Lecture 5
Representation Invariants
ADTs are defined by a specification

Abstract state + collection of procedural abstractions
  – Not a collection of procedures

Together, these procedural abstractions provide some set of values
  All the ways of directly using that set of values
  – Creating
  – Manipulating
  – Observing

• Creators and producers: make new values
• Mutators: change the value (but don’t affect ==)
• Observers: allow one to distinguish different values
ADTs and specs

Abs Values

ADT Values

- from producers
- from value in ADT + operation
ADTs and specifications

So far, we have only specified ADTs
  – Specification makes no reference to the implementation

Of course, we need [guidelines for how] to implement ADTs

Of course, we need [guidelines for how] to ensure our implementations satisfy our specifications

Two intellectual tools are really helpful…
Connecting implementations to specs

**Representation Invariant:** maps Object $\rightarrow$ boolean
- Indicates if an instance is *well-formed*
- Defines the set of valid concrete values
- Only values in the valid set make sense as implementations of an abstract value
- **For implementors/debuggers/maintainers of the abstraction:** no object should ever violate the rep invariant
  - Such an object has no useful meaning

**Abstraction Function:** maps Object $\rightarrow$ abstract value
- What the data structure *means* as an abstract value
- How the data structure is to be interpreted
- Only defined on objects meeting the rep invariant
- **For implementors/debuggers/maintainers of the abstraction:** Each procedure should meet its spec (abstract values) by “doing the right thing” with the concrete representation
Implementing a Data Abstraction (ADT)

To implement a data abstraction:
- Select the representation of instances, “the rep”
  - In Java, typically instances of some class you define
  - Implement operations in terms of that rep

Choose a representation so that:
- It is possible to implement required operations
- The most frequently used operations are efficient
  - But which will these be?
  - Abstraction allows the rep to change later
Example: CharSet Abstraction

// Overview: A CharSet is a finite mutable set of Characters
// @effects: creates a fresh, empty CharSet
public CharSet() {...}

// @modifies: this
// @effects: this_post = this_pre + {c}
public void insert(Character c) {...}

// @modifies: this
// @effects: this_post = this_pre - {c}
public void delete(Character c) {...}

// @return: (c ∈ this)
public boolean member(Character c) {...}

// @return: cardinality of this
public int size() {...}
An implementation: Is it right?

class CharSet {
    private List<Character> elts =
        new ArrayList<Character>();

    public void insert(Character c) {
        elts.add(c);
    }

    public void delete(Character c) {
        elts.remove(c);
    }

    public boolean member(Character c) {
        return elts.contains(c);
    }

    public int size() {
        return elts.size();
    }
}
An implementation: Is it right?

class CharSet {
    private List<Character> elts =
        new ArrayList<Character>();
    public void insert(Character c) {
        elts.add(c);
    }
    public void delete(Character c) {
        elts.remove(c);
    }
    public boolean member(Character c) {
        return elts.contains(c);
    }
    public int size() {
        return elts.size();
    }
}

 CharSet s = new CharSet();
 Character a = new Character('a');
 s.insert(a);
 s.insert(a);
 s.delete(a);
 if (s.member(a))
    System.out.print("wrong");
 else
    System.out.print("right");
An implementation: Is it right?

class CharSet {
    private List<Character> elts =
        new ArrayList<Character>();
    public void insert(Character c) {
        elts.add(c);
    }
    public void delete(Character c) {
        elts.remove(c);
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    public boolean member(Character c) {
        return elts.contains(c);
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Where is the error?
Where Is the Error?

If you can answer this, then you know what to fix

*Perhaps delete* is wrong
  – Should remove all occurrences?

*Perhaps insert* is wrong
  – Should not insert a character that is already there?

How can we know?
  – The *representation invariant* tells us
  – If it’s “our code”, this is how we document our choice for “the right answer”
The representation invariant

- Defines data structure well-formedness
- Must hold before and after every CharSet operation
- Operations (methods) may depend on it
- Write it like this:

  ```java
class CharSet {
    // Rep invariant:
    // elts has no nulls and no duplicates
    private List<Character> elts = ...
    ...
  }
```

Or, more formally (if you prefer):

- ∀ indices i of elts . elts.elementAt(i) ≠ null
- ∀ indices i, j of elts .
  elts.elementAt(i).equals(elts.elementAt(j)) ⇒ i = j
Now we can locate the error

// Rep invariant:
// elts has no nulls and no duplicates

public void insert(Character c) {
    elts.add(c);
}

public void delete(Character c) {
    elts.remove(c);
}
Another example

class Account {
    private int balance;
    // history of all transactions
    private List<Transaction> transactions;
    ...
}

Real-world constraints:
    • Balance ≥ 0
    • Balance = \sum_i \text{transactions.get}(i).amount

Implementation-related constraints:
    • Transactions ≠ null
    • No nulls in transactions
Checking rep invariants

Should code check that the rep invariant holds?

- Yes, if it’s inexpensive [depends on the invariant]
- Yes, for debugging [even when it’s expensive]
- Often hard to justify turning the checking off
- Some private methods need not check (Why?)

A great debugging technique:

*Design your code to catch bugs by implementing and using rep-invariant checking*
Checking the rep invariant

Rule of thumb: check on entry and on exit (why?)

```java
public void delete(Character c) {
    checkRep();
    elts.remove(c);

    // Is this guaranteed to get called?
    // (could guarantee it with a finally block)
    checkRep();
}
```

```java
/** Verify that elts contains no duplicates. */
private void checkRep() {
    for (int i = 0; i < elts.size(); i++) {
        assert elts.indexOf(elts.elementAt(i)) == i;
    }
}
```
Practice *defensive programming*

Assume that you will make mistakes

Write and incorporate code designed to catch them

– On entry:
  • Check rep invariant
  • Check preconditions

– On exit:
  • Check rep invariant
  • Check postconditions

Checking the rep invariant helps you *discover* errors

Reasoning about the rep invariant helps you *avoid* errors
Listing the elements of a CharSet

Consider adding the following method to CharSet

```java
// returns: a List containing the members of this
public List<Character> getElts();
```

Consider this implementation:

```java
// Rep invariant: elts has no nulls and no dups
public List<Character> getElts() { return elts; }
```

Does the implementation of `getElts` preserve the rep invariant?
Listing the elements of a CharSet

Consider adding the following method to CharSet

```java
// returns: a List containing the members of this
public List<Character> getElts();
```

Consider this implementation:

```java
// Rep invariant: elts has no nulls and no dups
public List<Character> getElts() { return elts; }
```

Does the implementation of `getElts` preserve the rep invariant? Kind of, sort of, not really....
Representation exposure

Consider this client code (outside the CharSet implementation):

```java
CharSet s = new CharSet();
Character a = new Character('a');
s.insert(a);
s.getElts().add(a);
s.delete(a);
if (s.member(a)) ...
```

Representation exposure is external access to the rep
Representation exposure

Consider this client code (outside the CharSet implementation):

```java
CharSet s = new CharSet();
Character a = new Character('a');
s.insert(a);
s.getElts().add(a);
s.delete(a);
if (s.member(a)) ...
```

Representation exposure is external access to the rep

Representation exposure is almost always **evil**

*A big deal, a common bug, you now have a name for it!*

If you do it, document why and how

– And feel guilty about it!
Avoiding representation exposure

**Understand** what representation exposure is

**Design** ADT implementations to make sure it doesn’t happen

Treat rep exposure as a bug: *fix* your bugs

**Test** for it with *adversarial clients*:
- Pass values to methods and then mutate them
- Mutate values returned from methods
**private is not enough**

Making fields *private* does *not* suffice to prevent rep exposure

- See our example
- Issue is *aliasing of mutable data inside and outside the abstraction*

- So *private* is a hint to you: no aliases outside abstraction to references to mutable data reachable from *private* fields
- Two general ways to avoid representation exposure...
Avoiding rep exposure (way #1)

One way to avoid rep exposure is to make copies of all data that cross the abstraction barrier

- Copy in [parameters that become part of the implementation]
- Copy out [results that are part of the implementation]

Examples of copying (assume Point is a mutable ADT):

```java
class Line {
    private Point s, e;
    public Line(Point s, Point e) {
        this.s = new Point(s.x, s.y);
        this.e = new Point(e.x, e.y);
    }
    public Point getStart() {
        return new Point(this.s.x, this.s.y);
    }
    ...
```
Need deep copying

“Shallow” copying is not enough
  – Prevent any aliasing to mutable data inside/outside abstraction

What’s the bug (assuming Point is a mutable ADT)?
  ```java
  class PointSet {
    private List<Point> points = ...
    public List<Point> getElts() {
      return new ArrayList<Point>(points);
    }
  }
  ```

Not in example: Also need deep copying on “copy in”
Avoiding rep exposure (way #2)

One way to avoid rep exposure is to exploit the immutability of (other) ADTs the implementation uses

- Aliasing is no problem if nobody can change data
  - Have to mutate the rep to break the rep invariant

Examples (assuming Point is an immutable ADT):

```java
class Line {
    private Point s, e;
    public Line(Point s, Point e) {
        this.s = s;
        this.e = e;
    }
    public Point getStart() {
        return this.s;
    }
    ...
```
Why [not] immutability?

Several advantages of immutability
- Aliasing does not matter
- No need to make copies with identical contents
- Rep invariants cannot be broken
- See CSE341 for more!

Does require different designs (e.g., if Point immutable)

```java
void raiseLine(double deltaY) {
    this.s = new Point(s.x, s.y+deltaY);
    this.e = new Point(e.x, e.y+deltaY);
}
```

Immutable classes in Java libraries include String, Character, Integer, …
Deepness, redux

An immutable ADT must be immutable “all the way down”
  – No references reachable to data that may be mutated

So combining our two ways to avoid rep exposure:
  – Must copy-in, copy-out “all the way down” to immutable parts
Recall our initial rep-exposure example:

class CharSet {
    // Rep invariant: elts has no nulls and no dups
    private List<Character> elts = ...;

    // returns: elts currently in the set
    public List<Character> getElts() {
        return new ArrayList<Character>(elts); //copy out!
    }
    ...
}

Back to **getElts**
An alternative

// returns: elts currently in the set
public List<Character> getElts() { // version 1
    return new ArrayList<Character>(elts); //copy out!
}

public List<Character> getElts() { // version 2
    return Collections.unmodifiableList<Character>(elts);
}

From the JavaDoc for Collections.unmodifiableList:

Returns an unmodifiable view of the specified list. This method allows
modules to provide users with "read-only" access to internal lists. Query
operations on the returned list "read through" to the specified list, and
attempts to modify the returned list… result in an
UnsupportedOperationException.
The good news

public List<Character> getElts() { // version 2
    return Collections.unmodifiableList(elts);
}

Clients cannot *modify (mutate)* the rep
    • So they cannot break the rep invariant

(For long lists,) more efficient than copy out

Uses standard libraries
public List<Character> getElts() { // version 1
    return new ArrayList<Character>(elts); //copy out!
}

public List<Character> getElts() { // version 2
    return Collections.unmodifiableList<Character>(elts);
}

The two implementations do not do the same thing!
- Both avoid allowing clients to break the rep invariant
- Both return a list containing the elements

But consider: xs = s.getElts();
    s.insert('a');
    xs.contains('a');

Version 2 is observing an exposed rep, leading to different behavior.
Different specifications

Ambiguity of “returns a list containing the current set elements”

“returns a fresh mutable list containing the elements in the set at the time of the call”

versus

“returns read-only access to a list that the ADT continues to update to hold the current elements in the set”

A third spec weaker than both [but less simple and useful!]

“returns a list containing the current set elements. Behavior is unspecified (!) if client attempts to mutate the list or to access the list after the set’s elements are changed”

Also note: Version 2’s spec also makes changing the rep later harder

– Only “simple” to implement with rep as a List