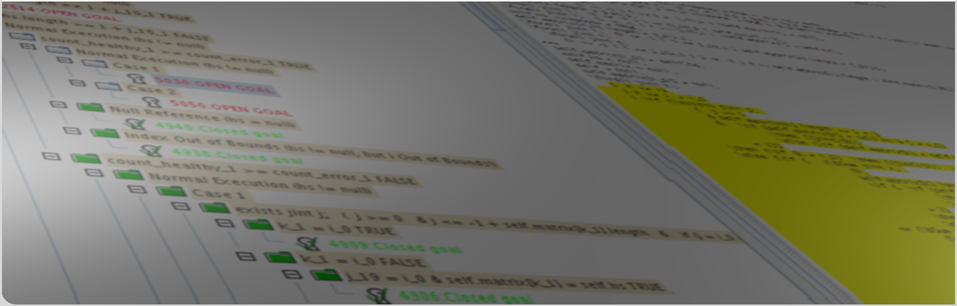
Program Verification with the KeY System

and Deductive Verification of Information-Flow Properties

B. Beckert V. Klebanov C. Scheben P. H. Schmitt | RS3, 10.–13.10.11

INSTITUTE FOR THEORETICAL COMPUTER SCIENCE



Part I

The KeY System – An Overview

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KeY Project

www.key-project.org

Project Consortium

- Bernhard Beckert and
  Peter H. Schmitt,
  Karlsruhe Institute of Technology
- Reiner Hähnle
  TU Darmstadt

KeY Tool

- Deductive rules for all Java features
- Symbolic execution
- 100% Java Card
- High degree of automation / usability

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- specified and annotated with the Java Modeling Language
- at program level

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AI Systems

LNAI 4334

Bernhard Beckert
Reiner Hähnle
Peter H. Schmitt (Eds.)

Verification of Object-Oriented Software

The KeY Approach

Foreword by K. Rustan M. Leino

Springer

Specific Features of the KeY Approach

- Part II: The Java Modeling Language
  - Program-level specification and annotation
- Part III: Program Verification with Dynamic Logic
  - Program logic, explicit JAVA in the logic, not translated away
  - Forward symbolic execution instead of backwards wp generation
- Part IV: Verifying Information Flow Properties
  - JML extended with information-flow concepts
  - Non-interference expressed in Dynamic Logic
- Not covered in this tutorial
  - Additional benefits: test case generation, symbolic debugging.

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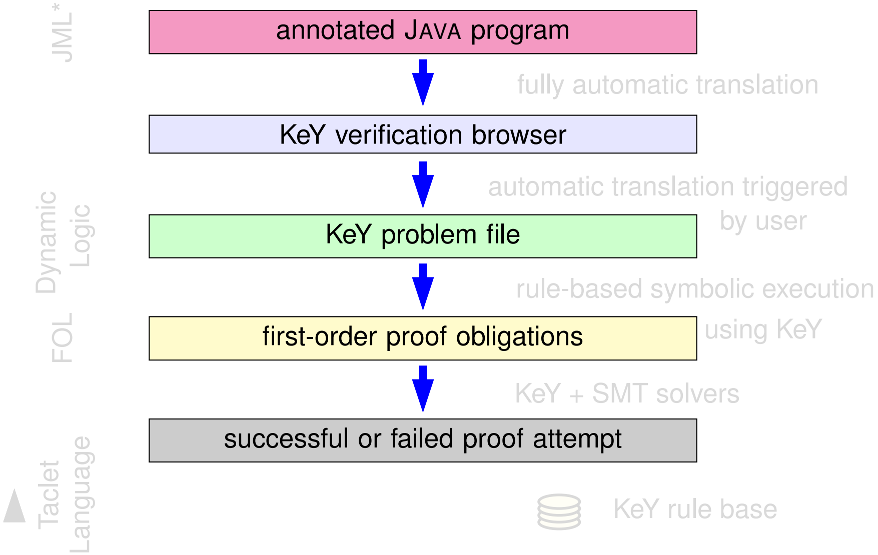

JML*

annotated JAVA program

fully automatic translation

KeY verification browser

automatic translation triggered by user

Dynamic Logic

KeY problem file

rule-based symbolic execution using KeY

FOL

first-order proof obligations

KeY + SMT solvers

successful or failed proof attempt

Taclet Language

KeY rule base

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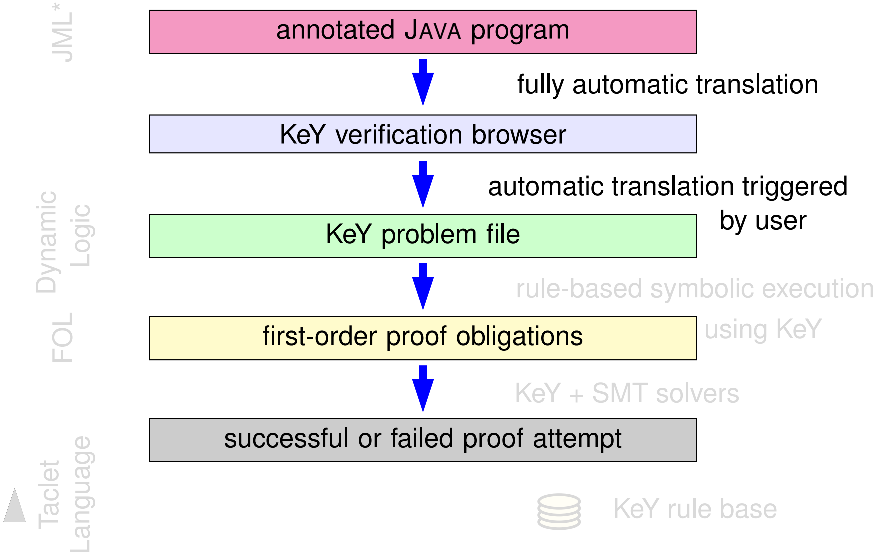

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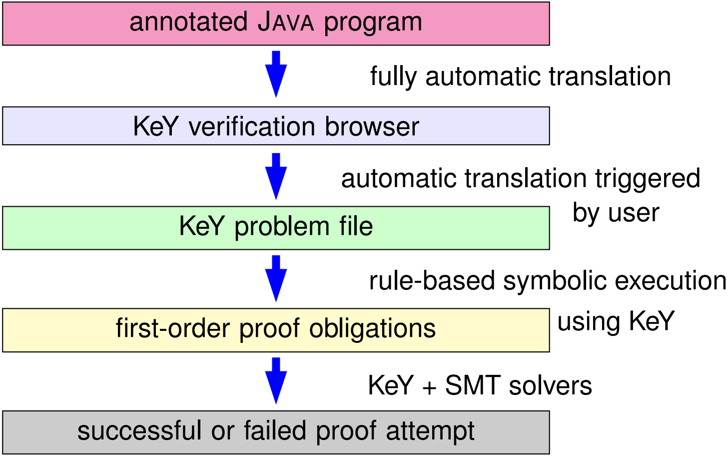

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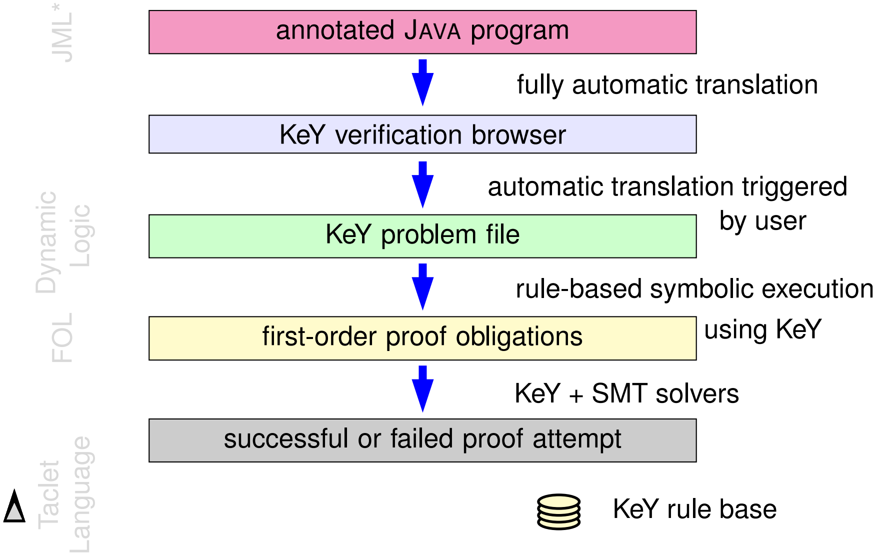

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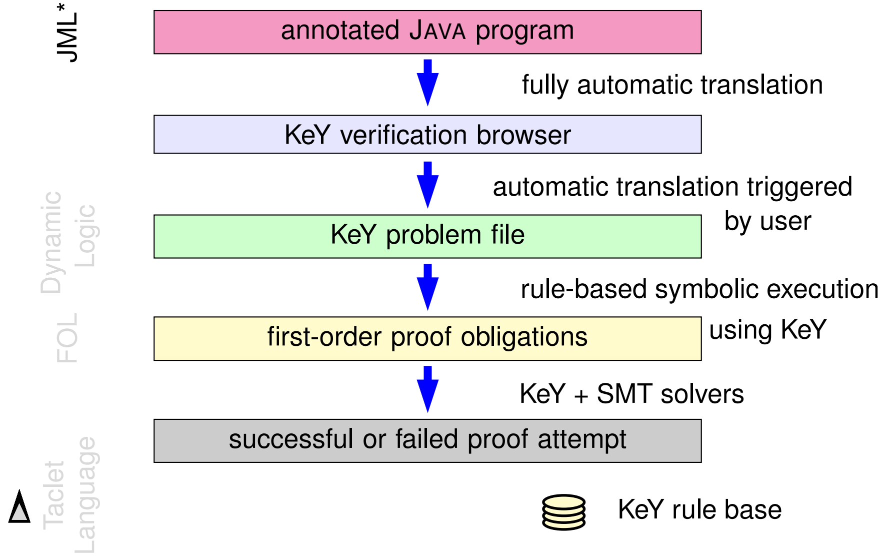

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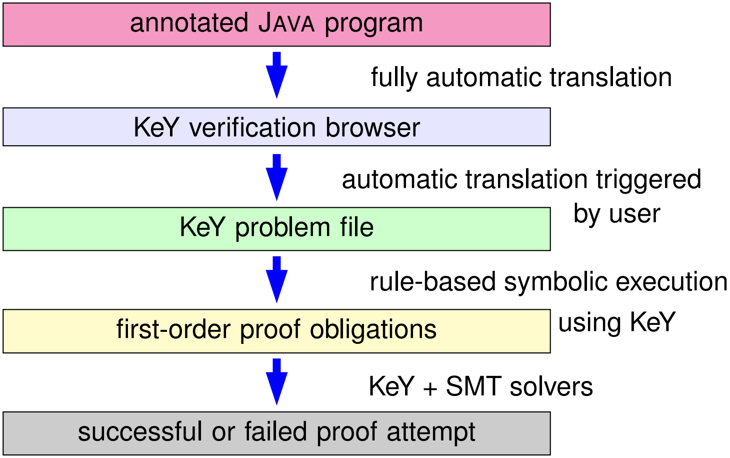

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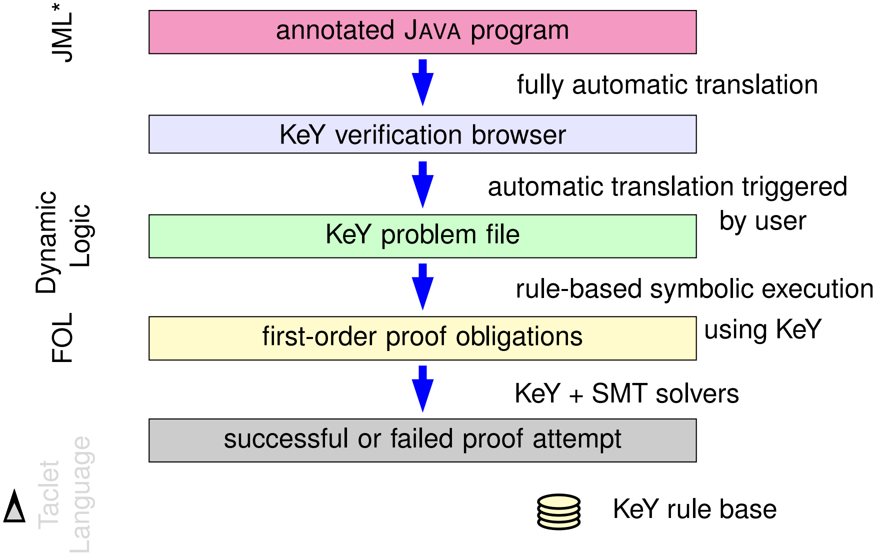

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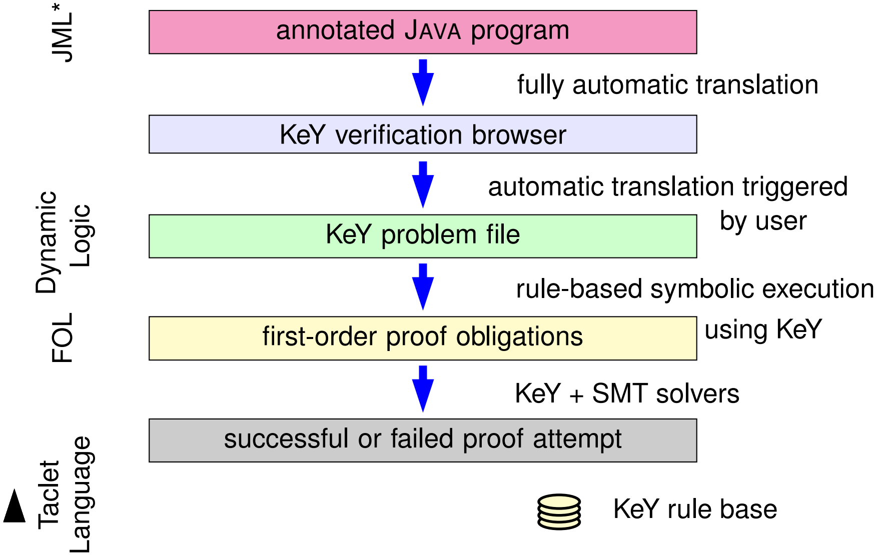

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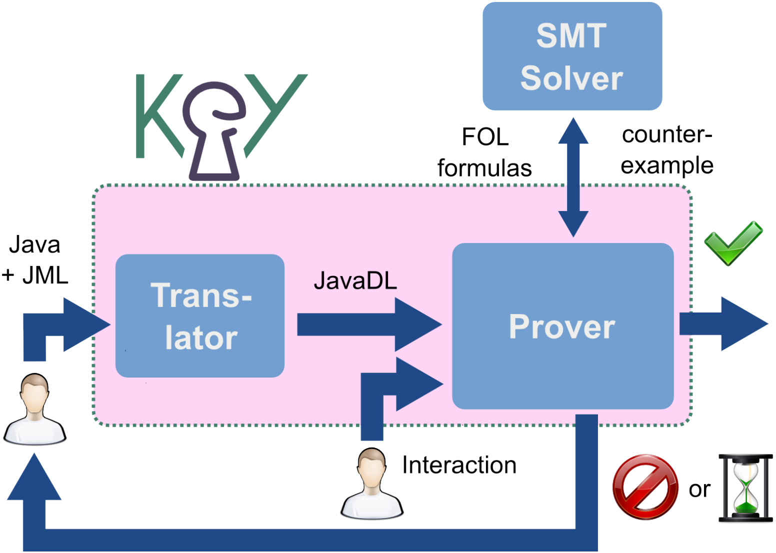
KeY Verification Process



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Part II

The Java Modeling Language
– By Example –

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The Java Modeling Language
– By Example –

1. Method Contracts
2. Quantifiers
3. Handling Loops
4. Frame Conditions
5. Using Contracts
6. Abstraction

Method Contracts

JML Spec of Postincrement

```
public class PostInc{
    public PostInc act;
    public int x,y;

/*@ public normal_behavior
  @  requires true;
  @  ensures  act.x == \old(act.y) &&
  @           act.y == \old(act.y) + 1;
  @*/
  public void postinc() { act.x = act.y++; }}
```

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```

JML annotation occur as special comments in source programm

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precondition

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postcondition

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```

JML operator `\old(e)` refers to value of `e` in prestate

Method Contracts

JML Spec of Postincrement

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All side-effect-free Java expressions allowed

Method Contracts

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  public void postinc() { act.x = act.y++; }}
```

Plus special operators (\ . . .)

Method Contracts

Non-null default

```
public class PostInc{
  public PostInc /*@ nullable @*/ act;
  public int x,y;

/*@ public normal_behavior
 @  requires act != null;
 @  ensures  act.x == \old(act.y) &&
 @           act.y == \old(act.y) + 1;
 @*/
 public void postinc() { act.x = act.y++; }}
```

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Non-null default

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```

By default JML assumes all fields and parameters to be non null

Method Contracts

Non-null default

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  @*/
  public void postinc() { act.x = act.y++; }}
```

The default is overwritten by the keyword `nullable`

Method Contracts

Non-null default

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  @*/
  public void postinc() { act.x = act.y++; }}
```

In this case the precondition has to be adapted accordingly

Method Contracts

Specification of `commonEntry`

```
class SITAPar{  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) { ... }
}
```

Method Contracts

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

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

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```

Method `commonEntry` looks for an index within the bounds

Method Contracts

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

such that the two arrays have the same entry

Method Contracts

Specification of `commonEntry`

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}
```

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

Method Contracts

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```

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

Part II

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– By Example –

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Quantifiers in JML

Specification of `commonEntry`

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@ ...
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@                                 a1[j] != a2[j] );
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```

Quantified formulas in JML consist of

- the quantifier
- the range restriction
- the body

Quantifiers in JML

Specification of `commonEntry`

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Quantified formulas in JML consist of

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- the body

Quantifiers in JML

Semantics

JML	`\forall T x; R; B;`
predicate logic	$\forall\, T{:}x\ (R \rightarrow B)$
JML	`\exists T x; R; B;`
predicate logic	$\exists\, T{:}x\ (R \wedge B)$

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Loop Invariants

Loop Invariant for `commonEntry`

```
class SITAPar{  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;}
}
```

Loop Invariants

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  @  assignable \nothing;
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  @*/
   while(k < r){ if(a1[k] == a2[k]){break;}   k++;}
   return k;}
}
```

The loop invariant

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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 Invariants

Loop Invariant for `commonEntry`

```
class SITAPar{  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;}
}
```

`l <= k && k <= r` follows from `k==l` and precondition `l<r`

Loop Invariants

Loop Invariant for `commonEntry`

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

`l <= k && k <= r` follows from `k==l` and precondition `l<r` and quantification is empty

Loop Invariants

Loop Invariant for `commonEntry`

```
class SITAPar{  public int[] a1,a2;   ...
  public int  commonEntry(int l, int r){ int k = l;
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  @    (\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;}
}
```

If the loop body is started in a state satisfying the invariant,
it terminates in a state satisfying the invariant

Loop Invariants

Loop Invariant for `commonEntry`

```
class SITAPar{  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;}
}
```

Distinguish `break` and non-`break` case!

Using a Loop Invariant

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 reason for termination of the loop

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

imply the postconditions

```
(l <= \result && \result < r && a1[\result] == a2[\result])
  || \result == r
```

and

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

Using a Loop Invariant

On termination of the loop
the invariant

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

```
\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 &&
  @ (\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;}
}
```

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

Loop Termination

```
  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] );
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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
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  public int  commonEntry(int l, int r){ int k = l;
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- is ≥ 0 on entering the loop
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Loop Termination

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The loop variant

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

Part II

The Java Modeling Language
– By Example –

Part II

The Java Modeling Language
– By Example –

1. Method Contracts
2. Quantifiers
3. Handling Loops
4. Frame Conditions
5. Using Contracts
6. Abstraction

Assignable Clauses

```
/*@ 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 Clauses

```
/*@ 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 in the assignable clause may be changed

Assignable Clauses

```
/*@ 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;}
```

Everything else must remain unchanged

Assignable Clauses

```
/*@ 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;}
```

Local variables need not be included

Assignable Clauses

```
/*@ 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 clauses are evaluated in the prestate

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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;
   @   a1[i] == a2[i] ==>
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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`

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;}}}}
```

Method `rearrange` uses methods `commonEntry`

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]));
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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;
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    if (m < a1.length) {swap(a1,m,k);
     if (a1 != a2) { swap(a2,m,k);} k = k+1 ; m = m+1;}}}}
```

Verification of `rearrange` uses their contracts, not their implementation

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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    if (m < a1.length) {swap(a1,m,k);
     if (a1 != a2) { swap(a2,m,k);} k = k+1 ; m = m+1;}}}}
```

Key to scalability

Part II

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– By Example –

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Model Fields

```
/*@ 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

```
/*@ model \seq seq1; model \seq seq2; @*/
/*@ represents seq1 = \dl_array2seq(a1);
  @ represents seq2 = \dl_array2seq(a2);
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/*@ public normal_behaviour
  @  ensures  \dl_seqPerm(seq1,\old(seq1)) &&
  @           \dl_seqPerm(seq2,\old(seq2)) ;
  @*/
 public void  rearrange(){ ... }
```

model fields are only for specification

Model Fields

```
/*@ model \seq seq1; model \seq seq2; @*/
/*@ represents seq1 = \dl_array2seq(a1);
  @ represents seq2 = \dl_array2seq(a2);
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/*@ public normal_behaviour
  @  ensures  \dl_seqPerm(seq1,\old(seq1)) &&
  @           \dl_seqPerm(seq2,\old(seq2)) ;
  @*/
 public void  rearrange(){ ... }
```

`\seq` is an abstract data type

Model Fields

```
/*@ model \seq seq1; model \seq seq2; @*/
/*@ represents seq1 = \dl_array2seq(a1);
  @ represents seq2 = \dl_array2seq(a2);
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  @  ensures  \dl_seqPerm(seq1,\old(seq1)) &&
  @           \dl_seqPerm(seq2,\old(seq2)) ;
  @*/
 public void  rearrange(){ ... }
```

`represents` clauses fix the semantics of model fields

Model Fields

```
/*@ model \seq seq1; model \seq seq2; @*/
/*@ represents seq1 = \dl_array2seq(a1);
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  @  ensures  \dl_seqPerm(seq1,\old(seq1)) &&
  @           \dl_seqPerm(seq2,\old(seq2)) ;
  @*/
 public void  rearrange(){ ... }
```

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

Model Fields

```
/*@ 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(){ ... }
```

Only additional postcondition show here

Model Fields

```
/*@ 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(){ ... }
```

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

Model Fields

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

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

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

Model Fields

```
/*@ model \seq seq1; model \seq seq2; @*/
/*@ represents seq1 = \dl_array2seq(a1);
  @ represents seq2 = \dl_array2seq(a2);
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  @  ensures  \dl_seqPerm(seq1,\old(seq1)) &&
  @           \dl_seqPerm(seq2,\old(seq2)) ;
  @*/
 public void  rearrange(){ ... }
```

Model fields allow abstraction and information hiding.
They can be defined and used in interfaces.

Part III

Program Verification with Dynamic Logic

Part III

Program Verification with Dynamic Logic

7 JAVA CARD DL

8 Sequent Calculus

9 Rules for Programs: Symbolic Execution

10 A Calculus for 100% JAVA CARD

11 Taclets – KeY's Rule Description Language

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)

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)

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  (partial correctness)
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Modal operators allow referring to the final state of p:

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  (total correctness)

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

- Programs are “first-class citizens”
- Real Java syntax

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

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

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

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

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

$\texttt{<x = 1;>}([\texttt{while (true) \{\}}]\, \mathit{false})$

- Program formulas can appear nested

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

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

Dynamic Logic Example Formulas

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

$\texttt{<x = 1;>}([\texttt{while (true) \{\}}]\, \mathit{false})$

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

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

Dynamic Logic Example Formulas

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

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

- Program formulas can appear nested

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

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Dynamic Logic Example Formulas

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

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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

Rigid and Flexible Terms

Example

$\texttt{<int i;>}\ \texttt{\textbackslash forall}\ \mathit{int}\ x;(\texttt{i} + 1 \doteq x \texttt{ -> } \texttt{<i++;>}(\texttt{i} \doteq x))$

- Interpretation of `i` depends on computation state ⇒ flexible
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Locations are always flexible
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A JAVA CARD DL formula is valid iff it is true in all states.

We need a calculus for checking validity of formulas

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Sequents and their Semantics

Syntax

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

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

Semantics

Same as the formula

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

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Sequent Rules

General form

$$\text{rule\_name}\ \frac{\overbrace{\Gamma_1 \Longrightarrow \Delta_1 \quad \cdots \quad \Gamma_r \Longrightarrow \Delta_r}^{\text{Premisses}}}{\underbrace{\Gamma \Longrightarrow \Delta}_{\text{Conclusion}}}$$

($r = 0$ possible: closing rules)

Soundness

If all premisses are valid, then the conclusion is valid

Use in practice

Goal is matched to conclusion

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imp_left $$\frac{\Gamma \Longrightarrow A, \Delta \qquad \Gamma, B \Longrightarrow \Delta}{\Gamma, A \mathrel{-\!\!>} B \Longrightarrow \Delta}$$

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

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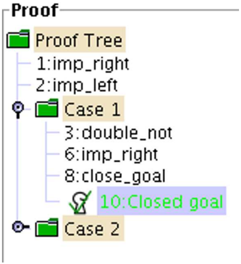
Sequent Calculus Proofs

Proof tree

- Proof is tree structure with goal sequent as root
- Rules are applied from conclusion (old goal) to premisses (new goals)
- Rule with no premiss closes proof branch
- Proof is finished when all goals are closed



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Proof
Proof Tree
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  Case 1
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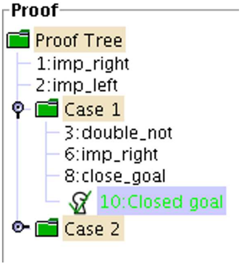

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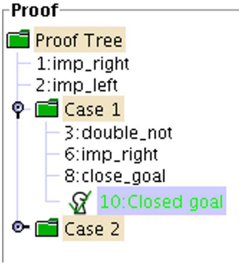

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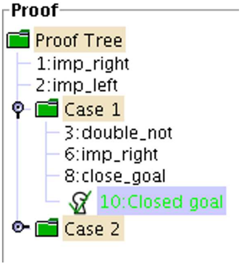

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Proof by Symbolic Program Execution

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Rules for Symbolic Program Execution

If-then-else rule

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

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

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

Simple assignment rule

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

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Extending DL by Explicit State Updates

Updates

explicit syntactic elements in the logic

Elementary Updates

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

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

Parallel Updates

$$\{loc_1 := t_1 \parallel \cdots \parallel loc_n := t_n\}\,\phi$$

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Symbolic Execution with Updates

(by Example)

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

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\texttt{x} < \texttt{y} & \Longrightarrow & \{\texttt{x:=y} \parallel \texttt{y:=x}\}\texttt{<>}\ \texttt{y} < \texttt{x} \\
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 & \vdots & \\
 & \Longrightarrow & \texttt{x} < \texttt{y} \ \texttt{->}\ \texttt{<int t=x; x=y; y=t;>}\ \texttt{y} < \texttt{x}
\end{array}
$$

Program State Representation

Local program variables

Modeled as non-rigid constants

Heap

Modeled with theory of arrays:

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

Heap axioms (excerpt)

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

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Handling Abrupt Termination

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

Example

TRY-THROW

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

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Part III

Program Verification with Dynamic Logic

7 JAVA CARD DL

8 Sequent Calculus

9 Rules for Programs: Symbolic Execution

10 A Calculus for 100% JAVA CARD

11 Taclets – KeY's Rule Description Language

Part III

Program Verification with Dynamic Logic

Supported Java Features

- method invocation with polymorphism/dynamic binding
- object creation and initialisation
- arrays
- abrupt termination
- throwing of NullPointerExceptions, etc.
- bounded integer data types
- transactions

All JAVA CARD language features are fully addressed in KeY

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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: 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

Karlsruhe Institute of Technology

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: 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
- Special-purpose extensions of program logic

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
2. Rules for reducing/simplifying the program (symbolic execution)
   Replace the program by
   - case distinctions (proof branches) and
   - sequences of updates
3. Rules for handling loops
   - using loop invariants
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4. Rules for replacing a method invocations by the method's contract
5. Update simplification

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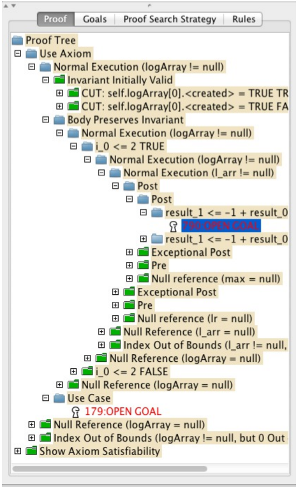
Taclets:
KeY's Rule Description Language

Taclets ...

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



- Proof Tree
  - Use Axiom
    - Normal Execution (logArray != null)
      - Invariant Initially Valid
        - CUT: self.logArray[0].<created> = TRUE TR
        - CUT: self.logArray[0].<created> = TRUE FA
      - Body Preserves Invariant
        - Normal Execution (logArray != null)
          - i_0 <= 2 TRUE
            - Normal Execution (logArray != null)
              - Normal Execution (l_arr != null)
                - Post
                  - Post
                    - result_1 <= -1 + result_0
                      - 790:OPEN GOAL
                    - result_1 <= -1 + result_0
                  - Exceptional Post
                  - Pre
                  - Null reference (max = null)
                - Exceptional Post
                - Pre
                - Null reference (lr = null)
              - Null Reference (l_arr = null)
              - Index Out of Bounds (l_arr != null,
            - Null Reference (logArray = null)
          - i_0 <= 2 FALSE
        - Null Reference (logArray = null)
      - Use Case
        - 179:OPEN GOAL
    - Null Reference (logArray = null)
    - Index Out of Bounds (logArray != null, but 0 Out
  - Show Axiom Satisfiability

Taclet Syntax

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

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

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Taclet Syntax

Some rules are only sound in a certain context

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

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```
modusPonens {
  \assumes ( A ==> )
  \find ( A -> B ==> )
  \replacewith( B ==> )
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```

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Taclet Syntax

Proof Splitting: andRight

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

```
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 ( ==> \forall x;phi )
  \varcond(\new(c,\dependingOn(phi)))
  \replacewith ( ==> {\subst x;c}phi )
};
```

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Proof Splitting: andRight

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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 )
```

Part IV

Verifying Information Flow Properties

12 Non-Interference
  - Definition
  - Reformulation and Formalisation – Alternating Quantifiers
  - Reformulation and Formalisation – Self Composition
  - Declassification

13 JML Non-Interference Specifications
  - Views and Security Policies
  - Non-Interference in JML

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Non-Interference

Prominent information flow property: **non-interference**

Simple case:

- program P
- partion of the program variables of P in
  - low security variables low and
  - high security variables $high$

Definition (Non-interference – Version 1)

For program P the high variables $high$ do not interfere with the low variables low

$$\Leftrightarrow$$

when starting P with arbitrary values for low, then the values of low after executing P, are independent of the choices of $high$.

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Examples

Which methods are secure?

```
class MiniExamples {
  public int l;
  private int h;

  void m_1() {
    l = h;
  }

  void m_2() {
    if (l>0) {h=1;}
    else {h=2;};
  }

  void m_3() {
    if (h>0) {l=1;}
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    h=0; l=h;
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Which methods are secure?

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```
void m_6() {
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```
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Formalisation in JavaDL – Alternating Quantifiers

Definition (Non-interference – Version 2)

For program P the high variables $high$ do not interfere with the low variables low $\Leftrightarrow$

for all low input values in_l there exist low output values r such that for all high input values in_h if we assign the values in_l to the program variables low and in_h to the program variables $high$ then after execution of P the values of low are r.

$$\forall in_l \exists r \forall in_h (\{low := in_l \mid\mid high := in_h\}[P]low = r)$$

- **Problem:** not suitable for automatic verification $\rightsquigarrow$ instantiation of existential quantifier difficult.

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Definition (Non-interference – Version 2)

For program P the high variables $high$ do not interfere with the low variables low $\Leftrightarrow$

for all low input values in_l there exist low output values r such that for all high input values in_h if we assign the values in_l to the program variables low and in_h to the program variables $high$ then after execution of P the values of low are r.

$$\forall in_l \exists r \forall in_h (\{low := in_l \mid\mid high := in_h\}[P]low = r)$$

- **Problem:** not suitable for automatic verification $\rightsquigarrow$ instantiation of existential quantifier difficult.

Formalisation in JavaDL – Self Composition

Definition (Non-interference – Version 3)

For program P the high variables $high$ do not interfere with the low variables low $\Leftrightarrow$

running two instances of P on the same low values but on arbitrary high values result in low variables which have the same values.

$$\begin{array}{l}\forall in_l \forall in_h^1 \forall in_h^2 \forall out_l^1 \forall out_l^2 \; (\\ \quad \{low := in_l \mid\mid high := in_h^1\}[P]out_l^1 = low \\ \quad \wedge \{low := in_l \mid\mid high := in_h^2\}[P]out_l^2 = low \\ \quad \rightarrow out_l^1 = out_l^2 \\ )\end{array}$$

Formalisation in JavaDL – Self Composition

Definition (Non-interference – Version 3)

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$$\Leftrightarrow$$

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$$
\begin{aligned}
&\forall in_l \forall in_h^1 \forall in_h^2 \forall out_l^1 \forall out_l^2\ (\\
&\qquad \{low := in_l \mid\mid high := in_h^1\}[P]out_l^1 = low\\
&\quad \wedge \{low := in_l \mid\mid high := in_h^2\}[P]out_l^2 = low\\
&\quad \rightarrow out_l^1 = out_l^2\\
&)
\end{aligned}
$$

Formalisation in JavaDL – Self Composition

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\begin{aligned}
&\forall in_l \forall in_h^1 \forall in_h^2 \forall out_l^1 \forall out_l^2 \; (\\
&\qquad \{low := in_l \;||\; high := in_h^1\}[P]out_l^1 = low \\
&\quad \wedge \{low := in_l \;||\; high := in_h^2\}[P]out_l^2 = low \\
&\quad \rightarrow out_l^1 = out_l^2 \\
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$$

Formalisation in JavaDL – Self Composition

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$$\begin{array}{l} \forall in_l \forall in_h^1 \forall in_h^2 \forall out_l^1 \forall out_l^2 \; (\\ \qquad \{low := in_l \mid\mid high := in_h^1\}[P] out_l^1 = low \\ \quad \wedge \{low := in_l \mid\mid high := in_h^2\}[P] out_l^2 = low \\ \quad \rightarrow out_l^1 = out_l^2 \\ ) \end{array}$$

Program Variables vs. Heaps

- **So far:** definitions and formalisations talk about program variables.

$$
\begin{aligned}
&\forall in_l \forall in_h^1 \forall in_h^2 \forall out_l^1 \forall out_l^2 \, (\\
&\qquad \{low := in_l \mid\mid high := in_h^1\}[P]out_l^1 = low \\
&\qquad \land \{low := in_l \mid\mid high := in_h^2\}[P]out_l^2 = low \\
&\qquad \rightarrow out_l^1 = out_l^2 \\
&)
\end{aligned}
$$

- **Problem:** formulas contain for every program variable a quantifier and an update.
- **Better:** talking about heaps and sets of heap locations ⇝ all heap locations can be updated at once.

Self Composition with Heaps

Definition (Non-interference for Heaps)

A program P satisfies *non-interference* for a partition of the heap locations in low security locations low and high security locations $high$

$$\Leftrightarrow$$

running two instances of P on arbitrary heaps result in heaps which agree on the low-locations low if the input heaps agree on low.

$$\begin{aligned}\forall\ Heap\ h^1_{in}, h^2_{in}, h^1_{out}, h^2_{out}\ (&\\ &\{heap := h^1_{in}\}[P]h^1_{out} = heap\\ \land\ &\{heap := h^2_{in}\}[P]h^2_{out} = heap\\ \rightarrow\ &(h^1_{in} \sim_{low} h^2_{in} \rightarrow h^1_{out} \sim_{low} h^2_{out})\ )\end{aligned}$$

$$\begin{aligned}h^1 \sim_{low} h^2 \leftrightarrow \forall\ Object\ o\ \forall\ Field\ f\ (&\\ &(o, f) \in low \rightarrow\ \{heap := h^1\}o.f = \{heap := h^2\}o.f\ )\end{aligned}$$

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Self Composition with Heaps

Karlsruhe Institute of Technology

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&\qquad (o, f) \in low \rightarrow\ \{heap := h^1\}o.f = \{heap := h^2\}o.f\ )
\end{aligned}$$

Declassification

- Declassification of terms.
- **Semantics:** the evaluation of the term in the pre-state of the program invocation is allowed to leak.

$$
\begin{aligned}
&\forall\, Heap\ h^1_{in}, h^2_{in}, h^1_{out}, h^2_{out}\ (\\
&\qquad \{heap := h^1_{in}\}[P]h^1_{out} = heap\\
&\quad \wedge \{heap := h^2_{in}\}[P]h^2_{out} = heap\\
&\quad \rightarrow (h^1_{in} \sim_{low} h^2_{in} \wedge \{heap := h^1_{in}\}term = \{heap := h^2_{in}\}term\\
&\qquad\quad \rightarrow h^1_{out} \sim_{low} h^2_{out})\ )
\end{aligned}
$$

Termination-Sensitivity

The formalisation can be made termination sensitive:

$$\begin{aligned}
&\forall\, Heap\ h_{in}^1, h_{in}^2, h_{out}^1, h_{out}^2\ (\\
&\qquad \{heap := h_{in}^1\}[P]h_{out}^1 = heap\\
&\quad\ \wedge \{heap := h_{in}^2\}[P]h_{out}^2 = heap\\
&\quad \rightarrow (h_{in}^1 \sim_{low} h_{in}^2 \rightarrow h_{out}^1 \sim_{low} h_{out}^2)\\
&\quad\ \vee \{heap := h_{in}^1\}[P]false\ \wedge\ \{heap := h_{in}^2\}[P]false\ )
\end{aligned}$$

Part IV

Verifying Information Flow Properties

12 Non-Interference
- Definition
- Reformulation and Formalisation – Alternating Quantifiers
- Reformulation and Formalisation – Self Composition
- Declassification

13 JML Non-Interference Specifications
- Views and Security Policies
- Non-Interference in JML

Goal

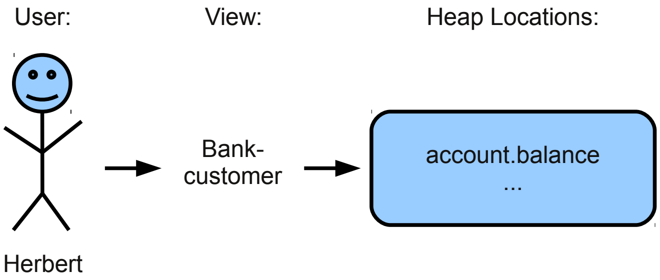
Modular program-level specification of information flow properties for **Java** programs.

- Extension of **JML** for information flow specification.
- Seamless integration of functional and information flow specifications.
- Suitable for the specification of interfaces.
- Should not transgress the principle of information hiding.
- Should not transgress the separation of specification and implementation.
- Precise (semantic) declassification.

Views

Users → Views → Heap Locations:

- **User** has some **view** on a system.
- A **view** observes a set of **heap locations**.



Not central: individual user ⇝ concentration on views.

Views

- **Security Requirement:** No (user of a) view may learn more about the initial program-state through the execution of a program than the values of the heap locations belonging to the view.
- Requirement implies security policy (and security lattice).
- **Information flow property:** language-based non-interference (with declassification)

Implicit Security Policy

Views define an implicit security policy:

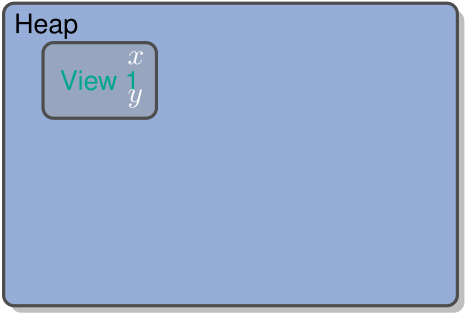
Heap

View 1

- Information may flow freely between $x \leftrightarrow y$.
- Information may flow $y \rightarrow z$, but $y \not\leftarrow z$.

Implicit Security Policy

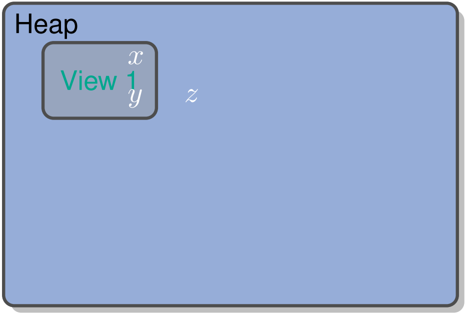
Views define an implicit security policy:



- Information may flow freely between $x \leftrightarrow y$.
- Information may flow $y \rightarrow z$, but $y \not\leftarrow z$.

Implicit Security Policy

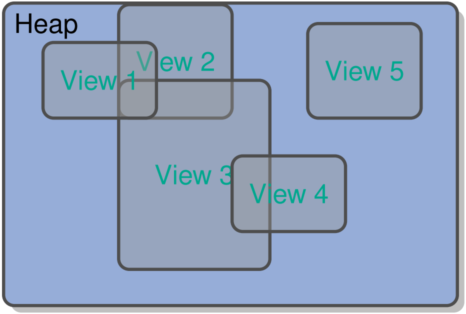
Views define an implicit security policy:



- Information may flow freely between $x \leftrightarrow y$.
- Information may flow $y \rightarrow z$, but $y \not\leftarrow z$.

Implicit Security Policy

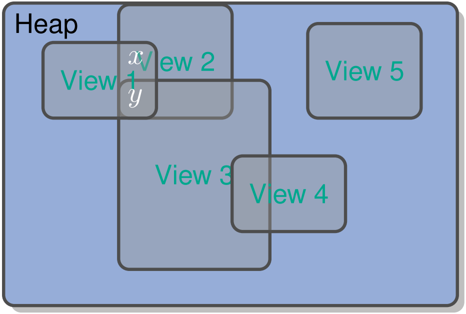
Views define an implicit security policy:



- Information may flow $y \rightarrow x$, but $y \not\leftarrow x$.
- Information may flow $y \rightarrow z$, but $y \not\leftarrow z$.
- Information may not flow $x \not\leftrightarrow z$.

Implicit Security Policy

Views define an implicit security policy:



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Implicit Security Policy

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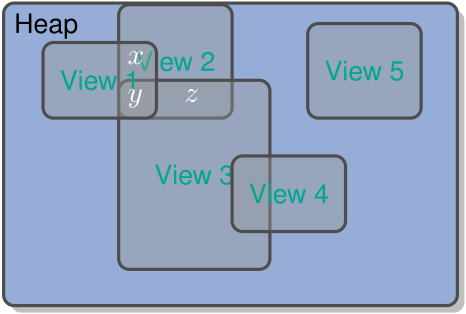
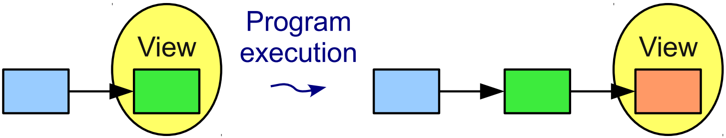


- Information may flow $y \rightarrow x$, but $y \nleftarrow x$.
- Information may flow $y \rightarrow z$, but $y \nleftarrow z$.
- Information may not flow $x \nleftrightarrow z$.

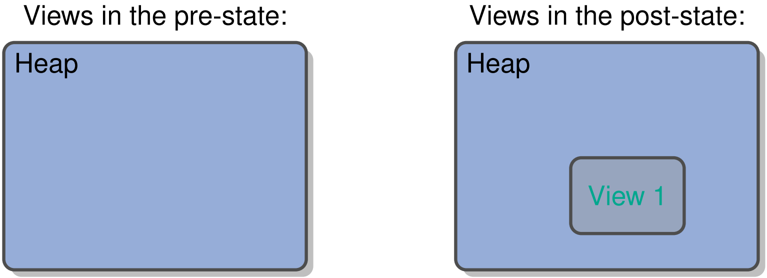
Dynamic Views

Feature:

- During program execution the set of heap locations belonging to a view may change.
- **Example:** view → last element of a linked list

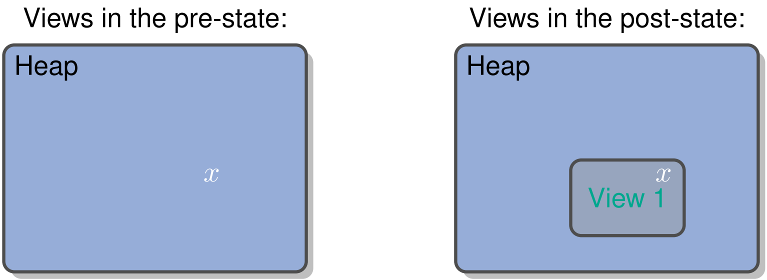


Security Policy for Dynamic Views



The value of x in the post-state has to be a constant.

Security Policy for Dynamic Views



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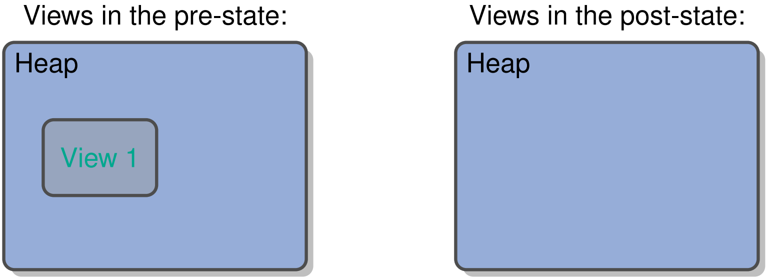
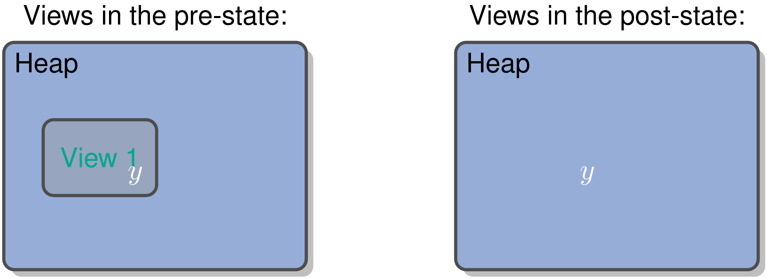
Security Policy for Dynamic Views



Nothing has to be checked.

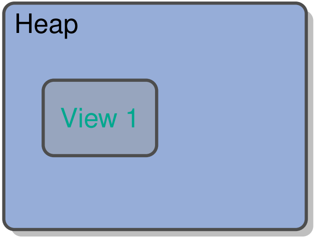
Security Policy for Dynamic Views



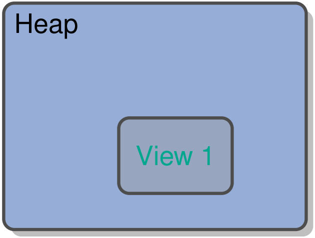
Nothing has to be checked.

Security Policy for Dynamic Views

Views in the pre-state:



Views in the post-state:



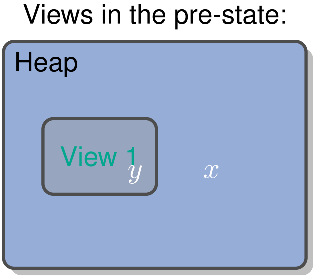
Information may flow

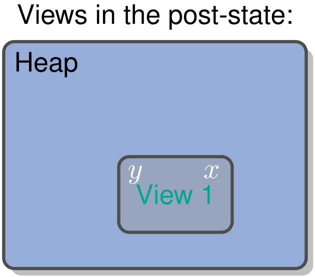
- $y \longrightarrow y$
- $y \longrightarrow x$

Information may *not* flow

- $x \not\longrightarrow y$
- $x \not\longrightarrow x$

Security Policy for Dynamic Views





Information may flow

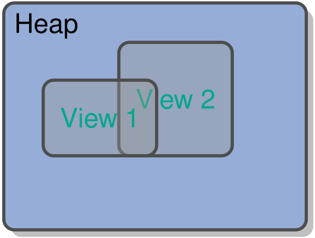
- $y \longrightarrow y$
- $y \longrightarrow x$

Information may *not* flow

- $x \not\rightarrow y$
- $x \not\rightarrow x$

Security Policy for Dynamic Views

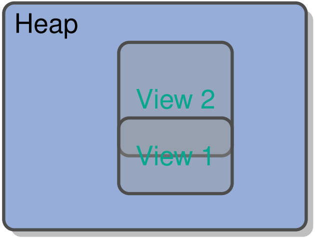
Views in the pre-state:



Information may flow

- $y \longrightarrow y$
- $y \longrightarrow x$
- $z \longrightarrow z$
- $y \longrightarrow z$
- $x \longrightarrow z$

Views in the post-state:

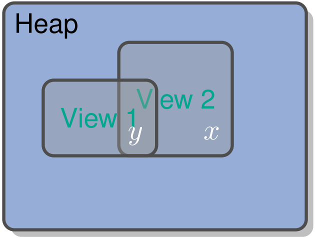


Information may *not* flow

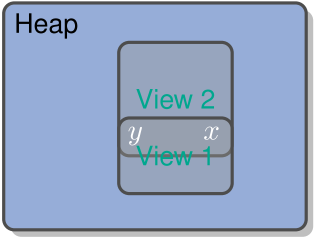
- $x \not\rightarrow y$
- $x \not\rightarrow x$
- $z \not\rightarrow y$
- $z \not\rightarrow x$

Security Policy for Dynamic Views

Views in the pre-state:



Views in the post-state:



Information may flow

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- $y \rightarrow x$
- $z \rightarrow z$
- $y \rightarrow z$
- $x \rightarrow z$

Information may *not* flow

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- $x \not\rightarrow x$
- $z \not\rightarrow y$
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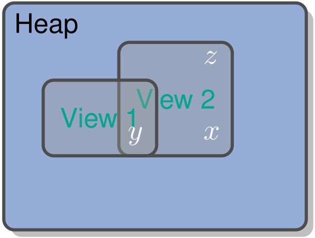
Security Policy for Dynamic Views

Views in the pre-state:



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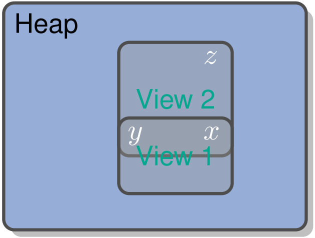

Information may flow

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- $y \rightarrow x$
- $z \rightarrow z$
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- $x \rightarrow z$

Information may *not* flow

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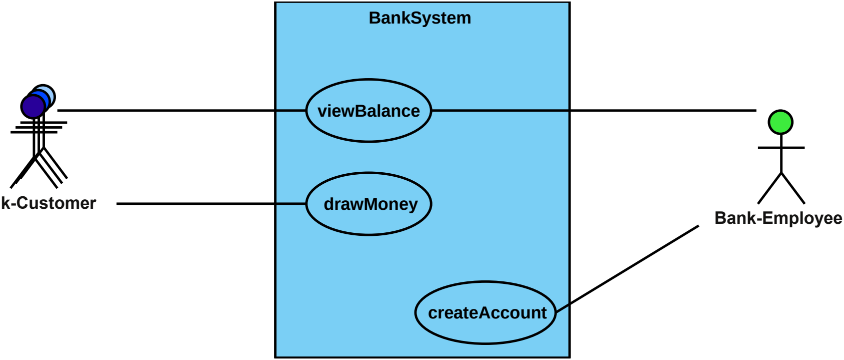
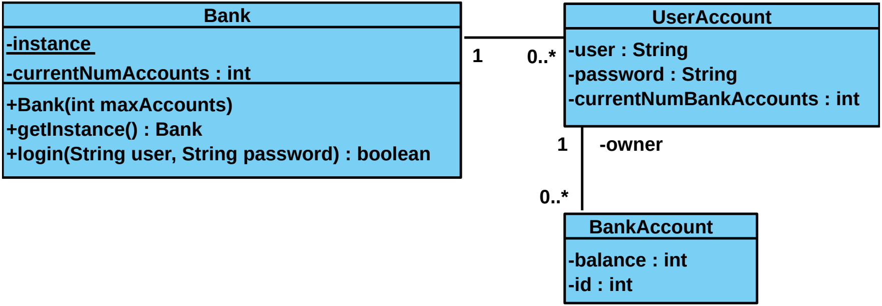
Example: Banking System – Use-Case Diagram



Example: Banking System – Class Diagram



Bank

<u>-instance</u>

-currentNumAccounts : int

+Bank(int maxAccounts)

+getInstance() : Bank

+login(String user, String password) : boolean

UserAccount

-user : String

-password : String

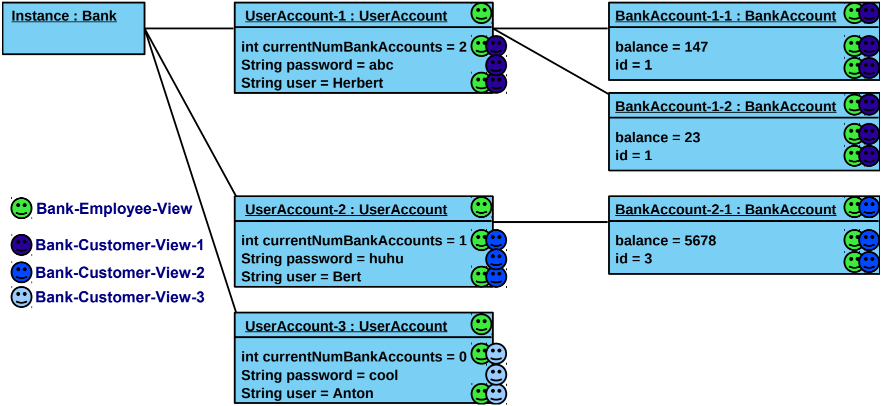
-currentNumBankAccounts : int

BankAccount

-balance : int

-id : int

Example: Banking System – Object Diagram



Instance : Bank

UserAccount-1 : UserAccount
int currentNumBankAccounts = 2
String password = abc
String user = Herbert

UserAccount-2 : UserAccount
int currentNumBankAccounts = 1
String password = huhu
String user = Bert

UserAccount-3 : UserAccount
int currentNumBankAccounts = 0
String password = cool
String user = Anton

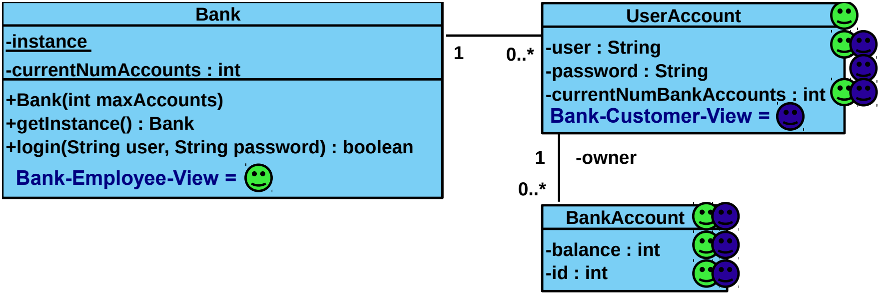
BankAccount-1-1 : BankAccount
balance = 147
id = 1

BankAccount-1-2 : BankAccount
balance = 23
id = 1

BankAccount-2-1 : BankAccount
balance = 5678
id = 3

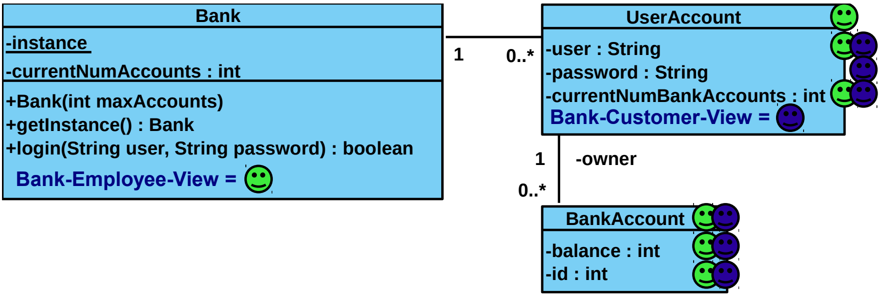
☺ Bank-Employee-View
☺ Bank-Customer-View-1
☺ Bank-Customer-View-2
☺ Bank-Customer-View-3

Example: Banking System – Views



$$\begin{aligned}\text{Bank-Employee-View} = {} & userAccounts[*] \\ & \cup\, userAccounts[*].user \\ & \cup\, userAccounts[*].currentNumBankAccounts \\ & \cup\, userAccounts[*].bankAccounts[*] \\ & \cup\, userAccounts[*].bankAccounts[*].balance \\ & \cup\, userAccounts[*].bankAccounts[*].id\end{aligned}$$

Example: Banking System – Views



Bank

-instance

-currentNumAccounts : int

+Bank(int maxAccounts)

+getInstance() : Bank

+login(String user, String password) : boolean

Bank-Employee-View = ☺

UserAccount ☺

-user : String ☺☻

-password : String ☻

-currentNumBankAccounts : int ☺☻

Bank-Customer-View = ☻

BankAccount ☺☻

-balance : int ☺☻

-id : int ☺☻

$$\begin{aligned}\text{Bank-Customer-View} = {} & user \\ & \cup\ password \\ & \cup\ currentNumAccounts \\ & \cup\ bankAccounts[*] \\ & \cup\ bankAccounts[*].balance \\ & \cup\ bankAccounts[*].id\end{aligned}$$

Non-Interference Specifications in JML

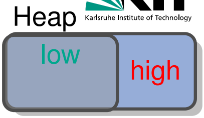
Specification as method contracts:

- Specification of the set of views which define the implicit security policy for the method *(respects-clause)*.
- Specification of the security level of the parameters *(parameter_dep-clause)*.

```
public int low;            void m(int param) {
private int high;            low = param;
                           }
```

- Specification of intentional information leakage *(declassify-clause)*.

Non-Interference Specifications in JML



$\text{low} \longrightarrow \text{high}$

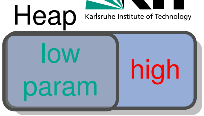
$\text{low} \not\leftarrow \text{high}$

```
public int low;
private int high;

/*@ respects      {low};

  @*/
public void m(int param) {
  low = param;
}
```

- **Views in JML:** expressions of type `\locset`.
- **Views can be named:** definition of model fields.
- Approach complies to the principle of information hiding!

Non-Interference Specifications in JML

```
public int low;
private int high;

/*@ respects       {low};
  @ parameter_dep {low};
  @*/
public void m(int param) {
  low = param;
}
```



low $\longrightarrow$ high

low $\not\longleftarrow$ high

param $\longleftrightarrow$ low

param $\longrightarrow$ high

param $\not\longleftarrow$ high

- **Views in JML:** expressions of type `\locset`.
- **Views can be named:** definition of model fields.
- Approach complies to the principle of information hiding!

Example: Password Checker

```
class PasswordFile {
  private int[] names, passwords;
  //@ invariant names.length == passwords.length;

  public boolean check(int user, int password) {
    for (int i = 0; i < names.length; i++) {
      if (names[i] == user &&
        passwords[i] == password) {
          return true;
      }
    }
    return false;
  }
}
```

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}
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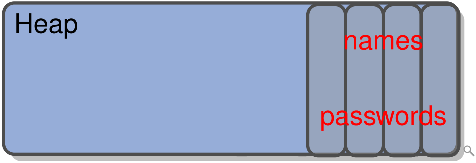

Example: Password Checker

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    return false;
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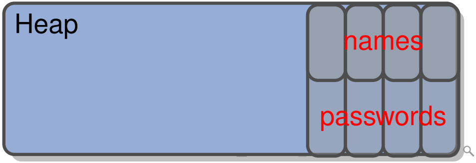
}
```



Example: Password Checker

```
class PasswordFile {
  private int[] names, passwords;
  //@ invariant names.length == passwords.length;

  public boolean check(int user, int password) {
    for (int i = 0; i < names.length; i++) {
      if (names[i] == user &&
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          return true;
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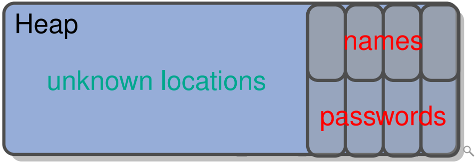
}
```



JML Specification Example

```
/*@ respects
  @   {names[0]},
  @   {names[0], passwords[0]},
  @   {names[1]},
  @   {names[1], passwords[1]},
  @   ...;
  @*/
public boolean check(int user, int password) { ...
```

JML Specification Example

```
/*@ model int userIndex;
  @ represents userIndex \such_that
  @       0 <= userIndex
  @    && userIndex < names.length;
  @*/

/*@ respects
  @   {names[userIndex]},
  @   {names[userIndex], passwords[userIndex]};
  @*/
public boolean check(int user, int password) { ...
```

JML Specification Example

```
/*@ model int userIndex;
  @ represents userIndex \such_that
  @        0 <= userIndex
  @     && userIndex < names.length;
  @
  @ model \locset nameUser;
  @ represents nameUser = {names[userIndex]};
  @
  @ model \locset loginUser;
  @ represents loginUser =
  @   {nameUser, passwords[userIndex]};
  @*/
//@ respects    nameUser, loginUser;
public boolean check(int user, int password) { ...
```

Example: Password Checker

```
class PasswordFile {
  private int[] names, passwords;
  //@ invariant names.length == passwords.length;

  public boolean check(int user, int password) {
    for (int i = 0; i < names.length; i++) {
      if (names[i] == user &&
        passwords[i] == password) {
          return true;
      }
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    return false;
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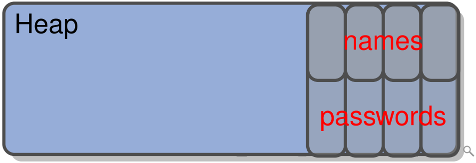
}
```



Example: Password Checker

```
class PasswordFile {
  private int[] names, passwords;
  //@ invariant names.length == passwords.length;

  public boolean check(int user, int password) {
    for (int i = 0; i < names.length; i++) {
      if (names[i] == user &&
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          return true;
      }
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    return false;
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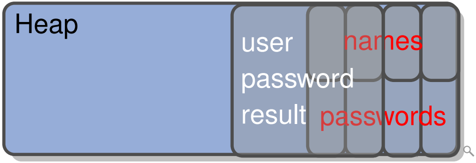
}
```



Heap

user

names

password

result

passwords

JML Specification Example

```
/*@ ...
  @ model \locset anyUser;
  @*/

/*@ respects      nameUser, loginUser;
  @ parameter_dep anyUser, anyUser: anyUser;
  @*/
public boolean check(int user, int password) { ...
```

Example: Password Checker

```
class PasswordFile {
  private int[] names, passwords;
  //@ invariant names.length == passwords.length;

  public boolean check(int user, int password) {
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    return false;
  }
}
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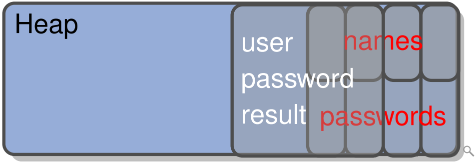

Declassification

Information is declassified in form of a term:

- Evaluation of the term in the pre-state of the method invocation is allowed to leak. (what-axes)

Restrictions:

- Leakage should be authorised by some view: leak only in case information can be computed by the authorising view. (who-axes)
- Flow should be restricted to some view: leak only to a specified view. (who-axes)
- Declassification bound to some condition: leak only if the condition evaluates to true in the pre-state of the method invocation. (when-axes)

JML Specification Example

```
/*@ normal_behavior
  @   respects      nameUser, loginUser;
  @   parameter_dep anyUser;
  @   declassify    ( \exists int i;
  @                     0 <= i && i < names.length;
  @                        names[i] == user
  @                     && passwords[i] == password
  @                 )
  @                 \from {names[*], passwords[*]}
  @                 \to anyUser;
  @*/
public boolean check(int user, int password) { ...
```

Notes

- Declassification is part of the method contract → separation of specification and implementation.
- Precise (semantic) declassification.
- Low references on objects with high fields need to be allowed.
- Static verification of data structures with elements of different security levels possible.

Part V

Wrap Up

Part V

Wrap Up

14 Further Usage of Verification Technology

15 Directions of Current Research in KeY

16 Different Approaches

Further Usage of Verification Technology

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

Verification Driven Test Generation

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

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Extending the scope of verification

- Concurrency and distribution
- Information-flow properties
- Floating-point arithmetic
- Safety-Critical Java (different memory model)
- Resource bounds (memory, time)
- Product lines
- Compiling verifier

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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

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Wrap Up

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Part V

Wrap Up

Different Approaches to Software Verification

General Purpose Systems

- General purpose
- Elaborate support for theories, abstract data types
- Target object level *and* meta level

Verification systems for OO languages

- Special purpose, tuned for that
- Close to programming language
- Integration into software development process/tools

Combining these advantages remains a challenge

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THE END

(for now)