Distributed Systems Programming F29NM1

LTL Reasoning: How It Works

Andrew Ireland

School of Mathematical and Computer Sciences
Heriot-Watt University
Edinburgh

Overview

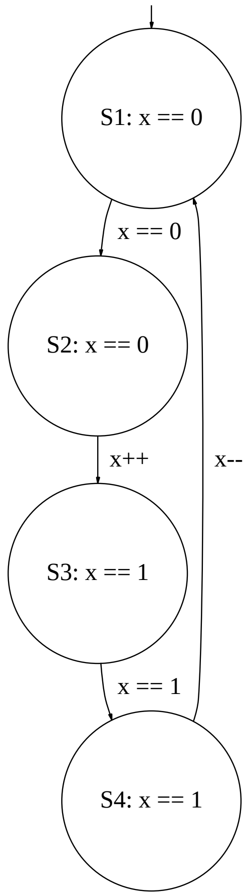
- How processes, system models and properties are represented in SPIN.
- How LTL properties are verified within SPIN.

Processes, Models and Automata

- A **process** is given meaning via an **automata**, *i.e.* a finite-state transition system:
  - set of states (unique initial state);
  - set of state-to-state transitions based upon input stimuli.
- *-Automata: the conventional notion of automata where there exists explicit initial and final states, *i.e.* recognizes finite sequence of stimuli. Acceptance corresponds to final state.
- ω-Automata: an automata which contains an explicit initial state but no final state *i.e.* recognizes an infinite sequence of stimuli (reactive systems). Acceptance requires a different criteria ... (more on slide 5).
- A **system model** is given meaning via an **asynchronous interleaving product of automata**.


```
bit x=0;
proctype A(){
   do
   :: (x==0) -> x++
   od
   }
proctype B(){
   do
   :: (x==1) -> x--
   od
   }
init {atomic{
        run A();
        run B()}
     }
```

Asynchronous interleaving product automata



Model

LTL Formula via Buchi Automata

- As mentioned above, we are interested in finite state models which give rise to infinite executions.
- A **Buchi Automata** provides one way of expressing acceptance properties for infinite executions.
- Acceptance for a Buchi automata means that there exists a state which is visited infinitely often.
- Any LTL formula can be expressed as a Buchi automata.

LTL Verification via Buchi Automata

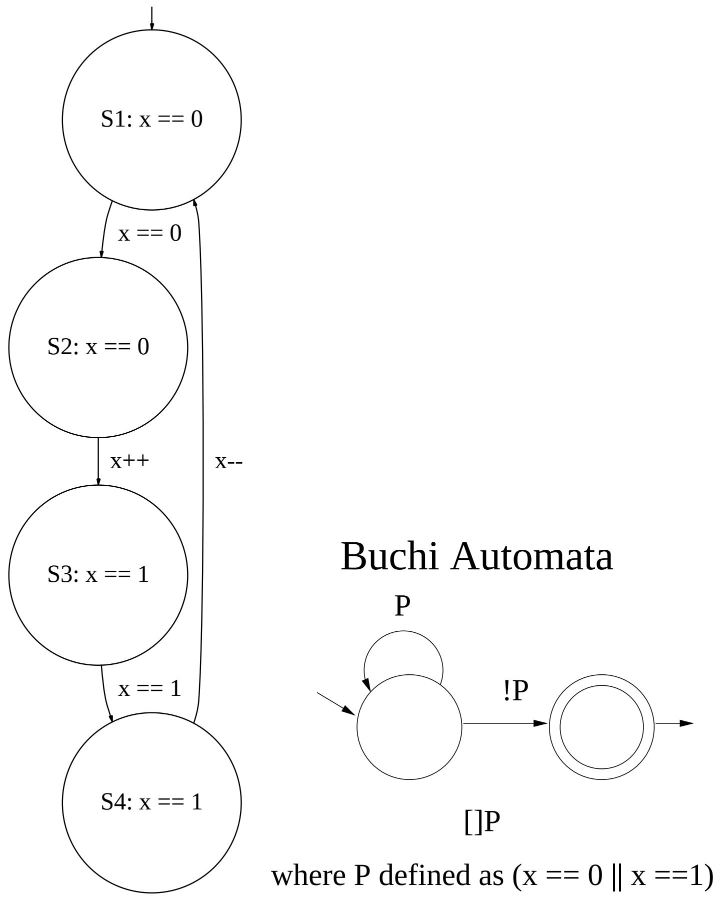
- To verify that model M satisfies LTL formula F generate:
  - P the asynchronous interleaving product for model M.
  - B the Buchi automata corresponding to the negation of F.
  - S the synchronous product of B and P.
- If S contains an acceptance cycle then a counter-example to F exists.
- Note that in a synchronous product automata each transition denotes a joint transition of the component transitions.
- The synchronous product allows one to check whether or not a model exhibits a particular LTL property as expressed via a Buchi automata.

A Simple Safety Example

```
bit x=0;
proctype A(){
   do
   :: (x==0) -> x++
   od
}
proctype B(){
   do
   :: (x==1) -> x--
   od
}
init {atomic{ run A(); run B()}}
```

Will the above model satisfy the following safety invariant?

```
[](x == 0 || x == 1)
```

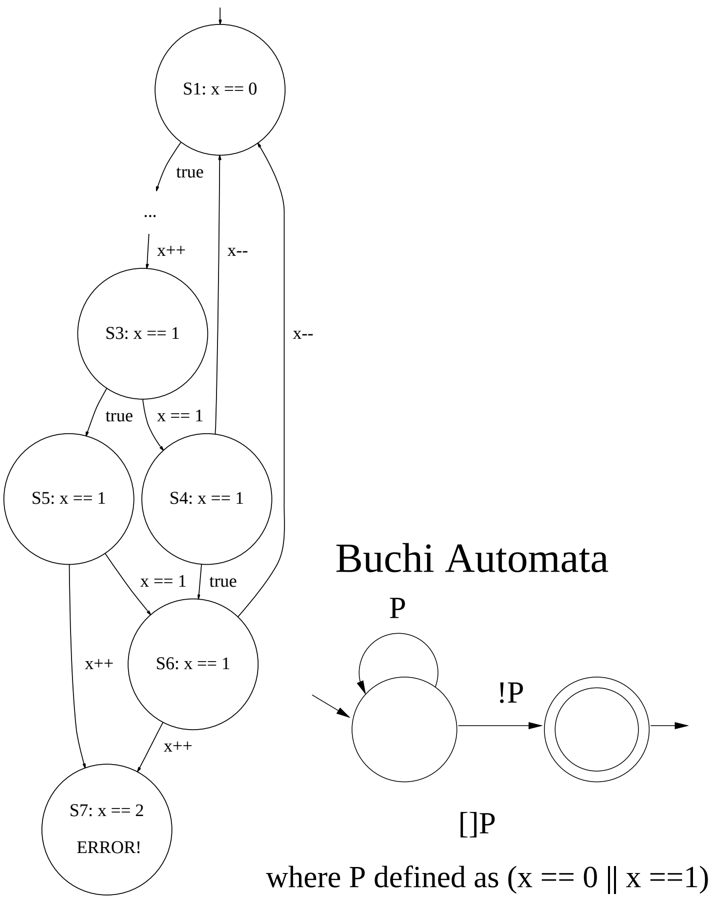
Model **Specification**

Buggy Model

```
byte x=0;
proctype A(){
   do
   :: true -> x++
   od
}
proctype B(){
   do
   :: (x==1) -> x--
   od
}
init {atomic{ run A(); run B()}}
```

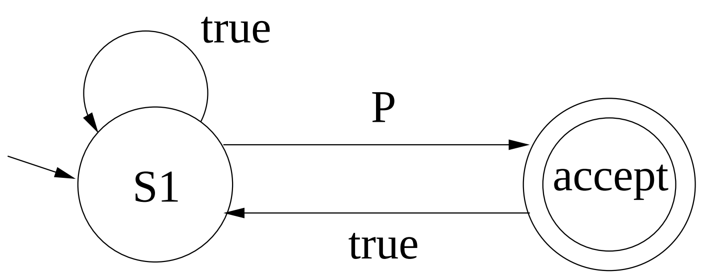
Will the above model satisfy the following safety invariant?

```
[](x == 0 || x == 1)
```

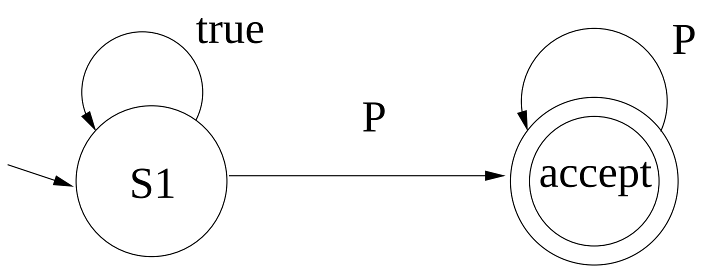
Buggy Model **Specification**

Always Eventually



`[]<> P`

Eventually Always

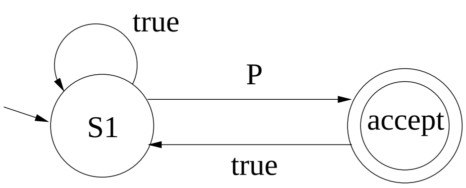


`<>[] P`

Buchi Automata via Promela

- Buchi automata are represented within SPIN via a special process, known as a **never claim**.
- A **never claim** is used to represent a property that should **never** be satisfied during the execution of a model.
- SPIN automatically interleaves the execution of a **never claim** along with the given Promela model.
- SPIN is looking to see if the execution of the **never claim** matches with the execution of the Promela model. A match corresponds to either:
  - an **acceptance cycle** being detected within the **never claim**
  - **termination** of the **never claim** (complete match)

Buchi Automata via Promela




```
never {    /* []<> p */
T0_init:
       if
       :: ((p)) -> goto accept_S9
       :: (1) -> goto T0_init
       fi;
accept_S9:
       if
       :: (1) -> goto T0_init
       fi;
}
```

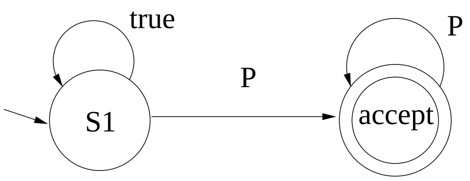
Generating Never Claims within SPIN

```
never {    /* []<> p */
T0_init:
      if
      :: ((p)) -> goto accept_S9
      :: (1) -> goto T0_init
      fi;
accept_S9:
      if
      :: (1) -> goto T0_init
      fi;
}
```

Given a LTL formula, the LTL property manager (XSPIN) displays the generated never claim. Using SPIN one can also directly generate a never claim for an arbitrary LTL formula, *e.g.* the above never claim was generated by the following command line:

```
spin -f '[]<>p'
```


Buchi Automata via Promela




```
never {    /* <>[] p */
T0_init:
     if
     :: ((p)) -> goto accept_S4
     :: (1) -> goto T0_init
     fi;
accept_S4:
     if
     :: ((p)) -> goto accept_S4
     fi;
}
```

Proving LTL Properties via Never Claims

- It is easier to prove that a model **does not satisfy** a property than it is to prove that it does, *i.e.* it only takes one counter-example to shown that a property is not satisfied.
- A never claim is therefore typically used to represent the **negation** of the formula (property) of interest.
- To prove F, a never claim is generated for $!F$ – the **negation** of F. SPIN then checks the model against $!F$:
  - If an **acceptance cycle** is detected then $!F$ is satisfied and a counter-example exists for F.
  - If **no acceptance cycle** is detected then $!F$ is not satisfied, and therefore F is satisfied by the model.

Safety Property via Never Claim

```
never {  /* ![]p */
T0_init:
     if
     :: (! ((p))) -> goto accept_all
     :: (1) -> goto T0_init
     fi;
accept_all:
     skip
}
```

Response Property via Never Claim

```
never {     /* ![](p -> <>q) */
T0_init:
     if
     :: (! ((q)) && (p)) -> goto accept_S4
     :: (1) -> goto T0_init
     fi;
accept_S4:
     if
     :: (! ((q))) -> goto accept_S4
     fi;
}
```


Precedence Property via Never Claim

```
never {     /* ![](p -> r U q) */
T0_init:
   if
   :: (! ((q)) && (p)) -> goto accept_S4
   :: (! ((q)) && ! ((r)) && (p)) -> goto accept_all
   :: (1) -> goto T0_init
   fi;
accept_S4:
   if
   :: (! ((q))) -> goto accept_S4
   :: (! ((q)) && ! ((r))) -> goto accept_all
   fi;
accept_all:
   skip
}
```

Summary

Learning outcomes:

- To understand and be able to describe how processes and system models are represented in SPIN.
- To understand and be able to convert between a Buchi automata and an equivalent LTL formula.
- To understand and be able to convert between LTL formulas and **never claims**.
- To be able to explain LTL reasoning within SPIN at the level of Buchi automata and **never claims**.

Recommended reading:

- "The SPIN Model Checker" Gerard J. Holzmann, Addison Wesley, 2004.