JML Framed!

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JML is joint work with Clyde Ruby, Yoonsik Cheon, Curtis Clifton, Rustan Leino, Bart Jacobs, Erik Poll, David Cok, Patrice Chalin, Steve Edwards, Michael Ernst, Peter Müller, ...

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jmlspecs.org

Outline

- Overview of JML
  - *Background and goals*
  - JML's key advances in language design
- Framing in JML
- Conclusions

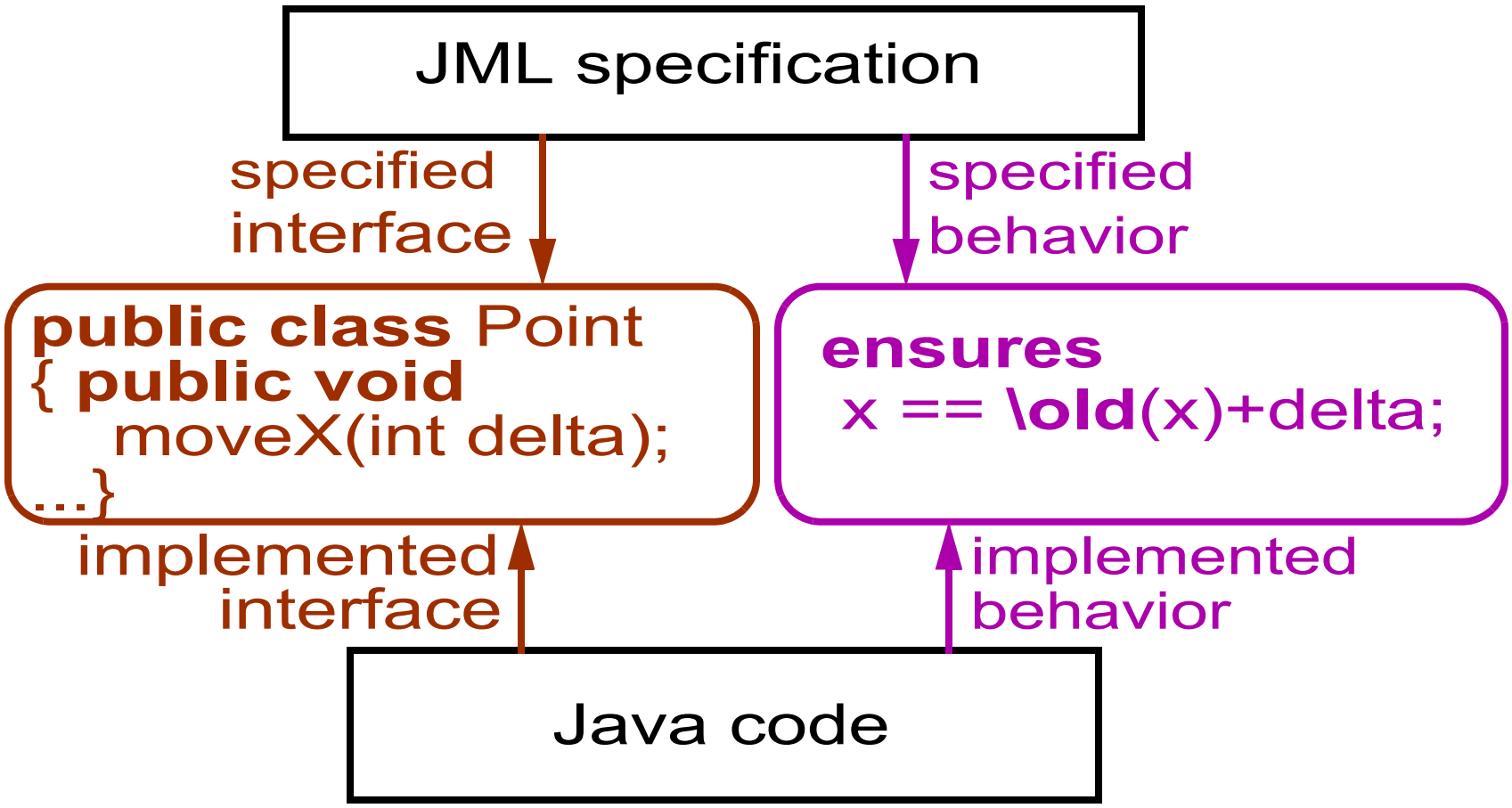
The Java Modeling Language (JML)

Behavioral interface specification language, tailored to Java

- Records detailed designs
- Pre- and postconditions, invariants, ...
- Synthesizes ideas in sequential specification

Used in Java Smart Card industry, Fulcrum,...

Behavioral Interface Specification



Like: Eiffel, Larch

Unlike: Z, VDM-SL, OCL

Example

```
public class Point {

   private /*@ spec_public @*/ int x, y;

   //@ requires delta > 0;
   //@ assignable x;
   //@ ensures x == \old(x + delta);
   public void moveRight(int delta) { x += delta; }

   //@ assignable \nothing;
   //@ ensures \result == x;
   public /*@ pure @*/ int getX() { return x; }

   // ...
}
```

JML is an Open Cooperative Project

- Leavens's group at Iowa State, Cheon at UTEP
- Hatcliff at Kansas State Univ. (Dwyer in Nebraska)
- Jacob's LOOP group at U. Nijmegen (Poll, Kiniry,...)
- Ernst's Daikon group, and others at MIT
- Chalin's group at Concordia, Montreal
- David Cok
- Edwards's group at Virginia Tech.
- Müller's group at ETH Zürich
- Poetzsch-Heffter's group at Kaiserslautern
- Logical group at INRIA Futurs & Université Paris-Sud
- Huisman's group at INRIA Sophia-Antipolis

Why Cooperate?

Common syntax and semantics

- Users benefit from multiple tools
- Tool builders share customers
- Helps exchange of ideas

The Overall Research Problem

Formal specification language good at:

- Documenting detailed designs, existing code
- Supporting a range of tools:
  - Documentation generators
  - Runtime assertion checking, unit testing
  - Static analysis, verification

Also

- Readable, Expressive, Modular

Approach

- Focus on sequential subset of Java
- For readability:
  - Java expressions for assertions (à la Eiffel)
  - Hide math behind class library
- For expressiveness:
  - Interface specifications (à la Larch)
  - Model-based (à la VDM, Larch)
  - Synthesize other ideas
- For use by verification tools
  - Statically check purity in assertions

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Key to Range of Tools: Purity Checking

If assertions might have side effects

- could cause hard-to-find errors
- mathematical models must be complex

Prohibit side-effects in assertions:

- No side-effecting expressions (e.g., ++)
- Assertions can only call "pure" methods

```
public /*@ pure @*/ int getX() { return x; }
```

- Pure methods may not:
  - assign (non-local) existing locations
  - perform I/O

Semantics

A method annotated as “pure” must satisfy:

```
assignable \nothing;
```

Purity inherited by method overrides.

Questions

Enforcement too conservative?

- Called methods must be pure.

Can synchronized methods be pure?

Purity annotations for Java’s libraries?

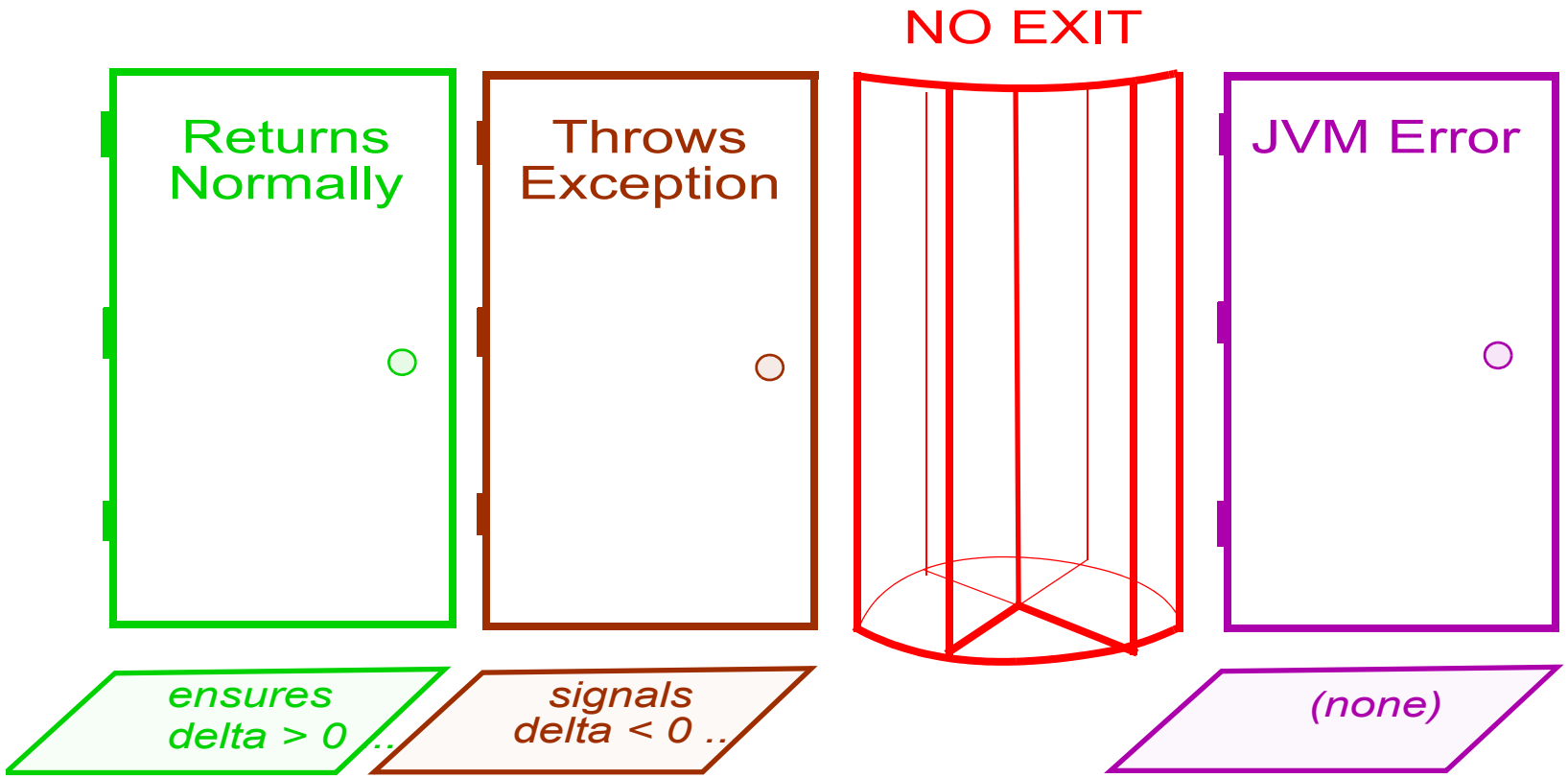
Specification of Exceptional Behavior

```
public class Point {

   private /*@ spec_public @*/ int x, y;

   /*@ requires x >= 0;
     @ assignable y;
     @ ensures delta > 0 && y == \old(y + delta)
     @         && \result == \old(y);
     @ signals (IllegalArgumentException e)
     @         delta < 0 && e != null && y == \old(y);
     @*/
   public int moveUp(int delta);
   // ...
}
```

Four “Outcomes”



No obligation if:

- JVM encounters an error [PH97]
- Precondition not satisfiable in pre-state

Case Analysis ("also"), Defaults

```
/*@  public normal_behavior
  @    requires x >= 0 && delta > 0;
  @    assignable y;
  @    ensures y == \old(y + delta)
  @          && \result == \old(y);
  @also
  @  public exceptional_behavior
  @    requires x >= 0 && delta < 0;
  @    assignable \nothing;
  @    signals (IllegalArgumentException e)
  @              e != null;
  @*/
public int moveUp(int delta);
```

Desugaring of Defaults

```
/*@  public behavior
  @    requires x >= 0 && delta > 0;
  @    assignable y;
  @    ensures y == \old(y + delta)
  @          && \result == \old(y);
  @    signals (Exception e) false;
  @also
  @  public behavior
  @    requires x >= 0 && delta < 0;
  @    assignable \nothing;
  @    ensures false;
  @    signals (IllegalArgumentException e)
  @                  e != null;
  @*/
public int moveUp(int delta);
```

Standardization of Frames

```
/*@  public behavior
  @    requires x >= 0 && delta > 0;
  @    assignable y;
  @    ensures y == \old(y + delta)
  @          && \result == \old(y);
  @    signals (Exception e) false;
  @also
  @  public behavior
  @    requires x >= 0 && delta < 0;
  @    assignable y;
  @    ensures false;
  @    signals (IllegalArgumentException e)
  @                  e != null && y == \old(y);
  @*/
public int moveUp(int delta);
```

Desugaring of “also” [Win83, Wil94]

```
/*@  public behavior
  @    requires (x >= 0 && delta > 0)
  @                || (x >= 0 && delta < 0);
  @    assignable y;
  @    ensures \old(x >= 0 && delta > 0)
  @                ==> (y == \old(y + delta)
  @                        && \result == \old(y));
  @    signals (IllegalArgumentException e)
  @       \old(x >= 0 && delta < 0)
  @        ==> e != null && y == \old(y);
  @*/
public int moveUp(int delta);
```

Specification Inheritance [DL96]

```
public class Super {
   /*@ public behavior B1 @*/ public T m();
      // ...
}

public class Sub extends Super {
   /*@ also public behavior B2 @*/ public T m();
      // ...
}
```

Completed Specification of Subclass

```
public class Sub extends Super {
   /*@        public behavior B1
     @ also public behavior B2 @*/ public T m();
      // ...
}
```

Less Restrictive than Eiffel

If superclass precondition doesn't apply, then its postcondition also doesn't apply.

```
public class Unchecked {
   /*@ public normal_behavior
     @    requires x > 0;
     @       ensures \result > 5; @*/
   public int f(int x);
      // ...
}

public class Checked extends Unchecked {
   /*@ also
     @    public exceptional_behavior
     @       requires x <= 0;
     @       signals (IllegalArgumentException e)
     @                  true;  @*/
   public int f(int x);
}
```

What Gets Inherited

- Specifications of instance methods (with "**also**")
- Fields and associated specifications
- Instance invariants and constraints.

Forces Behavioral Subtyping [DL96]

- Subtypes are behavioral subtypes.
- If try to avoid it, get unimplementable specification.
- Thus, need to underspecify supertypes

Other Features

- Model fields allow more complete specification of collections
- Quantifiers in expressions
- Redundancy: **implies_that**, **for_example**, ...

Eiffel Features not in JML

- Labels for assertions
- Specifications are statements in Eiffel

Outline

- Overview of JML
- Framing in JML
  (with Müller and Poetzsch-Heffter)
  - *Problems*
  - Approach
  - Related work
- Conclusions

Goal

Clearly specify what locations a method:

- may assign, and
- *cannot assign*

in a way that preserves information hiding.

Information Hiding Problem [Lei95, Lei98]

```
public abstract class LinkedList {

   protected Node first, last;

   /*@ public normal_behavior
     @     assignable first; @*/
   public void initializeFirst() {
      first = null;
   }

   /* ... */

}
```

What does “first” mean to a client?

Solution: Model Fields

```
//@ model import org.jmlspecs.models.*;
public class LinkedList {
   //@ public model JMLObjectSequence listValue;

   protected Node first, last;



   /*@ public normal_behavior
     @   assignable listValue;
     @   ensures listValue != null && listValue.isEmpty();
     @*/
   public void initializeFirst() {
      first = null;
   }
   /* ... */
}
```

Represents Clauses Connect Concrete and Abstract Fields [Hoa72]

```
//@ model import org.jmlspecs.models.*;
public class LinkedList {
   //@ public model JMLObjectSequence listValue;

   protected Node first, last;

   /*@ protected represents listValue <-
     @       (first==null ? new JMLObjectSequence()
     @                    : first.values); @*/

   /*@ public normal_behavior
     @   assignable listValue;
     @   ensures listValue != null && listValue.isEmpty();
     @*/
   public void initializeFirst() {
      first = null;
   }
   /* ... */
}
```

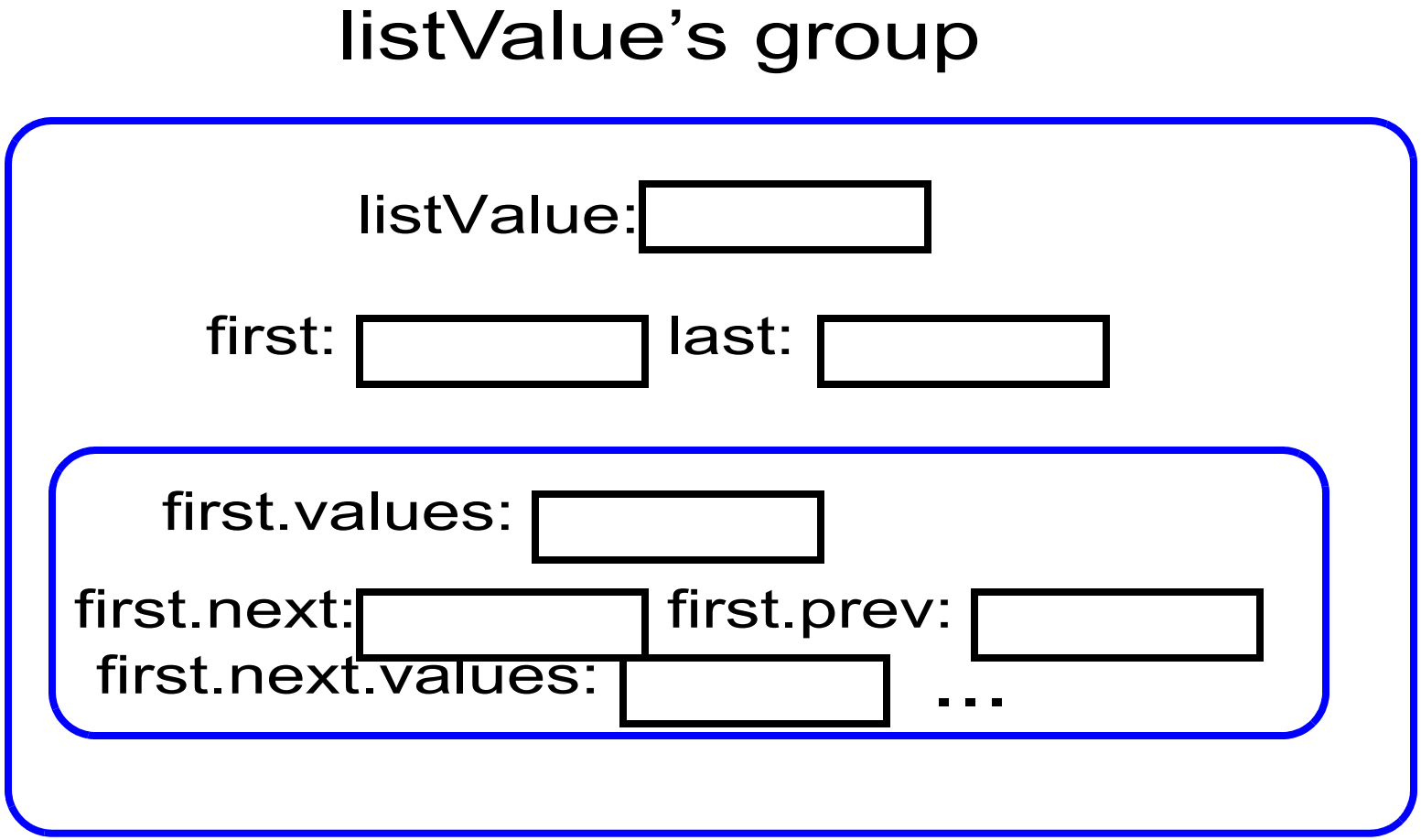
Modification of Concrete Locations

How can initializeFirst assign to first?

```
/*@ public normal_behavior
  @   assignable listValue;
  @   ensures listValue != null && listValue.isEmpty();
  @*/
public void initializeFirst() {
   first = null;
}
```

Solution Idea: Data Groups [Lei98]

A set of locations



associated to each model field

Data Group Declarations, Maps Clauses

```
//@ model import org.jmlspecs.models.*;
public class LinkedList {
   //@ public model JMLObjectSequence listValue;

   protected Node first, last; //@ in listValue;
   //@                 maps first.values \into listValue;

   /*@ protected represents listValue <-
     @       (first==null ? new JMLObjectSequence()
     @                    : first.values); @*/

   /*@ public normal_behavior
     @   assignable listValue;
     @   ensures listValue != null && listValue.isEmpty();
     @*/
   public void initializeFirst() {
      first = null;
   }
   /* ... */
}
```

```
//@ model import org.jmlspecs.models.*;
public class Node {
   //@public model non_null JMLObjectSequence values;

   public Node next, prev; //@ in values;
     //@                  maps next.values \into values;

   public /*@ readonly @*/ Object  val; //@ in values;

   /*@ protected represents values <-
     @       (next==null ? new JMLObjectSequence(val)
     @                   : next.values.insertFront(val)); @*/

   /* ... */
}
```

Data Groups and Frame Axioms

Better semantics: a method can assign to all locations in data groups mentioned in its assignable clause.

Modification of Extended State

```
public abstract class LengthCachedList
        extends LinkedList
 {

   protected int len;

   public void initializeFirst() {
      first = null;
      len = 0;        // illegal!
   }
   /* ... */
}
```

Data Groups also fix this Problem

```
public class LengthCachedList extends LinkedList {

   //@ public model int length; in listValue;

   protected int len; //@ in length;
   //@ protected represents length <- len;

   /*@ also
     @   assignable listValue;
     @   assignable_redundantly length;
     @   ensures length == 0;
     @*/
   public void initializeFirst() {
      first = null;
      len = 0;
      //@ assert length == 0;
   }
   /* ... */
}
```

Modularity (Layering) Problem [Mül02]

```
//@ model import org.jmlspecs.models.*;
public class Set {

   //@ public model non_null JMLObjectSet setValue;

   protected /*@ non_null @*/  LinkedList theList;
    //@ in setValue; maps theList.listValue \into setValue;
    /*@ protected represents setValue \such_that
      @       (\forall Object o; o != null;
      @            theList.listValue.has(o)
      @             <==> setValue.has(o));   @*/

   /*@ public normal_behavior
     @   assignable setValue;
     @   ensures setValue.isEmpty();
     @*/
   public void emptyOut() {
      theList.initializeFirst();
   }

   /* ... */
}
```

Modularity Problem

Set's call to List.initializeFirst:

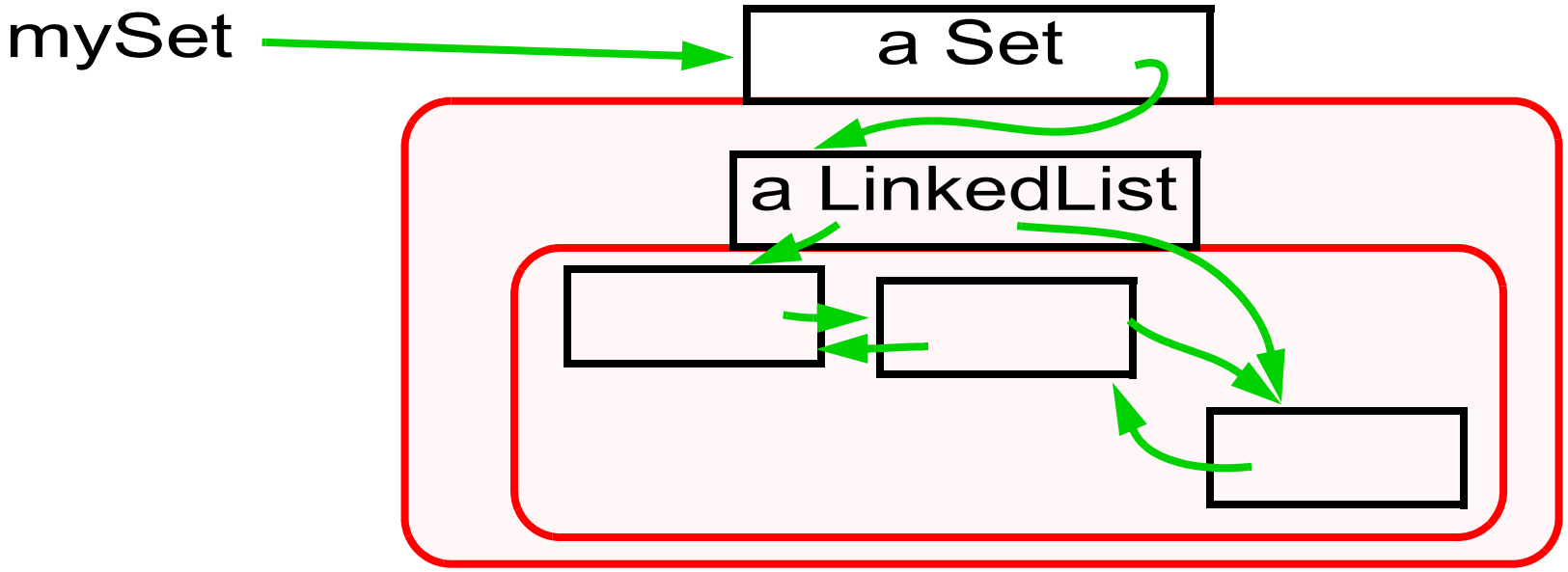
- changes theList.listValue,
- hence changes setValue.

So initializeFirst changes a location that it can't change!

```
/*@ public normal_behavior
  @   assignable listValue;
  @   ensures listValue != null && listValue.isEmpty();
  @*/
public void initializeFirst() {
   first = null;
}
```

Approach to Modular Framing [Mül02]

- Use an alias-controlling type system; gives a hierarchy of *contexts,* each with an *owner*



- Underspecify frames for modularity:
  - Only "relevant" locations are in receiver's context
- Use semantic restrictions for soundness

Using the Universe Type System

```
//@ model import org.jmlspecs.models.*;
public class Set {

   //@ public model non_null JMLObjectSet setValue;

   protected /*@ rep non_null @*/  LinkedList theList;
    //@ in setValue; maps theList.listValue \into setValue;
    /*@ protected represents setValue \such_that
      @       (\forall Object o; o != null;
      @            theList.listValue.has(o)
      @             <==> setValue.has(o));   @*/

   /*@ public normal_behavior
     @   assignable setValue;
     @   ensures setValue.isEmpty();
     @*/
   public void emptyOut() {
      theList.initializeFirst();
   }

   /* ... */
}
```

Modularity for Data Group Information

Data group membership declared when fields are declared.

So new code:

- can't change membership of existing field
- knows membership for each field it sees

Modularity for Verification for Frames

Verification for frames is divided:

- Method implementer verifies frame only for relevant locations
- Method caller uses:
  - the called method's frame
  - the data groups and represents clauses

  to accumulate the effect of the call.

```
/*@ public normal_behavior
  @   assignable setValue;
  @   ensures setValue.isEmpty();
  @*/
public void emptyOut() {
   theList.initializeFirst();
}
```

Current work [MPHL03]: Extension to Invariants

Problem: what invariants must hold when?

Approach: use ownership contexts...

- Invariants can only depend on owned locations
- Verification is only concerned with invariants of relevant objects

Related Work

- VDM-SL [And97]
  - has reads and writes clauses
  - doesn't solve info hiding or extended state
- Leino and Nelson [LN02]
  - More complex language
  - Scope dependent semantics: hard to prove sound
- Spec# (Boogie)
  - Better ownership transfer
  - Directly handles reentrance
  - More dynamic, so more expressive
  - But harder for programmers to use?

Future Work on Framing

- Checking more of JML's semantics statically
- Implementing the Universe type system (ongoing by Müller)
- Evaluating the design in practice
- Fixing the Universe type system's problems
- Blending the Spec# approach?

Framing Conclusions

- Alias control or ownership seems to help:
  - Prevent rep exposure
  - Prevent arg exposure
    (what invariant dependencies are allowed?)
  - Allows modular verification of frames
- Data groups easy to work with
  - Easier than explicit dependencies
  - Automatically guarantee crucial properties

JML Conclusions

- JML supports both run time checking and static verification
- JML combines Eiffel, Larch
  - Eiffel-style syntax: readability
  - Larch-style semantics: well-defined
- More expressive than Eiffel-style
- More practical than Larch-style
- Hiding model types behind Java classes
- We're open to new collaborators

See jmlspecs.org

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