Software Engineering using Formal Methods

Proof Obligations

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15 October 2013

This Part

making the connection between

JML

and

Dynamic Logic / KeY

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making the connection between

JML

and

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- generating,

This Part

making the connection between

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and

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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

Tutorial Example

we follow ‘KeY Quicktour for JML’ (cited below as [KQJ])

paper + sources:
see 'KeY Quicktour' on course page, under 'Links, Papers, and Software'

scenario: simple `PayCard`

Inspecting JML Specification

inspect `quicktour/jml/paycard/PayCard.java`

follow [KQJ, 2.2]

New JML Feature I: Nested Specification Cases

method `charge()` has nested specification case: X

```
@ public normal_behavior
@ requires amount > 0;
@ {|
@   requires amount + balance < limit && isValid()==true;
@   ensures \result == true;
@   ensures balance == amount + \old(balance);
@   assignable balance;
@
@   also
@
@   requires amount + balance >= limit;
@   ensures \result == false;
@   ensures unsuccessfulOperations
@           == \old(unsuccessfulOperations) + 1;
@   assignable unsuccessfulOperations;
@ |}
```

Nested Specification Cases

nested specification cases allow to factor out common preconditions

```
@ public normal_behavior
@ requires R;
@ {|
@   requires R1;
@   ensures E1;
@   assignable A1;
@
@   also
@
@   requires R2;
@   ensures E2;
@   assignable A2;
@ |}
```

expands to ... (next page)

Nested Specification Cases

(previous page) ... expands to

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Recall: pure vs. assignable \nothing

method charge() has exceptional behavior case:

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```

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difference to **pure**:

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- **assignable** clause is local to specification case

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difference to **pure**:

- **pure** is method-global, also prohibits non-termination & exceptions
- **assignable** clause is local to specification case
- **pure** not usable in this particular context

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generate **EnsuresPost** PO for normal behavior of `charge()`

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summary:

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- in `quicktour/jml`, open `paycard`
- select `paycard` > `PayCard` > `charge` and **EnsuresPost**
- inspect **Assumed Invariants**

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  (in JML: **`modifies`** synonymous for **`assignable`**)
- **Current Goal** pane displays proof obligation as DL sequent

Generating Proof Obligations

for loading more proof obligations:
re-open **Proof Obligation Browser** under **Tools** menu (or **Ctrl-B**)

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expressing that `charge()` preserves all invariants (of its own class)

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expressing that `charge()` preserves all invariants (of its own class)

follow [KQJ, 4.3.1+4.3.2]

Translating JML to POs in DL

in the following:

principles of translating JML to proof obligations in DL

- issues in translating arithmetic expressions
- translating **`this`**
- identifying the method's implementation
- translating boolean JML expressions to first-order logic formulas
- translating preconditions
- translating class invariants
- translating postconditions
- storing **`\old`** fields prior to method invocation
- storing actual parameters prior to method invocation
- expressing that 'exceptions are (not) thrown'
- *putting everything together*

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WARNING:

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- not fully precise
- simplifying
- omitting details/complications
- deviating from exact implementation in KeY

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aim of the following:

enable you to read/understand proof obligations

(notational remark: stick to ASCII syntax of KeY logic in this lecture)

Issues on Translating Arithmetic Expressions

often:

- KeY replaces arithmetic JAVA operators by generalized operators, generic towards various integer semantics (JAVA, Math).
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(no need to memorize this)

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both

- explicit
- implicit

`this` reference translated to `self`

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this reference translated to `self`

e.g., given class

```
public class MyClass {
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  private int f;
  ...
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`this` reference translated to `self`

e.g., given class

```
public class MyClass {
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- `f` translated to `self.f`
- `this.f` translated to `self.f`

Identifying the Method's Implementation

JAVA's dynamic dispatch selects a method's implementation *at runtime*

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for a method call `m(`*args*`)`,
KeY models selection of implementation from `package.Class` by
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JAVA's dynamic dispatch selects a method's implementation *at runtime*

for a method call `m(`*args*`)`,
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`m(`*args*`)@package.Class`

example:

`charge(x)@paycard.PayCard`

executes class `paycard.PayCard`'s implementation of method call `charge(x)`

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)

KeY logic

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

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

$\mathcal{F}$(`v`)	=	`v = TRUE`
$\mathcal{F}$(`f`)	=	$\mathcal{T}$(`f`) `= TRUE`
$\mathcal{F}$(`m()`)	=	$\mathcal{T}$(`m`)`()` `= TRUE`
$\mathcal{F}$(`!b_0`)	=	`!`$\mathcal{F}$(`b_0`)
$\mathcal{F}$(`b_0 && b_1`)	=	$\mathcal{F}$(`b_0`) `&` $\mathcal{F}$(`b_1`)
$\mathcal{F}$(`b_0 || b_1`)	=	$\mathcal{F}$(`b_0`) `|` $\mathcal{F}$(`b_1`)
$\mathcal{F}$(`b_0 ==> b_1`)	=	$\mathcal{F}$(`b_0`) `->` $\mathcal{F}$(`b_1`)
$\mathcal{F}$(`b_0 <==> b_1`)	=	$\mathcal{F}$(`b_0`) `<->` $\mathcal{F}$(`b_1`)
$\mathcal{F}$(`e_0 == e_1`)	=	$\mathcal{E}$(`e_0`) `=` $\mathcal{E}$(`e_1`)
$\mathcal{F}$(`e_0 != e_1`)	=	`!`$\mathcal{E}$(`e_0`) `=` $\mathcal{E}$(`e_1`)
$\mathcal{F}$(`e_0 >= e_1`)	=	$\mathcal{E}$(`e_0`) `>=` $\mathcal{E}$(`e_1`)

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

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

`e_0`, `e_1` JAVA expressions

$\mathcal{T}$ may add '`self.`' or '`@ClassName`' (see pp. 16, 17)

$\mathcal{E}$ may add casts, transform operators (see p. 15)

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

$\mathcal{F}$(`(\forall T x; e_0)`) = `\forall T x;`
`!x = null ->` $\mathcal{F}$(`e_0`)

$\mathcal{F}$(`(\exists T x; e_0)`) = `\exists T x;`
`!x = null &` $\mathcal{F}$(`e_0`)

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

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`&` $\mathcal{F}$(`e_0`) `&` $\mathcal{F}$(`e_1`)

Translating Preconditions

if selected contract *Contr* has preconditions

```
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@ ...
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$$\mathcal{PRE}(Contr) = \mathcal{F}(\texttt{b\_1})\ \texttt{\&}\ \ldots\ \texttt{\&}\ \mathcal{F}(\texttt{b\_n})$$

Translating Class Invariants

the invariant

```
class C {
   ...
   //@ invariant inv_i;
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is translated to

$$\mathcal{INV}(\texttt{inv\_i})$$

$$=$$

$$\texttt{\textbackslash forall C o; ((o.<created> = TRUE \& !o = null) ->} \quad \{\texttt{self:=o}\}\mathcal{F}(\texttt{inv\_i}))$$

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special treatment of expressions in post-condition: see next slide

Translating Expressions in Postconditions

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@ assignable <assignable_fields>;
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$$\mathcal{E}(\texttt{\textbackslash old(e)}) = \mathcal{E}_{old}(\texttt{e})$$

$\mathcal{E}_{old}$ defined like $\mathcal{E}$, with the exception of:

$$\mathcal{E}_{old}(\texttt{e.f}) = \texttt{fAtPre}(\mathcal{E}_{old}(\texttt{e}))$$
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'`fAtPre`' intuitively refers to field '`f`' *in the pre-state*
But the logic does not know. Must be expressed in formula (next slide).

Storing Pre-State of a Field

given an **assignable** field f of class C

```
class C {
  ...
  private T f;
  ...
}
```

translation of postcondition replaces f in **\old**(...) by fAtPre (p. 24)

left to do: store pre-state values of f in fAtPre

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$$\mathcal{STORE}(\texttt{f})$$
$$=$$

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```
\for C o; fAtPre(o) := o.f
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note: not a formula, but

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\for C o; fAtPre(o) := o.f

note: not a formula, but a quantified update
(more proper explanation next lecture)

Storing Pre-State of All Assignable Fields

if selected contract *Contr* has assignable clause:

```
@ assignable f_1, ..., f_n;
```

then pre-state of *all* assignable fields can be stored by

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$$\mathcal{STORE}(Contr) = \{\ \mathcal{STORE}(\texttt{f\_1})\ ||\ \ldots\ ||\ \mathcal{STORE}(\texttt{f\_n})\ \}$$

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how can you express in DL:
method call m() will not throw an exception
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note difference:

- JAVA assignments
- equation, i.e., formula

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\<{ exc = null;
    try {
      m()@p.C;
    } catch (Throwable e) {
      exc = e;
    }
  }\> !exc = null & <exc has right type>
```

PO for Normal Behavior Contract

PO for a normal behavior contract *Contr* for `void` method `m()`,
with chosen assumed invariants `inv_1`, ..., `inv_n`

```
==>
      INV(inv_1)
    & ...
    & INV(inv_n)
    & PRE(Contr)
 -> STORE(Contr)
      \<{ exc = null;
          try {
            m()@p.C;
          } catch (Throwable e) {
            exc = e;
          }
        }\> exc = null & POST(Contr)
```

PO for Normal Behavior Allowing Non-Termination

PO for a normal behavior contract *Contr* for method `m()`,
where *Contr* has clause **`diverges true;`**

```
==>
      INV(inv_1)
    & ...
    & INV(inv_n)
    & PRE(Contr)
 -> STORE(Contr)
      \[{ exc = null;
          try {
            m()@p.C;
          } catch (Throwable e) {
            exc = e;
          }
        }\] exc = null  & POST(Contr)
```

PO for Normal Behavior of Non-Void Method

PO for a normal behavior contract *Contr* for non-**void** method m(),

```
==>
      INV(inv_1)
    & ...
    & INV(inv_n)
    & PRE(Contr)
 -> STORE(Contr)
      \<{ exc = null;
          try {
            result = m()@p.C;
          } catch (Throwable e) {
            exc = e;
          }
        }\> exc = null & POST(Contr)
```

PO for Normal Behavior of Non-Void Method

PO for a normal behavior contract *Contr* for **non-void** method m(),

```
==>
      INV(inv_1)
    & ...
    & INV(inv_n)
    & PRE(Contr)
 -> STORE(Contr)
      \<{ exc = null;
          try {
            result = m()@p.C;
          } catch (Throwable e) {
            exc = e;
          }
        }\> exc = null & POST(Contr)
```

recall: $\mathcal{POST}$(*Contr*) translates **\result** to result (p. 24)

PO for Preserving Invariants

assume method `m()` has contracts $Contr_1$, ..., $Contr_j$

PO stating that:

Invariants `inv_1, ..., inv_n` are preserved
in all cases covered by a contracts.

```
==>
      INV(inv_1) & ... & INV(inv_n)
    & ( PRE(Contr_1) | ...  | PRE(Contr_1)  )
 -> \[{ exc = null;
        try {
          m()@p.C;
        } catch (Throwable e) {
          exc = e;
        }
      }\] INV(inv_1) & ... & INV(inv_n)
```

Examples

don't fit on slide: execute quicktour with KeY instead

Literature for this Lecture

Essential

KeY Quicktour see course page, under 'Links, Papers, and Software'