CSE 331
Software Design and Implementation

Lecture 5
Representation Invariants

Zach Tatlock / Spring 2018

ADTs are defined by a specification

Abstract state + collection of procedural *abstractions*

- Not a collection of procedures

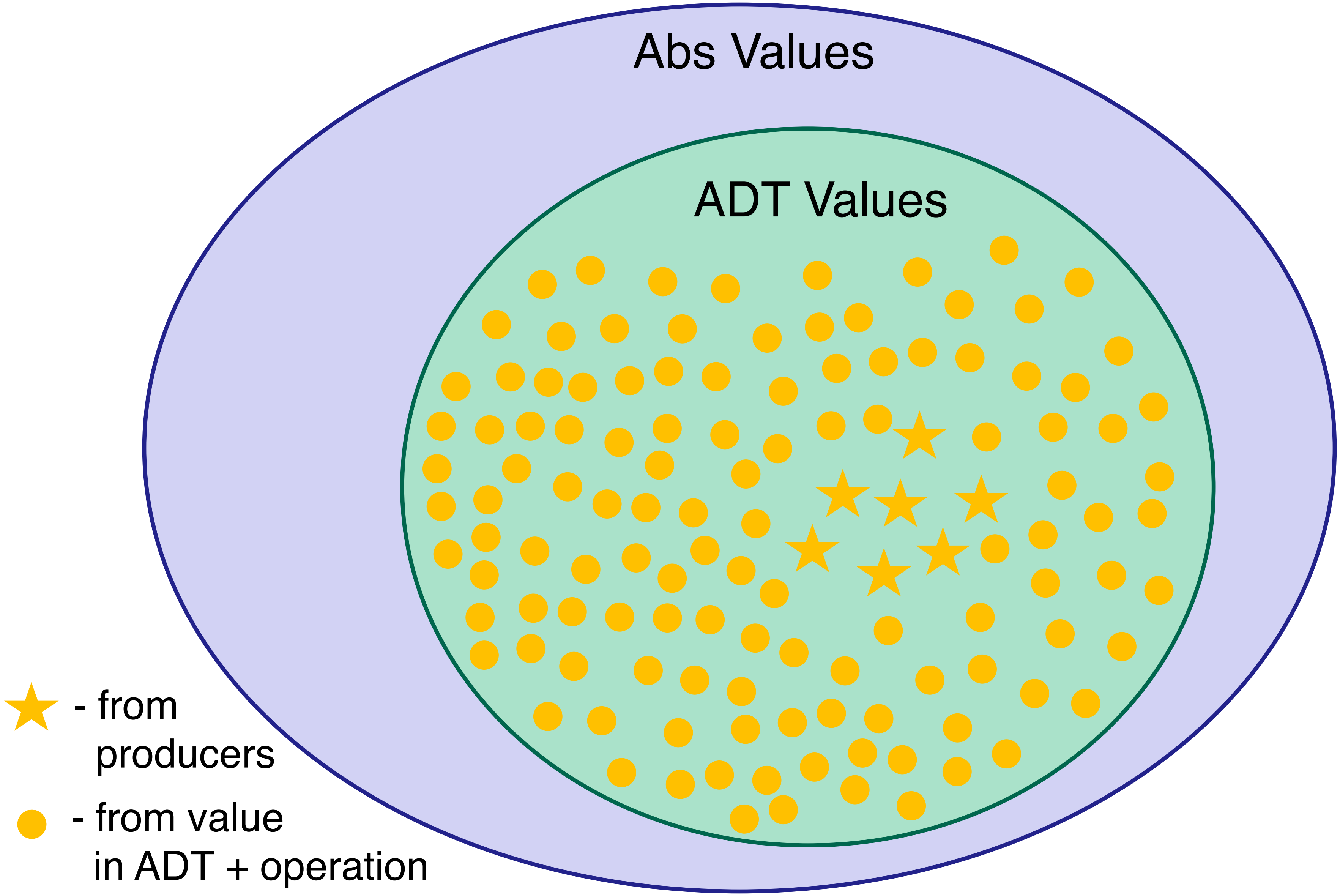
Together, these procedural abstractions provide some *set of values*

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



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();
  }
}
```

An implementation: Is it right?

```
class CharSet {
  private List<Character> elts =
      new ArrayList<Character>();
  public void insert(C
    elts.add(c);
  }
  public void delete(C
    elts.remove(c);
  }
  public boolean membe
    return elts.conta
  }
  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(
    elts.add(c);
  }
  public void delete(
    elts.remove(c);
  }
  public boolean membe
    return elts.conta
  }
  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?

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:

```
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 .

elts.elementAt(i).equals(elts.elementAt(j)) $\Rightarrow$ 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 = 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?)

```
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`**

```
// 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?

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….

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

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!

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

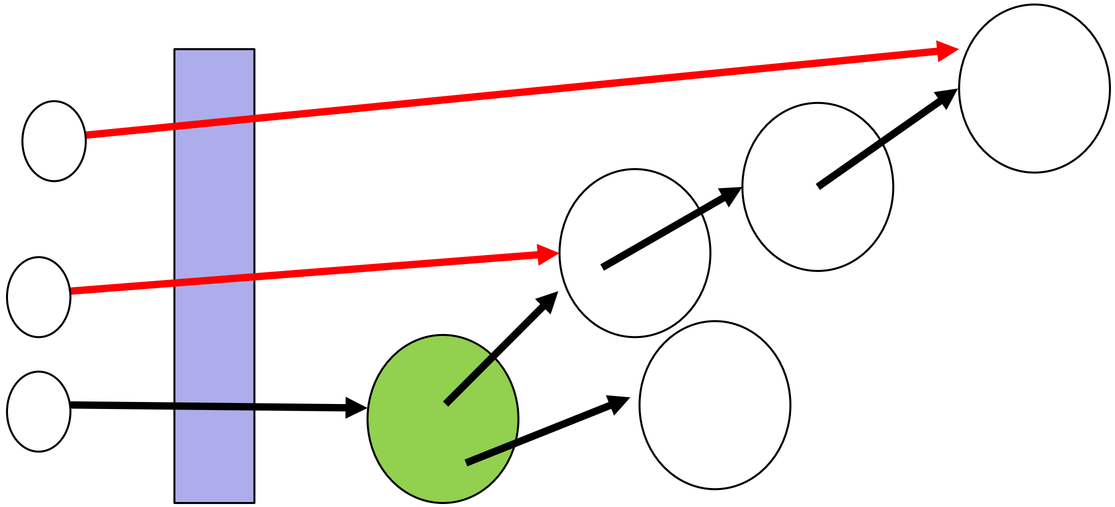
Test for it with *adversarial clients:*

- 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):

```
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):

```
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)

```
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

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!
  }
  …
}
```

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`**