CSE 331
Software Design & Implementation

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Representation Invariants

But first, a diversion….

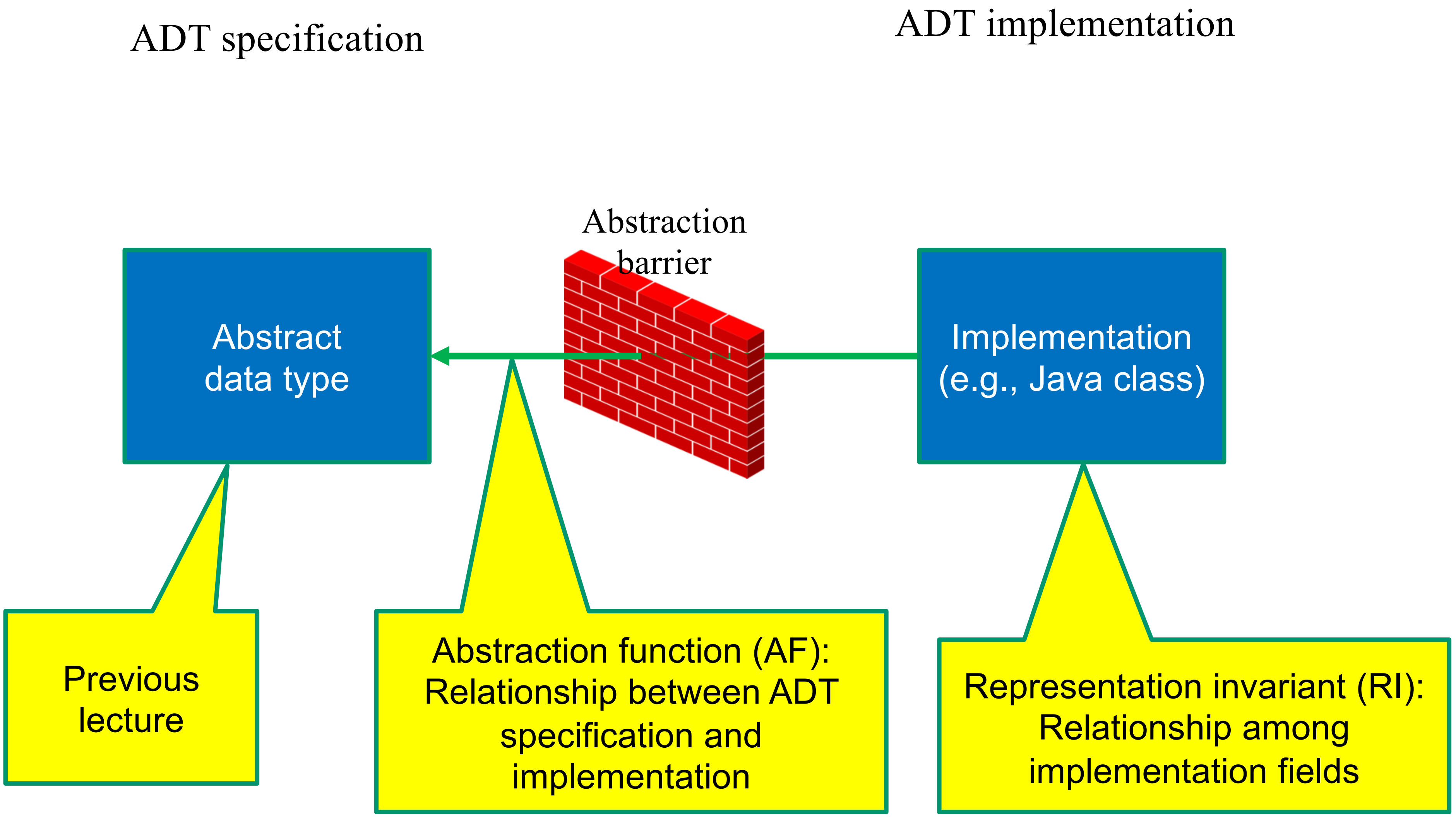
IntelliJ – feature or bug?

- Extremely powerful tool – worth learning well
- The interface can sometimes be less than “obvious”, but it’s important to figure out how to do things right
- Follow advice in cse331 docs carefully and let us know if there are goofs – what’s there is supposed to work
  - Example: commit/push code before creating tags like hw3-final
  - Example: find generated docs after running JavaDoc
- Getting all this right will take some work, but it’s worth knowing how to use the tools – hang in there.
  - (Don’t avoid learning – it is not the right tradeoff in the long run)

What about IntelliJ advice?

- IntelliJ is forever “suggesting” (but it seems more like “telling”) you to do things. Recent examples on ed:
  - Make variables final
  - Rearrange/change your imports
  - Change variable types in declarations
  - etc. etc. etc.
- How to think about this?
  - Can be useful advice
  - Can sometimes be aimed at situations well beyond what we need for 331, and not really relevant to us
  - Can sometimes be wrong or at least misleading
- Bottom line: you are responsible for your code – be sure to evaluate any suggestions and only use ones that are appropriate and that you understand precisely

Data abstraction outline



Review: 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 (affects **`equals(…)`** but not **`==`**)
- Observers: allow the client to distinguish different values

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

- An assertion about the object state
- 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 instance variables in objects of a class
- 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 new, 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(Ch
    elts.remove(c);
  }
  public boolean member
    return elts.contai
  }
  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 defect?

Where Is the defect?

- 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

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 example:

```
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 $\Rightarrow$ $\neg$ elts.elementAt(i).equals(elts.elementAt(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;
    …
}
```

Rep invariants often contain both problem domain and internal implementation parts. For this example:

- Real-world constraints:
  - balance ≥ 0
  - balance = Σ_i transactions.get(i).amount
- Implementation-related constraints:
  - transactions ≠ null
  - No nulls in transactions

A rep invariant is a pre/postcondition

- For any public ADT operation (method) the triple
  {rep invariant} method body {rep invariant}
  should be a valid Hoare triple
  - (Not necessarily true for private "helper" methods that execute while the rep is being updated)

- For constructors, the {rep invariant} is the constructor's postcondition, but not part of the precondition
  - The constructor establishes the rep invariant for a newly created object by initializing it; rep inv doesn't hold until that is done

- Our proof techniques, especially forward reasoning, can be helpful to check that the rep invariant is preserved by an ADT operation (or established by a constructor)

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?)
- Some private methods should 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 when feasible
  - On entry:
    - Check rep invariant
    - Check other preconditions
  - On exit:
    - Check rep invariant
    - Check other postconditions
- Checking the rep invariant helps you *discover* errors
- Reasoning about the rep invariant helps you *avoid* errors

New Question: 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**
  - Allows violation of abstraction boundaries and rep invariant
  - ***A big deal**, **a common bug**, you now have a name for it!*
- If you do it (should be rare), document how and why
  - And feel guilty about it!

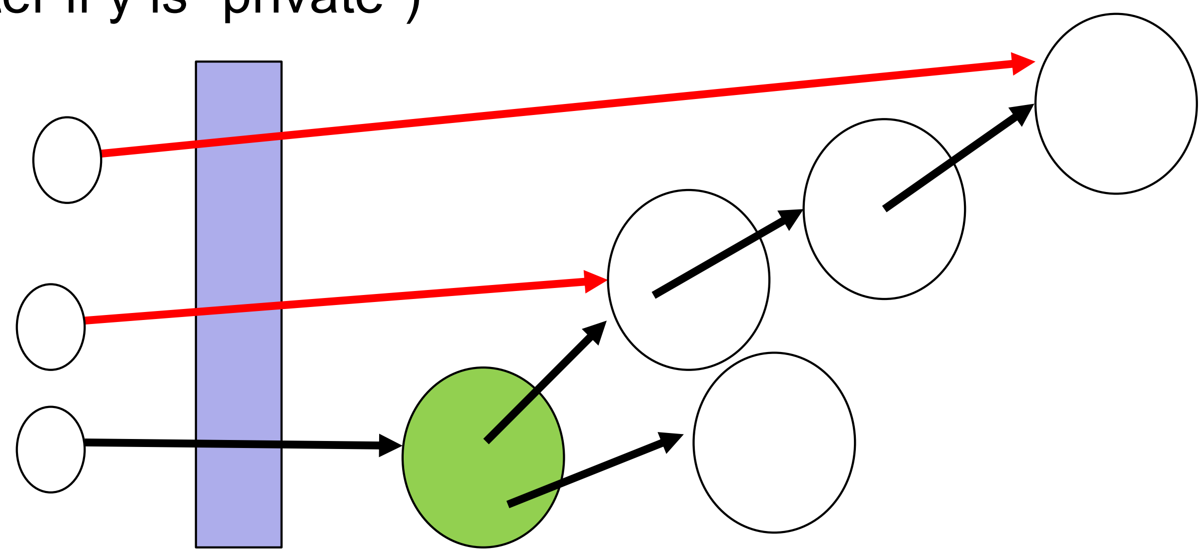
Avoiding representation exposure

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
  - Check the rep invariant in addition to client behavior

`private` is not enough

- Making fields **`private`** does *not* suffice to prevent rep exposure
  - Issue is ***aliasing of mutable data inside and outside the abstraction*** (remember, after assignment x=y; x and y both refer to the **same** object! If clients can access x, it doesn't matter if y is "private")



- **`private`** is a hint: be sure you don't create aliases that let clients reference mutable data reachable from **`private`** fields
  - And be sure to use **`private`** to prevent direct access to rep

Avoiding rep exposure #1: immutability

- Exploit the immutability of (other) ADTs the implementation uses
  - Aliasing is no problem if client cannot change data
- Examples (assuming **`Point`** is an *immutable* ADT):

```
class Line {
  private Point start, end;
  public Line(Point start, Point end) {
    this.start = start;
    this.end = end;
  }
  public Point getStart() {
    return this.start;
  }
  …
```

Why [not] immutability?

- Immutability greatly simplifies reasoning
  - Aliasing does not matter
  - No need to make copies with identical contents
  - Rep invariants cannot be broken
- Does require different designs
  Suppose **`Point`** is immutable but **`Line`** is mutable:

```
void raiseLine(double deltaY) {
    this.start =
        new Point(start.x, start.y+deltaY);
    this.end =
        new Point(end.x, end.y+deltaY);
}
```

- Immutable classes in Java libraries include **`String`**, **`Character`**, **`Integer`**, …

Avoiding rep exposure #2: copying

- 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 start, end;
  public Line(Point start, Point end) {
    this.start = new Point(start.x,start.y);
    this.end = new Point(end.x,end.y);
  }
  public Point getStart() {
    return new Point(this.start.x,this.start.y);
  }
  …
```

Shallow copying is not enough

- Example: assume **`Point`** and **`Line`** are mutable ADTs

```
class Line {
  private Point start;
  private Point end;

  public Line(Line other) {
    this.start = other.start;
    this.end = other.end;
  }
```

- Client code:

```
Line a = ...;
Line b = new Line(a);  // a and b share Points
a.translate(3, 4);     // also translates b!
…
```

Full deep copy is not always needed

- 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**

Our initial rep-exposure problem, fixed now with copy-out :

```
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!
  }
  …
}
```

Avoiding rep exposure #3: readonly wrapper (immutable “copy”)

```
public List<Character> getElts() {
  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`**.

The good news

```
public List<Character> getElts() { // version 2
  return Collections.unmodifiableList(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() {
 return new ArrayList<Character>(elts);  //copy out!
}
```

```
public List<Character> getElts() {
 return Collections.unmodifiableList(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

“returns a list containing the elements”

Could mean any of these things:

1. Returns a fresh mutable list containing the elements in the set *at the time of the call*
   - likely hard to implement efficiently
2. Returns read-only view that is *always up to date* with the current elements of the set
   - Makes it hard to change the rep
3. 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
   - Weaker than either #1 or #2
   - More complex, harder to use, but sufficient for some purposes

Lesson: a seemingly simple spec may be ambiguous and subtle

Next…

- Abstraction functions: mapping concrete representation to abstract values.