

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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Customization Mechanisms

Bogor -- Extensible Modeling Language

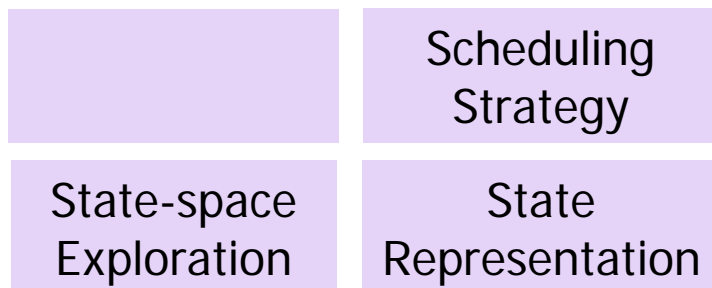
Threads,
Objects,
Methods,
Exceptions, etc.

+

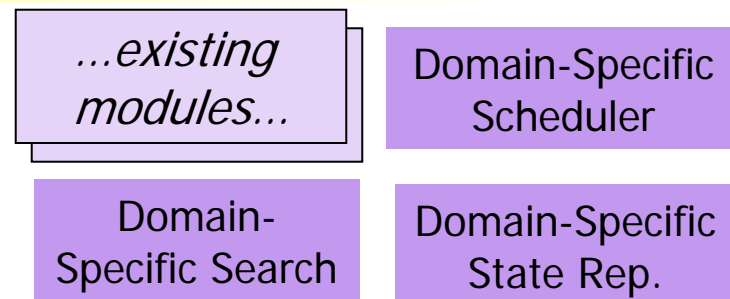
Domain-Specific
Abstractions

Core Modeling Language

Bogor -- Customizable Checking Engine Modules

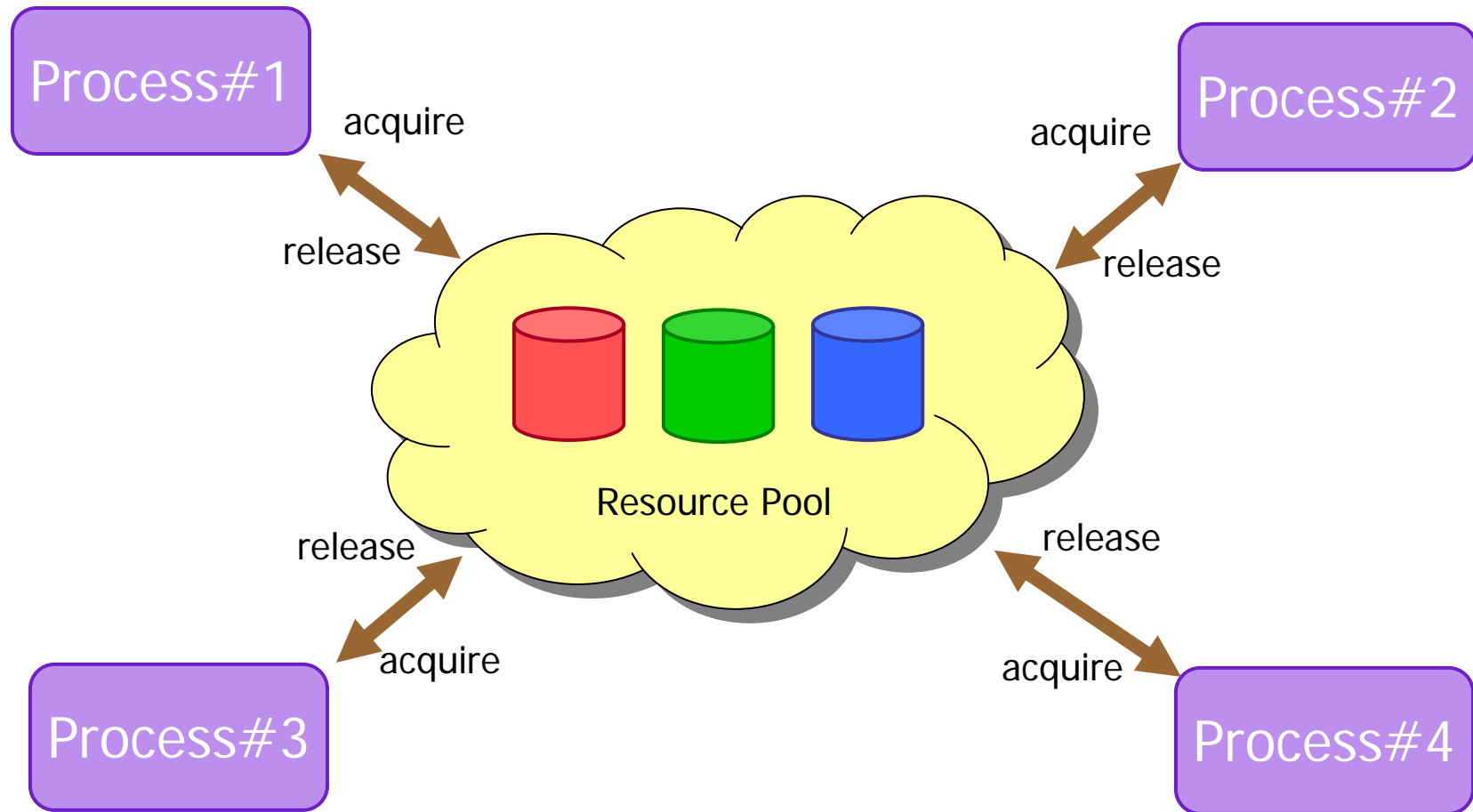


Core Checker Modules

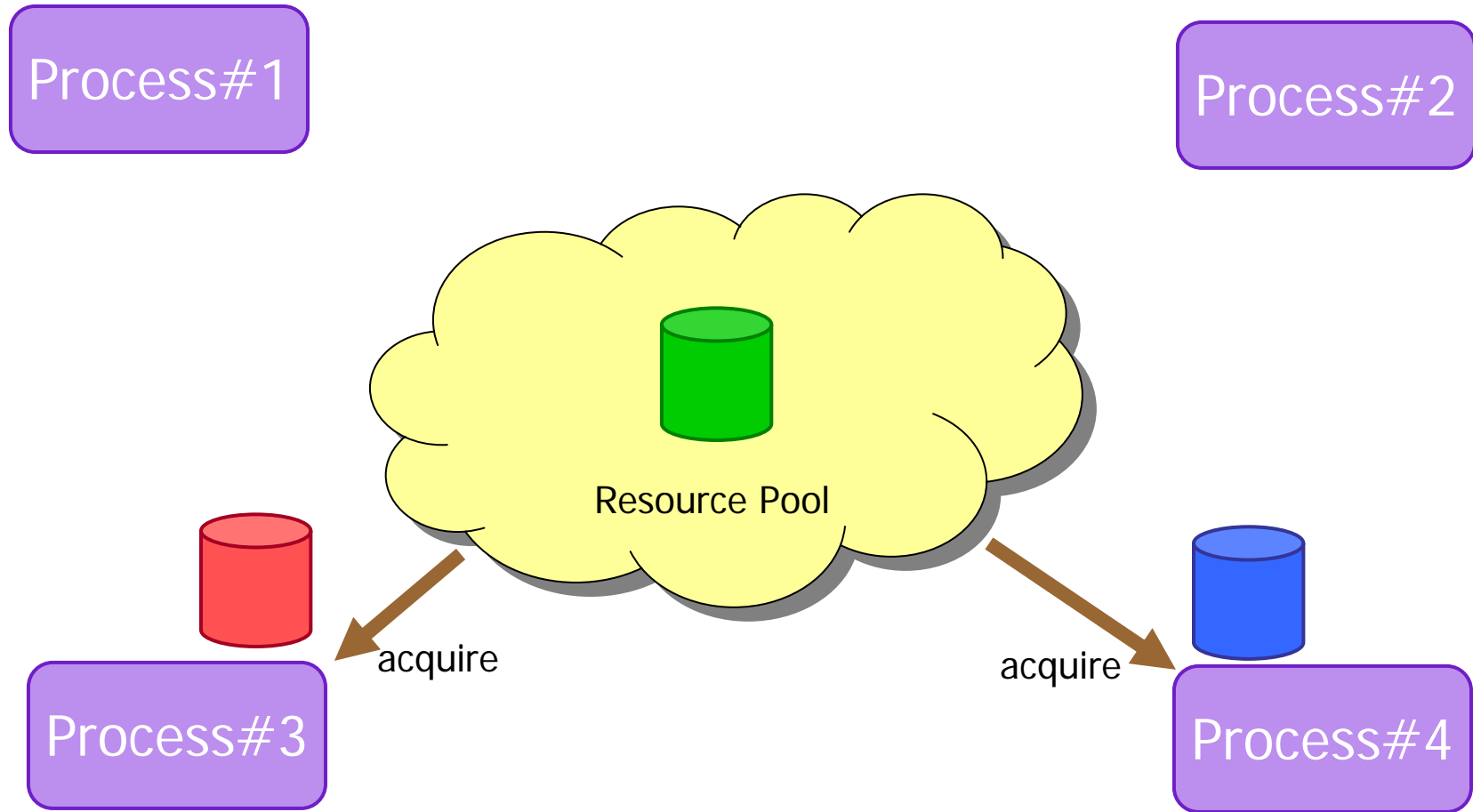


Customized Checker Modules

Extensible Input Language – Resource Contention Example



Extensible Input Language – Resource Contention Example

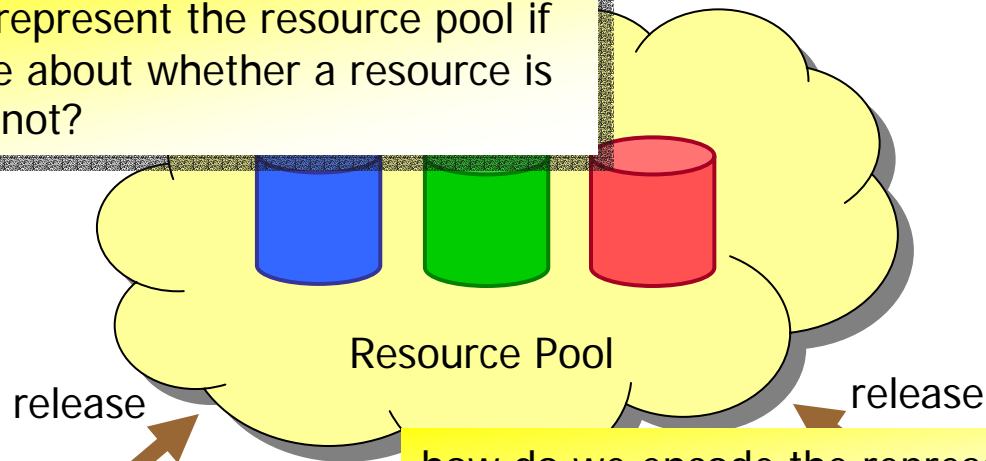


Extensible Input Language – Resource Contention Example

Process#1

Process#2

how do we represent the resource pool if we only care about whether a resource is acquired or not?



Process#3

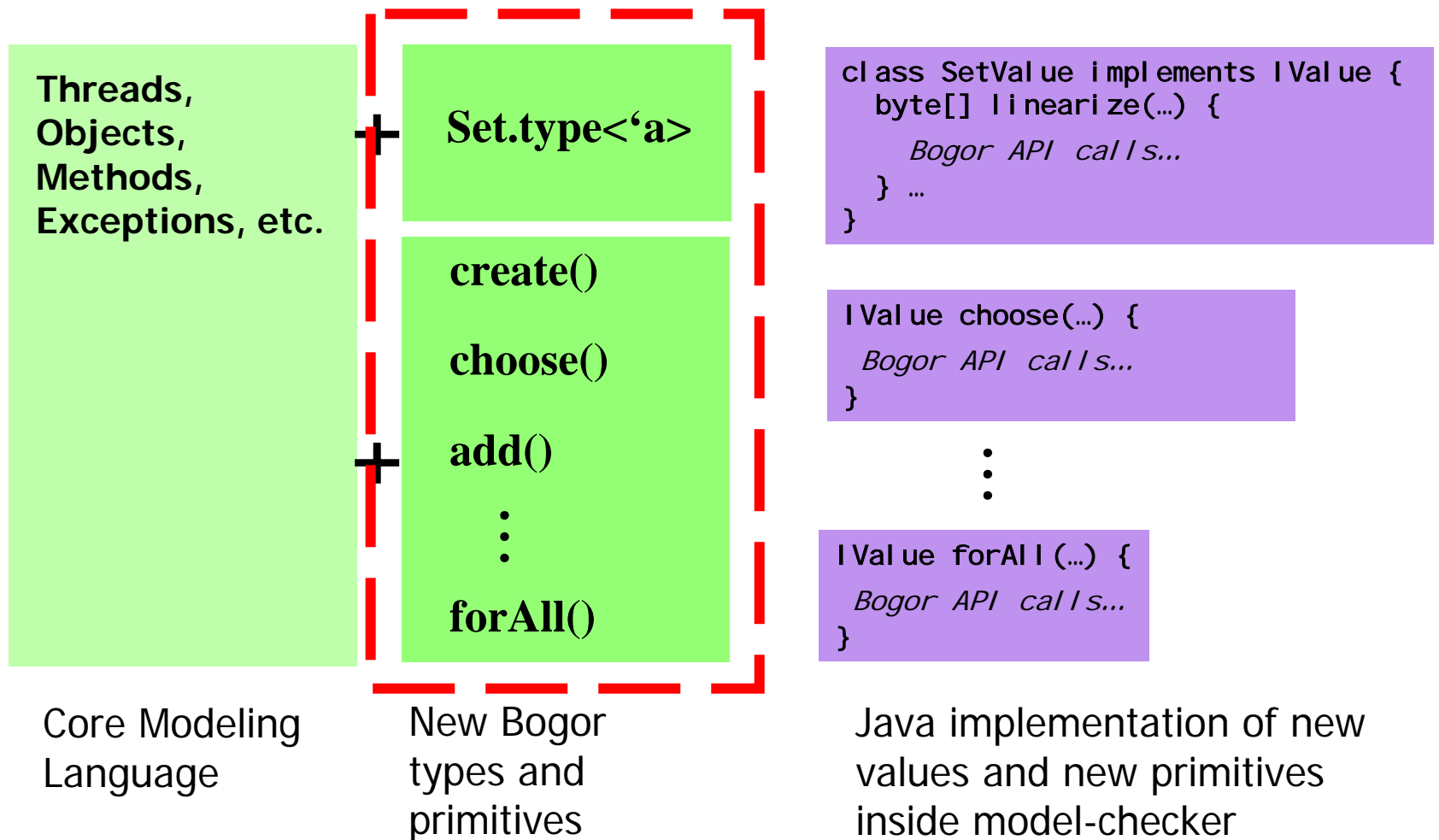
Process#4

how do we encode the representation in the model?

imagine using an array to represent the resource pool

Domain-Specific Modeling

Bogor -- Extensible Modeling Language



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>;

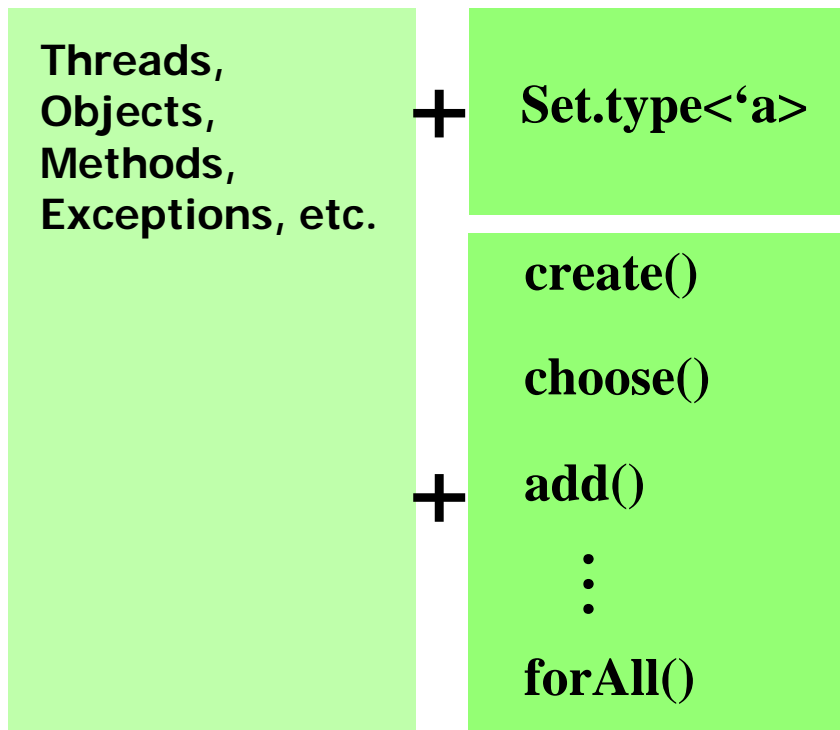
  expdef Set.type<'a> create<'a>('a ...);

  expdef 'a choose<'a>(Set.type<'a>).
  Higher-order function implements quantification over set elements
  Predicate on set element
  Set value to iterate over
  Set.type<'a>, 'a);

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

Domain-Specific Modeling

Bogor -- Extensible Modeling Language



Core Modeling
Language

New Bogor
types and
primitives

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

IValue choose(...) {
    Bogor API calls...
}

⋮

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

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) { 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;  
    }  
    ...  
}
```

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

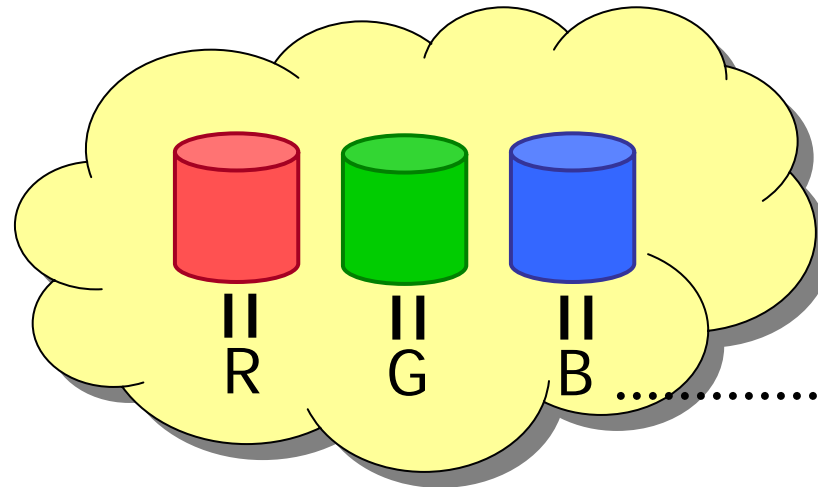
Extension Implementation

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() };  
    }  
    ...  
}
```

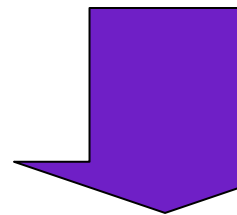
Convert the set value to a bit vector for state storage

Extensible Input Language – Set Extension Example (Semantics)



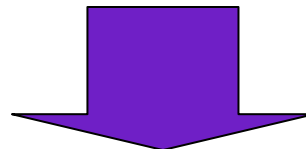
The state of the set consists of encodings of the references to resources

Suppose the references to resources are represented as integers R, G, B



.....<R, G, B>

...convert to canonical order!



.....<B, G, R>

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

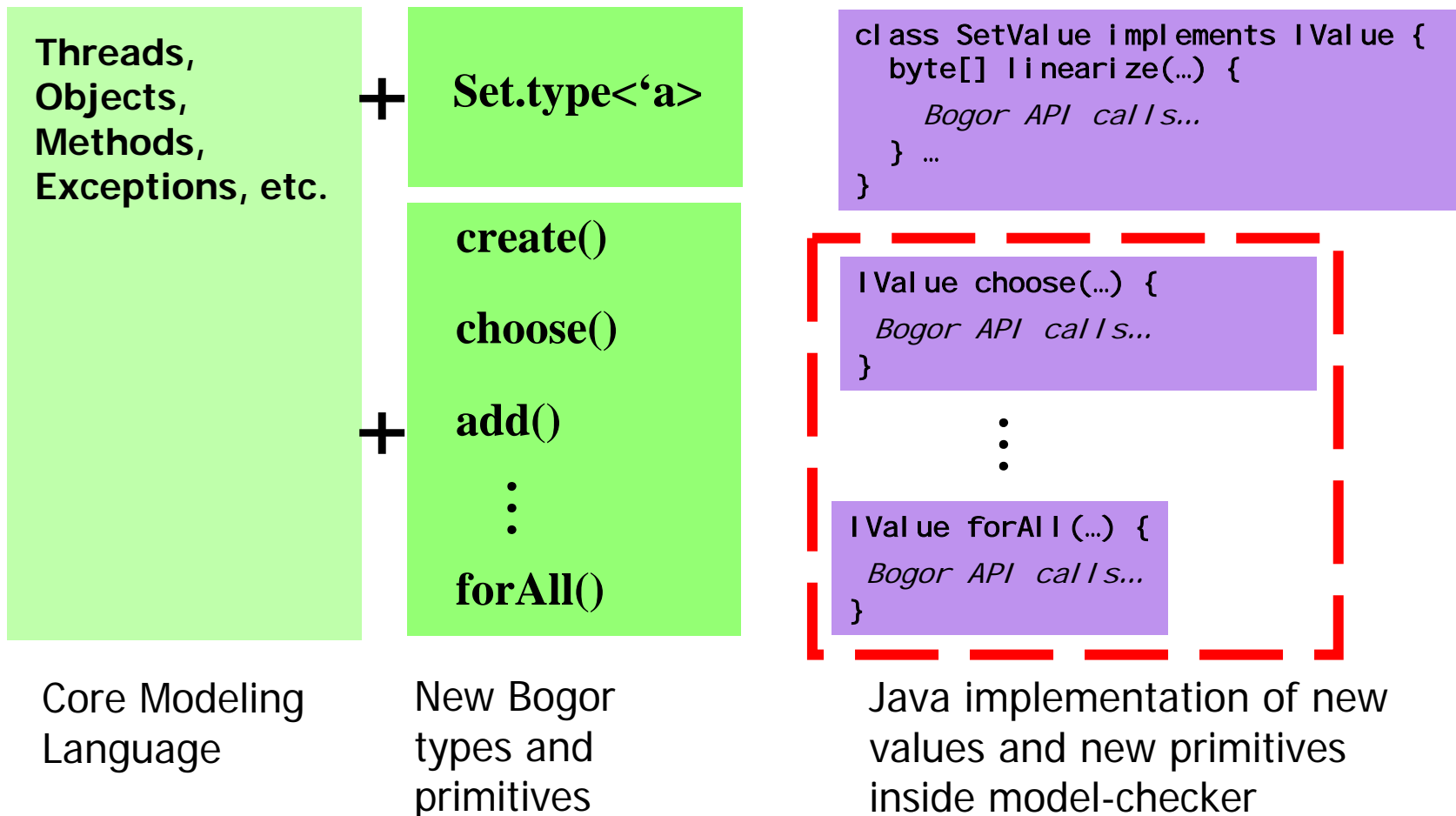
Implementing the XML externalization

```
<element id="Set.type<Resource>#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



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 ... .....  
    }  
    ...  
}
```

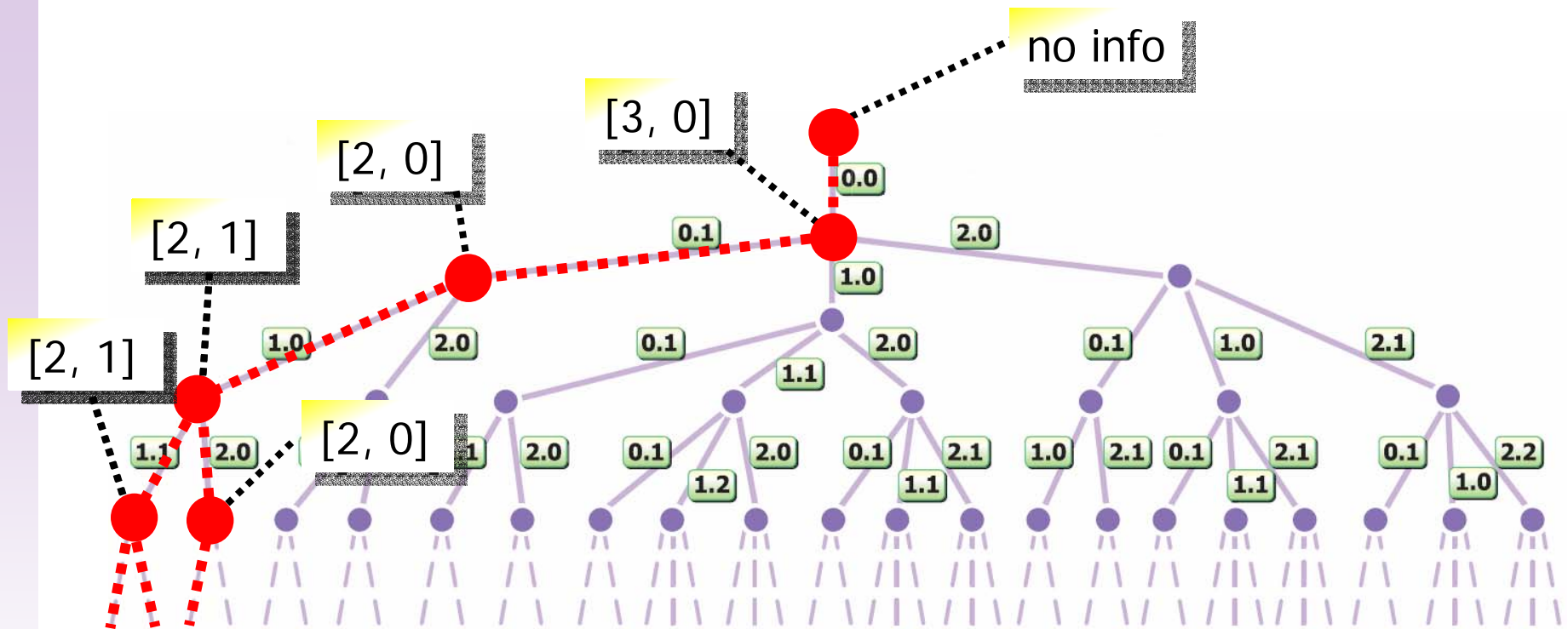
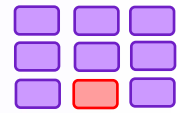
other element types
are handled differently
(more efficiently)

Extension Implementation

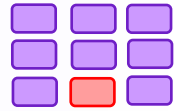
Implementing the set operations for the set type

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

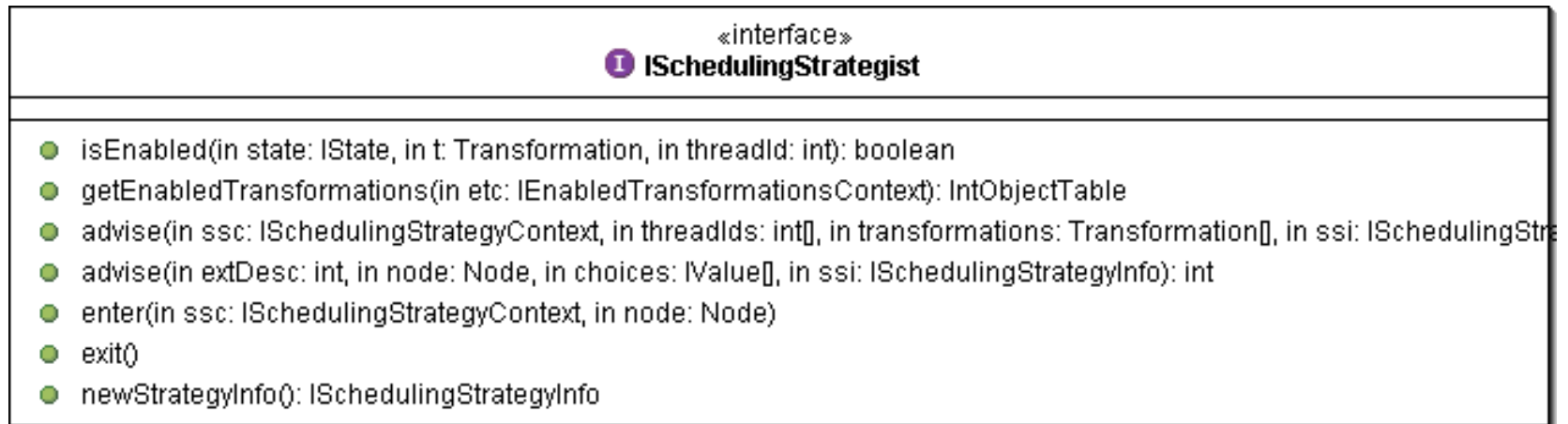
DefaultSchedulingStrategist & DefaultSchedulingStrategyInfo



[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