Introduction to SPIN

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Acknowledgments

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PROMELA/SPIN

PROMELA (PROcess MEta LAnguage) is:

- a language to describe concurrent (distributed) systems:
  - network protocols, telephone systems
  - multi-threaded (-process) programs
- similar with some structured languages (e.g. C, Pascal)

SPIN (Simple Promela INterpreter) is a tool for:

- detecting logical errors in the design of systems e.g:
  - deadlocks
  - assertions (e.g. race conditions)
  - temporal logic formulas

Features

Given a PROMELA model (program), SPIN can do:

- a random simulation i.e. it interprets the program
  - this mode cannot be used in exhaustive verification
  - useful for viewing error traces
- an exhaustive analysis
  - considers all possible executions of the program
  - finds all potential errors, both deadlock and user-specified

Deadlock:

- situation in which at least one process remains blocked forever while waiting for an inexistent event to happen

User specified constraints:

- assertions
- temporal (never) claims

Example

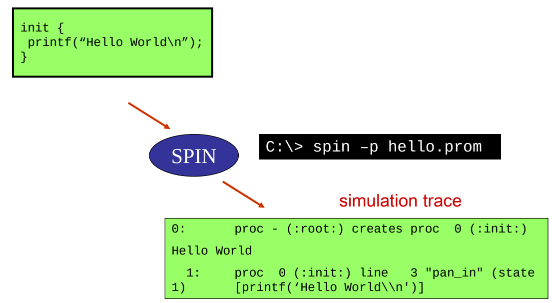
PROMELA “Hello World”

```
init {
    printf(“Hello World\n”);
}
```

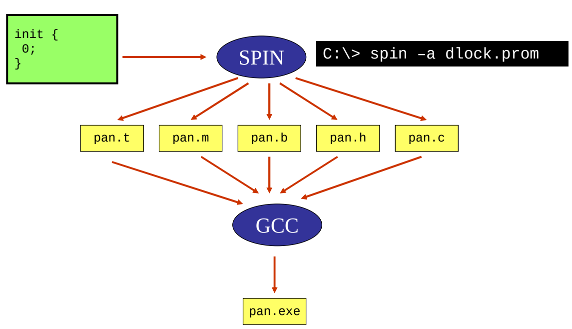
The simplest erroneous specification

```
init {
    0;
}
```

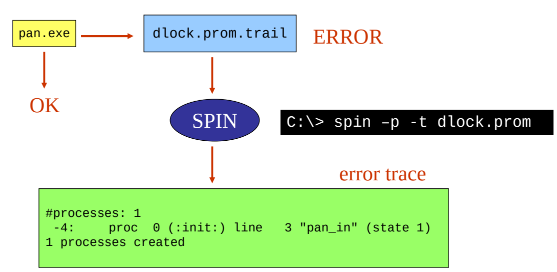

SPIN Simulation



SPIN Analysis (1)



SPIN Analysis (2)



The PROMELA language

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Similar to C

- all C pre-processor directives can be used

```
#define NAME 5
```

- definitions of types, variables, processes
- `if,do,break,goto` control flow constructs

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Basic Types and Ranges

`bit, bool`	0..1
`byte`	0..255
`short`	- 2^15 - 1 .. 2^15 - 1
`int`	-2^31 – 1 .. 2^31 - 1

Warning: type ranges are OS-dependent (just like in C)

At most one enumeration type

```
mtype = {one, two, three};
```


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Recode Types (user defined)

```
typedef S {
  short a, b;
  byte x;
};
```

- look like C structures

Variables

Variables (same C syntax)

```
int x, y;
int z = 0;
mtype m = one;
```


Procedures

there are no procedures, only processes

```
proctype foo(int x, y; bit b){...}
```

- the **init** process (like **main** in C)
  - has no parameters
- can be activated by

```
run foo(254, 255,0);
```

```
active proctype foo(int x, y; bit b){...}
```


Scoping

- variables are global if declared outside any process
- variables are local a process if declared within its `proctype` declaration
- local variables shadow globals with the same name

Arrays and Constants

- arrays declared like variables:

```
int vector[32];
```

- indexes are zero-based
- scoping rules apply (there might be global and local vectors)

Example

```
#define length 64
mtype = {red, yellow, green};
byte state = green;
int counter;
bit memory[length];
init {
...
}
```


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Expressions

– logical: `||, &&, !`
– arithmetic: `+, -, /, %`
– relational: `>,<,<=,>=,==,!=`
– vector access: `v[i]`
– record access: `x.f`
– process creation: `run X()`

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Statements (1)

– are execution steps of processes
– an important characteristic is executability:

For instance:

```
x <= 10;
```

is the (proper) way of expressing something like:

```
wait until(x <= 10);
```


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Statements (2)

- Expression statements
  - not executable iff expression evaluates to 0
- Assignment statements
  - always executable
- Skip statements
  - always executable
  - do “nothing” (only change control location)
- Print statements
  - always executable

Statements (3)

- Assert statements

```
assert( <expression> );
```

  - always executable
  - expression evaluates to zero => program exits

- Statements are atomic
  - in a concurrent program, each statement is executed without interleaving with other processes

Control Flow (1)

- Select construct

```
if
:: <choice1> -> <stat11>; <stat12>; …
:: <choice2> -> <stat21>; <stat22>; …
…
fi;
```

- What does it do?
  - if a (random) choice is executable, continues execution with the corresponding branch
  - if no choice is executable, the whole select is not executable
  - if more than one choice is executable, we say the selection is non-deterministic

Control Flow (2)

- Loop construct

```
do
:: <choice1> -> <stat11>; <stat12>; …
:: <choice2> -> <stat21>; <stat22>; …
…
od;
```

- What does it do?
  - same as the selection, except that at the end of a branch it loops back and repeats the choice selection

Control Flow (3)

- The `else` choice
  - is executable only when no other choice is executable
- The `break` statement
  - transfers control at the end of loop
- The `goto` statement
  - transfers control to a labeled location

Traffic Light Example

```
mtype = {red, yellow, green};
byte state = green;
init {
  do
  :: (state == green) -> state = yellow;
  :: (state == yellow) -> state = red;
  :: (state == red) -> state = green;
  od
}
```


Concurrency

- Processes can spawn other processes using the run expression

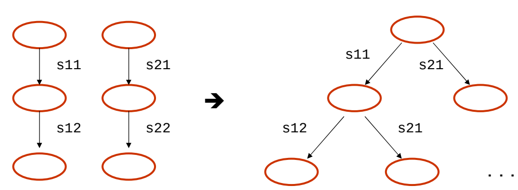
```
proctype foo(int x; byte y) {…}

init {
  int pid;
  pid = run foo(256, 255);
  /* or simply: */
  run foo(256, 255);
  …
}
```


Interleaving

- Premises:
  - two or more processes composed of atomic statements
  - one processor shared between processes
- Problems:
  - worst-case complexity is exponential in number of processes
  - improper mutex (locking) may cause race conditions

Complexity

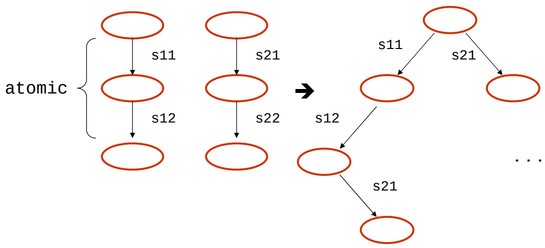


- how many states can be reached in this example?
- express this number as function of:

  K = number of processes

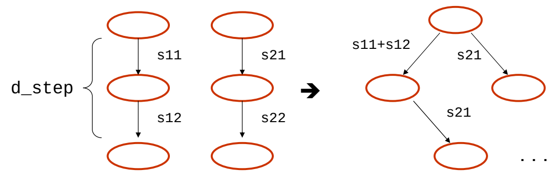
  N = number of states/process

Reducing Complexity (1)



- if a statement inside `atomic` is not executable, transfer temporarily control to another process

Reducing Complexity (2)



- if a statement inside d_`step` is not executable => error (block inside d_step)
- no `if, do, break, goto, run` allowed inside d_`step` (i.e., deterministic step)

Apprentice Example

- Good apprentice

```
int counter = 0;
active[2] proctype incr() {
  counter = counter + 1;
}
```

- creates 2 identical copies,
- share variable `counter`
- interleaving

Apprentice Example

- Good apprentice

```
int counter = 0;
active[2] proctype incr() {
  counter = counter + 1;
}
```

- Bad apprentice

```
int counter = 0;
active[2] proctype incr() {
  int tmp;
  tmp = counter + 1;
  counter = tmp;
}
```

Apprentice Example

- Good apprentice

```
int counter = 0;
active[2] proctype incr() {
  counter = counter + 1;
}
```

- Bad apprentice

```
int counter = 0;
active[2] proctype incr() {
  int tmp;
  tmp = counter + 1;  } atomic
  counter = tmp;      }
}
```


Mutual Exclusion (bad) Example

```
proctype Y() {
  x = 1;
  y == 0;
  mutex ++;
  mutex --;
  x = 0;
}
```

```
proctype X() {
  y = 1;
  x == 0;
  mutex ++;
  mutex --;
  y = 0;
}
```

```
proctype monitor() {
  assert(mutex != 2);
}
```


Dekker's Mutual Exclusion

```
proctype A() {
  x = 1;
  turn = Bturn;
  (y == 0) || (turn == Aturn);
  mutex ++;
  mutex --;
  x = 0;
}
```

```
proctype B() {
  y = 1;
  turn = Aturn;
  (x == 0) || (turn == Bturn);
  mutex ++;
  mutex --;
  y = 0;
}
```

```
proctype monitor() {
  assert(mutex != 2);
}
```


Bakery Mutual Exclusion

```
proctype A() {
  do
  :: 1 -> turnA = 1;
       turnA = turnB + 1;
       (turnB == 0) || (turnA < turnB);
       mutex ++; mutex --;
       turnA = 0;
  od
}
```

Communication

1. Message passing
2. Rendez-vous synchronization

- Both methods rely on channels:

```
chan q = [<dim>] of {<type>};
chan q; /* just declaration */
```

  - if `dim` is 0 then `q` is a rendez-vous port
  - otherwise `q` is an *asynchronous* channel

Communication (2)

- Send statement `q ! <expr>;`
  - for rendez-vous channels is executable iff another process is ready to receive at the same time ➔ both processes are involved in a rendez-vous
  - for asynchronous queues is executable iff the queue is not full

Communication (2)

- Receive statement

```
q ? <var>;
q ? _;
```

  - for rendez-vous channels is executable iff another process is ready to send at the same time ➔ both processes are involved in a rendez-vous
  - for asynchronous queues is executable iff the queue is not empty

Communication (3)

- Channel test statement `q ? <expr>;`
  - same as receive for rendez-vous channels
  - for asynchronous queues is executable iff the first value in the queue matches the result of `expr`

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Inter-locking Example

```
chan lock = [1] of bit;
proctype foo(chan q) {
  q ? 1;
  /* critical section */
  q ! 1;
}
init {
  lock ! 1;
  run foo(lock);
  run foo(lock);
}
```


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Correctness Claims

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Claims

- basic assertions
- end state labels
- progress state labels
- accept state labels
- never claims
- trace assertions

all provide means to check requirements

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Basic Assertions

```
assert {expression}
```

SPIN reports any violation of assertions during simulation or verification.

```
proctype monitor() {
  assert(mutex != 2);
}
```

```
spin: line 2 “pan”, Error: assertion violated
```

Meta Labels

- labels with special meaning
- reserved
- only available in verification mode

Labels for

- end states
- progress states
- accept states

End States

- an end state in PROMELA is a state with no successors
- end states can be labeled as valid by introducing labels that start with end
  - `end0,endsome, …`
- at the end of each process there is a default valid end state
- a deadlock is a state with no successors in which at least one process is not in a valid end state

Example End State

```
proctype Y() {
  x = 1;
endY:
  y == 0;
  mutex ++;
  mutex --;
  x = 0;
}
```

```
proctype X() {
  y = 1;
endX:
  x == 0;
  mutex ++;
  mutex --;
  y = 0;
}
```

Allow processes to block.

Progress States

- similar to end states
- progress states are introduced by labels that start with `progress`
  - `progress0,progresssome, …`
- verifier must in each execution reach progress label infinitely often
- typically requires fairness

Example Progress State

```
proctype Y() {
  x = 1;
  y == 0;
  mutex ++;
  mutex --;
progressY:
  x = 0;
}
```

```
proctype X() {
  y = 1;
  x == 0;
  mutex ++;
  mutex --;
progressX:
  y = 0;
}
```

Mutual exclusion infinitely many times for both processes.

Accept States

- dual to end states
- accept states are introduced by labels that start with `accept`
  - `accept0, acceptsome, …`
- verifier must not reach in any execution reach accept label in infinitely often

Example Accept State

```
proctype Y() {
  x = 1;
  y == 0;
  mutex ++;
  mutex --;
acceptY:
  x = 0;
}
```

```
proctype X() {
  y = 1;
  x == 0;
  mutex ++;
  mutex --;
y = 0;
}
```

Mutual exclusion infinitely many times for X only.

Never Claims (1)

```
never {statement}
```

- special type of process, is instantiated once
- used to detect illegal behaviors
- SPIN has LTL to never claim translator

Never Claims (2)

```
never {statement}
```

SPIN reports any violation of never claims during simulation or verification.

Invariant p:

```
never {
      do
      :: !p -> break
      :: else
      od
      }
```


SPIN Options

Simulation

random simulation: `spin model`

- -i performs interactive simulation
- -jN skips first N steps of random/guided sim.
- -p shows execution of states
- -s/-r shows details about send/receive
- -t interactive sim following on produced execution trace
- -v verbose

and many more!

Generating Verifier

- -a syntax check and verifier generation
- -f formula generates never claim from LTL
- -F file same but from file

Verification

-A suppresses basic assertion violations
-a use for accept cycle detection
-f uses weak fairness
-l use for progress cycles

References

- http://spinroot.com/
- quick references http://spinroot.com/spin/Man/Quick.html

you better read them ☺