

CSC 427: Data Structures and Algorithm Analysis

Fall 2006

Hash tables

- HashSet & HashMap
- hash table, hash function
- collisions
 - linear probing, lazy deletion, primary clustering
 - quadratic probing, rehashing
 - chaining

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HashSet & HashMap

recall: `TreeSet` & `TreeMap` use an underlying binary search tree (actually, a red-black tree) to store values

- as a result, add/put, contains/get, and remove are $O(\log N)$ operations
- iteration over the Set/Map can be done in $O(N)$

the other implementations of the `Set` & `Map` interfaces, `HashSet` & `HashMap`, use a "magic" data structure to provide $O(1)$ operations*

**legal disclaimer*: performance can degrade to $O(N)$ under bad/unlikely conditions
however, careful setup and maintenance can ensure $O(1)$ in practice

the underlying data structure is known as a *Hash Table*

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Hash tables

a hash table is a data structure that supports *constant time* insertion, deletion, and search *on average*

- degenerative performance is possible, but unlikely
- it may waste some storage
- iteration order is not defined (and may even change over time)

idea: data items are stored in a table, based on a key

- the key is mapped to an index in the table, where the data is stored/accessed

example: letter frequency

- want to count the number of occurrences of each letter in a file
- have an array of 26 counters, map each letter to an index
- to count a letter, map to its index and increment

"A" → 0	1
"B" → 1	0
"C" → 2	3
...	...
"z" → 25	0

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Mapping examples

extension: word frequency

- must map entire words to indices, e.g.,

"A" → 0	"AA" → 26	"BA" → 52	...
"B" → 1	"AB" → 27	"BB" → 53	...
...
"Z" → 25	"AZ" → 51	"BZ" → 77...	

- **PROBLEM?**

mapping each potential item to a unique index is generally not practical

of 1 letter words = 26
of 2 letter words = $26^2 = 676$
of 3 letter words = $26^3 = 17,576$
...

- even if you limit words to at most 8 characters, need a table of size 217,180,147,158
- for any given file, the table will be mostly empty!

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Table size < data range

since the actual number of items stored is generally MUCH smaller than the number of potential values/keys:

- can have a smaller, more manageable table

e.g., table size = 26

possible mapping: map word based on first letter

"A*" → 0 "B*" → 1 ... "Z*" → 25

e.g., table size = 1000

possible mapping: add ASCII values of letters, mod by 1000

"AB" → 65 + 66 = 131

"BANANA" → 66 + 65 + 78 + 65 + 78 + 65 = 417

"BANANABANANABANANA" → 417 + 417 + 417 = 1251 % 1000 = 251

- POTENTIAL PROBLEMS?

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Collisions

the mapping from a key to an index is called a *hash function*

- the hash function can be written independent of the table size
- if it maps to an index > table size, simply wrap-around (i.e., index % tableSize)

since $|\text{range}(\text{hash function})| < |\text{domain}(\text{hash function})|$,
can have multiple items map to the same index (i.e., a *collision*)

"ACT" → 67 + 65 + 84 = 216

"CAT" → 67 + 65 + 84 = 216

techniques exist for handling collisions, but they are costly (LATER)

it's best to avoid collisions as much as possible – HOW?

- want to be sure that the hash function distributes the key evenly
- e.g., "sum of ASCII codes" hash function
 - OK if table size is 1000
 - BAD if table size is 10,000most words are ≤ 8 letters, so max sum of ASCII codes = 1,016
so most entries are mapped to first 1/10th of table

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Better hash function

a good hash function should

- produce an even spread, regardless of table size
- take order of letters into account (to handle anagrams)
- the hash function used by `java.util.String` multiplies the ASCII code for each character by a power of 31

$$\text{hashCode}() = \text{char}_0 * 31^{(\text{len}-1)} + \text{char}_1 * 31^{(\text{len}-2)} + \text{char}_2 * 31^{(\text{len}-3)} + \dots + \text{char}_{(\text{len}-1)}$$

where `len = this.length()`, `chari = this.charAt(i)`:

```
/**
 * Hash code for java.util.String class
 * @return an int used as the hash index for this string
 */
private int hashCode() {
    int hashIndex = 0;

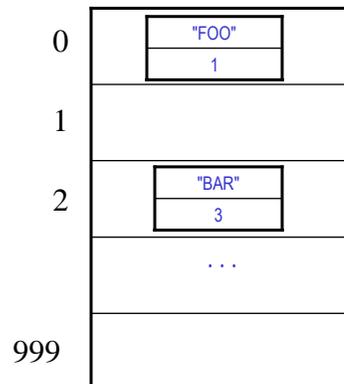
    for (int i = 0; i < this.length(); i++) {
        hashIndex = (hashIndex*31 + this.charAt(i));
    }
    return hashIndex;
}
```

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Word frequency example

returning to the word frequency problem

- pick a hash function
- pick a table size
- store word & associated count in the table
- as you read in words,
map to an index using the hash function
if an entry already exists, increment
otherwise, create entry with count = 1



WHAT ABOUT COLLISIONS?

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Linear probing

linear probing is a simple strategy for handling collisions

- if a collision occurs, try next index & keep looking until an empty one is found (wrap around to the beginning if necessary)

assume naïve "first letter" hash function

- insert "BOO"
- insert "COO"
- insert "BOW"
- insert "BAZ"
- insert "ZOO"
- insert "ZEBRA"

0	
1	
2	
3	
4	
	...
25	

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Linear probing (cont.)

with linear probing, will eventually find the item if stored, or an empty space to add it (if the table is not full)

what about deletions?

- delete "BIZ"

can the location be marked as empty?

can't delete an item since it holds a place for the linear probing

- search "COO"

0	"AND"
1	"BOO"
2	"BIZ"
3	"COO"
	...

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Lazy deletion

when removing an entry

- mark the entry as being deleted (i.e., mark location)
- subsequent searches must continue past deleted entries (probe until desired item or an empty location is found)
- subsequent insertions can use deleted locations

ADD "BOO"

ADD "AND"

ADD "BIZ"

ADD "COO"

DELETE "BIZ"

SEARCH "COO"

ADD "COW"

SEARCH "COO"

0	
1	
2	
3	
4	
5	
6	
7	

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Primary clustering

in practice, probes are not independent

- suppose table is half full

maps to 4-7 require 1 check
map to 3 requires 2 checks
map to 2 requires 3 checks
map to 1 requires 4 checks
map to 0 requires 5 checks

average = $18/8 = 2.25$ checks

0	"AND"
1	"BOO"
2	"BIZ"
3	"COO"
4	
5	
6	
7	

using linear probing, clusters of occupied locations develop

- known as *primary clusters*

insertions into the clusters are expensive & increase the size of the cluster

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Analysis of linear probing

the *load factor* λ is the fraction of the table that is full

empty table $\lambda = 0$ half full table $\lambda = 0.5$ full table $\lambda = 1$

THEOREM: assuming a reasonably large table, the average number of locations examined per insertion (taking clustering into account) is roughly $(1 + 1/(1-\lambda)^2)/2$

empty table	$(1 + 1/(1 - 0)^2)/2 = 1$
half full	$(1 + 1/(1 - .5)^2)/2 = 2.5$
3/4 full	$(1 + 1/(1 - .75)^2)/2 = 8.5$
9/10 full	$(1 + 1/(1 - .9)^2)/2 = 50.5$

as long as the hash function is fair and the table is not too full, then inserting, deleting, and searching are all $O(1)$ operations

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Rehashing

it is imperative to keep the load factor below 0.75

if the table becomes three-quarters full, then must resize

- find prime number twice as big
- just copy over table entries to same locations???
- NO! when you resize, you have to rehash existing entries
new table size \rightarrow new hash function (+ different wraparound)

LET hashCode = word.length()

	0	
ADD "UP"	1	
ADD "OUT"	2	
ADD "YELLOW"	3	

NOW
RESIZE
AND
REHASH

0	
1	
2	
3	
4	
5	
6	
7	

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Chaining

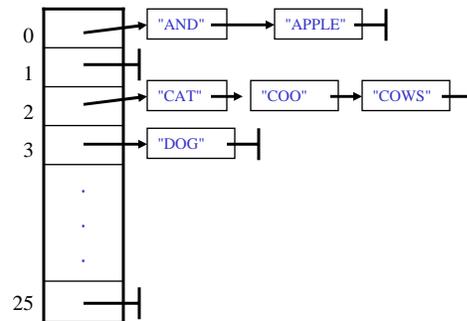
there are variations on linear probing that eliminate primary clustering

- e.g., quadratic probing increases index on each probe by square offset

Hash(key) → Hash(key) + 1 → Hash(key) + 4 → Hash(key) + 9 → Hash(key) + 16 → ...

however, the most commonly used strategy for handling collisions is *chaining*

- each entry in the hash table is a bucket (list)
- when you add an entry, hash to correct index then add to bucket
- when you search for an entry, hash to correct index then search sequentially



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Analysis of chaining

in practice, chaining is generally faster than probing

- cost of insertion is $O(1)$ – simply map to index and add to list
- cost of search is proportional to number of items already mapped to same index
e.g., using naïve "first letter" hash function, searching for "APPLE" might require traversing a list of all words beginning with 'A'

if hash function is fair, then will have roughly $\lambda / \text{tableSize}$ items in each bucket
→ average cost of a successful search is roughly $\lambda / 2 * \text{tableSize}$

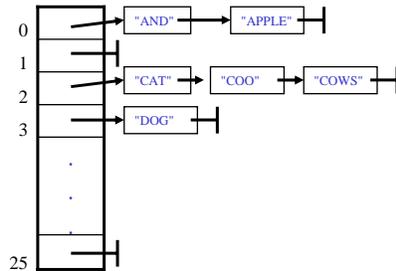
chaining is sensitive to the load factor, but not as much as probing – WHY?

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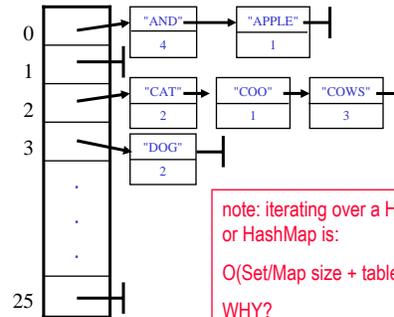
HashSet & HashMap

`java.util.HashSet` and `java.util.HashMap` use chaining

▪ e.g., `HashSet<String>`



`HashMap<String, Integer>`



note: iterating over a HashSet
or HashMap is:
 $O(\text{Set/Map size} + \text{table size})$
WHY?

- defaults: table size = 16, max capacity before rehash = 75%
can override these defaults in the HashSet/HashMap constructor call
- a default hash function is defined for every `Object` (based on its address)
- a class can define its own hash function by overriding `hashCode`
must ensure that `obj1.equals(obj2) → obj1.hashCode() == obj2.hashCode()`

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