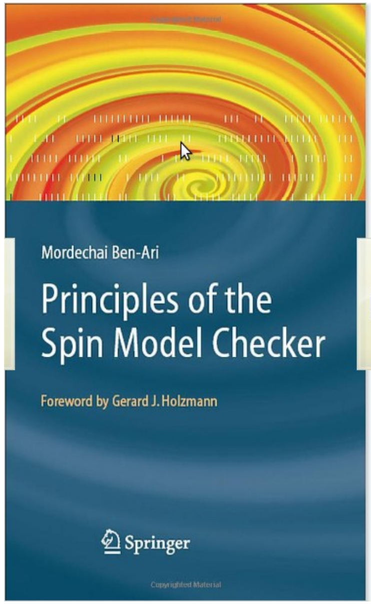


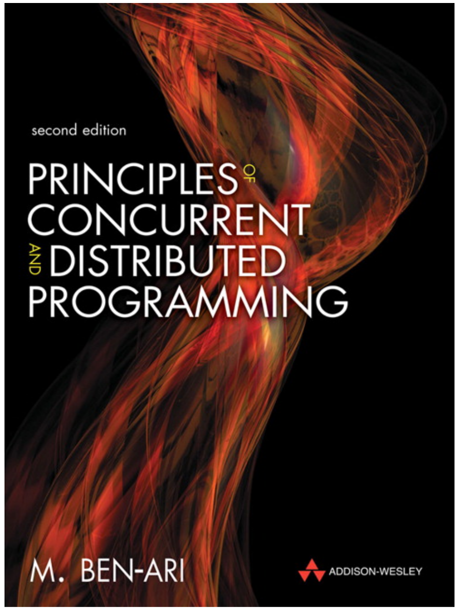

Mordechai Ben-Ari

Principles of the
Spin Model Checker

Springer, 2008

ISBN: 978-1-84628-769-5






Mordechai Ben-Ari

Principles of
Concurrent and
Distributed
Programming

Second Edition
Addison-Wesley, 2008

ISBN: 978-0-32131-283-9



http://www.springer.com/computer/swe/book/978-1-84628-769-5

Supplementary material (zip, 38 kB)

978-1-84628-769-5-additional material.zip



# Chapter 3

# Concurrency

A ***concurrent program*** is a set of sequential programs that can be executed in parallel.

We use the word ***process*** for the sequential programs that comprise a concurrent program and save the term ***program*** for this set of processes.



Traditionally, the word ***parallel*** is used for systems in which the executions of several programs overlap in time by running them on separate processors.

The word ***concurrent*** is reserved for potential parallelism, in which the execution may, but need not, overlap; instead, the parallelism may only be apparent since it may be implemented by sharing the resources of a small number of processors, often only one.



The challenge in concurrent programming comes from the need to ***synchronize*** the execution of different processes and to enable them to ***communicate***.

It turns out to be extremely difficult to implement safe and efficient synchronization and communication.



***Multitasking*** is a simple generalization from the concept of overlapping I/O with a computation to overlapping the computation of one program with that of another.

Multitasking is the central function of the *kernel* of all modern operating systems.

A ***scheduler*** program is run by the operating system to determine which process should be allowed to run for the next interval of time. The scheduler can take into account priority considerations, and usually implements *time-slicing*, where computations are periodically interrupted to allow a fair sharing of the computational resources, in particular, of the CPU.

A ***concurrent program*** consists of a finite set of (sequential) processes. The processes are written using a finite set of ***atomic statements***. The execution of a concurrent program proceeds by executing a sequence of the atomic statements obtained by ***arbitrarily interleaving*** the atomic statements from the processes. A ***computation*** is an execution sequence that can occur as a result of the interleaving. Computations are also called ***scenarios***.

During a computation the ***control pointer*** (*instruction pointer*, *location counter*) of a process indicates the next statement that can be executed by that process. Each process has its own control pointer.



## Hello World! (`hello_world.pml`, simulation 1)

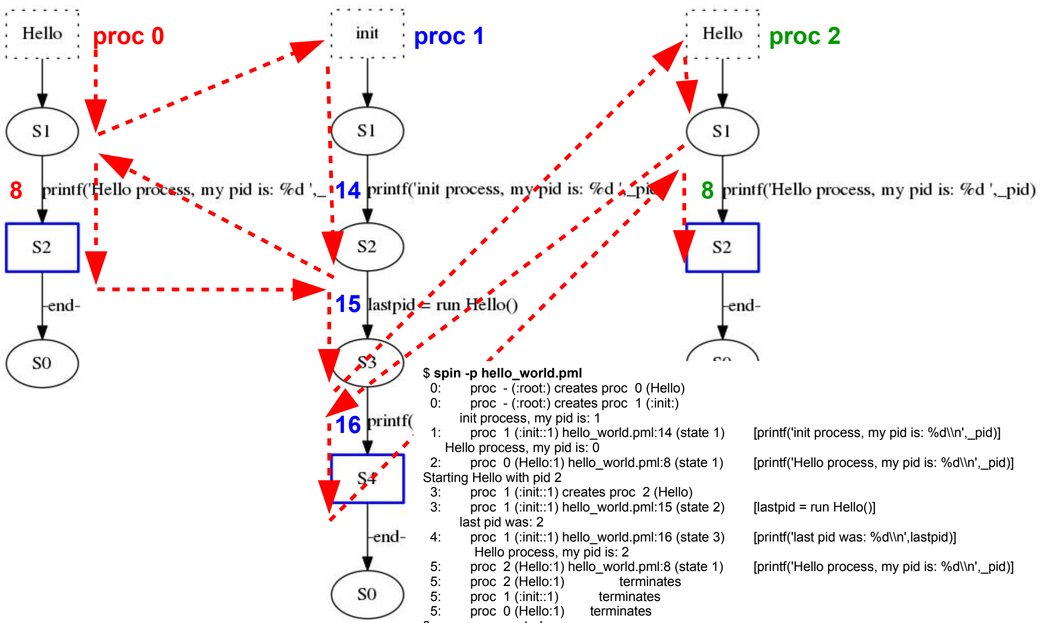
```
 1  /*
 2     A "Hello World" Promela model for SPIN
 3     Theo C. Ruys - SPIN Beginners' Tutorial
 4     spinroot.com/spin/Doc/SpinTutorial.pdf
 5  */
 6
 7  active proctype Hello() {
 8      printf("Hello process, my pid is: %d\n", _pid)
 9  }
10
11  init {
12      int lastpid;
13
14      printf("init process, my pid is: %d\n", _pid);
15      lastpid = run Hello();
16      printf("last pid was: %d\n", lastpid);
17  }
```

```
$ spin hello_world.pml
          init process, my pid is: 1
      Hello process, my pid is: 0
          last pid was: 2
              Hello process, my pid is: 2
3 processes created
```

14, 8, 15, 16, 8



## Hello World! (`hello_world.pml, simulation 1`)




```
$ spin -p hello_world.pml
  0:    proc  - (:root:) creates proc  0 (Hello)
  0:    proc  - (:root:) creates proc  1 (:init:)
        init process, my pid is: 1
  1:    proc  1 (:init::1) hello_world.pml:14 (state 1)    [printf('init process, my pid is: %d\\n',_pid)]
      Hello process, my pid is: 0
  2:    proc  0 (Hello:1) hello_world.pml:8 (state 1)      [printf('Hello process, my pid is: %d\\n',_pid)]
Starting Hello with pid 2
  3:    proc  1 (:init::1) creates proc  2 (Hello)
  3:    proc  1 (:init::1) hello_world.pml:15 (state 2)    [lastpid = run Hello()]
        last pid was: 2
  4:    proc  1 (:init::1) hello_world.pml:16 (state 3)    [printf('last pid was: %d\\n',lastpid)]
          Hello process, my pid is: 2
  5:    proc  2 (Hello:1) hello_world.pml:8 (state 1)      [printf('Hello process, my pid is: %d\\n',_pid)]
  5:    proc  2 (Hello:1)           terminates
  5:    proc  1 (:init::1)       terminates
  5:    proc  0 (Hello:1)      terminates
3 processes created
```



## Hello World! (`hello_world.pml`, simulation 2)

```
 1  /*
 2     A "Hello World" Promela model for SPIN
 3     Theo C. Ruys - SPIN Beginners' Tutorial
 4     spinroot.com/spin/Doc/SpinTutorial.pdf
 5  */
 6
 7  active proctype Hello() {
 8      printf("Hello process, my pid is: %d\n", _pid)
 9  }
10
11  init {
12      int lastpid;
13
14      printf("init process, my pid is: %d\n", _pid);
15      lastpid = run Hello();
16      printf("last pid was: %d\n", lastpid);
17  }
```

```
$ spin hello_world.pml
          init process, my pid is: 1
              Hello process, my pid is: 2
      Hello process, my pid is: 0
          last pid was: 2
3 processes created
```

14, 15, 8, 8, 16

## Hello World! (hello_world.pml, simulation 3)

```
 1  /*
 2     A "Hello World" Promela model for SPIN
 3     Theo C. Ruys - SPIN Beginners' Tutorial
 4     spinroot.com/spin/Doc/SpinTutorial.pdf
 5  */
 6
 7  active proctype Hello() {
 8      printf("Hello process, my pid is: %d\n", _pid)
 9  }
10
11  init {
12      int lastpid;
13
14      printf("init process, my pid is: %d\n", _pid);
15      lastpid = run Hello();
16      printf("last pid was: %d\n", lastpid);
17  }
```

```
$ spin hello_world.pml
      Hello process, my pid is: 0
          init process, my pid is: 1
              Hello process, my pid is: 2
          last pid was: 2
3 processes created
```

8, 14, 15, 8, 16



## Hello World! (hello_world.pml, simulation 4)

```
 1  /*
 2     A "Hello World" Promela model for SPIN
 3     Theo C. Ruys - SPIN Beginners' Tutorial
 4     spinroot.com/spin/Doc/SpinTutorial.pdf
 5  */
 6
 7  active proctype Hello() {
 8      printf("Hello process, my pid is: %d\n", _pid)
 9  }
10
11  init {
12      int lastpid;
13
14      printf("init process, my pid is: %d\n", _pid);
15      lastpid = run Hello();
16      printf("last pid was: %d\n", lastpid);
17  }
```

```
$ spin hello_world.pml
          init process, my pid is: 1
      Hello process, my pid is: 0
              Hello process, my pid is: 2
          last pid was: 2
3 processes created
```

14, 8, 15, 8, 16
14, 15, 8, 8, 16



## Hello World! (hello_world.pml.pml)

```
 1  /*
 2     A "Hello World" Promela model for SPIN
 3     Theo C. Ruys - SPIN Beginners' Tutorial
 4     spinroot.com/spin/Doc/SpinTutorial.pdf
 5  */
 6
 7  active proctype Hello() {
 8      printf("Hello process, my pid is: %d\n", _pid)
 9  }
10
11  init {
12      int lastpid;
13
14      printf("init process, my pid is: %d\n", _pid);
15      lastpid = run Hello();
16      printf("last pid was: %d\n", lastpid);
17  }
```

| | | |
|---|---|---|
| 8, 14, 15, 8, 16 | 14, 15, 8, 8, 16 | 14, 15, 8, 16, 8 |
| 8, 14, 15, 16, 8 | 14, 15, 8, 16, 8 | 14, 15, 16, 8, 8 |
| 14, 8, 15, 8, 16 | 14, 15, 8, 8, 16 | |
| 14, 8, 15, 16, 8 | 14, 15, 16, 8, 8 | |



# Section 3.1

# Interleaving

## Listing 3.1. Interleaving statements (`interleave1.pml`)

```
byte    n = 0;

active proctype P() {
  n = 1;
  printf("Process P, n = %d\n", n);
}

active proctype Q() {
  n = 2;
  printf("Process Q, n = %d\n", n);
}
```



```
$ spin interleave1.pml
      Process P, n = 2
          Process Q, n = 2
2 processes created

$ spin interleave1.pml
      Process P, n = 1
          Process Q, n = 1
2 processes created

$ spin interleave1.pml
      Process P, n = 1
          Process Q, n = 2
2 processes created

$ spin interleave1.pml
          Process Q, n = 2
      Process P, n = 1
2 processes created

$ spin interleave1.pml
      Process P, n = 1
          Process Q, n = 2
2 processes created
```

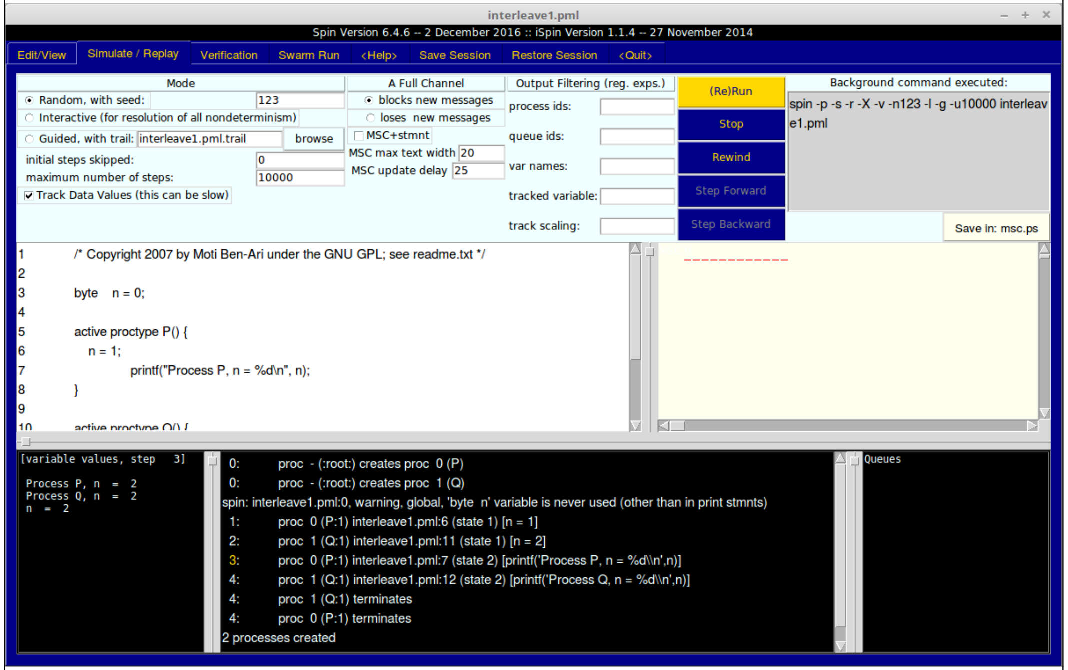


```
Process  Statement   n    Output
----------------------------------

P        n = 1       0

P        printf(P)   1

Q        n = 2       1    P, n = 1

Q        printf(Q)   2

                          Q, n = 2
```



## Six possible computations of the program:

```
-------------------------------------------------------------
    1     |    2     |    3     |    4     |    5     |    6
=============================================================
          |          |          |          |          |
 n = 1    |n = 1     |n = 1     |n = 2     |n = 2     |n = 2
          |          |          |          |          |
 printf(P)|n = 2     |n = 2     |printf(Q) |n = 1     |n = 1
          |          |          |          |          |
 n = 2    |printf(P) |printf(Q) |n = 1     |printf(Q) |printf(P)
          |          |          |          |          |
 printf(Q)|printf(Q) |printf(P) |printf(P) |printf(P) |printf(Q)
```






We say that the computations of a program are obtained by ***arbitrarily interleaving*** of the statements of the processes.

If each process $p_i$ were run by itself, a computation of the process would be a sequence of states $(s_i^0, s_i^1, s_i^2, \ldots)$, where state $s_i^{j+1}$ follows state $s_i^j$ if and only if it is obtained by executing the statement at the location counter of $p_i$ in $s_i^j$.

The word "interleaving" is intended to represent the image of "selecting" a statement from the possible computations of the individual processes and "merging" then into a computation of all the processes of the system.



For the program in Listing 3.1, a state is a triple consisting of the value of **n** and the location counters of processes **P** and **Q**.

The computation obtained by executing the processes by themselves can be represented as

```
(0, 6, -) -> (1, 7, -) -> (1, 8, -)
```

for process **P**, and

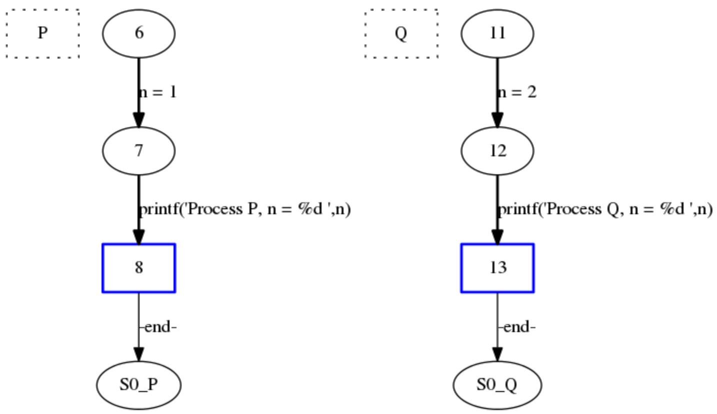
```
(0, -, 11) -> (2, -, 12) -> (2, -, 13)
```

for process **Q**.



The third computation above is obtained by interleaving the two separate computations:

```
(0, 6, -)   -> "select" from P
(1, 7, 11)  -> "select" from Q
(2, 7, 12)  -> "select" from Q
(2, 7, 13)  -> "select" from P
(2, 8, 13)
```






```
$ spin -p -g interleave1.pml # print all statements and global vars
  0:    proc  - (:root:) creates proc  0 (P)
  0:    proc  - (:root:) creates proc  1 (Q)
  1:    proc  1 (Q:1) interleave1.pml:11 (state 1)      [n = 2]
                n = 2
          Process Q, n = 2
  2:    proc  1 (Q:1) interleave1.pml:12 (state 2)      [printf('Process Q, n = 
%d\\n',n)]
  3:    proc  0 (P:1) interleave1.pml:6 (state 1)       [n = 1]
                n = 1
      Process P, n = 1
  4:    proc  0 (P:1) interleave1.pml:7 (state 2)       [printf('Process P, n = 
%d\\n',n)]
  4:    proc  1 (Q:1)       terminates
  4:    proc  0 (P:1)       terminates
2 processes created
```



# Section 3.2

# Atomicity



Statements in PROMELA are *atomic*. At each step, the statement pointed to by the location counter of some (arbitrary) process is executed in its entirely.

So, for example, in Listing 3.1 it is not possible for the assignment statements to overlap in a way that causes n to receive some value other than 1 or 2.

## Warning

Expressions in PROMELA are *statements*.

In an **if**- or **do**-statement it is possible for interleaving to occur between the evaluation of the expression (statement) that is the guard and the execution of the statement after the guard.



In the following example, assume that **a** is a global variable; you ***cannot*** infer that division by zero is impossible:

```
if
:: a != 0 ->
      c = b / a
:: else ->
      c = b
fi
```



## Collatz conjucture (`collatz.py`) (1/3)

```
$ cat -n collatz.py | expand
     1  import sys,threading
     2
     3  def odd():
     4      global n
     5      while True:
     6          if n==1: break
     7          if n& 1:
     8              n= 3*n+1
     9              print(n,end=' ')
    10
    11  def even():
    12      global n
    13      while True:
    14          if n==1: break
    15          if not n& 1:
    16              n>>= 1
    17              print(n,end=' ')
    18
...
```



## Collatz conjucture (`collatz.py`) (2/3)

```
...
    19  try:
    20      n= int(sys.argv[1])
    21  except IndexError:
    22      print("Missed o wrong input")
    23      sys.exit(1)
    24
    25  assert n>0, "Must be positive integer"
    26  print(n,end=' ')
    27  t1= threading.Thread(target=odd)
    28  t2= threading.Thread(target=even)
    29  t1.start(), t2.start()
    30  t1.join(), t2.join()
    31  print()
```

```
$ python3 collatz.py 12
12 6 3 10 5 16 8 4 2 1

$ python3 collatz.py 19
19 58 29 88 44 22 11 34 17 52 26 13 40 20 10 5 16 8 4 2 1
```

## Collatz conjucture (`collatz.py`) (3/3)

```
$ python3 collatz.py 19
^C19 58 29 88 44 22 11 34 17 52 26 13 40 20 10 5 16 8 4 2 1 4 Traceback
(most recent call last):
  File "collatz.py", line 30, in <module>
    t1.join(), t2.join()
  File "/usr/lib/python3.6/threading.py", line 1056, in join
    self._wait_for_tstate_lock()
  File "/usr/lib/python3.6/threading.py", line 1072, in
_wait_for_tstate_lock
    elif lock.acquire(block, timeout):
KeyboardInterrupt
^CException ignored in: <module 'threading' from
'/usr/lib/python3.6/threading.py'>
Traceback (most recent call last):
  File "/usr/lib/python3.6/threading.py", line 1294, in _shutdown
    t.join()
  File "/usr/lib/python3.6/threading.py", line 1056, in join
    self._wait_for_tstate_lock()
  File "/usr/lib/python3.6/threading.py", line 1072, in
_wait_for_tstate_lock
    elif lock.acquire(block, timeout):
KeyboardInterrupt
```



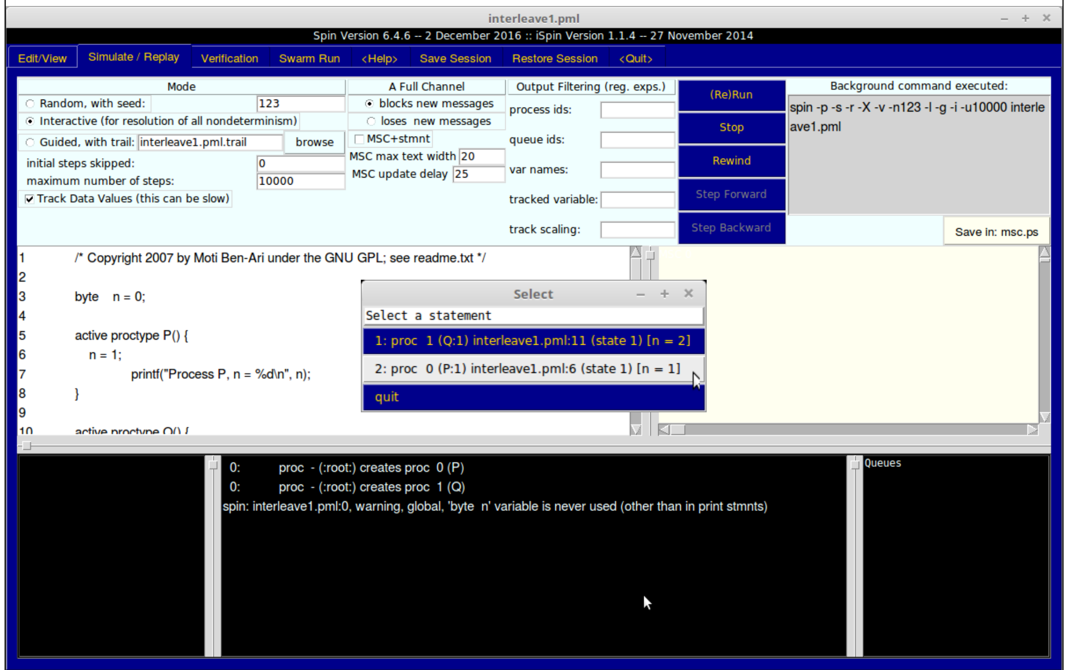
# Section 3.3

# Interactive simulation



```
$ spin -i interleave1.pml  # interactive (random simulation)
Select a statement
        choice 1: proc  1 (Q:1) interleave1.pml:11 (state 1) [n = 2]
        choice 2: proc  0 (P:1) interleave1.pml:6 (state 1) [n = 1]
Select [1-2]: 1
Select a statement
        choice 1: proc  1 (Q:1) interleave1.pml:12 (state 2) [printf('Process Q, n
= %d\\n',n)]
        choice 2: proc  0 (P:1) interleave1.pml:6 (state 1) [n = 1]
Select [1-2]: 2
Select a statement
        choice 1: proc  1 (Q:1) interleave1.pml:12 (state 2) [printf('Process Q, n
= %d\\n',n)]
        choice 2: proc  0 (P:1) interleave1.pml:7 (state 2) [printf('Process P, n =
%d\\n',n)]
Select [1-2]: q
$
```





# Section 3.4

# Interference between processes



## Listing 3.2. Interference between two processes (`interleave2.pml`)

```
byte    n = 0;

active proctype P() {
  byte temp;
  temp = n + 1;
  n = temp;
  printf("Process P, n = %d\n", n)
}

active proctype Q() {
  byte temp;
  temp = n + 1;
  n = temp;
  printf("Process Q, n = %d\n", n)
}
```

n = n + 1

**Sentencias atómicas!**



```
$ spin interleave2.pml
          Process Q, n = 2
      Process P, n = 2
2 processes created

$ spin interleave2.pml
          Process Q, n = 1
      Process P, n = 2
2 processes created

$ spin interleave2.pml
          Process Q, n = 1
      Process P, n = 1
2 processes created

$ spin interleave2.pml
          Process Q, n = 2
      Process P, n = 2
2 processes created

$ spin interleave2.pml
      Process P, n = 1
          Process Q, n = 2
2 processes created

$ spin interleave2.pml
          Process Q, n = 1
      Process P, n = 1
2 processes created
```



Un pequeño ejercicio:

Usando la simulación interactiva, obtener que el valor de la variable **`n`** se imprime dos veces como

**`n = 1`**

## Fig. 3.1. Perfect interleaving

| Process | Statement | n | P:temp | Q:temp | Output |
|---|---|---|---|---|---|
| P | temp = n + 1 | 0 | 0 | 0 | |
| Q | temp = n + 1 | 0 | 1 | 0 | |
| P | n = temp | 0 | 1 | 1 | |
| Q | n = temp | 1 | 1 | 1 | |
| P | printf(P) | 1 | 1 | 1 | |
| Q | printf(Q) | 1 | 1 | 1 | P, n = 1<br>Q, n = 1 |



This program is a simple model of a CPU that performs computation in registers:

```
load    R1, n
add     R1, #1
store   R1, n
```

In the Promela program the variable `n` represents a memory cell and the variables `temp` represent the register. In a multiprocess system each process has its own copy of the contents of the registers, which is loaded into the CPU registers and saved in memory during a context switch.



# Section 3.5

# Sets of processes



## Listing 3.3. Instantiating two processes (interleave3.pml)

```
byte    n = 0;

active [2] proctype P() {
        byte temp;
        temp = n + 1;
        n = temp;
        printf("Process P%d, n = %d\n", _pid, n)
}
```

```
$ spin interleave3.pml
          Process P1, n = 1
      Process P0, n = 1
2 processes created

$ spin interleave3.pml
          Process P1, n = 2
      Process P0, n = 2
2 processes created
```

Listing 3.4. The **init** process (`init.pml`)

```
byte n;

proctype P(byte id; byte incr) {
  byte temp;
  temp = n + incr;
  n = temp;
  printf("Process P%d, n = %d\n", id, n)
}

init {
  n = 1;
  atomic {
    run P(1, 10);
    run P(2, 15)
  }
}
```



# Warning

The formal parameters of a **proctype** are separated with semicolons, not commas.

# Advanced: The `run` operator

**run** is an *operator*, so **run** `P()` is an expression, not a statement, and it returns a value: the process ID of the process that is instantiated, or zero if the maximum number of processes (255) have already been instantiated.



# Section 3.6

# Interference revisited



`Count_s.java` (1/4)

```
/* Copyright (C) 2006 M. Ben-Ari */

class Count_s extends Thread {
  static volatile int n = 0;
  static int N;

  public void run() {
    int temp;
    for (int i = 0; i < N; i++) {
      /* temp = n; n = temp + 1; */
      n++;
    }
  }

...
```

## Count_s.java (2/4)

```java
  public static void main(String[] args) {
    if (args.length > 0) {
      try { N = Integer.parseInt(args[0]); }
      catch (NumberFormatException e) {
        System.err.println("Argument" + " must be an integer");
        System.exit(1);
      }
    }

    Count_s p = new Count_s();
    Count_s q = new Count_s();
    p.start();
    q.start();
    try { p.join(); q.join(); }
    catch (InterruptedException e) { }
    System.out.println(N + " + " + N + " = " + n);
  }
}
```



## Count_s.java (3/4)

```
$ java Count_s 10
10 + 10 = 20
$ java Count_s 10
10 + 10 = 20
$ java Count_s 10
10 + 10 = 12
$ java Count_s 10
10 + 10 = 20
$ java Count_s 10
10 + 10 = 20
$ java Count_s 100
100 + 100 = 200
$ java Count_s 100
100 + 100 = 200
$ java Count_s 100
100 + 100 = 200
$ java Count_s 100
100 + 100 = 200
```



## Count_s.java (4/4)

```
$ java Count_s 1000
1000 + 1000 = 1006
$ java Count_s 1000
1000 + 1000 = 1440
$ java Count_s 1000
1000 + 1000 = 1432
$ java Count_s 1000
1000 + 1000 = 2000
$ java Count_s 1000000
1000000 + 1000000 = 1464643
$ java Count_s 1000000
1000000 + 1000000 = 993030
$ java Count_s 1000000
1000000 + 1000000 = 1290665
$ java Count_s 1000000
1000000 + 1000000 = 1073888
$ java Count_s 1000000
1000000 + 1000000 = 1608788
```



## count.py (1/2)

count.py (~/clases/mf/04/progs)

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count.py

```python
import sys,threading

try:
    N = int(sys.argv[1])
except IndexError:
    print("You must supply iterations number")
    sys.exit(1)

count = 0

def incr():
    global count
    for i in range(N):
        count += 1

t1 = threading.Thread(target=incr)
t2 = threading.Thread(target=incr)
t1.start(), t2.start()
t1.join(), t2.join()
print("count =", count)

```

Python Ancho de la tabulación: 4 Ln 21, Col 1 INS

## count.py (2/2)

```
$ python3 count.py 1000
count = 2000

$ python3 count.py 10000
count = 20000

$ python3 count.py 100000
count = 107188

$ python3 count.py 100000
count = 199654

$ python3 count.py 1000000
count = 1219083

$ python3 count.py 1000000
count = 1559081
```



## Listing 3.5. Counting with interference

```
$ cat -n count_v6.pml
byte    n = 0, i = 0

proctype P() {
    byte i, temp
    for (i : 1 .. 10) {
        temp = n
        n = temp + 1
    }
}

init {
    atomic {
        run P()
        run P()
    }
    (_nr_pr == 1)
    printf("The value is %d\n", n)
}
```



## Listing 3.5. Counting with interference

```
$ spin count_v6.pml
      The value is 17    /* 16, 18, 15, 19, ... */
```

**¿Es posible el valor final 20?**
**¿Lo puede obtener? ¿Cómo?**

**¿Cómo se obtiene el valor final 2?**



## Counting without interference en Promela

```
$ cat -n count_v6_short.pml
byte    n = 0

proctype P() {
    byte i
    for (i : 1 .. 10) {
        n = n + 1
    }
}

init {
    atomic {
        run P()
        run P()
    }
    (_nr_pr == 1)
    printf("The value is %d\n", n)
    assert (n == 20)
}
```

## Counting without interference en Promela

```
$ spin -a count_v6_short.pml

$ gcc pan.c -o pan

$ ./pan
...
State-vector 36 byte, depth reached 71, errors: 0
```



# Section 3.7

# Deterministic sequences of statements



## Listing 3.6. Deterministic step (`dstep.pml`)

```
 3  byte    n = 0;
 4
 5  active proctype P() {
 6    byte temp;
 7    d_step {
 8      temp = n + 1;
 9      n = temp
10    }
11    printf("Process P, n = %d\n", n)
12  }
13
14  active proctype Q() {
15    byte temp;
16    d_step {
17      temp = n + 1;
18      n = temp
19    }
20    printf("Process Q, n = %d\n", n)
21  }
```



```
$ spin -p -g -l dstep.pml
  0:    proc  - (:root:) creates proc  0 (P)
  0:    proc  - (:root:) creates proc  1 (Q)
                Q(1):temp = 1
  2:    proc  1 (Q:1) dstep.pml:18 (state 2)    [n = temp]
                n = 1
          Process Q, n = 1
  3:    proc  1 (Q:1) dstep.pml:20 (state 4)    [printf('Process Q, n = %d\\n',n)]
  3:    proc  1 (Q:1)              terminates
                P(0):temp = 2
  5:    proc  0 (P:1) dstep.pml:9 (state 2)     [n = temp]
                n = 2
      Process P, n = 2
  6:    proc  0 (P:1) dstep.pml:11 (state 4)    [printf('Process P, n = %d\\n',n)]
  6:    proc  0 (P:1)          terminates
2 processes created
```

¿Puede verificar que el resultado siempre será 2?

# Section 3.8

# Verification with assertions



## Counting with interference (`count_v6_for2.pml`)

```
$ cat -n count_v6_for2.pml
     1 byte    n = 0
     2
     3 proctype P() {
     4     byte i, temp
     5     for (i : 1 .. 10) {
     6         temp = n
     7         n = temp + 1
     8     }
     9 }
    10
    11 init {
    12     atomic {
    13         run P()
    14         run P()
    15     }
    16     (_nr_pr == 1)
    17     printf("The value is %d\n", n)
    18
    19     assert (n > 2)
    20 }
```



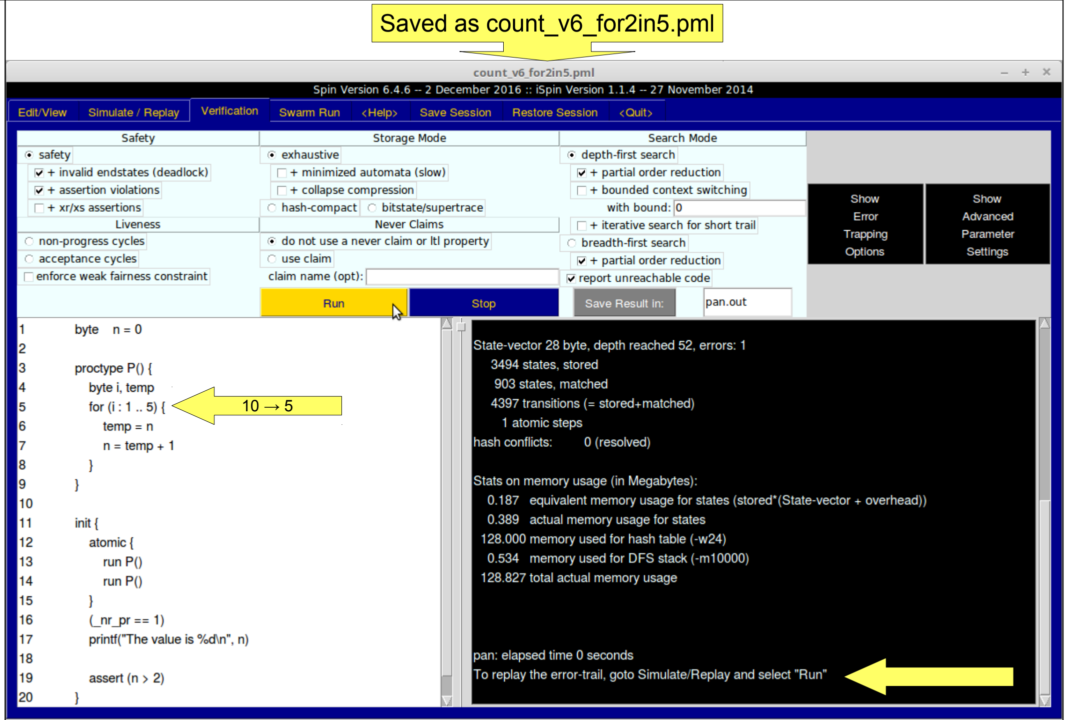
```
$ spin count_v6_for2.pml
      The value is 16

$ spin count_v6_for2.pml
      The value is 15

$ spin count_v6_for2.pml
      The value is 18

$ spin count_v6_for2.pml
      The value is 17

$ spin count_v6_for2.pml
      The value is 8

...
```



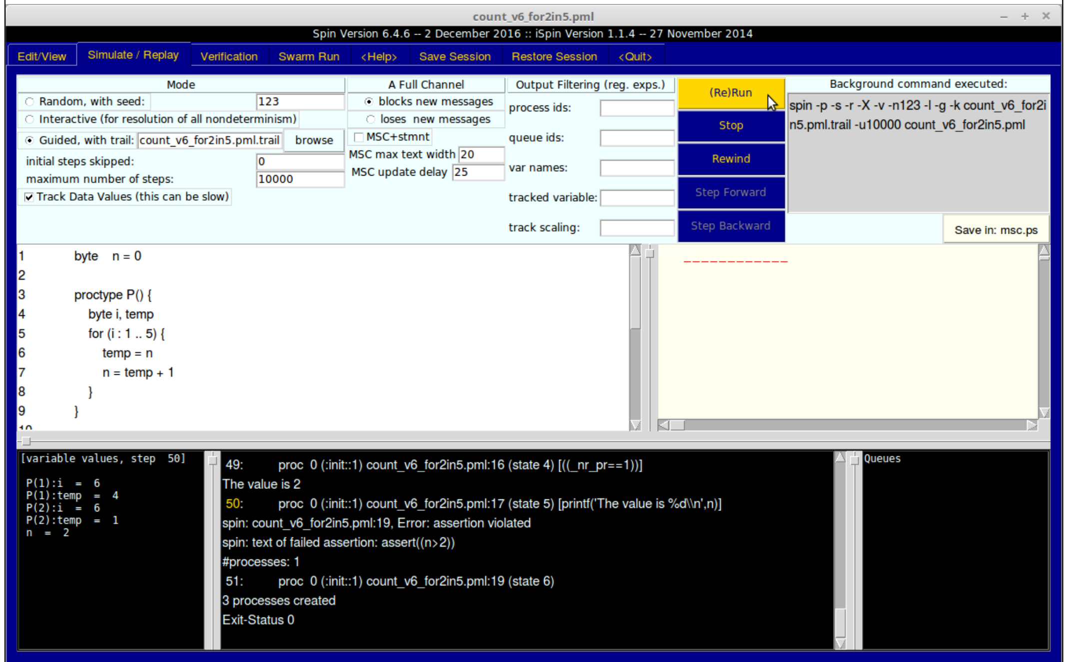
```
$ spin -a count_v6_for2.pml

$ gcc -o pan pan.c

$ ./pan
pan:1: assertion violated (n>2) (at depth 90)
pan: wrote count_v6_for2.pml.trail

(Spin Version 6.4.8 -- 2 March 2018)
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 92, errors: 1

...
```

```
$ spin -t -p -g count_v6_for2.pml
using statement merging
Starting P with pid 1
  1:     proc  0 (:init::1) count_v6_for2.pml:13 (state 1)      [(run P())]
Starting P with pid 2
  2:     proc  0 (:init::1) count_v6_for2.pml:14 (state 2)      [(run P())]
  3:     proc  2 (P:1) count_v6_for2.pml:5 (state 1)     [i = 1]
  4:     proc  2 (P:1) count_v6_for2.pml:5 (state 2)     [((i<=10))]
  5:     proc  1 (P:1) count_v6_for2.pml:5 (state 1)     [i = 1]
...
 41:     proc  2 (P:1) count_v6_for2.pml:7 (state 4)     [n = (temp+1)]
                 n = 9
 42:     proc  2 (P:1) count_v6_for2.pml:5 (state 5)     [i = (i+1)]
 43:     proc  2 (P:1) count_v6_for2.pml:5 (state 2)     [((i<=10))]
 44:     proc  1 (P:1) count_v6_for2.pml:7 (state 4)     [n = (temp+1)]
                 n = 1
...
 81:     proc  1 (P:1) count_v6_for2.pml:7 (state 4)     [n = (temp+1)]
                 n = 10
 82:     proc  1 (P:1) count_v6_for2.pml:5 (state 5)     [i = (i+1)]
 83:     proc  1 (P:1) count_v6_for2.pml:8 (state 6)     [else]
 84:     proc  2 (P:1) count_v6_for2.pml:7 (state 4)     [n = (temp+1)]
                 n = 2
 85:     proc  2 (P:1) count_v6_for2.pml:5 (state 5)     [i = (i+1)]
 86:     proc  2 (P:1) count_v6_for2.pml:8 (state 6)     [else]
 87: proc 2 terminates
 88: proc 1 terminates
 89:     proc  0 (:init::1) count_v6_for2.pml:16 (state 4)      [((_nr_pr==1))]
        The value is 2
 90:     proc  0 (:init::1) count_v6_for2.pml:17 (state 5)    [printf('The value is %d\\n',n)]
spin: count_v6_for2.pml:19, Error: assertion violated
spin: text of failed assertion: assert((n>2))
...
```










# Section 3.9

# The critical section problem

The specification of the problem:

A system consists of two or more concurrently executing processes. The statements of each process are divided into *critical* and *noncritical* sections that are repeatedly executed one after the other. A process may halt in its noncritical section, but not in its critical section. Design an algorithm for ensuring that the following specifications hold:

## Mutual exclusion

At most one process is executing its critical section at any time.



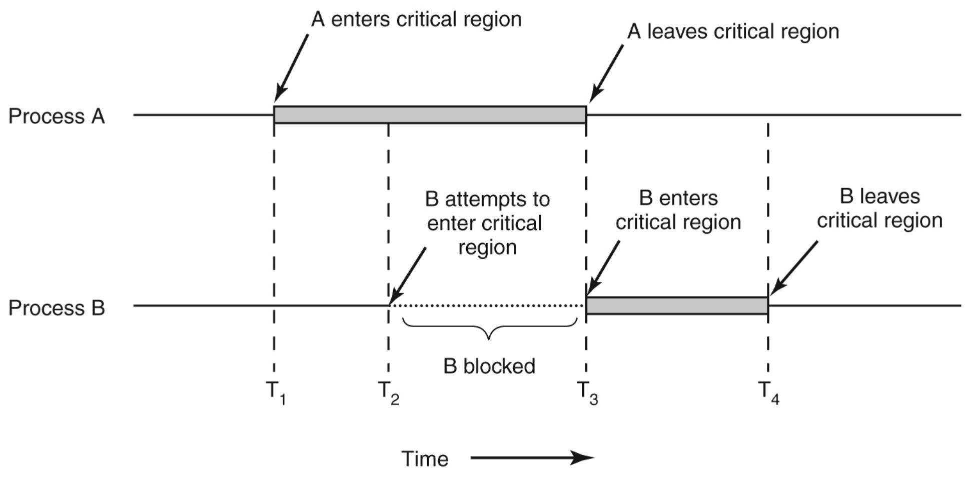



**Figure 2-22 (MOS4E). Mutual exclusion using critical regions**



## Absence of deadlock

It is impossible to reach a state in which *some processes* are trying to enter their critical sections, but *no process* is successful.

## Absence of starvation

If *any process* is trying to execute its critical section, then eventually *that process* is successful.



Listing 3.7. Incorrect solution for the critical section problem (`cs0.pml`)

```
bool wantP = false, wantQ = false;

active proctype P() {
  do
  :: printf("Noncritical section P\n");
     wantP = true;
     printf("Critical section P\n");
     wantP = false
  od
}

active proctype Q() {
  do
  :: printf("Noncritical section Q\n");
     wantQ = true;
     printf("Critical section Q\n");
     wantQ = false
  od
}
```

## Listing 3.8. Verifying mutual exclusion (`cs.pml`)

```
 3  bool wantP = false, wantQ = false;
 4  byte critical = 0;  /* a ghost variable */
 5
 6  active proctype P() {
 7    do
 8    :: printf("Noncritical section P\n");
 9       wantP = true;
10       critical++;
11       printf("Critical section P\n");
12       assert (critical <= 1);
13       critical--;
14       wantP = false
15    od
16  }
17
18  active proctype Q() {
19    do
20    :: printf("Noncritical section Q\n");
21       wantQ = true;
22       critical++;
23       printf("Critical section Q\n");
24       assert (critical <= 1);
25       critical--;
26       wantQ = false
27    od
28  }
```



```
$ spin -a cs.pml

$ gcc -o pan pan.c

$ ./pan
pan:1: assertion violated (critical<=1) (at depth 22)
pan: wrote cs.pml.trail

(Spin Version 6.4.8 -- 2 March 2018)
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 28 byte, depth reached 22, errors: 1

...
```



```
$ spin -t cs.pml
          Noncritical section Q
      Noncritical section P
          Critical section Q
          Noncritical section Q
          Critical section Q
      Critical section P
          Noncritical section Q
          Critical section Q
spin: cs.pml:24, Error: assertion violated
spin: text of failed assertion: assert((critical<=1))
spin: trail ends after 23 steps
#processes: 2
                wantP = 1
                wantQ = 1
                critical = 2
 23:   proc  1 (Q) cs.pml:25 (state 6)
 23:   proc  0 (P) cs.pml:12 (state 5)
2 processes created
```