The SPIN Model Checker

[Based on The SPIN Model Checker: Primer and Reference Manual, Gerard J. Holzmann]

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November 20, 2019

Agenda

- An Introduction to SPIN
- An Overview of PROMELA
- PROMELA semantics and search algorithms
- Embedded C code
- Verification in SPIN
- DEMO
- References

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- An Introduction to SPIN
  - History of SPIN
  - What is SPIN
- An Overview of PROMELA
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History of SPIN

- The tool was developed at Bell Labs in the original Unix group of the Computing Sciences Research Center, starting in 1980 by Gerard Holzmann and others.
- The software has been available freely since 1991, and continues to evolve to keep pace with new developments in the field.
- In April 2002 the tool was awarded the prestigious System Software Award for 2001 by the ACM.
- The current latest version is 6.5.0 compiled at Jul. 2019.

What is SPIN

- SPIN (Simple PROMELA INterpreter)
  - Is a popular open-source software that can be used for formal verification of distributed software systems.
  - It supports the design and verification of asynchronous process system.
  - The verification models of SPIN are focused on proving the correctness of process interactions, and abstract from internal sequential computations.

What is SPIN (cont.)

- As a formal methods tool, SPIN aims to provide:
  - an intuitive, program-like notation for specifying design choices unambiguously, without implementation detail,
  - a powerful, concise notation for expressing general correctness requirements,
  - a methodology for establishing the logical consistency of the design from above.
- The tool supports a high level language to specify system description, called PROMELA (PROcess MEta LAnguage).

What is SPIN (cont.)

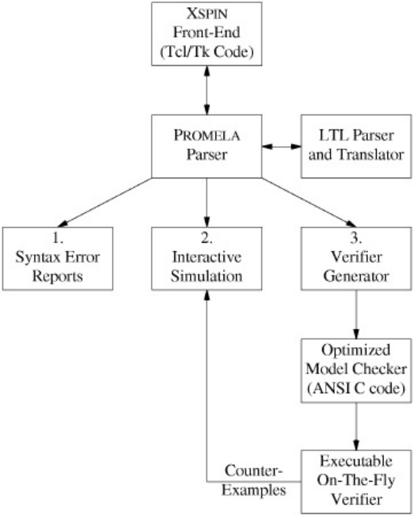

Fig. 1. The structure of SPIN simulation and verification.

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- An Introduction to SPIN
- An Overview of PROMELA
  - What is PROMELA
  - PROMELA Model
  - Correctness Claim
- PROMELA semantics and search algorithms
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What is PROMELA

- PROMELA (PROcess MEta-LAnguage)
  - PROMELA is *NOT* an implementation language but a system description language.
  - The emphasis is on the modeling of process synchronization and coordination, not on computation.
  - resembles the programming language C.

What is PROMELA (cont.)

- Models that can be specified in PROMELA are required to be bounded:
  - There can be only finite amount of running processes.
  - There can be only finite amount of statements in a *proctype*.
  - All data types have a finite range.
  - All message channels have an a bounded capacity.
- Enforcing that restriction helps to guarantee that any correctness property that can be stated in PROMELA is decidable.

What is PROMELA (cont.)

- A PROMELA model is constructed from three basic types of objects:
  - Processes
  - Data objects
  - Message channels

Process

- Defined by using proctype keyword or init keyword.
- There are two ways to instantiate a process:
  - Adding the prefix active to a proctype declaration
  - Using a run operator

Example1: Hello World

```
active proctype begin(){
    printf("Hello World\n")
}
```

Example2: Hello World

```
proctype begin2(){
    printf("Hello World Again\n")
}
init{
    run begin2()
}
```

- Note: Semicolon is defined as a separator, not terminator.

Process (cont.)

- By using run operator, we can pass the value to process (passing by value).
- If processes created through active keyword, their parameters are initialized to zero.
  - active means instantiate one process of this type
- proctype means to declare a new process type

Example: varaible passage

```
proctype value_pass ( byte x ){
    printf(" x = %d\n ",x)
}

init{
    run value_pass (0);
    run value_pass (1);
}

/*              Output will be :        x=0     */
/*                                      x=1      */
/*                         or                  */
/*             Output will be:          x=1   */
/*                                      x=0     */
```

Process (cont.)

- We can create multiple instantiations by adding the desired number in square brackets.
- Processes are executes concurrently with all other processes.
- They can interleave their statement executions in arbitrary ways with other processes.
- Each running process has a unique process instantiation number, and can be accessed by local variable _pid.

Example:Hello World

```
active [2] proctype main(){

    printf("my pid is: %d\n",_pid)

}

/*   Output will be:   my pid is: 0   */
/*                     my pid is: 1   */
/*                  or               */
/*   Output will be:   my pid is: 1   */
/*                     my pid is: 0   */
```

Process termination

- A process ”terminates” when it reaches the end of its code (the closing curly brace).
- A process can only ”die” and be removed if all processes instantiated later than this process have died first.
- Process can terminate in any order, but they can only die in the reverse order of their creation.

Data Objects

- The default initial value of all data objects is zero.

Type	Typical Range	Sample Declaration
bit	0, 1	bit turn = 1
bool	false, true	bool flag = true
byte	0..255	byte cnt
chan	1..255	chan q
mtype	1..255	mtype msg
pid	0..255	pid p
short	$-2^{15}..2^{15}-1$	short s = 100
int	$-2^{31}..2^{31}-1$	int x = 1
unsigned	$0..2^{n}-1,\ 1 \leq n \leq 32$	unsigned w : 3 = 5

- Support array.
- unsigned w : 3 = 5 means w ranged from 0 to 7, and initially is 5.
  - range: $0..2^{3}-1$(0 to 7)
  - initial value: 5

Data Objects (cont.)

- There are only 2 levels of scope in PROMELA models:
  - global (visible in the entire model)
  - process local (visible only to the process that contains the declaration)

Example: Variable scope

```
active proctype main(){
    int x;
    {
        int y;
        printf("x = %d,y = %d",x,y);   /* x=0 , y=0 */
        x++;
        y++;
    }
    printf("x = %d,y = %d",x,y);
    /*  Error: undeclared variable: y saw '')' = 41' */
}
```

Data Objects (cont.)

- Enumerated Types is a set of symbolic constants:
  - mtype stands for message type.
  - There can be multiple mtype declarations but they are equivalent to a single mtype declaration that contains the concatenation of all separate lists of symbolic names.

Example: enumerated type

```
mtype = { apple, pear, orange, banana };
mtype n = pear;
```

- User defined data type:

Example: user-defined type

```
typedef record{
    short f1;
    byte f2 = 4
};
```

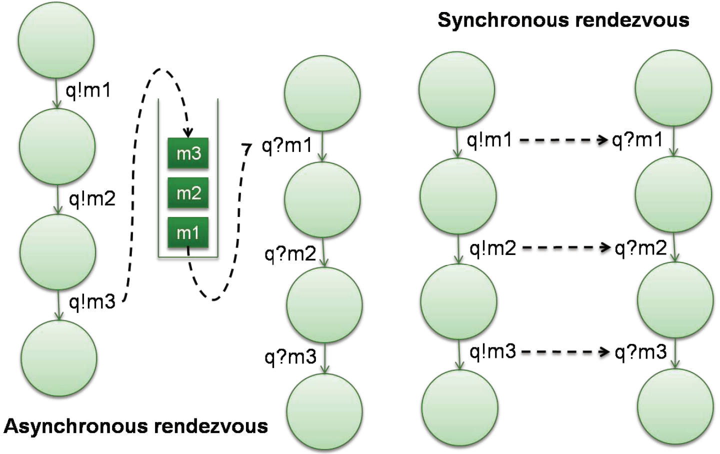
Message Channels

- Used to model the exchange of data between processes.
- They are declared either locally or globally, but the channel itself is always a global object.
- A locally declared and instantiated channel disappears, when the process that declare it dies.

```
   chan qname = [16] of { short, byte, bool}
/* 16 message buffers, and each message composed of 3 fields*/
```

- According to the capacity of channel, there are two types of channel:
  - $capacity > 0$: a FIFO buffered channel is initialized (asynchronous).
  - $capacity = 0$: a rendezvous channel is initialized (synchronous).

Asynchronous and Synchronous Message Passing



Message Passing

```
/*send message*/
qname ! expr1, expr2, expr3

/*receive message*/
qname ? var1, var2, var3
```

- Send a message to channel with corresponding values.
- Retrieves a message from the channel, and copies the values into corresponding variables.
- The message will be removed from the channel buffer (optional).
- It is an error to send or receive either more of fewer message fields than declared.

Message Passing (cont.)

- A send statement on buffered channel is executable when the target channel is non-full.
- A send statement on rendezvous channel contains two steps:
  - a rendezvous offer: can be made at any time.
  - a rendezvous accept: can be accepted only if another process can perform the matching receive operation immediately (i.e., with no intervening steps by any process).
- A receive statement is executable if the first message in the channel match the pattern from the receive statement.
- A match of a message is obtained if all message fields that contain constant values in the receive statement equal the values of the corresponding message fields in the message.

Rendezvous Communication

- The size of the channel is set to zero.
- That is, the channel can pass, but cannot store messages.

```
mtype = { msgtype};
chan name = [0] of {mtype, byte};

active proctype A() {
  name ! msgtype,124;
  name ! msgtype,121
}

active proctype B() {
  byte var;
  name?msgtype,var -> printf("msgtype = %d\n", var)
}
```

- output: megtype=124
- How to modify?

Rules for executability

- Any statement in PROMELA is either executable or blocked.
- 6 types of basic PROMELA statements: assign, print, assert, expression, communication (send/receive)
  - Print and assignment are always executable.
  - A expression statement is executable iff evaluates to true or to a non-zero integer value.
  - A statement is blocked iff the statement is unexecutable.

```
/*   In c language we have to write like that:  */

while (a!=b) {}

 /*   But we can achieve the same effect in PROMELA by  */

(a==b);
```

Control Flow

- Atomic sequences, making statements be uninterruptable:
  - atomic{...}
  - d_step{...}
- Non-deterministic selection and iteration
  - if...fi
  - do...od
- Goto, break and labels
- Escape sequences:
  - {...} unless {...}

Atomic Sequences

- atomic { guard -> stmt_1; stmt_2; ...; stmt_n; }
  - Executable if the guard statement is executable.
  - Any statement can serve as the guard statement.
  - Executes all statements in the sequence without interleaving with other processes.
  - If any statement other than the guard blocks, atomicity is lost. Atomicity can be regained when the statement becomes executable.

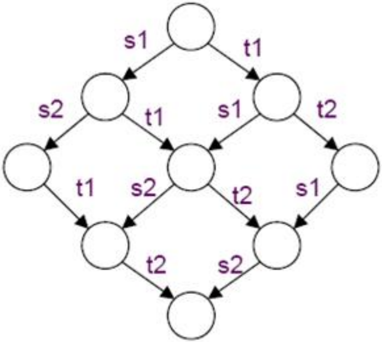
```
atomic{
     /* swap the values of a and b */
    tmp = b;
    b = a;
    a = tmp
}
```

D_step Sequences

- d_step { guard -> stmt_1; stmt_2; ...; stmt_n; }
  - Like atomic sequence, but must be deterministic and may not block anywhere inside the sequence.
  - It will be an error if any statement except the guard statement in a d_step sequence be unexecutable.
  - A Goto statement into or out of d_step sequences are forbidden.
  - Atomic and d_step sequences are often used as a model reduction method, to lower complexity of large models.

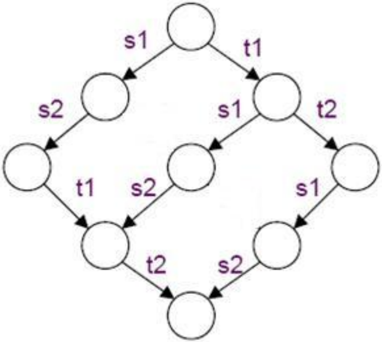
Atomic and D_step Sequences Example (1/3)

```
active proctype A() { s1; s2 }
active proctype B() { t1; t2 }
```



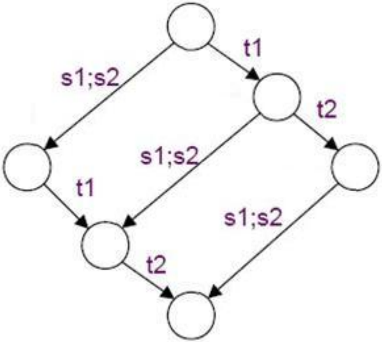
Atomic and D_step Sequences Example (2/3)

```
active proctype A() { atomic{ s1; s2 } }
active proctype B() { t1; t2 }
```



Atomic and D_step Sequences Example (3/3)

```
active proctype A() { d_step{ s1; s2 } }
active proctype B() { t1; t2 }
```



Selection

```
if
:: guard_1 -> stmt_1.1 ; stmt_1.2 ; ...
:: guard_2 -> stmt_2.1 ; stmt_2.2 ; ...
:: ...
:: guard_n -> stmt_n.1 ; stmt_n.2 ;...
fi
```

- The if statement is executable if at least one guard is executable.
- If more than one guard is executable, than selected non-deterministically.
- If none of the guard statements is executable, the if statement blocks until at least one of them can be selected.
- Any type of basic or compound statement can be used as a guard.

Repetition

```
do
:: guard_1 -> stmt_1.1 ; stmt_1.2 ;...
:: guard_2 -> stmt_2.1 ; stmt_2.2 ;...
:: ...
:: guard_n -> stmt_n.1 ; stmt_n.2 ;...
od
```

- The execution of the repetition structure is repeated.
- If there is none executable statement in the do-loop, the entire loop blocks.
- Any type of basic or compound statement can be used as a guard.
- Only a break or a goto can exit from a do-loop.

Timeout v.s. Else

- A special type of statement in selection and repetition is the else statement.
- An else statement become executable only if no other statement within same process, at the same control-flow point, is executable.
- Another similar global variable is timeout.
- Timeout becomes true iff there are no executable statements in all of currently running processes.

```
byte count;
active proctype counter(){
    do
    :: (count !=0 ) ->
        if
        ::count++
        ::count--
        ::else     //redundant
        fi
    :: else -> break
    od
}
```

Label

- To exit the repetition we can use goto statement and labeling.
- Multiple labels may be used to label the same statement.

```
int x, y
active proctype Euclid(){
    do
    :: (x > y ) -> x = x - y
    :: (x < y ) -> y = y - x
    :: (x == y) -> goto done
    od;

done: printf("answer: %d\n", x)
}
```

Unless Statement

- S unless E
  - S and E is any PROMELA fragments.
  - The statement of S has a lower execution priority than the statement of E.
  - The executability of S is constraint to the non-executability of guard statements in E.
  - If E ever becomes enabled during the execution of S, then S is aborted and the execution continues with E.

```
do
:: b1 -> B1
:: b2 -> B2
od unless { c -> C };
```

Correctness Claims

- Two types of correctness requirements:
  - Safety: the set of properties that the system may not violate.
  - Liveness: the set of properties that the system must satisfy.
- Correctness properties can be specified as system or process invariants (using assertions), as linear temporal logic requirements (LTL), as formal Büchi Automata in the syntax of never claims.

Correctness Claims (cont.)

- Correctness properties in PROMELA are formalized with following constructs:
  - Basic assertions
  - End-state labels
  - Progress-state labels
  - Never claims

Basic assertions

```
assert ( expression )
```

- Is always executable.
- If the expression evaluates to true, then has no effect.
- If the expression evaluates to false, an error message will be trigger during verifications with SPIN.
- An assertions statement is the only type of correctness property in PROMELA that can be checked during simulation runs with SPIN.

Basic assertions (cont.)

- If SPIN fails to find an assertion violation in simulation runs, this does not mean that assertions cannot be violated,
- Only a verification run with SPIN can assure that assertion wont be violated.
- The assertion statement can be used to check safety properties.
- An assertion statement can be used as a system invariant.
  - Because it is in an asynchronous process, this statement may be executed at any time.

End-state labels

- The verifier must be able to distinguish valid system end states from invalid ones (deadlock).
- By default, the only valid end states are the end of its code (the closing curly brace in the proctype body).
- But not all PROMELA processes are meant to reach the end of the code, some may linger in a known wait state or in a valid loop.
- We can use end-state label to tell the verifier that these states are also valid.
- Per PROMELA model can be any number of end-state labels, but in the same process, they should have unique identifers .
- Every label name starts with the three-letter prefix end defines an end-state label.
- The following label names are valid: endme, end0, end_of_this_part.

End-state labels

```
mtype {p,v};

chan sema = [0] of {mtype};

active proctype Dijkstra(){

    byte count = 1;

end: do
     :: (count == 1) ->
            sema ! p ; count = 0
     :: (count == 0) ->
            sema ? v ; count = 1
     od
}

active [3] proctype user() {
    do
    :: sema ? p;  /*enter*/
       skip;      /*leave*/
       sema ! v;
    od
}
```

End-state labels

- Above example is a process type Dijkstra
  - The process models a semaphore with the help of a rendevous port sema.
  - The semaphore guarantees that only one of three user processes can enter its critical section at a time.
  - The label defines it is not error that the execution of process has not reached its closing curly brace, but waits at the label.

Progress-state labels

- Checking whether a statement is idling or waiting for other process to make progress.
- A progress label states that at least one of the labeled states must be visited infinitely often in any infinite system execution.
- When we add the label of progress,
  - if the result of error is 0, means that there is no non-progress cycles are found.
    - no non-progress cycles shows that the label state would be visit infinite times.
  - if the result of error is over 0,means that there is a non-progress cycle.
    - non-progress cycles shows that the label state may not visit infinite times.
- Any violation of this requirement can be reported by verifier as a non-progress cycle.(possible starvation)
- The progress-state label can be used to check liveness properties.

Progress-state labels

```
active proctype Dijkstra(){      /* modify the last slide's example Dijkstra() */
                                 /* no non-progress cycles are found  */
    byte count = 1;

  end:  do
        :: (count == 1) ->
progress:   sema ! p ; count = 0
        :: (count == 0) ->
            sema ? v ; count = 1
        od
}
```

- Ask the verifier to make sure that in all infinite executions the semaphore process reach the progress label infinitely often.
- The output tell us that the error count is zero which means that no non-progress cycles were found.

Progress-state labels (cont.)

```
byte x = 2;

active proctype A()
{
    do
    ::x = 3 - x
    od
}

active proctype B()
{
    do
    ::x = 3 - x
    od
}
```

- The two processes will cause the value of the global variable x to alternate between 2 and 1.
- No progress labels were used, so every cycle is guaranteed to be a non-progress cycle.
- Every process is possibly not visit infinite times.

Progress-state labels (cont.)

- Below is a case where there is a non-progress cycle:
- The process of type B will alternate between a progress state and a non-progress state.
- In principle, the process of type B could pause forever in its non-progress state at the start of the loop.

```
byte x = 2;

active proctype A()
{
    do
    ::x = 3 - x
    od
}

active proctype B()
{
    do
    ::x = 3 - x; progress: skip
    od
}
```

Fair cycles

- weak fairness:
  - if a process reaches a point where an executable statement never change its executability, it will eventually executing the statement.
  - A process that remains enabled should eventually be executed.
  - Above example enforce weak fairness in the search for non-progress cycles.
- strong fairness:
  - if a process reaches a point where a statement become executable infinitely often, it will eventually executing the statement.

Never Claims

- A never claim gives us the capability to check properties just before and just after each statement execution
- Originally, a never claim was meant to match behavior that should never occur.
- That is, the verifier will flag it as an error if the full behavior specified in the claim be matched by any feasible system execution.

```
never{       /*  if p becomes false, an error occured  */
        do
        :: !p -> break
        :: else
        od
}
```

Never Claims (cont.)

- Never claim can either be written by hands or generated mechanically from LTL formula (SPIN has built-in translator).
  - command: `$ spin -f "![](p || q) "`
- To translate an LTL formulae into a never claim, we have to consider the property:
  - Positive property (good behavior): we have to negate it at first.
  - Negative property (bad behavior): just translate it.
- For example, we want to check the positive property [] p: (SPIN LTL syntax)

```
never {                 /*  ![]p = <>!p  */
            do
            :: true
            :: !p -> break
            od
}
```

SPIN's LTL Syntax

```
f ::=  p
    |  true
    |  false
    |  ( f )
    |  f binop f
    |  unop f

uniop ::= []      (always)
        | <>      (eventually)
        | !       (logical negation)

binop ::= U      (until)
        | &&     (logical and)
        | ||     (logical or)
        | ->     (implication)
        | <->    (equivalence)
```

Specifying LTL properties

- LTL Formulae examples:

Formula	Pronounced	Type/Template
[] p	always p	invariance
<> p	eventually p	guarantee
p -> (<> q)	p implies eventually q	response
p -> (q U r)	p implies q until r	precedence
[] <> p	always, eventually p	recurrence (progress)
<> [] p	eventually, always p	stability (non-progress/ persistence)
(<> p) -> (<> q)	eventually p implies eventually q	correlation

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PROMELA Semantics

- SPIN translates each process into a finite automaton.
- The global behavior of the concurrent system is obtained by computing an asynchronous interleaving product of automata, one automaton per asynchronous process behavior.
- The resulting global system behavior is itself again represented by an automaton.
- This interleaving product is often referred to as the state space of the system, and, because it can easily be represented as a graph, it is also commonly referred to as the global reachability graph.

PROMELA Semantics (cont.)

- By simulating the execution of a SPIN model we can generate a reachability graph.
- The PROMELA semantics rules define how the global reachability graph for any given PROMELA model is to be generated.
- Basic correctness claims in PROMELA can be interpreted as the presence or absence of specific types of nodes or edges.
- LTL properties can be interpreted as the presence or absence of specific types of sub-graph, or paths.

Transition Relation

- Every PROMELA proctype defines a finite state automaton, (S, s_0, L, T, F)

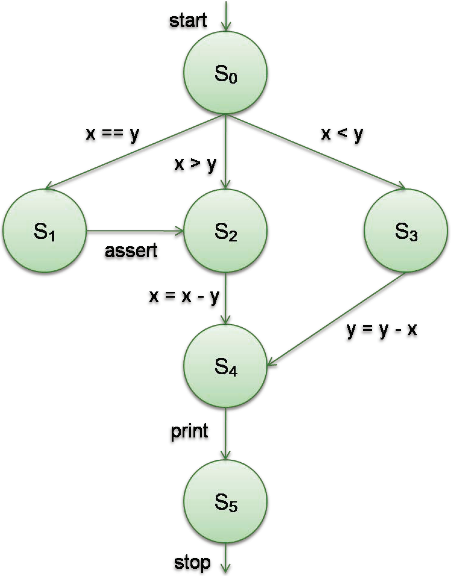
Symbol	Finite State Automaton	PROMELA Model
S	Set of states	Possible points of control within the proctype
L	Transition label set	Specific basic statement (six basic types)
T	Transition relation	Flow of control
F	Set of final states	End-state

Proctype and Automata(1/2)

Example: modified from Euclidean GCD

```
active proctype not_euclid(int x , y)
{
    if
    ::  (x > y) -> L: x = x - y
    ::  (x < y) -> y = y -x
    ::  (x == y) -> assert (x != y); goto L
    fi
    printf("%d\n'', x)
}
```

Proctype and Automata(2/2)



Operational Model(1/8)

- To define the semantics of the modeling language, we can define an operational model in terms of states and state transitions.
  - We have to define what a "state" is.
  - We have to define what a "transition" is.
    - i.e., how the 'next-state' relation is defined.
- Global system states are defined in terms of a small number of primitive objects:
  - We have to define: variables, messages, message channels, and processes.

Operational Model(2/8)

- State transitions require the definition of 3 things:
  - transition executability rules
  - transition selection rules
  - the effect of transition
- We only have to define one-step semantics to define the full language.
- The 3 parts of the semantics definition are defined over 4 types of objects:
  - variables, messages, channels, processes
- Well define these first.

Operational Model(3/8)

variables, messages, channels, processes, transitions, global states

- A PROMELA variable is defined by a five-tuple
  { name, scope, domain, inival, curval }

```
short x=2, y=1; /* global */
active proctype not_euclid(){
    S:  if  /* curval of x at S: 2 */
        :: x > y -> L: x = x - y
        :: x < y -> y = y - x
        :: x == y -> assert(x != y); goto L
        fi;
    E:  printf("%d\n'', x) /* curval of x at E: 1 */
}
```

- note: domain is a finite set of integers.

Operational Model(3/8)

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        :: x < y -> y = y - x
        :: x == y -> assert(x != y); goto L
        fi;
    E:  printf("%d\n'', x) /* curval of x at E: 1 */
}
```

- note: domain is a finite set of integers.

Operational Model(3/8)

variables, messages, channels, processes, transitions, global states

- A PROMELA variable is defined by a five-tuple
  { name, scope, domain, inival, curval }

```
short x=2, y=1; /* global */
active proctype not_euclid(){
    S:  if  /* curval of x at S: 2 */
        :: x > y -> L: x = x - y
        :: x < y -> y = y - x
        :: x == y -> assert(x != y); goto L
        fi;
    E:  printf("%d\n'', x) /* curval of x at E: 1 */
}
```

- note: domain is a finite set of integers.

Operational Model(4/8)

variables, messages, channels, processes, transitions, global states

- A message is a finite, ordered set of variables
  (Messages are stored in channels - defined next.)

Operational Model(5/8)

variables, messages, channels, processes, transitions, global states

- A message channel is defined by a 3-tuple
  { ch_id, nslots, contents }

```
chan q = [2] of { mtype, bit };
```

  - Channels always have global scope.
  - A ch_id is a positive integer uniquely identifies the channel.
  - An ordered set of messages with maximally nslots elements:
    { {slot1.field1 ,slot1.field2 }, {slot2.field1 ,slot2.field2 } }

Operational Model(5/8)

variables, messages, channels, processes, transitions, global states

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Operational Model(5/8)

variables, messages, channels, processes, transitions, global states

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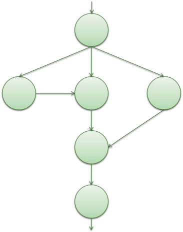
Operational Model(6/8)

variables, messages, channels, processes, transitions, global states

- A process is defined by a six-tuple
  { pid, lvars, lstates, inistate, curstate, transitions }
  - process instantiation number
  - finite set of local variables
  - a finite set of integers defining local states of a process
  - the initial state
  - the current state
  - a finite set of transitions (to be defined) between elements of lstates



Operational Model(6/8)

variables, messages, channels, processes, transitions, global states

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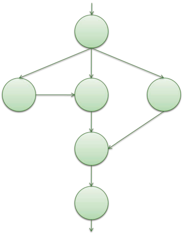

Operational Model(6/8)

variables, messages, channels, processes, transitions, global states

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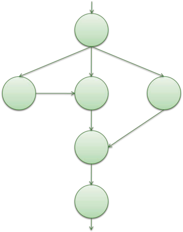

Operational Model(6/8)

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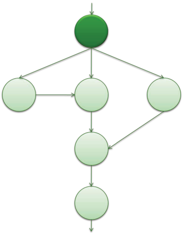

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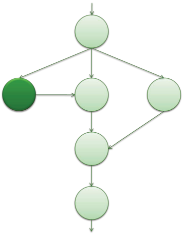

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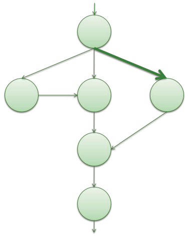
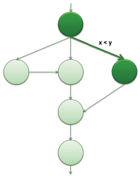


Operational Model(7/8)

variables, messages, channels, processes, transitions, global states

- A transition in process P is defined by a seven-tuple
  { tr_id, source-state, target-state, cond, effect, priority, rv }



- source-state and target-state are elements from set P.lstates
- Condition and effect are defined for each basic statement, and they are typically defined on variable and channel values, possibly also on process states.
  - if the condition is ture, the effect would be realize.
- Predefined system variables that are used to define the semantics of unless and rendezvous.
  - priority, which is used to enforce the sematics of the unless construct
  - rv, to enforce the sematics of the rendezvous operations

Operational Model(7/8)

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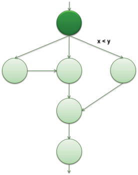

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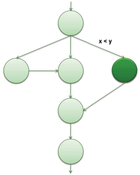

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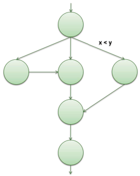

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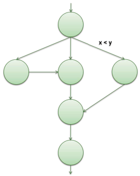

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Operational Model(8/8)

variables, messages, channels, processes, transitions, global states

- A global system state is defined by a eight-tuple
  { gvars, procs, chans, exclusive, handshake, timeout, else, stutter }
  - a finite set of global variables
  - a finite set of processes
  - a finite set of message channels
  - predefined integer system variables that are used to define the semantics of atomic, d_step
  - predefined integer system variables that are used to define the semantics of rendezvous operations
  - predefined boolean system variables: timeout, else, stutter
    - timeout and else, to enforce the sematics of the matching PROMELA statements
  - for stutter extension rule

Operational Model(8/8)

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  - for stutter extension rule

Stutter extension

- The reason why we have to use stutter extension is because PROMELA model is finite.
- When we use LTL as a correctness claim, the LTL formula will be translated into Büchi automaton.
- In Büchi automaton acceptance condition, there will be an infinite cycle pass at least one of the element of accept sets.
- If we want to do the interleaving product of the Büchi automaton with PROMELA model, we have to deal with the infinite execution.
- In stutter extension, we make the final state have a transition target to itself, with label ε.

Initial system state

- All processes are in their inital state
- All global variables have curval=inival
- All message channel have contents={}(empty)
- exclusive and handshake are zero
- timeout, else and stutter all have the initial value false

One-Step Semantics(1/3)

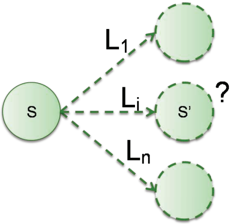
- Given an arbitrary global state of the system, determine the set of possible immediate successor states.
  - To define a one-step semantics, we have to define 3 more things:
    - transition executability rules
    - transition selection rules
    - the effect of transition

One-Step Semantics(2/3)

- We do so by defining an algorithm: an implementation-independent "semantics engine" for SPIN.
  - The semantics engine executes the model(system) in a stepwise mnner: selection and executing one basic statement at a time
  - In each step, one executable basic statement is selected.
  - To determine if a statement is executable or not, one of the conditions that must be evaluated is the corresponding executability clause.
  - If more than one statement is executable, any one of them can be selected.
- Overview of PROMELA Semantics Engine
  - For the selected statement, the effect clause from the statement is applied.
  - The control state of process that executes the statement is updated.
  - The sematics engine continues executing statements until no executable statements remain .
  - No executable statements happens when the number of processes drop to zero, or when the remaining processes reach a system deadlock state.

One-Step Semantics(3/3)

- We do so by defining an algorithm: an implementation-independent "semantics engine" for SPIN.
  - At the highest level of abstraction, the behavior of this engine is defined as follows:
    - Let E be a set of pairs (p,t), with p a process, and t a transition.
    - Let executable(s) be a function(later define), that returns a set of such pairs, one for each executable transition in system state s.



$L_1, \ldots, L_i, \ldots, L_n$

- **assignment statement**
- **assertion statement**
- **expression statement**
- **print statement**
- **send statement**
- **receive statement**

PROMELA Semantics Engine

```
global states s, s'
processes p, p'
transitions t, t'
//E is a set of pairs (p,t)

while ((E = executable(s)) != {}){
    for some (p, t) from E{
        s' = apply(t.effect, s)

        if (handshake == 0)
        {
             s = s'
             p.curstate = t.target
        }
        else
        {
                    /* try to complete rv handshake */
                    E' = executable(s')
                    /* if E' is {}, s is unchanged */

                    for some (p', t' ) from E'
                    {
                              s = apply(t' .effect, s')
                              p. curstate = t. taregt
                              p'. curstate = t'. target
                    }
                    handshake = 0
         }
    }
}
while (stutter){
   s = s    /* 'stutter' extension*/
}
```

PROMELA Semantics Engine(1/4)

```
global states s, s'
processes p, p'
transitions t, t'
//E is a set of pairs (p,t)

while ((E = executable(s)) != {}){
    for some (p, t) from E{
        s' = apply(t.effect, s)

        if (handshake == 0)
        {
             s = s'
             p.curstate = t.target
        }
        else
        {
                     /* try to complete rv handshake */
                     E' = executable(s')
                     /* if E' is {}, s is unchanged */

                     for some (p', t' ) from E'
                     {
                               s = apply(t' .effect, s')
                               p. curstate = t. taregt
                               p'. curstate = t'. target
                     }
                     handshake = 0
         }
     }
}
while (stutter){
   s = s    /* 'stutter' extension*/
}
```

PROMELA Semantics Engine(1/4)

- As long as there are executable transitions, the sematics engine repeatedly selects one of them at random and executes it.
- The function apply applies the effect of the selected transition to the system state, and modifies system, local variables, the contents of channels, the values of reserved variable(such as handshake and execlusive)

PROMELA Semantics Engine(2/4)

```
global states s, s'
processes p, p'
transitions t, t'
//E is a set of pairs (p,t)

while ((E = executable(s)) != {}){
    for some (p, t) from E{
        s' = apply(t.effect, s)

        if (handshake == 0)
        {
             s = s'
             p.curstate = t.target
        }
        else
        {
                    /* try to complete rv handshake */
                    E' = executable(s')
                    /* if E' is {}, s is unchanged */

                    for some (p', t' ) from E'
                    {
                              s = apply(t' .effect, s')
                              p. curstate = t. taregt
                              p'. curstate = t'. target
                    }
                    handshake = 0
         }
     }
}
while (stutter){
   s = s    /* 'stutter' extension*/
}
```

PROMELA Semantics Engine(2/4)

- If no rendezvous offer was made(line 10),
  - the global state change takes effect by an update of the system state(line 12),
  - and the current state of the process that executed the transition is updated(line 13).

PROMELA Semantics Engine(3/4)

```
global states s, s'
processes p, p'
transitions t, t'
//E is a set of pairs (p,t)

while ((E = executable(s)) != {}){
    for some (p, t) from E{
        s' = apply(t.effect, s)

        if (handshake == 0)
        {
             s = s'
             p.curstate = t.target
        }
        else
        {
                    /* try to complete rv handshake */
                    E' = executable(s')
                    /* if E' is {}, s is unchanged */

                    for some (p', t' ) from E'
                    {
                              s = apply(t' .effect, s')
                              p. curstate = t. taregt
                              p'. curstate = t'. target
                    }
                    handshake = 0
         }
     }
}
while (stutter){
   s = s    /* 'stutter' extension*/
}
```

PROMELA Semantics Engine(3/4)

- If a rendezvous offer was made in the last transition,
  - it cannot result in a global state change unless the offer can also be accepted
  - (line 18) the transitions that become executable are selected.
- The definition of the function exetuable guarantees that this set can only contain accepting transitions for the given offer.
  - If there are none, the global state change is declined,
  - and execution proceeds with the selection of a new executable candidate transition from theh original set E.

PROMELA Semantics Engine(4/4)

```
global states s, s'
processes p, p'
transitions t, t'
//E is a set of pairs (p,t)

while ((E = executable(s)) != {}){
    for some (p, t) from E{
        s' = apply(t.effect, s)

        if (handshake == 0)
        {
             s = s'
             p.curstate = t.target
        }
        else
        {
                    /* try to complete rv handshake */
                    E' = executable(s')
                    /* if E' is {}, s is unchanged */

                    for some (p', t' ) from E'
                    {
                              s = apply(t' .effect, s')
                              p. curstate = t. taregt
                              p'. curstate = t'. target
                    }
                    handshake = 0
         }
    }
}
while (stutter){
   s = s    /* 'stutter' extension*/
}
```

PROMELA Semantics Engine(4/4)

- If the offer can be matched,
  - the global state change takes effect(line 23)
  - In both process, the current control state is now updated from source to target state(line 24 and line 25).
- The definition of the function exetuable guarantees that this set can only contain accepting transitions for the given offer.
  - If there are none, the global state change is declined,
  - and execution proceeds with the selection of a new executable candidate transition from theh original set E.

Executability Rules

```
Set
executable (State s)
{     new Set E
      new Set e

       E = {}
       timeout = false
AllProcs:
 for each active process p
 {    if (exclusive == 0
      or  exclusive == p.pid)
 {        for u from high to low      /*  priority  */
           {    e = {};  else = false
 OneProc:       for each transition t in p. trans
                 {   if (t. source == p. curstate
                              and t. prty == u
                              and (handshake == 0
                              or    handshake == t.rv)
                              and  eval(t.cond) == true
                              {    add (p, t) to set e
                      }  }
                      if (e != {})
                      {  add all elements of e to E
                            break     /*  on to next process  */
                       }  else if (else == false)
                       {    else = true
                              goto OneProc
                       }  /*  or else lower the priority  */
 }     }    }
```

Executability Rules

```

  if (E == {} and exclusive != 0)
  {  exclusive = 0
     goto AllProcs
  }
  if (E == {} and timeout == false)
  {  timeout = true
     goto AllProcs
  }

  return E
}
```

- Executability Rules is specification of procedure executable()

Executability Rules(1)

```
Set
executable (State s)
{     new Set E
      new Set e

       E = {}
       timeout = false
AllProcs:
 for each active process p
 {    if (exclusive == 0
      or  exclusive == p.pid)
 {        for u from high to low      /*  priority  */
           {    e = {};  else = false
 OneProc:       for each transition t in p. trans
                 {   if (t. source == p. curstate
                          and t. prty == u
                          and (handshake == 0
                          or    handshake == t.rv)
                          and  eval(t.cond) == true
                          {    add (p, t) to set e
                      }  }
                      if (e != {})
                      {  add all elements of e to E
                           break     /*  on to next process  */
                       }  else if (else == false)
                       {    else = true
                             goto OneProc
                       }  /*  or else lower the priority  */
 }     }    }
```

Executability Rules(1)

```

  if (E == {} and exclusive != 0)
  {  exclusive = 0
     goto AllProcs
  }
  if (E == {} and timeout == false)
  {  timeout = true
     goto AllProcs
  }

  return E
}
```

Executability Rules(1)

- (line 10-11) The test checks the value of the reserved system variable exclusive.
- By default it is zero, and the sematics engine itself never changes the value to non-zero.
- Any transition that is part of an atomic sequence sets exclusive to the value of p.id,
  - to make sure that the sequence is not interrupted by other processes, unless the sequence itself blocks.
  - If the sequence itself blocks, the sematics engine restores the defaults.(line 32)

Executability Rules(2)

```
Set
executable (State s)
{     new Set E
      new Set e

       E = {}
       timeout = false
AllProcs:
 for each active process p
 {     if (exclusive == 0
       or  exclusive == p.pid)
 {         for u from high to low      /*  priority  */
               {    e = {};  else = false
 OneProc:           for each transition t in p. trans
                     {   if (t. source == p. curstate
                                  and t. prty == u
                                  and (handshake == 0
                                  or    handshake == t.rv)
                                  and  eval(t.cond) == true
                                  {    add (p, t) to set e
                          }  }
                          if (e != {})
                          {  add all elements of e to E
                                break     /*  on to next process  */
                           }  else if (else == false)
                           {    else = true
                                  goto OneProc
                           }  /*  or else lower the priority  */
 }     }    }
```

Executability Rules(2)

- (line 16) The test checks the priority level, set on line 12.
- Within each process, the semeatic engine selects the highest priority transitions that are executable.
- Note that priorities can affect the selection of transitions with a process, not between processes.
- Priorities are defined in PROMELA with the unless construct.

Executability Rules(3)

```
Set
executable (State s)
{     new Set E
      new Set e

       E = {}
       timeout = false
AllProcs:
 for each active process p
 {    if (exclusive == 0
      or  exclusive == p.pid)
 {        for u from high to low      /*  priority  */
           {    e = {};  else = false
 OneProc:       for each transition t in p. trans
                 {   if (t. source == p. curstate
                          and t. prty == u
                          and (handshake == 0
                          or    handshake == t.rv)
                          and  eval(t.cond) == true
                          {    add (p, t) to set e
                     }  }
                     if (e != {})
                     {  add all elements of e to E
                           break     /*  on to next process  */
                      }  else if (else == false)
                      {    else = true
                             goto OneProc
                      }  /*  or else lower the priority  */
 }     }    }
```

Executability Rules(3)

- (line 15) The test matches the source state of the transition in the labeles transition system with the current state of the process, selected on line 9.
- (line 17-18) The test makes sure that either no rendezvous offer is outstanding, or, if one is, that the transition being considered can accept the offer on the corresponding rendezvous port.
- (line 19) The test checks whether the executability condition for the transition itself is satisfied.

Executability Rules(4)

```
Set
executable (State s)
{     new Set E
      new Set e

       E = {}
       timeout = false
AllProcs:
 for each active process p
 {    if (exclusive == 0
      or  exclusive == p.pid)
 {        for u from high to low      /*  priority  */
           {    e = {};  else = false
 OneProc:       for each transition t in p. trans
                 {   if (t. source == p. curstate
                          and t. prty == u
                          and (handshake == 0
                          or    handshake == t.rv)
                          and  eval(t.cond) == true
                          {    add (p, t) to set e
                      }  }
                      if (e != {})
                      {  add all elements of e to E
                            break     /*  on to next process  */
                       }  else if (else == false)
                       {    else = true
                              goto OneProc
                       }  /*  or else lower the priority  */
 }     }    }
```

Executability Rules(4)

```
  if (E == {} and exclusive != 0)
  {  exclusive = 0
     goto AllProcs
  }
  if (E == {} and timeout == false)
  {  timeout = true
     goto AllProcs
  }

  return E
}
```

Executability Rules(4)

- (line 25-28) If no transition are found to be executable with the default value false for the system variable else, the transitions of the current process are checked again, this time with else equal to true.
- (line 35-38) If no transitions are executable in any process, the value of system variable timeout is changed to true and the entire selection is repeated.
- (line 7) The new value of timeout sticks for just one step, but it can cause any number of transitions in any number of processes to become executable in the current global state.

Interpreting PROMELA models

- The semantic engine
  - manipulate the basic objects of a PROMELA model.
  - does not have to know anything about control-flow constructs.
    - e.g., if, do, break, and goto
  - merely deals with local states and transitions.

PROMELA Models(1/2)

- Here are 3 examples:

```
chan x = [0] of {bit};
chan y = [0] of {bit};
active proctype A() {x?0 unless y!0}
active proctype B() {y?0 unless x!0}
```

```
chan x = [0] of {bit};
chan y = [0] of {bit};
active proctype A() {x!0 unless y!0}
active proctype B() {y?0 unless x?0}
```

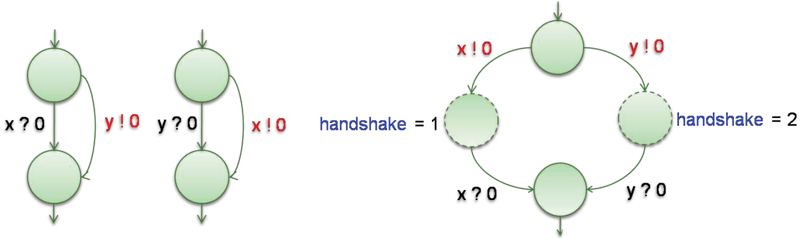
```
chan x = [0] of {bit};
chan y = [0] of {bit};
active proctype A() {x!0 unless y?0}
active proctype B() {y!0 unless x?0}
```

PROMELA Models(2/2)

- Rendezvous handshakes occur in two parts:
  - Sender offers
  - Receiver accepts

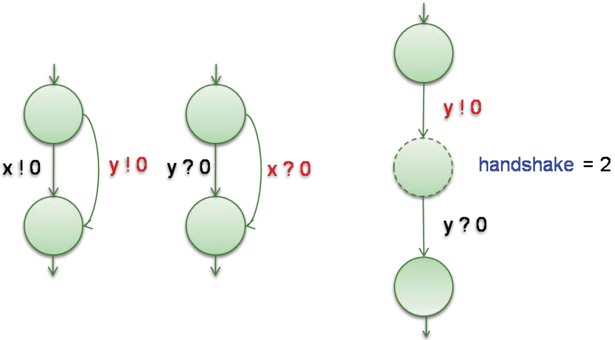
Example 1:3

```
chan x = [0] of {bit};
chan y = [0] of {bit};
active proctype A() {x?0 unless y!0}
active proctype B() {y?0 unless x!0}
```



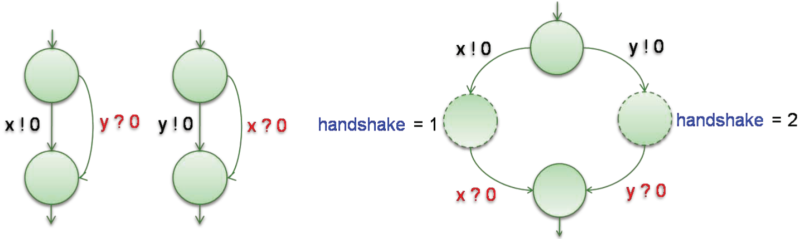
Example 2:3

```
chan x = [0] of {bit};
chan y = [0] of {bit};
active proctype A() {x!0 unless y!0}
active proctype B() {y?0 unless x?0}
```



Example 3:3

```
chan x = [0] of {bit};
chan y = [0] of {bit};
active proctype A() {x!0 unless y?0}
active proctype B() {y!0 unless x?0}
```



Search algorithms

- SPIN uses DFS algorithm for verification.
- How to check Safety properies in SPIN?
- How to check Liveness properies in SPIN?

DEPTH-FIRST SEARCH(1/4)

```
Stack D = {}
Statespace V = {}

Start()
{
     Add_Statespace(V, A.s0)
     Push_Stack(D, A.s0)
     Search()
}

Search()
{
     s = Top_Stack(D)
     for each (s.l,s') in A.T
          if In_Statespace(V, s') == false
          {     Add_Statespace(V, s')
                 Push_Stack(D, s')
                 Search()
          }
     Pop_Stack(D)
}
```

- Consider a finite state automatan A = (S, S0, L, T, F) that is generated by the PROMELA semantics engine.
- The algorithms performs a depth-first search to visit every state in set A.S that is reachable from the inital state A.s0.
- The algorithm uses two data structures: statck D and state space V.

DEPTH-FIRST SEARCH(2/4)

```
Stack D = {}
Statespace V = {}

Start()
{
     Add_Statespace(V, A.s0)
     Push_Stack(D, A.s0)
     Search()
}

Search()
{
     s = Top_Stack(D)
     for each (s.l,s') in A.T
          if In_Statespace(V, s') == false
          {    Add_Statespace(V, s')
               Push_Stack(D, s')
               Search()
          }
     Pop_Stack(D)
}
```

- A state space is an unordered set of states.
- Some of contents of set A.S is reproduced in state space V, using the definition of initial state A.s0 and transition relation A.T.
- Not all elements of A.S will appear in set V because not all these elements may be reachable from the given initial state.

DEPTH-FIRST SEARCH(3/4)

```
Stack D = {}
Statespace V = {}

Start()
{
     Add_Statespace(V, A.s0)
     Push_Stack(D, A.s0)
     Search()
}

Search()
{
     s = Top_Stack(D)
     for each (s.l,s') in A.T
          if In_Statespace(V, s') == false
          {     Add_Statespace(V, s')
                 Push_Stack(D, s')
                 Search()
          }
     Pop_Stack(D)
}
```

- Use two routines to update the contents of state space:
  - Add_Statespace(V, s): add state s as an element to state space V
  - In_Statespace(V, s): returns true if s is an element of V
- A stack is an ordered set of states.
  - Because of the ordering relation, a stack has an unique top and buttom element.(FILO)

DEPTH-FIRST SEARCH(4/4)

- The algorithm stores only states in set V, and no transition.
- When SPIN executes the DFS algorithm, it constructs both state set A.S and transition relation A.T on-the-fly,
  - as an interleaving product of small automata, each one of which represents an independent thread of control

Checking Safety properies in SPIN(1/2)

```
Stack D = {}
Statespace V = {}

Start()
{
     Add_Statespace(V, A.s0)
     Push_Stack(D, A.s0)
     Search()
}

Search()
{
     s = Top_Stack(D)
     if !Safety(s)
     {     Print_Stack(D)
     }
     for each (s.l,s') in A.T
          if In_Statespace(V, s')== false
          {     Add_Statespace(V, s')
                 Push_Stack(D, s')
                 Search()
          }
     Pop_Stack(D)
}
```

- The DFS algorithm visits every reachable state, and can check arbitary state or safety properties.
- It uses a generic routine for checking the state properties for any given state s, called Safety(s).

Checking Safety properies in SPIN(2/2)

- The routine can flag the violation of process assertions or system invariants that should hold at s.
- Since the algorithm visit all reachable states, it has the properties that it can identify all possible assertion violations.
- The algorithm can trace how the state property was violated.
  - The trace starts in initial state, and end at the property violation.
  - That information is contained in stack D.
- Print_Stack(D) prints out the elements of stack D in order, from the bottom element up to and including the top element.
- When SPIN uses, it prints each state that reached along the execution path from the inital state to the state where a property violation was discovered,
  - also adds some details on the transitions from set A.T that generated each new state in path.

Checking Liveness properies in SPIN(1/4)

```
Stack D = {}
Statespace V = {}
State seed = nil
Boolean toggle = false
Start() {
     Add_Statespace(V, A.s0, toggle)
     Push_Stack(D, A.s0, toggle)
     Search()
}
Search() {
     (s,toggle) = Top_Stack(D)
     for each (s, l, s') in A.T
         { /*check if seed is reachable from ifself*/
          if s' == seed or On_Stack(D, s' , false)
          {    PrintStack(D)
               PopStack(D)
               return
          }
          if In_Statespace(V, s', toggle) == false
          {    Add_Statespace(V, s', toggle)
                 Push_Stack(D, A.s', toggle)
                 Search()
          }  }
     if (s in A.F) and (toggle == false)
     {  seed = s   /* reachable accepting state */
          toggle == true
          Push_Stack(D, s, toggle)
          Search()  /* start 2nd search */
          PopStack(D)
          seed = nil
          toggle == false
     }
  PopStack(D)  }
```

Checking Liveness properies in SPIN(2/4)

- An acceptance cycle in the reachability graph of automaton A exists if and only if two conditions are met.
  - First, at least one accepting state is reachable from the inital state of the automaton A.s0
  - Second, at least one of those accepting states is reachable from itself.
- The algorithm that is used in SPIN to detect reachable accepting states that are also reachable form themselves.
- The state space and stack structure store pairs of element: a state and a boolean value toggle.

Checking Liveness properies in SPIN(3/4)

- When the algorithm determines they an accepting state has been reached,
  - and all successors of that state have also been explored,
  - it starts a nested search to see if the state is reachable from itself.
- It does so by storing a copy of the accepting state in a global called seed.
- If this seed state can be reached again in the second search, the accepting state was reachable from itself.
- If a successor state s' appears on the stack of the first search(that leads to the seed state), we know that there exists a path from s' back to the seed state.
- The path is contained in stack D, starting at the state that is matched here and ending at the first visit to the seed state, from which the nested search was started.

Checking Liveness properies in SPIN(4/4)

- When the first accepting state that is reachable from itself is generated the state space cannot contain any previously visited states with a true toggle attribute from which this state is reachable, and thus the self-loop is constructed.
- This algorithm can only guarantee that if one or more acceptance cycle exists, at least one of them will be found.

Agenda

- An Introduction to SPIN
- An Overview of PROMELA
- PROMELA semantics and search algorithms
- Embedded C code
- Verification in SPIN
- DEMO
- References

Embedded C code

- SPIN,versions 4.0 and later, support the inclusion of embedded C code into PROMELA models through the following five new primitives:
  - c_expr
  - c_code
  - c_decl
  - c_state
  - c_track

Embedded C code Example 1:2

```
c_decl{
    typedef struct Coord {
        int x, y;
    } Coord;
}

c_state "Coord pt" "Global" /*goes inside state vector*/

int z = 3;                  /*standard global declaration*/

active proctype example()
{
    c_code { now.pt.x = now.pt.y = 0; };

    do
    :: c_expr { now.pt.x == now.pt.y} ->
            c_code { now.pt.y++; }
    :: else -> break
    od;
    c_code{
       printf("values %d: %d, %d,%d\n",
            Pexample->_pid, now.z, now.pt.x, now.pt.y);
    };
    assert(false)           /* trigger an error trail */
}
```

In c_code and c_expr statments ,referencing to a global variable must use keyword now,such as "now.z".

Embedded C code Example 2:2

```
c_decl{
    typedef struct Coord {
        int x, y;
    } Coord;
}
c_code { Coord pt; }          /*embedded declaration*/
c_track "&pt" "sizeof(Coord)" /*track value of pt*/

int z = 3;                   /*standard global declaration*/

active proctype example()
{
    c_code { pt.x = pt.y = 0; }; /*no 'now.' prefixes */

    do
    :: c_expr { pt.x == pt.y} ->
            c_code { pt.y++; }
    :: else -> break
    od;
    c_code{
       printf("values %d: %d, %d,%d\n",
            Pexample->_pid, now.z, pt.x, pt.y);
    };
    assert(false)            /* trigger an error trail */
}
```

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Verification in SPIN

- The goal of system verification is to establish what is possible and what is not.
- When performing verification we are interested in whether design requirements could be violated, not how likely or unlikely such violations might be.
- To perform verification, SPIN takes a correctness claim that is specified as a LTL, converts that formula into a Büchi automaton, and computes the synchronous product of this claim and the automaton representing the global state space.
- The result is again a Büchi automaton.
- If the language accepted by this automaton is empty, this means that the original claim is not satisfied for the given system.
- If the language is nonempty, it contains precisely those behaviors that satisfy the original temporal logic formula.

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DEMO

- You can use the SPIN model checker in three types:
  - Using Command Line
  - Using XSPIN: old GUI (no longer supported)
  - Using iSPIN: new Tcl/Tk GUI for Spin version 6 or later.
  - Using JSPIN

DEMO

- Mutual_Exclusion_2.pml (using assertion)
- Mutual_Exclusion_3.pml (using a monitor as invariant)
- Mutual_Exclusion_4.pml (using LTL property)
- Peterson_Mutual_Exclusion.pml

Agenda

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References

- G.J. Holzmann, *The SPIN Model Checker: Primer and Reference Manual*, Addison-Wesley, 2003
- G.J. Holzmann, *The Model Checker SPIN*, IEEE Trans. Software Eng., vol. 23, no. 5, May 1997.
- SPIN Official website