Test #2: Wednesday, 13 November in class.

Today: Hashing (*Data Structures* Chapter 7).

Next topic: Sorting (*Data Structures* Chapter 8).
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 \( 0..2^{63} - 1 \).
  - Want to keep maximum search to \( L = 2 \) items.
  - Use hash function \( h(K) = K \mod M \), 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 the same length, but the average is $N/M = L$, the load factor.

To work well, the 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: \( h(K) + m \), \( h(K) + m^2 \), …
  - 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.

| 108 | 1 | 2 | 11 | 3 | 102 | 309 | 18 | 9 |

• 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, "s₀s₁⋯sₙ₋₁" want function that takes all characters and their positions into account.

• What’s wrong with s₀ + s₁ + ⋯ + sₙ₋₁?

• For strings, Java uses

  \[ h(s) = s₀ \cdot 3¹ⁿ⁻¹ + s₁ \cdot 3¹ⁿ⁻² + \ldots + sₙ₋₁ \]

  computed modulo \(2^{32}\) as in Java int arithmetic.

• To convert to a table index in \(0..N - 1\), compute \(h(s)\%N\) (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

   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:

   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);

map.put (key, value); // Map KEY -> VALUE.
// VALUE last mapped to by SOMEKEY.
... map.get (someKey)
    // VALUE last mapped to by SOMEKEY.
... map.containsKey (someKey)
    // Is SOMEKEY mapped?
... 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

Here, \( N \) is \#items, \( k \) is \#answers to query.

<table>
<thead>
<tr>
<th>Function</th>
<th>Unordered List</th>
<th>Sorted Array</th>
<th>Bushy Search Tree</th>
<th>“Good” Hash Table</th>
<th>Heap</th>
</tr>
</thead>
<tbody>
<tr>
<td>find</td>
<td>( \Theta(N) )</td>
<td>( \Theta(lg , N) )</td>
<td>( \Theta(lg , N) )</td>
<td>( \Theta(1) )</td>
<td>( \Theta(N) )</td>
</tr>
<tr>
<td>add</td>
<td>( \Theta(1) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(lg , N) )</td>
<td>( \Theta(1) )</td>
<td>( \Theta(lg , N) )</td>
</tr>
<tr>
<td>range query</td>
<td>( \Theta(N) )</td>
<td>( \Theta(k + lg , N) )</td>
<td>( \Theta(k + lg , N) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(N) )</td>
</tr>
<tr>
<td>find largest</td>
<td>( \Theta(N) )</td>
<td>( \Theta(1) )</td>
<td>( \Theta(lg , N) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(1) )</td>
</tr>
<tr>
<td>remove largest</td>
<td>( \Theta(N) )</td>
<td>( \Theta(1) )</td>
<td>( \Theta(lg , N) )</td>
<td>( \Theta(N) )</td>
<td>( \Theta(lg , N) )</td>
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