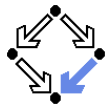


Extended Static Checking with ESC/Java2

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<http://www.risc.uni-linz.ac.at>



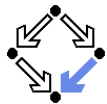
1. Overview

2. Examples

3. Handling of Loops

4. Internal Operation

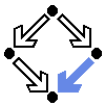
ESC/Java2



- Latest outcome of a series of projects.
 - Compaq: ESC/Modula-3 (–1996), ESC/Java (–2000).
 - Univ. Nijmegen (–2005), Univ. College Dublin (2005–): ESC/Java2.
 - <http://kind.ucd.ie/products/opensource/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.

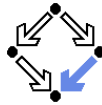
Theoretical Limitations



- 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 reasoning 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.

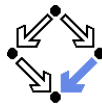
Practical Usefulness



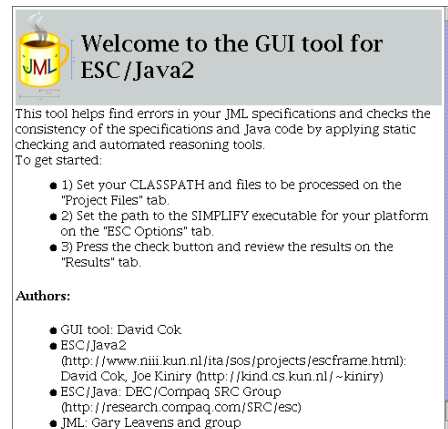
- ESC/Java2 detects many (most) programming errors.
 - Array index bound violations.
 - Division by zero.
 - Null-pointer dereferences.
 - Violation of properties depending on linear arithmetic.
 - ...
- Forces programmer to write method contracts.
 - Especially method preconditions.
 - Better documented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

A useful extension of compiler type checking.

Use of ESC/Java2



- Command-line interface.
`escjava2 [options]
File.java`
- Graphical interface.
`java -jar
esctools2.jar`
`escjava2 -help.`



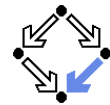
1. Overview

2. Examples

3. Handling of Loops

4. Internal Operation

Tutorial Program

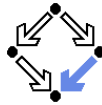


```
class Bag {
    int[] a; int n;

    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



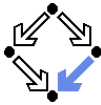
```
class Bag {
  /*@ non_null @*/ int[] a;
  int n; /*@ invariant 0 <= n && n <= a.length; @*/

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

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

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

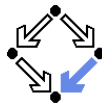
Tutorial Program: Guarantees



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

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

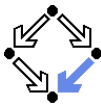
Tutorial Program: Wrong Guarantees



```
/*@ requires n>0;
   @ ensures n == \old(n)-1;
   @ ensures (\forallall 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

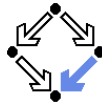


```
/*@ ensures \result == i;
static int f2(int i)
{
  int j = i+1;
  int k = 3*j;
  return k-2*i-3;
}

/*@ 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.

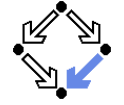
Example Program: Conditional



```
/*@ 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.

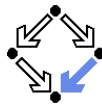
Example Program: Sort



```
/*@ 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

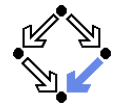


```
/*@ ensures \result == i*i;
static int f1(int i)
{
  return i*(i+1)-i;
} //@ nowarn Post;

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

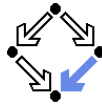
Does not master non-linear arithmetic.

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.

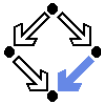


1. Overview

2. Examples

3. Handling of Loops

4. Internal Operation



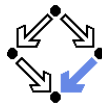
Loop Unrolling

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.

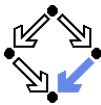
Verification of Unrolled Program



Let us consider how verification is affected by loop unrolling.

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

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

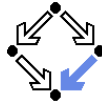


ESC/Java2 Loop Unrolling

- Faithful unrolling
 $\{P\} \text{ if}(e) \ \{c; \text{ if}(e) \ \{c; \text{ while } (e) \ c\}\} \ \{Q\}$
- ESC/Java2 default unrolling
 $\{P\} \text{ if}(e) \ \{c; \text{ if}(e) \ \{\text{assume false}; \}\} \ \{Q\}$
 - 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

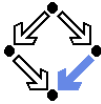


Let us consider the simplified verification problem.

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

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

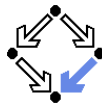
Expressive Power of Simplified Verification



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

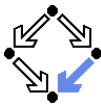
- Example program:


```
while (e) { c1 } c2
```
- Verified program:


```
if (e) { c1; if (e) { assume false } } c2
if (e) { c1; if (e) { assume false } c2 } else c2
if (e) { c1; if (e) { assume false; c2 } else c2 } else c2
if (e) { c1; if (e) skip else c2 } else c2
if (e) { c1; if (¬e) c2 } else c2
```
- 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



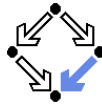
- ESC/Java2 control of loop unrolling


```
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



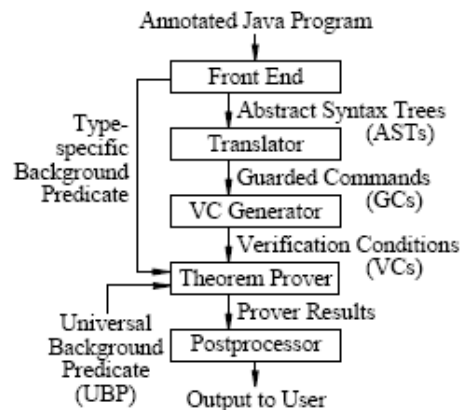
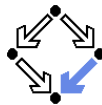
- Unsoundness of strategy can be easily shown.

```
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.

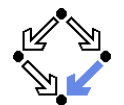
1. Overview

2. Examples

3. Handling of Loops

4. Internal Operation

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.
```

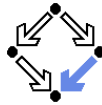
- Actually, first a **sugared** version of the language.

```
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 $\text{Java} \rightarrow \text{sugared GC} \rightarrow \text{core GC}$.

Monitoring the Translation



- Print guarded command version of language.

```
escjava2 -pgc Simple.java
```

- Java program.

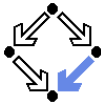
```
int y; if (x >= 0) y = x; else y = -x;
```

- 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.

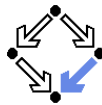
$$wp(cmd, N, X)$$

- 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.

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

Two ways how a command may terminate.

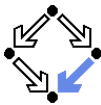
Core Language Semantics



```
wp(x = e, N, X) ⇔ N[e/x]
wp(skip, N, X) ⇔ N
wp(raise, N, X) ⇔ X
wp(assert e, N, X) ⇔ (e ⇒ N) ∧ (¬e ⇒ X)
wp(assume e, N, X) ⇔ (e ⇒ N)
wp(var x1, ... xn in c, N, X) ⇔ ∀x1, ... xn : wp(c, N, X)
wp(c1; c2, N, X) ⇔ wp(c1, wp(c2, N, X), X)
wp(c1!c2, N, X) ⇔ wp(c1, N, wp(c2, N, X))
wp(c1[]c2, N, X) ⇔ wp(c1, N, X) ∧ wp(c2, N, X)
```

Tuple of postconditions has to be considered.

Core Language Semantics

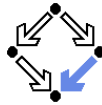


```
wp(skip, N, X) ⇔ N
wp(c1; c2, N, X) ⇔ wp(c1, wp(c2, N, X), X)
```

- Interpretation of **skip** rule
 - The command terminates normally but not exceptionally.
 - Thus the normal postcondition *N* must hold before the call.
- Interpretation of command composition 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

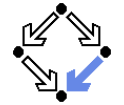


$$\begin{aligned} \text{wp}(\text{raise}, N, X) &\Leftrightarrow X \\ \text{wp}(c_1!c_2, N, X) &\Leftrightarrow \text{wp}(c_1, N, \text{wp}(c_2, N, X)) \end{aligned}$$

- 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



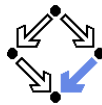
What is the weakest precondition such that

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

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

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

Example



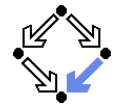
What is the weakest precondition such that

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

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

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

Translation of Java Loops

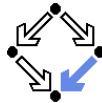


The guarded command language does not have while loops.

- 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

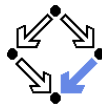


The guarded command language also does not have conditionals.

- Translation of `if (e) c1 else c2`.
`(assume e ; c1) [] (assume ¬e ; c2)`
- Translation of `if (e) c`.
`(assume e ; c) [] (assume ¬e ; skip)`
- Non-deterministic selection of two commands.
 - One of two branches is executed.
 - 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.

Procedure Calls



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

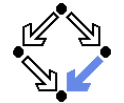
`call r(e0, e1)`

- Translation (simplified):

```
var p0 p1 in
  p0 = e0; p1 = e1;
  check precondition (involves p0, p1);
  var x0 in
    x0 = x;
    modify x;
    assume postconditions (involves p0, p1, x0, x);
  end
end
```
- `modify x` desugars to
`var x' in x = x' end`

Reduce complex procedure call rule to simpler constructs.

Checking Expressions



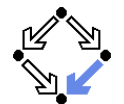
Handling of preconditions.

`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.

Loops



Execution of a core loop.

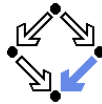
`loop { invariant expr } cmd end`

- 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.

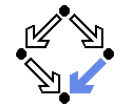
- Pretty-print generated verification conditions.

```
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
```

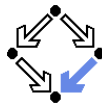
```
Simplify [-print] [-ax axfile] [-nosc] [-noprun]
[-help] [-version] [file]
```

```
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.
```

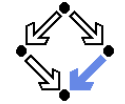
```
...
```

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

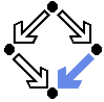
```
| (PROOF form1 ... formN)
```

is sugar for

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

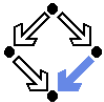
"func"'s are uninterpreted, except for "+", "-", and "*", which represent the obvious operations on integers.

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

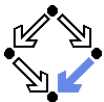


Simplify can be used as a “pocket calculator for reasoning”.

- 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).