Verifying Java Programs with KeY

Wolfgang Schreiner
Wolfgang.Schreiner@risc.uni-linz.ac.at

Research Institute for Symbolic Computation (RISC)
Johannes Kepler University, Linz, Austria
http://www.risc.uni-linz.ac.at

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, ICS, CVC3, CVCLite, Yices, ...

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` $\{x = a \land y = a^2\}$
  - Use of free mathematical variable a to denote the "old" value of x.
- Dynamic logic: $\forall a : x = a \Rightarrow [\mathtt{y:=x*x}]\ x = a \land y = a^2$
  - 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:
  - $\dfrac{\Gamma \vdash F[T/X]}{\Gamma \vdash [X := T]F}$
  - $\dfrac{\Gamma \vdash [C_1][C_2]F}{\Gamma \vdash [C_1; C_2]F}$
  - $\dfrac{\Gamma \vdash [C_1]F \qquad \Gamma \vdash [C_2]F}{\Gamma \vdash [C_1 \cup C_2]F}$
  - $\dfrac{\Gamma \vdash F \qquad \Gamma \vdash [C^*](F \Rightarrow [C]F)}{\Gamma \vdash [C^*]F}$
  - $\dfrac{\Gamma \vdash F \Rightarrow G}{\Gamma \vdash [F?]G}$

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:

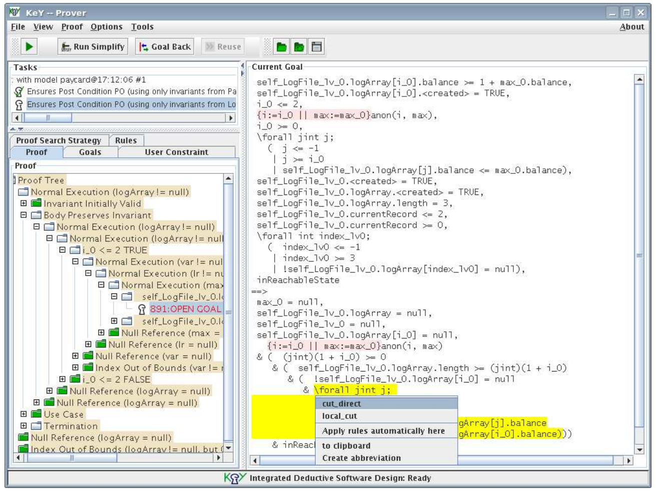
$$\frac{\Gamma, o = o' \vdash F(T) \qquad \Gamma, o \neq o' \vdash F(o'.a)}{\Gamma \vdash \{o.a \leftarrow T\}F(o'.a)}$$

    - 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 &
```



```
 self_LogFile_lv_0.logArray[i_0].balance >= 1 + max_0.balance,
 self_LogFile_lv_0.logArray[i_0].<created> = TRUE,
 i_0 <= 2,
 {i:=i_0 || max:=max_0}anon(i, max),
 i_0 >= 0,
 \forall jint j;
   (  j <= -1
    | j >= i_0
    | self_LogFile_lv_0.logArray[j].balance <= max_0.balance),
 self_LogFile_lv_0.<created> = TRUE,
 self_LogFile_lv_0.logArray.<created> = TRUE,
 self_LogFile_lv_0.logArray.length = 3,
 self_LogFile_lv_0.currentRecord <= 2,
 self_LogFile_lv_0.currentRecord >= 0,
 \forall int index_lv0;
   (  index_lv0 <= -1
    | index_lv0 >= 3
    | !self_LogFile_lv_0.logArray[index_lv0] = null),
 inReachableState
==>
 max_0 = null,
 self_LogFile_lv_0.logArray = null,
 self_LogFile_lv_0 = null,
 self_LogFile_lv_0.logArray[i_0] = null,
   {i:=i_0 || max:=max_0}anon(i, max)
 & (  (jint)(1 + i_0) >= 0
   & (  self_LogFile_lv_0.logArray.length >= (jint)(1 + i_0)
     & (  !self_LogFile_lv_0.logArray[i_0] = null
        & \forall jint j;
                                 gArray[j].balance
                                 gArray[i_0].balance))
   & inReac
```

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;
  }
}

  ...
}
```

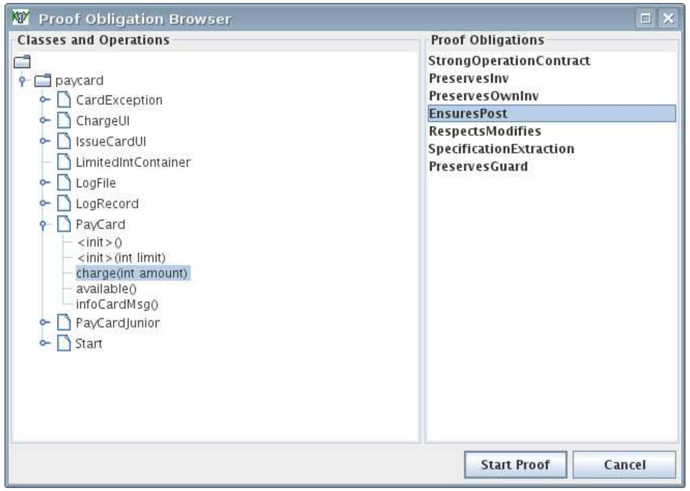
A Simple Example (Contd)

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;
```

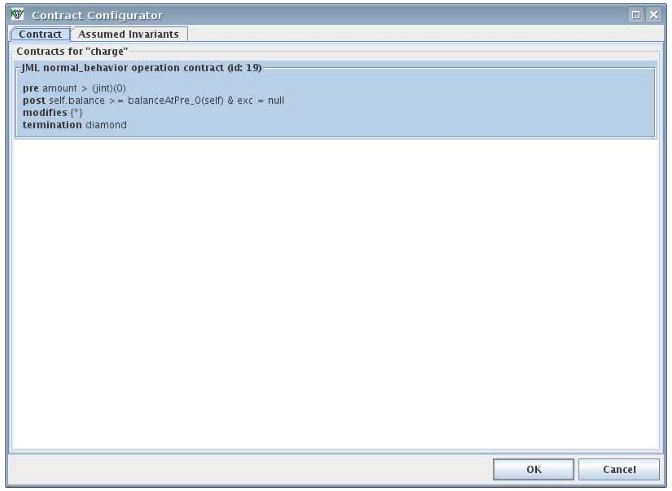
Needed (only) to look up sources of system classes.

A Simple Example (Contd'2)



Generate the proof obligations and choose one for verification.

A Simple Example (Contd'3)



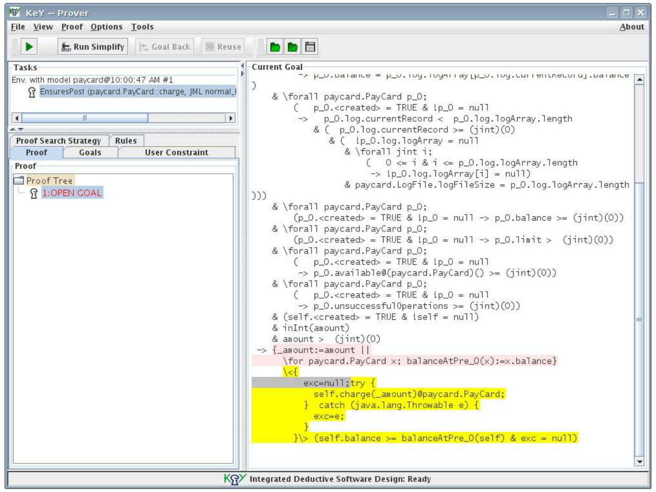
Contracts for "charge"

JML normal_behavior operation contract (id: 19)

pre amount > (jint)(0)
post self.balance >= balanceAtPre_0(self) & exc = null
modifies {*}
termination diamond

Display the chosen proof obligation and start the proof.

A Simple Example (Contd'4)



```
        -> p_0.balance = p_0.log.logArray[p_0.log.currentRecord].balance
)
   & \forall paycard.PayCard p_0;
       (   p_0.<created> = TRUE & !p_0 = null
        ->   p_0.log.currentRecord <  p_0.log.logArray.length
           & (  p_0.log.currentRecord >= (jint)(0)
             & (  !p_0.log.logArray = null
                & \forall jint i;
                    (   0 <= i & i <= p_0.log.logArray.length
                     -> !p_0.log.logArray[i] = null)
                & paycard.LogFile.logFileSize = p_0.log.logArray.length
)))
   & \forall paycard.PayCard p_0;
       (p_0.<created> = TRUE & !p_0 = null -> p_0.balance >= (jint)(0))
   & \forall paycard.PayCard p_0;
       (p_0.<created> = TRUE & !p_0 = null -> p_0.limit >  (jint)(0))
   & \forall paycard.PayCard p_0;
       (   p_0.<created> = TRUE & !p_0 = null
        -> p_0.available@(paycard.PayCard)() >= (jint)(0))
   & \forall paycard.PayCard p_0;
       (   p_0.<created> = TRUE & !p_0 = null
        -> p_0.unsuccessfulOperations >= (jint)(0))
   & (self.<created> = TRUE & !self = null)
   & inInt(amount)
   & amount >  (jint)(0)
 -> {_amount:=amount ||
      \for paycard.PayCard x; balanceAtPre_0(x):=x.balance}
      \<{
          exc=null;try {
            self.charge(_amount)@paycard.PayCard;
          }  catch (java.lang.Throwable e) {
            exc=e;
          }
        }\> (self.balance >= balanceAtPre_0(self) & exc = null)
```

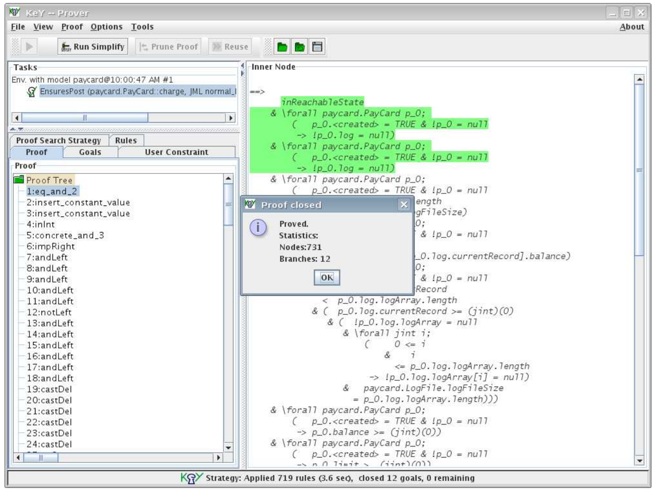
The proof obligation in Dynamic Logic.

A Simple Example (Contd'5)

```
==>
    inReachableState
 -> \forall int amount_lv;
      {amount:=amount_lv}
        \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 automated proof search".

A Simple Example (Contd'6)



Env. with model paycard@10:00:47 AM #1

EnsuresPost (paycard.PayCard::charge, JML normal_

```
Proof Tree
1:eq_and_2
2:insert_constant_value
3:insert_constant_value
4:inInt
5:concrete_and_3
6:impRight
7:andLeft
8:andLeft
9:andLeft
10:andLeft
11:andLeft
12:notLeft
13:andLeft
14:andLeft
15:andLeft
16:andLeft
17:andLeft
18:andLeft
19:castDel
20:castDel
21:castDel
22:castDel
23:castDel
24:castDel
```

```
==>
    inReachableState
  & \forall paycard.PayCard p_0;
      (   p_0.<created> = TRUE & !p_0 = null
       -> !p_0.log = null)
  & \forall paycard.PayCard p_0;
      (   p_0.<created> = TRUE & !p_0 = null
       -> !p_0.log = null)
  & \forall paycard.PayCard p_0;
      (   p_0.<created> = TRUE & !p_0 = null
                                  ength
                                  gFileSize)
                                  0;
                                  & !p_0 = null

                                  _0.log.currentRecord].balance)
                                  0;
                                  & !p_0 = null
                                  Record
              <  p_0.log.logArray.length
            & (  p_0.log.currentRecord >= (jint)(0)
              & (  !p_0.log.logArray = null
                & \forall jint i;
                    (     0 <= i
                      &     i
                         <= p_0.log.logArray.length
                     -> !p_0.log.logArray[i] = null)
                &   paycard.LogFile.logFileSize
                  = p_0.log.logArray.length)))
  & \forall paycard.PayCard p_0;
      (   p_0.<created> = TRUE & !p_0 = null
       -> p_0.balance >= (jint)(0))
  & \forall paycard.PayCard p_0;
      (   p_0.<created> = TRUE & !p_0 = null
       -> p_0.limit >  (jint)(0))
```

Proved.
Statistics:
Nodes:731
Branches: 12

Strategy: Applied 719 rules (3.6 sec), closed 12 goals, 0 remaining

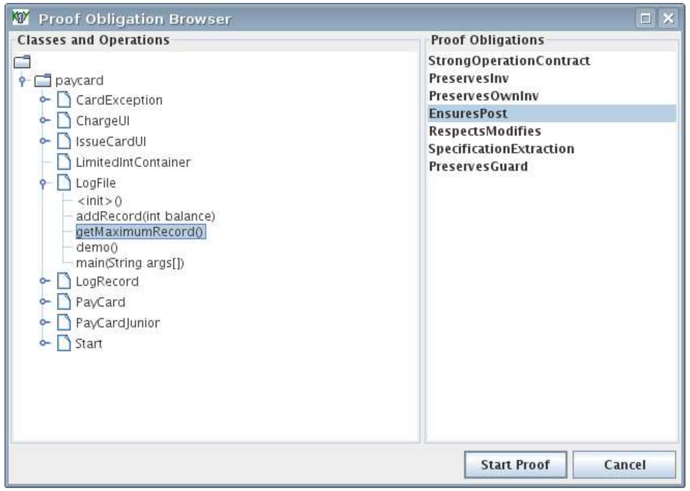
Proof runs through automatically.

A Loop Example

```
public class LogFile {

/*@ public invariant
  @ logArray.length
  @    == logFileSize &&
  @ currentRecord < logFileSize
  @ && currentRecord >= 0 &&
  @ \nonnullelements(logArray);
  @*/
private /*@ spec_public @*/
  static int logFileSize = 3;
private /*@ spec_public @*/
  int currentRecord;
private /*@ spec_public @*/
  LogRecord[] logArray =
  new LogRecord[logFileSize];

...
```

```
/*@ 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;
}
```

A Loop Example (Contd)

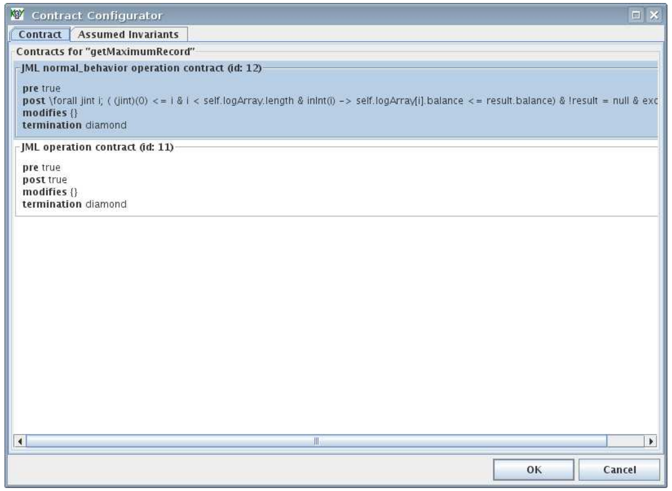


```
paycard
  CardException
  ChargeUI
  IssueCardUI
  LimitedIntContainer
  LogFile
    <init>()
    addRecord(int balance)
    getMaximumRecord()
    demo()
    main(String args[])
  LogRecord
  PayCard
  PayCardJunior
  Start
```

```
StrongOperationContract
PreservesInv
PreservesOwnInv
EnsuresPost
RespectsModifies
SpecificationExtraction
PreservesGuard
```

Press button "Start Proof".

A Loop Example (Contd'2)



Contracts for "getMaximumRecord"

JML normal_behavior operation contract (id: 12)

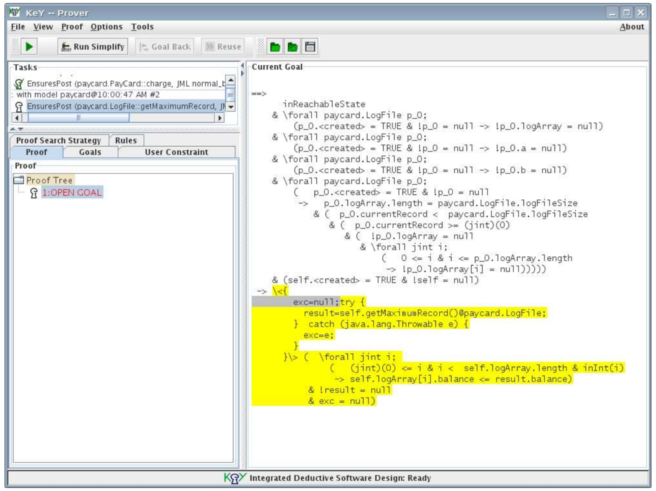
pre true
post \forall jint i; ((jint)(0) <= i & i < self.logArray.length & inInt(i) -> self.logArray[i].balance <= result.balance) & !result = null & exc
modifies {}
termination diamond

JML operation contract (id: 11)

pre true
post true
modifies {}
termination diamond

Press button "OK".

A Loop Example (Contd'3)



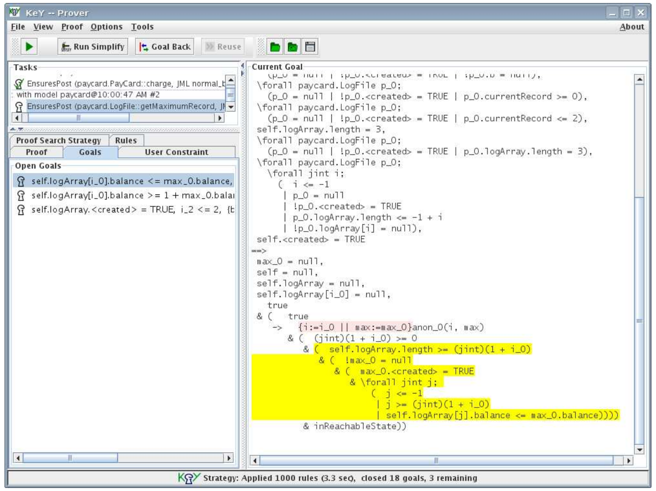
EnsuresPost (paycard.PayCard::charge, JML normal_b
with model paycard@10:00:47 AM #2
EnsuresPost (paycard.LogFile::getMaximumRecord, JM

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

Integrated Deductive Software Design: Ready

Press button "Start automated proof search".

A Loop Example (Contd'4)



EnsuresPost (paycard.PayCard::charge, JML normal_b
with model paycard@10:00:47 AM #2
EnsuresPost (paycard.LogFile::getMaximumRecord, JM

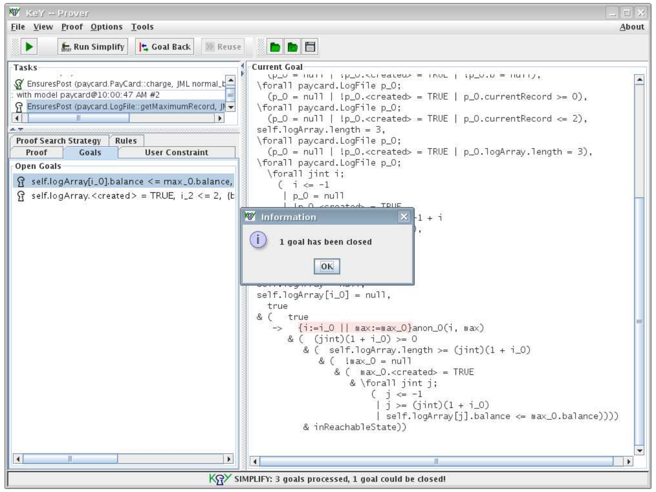
self.logArray[i_0].balance <= max_0.balance,
self.logArray[i_0].balance >= 1 + max_0.balan
self.logArray.<created> = TRUE, i_2 <= 2, {b

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

Strategy: Applied 1000 rules (3.3 sec), closed 18 goals, 3 remaining

Press button "Simplify".

A Loop Example (Contd'5)



EnsuresPost (paycard.PayCard::charge, JML normal_b
with model paycard@10:00:47 AM #2
EnsuresPost (paycard.LogFile::getMaximumRecord, JM

self.logArray[i_0].balance <= max_0.balance,
self.logArray.<created> = TRUE, i_2 <= 2, {b

```
\forall paycard.LogFile p_0;
  (p_0 = null | !p_0.<created> = TRUE | p_0.currentRecord >= 0),
\forall paycard.LogFile p_0;
  (p_0 = null | !p_0.<created> = TRUE | p_0.currentRecord <= 2),
self.logArray.length = 3,
\forall paycard.LogFile p_0;
  (p_0 = null | !p_0.<created> = TRUE | p_0.logArray.length = 3),
\forall paycard.LogFile p_0;
  \forall jint i;
    (  i <= -1
     | p_0 = null
```

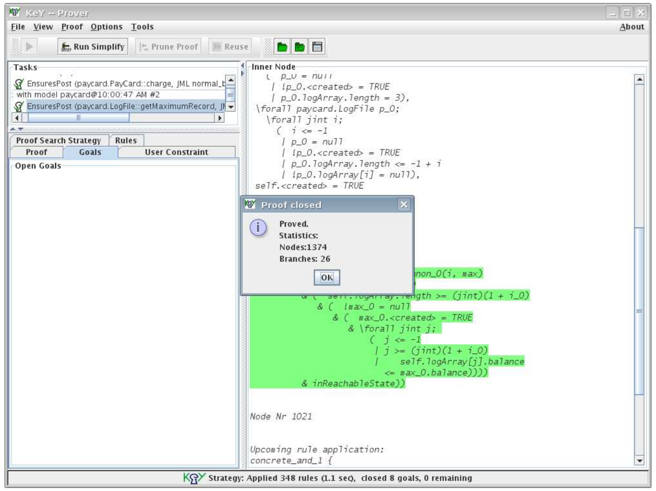
1 goal has been closed

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

SIMPLIFY: 3 goals processed, 1 goal could be closed!

Press button "Start automated proof search".

A Loop Example (Contd'6)



EnsuresPost (paycard.PayCard::charge, JML normal_b
with model paycard@10:00:47 AM #2
EnsuresPost (paycard.LogFile::getMaximumRecord, JM

```
   | !p_0.<created> = TRUE
   | p_0.logArray.length = 3),
\forall paycard.LogFile p_0;
  \forall jint i;
    (  i <= -1
     | p_0 = null
     | !p_0.<created> = TRUE
     | p_0.logArray.length <= -1 + i
     | !p_0.logArray[i] = null),
self.<created> = TRUE
```

Proved.
Statistics:
Nodes:1374
Branches: 26

```
               & (  !max_0 = null
                  & (  max_0.<created> = TRUE
                     & \forall jint j;
                         (  j <= -1
                          | j >= (jint)(1 + i_0)
                          |     self.logArray[j].balance
                            <= max_0.balance))))
         & inReachableState))


Node Nr 1021


Upcoming rule application:
concrete_and_1 {
```

Strategy: Applied 348 rules (1.1 sec), closed 8 goals, 0 remaining

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.
  - Beyond Hoare calculus on programs in toy languages.
- Enforce clearer understanding of language features.
  - Perhaps constructs with complex reasoning are not a good idea. . .
- Trend: modularization of reasoning.

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