Dynamic Frames in KeY

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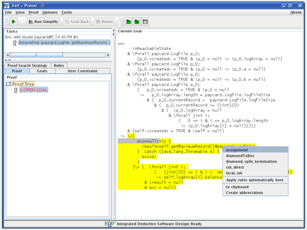
Overview

Context

- Object-oriented programming (Java)
- Design by contract (JML)
- Deductive verification (KeY)
- Goal: **Modularity**
  "Proofs remain valid if program is changed"



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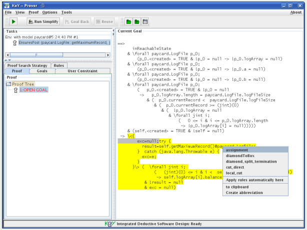

This talk

- JML*: JML meets *dynamic frames* (Kassios, 2006)
- KeYHeap: KeY version which verifies JML*

Motivating Example

```
interface Cell {
  void setX(int value);
  int getX();
}
```

Example adapted from Smans et al. (2008)

Motivating Example

```
interface Cell {
  void setX(int value);
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}
void m() {
  Cell c1 = new CellImpl();
  c1.setX(5);




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```

Example adapted from Smans et al. (2008)

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  //@ assert c1.getX() == 5;
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```

How to verify the assertion *without* looking into `CellImpl`?

Example adapted from Smans et al. (2008)

Specifying Cell

```
interface Cell {



  void setX(int value);


  int getX();
}
```

Specifying Cell

```
interface Cell {
  //@ model int m;


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Model fields

- abstractions of actual program state
- related to Hoare's *abstract variables* (1972), notions of *refinement*

Specifying Cell

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interface Cell {
  //@ model int m;

  //@ ensures m == value;
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class CellImpl implements Cell {
  private int x;
}
```

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How to verify the assertion?

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void m() {
  Cell c1 = new CellImpl();
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```

How to verify the assertion?

```
void m() {
  Cell c1 = new CellImpl();
  c1.setX(5);                 //c1.m==5

  Cell c2 = new CellImpl();
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How to verify the assertion?

```
void m() {
  Cell c1 = new CellImpl();
  c1.setX(5);                 //c1.m==5

  Cell c2 = new CellImpl();   //unknown state change
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}
```

$\rightsquigarrow$ Need to limit which locations may be changed by the methods

```
interface Cell {
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  //@ ensures m == value;
  void setX(int value);

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```

Modifies clauses for Cell

```
interface Cell {
  //@ model int m;



  //@ ensures m == value;
  void setX(int value);

  //@ ensures \result == m;
  /*@pure@*/ int getX();
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Modifies clauses for Cell

```
interface Cell {
  //@ model int m;
  //@ model \locset footprint;  //a "dynamic frame"


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How to verify the assertion?

```
void m() {
  Cell c1 = new CellImpl();
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⇝ Need knowledge about *dependencies* of `c1.m`

```
interface Cell {
  //@ model int m;
  //@ model \locset footprint;


}
```

Depends clauses for Cell

```
interface Cell {
  //@ model int m;
  //@ model \locset footprint;
  //@ accessible m: footprint;

}
```

Depends clauses for `Cell`

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interface Cell {
  //@ model int m;
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Depends clause "`accessible m: s`"

If the values of the locations in `s` do not change,
then `m` does not change

Depends clauses for Cell

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$\leadsto$ Need to know: $\texttt{c1.footprint} \cap \texttt{c2.footprint} = \emptyset$

Specifying footprint

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\fresh(s)

- usable in postconditions
- true iff all members of s belong to freshly created objects

Specifying footprint (cont.)

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  //@ assignable footprint;
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Specifying footprint (cont.)

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interface Cell {
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\new_elems_fresh(s)

- usable in postconditions
- true iff all members of s either
  - belong to freshly created objects, or
  - have already been in s before

We can verify the assertion!

```
void m() {
  Cell c1 = new CellImpl();
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independent of private data, method bodies & represents clauses

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- Nesting of dynamic frames $\hat{=}$ ownership hierarchy
- Dynamic frames can handle cases that ownership cannot
- Price: verbose specifications

KeY

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Java + JML $\longrightarrow$ JAVA DL sequent $\longrightarrow$ proof

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Example proof

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Verification process

Java + JML $\longrightarrow$ Java DL sequent $\longrightarrow$ proof

Example proof

$$\Rightarrow [\texttt{if (x<y) max=y; else max=x;}](\texttt{max} \geq \texttt{x})$$

conditional

$$\texttt{x} < \texttt{y} \Rightarrow [\texttt{max=y;}](\texttt{max} \geq \texttt{x}) \qquad \texttt{x} \geq \texttt{y} \Rightarrow [\texttt{max=x;}](\texttt{max} \geq \texttt{x})$$

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arithmetic

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Heaps as non-rigid functions

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"Explicit" heaps (theory of arrays)

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"Explicit" heaps (theory of arrays)

- Fields are constant symbols $\mathtt{f} : \mathit{Field}$
- Global program variable $\mathtt{H} : \mathit{Heap}$

Modelling the Java Heap

Heaps as non-rigid functions

- Fields are non-rigid function symbols $\mathtt{f} : \mathit{Object} \to A$
- $\mathtt{o.f}$ means $\mathtt{f}(\mathtt{o})$
- $\{\mathtt{f}(\mathtt{o}) := t\}$

"Explicit" heaps (theory of arrays)

- Fields are constant symbols $\mathtt{f} : \mathit{Field}$
- Global program variable $\mathtt{H} : \mathit{Heap}$
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For dynamic frames, an explicit modelling has clear advantages

Dynamic frames in JAVA DL

Sorts

- *Heap*, *Object*, *Field*

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Rules

- $\mathit{select}/\mathit{store}$, set theory

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Rules

- *select*/*store*, set theory
- $select(anon(h, s, h'), o, f) = \begin{cases} select(h', o, f) & \text{if } (o, f) \dot{\in} s \\ select(h, o, f) & \text{otherwise} \end{cases}$

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\fresh(s)	
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JML* $\rightsquigarrow$ Java DL

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JML* $\rightsquigarrow$ Java DL

`\locset`	LocSet
`o.f`	$\mathit{select}(\mathtt{H}, \mathtt{o}, \mathtt{f})$
`o.m`	$\mathtt{m}(\mathtt{H}, \mathtt{o})$
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`\new_elems_fresh(s)`	$\forall \mathit{Object}\ o; \forall \mathit{Field}\ f;$ $(o, f) \dot{\in} \mathtt{s} \rightarrow \neg \mathit{select}(\mathtt{H}^{old}, o, \mathit{created})$ $\lor\ (o, f)\ \dot{\in}\ \{\mathtt{H} := \mathtt{H}^{old}\}\mathtt{s}$

Method Contracts

Method contract $(pre, post, mod)$

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Proof obligation

$$pre \wedge GeneralAssumptions$$
$$\rightarrow [\texttt{self.m();}](post \wedge frame)$$

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Rule

$$\Rightarrow \{\mathcal{U}\}[\texttt{o.m();}\ \ldots]\varphi$$

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$$\Rightarrow \{\mathcal{U}\} pre \qquad\qquad \Rightarrow \{\mathcal{U}\}\{\texttt{H} := anon(\texttt{H}, mod, h')\}(post \rightarrow [\ldots]\varphi)$$

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& pre \land GeneralAssumptions \\
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& \quad \doteq \{\mathtt{H} := anon(\mathtt{H}, everything \mathbin{\dot\setminus} dep, h)\} \\
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$$m(\mathtt{H}, \mathtt{c1}) \doteq 5 \Rightarrow m(anon(\mathtt{H}, s, h'), \mathtt{c1}) \doteq 5$$

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- Experience with implementation:
  - Examples by Smans et al. (cell, list, stack)
  - List with iterator
  - Observer pattern