CSE373: Data Structures & Algorithms

Lecture 16: Software-Design Interlude – Preserving Abstractions

Dan Grossman
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Motivation

- Essential: knowing available data structures and their trade-offs
  - You're taking a whole course on it! ☺
- However, you will rarely if ever re-implement these "in real life"
  - Provided by libraries
- But the key idea of an *abstraction* arises *all the time* "in real life"
  - Clients do not know how it is implemented
  - Clients do not need to know
  - Clients cannot "break the abstraction" *no matter what they do*

Interface vs. implementation

- Provide a reusable interface without revealing implementation
- More difficult than it sounds due to aliasing and field-assignment
  - Some common pitfalls
- So study it in terms of ADTs vs. data structures
  - Will use priority queues as example in lecture, but any ADT would do
  - Key aspect of grading your homework on graphs

Recall the abstraction

Clients:
"not trusted by ADT implementer"

- Can perform any sequence of ADT operations
- Can do anything type-checker allows on any accessible objects

```
new PQ(…)
insert(…)
deleteMin(…)
isEmpty()
```

Data structure:

- Should document how operations can be used and what is checked (raising appropriate exceptions)
  - E.g., fields not **`null`**
- If used correctly, correct priority queue for any client
- Client "cannot see" the implementation
  - E.g., binary min heap

Our example

- A priority queue with to-do items, so earlier dates "come first"
  - Simpler example than using Java generics
- Exact method names and behavior not essential to example

```
public class Date {
   … // some private fields (year, month, day)
   public int getYear() {…}
   public void setYear(int y) {…}
   … // more methods
}
public class ToDoItem {
   … // some private fields (date, description)
   public void setDate(Date d) {…}
   public void setDescription(String d) {…}
   … // more methods
}
// continued next slide…
```


Our example

- A priority queue with to-do items, so earlier dates "come first"
  - Simpler example than using Java generics
- Exact method names and behavior not essential to example

```
public class Date { … }
public class ToDoItem { … }
public class ToDoPQ {
   … // some private fields (array, size, …)
   public ToDoPQ() {…}
   void insert(ToDoItem t) {…}
   ToDoItem deleteMin() {…}
   boolean isEmpty() {…}
}
```

An obvious mistake

- Why we trained you to "mindlessly" make fields **`private`**:

```
public class ToDoPQ {
   … // other fields
   public ToDoItem[] heap;
   public ToDoPQ() {…}
   void insert(ToDoItem t) {…}
   …
}
// client:
pq = new ToDoPQ();
pq.heap = null;
pq.insert(…); // likely exception
```

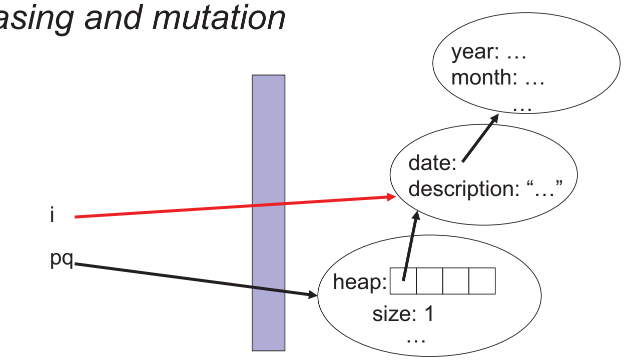
- Today's lecture: **`private`** does not solve all your problems!
  – Upcoming pitfalls can occur even with all **`private`** fields

Less obvious mistakes

```
public class ToDoPQ {
   … // all private fields
   public ToDoPQ() {…}
   void insert(ToDoItem i) {…}
   …
}

// client:
ToDoPQ   pq = new ToDoPQ();
ToDoItem i  = new ToDoItem(…);
pq.insert(i);
i.setDescription("some different thing");
pq.insert(i); // same object after update
x = deleteMin(); // x's description???
y = deleteMin(); // y's description???
```


Aliasing and mutation

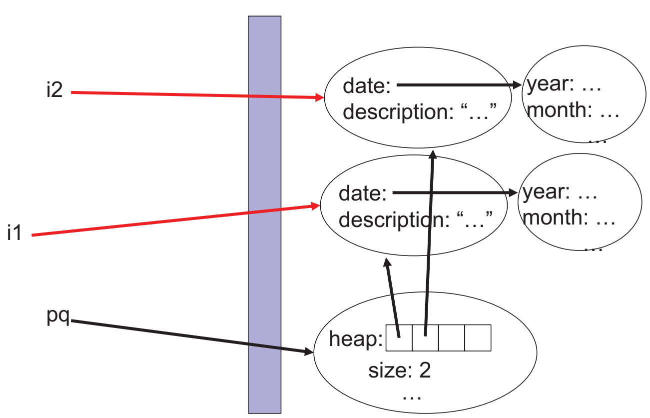


- Client was able to update something inside the abstraction because client had an alias to it!
  – It is too hard to reason about and document what should happen, so better software designs avoid the issue!

More bad clients

```
ToDoPQ   pq = new ToDoPQ();
ToDoItem i1 = new ToDoItem(…); // year 2013
ToDoItem i2 = new ToDoItem(…); // year 2014
pq.insert(i1);
pq.insert(i2);
i1.setDate(…); // year 2015
x = deleteMin(); // "wrong" (???) item?
       // What date does returned item have???
```


More bad clients



More bad clients

```
pq = new ToDoPQ();
ToDoItem i1 = new ToDoItem(…);
pq.insert(i1);
i1.setDate(null);
ToDoItem i2 = new ToDoItem(…);
pq.insert(i2); // NullPointerException???
```

Get exception inside data-structure code even if **`insert`** did a careful check that the date in the **`ToDoItem`** is not **`null`**

- Bad client later invalidates the check

The general fix

- Avoid aliases into the internal data (the “red arrows”) by copying objects as needed
  - Do not use the same objects inside and outside the abstraction because two sides do not know all mutation (field-setting) that might occur
  - “Copy-in-copy-out”
- A first attempt:

```
public class ToDoPQ {
  …
  void insert(ToDoItem i) {
    ToDoItem internal_i =
      new ToDoItem(i.date,i.description);
    … // use only the internal object
  }
}
```

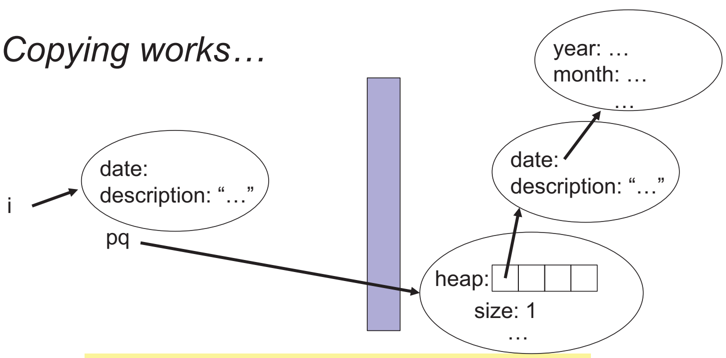

Must copy the object

```
public class ToDoPQ {
  …
  void insert(ToDoItem i) {
    ToDoItem internal_i =
      new ToDoItem(i.date,i.description);
    … // use only the internal object
  }
}
```

- Notice this version accomplishes nothing
  - Still the alias to the object we got from the client:

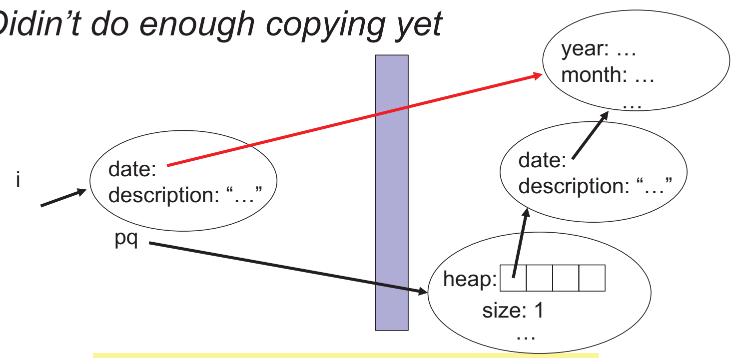
```
public class ToDoPQ {
  …
  void insert(ToDoItem i) {
    ToDoItem internal_i = i;
    … // internal_i refers to same object
  }
}
```


Copying works…




```
ToDoItem i = new ToDoItem(…);
pq = new ToDoPQ();
pq.insert(i);
i.setDescription(“some different thing”);
pq.insert(i);
x = deleteMin();
y = deleteMin();
```


Didin’t do enough copying yet




```
Date d = new Date(…)
ToDoItem i = new ToDoItem(d,“buy beer”);
pq = new ToDoPQ();
pq.insert(i);
d.setYear(2015);
…
```


Deep copying

- For copying to work fully, usually need to also make copies of all objects referred to (and that they refer to and so on…)
  - All the way down to **`int`**, **`double`**, **`String`**, …
  - Called *deep copying* (versus our first attempt *shallow-copy*)
- Rule of thumb: Deep copy of things passed into abstraction

```
public class ToDoPQ {
  …
  void insert(ToDoItem i) {
    ToDoItem internal_i =
      new ToDoItem(new Date(…),
                   i.description);
    … // use only the internal object
  }
}
```


Constructors take input too

- General rule: Do not “trust” data passed to constructors
  - Check properties and make deep copies
- Example: Floyd’s algorithm for **`buildHeap`** should:
  - Check the array (e.g., for **`null`** values in fields of objects or array positions)
  - Make a deep copy: new array, new objects

```
public class ToDoPQ {
  // a second constructor that uses
  // Floyd’s algorithm, but good design
  // deep-copies the array (and its contents)
  void PriorityQueue(ToDoItem[] items) {
    …
  }
}
```

That was copy-in, now copy-out…

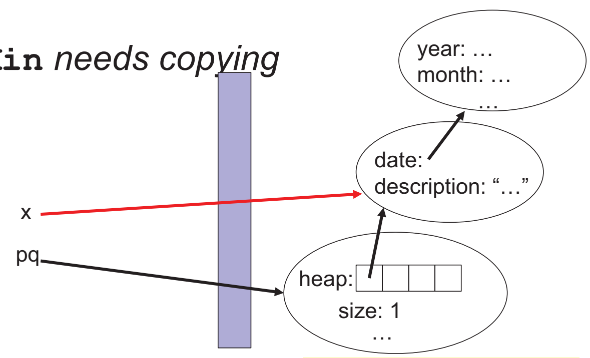
- So we have seen:
  - Need to deep-copy data passed into abstractions to avoid pain and suffering
- Next:
  - Need to deep-copy data passed out of abstractions to avoid pain and suffering (unless data is "new" or no longer used in abstraction)
- Then:
  - If objects are immutable (no way to update fields or things they refer to), then copying unnecessary

`deleteMin` *is fine*

```
public class ToDoPQ {
   …
   ToDoItem deleteMin() {
     ToDoItem ans = heap[0];
     … // algorithm involving percolateDown
     return ans;
}
```

- Does not create a "red arrow" because object returned is no longer part of the data structure
- Returns an alias to object that was in the heap, but now it is not, so conceptual "ownership" "transfers" to the client

`getMin` *needs copying*




```
ToDoItem i = new ToDoItem(…);
pq = new ToDoPQ();
x = pq.getMin();
x.setDate(…);
```

```
public class ToDoPQ {
   ToDoItem getMin() {
     int ans = heap[0];
     return ans;
   }
}
```

- Uh-oh, creates a "red arrow"

The fix

- Just like we deep-copy objects from clients before adding to our data structure, we should deep-copy parts of our data structure and return the copies to clients
- Copy-in *and* copy-out

```
public class ToDoPQ {
   ToDoItem getMin() {
     int ans = heap[0];
     return new ToDoItem(new Date(…),
                         ans.description);
   }
}
```


Less copying

- (Deep) copying is one solution to our aliasing problems
- Another solution is *immutability*
  - Make it so nobody can ever change an object or any other objects it can refer to (deeply)
  - Allows "red arrows", but immutability makes them harmless
- In Java, a **`final`** field cannot be updated after an object is constructed, so helps ensure immutability
  - But **`final`** is a "shallow" idea and we need "deep" immutability

This works

```
public class Date {
   private final int year;
   private final String month;
   private final String day;
}
public class ToDoItem {
   private final Date date;
   private final String description;
}
public class ToDoPQ {
   void insert(ToDoItem i){/*no copy-in needed!*/}
   ToDoItem getMin(){/*no copy-out needed!*/}
   …
}
```

Notes:

- `String` objects are immutable in Java
- (Using `String` for `month` and `day` is not great style though)

This does *not* work

```java
public class Date {
   private final int year;
   private String month; // not final
   private final String day;
   …
}
public class ToDoItem {
   private final Date date;
   private final String description;
}
public class ToDoPQ {
   void insert(ToDoItem i){/*no copy-in*/}
   ToDoItem getMin(){/*no copy-out*/}
   …
}
```

Client could mutate a **`Date`**'s **`month`** that is in our data structure

- So must do entire deep copy of **`ToDoItem`**

`final` *is shallow*

```java
public class ToDoItem {
   private final Date date;
   private final String description;
}
```

- Here, **`final`** means no code can update the **`year`** or **`description`** fields after the object is constructed
- So they will always refer to the same **`Date`** and **`String`** objects
- But what if those objects have *their* contents change
  – Cannot happen with **`String`** objects
  – For **`Date`** objects, depends how we define **`Date`**
- So **`final`** is a "shallow" notion, but we can use it "all the way down" to get deep immutability

This works

- When deep-copying, can "stop" when you get to immutable data
  – Copying immutable data is wasted work, so poor style

```java
public class Date { // immutable
   private final int year;
   private final String month;
   private final String day;
   …
}
public class ToDoItem {
   private Date date;
   private String description;
}
public class ToDoPQ {
   ToDoItem getMin(){
    int ans = heap[0];
    return new ToDoItem(ans.date, // okay!
                        ans.description);
   }
}
```


What about this?

```java
public class Date { // immutable
   …
}
public class ToDoItem { // immutable (unlike last slide)
   …
}
public class ToDoPQ {
  // a second constructor that uses
  // Floyd's algorithm
  void PriorityQueue(ToDoItem[] items) {
     // what copying should we do?
     …
   }
}
```


What about this?

```java
public class Date { // immutable
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public class ToDoItem { // immutable (unlike last slide)
   …
}
public class ToDoPQ {
  // a second constructor that uses
  // Floyd's algorithm
  void PriorityQueue(ToDoItem[] items) {
     // what copying should we do?
     …
   }
}
```

Copy the array, but do not copy the **`ToDoItem`** or **`Date`** objects

Homework 5

- You are implementing a graph abstraction
- As provided, **`Vertex`** and **`Edge`** are immutable
  – But **`Collection<Vertex>`** and **`Collection<Edge>`** are not
- You might choose to add fields to **`Vertex`** or **`Edge`** that make them not immutable
  – Leads to more copy-in-copy-out, but that's fine!
- *Or* you might leave them immutable and keep things like "best-path-cost-so-far" in another dictionary (e.g., a **`HashMap`**)

There is more than one good design, but preserve your abstraction
  – *Great practice with a key concept in software design*