Software Engineering using Formal Methods

Proof Obligations

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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,

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making the connection between

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- generating,
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making the connection between

JML

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Dynamic Logic / KeY

- generating,
- understanding,
- and proving

DL proof obligations from JML specifications

Tutorial Example

we follow 'KeY Quicktour' (for KeY 1.6) (cited below as [KQ])

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 [KQ, 2.2]

New JML Feature I: Nested Specification Cases

method `charge()` has nested specification case:

```
@ 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
@
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```

expands to ... (next page)

Nested Specification Cases

(previous page) ... expands to

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Recall: `pure` vs. `assignable \nothing`

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- **`assignable`** clause is local to specification case
- **`pure`** not usable in this particular context

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summary:

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- 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

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for loading more proof obligations:
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follow [KQ, 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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- simplifying
- omitting details/complications
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(notational remark: stick to ASCII syntax of KeY logic in this lecture)

Issues on Translating Arithmetic Expressions

often:

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(no need to memorize this)

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

Identifying the Method's Implementation

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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)`,
KeY models selection of implementation from `package.Class` by
`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

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

`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

$$\begin{aligned}
\mathcal{F}((\texttt{\textbf{\textbackslash forall} T x; e\_0})) &= \texttt{\textbf{\textbackslash forall} T x;}\\
&\qquad \texttt{!x = \textbf{null} ->\ }\mathcal{F}(\mathsf{e\_0})\\[1em]
\mathcal{F}((\texttt{\textbf{\textbackslash exists} T x; e\_0})) &= \texttt{\textbf{\textbackslash exists} T x;}\\
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if selected contract *Contr* has preconditions

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Translating Class Invariants

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```
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  //@ invariant inv_i;
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is translated to

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

$$=$$

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

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

Translating Expressions in Postconditions

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

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

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note: not a formula, but

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note: not a formula, but a quantified update

(more proper explanation next lecture)

Storing Pre-State of All Assignable Fields

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

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note difference:

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

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    }
  }\> !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;`**

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

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

recall: $\mathcal{POST}(\mathit{Contr})$ 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.

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