The University of Iowa

22c181: Formal Methods in Software Engineering

Lecture 19: Checking Properties of Java Code

Simple Example

- We'll go through the Bag.java example from the manual
- Illustrates
  - basic checks performed on unannotated code
  - Addition of assumptions
  - Addition of preconditions

```
class Bag {
  int[] a;
  int n;

  Bag(int[] input) {
    n = input.length;
    a = new int[n];
    System.arraycopy(input, 0, a, 0, n);
  }
```

```
int extractMin() {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for (int i = 1; i <= n; i++) {
      if (a[i] < m) {
        mindex = i;
        m = a[i];
      }
    }
    n--;
    a[mindex] = a[n];
    return m;
  }
}
```

Running ESC/Java

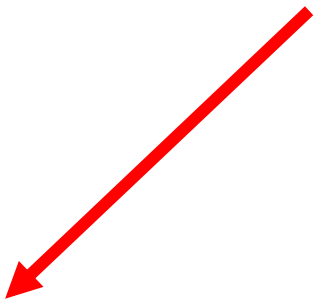
```
prompt>escjava -quiet Bag.java
Bag.java:6: Warning: Possible null dereference (Null)
    n = input.length;
              ^
Bag.java:15: Warning: Possible null dereference (Null)
      if (a[i] < m) {
            ^
Execution trace information:
    Reached top of loop after 0 iterations in
  "Bag.java", line 14, col 4.

2 warnings
```

```
class Bag {
  int[] a;

  int n;

  Bag(int[] input) {
    n = input.length;
    a = new int[n];
    System.arraycopy(input,0,a,0,n);
  }
```



```
class Bag {
  int[] a;
  int n;

  //@ requires input != null;
  Bag(int[] input) {
    n = input.length;
    a = new int[n];
    System.arraycopy(input,0,a,0,n);
  }
```

Running ESC/Java

```
prompt>escjava -quiet Bag.java
Bag.java:15: Warning: Possible null
  dereference (Null)
      if (a[i] < m) {
           ^
Execution trace information:
    Reached top of loop after 0 iterations
  in "Bag.java", line 15, col 4.

2 warnings
```

```
int extractMin() {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for (int i = 1; i <= n; i++) {
      if (a[i] < m) {
        mindex = i;
        m = a[i];
      }
    n--;
    a[mindex] = a[n];
    return m;
  }
```

Null?

Modular Checking

- Analysis of `extractMin` doesn't know that the constructor always ensures that `a` is not null
- It also doesn't know whether the constructor will be called before `extractMin` (although it could)
- Specify this property of `a`

```
class Bag {
  /*@ non_null */ int[] a;
  int n;

  //@ requires input != null;
  Bag(int[] input) {
    n = input.length;
    a = new int[n];
    System.arraycopy(input, 0, a, 0, n);
  }
```

Running ESC/Java

```
prompt>escjava -quiet Bag.java
Bag.java:16: Warning: Array index possibly too
  large (IndexTooBig)
        if (a[i] < m) {
              ^
Execution trace information:
    Reached top of loop after 0 iterations in
  "Bag.java", line 15, col 4.

2 warnings
```

```
int extractMin() {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for (int i = 1; i <= n; i++) {
      if (a[i] < m) {
        mindex = i;
        m = a[i];
      }
    }
    n--;
    a[mindex] = a[n];
    return m;
  }
}
```

i >= n = a.length?

```
int extractMin() {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for (int i = 0; i < n; i++) {
      if (a[i] < m) {
        mindex = i;
        m = a[i];
      }
    }
    n--;
    a[mindex] = a[n];
    return m;
  }
}
```

Running ESC/Java

```
prompt>escjava -quiet Bag.java
Bag.java:16: Warning: Array index possibly
  too large (IndexTooBig)
      if (a[i] < m) {
            ^
Execution trace information:
    Reached top of loop after 0 iterations in
  "Bag.java", line 15, col 4.

2 warnings
```

Different from manual

Problem is Modularity

- Analysis of extractMin doesn't see that all a fields have bounds of n and n only decreases after the allocation
- Several options
  - Local assumption, precondition
- Global property of field so we add

```
invariant 0<=n && n<=a.length;
```

```
class Bag {
  /*@ non_null */ int[] a;
  int n;
  //@ invariant 0<=n && n<=a.length;

  //@ requires input != null;
  Bag(int[] input) {
    n = input.length;
    a = new int[n];
    System.arraycopy(input, 0, a, 0, n);
  }
```

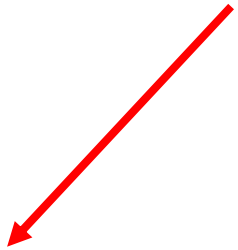
Running ESC/Java

```
prompt>escjava -quiet Bag.java
Bag.java:23: Warning: Possible negative
  array index (IndexNegative)
      a[mindex] = a[n]
                  ^
Execution trace information:
    Reached top of loop after 0 iterations
  in "Bag.java", line 16, col 4.

2 warnings
```

```
int extractMin() {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for (int i = 0; i < n; i++) {
      if (a[i] < m) {
        mindex = i;
        m = a[i];
      }
    }
    n--;
    a[mindex] = a[n];
    return m;
  }
}
```

Non-negative?



What about the Invariant?

- It constrains the value of n to be non-negative
- As in JML, invariants are enforced at method boundaries (call and return)
- If we call this method with n==0 that satisfies the invariant
  - but it will result in the index exception

Possible Solutions

- Add a special case to avoid decrementing `n` below `0`
- Require that `n` be positive on entry to the `extractMin` method
- We'll try both

```
int extractMin() {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for (int i = 0; i < n; i++) {
      if (a[i] < m) {
        mindex = i;
        m = a[i];
      }
    }
    if (n>0) {
      n--;
      a[mindex] = a[n];
    }
    return m;
  }
}
```

```
//@ requires n>=1;
int extractMin() {
    int m = Integer.MAX_VALUE;
    int mindex = 0;
    for (int i = 0; i < n; i++) {
      if (a[i] < m) {
        mindex = i;
        m = a[i];
      }
    }
    n--;
    a[mindex] = a[n];
    return m;
  }
}
```

Running ESC/Java

```
prompt>escjava Bag.java
ESC/Java version 1.2.2, 12 October 2000

Bag ...

Bag: Bag(int[]) ...
    [0.701 s]  passed

Bag: extractMin() ...
    [0.2 s]  passed
  [3.435 s total]
```

Exercise

- What additional specifications can you think of writing?
- Add them and try to check them

Catalog of Errors

- ESC Java reports a variety of errors
- Builtin JVM checks
  - Cast, Deadlock, NegSize, IndexNegative, IndexTooBig, ArrayStore, Null, Uninit, ZeroDiv
- Explicit annotation violations
  - Assert, Invariant, LoopInv, NonNull, NonNullInit, Pre, Post, Reachable
  - Exception [throw not in exsures]

Uniqueness Constraints

- When ESC/Java analyzes a method body it assumes that other Java statements may be executing simultaneously
- This can lead to some surprises for user's who take a purely sequential viewpoint
- Options
  - Assume there is no concurrency (very unsafe)
  - Analyze program for interference
  - Let programmers specify non-interference related properties

Ownership

- If an object, o, has a reference field that points to object, p, and p's reference is not stored elsewhere in the program then we say that o "owns" p
- This is a special form of a uniqueness constraint
- ESC/Java supports this via the
  - Implicit "owner" attribute of each object
  - "set" command to establish ownership

Consider the following example

```
class ObjStack {
   Object [] a;
   int n;
   //@ invariant (\forall int i; n <= i & i < a.length ==> a[i] == null);
   ObjStack(int l) {
      n = 0;
      a = new Object[l];
    }
    void Push(Object o) {
      a[n++] = o;
    }
    Object Pop() {
      Object o = a[--n];
      a[n] = null;
      return o;
    }
}
```

escjava -suggest

```
ESC/Java version 1.2.4, 27 September 2001

ObjStack ...

ObjStack: ObjStack(int) ...
------------------------------------------------------------------------
objstack.java:12: Warning: Possible attempt to allocate array of
    negative length (NegSize)
      a = new Object[l];
                     ^
Suggestion [12,20]: perhaps declare constructor 'ObjStack' at 10,4 in
    objstack.java with 'requires 0 <= l;'
------------------------------------------------------------------------
    [0.36 s]  failed
...
```

Consider the following example

```
class ObjStack {
    /*@ non_null */ Object [] a;
    //@ invariant \elemtype(\typeof(a)) == \type(Object);
    int n;
    //@ invariant (\forall int i; n <= i & i < a.length ==> a[i] == null);

    // requires l > 0;
    ObjStack() {
      n = 0;
      a = new Object[l];
    }

    void Push(Object o) {
      a[n++] = o;
    }

    Object Pop() {
      Object o = a[--n];
      a[n] = null;
      return o;
    }
}
```

escjava -suggest

ObjStack: Pop() ...

---

objstack.java:22: Warning: Possible negative array index (IndexNegative)

```
    Object o = a[--n];
               ^
```

Suggestion [22,18]: none <big expression>

In this case we can look to the arguments of the methods and define checkable annotations constraining n's range

Consider the following example

```
class ObjStack {
    /*@ non_null */ Object [] a;
    //@ invariant \elemtype(\typeof(a)) == \type(Object);
    int n;  //@ invariant 0 <= n & n <= a.length;
    //@ invariant (\forall int i; n <= i & i < a.length ==> a[i] == null);

    //@ requires l > 0;
    ObjStack() {
      n = 0;
      a = new Object[l];
   }

    //@ requires n < a.length;
    void Push(Object o) {
      a[n++] = o;
    }

    //@ requires n > 0;
    Object Pop() {
      Object o = a[--n];
      a[n] = null;
      return o;
    }
}
```

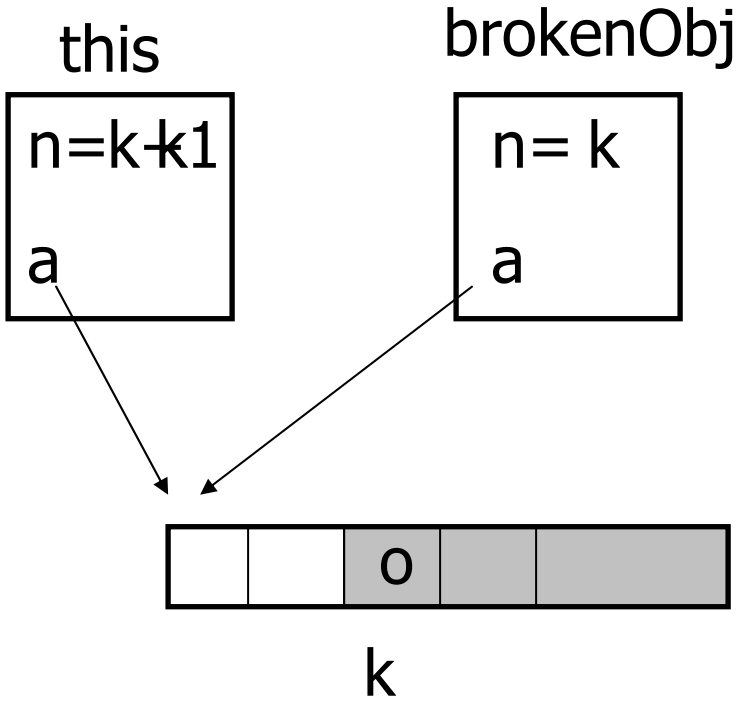
escjava -suggest

```
ObjStack: Pop() ...
ObjStack: Push(java.lang.Object) ...
------------------------------------------------------------------------
objstack.java:18: Warning: Possible violation of object invariant (Invariant)
    }
    ^
Associated declaration is "objstack.java", line 6, col 8:
    //@ invariant (\forall int i; n <= i & i < a.length ==> a[i] == nu ...
        ^
Possibly relevant items from the counterexample context:
  (0 <= (brokenObj<2>).(n:17.8))
  ((brokenObj<2>).(n:17.8) <= i:6.31)
  (vAllocTime(brokenObj<2>) < alloc)
  isAllocated(brokenObj<2> alloc)
  typeof(brokenObj<2>) <: T_java.lang.Object
  (brokenObj<2>).(a@pre:3.30) == tmp0!a:17.6
  typeof(brokenObj<2>) <: T_ObjStack
  classDown(T_java.lang.Object typeof(brokenObj<2>)) == T_ObjStack
  (brokenObj<2>).(n@pre:5.8) == (brokenObj<2>).(n:17.8)
  typeof((brokenObj<2>).(n:17.8)) <: T_int
  typeof(brokenObj<2>) <: T_ObjStack
  brokenObj<2> != this
  brokenObj<2> != null
(brokenObj* refers to the object for which the invariant is broken.)

Suggestion [18,4]: perhaps declare instance invariant 'invariant this.a.owner ==
 this;' in dass ObjStack (near associated declaration at "objstack.java", line
6, col 8)
------------------------------------------------------------------------
    [0.24 s]  failed
```

What's happening here

- ESC/Java doesn't know that instances of ObjStack "own" their array's (a)
- It assumes there may be two ObjStacks



this.a[this.n++] = o;

broken.a[k] != null

Consider the following example

```
//@ invariant this.a.owner == this;
class ObjStack {
    /*@ non_null */ Object [] a;
    //@ invariant \elemtype(\typeof(a)) == \type(Object);
    int n;  //@ invariant 0 <= n & n <= a.length;
    //@ invariant (\forall int i; n <= i & i < a.length ==> a[i] == null);

    // requires l > 0;
    ObjStack() {
      n = 0;
      a = new Object[l];
      //@ set a.owner = this;
    }

    //@ requires n < a.length;
    void Push(Object o) {
      a[n++] = o;
    }

    //@ requires n > 0;
    Object Pop() {
      Object o = a[--n];
      a[n] = null;
      return o;
    }
}
```

escjava -suggest

```
ESC/Java version 1.2.4, 27 September 2001

ObjStack ...

ObjStack: ObjStack(int) ...
    [0.301 s]  passed

ObjStack: Push(java.lang.Object) ...
    [0.1 s]  passed

ObjStack: Pop() ...
    [0.11 s]  passed
  [0.961 s total]
```

Interface Specifications

- Break visibility for purpose of spec
  - `spec_public f` [private field f]
  - Makes f visible at interface
  - Workaround for lack of calls in exprs
- Introduce specification only data
  - `ghost` [declare model field]
  - `set` [assign to model field]
- Example: Interface spec of queue

Example

```
public class Queue {
 //@ ghost public int size;
 //@ invariant size >= 0;
 //@ ghost public \TYPE elementType;
 //@ ghost public boolean canHoldNull;

 //@ ensures elementType == \type(Object);
 //@ ensures canHoldNull;
 //@ ensures size == 0;
 public Queue();
 …
```

- `elementType` records base type for all queue elements
- `canHoldNull` determines whether nulls can be inserted

Example cont.

```
…
/*@ requires \typeof(e) <: elementType |
              (e == null & canHoldNull);
*/
//@ modifies size;
//@ ensures size == \old(size) + 1;
public void enqueue(Object e);

//@ ensures \result == (size == 0);
public boolean isEmpty();
…
```

Example cont.

```
…
//@ requires size >= 1;
//@ modifies size;
/*@ ensures
    \typeof(\result) <: elementType |
    (\result == null & canHoldNull);
*/

//@ ensures size == \old(size) - 1;
public Object dequeue();
}
```

Subtypes of Queue

- Are obliged to satisfy pre/post conditions mentioned of supertype
- The representation of specification fields must be encoded explicitly in subtypes
  - Insert set pragmas for appropriate ghost variables at appropriate points in the implementation

```
//@ set size = size+1;
theVector.addElement(o);
```

Clients of Queue

- Can enable checking of pre conditions and assumption of post-conditions by setting ghost fields

```
Queue q = new SomeQueue();
//@ set q.elementType = \type(T);
//@ set q.canHoldNull = false;
```

Exercise

- Take your favorite implementation of a queue and implement it as a subtype of this interface
- Figure out how to map your fields onto the ghost fields
- Set elementType and canHoldNull
- Check to see if your implementation satisfies the spec