Formal Methods for Software Development

Reasoning about Programs with Dynamic Logic

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Symbolic Execution of Programs

Sequent calculus decomposes top-level operator in formula.
What is "top-level" in a sequential program `p; q; r;` ?

Symbolic Execution

- Follow the natural control flow when analysing a program
- Values of some variables unknown: symbolic state representation

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- Follow the natural control flow when analysing a program
- Values of some variables unknown: symbolic state representation

Example

Compute the final state after termination of

```
x=x+y; y=x-y; x=x-y;
```

Symbolic Execution of Programs Cont'd

Typical form of DL formulas in symbolic execution

$$\langle \texttt{stmt; } \mathit{rest} \rangle \phi \qquad [\texttt{stmt; } \mathit{rest}]\phi$$

- Rules symbolically execute *first* statement ("active statement")
- Repeated application of such rules corresponds to symbolic program execution

Symbolic Execution of Programs Cont'd

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Example (`symbolicExecution/simpleIf.key`, Demo, active statement only)

```
\programVariables {
 int x; int y; boolean b;
}
\problem {
 \<{ if (b) { x = 1; } else { x = 2; } y = 3; }\> y > x
}
```

Symbolic Execution of Programs Cont'd

Symbolic execution of conditional

$$\text{if}\ \frac{\Gamma, \mathtt{b} = \mathsf{TRUE} \Longrightarrow \langle \mathtt{p};\ \ \mathit{rest} \rangle \phi, \Delta \qquad \Gamma, \mathtt{b} = \mathsf{FALSE} \Longrightarrow \langle \mathtt{q};\ \ \mathit{rest} \rangle \phi, \Delta}{\Gamma \Longrightarrow \langle \mathbf{if}\ \mathtt{(b)}\ \mathtt{\{}\ \mathtt{p}\ \mathtt{\}}\ \mathbf{else}\ \mathtt{\{}\ \mathtt{q}\ \mathtt{\}}\ \mathtt{;}\ \ \mathit{rest} \rangle \phi, \Delta}$$

Symbolic execution must consider all possible execution branches

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Symbolic execution must consider all possible execution branches

Symbolic execution of loops: unwind

$$\text{unwindLoop}\ \frac{\Gamma \Longrightarrow \langle \textbf{if}\ \ \mathtt{(b)}\ \ \{\ \mathtt{p;}\ \ \textbf{while}\ \ \mathtt{(b)}\ \ \mathtt{p}\ \};\ \ \mathit{rest}\rangle\phi, \Delta}{\Gamma \Longrightarrow \langle \textbf{while}\ \ \mathtt{(b)}\ \ \{\mathtt{p}\};\ \ \mathit{rest}\rangle\phi, \Delta}$$

Updates for KeY-Style Symbolic Execution

Needed: a Notation for Symbolic State Changes

- Symbolic execution should "walk" through program in natural forward direction
- Need succinct representation of state changes, effected by each symbolic execution step
- Want to simplify effects of program execution early
- Want to apply state changes late (to branching conditions and post condition)

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We use dedicated notation for state changes: updates

Explicit State Updates

Definition (Syntax of Updates, Updated Terms/Formulas)

If v is program variable, t FOL term (of right type), t' any FOL term, and ϕ any DL formula, then

- $\{\mathrm{v} := t\}$ is an update
- $\{\mathrm{v} := t\}t'$ is DL term
- $\{\mathrm{v} := t\}\phi$ is DL formula

Definition (Semantics of Updates)

State $\mathcal{S}$ interprets program variables v with $\mathcal{I}_{\mathcal{S}}(v)$, β variable assignment for logical variables in t, define semantics ρ as:

$\rho_\beta(\{\mathrm{v} := t\})(\mathcal{S}) = \mathcal{S}'$ where $\mathcal{S}'$ identical to $\mathcal{S}$ except $\mathcal{I}_{\mathcal{S}'}(\mathrm{v}) = val_{\mathcal{S},\beta}(t)$

Explicit State Updates Cont'd

Facts about updates $\{\mathtt{v} := t\}$

- Update semantics similar to that of assignment
- Value of update also depends on $\mathcal{S}$ and logical variables in t, i.e., β
- Updates are not assignments: right-hand side is FOL term

  $\{\mathtt{x} := n\}\phi$ cannot be turned into assignment if n is a logical variable

  $\langle\mathtt{x=i++;}\rangle\phi$ cannot (immediately) be turned into update
- Updates are not equations: they change value of $\mathtt{v}$

Computing Effect of Updates (Automated)

Rewrite rules for update followed by ...

program variable	$\{\mathrm{x} := t\}\mathrm{x} \leadsto t$ $\{\mathrm{x} := t\}\mathrm{y} \leadsto \mathrm{y}$
logical variable	$\{\mathrm{x} := t\}w \leadsto w$
complex term	$\{\mathrm{x} := t\}f(t_1, \ldots, t_n) \leadsto f(\{\mathrm{x} := t\}t_1, \ldots, \{\mathrm{x} := t\}t_n)$
atomic formula	$\{\mathrm{x} := t\}p(t_1, \ldots, t_n) \leadsto p(\{\mathrm{x} := t\}t_1, \ldots, \{\mathrm{x} := t\}t_n)$
FOL formula	$\{\mathrm{x} := t\}(\phi \ \& \ \psi) \leadsto \{\mathrm{x} := t\}\phi \ \& \ \{\mathrm{x} := t\}\psi$ $\cdots$ $\{\mathrm{x} := t\}(\forall \tau\ y; \phi) \leadsto \forall \tau\ y; (\{\mathrm{x} := t\}\phi)$
program formula	No rewrite rule for $\{\mathrm{x} := t\}\langle \mathit{prog} \rangle \phi$

Substitution delayed until prog symbolically executed

Assignment Rule Using Updates

Symbolic execution of assignment using updates

$$\text{assign} \quad \frac{\Gamma \Longrightarrow \{\mathtt{x} := t\}\langle \mathit{rest} \rangle \phi, \Delta}{\Gamma \Longrightarrow \langle \mathtt{x}\ \mathtt{=}\ t\mathtt{;}\ \mathit{rest} \rangle \phi, \Delta}$$

- Works as long as t is 'simple' (has no side effects)
- For every built-in Java operation, we need a seperate rule (for `x = ` t_1`+`t_2 and `x = ` t_1`-`t_2 etc.)

Demo

`updates/assignmentToUpdate.key`

Parallel Updates

How to apply updates on updates?

Example

Symbolic execution of

```
t=x; x=y; y=t;
```

yields:

```
{t := x}{x := y}{y := t}
```

Need to compose three sequential state changes into a single one:

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Need to compose three sequential state changes into a single one:
parallel updates

Parallel Updates Cont'd

Definition (Parallel Update)

A parallel update has the form $\{v_1 := r_1 || \cdots || v_n := r_n\}$, where each $\{v_i := r_i\}$ is simple update

- All r_i computed in old state before update is applied
- Updates of all program variables v_i executed simultaneously
- Upon conflict $v_i = v_j$, $r_i \neq r_j$ later update ($\max\{i, j\}$) wins

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Definition (Parallelising Updates, Conflict Resolution)

$$\{v_1 := r_1\}\{v_2 := r_2\} \;=\; \{v_1 := r_1 || v_2 := \{v_1 := r_1\}r_2\}$$

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$$\{v_1 := r_1 || \cdots || v_n := r_n\}\mathtt{x} \;=\; \begin{cases} \mathtt{x} & \text{if } \mathtt{x} \notin \{v_1, \ldots, v_n\} \\ r_k & \text{if } \mathtt{x} = v_k,\ \mathtt{x} \notin \{v_{k+1}, \ldots, v_n\} \end{cases}$$

Symbolic Execution with Updates (by Example)

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

Symbolic Execution with Updates (by Example)

$$\mathtt{x} < \mathtt{y} \implies \{\mathtt{t{:=}x}\}\langle\mathtt{x{=}y;\ y{=}t;}\rangle\, \mathtt{y} < \mathtt{x}$$

$$\vdots$$

$$\implies \mathtt{x} < \mathtt{y}\ \texttt{->}\ \langle\mathtt{t{=}x;\ x{=}y;\ y{=}t;}\rangle\, \mathtt{y} < \mathtt{x}$$

Symbolic Execution with Updates (by Example)

$$x < y \implies \{\texttt{t:=x}\}\{\texttt{x:=y}\}\langle\texttt{y=t;}\rangle\, y < x$$

$$\vdots$$

$$x < y \implies \{\texttt{t:=x}\}\langle\texttt{x=y; y=t;}\rangle\, y < x$$

$$\vdots$$

$$\implies x < y \texttt{ -> } \langle\texttt{t=x; x=y; y=t;}\rangle\, y < x$$

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Parallel Updates Cont'd

Demo

`updates/swap1.key`

Parallel Updates Cont'd

Example

symbolic execution of `x=x+y; y=x-y; x=x-y;` gives

`({x := x+y}{y := x-y}){x := x-y}`

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Example

symbolic execution of `x=x+y; y=x-y; x=x-y;` gives

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({x := x+y}{y := x-y}){x := x-y}
{x := x+y || y := (x+y)-y}{x := x-y}
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In case of conflict, KeY only keeps winning update

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Parallel updates store intermediate state of symbolic computation

Another use of Updates

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Not allowed: $\forall \tau\ \mathtt{i}; \langle \ldots \mathtt{i} \ldots \rangle \phi$
(program variables $\cap$ logical variables $= \emptyset$)

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Not allowed: $\forall\,\tau\ \mathtt{i};\ \langle\ldots\mathtt{i}\ldots\rangle\phi$

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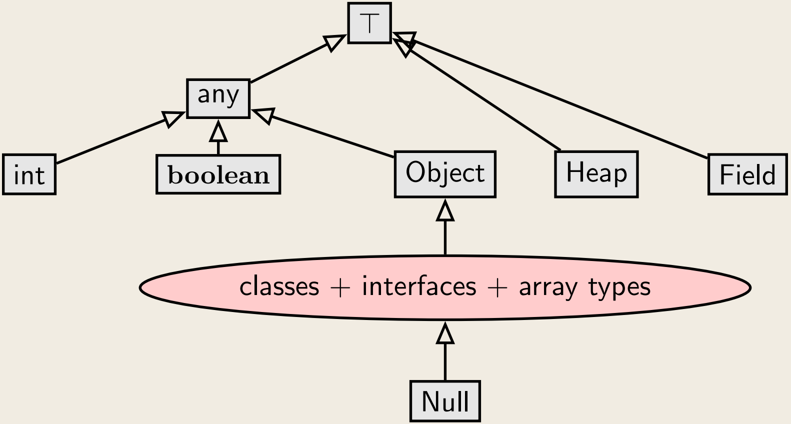
Instead

Quantify over value, and assign it to program variable:

$\forall\,\tau\ x;\ \{\mathtt{i} := x\}\langle\ldots\mathtt{i}\ldots\rangle\phi$

Modelling Java in FOL: Fixing a Type Hierarchy

Signature based on Java's type hierarchy



Each interface and class in application and API becomes type
with appropriate subtype relation

Modelling the Heap in FOL

The Java Heap

Objects are stored on (i.e., in) the heap.

- Status of heap changes during execution
- Each heap associates values to object/field pairs

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Each element of data type Heap represents a certain heap status.
Two functions involving heaps:

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- in F_{Σ}: Heap `store(`Heap, Object, Field, any`);`
  `store(`h, o, f, v`)` returns heap like h, but with v associated to $o.f$

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  `store`(h, o, f, v) returns heap like h, but with v associated to $o.f$
- in F_Σ: any `select`(Heap, Object, Field) ;
  `select`(h, o, f) returns value associated to $o.f$ in h

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Modelling instance fields

Person
int age int id
int setAge(int newAge) int getId()

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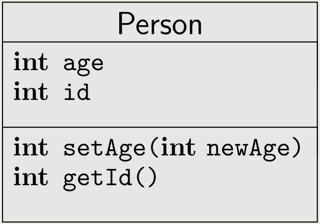

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Reading Field `id` of Person `p`

FOL notation $\mathtt{select}(h, \mathtt{p}, \mathtt{id})$

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KeY notation `p.id@`h (abbreviating $\mathtt{select}(h, \mathtt{p}, \mathtt{id})$)

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KeY notation $\mathtt{p.id@}h$ (abbreviating $\mathtt{select}(h, \mathtt{p}, \mathtt{id})$)

$\mathtt{p.id}$ (abbreviating $\mathtt{select}(\mathtt{heap}, \mathtt{p}, \mathtt{id})$)[a]

---

[a] `heap` is special program variable for "current" heap; mostly implicit in $o.f$

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Writing to Field `id` of Person `p`

FOL notation $\mathtt{store}(h, \mathtt{p}, \mathtt{id}, 6238)$

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FOL notation $\mathtt{store}(h, \mathtt{p}, \mathtt{id}, 6238)$

KeY notation $h[\mathtt{p}.\mathtt{id} := 6238]$ (notation for `store`, not update)

The Algebra of Heaps

We do *not* formalise the *structure* (implementation) of heaps.
We formalise the *behaviour*, with an algebra of heap operations:

$$\mathtt{select}(\mathtt{store}(h, o, f, v), o, f) =$$

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Example

$\texttt{select}(\texttt{store}(h, \texttt{o}, \texttt{f}, 15), \texttt{o}, \texttt{f}) \leadsto 15$
$\texttt{select}(\texttt{store}(h, \texttt{o}, \texttt{f}, 15), \texttt{o}, \texttt{g}) \leadsto \texttt{select}(h, \texttt{o}, \texttt{g})$
$\texttt{select}(\texttt{store}(h, \texttt{o}, \texttt{f}, 15), \texttt{u}, \texttt{f}) \leadsto$
$\quad \text{if } (\texttt{o} = \texttt{u}) \text{ then } (15) \text{ else } (\texttt{select}(h, \texttt{u}, \texttt{f}))$

Pretty Printing

Shorthand Notations for Heap Operations

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Very-Shorthand Notations for Current Heap

Current heap always in special variable $\mathtt{heap}$.

$\mathrm{o.f}$	is	$\mathtt{select}(\mathtt{heap}, \mathrm{o}, \mathrm{f})$
$\{\mathrm{o.f} := \mathrm{v}\}$	is update	$\{\mathtt{heap} := \mathtt{heap}[\mathrm{o.f} := \mathrm{v}]\}$

Modelling the Heap in FOL—The Full Story

Is formula $\texttt{select}(h, \texttt{p}, \texttt{id}) >= 0$ type-safe?

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Real Field Access

$\texttt{int::select}(h, \mathrm{p}, \mathsf{Person::}\texttt{\$id}) >= 0$ is type-safe

- `int::select` is a function name, not a cast
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General

For each `T` typed field `f` of class `C`, F_Σ contains

- a constant declared as Field `C::$f`
- a function declared as `T` `T::select`(Heap, `C`, Field)

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Everything blue is a function name

Field Update Assignment Rule

Changing the value of fields

How to (symbolically) execute assignment to field, e.g., `p.age=18;` ?

$$\text{assign}\ \frac{\Gamma \Longrightarrow \{\mathtt{o.f} := t\}\langle \mathit{rest}\rangle\phi, \Delta}{\Gamma \Longrightarrow \langle \mathtt{o.f\ =\ }t\mathtt{;}\ \mathit{rest}\rangle\phi, \Delta}$$

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But is this rule correct? See below.

Dynamic Logic: KeY input file

```
\javaSource "path to source code referenced in problem";

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Demo

`updates/firstAttributeExample.key`

Refined Semantics of Program Modalities

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Abrupt termination on top-level counts as non-termination!

Example Reconsidered: Exception Handling

```
\javaSource "path to source code";

\programVariables {
   ...
}

\problem {
       p != null -> \<{   p.age = 18;  }\> p.age = 18
}
```

Only provable when no top-level exception thrown

Demo

`updates/secondAttributeExample.key`

The Self Reference

Modeling reference this

Special name for the object whose Java code is currently executed:

in JML: `Object` **this**;

in Java: `Object` **this**;

in KeY: `Object self;`

Default assumption in JML-KeY translation: $\texttt{self} \mathrel{!=} \textbf{null}$

Which Objects do Exist?

How to model object creation with **new** ?

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Constant Domain Assumption

Assume that domain $\mathcal{D}$ is the same in all states $(\mathcal{D}, \delta, \mathcal{I}) \in \mathit{States}$

Consequence:
Quantifiers and modalities commute:

$$\models (\forall\ T\ x;\ [\mathrm{p}]\phi) \leftrightarrow [\mathrm{p}](\forall\ T\ x;\ \phi)$$

Object Creation (background; no need to remember this)

Realizing Constant Domain Assumption

- Implicitly declared field **boolean** `<created>` in class `Object`
- `<created>` has value **true** iff argument object has been created
- Object creation modeled as {`heap` := `create(heap, ob)`} for not (yet) created `ob` (essentially sets `<created>` field of `ob` to **true**)

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Alternatives exisit in the literature. E.g.:
[Ahrendt, de Boer, Grabe, *Abstract Object Creation in Dynamic Logic – To Be or Not To Be Created*, Springer, LNCS 5850]

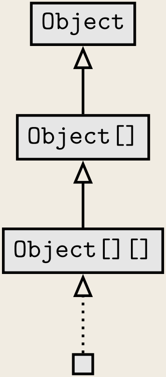
Dynamic Logic to (almost) full Java

KeY supports full sequential Java, with some limitations:

- Limited concurrency
- No generics
- No I/O
- No dynamic class loading or reflection
- Ongoing work to support floating point arithmetic
- API method calls: need either JML contract or implementation

Java Features in Dynamic Logic: Arrays

Arrays



- JAVA type hierarchy includes array types
- Types ordered according to JAVA subtyping rules
- Function $\texttt{arr} : \text{int} \to \text{Field}$ turns integer index into type Field (required in `store`).
- Store array elements on heap
- Value of `a[i]` in heap $\texttt{store}(\texttt{heap}, \texttt{a}, \texttt{arr}(\texttt{i}), 8)$ is 8
- Arrays `a` and `b` can refer to same object (aliasing)

Java Features in Dynamic Logic: Complex Expressions

Complex expressions with side effects

- JAVA expressions may have side effects, due to method calls, increment/decrement operators, nested assignments
- FOL terms have no side effect on the state

Example (Complex expression with side effects in Java)

`int i = 0; if ((i=2)>= 2) i++;` value of `i` ?

Complex Expressions Cont'd

Decomposition of complex terms by symbolic execution

Follow the rules laid down in JAVA Language Specification

Local code transformations

$$\text{evalOrderIteratedAssgnmt} \quad \frac{\Gamma \Longrightarrow \langle \texttt{y = t; x = y;}\ \omega\rangle\phi, \Delta}{\Gamma \Longrightarrow \langle \texttt{x = y = t;}\ \omega\rangle\phi, \Delta} \quad \texttt{t}\ \text{simple}$$

Temporary variables store result of evaluating subexpression

$$\text{ifEval} \quad \frac{\Gamma \Longrightarrow \langle \textbf{boolean}\ \texttt{v0; v0 = b; if (v0) p;}\ \omega\rangle\phi, \Delta}{\Gamma \Longrightarrow \langle \textbf{if}\ \texttt{(b) p;}\ \omega\rangle\phi, \Delta} \quad \texttt{b}\ \text{complex}$$

Java Features in Dynamic Logic: Abrupt Termination

Abrupt Termination: Exceptions and Jumps

Redirection of control flow via **return**, **break**, **continue**, exceptions

$$\langle \mathbf{try}\ \{\mathtt{p}\}\ \mathbf{catch}(\mathtt{T\ e})\ \{\mathtt{q}\}\ \mathbf{finally}\ \{\mathtt{r}\}\ \omega\rangle\phi$$

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Rule tryThrow matches try–catch in pre-/postfix and active throw

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$$\frac{\Longrightarrow \langle \texttt{if (e instanceof T) \{try\{x=e;q\} finally \{r\}\} else\{r; throw e;\}}\ \omega\rangle\phi}{\Longrightarrow \langle \texttt{try \{ throw e; p\} catch(T x) \{q\} finally \{r\}}\ \omega\rangle\phi}$$

Demo

`exceptions/try-catch.key`

Java Features in Dynamic Logic: Null

Null pointer exceptions

There are no "exceptions" in FOL: $\mathcal{I}$ total on FSym

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[a] Can be changed with Taclet Option runtimeExceptions

Field Update Assignment Rule Revisited (A)

Changing the value of fields

How to (symbolically) execute assignment to field?

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π is the "inactive prefix", any number of opening try blocks: $(\mathbf{try}\{)^*$

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Revisit: Field Assignment Demo

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Demo

updates/firstAttributeExample.key

Java Features in Dynamic Logic: Aliasing

Demo

`aliasing/attributeAlias1.key`

Java Features in Dynamic Logic: Aliasing

Demo

`aliasing/attributeAlias1.key`

Reference Aliasing

Alias resolution causes proof split

Summary

- Most JAVA features covered in KeY
- Degree of automation for loop-free programs is very high
- Handling of loops: last lecture

Literature for this Lecture

KeYbook *W. Ahrendt*, B. Beckert, R. Bubel, R. Hähnle, P. Schmitt, M. Ulbrich, editors.
Deductive Software Verification - The KeY Book
Vol 10001 of *LNCS*, Springer, 2016
(E-book at `link.springer.com`)

- B. Beckert, V. Klebanov, B. Weiß, Dynamic Logic for Java
  Chapter 3 in [KeYbook]
  on the surface only: Sections 3.1, 3.2, 3.4, 3.5.5, 3.5.6, 3.5.7, 3.6
- *W. Ahrendt*, S. Grebing, Using the KeY Prover
  Chapter 15 in [KeYbook]