STANDARD ADTS

Lecture 17
CS2110 – Spring 2013

Abstract Data Types (ADTs)

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- A method for achieving abstraction for data structures and algorithms
- ADT = model + operations
- Describes what each operation does, but not how it does it
- An ADT is independent of its implementation

- In Java, an interface corresponds well to an ADT
  - The interface describes the operations, but says nothing at all about how they are implemented
- Example: Stack interface/ADT

```
public interface Stack {
  public void push(Object x);
  public Object pop();
  public Object peek();
  public boolean isEmpty();
  public void clear();
}
```

Queues & Priority Queues

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- ADT Queue
  - Operations:
    - `void add(Object x);`
    - `Object poll();`
    - `Object peek();`
    - `boolean isEmpty();`
    - `void clear();`
- Where used:
  - Simple job scheduler (e.g., print queue)
  - Wide use within other algorithms

- ADT PriorityQueue
  - Operations:

```
void insert(Object x);
Object getMax();
Object peekAtMax();
boolean isEmpty();
void clear();
```

- Where used:
  - Job scheduler for OS
  - Event-driven simulation
  - Can be used for sorting
  - Wide use within other algorithms

A (basic) queue is "first in, first out". A priority queue ranks objects: getMax() returns the "largest" according to the comparator interface.

Sets

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- ADT Set
  - Operations:

```
void insert(Object element);
boolean contains(Object element);
void remove(Object element);
boolean isEmpty();
void clear();
for(Object o: mySet) { ... }
```

- Where used:
  - Wide use within other algorithms
- Note: no duplicates allowed
  - A "set" with duplicates is sometimes called a *multiset* or *bag*

A set makes no promises about ordering, but you can still iterate over it.

Dictionaries

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- ADT Dictionary (aka Map)
  - Operations:
    - `void insert(Object key, Object value);`
    - `void update(Object key, Object value);`
    - `Object find(Object key);`
    - `void remove(Object key);`
    - `boolean isEmpty();`
    - `void clear();`
- Think of: key = word; value = definition
- Where used:
  - Symbol tables
  - Wide use within other algorithms

A HashMap is a particular implementation of the Map interface

Data Structure Building Blocks

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- These are *implementation* "building blocks" that are often used to build more-complicated data structures
  - Arrays
  - Linked Lists
    - Singly linked
    - Doubly linked
  - Binary Trees
  - Graphs
    - Adjacency matrix
    - Adjacency list

From interface to implementation

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- Given that we want to support some interface, the designer still faces a choice
  - What will be the best way to implement this interface for my expected type of use?
  - Choice of implementation can reflect many considerations
- Major factors we think about
  - Speed for typical use case
  - Storage space required

Array Implementation of Stack

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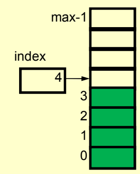
```
class ArrayStack implements Stack {

   private Object[] array; //Array that holds the Stack
   private int index = 0; //First empty slot in Stack

   public ArrayStack(int maxSize)
      { array = new Object[maxSize]; }

   public void push(Object x) { array[index++] = x; }
   public Object pop() { return array[--index]; }
   public Object peek() { return array[index-1]; }
   public boolean isEmpty() { return index == 0; }
   public void clear() { index = 0; }
}
```



O(1) worst-case time for each operation

Question: What can go wrong?

.... What if maxSize is too small?

Linked List Implementation of Stack

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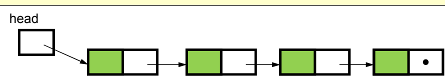
```
class ListStack implements Stack {
   private Node head = null;  //Head of list that
                              //holds the Stack

   public void push(Object x) { head = new Node(x, head); }
   public Object pop() {
      Node temp = head;
      head = head.next;
      return temp.data;
   }
   public Object peek() { return head.data; }
   public boolean isEmpty() { return head == null; }
   public void clear() { head = null; }
}
```

O(1) worst-case time for each operation (but constant is larger)

Note that array implementation can overflow, but the linked list version cannot



Queue Implementations

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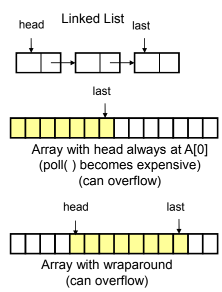
- Possible implementations



- Recall: operations are **add, poll, peek,…**
- For linked-list
  - All operations are O(1)
- For array with head at A[0]
  - poll takes time O(n)
  - Other ops are O(1)
  - Can overflow
- For array with wraparound
  - All operations are O(1)
  - Can overflow

A Queue From 2 Stacks

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- Add pushes onto stack A
- Poll pops from stack B
- If B is empty, move all elements from stack A to stack B
- Some individual operations are costly, but still O(1) time per operations over the long run

Dealing with Overflow

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- For array implementations of stacks and queues, use *table doubling*
- Check for overflow with each insert op
- If table will overflow,
  - Allocate a new table twice the size
  - Copy everything over
- The operations that cause overflow are expensive, but still constant time per operation over the long run (proof later)

Goal: Design a *Dictionary* (aka *Map*)

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- Operations

Array implementation: Using an array of (key,value) pairs

- `void insert(key, value)`
- `void update(key, value)`
- `Object find(key)`
- `void remove(key)`
- `boolean isEmpty()`
- `void clear()`

	Unsorted	Sorted
insert	O(1)	O(n)
update	O(n)	O(log n)
find	O(n)	O(log n)
remove	O(n)	O(n)

n is the number of items currently held in the dictionary

Hashing

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- Idea: compute an array index via a *hash function* h
- U is the universe of keys
- h: U → [0,…,m-1] where m = hash table size
- Usually |U| is much bigger than m, so *collisions* are possible (two elements with the same hash code)
- h should
  - be easy to compute
  - avoid collisions
  - have roughly equal probability for each table position

Typical situation:
U = all legal identifiers

Typical hash function:
h converts each letter to a number, then compute a function of these numbers

Best hash functions are highly random
This is connected to cryptography
We'll return to this in a few minutes

A Hashing Example

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- Suppose each word below has the following hashCode
  - jan 7
  - feb 0
  - mar 5
  - apr 2
  - may 4
  - jun 7
  - jul 3
  - aug 7
  - sep 2
  - oct 5

- How do we resolve collisions?
  - use chaining: each table position is the head of a list
  - for any particular problem, this *might* work terribly
- In practice, using a good hash function, we can assume each position is equally likely

Analysis for Hashing with Chaining

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- Analyzed in terms of *load factor* λ = n/m = (items in table)/(table size)
- We count the expected number of *probes* (key comparisons)
- Goal: Determine expected number of probes for an *unsuccessful* search

- Expected number of probes for an unsuccessful search = average number of items per table position = n/m = λ
- Expected number of probes for a *successful* search = 1 + λ = O(λ)
- Worst case is O(n)

Table Doubling

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- We know each operation takes time O(λ) where λ λ =n/m
- So it gets worse as n gets large relative to m
- Table Doubling:
- Set a bound for λ (call it λ_0)
- Whenever λ reaches this bound:
  - Create a new table twice as big
  - Then rehash all the data
- As before, operations *usually* take time O(1)
  - But sometimes we copy the whole table

Analysis of Table Doubling

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- Suppose we reach a state with n items in a table of size m and that we have just completed a table doubling

	Copying Work
Everything has just been copied	n inserts
Half were copied previously	n/2 inserts
Half of those were copied previously	n/4 inserts
…	…
Total work	n + n/2 + n/4 + … = 2n

Analysis of Table Doubling, Cont'd

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- Total number of insert operations needed to reach current table = copying work + initial insertions of items = 2n + n = 3n inserts
- Each insert takes expected time O(λ_0) or O(1), so total expected time to build entire table is O(n)
- Thus, expected time per operation is O(1)

- Disadvantages of table doubling:
  - Worst-case insertion time of O(n) is definitely achieved (but rarely)
  - Thus, not appropriate for time critical operations

Concept: "hash" codes

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- Definition: a *hash code* is the output of a function that takes some input and maps it to a pseudo-random number (a *hash*)
  - Input could be a big object like a string or an Animal or some other complex thing
  - Same input always gives same out
  - Idea is that hashCode for distinct objects will have a very low likelihood of collisions
- Used to create *index* data structures for finding an object given its hash code

Java Hash Functions

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- Most Java classes implement the **`hashCode()`** method
- **`hashCode()`** returns an int
- Java's **`HashMap`** class uses h(X) = X.hashCode() mod m
- h(X) in detail:
  - `int hash = X.hashCode();`
  - `int index = (hash & 0x7FFFFFFF) % m;`

- What **`hashCode()`** returns:
  - Integer:
    - uses the int value
  - Float:
    - converts to a bit representation and treats it as an int
  - Short Strings:
    - 37*previous + value of next character
  - Long Strings:
    - sample of 8 characters; 39*previous + next value

`hashCode()` Requirements

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- Contract for **`hashCode()`** method:
  - Whenever it is invoked in the same object, it must return the same result
  - Two objects that are equal (in the sense of **`.equals(...)`**) must have the same hash code
  - Two objects that are not equal should return different hash codes, but are not required to do so (i.e., collisions are allowed)

Hashtables in Java

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- **`java.util.HashMap`**
- **`java.util.HashSet`**
- **`java.util.Hashtable`**
- Use chaining
- Initial (default) size = 101
- Load factor = λ_0 = 0.75
- Uses table doubling (2*previous+1)

- A node in each chain looks like this:

hashCode	key	value	next

original hashCode (before mod m)

Allows faster rehashing and (possibly) faster key comparison

Linear & Quadratic Probing

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- These are techniques in which all data is stored directly within the hash table array
- Linear Probing
  - Probe at h(X), then at
    - h(X) + 1
    - h(X) + 2
    - …
    - h(X) + i
  - Leads to *primary clustering*
    - Long sequences of filled cells

- Quadratic Probing
  - Similar to Linear Probing in that data is stored within the table
  - Probe at h(X), then at
    - h(X)+1
    - h(X)+4
    - h(X)+9
    - …
    - h(X)+ i^2
  - Works well when
    - λ < 0.5
    - Table size is prime

Universal Hashing

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- In in doubt, choose a hash function at random from a large parameterized family of hash functions (e.g., h(x) = ax + b, where a and b are chosen at random)
  - With high probability, it will be just as good as any custom-designed hash function you dream up

Dictionary Implementations

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- Ordered Array
  - Better than unordered array because Binary Search can be used
- Unordered Linked List
  - Ordering doesn't help
- Hashtables
  - O(1) expected time for Dictionary operations

Aside: Comparators

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- When implementing a comparator interface you normally must
  - Override compareTo() method
  - Override hashCode()
  - Override equals()
- Easy to forget and if you make that mistake your code will be very buggy

`hashCode()` and `equals()`

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- We mentioned that the hash codes of two equal objects must be equal — this is necessary for hashtable-based data structures such as **`HashMap`** and **`HashSet`** to work correctly
- In Java, this means if you override **`Object.equals()`**, you had better also override **`Object.hashCode()`**
- But how???

`hashCode()` and `equals()`

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```
class Identifier {
   String name;
   String type;

   public boolean equals(Object obj) {
      if (obj == null) return false;
      Identifier id;
      try {
         id = (Identifier)obj;
      } catch (ClassCastException cce) {
         return false;
      }
      return name.equals(id.name) && type.equals(id.type);
   }



}
```

`hashCode()` and `equals()`

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```
class Identifier {
   String name;
   String type;

   public boolean equals(Object obj) {
      if (obj == null) return false;
      Identifier id;
      try {
         id = (Identifier)obj;
      } catch (ClassCastException cce) {
         return false;
      }
      return name.equals(id.name) && type.equals(id.type);
   }

   public int hashCode() {
      return 37 * name.hashCode() + 113 * type.hashCode() + 42;
   }
}
```

hashCode() and equals()

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```
class TreeNode {
   TreeNode left, right;
   String datum;

   public boolean equals(Object obj) {
      if (obj == null || !(obj instanceof TreeNode)) return false;
      TreeNode t = (TreeNode)obj;
      boolean lEq = (left != null)?
         left.equals(t.left) : t.left == null;
      boolean rEq = (right != null)?
         right.equals(t.right) : t.right == null;
      return datum.equals(t.datum) && lEq && rEq;
   }
}
```

hashCode() and equals()

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```
class TreeNode {
   TreeNode left, right;
   String datum;

   public boolean equals(Object obj) {
      if (obj == null || !(obj instanceof TreeNode)) return false;
      TreeNode t = (TreeNode)obj;
      boolean lEq = (left != null)?
         left.equals(t.left) : t.left == null;
      boolean rEq = (right != null)?
         right.equals(t.right) : t.right == null;
      return datum.equals(t.datum) && lEq && rEq;
   }

   public int hashCode() {
      int lHC = (left != null)? left.hashCode() : 298;
      int rHC = (right != null)? right.hashCode() : 377;
      return 37 * datum.hashCode() + 611 * lHC - 43 * rHC;
   }
}
```

Professional quality hash codes?

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- For large objects we often compute an MD5 hash
  - MD5 is the fifth of a series of standard "message digest" functions
  - They are fast to compute (like an XOR over the bytes of the object)
  - But they also use a cryptographic key: without the key you can't guess what the MD5 hashcode will be
    - For example key could be a random number you pick when your program is launched
    - Or it could be a password
- With a password key, an MD5 hash is a "proof of authenticity"
  - If object is tampered with, the hashcode will reveal it!