Extended Static Checking with ESC/Java2

Wolfgang Schreiner
Wolfgang.Schreiner@risc.uni-linz.ac.at

Research Institute for Symbolic Computation (RISC)
Johannes Kepler University, Linz, Austria
http://www.risc.uni-linz.ac.at

1. **Overview**

2. **Examples**

3. **Handling of Loops**

4. **Internal Operation**

ESC/Java2

- Latest outcome of a series of projects.
  - Compaq: ESC/Modula-3 (–1996), ESC/Java (–2000).
  - Univ. Nijmegen: ESC/Java2 (2003–).
  - http://www.cs.kun.nl/sos/research/escjava
- Extended Static Checking for Java.
  - Find programming errors by automated reasoning techniques.
    - Simplified variant of Hoare/weakest precondition calculus.
  - Full Java 1.4, 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.

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Use of ESC/Java2

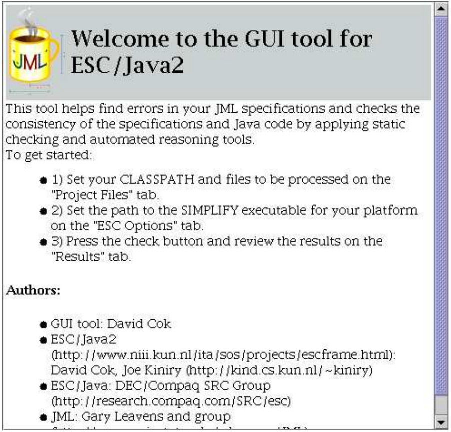
- Command-line interface.

  `escjava2` [*options*] *File*.java

- Graphical interface.

  ```
  java -jar esctools2.jar
  ```

`escjava2 -help`.



Welcome to the GUI tool for ESC/Java2

This tool helps find errors in your JML specifications and checks the consistency of the specifications and Java code by applying static checking and automated reasoning tools.
To get started:

- 1) Set your CLASSPATH and files to be processed on the "Project Files" tab.
- 2) Set the path to the SIMPLIFY executable for your platform on the "ESC Options" tab.
- 3) Press the check button and review the results on the "Results" tab.

Authors:

- GUI tool: David Cok
- ESC/Java2 (http://www.niii.kun.nl/ita/sos/projects/escframe.html): David Cok, Joe Kiniry (http://kind.cs.kun.nl/~kiniry)
- ESC/Java: DEC/Compaq SRC Group (http://research.compaq.com/SRC/esc)
- JML: Gary Leavens and group

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;
  }
}
```

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.

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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 $\{Q\}$
  - $\underline{P \Rightarrow \mathrm{wp}(\mathrm{while}(e)\ c, Q)}$ (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)
    - $\underline{\{P \wedge e\}\ c\ \{e \Rightarrow \mathrm{wp}(c; \mathrm{while}\ (e)\ c, Q)\}}$ (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$\}\}$ $\{Q\}$
  - $\underline{(P \land \neg e) \Rightarrow Q}$ (1)
  - $\{P \land e\}$ $c;$ if(e) $\{$ **assume** false$\}\}$ $\{Q\}$
    - $\underline{\{P \land e\}\ c\ \{\neg e \Rightarrow Q\}}$ (2)
    - $\{P \land e\}\ c\ \{e \land \text{ false} \Rightarrow Q\}$
      $\Leftrightarrow \{P \land e\}\ c\ \{\text{true}\}$
      $\Leftrightarrow$ true

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

Expressive Power of Simplified Verification

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

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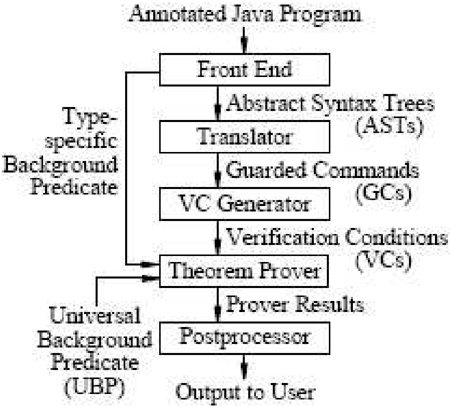
Internal Operation



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 >= y) 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.

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

- 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.

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

Two ways how a command may terminate.

Core Language Semantics

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

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

$$\mathrm{wp}(\mathbf{raise}, N, X) \Leftrightarrow X$$
$$\mathrm{wp}(c_1 ! c_2, N, X) \Leftrightarrow \mathrm{wp}(c_1, N, wp(c_2, N, X))$$

- 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 $x = 3$?

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

Example

What is the weakest preconditon such that

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

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

$$
\begin{aligned}
&\mathrm{wp}(((x = x+1; \textbf{raise}; x = x-2)\ !\ x = x+2), x = 3, \mathrm{false})\\
&\Leftrightarrow \mathrm{wp}((x = x+1; \textbf{raise}; x = x-2), x = 3, \mathrm{wp}(x = x+2, x = 3, \mathrm{false}))\\
&\Leftrightarrow \mathrm{wp}((x = x+1; \textbf{raise}; x = x-2), x = 3, x+2 = 3)\\
&\Leftrightarrow \mathrm{wp}((x = x+1; \textbf{raise}; x = x-2), x = 3, x = 1)\\
&\Leftrightarrow \mathrm{wp}(x = x+1, \mathrm{wp}((\textbf{raise}; x = x-2), x = 3, x = 1), x = 1)\\
&\Leftrightarrow \mathrm{wp}(x = x+1, \mathrm{wp}(\textbf{raise}; \mathrm{wp}(x = x-2, x = 3, x = 1), x = 1), x = 1)\\
&\Leftrightarrow \mathrm{wp}(x = x+1, x = 1, x = 1)\\
&\Leftrightarrow x+1 = 1\\
&\Leftrightarrow x = 0
\end{aligned}
$$

Translation of Java Loops

The guarded command language does not have while loops.

- Translation of `while (`e`) {` c_1 `}` c_2

  loop `if (`$\neg e$`)` **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`)` c_1 `else` c_2.

  (**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.

$$\textbf{call } r(e_0, e_1)$$

- 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.

$$\textbf{loop} \ \{ \ \textbf{invariant} \ \mathit{expr} \ \} \ \mathit{cmd} \ \textbf{end}$$

- 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.
  - Arithmetic reasoning actually uses $\mathbb{Q}$, not $\mathbb{Z}$.

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).