Formal Correctness Proofs of Refactorings

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⟵ Our KeY updates — for the paper, see ISoLA (2)!

Refactoring and relational verification

Refactoring:

Improve structure of code, preserve behavior of executions

```
if(E) {S1;} else {S2;} return;    ~    if(!E) {S2;return;} S1; return;
```

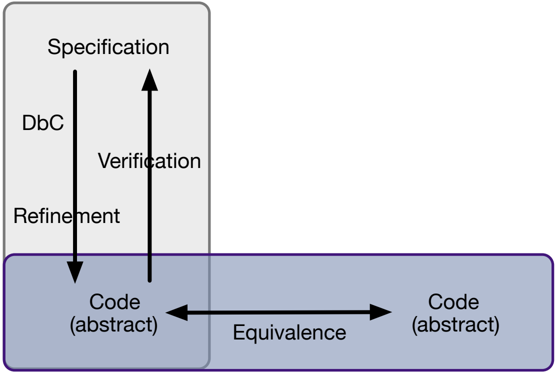
placeholders

Relational verification:

Relate pairs of executions, given initial state satisfy Φ then final state satisfy Ψ

$$\text{original} \sim \text{refactored} : \Phi \implies \Psi$$

Applications to Security



- KeY framework: information flow, non-interference for Java programs
- REFINITY/abstract execution: proofs on code-fragments (as specifications)

A fundamental relational property

Program equivalence

Two programs are equivalent iff they produce the same output when executed on the same input.

Here: let's look at Java fragments that we consider equivalent.

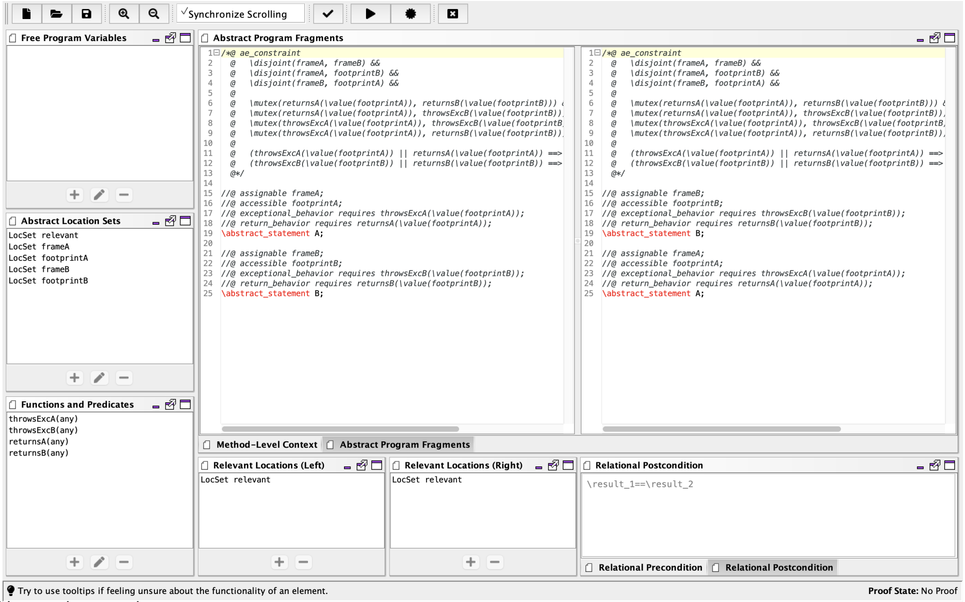
- How far can current tool support take us?
- Other definitions of equivalence?

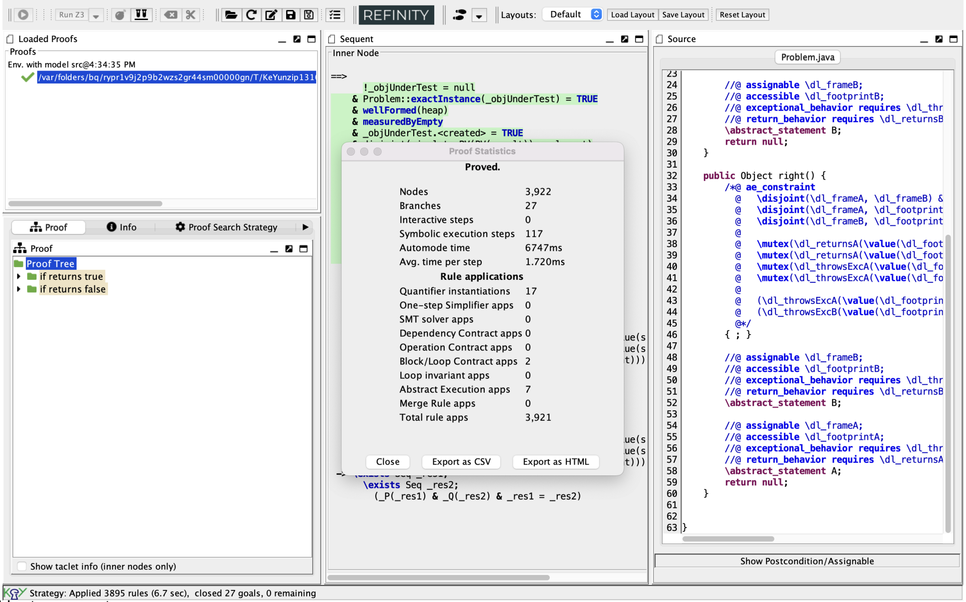
Relational verification in practice

REFINITY

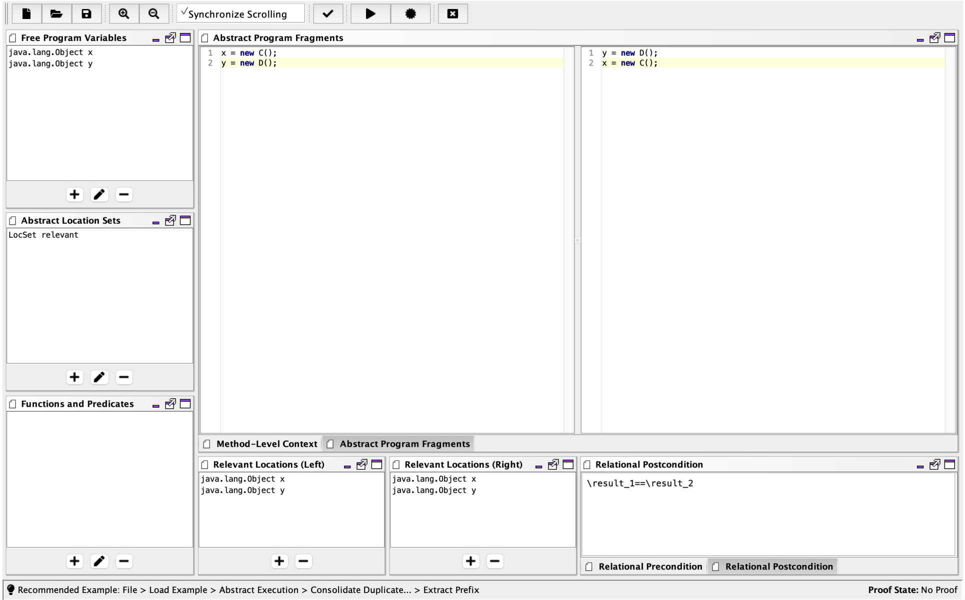
- Built on top of the KeY automated theorem prover
- Enables relational verification of “Java” with placeholders
- Placeholders are subject to Abstract Execution
- Has been sufficiently powerful to verify statement level refactorings[1]

[1] See Dominic Steinhöfel’s PhD thesis: https://tuprints.ulb.tu-darmstadt.de/8540/

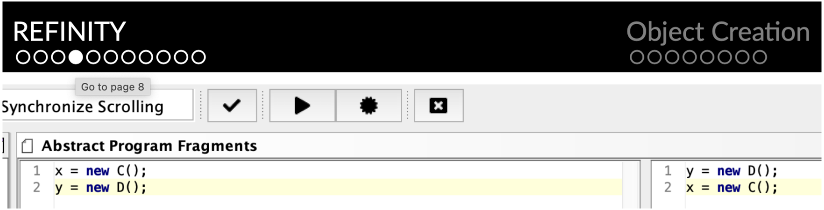

Synchronize Scrolling
Free Program Variables
Abstract Program Fragments
/*@ ae_constraint
@ \disjoint(frameA, frameB) &&
@ \disjoint(frameA, footprintB) &&
@ \disjoint(frameB, footprintA) &&
@
@ \mutex(returnsA(\value(footprintA)), returnsB(\value(footprintB))) &
@ \mutex(returnsA(\value(footprintA)), throwsExcB(\value(footprintB)),
@ \mutex(throwsExcA(\value(footprintA)), throwsExcB(\value(footprintB
@ \mutex(throwsExcA(\value(footprintA)), returnsB(\value(footprintB)),
@
@ (throwsExcA(\value(footprintA)) || returnsA(\value(footprintA)) ==>
@ (throwsExcB(\value(footprintB)) || returnsB(\value(footprintB)) ==>
@*/
//@ assignable frameA;
//@ accessible footprintA;
//@ exceptional_behavior requires throwsExcA(\value(footprintA));
//@ return_behavior requires returnsA(\value(footprintA));
\abstract_statement A;
//@ assignable frameB;
//@ accessible footprintB;
//@ exceptional_behavior requires throwsExcB(\value(footprintB));
//@ return_behavior requires returnsB(\value(footprintB));
\abstract_statement B;
/*@ ae_constraint
@ \disjoint(frameA, frameB) &&
@ \disjoint(frameA, footprintB) &&
@ \disjoint(frameB, footprintA) &&
@
@ \mutex(returnsA(\value(footprintA)), returnsB(\value(footprintB))) &
@ \mutex(returnsA(\value(footprintA)), throwsExcB(\value(footprintB)),
@ \mutex(throwsExcA(\value(footprintA)), throwsExcB(\value(footprintB
@ \mutex(throwsExcA(\value(footprintA)), returnsB(\value(footprintB)),
@
@ (throwsExcA(\value(footprintA)) || returnsA(\value(footprintA)) ==>
@ (throwsExcB(\value(footprintB)) || returnsB(\value(footprintB)) ==>
@*/
//@ assignable frameB;
//@ accessible footprintB;
//@ exceptional_behavior requires throwsExcB(\value(footprintB));
//@ return_behavior requires returnsB(\value(footprintB));
\abstract_statement B;
//@ assignable frameA;
//@ accessible footprintA;
//@ exceptional_behavior requires throwsExcA(\value(footprintA));
//@ return_behavior requires returnsA(\value(footprintA));
\abstract_statement A;
Abstract Location Sets
LocSet relevant
LocSet frameA
LocSet footprintA
LocSet frameB
LocSet footprintB
Functions and Predicates
throwsExcA(any)
throwsExcB(any)
returnsA(any)
returnsB(any)
Method-Level Context
Abstract Program Fragments
Relevant Locations (Left)
LocSet relevant
Relevant Locations (Right)
LocSet relevant
Relational Postcondition
\result_1==\result_2
Relational Precondition
Relational Postcondition
Try to use tooltips if feeling unsure about the functionality of an element.
Proof State: No Proof



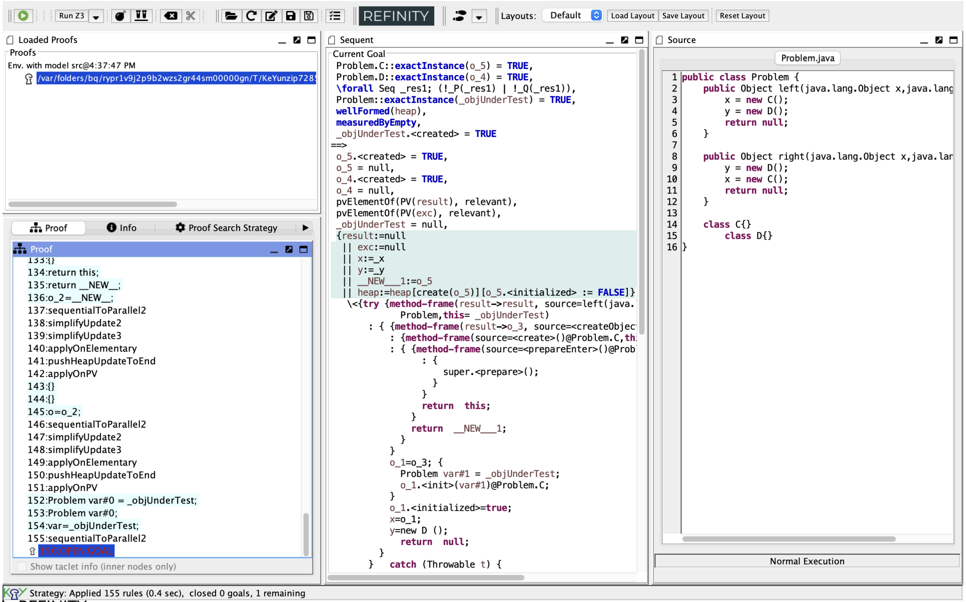
Example - slide stm. concrete ▷



Example - slide stm. conc. open goal ▷



Example - slide stm. conc. open goal ▷



Run Z3
REFINITY
Layouts: Default
Load Layout
Save Layout
Reset Layout
Loaded Proofs
Proofs
Env. with model src@4:37:47 PM
/var/folders/bq/rypr1v9j2p9b2wzs2gr44sm00000gn/T/KeYunzip728
Proof
Info
Proof Search Strategy
134:return this;
135:return __NEW__;
136:o_2=__NEW__;
137:sequentialToParallel2
138:simplifyUpdate2
139:simplifyUpdate3
140:applyOnElementary
141:pushHeapUpdateToEnd
142:applyOnPV
143:{}
144:{}
145:o=o_2;
146:sequentialToParallel2
147:simplifyUpdate2
148:simplifyUpdate3
149:applyOnElementary
150:pushHeapUpdateToEnd
151:applyOnPV
152:Problem var#0 = _objUnderTest;
153:Problem var#0;
154:var=_objUnderTest;
155:sequentialToParallel2
156:OPEN GOAL
Show taclet info (inner nodes only)
Sequent
Current Goal
Problem.C::exactInstance(o_5) = TRUE,
Problem.D::exactInstance(o_4) = TRUE,
\forall Seq _res1; (!_P(_res1) | !_Q(_res1)),
Problem::exactInstance(_objUnderTest) = TRUE,
wellFormed(heap),
measuredByEmpty,
_objUnderTest.<created> = TRUE
==>
o_5.<created> = TRUE,
o_5 = null,
o_4.<created> = TRUE,
o_4 = null,
pvElementOf(PV(result), relevant),
pvElementOf(PV(exc), relevant),
_objUnderTest = null,
{result:=null
|| exc:=null
|| x:=_x
|| y:=_y
|| __NEW___1:=o_5
|| heap:=heap[create(o_5)][o_5.<initialized> := FALSE]}
\<{try {method-frame(result->result, source=left(java.
Problem,this= _objUnderTest)
: { {method-frame(result->o_3, source=<createObjec
: {method-frame(source=<create>()@Problem.C,th
: { {method-frame(source=<prepareEnter>()@Prob
: {
super.<prepare>();
}
}
return this;
}
return __NEW___1;
}
}
o_1=o_3; {
Problem var#1 = _objUnderTest;
o_1.<init>(var#1)@Problem.C;
}
o_1.<initialized>=true;
x=o_1;
y=new D ();
return null;
}
} catch (Throwable t) {
Source
Problem.java
public class Problem {
public Object left(java.lang.Object x,java.lang
x = new C();
y = new D();
return null;
}
public Object right(java.lang.Object x,java.lar
y = new D();
x = new C();
return null;
}
class C{}
class D{}
}
Normal Execution
Strategy: Applied 155 rules (0.4 sec), closed 0 goals, 1 remaining

Equivalence

REFINITY checks that the following are identical by default:

- return values
- exceptions
- objects in the so-called relevant location set

Equivalent?

Refactoring tools often get this wrong:

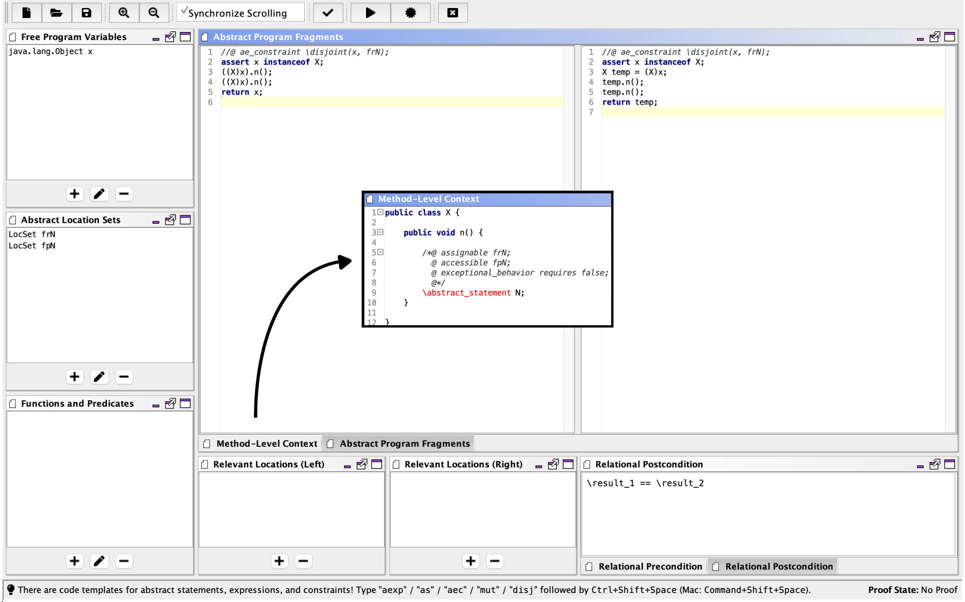
```
x.n();
x.n();
```

(a) Before

```
X temp = x;
temp.n();
temp.n();    //change?
```

(b) After

REFINITY won't close the proof unless you can show the required side-conditions on method `n()`.

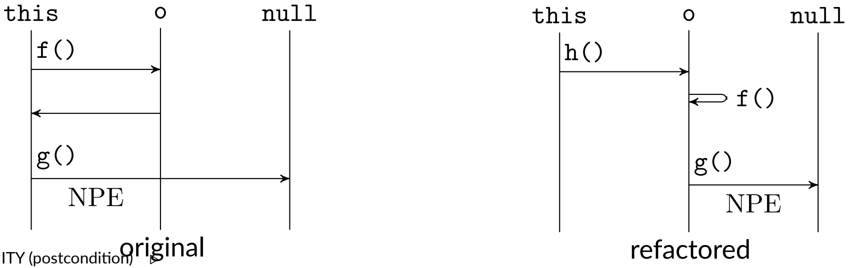

Synchronize Scrolling
Free Program Variables
java.lang.Object x
Abstract Location Sets
LocSet frN
LocSet fpN
Functions and Predicates
Abstract Program Fragments
//@ ae_constraint \disjoint(x, frN);
assert x instanceof X;
((X)x).n();
((X)x).n();
return x;
//@ ae_constraint \disjoint(x, frN);
assert x instanceof X;
X temp = (X)x;
temp.n();
temp.n();
return temp;
Method-Level Context
public class X {
public void n() {
/*@ assignable frN;
@ accessible fpN;
@ exceptional_behavior requires false;
@*/
\abstract_statement N;
}
}
Method-Level Context
Abstract Program Fragments
Relevant Locations (Left)
Relevant Locations (Right)
Relational Postcondition
\result_1 == \result_2
Relational Precondition
Relational Postcondition
There are code templates for abstract statements, expressions, and constraints! Type "aexp" / "as" / "aec" / "mut" / "disj" followed by Ctrl+Shift+Space (Mac: Command+Shift+Space).
Proof State: No Proof

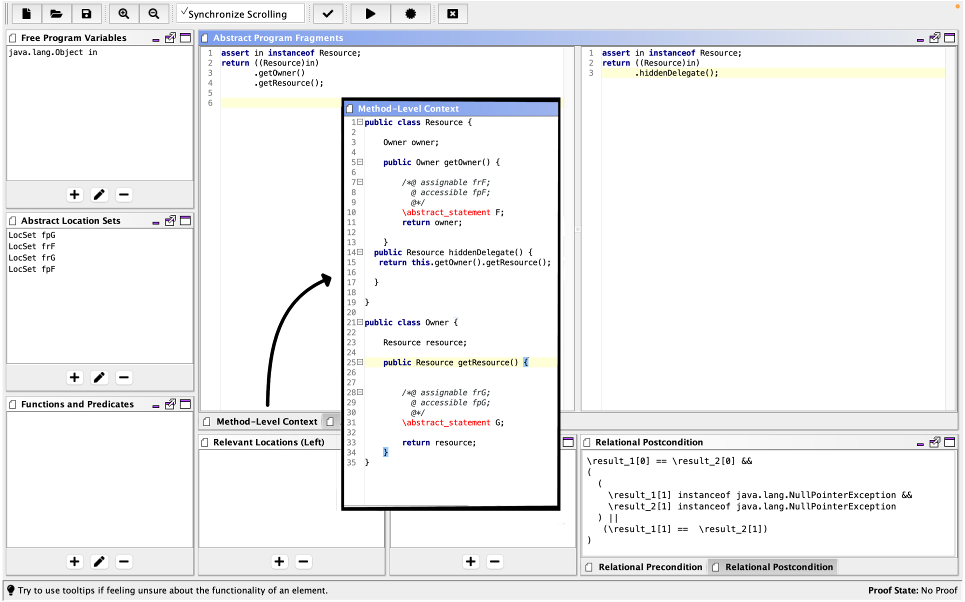
Different output, but equivalent?

Exception origin moved, no additional capture in `h()`

$$\begin{array}{ll} & \texttt{o.f().g();} \\ \rightarrow & \texttt{o.h();} \end{array}$$

with `h(){ this.f().g();}`




Synchronize Scrolling
Free Program Variables
java.lang.Object in
Abstract Location Sets
LocSet fpG
LocSet frF
LocSet frG
LocSet fpF
Functions and Predicates
Abstract Program Fragments
assert in instanceof Resource;
return ((Resource)in)
.getOwner()
.getResource();
assert in instanceof Resource;
return ((Resource)in)
.hiddenDelegate();
Method-Level Context
public class Resource {
Owner owner;
public Owner getOwner() {
/*@ assignable frF;
@ accessible fpF;
@*/
\abstract_statement F;
return owner;
}
public Resource hiddenDelegate() {
return this.getOwner().getResource();
}
}
public class Owner {
Resource resource;
public Resource getResource() {
/*@ assignable frG;
@ accessible fpG;
@*/
\abstract_statement G;
return resource;
}
}
Method-Level Context
Relevant Locations (Left)
Relational Postcondition
\result_1[0] == \result_2[0] &&
(
(
\result_1[1] instanceof java.lang.NullPointerException &&
\result_2[1] instanceof java.lang.NullPointerException
) ||
(\result_1[1] == \result_2[1])
)
Relational Precondition
Relational Postcondition
Try to use tooltips if feeling unsure about the functionality of an element.
Proof State: No Proof

Challenges in complex refactorings

Succesfully verified variants of *Extract Local Variable* and *Hide Delegate* and investigated how to approach others.

We discuss

Simplifying postcondition specifications

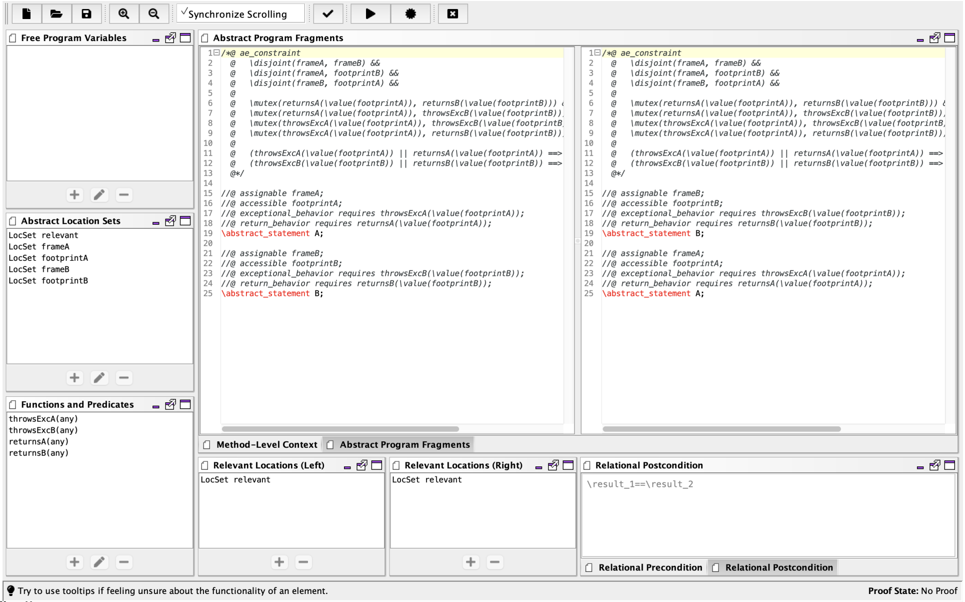
Unresolved

Making the proofs useful artefacts:
what about *instantitations*?

Object equality

REFINITY lacked rules for object equality over multiple modalities:

- can verify SLIDE STATEMENT with abstract statements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//@ return_behavior requires returnsB(\value(footprintB));
\abstract_statement B;
/*@ ae_constraint
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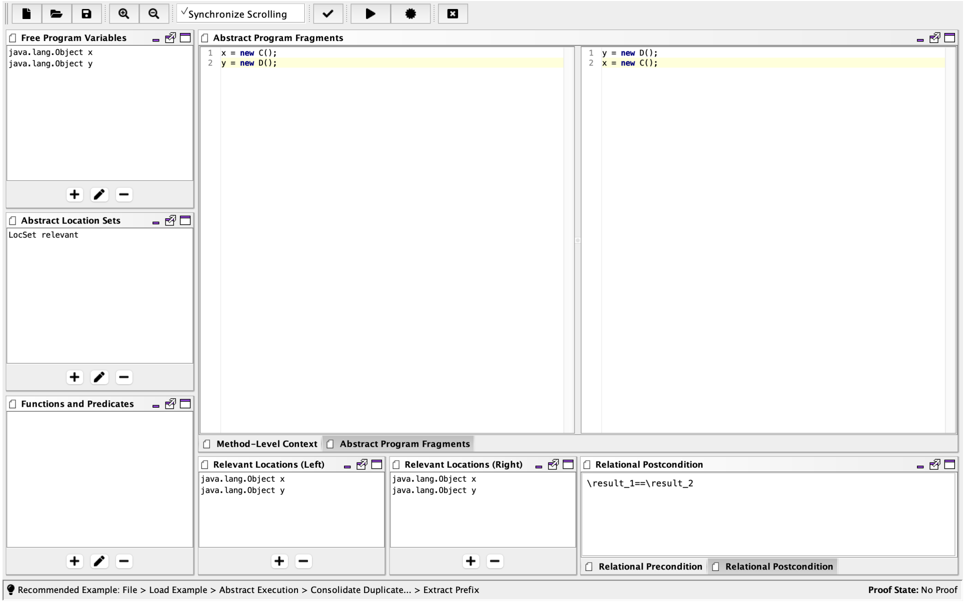
@ \disjoint(frameA, footprintB) &&
@ \disjoint(frameB, footprintA) &&
@
@ \mutex(returnsA(\value(footprintA)), returnsB(\value(footprintB))) &
@ \mutex(returnsA(\value(footprintA)), throwsExcB(\value(footprintB)),
@ \mutex(throwsExcA(\value(footprintA)), throwsExcB(\value(footprintB,
@ \mutex(throwsExcA(\value(footprintA)), returnsB(\value(footprintB)),
@
@ (throwsExcA(\value(footprintA)) || returnsA(\value(footprintA)) ==>
@ (throwsExcB(\value(footprintB)) || returnsB(\value(footprintB)) ==>
@*/
//@ assignable frameB;
//@ accessible footprintB;
//@ exceptional_behavior requires throwsExcB(\value(footprintB));
//@ return_behavior requires returnsB(\value(footprintB));
\abstract_statement B;
//@ assignable frameA;
//@ accessible footprintA;
//@ exceptional_behavior requires throwsExcA(\value(footprintA));
//@ return_behavior requires returnsA(\value(footprintA));
\abstract_statement A;
Method-Level Context
Abstract Program Fragments
Relevant Locations (Left)
LocSet relevant
Relevant Locations (Right)
LocSet relevant
Relational Postcondition
\result_1==\result_2
Relational Precondition
Relational Postcondition
Try to use tooltips if feeling unsure about the functionality of an element.
Proof State: No Proof

Object equality

REFINITY lacked rules for object equality over multiple modalities:

- can verify Slide Statement with abstract statements
- can't verify Slide Statement with statements involving concrete objects


Synchronize Scrolling
Free Program Variables
java.lang.Object x
java.lang.Object y
Abstract Location Sets
LocSet relevant
Functions and Predicates
Abstract Program Fragments
1 x = new C();
2 y = new D();
1 y = new D();
2 x = new C();
Method-Level Context
Abstract Program Fragments
Relevant Locations (Left)
java.lang.Object x
java.lang.Object y
Relevant Locations (Right)
java.lang.Object x
java.lang.Object y
Relational Postcondition
\result_1==\result_2
Relational Precondition
Relational Postcondition
Recommended Example: File > Load Example > Abstract Execution > Consolidate Duplicate... > Extract Prefix
Proof State: No Proof

Why? ▷

REFINITY Internals

Core issue:

- Objects are placed in a symbolic heap during SE
- Before and After program executed in same proof

Not sufficient for two new objects to be equal:

- the allocation must, additionally, be deterministic

Schematic sequent rules in KeY are specified as *taclets*:

- we add rules to make objects indistinguishable under under certain conditions

New *taclet* for object creation

$$\frac{\Gamma, \{U\}(\mathtt{v} \neq \mathtt{null} \land \mathtt{v} \doteq \mathtt{C} :: \mathtt{allocate}(\mathtt{heap}) \land \mathtt{C} :: \mathtt{exactInstance}(\mathtt{v}) \doteq \mathtt{TRUE}) \Rightarrow \{U\}\{\mathtt{heap} := \mathtt{create}(\mathtt{heap}, \mathtt{v})\}[\mathtt{s}]\phi, \Delta}{\Gamma \Rightarrow \{U\}[\mathtt{v\ =\ C.allocate();\ s}]\phi, \Delta}$$

Additionally, we give two simplification rules for heaps within any `allocate` *function application. Let* $\sqsubseteq$ *be the subtype relation and* $T(t)$ *the type of a term.*

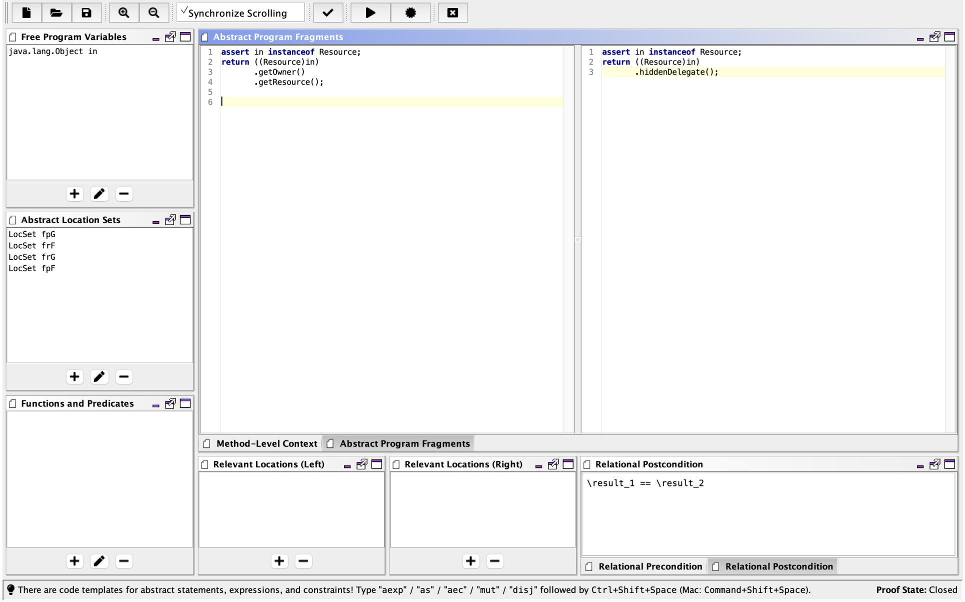
$$\mathtt{C} :: \mathtt{allocate}(\mathtt{store}(\mathtt{h}, \mathtt{o}, \mathtt{f}, \mathtt{v})) \rightsquigarrow \mathtt{C} :: \mathtt{allocate}(\mathtt{h}) \quad \textit{if } f \neq \texttt{<allocated>}$$

$$\mathtt{C} :: \mathtt{allocate}(\mathtt{create}(\mathtt{h}, \mathtt{o})) \rightsquigarrow \mathtt{C} :: \mathtt{allocate}(\mathtt{h}) \quad \textit{if } C \not\sqsubseteq T(o)$$

Postcondition simplification

In HIDE DELEGATE exception objects now equivalent

- we need no special postcondition to handle exceptions...
- ...although we should because in practice exceptions capture state! (Not *our* problem, though 🙃)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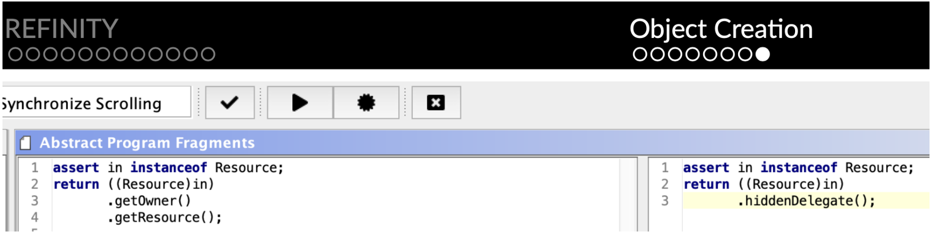
Relational Postcondition
There are code templates for abstract statements, expressions, and constraints! Type "aexp" / "as" / "aec" / "mut" / "disj" followed by Ctrl+Shift+Space (Mac: Command+Shift+Space).
Proof State: Closed


REFINITY
Object Creation
Synchronize Scrolling
Abstract Program Fragments
assert in instanceof Resource;
return ((Resource)in)
.getOwner()
.getResource();
assert in instanceof Resource;
return ((Resource)in)
.hiddenDelegate();

Future Challenge

Trace based notions of equivalence

```
File f = new File();
String s = "";
/*@  ensures finite ** call(f.open) ** finite; */
\abstract_statement A;
s = f.read();
f.write(s);
/*@  ensures finite ** call(f.close) ** finite; */
\abstract_statement B;
```

(a) Before

```
File f = new File();
String s = "";
/*@  ensures finite ** call(f.open) ** finite; */
\abstract_statement A;
f.write(s);
s = f.read();
/*@  ensures finite ** call(f.close) ** finite; */
\abstract_statement B;
```

(b) After

$$\theta ::= \lceil \phi \rceil$$

$$\mid \mathsf{call}(\mathtt{m})$$

$$\mid \mathbf{finite}$$

$$\mid \theta \ast\ast \theta$$

Summary

- REFINITY/KeY excellent foundation for reasoning about OO in general
- abstract code + side conditions
- initial application area: checking refactorings via symbolic execution
- next: application-specific?

SILM Workshop

SILM Workshop

Dates | Call for Papers | Submission | Program | Registration | Past Events

SILM 2024

Welcome to the 6th edition of our workshop on the **Security of Software/Hardware Interfaces.** SILM 2024* will take place on **Friday, July 12 2024, in Vienna (Austria),** co-located with the 9th IEEE European Symposium on Security and Privacy (EuroS&P 2024)

Submissions

Submission deadline is **March 29, 2024 -- 11:59pm AoE** (was: ~~March 15, 2024 -- 11:59pm AoE~~); check our Call for Papers for details.