CSE 331
Software Design and Implementation

Lecture 5
Representation Invariants

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Announcements

Announcements

- Happy Friday!
  - My t-shirt
- Next week
  - HW2 due Monday, July 4 at 10pm
    - It's harder than HW1
    - Please take advantage of today's office hours!
  - July 4 holiday on Wednesday -- no class!
    - TAs will announce OH changes
  - HW3 due Thursday

Motivation

Review

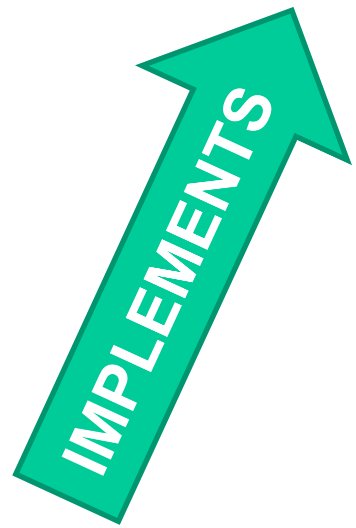
lec04

Method Specification
(abstraction)

Method Body
`(concrete code)`

lec05

Abstract Data Type
(abstraction)



Data Structure
`(concrete code)`

An ADT is a specification

Abstract state + collection of procedural abstractions (aka method specs)

- Not a collection of procedures

Together, these procedural abstractions provide some set of values

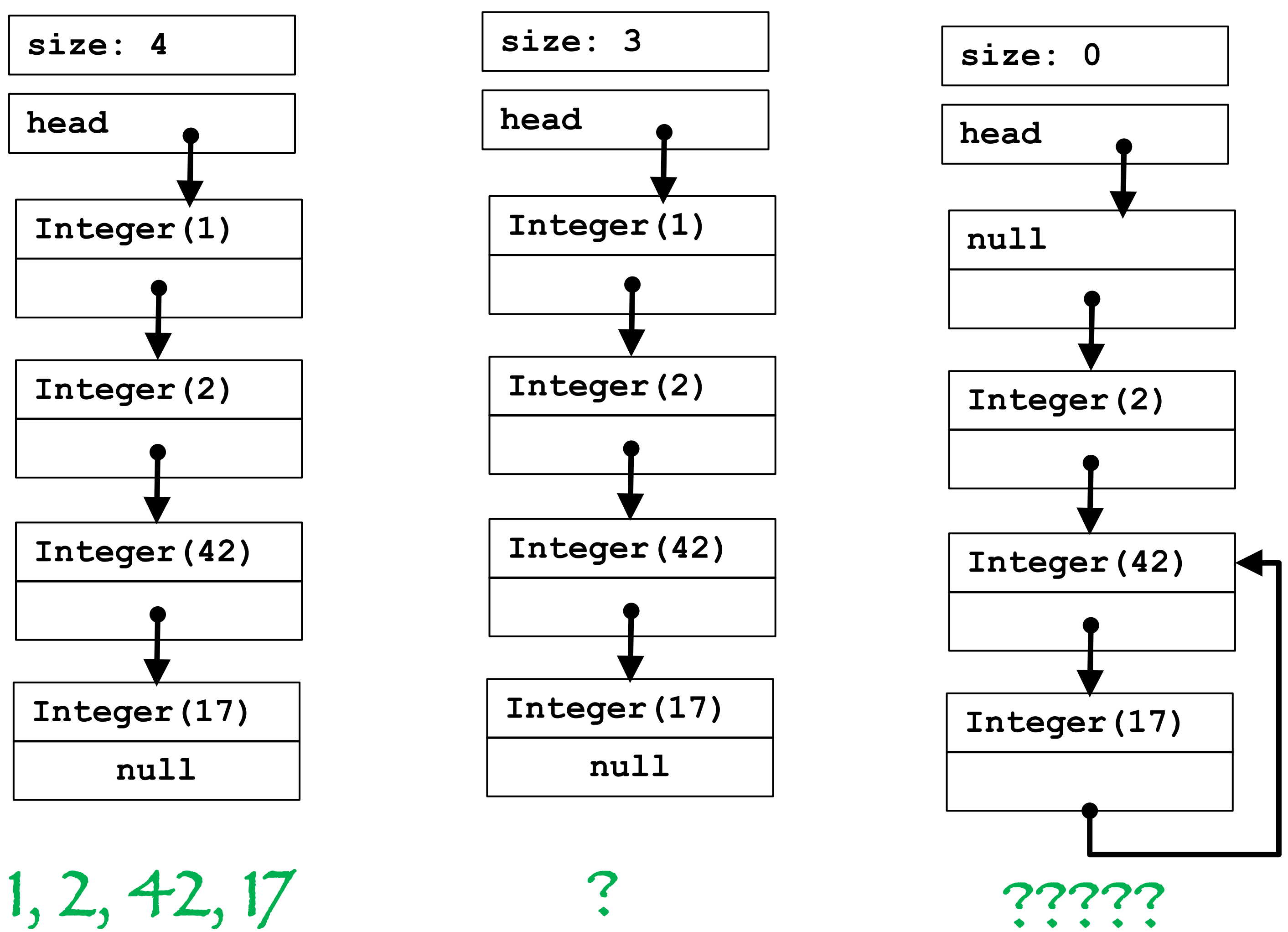
All the ways of directly using that set of values

- Creating
- Manipulating
- Observing

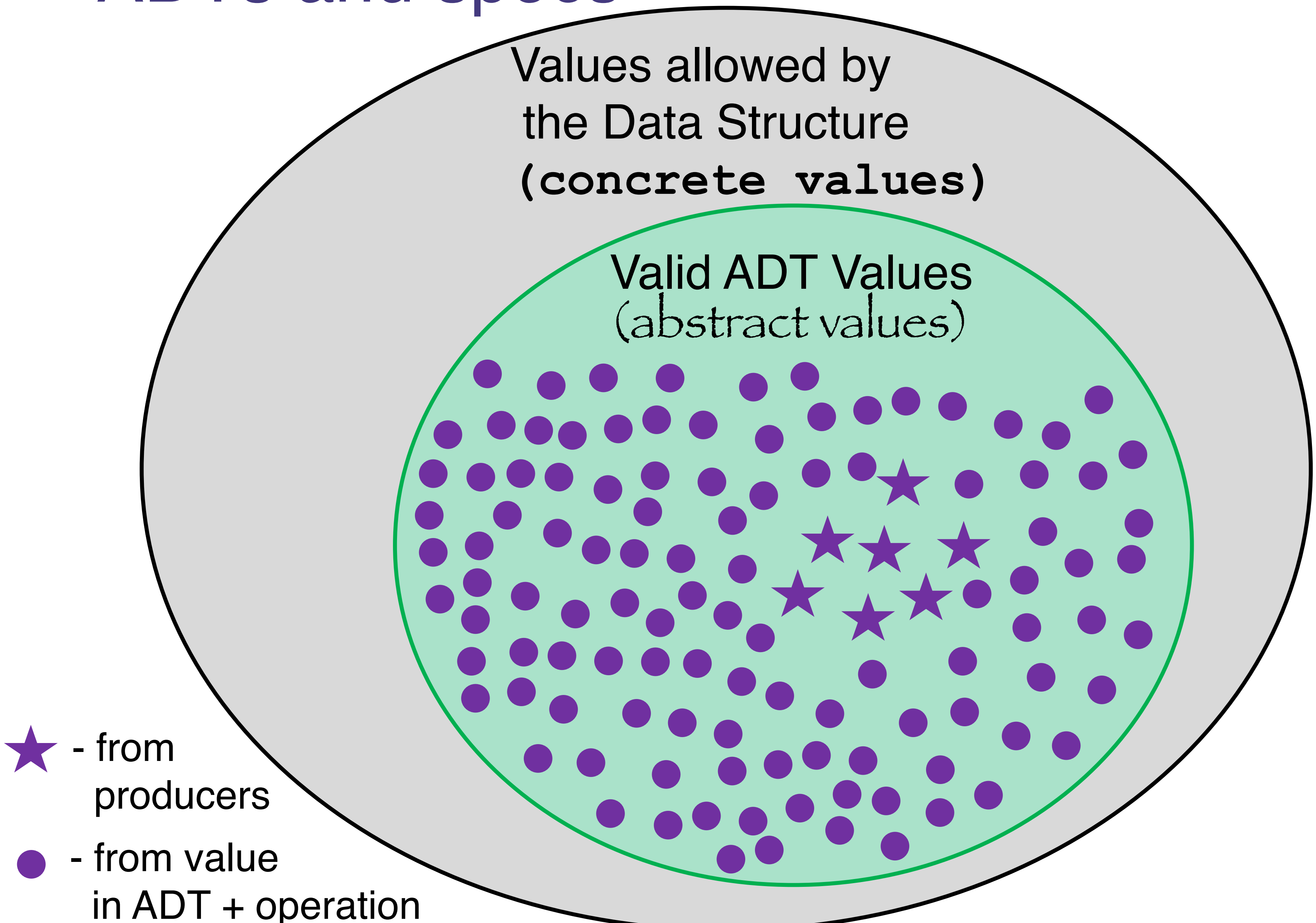
- Creators and producers: make new values
- Mutators: change the value
- Observers: allow one to distinguish different values

An ADT has an abstract value

Abstract Value: An Int List is a finite sequence of integer values



ADTs and specs



ADTs and specifications

So far, we have only specified ADTs

lec05

- Specification makes no reference to the implementation

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

- **`Data Structure`** implements an ADT

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

lec06 (today)

- 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

lec07

- 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

Representation Invariants

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() {…}
```

`set` – see Wolfram Alpha definition

set union

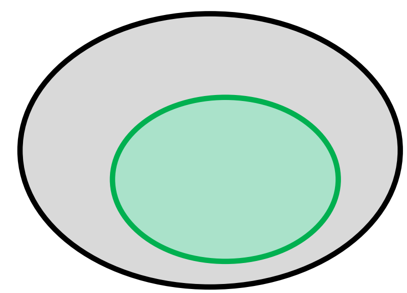
set difference

Informal notation warning

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();
  }
}
```

the rep



Does this implementation prevent poorly formed values?

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(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();
  }
}
```

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:
    //   this.elts has no nulls and no duplicates
    private List<Character> elts = …
    …
```

Or, more formally (if you prefer):

$\forall$ indices i of this.elts , this.elts.elementAt(i) $\neq$ null

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

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

$\forall$ = "for all"
$\Rightarrow$ = logical implication

The representation invariant

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

- Written in terms of the representation **`(this.elts)`**
- Internal comment (not javadoc)
  - located just inside of the class definition at the very beginning

The representation invariant

```
class CharSet {
  // Rep Invariant:
  // for all indices i of this.elts ,
  //        this.elts.elementAt(i) is not null
  // for all indices i, j of this.elts ,
  //     this.elts.elementAt(i).
  //          equals(this.elts.elementAt(j))
  //          implies that i = j
  private List<Character> elts = …
      …
}
```

- Written in terms of the representation **(this.elts)**
- Internal comment (not javadoc)
  – located just inside of the class definition at the very beginning

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;
    …
}
```

the rep

Σ_i … = the sum, over all values of i, of …

Real-world constraints:

- Balance ≥ 0
- Balance = Σ_i transactions.get(i).amount

Implementation-related constraints:

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

Checking rep invariants

Should code check that the rep invariant holds?

- **Short answer: YES!!!!**

More considerations

- Development vs. Production
  - Always yes in development [even when it's expensive]
  - Production... usually yes
    - (See Pragmatic Programmer: Assertive Programming)
- computational cost [depends on the invariant]
  - sometimes no for expensive checks, in production
- Some private methods need not check (Why?)

A great debugging technique:

Design your code to catch bugs early by implementing and using rep-invariant checking

Checking the rep invariant

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

```
/** Verify elts has no nulls or duplicates and... */
private void checkRep() {
  for (int i = 0; i < elts.size(); i++) {
    assert elts.elementAt(i) != null;
    assert elts.indexOf(elts.elementAt(i)) == i;
  }
  ... // more checks
}

public void delete(Character c) {
  checkRep();
  elts.remove(c);
  // Is this guaranteed to get called?
  // (could guarantee it with a finally block)
  checkRep();
}
```

What does **`assert`** mean?

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

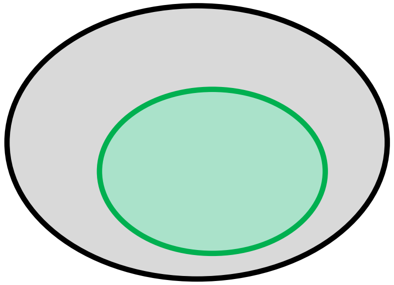
Checking the rep invariant helps you *discover* errors

Reasoning about the rep invariant helps you *avoid* errors

Summary so far...

- We implement an Abstract Data Type with a `Data Structure`
- Every Data Structure has a Representation that is a concrete way of representing an object's abstract value

- The representation allows concrete values that do not correspond to an abstract value
  - "gray area" -------------------------------→



- **Representation Invariant** describes what makes the concrete representation valid (green area)
- `checkRep()` method verifies that the rep is valid, throws exception if not, protects you from yourself
- Check your rep all the time!
  - generally at beginning and end of every public method

Representation Exposure

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 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

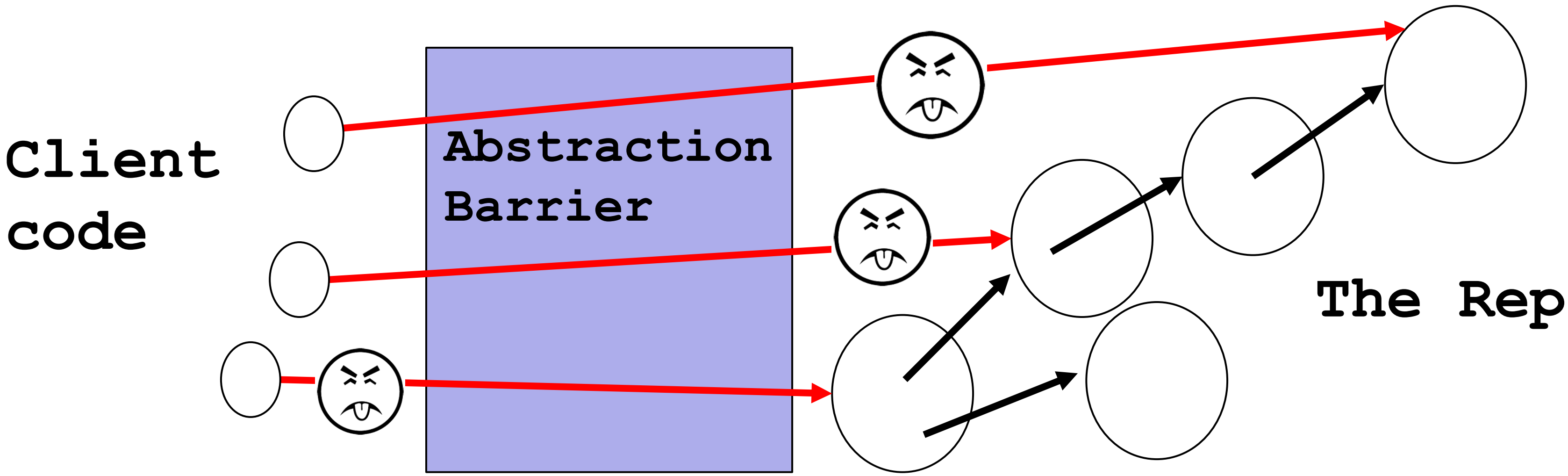
Design ADT implementations to make sure it doesn't happen

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
- 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);
   }
   …
```

copy in

copy out

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);
    }
}
```

`copy out?`

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
- Take CSE 341: Programming Languages 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 revisited

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

Caveat

```
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

Ambiguous spec: “returns a list containing the current set elements”

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

versus

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

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

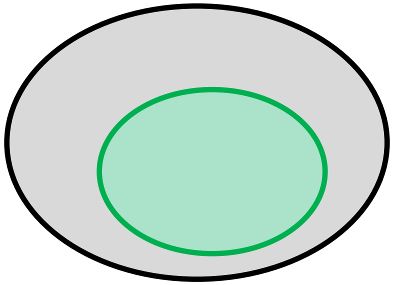
“returns a list containing the current set elements. *Behavior is unspecified (!) if* client attempts to mutate the list or to access the list after the set’s elements are changed”

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

- Only “simple” to implement with rep as a **`List`**

Summary

- A data structure's representation allows concrete values that do not correspond to an abstract value allowed by the ADT
  - "gray area" -------→



- **Representation Invariant** describes what makes the concrete representation valid (green area)
- **`checkRep()`** method verifies that the rep is valid

- **Rep Exposure** occurs when a client can modify the rep
  - Never let this happen!!!!

Closing

Closing Announcements

- HW2 due Monday 10 pm
  - Start early!
  - Go to office hours today!

- Thank you for coming to class!

- Enjoy your weekend!