CS61B Lecture #24: Hashing
Back to Simple Search

• 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.

  “\textit{hash} /hæʃ/ 2 a a mixture; a jumble. \textit{b} a mess.” Concise Oxford Dictionary, eighth edition

• 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 \( h(K) = K \% M \), 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.

![Diagram showing external chaining]

- 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.
• 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: $h(K) = K \% M$, with $M = 10$, linear probes with $m = 1$.
  - Add 1, 2, 11, 3, 102, 9, 18, 108, 309 to empty table.

<table>
<thead>
<tr>
<th>108</th>
<th>1</th>
<th>2</th>
<th>11</th>
<th>3</th>
<th>102</th>
<th>309</th>
<th>18</th>
<th>9</th>
</tr>
</thead>
</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, \( s_0 s_1 \ldots s_{n-1} \) 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 \( 0..N - 1 \), 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

```java
hash(T):
    if (T == null)
        return 0;
    else return someHashFunction (T.label ()) ^ hash(T.left ()) ^ hash(T.right ());
```
Identity Hash Functions

• Can use address of object ("hash on identity") if distinct (\(!=\)) objects are never considered equal.

• But careful! Won’t work for Strings, because \(\text{.equals}\) Strings could be in different buckets:

    ```java
    String H = "Hello",
    S1 = H + ", world!",
    S2 = "Hello, world!";
    
    Here \(S1\text{.equals}(S2)\), but \(S1 \neq S2\).
    ```
What Java Provides

- **In class** `Object`, is function `hashCode()`.
- **By default**, returns the identity hash function, or something similar. [*Why is this OK as a default?]*
- **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<>(approximate size, load factor);
map.put(key, value); // Map KEY -> VALUE.
... map.get(someKey) // VALUE last mapped to by SOMEKEY.
... map.containsKey(someKey) // Is SOMEKEY mapped?
... map.keySet() // All keys in MAP (a Set)
```
Special Case: Monotonic Hash Functions

- Suppose our hash function is monotonic: either nonincreasing or nondescreasing.

- So, e.g., if key \( k_1 > k_2 \), then \( h(k_1) \geq h(k_2) \).

- Example:
  - Items are time-stamped records; key is the time.
  - Hashing function is to have one bucket for every hour.

- In this case, you can use a hash table to speed up range queries [How?]

- Could this be applied to strings? When would it work well?
Perfect Hashing

- Suppose set of keys is \textit{fixed}.
- A tailor-made hash function might then hash every key to a different value: \textit{perfect hashing}.
- In that case, there is no search along a chain or in an open-address table: either the element at the hash value is or is not equal to the target key.
- For example, might use first, middle, and last letters of a string (read as a 3-digit base-26 numeral). Would work if those letters differ among all strings in the set.
- Or might use the Java method, but tweak the multipliers until all strings gave different results.
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?]
- 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>&quot;Good&quot; 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 (amortized)</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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