Verification, Testing, and Debugging with the KeY System

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Part I

The KeY System – an Overview

Overview

annotated JAVA program

↓

KeY verification browser

↓

KeY problem file

↓

first-order proof obligations

↓

successful or failed proof attempt

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annotated JAVA program

fully automatic translation

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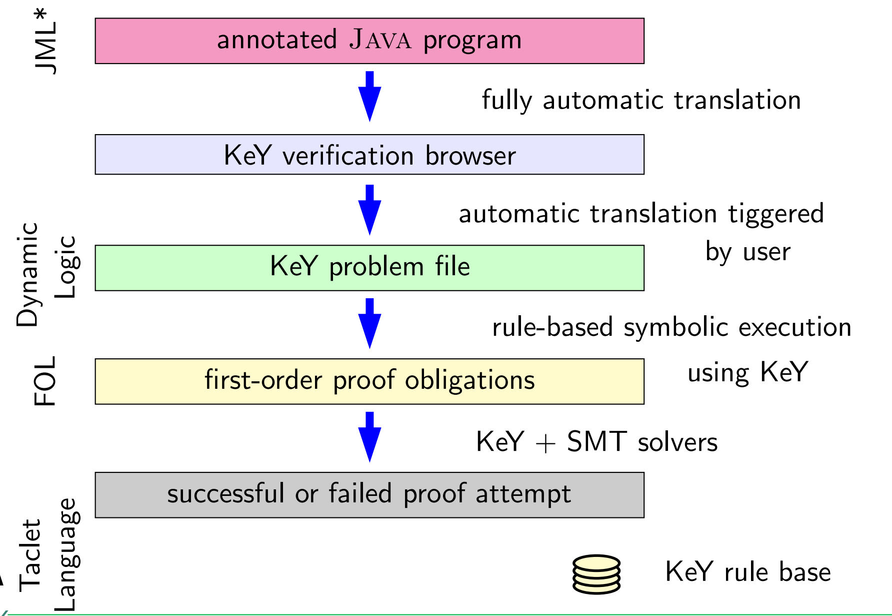

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- Integration of verification into the software development process.

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- Additional benefits: test case generation, symbolic debugging.

Specific Features of the KeY Approach

- Part II (P.H.Schmitt)
  - Integration of verification into the software development process.
- Part III (V.Klebanov)
  - Program logic, explicit JAVA in the logic, not translated away
  - Forward symbolic execution instead of backwards wp generation.
- Part IV (R.Bubel)
  - Interleaving of vcg and interactive proving.
- Part V (W.Ahrendt)
  - Additional benefits: test case generation, symbolic debugging.

Part II

The Java Modeling Language

Specification of `commonEntry`

```
class SITA3{  public int[] a1,a2;
 /*@ public normal_behaviour
   @   requires 0 <= l && l < r &&
   @    r <= a1.length && r <= a2.length;
   @    assignable  \nothing;
   @    ensures  (  l <= \result && \result < r  &&
   @    a1[\result] ==  a2[\result] )
   @   | \result == r ;
   @   ensures (\forall int j; l <= j && j < \result;
   @    a1[j] !=  a2[j] );
   @*/
  public int  commonEntry(int l, int r) { ... }
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```

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  public int  commonEntry(int l, int r) { ... }
}
```

JML annotation occur as special comments in source programm

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   @*/
  public int  commonEntry(int l, int r) { ... }
}
```

precondition

Specification of commonEntry

```
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   @    ensures   (  l <= \result && \result < r  &&
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  public int  commonEntry(int l, int r) { ... }
}
```

postcondition

Specification of `commonEntry`

```
class SITA3{  public int[] a1,a2;
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   @    a1[j] !=  a2[j] );
   @*/
  public int  commonEntry(int l, int r) { ... }
}
```

Specification of the set of locations that may at most be changed.
Here: `commonEntry` is a pure method

Specification of `commonEntry`

```
class SITA3{  public int[] a1,a2;
 /*@ public normal_behaviour
   @   requires 0 <= l && l < r &&
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   @   ensures (  l <= \result && \result < r  &&
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   @    a1[j] !=  a2[j] );
   @*/
  public int  commonEntry(int l, int r) { ... }
}
```

JML uses `\result` to refer to the return value of a method.

Specification of `commonEntry`

```
class SITA3{  public int[] a1,a2;
 /*@ public normal_behaviour
   @   requires 0 <= l && l < r &&
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Method `commonEntry` looks for an index within the bounds of the parameters

Specification of `commonEntry`

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class SITA3{  public int[] a1,a2;
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   @   requires 0 <= l && l < r &&
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   @   assignable \nothing;
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   @    a1[\result] ==  a2[\result] )
   @   | \result == r ;
   @   ensures (\forall int j; l <= j && j < \result;
   @    a1[j] !=  a2[j] );
   @*/
  public int  commonEntry(int l, int r) { ... }
}
```

Method `commonEntry` looks for an index within the bounds of the parameters such that the two arrays have the same entry.

Specification of `commonEntry`

```
class SITA3{  public int[] a1,a2;
 /*@ public normal_behaviour
   @   requires 0 <= l && l < r &&
   @    r <= a1.length && r <= a2.length;
   @   assignable \nothing;
   @   ensures (  l <= \result && \result < r  &&
   @    a1[\result] ==  a2[\result] )
   @   | \result == r ;
   @   ensures (\forall int j; l <= j && j < \result;
   @    a1[j] !=  a2[j] );
   @*/
  public int  commonEntry(int l, int r) { ... }
}
```

If no such index exists the return value is the upper bound.

Specification of `commonEntry`

```
class SITA3{  public int[] a1,a2;
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   @   | \result == r ;
   @   ensures (\forall int j; l <= j && j < \result;
   @    a1[j] !=  a2[j] );
   @*/
  public int  commonEntry(int l, int r) { ... }
}
```

Furthermore, `\result` should be the first index of this kind.

Loop Invariant for commonEntry

```
class SITA3{  public int[] a1,a2;   ...
  public int  commonEntry(int l, int r){ int k = l;
/*@ loop_invariant   l <= k && k <= r &&
  @ (\forall int i; l <= i && i < k; a1[i] != a2[i] );
  @  assignable \nothing;
  @  decreases a1.length - k;
  @*/
   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
   return k;}
}
```

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The loop invariant

Loop Invariant for commonEntry

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  @  decreases a1.length - k;
  @*/
   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
   return k;}
}
```

The loop invariant is valid before entering the loop since

Loop Invariant for `commonEntry`

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class SITA3{  public int[] a1,a2;   ...
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   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
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```

`l <= l && l <= r` follows from the preconditions and

Loop Invariant for `commonEntry`

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class SITA3{  public int[] a1,a2;   ...
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  @  assignable \nothing;
  @  decreases a1.length - k;
  @*/
   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
   return k;}
}
```

`l <= l && l <= r` follows from the preconditions and quantification is empty

Loop Invariant for `commonEntry`

```
class SITA3{  public int[] a1,a2;   ...
  public int  commonEntry(int l, int r){ int k = l;
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  @*/
   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
   return k;}
}
```

If the loop body is executed in a state satisfying the invariant it will terminate in a state satisfying the invariant.

Loop Invariant for `commonEntry`

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   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
   return k;}
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```

If the loop body is executed in a state satisfying the invariant it will terminate in a state satisfying the invariant.
Distinguish `break` and non-`break` case

Loop Invariant for `commonEntry`

On termination of the loop

Loop Invariant for `commonEntry`

On termination of the loop
the invariant

```
l <= k && k <= r &&
(\forall int i; l <= i && i < k; a1[i] != a2[i])
```

plus

```
\result = k
```

plus

`k == r` or `k < r && a1[k] == a2[k]`

imply the postcondition

```
((l <= \result && \result < r && a1[\result] == a2[\result])
| \result == r ) &&
(\forall int j; l <= j && j < \result; a1[j] != a2[j])
```

Loop Termination

```
  public int  commonEntry(int l, int r){ int k = l;
/*@ loop_invariant   l <= k && k <= r &&
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  @*/
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  @*/
   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
   return k;}
}
```

The loop variant

Loop Termination

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  public int  commonEntry(int l, int r){ int k = l;
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   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
   return k;}
}
```

The loop variant

- is ≥ 0 on entering the loop

Loop Termination

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  public int  commonEntry(int l, int r){ int k = l;
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  @*/
   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
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}
```

The loop variant

- is ≥ 0 on entering the loop
- strictly decreases in every loop iteration

Loop Termination

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  public int  commonEntry(int l, int r){ int k = l;
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  @  decreases a1.length - k;
  @*/
   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
   return k;}
}
```

The loop variant

- is ≥ 0 on entering the loop
- strictly decreases in every loop iteration
- but always stays ≥ 0.

Assignable Clause

```
/*@ public normal_behaviour
  @  requires  0<= pos1 && 0<= pos2 &&
  @  pos1 < a.length && pos2 < a.length ;
  @  ensures  a[pos1]  == \old(a[pos2]) &&
  @           a[pos2]  == \old(a[pos1]);
  @  assignable a[pos1], a[pos2];
  @*/
 public void  swap(int[] a,int pos1, int pos2) {
  int temp;
  temp = a[pos1]; a[pos1] = a[pos2] ; a[pos2] = temp;}
```

Assignable Clause

```
/*@ public normal_behaviour
  @  requires  0<= pos1 && 0<= pos2 &&
  @  pos1 < a.length && pos2 < a.length ;
  @  ensures   a[pos1]  == \old(a[pos2]) &&
  @            a[pos2]  == \old(a[pos1]);
  @  assignable a[pos1], a[pos2];
  @*/
 public void  swap(int[] a,int pos1, int pos2) {
  int temp;
  temp = a[pos1]; a[pos1] = a[pos2] ; a[pos2] = temp;}
```

This is an example with a non-trivial assignable clause.

Assignable Clause

```
/*@ public normal_behaviour
  @  requires  0<= pos1 && 0<= pos2 &&
  @  pos1 < a.length && pos2 < a.length ;
  @  ensures   a[pos1]  == \old(a[pos2]) &&
  @            a[pos2]  == \old(a[pos1]);
  @  assignable a[pos1], a[pos2];
  @*/
 public void  swap(int[] a,int pos1, int pos2) {
  int temp;
  temp = a[pos1]; a[pos1] = a[pos2] ; a[pos2] = temp;}
```

At most the locations `a[pos1], a[pos2]` may be changed by method `swap`

Using Contracts

```
class SITA3{ public int[] a1, a2;
  /*@ public normal_behaviour
   @  requires  a1.length == a2.length;
   @  ensures  (\forall int i;0<= i && i < a1.length;
   @   a1[i] == a2[i] ==>
   @   (\forall int j;0<= j && j < i; a1[j] == a2[j]));
   @  assignable a1[*],a2[*];
   @*/
  public void  rearrange(){ int m = 0 ; int k = 0;
   while (m < a1.length) { m = commonEntry(m,a1.length);
    if (m < a1.length) {swap(a1,m,k);
     if (a1 != a2) { swap(a2,m,k);} k = k+1 ; m = m+1;}}}}
```

Using Contracts

```
class SITA3{ public int[] a1, a2;
  /*@ public normal_behaviour
   @  requires  a1.length == a2.length;
   @  ensures  (\forall int i;0<= i && i < a1.length;
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   @*/
  public void  rearrange(){ int m = 0 ; int k = 0;
   while (m < a1.length) { m = commonEntry(m,a1.length);
    if (m < a1.length) {swap(a1,m,k);
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```

Method `rearrange`

Using Contracts

```
class SITA3{ public int[] a1, a2;
  /*@ public normal_behaviour
   @  requires  a1.length == a2.length;
   @  ensures  (\forall int i;0<= i && i < a1.length;
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   @   (\forall int j;0<= j && j < i; a1[j] == a2[j]));
   @  assignable a1[*],a2[*];
   @*/
  public void  rearrange(){ int m = 0 ; int k = 0;
   while (m < a1.length) { m = commonEntry(m,a1.length);
    if (m < a1.length) {swap(a1,m,k);
     if (a1 != a2) { swap(a2,m,k);} k = k+1 ; m = m+1;}}}}
```

Method `rearrange` uses methods `commonEntry`

Using Contracts

```
class SITA3{ public int[] a1, a2;
  /*@ public normal_behaviour
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   @*/
  public void  rearrange(){ int m = 0 ; int k = 0;
   while (m < a1.length) { m = commonEntry(m,a1.length);
    if (m < a1.length) {swap(a1,m,k);
     if (a1 != a2) { swap(a2,m,k);} k = k+1 ; m = m+1;}}}}
```

Method `rearrange` uses methods `commonEntry` and `swap`.

Using Contracts

```
class SITA3{ public int[] a1, a2;
  /*@ public normal_behaviour
   @  requires  a1.length == a2.length;
   @  ensures  (\forall int i;0<= i && i < a1.length;
   @   a1[i] == a2[i] ==>
   @   (\forall int j;0<= j && j < i; a1[j] == a2[j]));
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```

Verification of `rearrange` uses the contracts of these methods not their code.

Using Contracts

```
class SITA3{ public int[] a1, a2;
  /*@ public normal_behaviour
   @  requires  a1.length == a2.length;
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     if (a1 != a2) { swap(a2,m,k);} k = k+1 ; m = m+1;}}}}
```

Key to scalability

DEMO

Model Fields

```
class SITA4{ ....
 /*@ model \seq seq1; model \seq seq2; @*/
 /*@ represents seq1 = \dl_array2seq(a1);
   @ represents seq2 = \dl_array2seq(a2);
   @*/

 /*@ public normal_behaviour
   @  ensures  \dl_seqPerm(seq1,\old(seq1)) &&
   @           \dl_seqPerm(seq2,\old(seq2)) ;
   @*/
    public void  rearrange(){....}
```

Model Fields

```
class SITA4{ ....
 /*@ model \seq seq1; model \seq seq2; @*/
 /*@ represents seq1 = \dl_array2seq(a1);
   @ represents seq2 = \dl_array2seq(a2);
   @*/

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```

JML provides model fields, that do not occur in the code, but are solely used for specification.

Model Fields

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```

\seq is an abstract data type

Model Fields

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JML `represents` clauses fix the semantics of model fields.

Model Fields

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the function `array2seq(a)` yields the abstract sequence associated with array *a*.

Model Fields

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Only additional postcondition show here.

Model Fields

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`arrayPerm(s1,s2)` is a predicate in the data type \seq,
true if s1 is a permutation of s2.

Model Fields

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class SITA4{ ....
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```

The `\dl` prefix is a technical detail necessary since `\seq` is not (yet) part of official JML.

Part III

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Syntax and Semantics

Syntax

- Basis: Typed first-order predicate logic
- Modal operators $\langle p \rangle$ and $[p]$ for each (JAVA CARD) program p
- Class definitions in background (not shown in formulas)

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Semantics (Kripke)

Modal operators allow referring to the final state of p:

- `[p] F`: If p terminates, then F holds in the final state
  (partial correctness)
- `<p> F`: p terminates and F holds in the final state
  (total correctness)

Why Dynamic Logic?

- Transparency wrt target programming language

- Programs are "first-class citizens"
- Real Java syntax

Why Dynamic Logic?

- Transparency wrt target programming language
- Encompasses Hoare Logic

Hoare triple $\{\psi\}\ \alpha\ \{\phi\}$ equiv. to DL formula ψ -> $[\alpha]\ \phi$

Why Dynamic Logic?

- Transparency wrt target programming language
- Encompasses Hoare Logic
- More expressive and flexible than Hoare logic

Not merely partial/total correctness:

- can employ programs for specification (e.g., verifying program transformations)
- can express security properties (two runs are indistinguishable)
- extension-friendly (e.g., temporal modalities)

Why Dynamic Logic?

- Transparency wrt target programming language
- Encompasses Hoare Logic
- More expressive and flexible than Hoare logic
- Symbolic execution is a natural interactive proof paradigm

Dynamic Logic Example Formulas

$(\texttt{balance} >= c \ \& \ \texttt{amount} > 0) \texttt{->} \texttt{<charge(amount);>} \ \texttt{balance} > c$

Dynamic Logic Example Formulas

$(\texttt{balance} >= c \ \& \ \texttt{amount} > 0) \rightarrow$ `<charge(amount);>` $\texttt{balance} > c$

`<x = 1;>([while (true) {}]` *false*`)`

Dynamic Logic Example Formulas

`(balance >= c & amount > 0) -> <charge(amount);> balance > c`

`<x = 1;>([while (true) {}] false)`

- Program formulas can appear nested

Dynamic Logic Example Formulas

$(\texttt{balance} >= c \ \& \ \texttt{amount} > 0) \ {-}{>} \ \texttt{<charge(amount);>} \ \texttt{balance} > c$

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- Program formulas can appear nested

$\backslash\texttt{forall} \ \mathit{int} \ \mathit{val}; ((\texttt{<p>} \, \texttt{x} \doteq \mathit{val}) \ <\!\!-\!\!> \ (\texttt{<q>} \, \texttt{x} \doteq \mathit{val}))$

Dynamic Logic Example Formulas

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- p, q equivalent relative to computation state restricted to x

Dynamic Logic Example Formulas

```
  a != null
->
  <
    int max = 0;
    if ( a.length > 0 ) max = a[0];
    int i = 1;
    while ( i < a.length ) {
      if ( a[i] > max ) max = a[i];
      ++i;
    }
  >
    (
      \forall int j; (j >= 0 & j < a.length -> max >= a[j])
      &
      (a.length > 0 ->
        \exists int j; (j >= 0 & j < a.length & max = a[j]))
    )
```

Variables

- Logical variables disjoint from program variables
  - No quantification over program variables
  - Programs do not contain logical variables
  - "Program variables" actually non-rigid functions

Validity

A JAVA CARD DL formula is valid iff it is true in all states.

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We need a calculus for checking validity of formulas

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Sequents and their Semantics

Syntax

$$\underbrace{\psi_1, \ldots, \psi_m}_{\textit{Antecedent}} \quad \Longrightarrow \quad \underbrace{\phi_1, \ldots, \phi_n}_{\textit{Succedent}}$$

where the ϕ_i, ψ_i are formulae (without free variables)

Sequents and their Semantics

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where the ϕ_i, ψ_i are formulae (without free variables)

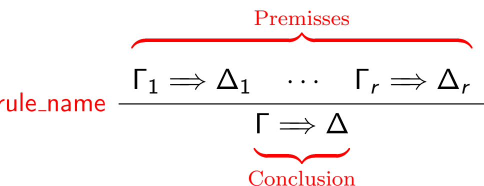
Semantics

Same as the formula

$$(\psi_1 \ \& \ \cdots \ \& \ \psi_m) \quad -> \quad (\phi_1 \ | \ \cdots \ | \ \phi_n)$$

Sequent Rules

General form



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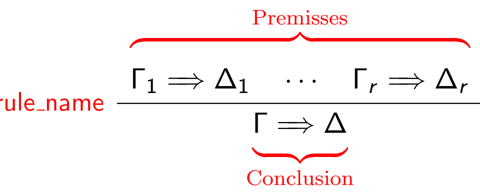

($r = 0$ possible: closing rules)

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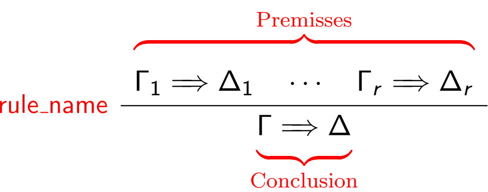

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Soundness

If all premisses are valid, then the conclusion is valid

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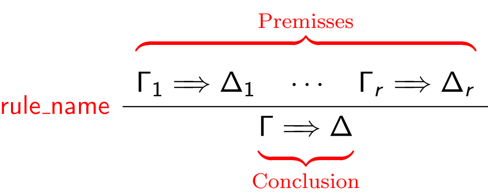

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Soundness

If all premisses are valid, then the conclusion is valid

Use in practice

Goal is matched to conclusion

Some Simple Sequent Rules

$$\text{not_left} \quad \frac{\Gamma \Longrightarrow A, \Delta}{\Gamma, !\, A \Longrightarrow \Delta}$$

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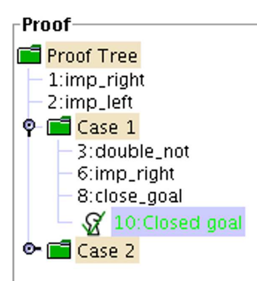
$$\text{all_left} \quad \frac{\Gamma, \backslash\texttt{forall}\ t\ x; \phi,\ \{x/e\}\phi \Longrightarrow \Delta}{\Gamma, \backslash\texttt{forall}\ t\ x; \phi \Longrightarrow \Delta}$$

where e var-free term of type $t' \prec t$

Sequent Calculus Proofs

Proof tree

- Proof is tree structure with goal sequent as root



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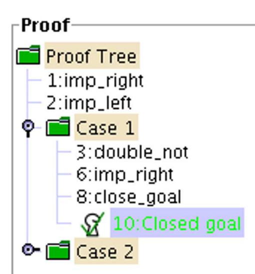

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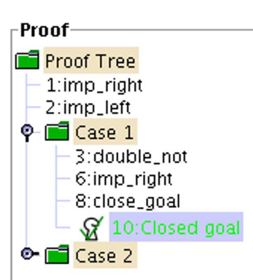

Sequent Calculus Proofs

Proof tree

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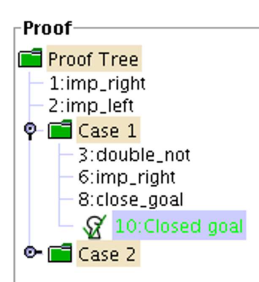
- Proof is finished when all goals are closed



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Proof by Symbolic Program Execution

- Sequent rules for program formulas?
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passive prefix	π
active statement	`i=0;`
rest	ω

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- Sequent rules execute symbolically the active statement

Rules for Symbolic Program Execution

If-then-else rule

$$\frac{\Gamma, B = \mathit{true} \Longrightarrow \texttt{<}p\ \ \omega\texttt{>}\,\phi, \Delta \qquad \Gamma, B = \mathit{false} \Longrightarrow \texttt{<}q\ \ \omega\texttt{>}\,\phi, \Delta}{\Gamma \Longrightarrow \texttt{<if (}B\texttt{) \{ }p\texttt{ \} else \{ }q\texttt{ \} }\omega\texttt{>}\,\phi, \Delta}$$

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Complicated statements/expressions are simplified first, e.g.

$$\frac{\Gamma \Longrightarrow \texttt{<v=y; y=y+1; x=v; }\omega\texttt{>}\,\phi, \Delta}{\Gamma \Longrightarrow \texttt{<x=y++; }\omega\texttt{>}\,\phi, \Delta}$$

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Simple assignment rule

$$\frac{\Gamma \Longrightarrow \{\mathit{loc} := \mathit{val}\}\texttt{<}\omega\texttt{>}\,\phi, \Delta}{\Gamma \Longrightarrow \texttt{<}\mathit{loc}\texttt{=}\mathit{val}\texttt{; }\omega\texttt{>}\,\phi, \Delta}$$

Extending DL by Explicit State Updates

Updates

explicit syntactic elements in the logic

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Elementary Updates

$$\{\mathit{loc} := \mathit{val}\}\,\phi$$

where (roughly)

- *loc* a program variable x, an attribute access $o.attr$, or an array access $a[i]$
- *val* is same as *loc*, or a literal, or a logical variable

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Parallel Updates

$$\{\mathit{loc}_1 := t_1 \mid\mid \cdots \mid\mid \mathit{loc}_n := t_n\}\,\phi$$

no dependency between the n components (but 'right wins' semantics)

Why Updates?

Updates are:

- *lazily applied* (i.e. substituted into postcondition)
- *eagerly parallelised* + simplified

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Advantages

- no renaming required
- delayed/minimized proof branching (efficient aliasing treatment)

Symbolic Execution with Updates (by Example)

$\Longrightarrow$ $x < y$ -> `<int t=x; x=y; y=t;>` $y < x$

Symbolic Execution with Updates (by Example)

$$\mathtt{x} < \mathtt{y} \implies \{\mathtt{t:=x}\}\mathtt{<x=y;\ y=t;>}\ \mathtt{y} < \mathtt{x}$$

$$\vdots$$

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Program State Representation

Local program variables

Modeled as non-rigid constants

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Modeled as non-rigid constants

Heap

Modeled with theory of arrays:

$$
\begin{array}{ll}
\mathit{heap}: & \to \mathit{Heap} \text{ (the heap in the current state)} \\
\mathit{select}: & \mathit{Heap} \times \mathit{Object} \times \mathit{Field} \to \mathit{Any} \\
\mathit{store}: & \mathit{Heap} \times \mathit{Object} \times \mathit{Field} \times \mathit{Any} \to \mathit{Heap}
\end{array}
$$

Program State Representation

Local program variables

Modeled as non-rigid constants

Heap

Modeled with theory of arrays:

$heap: \quad \rightarrow Heap$ (the heap in the current state)
$select: \quad Heap \times Object \times Field \rightarrow Any$
$store: \quad Heap \times Object \times Field \times Any \rightarrow Heap$

Heap axioms (excerpt)

$select(store(h, o, f, x), o, f) = x$
$select(store(h, o, f, x), u, f) = select(h, u, f)$ if $o \neq u$

Handling Abrupt Termination

- Abrupt termination handled by program transformations
- Changing control flow $=$ rearranging program parts

Example

TRY-THROW

$$\Gamma \Longrightarrow \langle \texttt{try\{throw exc; q\} catch(T e)\{r\} finally\{s\}}\ \omega \rangle \phi, \Delta$$

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TRY-THROW

$$\frac{\Gamma \Longrightarrow \left\langle \begin{array}{l}\texttt{if (exc instanceof T)} \\ \quad \texttt{\{try \{e=exc; r\} finally \{s\}\}} \\ \quad \texttt{else \{s throw exc;\}} \quad \omega \end{array} \right\rangle \phi, \Delta}{\Gamma \Longrightarrow \texttt{<try\{throw exc; q\} catch(T e)\{r\} finally\{s\}} \ \omega\texttt{>} \phi, \Delta}$$

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TRY-THROW

$$\frac{\Gamma \Longrightarrow \left\langle \pi\ \texttt{if (exc instanceof T)} \atop \texttt{\{try \{e=exc; r\} finally \{s\}\} else \{s throw exc;\}}\ \omega \right\rangle \phi, \Delta}{\Gamma \Longrightarrow \texttt{<}\pi\ \texttt{try\{throw exc; q\} catch(T e)\{r\} finally\{s\}}\ \omega\texttt{>} \phi, \Delta}$$

Part III

Dynamic Logic

Java Card DL

Sequent Calculus

Rules for Programs: Symbolic Execution

A Calculus for 100% Java Card

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Rules for Programs: Symbolic Execution

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Supported Java Features

- method invocation with polymorphism/dynamic binding
- object creation and initialisation
- arrays
- abrupt termination
- throwing of NullPointerExceptions, etc.
- bounded integer data types
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All JAVA CARD language features are fully addressed in KeY

Java—A Language of Many Features

Ways to deal with Java features

- Program transformation, up-front

Pro: Feature needs not be handled in calculus
Contra: Modified source code
Example in KeY: Very rare: treating inner classes

Java—A Language of Many Features

Ways to deal with Java features

- Program transformation, up-front
- Local program transformation, done by a rule on-the-fly

Pro: Flexible, easy to implement, usable
Contra: Not expressive enough for all features
Example in KeY: Complex expression eval, method inlining, etc., etc.

Java—A Language of Many Features

Ways to deal with Java features

- Program transformation, up-front
- Local program transformation, done by a rule on-the-fly
- Modeling with first-order formulas

Pro: No logic extensions required, enough to express most features
Contra: Creates difficult first-order POs, unreadable antecedents
Example in KeY: Dynamic types and branch predicates

Java—A Language of Many Features

Ways to deal with Java features

- Program transformation, up-front
- Local program transformation, done by a rule on-the-fly
- Modeling with first-order formulas
- Special-purpose extensions of program logic

Pro: Arbitrarily expressive extensions possible
Contra: Increases complexity of all rules
Example in KeY: Method frames, updates

Components of the Calculus

1. Non-program rules
   - first-order rules
   - rules for data-types
   - first-order modal rules
   - induction rules

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5. Update simplification

Advertisment

COST Action IC0701 presents **VerifyThus**—
a Linux distribution with 10 program verification tools.

Available as:

- bootable USB stick
- bootable DVD
- virtual machine image

Included verification tools:
Boogie, Dafny, ESC/Java2, Jahob, JavaFAN, jStar, KeY, KIV, Krakatoa, Verifast

`http://verifythus.cost-ic0701.org`

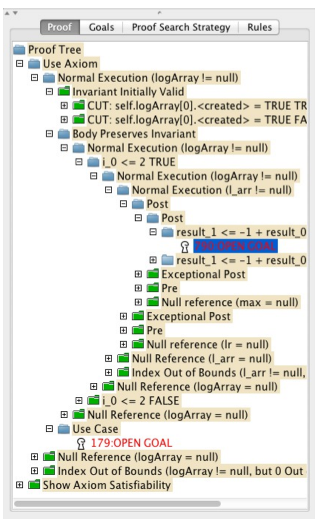
Part IV

Proof Construction

Taclets – KeY's Rule Description Language

Taclets ...

- represent sequent calculus rules in KeY
- use a simple text-based format
- are descriptive, but with operational flavor
- are *not* a tactic metalanguage



Taclet Syntax—Basics

$$\text{andLeft}\ \frac{\Gamma, A, B \Longrightarrow \Delta}{\Gamma, A \,\&\, B \Longrightarrow \Delta}$$

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Taclet

```
andLeft {

};
```

- Unique name

Taclet Syntax—Basics

$$\text{andLeft}\ \frac{\Gamma, A, B \Longrightarrow \Delta}{\Gamma, A \mathbin{\&} B \Longrightarrow \Delta}$$

Taclet

```
andLeft {
    \find ( A & B ==> )


};
```

- Unique name
- Find expression:
  - Formula (Term) to be modified

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$$\text{andLeft}\ \frac{\Gamma, A, B \Longrightarrow \Delta}{\Gamma, A \,\&\, B \Longrightarrow \Delta}$$

Taclet

```
andLeft {
    \find ( A & B ==> )

    \replacewith (A, B ==>)
};
```

- Unique name
- Find expression:
  - Formula (Term) to be modified
  - Sequent arrow –> formula must occur top level *and* on the corresponding side of the sequent.
- Goal Description: describes new sequent

Taclet Syntax—Basics (II)

Some rules are only sound in a certain context

$$\text{modusPonens}\ \frac{\Gamma, A, B \Longrightarrow \Delta}{\Gamma, A, A \mathrel{-\!\!>} B \Longrightarrow \Delta}$$

Taclet

modusPonens {

};

Taclet Syntax—Basics (II)

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$$\text{modusPonens}\ \frac{\Gamma, A, B \Longrightarrow \Delta}{\Gamma, A, A \mathbin{->} B \Longrightarrow \Delta}$$

Taclet

```
modusPonens {


  \find ( A -> B ==>)
  \replacewith (B ==>)
};
```

Taclet Syntax—Basics (II)

Some rules are only sound in a certain context

$$\text{modusPonens} \; \frac{\Gamma, A, B \Longrightarrow \Delta}{\Gamma, A, A -> B \Longrightarrow \Delta}$$

Taclet

```
modusPonens {
  \assumes (A ==>)

  \find ( A -> B   ==>)
  \replacewith     (B   ==>)
};
```

Taclet Syntax—Basics (II)

Some rules are only sound in a certain context

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Taclet

```
modusPonens {
  \assumes (A ==>)

  \find  ( A -> B   ==>)
  \add              (B   ==>)
};
```

Taclet Syntax—Basics (III)

Proof Splitting: andRight

$$\frac{\Gamma \Longrightarrow A, \Delta \quad \Gamma \Longrightarrow B, \Delta}{\Gamma \Longrightarrow A \,\&\, B, \Delta}$$

```
andRight {
  \find (==> A & B)
  \replacewith (==> A);
  \replacewith (==> B )
};
```

Taclet Syntax—Basics (III)

Proof Splitting: andRight

$$\frac{\Gamma \Longrightarrow A, \Delta \quad \Gamma \Longrightarrow B, \Delta}{\Gamma \Longrightarrow A \,\&\, B, \Delta}$$

```
andRight {
  \find (==> A & B)
  \replacewith (==> A);
  \replacewith (==> B )
};
```

Variable Conditions: allRight

$$\frac{\Gamma \Longrightarrow \{x/c\}\Phi, \Delta}{\Gamma \Longrightarrow \forall T\ x; \Phi, \Delta}, \text{ c new}$$

```
allRight {
  \find (==> ∀x; φ)
  \varcond(\new(c,\dependingOn(Φ)))
  \replacewith (==> {\subst x; c }Φ)
};
```

Well-Formed Taclets

Syntactic checks avoid common user errors

- prevent introduction of free variables

```
\find (\forall v;(A & B) ==>)

\replacewith (A & \forall v;B ==>)
```

Well-Formed Taclets

Syntactic checks avoid common user errors

- prevent introduction of free variables

```
\find (\forall v;(A & B) ==>)
\varcond(\notFreeIn(v, A))
\replacewith (A & \forall v;B ==>)
```

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- prevent introduction of free variables

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- accidental capturing of variables

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- accidental capturing of variables
- prevent ambiguous variable binding

Limited reflection support for non-program taclets

Taclets for Program Transformations

$$\frac{\Gamma \Longrightarrow \left\langle \begin{array}{l} \pi\ \texttt{if (exc == null) \{} \\ \quad \texttt{try\{ throw new NPE(); catch(T e) \{r\};} \\ \texttt{\} else if (exc instanceof T) \{e=exc; r\}} \\ \texttt{else throw exc;}\ \omega \end{array} \right\rangle \phi}{\Gamma \Longrightarrow \texttt{<}\pi\ \texttt{try\{throw exc; q\} catch(T e)\{r\};}\ \omega\texttt{>}\phi}$$

```
\find (<.. try { throw #se; #slist }
            catch ( #t #v0 ) { #slist1 } ... > post)
\replacewith (
  <.. if (#se == null) {
        try { throw new NullPointerException (); }
        catch (#t #v0) { #slist1 }
      } else if (#se instanceof #t) {
        #t #v0 = (#t) #se;
        #slist1
      } else throw #se; ... > post )
```

Interactive Proof Construction: Demo

Taclets can be compiled into GUI

- Highlighted term matched against all find expressions
- Successful match returns (partial) instantiation of schema variables
- Possibly missing instantiations
  - user provided (dialog box)
  - drag and drop
- User can select from matching rules which to apply
- Application generates new sequents (goals) and appends them on the proof tree (*explicit proof object*)

Automated Proof Construction

- Automated proof search strategies implemented in Java
- Automated built-in prover uses same datastructure as interactive prover
  - Produces complete proof trace browsable by user
  - User can take over at any time
- Highlights (built-in prover):
  - Instantiation-based quantifier instantiation (triggers adopted from Simplify)
  - Linear and non-linear arithmetic reasoning (e.g., Groebner bases computation,Fourier-Motzkin, omega test etc.)
- Can export sub problems to SMT provers

Part V

Software Engineering Applications

Further Usage of Verification Technology

- Verification performs deep *Program Analysis*
- Information in (partial) proofs usable for other purposes

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  1. Test Case Generation
  2. Symbolic Debugging

Verification Driven Test Generation

- Specification- and code-based approach

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- Specification- and code-based approach
- Achieve strong hybrid coverage criteria

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Verification Driven Test Generation

- Specification- and code-based approach
- Achieve strong hybrid coverage criteria
- Exploit strong correspondence:
  proof branches $\leftrightarrow$ program execution paths
- Each leaf of (partial) proof branch contains
  constraint on inputs
  resulting in
  corresponding execution path

Using Symbolic Execution and Updates

$\mathit{PRE} \implies$ `<x=x+y; y=x-y; x=x-y; if(x>2*y)` α `else` β`>` POST

Using Symbolic Execution and Updates

$$\mathit{PRE} \implies \{\texttt{x:=y} \parallel \texttt{y:=x}\}\texttt{<if(x>2*y)}\ \alpha\ \texttt{else}\ \beta\texttt{>}\ \mathit{POST}$$

⋮

$$\mathit{PRE} \implies \texttt{<x=x+y; y=x-y; x=x-y; if(x>2*y)}\ \alpha\ \texttt{else}\ \beta\texttt{>}\ \mathit{POST}$$

Using Symbolic Execution and Updates

$$PRE, \texttt{y}>\texttt{2*x} \implies \{\texttt{x:=y} \parallel \texttt{y:=x}\}\texttt{<}\alpha\texttt{>}\, POST$$

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Using Symbolic Execution and Updates

$$PRE, \mathtt{y}\leq\mathtt{2*x} \implies \{\mathtt{x:=y} \mid\mid \mathtt{y:=x}\}\mathtt{<}\beta\mathtt{>}\ POST$$

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1. Extract 'Execution Tree'
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From (partial) Proofs to Test Cases

1. Extract 'Execution Tree'
   (stripped down proof tree)

2. For each leaf, generate at least one test
   - Isolate input constraint
   - Generate data satisfying the constraint
     (Model Generation, SMT solving)
   - Construct test input(s) in JUnit format

Postcondition not used for Generating Test Inputs

$PRE, \mathtt{y} \leq \mathtt{2*x} \implies \{\mathtt{x:=y} \mid\mid \mathtt{y:=x}\}\mathtt{<}\beta\mathtt{>}\ POST$

$PRE, \mathtt{y} > \mathtt{2*x} \implies \{\mathtt{x:=y} \mid\mid \mathtt{y:=x}\}\mathtt{<}\alpha\mathtt{>}\ POST$

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Test Oracle Generation

Test Oracle program routine to check test success or failure

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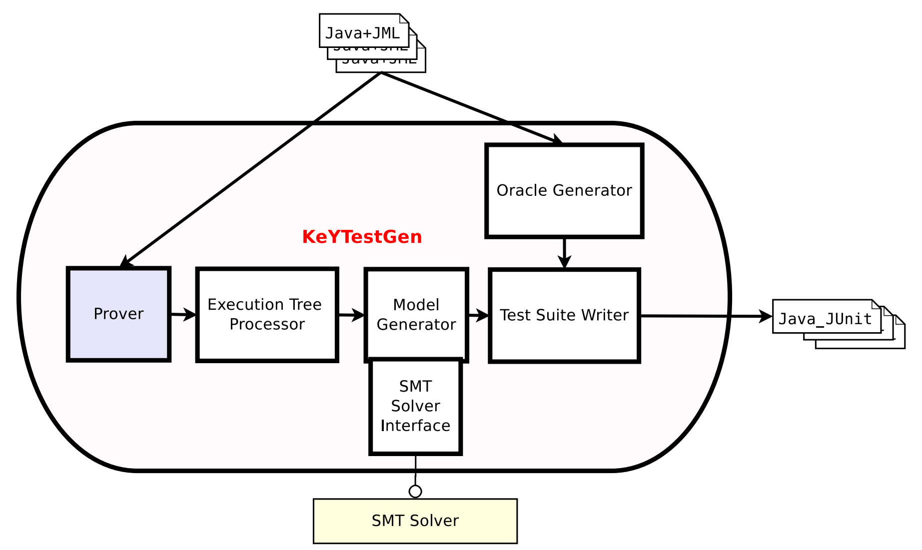
KeYTestGen constructs generic oracle from post-condition of tested code

Architecture of KeYTestGen



Eclipse integration

- Eclipse plugin for KeYTestGen (we)

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- Eclipse plugin for JUnit (standard)

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  - Top level Boolean Decision Coverage (DC)
  - Atomic Boolean Condition Coverage (CC)
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    (all possible combinations)
  - Modified Condition/Decision Coverage (MCDC)
    (required in Avionics certification standards)

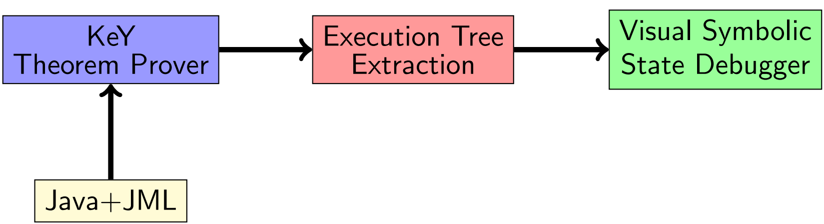
Test Generation Case Study

- applied to implementations of 40 methods in Real-Time Java API

Test Generation Case Study

- applied to implementations of 40 methods in Real-Time Java API
- KeYTestGen produced a failing test case,
  i.e., detected a bug in Real-Time Java library code

Visual Symbolic State Debugger



- Symbolic execution tree extraction (as for KeYTestGen)
- Enhanced omniscient debugging
  - enhanced: *all* possible execution paths
  - classic debugger navigation
  - variable inspection: symbolic variable values
  - semantic watchpoints
- Heap visualization

Part VI

Wrap Up

Further Directions of Current Research in KeY

Extending the scope of verification

- Concurrency and distribution

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- Modular specification of heap structures
  dynamic frames, abstract data types

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Modelling and specification

- Modular specification of heap structures
  dynamic frames, abstract data types
- Compositional models of concurrency and distribution
- Refinement
- Support for the specification process

Different Approaches Software Verification

General Purpose Systems

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- General purpose

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- General purpose
- Elaborate support for theories, abstract data types

Different Approaches Software Verification

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- Target object level *and* meta level

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Combining these advantages remains a challenge

THE END

Security Case Studies: Java Card Software

Safety/security properties specified in dynamic logic

- 'Only certain exceptions can be thrown'
- Transactions are properly used
  (do not commit or abort a transaction that was never started,
  all started Transactions are also closed)
- Data consistency
  (also if a smartcard is "ripped out" during operation)
- Absence of overflows for integer operations

Two studies in this area (for which some critical parts were verified)

- Demoney (about 3000 lines):
  Electronic purse application provided by Trusted Logic S.A.
- SafeApplet (about 600 lines): RSA based authentication applet

Safety Case Study

Computation of Railway Speed Restrictions

- Software by DBSystems for computing schedules for train drivers: Speed restrictions, required break powers
- Software formally specified using UML/OCL (based on existing informal specification)
- Program translated from Smalltalk to JAVA

Avionics Software

- JAVA implementation of a Flight Manager module at Thales Avionics
- Comprehensive specification using JML, emphasis on class invariants
- Verification of some nested method calls using contracts

Virtual Machine for Real Time Secure Java

- Verification of some library functions of the Jamaica VM from Aicas