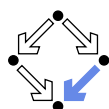


# Extended Static Checking with ESC/Java2

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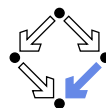
## 1. Overview

## 2. Examples

## 3. Handling of Loops

## 4. Internal Operation

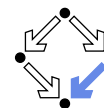
# ESC/Java2



- 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://kindsoftware.com/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.

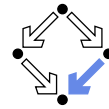
# Theoretical Limitations



- 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.

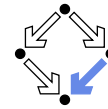
Not every error is detected, not every warning actually denotes an error.

## 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.



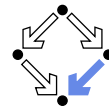
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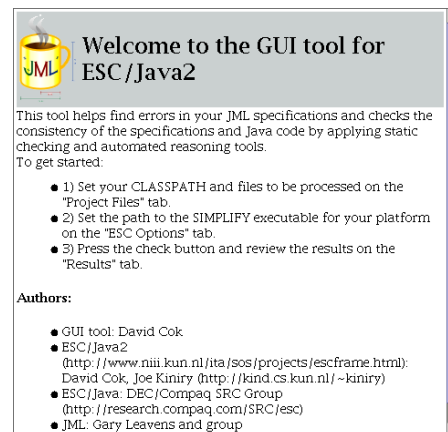
## 4. Internal Operation

## Use of ESC/Java2

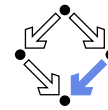


- Command-line interface.  
`escjava2 [options]`  
`File.java`
- Graphical interface.  
`java -jar`  
`esctools2.jar`
- Eclipse 3.5 plugin.  
See web site.

`escjava2 -help`.



## Tutorial Program

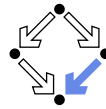


```
class Bag {
    int[] a; int n;

    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



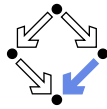
```
class Bag {
  /*@ non_null @*/ int[] a;
  int n; /*@ invariant 0 <= n && n <= a.length; @*/

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

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

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

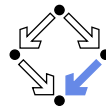
## Tutorial Program: Guarantees



```
/*@ 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).

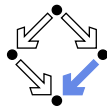
## Tutorial Program: Wrong Guarantees



```
/*@ 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

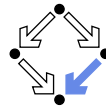


```
//@ ensures \result == i;
static int f2(int i)
{
  int j = i+1;
  int k = 3*j;
  return k-2*i-3;
}

/*@ 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.

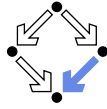
## Example Program: Conditional



```
/*@ 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.

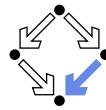
## Example Program: Sort



```
/*@ 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

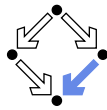


```
//@ ensures \result == i*i;
static int f1(int i)
{
  return i*(i+1)-i;
} //@ nowarn Post;

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

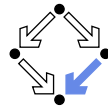
Does not master non-linear arithmetic.

## 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.



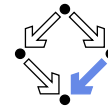
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## Loop Unrolling

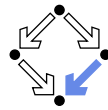


We will now use a high-level description of the ESC/Java2 handling of loops by **loop unrolling**.

- 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

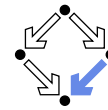


Let us consider how verification is affected by loop unrolling.

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

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

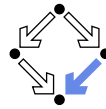
## ESC/Java2 Loop Unrolling



- 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

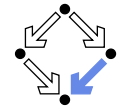


Let us consider the simplified verification problem.

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

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

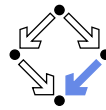
## Expressive Power of Simplified Verification



- 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

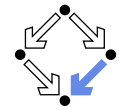


What does this mean for the whole verification process?

- 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<sub>2</sub> is only considered in such program runs.

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

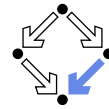
## Control of Loop Unrolling



- 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

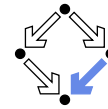


- Unsoundness of strategy can be easily shown.

```
int i=0;
while (i < 1000)
  i = i+1;
/*@ assert i < 2;
```

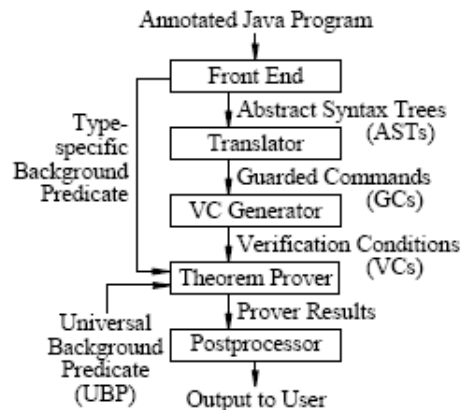
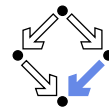
- For unrolling with  $n < 1000$ , this postcondition is true.
  - For any execution, that terminates after at most  $n$  iterations (i.e. **none**), the postcondition is true.

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



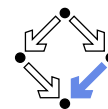
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# Internal Operation



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

# Guarded Commands

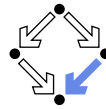


Java program is first translated into a much simpler language.

- Variant of **Dijkstra's guarded command (GC) language**.  
 $cmd ::= variable = expr \mid skip \mid raise \mid assert \ expr \mid assume \ expr \mid$   
 $var \ variable^+ \ in \ cmd \ end \mid cmd ; cmd \mid cmd ! \ cmd \mid cmd [] \ cmd.$
- Actually, first a **sugared** version of the language.  
 $cmd ::= \dots \mid$   
 $check \ expr \mid call \ p(expr^*) \mid loop \ { \ invariant \ expr \} \ cmd \ end.$
- 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  $\rightarrow$  sugared GC  $\rightarrow$  core GC.

## Monitoring the Translation



- Print guarded command version of language.

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

- Java program.

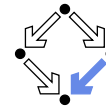
```
int y; if (x >= 0) y = x; else y = -x;
```

- 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.

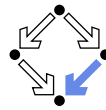
$$wp(cmd, N, X)$$

- 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



$$wp(x = e, N, X) \Leftrightarrow N[e/x]$$

$$wp(\mathbf{skip}, N, X) \Leftrightarrow N$$

$$wp(\mathbf{raise}, N, X) \Leftrightarrow X$$

$$wp(\mathbf{assert} e, N, X) \Leftrightarrow (e \Rightarrow N) \wedge (\neg e \Rightarrow X)$$

$$wp(\mathbf{assume} e, N, X) \Leftrightarrow (e \Rightarrow N)$$

$$wp(\mathbf{var} x_1, \dots, x_n \mathbf{in} c, N, X) \Leftrightarrow \forall x_1, \dots, x_n : wp(c, N, X)$$

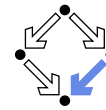
$$wp(c_1; c_2, N, X) \Leftrightarrow wp(c_1, wp(c_2, N, X), X)$$

$$wp(c_1 ! c_2, N, X) \Leftrightarrow wp(c_1, N, wp(c_2, N, X))$$

$$wp(c_1 [] c_2, N, X) \Leftrightarrow wp(c_1, N, X) \wedge wp(c_2, N, X)$$

Tuple of postconditions has to be considered.

## Core Language Semantics



$$wp(\mathbf{skip}, N, X) \Leftrightarrow N$$

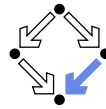
$$wp(c_1; c_2, N, X) \Leftrightarrow wp(c_1, wp(c_2, N, X), X)$$

- Interpretation of **skip** rule
  - The command terminates normally but not exceptionally.
  - Thus the normal postcondition *N* must hold before the call.
- Interpretation of command composition rule (;).
  - If *c*<sub>1</sub> terminates exceptionally, the exceptional postcondition *X* must hold (because *c*<sub>2</sub> is not executed).
  - If *c*<sub>1</sub> terminates normally, it must be in a state such that the execution of *c*<sub>2</sub> ensures the required postconditions *N* and *X*.

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



## Core Language Semantics

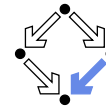


$$\text{wp}(\text{raise}, N, X) \Leftrightarrow X$$
$$\text{wp}(c_1!c_2, N, X) \Leftrightarrow \text{wp}(c_1, N, \text{wp}(c_2, N, X))$$

- 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



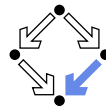
What is the weakest precondition such that

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

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



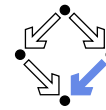
What is the weakest precondition such that

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

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

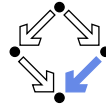


The guarded command language does not have while loops.

- 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

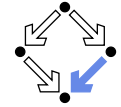


The guarded command language also does not have conditionals.

- 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.

## Checking Expressions



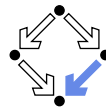
Handling of preconditions.

`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`.
  - Treat violation as error.  
`assert expr`
  - Ignore violation (user has switched warning off).  
`assume expr`
  - 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`.

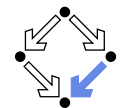
`call r(e0, e1)`

- 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.

## Loops



Execution of a core loop.

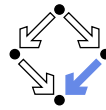
`loop { invariant expr } cmd end`

- 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.

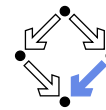
- Pretty-print generated verification conditions.

```
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

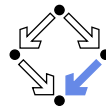
Simplify [-print] [-ax axfile] [-nosc] [-noprune]  
[-help] [-version] [file]

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.

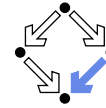
...

## 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

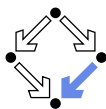
```
| (PROOF form1 ... formN)
```

is sugar for

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

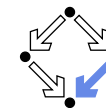
"func"'s are uninterpreted, except for "+", "-", and "\*", which represent the obvious operations on integers.

## 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

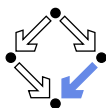


Simplify can be used as a “pocket calculator for reasoning”.

- 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).