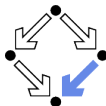
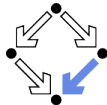


Verifying Java Programs with KeY

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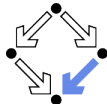


Verifying Java Programs

- **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.

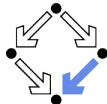
The KeY Tool



<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: “Deductive Software Verification – The KeY Book: From Theory to Practice”, Springer, 2016.
 - “Chapter 16: Formal Verification with KeY: A Tutorial”
- **Specification language:** JML.
 - Original: OCL (Object Constraint Language), part of UML standard.
- **Logical framework:** Dynamic Logic (DL).
 - Successor/generalization of Hoare Logic.
 - Integrated prover with interfaces to external decision procedures.
 - Z3, CVC4, CVC5.

Now only JML is supported as a specification language.



Further development of Hoare Logic to a modal logic.

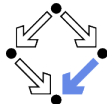
- **Hoare logic:** two separate kinds of statements.
 - Formulas P, Q constraining program states.
 - Hoare triples $\{P\}C\{Q\}$ constraining state transitions.
- **Dynamic logic:** single kind of statement.

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.

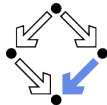
Dynamic Logic versus Hoare Logic



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.

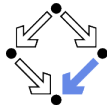


Advantages of Dynamic Logic

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

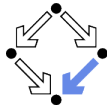
■ A core language of commands (non-deterministic):

$X := T$... 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:

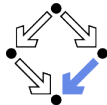
- Rules for predicate logic extended by general rules for modalities.

■ Command-related rules:

- $$\frac{\Gamma \vdash F[T/X]}{\Gamma \vdash [X := T]F}$$
- $$\frac{\Gamma \vdash [C_1][C_2]F}{\Gamma \vdash [C_1; C_2]F}$$
- $$\frac{\Gamma \vdash [C_1]F \quad \Gamma \vdash [C_2]F}{\Gamma \vdash [C_1 \cup C_2]F}$$
- $$\frac{\Gamma \vdash F \Rightarrow [C]F}{\Gamma \vdash F \Rightarrow [C^*]F}$$
- $$\frac{\Gamma \vdash F \Rightarrow G}{\Gamma \vdash [F?]G}$$

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:**

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

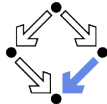
- **Field access rule:**

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

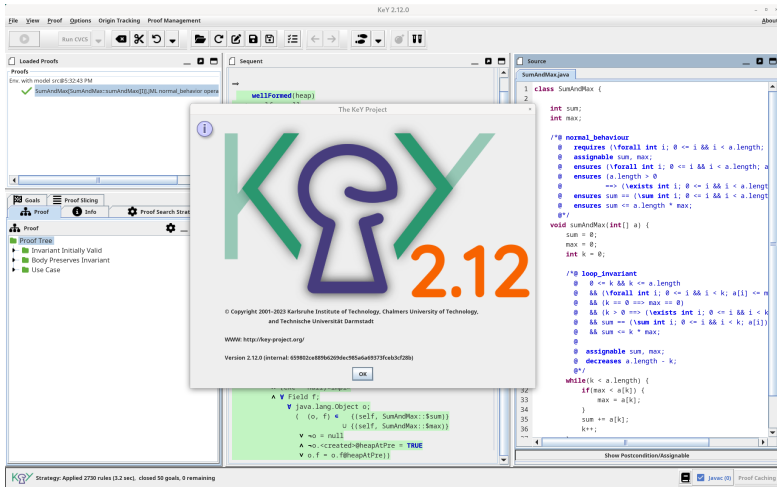
- Case distinction depending on whether o and o' refer to same object.
- Only applied as last resort (after all other rules of the calculus).

Considerable complication of verifications.

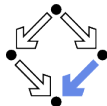
The KeY Prover



> KeY &



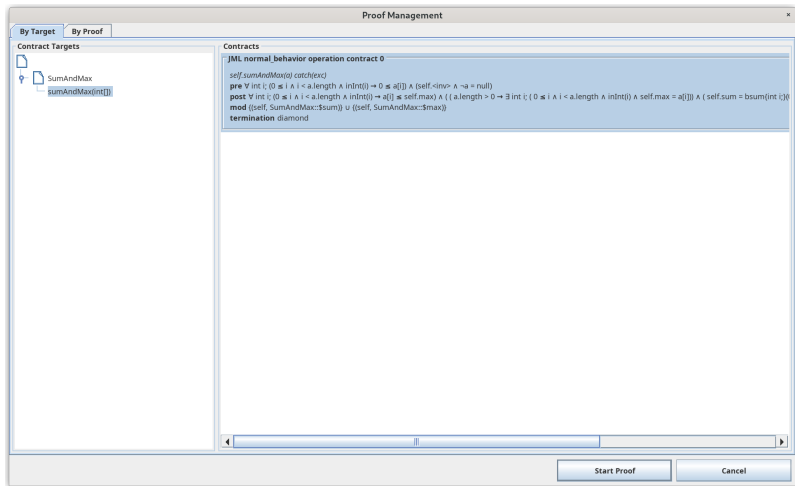
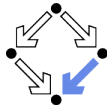
A Simple Example



File/Load Example/Getting Started/Sum and Max

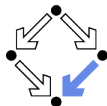
```
class SumAndMax {
    int sum; int max;
    /*@ requires (\forall int i;
        @ 0 <= i && i < a.length; 0 <= a[i]);
        @ assignable sum, max;
        @ ensures (\forall int i;
            @ 0 <= i && i < a.length; a[i] <= max);
        @ ensures (a.length > 0 ==>
            @ (\exists int 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
            @ && (\forall 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 screenshot displays the KeY 2.12.0 IDE interface. The main window is divided into several panes:

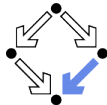
- Left Pane:** Contains a 'Goals' tab with a list of loaded proofs. Below it, a 'Proof Tree' tab shows a tree structure with a goal labeled 'OPEN GOAL'.
- Center Pane:** Displays the source code of the `SumAndMax` class. The code includes a `wellformed` method and a `sumAndMax` method. The `wellformed` method contains a loop that iterates over the array `a` and updates `sum` and `max`. The `sumAndMax` method calls `wellformed` and returns the `sum`.
- Right Pane:** Shows the proof obligations for the `wellformed` method. The obligations are listed as a sequence of steps, including `assignable`, `ensures`, and `loop_invariant`. The obligations are numbered 1 through 26.

The `wellformed` method code is as follows:

```
wellformed(heap)
A {self = null
  A self.<created> = TRUE
  A SumAndMax::exactInstance(self) = TRUE
  A {a = null ∨ a.<created> = TRUE} <SC>
  A measuredByEmpty
  A { ∨ int i;
    { 0 ≤ i ∧ i < a.length } <SC> a.inInt(i) - 0 ≤ a[i]
    A { (self.<inv>impl) ∧ (a = null) <impl> <SC> } <SC>
    - { heapAtPre: heap [i, a] }
    {
      exc = null;
      try {
        self.sumAndMax(a) @ SumAndMax;
      } catch (java.lang.Throwable e) {
        exc = e;
      }
    }
  }
  A { ∨ int i;
    { 0 ≤ i ∧ i < a.length } <SC> a.inInt(i)
    A {
      self.sum
      = bsum(int i; 0, a.length, a[i])
      A { (self.sum ≤ a.length * self.max
        A self.<inv>impl <SC> } <SC> } <SC> } <SC>
    A { exc = null } <impl>
    A Field f;
    ∨ java.lang.Object o;
    { (o, f) ∈ ((self, SumAndMax::sum))
      ∨ ((self, SumAndMax::max))
      ∨ o = null
      ∨ o.<created> @ heapAtPre = TRUE
      ∨ o.f = 0. @ heapAtPre }
```

The proof obligation in Dynamic Logic.

Proof Obligation



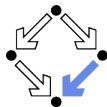
Two lists of formulas separated by a horizontal line.

$$\begin{array}{c} A_1 \\ \dots \\ A_n \\ \hline B_1 \\ \dots \\ B_m \end{array}$$

- **Interpretation:** $(A_1 \wedge \dots \wedge A_n) \Rightarrow (B_1 \vee \dots \vee B_m)$.
 - Proof is completed if some A_i is false or some B_j is true.
- All formulas are *unnegated*:
 - $(A_1 \wedge \neg A_2) \Rightarrow (B_1 \vee B_2) \rightsquigarrow A_1 \Rightarrow (B_1 \vee B_2 \vee A_2)$
 - $(A_1 \wedge A_2) \Rightarrow (B_1 \vee \neg B_2) \rightsquigarrow (A_1 \wedge A_2 \wedge B_2) \Rightarrow B_1$

A formula below the line may represent a “negated assumption”;
a formula above the line may represent a “negated goal”:

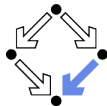
A Simple Example (Contd'3)



```
==>
    wellFormed(heap)
& ...
& (( \forall int i;
      ((0 <= i & i < a.length) & inInt(i) -> 0 <= a[i])
      & ((self_25.<inv> & (!a = null))))))
-> {heapAtPre_0:=heap || _a:=a}
  \<{
    exc_25=null;try {
      self_25.sumAndMax(_a)@SumAndMax;
    } catch (java.lang.Throwable e) { exc_25=e; }
  }> ( (\forall int i;
        ( (0 <= i & i < a.length) & inInt(i) -> a[i] <= self_25.max)
        & (( ( a.length > 0
              -> \exists int i;
                (( (0 <= i & i < a.length) & inInt(i) & self_25.max = a[i]))
                & (( self_25.sum = javaCastInt(bsum{int i;}(0, a.length, a[i]))
                    & (( self_25.sum <= javaMulInt(a.length, self_25.max)
                        & self_25.<inv>))))))))
        & (exc_25 = null)
        & \forall Field f;
          \forall java.lang.Object o;
            ( (o, f) \in {(self_25, SumAndMax::$sum)}
              \cup {(self_25, SumAndMax::$max)}
              | !o = null
              & !o.<created>@heapAtPre_0 = TRUE
              | o.f = o.f@heapAtPre_0))
```

Press button “Start/stop automated proof search” (green arrow).

A Simple Example (Contd'4)



Proof Statistics

Proved.	
Nodes	2,780
Branches	50
Interactive steps	0
Symbolic execution steps	219
Automode time	3032ms
Avg. time per step	1.091ms
Rule applications	
Quantifier instantiations	12
One-step Simplifier apps	360
SMT solver apps	0
Dependency Contract apps	0
Operation Contract apps	0
Block/Loop Contract apps	0
Loop invariant apps	1
Merge Rule apps	0
Total rule apps	4,842

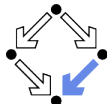
Buttons: Close, Export as CSV, Export as HTML, Save proof, Save proof bundle

Source

```
SumAndMax.java
1  /*@ task,
2
3  4  /*@ normal_behaviour
5  6  @ requires (\forall int i; 0 <= i && i < a.length;
6  7  @ assignable sum, max;
7  8  @ ensures (\forall int i; 0 <= i && i < a.length; a
8  9  @ ensures (a.length > 0
9  10  ==> (\exists int i; 0 <= i && i < a.length
10 11 @ ensures sum == (\sum int i; 0 <= i && i < a.length
11 12 @ ensures sum <= a.length * max;
12 13
13 14 */
14 15 void sumAndMax(int[] a) {
15 16     sum = 0;
16 17     max = 0;
17 18     int k = 0;
18 19
19 20     /*@ loop_invariant
20 21     @ 0 <= k && k <= a.length
21 22     @&& (\forall int i; 0 <= i && i < k; a[i] <= max
22 23     @&& (k > 0 ==> max == 0)
23 24     @&& (k > 0 ==> (\exists int i; 0 <= i && i < k
24 25     @&& sum == (\sum int i; 0 <= i && i < k; a[i])
25 26     @&& sum <= k * max;
26 27     @
27 28     @ assignable sum, max;
28 29     @ decreases a.length - k;
29 30     */
30 31     while(k < a.length) {
31 32         if(max < a[k]) {
32 33             max = a[k];
33 34         }
34 35         sum += a[k];
35 36         k++;
36 37     }
37 38 }
38 39
39 40
40 41
41 42
42 43
43 44
44 45
45 46
46 47
47 48
48 49
49 50
```

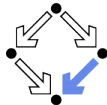
The proof runs through automatically.

Linear Search



```
/*@ 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;
}
```

Linear Search (Contd)



Proof Statistics

Proved.	
Nodes	843
Branches	15
Interactive steps	0
Symbolic execution steps	110
Automate time	1197ms
Avg. time per step	1.421ms

Rule applications	
Quantifier instantiations	1
One-step Simplifier apps	129
SMT solver apps	0
Dependency Contract apps	0
Operation Contract apps	0
Block/Loop Contract apps	0
Loop Invariant apps	1
Merge Rule apps	0
Total rule apps	2,062

Buttons: Close, Export as CSV, Export as HTML, Save proof, Save proof bundle

Proof Tree

- Normal Execution (a != null)
- Invariant Initially Valid
- Body Preserves Invariant
- Use Case
- Null Reference (a == null)

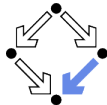
Source

```
1 package linearch;
2
3 public class Main0
4 {
5     /* requires a != null;
6      * assignable <nothing>;
7      * ensures
8      *   @ (\result == -1 &&
9      *     (\forallall int j; 0 <= j && j < a.length; a[j] != x))
10     *   @ (0 <= \result && \result < a.length && a[\result] ==
11     *     (\forallall int j; 0 <= j && j < \result; a[j] != x));
12     */
13     public static int search(int[] a, int x)
14     {
15         int n = a.length;
16         int i = 0;
17         int r = -1;
18         /* loop_invariant
19          *   @ a != null && n == a.length &&
20          *   @ 0 <= i && i <= n &&
21          *   @ (\forallall int j; 0 <= j && j < i; a[j] != x) &&
22          *   @ (x == -1 || (x == i && i < n && a[i] == x));
23          *   @ decreases r == -1 ? n-1 : 0;
24          *   @ assignable r,i;
25          */
26         while (x == -1 && i < n)
27         {
28             if (a[i] == x)
29                 r = i;
30             else
31                 i = i+1;
32         }
33         return r;
34     }
35 }
36
```

Strategy: Applied 828 rules (1.1 sec), closed 15 goals, 0 remaining

Also this verification is completed automatically.

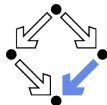
Proof Structure



- Multiple conditions (Taclet option “javaLoopTreatment::teaching”):
 - Invariant Initially Valid.
 - Body Preserves Invariant.
 - Use Case (on loop exit, 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 CVC5”).

Summary



- Various academic approaches to verifying Java(Card) programs.
 - Jack: <http://www-sop.inria.fr/everest/soft/Jack/jack.html>
 - VeriFast: <https://github.com/verifast/>
 - Various tools for byte code verification.
- 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). . .