Back to Simple Search: Hashing

- Linear search is OK for small data sets, bad for large.
- So linear search would be OK if we could rapidly narrow the search to a few items.
- Suppose that in constant time could put any item in our data set into a numbered bucket, where # buckets stays within a constant factor of # keys.
- Suppose also that buckets contain roughly equal numbers of keys.
- Then search would be constant time.

Hash functions

- To do this, must have way to convert key to bucket number: a hash function.
- Example:
  - \( N = 200 \) data items.
  - keys are longs, evenly spread over the range \( 0..2^{61} - 1 \).
  - Want to keep maximum search to \( L = 2 \) items.
  - Use hash function \( h(K) = K \% M \), where \( M = N/L = 100 \) is the number of buckets: \( 0 \leq h(K) < M \).
  - So 100232, 433, and 10002332482 go into different buckets, but 10, 400210, and 210 all go into the same bucket.

External chaining

- Array of \( M \) buckets.
- Each bucket is a list of data items.
  - Not all buckets have same length, but average is \( N/M = L \), the load factor.
  - To work well, hash function must avoid collisions: keys that "hash" to equal values.
Open Addressing

- Idea: Put one data item in each bucket.
- When there is a collision, and bucket is full, just use another.
- Various ways to do this:
  - Linear probes: If there is a collision at \( h(K) \), try \( h(K) + m \), \( h(K) + 2m \), etc. (wrap around at end).
  - Quadratic probes: \( h(K) + m \), \( h(K) + m^2 \), \( h(K) + 2m^2 \), etc.
  - Double hashing: \( h(K) + h'(K) \), \( h(K) + 2h'(K) \), etc.
- Example: \( h(K) = K \mod M \), with \( M = 10 \), linear probes with \( m = 1 \).
  - Add 1, 2, 11, 3, 102, 9, 18, 108, 309 to empty table.

Things can get slow, even when table is far from full.

Lots of literature on this technique, but personally, I just settle for external chaining.

Filling the Table

- To get (likely to be) constant-time lookup, need to keep \#buckets within constant factor of \#items.
- So resize table when load factor gets higher than some limit.
- In general, must re-hash all table items.
- Still, this operation constant time per item,
- So by doubling table size each time, get constant amortized time for insertion and lookup
  - (Assuming, that is, that our hash function is good).

Hash Functions: Strings

- For String, \"s_0s_1 \ldots s_{n-1}\" want function that takes all characters and their positions into account.
- What’s wrong with \( s_0 + s_1 + \ldots + s_{n-1} \)?
- For strings, Java uses \( h(s) = s_0 \cdot 31^{n-1} + s_1 \cdot 31^{n-2} + \ldots + s_{n-1} \) computed modulo \( 2^{32} \) as in Java int arithmetic.
- To convert to a table index in \( 0 \ldots N - 1 \), compute \( h(s) \mod N \) (but don’t use table size that is multiple of 31!)
- Not as hard to compute as you might think; don’t even need multiplication!
  
  ```java
  int r; r = 0;
  for (int i = 0; i < s.length (); i += 1)
    r = (r << 5) - r + s.charAt (i);
  ```

Hash Functions: Other Data Structures I

- Lists (ArrayList, LinkedList, etc.) are analogous to strings: e.g., Java uses
  ```java
  hashCode = 1; Iterator i = list.iterator();
  while (i.hasNext()) {
    Object obj = i.next();
    hashCode =
      31*hashCode + (obj==null ? 0 : obj.hashCode());
  }
  ```
- Can limit time spent computing hash function by not looking at entire list. For example: look only at first few items (if dealing with a List or SortedSet).
- Causes more collisions, but does not cause equal things to go to different buckets.
Hash Functions: Other Data Structures II

- Recursively defined data structures ⇒ recursively defined hash functions.
- For example, on a binary tree, one can use something like
  
  ```java
  hash(T):
  if (T == null)
    return 0;
  else return someHashFunction(T.label())
    + 255 * hash(T.left())
    + 255*255 * hash(T.right());
  ```
- Can use address of object ("hash on identity") if distinct (!=) objects are never considered equal.
- But careful! Won’t work for Strings, because .equals Strings could be in different buckets:
  ```java
  String H = "Hello",
  S1 = H + ", world!",
  S2 = "Hello, world!";
  ```
- Here S1.equals(S2), but S1 != S2.

What Java Provides

- In class Object, is function hashCode().
- By default, returns address of this, or something similar.
- Can override it for your particular type.
- For reasons given on last slide, is overridden for type String, as well as many types in the Java library, like all kinds of List.
- The types Hashtable, HashSet, and HashMap use hashCode to give you fast look-up of objects.
  ```java
  HashMap<KeyType,ValueType> map =
  new HashMap<KeyType,ValueType> (approximate size, load factor);
  ```
  ```java
  map.put (key, value); // Map KEY -> VALUE.
  ... map.get (someKey)
  ... map.contains (someKey)
  ... map.keySet () // All keys in MAP (a Set)
  ```

Characteristics

- Assuming good hash function, add, lookup, deletion take \( \Theta(1) \) time, amortized.
- Good for cases where one looks up equal keys.
- Usually bad for range queries: "Give me every name between Martin and Napoli." [Why?]
- But sometimes OK, if hash function is monotonic (i.e., when key \( k_1 > k_2 \), then \( h(k_1) \geq h(k_2) \)). For example,
  - Items are time-stamped records; key is the time.
  - Hashing function is to have one bucket for every hour.
- Hashing is probably not a good idea for small sets that you rapidly create and discard [why?]

Comparing Search Structures

<table>
<thead>
<tr>
<th>Function</th>
<th>Unordered List</th>
<th>Sorted Array</th>
<th>Bushy Search Tree</th>
<th>&quot;Good&quot; Hash Table</th>
<th>Heap</th>
</tr>
</thead>
<tbody>
<tr>
<td>find</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
<td></td>
</tr>
<tr>
<td>add</td>
<td>( \Theta(1) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
<td></td>
</tr>
<tr>
<td>range query</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
<td></td>
</tr>
<tr>
<td>find largest</td>
<td>( \Theta(N) )</td>
<td>( \Theta(1) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
<td></td>
</tr>
<tr>
<td>remove largest</td>
<td>( \Theta(N) )</td>
<td>( \Theta(1) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
<td></td>
</tr>
</tbody>
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