Extended Static Checking with ESC/Java2

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ESC/Java2

- Latest outcome of a series of projects.
  - Compaq: ESC/Modula-3 (–1996), ESC/Java (–2000).
  - Univ. Nijmegen (–2005), Univ. College Dublin (2005–): ESC/Java2.
  - https://github.com/GaloisInc/ESCJava2
- Extended Static Checking for Java.
  - Find programming errors by automated reasoning techniques.
    - Simplified variant of Hoare/weakest precondition calculus.
  - Full Java 1.4 (much of Java 1.5), fully automatic.
    - Feels like type-checking.
  - Uses JML for specification annotations (ESC/Java2).
    - ESC/Modula-3 and ESC/Java had their own annotation language.
- Based on the Simplify prover.
  - Greg Nelson et al, written in Modula-3 for ESC/Modula-3.

Finding errors in a program rather than verifying it.

Theoretical Limitations

- ESC/Java2 is not sound.
  - Soundness: if $\{P\}c\{Q\}$ does not hold, it cannot be proved.
    - ESC/Java2 may not produce warning on wrong $\{P\}c\{Q\}$.
  - Sources of unsoundness:
    - Loops are handled by unrolling, arithmetic is on $\mathbb{Z}$.
    - JML annotation `assume` adds unverified knowledge.
    - Object invariants are not verified on all existing objects.
- ESC/Java2 is not complete.
  - Completeness: if $\{P\}c\{Q\}$ cannot be proved, it does not hold.
    - ESC/Java2 may produce superfluous warnings.
  - Sources of incompleteness:
    - Simplify's limited reasononing capabilities (arithmetic, quantifiers).
  - JML annotation `nowarn` to turn off warnings.
    - Potentially not sound.

Not every error is detected, not every warning actually denotes an error.

Practical Usefulness

- ESC/Java2 detects many (most) programming errors.
  - Array index bound violations.
  - Division by zero.
  - Null-pointer dereferences.
  - Violation of properties depending on linear arithmetic.
  - ...
- Forces programmer to write method contracts.
  - Especially method preconditions.
  - Better documented and better maintainable code.

A useful extension of compiler type checking.

Tutorial Program

```
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;
  }
}
```

```
> escjava2 Bag.java
```


Tutorial Program: Assumptions

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

  /*@ requires input != null; @*/
  Bag(int[] input) {
    ...
  }

  /*@ requires n>0; @*/
  int extractMin() {
    ...
  }
```

Invariants and preconditions have to be added to pass the checking.

Tutorial Program: Guarantees

```
/*@ requires n>0;
  @ ensures n == \old(n)-1;
  @ ensures (\forall int i; 0 <= i && i < \old(n);
  @             \result <= \old(a[i]));
  @*/
int extractMin() {
  ...
}
```

Postconditions may be added (and are checked to some extent).

Tutorial Program: Wrong Guarantees

```
/*@ requires n>0;
  @ ensures n == \old(n)-1;
  @ ensures (\forall int i; 0 <= i && i < \old(n);
  @             \result <= \old(a[i])); @*/
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[0]; // ERROR: a[0] rather than a[i]
    }
  }
  n--;
  a[mindex] = a[n];
  return m;
}
```

But also this program passes the check!

Example Program: `Arithmetic1`

```
//@ ensures \result == i;
static int f2(int i)
{
  int j = i+1;
  int k = 3*j;
  return k-2*i-3;
}

//@ requires i < j;
//@ ensures \result >= 1;
static int f4(int i, int j)
{
  return 2*j-2*i-1;
}
```

Masters linear integer arithmetic with inequalities.

Example Program: `Conditional`

```
/*@ ensures (\result == i || \result == j || \result == k)
  @      && (\result <= i && \result <= j && \result <= k); @*/
static int min(int i, int j, int k)
{
  int m = i;
  if (j < m) m = j;
  if (k < m) m = k;
  return m;
}
```

Masters conditionals.

Example Program: Sort

```
/*@ requires a != null;
  @ ensures (\forall int i; 0 <= i && i < a.length-1; a[i] <= a[i+1])
  @*/
static void insertSort(int[] a)
{
  int n = a.length;
  for (int i = 1; i < n; i++) {
    int x = a[i];
    int j = i-1;
    while (j >= 0 && a[j] > x) {
      a[j+1] = a[j];
      j = j-1;
    }
    a[j+1] = x;
  }
}
```

Detects many errors in array-based programs.

Example Program: Arithmetic2

```
//@ ensures \result == i*i;
static int f1(int i)
{
  return i*(i+1)-i;
} //@ nowarn Post;

//@ ensures \result >= 0;
static int f2(int i)
{
  return i*i;
} //@ nowarn Post;
```

Does not master non-linear arithmetic.

Example Program: Loop

```
//@requires n >= 0;
static void loop(final int n)
{
  int i=0;
  while (i < n)
  {
    i = i+1;
  }
  //@ assert i==n;
  //@ assert i<3;
}
```

Does only partially master post-conditions of programs with loops.

Loop Unrolling

We will now use a high-level description of the ESC/Java2 handling of loops by loop unrolling.

- Original program.

  while (e) c;

- Unrolling the loop once.

  if (e) { c; while (e) c; }

- Unrolling the loop twice.

  if (e) { c; if (e) { c; while (e) c; } }

Faithful loop unrolling preserves the meaning of a program.

Verification of Unrolled Program

Let us consider how verification is affected by loop unrolling.

- Original: $\{P\}$ while(e) c $\{Q\}$
  - $\underline{P \Rightarrow \text{wp}(\text{while}(e)\ c, Q)}$ (0)
- Unrolled: $\{P\}$ if (e) $\{c;$ if (e) $\{c;$ while (e) $c\}\}$ $\{Q\}$
  - $\underline{(P \wedge \neg e) \Rightarrow Q}$ (1)
  - $\{P \wedge e\}$ $c;$ if (e) $\{c;$ while (e) $c\}$ $\{Q\}$
    - $\underline{\{P \wedge e\}\ c\ \{\neg e \Rightarrow Q\}}$ (2)
    - $\underline{\{P \wedge e\}\ c\ \{e \Rightarrow \text{wp}(c; \text{while}\ (e)\ c, Q)\}}$ (3)

Three obligations (1-3) equivalent to original obligation (0).

ESC/Java2 Loop Unrolling

- Faithful unrolling

  $\{P\}$ if(e) $\{c;$ if(e) $\{c;$ while (e) $c\}\}$ $\{Q\}$

- ESC/Java2 default unrolling

  $\{P\}$ if(e) $\{c;$ if(e) { **assume** false; }} $\{Q\}$

  - Not unrolled execution of loop is replaced by "**assume** false".
  - **assume** false: from false, everything can be concluded.
  - No more verification takes place in this branch.

Only simplified program is verified by ESC/Java2.

Verification of Unrolled Program

Let us consider the simplified verification problem.

- $\{P\}$ if(e) $\{c;$ if(e) { **assume** false}} $\{Q\}$
  - $\underline{(P \wedge \neg e) \Rightarrow Q}$ (1)
  - $\{P \wedge e\}$ $c;$ if(e) { **assume** false}} $\{Q\}$
    - $\underline{\{P \wedge e\}\ c\ \{\neg e \Rightarrow Q\}}$ (2)
    - $\underline{\{P \wedge e\}\ c\ \{e \wedge \text{false}} \Rightarrow Q\}$

      $\Leftrightarrow \{P \wedge e\}\ c\ \{\text{true}\}$

      $\Leftrightarrow$ true

Proof obligation (3) of the original problem is dropped.

Expressive Power of Simplified Verification

- Checked proof obligations
  - $(P \land \neg e) \Rightarrow Q$
    - Postcondition holds, if loop terminates after zero iterations.
  - $\{P \land e\}\ c\ \{\neg e \Rightarrow Q\}$
    - Postcondition holds, if loop terminates after one iteration.
- Unchecked proof obligation
  - $\{P \land e\}\ c\ \{e \Rightarrow \text{wp}(c; \text{while } (e)\ c, Q)\}$
    - Postcondition holds, if loop terminates after more than one iteration.

Only partial verification of loops in ESC/Java 2.

Expressive Power of Simplified Verification

What does this mean for the whole verification process?

- Example program:

  while (e) { c_1 } c_2
- Verified program:

  if (e) { c_1; if (e) { **assume** false } } c_2
  if (e) { c_1; if (e) { **assume** false } c_2 } else c_2
  if (e) { c_1; if (e) { **assume** false; c_2 } else c_2 } else c_2
  if (e) { c_1; if (e) **skip** else c_2 } else c_2
  if (e) { c_1; if $(\neg e)$ c_2 } else c_2
- In verified program, only runs are considered where
  - loop terminates after at most one iteration, i.e.
  - execution of c_2 is only considered in such program runs.

After a loop, only special contexts are considered for verification.

Control of Loop Unrolling

- ESC/Java2 control of loop unrolling

  ```
  escjava2 -loop n.5
  ```
  - Loop is unrolled n times (default $n = 1$).
  - .5: also loop condition after n-th unrolling is checked.
- Preconditions.
  - All preconditions are checked that arise from the loop expression and the loop body in the first n iterations.
- Postconditions.
  - It is checked whether the postcondition of the loop holds in all executions that require at most n iterations.

All program paths with more than n iterations are "cut off".

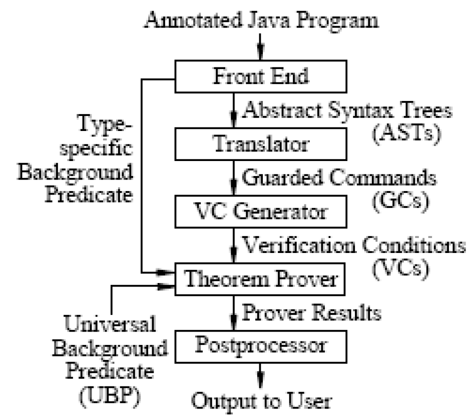
Unsoundness of Loop Unrolling

- Unsoundness of strategy can be easily shown.

  ```
  int i=0;
  while (i < 1000)
    i = i+1;
  //@ assert i < 2;
  ```
- For unrolling with $n < 1000$, this postcondition is true.
  - For any execution, that terminates after at most n iterations (i.e. none), the postcondition is true.

For true verification of loop programs, reasoning about a loop invariant is required.

Internal Operation



From Leino et al (2002): Extended Static Checking for Java.

Guarded Commands

Java program is first translated into a much simpler language.

- Variant of Dijkstra's guarded command (GC) language.

  cmd ::= *variable* = *expr* | **skip** | **raise** | **assert** *expr* | **assume** *expr* |
  var *variable*+ **in** *cmd* **end** | *cmd* ; *cmd* | *cmd* ! *cmd* | *cmd* [] *cmd*.
- Actually, first a sugared version of the language.

  cmd ::= . . . |
  check *expr* | **call** *p*(*expr**) | **loop** { **invariant** *expr* } *cmd* **end**.
- Then desugar program, i.e. translate it into core language.
  - Various desugaring strategies possible.
- Then generate verification conditions for program in core language.
  - Verification conditions are forwarded to theorem prover.

We first discuss the semantics of the core language and then the translation process Java → sugared GC → core GC.

Monitoring the Translation

- Print guarded command version of language.

  ```
  escjava2 -pgc Simple.java
  ```
- Java program.

  int y; if (x >= 0) y = x; else y = -x;
- Guarded command program (simplified).

  ```
  VAR int y IN
  {
    ASSUME integralGE(x, 0); y = x;
  []
    ASSUME boolNot(integralGE(x,0)); y = -x;
  }
  END
  ```

Low-level program; only necessary for understanding details.

Core Language Semantics

Defined by weakest preconditions.

$$\text{wp}(\mathit{cmd}, N, X)$$

- Weakest condition on state in which *cmd* may be executed such that
  - either *cmd* terminates normally in a state in which N holds,
  - or *cmd* terminates exceptionally in a state in which X holds.
- All commands in the core language terminate.
  - No distinction to weakest liberal precondition.
- Relationship to total correctness.

  $\{P\}\ c\ \{Q\} \Leftrightarrow (P \Rightarrow \text{wp}(c, Q, \text{false}))$

Two ways how a command may terminate.

Core Language Semantics

$\text{wp}(x = e, N, X) \Leftrightarrow N[e/x]$
$\text{wp}(\textbf{skip}, N, X) \Leftrightarrow N$
$\text{wp}(\textbf{raise}, N, X) \Leftrightarrow X$
$\text{wp}(\textbf{assert}\ e, N, X) \Leftrightarrow (e \Rightarrow N) \wedge (\neg e \Rightarrow X)$
$\text{wp}(\textbf{assume}\ e, N, X) \Leftrightarrow (e \Rightarrow N)$
$\text{wp}(\textbf{var}\ x_1, \ldots x_n\ \textbf{in}\ c, N, X) \Leftrightarrow \forall x_1, \ldots, x_n : \text{wp}(c, N, X)$
$\text{wp}(c_1; c_2, N, X) \Leftrightarrow \text{wp}(c_1, wp(c_2, N, X), X)$
$\text{wp}(c_1!c_2, N, X) \Leftrightarrow \text{wp}(c_1, N, wp(c_2, N, X))$
$\text{wp}(c_1[]c_2, N, X) \Leftrightarrow \text{wp}(c_1, N, X) \wedge wp(c_2, N, X)$

Tuple of postconditions has to be considered.

Core Language Semantics

$\text{wp}(\textbf{skip}, N, X) \Leftrightarrow N$
$\text{wp}(c_1; c_2, N, X) \Leftrightarrow \text{wp}(c_1, wp(c_2, N, X), X)$

- Interpretation of **skip** rule
  - The command terminates normally but not exceptionally.
  - Thus the normal postcondition N must hold before the call.
- Interpretation of command compositon rule (;).
  - If c_1 terminates exceptionally, the exceptional postcondition X must hold (because c_2 is not executed).
  - If c_1 terminates normally, it must be in a state such that the execution of c_2 ensures the required postconditions N and X.

Slight generalization of the basic rule of the weakest precondition of command composition.

Core Language Semantics

$\text{wp}(\textbf{raise}, N, X) \Leftrightarrow X$
$\text{wp}(c_1!c_2, N, X) \Leftrightarrow \text{wp}(c_1, N, wp(c_2, N, X))$

- Interpretation of **raise** rule
  - The command terminates not normally but exceptionally.
  - Thus the exceptional postcondition X must hold before the call.
- Interpretation of signal handling rule (!).
  - If c_1 terminates normally, the normal postcondition N must hold (because c_2 is not executed).
  - If c_1 terminates exceptionally, it must be in a state such that the execution of c_2 ensures the required postconditions N and X.

Note the symmetry of command composition and exception handling.

Example

What is the weakest preconditon such that

$$(x = x + 1; x = x - 2) \ ! \ x = x + 2$$

normally terminates in a state with $x = 3$?

$\mathrm{wp}(((x = x + 1; x = x - 2) \ ! \ x = x + 2), x = 3, \mathrm{false})$
$\Leftrightarrow \mathrm{wp}((x = x + 1; x = x - 2), x = 3, \mathrm{wp}(x = x + 2, x = 3, \mathrm{false}))$
$\Leftrightarrow \mathrm{wp}((x = x + 1; x = x - 2), x = 3, x + 2 = 3)$
$\Leftrightarrow \mathrm{wp}((x = x + 1; x = x - 2), x = 3, x = 1)$
$\Leftrightarrow \mathrm{wp}(x = x + 1, \mathrm{wp}(x = x - 2, x = 3, x = 1), x = 1)$
$\Leftrightarrow \mathrm{wp}(x = x + 1, x - 2 = 3, x = 1)$
$\Leftrightarrow \mathrm{wp}(x = x + 1, x = 5, x = 1)$
$\Leftrightarrow x + 1 = 5$
$x = 4$

Example

What is the weakest preconditon such that

$$(x = x + 1; \mathbf{raise}; x = x - 2) \ ! \ x = x + 2$$

normally terminates in a state with $x = 3$?

$\mathrm{wp}(((x = x + 1; \mathbf{raise}; x = x - 2) \ ! \ x = x + 2), x = 3, \mathrm{false})$
$\Leftrightarrow \mathrm{wp}((x = x + 1; \mathbf{raise}; x = x - 2), x = 3, \mathrm{wp}(x = x + 2, x = 3, \mathrm{false}))$
$\Leftrightarrow \mathrm{wp}((x = x + 1; \mathbf{raise}; x = x - 2), x = 3, x + 2 = 3)$
$\Leftrightarrow \mathrm{wp}((x = x + 1; \mathbf{raise}; x = x - 2), x = 3, x = 1)$
$\Leftrightarrow \mathrm{wp}(x = x + 1, \mathrm{wp}((\mathbf{raise}; x = x - 2), x = 3, x = 1), x = 1)$
$\Leftrightarrow \mathrm{wp}(x = x + 1, \mathrm{wp}(\mathbf{raise}; \mathrm{wp}(x = x - 2, x = 3, x = 1), x = 1), x = 1)$
$\Leftrightarrow \mathrm{wp}(x = x + 1, x = 1, x = 1)$
$\Leftrightarrow x + 1 = 1$
$\Leftrightarrow x = 0$

Translation of Java Loops

The guarded command language does not have while loops.

- Translation of `while (e) { c1 } c2`
  - **loop** `if (¬e)` **raise**; c_1 **end** ! c_2
- Construct **loop** runs forever.
  - Loop is terminated by signalling an exception in the body.
  - Exception is caught and c_2 is executed.

Replacement of while loops by core **loop** and exceptions.

Translation of Java Conditionals

The guarded command language also does not have conditionals.

- Translation of `if (e) c1 else c2`.
  - (**assume** e ; c_1) [] (**assume** $\neg e$; c_2)
- Translation of `if (e) c`.
  - (**assume** e ; c) [] (**assume** $\neg e$; **skip**)
- Non-deterministic selection of two commands.
  - One of two branches is exexecuted.
  - Each branch is guarded by a condition which can be assumed to be true in that branch
  - Conditions are mutually exclusive, thus actually only one branch can be executed.

Replacement of conditionals by guarded selection of commands.

Checking Expressions

Handling of preconditions.

check *expr*;

- Occurs e.g. in translation of object dereferencing `v = o.f`
  - **check** o != null; v = select(o, f)
- Possible translation of **check** *expr*.
  1. Treat violation as error.
     - **assert** *expr*
  2. Ignore violation (user has switched warning off).
     - **assume** *expr*
  3. Treat violation as runtime exception.
     - `if (!`*expr*`)` **raise**

Translation partially controlled by `nowarn` annotations.

Procedure Calls

Call of a procedure r that is allowed to modify a variable x.

call $r(e_0, e_1)$

- Translation (simplified):

var p_0 p_1 **in**
  $p_0 = e_0$; $p_1 = e_1$;
  check *precondition* (involves p_0, p_1);
  var x_0 **in**
    $x_0 = x$;
    modify x;
    assume postconditions (involves p_0, p_1, x_0, x);
  end
end

- **modify** x desugars to
  - **var** x' **in** x = x' **end**

Reduce complex procedure call rule to simpler constructs.

Loops

Execution of a core loop.

loop { **invariant** *expr* } *cmd* **end**

- Handling by loop unrolling.

check *expr*; *cmd*;
check *expr*; *cmd*;
...
check *expr*; **assume** false.

- By default, loops are unrolled just once.
  - `escjava2 -loop 1.5`

We have already investigated the consequence of this.

Verification Conditions

For program in core language, verification conditions are generated.

- Pretty-print generated verification conditions.

```
escjava2 -v -ppvc Simple.java
```

```
...
(OR
  (AND (>= |x| 0) (EQ |@true| |@true|))
  (AND
    (NOT (>= |x| 0))
    (EQ |@true| |@true|)
  )
  (EQ |y| (- 0 |x|))
  ...
)
...
```

Hardly readable, only for understanding details.

Simplify

```
Simplify(1)

NAME
Simplify  -- attempt to prove first-order formulas.


SYNTAX
Simplify [-print] [-ax axfile] [-nosc] [-noprune]
[-help] [-version] [file]


DESCRIPTION
*Simplify* accepts a sequence of first order formulas as input, and
attempts to prove each one. *Simplify* does not implement a decision
procedure for its inputs: it can sometimes fail to prove a valid
formula. But it is conservative in that it never claims that an
invalid formula is valid.
...
```


Formula Syntax

```
|  formula ::= "(" ( AND | OR )  { formula } ")" |
|                "(" NOT formula ")" |
|                "(" IMPLIES formula formula ")" |
|                "(" IFF formula formula ")" |
|                "(" FORALL "(" var* ")" formula ")" |
|                "(" EXISTS "(" var* ")" formula ")" |
|                "(" PROOF formula* ")" |
|                literal
|
|  literal ::= "(" ( "EQ" | "NEQ" | "<" | "<=" | ">" | ">=" )
|                term term ")" |
                 "(" "DISTINCT" term term+ ")" |
|                 "TRUE" | "FALSE" | <propVar>
|
|  term    ::= var | integer | "(" func { term } ")"
```


Formula Syntax

```
The formula

| (DISTINCT term1 ... termN)

represents a conjunction of distinctions between all pairs of terms in
the list.

The formula

| (PROOF form1 ... formN)

is sugar for

| (AND (IMPLIES form1 form2)
|      (IMPLIES (AND form1 form2) form3)
|      ...
|      (IMPLIES (AND form1 ... formN-1) formN))

"func"'s are uninterpreted, except for "+", "-", and "*", which
represent the obvious operations on integers.
```


Default Axioms

```
(FORALL (a i x k)
   (EQ (select (store a i x) i k) x))
(FORALL (a i n)
   (EQ (len (subMap a i n)) n))
(FORALL (a i n j k)
   (EQ (select (subMap a i n) j k) (select a (+ i j) k)))
(FORALL (a i x)
   (EQ (len (store a i x)) (len a)))
(FORALL (a i n b)
   (EQ (len (storeSub a i n b)) (len a)))
(FORALL (v i)
   ( EQ (select (mapFill v) i) v))
(FORALL (i j a x k)
   (OR (EQ i j) (EQ (select (store a i x) j k) (select a j k))))
(FORALL (j i a n b k)
   (OR (AND (OR (< j i) (>= j (+ i n)))
(EQ (select (storeSub a i n b) j k) (select a j k)))
   (AND (>= j i)
(< j (+ i n))
   (EQ (select (storeSub a i n b) j k) (select b (- j i) k)))))
```

Power of Simplify

Simplify can be used as a "pocket calculator for reasoning".

- Prover for first-order logic with equality and integer arithmetic.
  - For proving formula F, the satisfiability of $\neg F$ is checked.
  - If $\neg F$ is not satisfiable, the prover returns "valid".
  - If $\neg F$ is satisfiable, the prover returns a counterexample context.
    - Conjunction of literals (atomic formulas, plain or negated) that is believed to satisfy $\neg F$.
- Proving strategy is sound.
  - If F is reported "valid", this is the case.
- Proving strategy is not complete.
  - A reported counterexample context may be wrong.

Sound, not complete, highly optimized.

Conclusions

- ESC/Java2 is a good tool for finding program errors.
  - Reports many/most common programming errors.
  - Forces programmer to write method preconditions/assertions.
  - Stable, acceptably fast.
- ESC/Java2 is not a verification environment.
  - Postconditions of methods with loops are not appropriately verified.
  - Arithmetic is treated as arbitrary size, not finite.
- Resources:
  - Surveys: Extended Static Checking for Java (2002); ESC/Java2: Uniting ESC/Java and JML (2004).
  - Manual: ESC/Java User Manual (2000), ESC/Java2 Implementation Notes (2004).
  - Guarded Commands: Checking Java Programs via Guarded Commands (1999).
  - Simplify: A Theorem Prover for Program Checking (2003).