Formal Methods for Software Development

Proof Obligations

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Master Theses in Formal Methods

- Presentation of Master thesis topics by Formal Methods group
- Thursday, 22nd Oct 10:30-11:30
- online meeting (via Zoom)
- link will be announced also via our course Canvas

This Part

making the connection between

JML

and

Dynamic Logic / KeY

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making the connection between

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- generating,

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making the connection between

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- generating,
- understanding,

This Part

making the connection between

JML

and

Dynamic Logic / KeY

- generating,
- understanding,
- and proving

DL proof obligations from JML specifications

From JML Contracts via Intermediate Format to Proof Obligations (PO)

```
public class A {
 /*@ public normal_behavior
   @ requires <Precondition>;
   @ ensures <Postcondition>;
   @ assignable <locations>;
   @*/
 public int m(params) {..}
}
```

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Translation →

Intermediate Format

$(pre, post, div, var, mod)$

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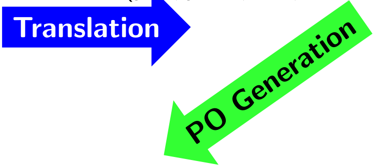

Proof obligation as DL formula

$$pre \rightarrow \langle \texttt{this.m(params);} \rangle (post \ \wedge \ frame)$$

JML Translation: Normalizing JML Contracts

Normalization of JML Contracts

1. Flattening of nested specifications
2. Making implicit specifications explicit
3. Processing of modifiers
4. Adding of default clauses if not present
5. Contraction of several clauses

Tho following introduces principles of this process

Normalisation: Making Implicit Information Explicit

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Implicit Information

- Meaning of `normal_` and `exceptional_behavior`
- `non_null` by default
- `\invariant_for(this)` in `requires`, `ensures`, `signals` clauses

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Turn into general `behavior` spec. case

1. Add to
   - `normal_behavior` the clause **`signals (Throwable t) false;`**

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- non_null by default
- \invariant_for(this) in requires, ensures, signals clauses

Turn into general behavior spec. case

1. Add to
   - normal_behavior the clause **signals (Throwable t) false;**
   - exceptional_behavior the clause **ensures false;**
2. Replace normal_behavior/exceptional_behavior by behavior

Normalisation: Making Implicit Information Explicit

Implicit Information

- Meaning of `normal_` and `exceptional_behavior`
- `non_null` by default
- `\invariant_for(this)` in `requires`, `ensures`, `signals` clauses

Making `non_null` explicit in method specifications

1. Where `nullable` is absent, add **`o != null`** to preconditions (for parameters[a]) and postconditions (for return values[a]). E.g., for method `void m(Object o)` add **`requires o != null;`**
2. Thereafter add **`nullable`**, where absent, to *all* parameter[a] and return type[a] declarations

[a]of reference type

Normalisation: Making Implicit Information Explicit

Implicit Information

- Meaning of `normal_` and `exceptional_behavior`
- `non_null` by default
- `\invariant_for(this)` in `requires`, `ensures`, `signals` clauses

Making `\invariant_for(this)` explicit in method specifications

1. Add explicit `\invariant_for(this)` to non-helper method specs:
   - `requires \invariant_for(this);`
   - `ensures \invariant_for(this);`
   - `signals (Throwable t) \invariant_for(this);`
2. Thereafter add **`helper`**, where absent, to *all* methods

Normalisation: Example

```
/*@ public normal_behavior
  @ requires c.id >= 0;
  @ ensures \result == ( ... );
  @*/
  public boolean addCategory(Category c) {
```

becomes

```
/*@ public behavior
  @ requires c.id >= 0;
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/*@ public behavior
  @ requires c.id >= 0;
  @ requires c != null;
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  @ signals (Throwable exc) false;
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```

becomes

```
/*@ public behavior
  @ requires c.id >= 0;
  @ requires c != null;
  @ requires \invariant_for(this);
  @ ensures \result == (...);
  @ ensures \invariant_for(this);
  @ signals (Throwable exc) false;
  @ signals (Throwable exc) \invariant_for(this);
  @*/
public /*@ helper @*/
 boolean addCategory(/*@ nullable @*/Category c) {
```

Normalisation

Next Normalisation Steps (Not detailed)

- Expanding `pure` modifier:
  - add to each specification case
    - **`assignable \nothing;`**
    - **`diverges false;`**
  - remove `pure`
- Where clauses with defaults (e.g., `diverges`, `assignable`) are absent, add explicit clauses

Normalisation: Clause Contraction

Merge multiple clauses of the same kind into a single one of that kind.

For instance,

```
/*@ public behavior
  @ requires R1;
  @ requires R2;
  @ ensures E1;
  @ ensures E2;
  @ signals (T1 exc) S1;
  @ signals (T2 exc) S2:
  @*/
```

Normalisation: Clause Contraction

Merge multiple clauses of the same kind into a single one of that kind.

For instance,

```
/*@ public behavior
  @ requires R1;
  @ requires R2;
  @ ensures E1;
  @ ensures E2;
  @ signals (T1 exc) S1;
  @ signals (T2 exc) S2:
  @*/
```

```
/*@ public behavior
  @ requires R1 && R2;
  @ ensures E1 && E2;
  @ signals (Throwable exc)
  @  (exc instanceof T1 ==> S1)
  @  &&
  @  (exc instanceof T2 ==> S2);
  @*/
```

Translating JML into Intermediate Format

Intermediate format for contract of method m

$$(pre, post, div, var, mod)$$

with

- a precondition DL formula *pre*,
- a postcondition DL formula *post*,
- a divergence indicator $div \in \{TOTAL, PARTIAL\}$,
- a variant term *var*
- a modifies set *mod*, either of type `LocSet` or `\strictly_nothing`

Translating JML Expressions to DL-Terms: Arithmetic Expressions

Translation replaces arithmetic JAVA operators by generalized operators

Generic towards various integer semantics (JAVA, Math).

Example:

"+" becomes "`javaAddInt`" or "`javaAddLong`"

"-" becomes "`javaSubInt`" or "`javaSubLong`"

...

Translating JML Expressions to DL-Terms: The `this` Reference

The **this** reference, explicit or implicit, has only a meaning within a program (refers to currently executing instance).

On logic level (outside the modalities) no such context exists.

`this` reference translated to a program variable (named by convention) `self`

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e.g., given class

```
public class MyClass {
  int f;
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```

JML expressions `f` and `this.f`
translated to
DL term `select(heap, self, f)`, pretty-printed as `self.f`

Translating Boolean JML Expressions

First-order logic treated fundamentally different in JML and KeY logic

JML

- Formulas no separate syntactic category
- Instead: Java's **`boolean`** expressions extended with first-order concepts (i.p. quantifiers)

Dynamic Logic

- Formulas and expressions completely separate
- **`true`**, **`false`** are formulas,
  `boolean` constants `TRUE`, `FALSE` are terms
- Atomic formulas take terms as arguments; e.g.:
  - `x - y < 5`
  - `b = TRUE`

Translating Boolean JML Expressions

$$
\begin{array}{lcl}
\mathcal{F}(\texttt{v}) & = & \texttt{v = TRUE} \\
\mathcal{F}(\texttt{o.f}) & = & \mathcal{E}(\texttt{o.f})\texttt{ = TRUE} \\
\mathcal{F}(\texttt{m()}) & = & \mathcal{E}(\texttt{m})\texttt{() = TRUE} \\
\mathcal{F}(\texttt{!b\_0}) & = & \texttt{!}\mathcal{F}(\texttt{b\_0}) \\
\mathcal{F}(\texttt{b\_0 \&\& b\_1}) & = & \mathcal{F}(\texttt{b\_0})\texttt{ \& }\mathcal{F}(\texttt{b\_1}) \\
\mathcal{F}(\texttt{b\_0 || b\_1}) & = & \mathcal{F}(\texttt{b\_0})\texttt{ | }\mathcal{F}(\texttt{b\_1}) \\
\mathcal{F}(\texttt{b\_0 ==> b\_1}) & = & \mathcal{F}(\texttt{b\_0})\texttt{ -> }\mathcal{F}(\texttt{b\_1}) \\
\mathcal{F}(\texttt{b\_0 <==> b\_1}) & = & \mathcal{F}(\texttt{b\_0})\texttt{ <-> }\mathcal{F}(\texttt{b\_1}) \\
\mathcal{F}(\texttt{e\_0 == e\_1}) & = & \mathcal{E}(\texttt{e\_0})\texttt{ = }\mathcal{E}(\texttt{e\_1}) \\
\mathcal{F}(\texttt{e\_0 != e\_1}) & = & \texttt{!(}\mathcal{E}(\texttt{e\_0})\texttt{ = }\mathcal{E}(\texttt{e\_1})\texttt{)} \\
\mathcal{F}(\texttt{e\_0 >= e\_1}) & = & \mathcal{E}(\texttt{e\_0})\texttt{ >= }\mathcal{E}(\texttt{e\_1})
\end{array}
$$

`v`/`f`/`m()` **`boolean`** variables/fields/pure methods

b_0, b_1 **`boolean`** JML expressions, e_0, e_1 JML expressions

$\mathcal{E}$ translates JML expressions to DL terms

$\mathcal{F}$ Translates `boolean` JML Expressions to Formulas

Quantified formulas over reference types:

```
F((\forall T x; e_0; e_1)) =
 \forall T x; (
      (!x=null  &  x.<created> = TRUE  &  F(e_0))
   -> F(e_1))

F((\exists T x; e_0; e_1)) =
 \exists T x; (
      (!x=null  &  x.<created> = TRUE  &  F(e_0))
   &  F(e_1))
```

$\mathcal{F}$ Translates `boolean` JML Expressions to Formulas

Quantified formulas over primitive types, e.g., **int**

$\mathcal{F}($`(\forall int x; e_0; e_1)`$) =$
`\forall int x;` $(($`inInt(x)` `&` $\mathcal{F}($`e_0`$))$ `->` $\mathcal{F}($`e_1`$))$

$\mathcal{F}($`(\exists int x; e_0; e_1)`$) =$
`\exists int x;` $($`inInt(x)` `&` $\mathcal{F}($`e_0`$)$ `&` $\mathcal{F}($`e_1`$))$

`inInt` (similar `inLong`, `inByte`):

Predefined predicate symbol with fixed interpretation

Meaning: Argument is within the range of the Java **int** datatype.

Translating Class Invariants

$$\mathcal{F}(\texttt{\textbackslash invariant\_for}(\texttt{e})) \quad = \quad \texttt{Object}::\texttt{<inv>}(\texttt{heap}, \mathcal{E}(\texttt{e}))$$

- \invariant_for(e) translated to built-in predicate $\texttt{Object}::\texttt{<inv>}$, applied to heap and the translation of e

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- Given that o is of type T, KeY can expand (during proof construction) 'Object ::<inv>(heap, o)' to the invariant of T

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- Given that o is of type T, KeY can expand (during proof construction) '$\texttt{Object}::\texttt{<inv>}(\texttt{heap}, o)$' to the invariant of T
- $\texttt{Object}::\texttt{<inv>}(\texttt{heap}, o)$ pretty printed as $o.\texttt{<inv>}$

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- Given that o is of type T, KeY can expand (during proof construction) '$\texttt{Object}::<\texttt{inv}>(\texttt{heap}, o)$' to the invariant of T
- $\texttt{Object}::<\texttt{inv}>(\texttt{heap}, o)$ pretty printed as $o.<\texttt{inv}>$
- Read 'invariant of o'

Translating JML into Intermediate Format

Intermediate format for contract of method m

$$(pre, post, div, var, mod)$$

with

- a precondition DL formula pre ✔,
- a postcondition DL formula $post$ ✔?
- a divergence indicator $div \in \{TOTAL, PARTIAL\}$,
- a variant term var
- a modifies set mod, either of type `LocSet` or `\strictly_nothing`

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- a precondition DL formula *pre* ✔,
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Translation of Ensures Clauses

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- Translation of `\result`
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Translating `\result`

For `\result` used in ensures clause of method $T\ m(\ldots)$:

$$\mathcal{E}(\texttt{\textbackslash result}) = \texttt{result}$$

where $\texttt{result} \in PVar$ of type T does not occur in the program.

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`\old`(e) evaluates e in the prestate of the method

Accesses to `heap` must be evaluated w.r.t. to the 'old' heap

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2. Define:
   $\mathcal{E}(\texttt{\textbackslash old}(e)) = \mathcal{E}_{\texttt{heap}}^{\texttt{heapAtPre}}(e)$

   ($\mathcal{E}_x^y(e)$ replaces all occurrences of x in $\mathcal{E}(e)$ by y)

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Example

$\mathcal{F}($o.f == \old(o.f)+ 1$)$ $=$

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$\mathcal{E}(\texttt{o.f})$ = $\mathcal{E}^{\texttt{heapAtPre}}_{\texttt{heap}}(\texttt{o.f})$ + 1 $\quad =$

`select(heap, o, f) = select(heapAtPre, o, f) + 1` $=$

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$\mathcal{E}(\texttt{o.f}) \texttt{ = } \mathcal{E}^{\texttt{heapAtPre}}_{\texttt{heap}}(\texttt{o.f}) \texttt{ + 1} =$

`select(heap, o, f) = select(heapAtPre, o, f) + 1` $=$

`o.f = o.f@heapAtPre + 1` *(by pretty printing)*

Translation of Ensures and Signals Clauses

Given the normalised JML contract

```
/*@ public behavior
  @ ...
  @ ensures E;
  @ signals (Throwable exc) S;
  @ ...
  @*/
```

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$\mathcal{F}_{\text{signals}} = \mathcal{F}(\texttt{S})$

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/*@ public behavior
  @ ...
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  @ ...
  @*/
```

Define
$\mathcal{F}_{\text{ensures}} = \mathcal{F}(\texttt{E})$
$\mathcal{F}_{\text{signals}} = \mathcal{F}(\texttt{S})$

Recall (pp.8,12) that `S` is either `false`, or it has the form

```
(exc instanceof ExcType1 ==> ExcPost1) && ...;
```

In the following, assume `exc` is fresh program variable of type `Throwable`

Combining Ensures and Signals to *post*

The DL formula *post* is then defined as

$$(\texttt{exc} = \mathbf{null} \rightarrow \mathcal{F}_{\mathsf{ensures}}) \ \land \ (\texttt{exc} \neq \mathbf{null} \rightarrow \mathcal{F}_{\mathsf{signals}})$$

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Important special case:

Normalisation of `normal_behavior` contract gives

```
signals (Throwable exc) false;
```

Combining Ensures and Signals to *post*

The DL formula *post* is then defined as

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Important special case:

Normalisation of `normal_behavior` contract gives

`signals (Throwable exc) false;`

In that case, *post* is:

$$\begin{array}{ll} & (\mathtt{exc} = \textbf{null} \rightarrow \mathcal{F}_{\textsf{ensures}}) \;\wedge\; (\mathtt{exc} \neq \textbf{null} \rightarrow \mathcal{F}_{\textsf{signals}}) \\ \Leftrightarrow & (\mathtt{exc} = \textbf{null} \rightarrow \mathcal{F}_{\textsf{ensures}}) \;\wedge\; (\mathtt{exc} \neq \textbf{null} \rightarrow \mathcal{F}(\mathtt{false})) \\ \Leftrightarrow & (\mathtt{exc} = \textbf{null} \rightarrow \mathcal{F}_{\textsf{ensures}}) \;\wedge\; (\mathtt{exc} \neq \textbf{null} \rightarrow \mathtt{false}) \\ \Leftrightarrow & (\mathtt{exc} = \textbf{null} \rightarrow \mathcal{F}_{\textsf{ensures}}) \;\wedge\; \mathtt{exc} = \textbf{null} \\ \Leftrightarrow & \mathtt{exc} = \textbf{null} \;\wedge\; \mathcal{F}_{\textsf{ensures}} \end{array}$$

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with

- a precondition DL formula pre ✔,
- a postcondition DL formula $post$ ✔,
- a divergence indicator $div \in \{TOTAL, PARTIAL\}$,
- a variant term var ,
- a modifies set mod, either of type `LocSet` or `\strictly_nothing`

Translating JML into Intermediate Format

Intermediate format for contract of method m

$$(pre, post, div, var, mod)$$

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The Divergence Indicator

$$div = \begin{cases} TOTAL & \text{if normalised JML contract contains clause } \texttt{diverges false;} \\ PARTIAL & \text{if normalised JML contract contains clause } \texttt{diverges true;} \end{cases}$$

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- a precondition DL formula pre ✔,
- a postcondition DL formula $post$ ✔,
- a divergence indicator $div \in \{TOTAL, PARTIAL\}$,✔
- a variant term var (postponed to later lecture),
- a modifies set mod, either of type `LocSet` or `\strictly_nothing`

Translating Assignable Clauses: The DL Type `LocSet`

Assignable clauses are translated to

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a term of type `LocSet` or the special value `\strictly_nothing`

Intention: A term of type `LocSet` represents a set of locations

Definition (Locations)

A location is a tuple (o, f) with $o \in D^{\texttt{Object}}$, $f \in D^{\texttt{Field}}$

The DL Type `LocSet`

Predefined type with $D(\texttt{LocSet}) = 2^{Location}$
and the functions (all with result type `LocSet`):

`empty`	empty set of locations: $\mathcal{I}(\texttt{empty}) = \emptyset$
`allLocs`	set of all locations, i.e., $\mathcal{I}(\texttt{allLocs}) = \{(d, f) \mid f.a.\ d \in D^{\texttt{Object}}, f \in D^{\texttt{Field}}\}$
`singleton(Object, Field)`	singleton set
`union(LocSet, LocSet)`	
`intersect(LocSet, LocSet)`	
`allFields(Object)`	set of all locations for the given object
`allObjects(Field)`	set of all locations for the given field; e.g., $\{(d, f) \mid \text{f.a. } d \in D^{\texttt{Object}}\}$
`arrayRange(Object, int, int)`	set representing all array locations in the specified range (both inclusive)

Translating Assignable Clauses—Example

Example

```
assignable \everything;
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is translated into the DL term

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$$\texttt{allLocs}$$

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is translated into the DL term

$$\texttt{union}(\texttt{singleton}(\texttt{self}, \texttt{next}),\\ \texttt{arrayRange}(\texttt{self.content}, 5, 9))$$

Translating JML into Intermediate Format

Intermediate format for contract of method m

$$(pre, post, div, var, mod)$$

with

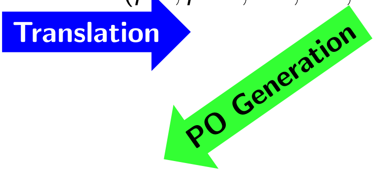
- a precondition DL formula *pre* ✔,
- a postcondition DL formula *post* ✔,
- a divergence indicator $div \in \{TOTAL, PARTIAL\}$ ✔,
- a variant *var* a term of type `any` (postponed),
- a modifies set *mod*, either of type `LocSet` or `\strictly_nothing` ✔

From JML Contracts via Intermediate Format to Proof Obligations (PO)

```
public class A {
 /*@ public normal_behavior
   @ requires <Precondition>;
   @ ensures <Postcondition>;
   @ assignable <locations>;
   @*/
 public int m(params) {..}
}
```

Intermediate Format

(pre, $post$, div, var, mod)



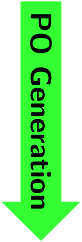
Proof obligation as DL formula

$$pre \rightarrow \\ \quad \langle \texttt{this.m(params);} \rangle \\ \qquad (post \; \wedge \; frame)$$

Generating a PO from the Intermediate Format: Idea

Given intermediate format of contract of `m` implemented in class `C`:

$$(\mathit{pre}, \mathit{post}, \texttt{TOTAL}, \mathit{var}, \mathit{mod})$$



$$\mathit{pre} \rightarrow \langle \texttt{self.m(args)} \rangle (\mathit{post} \;\wedge\; \underbrace{\mathit{frame}}_{\text{correctness of assignable}} \;)$$

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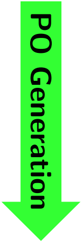

$$\mathit{pre} \rightarrow \langle \mathtt{self.m(args)} \rangle (\mathit{post} \ \wedge \ \underbrace{\mathit{frame}}_{\text{correctness of assignable}} \ )$$

In case of $\mathit{div} = \mathtt{PARTIAL}$, box modality is used

Generating a PO from Intermediate Format: Method Identification

$$pre \rightarrow \langle \texttt{self.m(args)} \rangle (post \ \land \ frame)$$

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- Dynamic dispatch: `self.m(...)` causes split into all possible implementations
- Special statement Method Body Statement:

$$\texttt{m(}\mathit{args}\texttt{)@C}$$

Meaning: implementation of `m` in class `C`

Generating a PO from Intermediate Format: Exceptions

$$\mathit{pre} \to \langle \texttt{self.m(args)@C} \rangle (\mathit{post} \ \land \ \mathit{frame})$$

Postcondition *post* states either

- that no exception is thrown or
- that in case of an exception the exceptional postcondition holds

but: $\langle \mathbf{throw} \ \texttt{exc;} \rangle \varphi$ is trivially false

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How to refer to an exception in post-state?

$$\mathit{pre} \rightarrow \left\langle \begin{array}{l} \texttt{exc = } \textbf{null}\texttt{;} \\ \textbf{try} \ \texttt{\{} \\ \mathit{self.m(args)@C} \\ \texttt{\}} \ \textbf{catch} \ \texttt{(Throwable e)\{exc = e;\}} \end{array} \right\rangle (\mathit{post} \ \land \ \mathit{frame})$$

Recall: generation of *post* (pp.23,24) uses program variable `exc`

The Generic Precondition *genPre*

$$pre \rightarrow \langle \texttt{exc=}\textbf{null}\texttt{;}\ \textbf{try}\ \texttt{\{self.m(args)@C\}}\ \textbf{catch}\ \ldots\ \rangle(post\ \land\ frame)$$

is still not complete.

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Additional properties (known to hold in Java, but not in DL), e.g.,

- **this** is not **null**
- created objects can only point to created objects (no dangling references)
- integer parameters have correct range
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- integer parameters have correct range
- ...

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Idea: Formalise assumption as additional precondition *genPre*

$$(genPre \wedge pre) \rightarrow \langle \texttt{exc=}\mathbf{null}\texttt{;}\ \mathbf{try}\ \texttt{\{self.m(args)@C\}}\ \mathbf{catch}\ \ldots\ \rangle(post\ \wedge\ frame)$$

The Generic Precondition *genPre* (background info)

$$\begin{aligned} \textit{genPre} := \quad & \mathtt{wellFormed(heap)} \\ & \land \mathtt{self} \neq \mathbf{null} \\ & \land \mathtt{self}.\!<\!\mathtt{created}\!> = \mathtt{TRUE} \\ & \land \mathtt{C} :: \mathtt{exactInstance(self)} \\ & \land \textit{paramsInRange} \end{aligned}$$

- `wellFormed(h)`: predefined predicate;
  true iff `h` is regular Java heap
- `C :: exactInstance(o)`: predefined predicate;
  true iff `o` has exact type `C` (not just subtype of `C`)
- *paramsInRange* formula stating that method arguments are in range

The Generic Precondition *genPre*

$$(\mathit{genPre} \land \mathit{pre}) \rightarrow \langle \texttt{exc=}\mathbf{null}\texttt{;}\ \mathbf{try}\ \texttt{\{self.m(args)@C\}}\ \mathbf{catch}\ \ldots\ \rangle(\mathit{post}\ \land\ \mathit{frame})$$

is still not complete.

- Need to refer to prestate in post, e.g. for old-expressions

The Generic Precondition *genPre*

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$$(genPre \wedge pre) \rightarrow \{\texttt{heapAtPre} := \texttt{heap}\} \langle \texttt{exc=}\mathbf{null}\texttt{; } \mathbf{try}\ \texttt{\{self.m(args)@C\}}\ \mathbf{catch}\ \ldots\ \rangle(post\ \wedge\ frame)$$

Recall: `heapAtPre` was used in translation of `\old`, p.22

Generating a PO from Intermediate Format: The *frame* DL Formula

$$(genPre \land pre) \rightarrow \{\texttt{heapAtPre} := \texttt{heap}\}$$
$$\langle \texttt{exc=}\textbf{null}\texttt{;}\ \textbf{try}\ \texttt{\{self.m(args)\}}\ \textbf{catch}\ \ldots\ \rangle$$
$$(post\ \land\ frame)$$

If mod = `\strictly_nothing` then *frame* is defined as:

$$\forall o; \forall f; (o.f = o.f@\texttt{heapAtPre})$$

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If *mod* is a location set, then *frame* is defined as:

$$\forall o; \forall f; \big(\ (o, f) \in \{\texttt{heap} := \texttt{heapAtPre}\} mod$$
$$\vee\ o.\texttt{<created>@heaptAtPre} = \texttt{FALSE}$$
$$\vee\ o.f = o.f\texttt{@heapAtPre}\ \big)$$

Generating a PO from Intermediate Format: The *frame* DL Formula

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$$\lor\ o.\texttt{<created>@heaptAtPre} = \texttt{FALSE}$$
$$\lor\ o.f = o.f\texttt{@heapAtPre}\quad)$$

Says that every location (o, f) either

- belongs to the modifies set (evaluated in the pre-state), or
- was not (yet) created before the method invocation, or
- holds the same value before and after the method execution

Generating a PO from Intermediate Format: Result Value

$$(\mathit{genPre} \land \mathit{pre}) \rightarrow \{\texttt{heapAtPre} := \texttt{heap}\}$$
$$\langle \texttt{exc=}\textbf{null}\texttt{;}\ \textbf{try}\ \texttt{\{self.m(args)\}}\ \textbf{catch}\ \ldots\ \rangle$$
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is still not complete.

- For non-void methods, need to refer to result in *post*

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$$(\mathit{genPre} \land \mathit{pre}) \rightarrow \{\texttt{heapAtPre} := \texttt{heap}\}$$
$$\langle \texttt{exc=}\textbf{null}\texttt{;}\ \textbf{try}\ \texttt{\{result = self.m(args)\}}\ \textbf{catch}\ \ldots\ \rangle$$
$$(\mathit{post}\ \land\ \mathit{frame})$$

Recall: `\result` was translated to program variable `result`, see p.21

Examples

Demo