
CSE 331

Software Design & Implementation

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Representation Invariants

(Based on slides by Mike Ernst, 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

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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...

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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

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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

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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() {...}
```

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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 a) {
        return elts.contains(a);
    }
    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?

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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"

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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 indices i of `elts` . `elts.elementAt(i) ≠ null`
- \forall indices i, j of `elts` .
 $i \neq j \Rightarrow \neg \text{elts.elementAt}(i).\text{equals}(\text{elts.elementAt}(j))$

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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);
}
```

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Another example

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

Real-world constraints:

- Balance ≥ 0
- Balance = $\sum_i \text{transactions.get}(i).\text{amount}$

Implementation-related constraints:

- Transactions \neq null
- No nulls in transactions

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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

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Checking the rep invariant

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

```
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;
    }
}
```

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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

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Listing the elements of a CharSet

Consider adding the following method to CharSet

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

Consider this implementation:

```
// 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....

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Representation exposure

Consider this client code (outside the CharSet implementation):

```
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!

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Avoiding representation exposure

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

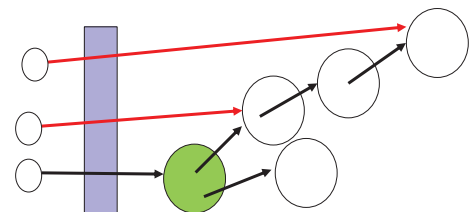
- *Understand* what representation exposure is
- *Design* ADT implementations to make sure it doesn't happen
- Treat rep exposure as a bug: *fix* your bugs
- *Test* for it with *adversarial clients*:
 - Pass values to methods and then mutate them
 - Mutate values returned from methods

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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...

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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):

```
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);
  }
}
```

...

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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”

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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):

```
class Line {
  private Point s, e;
  public Line(Point s, Point e) {
    this.s = s;
    this.e = e;
  }
  public Point getStart() {
    return this.s;
  }
}
```

...

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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)

```
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`, ...

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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

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Back to getElts

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!
  }
  ...
}
```

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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<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: `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`