ESC/Java2 Warnings

David Cok, Joe Kiniry, and Erik Poll

Eastman Kodak Company, University College Dublin,

and Radboud University Nijmegen

Types of ESC/Java2 warnings

ESC/Java2 warnings fall into various categories:

- warnings about possible runtime exceptions: (Cast, Null, NegSize, IndexTooBig, IndexNegative, ZeroDiv, ArrayStore)

- **These are the most common runtime exceptions caused by coding problems (that is, not by explicitly throwing an exception)**
- **They do not include nearly all of the possible runtime exceptions**
- **Most of the others are explicitly thrown by various library methods**

Cast Warning

The Cast warning occurs when ESC/Java2 cannot verify that a ClassCastException will not be thrown:

```
public class CastWarning {
  public void m(Object o) {
    String s = (String)o;
  }
}
```

results in

```
-------------------------------------------------------------------------
CastWarning.java:3: Warning: Possible type cast error (Cast)
    String s = (String)o;
               ^

-------------------------------------------------------------------------
```

But this is OK:

```
public class CastWarningOK {
  public void m(Object o) {
    if (o instanceof String) { String s = (String)o; }
  }
}
```

Cast Warning

So is this:

```
public class CastWarningOK2 {
  //@ requires o instanceof String;
  public void m(Object o) {
    String s = (String)o;
  }
}
```

Null Warning

The Null warning occurs when ESC/Java2 cannot verify that a NullPointerException will not be thrown:

```
public class NullWarning {
  public void m(Object o) {
    int i = o.hashCode();
  }
}
```

results in

```
-------------------------------------------------------------------------------
NullWarning.java:3: Warning: Possible null dereference (Null)
    int i = o.hashCode();
            ^

-------------------------------------------------------------------------------
```

But this is OK:

```
public class NullWarningOK {
  public void m(/*@ non_null */ Object o) {
    int i = o.hashCode();
  }
}
```

ArrayStore Warning

The ArrayStore warning occurs when ESC/Java2 cannot verify that the assignment of an object to an array element will not result in an ArrayStoreException:

```
public class ArrayStoreWarning {
  public void m(Object o) {
    Object[] s = new String[10];
    s[0] = o;
  }
}
```

results in

```
-------------------------------------------------------------------
ArrayStoreWarning.java:4: Warning: Type of right-hand side possibly not
a subtype of array element type (ArrayStore)
    s[0] = o;
         ^

-------------------------------------------------------------------
```

But this is OK:

```
public class ArrayStoreWarningOK {
  public void m(Object o) {
    Object[] s = new String[10];
    if (o instanceof String) s[0] = o;
  }
}
```

ZeroDiv, index Warnings

- **ZeroDiv - issued when a denominator (integer division) may be 0**
- **NegSize - issued when the array size in an array allocation expression may be negative**
- **IndexNegative - issued when an array index may be negative**
- **IndexTooBig - issued when an array index may be greater than or equal to the array length**

```
public class Index {
  void m() {
    int i = 0;
    int j = 8/i;  // Causes a ZeroDiv warning
    Object[] oo = new Object[i-1]; // NegSize warning
    oo = new Object[10];
    i = oo[-1].hashCode(); // IndexNegative warning
    i = oo[20].hashCode(); // IndexTooBig warning
  }
}
```

Types of ESC/Java2 warnings

ESC/Java2 warnings fall into various categories:

- warnings about possible runtime exceptions: (Cast, Null, NegSize, IndexTooBig, IndexNegative, ZeroDiv, ArrayStore)

- warnings about possible method specification violations: (Precondition, Postcondition, Modifies)

- **These are all caused by violations of explicit user-written method specifications**

Pre, Post warnings

These warnings occur in response to user-written preconditions (requires), postconditions (ensures, signals), or assert statements.

```
public class PrePost {
  //@ requires i >= 0;
  //@ ensures \result == i;
  public int m(int i);

  //@ ensures \result > 0;
  public int mm() {
    int j = m(-1); // Pre warning - argument must be >= 0
  }

  //@ ensures \result > 0;
  public int mmm() {
    int j = m(0);
    return j;
  }  // Post warning - result is 0 and should be > 0
}
```

Frame conditions

- **To reason (modularly) about a call of a method, one must know what that method might modify: this is specified by**
  - **assignable clauses**

    ```
    //@ assignable x, o.x, this.*, o.*, a[*], a[3], a[4..5];
    ```
  - **modifies clauses (a synonym)**
  - **pure modifier**

    ```
    //@ pure
    public int getX() { return x; }
    ```
- **Assignable clauses state what fields may be assigned within a method - this is the set of what might be modified**
- **The default assignable clause is assignable \everything; (but it is better to be explicit because \everything; is not fully implemented and ESC/Java2 can reason better with more explicit frame conditions)**
- **A pure method is assignable \nothing;**

Frame conditions

- A Modifies warning indicates an attempt to assign to an object field that is not in a modifies clause
- Note: Some violations of modifies clauses can be detected at typecheck time.
- Note also: Handling of frame conditions is an active area of research.

Modifies warnings

For example, in

```
public class ModifiesWarning {
  int i;

  //@ assignable i;
  void m(/*@ non_null */ ModifiesWarning o) {
    i = 1;
    o.i = 2; // Modifies warning
  }
}
```

we don't know if o equals this; since only this.i may be assigned, ESC/Java2 produces

```
------------------------------------------------------------------------
ModifiesWarning.java:7: Warning: Possible violation of modifies clause (Mo
    o.i = 2; // Modifies warning
    ^
Associated declaration is "ModifiesWarning.java", line 4, col 6:
  //@ assignable i;
      ^
------------------------------------------------------------------------
```

Types of ESC/Java2 warnings

ESC/Java2 warnings fall into various categories:

- **warnings about possible runtime exceptions: (Cast, Null, NegSize, IndexTooBig, IndexNegative, ZeroDiv, ArrayStore)**
- **warnings about possible specification violations: (Precondition, Postcondition, Modifies)**
- **non null violations (NonNull, NonNullInit)**
  - **These warnings relate to explicit non_null field or parameter specifications**

NonNullInit warning

Class fields declared non_null must be initialized to values that are not null in each constructor, else a NonNullInit warning is produced.

```
public class NonNullInit {
  /*@ non_null */ Object o;

  public NonNullInit() { }
}
```

produces

```
------------------------------------------------------------------------
NonNullInit.java:4: Warning: Field declared non_null possibly
not initialized (NonNullInit)
  public NonNullInit() { }
                         ^
Associated declaration is "NonNullInit.java", line 2, col 6:
  /*@ non_null */ Object o;
      ^
------------------------------------------------------------------------
```

NonNull warning

A NonNull warning is produced whenever an assignment is made to a field or variable that has been declared non_null but ESC/Java2 cannot determine that the right-hand-side value is not null.

```
public class NonNull {
  /*@ non_null */ Object o;

  public void m(Object oo) { o = oo; } // NonNull warning
}
```

produces

```
------------------------------------------------------------------------
NonNull.java:4: Warning: Possible assignment of null to variable
declared non_null (NonNull)
  public void m(Object oo) { o = oo; } // NonNull warning
                             ^

Associated declaration is "NonNull.java", line 2, col 6:
  /*@ non_null */ Object o;
      ^

------------------------------------------------------------------------
```

NonNull warning

But this is OK

```
public class NonNull {
  /*@ non_null */ Object o;
  public void m(/*@ non_null */ Object oo) { o = oo; }
}
```

So is this

```
public class NonNull {
  /*@ non_null */ Object o;
  public void m(Object oo) {
    if (oo != null) o = oo;
  }
}
```

So is this

```
public class NonNull {
  /*@ non_null */ Object o;
  public void m() {
    o = new Object();
  }
}
```

non_null can be applied to

- a field
- a formal parameter
- a return value
- a local variable
- ghost and model variables

Types of ESC/Java2 warnings

ESC/Java2 warnings fall into various categories:

- warnings about possible runtime exceptions: (Cast, Null, NegSize, IndexTooBig, IndexNegative, ZeroDiv, ArrayStore)
- warnings about possible method specification violations: (Precondition, Postcondition, Modifies)
- non null violations (NonNull, NonNullInit)
- loop and flow specifications (Assert, Reachable, LoopInv, DecreasesBound)
  - These are caused by violations of specifications in a routine body

Body assertions

- **Assert: warning occurs when an assert annotation may not be satisfied**
- **Reachable: not in JML, only in ESC/Java2; occurs with the //@ unreachable; annotation, which is equivalent to //@ assert false;**

Example:

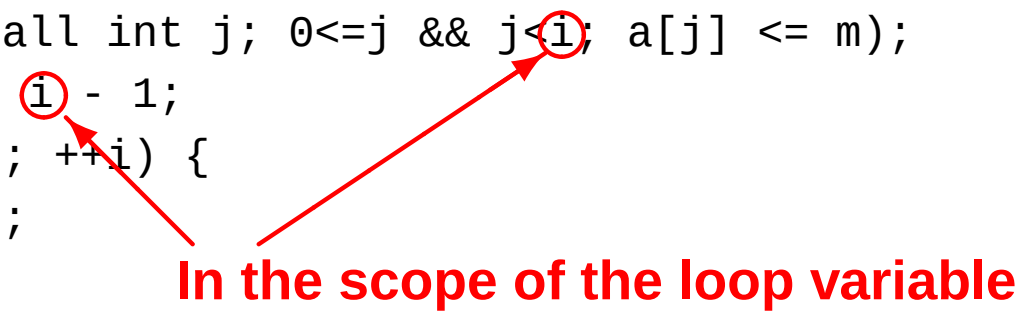
```
public class AssertWarning {
  //@ requires i >= 0;
  public void m(int i) {
    //@ assert i >= 0; // OK
    --i;
    //@ assert i >= 0; // FAILS
  }
  public void n(int i) {
    switch (i) {
      case 0,1,2: break;
      default:   //@ unreachable; // FAILS
    }
  }
}
```

Loop assertions

- A loop_invariant assertion just before a loop asserts a predicate that is true prior to each iteration and at the termination of the loop (or a LoopInv warning is issued).
- A decreases assertion just before a loop asserts a (int) quantity that is non-negative and decreases with each iteration (or a DecreasesBound warning is issued).
- Caution: Loops are checked by unrolling a few times.

Example:

```
public class LoopInvWarning {
  public int max(/*@ non_null */ int[] a) {
    int m;
    //@ loop_invariant (\forall int j; 0<=j && j<i; a[j] <= m);
    //@ decreases a.length - i - 1;
    for (int i=0; i<a.length; ++i) {
      if (m < a[i]) m = a[i];
    }
    return m;
  }
}
```



Types of ESC/Java2 warnings

ESC/Java2 warnings fall into various categories:

- warnings about possible runtime exceptions: (Cast, Null, NegSize, IndexTooBig, IndexNegative, ZeroDiv, ArrayStore)
- warnings about possible method specification violations: (Precondition, Postcondition, Modifies)
- non null violations (NonNull, NonNullInit)
- loop and flow specifications (Assert, Reachable, LoopInv, DecreasesBound)
- **warnings about possible class specification violations: (Invariant, Constraint, Initially)**

class invariant warnings

Invariant and constraint clauses generate additional postconditions for every method. If they do not hold, appropriate warnings are generated:

```
public class Invariant {
  public int i,j;
  //@ invariant i > 0;
  //@ constraint j > \old(j);

  public void m() {
    i = -1; // will provoke an Invariant error
    j = j-1; // will provoke a Constraint error
  }
}
```

Initially warning

An initially clause is a postcondition for every constructor:

```
public class Initially {

  public int i; //@ initially i == 1;

  public Initially() { } // does not set i - Initially warning
}
```

produces

```
------------------------------------------------------------------------
Initially.java:5: Warning: Possible violation of initially condition
at constructor exit (Initially)
  public Initially() { } // does not set i - Initially warning
                       ^
Associated declaration is "Initially.java", line 3, col 20:
  public int i; //@ initially i == 1;
                    ^
------------------------------------------------------------------------
```

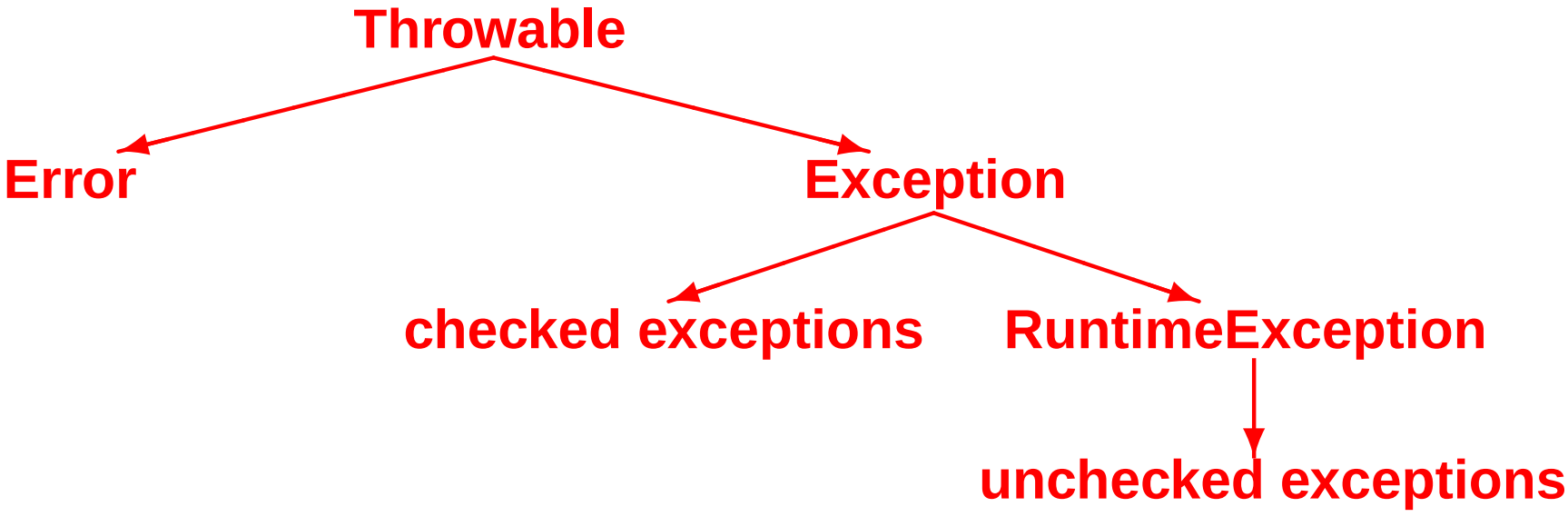
Types of ESC/Java2 warnings

ESC/Java2 warnings fall into various categories:

- warnings about possible runtime exceptions: (Cast, Null, NegSize, IndexTooBig, IndexNegative, ZeroDiv, ArrayStore)
- warnings about possible method specification violations: (Precondition, Postcondition, Modifies)
- non null violations (NonNull, NonNullInit)
- loop and flow specifications (Assert, Reachable, LoopInv, DecreasesBound)
- warnings about possible class specification violations: (Invariant, Constraint, Initially)
- **exception problems (Exception)**
  - **These warnings are caused by undeclared exceptions**

Exceptions - Errors

- Java Errors (e.g. OutOfMemoryError) can be thrown at any time
  - No declarations are needed in throws clauses
  - No semantics are implied by JML
  - No checking is performed by ESC/Java2



Checked Exceptions

- Java checked exceptions (e.g. FileNotFoundException) are Exceptions that are not RuntimeExceptions:
  - Declarations of exceptions mentioned in the body are required in throws clauses
  - ESC/Java2 checks during typechecking that throws declarations are correct (as a Java compiler does)
  - Typically specified in signals clauses in JML
  - ESC/Java2 checks via reasoning that signals conditions hold
  - Default specification is that *declared* exceptions may occur: signals (Exception) true;
  - ESC/Java2 presumes that checked exceptions not declared in a throws clause will not occur.

Unchecked Exceptions

- **Java unchecked exceptions (e.g. NoSuchElementException) are RuntimeExceptions:**
  - **Java does not require these to be declared in throws clauses**
  - **ESC/Java2 is stricter than Java - it will issue an Exception warning if an unchecked exception might be *explicitly* thrown but is not declared in a throws declaration**
  - **Caution: currently ESC/Java2 will assume that an undeclared unchecked exception will not be thrown, even if it is specified in a signals clause -**
    Declare all unchecked exceptions that might be thrown!
    (e.g. especially when there is no implementation to check).

So this

Exception warning

```
public class Ex {
  public void m(Object o) {
    if (!(o instanceof String)) throw new ClassCastException();
  }
}
```

produces

```
--------------------------------------------------------------------
Ex.java:4: Warning: Possible unexpected exception (Exception)
  }
  ^
Execution trace information:
    Executed then branch in "Ex.java", line 3, col 32.
    Executed throw in "Ex.java", line 3, col 32.

--------------------------------------------------------------------
```

Turn off this warning by

- declaring the exception in a throws clause
- using //@ nowarn Exception; on the offending line
- using a -nowarn Exception command-line option

Types of ESC/Java2 warnings

ESC/Java2 warnings fall into various categories:

- warnings about possible runtime exceptions: (Cast, Null, NegSize, IndexTooBig, IndexNegative, ZeroDiv, ArrayStore)
- warnings about possible method specification violations: (Precondition, Postcondition, Modifies)
- non null violations (NonNull, NonNullInit)
- loop and flow specifications (Assert, Reachable, LoopInv, DecreasesBound)
- warnings about possible class specification violations: (Invariant, Constraint, Initially)
- exception problems (Exception)
- **multithreading (Race, RaceAllNull, Deadlock)**
  - **These warnings are caused by potential problems with monitors**
  - **Multithreading problems caused by the absence of any synchronization are not detected.**

Race conditions

- Java defines monitors associated with any object and allows critical sections to be guarded by synchronization statements.
- ESC/Java permits fields to be declared as monitored by one or more objects.
- To read a monitored field, at least one monitor must be held (or a Race warning is issued).
- To write a monitored field, all non-null monitors must be held (or a Race warning is issued).
- To write a monitored field, at least one of its monitors must be non-null (or a RaceAllNull warning is issued).

Race warnings

For example,

```
public class RaceWarning {
  //@ monitored
  int i;

  void m() {
    i = 0; // should have a synchronization guard
  }
}
```

produces

```
----------------------------------------------------------------------
RaceWarning.java:6: Warning: Possible race condition (Race)
    i = 0; // should have a synchronization guard
      ^
Associated declaration is "RaceWarning.java", line 2, col 6:
  //@ monitored
      ^
----------------------------------------------------------------------
```

Deadlocks

- Deadlocks occur when each thread of a group of threads needs monitors held by another thread in the group.
- One way to avoid this is to always acquire monitors in a specific order.
- This requires
  - the user state a (partial) order for monitors (typically using an axiom)
  - that it be clear before acquiring a monitor that the thread does not hold any ‘larger’ monitors (typically a precondition)
- Checking for Deadlock warnings is off by default but can be turned on with **-warn Deadlock**.

Deadlock warnings

For example:

```
public class DeadlockWarning {
  /*@ non_null */ final static Object o = new Object();
  /*@ non_null */ final static Object oo = new Object();

  //@ axiom o < oo;

  //@ requires \max(\lockset) < o;
  public void m() {
      synchronized(o) { synchronized(oo) { }}
  }

  //@ requires \max(\lockset) < o;
  public void mm() {
     synchronized(oo) { synchronized(o) { }} // Deadlock warning
  }
}
```

Types of ESC/Java2 warnings

ESC/Java2 warnings fall into various categories:

- warnings about possible runtime exceptions: (Cast, Null, NegSize, IndexTooBig, IndexNegative, ZeroDiv, ArrayStore)
- warnings about possible method specification violations: (Precondition, Postcondition, Modifies)
- non null violations (NonNull, NonNullInit)
- loop and flow specifications (Assert, Reachable, LoopInv, DecreasesBound)
- warnings about possible class specification violations: (Invariant, Constraint, Initially)
- exception problems (Exception)
- multithreading (Race, RaceAllNull, Deadlock)
- **a few others (OwnerNull, Uninit, Unreadable, Writable)**

Other warnings

- **Uninit: used with the uninitialized annotation**
- **OwnerNull: see the ESC/Java User Manual for a description**
- **Unreadable: occurs with the readable_if annotation on shared variables. [JML's change of syntax from readable_if to readable is not complete in ESC/Java2.]**
- **Writable: occurs with the writable_if annotation on shared variables. [JML's change of syntax from writable_if to writable is not complete in ESC/Java2.]**

trace information

For complicated bodies, the warning messages give some information about which if-then-else branches caused the warning:

```
public class Trace {
  //@ ensures \result > 0;
  int m(int i) {
    if (i == 0) return 1;
    if (i == 2) return 0;
    return 4;
  }
}
```

produces

```
Trace.java:8: Warning: Postcondition possibly not established (Post)
  }
  ^
Associated declaration is "Trace.java", line 2, col 6:
  //@ ensures \result > 0;
      ^
Execution trace information:
    Executed else branch in "Trace.java", line 4, col 4.
    Executed then branch in "Trace.java", line 5, col 16.
    Executed return in "Trace.java", line 5, col 16.
```

Counterexamples

- **Sometimes when a specification is found to be invalid, ESC/Java2 will produce a *counterexample context*.**
- **A full context will be produced with the -counterexample option**
- **These are difficult to read, but can give information about the reason for failure.**
- **They state formulae that the prover believes to be true; if there is something you think should not be true, that is a hint about the problem.**

- **Note also: Typically only one warning will be issued in a given run.**