# CS61B Lecture #26

**Test #2:**   Wednesday, 7 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 $h(K) = K\%M$, where $M = N/L = 100$ is the number of buckets: $0 \le h(K) < M$.
  - 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.
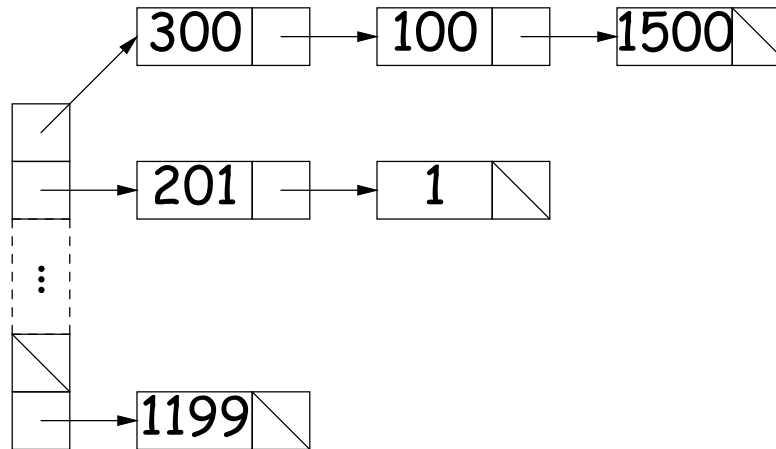


- Not all buckets have same length, but average is $N/M = L$, the *load factor*.

- 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: $h(K) + m$, $h(K) + m^2$, ...
  - 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.

| 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, $"s_0 s_1 \cdots s_{n-1}"$ 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!

```
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 analagous to strings: e.g., Java uses

```
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 `.equal` 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.

```
HashMap<KeyType,ValueType> map =
    new HashMap<KeyType,ValueType> (approximate size, load fac-
    tor);

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.

| Function | Unordered List | Sorted Array | Bushy Search Tree | "Good" Hash Table | Heap |
|---|---|---|---|---|---|
| find | $\Theta(N)$ | $\Theta(\lg N)$ | $\Theta(\lg N)$ | $\Theta(1)$ | $\Theta(N)$ |
| add | $\Theta(1)$ | $\Theta(N)$ | $\Theta(\lg N)$ | $\Theta(1)$ | $\Theta(\lg N)$ |
| range query | $\Theta(N)$ | $\Theta(k + \lg N)$ | $\Theta(k + \lg N)$ | $\Theta(N)$ | $\Theta(N)$ |
| find largest | $\Theta(N)$ | $\Theta(1)$ | $\Theta(\lg N)$ | $\Theta(N)$ | $\Theta(1)$ |
| remove largest | $\Theta(N)$ | $\Theta(1)$ | $\Theta(\lg N)$ | $\Theta(N)$ | $\Theta(\lg N)$ |