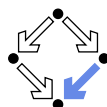


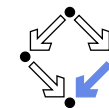
Verifying Java Programs with KeY

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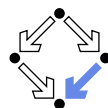
Verifying Java Programs



- **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

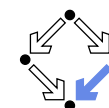


<http://www.key-project.org>

- **KeY:** environment for verification of JavaCard programs.
 - Subset of Java for smartcard applications and embedded systems.
 - Universities of Karlsruhe, Koblenz, Chalmers, 1998–
 - Beckert et al: "Verification of Object-Oriented Software: The KeY Approach", Springer, 2007. (book)
 - Ahrendt et al: "The KeY Tool", 2005. (paper)
 - Engel and Roth: "KeY Quicktour for JML", 2006. (short paper)
- **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, Yices, Z3.

We will only deal with the tool's JML interface "JMLKeY".

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

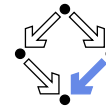


Hoare triple $\{P\}C\{Q\}$ can be expressed as a DL formula.

- **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

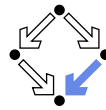


Modal formulas can also occur in the context of quantifiers.

- **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):**

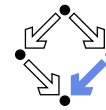
$X := T$... assignment
 $C_1; C_2$... sequential composition
 $C_1 \cup C_2$... non-deterministic choice
 C^* ... iteration (zero or more times)
 $F?$... test (blocks if F is false)

- **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:**

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

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

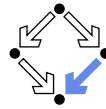
$$\frac{\Gamma \vdash [C_1]F \quad \Gamma \vdash [C_2]F}{\Gamma \vdash [C_1 \cup C_2]F}$$

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

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

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:**

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

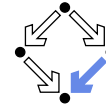
■ **Field access rule:**

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

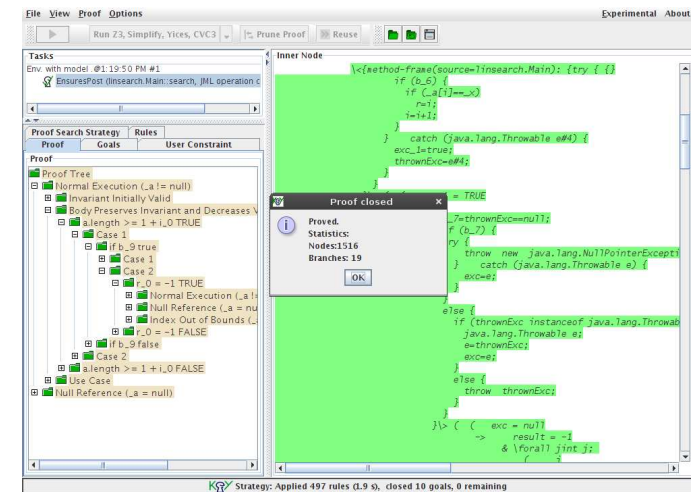
- Case distinction depending on whether o and o' refer to same object.
- Only applied as last resort (after all other rules of the calculus).

Considerable complication of verifications.

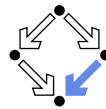
The JMLKey Prover



/zvol/formal/bin/startProver &



A Simple Example



Engel et al: "KeY Quicktour for JML", 2005.

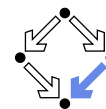
```
package paycard;
public class PayCard {
    /*@ public instance invariant
    @ log != null
    @ && balance >= 0
    @ && limit > 0
    @ && unsuccessfulOperations >= 0;
    /*/

    /*@ spec_public @*/ int limit=1000;
    /*@ spec_public @*/
    int unsuccessfulOperations;
    /*@ spec_public @*/ int id;
    /*@ spec_public @*/ int balance=0;
    /*@ spec_public @*/
    protected LogFile log;

    /*@
    @ public normal_behavior
    @ requires amount>0 ;
    @ assignable
    @ unsuccessfulOperations, balance;
    @ ensures balance >= \old(balance);
    /*/

    public boolean charge(int amount) {
        if (this.balance+amount>this.limit) {
            this.unsuccessfulOperations++;
            return false;
        } else {
            this.balance=this.balance+amount;
            return true;
        }
    }
    ...
}
```

A Simple Example (Contd)



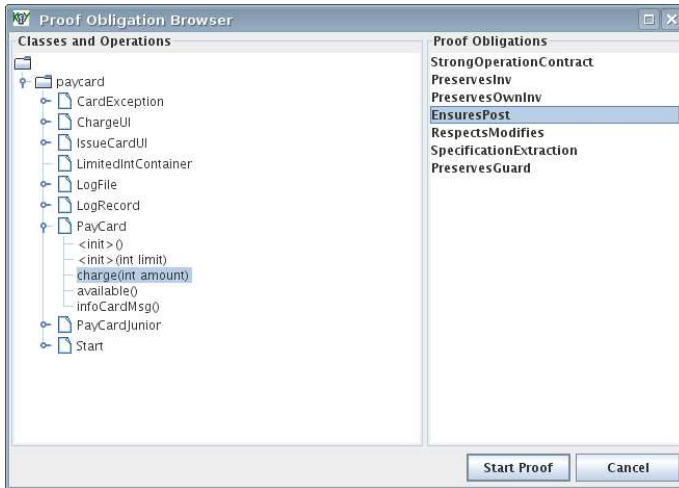
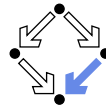
Choose in Menu "File/Load" a package directory or a KeY file.

```
// paycard.key
// This file is part of KeY - Integrated Deductive Software Design
// Copyright (C) 2001-2009 Universitaet Karlsruhe, Germany
//                               Universitaet Koblenz-Landau, Germany
//                               Chalmers University of Technology, Sweden
//
// The KeY system is protected by the GNU General Public License.
// See LICENSE.TXT for details.

\classpath "classpath";
\javaSource "paycard";
\chooseContract;
```

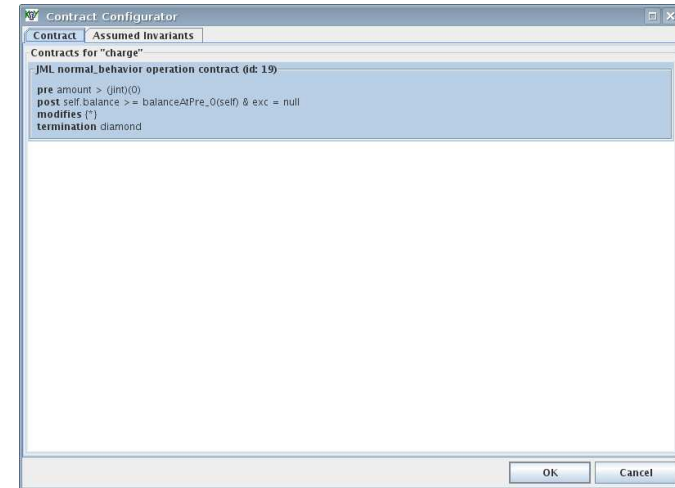
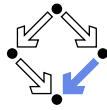
Needed (only) to look up sources of system classes.

A Simple Example (Contd'2)



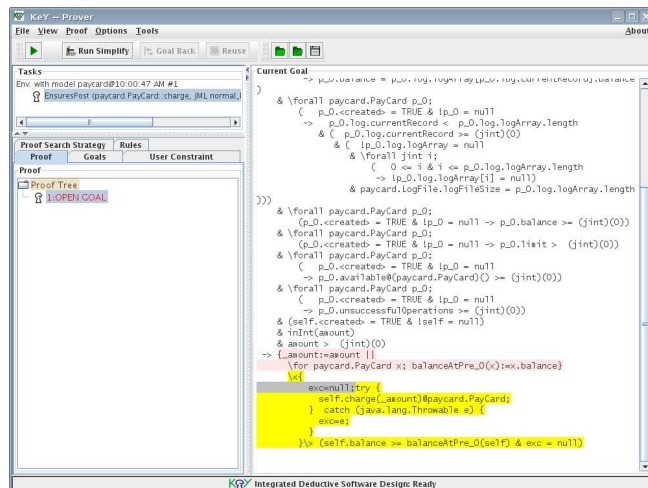
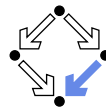
Generate the proof obligations and choose one for verification.

A Simple Example (Contd'3)



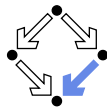
Display the chosen proof obligation and start the proof.

A Simple Example (Contd'4)



The proof obligation in Dynamic Logic.

A Simple Example (Contd'5)

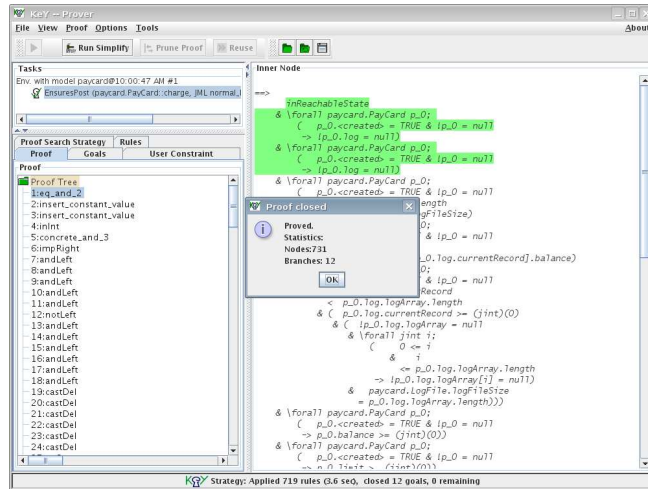
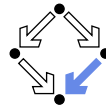


```

==>
inReachableState
-> \forall forall int amount_lv;
    {amount:=amount_lv}
    \forall forall paycard.PayCard self_PayCard_lv;
        {self_PayCard:=self_PayCard_lv}
        {_old13:=self_PayCard.balance}
        (
            !self_PayCard = null
            & self_PayCard.<created> = TRUE
            & amount > 0
            & ( !self_PayCard.log = null
                & ...
                & self_PayCard.balance >= 0
                & self_PayCard.limit > 0
                & self_PayCard.available@(paycard.PayCard)() >= 0
                & self_PayCard.unsuccessfulOperations >= 0)
        )
-> \<{ {
    self_PayCard.charge(amount)@paycard.PayCard;
} }> self_PayCard.balance >= _old13
    
```

Press button "Start" (green arrow).

A Simple Example (Contd'6)



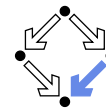
Proof runs through automatically.

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17/25

A Loop Example



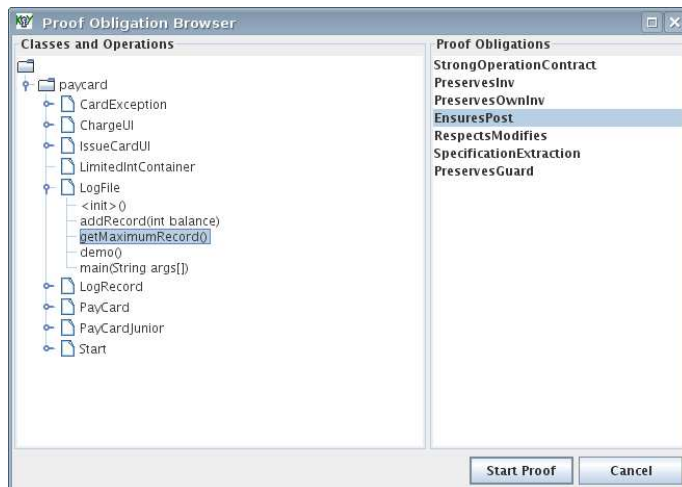
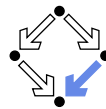
```
public class LogFile {
    /*@ public normal_behavior
       @ ensures
       @ (\forall int i; 0 <= i && i < logArray.length;
       @   logArray[i].balance <= \result.balance); */
    public /*@pure@*/
    LogRecord getMaximumRecord(){
        LogRecord max = logArray[0];
        int i=1;
        /*@ loop_invariant
           @ 0<=i && i <= logArray.length &&
           @ max!=null &&
           @ (\forall int j; 0 <= j && j<i;
           @   max.balance >= logArray[j].balance);
           @ assignable max, i;
           @ decreases logArray.length - i; */
        while(i<logArray.length){
            LogRecord lr = logArray[i++];
            if (lr.getBalance() > max.getBalance())
                max = lr;
        }
        return max;
    }
}
```

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18/25

A Loop Example (Contd)



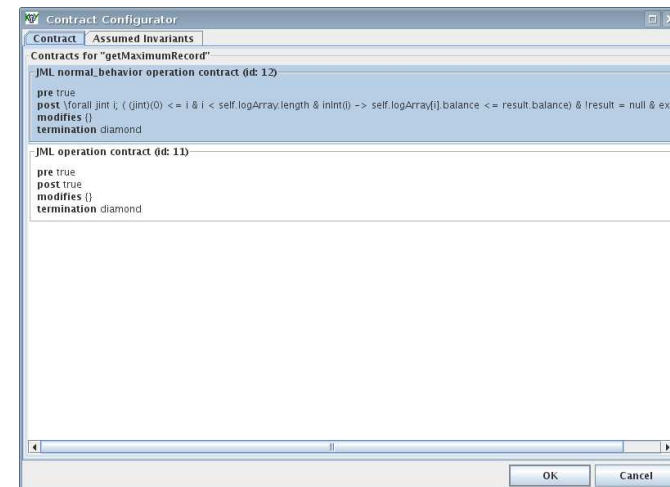
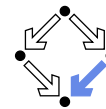
Press button "Start Proof".

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19/25

A Loop Example (Contd'2)



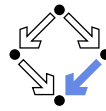
Press button "OK".

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20/25

A Loop Example (Contd'3)

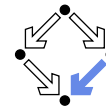


```

inReachableState
& \forall forall paycard.LogFile p_0:
  (p_0.<created> = TRUE & lp_0 = null => lp_0.logArray = null)
& \forall forall paycard.LogFile p_0:
  (p_0.<created> = TRUE & lp_0 = null => lp_0.a = null)
& \forall forall paycard.LogFile p_0:
  (p_0.<created> = TRUE & lp_0 = null => lp_0.b = null)
& \forall forall paycard.LogFile p_0:
  ( p_0.<created> = TRUE & lp_0 = null
  => p_0.logArray.length = paycard.LogFile.logFileSize
  & ( p_0.currentRecord <= paycard.LogFile.logFileSize
  & ( p_0.currentRecord >= (jint)0)
  & ( lp_0.logArray = null)
  & \forall forall jint i:
    ( 0 <= i & i <= p_0.logArray.length
    => lp_0.logArray[i] = null)))))
-> \Vc
excOrNull {
  result = self.f.getMaxiumRecord()@paycard.LogFile;
} catch (java.lang.Throwable e) {
  exc = e;
}
\forall ( \forall forall jint i:
  ( (jint)0 <= i & i <= self.logArray.length & i <= (jint)0)
  => self.logArray[i].balance <= result.balance)
& !result = null
& exc = null)
    
```

Press button "Start" (green arrow).

A Loop Example (Contd'4)

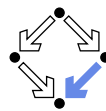


```

\forall forall jint i:
  ( p_0 = null
  | lp_0.<created> = TRUE | p_0.currentRecord >= 0,
  \forall forall paycard.LogFile p_0:
    (p_0 = null | lp_0.<created> = TRUE | p_0.currentRecord <= 2),
  self.logArray.length = 3,
  \forall forall paycard.LogFile p_0:
    (p_0 = null | lp_0.<created> = TRUE | p_0.logArray.length = 3),
  \forall forall jint i:
    ( i <= -1
    | lp_0.<created> = TRUE
    | p_0.logArray.length <= -1 + i
    | lp_0.logArray[i] = null),
  self.<created> = TRUE
  =>
  max_0 = null,
  self = null,
  self.logArray = null,
  self.logArray[i_0] = null,
  true
  & ( true
  & ( !i <= 0 || max_0 <= anon_0(i, max)
  & ( (jint)(1 + i_0) >= 0
  & ( self.logArray.length == (jint)(1 + i_0)
  & ( !max_0.<created> = TRUE
  & \forall forall jint j:
    ( j <= -1
    | j >= (jint)(1 + i_0)
    | self.logArray[j].balance <= max_0.balance)))
  & !inReachableState))
    
```

Press button "Run Simplify".

A Loop Example (Contd'5)

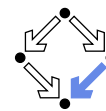


```

\forall forall jint i:
  ( i <= -1
  | p_0 = null
  | lp_0.<created> = TRUE
  | p_0.logArray.length <= -1 + i
  | lp_0.logArray[i] = null),
  self.<created> = TRUE
  =>
  self.logArray[i_0] = null,
  true
  & ( true
  & ( !i <= 0 || max_0 <= anon_0(i, max)
  & ( (jint)(1 + i_0) >= 0
  & ( !max_0.<created> = TRUE
  & \forall forall jint j:
    ( j <= -1
    | j >= (jint)(1 + i_0)
    | self.logArray[j].balance <= max_0.balance)))
  & !inReachableState))
    
```

Press button "Start" (green arrow).

A Loop Example (Contd'6)

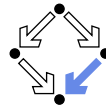


```

\forall forall jint i:
  ( p_0 = null
  | lp_0.<created> = TRUE
  | p_0.logArray.length = 3,
  \forall forall paycard.LogFile p_0:
    (p_0 = null | lp_0.<created> = TRUE | p_0.currentRecord <= 2),
  self.logArray.length = 3,
  \forall forall paycard.LogFile p_0:
    (p_0 = null | lp_0.<created> = TRUE | p_0.logArray.length = 3),
  \forall forall jint i:
    ( i <= -1
    | lp_0.<created> = TRUE
    | p_0.logArray.length <= -1 + i
    | lp_0.logArray[i] = null),
  self.<created> = TRUE
  =>
  self.logArray[i_0] = null,
  true
  & ( true
  & ( !i <= 0 || max_0 <= anon_0(i, max)
  & ( (jint)(1 + i_0) >= 0
  & ( !max_0.<created> = TRUE
  & \forall forall jint j:
    ( j <= -1
    | j >= (jint)(1 + i_0)
    | self.logArray[j].balance <= max_0.balance)))
  & !inReachableState))
    
```

Verification is successful.

Summary



- Various academic approaches to verifying Java(Card) programs.
 - Jack: <http://www-sop.inria.fr/everest/soft/Jack/jack.html>
 - Jive: <http://www.sct.ethz.ch/research/jive>
 - Mobius: <http://kind.ucd.ie/products/opensource/Mobius>
- Do not yet scale to verification of large Java applications.
 - General language/program model is too complex.
 - Simplifying assumptions about program may be made.
 - Possibly only special properties may be verified.
- Nevertheless 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)...