

## Hashing

## Searching

- Consider the problem of searching an array for a given value
  - If the array is not sorted, the search requires  $O(n)$  time
    - If the value isn't there, we need to search all  $n$  elements
    - If the value is there, we search  $n/2$  elements on average
  - If the array is sorted, we can do a binary search
    - A binary search requires  $O(\log n)$  time
    - About equally fast whether the element is found or not
  - It doesn't seem like we could do much better
    - How about an  $O(1)$ , that is, constant time search?
    - We can do it *if* the array is organized in a particular way

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## Hashing

- Suppose we were to come up with a "magic function" that, given a value to search for, would tell us exactly where in the array to look
  - If it's in that location, it's in the array
  - If it's not in that location, it's not in the array
- This function would have no other purpose
- If we look at the function's inputs and outputs, they probably won't "make sense"
- This function is called a hash function because it "makes hash" of its inputs

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## Example (ideal) hash function

- Suppose our hash function gave us the following values:
  - `hashCode("apple") = 5`
  - `hashCode("watermelon") = 3`
  - `hashCode("grapes") = 8`
  - `hashCode("cantaloupe") = 7`
  - `hashCode("kiwi") = 0`
  - `hashCode("strawberry") = 9`
  - `hashCode("mango") = 6`
  - `hashCode("banana") = 2`

0	kiwi
1	
2	banana
3	watermelon
4	
5	apple
6	mango
7	cantaloupe
8	grapes
9	strawberry

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## Why hash tables?

- We don't (usually) use hash tables just to see if something is there or not—instead, we put key/value pairs into the table
  - We use a *key* to find a place in the table
  - The *value* holds the information we are actually interested in

	key	value
141		
142	robin	robin info
143	sparrow	sparrow info
144	hawk	hawk info
145	seagull	seagull info
146		
147	bluejay	bluejay info
148	owl	owl info

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## Finding the hash function

- How can we come up with this magic function?
- In general, we cannot—there is no such magic function ☹
  - In a few specific cases, where all the possible values are known in advance, it has been possible to compute a perfect hash function
- What is the next best thing?
  - A perfect hash function would tell us exactly where to look
  - In general, the best we can do is a function that tells us where to *start* looking!

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## Example imperfect hash function

- Suppose our hash function gave us the following values:

- hash("apple") = 5
  - hash("watermelon") = 3
  - hash("grapes") = 8
  - hash("cantaloupe") = 7
  - hash("kiwi") = 0
  - hash("strawberry") = 9
  - hash("mango") = 6
  - hash("banana") = 2
  - hash("honeydew") = 6

- Now what?

0	kiwi
1	
2	banana
3	watermelon
4	
5	apple
6	mango
7	cantaloupe
8	grapes
9	strawberry

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## Collisions

- When two values hash to the same array location, this is called a collision
- Collisions are normally treated as “first come, first served”—the first value that hashes to the location gets it
- We have to find something to do with the second and subsequent values that hash to this same location

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## Handling collisions

- What can we do when two different values attempt to occupy the same place in an array?
  - Solution #1:** Search from there for an empty location
    - Can stop searching when we find the value or an empty location
    - Search must be end-around
  - Solution #2:** Use a second hash function
    - ...and a third, and a fourth, and a fifth, ...
  - Solution #3:** Use the array location as the header of a linked list of values that hash to this location
- All these solutions work, provided:
  - We use the same technique to *add* things to the array as we use to *search* for things in the array

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## Insertion, I

- Suppose you want to add **seagull** to this hash table
- Also suppose:
  - hashCode(seagull) = 143
  - table[143] is not empty
  - table[143] != seagull
  - table[144] is not empty
  - table[144] != seagull
  - table[145] is empty
- Therefore, put **seagull** at location 145

...	
141	
142	robin
143	sparrow
144	hawk
145	seagull
146	
147	bluejay
148	owl
...	

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## Searching, I

- Suppose you want to look up **seagull** in this hash table
- Also suppose:
  - hashCode(seagull) = 143
  - table[143] is not empty
  - table[143] != seagull
  - table[144] is not empty
  - table[144] != seagull
  - table[145] is not empty
  - table[145] == seagull !
- We found **seagull** at location 145

...	
141	
142	robin
143	sparrow
144	hawk
145	seagull
146	
147	bluejay
148	owl
...	

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## Searching, II

- Suppose you want to look up **cow** in this hash table
- Also suppose:
  - hashCode(cow) = 144
  - table[144] is not empty
  - table[144] != cow
  - table[145] is not empty
  - table[145] != cow
  - table[146] is empty
- If **cow** were in the table, we should have found it by now
- Therefore, it isn't here

...	
141	
142	robin
143	sparrow
144	hawk
145	seagull
146	
147	bluejay
148	owl
...	

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## Insertion, II

- Suppose you want to add **hawk** to this hash table
- Also suppose
  - $\text{hashCode}(\text{hawk}) = 143$
  - $\text{table}[143]$  is not empty
  - $\text{table}[143] \neq \text{hawk}$
  - $\text{table}[144]$  is not empty
  - $\text{table}[144] \neq \text{hawk}$
- hawk** is already in the table, so do nothing

...	
141	
142	robin
143	sparrow
144	hawk
145	seagull
146	
147	bluejay
148	owl
...	

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## Insertion, III

- Suppose:
  - You want to add **cardinal** to this hash table
  - $\text{hashCode}(\text{cardinal}) = 147$
  - The last location is 148
  - 147 and 148 are occupied
- Solution:
  - Treat the table as circular; after 148 comes 0
  - Hence, cardinal goes in location 0 (or 1, or 2, or ...)

...	
141	
142	robin
143	sparrow
144	hawk
145	seagull
146	
147	bluejay
148	owl

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## Clustering

- One problem with the above technique is the tendency to form "clusters"
- A cluster is a group of items not containing any open slots
- The bigger a cluster gets, the more likely it is that new values will hash into the cluster, and make it ever bigger
- Clusters cause efficiency to degrade
- Here is a *non*-solution: instead of stepping one ahead, step  $n$  locations ahead
  - The clusters are still there, they're just harder to see
  - Unless  $n$  and the table size are mutually prime, some table locations are never checked

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## Efficiency

- Hash tables are actually surprisingly efficient
- Until the table is about 70% full, the number of probes (places looked at in the table) is typically only 2 or 3
- Sophisticated mathematical analysis is required to *prove* that the expected cost of inserting into a hash table, or looking something up in the hash table, is  $O(1)$
- Even if the table is nearly full (leading to long searches), efficiency is usually still quite high

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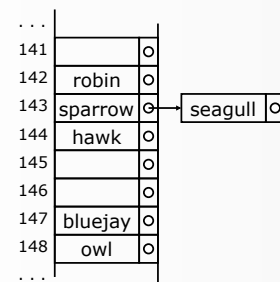
## Solution #2: Rehashing

- In the event of a collision, another approach is to rehash: compute another hash function
  - Since we may need to rehash many times, we need an easily computable sequence of functions
- Simple example: in the case of hashing Strings, we might take the previous hash code and add the length of the String to it
  - Probably better if the length of the string was not a component in computing the original hash function
- Possibly better yet: add the length of the String plus the number of probes made so far
  - Problem: are we sure we will look at every location in the array?
- Rehashing is a fairly uncommon approach, and we won't pursue it any further here

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## Solution #3: Bucket hashing

- The previous solutions used open hashing: all entries went into a "flat" (unstructured) array
- Another solution is to make each array location the header of a linked list of values that hash to that location



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## The hashCode function

- `public int hashCode()` is defined in `Object`
- Like `equals`, the default implementation of `hashCode` just uses the address of the object—probably not what you want for your own objects
- You can override `hashCode` for your own objects
- As you might expect, `String` overrides `hashCode` with a version appropriate for strings
- Note that the supplied `hashCode` method *does not know the size of your array*—you have to adjust the returned `int` value yourself

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## Writing your own hashCode method

- A `hashCode` method *must*:
  - Return a value that is (or can be converted to) a legal array index
  - Always return the same value for the same input
    - It can't use random numbers, or the time of day
  - Return the same value for *equal* inputs
    - Must be consistent with your `equals` method
- It does *not* need to return different values for different inputs
- A *good* `hashCode` method *should*:
  - Be efficient to compute
  - Give a uniform distribution of array indices
  - *Not* assign similar numbers to similar input values

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## Other considerations

- The hash table might fill up; we need to be prepared for that
  - Not a problem for a bucket hash, of course
- You cannot delete items from an open hash table
  - This would create empty slots that might prevent you from finding items that hash before the slot but end up after it
  - Again, not a problem for a bucket hash
- Generally speaking, hash tables work best when the table size is a prime number

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## Hash tables in Java

- Java provides two classes, `Hashtable` and `HashMap` classes
- Both are maps: they associate *keys* with *values*
- `Hashtable` is synchronized; it can be accessed safely from multiple threads
  - `Hashtable` uses an open hash, and has a `rehash` method, to increase the size of the table
- `HashMap` is newer, faster, and usually better, but it is not synchronized
  - `HashMap` uses a bucket hash, and has a `remove` method

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## Hash table operations

- Both `Hashtable` and `HashMap` are in `java.util`
- Both have no-argument constructors, as well as constructors that take an integer table size
- Both have methods:
  - `public Object put(Object key, Object value)`
    - (Returns the previous value for this key, or `null`)
  - `public Object get(Object key)`
  - `public void clear()`
  - `public Set keySet()`
    - Dynamically reflects changes in the hash table
  - ...and many others

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## The End

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