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: $\forall a : x = a \Rightarrow [\texttt{y:=x*x}]\ x = a \wedge y = a^2$
  - 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:
  - $$\frac{\Gamma \vdash F[T/X]}{\Gamma \vdash [X := T]F}$$
  - $$\frac{\Gamma \vdash [C_1][C_2]F}{\Gamma \vdash [C_1; C_2]F}$$
  - $$\frac{\Gamma \vdash [C_1]F \qquad \Gamma \vdash [C_2]F}{\Gamma \vdash [C_1 \cup C_2]F}$$
  - $$\frac{\Gamma \vdash F \qquad \Gamma \vdash F \Rightarrow [C]F}{\Gamma \vdash [C^*]F}$$
  - $$\frac{\Gamma \vdash F \Rightarrow G}{\Gamma \vdash [F?]G}$$

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:

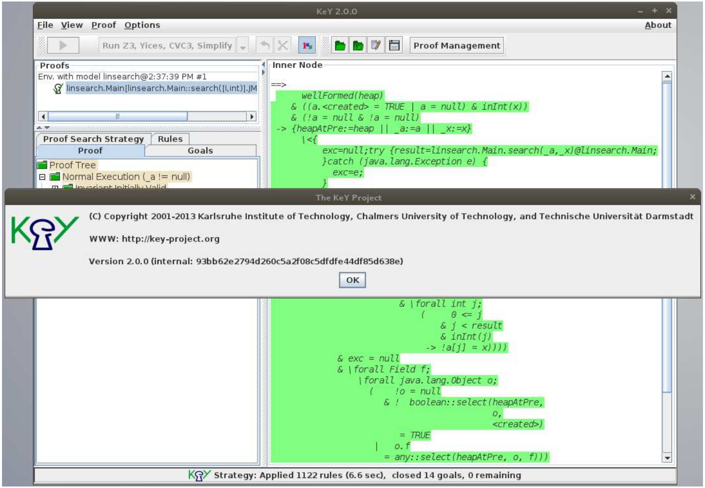
$$\frac{\Gamma, o = o' \;\vdash\; F(T) \qquad \Gamma, o \neq o' \;\vdash\; F(o'.a)}{\Gamma \;\vdash\; \{o.a \leftarrow T\}F(o'.a)}$$

  - 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 &`



A Simple Example

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

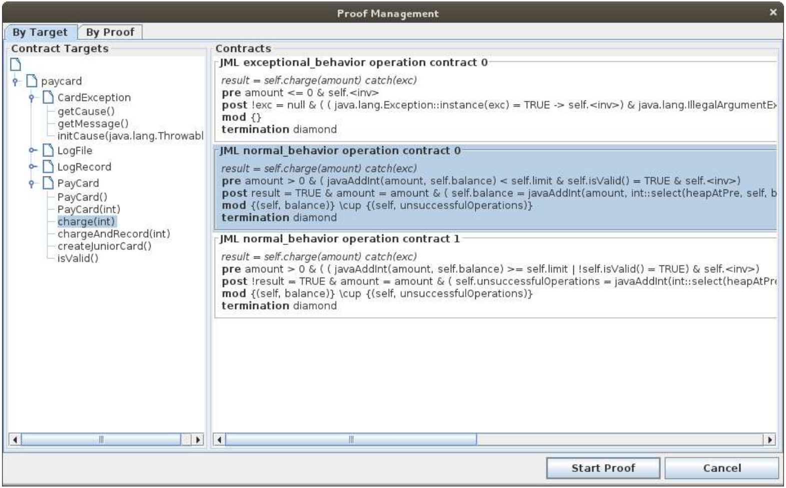
```
package paycard;

public class PayCard {
/*@ public invariant log.\inv;
  @ public invariant balance >= 0;
  @ public invariant limit > 0;
  @ public invariant unsucc >= 0;
  @ public invariant log != null;
  @*/

/*@ spec_public @*/ int limit=1000;
/*@ spec_public @*/ int unsucc;
/*@ spec_public @*/ int id;
/*@ spec_public @*/ int balance=0;
/*@ spec_public @*/
      protected LogFile log;
...
```

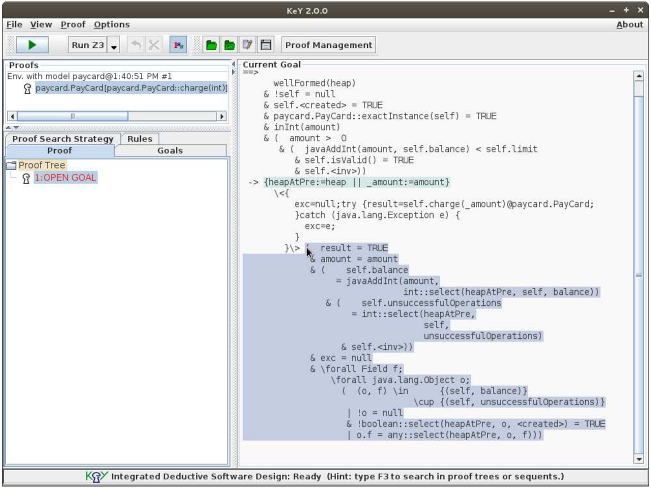
```
/*@ public normal_behavior
  @ requires amount>0;
  @ requires amount+balance<limit && isValid(
  @ ensures \result == true;
  @ ensures balance == amount+\old(balance);
  @ ensures unsucc == \old(unsucc);
  @ assignable balance, unsucc;
  @ also ...
  @*/
public boolean charge(int amount)
  throws IllegalArgumentException {
  if (amount <= 0)
    throw new IllegalArgumentException();
  if (balance+amount<limit && isValid()) {
    balance=balance+amount;
    return true;
  }
 ...
}
```

A Simple Example (Contd)



Generate the proof obligations and choose one for verification.

A Simple Example (Contd'2)



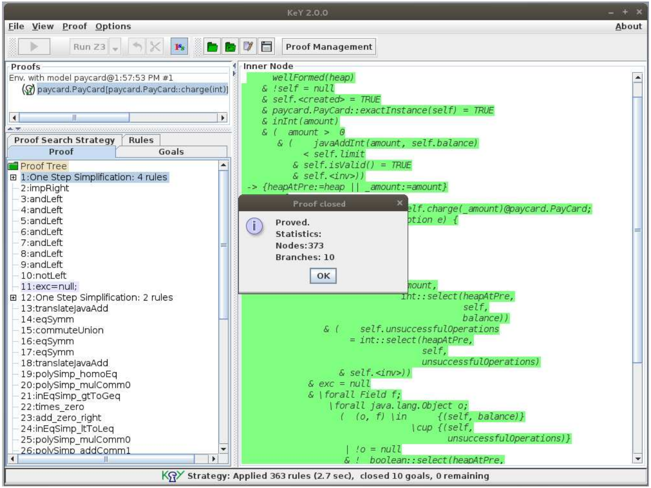
The proof obligation in Dynamic Logic.

A Simple Example (Contd'3)

```
==>
      wellFormed(heap)
    & !self = null & ...
    & (  amount >  0
       & (  javaAddInt(amount, self.balance) < self.limit
          & self.isValid() = TRUE & self.<inv>))
 -> {heapAtPre:=heap || _amount:=amount}
      \<{
          exc=null;try {result=self.charge(_amount)@paycard.PayCard;
          }catch (java.lang.Exception e) {exc=e;}
        }\> (  result = TRUE
             & amount = amount
             & (    self.balance
                  = javaAddInt(amount,
                               int::select(heapAtPre, self, balance))
                & (    self.unsucc
                     = int::select(heapAtPre,
                                   self,
                                   unsucc)
                  & self.<inv>))
             & exc = null & ...
```

Press button "Start" (green arrow).

A Simple Example (Contd'4)

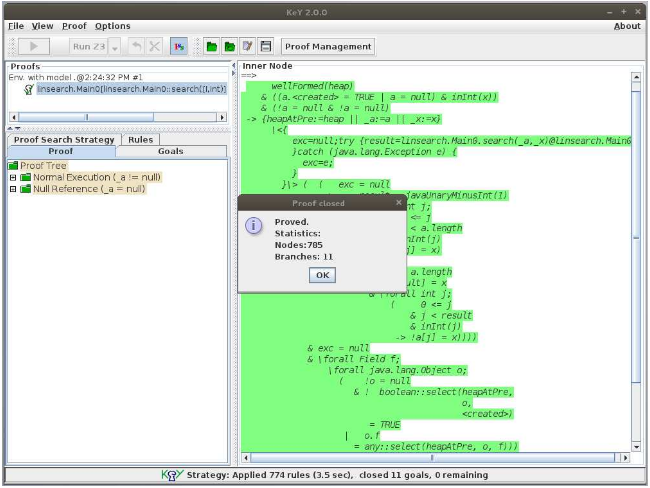


Proof runs through automatically.

A Loop Example

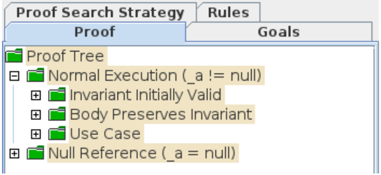
```
/*@ requires a != null;
  @ assignable \nothing;
  @ ensures
  @   (\result == -1 &&
  @     (\forall int j; 0 <= j && j < a.length; a[j] != x)) ||
  @   (0 <= \result && \result < a.length && a[\result] == x &&
  @     (\forall int j; 0 <= j && j < \result; a[j] != x));
  @*/
public static int search(int[] a, int x) {
  int n = a.length; int i = 0; int r = -1;
  /*@ loop_invariant
    @   a != null && n == a.length && 0 <= i && i <= n &&
    @   (\forall 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;
}
```

A Loop Example (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)...