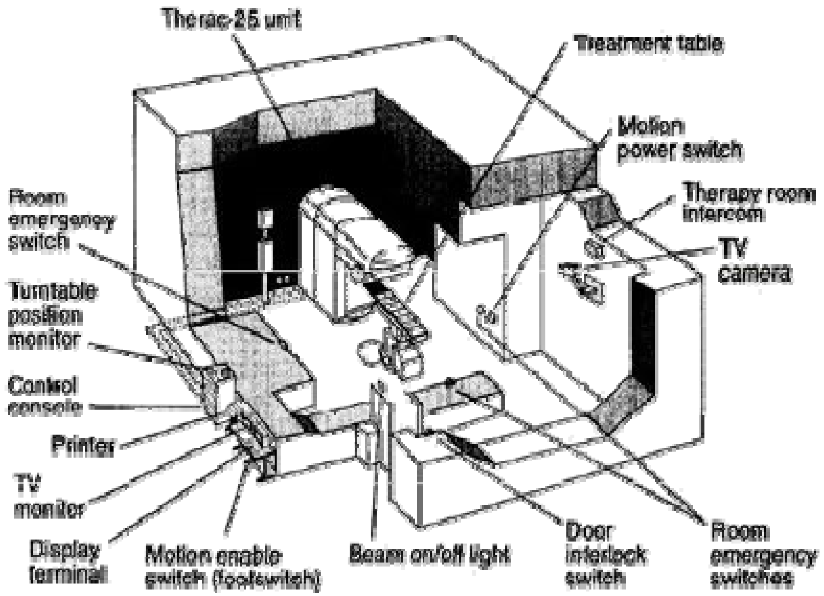
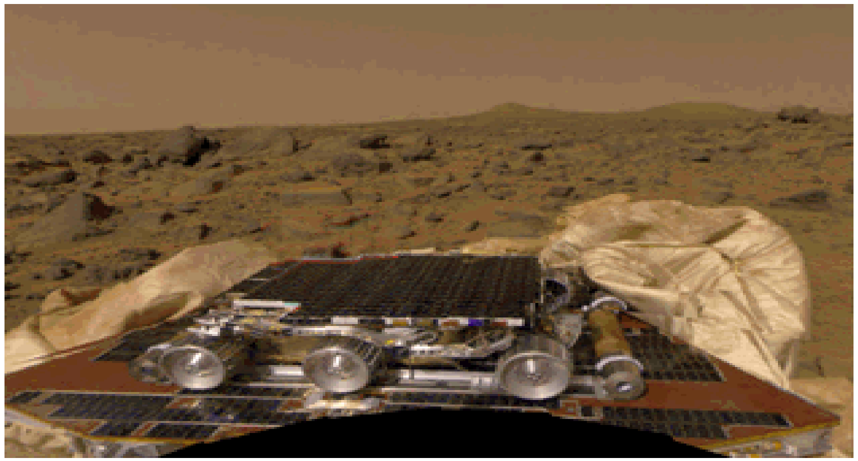
The Spin Model Checker : Part I/II

Moonzoo Kim

CS Dept. KAIST

Motivation: Tragic Accidents Caused by SW Bugs





Cost of Software Errors

June 2002

"Software bugs, or errors, are so prevalent and so detrimental that they cost the U.S. economy an estimated $59.5 billion annually, or about 0.6 percent of the gross domestic product

…

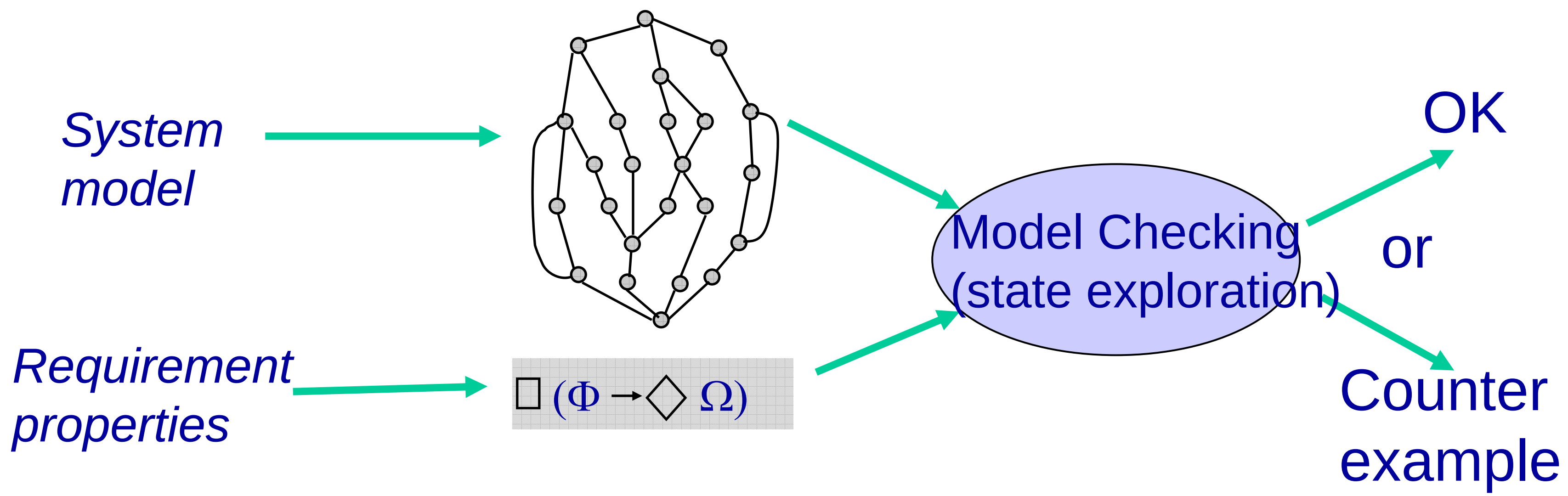
At the national level, over half of the costs are borne by software users and the remainder by software developers/vendors."

…

The study also found that, although all errors cannot be removed, more than a third of these costs, or an estimated $22.2 billion, could be eliminated by an improved testing infrastructure that enables earlier and more effective identification and removal of software defects."

NIST Planning Report 02-3
The Economic Impacts of Inadequate Infrastructure for Software Testing

- Specify requirement properties and build system model
- Generate possible states from the model and then check exhaustively whether given requirement properties are satisfied within the state space



Model Checking (cont.)

- Developed independently by Clarke and Emerson and by Queille and Sifakis in early 1980's.
- Model checking **complements** testing/simulation.
- Advantages
  - **No proofs!!!**
  - **Fast (compared to other rigorous methods)**
  - **Diagnostic counterexamples**
  - **Logics can easily express many concurrency properties**

Example. Mutual Exclusion Algorithm

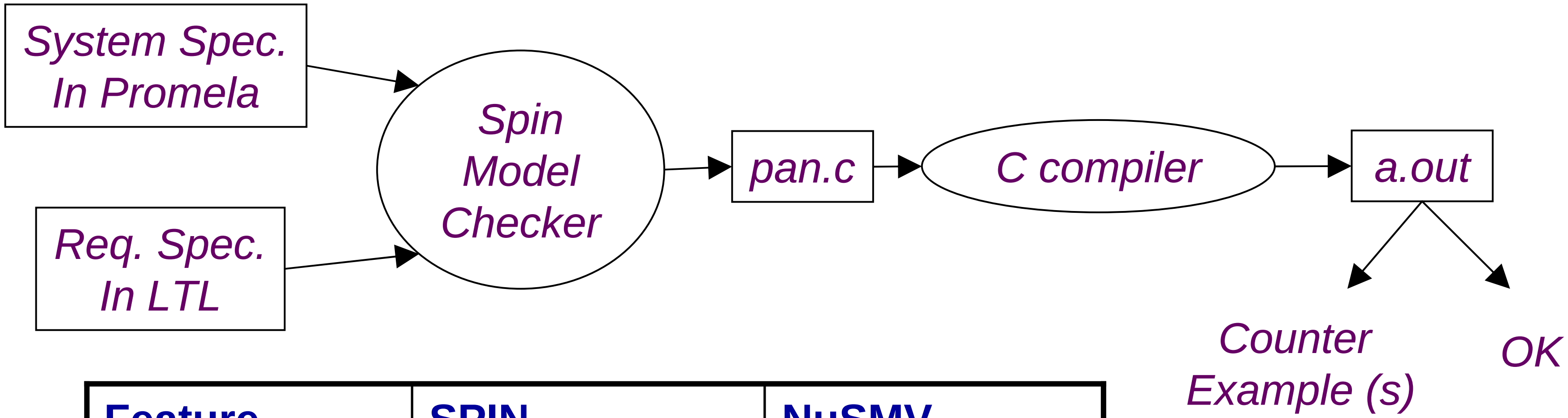
```
char cnt=0,x=0,y=0,z=0;

void process() {
        char me = _pid +1; /* me is 1 or 2*/
again:
        x = me;
        If (y ==0 || y== me) ;
        else goto again;

        z =me;
        If (x == me) ;
        else goto again;

        y=me;
        If(z==me);
        else goto again;

        /* enter critical section */
        cnt++;
        /* assert( cnt ==1); */
        cnt --;
        goto again;
}
```

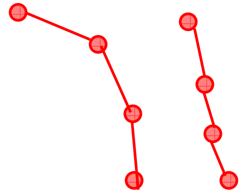
Mutual Exclusion Algorithm

Process 0	***Process 1***
	x = 2
	y==0 || y ==2
	z = 2
	x==2
x = 1	
y==0 || y == 1	
	y=2
	(z==2)
	cnt++
z = 1	
x==1	
y = 1	
z == 1	
cnt++	

Counter Example

Overview of the Spin Architecture





Feature	**SPIN**	**NuSMV**
Req. Logic	Linear Temporal Logic	CTL + LTL
Main model of execution	Asynchronous execution (SW)	Synchronous (HW)
State management	Explicit (hash table)	Symbolic (BDD)
Main communication model	Explicit buffered channel	Global variable
Tool maturity	High	Medium

Spin's modeling language - PROMELA

- Promela (process meta-language)
  - Syntax is similar to that of C, but simplified
    - No float type, no functions, no pointers etc
  - Underlying paradigm
    - Communication and concurrency
    - Clear operational semantics
    - Interleaved semantics
    - Asynchronous process execution
    - Two-way communication
  - Unique features not found in programming languages
    - Non-determinism (process level and statement level)
    - Executability

Overview of the Promela

```
byte x;
chan ch1= [3] of {byte};
```

Global variables (including channels)

```
active[2] proctype A() {
   byte z;
   printf("x=%d\n",x);
   z=x+1;
   ch1!z
}
```

Process (thread) definition and creation

```
proctype B(byte y) {
   byte z;
   ch1?z;
}
```

Another process definition

```
Init {
      run B(2);
}
```

System initialization

- Processes are communicating with each other using
  - Global variables
  - Message channels
- Process can be dynamically created
- Scheduler executes one process at a time using interleaving semantics

Variables and Types

- Basic types
  - bit
  - bool
  - Byte (8 bit unsigned integer)
  - short (16 bits signed integer)
  - Int (32 bits signed integer)
- Arrays
  - bool x[10];
- Records
  - typedef R { bit x; byte y;}
- Default initial value of variables is 0
- Most arithmetic (e.g.,+,-), relational (e.g. >,==) and logical operators of C are supported
  - bitshift operators are supported too.

- Promela spec generates only a finite state model because
  - Max # of active process <= 255
  - Each process has only finite length of codes
  - Each variable is of finite datatype
  - All message channels have bounded capability <= 255

- Each Promela statement is either
  - executable:
  - blocked
- There are six types of statement
  - Assignment: always executable
    - Ex. **`x=3+x`**, **`x=run A()`**
  - Print: always executable
    - Ex. **`printf("Process %d is created.\n",_pid);`**
  - Assertion: always executable
    - Ex. **`assert( x + y == z)`**
  - Expression: depends on its value
    - Ex. **`x+3>0`**, **`0`**, **`1`**, **`2`**
    - Ex. **`skip, true`**
  - Send: depends on buffer status
    - Ex. **`ch1!m`** is executable only if **`ch1`** is not full
  - Receive: depends on buffer status
    - Ex. **`ch1?m`** is executable only if **`ch1`** is not empty

- An expression is also a statement
  - It is executable if it evaluates to non-zero
  - 1 : always executable
  - 1<2:always executable
  - x<0: executable only when x < 0
  - x-1:executable only when x !=0
- If an expression statement in blocked, it remains blocked until other process changes the condition
  - an expression e is equivalent to while(!e); in C

- assert(expr)
  - assert is always executable
  - If expr is 0, SPIN detects this violation
  - assert is most frequently used checking method, especially as a form of invariance
    - ex. active proctype inv() { assert(x== 0);}
      - Note that inv() is equivalent to [] (x==0) in LTL with thanks to interleaving semantics

Program Execution Control

- Promela provides low-level control mechanism, i.e., goto and label as well as if and do
- Note that non-deterministic selection is supported
- else is predefined variable which becomes true if all guards are false; false otherwise

```
proctype A() {
    byte x;
    starting:
    x= x+1;
    goto starting;
}
```

```
proctype A() {
    byte x;
    if
    :: x <= 0 -> x=x+1
    :: x == 0 -> x=1
    fi
}
```

```
proctype A() {
    byte x;
    do
    :: x <= 0 -> x=x+1;
    :: x == 0 -> x=1;
    :: else -> break
    od
}
```

Critical Section Example

```
bool lock;
byte cnt;

active[2] proctype P() {
	!lock -> lock=true;
	cnt=cnt+1;
	printf("%d is in the crt sec!\n",_pid);
	cnt=cnt-1;
	lock=false;
}

active proctype Invariant() {
	assert(cnt <= 1);
}
```

```
[root@moonzoo spin_test]# ls
crit.pml
[root@moonzoo spin_test]# spin -a crit.pml
[root@moonzoo spin_test]# ls
crit.pml  pan.b  pan.c  pan.h  pan.m  pan.t
[root@moonzoo spin_test]# gcc pan.c
[root@moonzoo spin_test]# a.out
pan: assertion violated (cnt<=1) (at depth 8)
pan: wrote crit.pml.trail
Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        acceptance   cycles     - (not selected)
        invalid end states      +
State-vector 36 byte, depth reached 16, errors: 1
     119 states, stored
      47 states, matched
     166 transitions (= stored+matched)
       0 atomic steps
hash conflicts: 0 (resolved)
4.879   memory usage (Mbyte)
[root@moonzoo spin_test]# ls
a.out  crit.pml  crit.pml.trail  pan.b  pan.c  pan.h
pan.m  pan.t
```

Critical Section Example (cont.)

```
[root@moonzoo spin_test]# spin -t -p crit.pml
Starting P with pid 0
Starting P with pid 1
Starting Invariant with pid 2
  1:    proc  1 (P) line   5 "crit.pml" (state 1)      [(!(lock))]
  2:    proc  0 (P) line   5 "crit.pml" (state 1)      [(!(lock))]
  3:    proc  1 (P) line   5 "crit.pml" (state 2)      [lock = 1]
  4:    proc  1 (P) line   6 "crit.pml" (state 3)      [cnt = (cnt+1)]
          1 is in the crt sec!
  5:    proc  1 (P) line   7 "crit.pml" (state 4)      [printf('%d is in the crt sec!\\n',_pid)]
  6:    proc  0 (P) line   5 "crit.pml" (state 2)      [lock = 1]
  7:    proc  0 (P) line   6 "crit.pml" (state 3)      [cnt = (cnt+1)]
      0 is in the crt sec!
  8:    proc  0 (P) line   7 "crit.pml" (state 4)      [printf('%d is in the crt sec!\\n',_pid)]
spin: line  13 "crit.pml", Error: assertion violated
spin: text of failed assertion: assert((cnt<=1))
  9:    proc  2 (Invariant) line  13 "crit.pml" (state 1)      [assert((cnt<=1))]
spin: trail ends after 9 steps
#processes: 3
                lock = 1
                cnt = 2
  9:    proc  2 (Invariant) line  14 "crit.pml" (state 2) <valid end state>
  9:    proc  1 (P) line   8 "crit.pml" (state 5)
  9:    proc  0 (P) line   8 "crit.pml" (state 5)
3 processes created
```

Revised Critical Section Example

```
bool lock;
byte cnt;

active[2] proctype P() {
      atomic{ !lock -> lock=true;}
      cnt=cnt+1;
      printf("%d is in the crt sec!\n",_pid);
      cnt=cnt-1;
      lock=false;
}

active proctype Invariant() {
      assert(cnt <= 1);
}
```

```
[root@moonzoo revised]# a.out
Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        acceptance   cycles     - (not selected)
        invalid end states      +

State-vector 36 byte, depth reached 14, errors: 0
      62 states, stored
      17 states, matched
      79 transitions (= stored+matched)
       0 atomic steps
hash conflicts: 0 (resolved)

4.879   memory usage (Mbyte)
```

Deadlocked Critical Section Example

```
bool lock;
byte cnt;

active[2] proctype P() {
      atomic{ !lock -> lock==true;}
      cnt=cnt+1;
      printf("%d is in the crt sec!\n",_pid);
      cnt=cnt-1;
      lock=false;
}

active proctype Invariant() {
      assert(cnt <= 1);
}
```

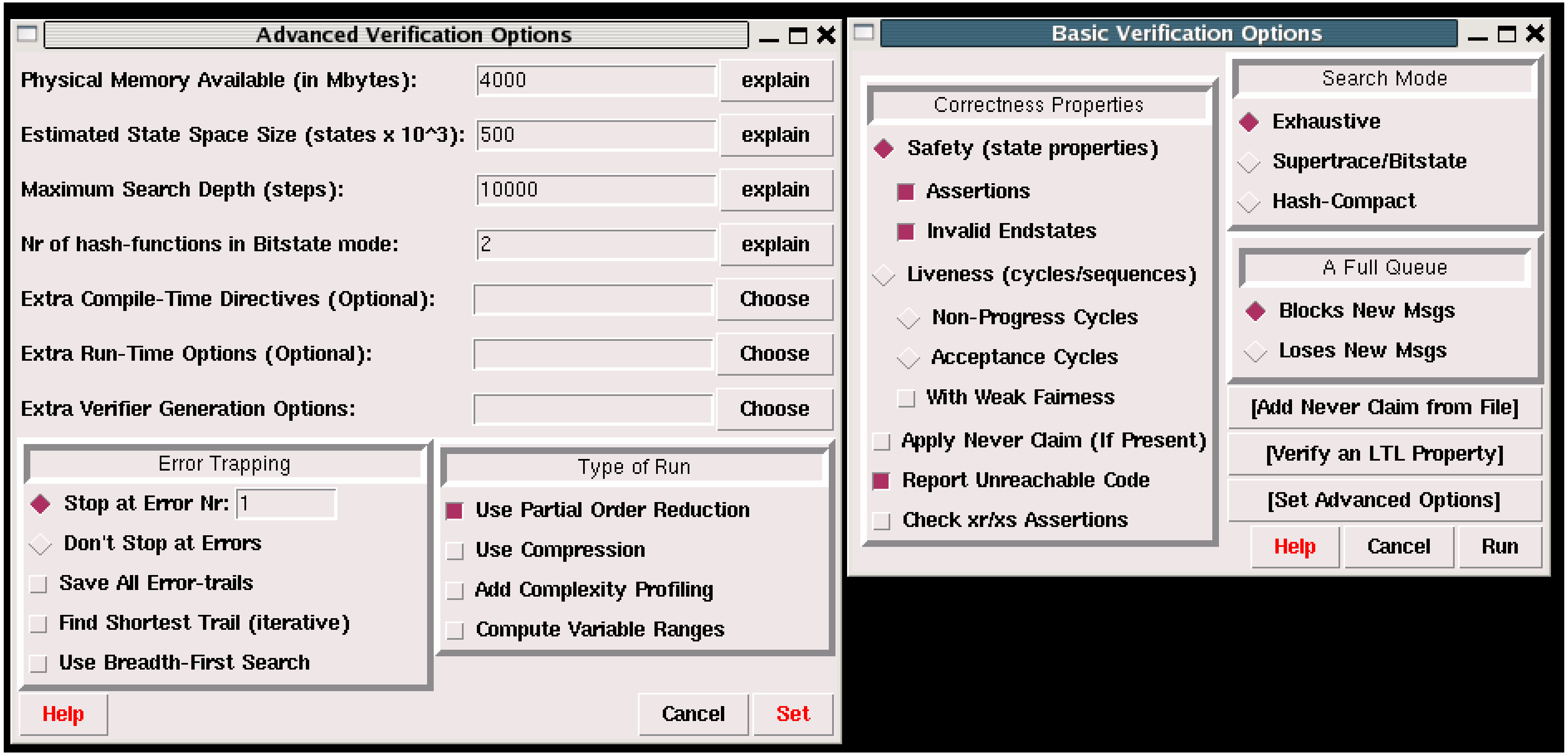
```
[[root@moonzoo deadlocked]# a.out
pan: invalid end state (at depth 3)

(Spin Version 4.2.7 -- 23 June 2006)
Warning: Search not completed
        + Partial Order Reduction

Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        acceptance   cycles     - (not selected)
        invalid end states      +

State-vector 36 byte, depth reached 4, errors: 1
       5 states, stored
       0 states, matched
       5 transitions (= stored+matched)
       2 atomic steps
hash conflicts: 0 (resolved)

4.879   memory usage (Mbyte)
```

Deadlocked Critical Section Example (cont.)

[root@moonzoo deadlocked]# spin -t -p deadlocked_crit.pml
Starting P with pid 0
Starting P with pid 1
Starting Invariant with pid 2
  1:    proc 2 (Invariant) line 13 "deadlocked_crit.pml" (state 1)
[assert((cnt<=1))]
  2: proc 2 terminates
  3:    proc 1 (P) line   5 "deadlocked_crit.pml" (state 1)   [(!(lock))]
  4:    proc 0 (P) line   5 "deadlocked_crit.pml" (state 1)   [(!(lock))]
spin: trail ends after 4 steps
#processes: 2
                lock = 0
                cnt = 0
  4:    proc 1 (P) line   5 "deadlocked_crit.pml" (state 2)
  4:    proc 0 (P) line   5 "deadlocked_crit.pml" (state 2)
3 processes created

Options in XSPIN

- Now you have learned all necessary techniques to verify common problems in the SW development



- Spin home page
  - http://www.spinroot.com
    - Tool downloads and documents (tutorials, online reference, etc)
- The Spin Model Checker by G.Holzmann – 2nd ed, Addison Wesley