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 03: Bogor Architecture

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

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US Army Research Office (ARO)
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Core DFS Algorithm

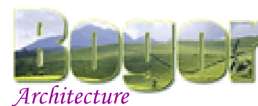
```
seen := {s0}                    ...put initial state in seen set
stack := [s0]                   ...current path being explored in
                                   computation tree begins with initial state
DFS ()

DFS ()
  while stack ≠ ∅ do            ...iterate if there exists an unexpanded state
    s := pop (stack )           ...current state to expand
    workSet := enabled (s )     ...get the transitions to explore at this state
    for each α ∈ workSet do     ...for each transition
      s′ := α (s )              ...calculate the successor state
      if s′ ∉ seen then
        seen := seen ∪ {s′}     ...if s′ has not been seen before, then
                                   put it in the seen set
        push (stack, s′)        ...put s′ on the stack which represents
                                   the current path in the tree
end DFS
```

Motivations and Goals

- If you're going to customize Bogor, you need to understand what is going on in the guts of the code.
- We've learned the basic DFS algorithm, and the basic data structures, now we are going to learn how they are implemented in Bogor.
- We'll survey the architecture of Bogor
  - many details will be omitted
  - for more info, see the API documentation and the code!

Outline



Overview
- Bogor components
- Configuration
- Initialization

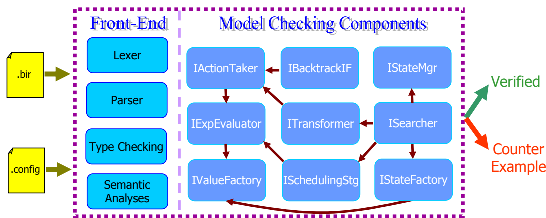
State Representation
- Types & Values
- Value Factory
- State Factory

DFS Stack
- Search algorithm
- Scheduler

Seen Before Set
- State Manager

Bogor Architecture

Bogor -- Customizable Checking Engine Modules



...modular components with clean and well-designed API using design patterns

Bogor Configuration

A Bogor configuration is a key-value set

Keys for component interfaces — Java class implementation for each interface

```
IActionTaker                  = DefaultActionTaker
IExpEvaluator                 = DefaultExpEvaluator
ISchedulingStrategist         = DefaultSchedulingStrategist
ISearcher                     = DefaultSearcher
IStateManager                 = DefaultStateManager
ITransformer                  = DefaultTransformer
IBacktrackingInfoFactory      = DefaultBacktrackingInfoFactory
IStateFactory                 = DefaultStateFactory
IValueFactory                 = DefaultValueFactory

ISearcher.maxErrors           = 1
…
```

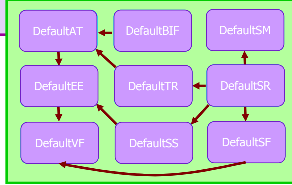
Options for components

Bogor Initialization

```
IActionTaker                = DefaultActionTaker
IExpEvaluator               = DefaultExpEvaluator
ISchedulingStrategist       = DefaultSchedulingStrategist
ISearcher                   = DefaultSearcher
IStateManager               = DefaultStateManager
ITransformer                = DefaultTransformer
IBacktrackingInfoFactory    = DefaultBacktrackingInfoFactory
IStateFactory               = DefaultStateFactory
IValueFactory               = DefaultValueFactory

ISearcher.maxErrors         = 1
…
```

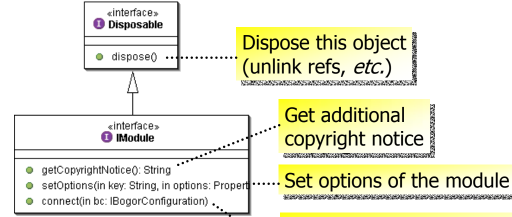
Given a configuration, Bogor instantiate the specified components



Options are passed to each component, and connections are established

Bogor Module Interface

Each Bogor component must implement IModule



Dispose this object (unlink refs, *etc.*)

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Set options of the module

Connect this module with other modules in the current configuration

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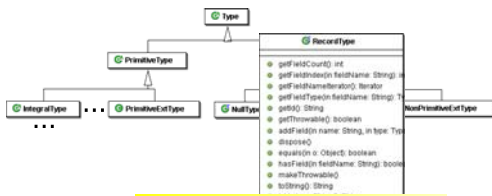
Type and Value Representations

- BIR types are categorized into two
  - Primitive types: int, long, float, double, *etc.*
  - Non-primitive types: null, record, lock, *etc.*
- Types are created using a TypeFactory
- Each type class has methods to access information about the type represented

Package: `bogor.type`

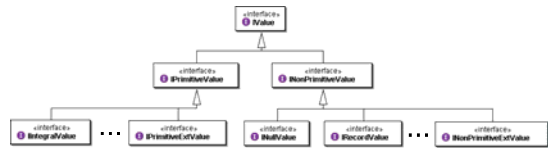
Type and Value Representations



For example, the record type class has methods to access its fields's names, types, and indices

Package: `bogor.type`

Type and Value Representations



- BIR values mimic BIR types structure
  - Primitive values: int, long, float, double, *etc.*
  - Non-primitive values: null, record, lock, *etc.*
- Values are created using a ValueFactory

Package: `bogor.module.value`

Type and Value Representations

«interface» IValue
«interface» IPrimitiveValue
«interface» IRecordValue
getFieldCount(): int
setFieldValue(in fieldIndex: int, in fieldValue: IValue)
getFieldValue(in fieldIndex: int): IValue
getFieldValues(): IValueArray
getLockValue(): ILockValue
linearize(in bitsPerNonPrimitiveValue: int, in nonPri
toVerboseString(): String
«interface» IIntegralValue …
«interface» IPrimitiveExtValue
«interface» INonPrimitiveExtValue
…

Similar to the record type, the record value interface has methods to access its fields' values

Package: `bogor.module.value`

State Representation

«interface» IState
getGlobalCount(): int
setGlobalValue(in globalIndex: int, in value: IValue)
getGlobalValue(in globalIndex: int): IValue
getGlobalValues(): IValueArray
getLocalCount(in threadId: int): int
setLocalValue(in threadId: int, in localIndex: int, in value: IValue)
getLocalValue(in threadId: int, in localIndex: int): IValue
getLocalValues(in threadId: int): IValueArray
getLocalValuesStack(in threadId: int): IValueArray[]
setLocation(in threadId: int, in locationDesc: int)
getLocation(in threadId: int): int
getLocationStack(in threadId: int): int[]
getStackHeight(in threadId: int): int
isThreadAlive(in threadId: int): boolean
getThreadIds(): int[]
clone(in cloneMap: Map): IState
enterFunction(in threadId: int, in localValues: IValueArray, in beginLocationDe
exitFunction(in threadId: int): IValueArray
exitThread(in threadId: int): IValueArray
newThread(in threadId: int, in localValues: IValueArray, in beginLocationDes

- The state interface has methods to access
  - global values
  - active threads, their program counters and local vars.
  - create or kill threads, and enter or exit functions
- States are created using a StateFactory

Package: `bogor.module.state`

Outline

Bogor *Architecture*

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Search Module

«interface» ISearcher
getBacktrackingInfos(): ArrayList
getErrorCount(): int
getNextThreadId(): int
getState(): IState
backtrack(): boolean
createInitialState()
doTransition(in threadId: int, in t: Transformation, in a: A
error(in errCode: int)
search()
shouldStore(): boolean
step(): boolean
store(): boolean
writeCounterExamples()

- ISearcher
  - create initial state
  - step
  - backtrack
- DefaultSearcher
  - depth-first search
  - iteration-based

Package: `bogor.module`

DefaultSearcher

A DFS implementation of the state-space exploration

seen := $\{s_0\}$
stack := $[s_0]$
DFS ()

DFS ()
  while *stack* ≠ ∅ **do**
    s := *pop* (*stack*)
    workSet := *enabled* (*s*)
    for each $\alpha \in$ *workSet* **do**
      s' := $\alpha(s)$
      if $s' \notin$ *seen* **then**
        seen := *seen* ∪ $\{s'\}$
        push (*stack, s'*)
end *DFS*

```
public class DefaultSearcher
      extends ISearcher {
  IState s;
  ISchedulingStrategist ss;
  void search() {

    s=createInitialState();

    while (true) {
      if (!step()) {
        if (!backtrack()) {
          break;
        }
      }
    }
  } …
}
```

DefaultSearcher.step()

A DFS implementation of the state-space exploration

step ()
  if *shouldBacktrack* () ∨ *isSeen* () ∨
      hasNoRunnableThreads () **then**
    return false

  if *isInvalidEndState* () **then**
    error (INVALID_END_STATE)
    return false

  T := ss.*getEnabledTransformations* (s)

  ssi := ss.*newStrategyInfo* ()
  α := ss.*advise* (s, *T*, *ssi*)

  push (*newBacktrackingInfo* (s, *T*, α, *ssi*))

  doTransition (s, α, *ssi*)
  return true
end *step*

```
public class DefaultSearcher
      extends ISearcher {
  IState s;
  ISchedulingStrategist ss;
  void search() {

    s=createInitialState();

    while (true) {
      if (!step()) {
        if (!backtrack()) {
          break;
        }
      }
    }
  } …
}
```

DefaultSearcher.step()

A DFS implementation of the state-space exploration

```
step ()
   if shouldBacktrack () ∨ isSeen () ∨
         hasNoActiveThreads () then
      return false

   if isInvalidEndState () then
      error ( INVALID_END_STATE )
      return false

   T := ss.getEnabledTransformations (s)

   ssi := ss.newStrategyInfo ()
   α := ss.advise (s, T, ssi )

   push (newBacktrackingInfo (s,T,α, ssi))

   doTransition (s, α, ssi )
   return true
end step
```

- …if we are forced to backtrack, we have visited the current state, or if all threads have completed, then we cannot step
- …check if the current state is an invalid state
- …get all the enabled transformations by calling the ISchedulingStrategist
- …call the ISchedulingStrategist to pick the next transition; *ssi* is used to record necessary information to make sure each transition will be executed eventually
- …store the backtracking info necessary for reversing the transition, and for counter example generation
- …execute the transition and return true to indicate a successful step

DefaultSearcher.backtrack()

A DFS implementation of the state-space exploration

```
backtrack ()
   bi := pop ()

   while ¬bi.getSSI ().hasInfo () do
      bi.backtrack (s)
      if isStackEmpty ()
         return false
      bi := pop ()

   T := bi.getTransformations ()

   ssi := bi.getSSI ()
   α := ss.advise (s, T, ssi )

   push (newBacktrackingInfo (s,T,α, ssi))

   doTransition (s, α, ssi )
   return true
end backtrack
```

```java
public class DefaultSearcher
      extends ISearcher {
   IState s;
   ISchedulingStrategist ss;
   void search() {

      s=createInitialState();

      while (true) {
         if (!step()) {
            if (!backtrack()) {
               break;
            }
         }
      }
   } …
}
```

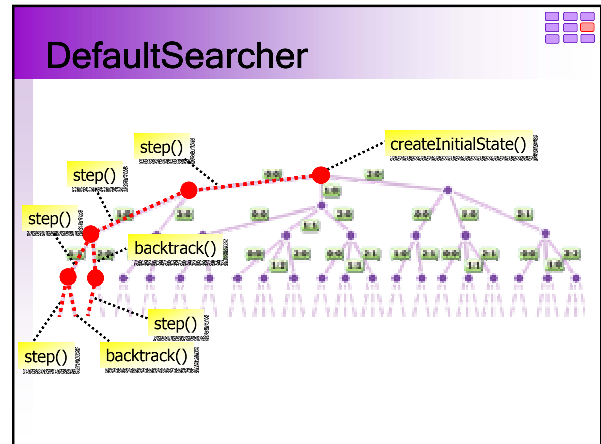
DefaultSearcher.backtrack()

A DFS implementation of the state-space exploration

```
backtrack ()
   bi := pop ()

   while ¬bi.getSSI ().hasInfo () do
      bi.backtrack (s)
      if isStackEmpty ()
         return false
      bi := pop ()

   T := bi.getTransformations ()

   ssi := bi.getSSI ()
   α := ss.advise (s, T, ssi )

   push (newBacktrackingInfo (s,T,α, ssi))

   doTransition (s, α, ssi )
   return true
end backtrack
```

- …get the last backtracking info
- …keep backtracking until we find a state that is not fully expanded (i.e., all of its enabled transitions have not been explored); if it does not exist, then return false (i.e., all states have been fully expanded)
- …get the enabled transformations
- …call the ISchedulingStrategist to pick the next transition
- …store the backtracking info necessary for reversing the transition, and for counter example generation
- …execute the transition and return true to indicate a successful backtrack

DefaultSearcher



Backtracking Information

«interface»
IBacktrackingInfo
- getNode(): Node
- getSchedulingStrategyInfo(): ISchedulingStrategy
- getStateId(): int
- getThreadId(): int
- backtrack(in state: IState)
- clone(in cloneMap: Map): IBacktrackingInfo

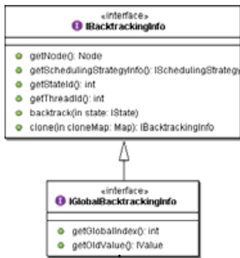
- Used to keep track information for
  - "undo"-ing transition
  - scheduling information for counter-example generation

Backtracking Information

«interface»
IBacktrackingInfo
- getNode(): Node
- getSchedulingStrategyInfo(): ISchedulingStrategy
- getStateId(): int
- getThreadId(): int
- backtrack(in state: IState)
- clone(in cloneMap: Map): IBacktrackingInfo

- Information needed to backtrack
  - state, thread ID, *etc.*
  - scheduling information
    - which non-deterministic choice was made, if any
  - specific info for each kind of action, transformation, etc.

Backtracking Information



...for backtracking a global variable assignment, we need the index of global variable and its value before the assignment

- Information needed to backtrack
  - state, thread ID, *etc.*
  - scheduling information
    - which non-deterministic choice was made, if any
  - specific info for each kind of action, transformation, etc.

Backtracking Example

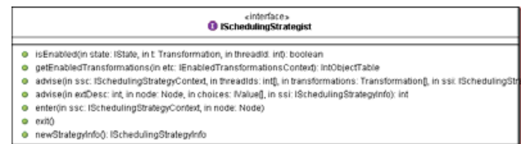
- Show simple assignment to global, and then annotations to show states and backtracking info.

Scheduler

```
seen := {s0}
stack := [s0]
DFS()

DFS()
  while stack ≠ ∅ do
    s := pop(stack)
    workSet := enabled(s)
    for each α ∈ workSet do
      s′ := α(s)
      if s′ ∉ seen then
        seen := seen ∪ {s′}
        push(stack, s′)
end DFS
```

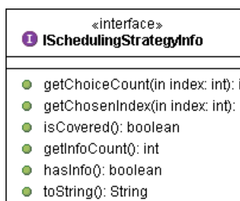
- Used to determine
  - enabled transitions
  - which transition to take

ISchedulingStrategist



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

ISchedulingStrategyInfo

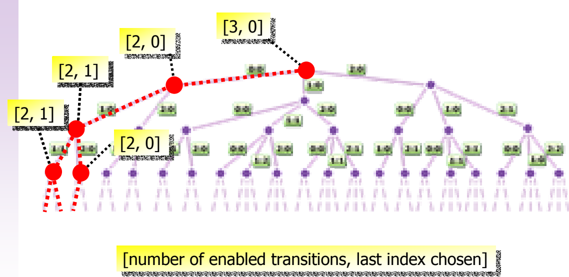


- Used to keep track
  - whether there is a non-deterministic choice
  - if yes, which transition has been taken

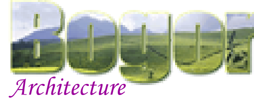
DefaultSchedulingStrategist

- Full state-space exploration
  - the scheduling policy ensure that each state is visited
- At each choice point, the info contains
  - the number of enabled transitions
  - the last chosen transition index
- **`advise()`** simply increase the last chosen transition index until all are chosen

DefaultSchedulingStrategist & DefaultSchedulingStrategyInfo



Outline



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- Search algorithm
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- State Manager

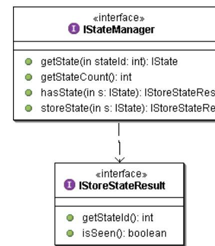
Seen Before Set

seen := $\{s_0\}$
stack := $[s_0]$
DFS ()

DFS ()
  while *stack* $\neq \emptyset$ **do**
    s := *pop* (*stack*)
    workSet := *enabled* (*s*)
    for each $\alpha \in$ *workSet* **do**
      s' := α (*s*)
      if $s' \notin$ *seen* **then**
        seen := *seen* $\cup \{s'\}$
        push (*stack*, s')
end *DFS*

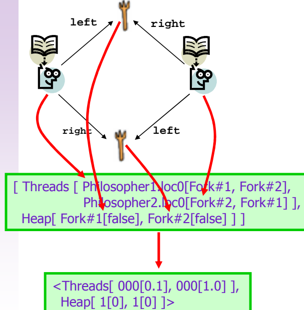
- Used to keep track states that have been visited before
- Usually done by linearizing the state into a bit-vector
- For efficiency,
  - store the state using the least number of bits possible (fingerprinting)
- For full state-space exploration
  - should preserve state equality (analogous to loss-less compressions)

IStateManager



- Used to keep track states
- Also assign a unique number for each stored state (stateId)
  - use the number instead of the actual state in the DFS stack

State Linearization



- Bogor states consist of
  - global variables
  - heap (consisting non-primitive values)
  - thread stores
- …represented as shape graphs
- To efficiently compare them, we convert them to bit-vectors
  - each primitive value is converted to its bit-vector representation
    - want to make sure we use the least number of bits possible

State Linearization

- For each integral type, we need *ceil* (*lg N*) bits, where *N* is the number of values the type can have, *e.g.*,
  - Each thread is represented by its *program counter*
    - *N* is number of locations in the model
  - Each variable is represented by its *value*
    - for each ranged integer, *N* is max – min + 1
      - value *x* is represented as *x* + min using *N* bits
    - for enumeration, *N* is the number of enumeration elements

State Linearization

For the TwoDiningPhilosophers.bir example

- there are 5 locations, thus, we need 3 bits
  - the first declared location is numbered 0, and
  - the last declared location is numbered 4
- each fork is boolean, thus, we need 1 bit for each
- suppose we use 1 bit to encode object refs
- suppose we use 1 bit to encode record type
- The initial state

  [Threads [Philosopher1.loc0[Fork#1, Fork#2],
  Philosopher2.loc0[Fork#2, Fork#1]],
  Heap[Fork#1[false], Fork#2[false]]]

  is represented as the bit vector

  <Threads[000[0.1], 000[1.0]],
  Heap[1[0], 1[0]]>

State Linearization

<Threads[000[0.1], 000[1.0]],
Heap[1[0], 1[0]]>

…similar bit-patterns can be leveraged for reducing state-space representation (i.e., collapse compression)

<Threads[001[0.1], 000[1.0]],
Heap[1[1], 1[0]]>

DefaultStateManager

- Convert each state to a bit-vector
- Use a table to map each state to its unique integer
- If a new state is stored, its unique number is the number of states stored so far

Assessment

- Bogor architecture is highly modular
  - clean API using design patterns
  - customizable components allows easy incorporation of targeted algorithms for particular family of software artifacts