivalent to doing a linear search from  $h(\text{key})$  until we find an empty slot.
- Example: Hash table size  $n = 9$ ,  $h(\text{key}) = \text{key} \% 9$ 
  - Thus  $h_i(\text{key}) = (\text{key} \% 9 + i) \% 9$
  - Suppose we insert 1, 5, 11, 2, 17, 21, 31 in sequence

	1	11			5			
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]

How about 2?

# Linear Probing

## Example

- Hash table size  $n = 9$ ,  $h(\text{key}) = \text{key} \% 9$ 
  - Thus  $h_i(\text{key}) = (\text{key} \% 9 + i) \% 9$
  - Suppose we insert 1, 5, 11, 2, 17, 21, 31 in sequence.

	1	11	2	21	5	31		17
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]

- $h_0(2) = 2$ . Not empty!
- So we try  $h_1(2) = 3$ . It is empty, so we insert there!
- $h_0(21) = 3$ . Not empty!
- $h_1(21) = 4$ . It is empty, so we insert there!
- $h_0(31) = 4$ . Not empty!
- $h_1(31) = 5$ . Not empty!
- $h_2(31) = 6$ . It is empty, so we insert there!

# Linear Probing

find()

	1	11	2	21	5	31		17
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]

- With linear probing  $h_i(\text{key}) = (\text{key} \% 9 + i) \% 9$ 
  - How will you **search** an item with key = 31?
  - How will you **search** an item with key = 10?
- Procedure: probe in the buckets given by  $h_0(\text{key})$ ,  $h_1(\text{key})$ , ..., in sequence **until**
  - we find the key,
  - or we find an empty slot, which means the key is not found.

# Linear Probing

remove()

	1	11	2	21	5	31		17
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]

- With linear probing  $h_i(\text{key}) = (\text{key} \% 9 + i) \% 9$ 
  - How will you **remove** an item with key = 11?
  - If we just find 11 and delete it, will this work?

	1		2	21	5	31		17
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]

What is the result for searching key = 2 with the above hash table?

# Linear Probing

remove()

**cluster**

	1		2	21	5	31		17
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]

- After deleting 11, we need to **rehash** the following “cluster” to fill the vacated bucket.
- However, we cannot move an item **beyond** its **actual** hash position. In this example, 5 cannot be moved ahead.

	1		2	21	5	31		17
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]



# Linear Probing

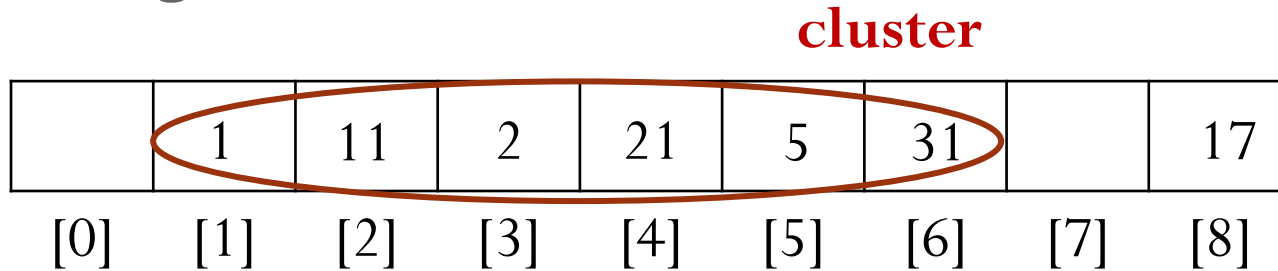
Alternative implementation of remove()

	1	del	2	21	5	31		17
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]

- **Lazy deletion**: we mark deleted entry as “**deleted**”.
  - “deleted” is not the same as “empty”.
  - Now each bucket has three states: “occupied”, “empty”, and “deleted”.
- We can overwrite the “deleted” entry when inserting.
- When we **search**, we will keep looking if we encounter a “deleted” entry.

# Linear Probing

## Clustering Problem



- Clustering: when **contiguous** buckets are all occupied.
- **Claim**: Any hash value inside the cluster adds to **the end** of that cluster.
- Problems with a **large** cluster:
  - It becomes more likely that the next hash value will collide with the cluster.
  - Collisions in the cluster get more expensive to resolve.

# Linear Probing

## Clustering Problem

- Assuming input size  $N$ , table size  $2N$ :
  - What is the best-case cluster distribution?



- What is the worst-case cluster distribution?





# Which Statements Are Correct?

- Assuming input size  $N$ , table size  $2N$ . Analyze the average number of probes to find an empty slot for best-case and worst-case clusters. Select all the correct answers.
- A. The average number for best-case cluster is 1.5.
- B. The average number for best-case cluster is 1.
- C. The average number for worst-case cluster is roughly  $\frac{1}{4}N$ .
- D. The average number for worst-case cluster is roughly  $\frac{1}{2}N$ .

Best Case	X		X		X		X	
-----------	---	--	---	--	---	--	---	--

Worst Case			X	X	X	X		
------------	--	--	---	---	---	---	--	--

# Short Break

# Outline

- Collision Resolution: Separate Chaining
- Collision Resolution: Open Addressing
  - Linear Probing
  - Quadratic Probing and Double Hashing
  - Performance of Open Addressing

# Quadratic Probing

$$h_i(\text{key}) = (h(\text{key}) + i^2) \% n$$

- It is less likely to form large clusters.
- Example: Hash table size  $n = 7$ ,  $h(\text{key}) = \text{key} \% 7$ 
  - Thus  $h_i(\text{key}) = (\text{key} \% 7 + i^2) \% 7$
  - Suppose we insert 9, 16, 11, 2 in sequence.

		9	16	11		2
[0]	[1]	[2]	[3]	[4]	[5]	[6]

- $h_0(16) = 2$ . Not empty!
- $h_1(16) = 3$ . It is empty, so we insert there.
- $h_0(2) = 2$ . Not empty!
- $h_1(2) = 3$ . Not empty!
- $h_2(2) = 6$ . It is empty, so we insert there.

# Problem of Quadratic Probing

- However, sometimes we will never find an empty slot even if the table isn't full!
- Luckily, if the **load factor**  $L \leq 0.5$ , we are guaranteed to find an empty slot.
  - Definition: given a hash table with  $n$  buckets that stores  $m$  objects, its **load factor** is

$$L = \frac{m}{n} = \frac{\text{\#objects in hash table}}{\text{\#buckets in hash table}}$$



# More on Load Factor of Hash Table

- Question: which collision resolution strategy is feasible for load factor larger than 1?
  - Answer: separate chaining.
  - Note: for open addressing, we require  $L \leq 1$ .
- Claim:  $L = O(1)$  is a necessary condition for operations to run in constant time.

# Double Hashing

$$h_i(x) = (h(x) + i * g(x)) \% n$$

- Uses 2 distinct hash functions.
- Increment **differently** depending on the key.
  - If  $h(x) = 13$ ,  $g(x) = 17$ , the probe sequence is 13, 30, 47, 64, ...
  - If  $h(x) = 19$ ,  $g(x) = 7$ , the probe sequence is 19, 26, 33, 40, ...
  - For linear and quadratic probing, the incremental probing patterns are **the same** for all the keys.

# Double Hashing

## Example

- Hash table size  $n = 7$ ,  $h(\text{key}) = \text{key} \% 7$ ,  
 $g(\text{key}) = (5 - \text{key}) \% 5$ 
  - Thus  $h_i(\text{key}) = (\text{key} \% 7 + (5 - \text{key}) \% 5 * i) \% 7$
  - Suppose we insert 9, 16, 11, 2 in sequence.

		9		11	2	16
[0]	[1]	[2]	[3]	[4]	[5]	[6]

- $h_0(16) = 2$ . Not empty!
- $h_1(16) = 6$ . It is empty, so we insert there.
- $h_0(2) = 2$ . Not empty!
- $h_1(2) = 5$ . It is empty, so we insert there.

# Outline

- Collision Resolution: Separate Chaining
- Collision Resolution: Open Addressing
  - Linear Probing
  - Quadratic Probing and Double Hashing
  - Performance of Open Addressing

# Performance of Open Addressing

- Hard to analyze rigorously.
- The runtime is dominated by the number of comparisons.
- The number of comparisons depends on the load factor  $L$ .
- Define the expected number of comparisons in an **unsuccessful search** as  $U(L)$ .
- Define the expected number of comparisons in a **successful search** as  $S(L)$ .

# Expected Number of Comparisons

- Linear probing

$$U(L) = \frac{1}{2} \left[ 1 + \left( \frac{1}{1-L} \right)^2 \right]$$
$$S(L) = \frac{1}{2} \left[ 1 + \frac{1}{1-L} \right]$$

$L$	$U(L)$	$S(L)$
0.5	2.5	1.5
0.75	8.5	2.5
0.9	50.5	5.5

$L \leq 0.75$  is recommended.

# Expected Number of Comparisons

- Quadratic probing and double hashing

$$U(L) = \frac{1}{1-L}$$
$$S(L) = \frac{1}{L} \ln \frac{1}{1-L}$$

$L$	$U(L)$	$S(L)$
0.5	2	1.4
0.75	4	1.8
0.9	10	2.6

# Which Strategy to Use?

- Both separate chaining and open addressing are used in real applications.
- Some basic guidelines:
  - If space is important, better to use open addressing.
  - If need removing items, better to use separate chaining.
    - **remove ( )** is tricky in open addressing.
  - In mission critical application, prototype both and compare.