Representation Invariants
(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins)
A data abstraction is defined by a specification

A 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 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 → 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 → 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();
}
}

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");

Where is the error?
Where Is the Error?

• Answer this and 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:

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

Or, more formally (if you prefer):

\[
\forall \text{indices } i \text{ of } elts . \ elts\text{.elementAt}(i) \neq \text{null} \\
\forall \text{indices } i, j \text{ of } elts . \ \ i \neq j \Rightarrow \neg \ elts\text{.elementAt}(i)\text{.equals} (elts\text{.elementAt}(j))
\]
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 = Σ_i 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();
}
...
/** 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?

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 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

The first step for getting help is to recognize you have a problem 😊

- **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*

![Diagram showing aliasing of mutable data]

- 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)?
  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 \texttt{Point} immutable)
  \begin{verbatim}
  void raiseLine(double deltaY) {
    this.s = new Point(s.x, s.y+deltaY);
    this.e = new Point(e.x, e.y+deltaY);
  }
  \end{verbatim}

• Immutable classes in Java libraries include \texttt{String}, \texttt{Character}, \texttt{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:

```java
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

```java
public List<Character> getElts() { // version 2
    return Collections.unmodifiableList<Character>(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
The bad news

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:    \texttt{xs = s.getElts();}
                 \texttt{s.insert('a');}
                 \texttt{xs.contains('a');}

Version 2 is \textit{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