# Design by Contract with JML

- Design by contract
- Java Modeling Language (JML)
- Formal specifications in JML
- JML tools – JML compiler (jmlc)♪

Thanks to Gary Leavens for allowing us to adapt his lecture notes.

# Design by Contract (DBC)

- A way of recording:
  - Details of method responsibilities
  - Avoiding constantly checking arguments
  - Assigning blame across interfaces

# Contracts in Software

```
 /*@ requires x >= 0.0;
  @ ensures JMLDouble.approximatelyEqualTo(x,
  @                \result * \result, eps);
  @*/
public static double sqrt(double x) { … }
```

| | Obligations | Rights |
|---|---|---|
| Client | Passes non-negative number | Gets square root approximation |
| Implementor | Computes and returns square root | Assumes argument is non-negative |

# Pre and Postconditions

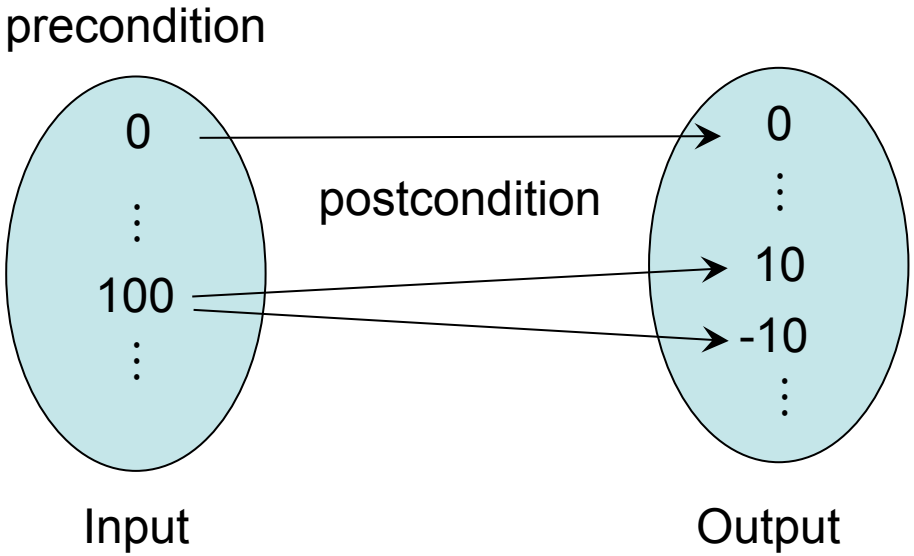
- Definition
  - A method's *precondition* says what must be true to call it.
  - A method's *normal postcondition* says what is true when it returns normally (i.e., without throwing an exception).
  - A method's *exceptional postcondition* says what is true when a method throws an exception.

```
/*@ signals (IllegalArgumentException e) x < 0;
  @*/
```

# Relational Model of Methods

- Can think of a method as a relation:

  Inputs ↔ Outputs



# Contracts as Documentation

- For each method say:
  - What it requires (if anything), and
  - What it ensures.
- Contracts are:
  - More abstract than code,
  - Not necessarily constructive,
  - Often machine checkable, so can help with debugging, and
  - Machine checkable contracts can always be up-to-date.

# Abstraction by Specification

- A contract can be satisfied in many ways:

  E.g., for square root:

  – Linear search
  – Binary search
  – Newton's method
  – …
- These will have varying non-functional properties
  – Efficiency
  – Memory usage
- So, a contract abstracts from all these implementations, and thus can change implementations later.

# More Advantages of Contracts

- Blame assignment
  - Who is to blame if:
    - Precondition doesn't hold?
    - Postcondition doesn't hold?
- Avoids inefficient defensive checks

```
//@ requires a != null && (* a is sorted *);
public static int binarySearch(Thing[] a, Thing x) { … }
```

# Modularity of Reasoning

- Typical OO code:

```
…
source.close();
dest.close();
getFile().setLastModified(loc.modTime().getTime());
…
```

- How to understand this code?
  - Read the code for all methods?
  - Read the contracts for all methods?

# Rules for Reasoning

- Client code
  - Must work for every implementation that satisfies the contract, and
  - Can thus only use the contract (not the code!), i.e.,
    - Must establish precondition, and
    - Gets to assume the postcondition

```
//@ assert 9.0 >= 0;
double result = sqrt(9.0);
//@ assert result * result ≈ 9.0; // can assume result == 3.0?
```

- Implementation code
  - Must satisfy contract, i.e.,
    - Gets to assume precondition
    - Must establish postcondition
  - But can do anything permitted by it.

# Contracts and Intent

- Code makes a poor contract, because can't separate:
  - What is intended (contract)
  - What is an implementation decision

    E.g., if the square root gives an approximation good to 3 decimal places, can that be changed in the next release?
- By contrast, contracts:
  - Allow vendors to specify intent,
  - Allow vendors freedom to change details, and
  - Tell clients what they can count on.
- Question
  - What kinds of changes might vendors want to make that don't break existing contracts?

# JML

- What is it?
  - Stands for “Java Modeling Language”
    - A formal behavioral interface specification language for Java
  - Design by contract for Java
  - Uses Java 1.4 or later
  - Available from www.jmlspecs.org

# Annotations

- JML specifications are contained in annotations, which are comments like:

  //@ …

  or

  /*@ …
  @ …
  @*/

  At-signs (@) on the beginning of lines are ignored within annotations.
- Question
  - What's the advantage of using annotations?

# Informal Description

- An informal description looks like:

  (* some text describing a property *)

  – It is treated as a boolean value by JML, and
  – Allows
    - Escape from formality, and
    - Organize English as contracts.

```
public class IMath {
   /*@ requires (* x is positive *);
     @ ensures \result >= 0 &&
     @    (* \result is an int approximation to square root of x *)
     @*/
   public static int isqrt(int x) { … }
}
```

# Exercise

- Write informal pre and postconditions for methods of the following class.

```
public class Person {
  private String name;
  private int weight;

  /*@ also
    @ ensures \result != null &&
    @     (* \result is a displayable
    @        form of this person *);
  public String toString() {
     return “Person(\” + name +
       “\”, “ + weight + ”)”;
  }


  public int getWeight() {
     return weight;
  }♪
```

```
public void addKgs(int kgs) {
    if (kgs >= 0) {
       weight += kgs;
    } else {
       throw new IllegalArgumentException();
    }
 }


 public Person(String n) {
    name = n; weight = 0;
 }
}♪
```

# Formal Specifications

- Formal assertions are written as Java expressions, but:
  - Cannot have side effects
    - No use of =, ++, --, etc., and
    - Can only call *pure* methods.
  - Can use some extensions to Java:

| Syntax | Meaning |
|---|---|
| \result | result of method call |
| a ==> b | a implies b |
| a <== b | b implies a |
| a <==> b | a iff b |
| a <=!=> b | !(a <==> b) |
| \old(E) | value of E in pre-state |

# Example

```
// File: Person.refines-java

//@ refine “Person.java”

public class Person {
   private /*@ spec_public non_null @*/ String name;
   private /*@ spec_public @*/ int weight;

   //@ public invariant !name.equals(“”) && weight >= 0;

   /*@ also
     @ ensures \result != null;
     @*/
   public String toString();

   //@ also ensures \result == weight;
   public int getWeight();
♪
```

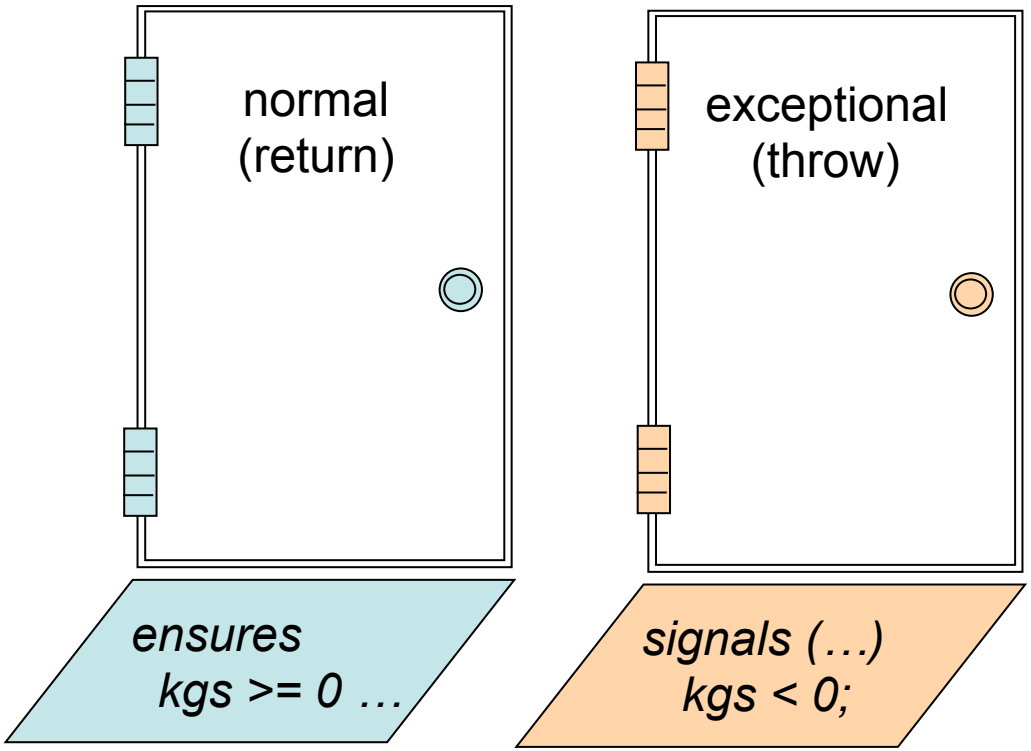
<<*continues to next slide*>>

# Example (Cont.)

```
  /*@ also
    @ ensures kgs >= 0 && weight == \old(kgs + weight);
    @ signals (Exception e) kgs < 0 &&
    @                              (e instanceof IllegalArgumentException);
    @*/
  public void addKgs(int kgs);

  /*@ also
    @ requires !n.equals("");
    @ ensures n.equals(name) && weight == 0;
    @*/
  public Person(/*@ non_null @*/ String n);
}
```

# Meaning of Postconditions



# Invariants

- Definition
  - An *invariant* is a property that is always true of an object's state (when control is not inside the object's methods).
- Invariants allow you to define:
  - Acceptable states of an object, and
  - Consistency of an object's state.

```
//@ public invariant !name.equals("") && weight >= 0;
```

# Exercise

- Formally specify the following method (in Person)

```
public void changeName(String newName) {
    name = newName;
}
```

Hint: watch out for the invariant!

# Quantifiers

- JML supports several forms of quantifiers
  - Universal and existential (\forall and \exists)
  - General quantifiers (\sum, \product, \min, \max)
  - Numeric quantifier (\num_of)

```
(\forall Student s; juniors.contains(s); s.getAdvisor() != null)

(\forall Student s; juniors.contains(s) ==> s.getAdvisor() != null)
```

# Exercise

- Formally specify the missing part, i.e., the fact that a is sorted in ascending order.

```
/*@ old boolean hasx = (\exists int i; i >= 0 && i < a.length; a[i] == x);
  @ requires
  @
  @ ensures (hasx ==> a[\result] == x) && (!hasx ==> \result == -1);
  @ requires_redundantly (* a is sorted in ascending order *);
  @*/
public static int binarySearch(/*@ non_null @*/ int[] a, int x) { … }
```

Hint: use a nested quantification!

# Model Declarations

- What if you want to change a spec_public field's name?

  private /*@ spec_public non_null @*/ String name;

  to

  private /*@ non_null @*/ String fullName;

- For specification:
  - need to keep the old name public
  - but don't want two strings.
- So, use a model field:

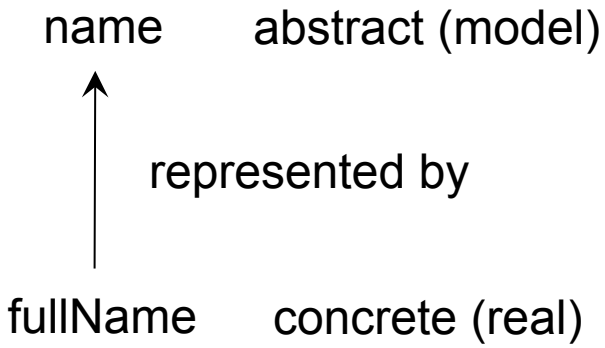
  //@ public model non_null String path;

  and a represents clause

  //@ private represents path <- fullName;

# Model Variables

- Are specification-only variables
  - Like domain-level constructs
  - Given value only by represents clauses:



# Question

- What changes would you make to change the representation of a person's weight from kilograms to pounds?

# Tools for JML

- JML compiler (jmlc)
- JML/Java interpreter (jmlrac)
- JML/JUnit unit test tool (jmlunit)
- HTML generator (jmldoc)

# JML Compiler (jmlc)

- Basic usage

  $ jmlc Person.java

  produces Person.class

  $ jmlc –Q *.java

  produces *.class, quietly

  $ jmlc –d ../bin Person.java

  produces ../bin/Person.class

# Running Code Compiled with jmlc

- Must have JML's runtime classes (jmlruntime.jar) in Java's boot class path
- Automatic if you use script jmlrac, e.g.,

  $ jmlrac PersonMain

# A Main Program

```
public class PersonMain {
   public static void main(String[] args) {
       System.out.println(new Person(null));
       System.out.println(new Person(“”));
   }
}
```

# Example (Formatted)

```
$ jmlc –Q Person.java
$ javac PersonMain.java
$ jmlrac PersonMain
Exception in thread "main" org.jmlspecs.jmlrac.runtime.JMLEntryPreconditionError
: by method Person.Person regarding specifications at
File "Person.refines-java", line 52, character 20 when
        'n' is null
        at org.jmlspecs.samples.jmltutorial.Person.checkPre$$init$$Person(
           Person.refines-java:1060)
        at org.jmlspecs.samples.jmltutorial.Person.<init>(Person.refines-java:51)
        at org.jmlspecs.samples.jmltutorial.PersonMain.main(PersonMain.java:27)
```

# Summary

- JML is a powerful DBC tool for Java.
- For details, refer to the JML web page at

www.jmlspecs.org