

# CSE 332 Winter 2026

## Lecture 11: hashing 2

Nathan Brunelle

<http://www.cs.uw.edu/332>

# Dictionary (Map) ADT

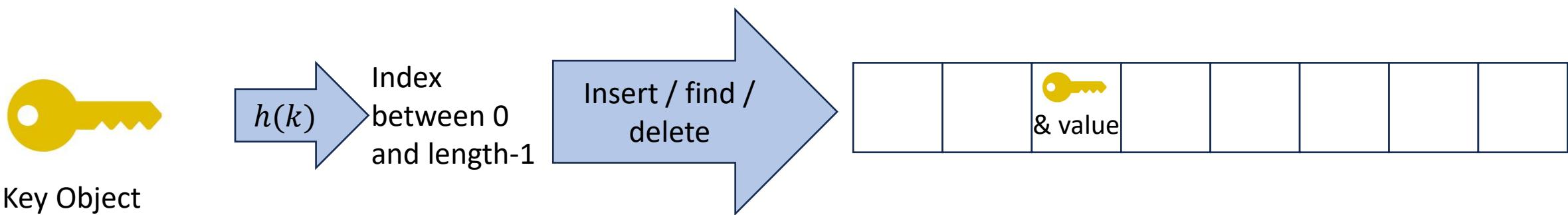
- Contents:
  - Sets of key+value pairs
  - ~~Keys must be comparable~~ Keys have a hash function
- Operations:
  - **insert(key, value)**
    - Adds the (key,value) pair into the dictionary
    - If the key already has a value, overwrite the old value
      - Consequence: Keys cannot be repeated
  - **find(key)**
    - Returns the value associated with the given key
  - **delete(key)**
    - Remove the key (and its associated value)

# Next topic: Hash Tables

Data Structure	Time to insert	Time to find	Time to delete
Unsorted Array	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Unsorted Linked List	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Sorted Array	$\Theta(n)$	$\Theta(\log n)$	$\Theta(n)$
Sorted Linked List	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Binary Search Tree	$\Theta(\text{height})$	$\Theta(\text{height})$	$\Theta(\text{height})$
AVL Tree	$\Theta(\log n)$	$\Theta(\log n)$	$\Theta(\log n)$
Hash Table (Worst case)	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Hash Table (Average)	$\Theta(1)$	$\Theta(1)$	$\Theta(1)$

# Hash Tables

- Idea:
  - Have a small array to store information
  - Use a **hash function** to convert the key into an index
    - Hash function should “scatter” the keys, behave as if it randomly assigned keys to indices
  - Store key at the index given by the hash function
  - Do something if two keys map to the same place (should be very rare)
    - Collision resolution



# Properties of a “Good” Hash

- Definition: A hash function maps objects to integers
- **Consistent**
  - Objects considered “equal” should hash to the same value
  - Deterministic: running the hash function on the same object twice should yield the same result
- **Uniform**
  - Should be able to use every index in a fixed-size array
  - Should use every index at roughly equal rates
- **Effective**
  - It should be difficult to find two objects which hash to the same value
  - Given an object, it should be hard to find a different object which hashes to the same value
  - “Avalanche effect”: making a small change to the object yields big changes in the value it hashes to
- **Efficient**
  - Time to calculate the hash should be very small

# Ideal Insert procedure

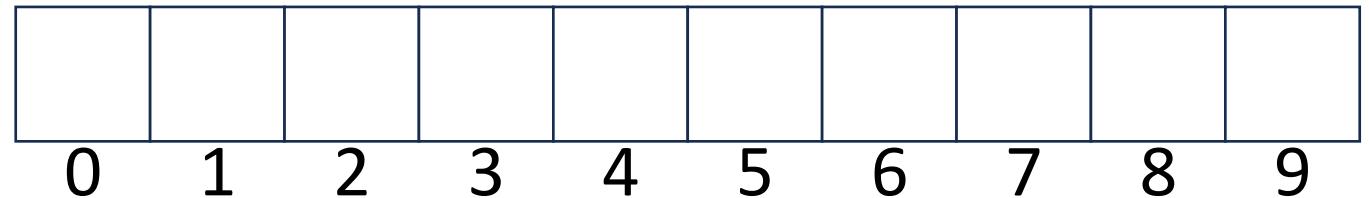
Supposing we have a “good” hash function:

```
insert(key, value){  
    h = key.hash();  
    table[h % table.length] = value;  
}
```

Problem: It's possible that two different keys map to the same index!  
This is called a “collision”

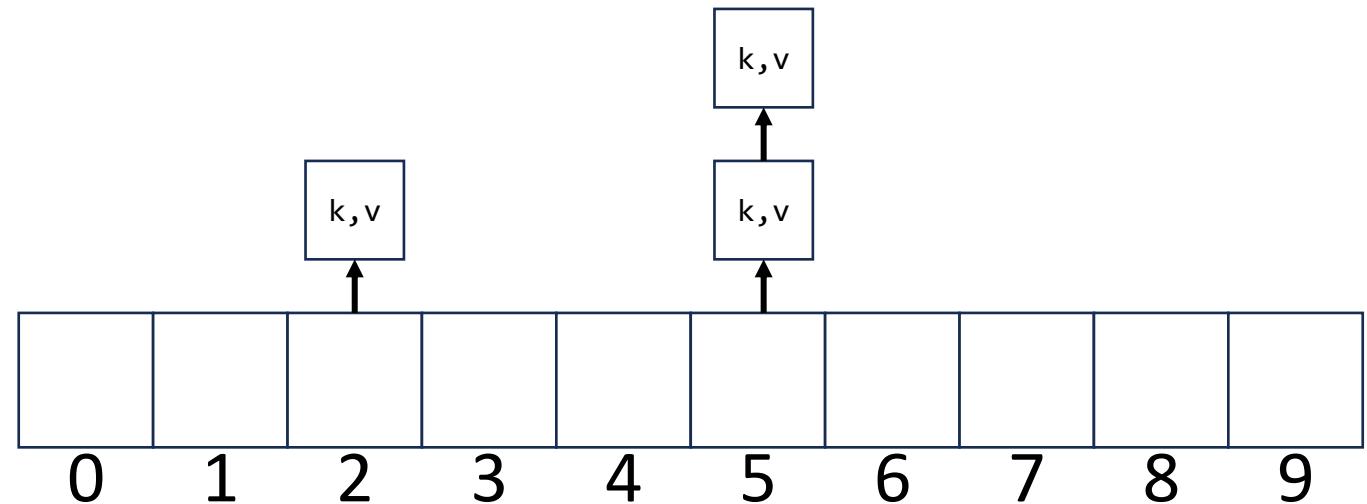
# Collision Resolution

- A Collision occurs when we want to insert something into an already-occupied position in the hash table
- 2 main strategies:
  - Separate Chaining
    - Use a secondary data structure to contain the items
      - E.g. each index in the hash table is itself a linked list
  - Open Addressing
    - Use a different spot in the table instead
      - Linear Probing
      - Quadratic Probing
      - Double Hashing



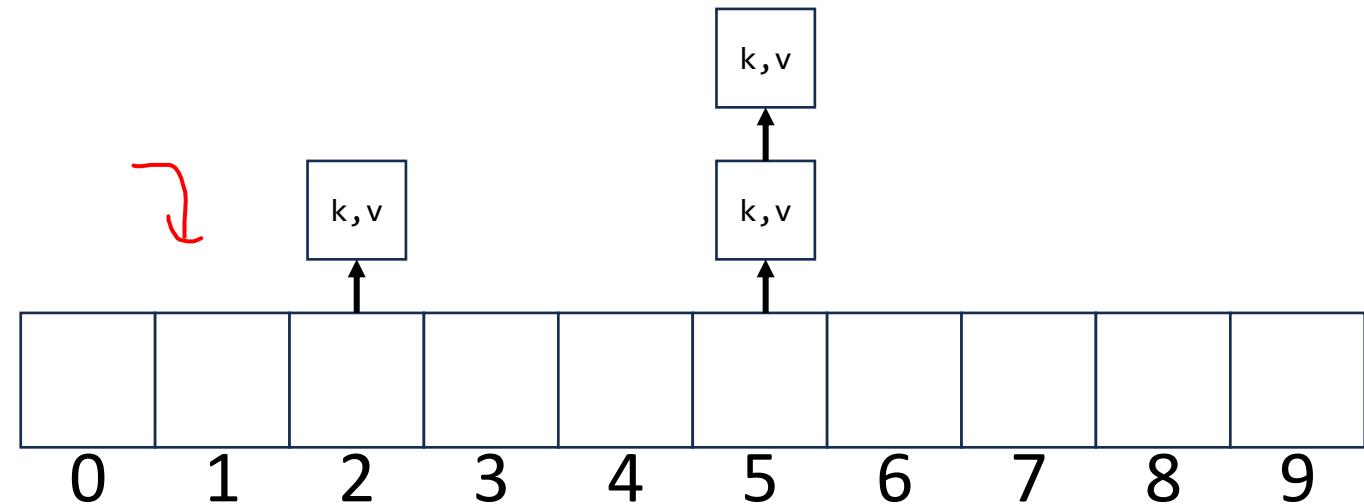
# Separate Chaining Insert

- To insert  $k, v$ :
  - Compute the index using  $i = h(k) \% \text{table.length}$
  - Add the key-value pair to the data structure at  $\text{table}[i]$



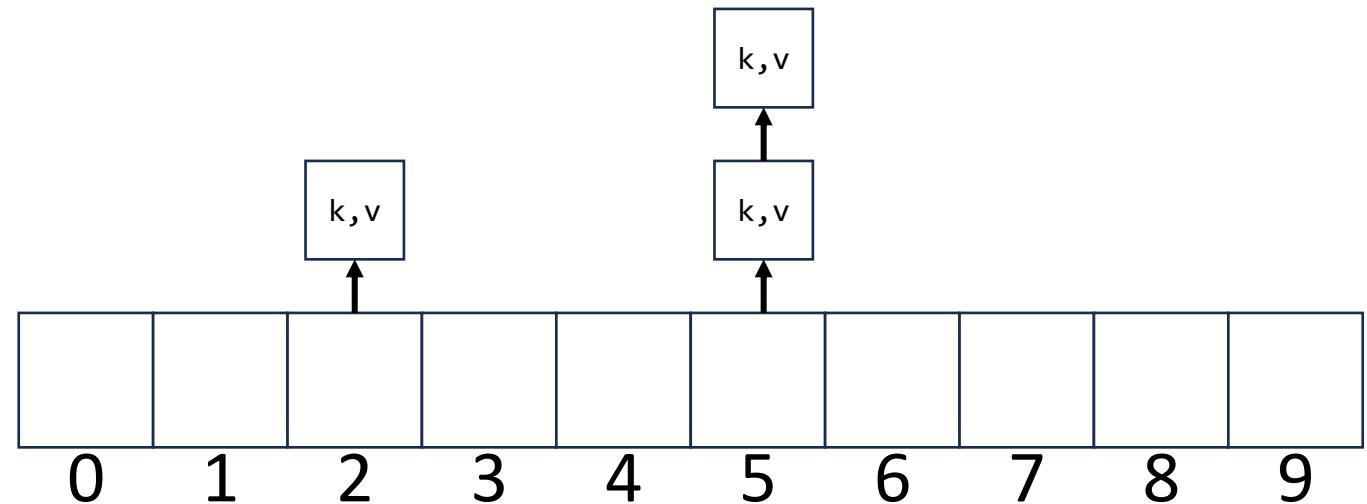
# Separate Chaining Find

- To find  $k$ :
  - Compute the index using  $i = h(k) \% \text{table.length}$
  - Call find with the key on the data structure at  $\text{table}[i]$



# Separate Chaining Delete

- To delete  $k$ :
  - Compute the index using  $i = h(k) \% \text{table.length}$
  - Call delete with the key on the data structure at  $\text{table}[i]$



# Formal Running Time Analysis

1)

- The **load factor** of a hash table represents the average number of items per “bucket”
  - $\lambda = \frac{n}{length}$
- Assume we have a hash table that uses a linked-list for separate chaining
  - What is the expected number of comparisons needed in an unsuccessful find?
  - What is the expected number of comparisons needed in a successful find?
  - How can we make the expected running time  $\Theta(1)$ ?

1  
2

# Formal Running Time Analysis

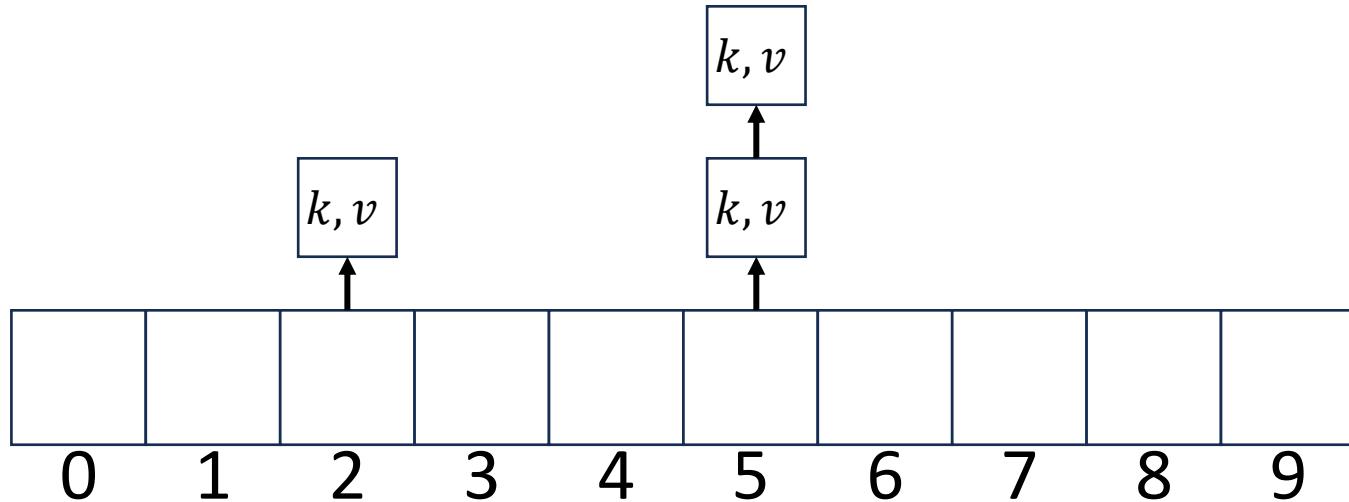
- The **load factor** of a hash table represents the average number of items per “bucket”
  - $\lambda = \frac{n}{length}$
- Assume we have a hash table that uses a linked-list for separate chaining
  - What is the expected number of comparisons needed in an unsuccessful find?
    - $\lambda$
  - What is the expected number of comparisons needed in a successful find?
    - $\frac{\lambda}{2}$
- How can we make the expected running time  $\Theta(1)$ ?
  - Pick a constant value, resize the array whenever  $\lambda$  exceeds that constant

# Rehashing

- If your load factor  $\lambda$  gets too large, copy everything over to a larger hash table
  - To do this: make a new, larger array
  - Re-insert all items into the new hash table by reapplying the hash function
    - We need to reapply the hash function because items should map to a different index
  - New array should be “roughly” double the length (but probably still want it to be prime)
- What does “too large” mean?
  - For separate chaining, typically we want  $\lambda < 2$
  - For open addressing, typically we want  $\lambda < \frac{1}{2}$

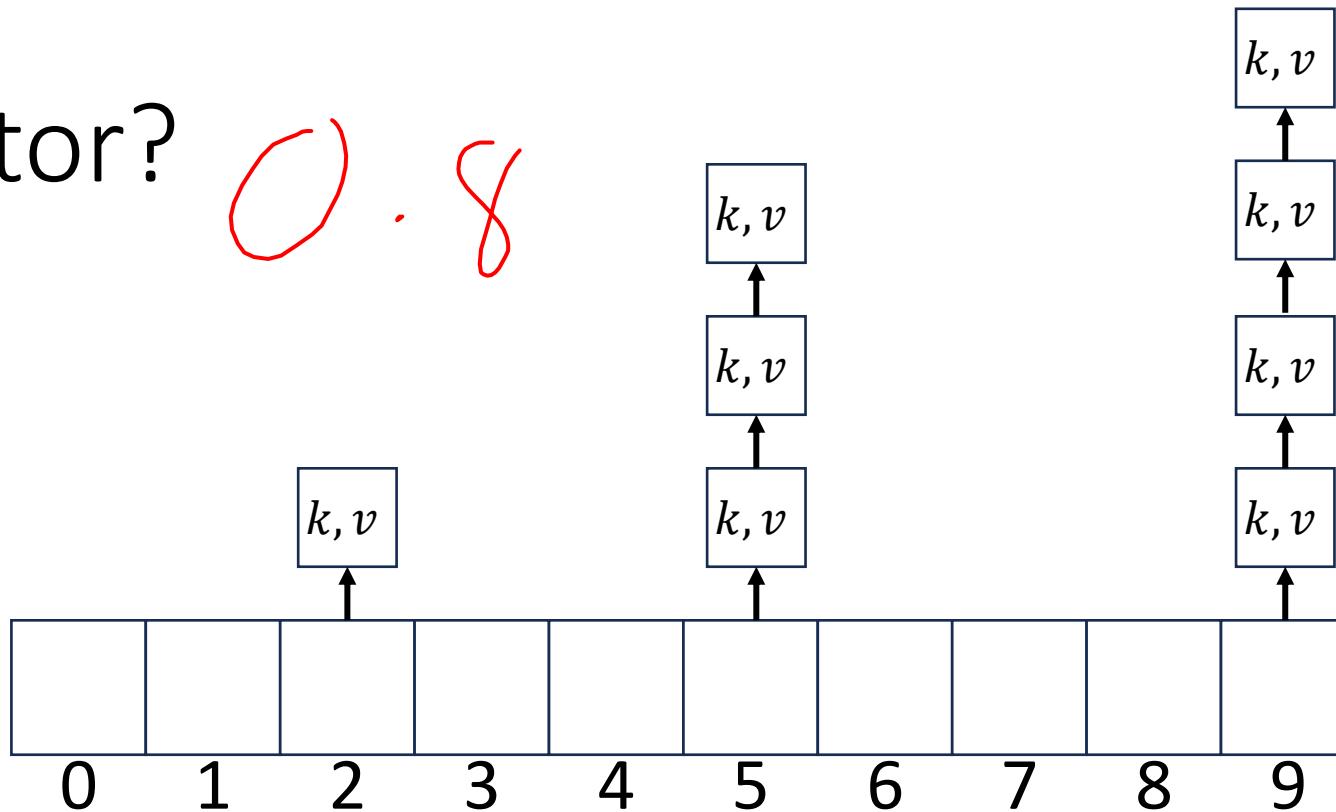
# Load Factor?

0.3



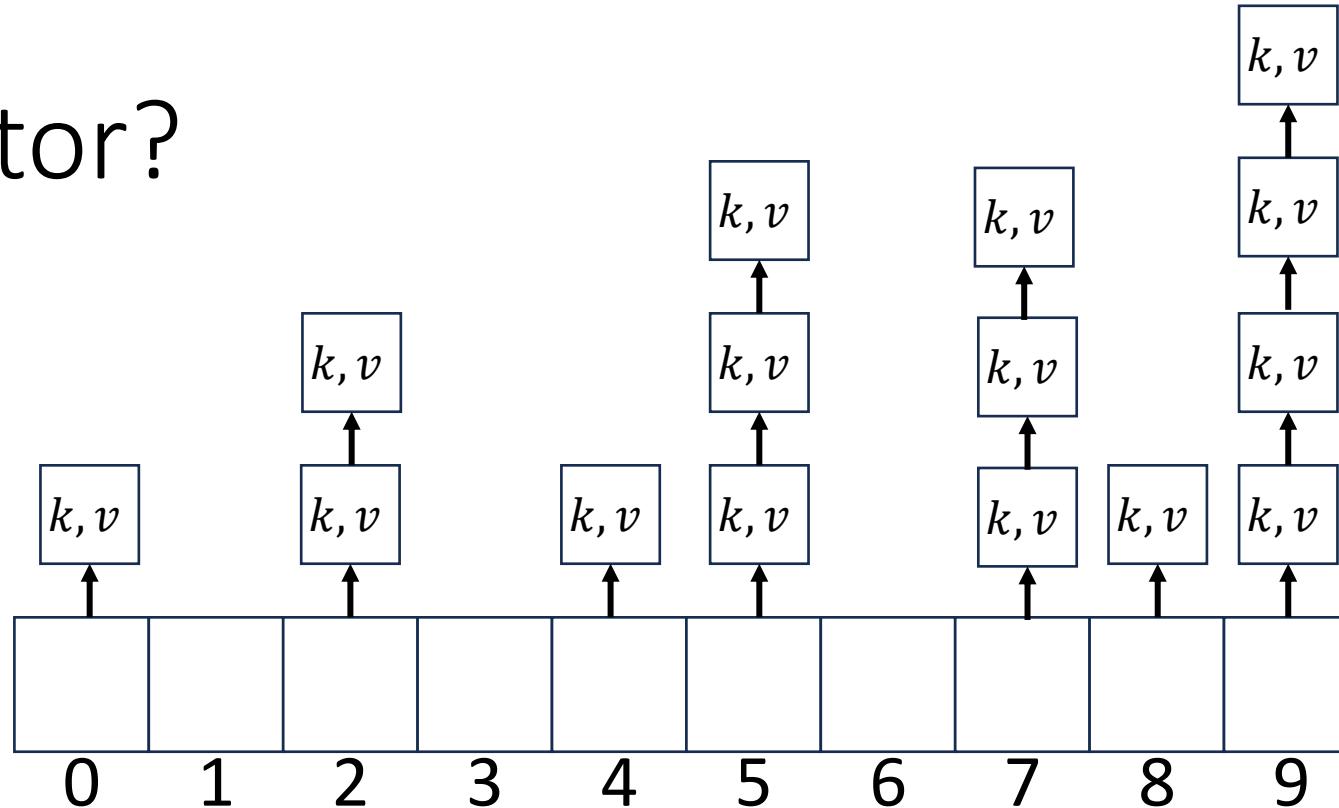
Load Factor?

0.8



# Load Factor?

1.5



# Formal Running Time Analysis

- The **load factor** of a hash table represents the average number of items per “bucket”
  - $\lambda = \frac{n}{length}$
- Assume we have a hash table that uses a linked-list for separate chaining
  - What is the expected number of comparisons needed in an unsuccessful find?
  - What is the expected number of comparisons needed in a successful find?
- How can we make the expected running time  $\Theta(1)$ ?

# Formal Running Time Analysis

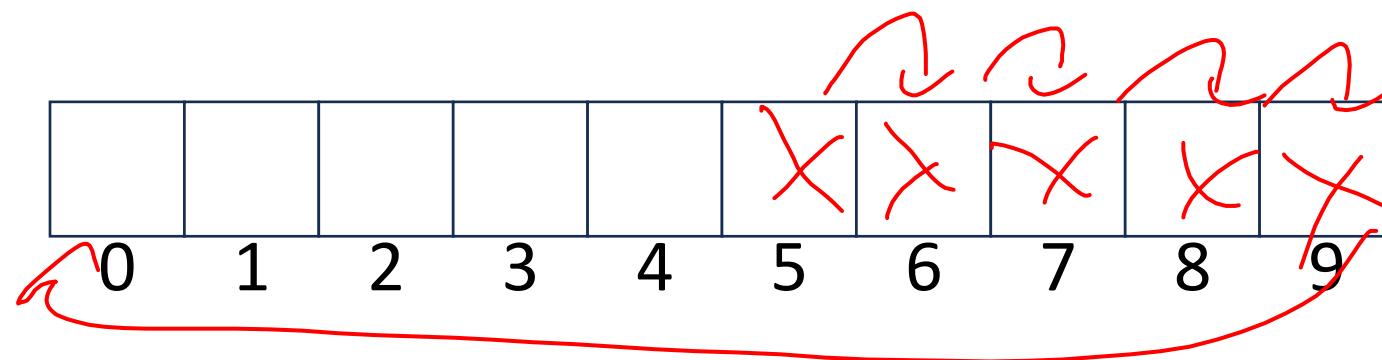
- The **load factor** of a hash table represents the average number of items per “bucket”
  - $\lambda = \frac{n}{length}$
- Assume we have a hash table that uses a linked-list for separate chaining
  - What is the expected number of comparisons needed in an unsuccessful find?
    - $\lambda$
  - What is the expected number of comparisons needed in a successful find?
    - $\frac{\lambda}{2}$
- How can we make the expected running time  $\Theta(1)$ ?
  - Pick a constant value, resize the array whenever  $\lambda$  exceeds that constant

# Rehashing

- If your load factor  $\lambda$  gets too large, copy everything over to a larger hash table
  - To do this: make a new, larger array
  - Re-insert all items into the new hash table by reapplying the hash function
    - We need to reapply the hash function because items should map to a different index
  - New array should be “roughly” double the length (but probably still want it to be prime)
- What does “too large” mean?
  - For separate chaining, typically we want  $\lambda < 2$
  - For open addressing, typically we want  $\lambda < \frac{1}{2}$

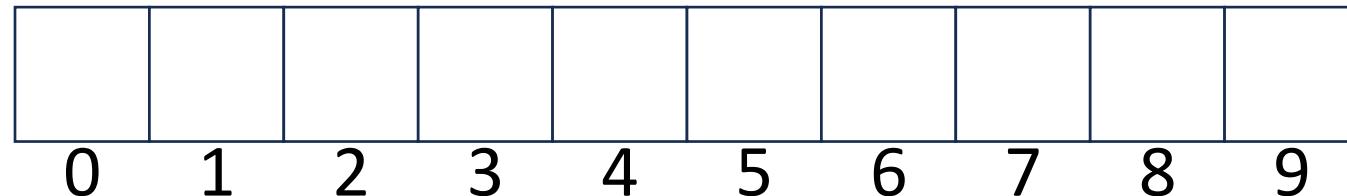
# Collision Resolution: Linear Probing

- When there's a collision, use the next open space in the table

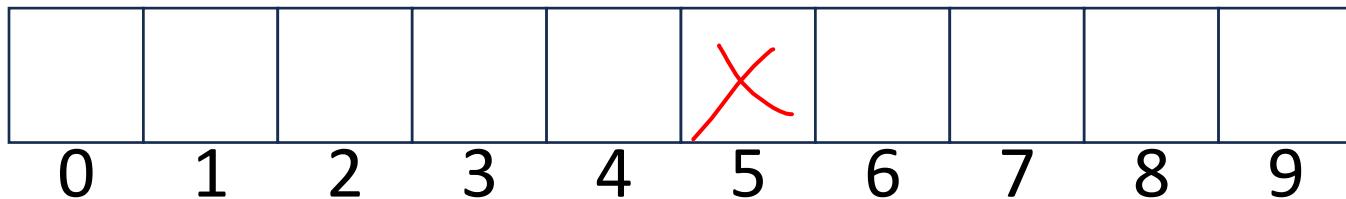


# Linear Probing: Insert Procedure

- To insert  $k, v$ 
  - Calculate  $i = h(k) \% \text{table.length}$
  - If  $\text{table}[i]$  is occupied then try index  $(i+1) \% \text{table.length}$
  - If that is occupied try index  $(i+2) \% \text{table.length}$
  - If that is occupied try index  $(i+3) \% \text{table.length}$
  - ...

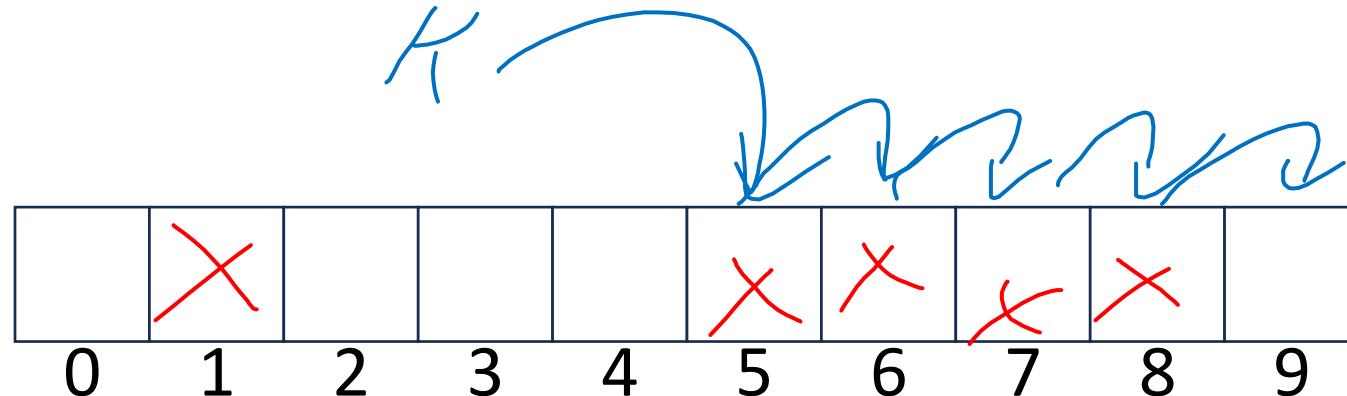


# Linear Probing: Find



# Linear Probing: Find

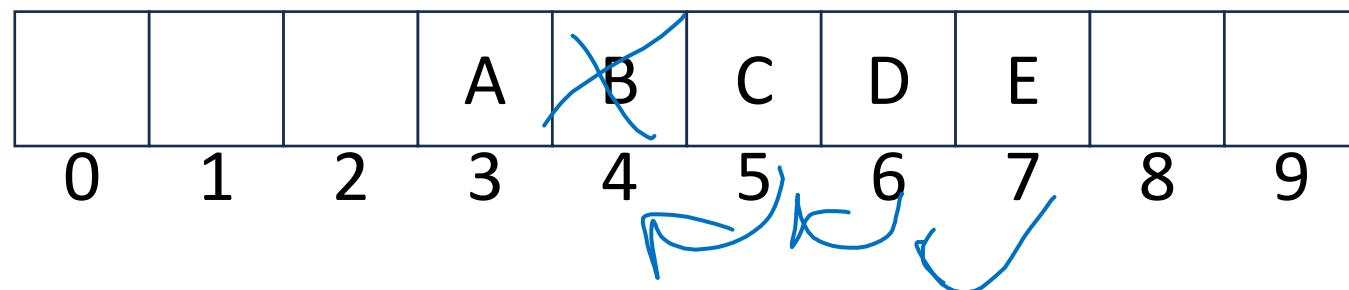
- To find key  $k$ 
  - Calculate  $i = h(k) \% \text{table.length}$
  - If  $\text{table}[i]$  is occupied but doesn't have  $k$ , check  $(i+1) \% \text{table.length}$
  - If that is occupied and doesn't contain  $k$ , check  $(i+2) \% \text{table.length}$
  - If that is occupied and doesn't contain  $k$ , check  $(i+3) \% \text{table.length}$
  - Repeat until you either find  $k$  or else you reach an empty cell in the table



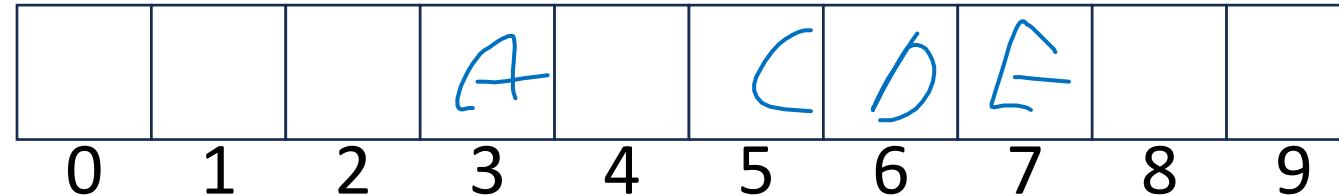
# Linear Probing: Delete

- Suppose A, B, C, D, and E all hashed to 3
- Now let's delete B

Before:



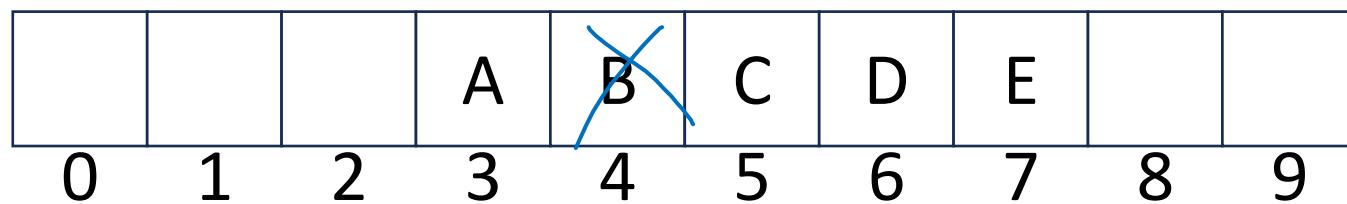
After:



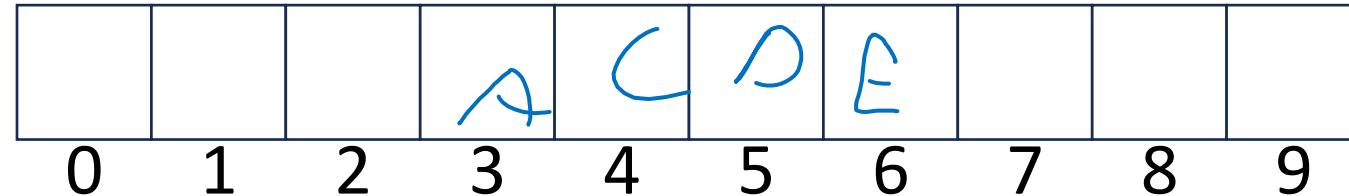
# Linear Probing: Delete

- Suppose A, B, and E all hashed to 3, and C and D hashed to 5
- Now let's delete B

Before:



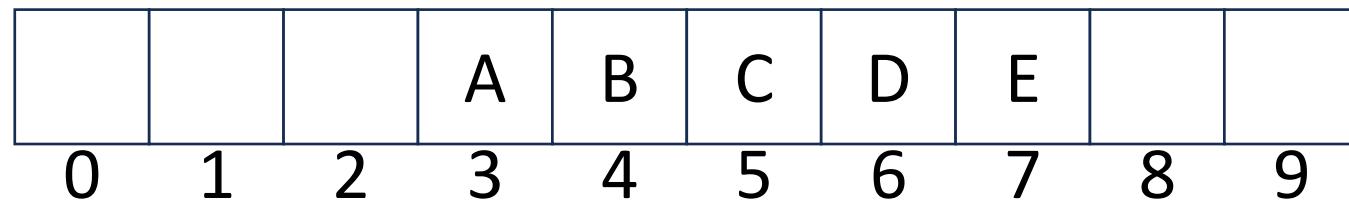
After:



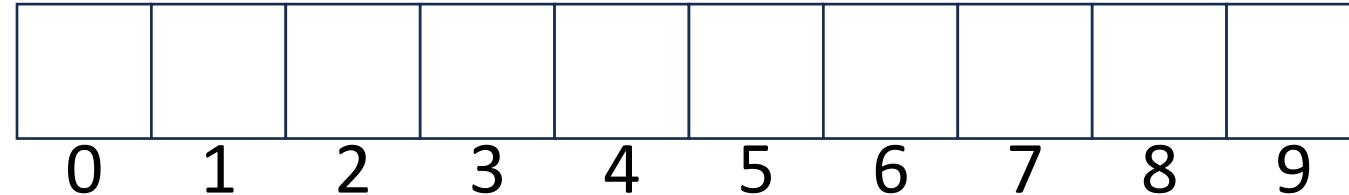
# Linear Probing: Delete

- Suppose A and E hashed to 3, and B,C, and D hashed to 4
- Now let's delete B

Before:



After:



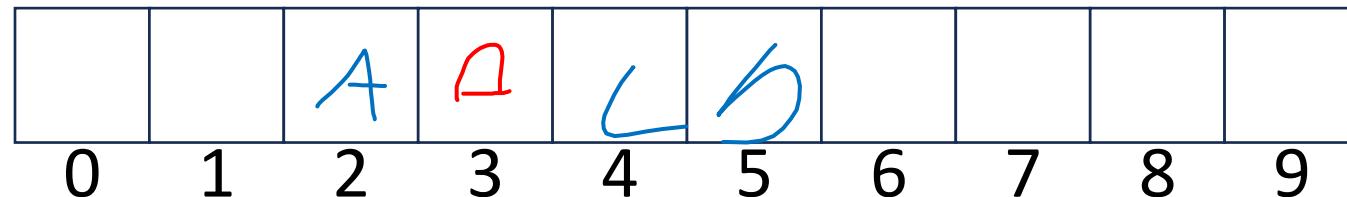
# Linear Probing: Delete

- **Option 1 (harder)**: Plug the hole with other items in a way that makes probes behave correctly
- **Option 2 (easier)**: “Tombstone” deletion. Leave a special object that indicates something was deleted from there
  - The tombstone does not act as an open space when finding (so keep looking after it's reached)
  - When inserting you can replace a tombstone with a new item

$k, v$		$k, v$	$k, v$		$k, v$				
0	1	2	3	4	5	6	7	8	9

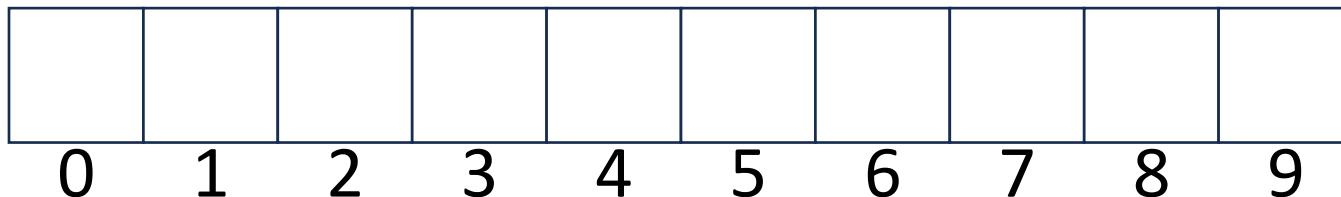
# Linear Probing + Tombstone: Find

- To find key  $k$ 
  - Calculate  $i = h(k) \% \text{table.length}$
  - While  $\text{table}[i]$  has a key other than  $k$ , set  $i = (i+1) \% \text{table.length}$
  - If you come across  $k$  return  $\text{table}[i]$
  - If you come across an empty index, the find was unsuccessful



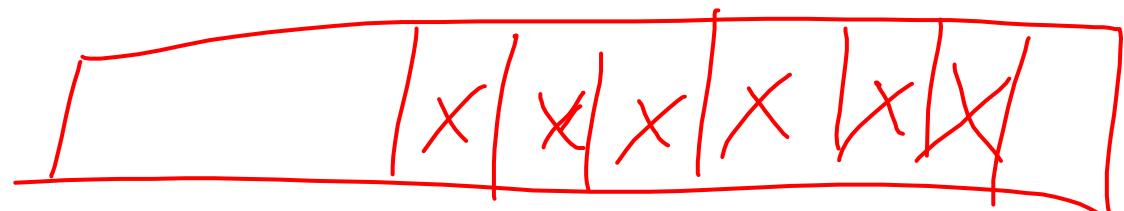
# Linear Probing + Tombstone: Insert

- To insert  $k, v$ 
  - Calculate  $i = h(k) \% \text{table.length}$
  - While  $\text{table}[i]$  has a key other than  $k$ , set  $i = (i+1) \% \text{table.length}$ 
    - If  $\text{table}[i]$  has a tombstone, set  $x = i$ 
      - That is where we will insert if the find is unsuccessful
  - If you come across  $k$ , set  $\text{table}[i] = k, v$
  - If you come across an empty index, the find was unsuccessful
    - Set  $\text{table}[x] = k, v$  if we saw a tombstone
    - Set  $\text{table}[x] = k, v$  otherwise



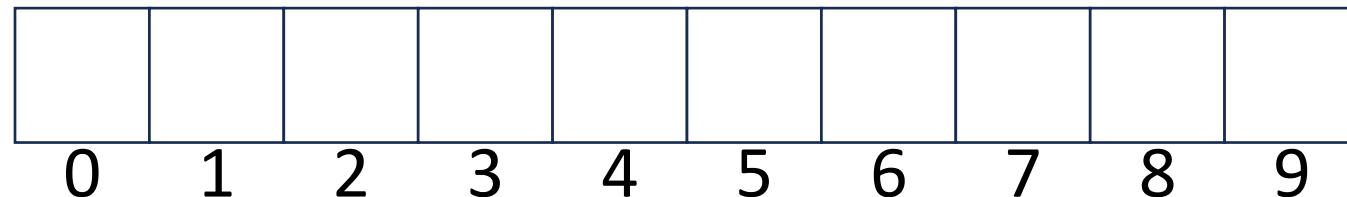
# Downsides of Linear Probing

- What happens when  $\lambda$  approaches 1?
  - Get longer and longer contiguous blocks
  - A collision is guaranteed to grow a block
    - Larger blocks experience more collisions
    - Feedback loop!
- What happens when  $\lambda$  exceeds 1?
  - Impossible!
  - You can't insert more stuff



# Quadratic Probing: Insert Procedure

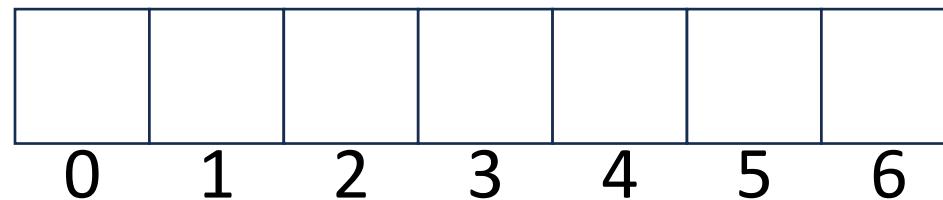
- To insert  $k, v$ 
  - Calculate  $i = h(k) \% \text{table.length}$
  - If  $\text{table}[i]$  is occupied then try  $(i+1^2) \% \text{table.length}$
  - If that is occupied try  $(i+2^2) \% \text{table.length}$
  - If that is occupied try  $(i+3^2) \% \text{table.length}$
  - If that is occupied try  $(i+4^2) \% \text{table.length}$
  - ...



# Quadratic Probing: Example

- Insert:

- 76
- 40
- 48
- 5
- 55
- 47



# Using Quadratic Probing

- If you probe `table.length` times, you start repeating indices
- If `table.length` is prime and  $\lambda < \frac{1}{2}$  then you're guaranteed to find an open spot in at most `table.length/2` probes
- Helps with the clustering problem of linear probing, but does not help if many things hash to the same value

# Double Hashing: Insert Procedure

- Given  $h$  and  $g$  are both good hash functions
- To insert  $k, v$ 
  - Calculate  $i = h(k) \% \text{table.length}$
  - If  $\text{table}[i]$  is occupied then try  $(i+g(k)) \% \text{table.length}$
  - If that is occupied try  $(i+2*g(k)) \% \text{table.length}$
  - If that is occupied try  $(i+3*g(k)) \% \text{table.length}$
  - If that is occupied try  $(i+4*g(k)) \% \text{table.length}$
  - ...

