

Data Structures and Algorithms

Hashing

For efficient look-up in a table

Acknowledgement

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Policies for students

- These contents are only used for students PERSONALLY.
- Students are NOT allowed to modify or deliver these contents to anywhere or anyone for any purpose.

Recording of modifications

- Course website address is changed to <http://sakai.it.tdt.edu.vn>
- Course codes cs1010, cs1020, cs2010 are placed by 501042, 501043, 502043 respectively.

Objectives

1

- To understand how **hashing** is used to accelerate table lookup

2

- To study the issue of **collision** and techniques to resolve it

References



Book

- **Chapter 13**, section 13.2, pages 761 to 787.
- Visualgo: <http://visualgo.net>



IT-TDT Sakai → 501043 website
→ Lessons

- <http://sakai.it.tdt.edu.vn>

Outline

1. Direct Addressing Table
2. Hash Table
3. Hash Functions
 - Good/bad/perfect/uniform hash function
4. Collision Resolution
 - Separate Chaining
 - Linear Probing
 - Quadratic Probing
 - Double Hashing
5. Summary
6. Java HashMap Class

What is Hashing?

- **Hashing** is an algorithm (via a **hash function**) that maps large data sets of variable length, called **keys**, to smaller data sets of a fixed length.
- A hash table (or hash map) is a data structure that uses a hash function to efficiently map keys to values, for efficient search and retrieval.
- Widely used in many kinds of computer software, particularly for associative arrays, database indexing, caches, and sets.

ADT Table Operations

	Sorted Array	Balanced BST	Hashing
Insertion	$O(n)$	$O(\log n)$	$O(1)$ avg
Deletion	$O(n)$	$O(\log n)$	$O(1)$ avg
Retrieval	$O(\log n)$	$O(\log n)$	$O(1)$ avg

Note: Balanced Binary Search Tree (BST) will be covered in 502043 Data Structures and Algorithms II.

- Hence, hash table supports the table ADT in constant time on average for the above operations. It has many applications.

1 Direct Addressing Table

A simplified version of hash table

1 SBS Transit Problem

- Retrieval: **find**(*num*)
 - Find the bus route of bus service number *num*
- Insertion: **insert**(*num*)
 - Introduce a new bus service number *num*
- Deletion: **delete**(*num*)
 - Remove bus service number *num*

1 SBS Transit Problem

Assume that bus numbers are integers between 0 and 999, we can create an array with 1000 Boolean values.

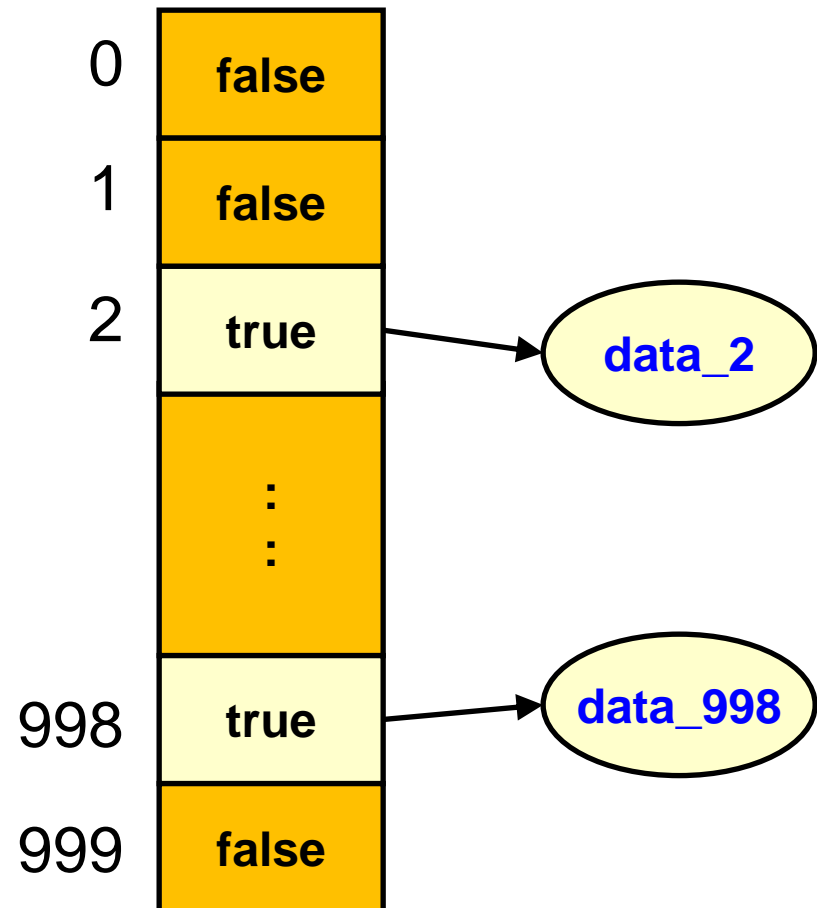
If bus **service num** exists, just set **position num** to **true**.

0	false
1	false
2	true
	⋮
998	true
999	false

1 Direct Addressing Table (1/2)

If we want to maintain **additional data** about a bus, use an array of 1000 slots, each can **reference** to an object which contains the details of the bus route.

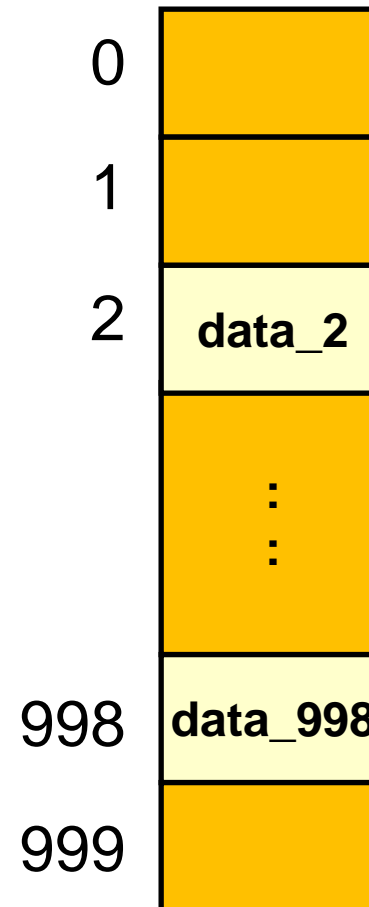
Note: You may want to store the key values, i.e. bus numbers, also.



1 Direct Addressing Table (2/2)

Alternatively, we can store the data **directly in the table slots** also.

Q: What are the advantages and disadvantages of these 2 approaches?



1 Direct Addressing Table: Operations

insert (key, data)

$a[\text{key}] = \text{data}$ // where $a[]$ is an array – the table

delete (key)

$a[\text{key}] = \text{null}$

find (key)

return $a[\text{key}]$

1 Direct Addressing Table: Restrictions

- Keys must be **non-negative integer values**
 - What happens for key values 151A and NR10?
- Range of keys must be **small**
- Keys must be **dense**, i.e. not many gaps in the key values.
- How to overcome these restrictions?

2 Hash Table

Hash Table is a **generalization** of direct addressing table, to remove the latter's restrictions.

2 Origins of the term Hash

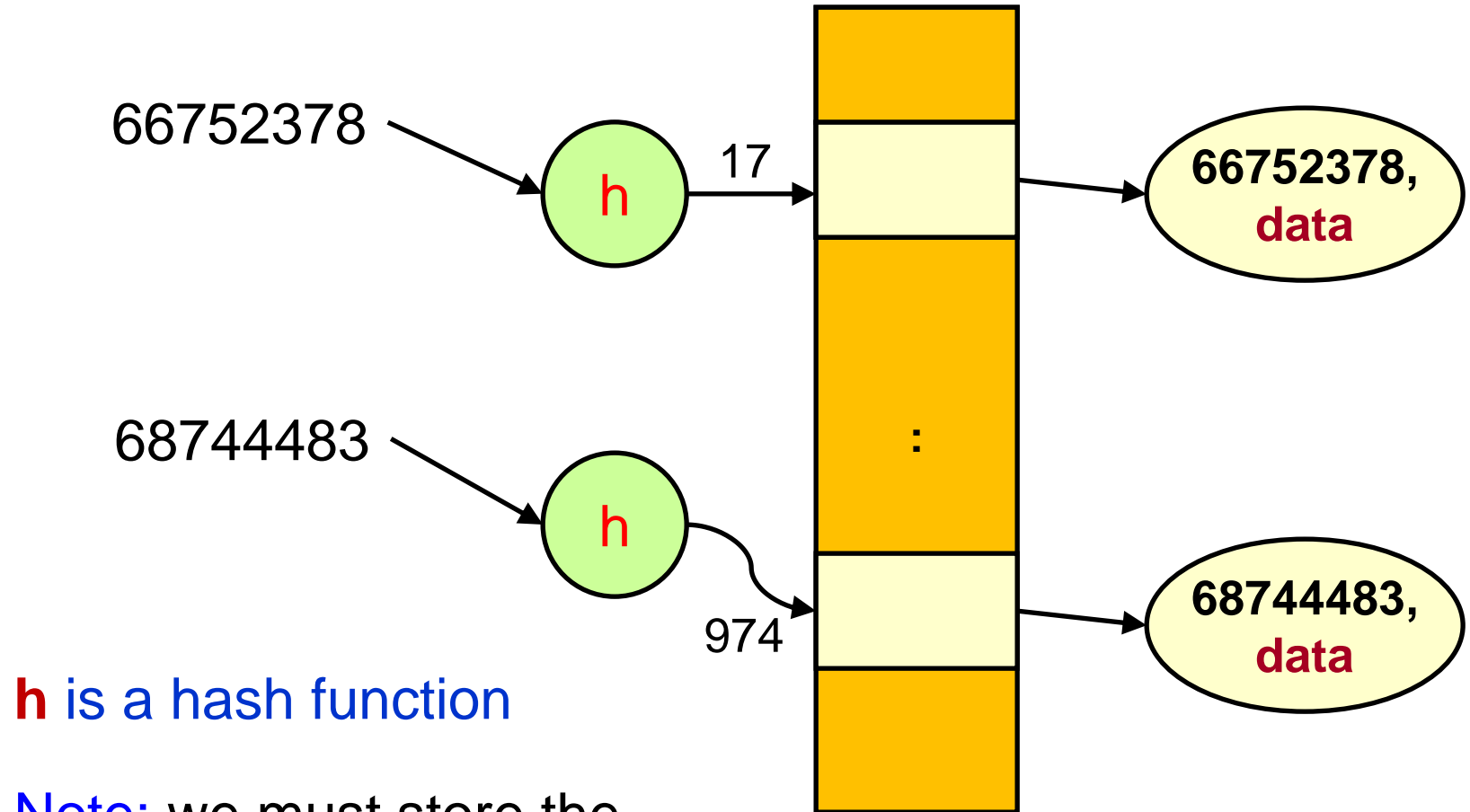
- The term "hash" comes by way of analogy with its standard meaning in the physical world, to "chop and mix".
- Indeed, typical hash functions, like the mod operation, “chop” the input domain into many sub-domains that get “mixed” into the output range.
- Donald Knuth notes that Hans Peter Luhn of IBM appears to have been the first to use the concept, in a memo dated January 1953, and that Robert Morris used the term in a survey paper in CACM which elevated the term from technical jargon to formal terminology.

2 Ideas

- Map **large** integers to **smaller** integers
- Map **non-integer** keys to **integers**

HASHING

2 Hash Table



h is a hash function

Note: we must store the key values. **Why?**

2 Hash Table: Operations

insert (key, data)

$a[h(\text{key})] = \text{data}$ // h is a hash function and $a[]$ is an array

delete (key)

$a[h(\text{key})] = \text{null}$

find (key)

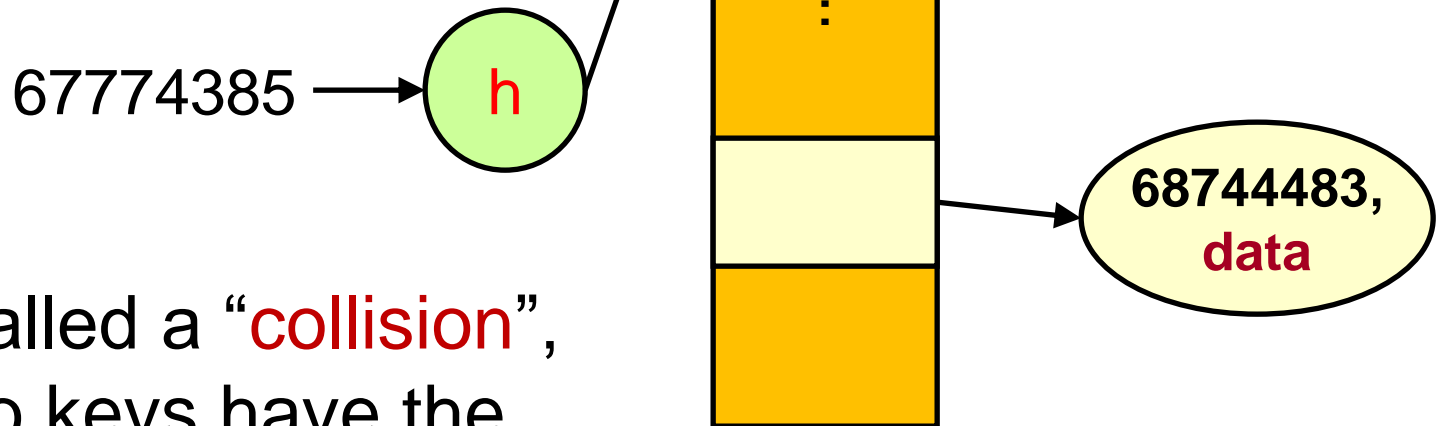
return $a[h(\text{key})]$

However, this does **not** work for **all** cases!
(Why?)

2 Hash Table: Collision

A hash function does **not** guarantee that two different keys go into **different slots**! It is usually a **many-to-one** mapping and not one-to-one.

E.g. 67774385 hashes to the same location of 66752378.



This is called a “**collision**”, when two keys have the same hash value.

2 Two Important Issues

- How to **hash**?
- How to **resolve collisions**?
- These are important issues that can affect the efficiency of hashing

3 Hash Functions

3 Criteria of Good Hash Functions

- Fast to compute
- Scatter keys **evenly** throughout the hash table
- Less collisions
- Need **less slots** (space)

3 Example of Bad Hash Function

- Select Digits — e.g. choose the 4th and 8th digits of a phone number
 - $\text{hash}(67754378) = 58$
 - $\text{hash}(63497820) = 90$
- What happen when you hash Singapore's house phone numbers by selecting the first three digits?

3 Perfect Hash Functions

- Perfect hash function is a one-to-one mapping between keys and hash values. So no collision occurs.
- Possible if all keys are known.
- Applications: compiler and interpreter search for reserved words; shell interpreter searches for built-in commands.
- GNU gperf is a freely available perfect hash function generator written in C++ that automatically constructs perfect functions (a C++ program) from a user supplied list of keywords.
- Minimal perfect hash function: The table size is the same as the number of keywords supplied.

3 Uniform Hash Functions

- Distributes keys **evenly** in the hash table
- Example
 - If k integers are **uniformly** distributed among **0** and **$X-1$** , we can map the values to a hash table of size **m** ($m < X$) using the hash function below

$$k \in [0, X)$$

$$\text{hash}(k) = \left\lfloor \frac{km}{X} \right\rfloor$$

k is the key value

$[]$: close interval

$()$: open interval

Hence, $0 \leq k < X$

$\lfloor \rfloor$ is the **floor** function

3 Division method (**mod** operator)

- Map into a hash table of m slots.
- Use the **modulo** operator (**%** in Java) to map an integer to a value between 0 and $m-1$.
- $n \bmod m$ = remainder of n divided by m , where n and m are positive integers.

$$\text{hash}(k) = k \% m$$

The most popular method.

3 How to pick m ?

- The choice of m (or **hash table size**) is important. If m is power of two, say 2^n , then key modulo of m is the same as extracting the last n bits of the key.
- If m is 10^n , then our hash values is the last n digit of keys.
- Both are no good.
- **Rule of thumb:**
 - Pick a **prime number** close to a power of two to be m .

3 Multiplication method

1. Multiply by a constant real number A between 0 and 1
2. Extract the fractional part
3. Multiply by m , the hash table size

$$hash(k) = \lfloor m(kA - \lfloor kA \rfloor) \rfloor$$

The reciprocal of the golden ratio
= $(\sqrt{5} - 1)/2 = 0.618033$ seems to be a good
choice for A (recommended by Knuth).

3 Hashing of strings (1/4)

- An example hash function for strings:

```
hash(s) { // s is a string
    sum = 0
    for each character c in s {
        sum += c // sum up the ASCII values of all characters
    }
    return sum % m // m is the hash table size
}
```


3 Hashing of strings: Examples (2/4)

hash("Tan Ah Teck")

= ("T" + "a" + "n" + " " +
"A" + "h" + " " +
"T" + "e" + "c" + "k") % 11 // hash table size is 11

= (84 + 97 + 110 + 32 +
65 + 104 + 32 +
84 + 101 + 99 + 107) % 11

= 825 % 11

= 0

3 Hashing of strings: Examples (3/4)

- All 3 strings below have the same hash value!
Why?
 - Lee Chin Tan
 - Chen Le Tian
 - Chan Tin Lee
- **Problem:** This hash function value does not depend on positions of characters! – Bad

3 Hashing of strings (4/4)

- A better hash function for strings is to “shift” the sum after each character, so that the positions of the characters affect the hash value.

hash(s)

sum = 0

for each character c in s {

sum = sum*31 + c

}

return sum % m // m is the hash table size

Java's String.hashCode() uses *31 as well.

4 Collision Resolution

4 Probability of Collision (1/2)

- **von Mises Paradox (The Birthday Paradox):**

“How many people must be in a room before the probability that some **share a birthday**, ignoring the year and leap days, becomes at least 50 percent?”

$Q(n)$ = Probability of **unique** birthday for n people

$$= \frac{365}{365} \times \frac{364}{365} \times \frac{363}{365} \times \frac{362}{365} \dots \frac{365 - n + 1}{365}$$

$P(n)$ = Probability of **collisions** (same birthday) for n people
 $= 1 - Q(n)$

$$P(\mathbf{23}) = \mathbf{0.507}$$

Hence, you need only 23 people in the room!

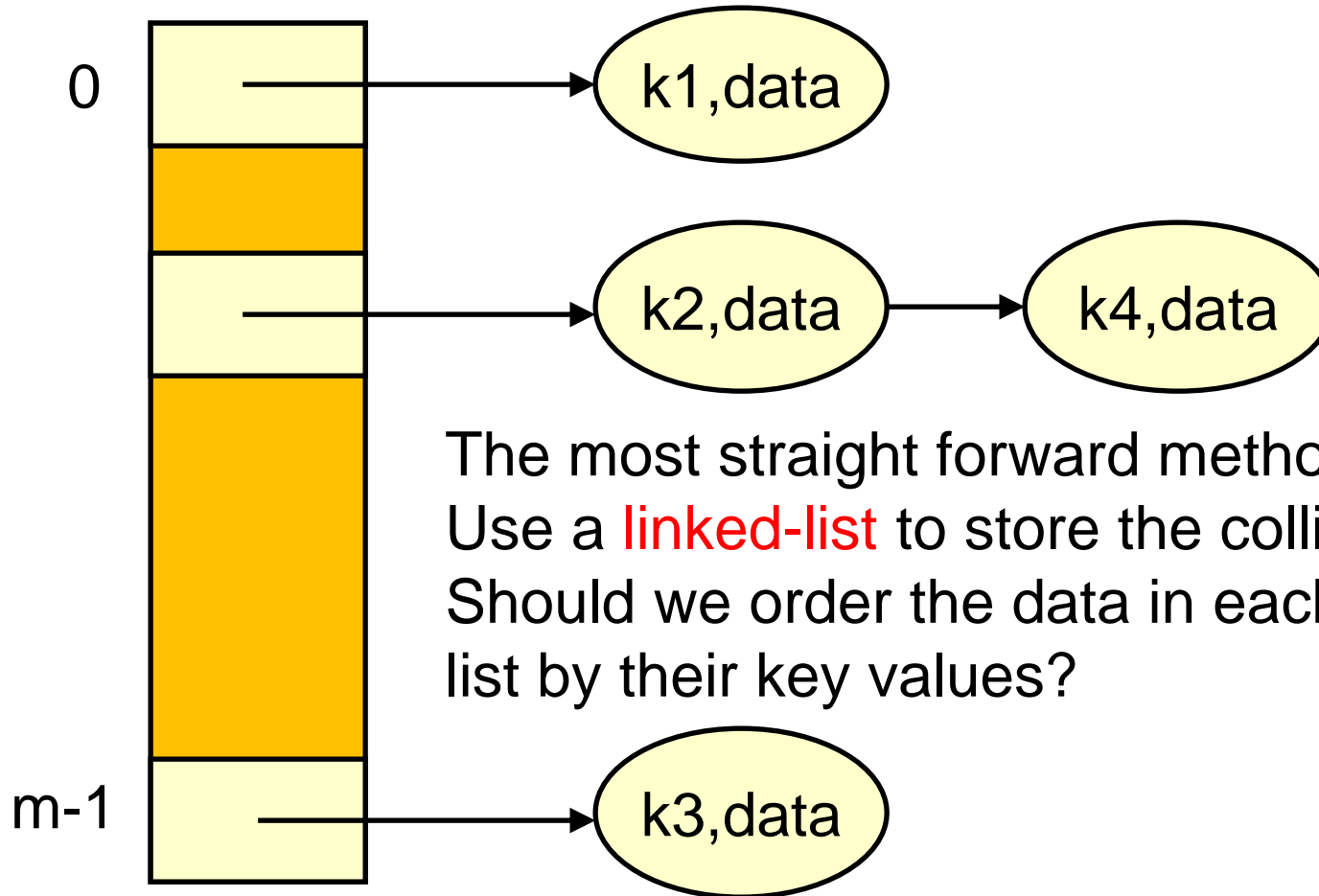
4 Probability of Collision (2/2)

- This means that if there are **23** people in a room, the probability that some people share a birthday is **50.7%**!
- In the hashing context, if we insert **23** keys into a table with **365** slots, more than half of the time we will get collisions! Such a result is counter-intuitive to many.
- So, collision is very likely!

4 Collision Resolution Techniques

- Separate Chaining
- Linear Probing
- Quadratic Probing
- Double Hashing

4.1 Separate Chaining



The most straight forward method.
Use a **linked-list** to store the collided keys.
Should we order the data in each linked list by their key values?

4.1 Hash operations

insert (key, data)

Insert data into the list $a[h(\text{key})]$

Takes $O(1)$ time

find (key)

Find key from the list $a[h(\text{key})]$

Takes $O(n)$ time, where n is length of the chain

delete (key)

Delete data from the list $a[h(\text{key})]$

Takes $O(n)$ time, where n is length of the chain

4.1 Analysis: Performance of Hash Table

- n : number of keys in the hash table
- m : size of the hash tables – number of slots
- α : load factor

$$\alpha = n/m$$

a measure of **how full** the hash table is. If table size is the number of linked lists, then α is the average length of the linked lists.

4.1 Reconstructing Hash Table

- To keep α bounded, we may need to **reconstruct** the whole table when the load factor exceeds the bound.
- Whenever the load factor exceeds the bound, we need to **rehash** all keys into a **bigger** table (increase m to reduce α), say double the table size m .

4.2 Linear Probing

$$\text{hash}(k) = k \bmod 7$$

Here the table size $m=7$

Note: 7 is a prime number.

0	
1	
2	
3	
4	
5	
6	

In **linear probing**, when we get a **collision**, we scan through the table looking for the **next empty slot** (wrapping around when we reach the last slot).

4.2 Linear Probing: Insert 18

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(18) = 18 \bmod 7 = 4$$

0	
1	
2	
3	
4	18
5	
6	

4.2 Linear Probing: Insert 14

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(18) = 18 \bmod 7 = 4$$

$$\text{hash}(14) = 14 \bmod 7 = 0$$

0	14
1	
2	
3	
4	18
5	
6	

4.2 Linear Probing: Insert 21

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(18) = 18 \bmod 7 = 4$$

$$\text{hash}(14) = 14 \bmod 7 = 0$$

$$\text{hash}(21) = 21 \bmod 7 = 0$$

0	14
1	21
2	
3	
4	18
5	
6	

Collision occurs!
Look for next empty slot.

4.2 Linear Probing: Insert 1

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(18) = 18 \bmod 7 = 4$$

$$\text{hash}(14) = 14 \bmod 7 = 0$$

$$\text{hash}(21) = 21 \bmod 7 = 0$$

$$\text{hash}(1) = 1 \bmod 7 = 1$$

0	14
1	21
2	1
3	
4	18
5	
6	

Collides with 21
(hash value 0). Look
for **next empty slot**.

4.2 Linear Probing: Insert 35

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(18) = 18 \bmod 7 = 4$$

$$\text{hash}(14) = 14 \bmod 7 = 0$$

$$\text{hash}(21) = 21 \bmod 7 = 0$$

$$\text{hash}(1) = 1 \bmod 7 = 1$$

$$\text{hash}(35) = 35 \bmod 7 = 0$$

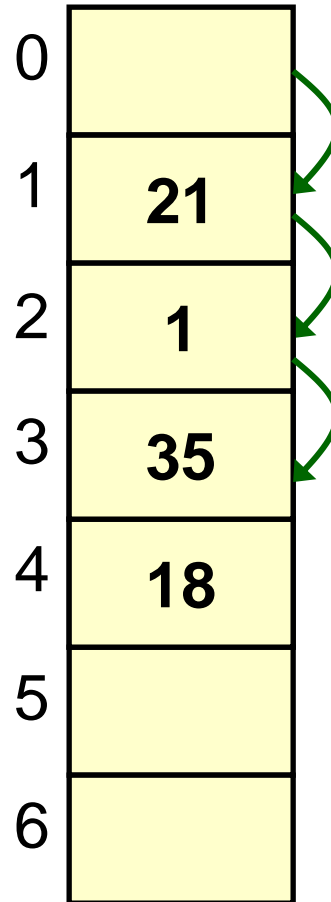
0	14
1	21
2	1
3	35
4	18
5	
6	

Collision, need to check **next 3 slots**.

4.2 Linear Probing: Find 35

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(35) = 0$$



Found 35, after 4 probes.

4.2 Linear Probing: Find 8

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(8) = 1$$

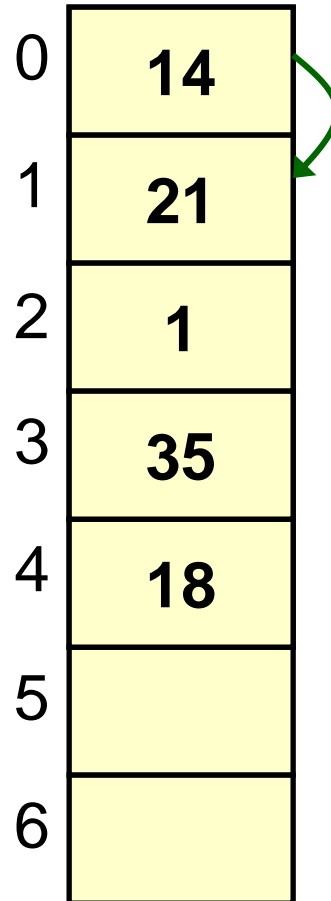
0	14
1	21
2	1
3	35
4	18
5	
6	

8 NOT found.
Need **5** probes!

4.2 Linear Probing: Delete 21

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(21) = 0$$



0	14
1	21
2	1
3	35
4	18
5	
6	

We **cannot** simply **remove** a value, because it can affect **find()**!

4.2 Linear Probing: Find 35

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(35) = 0$$

Hence for deletion, **cannot** simply remove the key value!

0	14
1	
2	1
3	35
4	18
5	
6	

We **cannot** simply **remove** a value, because it can affect **find()**!

35 NOT found!
Incorrect!

4.2 How to delete?

- **Lazy** Deletion
- Use **three** different **states** of a slot
 - Occupied
 - Occupied but mark as deleted
 - Empty
- When a value is removed from linear probed hash table, we just **mark** the status of the slot as “**deleted**”, instead of emptying the slot.

4.2 Linear Probing: Delete 21

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(21) = 0$$

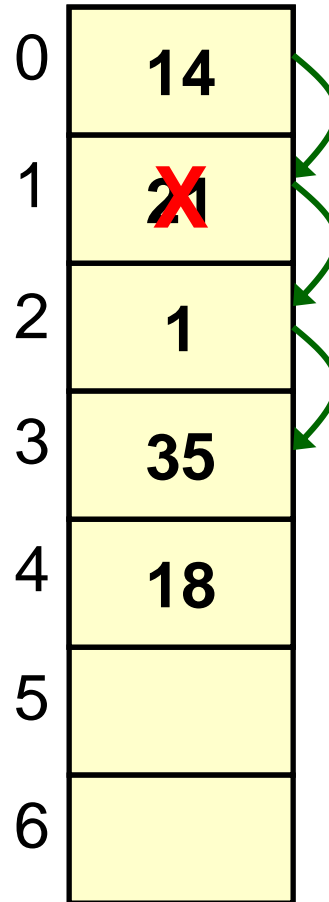
0	14
1	21
2	1
3	35
4	18
5	
6	

Slot 1 is occupied but now **marked as deleted**.

4.2 Linear Probing: Find 35

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(35) = 0$$



0	14
1	21
2	1
3	35
4	18
5	
6	

Found 35
Now we can find 35

4.2 Linear Probing: Insert 15 (1/2)

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(15) = 1$$

0	14
1	21
2	1
3	35
4	18
5	
6	

Slot 1 is marked as deleted.

We **continue to search** for 15, and found that 15 is not in the hash table (total 5 probes).

So, we insert this new value 15 into the slot that has been marked as deleted (i.e. slot 1).

4.2 Linear Probing: Insert 15 (2/2)

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(15) = 1$$

0	14
1	15
2	1
3	35
4	18
5	
6	

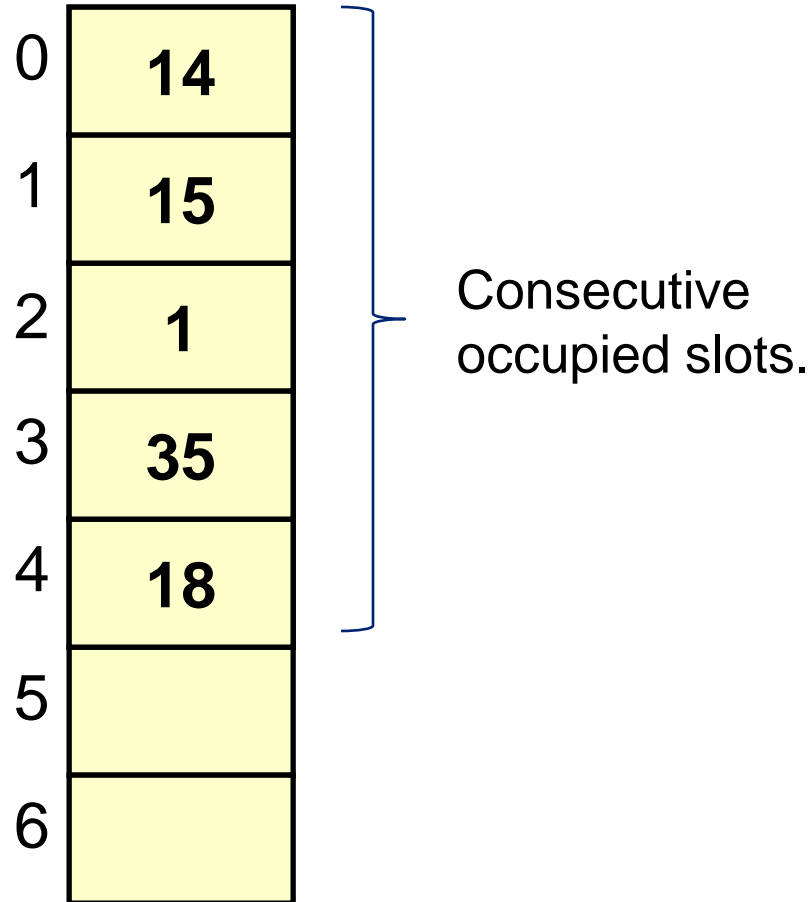
So, 15 is inserted into slot **1**, which was marked as deleted.

Note: We should insert a new value in **first** available slot so that the find operation for this value will be the fastest.

4.2 Problem of Linear Probing

It can create many **consecutive occupied slots**, increasing the running time of find/insert/delete.

This is called **Primary Clustering**



4.2 Linear Probing

The **probe sequence** of this linear probing is:

$$\begin{aligned} & \text{hash(key)} \\ & (\text{hash(key)} + \mathbf{1}) \% m \\ & (\text{hash(key)} + \mathbf{2}) \% m \\ & (\text{hash(key)} + \mathbf{3}) \% m \\ & \vdots \end{aligned}$$

4.2 Modified Linear Probing

Q: How to modify linear probing to **avoid primary clustering**?

We can modify the **probe sequence** as follows:

$$\begin{aligned} & \text{hash}(\text{key}) \\ & (\text{hash}(\text{key}) + \mathbf{1} * \mathbf{d}) \% m \\ & (\text{hash}(\text{key}) + \mathbf{2} * \mathbf{d}) \% m \\ & (\text{hash}(\text{key}) + \mathbf{3} * \mathbf{d}) \% m \\ & \vdots \end{aligned}$$

where \mathbf{d} is some constant integer >1 and is co-prime to \mathbf{m} .

Note: Since \mathbf{d} and \mathbf{m} are co-primes, the probe sequence **covers all** the slots in the hash table.

4.3 Quadratic Probing

For **quadratic probing**, the probe sequence is:

$$\begin{aligned} & \text{hash(key)} \\ & (\text{hash(key)} + \mathbf{1}) \% m \\ & (\text{hash(key)} + \mathbf{4}) \% m \\ & (\text{hash(key)} + \mathbf{9}) \% m \\ & \vdots \\ & (\text{hash(key)} + \mathbf{k^2}) \% m \end{aligned}$$

4.3 Quadratic Probing: Insert 3

$$\text{hash}(k) = k \bmod 7$$

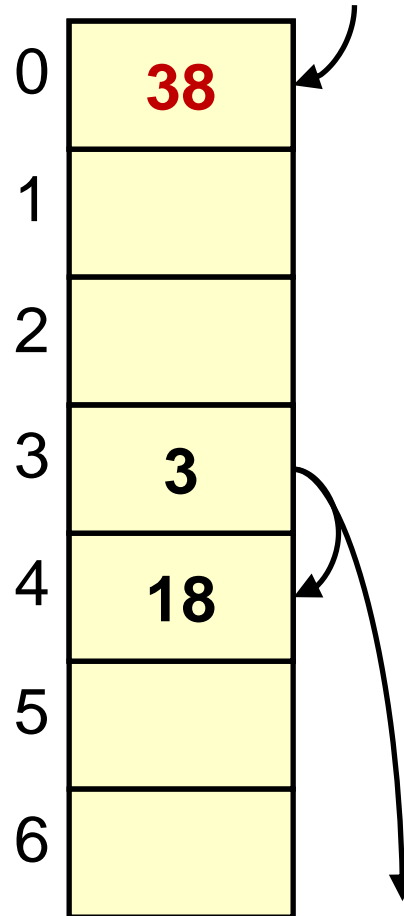
$$\text{hash}(3) = 3$$

0	
1	
2	
3	3
4	18
5	
6	

4.3 Quadratic Probing: Insert 38

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}(38) = 3$$



4.3 Theorem of Quadratic Probing

- If $\alpha < 0.5$, and m is prime, then we can always find an empty slot.
(m is the table size and α is the load factor)
- Note: $\alpha < 0.5$ means the hash table is less than half full.
- Q: How can we be sure that quadratic probing always terminates?
- Insert 12 into the previous example, followed by 10. See what happen?

4.3 Problem of Quadratic Probing

- If two keys have the **same** initial position, their probe sequences are the **same**.
- This is called **secondary clustering**.
- But it is not as bad as linear probing.

4.4 Double Hashing

Use 2 hash functions:

$\text{hash}(\text{key})$

$(\text{hash}(\text{key}) + 1 * \text{hash}_2(\text{key})) \% m$

$(\text{hash}(\text{key}) + 2 * \text{hash}_2(\text{key})) \% m$

$(\text{hash}(\text{key}) + 3 * \text{hash}_2(\text{key})) \% m$

:

hash_2 is called the **secondary hash function**, the number of slots to jump each time a collision occurs.

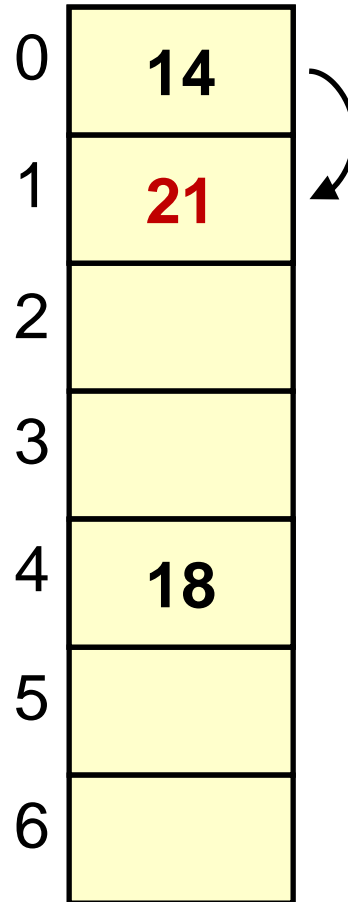
4.4 Double Hashing: Insert 21

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}_2(k) = k \bmod 5$$

$$\text{hash}(21) = 0$$

$$\text{hash}_2(21) = 1$$



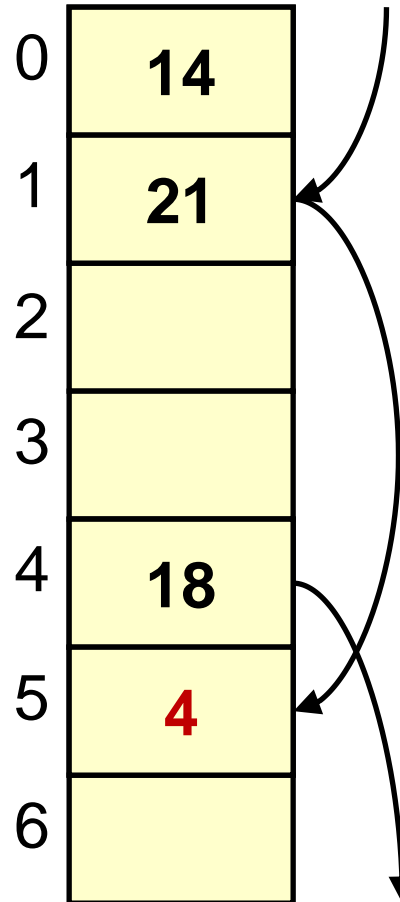
4.4 Double Hashing: Insert 4

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}_2(k) = k \bmod 5$$

$$\text{hash}(4) = 4$$

$$\text{hash}_2(4) = 4$$



If we insert 4, the probe sequence is 4, 8, 12, ...

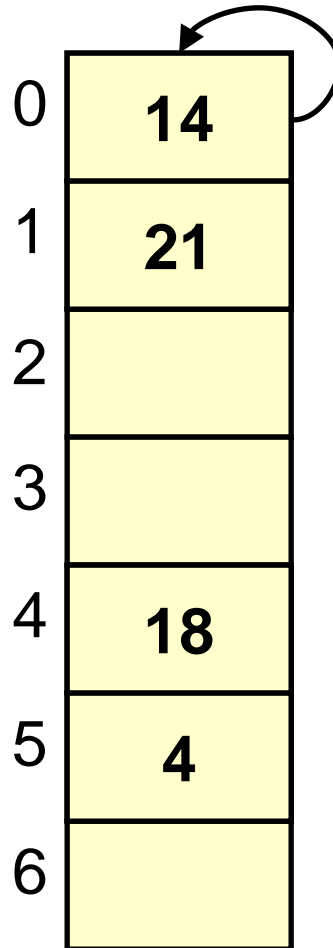
4.4 Double Hashing: Insert 35

$$\text{hash}(k) = k \bmod 7$$

$$\text{hash}_2(k) = k \bmod 5$$

$$\text{hash}(35) = 0$$

$$\text{hash}_2(35) = 0$$



But if we insert 35,
the probe sequence
is **0, 0, 0, ...**

What is wrong?
Since $\text{hash}_2(35) = \mathbf{0}$.
Not acceptable!

4.4 Warning

- Secondary hash function must **not** evaluate to **0**!
- To solve this problem, simply change $\text{hash}_2(\text{key})$ in the above example to:

$$\text{hash}_2(\text{key}) = 5 - (\text{key} \% 5)$$

Note:

- If $\text{hash}_2(k) = 1$, then it is the same as linear probing.
- If $\text{hash}_2(k) = d$, where d is a constant integer > 1 , then it is the same as modified linear probing.

4.5 Criteria of Good Collision Resolution Method

- Minimize clustering
- Always find an empty slot if it exists
- Give different probe sequences when 2 initial probes are the same (i.e. no secondary clustering)
- Fast

ADT Table Operations

	Sorted Array	Balanced BST	Hashing
Insertion	$O(n)$	$O(\log n)$	$O(1)$ avg
Deletion	$O(n)$	$O(\log n)$	$O(1)$ avg
Retrieval	$O(\log n)$	$O(\log n)$	$O(1)$ avg

Note: Balanced Binary Search Tree (BST) will be covered in 502043 Data Structures and Algorithms II.

5 Summary

- How to hash? Criteria for good hash functions?
- How to **resolve collision**?
Collision resolution techniques:
 - separate chaining
 - linear probing
 - quadratic probing
 - double hashing
- Problem on deletions
- **Primary** clustering and **secondary** clustering.

6 Java HashMap Class

6 Class HashMap <K, V>

```
public class HashMap<K,V>  
    extends AbstractMap<K,V>  
    implements Map<K,V>, Cloneable, Serializable
```

- This class implements a hash map, which maps **keys** to **values**. Any non-null object can be used as a key or as a value.
 e.g. We can create a hash map that maps people names to their ages. It uses the names as keys, and the ages as the values.
- The **AbstractMap** is an abstract class that provides a skeletal implementation of the **Map** interface.
- Generally, the default **load factor** (**0.75**) offers a good tradeoff between time and space costs.
- The default HashMap capacity is **16**.

6 Class HashMap <K, V>

■ Constructors summary

□ HashMap()

Constructs an empty HashMap with a default initial capacity (16) and the default load factor of 0.75.

□ HashMap(int initialCapacity)

Constructs an empty HashMap with the specified initial capacity and the default load factor of 0.75.

□ HashMap(int initialCapacity, float loadFactor)

Constructs an empty HashMap with the specified initial capacity and load factor.

□ HashMap(Map<? extends K, ? extends V> m)

Constructs a new HashMap with the same mappings as the specified Map.

6 Class HashMap <K, V>

Some methods

- `void clear()`
Removes all of the mappings from this map.
- `boolean containsKey(Object key)`
Returns true if this map contains a mapping for the specified key.
- `boolean containsValue(Object value)`
Returns true if this map maps one or more keys to the specified value.
- `V get(Object key)`
Returns the value to which the specified key is mapped, or null if this map contains no mapping for the key.
- `V put(K key, V value)`
Associates the specified value with the specified key in this map.
- ...

6 Example

- **Example:** Create a hashmap that maps people names to their ages. It uses **names** as **key**, and the **ages** as their **values**.

```
HashMap<String, Integer> hm = new HashMap<String, Integer>();  
// placing items into the hashmap  
hm.put("Mike", 52);  
hm.put("Janet", 46);  
hm.put("Jack", 46);  
// retrieving item from the hashmap  
System.out.println("Janet => " + hm.get("Janet"));
```

TestHash.java

The output of the above code is:

Janet => 46

End of file

■ 9 1 20 5 101 66 15