Domain-specific Model Checking with Bogor

SAnToS Laboratory, Kansas State University, USA

http://bogor.projects.cis.ksu.edu

Robby   Matthew B. Dwyer   John Hatcliff

Matthew Hoosier

Session II: DFS in Explicit Model Checking

Support

US Army Research Office (ARO)
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Rockwell-Collins ATC
Sun Microsystems

SumToN

declare a namespace PARAM with a constant N so that we can easily modify N's value.

```
system SumToN {
  const PARAM { N = 1 };
  typealias byte int wrap (0,255);

  byte x := 1;
  byte t1;
  byte t2;

  active thread Thread1() {
    loc loc0:
      do { t1 := x; }
      goto loc1;

    loc loc1:
      do { t2 := x; }
      goto loc2;

    loc loc2:
      do { x := t1 + t2; }
      goto loc0;
  }
```

```
      do { t1 := x; }
      goto loc1;

    loc loc1:
      do { t2 := x; }
      goto loc2;

    loc loc2:
      do { x := t1 + t2; }
      goto loc0;
  }

  active thread Thread0() {
    loc loc0:
      do { assert (x != (byte)PARAM.N); }
      return;
  }
}
```

SumToN

```
system SumToN {
  const PARAM { N = 1 };
  typealias byte int wrap (0,255);

  byte x := 1;
  byte t1;
  byte t2;

  active thread Thread1() {
    loc loc0:
      do { t1 := x; }
      goto loc1;

    loc loc1:
      do { t2 := x; }
      goto loc2;

    loc loc2:
      do { x := t1 + t2; }
      goto loc0;
  }
```

```
  active thread Thread2() {
    loc loc0:
      do { t1 := x; }
      goto loc1;

      goto loc0;
  }

  active thread Thread0() {
    loc loc0:
      do { assert (x != (byte)PARAM.N); }
      return;
  }
}
```

declare a 'byte' to be an integer with range 0..255 that will 'wrap around' when operated on.

SumToN

```
system SumToN {
  const PARAM { N = 1 };
  typealias byte int wrap (0,255);

  byte x := 1;
  byte t1;
  byte t2;

  active thread Thread1() {
    loc loc0:
      do { t1 := x; }
      goto loc1;

    loc loc1:
      do { t2 := x; }
      goto loc2;

    loc loc2:
      do { x := t1 + t2; }
      goto loc0;
  }
```

declare three byte-sized variables

```
  active thread Thread2() {
    loc loc0:
      do { t1 := x; }
      goto loc1;

    loc loc2:
      do { x := t1 + t2; }
      goto loc0;
  }

  active thread Thread0() {
    loc loc0:
      do { assert (x != (byte)PARAM.N); }
      return;
  }
}
```

SumToN

```
system SumToN {
  const PARAM { N = 1 };
  typealias byte int wrap (0,255);

  byte x := 1;
  byte t1;
  byte t2;

  active thread Thread1() {
    loc loc0:
      do { t1 := x; }
      goto loc1;

    loc loc1:
      do { t2 := x; }
      goto loc2;

    loc loc2:
      do { x := t1 + t2; }
      goto loc0;
  }
```

```
  active thread Thread2() {
    loc loc0:
      do { t1 := x; }
      goto loc1;

    loc loc1:
      do { t2 := x; }
      goto loc2;

    loc loc2:
      do { x := t1 + t2; }
      goto loc0;
  }

  Thread0() {
  != (byte)PARAM.N); }
```

Each thread reads the value of x in t1, then t2, then sums t1 and t2 to get a new value for x.

SumToN

```
system SumToN {
  const PARAM { N = 1 };
  typealias byte int wrap (0,255);

  byte x := 1;
  byte t1;
  byte t2;

  active thread Thread1(
    loc loc0:
      do { t1 := x; }
      goto loc1;

    loc loc1:
      do { t2 := x; }
      goto loc2;

    loc loc2:
      do { x := t1 + t2; }
      goto loc0;
  }
```

The "monitoring" thread asserts that x is not equal to the value of N.

```
  active thread Thread2() {
    loc loc0:
      do { t1 := x; }
      goto loc1;

          1:
          t2 := x; }
          loc2;

          2:
      do { x := t1 + t2; }
      goto loc0;
  }

  active thread Thread0() {
    loc loc0:
      do { assert (x != (byte)PARAM.N); }
      return;
  }
}
```

SumToN

```
system SumToN {
  const PARAM { N = 1 };
  typealias byte int wrap (0,255);

  byte x := 1;
  byte t1;
  byte t2;

  active threa
    loc loc0:
      do { t1 :=
      goto loc1;

    loc loc1:
      do { t2 := x; }
      goto loc2;

    loc loc2:
      do { x := t1 + t2; }
      goto loc0;
  }
```

Note: *This transition can be arbitrarily interleaved with all others from Thread1 and Thread2.*

```
  active thread Thread2() {
    loc loc0:
      do { t1 := x; }
      goto loc1;

    loc loc1:
      do { t2 := x; }
      goto loc2;

    loc loc2:
      do { x := t1 + t2; }
      goto loc0;
  }

  active thread Thread0() {
    loc loc0:
      do { assert (x != (byte)PARAM.N); }
      return;
  }
}
```

Assessment

Pick a value of N (e.g., 5) Can the assertion in the SumToN example be violated (i.e., can x ever have the value 5)?

- Answering this question requires us to reason about possible *schedules* (i.e., orderings of instruction execution)

- Let's try to find schedules that cause the assertion to be violated for various values of N...

SumToN Assertion Violation

```
active thread Threadk() {
k:0   loc loc0:
        do  { t1 := x; }
        goto loc1;

k:1   loc loc1:
        do { t2 := x; }
        goto loc2;

k:2   loc loc2:
        do { x := t1 + t2; }
        goto loc0;
   }

  active thread Thread0() {
0:0   loc loc0:
        do {
          assert (x !=
            (byte)PARAM.N); }
        return;
   }
}
```

Violating schedule for $N = 1$

(initial values) [0, 0, 0, x = 1, t1 = 0, t2 = 0]

0:0 [-, 0, 0, x = 1, t1 = 0, t2 = 0]

violation

Move this thread first….

…that was easy!

SumToN Assertion Violation

```
active thread Threadk() {
  loc loc0:                      k:0
    do  { t1 := x; }
    goto loc1;

  loc loc1:                      k:1
    do { t2 := x; }
    goto loc2;

  loc loc2:                      k:2
    do { x := t1 + t2; }
    goto loc0;
 }

 active thread Thread0() {
  loc loc0:                      0:0
    do {
      assert (x !=
        (byte)PARAM.N); }
    return;
  }
}
```

Violating schedule for $N = 2$

(initial values)	[0, 0, 0, x = 1, t1 = 0, t2 = 0]
1:0	[0, 1, 0, x = 1, t1 = 1, t2 = 0]
1:1	[0, 2, 0, x = 1, t1 = 1, t2 = 1]
1:2	[0, 0, 0, x = 2, t1 = 1, t2 = 1]
0:0	[-, 0, 0, x = 2, t1 = 1, t2 = 1]

violation

Move only Thread1 until x = 2, then check assertion

SumToN Assertion Violation

```
k:0   active thread Threadk()   Another
        loc loc0:
          do  { t1 := x; }
          goto loc1;

k:1     loc loc1:
          do { t2 := x; }
          goto loc2;

k:2     loc loc2:
          do { x := t1 + t2; }
          goto loc0;
      }
```

```
      active thread Thread0() {
0:0     loc loc0:
          do {
            assert (x !=
              (byte)PARAM.N); }
          return;
      }
    }
```

Violating schedule for $N = 2$

(initial values)	[0, 0, 0, x = 1, t1 = 0, t2 = 0]
2:0	[0, 0, 1, x = 1, t1 = 1, t2 = 0]
2:1	[0, 0, 2, x = 1, t1 = 1, t2 = 1]
2:2	[0, 0, 0, x = 2, t1 = 1, t2 = 1]
0:0	[-, 0, 0, x = 2, t1 = 1, t2 = 1]

violation

Move only Thread2 until x = 2, then check assertion

SumToN Assertion Violation

Yet Another

```
    active thread Thread1() {
k:0   loc loc0:
        do  { t1 := x; }
        goto loc1;

k:1   loc loc1:
        do { t2 := x; }
        goto loc2;

k:2   loc loc2:
        do { x := t1 + t2; }
        goto loc0;
    }

    active thread Thread0() {
0:0   loc loc0:
        do {
          assert (x !=
            (byte)PARAM.N); }
        return;
      }
    }
```

Violating schedule for $N = 2$

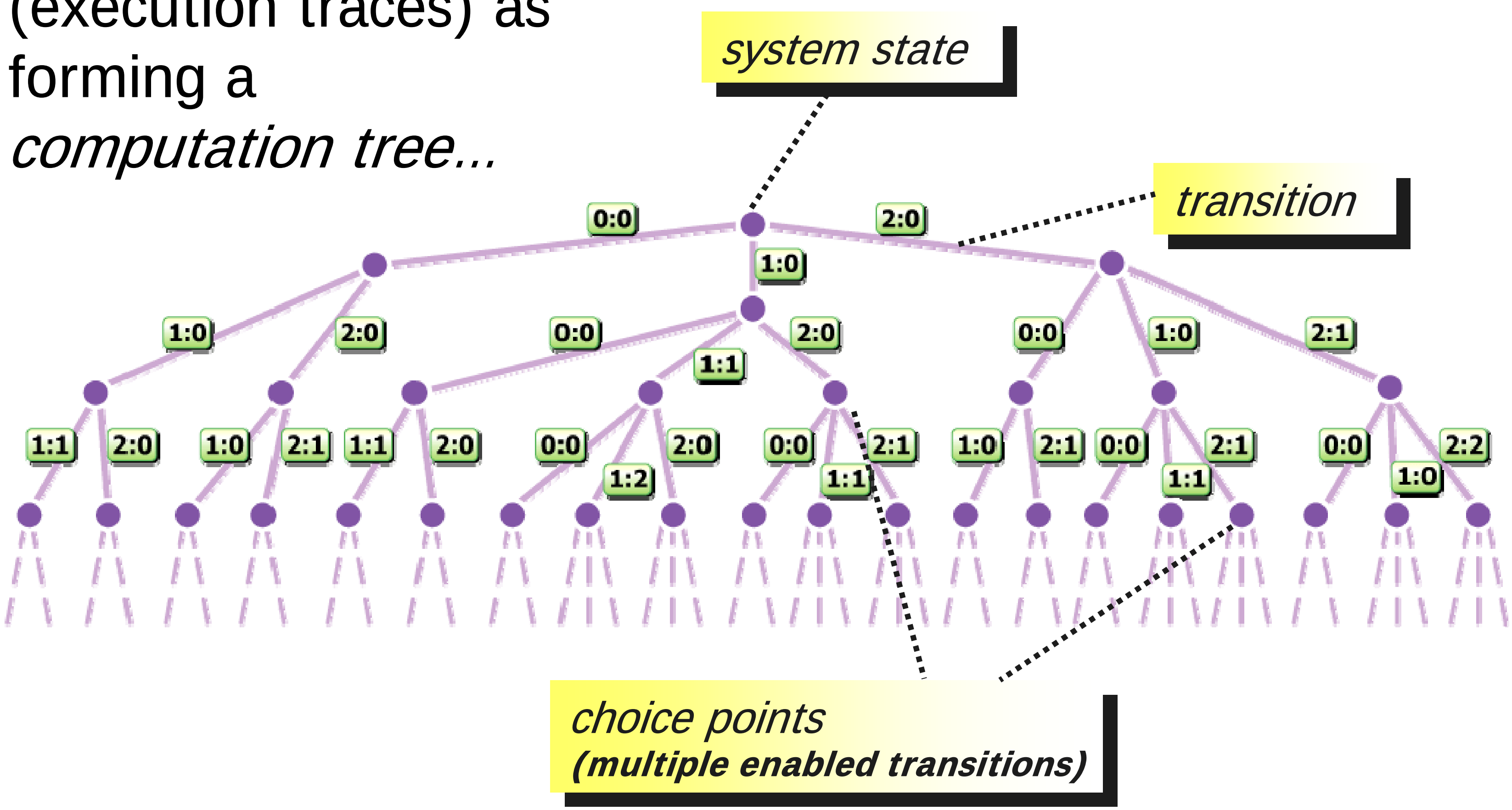
(initial values)	[0, 0, 0, x = 1, t1 = 0, t2 = 0]
1:0	[0, 1, 0, x = 1, t1 = 1, t2 = 0]
2:0	[0, 1, 1, x = 1, t1 = 1, t2 = 0]
2:1	[0, 1, 2, x = 1, t1 = 1, t2 = 1]
2:2	[0, 1, 0, x = 2, t1 = 1, t2 = 1]
0:0	[-, 1, 0, x = 2, t1 = 1, t2 = 1]

violation

Move only Thread1 for one step, then move Thread2 three steps as before....

Computation Tree

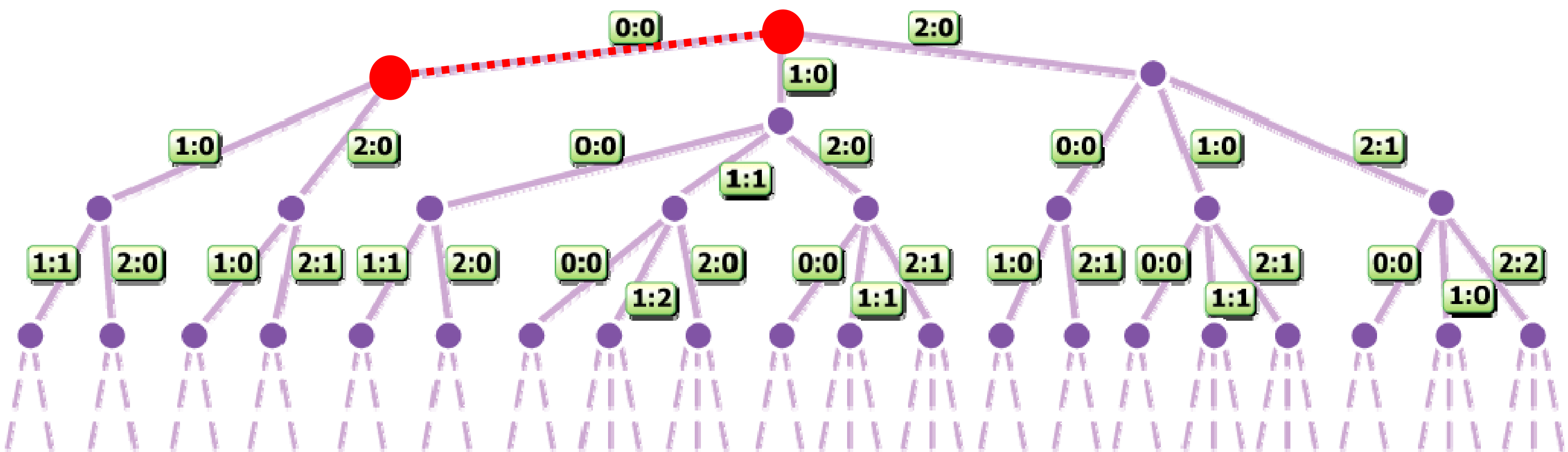
- We can think of the possible schedules (execution traces) as forming a *computation tree*...



Computation Tree

- We can think of the possible schedules (execution traces) as forming a *computation tree*...

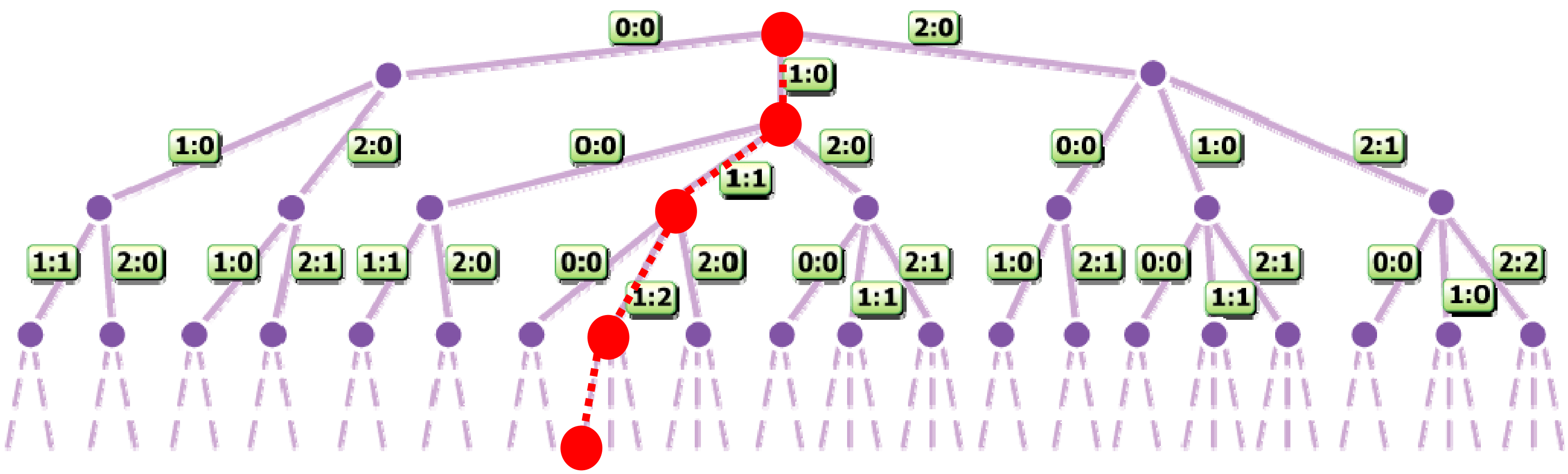
First example trace (schedule)



Computation Tree

- We can think of the possible schedules (execution traces) as forming a *computation tree*...

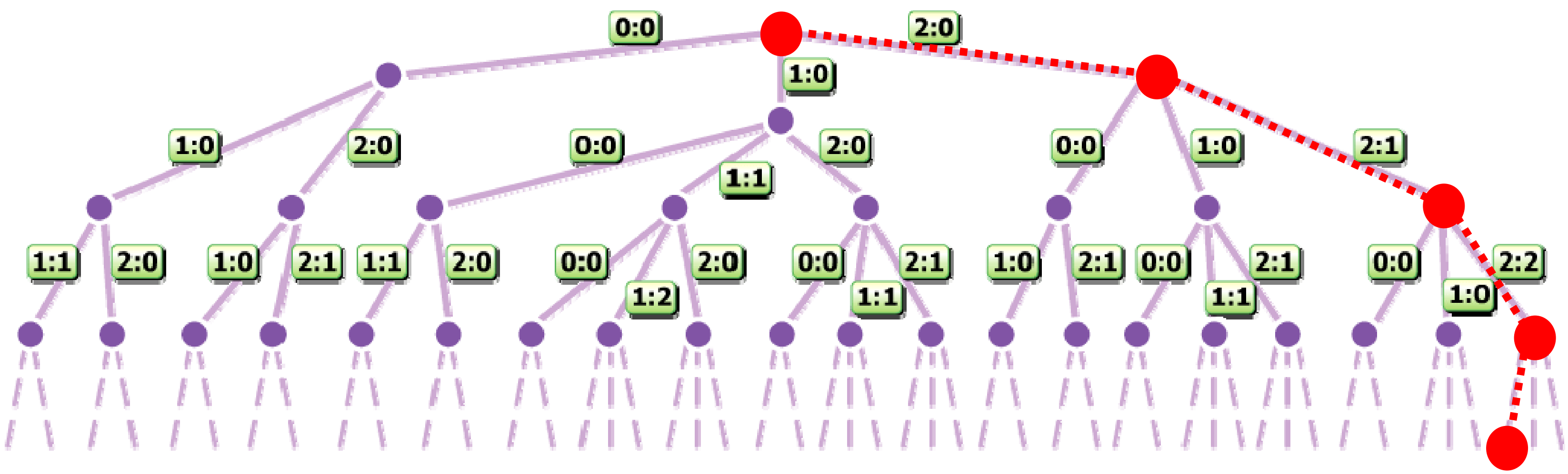
Second example trace (schedule)



Computation Tree

- We can think of the possible schedules (execution traces) as forming a *computation tree*...

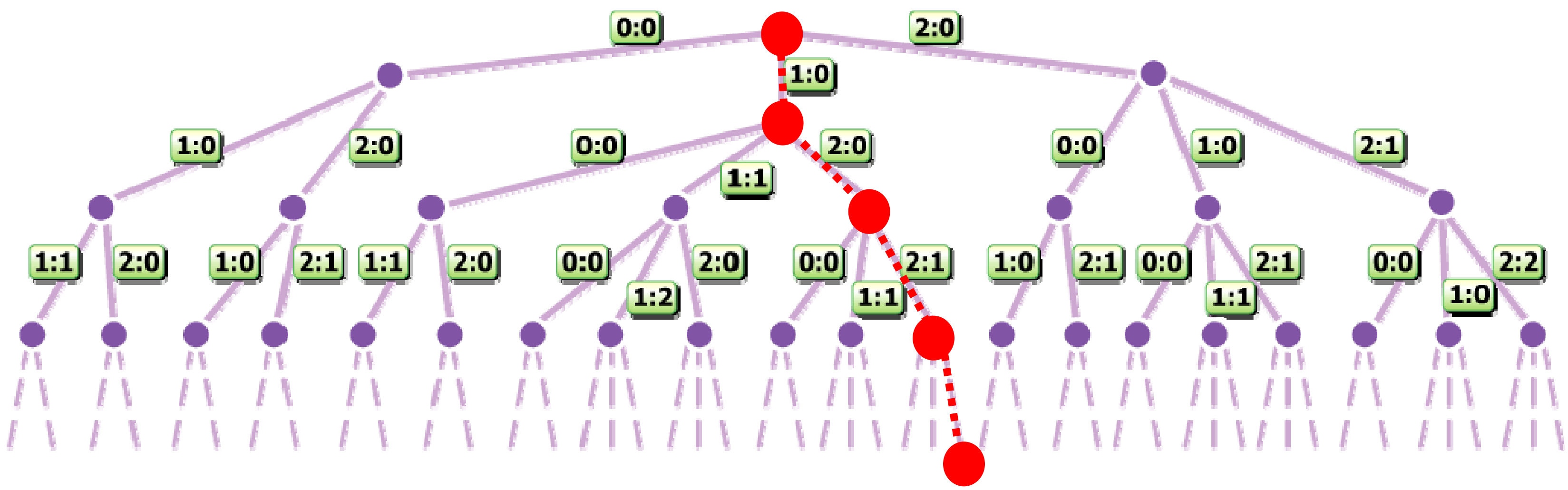
Third example trace (schedule)



Computation Tree

- We can think of the possible schedules (execution traces) as forming a *computation tree*...

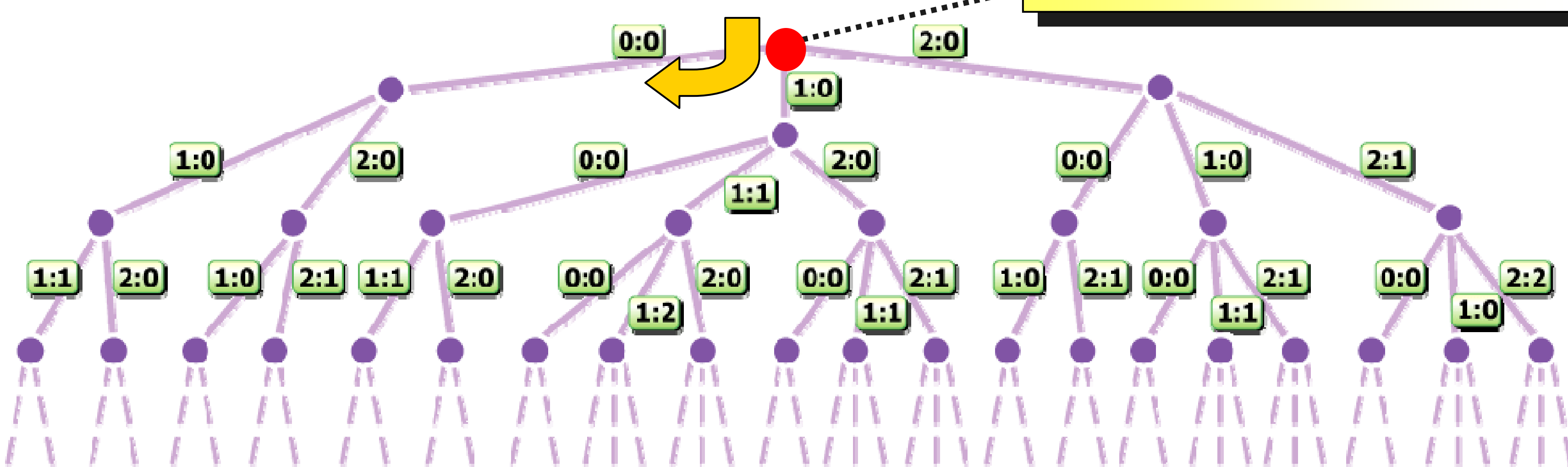
Fourth example trace (schedule)



Exhaustive Depth-first Search

- Bogor can perform exhaustive depth-first searches of a system's state-space.

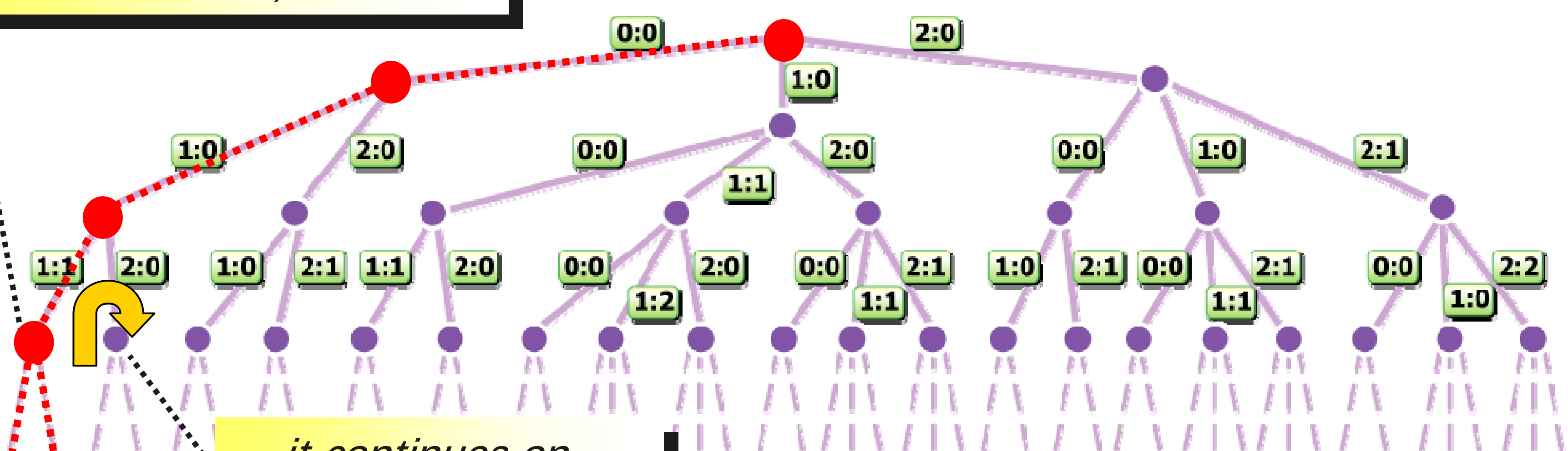
At choice points, Bogor chooses an unexplored transition and remembers that it needs to come back and explore the others…



Exhaustive Depth-first Search

- Bogor can perform exhaustive depth-first searches of a system's state-space.

When Bogor has finished with one subtree, ...

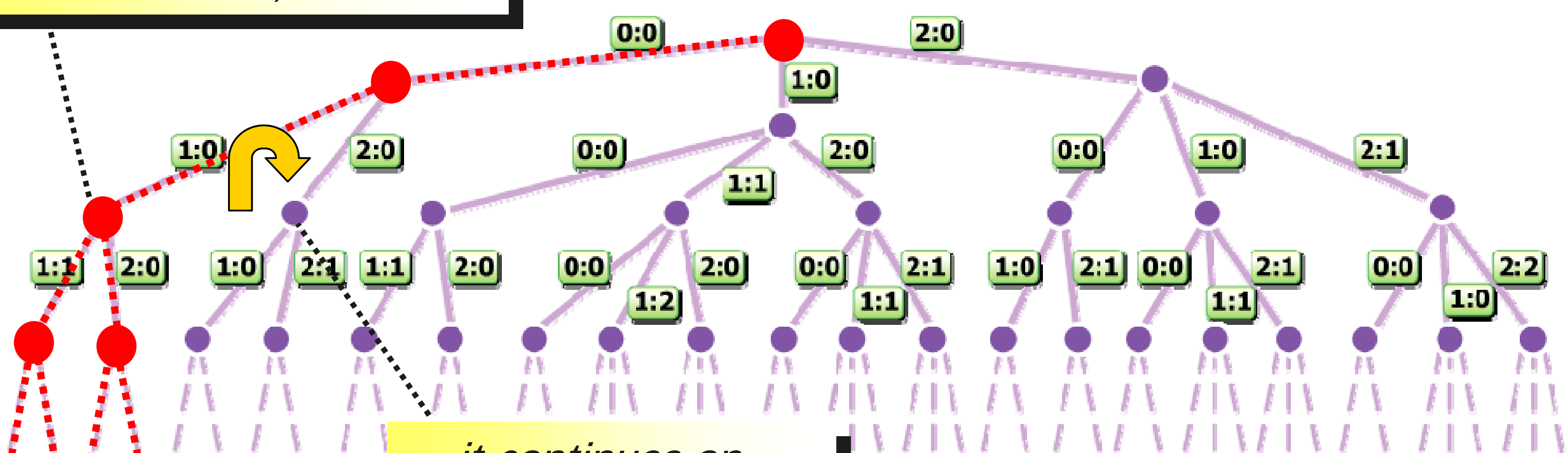


... it continues on with the siblings.

Exhaustive Depth-first Search

- Bogor can perform exhaustive depth-first searches of a system's state-space.

When Bogor has finished with one subtree, …



… it continues on with the siblings.

Exhaustive Depth-first Search

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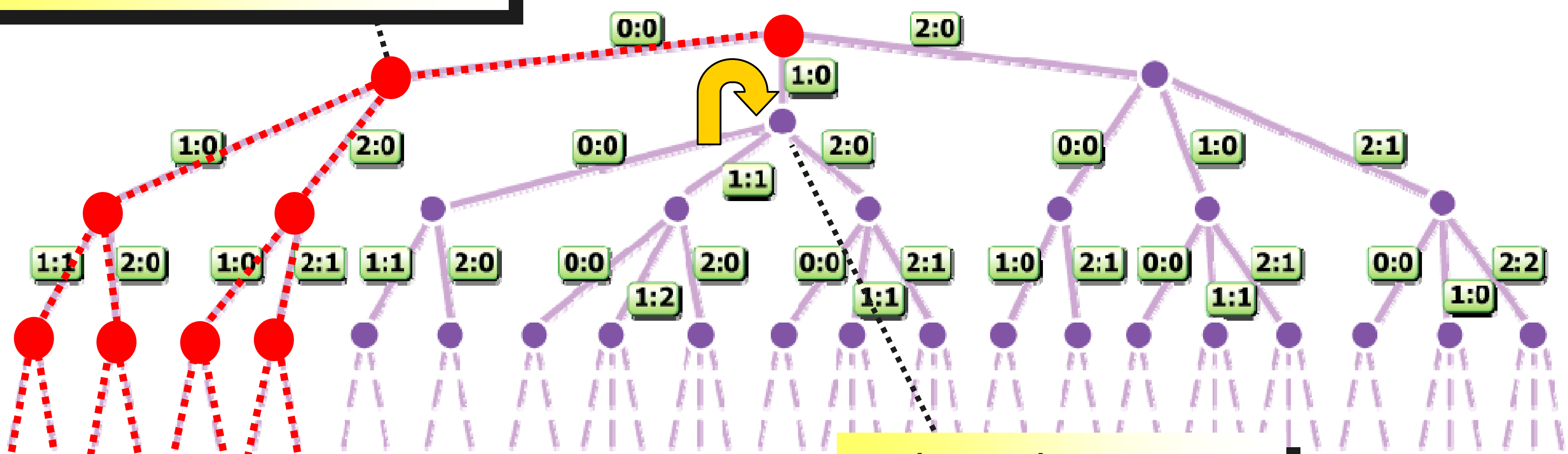
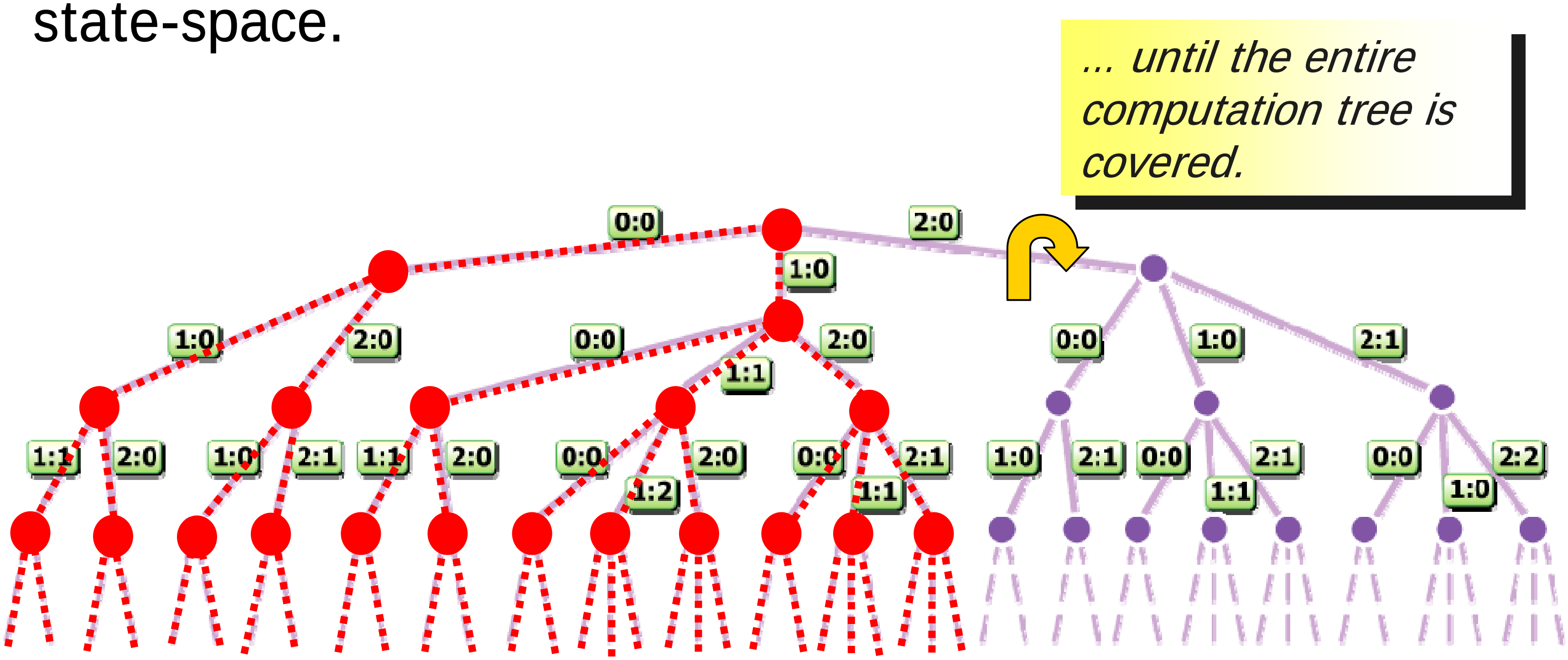
When Bogor has finished with one subtree, …



… it continues on with the siblings.

Exhaustive Depth-first Search

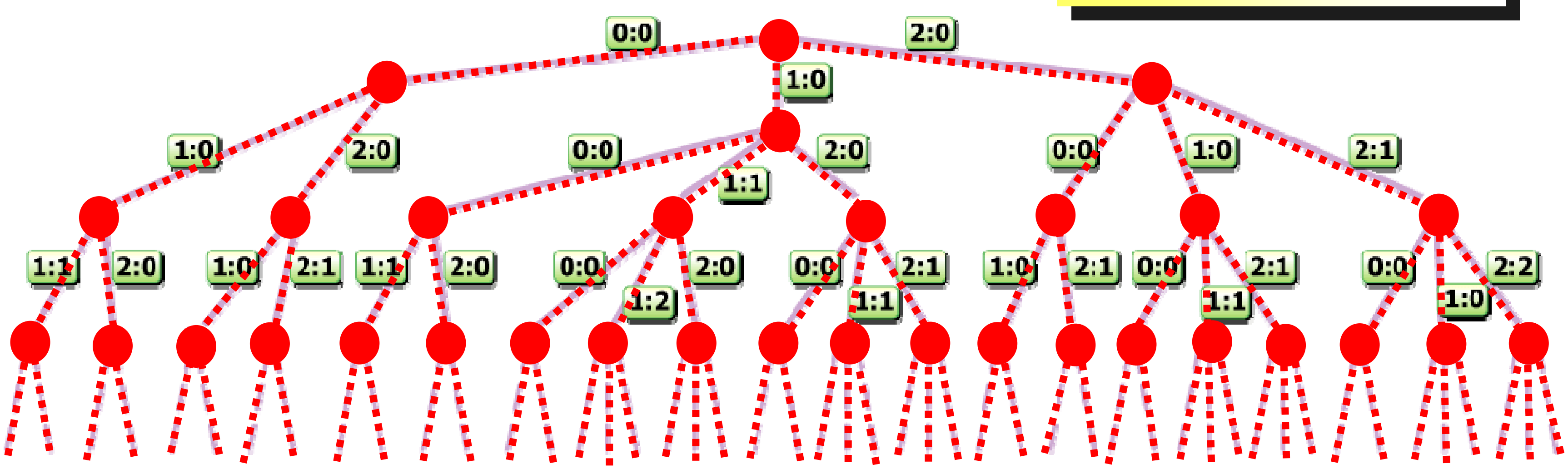
- Bogor can perform exhaustive depth-first searches of a system's state-space.



Exhaustive Depth-first Search

- Bogor can perform exhaustive depth-first searches of a system's state-space.

... until the entire computation tree is covered.



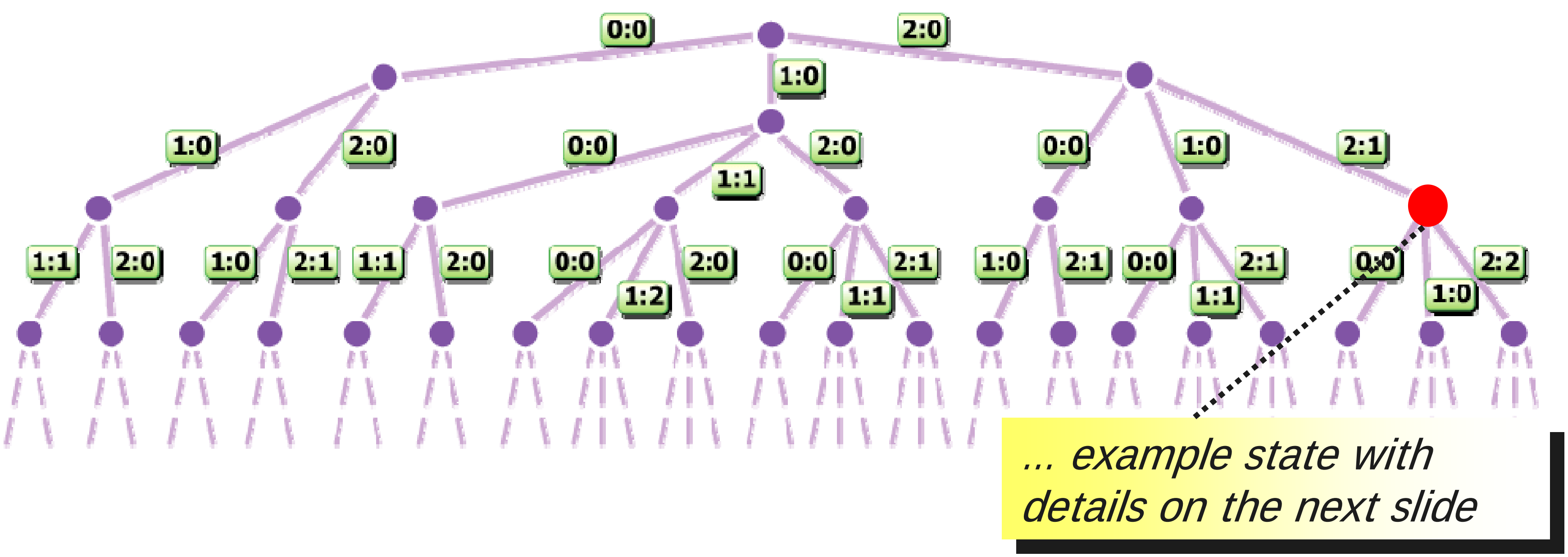
DFS Basic Data Structures

- State vector
  - holds the value of all variables as well as program counters (current position of execution) for each process, and indicates a particular position in the computation tree (as previously covered when discussing state transition systems for BIR).
- Depth-first stack
  - holds the states (or transitions) encountered down a certain path in the computation tree.
- Seen state set
  - holds the state vectors for all the states that have been checked already (seen) in the depth-first search.

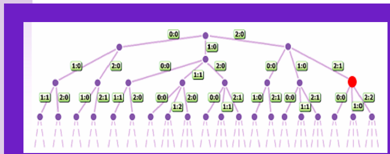
Note: we will represent the values of these data structures in an abstract manner that captures the essence of the issues, but not the actual implementation. Bogor and most other model-checkers actually use multiple clever representations to obtain a highly space/speed optimized search algorithm.

SumToN State Vector Example

- The state vector is the data structure corresponding to the *state* (as previously covered when discussing state transition systems for BIR). It holds the value of all variables as well as program counters for each process, and indicates a particular position in the computation tree.



SumToN State Vector Example



```
{
N = 1 };
int wrap (0,25

byte x := 1;
byte t1;
byte t2;

active thread Thread1() {
  loc loc0:
    do { t1 := x; }
    goto loc1;

  loc loc1:
    do { t2 := x; }
    goto loc2;

  loc loc2:
    do { x := t1 + t2; }
    goto loc0;
}
```

...program counters for each thread

```
active thread Thread2() {
  loc loc0:
    do { t1 := x; }
    goto loc1;

  loc loc1:
    do { t2 := x; }
    goto loc2;

  loc loc2:
    do { x := t1 + t2; }
    goto loc0;
  }

  active thread Thread0() {
  loc loc0:
    do { assert (x != (byte)PARAM.N); }
    return;
  }
}
```

Example State Vector: [0,0,2,1,1,1]

SumToN Assertion Violation

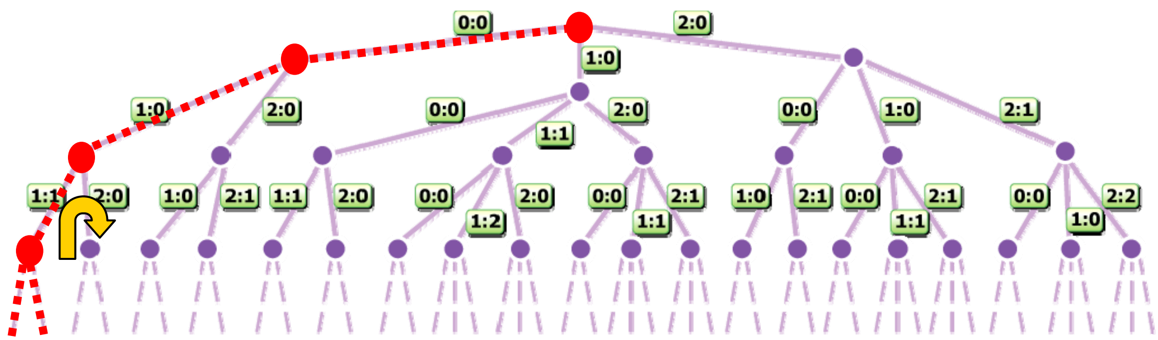
```
active thread Threadk() {
  loc loc0:                          k:0
    do  { t1 := x; }
    goto loc1;

  loc loc1:                          k:1
    do { t2 := x; }
    goto loc2;

  loc loc2:                          k:2
    do { x := t1 + t2; }
    goto loc0;
 }

 active thread Thread0() {
  loc loc0:                          0:0
    do {
      assert (x !=
        (byte)PARAM.N); }
    return;
  }
}
```

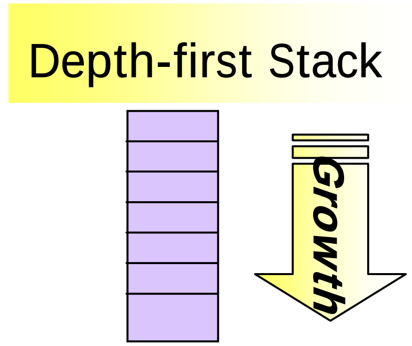
Violating schedule for $N = 2$

(initial values)	[0, 0, 0, x = 1, t1 = 0, t2 = 0]
1:0	[0, 1, 0, x = 1, t1 = 1, t2 = 0]
2:0	[0, 1, 1, x = 1, t1 = 1, t2 = 0]
2:1	[0, 1, 2, x = 1, t1 = 1, t2 = 1]
2:2	[0, 1, 0, x = 2, t1 = 1, t2 = 1]
0:0	[-, 1, 0, x = 2, t1 = 1, t2 = 1]

...recall state vectors leading to violation of assertion

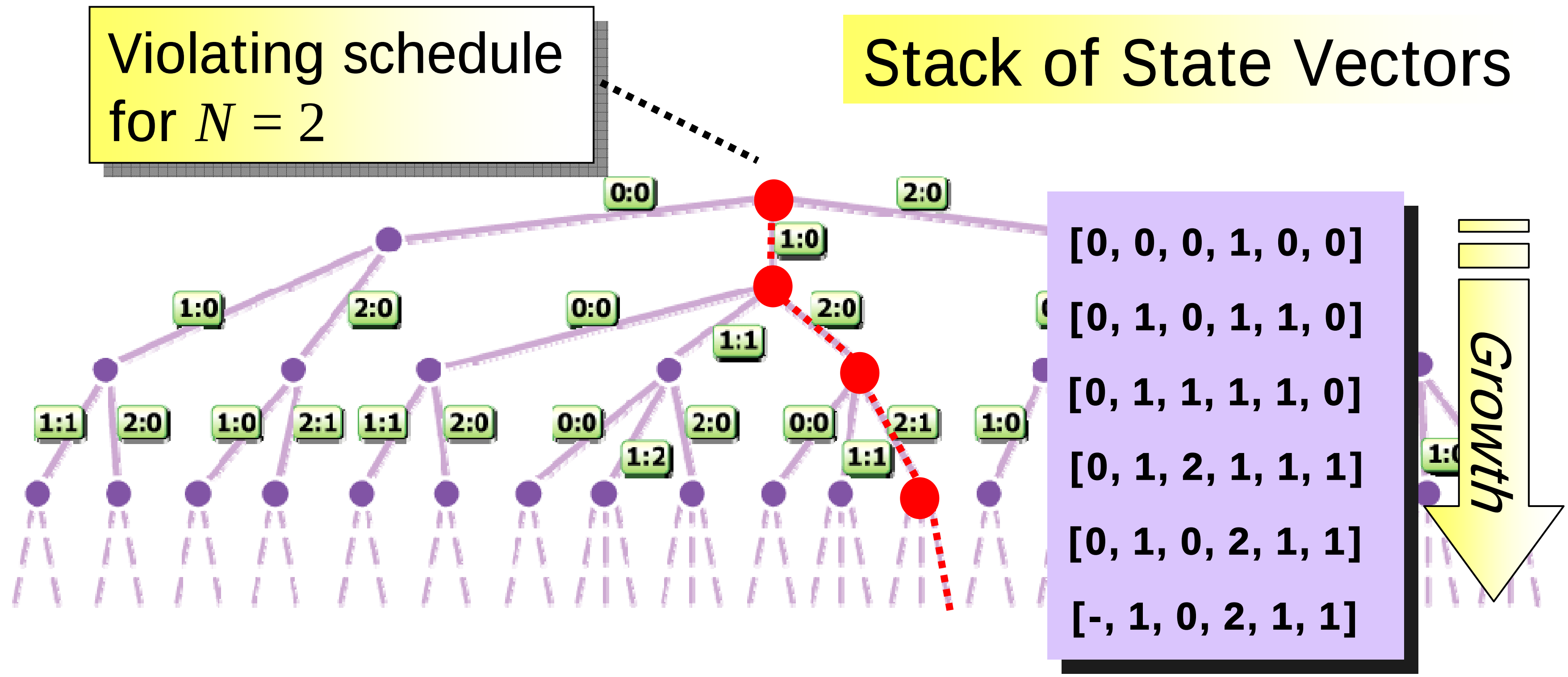
Depth-first Stack





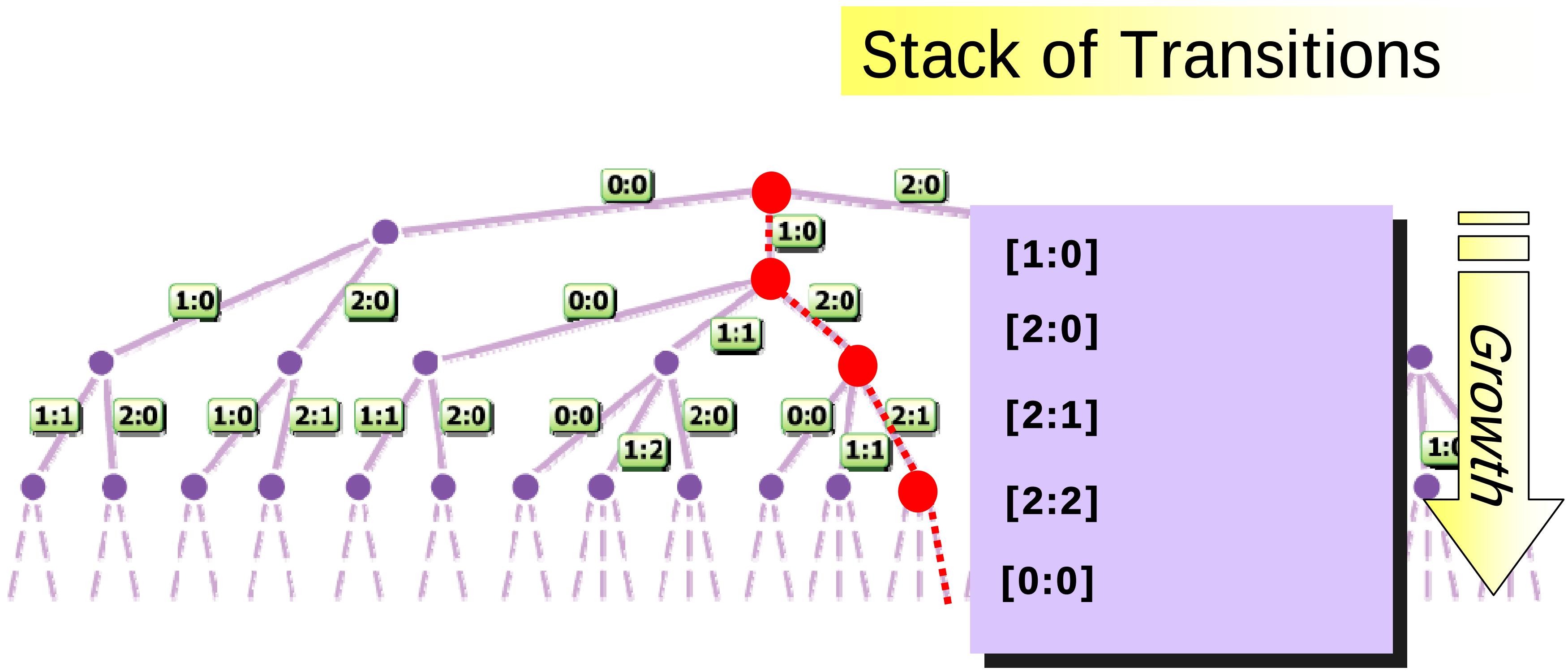
- The depth-first stack serves two purposes
  - When we come to the end of a path (or a state that we have seen before) and backtrack, the stack tells us where to backtrack to.
  - If an error is encountered, the current value of the stack gives the computation path that leads to the error.

Depth-first Stack



- The depth-first stack can be implemented to hold state vectors
  - straight-forward implementation

Depth-first Stack



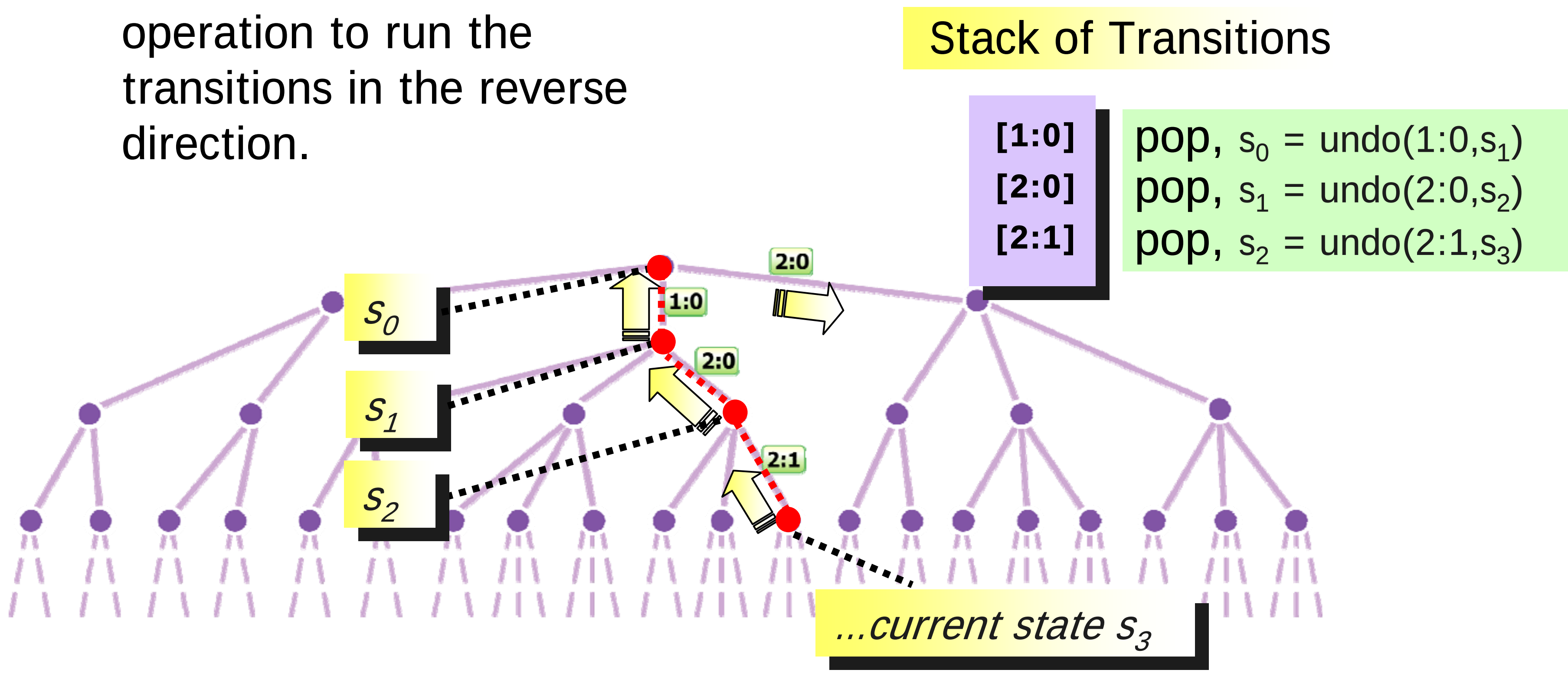
- The depth-first stack can be implemented to hold transitions
  - requires less space, but ...(see next slide)...

Depth-first Stack of Transitions

- Generating a new state requires that the analyzer run a transition on the current state.
- Since the analyzer is not holding states in the stack, if it needs to back-track and return to a previously encountered state, it needs an "undo" operation to run the transitions in the reverse direction.
- Since the analyzer is not holding states in the stack, when providing variable values as diagnostic information for an error path, the analyzer needs a simulation mode where choice points are decided by the stacked transitions.

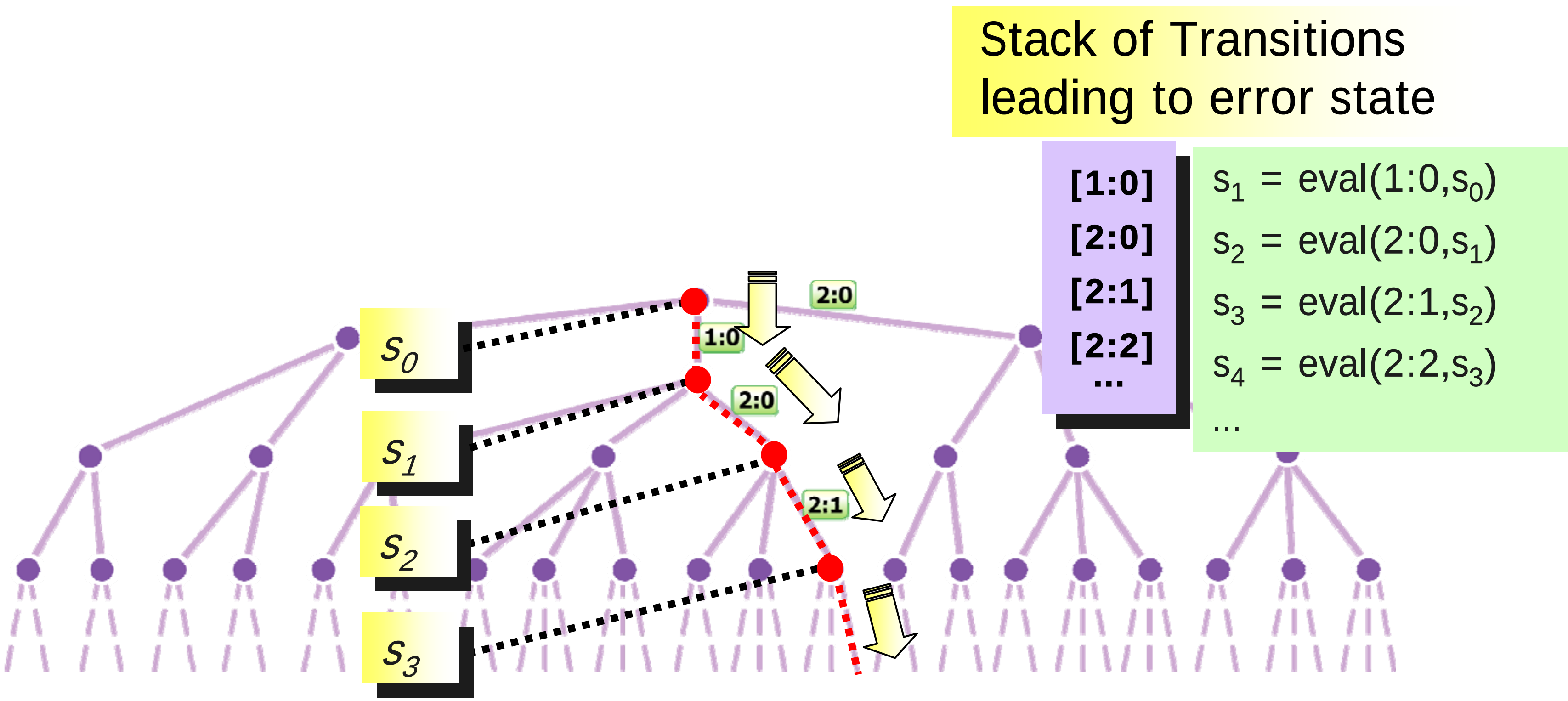
Depth-first Stack of Transitions

- Since the analyzer is not holding states in the stack, if it needs to back-track and return to a previously encountered state, it needs an "undo" operation to run the transitions in the reverse direction.



Depth-first Stack of Transitions

- Since the analyzer is not holding states in the stack, when providing variable values as diagnostic information for an error path, the analyzer needs a simulation mode where choice points are decided by the transitions

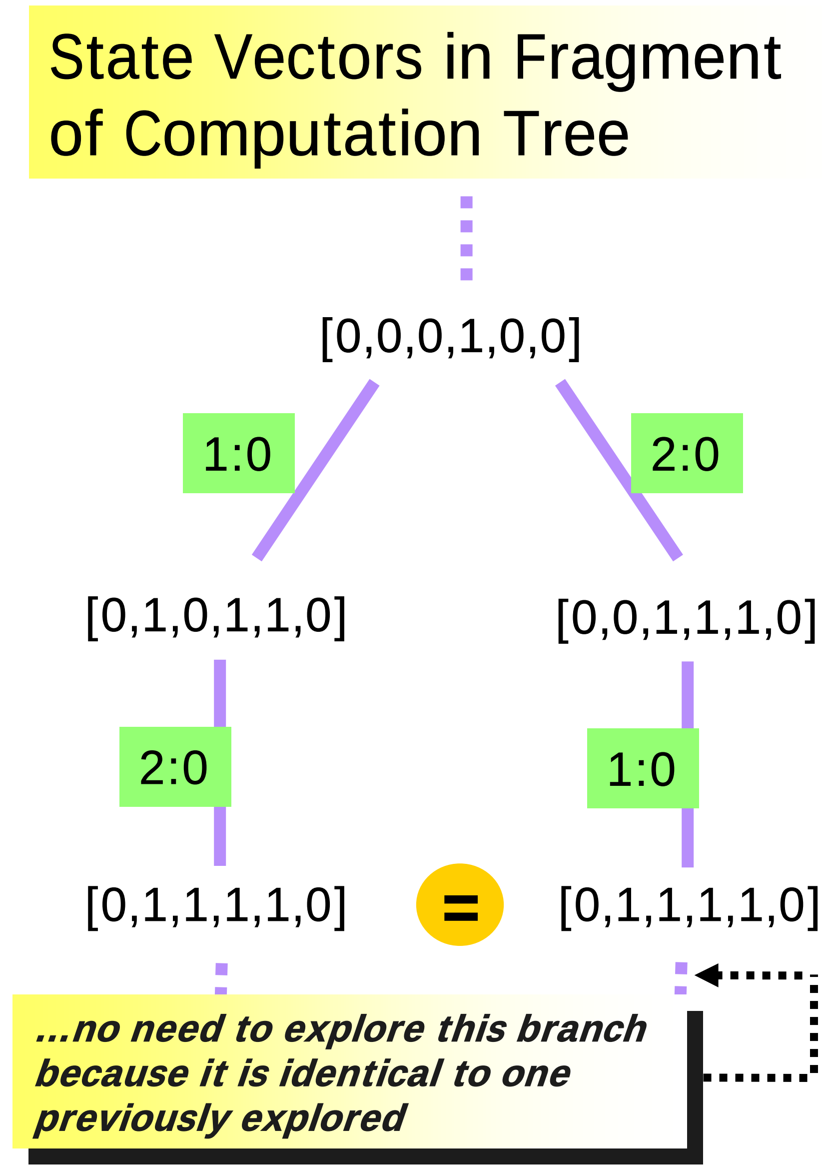


Seen State Set

- Often the analyzer will proceed along a different path to a state S that it has checked before.
- In such a case, there is no need to check S again (or any of S's children in the computation tree) since these have been checked before.
- Bogor maintains a Seen State set (implemented as a hash table) of states that have been seen before, and it consults this set to avoid exploring/checking a part of the computation tree that is identical to a part that has already been explored before.

Revisting Via A Different Path

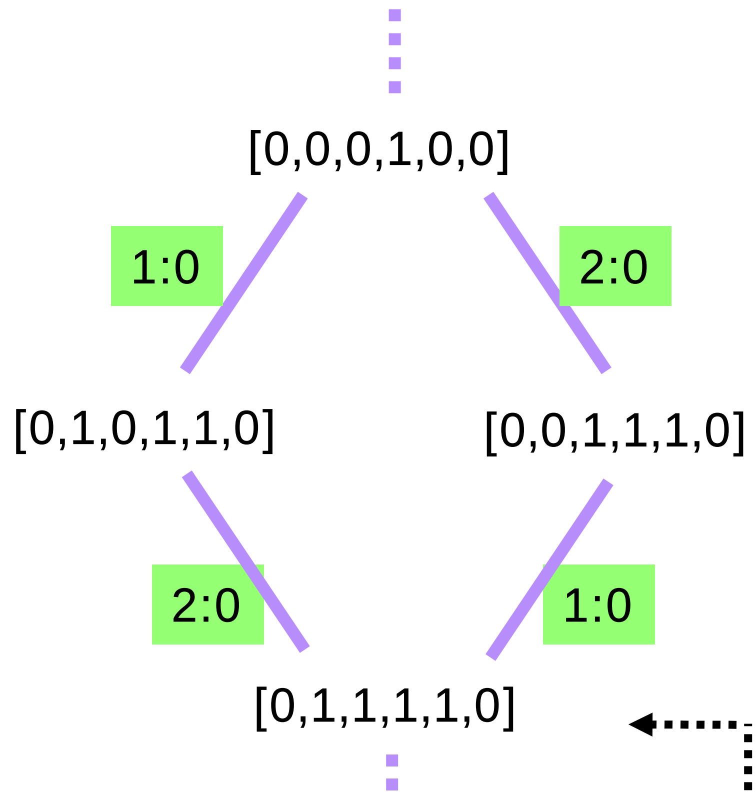
```
active thread Threadk() {
  loc loc0:
k:0  do  { t1 := x; }
     goto loc1;

  loc loc1:
k:1  do { t2 := x; }
     goto loc2;

  loc loc2:
k:2  do { x := t1 + t2; }
     goto loc0;
 }

 active thread Thread0() {
  loc loc0:
0:0  do {
      assert (x !=
        (byte)PARAM.N); }
     return;
  }
}
```



Computation Tree as Graph

```
     active thread Threadk() {
       loc loc0:
k:0      do  { t1 := x; }
         goto loc1;

       loc loc1:
k:1      do { t2 := x; }
         goto loc2;

       loc loc2:
k:2      do { x := t1 + t2; }
         goto loc0;
     }

     active thread Thread0() {
       loc loc0:
0:0      do {
           assert (x !=
             (byte)PARAM.N); }
         return;
     }
   }
```

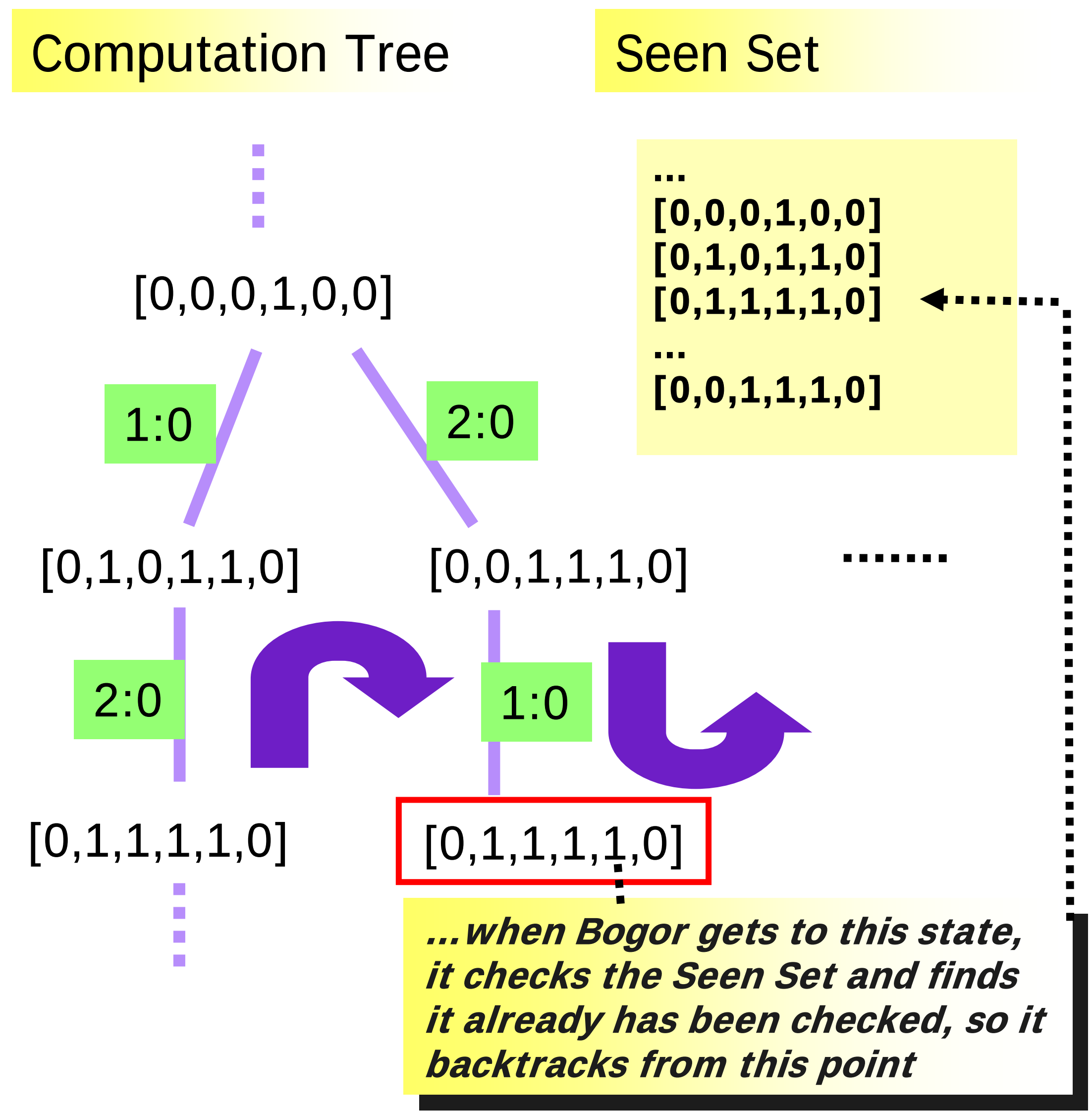
Some times we view the computation tree as a graph



...sharing a node corresponds to (re)visiting a node that has been seen before.

Seen State Set

```
     active thread Threadk() {
       loc loc0:
k:0     do  { t1 := x; }
        goto loc1;

       loc loc1:
k:1     do { t2 := x; }
        goto loc2;

       loc loc2:
k:2     do { x := t1 + t2; }
        goto loc0;
     }

     active thread Thread0() {
       loc loc0:
0:0     do {
          assert (x !=
            (byte)PARAM.N); }
        return;
      }
    }
```



Non-Terminating Systems

- Due to the use of the Seen Set, checking a non-terminating system may terminate if the system only has a finite number of states.
- In *basic* BIR, all systems are “finite” because of the bounds on basic data types.
- However, some systems are “more finite” than others.
  - i.e., they have a much smaller state-space.

Non-Terminating Systems

```
system Loops {

  boolean x;

  active thread Thread1() {
   loc loc0: do { x := !x; }
            goto loc0;
  }

  active thread Thread2() {
   loc loc0: do { x := !x; }
            goto loc0;
  }
}
```

- Consider this example system...
  - How many states does it have?
  - Does execution of the system terminate?
  - Does an exhaustive analysis of the state-space of the system terminate?