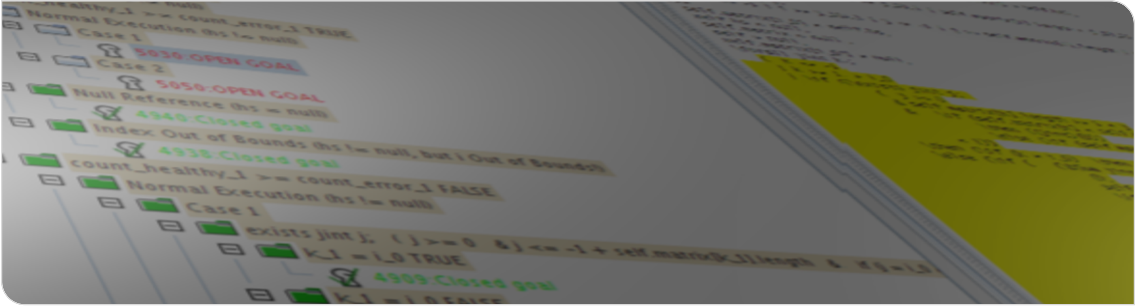
Karlsruher Institut für Technologie

KeY Tutorial

Verify This 2021

Mattias Ulbrich | 26 March 2021



KeY

more than 20 years experience

KeY

Karlsruher Institut für Technologie

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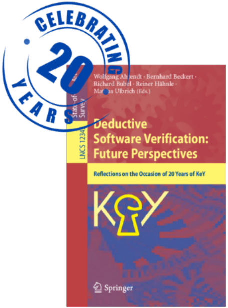
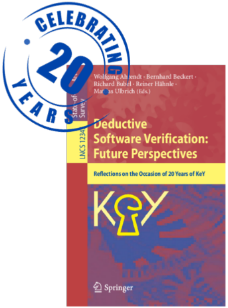


LNCS 12345

more than 20
years experience

many, many, many
contributors



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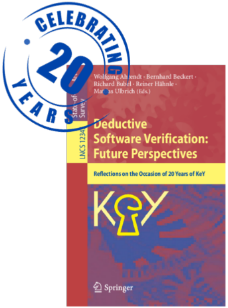

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Karlsruhe Institute of Technology

TECHNISCHE UNIVERSITÄT DARMSTADT

KeY

www.key-project.org

Java

www.key-project.org

Java

Deductive Verification

www.key-project.org

Java

Deductive Verification

Java Modeling Language JML

www.key-project.org

Java

Deductive Verification

Java Modeling Language JML

Source Code Analysis

`www.key-project.org`

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Java

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Java Modeling Language JML

Dynamic Logic / Symbolic Execution

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KeY

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Java Modeling Language JML

Source Code Analysis

Sequential Code

Dynamic Logic / Symbolic Execution

www.key-project.org

Java

Java 1.4
(+ a bit)

Deductive
Verification

Sequential
Code

Java Modeling
Language JML

Dynamic Logic /
Symbolic Execution

Source Code
Analysis

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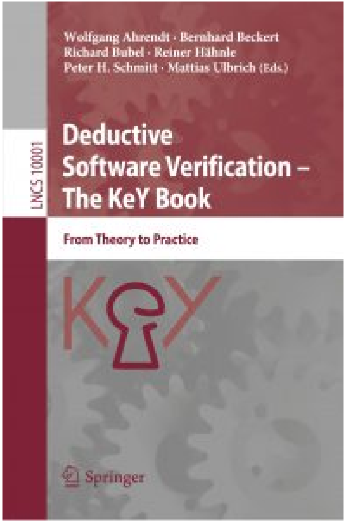
The KeY Book

The reference for the system:

Deductive Software Verification – The KeY Book

LNCS volume 10001

Springer 2016.



KeY Workflow

annotated Java program

↓

KeY proof management

↓

contract proof obligation

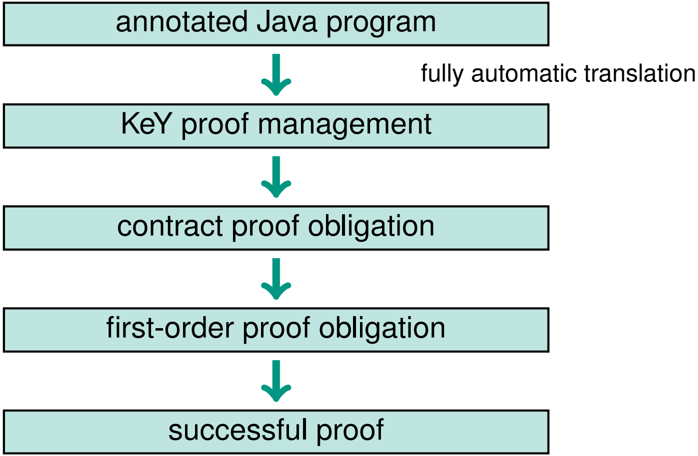
↓

first-order proof obligation

↓

successful proof

KeY Workflow



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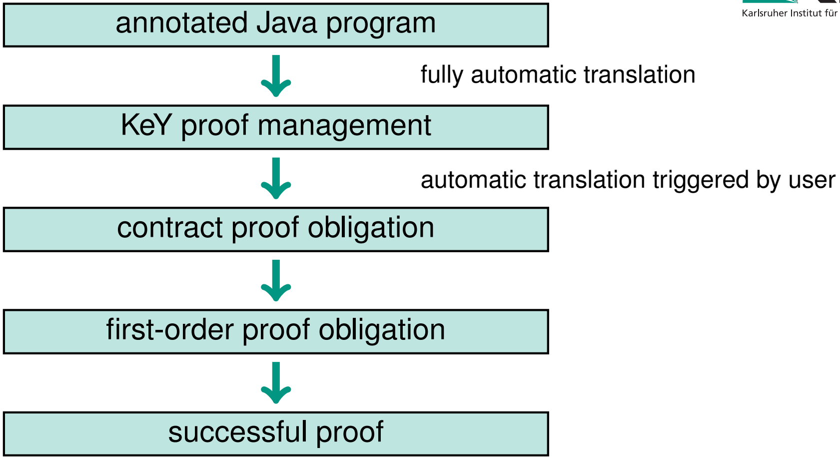

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↓ fully automatic translation

KeY proof management

↓ automatic translation triggered by user

contract proof obligation

↓ rule-based symbolic execution using KeY

first-order proof obligation

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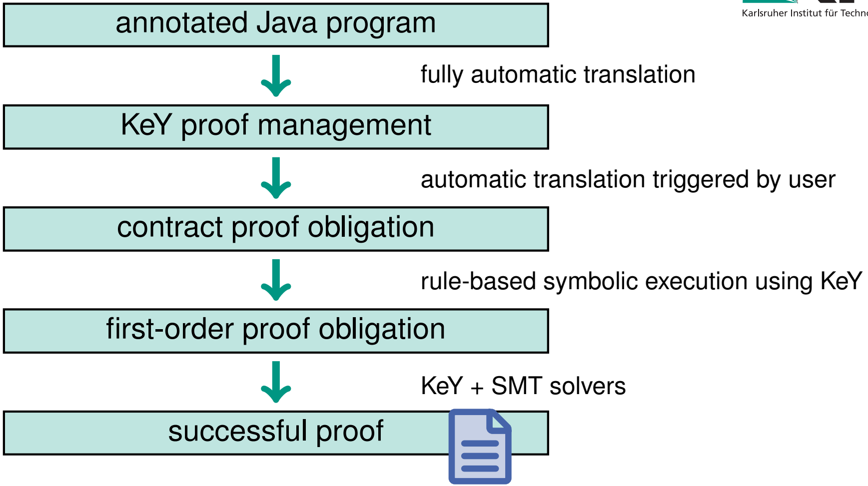

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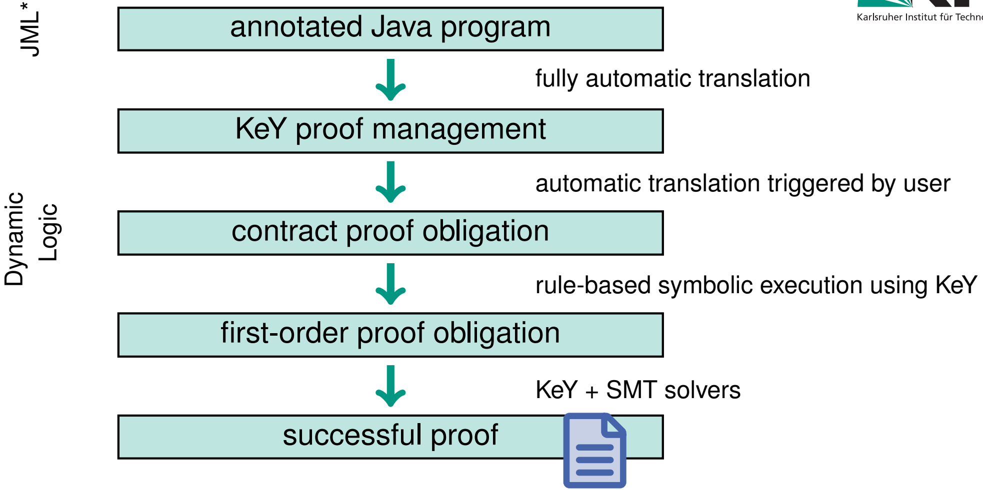

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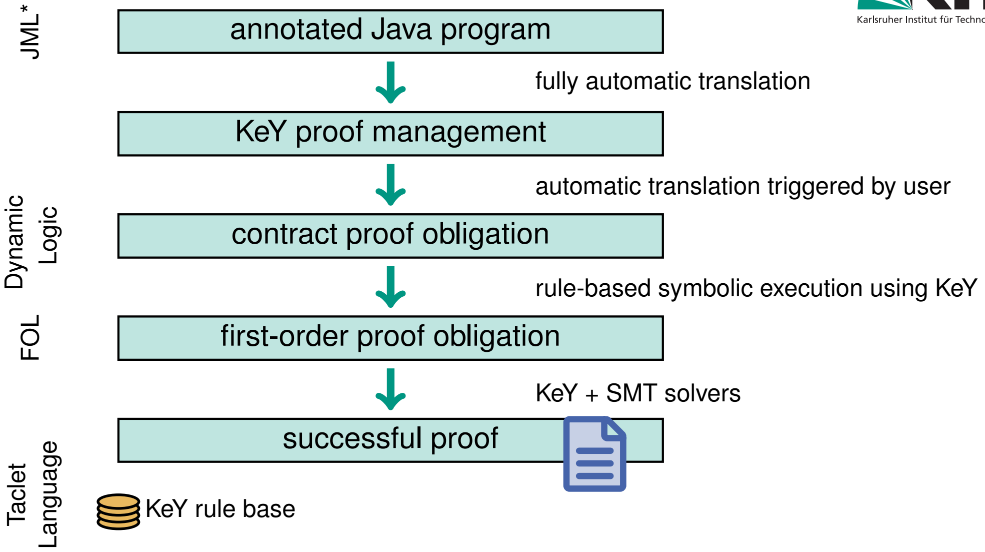
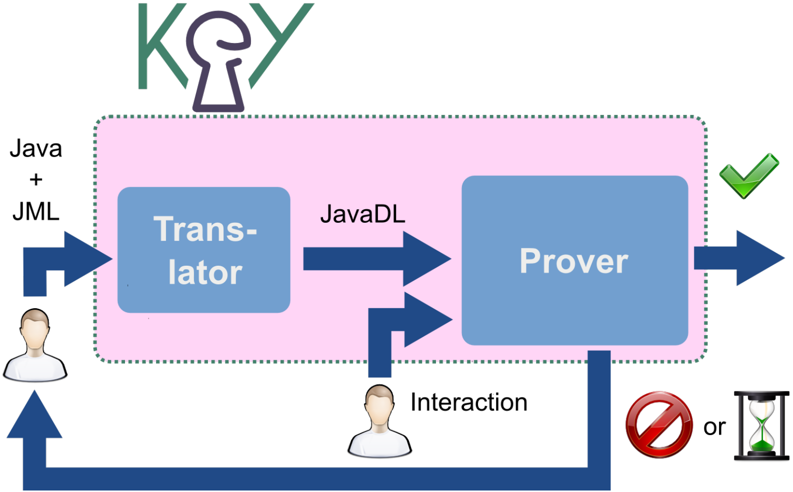


KeY Verification Process



A Case Study: The TimSort Bug

[De Gouw et al., CAV 2015]

TimSort

- Standard algorithm: Open JDK, Android, Apache, Haskell, Python
- Clever combination of merge sort and insertion sort

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Bug found during (failed) verification attempt with KeY

- Throws uncaught `ArrayIndexOutOfBoundsException` for certain inputs
- Symbolic counter example generation & analysis lead to witness
- Interaction (understanding intermediate proof state) crucial

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Verification of fixed version with KeY

- Proof: JDK code with bug fix does not throw an exception
- 2,200,000 rule applications – 99.8 % automatic

The Java Modeling Language

JML

- JML independent of KeY.
- There is a JML community on its own.
- Main person: Gary Leavens (UCF Orlando)
- KeY is one tool amonst others, in particular OpenJML (David Cok)
- Influenced other specification languages, e.g., ACSL

Method Contracts

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Post increment

```
class Increment {
    int x, y;

    /*@ behavior
      @  requires true;
      @  ensures x == \old(y);
      @  ensures y == \old(y)+1;
      @  assignable this.x, this.y;
      @  signals (Exception e) false;
      @*/
    public void increment() {
        x = y++;
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Method contracts in JML:

- B. Meyer's *Design by contract*

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- JML keywords start with backslash (`\old`, `\forall`, . . .)
- Exceptional cases specified separately (`signals`)
- mostly interested in the `normal_behavior`

Object Invariants

Array access

```
class SomeClass {
    int[] array;
    int index;
    // ...

    //@ invariant



    /*@ normal_behavior
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    public int getAtIndex() {
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Object invariants in JML:

Object Invariants

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- “visible state semantics”

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Object invariants in KeY (JML*):

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- Explicit predicate: `\invariant_for(·)`

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  - `requires \invariant_for(this);`
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Loop Specifications

Loop Specifications

```
/*@ loop_invariant 0 <= i && i < a.length;
  @ loop_invariant (\forall int k;
  @              0 <= k && k < i; a[k] == k);
  @ decreases a.length - i;
  @ assignable a[*];
  @*/
for(int i = 0; i < a.length; i++) {
  a[i] = i;
}
```

Three specification items

- Loop invariant(s) `loop_invariant` (must hold before and after every loop iteration)
- Loop variant `decreases`
- A loop frame `assignable`

Loop Specifications

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/*@ loop_inva
  @ loop_inva
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  @*/
for(int i = 0
  a[i] = i;
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```

riant

every loop

Java allows more than we'd whish for.

Find invariants for these loops:

```
do {
  [...]
} while (a[++left] >= a[left - 1]);

for (int k = left; ++left <= right; k = ++left) {
  [...]
}
```

(taken verbatim from `java.util.DualPivotQuicksort`, openjdk-7)

Proving JDK's Dual Pivot Quicksort Correct [Beckert et al. VSTEE 2017]

Expressions

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JML extends Java

Any side-effect-free Java expression is also a JML expression.

JML expressions

- *A* `==>` *B* ... logical implication
- *A* `<==>` *B* ... logical equivalence
- `\old(·)` ... value at method start

Quantifiers

- **always** in parentheses
- mostly used with integers
- allowed to quantify over all types, not only integer (which raises questions on the domain of all objects ...)
- generalisations exist: `\sum`, `\count`, etc.

```
(\exists int x; x/2 == x/4)
(\forall int i,j; 0<=j && i<j && j<a.length; a[i] < a[
(\sum int i; 0<=i && i<a.length; a[i])
```

Java Dynamic Logic

JavaDL

- Dynamic Logic proposed late 70s/early 80s
- Pratt, Vaughan, Fisher, Ladner
- Harel has good theory

Dynamic Logic

- Basis: Typed first-order logic
- Modal logic
- Programs constitute the modalities.
- Class declarations remain in background

$[p]\varphi$: If p terminates, then φ holds in the final state (partial)
$\langle p\rangle\varphi$: p terminates and φ holds in the final state (total)

Other Program Logics

$\psi \to [p]\varphi$	$\Longleftrightarrow$	$\{\psi\}\ p\ \{\varphi\}$	$\Longleftrightarrow$	$\psi \to wlp(p, \varphi)$
DL		Hoare calculus		weakest (liberal) precondition

(mostly)

The Calculus

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- Sequent calculus (Gentzen-style calculus)
- Sequent is of the shape

$$\gamma_1, \ldots, \gamma_n \Longrightarrow \delta_1, \ldots, \delta_m$$

(meaning $\bigwedge \gamma_i \to \bigvee \delta_i$)

- Rules are of the form

$$\frac{\Gamma_1 \Longrightarrow \Delta_1 \quad \ldots \quad \Gamma_n \Longrightarrow \Delta_n}{\Gamma \Longrightarrow \Delta}$$

- Rules are applied from bottom to top:
  "If I have to show the conclusion, I can instead show the premisses."

Sample FOL rules

$$\frac{a, b \Longrightarrow}{a \wedge b \Longrightarrow}$$

$$\frac{\Longrightarrow a \qquad \Longrightarrow b}{\Longrightarrow a \wedge b}$$

$$\frac{\Longrightarrow \varphi[x/c]}{\Longrightarrow \forall x.\varphi}$$

for a fresh constant c

The Calculus: Symbolic Execution

Local variable assignment

$$\frac{\Longrightarrow \quad \{x := v\}\varphi}{\Longrightarrow \quad [\mathtt{x\ =\ v;}]\varphi}$$

Think of $\{x := v\}\varphi$ as "let $x = v$ in φ"

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Field assignment

$$\frac{\begin{array}{rll} [\text{NULL}] & o = \texttt{null} \Longrightarrow & [\texttt{throw new NullPointerException();}]\varphi \\ [\text{NORMAL}] & o \neq \texttt{null} \Longrightarrow & \{\mathit{heap} := \mathit{store}(\mathit{heap}, o, \texttt{C::f}, v)\}\varphi \end{array}}{\Longrightarrow \quad [\texttt{o.f = v;}]\varphi}$$

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Heaps are 2-dimensional McCarthy arrays

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and many, many more rules

about 200 rules for symbolic execution
over 1500 rules in total

Loops

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$$\text{simpleInv}\ \frac{\begin{array}{l}\Longrightarrow inv \\ \Longrightarrow \mathcal{A}_{heap}\mathcal{A}_{local}\big((inv \land se \doteq TRUE) \rightarrow [p_{norm}]inv\big) \\ \Longrightarrow \mathcal{A}_{heap}\mathcal{A}_{local}\big((inv \land se \doteq FALSE) \rightarrow [\pi\ \omega]\varphi\big)\end{array}}{\Longrightarrow [\pi\ \texttt{while}(se)\ \{\ p_{norm}\ \}\ \omega]\varphi}$$

where

- se is a simple expression and p_{norm} cannot terminate abruptly;
- $(inv, mod, term)$ is a loop specification for the loop to which the rule is applied;
- $\mathcal{A}_{heap} = \{\texttt{heap} := c_h\}$ anonymizes the heap; $c_h{:}Heap$ is a fresh constant;
- $\mathcal{A}_{local} = \{l_1 := c_1 \parallel \cdots \parallel l_n := c_n\}$ anonymizes all local variables $l_1, \ldots, l_n$ that are the target of an assignment (left-hand side of an assignment statement) in p_{norm}; each c_i is a fresh constant of the same type as l_i.

Loops

$$\text{abruptTermInv}\;\frac{\begin{array}{l}\Longrightarrow inv\\ \Longrightarrow \mathscr{A}_{heap}\mathscr{A}_{local}\big((inv \wedge [\mathsf{b}{=}nse;]\mathsf{b} \doteq TRUE) \;\rightarrow\; [\widehat{\mathsf{b}{=}nse;\,p}]post\big)\\ \Longrightarrow \mathscr{A}_{heap}\mathscr{A}_{local}\big((inv \wedge [\mathsf{b}{=}nse;]\mathsf{b} \doteq FALSE) \;\rightarrow\; [\pi\;\mathsf{b}{=}nse;\;\omega]\varphi\big)\end{array}}{\Longrightarrow [\pi\;\mathtt{while}(nse)\;\{\;p\;\}\;\omega]\varphi}$$

$$\begin{array}{lll} post & & (\textsc{Exception} \not\doteq null \rightarrow [\pi\;\mathtt{throw\;Exception;}\;\omega]\varphi)\\ & \wedge & (\textsc{Break} \doteq TRUE \rightarrow [\pi\;\omega]\varphi)\\ & \wedge & (\textsc{Return} \doteq TRUE \rightarrow [\pi\;\mathtt{return\;res;}\;\omega]\varphi)\\ & \wedge & (\textsc{Normal} \rightarrow inv)\end{array}$$

Dynamic Frames

Karlsruher Institut für Technologie

Observation: Framing Problem

It may be more challenging to prove that things do *not* happen than that they happen.

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Typical pattern (+ a grain of salt)

```
//@ ghost \locset footprint;

//@ invariant footprint =
//@   this.* \cup next.footprint;

//@ ...
//@ ensures \new_elems_fresh(footprint);
//@ assignable footprint;
void m();

//@ ...
//@ accessible footprint;
int /*@pure*/ query();
```

Dynamic Frames – Dependency Analysis

Karlsruher Institut für Technologie

Typical problem

```
o.query() == o.query()@heap[p.g:=5]
```

Pure method

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- With `accessible` no need to look inside the definitions

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- Proof obligation:

$$\frac{\begin{array}{l}\texttt{o.footprint@}h_1 = \texttt{o.footprint@}h_2, \\ \{heap := h_1\}[\texttt{r} = \texttt{o.query();}]q_1 = r, \\ \{heap := h_2\}[\texttt{r} = \texttt{o.query();}]q_2 = r\end{array}}{\Longrightarrow \quad q_1 = q_2}$$

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- Caution with recursive queries ...
- Automation ...

KeY as a Platform

Karlsruher Institut für Technologie

`https://www.key-project.org/download/` “Single Click Jar”

- deductive Java verification
- also for concurrent code (permissions)
- support for the full JavaCard language (incl. transactions)
- test case generation
- counterexample generation
- symbolic execution engine for Java
- symbolic execution debugger
- deductive information flow analysis (with two DL-operators)
- floating point support (brand new)
- open source (GPL / EPL)

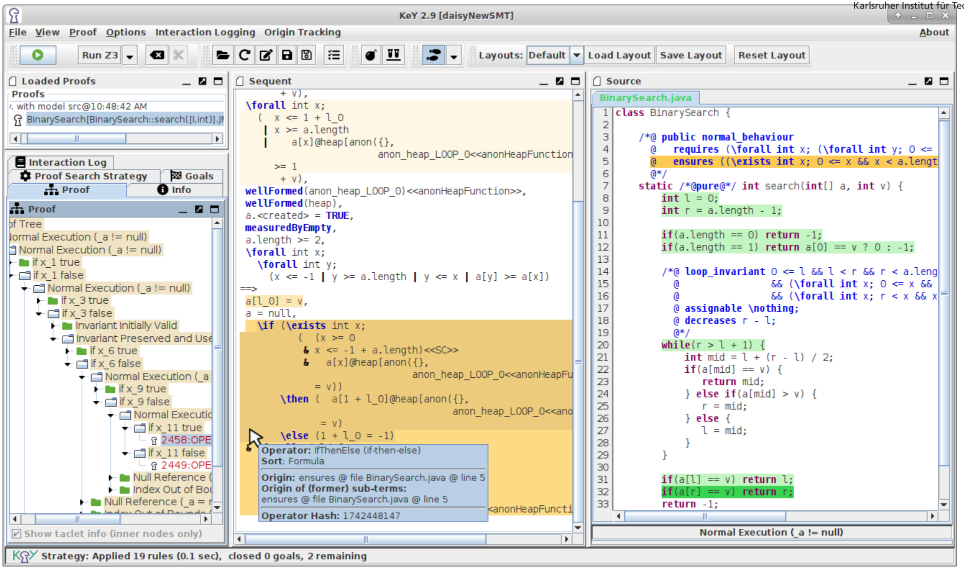
The tool

`https://www.key-project.org/download/` “Single Click Jar”

“Single Click Jar”

```
java -jar key-2.8.0-exe.jar
```

Demo

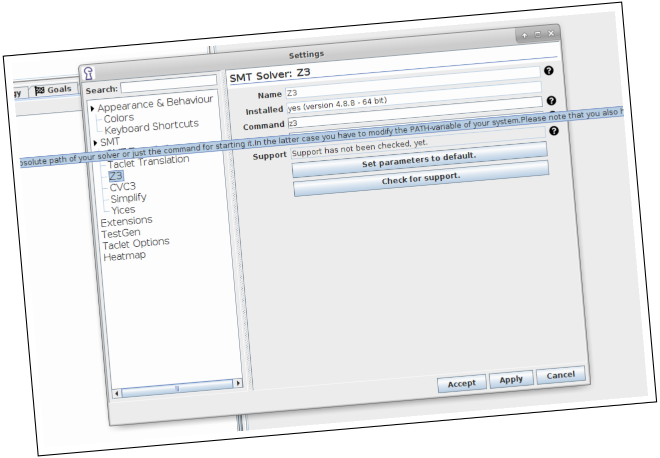


KeY 2.9 [daisyNewSMT]
File View Proof Options Interaction Logging Origin Tracking About
Run Z3
Layouts: Default Load Layout Save Layout Reset Layout
Loaded Proofs
Sequent
Source
BinarySearch.java
Interaction Log
Proof Search Strategy
Goals
Proof
Info
Operator: IfThenElse (if-then-else)
Sort: Formula
Origin: ensures @ file BinarySearch.java @ line 5
Origin of (former) sub-terms:
ensures @ file BinarySearch.java @ line 5
Operator Hash: 1742448147
Normal Execution (_a != null)
Strategy: Applied 19 rules (0.1 sec), closed 0 goals, 2 remaining

Cheat Sheet

1. KeY usually loads **all** `.java` files in a directory and all subdirectories.
2. Good workflow:
   - Load proof obligation
   - Right click on $\Longrightarrow$.
   - Choose the "Full Auto Pilot" Macro
   - Inspect unclosed goals.
   - When hoping for a closed goal apply macro "Try close goals below".
3. "Hide Intermediate ProofSteps", "Expand Goals Only" from context menu in proof make that a lot more readible.
4. Prefer `\strictly_nothing` over `\nothing`
5. The origin of a formula is highlighted when hovering (orange)
6. Symbolic execution trace is highlighted (green)
7. The challenges should work without help of an smt solver

Micro Challenge



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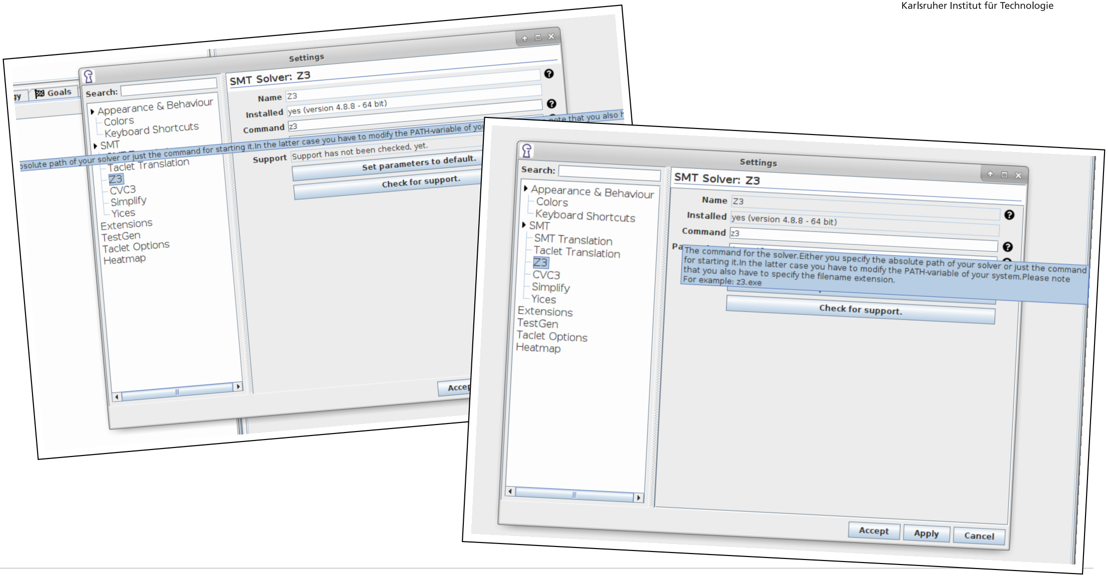

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