Formal Methods for Java

Lecture 13: Invariants with Pack and Unpack

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December 4, 2012

The Invariant Problem

There are some problems with invariants:

- Ownership: invariants can depend on fields of other objects.
  For example, the invariant of list accesses node fields.
- Callback: invariants can be temporarily violated.
  While invariant is violated we call a different method that calls back.
- Atomicity: invariants can be temporarily violated.
  While invariant is violated another thread accesses object.

Temporarily Violating Invariants

```
public class Container {
  int[] content;
  int size;
  /*@ invariant 0 <= size && size <= content.length; @*/

  public void add(int v) {
    /* 1 */
    size++;
    /* 2 */
    if (size > content.length) {
      newContent = new int[2*size+1];
      ...
      content = newContent;
    }
    ...
    /* 3 */
  }
}
```

When do Invariants Hold?

- Before a public method is called. `/* 1 */`
- After a public method returns. `/* 3 */`
- However, it may be violated in between. `/* 2 */`

Private Methods

```
public class Container {
  int[] content;
  int size;
  /*@ invariant 0 <= size && size <= content.length; @*/

  private void growContent() {

  private /*@ helper @*/ void growContent() {

    ...
    content = newContent;
  }

  public void add(int v) {
    /* invariant should hold */
    size++;
    /* invariant may be violated */
    if (size > content.length)
      growContent();
    ...
    /* invariant should hold, again */
  }
}
```

- Sometimes an invariant should not hold for a private method.
- JML has the keyword `/*@ helper @*/`.

Calling Methods of Other Classes

```
public class Container {
  int[] content;
  int size;
  /*@ invariant 0 <= size && size <= content.length; @*/

  public void add(int v) {
    /* invariant should hold */
    size++;
    /* invariant may be violated */
    if (size > content.length) {
      newContent = new int[2*size+1];
      System.arraycopy(content, 0, newContent, 0, content.length);
      content = newContent;
    }

    ...
    /* invariant should hold, again */
  }
}
```

- The invariant need not to hold, when calling other methods.
- However there is the callback problem.

The Callback Problem

```
public class Log {
  public void log(String p) {
    logfile.write("Log:␣"+p+"␣list␣is␣"+Global.theList);
} }

public class Container {
  int[] content;
  int size;
  /*@ invariant 0 <= size && size <= content.length; @*/

  public void add(int v) {
    /* invariant should hold */
    size++;
    /* invariant may be violated */
    if (size > content.length) {
      Logger.log("growing␣array.");
    ...
  }

  public String toString() {
    /* invariant should hold */
    ...
} }
```

The Callback Problem

- A method of a different class can be called while invariant is violated.
- This method may call a method of the first class.
- Who has to ensure that the invariant holds?
- jmlrac complains that invariant does not hold
- ESC/Java checks that most invariants hold at every method call, but not all invariants; this may lead to unsoundness.

A Ghost Variable for Invariants

Idea of David A. Naumann and Mike Barnett:

- Make the places where an invariant does not hold explicit.
- Add a ghost variable *packed* that indicates if the invariant should hold.
- Before modifying an object set this variable to `false`.
- When modification is finished, set it to `true`.
- The following invariant should always hold:
  packed ==> invariants of object
- The caller has to ensure that the objects he uses are packed.

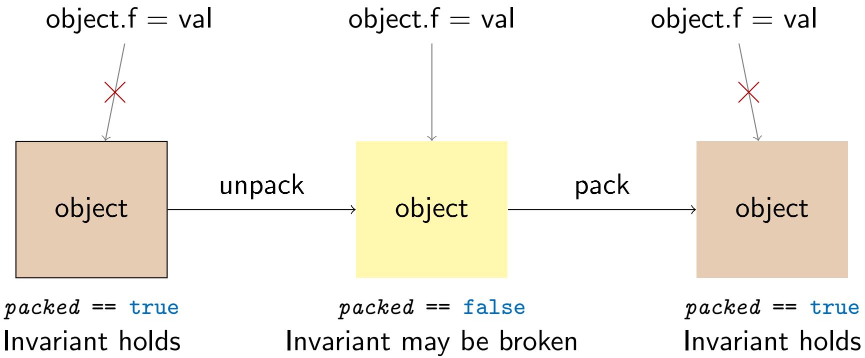
Example: A Ghost Variable for Invariants

```
//@ public ghost boolean packed;
//@ private invariant packed ==> (size >= 0 && size <= content.length);

/*@ requires packed;
  @ ensures packed;
  @*/
public void add(int v) {
  unpack this;
  size++;
  ...
  pack this;
}
```

- The pre- and post-conditions explicitly states that invariant holds
- `unpack this` is an abbrevation for:
  ```
  assert this.packed;
  set this.packed = false;
  ```
- `pack this` is an abbrevation for:
  ```
  assert !this.packed;
  assert /*invariant of this holds*/;
  set this.packed = true;
  ```

The pack/unpack Mechanism



- An object must be unpacked before fields may be accessed.
- The invariant has to hold only while object is packed.
- The invariant may only depend on fields of the object.

Checking with Atomicity

Static Checking with *packed* ghost field:

- Fields may only be modified if *packed* is false.
- For each `pack` operation check that invariant holds again.
- Thus *packed* ==> *invariants* holds for all states.

Tree Example

```
class TreeNode {
  int key, value;
  TreeNode left, right;
  /*@ invariant left != null ==> left.key <= key; @*/
  /*@ invariant right != null ==> right.key >= key; @*/

  public void add(Node n) {
    if (n.key < key) {
      if (left == null)
        left = n;
      else
        left.add(n);
    } else {
      ...
    }
  }
}
```

Adding Packed variable

```
class TreeNode {
  int key, value;
  TreeNode left, right;
  //@ public ghost boolean packed = false;

  /*@ invariant packed ==> (left != null ==> left.key <= key); @*/
  /*@ invariant packed ==> (right != null ==> right.key >= key); @*/

  //@ requires packed;
  //@ ensures packed;
  public void add(/*@non_null@*/ TreeNode n) {
    // unpack this
    if (n.key < key) {
      if (left == null)
        left = n;
      else
        left.add(n);
    } else {
      ...
    }
    // pack this
  }
}
```

Running ESC/Java gives:

```
> escjava2 -q TreeNode.java
TreeNode.java:19: Warning: Precondition possibly not established (Pre)
                left.add(n);
                        ^
Associated declaration is "TreeNode.java", line 9, col 8:
    //@ requires packed;
```

The nodes *left* and *right* must be packed!

Fixing the invariant

```
class TreeNode {
  int key, value;
  TreeNode left, right;
  //@ public ghost boolean packed = false;

  /*@ invariant packed ==> (left != null ==>
                         left.packed && left.key <= key); @*/
  /*@ invariant packed ==> (right != null ==>
                         right.packed && right.key >= key); @*/

  //@ requires packed;
  //@ ensures packed;
  public void add(/*@non_null@*/ TreeNode n) {
    ...
  }
}
```

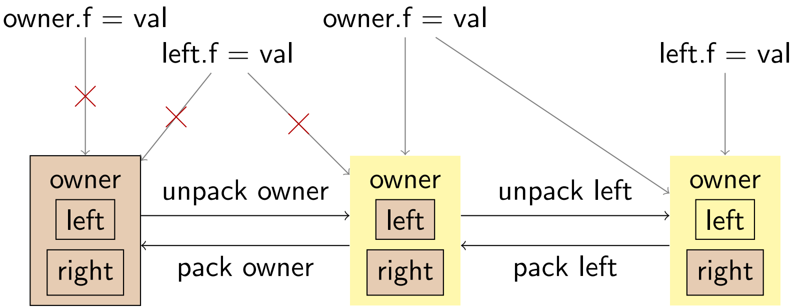
Adding Ownership

There are still problems:

- The invariant also depends on fields of *left* and *right*.
  In particular the *left.key* and *left.packed*.
- Can `unpack this` violate the invariant of another TreeNode?
- How can we exclude undesired sharing,
  e.g., *left* == `this` or *left* == *n*?

Solution: Use the ownership principle

Ownership and pack/unpack



owner.packed == `true`	*owner.packed* == `false`	*owner.packed* == `false`
left.packed == `true`	*left.packed* == `true`	*left.packed* == `false`

- The owner must be unpacked before an owned object can be unpacked.
- The invariant of owner may depend on owned objects.

Ownership And pack/unpack

How does pack/unpack work with ownership?

- To modify an object, you must `unpack` it first.
- To `unpack` an object, you must `unpack` the owner.
- To `pack` the owner again, its invariant must hold.

`unpack` *obj* is an abbreviation for:

```
assert(obj.packed);
assert(obj.owner == null || !obj.owner.packed);
set obj.packed = false;
```

`pack` *obj* ensures that its owned classes are packed.

```
assert(!obj.packed);
assert(left != null ==> (left.owner == this && left.packed));
assert(right != null ==> (right.owner == this && right.packed));
assert(/* other invariants of obj holds*/);
set obj.packed = true;
```

Adding Ownership

```
class TreeNode {
  int key, value;
  TreeNode left, right;
  //@ public ghost boolean packed = false;

  /*@ invariant packed ==> (left != null ==>
          left.owner == this && left.packed && left.key <= key); @*/
  /*@ invariant packed ==> (right != null ==>
          right.owner == this && right.packed && right.key >= key); @*/

  //@ requires packed && n.packed && n.owner == null;
  //@ ensures packed;
  public void add(/*@non_null@*/ TreeNode n) {
    ...
  }
}
```

Ownership vs. Friendship

The ownership discipline has a few restrictions.

- An object invariant can only depend on fields of owned objects.
- An object can have at most one owner.
- A field may only be changed by the owner, or if the owner is unpacked.

Sometimes too restrictive!

Friendship offers another way to depend on other objects:

- An invariant can also depend on fields of granters.
- The class must define update guards for all fields it depends on.
- A granter object has a list of friends that depend on fields.
- A field may be changed if the update guards of all friends holds.

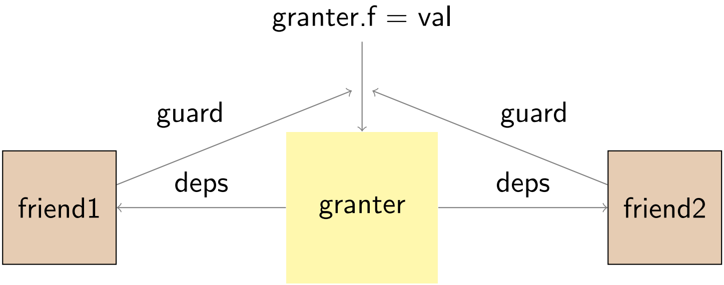
Friendship

Friendship is not symmetric. The allies are:

- Granter G that gives rights to depend on a field.
- Friend C whose invariant depends on a field.

Every class that changes a field of G has to check the friend's update condition.

Friendship and field accesses



- Friend's invariant can depend on granted fields.
- Access to granted fields is checked against update guards.
- A granter can have many friends.
- All current friends must be checked.
- The friend objects can be packed or unpacked.

Friendship Example

```
class Object {
  /*@ spec_public @*/ int hashCode;
  //@ friend Map reads hashCode;
  //@ ghost JMLObjectSet deps;
}

class Map {
  JMLObjectSet buckets[];
  /*@ invariant
      \forall int i ; 0 <= i && i < buckets.length;
        (\forall Object o; buckets[i].has(o); o.deps.has(this) &&
             Math.abs(o.hashCode % buckets.length) == i); @*/

  /*@ guard obj.hashCode := val by
        val % buckets.length == obj.hashCode % buckets.length; @*/
}
```

Update Guard and Invariant

```
class FriendClass {
  //@ invariant friendInvariant(granter.field)
  //@ guard granter.field := val by updateGuardForField(granter, val);
}
```

The update guard must guarantee that the invariant is not invalidated:

```
friends.packed && friendInvariant(granter.field)
  && updateGuardForField(granter, val) ==> friendInvariant(val)
```

What May Appear in an Invariant

Only the following field accesses are allowed in an invariant:

- `this.`*field* for all fields.
- *x.field* if it appears in a subformula:
  `\forall Object x ; x.owner == this ==> ...`
- *object.field* if `object != null && object.owner == this` can be proven.
- *x.field* if it appears in a subformula:
  `\forall Object x ; x.deps.has(this) ==> ...`
- *object.field* if `object != null && object.deps.has(this)` can be proven.

Why Is This Sound?

A field access *obj.f=val* only affects invariants of

- *obj*,
- *obj.owner* if it is not null,
- and the objects in *obj.deps*.

obj and *obj.owner* must be unpacked if field is accessed. Thus their invariants need not to hold afterwards.

For the objects in *obj.deps* the update guard must hold. Therefore, the invariant holds also with the new value *val* for *obj.f*.