

Exercise 9

Information Hiding and Encapsulation

November 25, 2016

Task 1

Suppose that the following Java classes are part of a package, to which an external user cannot add classes.

```
public abstract class BankAccount {
    ... boolean importantCustomer=false;
    ... int amount=0;
    ... final int maxDebit=1000;

    /// invariant amount >= -maxDebit &&
    /// !importantCustomer => amount>=0 &&
    /// importantCustomer <=> this instanceof RichCustomer

    ... void deposit(int amount);
    ... void withdraw(int amount);
}

public final class PoorCustomer extends BankAccount {
    ... void deposit(int amount) {
        if(amount>=0)
            this.amount+=amount;
    }
    ... void withdraw(int amount) {
        if(amount<=this.amount)
            this.amount-=amount;
    }
}

public final class RichCustomer extends BankAccount {
    public RichCustomer() {importantCustomer=true;}
    ... void deposit(int amount) {
        if(this.amount+amount >= -maxDebit)
            this.amount+=amount;
    }
    ... void withdraw(int amount) {
        if(-maxDebit<=this.amount-amount)
            this.amount-=amount;
    }
}
```

Provide the most permissive access modifiers for each field and method, such that the class invariant cannot be broken from outside the package. Assume that no integer over/underflow occurs.

— solution —

For the fields of class `BankAccount`, the most permissive access modifiers are:

`importantCustomer`: default modifier. In this way, it would be accessible by other classes in the same package but not by subclasses. Otherwise, we may have a class that extends `BankAccount` and sets to true `importantCustomer` without being a `RichCustomer`.

`maxDebit`: `public`, since it is `final` and it cannot be modified by other classes.

`amount`: default, since we need to access it from the other classes of this package (e.g. `PoorCustomer` and `RichCustomer`), but we must prevent external attackers from modifying it.

Methods `withdraw` and `deposit` can be declared `public`, since they preserve the invariants.

In Scala, a class can be declared as sealed. That means that the class can be extended only by classes written in the same `.scala` file. Suppose that the class `BankAccount` is declared as sealed, and `PoorCustomer` and `RichCustomer` are part of the same `.scala` file. Does this allow you to choose more permissive access modifiers?

— solution —

If class `BankAccount` had been declared as sealed, we could choose `protected` as the access modifier of the `amount` and `importantCustomer` fields, since external classes would not be allowed to extend it and so would not be able to gain access to these fields. More generally, if a class is sealed, the default and `protected` levels are equivalent, since it is not possible to extend the current class outside the current package.

Task 2

From a previous exam

Consider the following Java program consisting of two packages:

```
1 package A;
2
3 public abstract class Person {
4     _____ int tickets = 0;
5     _____ final int maxTickets = 3;
6
7     /// invariant 0 <= tickets <= maxTickets
8
9     _____ abstract void buy(int t);
10 }
11
12 public class Buyer extends Person {
13     _____ void inc(int t) {
14         if (this.tickets+t <= this.maxTickets) this.tickets += t;
15     }
16     _____ void buy(int t) { if (t >= 0) inc(t); }
17 }
18
19
20
21 package B;
22 import A.*;
23
24 public class SmartBuyer extends Buyer {
25     _____ void inc(int t) { this.tickets += t; }
26 }
```

```

27
28 public class Main {
29     public static void main(String args[]) {
30         Buyer b = new SmartBuyer();
31         b.buy(9);
32     }
33 }

```

A) Provide the *most restrictive* access modifiers for the fields `tickets` and `maxTickets` and the methods `inc()` and `buy()` such that the program is still accepted by the compiler.

— solution —

The field `tickets` must be protected (since we need to access it from the class `SmartBuyer` which belongs to another package). The field `maxTickets` must have a default access modifier (because we need to access it from the class `Buyer` which belongs to the same package). The method `inc()` can be declared private in both `Buyer` and `SmartBuyer`. The method `buy()` in class `Person` must have a default access modifier (because abstract methods cannot be private), while the method `buy()` in class `Buyer` must be public (because we need to access it from the class `Main` which belongs to another package and is not a subclass of `Buyer`).

B) With respect to the access modifiers that you provided in part A, add code to the class `SmartBuyer` such that the execution of the `main()` method of the class `Main` breaks the invariant of the class `Person`.

— solution —

One possible solution consists in overriding the method `buy()` in `SmartBuyer` as follows:

```
public void buy(int t) { inc(t); }
```

Task 3

Consider the following Java code:

```

package p;

public final class List {
    ///invariant 1: The list starting at head is acyclic
    ///invariant 2: The list starting at head is non-decreasing

    public void prepend(int x){
        if (head==null || x <= head.getValue())
            head = new Node(x,head);
    }

    public Node getHead(){ return head; }
    public Node head = null;
}

public final class Node {
    Node(int x, Node n) {
        value = x;
        next = n;
    }

    public Node getNext(){ return next; }
}

```

```

    public int getValue(){ return value; }
    private Node next;
    private int value;
}

```

Assuming that we cannot modify the classes `List` and `Node`, we would like to see whether or not the invariants can be broken, either by adding classes to package `p`, or by clients outside of package `p`. Assume reflection is not used at all.

A) Can invariant 1 be broken by adding clients outside of package `p`? If yes, show code, that when run ends in a state in which the invariant is broken; if not explain why.

— solution —

Invariant 1 cannot be broken by clients outside `p` because the field `Node.next` is private and can only be set in the constructor to an argument of the constructor, which must point to an already existing list that does not include the object currently being created.

B) Can invariant 1 be broken by adding classes to package `p`? If yes, show code, that when run ends in a state in which the invariant is broken; if not explain why.

— solution —

Invariant 1 cannot be broken from inside `p` for the same reasons as above.

C) Can invariant 2 be broken by adding clients outside of package `p`? If yes, show code, that when run ends in a state in which the invariant is broken; if not explain why.

— solution —

Invariant 2 cannot be broken from outside `p` because:
 The invariant depends only on the fields `Node.next`, `Node.value`, and `List.head`.
 Both `Node` fields are only written to in the constructor of `Node` and cannot be modified later as they are private.
 The constructor of `Node` is of package access and so cannot be called directly by the client.
 The only public method that calls it is `List.prepend`, which ensures invariant 2 - hence no decreasing list of nodes (whether or not attached to a `List`) can be created by clients of the package. So, although we can assign `List.head` any value, we cannot obtain a value (a `Node`) that would break the invariant.

D) Can invariant 2 be broken by adding classes to package `p`? If yes, show code, that when run ends in a state in which the invariant is broken; if not explain why.

— solution —

Invariant 2 can be broken as follows (all code inside `p`):

```

class Client{
    void client(){
        List l = new List();
        l.prepend(0);
        Node n = new Node(l,l.getHead());
        l.head = n;
    }
}

```

Task 4

Consider the following Java code:

```
public class Hour {
    public int h=0;
}

public class Time {
    private Hour hour=new Hour();
    private int m=0;
    /// invariant hour.h>=0 && hour.h<24

    public void setHour(int h) {
        if(h>=0 && h<24) this.hour.h=h;
    }

    public Hour getHour() {return hour;}
}
```

A) Provide an example that breaks the invariant of Time without changing the code above and without using reflection.

— solution —

We can easily break the invariants through alias leaking. For instance, the following code breaks the invariant of class Time:

```
Time t=new Time();
Hour h=t.getHour();
h.h=-1;
```

B) There are two immediate ways to fix the problem. In one of them, signatures of methods are modified, while in the other they are not. What are these ways of fixing the problem?

— solution —

We can fix this in two ways. We have to avoid the alias leaking. We can reach this goal returning an integer value instead of an object, or a copy of the Hour object stored in the current Time object.

```
public int getHour() {return hour.h;}
public Hour getHour() {return (Hour) hour.clone();}
```

In general, it is simpler for reasoning, if possible, to return only primitive values, or to avoid exposing aliases of the local state of the object, by instead returning copies of the stored objects. In this way, we can avoid alias leaking, thus no external code can modify the values contained in the current object.

C) Clearly, we would prefer to keep the signatures the same as before. Are there any drawbacks to this approach?

— solution —

The drawback of the second approach is that we are creating a new object and thus are using more memory.

D) Would it be possible to introduce an interface with no mutator methods and use it to solve the problem? Explain how this approach would look and whether there would still be a way to break the invariant.

— solution —

We could hide the `h` field of `Hour` by making `Hour` implement an interface `IMHour` that has no mutator methods. `Time.getHour()` could then return this interface.

The client could still downcast from `IMHour` to `Hour` and break the invariant but aside from that the invariant is protected. This could be prevented by making `Hour` a private inner class of `IMHour`.

Task 5

Consider the following Java programs:

Program 1	Program 2	Program 3	Program 4
<pre>package A1; public class X { int x; }</pre>	<pre>package A1; public class X { protected int x; }</pre>	<pre>package A1; public class X { private int x; }</pre>	<pre>package A1; public class X { protected int x; }</pre>
<pre>package A2; import A1.X; class Y extends X { int f(X v) { return v.x; } }</pre>	<pre>package A2; import A1.X; class Y extends X { int f(X v) { return v.x; } }</pre>	<pre>package A2; import A1.X; class Y extends X { int f(X v) { return v.x; } }</pre>	<pre>package A2; import A1.X; class Y extends X { int f() { return this.x; } }</pre>

Only one of these programs compiles. Which one? Why are the other programs rejected?

— solution —

- *Program 1* does not compile because method `f` of class `Y` tries to access a field of the superclass with default access modifier (that is, it can be accessed only by classes in the same package) from an external package.
- *Program 2* does not compile because method `f` of class `Y` tries to access a protected field of an object instance of the superclass, but from a different package (`A2`, while the superclass belongs to `A1`). Note that Java does not allow subclasses to access protected fields of other objects instance of the superclass if they belong to a different package.
- *Program 3* does not compile because method `f` of class `Y` tries to access a private field of the superclass.
- *Program 4* compiles. In fact, method `f` of class `Y` is allowed to access `this.x` since it is a protected field of class `X`.

Task 6

Data structures often intentionally share aliases. For instance, consider the following Java class:

```
class ArrayList<T> {
    private T[] elements=...;
    private int lastEl=0;
    public T get(int i) {return elements[i];}
```

```

    public int size() {return lastEl;}
    public void add(T el) {elements[lastEl++]=el;}
}

```

Imagine that this class is extended as follows

```

class Coordinates {
    int x, y;
    public Coordinates(int xx, int yy) {x=xx; y=yy;}
}

class CList extends ArrayList<Coordinates> {
    /// invariant  $\forall i:\text{int} \mid 0 \leq i \wedge i < \text{size}() \Rightarrow \text{get}(i).x > \text{get}(i).y$ 
    public void add(Coordinates el) {
        if (el.x > el.y) super.add(el);
    }
}

```

A) Write a program that breaks the invariant of CList.

— solution —

The invariant can be broken by exploiting the fact that CList captures and stores Coordinates objects.

```

CList list=new CList();
Coordinates c=new Coordinates(2, 1);
list.add(c);
c.x=0;

```

B) How can we fix this problem?

— solution —

To fix CList we need two things

- We need to clone the Coordinates element before storing it.

```

public void add(Coordinates el) {
    if (el.x > el.y) super.add((Coordinates) el.clone());
}

```

- We also need to clone the Coordinates element before returning it, as otherwise we leak a reference that could be modified.

```

public Coordinates get(int i) {
    return (Coordinates) super.get(i).clone();
}

```

The limit of such an approach is that we create a copy of all the elements stored in the list. It is not possible to make sure the invariant is preserved without creating objects that are only in the current CList object.

C) Is it possible to fix it without allocating new objects (either directly or indirectly), that is, without consuming additional memory? What new problems might arise from your changes?

— solution —

A possible solution would be to have final fields in class `Coordinates`. This would ensure that the invariant cannot be broken, but it requires the allocation of new objects each time we want to modify the fields. For instance, the following code:

```
Coordinates c=new Coordinates(2, 1);  
c.x=0;
```

should be re-written to

```
Coordinates c=new Coordinates(2, 1);  
c=new Coordinates(0,1);
```

which allocates a new object even though this is not necessary (since the object pointed by `c` is not shared, and so changing its fields cannot break the invariants of other objects).

D) Discuss the benefits and the drawbacks of using alias sharing in data structures.

— solution —

The main benefit of alias sharing in data structures is to minimize the consumption of memory. In addition, we may want to share aliases on data structures, for instance, in order to further update the content of an element in a list. The main drawback is that alias sharing does not allow us to reason locally about the objects stored in the data structure, since clients could retain references to objects they store in the data structure, and might therefore modify the contents of these objects after they were stored.

Task 7

The following Java classes, all part of the `security` package, were written by an inexperienced programmer and contain a number of issues:

```
package security;
```

```
public class User {  
    public String name;  
    public String password;  
    public User(String name, String password) {  
        this.name = name;  
        this.password = password;  
    }  
}  
  
public class LoginException extends RuntimeException {  
    public User problemUser;  
    public LoginException(String message, User problemUser) {  
        super(message);  
        this.problemUser = problemUser;  
    }  
}  
  
public class Login {  
    private List<User> users = new LinkedList<User>();  
    public void registerUser(User u) {  
        if (u == null || u.name == null || u.password == null  
            || u.name.isEmpty() || u.password.isEmpty()) return;  
        users.add(u);  
    }  
}
```



```

// Returns true if the user 'u' was successfully logged in.
// Otherwise returns false or throws an exception.
public boolean login(User u) throws LoginException {
    if (u == null) return false;
    User current = null;
    try{
        for(User registered : users) {
            boolean nameEqual = registered.name.equals(u.name);
            current = registered;

            if (nameEqual) {
                if (registered.password.equals(u.password))
                    return true;
            }

            if (nameEqual)
                throw new LoginException("Invalid password for user",u);
        }

        return false;
    }
    catch(Exception e) {
        throw new LoginException("Invalid user",current);
    }
}
}

```

The malicious method is in a different package:

```
void malicious(Login l) { ... }
```

Assume the Login object that is passed into the method already has registered users.

A) Complete the body of the malicious method so that you manage to log-in as an already existing user. You do not know any names or passwords of existing users. Do not use reflection.

— solution —

The body of the malicious method could look like:

```

void malicious(Login l) {
    User u = new User("user", "pass");
    l.registerUser(u);
    u.name = null;

    try {
        l.login(u);
    }
    catch(LoginException e) {
        boolean success = l.login(e.problemUser);
        //Logged in as the user that was registered before user u
    }
}

```

B) Is it possible to fix the problem under the following restrictions? In each of these cases, explain how you can prevent the malicious login or why it is not possible.

- only modifying the User class?

solution

- We could make both fields of User have the default (package) access:

```
public class User {  
    String name;  
    String password;  
    public User(String name, String password) {  
        this.name = name;  
        this.password = password;  
    }  
}
```

Therefore, code outside the package will not be able to change existing User objects and the malicious method could not cause the exception as before.

- only modifying the LoginException class?

solution

The LoginException class currently captures the value of the problematic user. Instead it could create a new user that has the same name as problemUser but hides the password.

```
public class LoginException extends RuntimeException {  
    public User problemUser;  
    public LoginException(String message, User problemUser) {  
        super(message);  
        this.problemUser = new User(problemUser.name, "****");  
    }  
}
```

This way, even if an exception is thrown, that refers to the wrong user name, the user's password will not be leaked.

- only modifying the registerUser method?

solution

We can change the registerUser method so that it does not capture its argument:

```
public void registerUser(User u) {  
    if (u == null || u.name == null || u.password == null  
        || u.name.isEmpty() || u.password.isEmpty()) return;  
    users.add(new User(u.name, u.password));  
}
```

Now we would not be able to modify the internal structure of the Login class by modifying the user we just registered in the malicious method.

- only modifying the body of the for loop inside the login method?

solution

This for loop actually contains a bug which allows the exploit to work. To fix it we must move the assignment to the current variable to the beginning of the loop:

```
for (User registered : users) {  
    current = registered;  
    boolean nameEqual = registered.name.equals(u.name);  
    ...  
}
```

```
}
```

In the original code we were able to cause an exception regarding a particular user, but report the previous user as an invalid, since `current` was not updated yet. This is no longer the case.