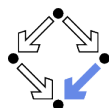


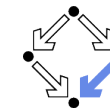
Verifying Java Programs with KeY

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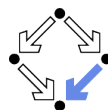
Verifying Java Programs



- **Extended static checking of Java programs:**
 - Even if no error is reported, a program may violate its specification.
 - Unsound calculus for verifying while loops.
 - Even correct programs may trigger error reports:
 - Incomplete calculus for verifying while loops.
 - Incomplete calculus in automatic decision procedure (Simplify).
- **Verification of Java programs:**
 - Sound verification calculus.
 - Not unfolding of loops, but loop reasoning based on invariants.
 - Loop invariants must be typically provided by user.
 - Automatic generation of verification conditions.
 - From JML-annotated Java program, proof obligations are derived.
 - Human-guided proofs of these conditions (using a proof assistant).
 - Simple conditions automatically proved by automatic procedure.

We will now deal with an integrated environment for this purpose.

The KeY Tool

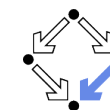


<http://www.key-project.org>

- **KeY:** environment for verification of JavaCard programs.
 - Subset of Java for smartcard applications and embedded systems.
 - Universities of Karlsruhe, Koblenz, Chalmers, 1998–
 - Beckett et al: "Deductive Software Verification – The KeY Book: From Theory to Practice", Springer, 2016.
 - "Chapter 16: Formal Verification with KeY: A Tutorial"
- **Specification languages:** OCL and JML.
 - Original: OCL (Object Constraint Language), part of UML standard.
 - Later added: JML (Java Modeling Language).
- **Logical framework:** Dynamic Logic (DL).
 - Successor/generalization of Hoare Logic.
 - Integrated prover with interfaces to external decision procedures.
 - Simplify, CVC3, CVC4, Yices, Z3.

Now only JML is supported as a specification language.

Dynamic Logic

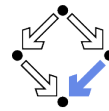


Further development of Hoare Logic to a modal logic.

- **Hoare logic:** two separate kinds of statements.
 - Formulas P, Q constraining program states.
 - Hoare triples $\{P\}C\{Q\}$ constraining state transitions.
- **Dynamic logic:** single kind of statement.
 - Predicate logic formulas extended by two kinds of modalities.
 - $[C]Q$ ($\Leftrightarrow \neg\langle C\rangle\neg Q$)
 - Every state that can be reached by the execution of C satisfies Q .
 - The statement is trivially true, if C does not terminate.
 - $\langle C\rangle Q$ ($\Leftrightarrow \neg[C]\neg Q$)
 - There exists some state that can be reached by the execution of C and that satisfies Q .
 - The statement is only true, if C terminates.

States and state transitions can be described by DL formulas.

Dynamic Logic versus Hoare Logic

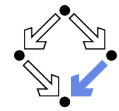


Hoare triple $\{P\}C\{Q\}$ can be expressed as a DL formula.

- **Partial correctness interpretation:** $P \Rightarrow [C]Q$
 - If P holds in the current state and the execution of C reaches another state, then Q holds in that state.
 - Equivalent to the partial correctness interpretation of $\{P\}C\{Q\}$.
- **Total correctness interpretation:** $P \Rightarrow \langle C \rangle Q$
 - If P holds in the current state, then there exists another state that can be reached by the execution of C in which Q holds.
 - If C is deterministic, there exists at most one such state; then equivalent to the total correctness interpretation of $\{P\}C\{Q\}$.

For deterministic programs, the interpretations coincide.

Advantages of Dynamic Logic

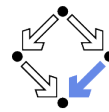


Modal formulas can also occur in the context of quantifiers.

- **Hoare Logic:** $\{x = a\} y := x * x \{x = a \wedge y = a^2\}$
 - Use of free mathematical variable a to denote the “old” value of x .
- **Dynamic logic:** $\forall a : x = a \Rightarrow [y := x * x] x = a \wedge y = a^2$
 - Quantifiers can be used to restrict the scopes of mathematical variables across state transitions.

Set of DL formulas is closed under the usual logical operations.

A Calculus for Dynamic Logic



- **A core language of commands (non-deterministic):**

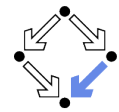
$X := T$... assignment
 $C_1; C_2$... sequential composition
 $C_1 \cup C_2$... non-deterministic choice
 C^* ... iteration (zero or more times)
 $F?$... test (blocks if F is false)

- **A high-level language of commands (deterministic):**

skip = true?
abort = false?
 $X := T$
 $C_1; C_2$
if F **then** C_1 **else** C_2 = $(F?; C_1) \cup ((\neg F)?; C_2)$
if F **then** C = $(F?; C) \cup (\neg F)?$
while F **do** C = $(F?; C)^*; (\neg F)?$

A calculus is defined for dynamic logic with the core command language.

A Calculus for Dynamic Logic



- **Basic rules:**

■ Rules for predicate logic extended by general rules for modalities.

- **Command-related rules:**

$$\frac{\Gamma \vdash F[T/X]}{\Gamma \vdash [X := T]F}$$

$$\frac{\Gamma \vdash [C_1][C_2]F}{\Gamma \vdash [C_1; C_2]F}$$

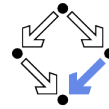
$$\frac{\Gamma \vdash [C_1]F \quad \Gamma \vdash [C_2]F}{\Gamma \vdash [C_1 \cup C_2]F}$$

$$\frac{\Gamma \vdash F \quad \Gamma \vdash [C^*](F \Rightarrow [C]F)}{\Gamma \vdash [C^*]F}$$

$$\frac{\Gamma \vdash F \Rightarrow G}{\Gamma \vdash [F?]G}$$

From these, Hoare-like rules for the high-level language can be derived.

Objects and Updates



Calculus has to deal with the pointer semantics of Java objects.

- **Aliasing:** two variables o, o' may refer to the same object.
 - Field assignment $o.a := T$ may also affect the value of $o'.a$.
- **Update formulas:** $\{o.a \leftarrow T\}F$
 - Truth value of F in state after the assignment $o.a := T$.

■ **Field assignment rule:**

$$\frac{\Gamma \vdash \{o.a \leftarrow T\}F}{\Gamma \vdash [o.a := T]F}$$

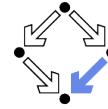
■ **Field access rule:**

$$\frac{\Gamma, o = o' \vdash F(T) \quad \Gamma, o \neq o' \vdash F(o'.a)}{\Gamma \vdash \{o.a \leftarrow T\}F(o'.a)}$$

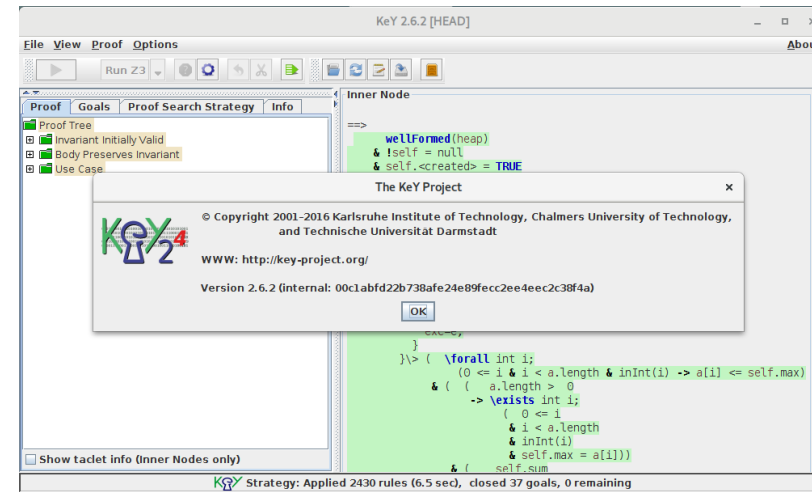
- Case distinction depending on whether o and o' refer to same object.
- Only applied as last resort (after all other rules of the calculus).

Considerable complication of verifications.

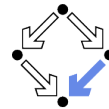
The JMLKey Prover



> Key &



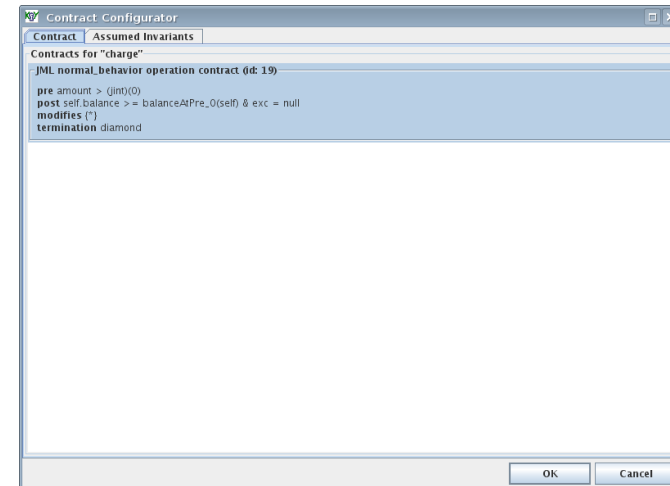
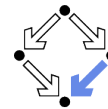
A Simple Example



File/Load Example/Getting Started/Sum and Max

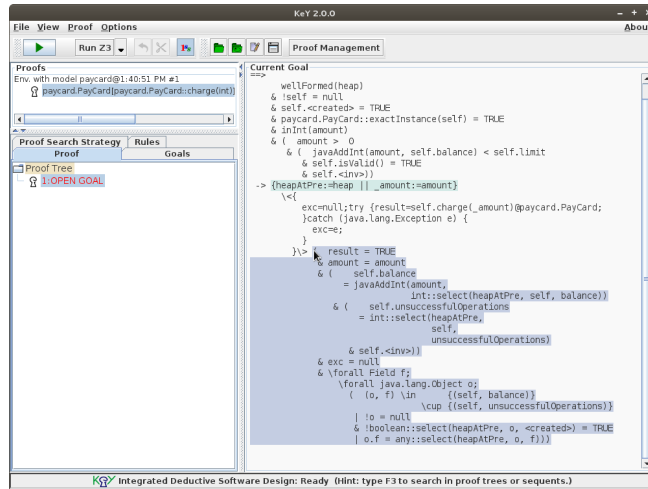
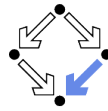
```
class SumAndMax {
    int sum; int max;
    /*@ requires (\forallall int i;
        @ 0 <= i && i < a.length; 0 <= a[i]);
        @ assignable sum, max;
        @ ensures (\forallall int i;
            @ 0 <= i && i < a.length; a[i] <= max);
        @ ensures (a.length > 0 ==>
            @ (\exists int i;
                @ 0 <= i && i < a.length;
                @ max == a[i]));
        @ ensures sum == (\sum int i;
            @ 0 <= i && i < a.length; a[i]);
        @ ensures sum <= a.length * max;
    @*/
    void sumAndMax(int[] a) {
        sum = 0;
        max = 0;
        int k = 0;
        /*@ loop_invariant
            @ 0 <= k && k <= a.length
            @ && (\forallall int i;
                @ 0 <= i && i < k; a[i] <= max)
            @ && (k == 0 ==> max == 0)
            @ && (k > 0 ==> (\exists int i;
                @ 0 <= i && i < k; max == a[i]))
            @ && sum == (\sum int i;
                @ 0 <= i && i < k; a[i])
            @ && sum <= k * max;
            @ assignable sum, max;
            @ decreases a.length - k;
        @*/
        while (k < a.length) {
            if (max < a[k]) max = a[k];
            sum += a[k];
            k++;
        } }
}
```

A Simple Example (Contd)



Generate the proof obligations and choose one for verification.

A Simple Example (Contd'2)



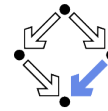
The proof obligation in Dynamic Logic.

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A Simple Example (Contd'3)



```
wellFormed(heap)
==>
true
& !self=null
& ...
& (\forallforall int i; (0 <= i & i < a.length & inInt(i) -> 0 <= a[i])
& (self.<inv> & !a = null))
-> {heapAtPre:=heap || !_a:=a}
\<{
exc=null;try {
self.sumAndMax(_a)@SumAndMax;
} catch (java.lang.Throwable e){ exc=e; }
}\>(\forallforall int i;
(0 <= i & i < a.length & inInt(i) -> a[i] <= self.max)
& (( a.length > 0
-> \exists int i;
(0 <= i & i < a.length & inInt(i) & self.max = a[i]))
& ( self.sum = javaCastInt(bsum{int i;}(0, a.length, a[i]))
& (self.sum <= javaMulInt(a.length, self.max) & self.<inv>)))
& exc = null
& \forallforall Field f;
\forallforall java.lang.Object o;
( ( o, f) \in (self,SumAndMax::$sum)
\cup {(self,SumAndMax::$max)
| !o = null
& !o.<created>@heapAtPre = TRUE
| o.f = o.f@heapAtPre))
```

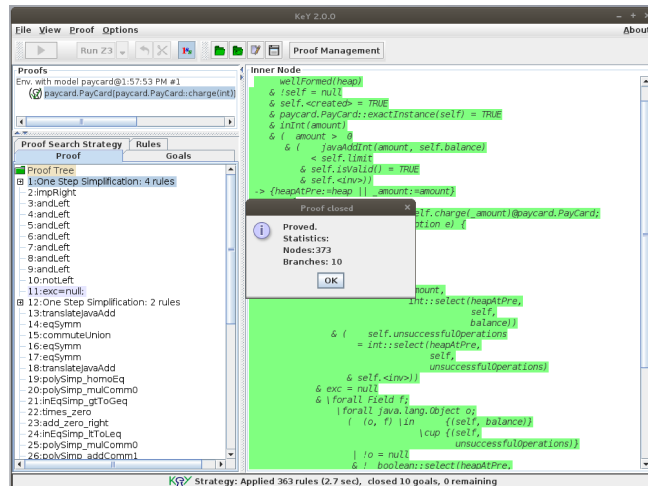
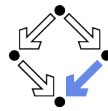
Press button "Start" (green arrow).

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A Simple Example (Contd'4)



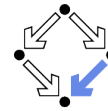
Proof runs through automatically.

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Linear Search



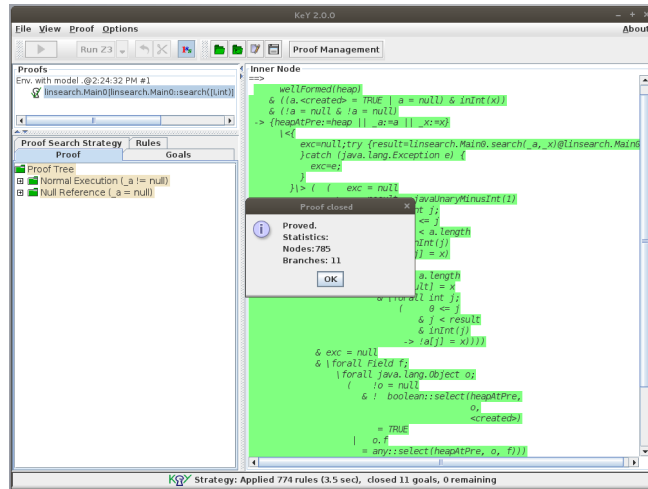
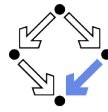
```
/*@ requires a != null;
@ assignable \nothing;
@ ensures
@ (\result == -1 &&
@ (\forallforall int j; 0 <= j && j < a.length; a[j] != x)) ||
@ (0 <= \result && \result < a.length && a[\result] == x &&
@ (\forallforall int j; 0 <= j && j < \result; a[j] != x));
@*/
public static int search(int[] a, int x) {
int n = a.length; int i = 0; int r = -1;
/*@ loop_invariant
@ a != null && n == a.length && 0 <= i && i <= n &&
@ (\forallforall int j; 0 <= j && j < i; a[j] != x) &&
@ (r == -1 || (r == i && i < n && a[r] == x));
@ decreases r == -1 ? n-i : 0;
@ assignable r, i; // required by KeY, not legal JML
@*/
while (r == -1 && i < n) {
if (a[i] == x) r = i; else i = i+1;
}
return r;
}
```

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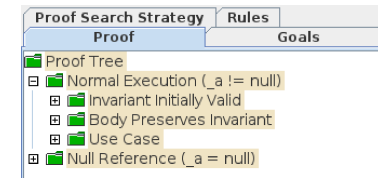
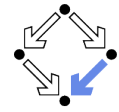
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Linear Search (Contd)



Also this verification is completed automatically.

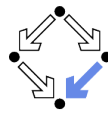
Proof Structure



- Multiple conditions:
 - Invariant initially valid.
 - Body preserves invariant.
 - Use case (invariant implies postcondition).
- If proof fails, elaborate which part causes trouble and potentially correct program, specification, loop annotations.

For a successful proof, in general multiple iterations of automatic proof search (button "Start") and invocation of separate SMT solvers required (button "Run Z3, Yices, CVC3, Simplify").

Summary



- Various academic approaches to verifying Java(Card) programs.
 - Jack: <http://www-sop.inria.fr/everest/soft/Jack/jack.html>
 - Jive: <http://www.pm.inf.ethz.ch/research/jive>
 - Mobius: <http://kindsoftware.com/products/opensource/Mobius/>
- Do not yet scale to verification of full Java applications.
 - General language/program model is too complex.
 - Simplifying assumptions about program may be made.
 - Possibly only special properties may be verified.
- Nevertheless very helpful for reasoning on Java in the small.
 - Much beyond Hoare calculus on programs in toy languages.
 - Probably all examples in this course can be solved automatically by the use of the KeY prover and its integrated SMT solvers.
- Enforce clearer understanding of language features.
 - Perhaps constructs with complex reasoning are not a good idea...

In a not too distant future, customers might demand that some critical code is shipped with formal certificates (correctness proofs)...