CSE 331
Software Design & Implementation

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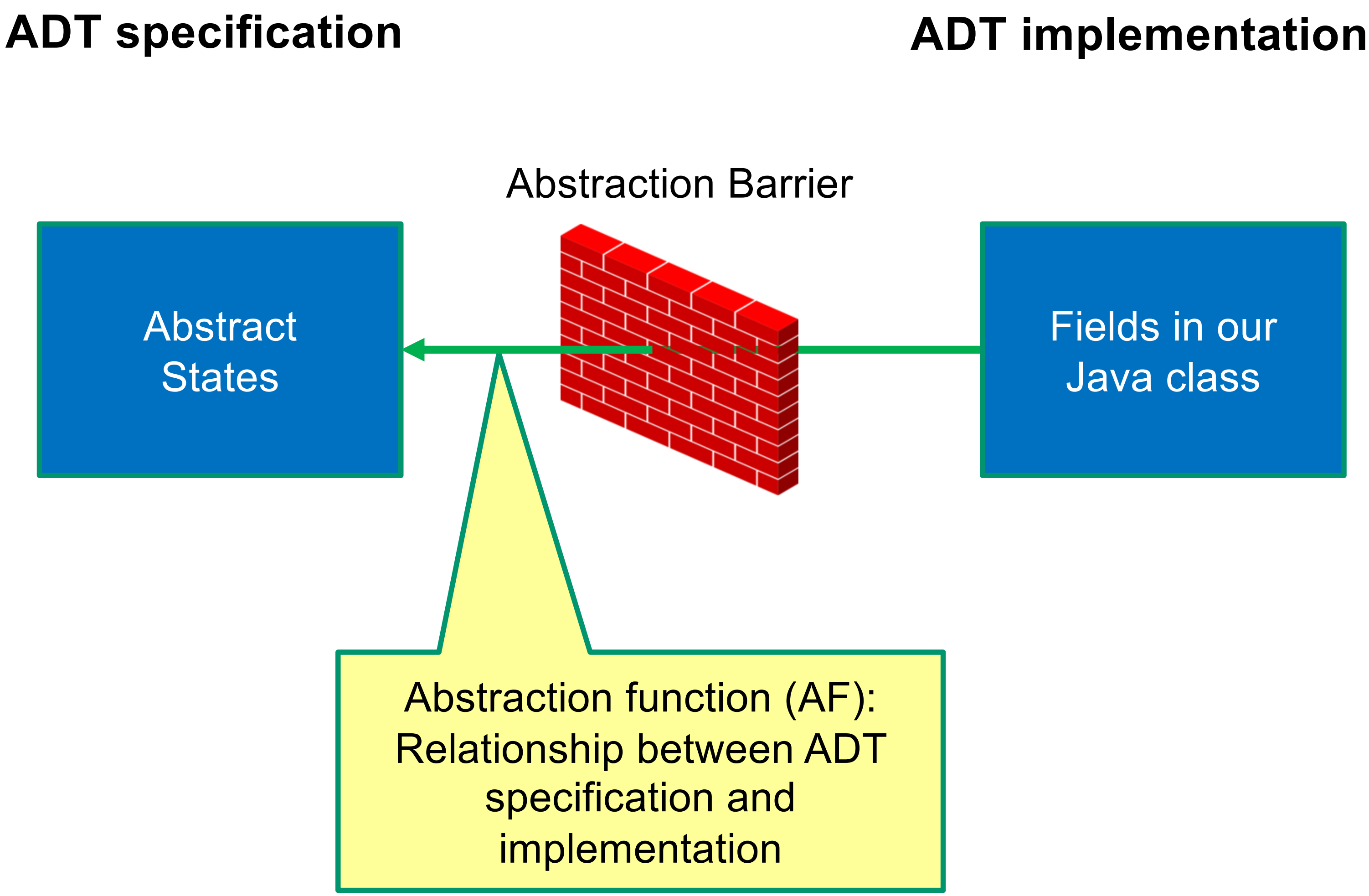
ADT Implementation: Representation Invariants

Data abstraction outline



Last time: abstraction function

- Allows us to check correctness
  - use reasoning to show that the method leaves the abstract state such that it satisfies the postcondition

```
// AF(this) = vals[0..len-1]
private int[] vals;
private int len;

// @requires length > 0
// @modifies this
// @effects this = this[0..length-2]
public void pop() { ... }
```

Last time: abstraction function

- Allows us to check correctness
  - use reasoning to show that the method leaves the abstract state such that it satisfies the postcondition

```
// AF(this) = vals[0..len-1]

// @requires length > 0
// @modifies this
// @effects this = this[0..length-2]
public void pop() {
```

{{ length > 0 }} → {{ len > 0 }}

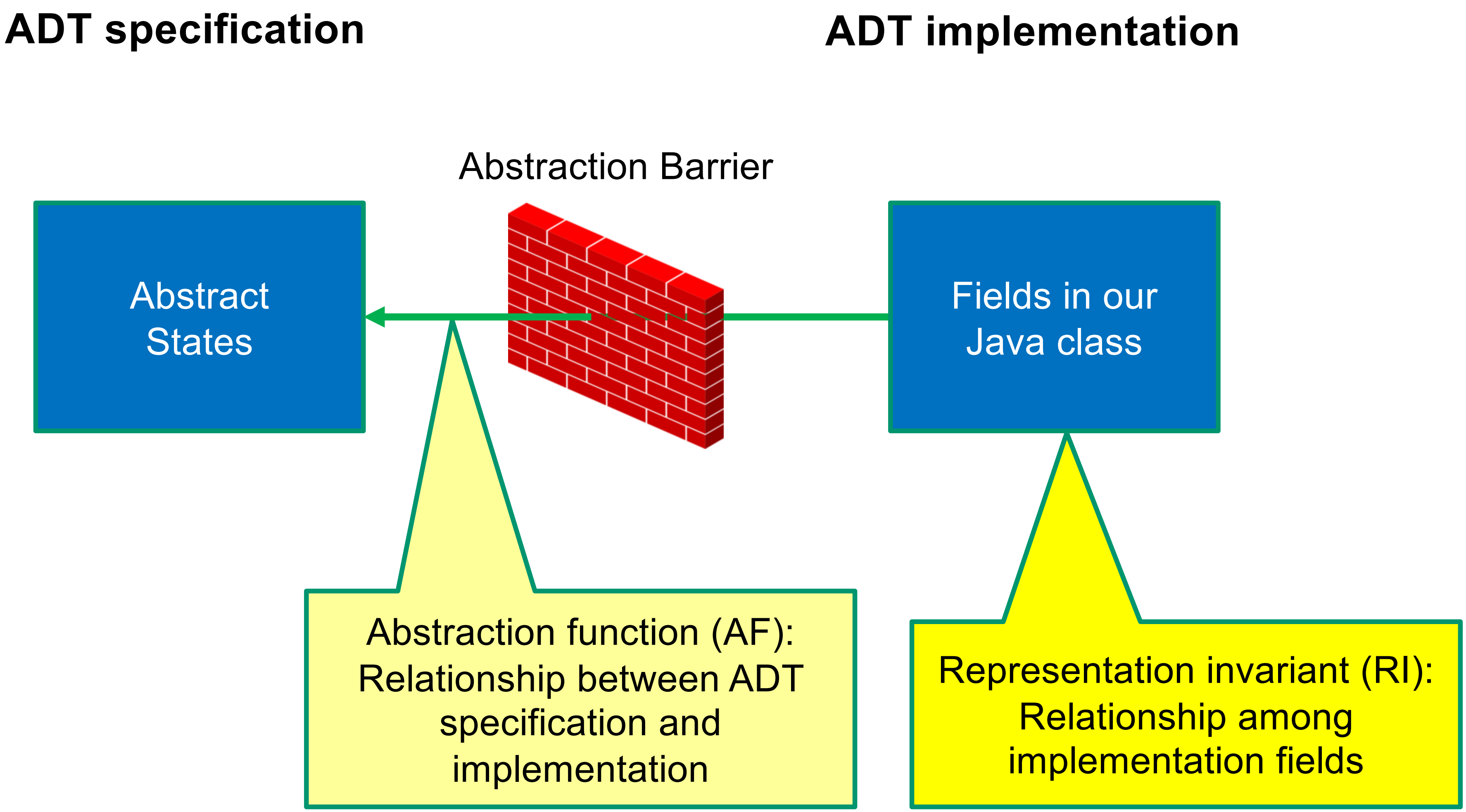
```
  len = len - 1;
```

{{ this = $this_{pre}$[0 .. $length_{pre}$ – 2] }}

```
}
```

{{ len = len_{pre} - 1 }}
⇒ {{ this = vals[0..len-1]
= vals[0..len_{pre}-2] }}

Data abstraction outline



Connecting implementations to specs

For implementers / debuggers / maintainers of the implementation:

Representation Invariant: maps Object → boolean

- defines the set of valid concrete values
- must hold at all times (outside of mutators)
- **no object should *ever* violate the rep invariant**
  - such an object has no useful meaning

Abstraction Function: maps Object → abstract state

- says what the data structure *means* in vocabulary of the ADT
- **only defined** on objects meeting the rep invariant

Example: Circle

```
/** Represents a mutable circle in the plane. For example,
  * it can be a circle with center (0,0) and radius 1. */
public class Circle {

  // Rep invariant: center != null and rad > 0
  private Point center;
  private double rad;

  // Abstraction function:
  // AF(this) = a circle with center at this.center
  //   and radius this.rad

  //  ...
}
```

Example: Circle 2

```
/** Represents a mutable circle in the plane. For example,
  * it can be a circle with center (0,0) and radius 1. */
public class Circle {

  // Rep invariant: center != null and edge != null
  //   and !center.equals(edge)
  private Point center, edge;

  // Abstraction function:
  // AF(this) = a circle with center at this.center
  //   and radius this.center.distanceTo(this.edge)

  //  ...
}
```

Example: CharSet ADT

```
// Overview: A CharSet is a finite mutable set of Characters

// @effects: creates a fresh, empty CharSet
public CharSet() {…}

// @modifies: this
// @effects: this changed to this + {c}
public void insert(Character c) {…}

// @modifies: this
// @effects: this changed to this - {c}
public void delete(Character c) {…}

// @return: true iff c is in this set
public boolean member(Character c) {…}

// @return: cardinality of this set
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 implementa

```
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");
```

```
class CharSet {
  private List<Chara
      new ArrayList<C

  public void insert
    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?

- *Perhaps* **`insert`** is wrong
  - should not insert a character that is already there?
- *Perhaps* **`delete`** (and **`size`**) is wrong
  - should remove all occurrences?
- In this case, the representation invariant tells us which is correct
  - RI says if character can appear multiple times or not
  - this is how we document our choice for “the right answer”
    - again, good invariant makes the code write itself...

The representation invariant

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):

for all indices i of elts, we have elts.elementAt(i) ≠ null

for all indices i, j of elts with i != j,

we have ! elts.elementAt(i).equals(elts.elementAt(j))

The representation invariant

Write it like this:

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

- Must hold before and after every **`CharSet`** operation
- Methods may assume it *implicitly* (along with @requires)
  - no need to state your assumption that RI holds

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);
}
```

Example: Polynomial

```
/** An immutable polynomial with integer coefficients.
  * Examples include 0, 2x, and x + 3x^2 + 5x. */
public class IntPoly {

  // Rep invariant: coeffs != null and
  //                coeffs[coeffs.length-1] != 0
  private final int[] coeffs;

  // Abstraction function:
  // AF(this) = sum of this.coeffs[i] * x^i
  //   for i = 0 .. this.coeffs.length

  /** Returns the highest exponent with nonzero coefficient
    * or zero if none exists. */
  public int degree() { ... }

  //  ...
```

Example: Polynomial 2

```
/** An immutable polynomial with integer coefficients.
  * Examples include 0, 2x, and x + 3x^2 + 5x. */
public class IntPoly {

  // Rep invariant: terms != null and
  //      terms is sorted by degree and
  //      no two terms have the same degree
  private final List<IntTerm> terms;

  // Abstraction function:
  // AF(this) = sum of monomials in this.terms

  /** Returns the highest exponent with nonzero coefficient
    * or zero if none exists. */
  public int degree() { ... }

  //  ...
```

Checking rep invariants

Should you write code to 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
  - better argument is removing clutter (improve understandability)
- Some private methods need not check (Why?)

A great debugging technique:

Design your code to catch bugs by implementing and using a function to check the rep-invariant

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;
  }
}
```

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
private List<Character> elts;
public List<Character> getElts() { return elts; }
```

Does the implementation of **`getElts`** preserve the rep invariant?

Can't say!

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 **bad**
  - can cause bugs that will be **very hard to detect**

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 via exposure
  - see CSE341 for more!

- Does require different code (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!
  }
  …
}
```

Alternative #3

```
// 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(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`**.

Suggestions

Best options for implementing `getElts()`

- if O(n) time is acceptable for relevant use cases, copy the list
  - safest option
  - best option for changeability
- if O(1) time is required, then return an unmodifiable list
  - prevents breaking rep invariant
  - clearly document that behavior is unspecified after mutation
  - ideally, write a your own unmodifiable view of the list that throws an exception on all operations after mutation
- if O(1) time is required and there is no unmodifiable version and you don't have time to write one, expose rep and feel guilty