Design by Contract with JML

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rheinjug Java User Group
Introduction
The Java Modeling Language (JML)

• initiative of Prof. Gary Leavens [UCF]
• Behavioral Interface Specification Language (BISL) for Java
• annotations for Java programs expressing pre- and postconditions, invariants, etc.
• inspired by Eiffel’s DBC and Larch
• primary design goal: easy to learn is a simple extension to Java’s syntax
JML Overview

- formal language for expressing the behavior of your Java programs
- focuses on sequential Java
- describes functional behavior of APIs
- supports data and specification refinement
- includes mathematical models as Java library
- old tools: Java 1.4 — new tools: Java 1.6+
Current Work

- large array of tools supporting Java 1.6+
- detailed semantics
- multithreading
- temporal logic
JML’s Goals

• practical and effective for describing detailed designs
• works with existing code
• you can use it where it works (not an all-or-nothing approach)
• wide range of tools
Detailed Design Specification

- JML handles
  - inter-module interfaces
  - classes and interfaces
  - data (fields)
  - methods

- JML does not handle
  - user interface
  - architecture
  - packages
  - dataflow
  - design patterns
A JML Example
private int balance;
final static int MAX_BALANCE;

/*@ invariant 0 <= MAX_BALANCE && balance < MAX_BALANCE; @*/
A JML Example

/*@ requires 0 <= amount;
  assignable balance;
  ensures balance ==
      \old(balance) - amount;
  signals (PurseException)
      balance == \old(balance);
@*/

public void debit(int amount) { ... }
A JML Example

//@ requires 0 <= amount;
 assignable balance;
 ensures balance ==
 \old(balance) - amount;
 signals (PurseException)
 balance == \old(balance);

public void debit(int amount) { ... }
A JML Example

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public void debit(int amount) { ... }
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 public void debit(int amount);
A JML Example

/*@ requires 0 <= amount;
 assignable balance;
 ensures balance == \old(balance) - amount;
signals (PurseException)
   balance == \old(balance);
@*/

public void debit(int amount);
@ requires 0 <= amount;
assignable balance;
ensures balance == \old(balance - amount);
signals (PurseException)
  balance == \old(balance);
@*/
public void debit(int amount);
A JML Example

private byte[] pin;
private byte appletState;
/*@ invariant appletState == PERSONALIZED ==> pin != null && pin.length == 4 &&
\forall int i; 0 <= i && i < 4;
  0 <= pin[i] && pin[i] <= 9); */
@*/
Design by Contract
Specification in Process

- “Contract the Design”
  - you are given an architecture with no specification, little documentation and you must somehow check the system is correct

- “Design by Contract”
  - you are designing and building a system yourself, relying upon existing components and frameworks
Contract the Design

- a body of code exists and must be annotated
- the architecture is typically ill-specified
- the code is typically poorly documented
- the number and quality of unit tests is typically very poor
- the goal of annotation is typically unclear
Goals of Contract the Design

• improve understanding of architecture with high-level specifications
• improve quality of subsystems with medium-level specifications
• realize and test against critical design constraints using specification-driven code and architecture evaluation
• evaluate system quality through rigorous testing or verification of key subsystems
A Process Outline for Contract the Design

- directly translate high-level architectural constraints into invariants
- key constraints on data models, custom data structures, and legal requirements
- express medium-level design decisions with invariants and pre-conditions
- use JML models only where appropriate
- generate unit tests for all key data values
Design by Contract

- writing specifications first is difficult but very rewarding in the long-run
- you *design* the system by writing *contracts*
- a refinement-centric process akin to early instruction in Dijkstra/Hoare approach
- ESC/Java2 works well for checking the consistency of formal designs
- resisting the urge to write code is *hard*
Goals of Design by Contract

- work out application design by writing contracts rather than code
- express design at multiple levels
  - BON/UML $\rightarrow$ JML $\rightarrow$ JML w/ privacy
- refine design by refining contracts
- write code once when architecture is stable
A Process Outline for Design by Contract

- outline architecture by realizing classifiers with classes
- capture system constraints with invariants
- use JML models only where appropriate
- focus on preconditions over postconditions
- develop test suite for your design by writing a data generator for your types
Assertions

- the **assert** statement is the fundamental construct used to specify the correct behavior of software

- the statement

  ```
  assert S;
  ```

  means

  “**S must** be true at **this** point in the program’s execution”
Assertion Syntax in Java

• all modern programming languages have an assert statement

• beginning in Java 1.4, assert is a keyword

• the syntax of a Java assert statement is

  `assert <boolean>[: <String>]`

• boolean is the predicate that must be true

• String is an optional message that will be printed if/when the assertion fails
Examples of Assertion Use

assert z != 0;
x = y/z;

assert (x > MIN_WIDTH);
my_window.setWidth(x);

assert p(x) : “p failed when x=” + x;
a_method_that_depends_upon_p(x);
Assertions vs. Logging

• if an assertion fails, the program **halts**

• thus, assertion failures are **critical** failures

• to assert something that is not critical, then a logging message is appropriate

```java
if (Debug.DEBUG && !p(x))
    System.err.println("p("+x+") fails");
    a_method_that_depends_upon_p(x);
```
Logging Frameworks

• it is **always** wiser to use a logging framework than to use embedded `printlns`

• if a `println` must be used, guard it with a conditional on a constant boolean

  • setting the guard false eliminates all logging code (saves space and time)

• the premier logging frameworks are `java.util.logging`, `log4j`, and `IDebug`
Specifications

• specifications of software range in formality
  • informal - English documentation (e.g., “normal” comments)
  • semi-formal - structured English documentation (e.g., Javadoc)
  • formal - annotations and assertions (e.g., assert statements and contracts)

• contracts are a key concept in robust software design and construction
Informal Specifications

/* Deduct some cash from this account and return how much money is left. */

public int debit(int amount)

• what happens when:
  • amount is negative?
  • amount is bigger than the balance?
  • is the balanced changed when failure?
Semi-Formal Specifications

/** Debit this account.
 * @param amount the amount to debit.
 *        <code>amount</code> must be non-negative.
 * @result the balance of this account after the debit successfully occurs.
 */
public int debit(int amount)

• many of the same questions arise even though the documentation is much clearer
/** Debit this account.
 * @param amount the amount to debit.
 * @result the resulting balance.
 */

/*@ requires amount >= 0;
@ ensures balance == \old(balance-amount) &&
@ \result == balance;
@*/

public int debit(int amount)
Writing and Calling Methods Incorrectly

/* Deduct some cash from this account and return how much money is left */
public int debit(int amount) {
  if (amount < 0) throw NDE(amount);
  if (balance < amount)
    throw NBE(balance);
  ...
  try {
    b = debit(a);
    if (b < 0) throw NBE();
  } catch (Exception e) {
    System.exit(-1);
  }
}
Calling Methods Correctly

/*@ requires amount >= 0;
@ ensures balance == \old(balance-amount) &&
@ \result == balance;
@*/

    public int debit(int amount) {
        ...all conditionals are gone!
        ... 
    }

    if (debit_amount < 0)
         handle_bad_debit(debit_amount);
    else
         resulting_balance = debit(debit_amount);
Design by Contract

• capture architectural, class-level decisions early as **constraints**
  • e.g., all Citizens have two parents

• realize constraints in software as **invariants**
  • an **invariant** is an assertion that must **always** be true whenever a method is called or exits

• capture contracts at method-level in medium-level design using English
  • realize contracts in code using **requires** and **ensures** statements
An Example Use of Design by Contract

<table>
<thead>
<tr>
<th>CLASS</th>
<th>CITIZEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE OF OBJECT</td>
<td>Person born or living in a country</td>
</tr>
<tr>
<td>INDEXING</td>
<td>cluster: CIVIL_STATUS</td>
</tr>
<tr>
<td></td>
<td>created: 1993-03-15 jmn</td>
</tr>
<tr>
<td></td>
<td>revised: 1993-05-12 kw</td>
</tr>
<tr>
<td>Queries</td>
<td>Name, Sex, Age, Single, Spouse, Children, Parents, Impediment to marriage</td>
</tr>
<tr>
<td>Commands</td>
<td>Marry. Divorce.</td>
</tr>
<tr>
<td>Constraints</td>
<td>Each citizen has two parents.</td>
</tr>
<tr>
<td></td>
<td>At most one spouse allowed.</td>
</tr>
<tr>
<td></td>
<td>May not marry children or parents or person of same sex.</td>
</tr>
<tr>
<td></td>
<td>Spouse s spouse must be this person.</td>
</tr>
<tr>
<td></td>
<td>All children, if any, must have this person among their parents.</td>
</tr>
</tbody>
</table>
Related Class Features

• queries
  • spouse? single?
• command
  • marry! divorce!
• constraints
  • at most one spouse is allowed
  • spouse’s spouse must be this person
Class Sketch

Citizen my_spouse;
//@ invariant (my_spouse != null) ==> 
//@ my_spouse.my_spouse == this;

Citizen spouse() { return spouse; }
boolean single() { return spouse == null; }
//@ requires single();
//@ ensures !single() && spouse() == new_spouse;
void marry(Citizen new_spouse)
    { my_spouse = new_spouse;
      new_spouse.my_spouse = this; }
//@ requires !single();
//@ ensures single();
void divorce() { my_spouse.my_spouse = null;
               my_spouse = null; }
Impact of DBC
Impact on Design

- minimality and elegance becomes the natural order of design
- fewer classes and methods
- methods that have simpler purpose
- implementations have lower complexity
- you understand what you are building before you build it!
Impact on Documentation

- less documentation written in English
- less ambiguity in documentation
- documentation is kept in-sync with implementation
Impact on Implementation

- fewer exceptions
- fewer try/catch blocks
- no manual parameter checking
- better error handling
- method bodies shrink dramatically
- Joe’s four finger rule:
  - “If you can’t cover your method body with four fingers, you probably don’t understand it.”
Impact on Testing

• specifications mean that no valid parameter testing is necessary in implementations

• the precondition is requiring the client to fulfill their side of the contract for supplier

• when calling a method that has a specification, checking for errors, return values, etc. is no longer necessary

• the supplier is ensuring (guaranteeing) their side of the contract to client
Unit Testing and Programming with Specs

• ~90% of your method-level unit tests are automatically generated
• ~25% less code is written because there is no need to test parameters values nor results of method calls for correctness
• code is not littered with try/catch blocks to catch exceptions
Tool Support
Analysis & Design and Specification Generation

- **BONc** = architecture specification in BON language (like mini-UML)
- **Beetlz** = refinement checker and generator from BON to JML
- **Daikon** = generate invariants by analyzing the heap at runtime as the system runs unit tests
- **Houdini** = statically generates simple contracts
- several tools do loop invariant derivation
Documentation and Embedding Specs

- jmldoc = JML + Javadoc
- Umbra/BMLlib = compile JML specs at the source level into BML specs in bytecode
- JMLEclipse = compile JML specs at the source level into JIR specs in bytecode
Runtime Checking

- JML runtime assertion checker
- JML2 ("classic" JML tool suite) = Java 1.4
- JML4c = JML on Eclipse JDT
- OpenJML = JML on OpenJDK
- JAJML = JML + JastAdd
- AJML2 = JML + Aspect/J
Dynamic and Static Checking

• unit testing
  • JMLJUnit = JML + JUnit
  • JMLUnitNG = JML + TestNG

• static checking
  • ESC/Java2 = JML + ESC/Java for Java 1.4
  • JMLe = execute JML specs using CSP
  • JMLEclipse = JML + Eclipse JDT for Java 1.6+
  • OpenJML = JML + OpenJDK for Java 1.6+
  • Chase = frame condition checker
Verification

- LOOP tool = verification using HOL in PVS
- Jack = verification of JavaCard applets
- RCC = race condition checker
- Jive = verification using custom prover
- Bandera = verification via model checking
- Kiason = verification via symbolic interpretation
- Krakatoa = verification using Coq and Why
- KeY system = verification using dynamic logic
- Mobius Program Verification Environment (PVE) = verification using HOL and Coq with Proof-Carrying Code (PCC)
Case Studies
Industrial

- JavaCard smart card applets
- electronic voting systems in NL and IE
- VLSI CAD software
- mobile phone applets
- systems and customers I cannot talk about
Academic Pedagogy

• teaching at all levels (freshman to postgrad)
  • introductory programming, programming languages, software engineering, applied formal methods, semantics, etc.

• class projects
  • cellular automaton simulator, digital cash, petrol rationing, supermarket purchase tracking, high-level computer simulators

• student projects
  • The Guinness Simulator
  • verified video games
For More Information

• the JML home page
  • http://www.jmlspecs.org/

• Design by Contract
  • Meyer, B. Object-oriented Software Construction

• Mobius Program Verification Environment
  • http://mobius.ucd.ie/

• ESC/Java2, BONc, and other tools
  • http://kindsoftware.com/products/opensource/
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Questions?