Software Model Checking Using Bogor

- a Modular and Extensible Model Checking Framework

3rd Estonian Summer School in Computer and System Science (ESSCaSS'04)

Slide Set 04: Bogor Extensions

http://bogor.projects.cis.ksu.edu
http://www.cis.ksu.edu/~hatcliff/ESSCaSS04

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Support

US Army Research Office (ARO)
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Customization Mechanisms

Bogor -- Extensible Modeling Language

Threads, Objects, Methods, Exceptions, etc. + Domain-Specific Abstractions

Core Modeling Language

Bogor -- Customizable Checking Engine Modules

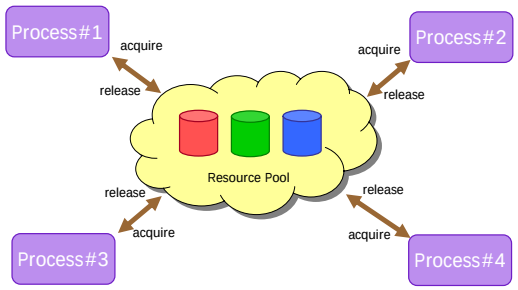
Scheduling Strategy | State-space Exploration | State Representation

Core Checker Modules

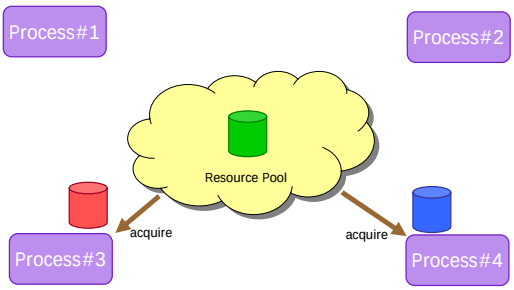
...existing modules... | Domain-Specific Scheduler | Domain-Specific Search | Domain-Specific State Rep.

Customized Checker Modules

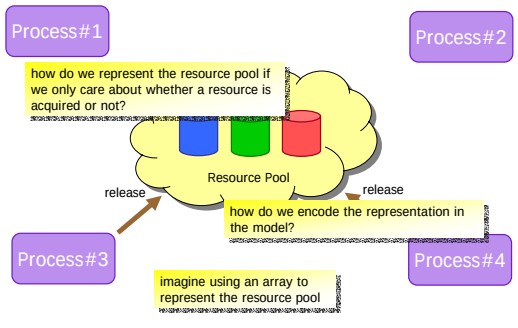
Extensible Input Language – Resource Contention Example



Extensible Input Language – Resource Contention Example



Extensible Input Language – Resource Contention Example



Domain-Specific Modeling

Bogor -- Extensible Modeling Language

Threads, Objects, Methods, Exceptions, etc. + **Set.type<'a>**

create()
choose()
+ **add()**
⋮
forAll()

```
class SetValue implements IValue {
  byte[] linearize(…) {
    Bogor API calls…
  } –
}
```

```
IValue choose(…) {
  Bogor API calls…
}
```

⋮

```
IValue forAll(…) {
  Bogor API calls…
}
```

Core Modeling Language

New Bogor types and primitives

Java implementation of new values and new primitives inside model-checker

Modeling Language Extensions

Bogor allows definitions of new abstract types and abstract operations as first-class constructs

```
extension Set for SetModule
{
  typedef type<'a>;

  expdef Set.type<'a> create<'a>('a ...);

  expdef 'a choose<'a>(Set.type<'a>);

  actiondef add<'a>(Set.type<'a>, 'a);

  actiondef remove<'a>(Set.type<'a>, 'a);

  expdef boolean forAll<'a>('a -> boolean, Set.type<'a>);
}
```

A new *type* to represent polymorphic symmetric sets

Modeling Language Extensions

Bogor allows definitions of new abstract types and abstract operations as first-class constructs

```
extension Set for SetModule
{
  typedef type<'a>;

  expdef Set.type<'a> create<'a>('a ...);

  expdef 'a choose<'a>(Set.type<'a>);

  actiondef add<'a>(Set.type<'a>, 'a);

  actiondef remove<'a>(Set.type<'a>, 'a);

  expdef boolean forAll<'a>('a -> boolean, Set.type<'a>);
}
```

Variable arity function for creating symmetric sets

Modeling Language Extensions

Bogor allows definitions of new abstract types and abstract operations as first-class constructs

```
extension Set for SetModule
{
  typedef type<'a>;

  expdef Set.type<'a> create<'a>('a ...);

  expdef 'a choose<'a>(Set.type<'a>);

  actiondef add<'a>(Set.type<'a>, 'a);

  actiondef remove<'a>(Set.type<'a>, 'a);

  expdef boolean forAll<'a>('a -> boolean, Set.type<'a>);
}
```

Non-deterministically pick an element of the set to return

Modeling Language Extensions

Bogor allows definitions of new abstract types and abstract operations as first-class constructs

```
extension Set for SetModule
{
  typedef type<'a>;

  expdef Set.type<'a> create<'a>('a ...);

  expdef 'a choose<'a>(Set.type<'a>);

  actiondef add<'a>(Set.type<'a>, 'a);

  actiondef remove<'a>(Set.type<'a>, 'a);

  expdef boolean forAll<'a>('a -> boolean, Set.type<'a>);
}
```

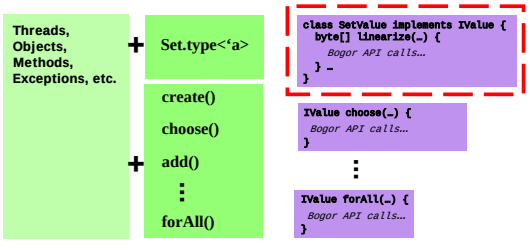
Higher-order function implements quantification over set elements

Predicate on set element

Set value to interate over

Domain-Specific Modeling

Bogor -- Extensible Modeling Language



Core Modeling Language

New Bogor types and primitives

Java implementation of new values and new primitives inside model-checker

Extension Implementation

Implementing the set value for the set type

- operations on the value
  - *e.g.*, add, remove, isEmpty, *etc.*
- visitor pattern for the value
  - used for linearization, *etc.*
- linearization for state storage
  - fine-grained control over the value representation
- XML externalization for counter-example display

Extension Implementation

Implementing the set value for the set type

```
public interface ISetValue
       extends INonPrimitiveExtValue {

  void add(IValue v);

  boolean contains(IValue v);

  IValue[] elements();

  boolean isEmpty();

  void remove(IValue v);
}
```

Create an interface for all implementations of set values

Extension Implementation

Implementing the set value for the set type

```
public class ReferenceElementSetValue
       implements ISetValue {

  protected HashSet set = new HashSet();

  public void add(IValue v) { set.add(v); }

  public boolean contains(IValue v) { retu

  public boolean isEmpty() { return set.size() == 0; }

  public void remove(IValue v) { set.remove(v); }

  public IValue[] elements() {
    Object[] elements = set.toArray();
    orderValues(elements);

    IValue[] result = new IValue[elements.length];
    System.arraycopy(elements, 0, result, 0, elements.length);

    return result;
  }
  …
```

A set value implementation where its elements are of reference types

Extension Implementation

Implementing the set value for the set type

```
public class ReferenceElementSetValue
       implements ISetValue {

  protected HashSet set = new HashSet();

  public void add(IValue v) { set.add(v); }

  public boolean contains(IValue v) { return set.contains(v); }

  public boolean isEmpty() { return set.size() == 0; }

  public void remove(IValue v) { set.remove(v); }

  public IValue[] elements() {
    Object[] elements = set.toArray();
    orderValues(elements);

    IValue[] result = new IValue[elements.length];
    System.arraycopy(elements, 0, result, 0, elements.length);

    return result;
  }
  …
```

Reuse Java collection class

Extension Implementation

Implementing the set value for the set type

```
public class ReferenceElementSetValue
       implements ISetValue {

  protected HashSet set = new HashSet();

  public void add(IValue v) { set.add(v); }

  public boolean contains(IValue v) { return set.contains(v); }

  public boolean isEmpty() { return set.size() == 0; }

  public void remove(IValue v) { set.remove(v); }

  public IValue[] elements() {
    Object[] elements = set.toArray();
    orderValues(elements);

    IValue[] result = new IValue[elements.length];
    System.arraycopy(elements, 0, result, 0, elements.length);

    return result;
  }
  …
```

Most set operations are wrapper calls to HashSet methods

order elements for consistency

Extension Implementation

Implementing the set value for the set type

- operations on the value
  - *e.g.*, add, remove, isEmpty, *etc.*
- visitor pattern for the value
  - used for garbage collection, *etc.*
- linearization for state storage
  - fine-grained control over the value representation
- XML externalization for counter-example display

Extension Implementation

Implementing the visitor pattern for set values

```
public class ReferenceElementSetValue implements ISetValue {

  public IValue[] elements() { … }

  public void visit(…, boolean depthFirst, Set seen,
        LinkedList workList, …) {

    IValue[] elements = elements();

    if (depthFirst) {
      for (int i = 0; i < elements.length; i++) {
        workList.addFirst(elements[i]);
      }
    } else {
      for (int i = 0; i < elements.length; i++) {
        workList.add(elements[i]);
      }
    }
  }
  …
```

Visitor pattern for traversing element values in the set (used for GC, symmetry, *etc.*)

Extension Implementation

Implementing the set value for the set type

- operations on the value
  - *e.g.*, add, remove, isEmpty, *etc.*
- visitor pattern for the value
  - used for garbage collection, *etc.*
- linearization for state storage
  - fine-grained control over the value representation
- XML externalization for counter-example display

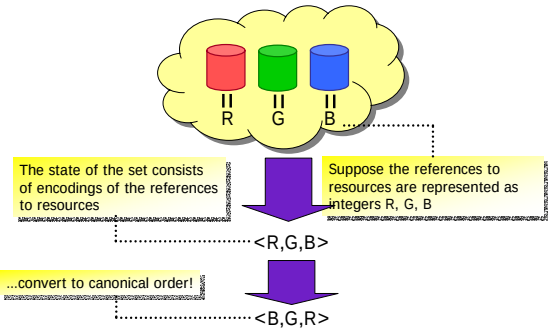
Extension Implementation

Implementing the linearization function

```
public class ReferenceElementSetValue implements ISetValue {

  public byte[][] linearize(int bitsPerNonPrimitiveValue,
                            ObjectIntTable nonPrimitiveValueIdMap, …) {
    IValue[] elements = elements();
    BitBuffer bb = new BitBuffer();

    if (elements.length > 0) {
      int[] elementIds = new int[elements.length];
      for (int i = 0; i < elements.length; i++) {
        elementIds[i] = nonPrimitiveValueIdMap.get(elements[i]);
      }

      Arrays.sort(elementIds);

      for (int i = 0; i < elements.length; i++) {
        bb.append(elementIds[i], bitsPerNonPrimitiveValue);
      }
    }

    return new byte[][] { bb.toByteArray() };
  }
  …
```

Convert the set value to a bit vector for state storage

Extensible Input Language – Set Extension Example (Semantics)



Extension Implementation

Implementing the set value for the set type

- operations on the value
  - *e.g.*, add, remove, isEmpty, *etc.*
- visitor pattern for the value
  - used for garbage collection, *etc.*
- linearization for state storage
  - fine-grained control over the value representation
- XML externalization for counter-example display

Extension Implementation

Implementing the XML externalization

```
public class ReferenceElementSetValue implements ISetValue {

  public void externalize(PrintWriter pw,
      INonPrimitiveValueIdTracker npvIdTracker) {
        IValue[] elements = elements();
        pw.println("<fields>");
        Type elementType = type.getTypeArg(0);
        for (int i = 0; i < elements.length; i++) {
            pw.println("<field>");
            pw.println("<id>element</id>");
            INonPrimitiveValue value =
                              (INonPrimitiveValue) elements[i];
            pw.print("<value type=\"");
            pw.print(Util.encodeXML(elementType.toString()));
            pw.print("\" val=\"");
            pw.print(npvIdTracker.getNonPrimitiveValueId(value));
            pw.print("\"");
            pw.println(" />");
            pw.println("</field>");
        }
        pw.println("</fields>");
        pw.flush();
    }
  …
```

Convert the set value to an XML representation for counter-example display

Extension Implementation

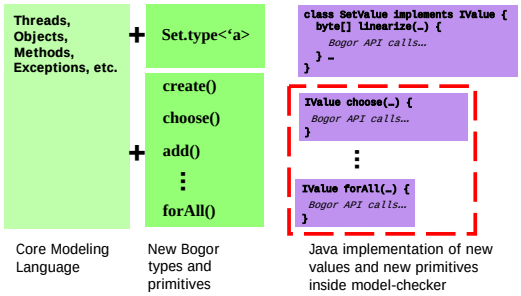
Implementing the XML externalization

```
<element id="Set.type&lt;Resource&gt;#1" isExt="true">
  <fields>
    <field>
      <id>element</id>
      <value type="Resource" val="Disk#1"/>
    </field>
    <field>
      <id>element</id>
      <value type="Resource" val="Disk#2"/>
    </field>
    <field>
      <id>element</id>
      <value type="Resource" val="Display#1"/>
    </field>
  </fields>
</element>
```

An example XML representation of a set value with three elements: Disk#1, Disk#2, Display#1

Domain-Specific Modeling

Bogor -- Extensible Modeling Language



Core Modeling Language

New Bogor types and primitives

Java implementation of new values and new primitives inside model-checker

Extension Implementation

Implementing the set operations for the set type

- set module extension
- set creation
- non-deterministically choose a set element
- adding an element

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  protected SymbolTable symbolTable;
  protected TypeFactory tf;
  protected IExpEvaluator ee;
  protected IValueFactory vf;
  protected ISchedulingStrategist ss;

  public String getCopyrightNotice() { return null; }

  public void setOptions(String key, Properties options) {}

  public void connect(IBogorConfiguration bc) {
    symbolTable = bc.getSymbolTable();
    tf = symbolTable.getTypeFactory();
    ee = bc.getExpEvaluator();
    ss = bc.getSchedulingStrategist();
    vf = bc.getValueFactory();
  }

  public void dispose() {
    symbolTable = tf = ee = ss = vf = null;
  }
  …
```

The set module must implement IModule

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  protected SymbolTable symbolTable;
  protected TypeFactory tf;
  protected IExpEvaluator ee;
  protected IValueFactory vf;
  protected ISchedulingStrategist ss;

  public String getCopyrightNotice() { return null; }

  public void setOptions(String key, Properties options) {}

  public void connect(IBogorConfiguration bc) {
    symbolTable = bc.getSymbolTable();
    tf = symbolTable.getTypeFactory();
    ee = bc.getExpEvaluator();
    ss = bc.getSchedulingStrategist();
    vf = bc.getValueFactory();
  }

  public void dispose() {
    symbolTable = tf = ee = ss = vf = null;
  }
  …
```

Store references to other Bogor modules as needed

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  protected SymbolTable symbolTable;
  protected TypeFactory tf;
  protected IExpEvaluator ee;
  protected IValueFactory vf;
  protected ISchedulingStrategist ss;

  public String getCopyrightNotice() { return null; }

  public void setOptions(String key, Properties options) {}

  public void connect(IBogorConfiguration bc) {
    symbolTable = bc.getSymbolTable();
    tf = symbolTable.getTypeFactory();
    ee = bc.getExpEvaluator();
    ss = bc.getSchedulingStrategist();
    vf = bc.getValueFactory();
  }

  public void dispose() {
    symbolTable = tf = ee = ss = vf = null;
  }
  …
```

Used for displaying copyright notices

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  protected SymbolTable symbolTable;
  protected TypeFactory tf;
  protected IExpEvaluator ee;
  protected IValueFactory vf;
  protected ISchedulingStrategist ss;

  public String getCopyrightNotice() { return null; }

  public void setOptions(String key, Properties options) {}

  public void connect(IBogorConfiguration bc) {
    symbolTable = bc.getSymbolTable();
    tf = symbolTable.getTypeFactory();
    ee = bc.getExpEvaluator();
    ss = bc.getSchedulingStrategist();
    vf = bc.getValueFactory();
  }

  public void dispose() {
    symbolTable = tf = ee = ss = vf = null;
  }
  …
```

Used for setting options of Bogor modules

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  protected SymbolTable symbolTable;
  protected TypeFactory tf;
  protected IExpEvaluator ee;
  protected IValueFactory vf;
  protected ISchedulingStrategist ss;

  public String getCopyrightNotice() { return null; }

  public void setOptions(String key, Properties options) {}

  public void connect(IBogorConfiguration bc) {
    symbolTable = bc.getSymbolTable();
    tf = symbolTable.getTypeFactory();
    ee = bc.getExpEvaluator();
    ss = bc.getSchedulingStrategist();
    vf = bc.getValueFactory();
  }

  public void dispose() {
    symbolTable = tf = ee = ss = vf = null;
  }
  …
```

Connect to other Bogor modules

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  protected SymbolTable symbolTable;
  protected TypeFactory tf;
  protected IExpEvaluator ee;
  protected IValueFactory vf;
  protected ISchedulingStrategist ss;

  public String getCopyrightNotice() { return null; }

  public void setOptions(String key, Properties options) {}

  public void connect(IBogorConfiguration bc) {
    symbolTable = bc.getSymbolTable();
    tf = symbolTable.getTypeFactory();
    ee = bc.getExpEvaluator();
    ss = bc.getSchedulingStrategist();
    vf = bc.getValueFactory();
  }

  public void dispose() {
    symbolTable = tf = ee = ss = vf = null;
  }
  …
```

Unlink references to other Bogor modules

Extension Implementation

Implementing the set operations for the set type

- set module extension
- set creation
- non-deterministically choose a set element
- adding an element

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  // expdef Set.type<'a> create<'a>('a ...);
  public IValue create(IExtArguments arg) {

    if (arg.getTypeVariableArgument(0)
                  instanceof NonPrimitiveType) {

      ISetValue result = new ReferenceElementSetValue(
                        (NonPrimitiveExtType) arg.getExpType(),
                        vf.newReferenceId());

      int size = arg.getArgumentCount();

      for (int i = 0; i < size; i++) {
              result.add(arg.getArgument(i));
      }

      return result;
    }
    else if …
  }
  …
```

If the type argument is reference type then use the previously implemented set value

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  // expdef Set.type<'a> create<'a>('a ...);
  public IValue create(IExtArguments arg) {

    if (arg.getTypeVariableArgument(0)
                  instanceof NonPrimitiveType) {

      ISetValue result = new ReferenceElementSetValue(
                        (NonPrimitiveExtType) arg.getExpType(),
                        vf.newReferenceId());

      int size = arg.getArgumentCount();

      for (int i = 0; i < size; i++) {
              result.add(arg.getArgument(i));
      }

      return result;
    }
    else if …
  }
  …
```

Add arguments to the set value

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  // expdef Set.type<'a> create<'a>('a ...);
  public IValue create(IExtArguments arg) {

    if (arg.getTypeVariableArgument(0)
                  instanceof NonPrimitiveType) {

      ISetValue result = new ReferenceElementSetValue(
                        (NonPrimitiveExtType) arg.getExpType(),
                        vf.newReferenceId());

      int size = arg.getArgumentCount();

      for (int i = 0; i < size; i++) {
              result.add(arg.getArgument(i));
      }

      return result;
    }
    else if …
  }
  …
```

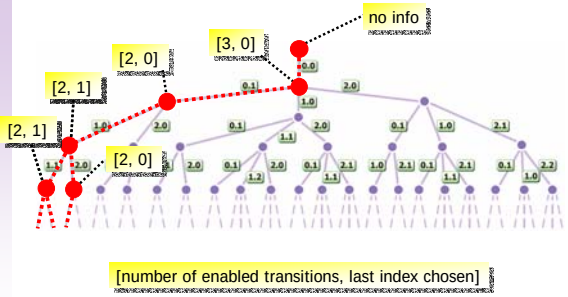
other element types are handled differently (more efficiently)

Extension Implementation

Implementing the set operations for the set type

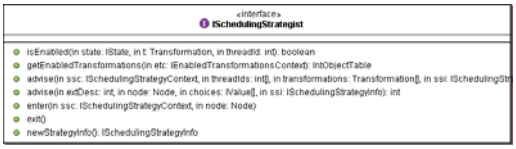
- set module extension
- set creation
- non-deterministically choose a set element
- adding an element

DefaultSchedulingStrategist & DefaultSchedulingStrategyInfo



[number of enabled transitions, last index chosen]

ISchedulingStrategist



- Used to determine
  - enabled transitions: isEnabled(), getEnabledTransformations()
  - which transition to take: advise()
- create strategy info

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  // expdef 'a choose<'a>(Set.type<'a>);
  public IValue choose(IExtArguments arg) {

    ISetValue set = (ISetValue) arg.getArgument(0);

    IValue[] elements = set.elements();

    int size = elements.length;

    int index = 0;

    if (size > 1) {
      index = ss.advise(arg.getExtDesc(),
                        arg.getNode(),
                        elements,
                        arg.getSchedulingStrategyInfo());
    }

    return elements[index];
  }
  …
```

Get the set value

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  // expdef 'a choose<'a>(Set.type<'a>);
  public IValue choose(IExtArguments arg) {

    ISetValue set = (ISetValue) arg.getArgument(0);

    IValue[] elements = set.elements();

    int size = elements.length;

    int index = 0;

    if (size > 1) {
      index = ss.advise(arg.getExtDesc(),
                        arg.getNode(),
                        elements,
                        arg.getSchedulingStrategyInfo());
    }

    return elements[index];
  }
  …
```

Get the set elements

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  // expdef 'a choose<'a>(Set.type<'a>);
  public IValue choose(IExtArguments arg) {

    ISetValue set = (ISetValue) arg.getArgument(0);

    IValue[] elements = set.elements();

    int size = elements.length;

    int index = 0;

    if (size > 1) {
      index = ss.advise(arg.getExtDesc(),
                        arg.getNode(),
                        elements,
                        arg.getSchedulingStrategyInfo());
    }

    return elements[index];
  }
  …
```

Ask the scheduler which one to pick if there are two or more elements

Extension Implementation

Implementing the set operations for the set type

- set module extension
- set creation
- non-deterministically choose a set element
- adding an element

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  // actiondef add<'a>(Set.type<'a>, 'a);
  public IBacktrackingInfo[] add(IExtArguments arg) {
    ISetValue set = (ISetValue) arg.getArgument(0);

    IValue element = (IValue) arg.getArgument(1);

    if (!set.contains(element)) {
      set.add(element);

      ISchedulingStrategyContext ssc =
           arg.getSchedulingStrategyContext();

      return new IBacktrackingInfo[] {
        createAddBacktrackingInfo(set, element, arg.getNode()
                          ssc.getStateId(), ssc.getThreadId(),
                              arg.getSchedulingStrategyInfo())

      };
    } else {
      return new IBacktrackingInfo[0];
    }
  }
…
```

Get the set and the element

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  // actiondef add<'a>(Set.type<'a>, 'a);
  public IBacktrackingInfo[] add(IExtArguments arg) {
    ISetValue set = (ISetValue) arg.getArgument(0);

    IValue element = (IValue) arg.getArgument(1);

    if (!set.contains(element)) {
      set.add(element);

      ISchedulingStrategyContext ssc =
           arg.getSchedulingStrategyContext();

      return new IBacktrackingInfo[] {
        createAddBacktrackingInfo(set, element, arg.getNode()
                          ssc.getStateId(), ssc.getThreadId(),
                              arg.getSchedulingStrategyInfo())

      };
    } else {
      return new IBacktrackingInfo[0];
    }
  }
…
```

Add the element if it is not already in the set value

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  // actiondef add<'a>(Set.type<'a>, 'a);
  public IBacktrackingInfo[] add(IExtArguments arg) {
    ISetValue set = (ISetValue) arg.getArgument(0);

    IValue element = (IValue) arg.getArgument(1);

    if (!set.contains(element)) {
      set.add(element);

      ISchedulingStrategyContext ssc =
           arg.getSchedulingStrategyContext();

      return new IBacktrackingInfo[] {
        createAddBacktrackingInfo(set, element, arg.getNode()
                          ssc.getStateId(), ssc.getThreadId(),
                              arg.getSchedulingStrategyInfo())

      };
    } else {
      return new IBacktrackingInfo[0];
    }
  }
…
```

Create the backtracking information

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  // actiondef add<'a>(Set.type<'a>, 'a);
  public IBacktrackingInfo[] add(IExtArguments arg) {
    ISetValue set = (ISetValue) arg.getArgument(0);

    IValue element = (IValue) arg.getArgument(1);

    if (!set.contains(element)) {
      set.add(element);

      ISchedulingStrategyContext ssc =
           arg.getSchedulingStrategyContext();

      return new IBacktrackingInfo[] {
        createAddBacktrackingInfo(set, element, arg.getNode()
                          ssc.getStateId(), ssc.getThreadId(),
                              arg.getSchedulingStrategyInfo())

      };
    } else {
      return new IBacktrackingInfo[0];
    }
  }
…
```

If the element is already in the set then do nothing

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  protected IBacktrackingInfo createAddBacktrackingInfo(
                final ISetValue set, final IValue element, … ) {

    return new IBacktrackingInfo() {

      public void backtrack(IState state) {
        set.remove(element);
      }

      public IBacktrackingInfo clone(Map cloneMap) {
        return createAddBacktrackingInfo(
          (ISetValue) cloneMap.get(set),
          (IValue) ((element instanceof INonPrimitiveValue) ?
                      cloneMap.get(element) : element),
          node, stateId, threadId, ssi.clone(cloneMap));
      }
…
    };
  }
…
```

Backtrack by removing the element from the set

Extension Implementation

Implementing the set operations for the set type

```
public class SetModule implements IModule {

  protected IBacktrackingInfo createAddBacktrackingInfo(
                final ISetValue set, final IValue element, … ) {

    return new IBacktrackingInfo() {

      public void backtrack(IState state) {
        set.remove(element);
      }

      public IBacktrackingInfo clone(Map cloneMap) {
        return createAddBacktrackingInfo(
          (ISetValue) cloneMap.get(set),
          (IValue) ((element instanceof INonPrimitiveValue) ?
                    cloneMap.get(element) : element),
           node, stateId, threadId, ssi.clone(cloneMap));
      }
      …
    };
  }
  …
```

(Deep) clone the backtracking information

A BIR Example – Resource Contention

Demo

- Model with the Set extension
- Incorporating the extension in the Bogor Eclipse plugin
- Run the example
  - invalid end state
  - invariant checking

Assessment

- Bogor provides a clean and well-designed framework for extending its modeling language
  - Allows introduction of new abstract types and abstract operations as first-class construct
    - Complete control over value representation (linearization)
    - No double interpretation (the operations are executed as atomic actions in the model checker instead of being interpreted by the model checker)
  - Analogous to adding new instructions to a Virtual Machine
    - essentially, we are building abstract machines for particular domains