Announcements

- Submit Prelim 2 conflicts by Wednesday (tomorrow) night
- A6 is due April 18 (Thursday!)
- Prof. Clarkson diagnosed with a concussion and is staying home this week. Don’t send him email — he’s supposed to stay away from his computer.

Material in for Hashing

- Tutorial on hashing: in lower navigation bar in JavaHyperText
- Entry hash in JavaHyperText
- Specific to Java. API documentation for: hashCode() and function equals(Object ob)
- Lecture notes page of course website. Demo code for hashing with chaining and hashing with open addressing

Ideal Data Structure

<table>
<thead>
<tr>
<th>Data Structure</th>
<th>add(val x)</th>
<th>get(i)</th>
<th>contains(val x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ArrayList</td>
<td>O(n)</td>
<td>O(1)</td>
<td>O(n)</td>
</tr>
<tr>
<td>LinkedList</td>
<td>O(1)</td>
<td>O(n)</td>
<td>O(n)</td>
</tr>
</tbody>
</table>

Goal: O(1) O(1) O(1)

New Data Structure: Hash Set

<table>
<thead>
<tr>
<th>Data Structure</th>
<th>add(val x)</th>
<th>get(i)</th>
<th>contains(val x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HashSet</td>
<td>O(1)</td>
<td>O(1)</td>
<td>O(1)</td>
</tr>
</tbody>
</table>

Notion of hashing

Hash: to chop to pieces; to make a confused muddle of; to jumble; to dice, chop, mince.

In computing: Produce a relatively small number or string from something a lot bigger, like a file, or an Java object.

Look at CMS page for A2 submission. Md5 is a hash function. Given your A2.java file, it produces a 128-bit number from it. Sometimes called a checksum. Compare the Md5 number for your file to the Md5 number of the one that was uploaded. If different, uploading corrupted the file.
Hash functions are used to store passwords.

Could store plaintext passwords

- Problem: Password files get stolen

**Application: Password Storage**

$h(password)$: $h$ is the hash function. It produces some jumbled version of the password.

Hash functions are used in various applications for hashing.

- **Application: Password Storage**

- **Application: Hashing history**

- **Application: Intuition behind a Hash Set**

  - **Idea:** finding an element in an array takes constant time when you know which index it is. So... let's place elements in the array based on their starting letter! (A=0, B=1, ...)

  - **add(“CA”)**
    - CA  # of 1st letter  2

  - **contains(“DE”)**
    - DE  # of 1st letter  3

**What could go wrong?**

- Some buckets get used quite a bit!
  - Connecticut, Colorado
- Not all buckets get used

bucket: one of the array elements

**Hashing history**

We will use hashing — a hash function — to implement sets of values in a hash table.

1953. Hand Peter Luhn wrote an internal IBM memorandum that used hashing with chaining.

A few others did it roughly the same time.

Ershov (Russian) and Amdahl independently invented hashing with open addressing and linear probing.

**Intuition behind a Hash Set**

- **Idea:** finding an element in an array takes constant time when you know which index it is. So... let's place elements in the array based on their starting letter! (A=0, B=1, ...)

  - **add(“CA”)**
    - CA  # of 1st letter  2

  - **contains(“DE”)**
    - DE  # of 1st letter  3

**What could go wrong?**

- Some buckets get used quite a bit!
  - Connecticut, Colorado
- Not all buckets get used

bucket: one of the array elements

**Hash Function**

Given a value to be put into the table, a hash function returns an index where to put it.

E.g. hash function($\text{stateName}$) could return value depending on first character:
- 0 for A, 1 for B, 2 for C, etc.

Example: hashFunction("Oregon")

- $h(\text{stateName})$ could return value depending on first character:
  - 0 for A, 1 for B, 2 for C, etc.

Example: hashFunction("Oregon") mod 10 = 14 mod 10 = 4

So put "Oregon" in bucket 4.

**Example: hashCode()**

- $\text{hashCode()}$ defined in java.lang.Object
- Default implementation: uses memory address of object
- If you override equals, you must override $\text{hashCode()}$!!!
  - We'll explain why later.

String overrides $\text{hashCode()}$:

$s.\text{hashCode}() : = s[0] + 31^{n-1} + s[1] + 31^{n-2} + ... + s[n-1]$

**Do we like this $\text{hashCode}()$?**
Can we have perfect hash functions?

- A perfect hash function will map each value to a different index in the hash table.
- Impossible in practice:
  - Don’t know size of the array
  - Number of possible values far far exceeds the array size
  - No point in a perfect hash function if it takes too much time to compute
- Forget about perfect hash functions!

Collision Resolution

Two ways of handling collisions:

1. Chaining
   - A bucket contains a linked list of items that hash to it
2. Open Addressing
   - A bucket contains one item of the set. Look in successive array elements to find a place for a new item

Chaining (1)

Each bucket is the beginning of a LinkedList

```
add("NY")
```

Chaining (2)

Each bucket is the beginning of a LinkedList

```
add("NY")
add("NJ")
```

Chaining (3)

Each bucket is the beginning of a LinkedList

```
add("NY")
add("NJ")
rem("NJ")
```

Chaining in Action

Insert the following elements (in order) into an array of size 6:
Use (hashCode % n_buckets)

<table>
<thead>
<tr>
<th>element</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
</tr>
</thead>
<tbody>
<tr>
<td>hashCode</td>
<td>0</td>
<td>9</td>
<td>17</td>
<td>11</td>
<td>19</td>
</tr>
</tbody>
</table>
Open Addressing (1)

Probe: One test in finding space for a new item or when searching for an item

add("NY")

NY # of 1st letter 13

Open Addressing (2)

Probe: One test in finding space for a new item or when searching for an item

add("NJ")

NJ # of 1st letter 13

Open Addressing (3)

Probe: One test in finding space for a new item or when searching for an item

add("NY")

add("NJ")

rem("NJ")

rem("NY")

What could possibly go wrong?

add("NY"), add("NJ"), get("NY"), get("NJ")

Open Addressing (4)

Probe: One test in finding space for a new item or when searching for an item

add("NY")

add("NJ")

rem("NJ")

rem("NY")

Search for NJ

Search for NJ

(Stop searching b/c element b[13] is null)

Deletion Problem w/Open Addressing

Probe: One test in finding space for a new item or when searching for an item

add("NY")

add("NJ")

rem("NY")

rem("NJ")

Search for NJ

Search for NJ

(Stop searching if element is null)

Deletion Solution for Open Addressing

Probe: One test in finding space for a new item or when searching for an item

to mark element as "not present"

Indicates to search that it should keep looking

add("NY")

add("NJ")

get("NY")

get("NJ")

Search for NJ

(search until it finds a null element or the element it's searching for)

Different probing strategies

When a collision occurs, how do we search for an empty space?

clustering: problem where nearby hashes have similar probe sequences so we get more collisions

linear probing: search the array in this sequence:

i, i+1, i+2, i+3, ...

Quadratic probing requires the size of the array to be a prime in order to have access to every bucket.
Linear Probing in Action

Insert the following elements (in order) into an array of size 5:

<table>
<thead>
<tr>
<th>element</th>
<th>hashCode</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0</td>
</tr>
<tr>
<td>b</td>
<td>8</td>
</tr>
<tr>
<td>c</td>
<td>17</td>
</tr>
<tr>
<td>d</td>
<td>12</td>
</tr>
</tbody>
</table>

Insert d:
- probe #1: insert d at i, full!
- probe #2: insert d at i+1, full!
- probe #3: insert d at i+2, has space!

Quadratic Probing in Action

Insert the following elements (in order) into an array of size 5:

<table>
<thead>
<tr>
<th>element</th>
<th>hashCode</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0</td>
</tr>
<tr>
<td>b</td>
<td>8</td>
</tr>
<tr>
<td>c</td>
<td>17</td>
</tr>
<tr>
<td>d</td>
<td>12</td>
</tr>
</tbody>
</table>

Insert d:
- probe #1: insert d at i, full!
- probe #2: insert d at i+1, full!
- probe #3: insert d at i+2, has space!

In Java, functions hashCode and equals

HashSet, HashMap use functions hashCode(), equals(…)

c.hashCode() in class Object returns the address in memory of object c

c.equals(c1) in class Object is true iff c and c1 point to the same object

In Java, functions hashCode and equals

Elements of set HashSet have class type, e.g. Pt

Rewrite equals

```
/** Return true iff this and ob are of the same
 * class type, their x fields are equal, and
 * their y fields are equal. */
public boolean equals(Object ob) {…}
```

Because b and c are equal, only one of them should be put in the set

```
c b
```

Rewrite equals

```
public int hashCode() {
    return abs(x + y);
}
```

Elements of set HashSet have class type, e.g. Pt

Rewrite equals

```
/** Return true iff this and ob are of the same
 * class type, their x fields are equal, and
 * their y fields are equal. */
public boolean equals(Object ob) {…}
```

```
Class Pt {
    int x;
    int y;
    …
}
```

```
b and c are different Pt objects but
b.x = c.x
b.y = c.y
```

```
Class Pt {
    int x;
    int y;
    …
}
```

```
b and c are different Pt objects but
b.x = c.x
b.y = c.y
```
Load Factor

Load factor: \[ \lambda = \frac{\text{# of entries}}{\text{length of array}} \]

If load factor = \( \frac{1}{2} \), expected # of probes is 2.
What happens when the array becomes too full?
\( i.e. \text{load factor gets a lot bigger than } \frac{1}{2} \?
\[ \text{no longer expected constant time operations} \]

waste of memory

best range

too slow

Chaining: Worst case time \( O(n) \)

Chaining worst case time 0 8999

Suppose everything hashes to the last array element, so that all array elements are null except the last, and that last linked list has \( n \) elements in it ---the set has size \( n \).

In this case, operations add, contains, and remove all take time \( O(n) \). That's the worst case.

Chaining: Expected time if load factor small: \( O(1) \)

Example. 6000 elements, table size 9000, load factor 6/9

Find average length of chain over all possibilities.
\[ e \text{ hashes to a number in } 0..8999 \text{ with equal probability.} \]
8999 of the possibilities have length 0.
The other 1 possibility has length 6000.
\[ (8999*0 + 1*6000) / 9000 = 6/9 \text{ (load factor)} \]

Chaining: Expected time if load factor small: \( O(1) \)

Example: 6 elements, table size 9, load factor 6/9

Consider any configuration of a set with load factor 6/9.
The average chain length is the load factor: 6/9

Average chain length: 6/9

Linear probing: Worst case time \( O(n) \)

Chaining worst case time 0 n 8999

Suppose everything hashes to 0, so that \( b[0..n-1] \)
contains the set of elements and \( b[n..] \) are all null.

In this case, operations add, contains, and remove all take time \( O(n) \). That's the worst case.

Example.
6 elements, table size 9, load factor 6/9

Consider searching for \( e \) ---not in the set.
Find average length of chain over all possibilities.
\( e \text{ hashes to a number in } 0..8 \text{ with equal probability.} \]
8 of the possibilities have length 0.
The other 1 possibility has length 6.
\( (8*0 + 1*6) / 9 = 6/9 \text{ (load factor)} \)
Chaining: Expected time if load factor small: $O(1)$

Searching for a value, whether in the set or not.
If the distribution of elements to buckets is sufficiently uniform, the average cost of a lookup depends only on the average number of elements per bucket.
That is: \( \frac{\text{size of set}}{\text{size of array}} \)
That's the load factor!
Load factor .75: average of .75 elements per bucket
Load factor 1: average of 1 element per bucket
Load factor 2: average of 2 elements per bucket

Java HashMap uses chaining with load factor .75

Linear probing: Expected time, small load factor: $O(1)$

This analysis is more complicated, harder.
State without proof:
The number of probes (buckets examined) to insert a value in a hash table with load factor $l$ is
\[ \frac{1}{1 - l} \]
Choose $l = \frac{1}{2}$ and get average number of probes: 2

Resizing

When the load factor gets too big, create a new array twice the size, move the values to the new array, and then use the new array going forward.

YOU DID THIS IN A5, method ensureSpace()!

Collections class ArrayList does the same.

Collections classes HashSet and HashMap resize when the load factor becomes greater than .75, but you can change it.

Resizing takes constant amortized time

Say it cost $100.00

We bought a machine that makes fizzy water.
The machine cost $100.

Make one glass of fizzy water:
glass cost $1.00.
Make 100 glasses of fizzy water:
Each glass cost $1.00.
Make 1,000 glasses:
Each glass cost 10 cents.

Amortizing cost of machine over use of machine, over number of operations “make a glass …”.

Amortizing the cost of resizing

Each element of the array took at most constant time $C$ (say) to add it to the set.

Double the size of the array:
Each element has to be rehashed into the new array, taking time at most $C$.
So we say that the time for each element is $2C$—we amortize the cost of resizing over the time for the add operation.
Collision Resolution Summary

<table>
<thead>
<tr>
<th>Chaining</th>
<th>Open Addressing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Store entries in separate chains (linked lists)</td>
<td>Store all entries in table</td>
</tr>
<tr>
<td>Uses more memory</td>
<td>Use linear or quadratic probing to place items</td>
</tr>
<tr>
<td></td>
<td>Uses less memory</td>
</tr>
<tr>
<td></td>
<td>Clustering can be a problem — need to be more careful with choice of hash function</td>
</tr>
</tbody>
</table>

**Application: Hash Map**

```java
Map<K,V> {
    void put(K key, V value);
    void update(K key, V value);
    V get(K key);
    V remove(K key);
}
```

- Use the key for lookups
- Store the value

Example: key is the word, value is its definition

**HashMap in Java**

- Computes hash using key.hashCode()
- No duplicate keys
- Uses chaining to handle collisions
- Default load factor is .75
- Java 8 attempts to mitigate worst-case performance by switching to a BST-based chaining!

**Hash Maps in the Real World**

- Network switches
- Distributed storage
- Database indexing
- Heaps with the ability to change a priority
- Index lookup (e.g. Dijkstra’s shortest-path algorithm)
- Useful in lots of applications...