

## CS61B Lecture #24: Hashing

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## 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.

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## Hash functions

- To do this, must have way to convert key to bucket number: a *hash function*.

"hash /hæʃ/ 2a a mixture; a jumble. b a mess." *Concise Oxford Dictionary, eighth edition*

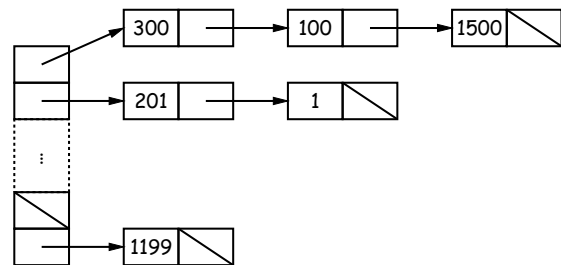
- Example:
  - $N = 200$  data items.
  - keys are longs, evenly spread over the range  $0..2^{63} - 1$ .
  - Want to keep maximum search to  $L = 2$  items.
  - Use hash function  $h(K) = K \% M$ , where  $M = N/L = 100$  is the number of buckets:  $0 \leq h(K) < M$ .
  - So 100232, 433, and 10002332482 go into different buckets, but 10, 400210, and 210 all go into the same bucket.

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## 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.

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## Ditching the Chains: 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:  $h(K) + 1 \cdot m$ ,  $h(K) + 2^2 \cdot m$ ,  $h(K) + 3^2 \cdot m$ , ... (corrected 3/24)
  - 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
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- 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.

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## 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).

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## Hash Functions: Strings

- For String, " $s_0s_1 \dots s_{n-1}$ " want function that takes all characters and their positions into account.
- What's wrong with  $s_0 + s_1 + \dots + s_{n-1}$ ?
- For strings, Java uses

$$h(s) = s_0 \cdot 31^{n-1} + s_1 \cdot 31^{n-2} + \dots + s_{n-1}$$

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);
```

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## Hash Functions: Other Data Structures I

- Lists (ArrayList, LinkedList, etc.) are analogous 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.

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## Hash Functions: Other Data Structures II

- Recursively defined data structures  $\Rightarrow$  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 ())
        ^ hash(T.left ()) ^ hash(T.right ());
```

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## Identity Hash Functions

- Can use address of object ("hash on identity") if distinct ( $\neq$ ) 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`.

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## 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.

```
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)
```

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## Special Case: Monotonic Hash Functions

- Suppose our hash function is *monotonic*: either nonincreasing or nondecreasing.
- 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?

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## Perfect Hashing

- Suppose set of keys is *fixed*.
- A tailor-made hash function might then hash every key to a different value: *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.

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## 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?]

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## Comparing Search Structures

Here,  $N$  is #items,  $k$  is #answers to query.

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

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