CnC: Check 'n' Crash

Combining static checking and testing

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Goal: Generate good test cases

Testing in software development

(+) Widespread, for good reasons

(–) Expensive

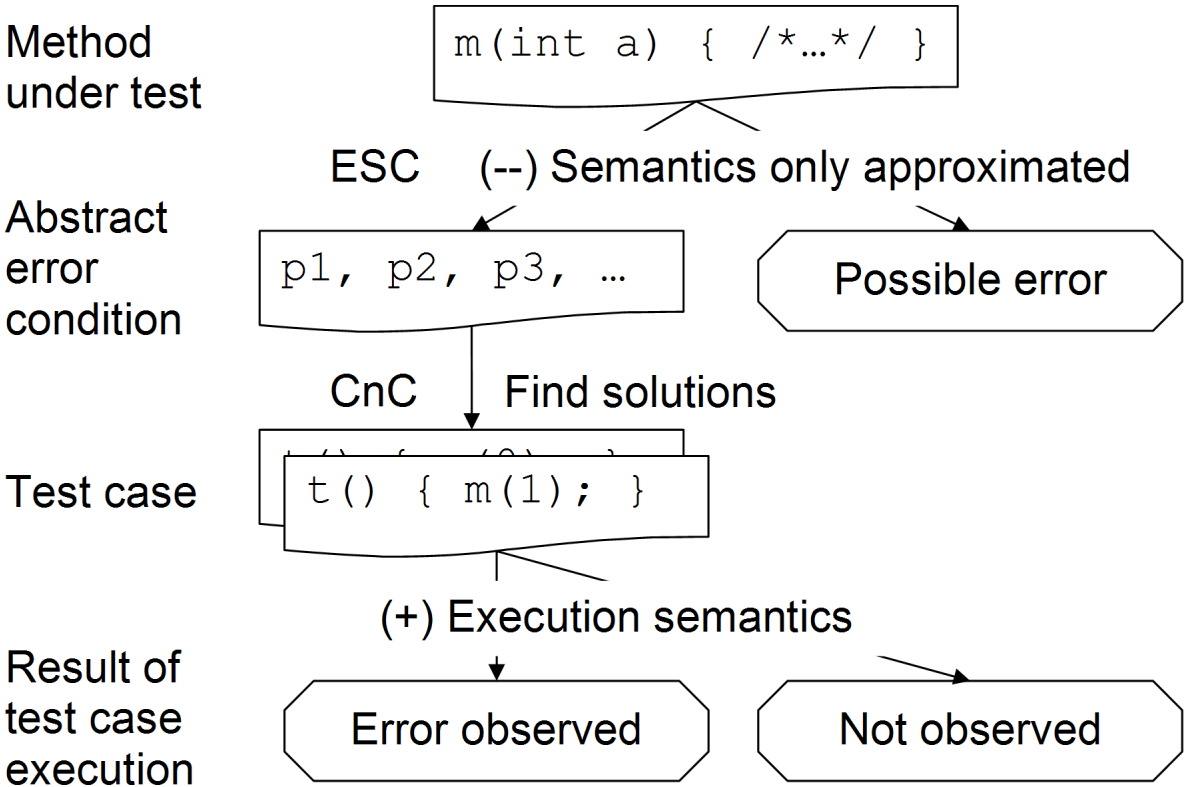
Automate as much as possible

Do not replace testing with full correctness proofs

But use proof techniques to automate testing

Generate tests that have a high probability of exposing errors

CnC: Check 'n' Crash



Outline

1. **JCrasher**: Our completely automatic robustness tester
   (–) Undirected: Black box
   (+) Generates and dynamically filters JUnit test cases
   (+) Precise: Execution semantics
2. **ESC**: Extended Static Checking [Flanagan, Leino, et al.]
   (+) Directed: White box
   (–) Abstract error conditions hard to understand
   (–) Spurious warnings: Java semantics only approximated
3. **Check 'n' Crash**: JCrasher testing directed by ESC/Java
   (+) Directed by ESC/Java
   (+) JUnit test cases for every abstract error condition
   (+) No spurious warnings: Filtered via test execution

JCrasher: Generate random test cases

Completely automatic

Predefined values, e.g.:
`int` ← `1`
`int` ← `0`
`A` ← `null`

Infer method signatures from code under test, e.g.:
`A` ← `(B,int)` from method `A B.m(int)`

Generate random JUnit test cases

Method parameters by recursively chained constructors

JCrasher: Example

`f(A,int)` is the method under test

Inferred method signatures via Java reflection:
`A` ← `null`
`A` ← `(B,int)` from method `A B.m(int)`
`B` ← `null`
`B` ← `()` from constructor `B()`
`int` ← `1`
`int` ← `0`

JCrasher can generate the following test cases:
`f(null,0)`
`f((new B()).m(0), 1)`
etc.

JCrasher: Monitor test execution

JUnit extension monitors execution of generated test cases

Filter runtime exceptions—crashes

Group similar reports together

Robustness heuristic

Some exceptions are mostly thrown by the Java runtime

Indicate abnormal termination of a Java language operation

Likely to be real bugs

E.g.: Public method under test attempts an illegal type cast
→ `ClassCastException`

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ESC/Java by Flanagan, Leino, et al.

We use ESC/Java 2 (supports Java 1.4 and JML)

Checks for potential invariant violations

Invariant: Precondition on entry, postcondition on exit

ESC knows pre- and postconditions of language operations (pointer dereference, class cast, array access, etc.)

ESC compiles each method in isolation:

Postcondition $\rightarrow$ assertion check appended to body

Call in body $\rightarrow$ check precondition, assume postcondition

Method body $\rightarrow$ its weakest precondition

ESC/Java

Weakest precondition `wp(method body, true)` = States from which execution terminates normally

Remaining states lead execution to an error: Violate some pre- or postcondition

ESC uses Simplify to derive abstract error conditions

We are interested in those that throw a runtime exception:

- Dereferencing null
- Illegal type cast
- Illegal array allocation or access
- Division by zero
- Violating explicit (JML) invariants

Drawbacks of ESC

Incomplete: Miss some errors (limited loop unrolling)

Imprecise = Unsound: Produces spurious error reports

Cases that cannot occur (Java semantics approximated)

Example: ESC/Java ignores implementation of called methods

```
public int get10() {return 10;}

public int meth(int p) {return p / get10();}
```

ESC warns of a division by zero in `meth`

Need to improve soundness

Flanagan et al. conclude in PLDI 2002:

> "[ESC/Java] has not reached the desired level of cost effectiveness. In particular, **users complain** about an annotation burden that is perceived to be heavy, and **about excessive warnings about non-bugs**, particularly on unannotated or partially-annotated programs."
>
> "[Additional] research on **reducing spurious warnings** and lowering the perceived annotation burden [..] **could add significant value** to the process of engineering software."

Our experience: Roughly half of ESC's warnings were spurious (Spurious = cannot occur in any execution)

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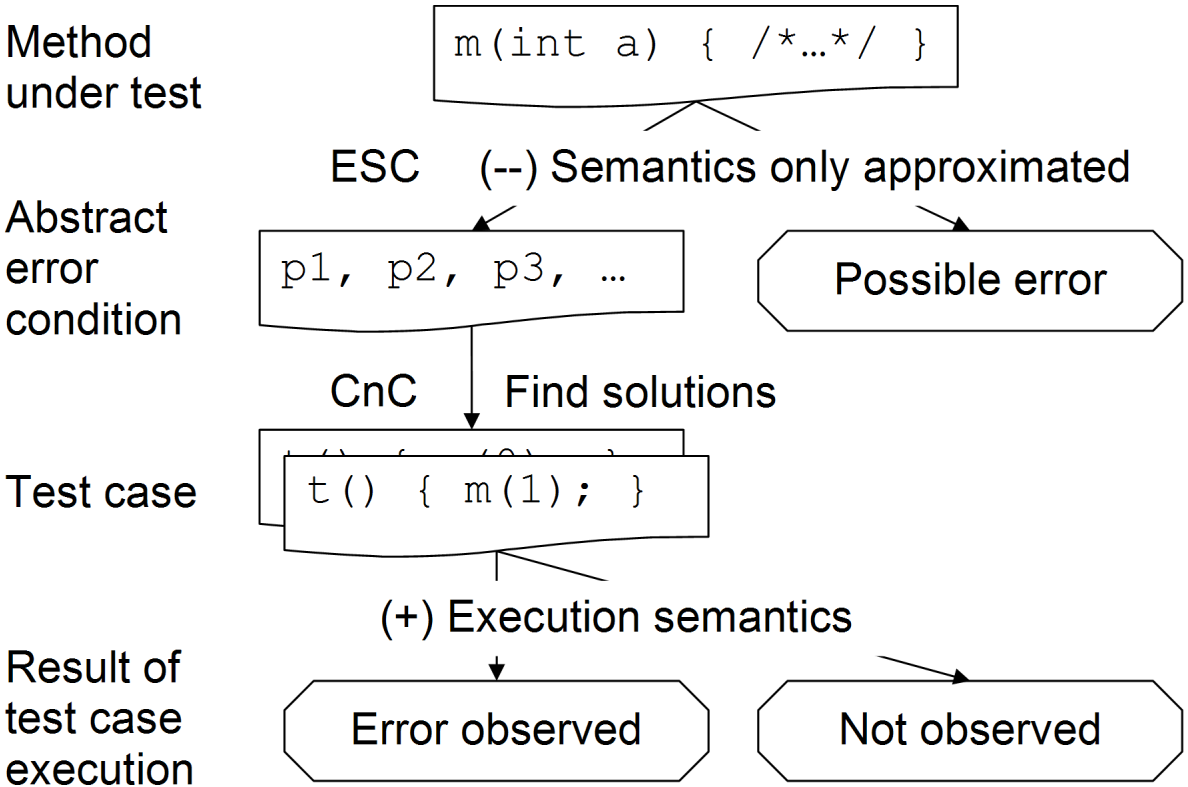
CnC: Check 'n' Crash



Solving ESC's abstract error condition

Integer: int, boolean, byte, short, and long

ESC uses Simplify [Detlefs, Nelson, and Saxe]

Does not know multiplication, except by constants

For absolute values $> 10^6$ only knows ordering

Linear reasoning precise for absolute values $\leq 10^6$

CnC uses POOC [Schlenker and Ringwelski]

Map to int, use third-party integer solver POOC

Solve constraints on integers $\leq 10^6$

Solving ESC's abstract error condition

float and double

ESC very imprecise: Does not know that $1.0 \neq 2.0$

Currently ignored by CnC

Object reference

Own simple solver in CnC: Equivalence relation

Array: Reference to a special object

Integer constraints on array length and indices: POOC

Hack: Retrieve solutions until $\{a[b] \neq a[c]\} \Rightarrow \{b \neq c\}$

Better constraint solving would improve results

Any unconstrained variable: Use random values from JCrasher

Example: Testee

Consider the following student homework solution

```
public static void swapArrays
 (double[] fstArray, double[] sndArray)
{ //..
  for(int m=0; m<fstArray.length; m++) {
    //..
    fstArray[m]=sndArray[m]; //..
  }
}
```

The method's informal specification states that the method swaps the elements from `fstArray` to `sndArray` and vice versa. If the arrays differ in length the method should return without modifying any parameter.

Example: ESC's warning

```
Array index possibly too large (IndexTooBig)
  fstArray[m]=sndArray[m];
                      ^
```

ESC's abstract counterexample

Error condition as conjunction of constraints

5 instructions in `swapArrays` testee

100 constraints (at least) in ESC's abstract counterexample

```
0 < fstArray.length
sndArray.length == 0
...
```

Example: ESC's counterexample

```
(arrayLength(firstArray:294.43) <= intLast)
(firstArray:294.43 < longFirst)
(tmp0!new!double[]:297.27 < longFirst)
(secondArray:295.43 < longFirst)
(longFirst < intFirst)
(vAllocTime(tmp0!new!double[]:297.27) < alloc<1>)

(0 < arrayLength(firstArray:294.43))

(null <= max(LS))
(vAllocTime(firstArray:294.43) < alloc)
(alloc <= vAllocTime(tmp0!new!double[]:297.27))
(eClosedTime(elems@loopold) < alloc)
(vAllocTime(out:6..) < alloc)
(vAllocTime(secondArray:295.43) < alloc)
(intLast < longLast)
(1000001 <= intLast)
((intFirst + 1000001) <= 0)
(out:6.. < longFirst)
arrayLength(tmp0!new!double[]:297.27) ==
  arrayLength(firstArray:294.43)
typeof(0) <: T_int
```

```
null.LS == @true
typeof(firstArray:294.43[0]) <: T_double
isNewArray(tmp0!new!double[]:297.27) == @true
typeof(arrayLength(firstArray:294.43)) <: T_int
T_double[] <: arrayType
typeof(firstArray:294.43) == T_double[]
T_double[] <: T_double[]
elemtype(T_double[]) == T_double
T_double <: T_double
typeof(secondArray:295.43) <: T_double[]
typeof(secondArray:295.43) == T_double[]
arrayFresh(tmp0!new!double[]:297.27 alloc alloc<1>
  elems@loopold arrayShapeOne(arrayLength(firstArray:294.43))
  T_double[] F_0.0)
typeof(firstArray:294.43) <: T_double[]
typeof(tmp0!new!double[]:297.27) == T_double[]
(null <= max(LS))
tmp0!new!double[]:297.27[0] == firstArray:294.43[0]
```

arrayLength(secondArray:295.43) == 0

```
elems@loopold == elems
elems@pre == elems
state@pre == state
state@loopold == state
m@loopold:299.12 == 0
```

```
out@pre:6.. == out:6..
EC@loopold == EC
alloc@pre == alloc
!typeof(out:6..) <: T_float
!typeof(out:6..) <: T_byte
!typeof(secondArray:295.43) <: T_boolean
!typeof(firstArray:294.43) <: T_double
!typeof(secondArray:295.43) <: T_short
!typeof(tmp0!new!double[]:297.27) <: T_boolean
!typeof(tmp0!new!double[]:297.27) <: T_short
!typeof(firstArray:294.43) <: T_boolean
!typeof(out:6..) <: T_char
!typeof(secondArray:295.43) <: T_double
!typeof(firstArray:294.43) <: T_float
!typeof(out:6..) <: T_int
!isAllocated(tmp0!new!double[]:297.27 alloc)
!typeof(secondArray:295.43) <: T_long
!typeof(firstArray:294.43) <: T_char
!typeof(tmp0!new!double[]:297.27) <: T_double
!typeof(tmp0!new!double[]:297.27) <: T_long
T_double[] != T_boolean
T_double[] != T_char
T_double[] != T_byte
T_double[] != T_long
T_double[] != T_short
T_double[] != T_int
```

```
T_double[] != T_float
!typeof(firstArray:294.43) <: T_byte
!typeof(out:6..) <: T_boolean
!typeof(secondArray:295.43) <: T_float
!typeof(out:6..) <: T_short
!typeof(secondArray:295.43) <: T_byte
!typeof(tmp0!new!double[]:297.27) <: T_float
!typeof(firstArray:294.43) <: T_long
!typeof(tmp0!new!double[]:297.27) <: T_byte
!typeof(out:6..) <: T_double
!typeof(firstArray:294.43) <: T_short
!typeof(out:6..) <: T_long
typeof(out:6..) != T_boolean
typeof(out:6..) != T_char
typeof(out:6..) != T_byte
typeof(out:6..) != T_long
typeof(out:6..) != T_short
typeof(out:6..) != T_int
typeof(out:6..) != T_float
!typeof(secondArray:295.43) <: T_char
!typeof(secondArray:295.43) <: T_int
!typeof(tmp0!new!double[]:297.27) <: T_char
!typeof(firstArray:294.43) <: T_int
!typeof(tmp0!new!double[]:297.27) <: T_int
bool$false != @true
secondArray:295.43 != null
```

```
firstArray:294.43 != null
T_double != typeof(out:6..)
T_double != T_double[]
tmp0!new!double[]:297.27 != null
```

Example: CnC processing

Parse ESC's abstract counterexample

Feed relevant constraints to constraint solvers:
Above linear integer constraints to the POOC solver

Get some solutions and compile each into a JUnit test case:

```
public void test0() throws Throwable {
  try {
    double[] d1 = new double[]{1.0};
    double[] d3 = new double[]{};
    P1s1.swapArrays(d1, d3);
  }
  catch (Exception e) {dispatchException(e);}
}
```

Example: Test execution

Test case passes any exception to the JCrasher filtering heuristic

Here, `test0` causes:

```
1) test0(P1s1Test1)
java.lang.ArrayIndexOutOfBoundsException: 0
    at P1s1.swapArrays(P1s1.java:301)
    at P1s1Test1.test0(P1s1Test1.java:49)
    ...
```

The user classifies this as a bug

Benefits relative to JCrasher

	Public meth	Test Cases JCrasher	Test Cases CnC	Crashes JCr.	Crashes CnC	Reports JCr.	Reports CnC	Bugs JCr.	Bugs CnC
1	6	14382	30	12667	21	3	2	0–1	0–1
2	16	104	40	8	40	3	3	1–2	2–3
3	15	95	40	27	40	4	4	1–2	2–3
4	16	239	50	44	50	3	2	0	1
5	18	116	45	26	45	4	4	2	3
6	15	95	10	22	10	2	1	1	1
7	24	3872	13	1547	8	4	2	1	1
8	11	16	110	0	0	0	0	0	0

1..Canvas [SPEC JVM 98], 2–7..Student homework, 8..UB-stack [Stotts et al.]

2–8 available at CnC website

CnC found a superset of the bugs using fewer test cases

Experience with realistic applications

Testee		CnC			
Package	Size [NCSS]	Creation [min:s]	Test Cases	Crashes	Reports
jaba	17.9 k	25:58	18.3 k	4.4 k	56
jboss.jms	5.1 k	1:35	3.9 k	0.6 k	95

JBoss 4.0 RC1, JABA bytecode analysis framework [Harrold, Orso, et al.]

NCSS..Non-comment source statements

Found bugs in both applications

No formal specification: Completely automatic

Little informal specification: Some cases hard to decide

Conclusions

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Pointers

JCrasher: An automatic robustness tester for Java

Christoph Csallner and Yannis Smaragdakis. Software–Practice & Experience, 34(11):1025-1050, September 2004

Download JCrasher

`http://www.cc.gatech.edu/jcrasher/`

Download Check ’n’ Crash

`http://www.cc.gatech.edu/cnc/`

Need to improve the clarity of reports

Musuvathi and Engler write in SoftMC 2003 about a slightly different domain:

> "**A surprise for us** from our static analysis work **was just how important ease-of-inspection is.** Errors that are too hard to inspect might as well not be flagged since the user will ignore them (and, for good measure, may ignore other errors on general principle)."

ESC: Aliasing Example

```
public int alias(HeapNode n) {
  for (int i=0; i<1; i++) {n = n.next;}
  return 1/n.i;
}
```

Relevant constraints, reordered for comprehension:

```
(n-165.2#0:166.4).(i:7.15.12) == 0
n-165.2#0:166.4 == n:164.27<1>
(n@loopold:164.27).(next:7.14.17) == n:164.27<1>
n@loopold:164.27 == n:164.27
```

More constraints that look similar: Hard to filter

CnC: Constraints on complex types

Maintain an equivalence relation

Constraint a=b
→ a and b point to the same object
→ Merge equivalence classes of a and b

Example:

```
public class Point{public int x;}
public int m2(Point a, Point b) {
  if (a==b) {return 100/b.x;}
  else {return 0;}
}
```

Constraints `a.x=0, a=b`

CnC: Constraints on complex types

Constraints `a.x=0, a=b`

Set fields with reflection:

```
Point p1 = new Point();                 //JCrasher
Point.class.getDeclaredField("x"). //Reflection
  set(p1, new Integer(0));              //a.x=0
Point p2 = p1;                          //a=b
Testee t = new Testee();                //JCrasher
t.m2(p1, p2);
```

CnC: Arrays

Additional variables: length and indices

Example:

```
public int m3(int[] a, int b) {
  if (a[a[b]] = 5) {return 1/0;}
  else {return 0;}
}
```

Constraints for division by zero:

```
0 <= b
a[b] < arrayLength(a)
0 <= a[b]
b < arrayLength(a)
a[a[b]] = 5
```

CnC: Array example

Solver cannot model that `a[b]!=a[c]` implies `b!=c`

```
0 <= b < arrayLength(a)
0 <= a[b] < arrayLength(a)
a[a[b]] = 5
```

First solution: `b:=0`, `a[b]:=0`, `a[a[b]]:=5` illegal

Second solution: `b:=0`, `a[b]:=1`, `a[a[b]]:=5`

CnC: Example bug found in JBoss

From `org.jboss.jms.BytesMessageImpl`

```
public void writeObject(Object value)
  throws JMSException
{
  //..
  if (value instanceof Byte[]) {
    this.writeBytes((byte[]) value);
  }  //..
}
```

CnC: Example 2 found in JBoss

From `org.jboss.jms.container.Container`

Bad coding pattern or bug?

```
public static Container getContainer
 (Object object) throws Throwable
{
  Proxy proxy = (Proxy) object;  //..
}
```

CnC: Automate with ANT (Java make)

```
<project name="MyProject" [..]>
  <!-- set properties, compile -->
  <!-- test: call use.xml -->
</project>
```

CnC distribution contains a generic Ant build file `use.xml`:

```
<project name="CnC" [..]>
  <!-- test.generate -->
  <!-- test.compile -->
  <!-- test.run -->
  <!-- test.archive -->
</project>
```