CSE 331
Software Design & Implementation

Hal Perkins

Autumn 2012

Data Abstraction: Abstract Data Types (ADTs)

(Based on slides by Mike Ernst and David Notkin)

Outline

First:

- Data Abstraction – ADTs
- ADT specification and Implementation

Then: Reasoning about ADTs

- Representation Invariants (RIs)
- Abstraction Functions (AFs)

Review: Satisfaction of a specification

Let P be an implementation and S a specification

- Think “procedures/methods/functions” for the moment

P satisfies S iff

- Every behavior of P is permitted by S
- “The behavior of P is a subset of S”

The statement “P is correct” is meaningless

- Though often made!

If P does not satisfy S, either (or both!) could be “wrong”

- *“One person’s feature is another person’s bug.”*
- It’s usually better to change the program than the spec

Scaling Up Specifications

Procedural abstraction:

- Abstracts from details of procedures
- A specification mechanism
- Satisfy the specification with an implementation

Data abstraction:

- Abstracts from details of data representation
- A specification mechanism
  - A way of thinking about programs and design
- Standard terminology: Abstract Data Type, or ADT

Why we need Abstract Data Types

Organizing and manipulating data is pervasive

- Inventing and describing algorithms is rare

Start your design by designing data structures

Potential problems with choosing a data abstraction:

- Decisions about data structures often made too early
- Duplication of effort in creating derived data
- Very hard to change key data structures

An ADT is a set of operations

ADT abstracts from the organization to meaning of data

ADT abstracts from structure to use

Representation does not matter; this choice is (or should be) irrelevant to the client:

```
class RightTriangle {
  float base, altitude;
}
```

```
class RightTriangle {
  float base, hypot, angle;
}
```

Instead, think of a type as a set of operations

create, getBase, getAltitude, getBottomAngle, ...

Force clients (users) to use operations to access data

Are these classes the same?

```
class Point {                class Point {
  public float x;              public float r;
  public float y;              public float theta;
}                            }
```

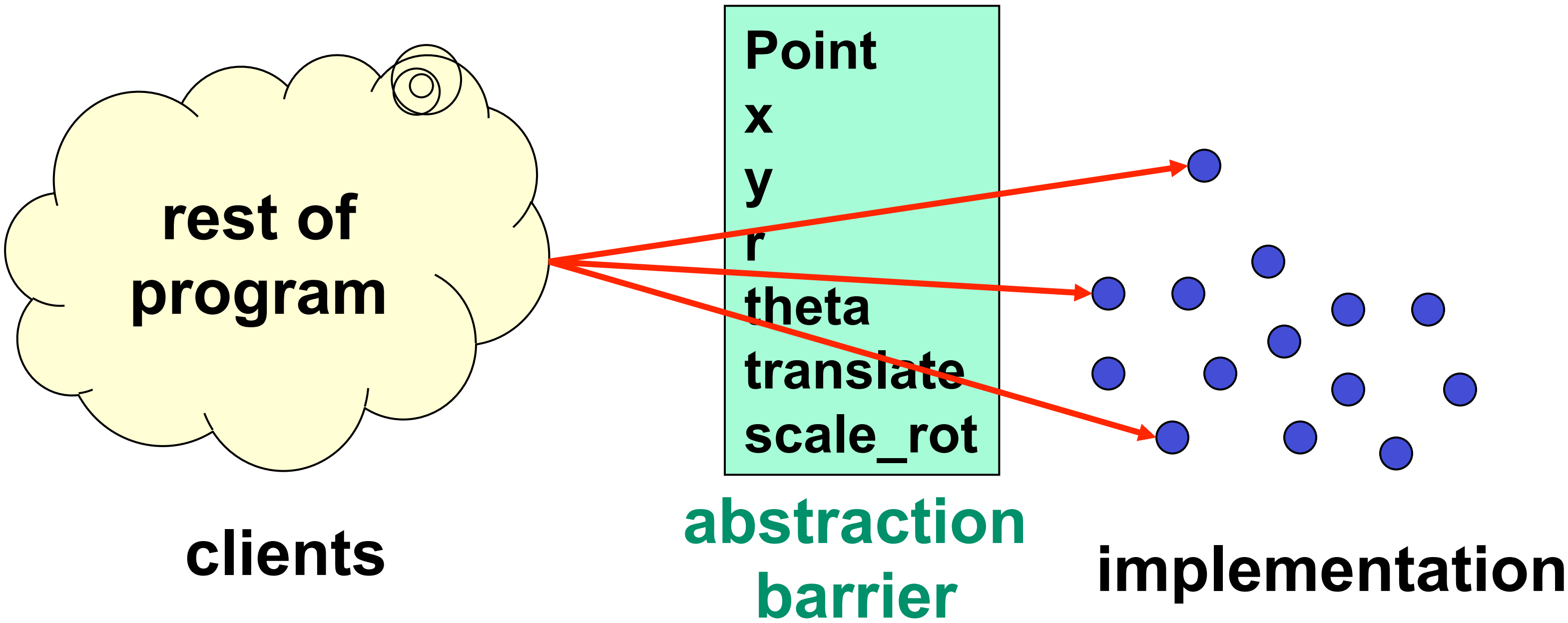
Different: can't replace one with the other

Same: both classes implement the concept "2-d point"

Goal of ADT methodology is to express the sameness:

- Clients depend only on the concept "2-d point"
- Can delay implementation decisions, fix bugs, change algorithms without affecting clients

Abstract data type = objects + operations



The implementation is hidden

The only operations on objects of the type are those provided by the abstraction

Concept of 2-d point, as an ADT

```
class Point {
  // A 2-d point exists somewhere in the plane, ...

  public float x();
  public float y();
  public float r();                      Observers
  public float theta();

  // ... can be created, ...
  public Point();        // new point at (0,0)   Creators/
  public Point centroid(Set<Point> points);     Producers

  // ... can be moved, ...
  public void translate(float delta_x,
                        float delta_y);
  public void scaleAndRotate(float delta_r,     Mutators
                             float delta_theta);
}
```

A data abstraction is defined by a specification

A collection of procedural abstractions

- Not a collection of procedures

Together, these procedural abstractions provide a 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 tell values apart

Connecting specifications and implementations

Specification: describes ADT only in terms of the abstraction

- Never mentions the representation

Abstraction Function: maps object → abstract value

- What the data structure *means* as an abstract value
  - How the data structure is to be interpreted
  - Ex: point in the plane represented by Point object

Representation Invariant: maps object → boolean

- Indicates whether a data structure is *well-formed*
- Defines set of valid values of the data structure
- Only well-formed representations (values) make sense as implementations of an abstract value

Implementing an ADT

To implement a data abstraction

- Select the representation of instances, the “rep”
- Implement operations in terms of that rep
  - In Java this is typically done with a class

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 an empty CharSet
public CharSet ( )

// modifies: this
// effects: this_post = this_pre U {c}
public void insert (Character c);

// modifies: this
// effects: this_post = this_pre - {c}
public void delete (Character c);

// returns: (c ∈ this)
public boolean member (Character c);

// returns: cardinality of this
public int size ( );
```

A CharSet implementation: Is it OK?

```
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();
  }
}
```

```
CharSet s = new CharSet();
Character a = new Character('a');
s.insert(a);
s.insert(a);
s.delete(a);
if (s.member(a))
    // print "wrong";
else
    // print "right";
```

Where Is the Error?

Answer this and you know what to fix

Perhaps `delete` is wrong

  It should remove all occurrences

Perhaps `insert` is wrong

  It should not insert a character that is already there

How can we know?

  The representation invariant tells us

The representation invariant

States data structure well-formedness

Must hold before and after every **`CharSet`** operation

Operations (methods) may depend on it

Write it this way

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

Or, more formally:

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

$\forall$ indices i, j of elts .

$\quad$ 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);
}
```

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 the 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**

If you do it, document why and how

- And feel guilty about it!

Ways to avoid rep exposure

1. Exploit immutability
```
Character choose() {
  return elts.elementAt(0);
}
```
Character is immutable.

2. Make a copy
```
List<Character> getElts() {
  return new ArrayList<Character>(elts);
  // or: return (ArrayList<Character>) elts.clone();
}
```
Mutating a copy doesn’t affect the original.
Don’t forget to make a copy on the way in!

3. Make an immutable copy
```
List<Character> getElts() {
  return Collections.unmodifiableList<Character>(elts);
}
```
Client cannot mutate
Still need to make a copy on the way in

Checking rep invariants

Should code check that the rep invariant holds?

- Yes, if it’s inexpensive
- Yes, for debugging (even when it’s expensive)
- It’s quite hard to justify turning the checking off
- Some private methods need not check (Why?)

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?
  // (there are ways to guarantee it)
  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 (<u>requires</u> clause)
- On exit:
  - Check rep invariant
  - Check postconditions

Checking the rep invariant helps you discover errors

Reasoning about the rep invariant helps you avoid errors

- Or prove that they do not exist!

Rep inv. constrains structure, not meaning

New implementation of insert that preserves the rep invariant:

```
public void insert(Character c) {
  Character cc = new Character(encrypt(c));
  if (!elts.contains(cc))
    elts.addElement(cc);
}
public boolean member(Character c) {
  return elts.contains(c);
}
```

The program is still wrong

- Clients observe incorrect behavior
- What client code exposes the error?
- Where is the error?
- We must consider the meaning
- The *abstraction function* helps us

```
CharSet s = new CharSet();
Character a = new
Character('a'));
s.insert(a);
if (s.member(a))
    // print "right";
else
    // print "wrong";
```

Abstraction function: rep→abstract value

The abstraction function maps the concrete representation to the abstract value it represents

AF: Object → abstract value

AF(CharSet this) = { c | c is contained in this.elts }

"set of Characters contained in this.elts"

Typically *not* executable

The abstraction function lets us reason about behavior from the client perspective

Abstraction function and insert

Our real goal is to satisfy the specification of insert:

// modifies: this

// effects: $this_{post}$ = $this_{pre}$ U {c}

public void insert (Character c);

Once again we can place the blame

- Applying the abstraction function to the result of the call to insert yields AF(elts) U {encrypt('a')}
- What if we used this abstraction function?
  - AF(this) = { c | encrypt(c) is contained in this.elts }
    - = { decrypt(c) | c is contained in this.elts }

Summary

Rep invariant

- Which concrete values represent abstract values

Abstraction function

- For each concrete value, which abstract value it represents

Together, they modularize the implementation

- Can examine operators one at a time
- Neither one is part of the abstraction (the ADT)

In practice

- Always write a representation invariant
- Write an abstraction function when you need it
  - Write an informal one for most non-trivial classes
  - A formal one is harder to write and usually less useful

Next time: more examples and perspective