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# CSE 331

# Software Design & Implementation

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## Representation Invariants

(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins, Zach Tatlock)

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# A data abstraction is defined by a specification

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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

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- 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

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**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)

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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

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

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

// @modifies: this
// @effects: thispost = thispre - {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?

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```
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?

# Where Is the Error?

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- 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

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- 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)  $\neq$  null`

$\forall$  indices  $i, j$  of `elts` .

$i \neq j \Rightarrow \neg \text{elts.elementAt}(i).\text{equals}(\text{elts.elementAt}(j))$

# Now we can locate the error

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```
// 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

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

Real-world constraints:

- Balance  $\geq 0$
- Balance =  $\sum_i$  transactions.get(i).amount

Implementation-related constraints:

- Transactions  $\neq$  null
- No nulls in transactions

# Checking rep invariants

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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

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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;
    }
}
```

# Practice *defensive programming*

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- 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

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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....

# Representation exposure

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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 how and why
  - And feel guilty about it!



# Avoiding representation exposure

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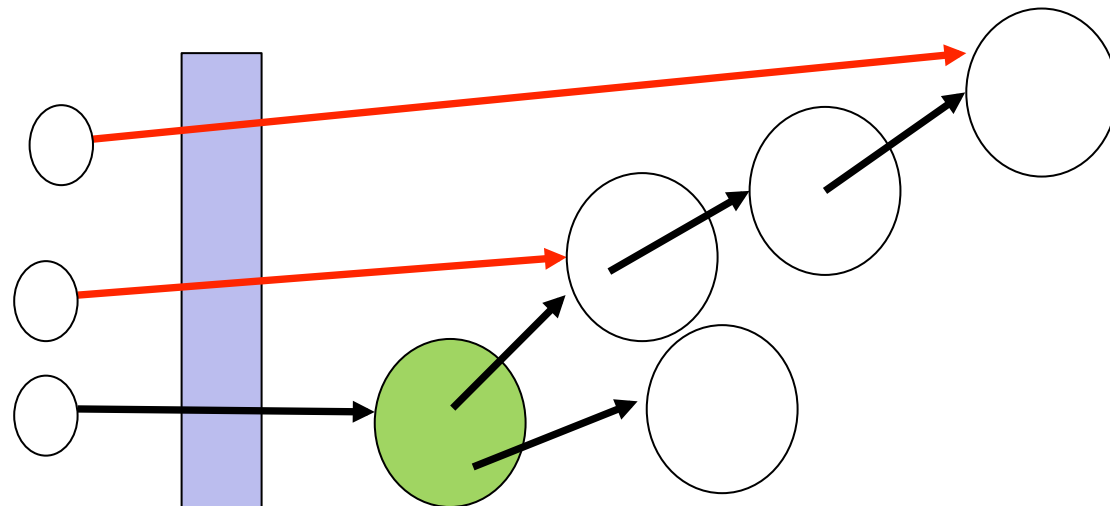
The first step for getting help is to recognize you have a problem 😊

- *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

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- 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)

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- 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);
    }
}
```

...

# Need deep copying

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- “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)

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- 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;
    }
}
```

...

# Why [not] immutability?

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- 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`, ...

# Deepness, redux

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- 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

# Back to getElts

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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!
    }
    ...
}
```



# An alternative

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```
// 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

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```
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

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```
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

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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**