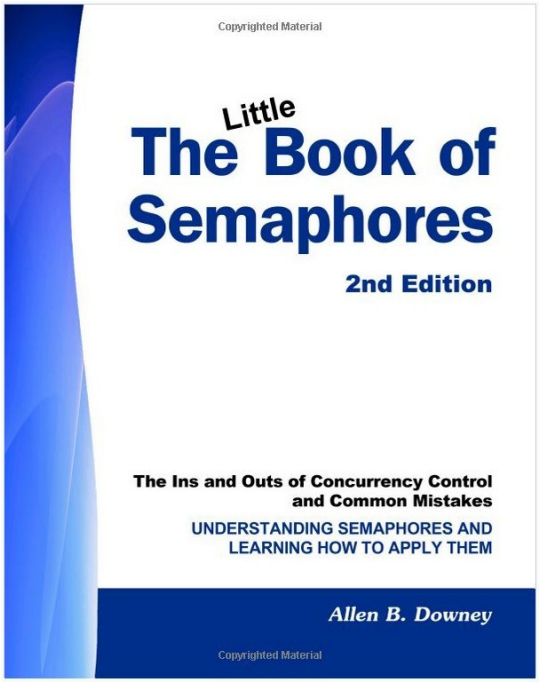



Allen B. Downey

# The Little Book of Semaphores

Version 2.2.1



http://www.greenteapress.com/semaphores/LittleBookOfSemaphores.pdf



TLBOS, Chapter 3

## Basic synchronization patterns

### 3.1 Signaling

Signaling makes it possible to guarantee that a section of code in one thread will run before a section of code in another thread; in other words, it solves the **serialization problem**.

The semaphore in the next program guarantee that the process **A** has completed the assignment to the variable **x** before the process **B** begins its assignment to the same variable.



### 3.1 Signaling (`3.1.signaling.pml`)

```
15  #define wait(sem)   atomic { sem > 0; sem-- }
16  #define signal(sem) sem++
17
18  byte sem = 0
19  byte x = 0
20
21  proctype A() {
22    x = 1
23    signal(sem)
24  }
25
26  proctype B() {
27    wait(sem)
28    x = 2
29  }
30
31  init {
32    atomic { run A(); run B() }
33    _nr_pr == 1
34    assert( x == 2 )
35  }
```

## 3.1 Signaling (3.1.signaling.pml)

```
$ spin -run 3.1.signaling.pml


(Spin Version 6.4.8 -- 2 March 2018)
        + Partial Order Reduction

Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      +

State-vector 28 byte, depth reached 11, errors: 0
...
```



TLBOS, Chapter 3

# Basic synchronization patterns

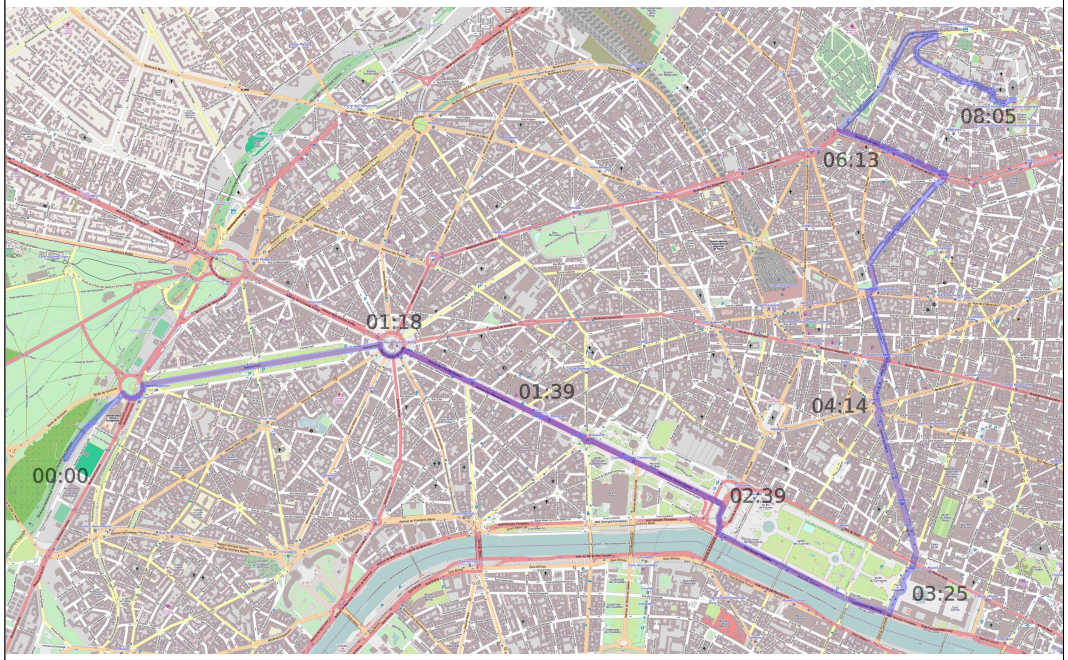
## 3.3 Rendezvous

The idea is that two threads rendezvous at a point of execution, and neither is allowed to proceed until both have arrived.




Claude Lelouch, 1976, 8 min 38 seconds





## 3.3 Rendezvous (3.3.0.rendezvous.pml)

```
$ cat -n 3.3.0.rendezvous.pml
     1 /*  The Little Book of Semaphores (2.2.1)
     2     by A. Downey
     3
     4     Chapter 3. Basic synchronization patterns
     5
     6     3.1 Signaling
     7     3.3 Rendezvous
     8                     Thread A                Thread 2
     9                     1  statement a1        1  statement b1
    10                     2  statement a2        2  statement b2
    11
    12     We want to guarantee that a1 happens before b2 and b1 happens
before a2:
    13         a1,b1,b2,a2;   a1,b1,a2,b2;   b1,a1,a2,b2;   b1,a1,b2,a2
    14     prohibiting
    15         b1,b2,a1,a2;   a1,a2,b1,b2
    16
    17     3.3.0.rendezvous.pml: all 6 possible sequences
    18 */
    19
...
```



## 3.3 Rendezvous (3.3.0.rendezvous.pml)

```
...
    20 int x = 0
    21
    22 proctype A() {
    23   x = 10*x + 1
    24   x = 10*x + 2
    25 }
    26
    27 proctype B() {
    28   x = 10*x + 3
    29   x = 10*x + 4
    30 }
    31
    32 init {
    33   atomic { run A(); run B() }
    34   _nr_pr == 1
    35   printf("x = %d\n", x)
    36   assert(x==1234 || x==1324 || x==1342 || x==3412 || x==3142 ||
x==3124)
    37 /* must be prohibited: 3412 and 1234 */
    38 }
```



## 3.3 Rendezvous (3.3.0.rendezvous.pml)

```
$ spin 3.3.0.rendezvous.pml
      x = 1342
3 processes created

$ spin 3.3.0.rendezvous.pml
      x = 1234
3 processes created

$ spin 3.3.0.rendezvous.pml
      x = 1234
3 processes created

$ spin 3.3.0.rendezvous.pml
      x = 3142
3 processes created

$ spin 3.3.0.rendezvous.pml
      x = 3412
3 processes created

...
```



## 3.3 Rendezvous (3.3.0.rendezvous.pml)

```
$ spin -run 3.3.0.rendezvous.pml

(Spin Version 6.4.8 -- 2 March 2018)
        + Partial Order Reduction

Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      +

State-vector 36 byte, depth reached 12, errors: 0
...
```

**Only these 6 sequences are possible, but two of them are prohibited!**

## 3.3.2 Rendezvous (efficient) solution (3.3.2a.rendezvous.pml)

```
$ cat -n 3.3.2a.rendezvous.pml
     1 /*  The Little Book of Semaphores (2.2.1)
     2     by A. Downey
     3
     4     Chapter 3. Basic synchronization patterns
     5
     6     3.1 Signaling
     7     3.3 Rendezvous
     8                     Thread A                Thread 2
     9                     1  statement a1         1  statement b1
    10                     2  statement a2         2  statement b2
    11
    12     We want to guarantee that a1 happens before b2 and b1 happens
before a2:
    13         a1,b1,b2,a2; a1,b1,a2,b2; b1,a1,a2,b2; b1,a1,b2,a2
    14     prohibiting
    15         b1,b2,a1,a2; a1,a2,b1,b2
    16
    17     3.3.2a Rendezvous solution (efficient)
    18 */
    19
...
```



## 3.3.2 Rendezvous (efficient) solution (3.3.2a.rendezvous.pml)

```
...
    20 #define wait(sem)   atomic { sem > 0; sem-- }
    21 #define signal(sem) sem++
    22
    23 byte aArrived = 0, bArrived = 0
    24 int x = 0
    25
    26 proctype A() {
    27   x = 10*x + 1
    28   signal(aArrived)   # a) "llegaré en 10 minutos"
    29   wait(bArrived)     # b) llega en 8, debe esperar (context switch)
    30   x = 10*x + 2
    31 }
    32
    33 proctype B() {
    34   x = 10*x + 3
    35   signal(bArrived)   # c) "ya llegué"
    36   wait(aArrived)     # d) puede seguir sin cambio del contexto (1342)
    37   x = 10*x + 4
    38 }
    39
...
```



## 3.3.2 Rendezvous (efficient) solution (3.3.2a.rendezvous.pml)

```
...
    40 init {
    41   atomic { run A(); run B() }
    42   _nr_pr == 1
    43   assert(x!=1234 && x!=3412)
    44 }
```



## 3.3.2 Rendezvous (efficient) solution (3.3.2a.rendezvous.pml)

```
$ spin -run 3.3.2a.rendezvous.pml

(Spin Version 6.4.8 -- 2 March 2018)
        + Partial Order Reduction

Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      +

State-vector 36 byte, depth reached 15, errors: 0
...
```

## 3.3.2 Rendezvous (less efficient) solution (3.3.2b.rendezvous.pml)

```
$ cat -n 3.3.2b.rendezvous.pml
     1 /*  The Little Book of Semaphores (2.2.1)
     2     by A. Downey
     3
     4     Chapter 3. Basic synchronization patterns
     5
     6     3.1 Signaling
     7     3.3 Rendezvous
     8                     Thread A                Thread 2
     9                     1  statement a1         1  statement b1
    10                     2  statement a2         2  statement b2
    11
    12     We want to guarantee that a1 happens before b2 and b1 happens
before a2:
    13         a1,b1,b2,a2; a1,b1,a2,b2; b1,a1,a2,b2; b1,a1,b2,a2
    14     prohibiting
    15         b1,b2,a1,a2; a1,a2,b1,b2
    16
    17     3.3.2b Rendezvous solution (less efficient)
    18 */
    19
...
```



## 3.3.2 Rendezvous (less efficient) solution (3.2.2b.rendezvous.pml)

```
...
    20 #define wait(sem)   atomic { sem > 0; sem-- }
    21 #define signal(sem) sem++
    22
    23 byte aArrived = 0, bArrived = 0
    24 int x = 0
    25
    26 proctype A() {
    27   x = 10*x + 1
    28   wait(bArrived)      # a) "¿cuándo llegaras?" (context switch)
    29   signal(aArrived)    # d) "pardon, ya estoy" (1324 o 1342)
    30   x = 10*x + 2
    31 }
    32
    33 proctype B() {
    34   x = 10*x + 3
    35   signal(bArrived)    # b) "ya llegué"
    36   wait(aArrived)      # c) "pero tú no estás" (context switch extra)
    37   x = 10*x + 4
    38 }
    39
...
```



## 3.3.2 Rendezvous (less efficient) solution (3.3.2b.rendezvous.pml)

```
...
    40 init {
    41   atomic { run A(); run B() }
    42   _nr_pr == 1
    43   assert(x!=1234 && x!=3412)
    44 }
    45
```



## 3.3.2 Rendezvous (less efficient) solution (3.3.2b.rendezvous.pml)

```
$ spin -a 3.3.2b.rendezvous.pml

(Spin Version 6.4.8 -- 2 March 2018)
        + Partial Order Reduction

Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      +

State-vector 36 byte, depth reached 15, errors: 0
...
```

## 3.3.3 Rendezvous Deadlock #1 (3.3.3.rendezvous.pml)

```
$ cat -n 3.2.3.rendezvous.pml
     1 /*  The Little Book of Semaphores (2.1.5)
     2     by A. Downey
     3
     4     Chapter 3. Basic synchronization patterns
     5
     6     3.1 Signaling
     7     3.2 Rendezvous
     8                     Thread A                Thread 2
     9                     1  statement a1         1  statement b1
    10                     2  statement a2         2  statement b2
    11
    12     We want to guarantee that a1 happens before b2 and b1 happens
before a2:
    13         a1,b1,b2,a2; a1,b1,a2,b2; b1,a1,a2,b2; b1,a1,b2,a2
    14     prohibiting
    15         b1,b2,a1,a2; a1,a2,b1,b2
    16
    17     3.2.3 Deadlock #1
    18 */
    19
...
```



## 3.3.3 Rendezvous Deadlock #1 (3.3.3.rendezvous.pml)

```
...
    20 #define wait(sem)   atomic { sem > 0; sem-- }
    21 #define signal(sem) sem++
    22
    23 byte aArrived = 0, bArrived = 0;
    24 int x = 0
    25
    26 proctype A() {
    27   x = 10*x + 1
    28   wait(bArrived)
    29   signal(aArrived)
    30   x = 10*x + 2
    31 }
    32
    33 proctype B() {
    34   x = 10*x + 3
    35   wait(aArrived)
    36   signal(bArrived)
    37   x = 10*x + 4
    38 }
    39
...
```



## 3.3.3 Rendezvous Deadlock #1 (3.3.3.rendezvous.pml)

```
...
    40 init {
    41   atomic { run A(); run B() }
    42   _nr_pr == 1
    43   assert(x!=1234 && x!=3412)
    44 }
```



## 3.3.3 Rendezvous Deadlock #1 (3.3.3.rendezvous.pml)

```
$ spin -run 3.3.3.rendezvous.pml
pan:1: invalid end state (at depth 3)
pan: wrote 3.3.3.rendezvous.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    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      +

State-vector 36 byte, depth reached 4, errors: 1
...
```

## 3.3.3 Rendezvous Deadlock #1 (3.3.3.rendezvous.pml)

```
$ spin 3.3.3.rendezvous.pml
      timeout
#processes: 3
                aArrived = 0
                bArrived = 0
                x = 31
  4:    proc  2 (B:1) 3.3.3.rendezvous.pml:35 (state 4)
  4:    proc  1 (A:1) 3.3.3.rendezvous.pml:28 (state 4)
  4:    proc  0 (:init::1) 3.3.3.rendezvous.pml:42 (state 4)
3 processes created
```



## 3.3.3 Rendezvous Deadlock #1 (3.3.3.rendezvous.pml)

```
$ spin -p 3.3.3.rendezvous.pml
  0:    proc  - (:root:) creates proc  0 (:init:)
Starting A with pid 1
  1:    proc  0 (:init::1) creates proc  1 (A)
  1:    proc  0 (:init::1) 3.3.3.rendezvous.pml:41 (state 1)    [(run A())]
Starting B with pid 2
  2:    proc  0 (:init::1) creates proc  2 (B)
  2:    proc  0 (:init::1) 3.3.3.rendezvous.pml:41 (state 2)    [(run B())]
  3:    proc  1 (A:1) 3.3.3.rendezvous.pml:27 (state 1) [x = ((10*x)+1)]
  4:    proc  2 (B:1) 3.3.3.rendezvous.pml:34 (state 1) [x = ((10*x)+3)]
      timeout
#processes: 3
                aArrived = 0
                bArrived = 0
                x = 13
  4:    proc  2 (B:1) 3.3.3.rendezvous.pml:35 (state 4)
  4:    proc  1 (A:1) 3.3.3.rendezvous.pml:28 (state 4)
  4:    proc  0 (:init::1) 3.3.3.rendezvous.pml:42 (state 4)
3 processes created
```



## 3.4.0 Shared variable (3.4.0.shared_var.pml)

```
$ cat -n 3.4.0.shared_var.pml

     1 /*  The Little Book of Semaphores (2.2.1)
     2     by A. Downey
     3
     4     Chapter 3. Basic synchronization patterns
     5
     6     3.4 Mutex
     7                     Thread A                    Thread B
     8                     1  count = count + 1       1  count = count + 1
     9
    10     3.4.0.shared_var.pml
    11 */
    12
...
```



## 3.4.0 Shared variable (3.4.0.shared_var.pml)

```
...
    13 byte count = 0
    14
    15 proctype Th(byte i) {
    16   byte temp
    17
    18   temp = count
    19   count = temp + 1
    20   printf("%c: count=%d\n",i,count)
    21 }
    22
    23 init {
    24   atomic { run Th('A'); run Th('B') }
    25   _nr_pr == 1
    26   assert(count==2)
    27 }
```

## 3.4.0 Shared variable (3.4.0.shared_var.pml)

```
$ spin 3.4.0.shared_var.pml
             B: count=1
          A: count=2
3 processes created
```

```
$ spin 3.4.0.shared_var.pml
             B: count=1
          A: count=1
spin: 3.4.0.shared_var.pml:26, Error: assertion violated
spin: text of failed assertion: assert((count==2))
#processes: 1
                count = 1
 10:    proc  0 (:init::1) 3.4.0.shared_var.pml:26 (state 5)
3 processes created
```



## 3.4.2 Mutex (3.4.2.mutex.pml)

```
$ cat -n 3.4.2.mutex.pml

     1 /*  The Little Book of Semaphores (2.2.1)
     2     by A. Downey
     3
     4     Chapter 3. Basic synchronization patterns
     5
     6     3.4 Mutex
     7                 Thread A                    Thread B
     8                 1  mutex.wait()            1  mutex.wait()
     9                 2    # critical section    2    # critical section
    10                 3    count = count + 1     3    count = count + 1
    11                 4  mutex.signal()          4  mutex.signal()
    12
    13     3.4.2.mutex.pml
    14 */
    15
...
```



## 3.4.2 Mutex (3.4.2.mutex.pml)

```
...
    16 #define wait(sem)   atomic { sem > 0; sem-- }
    17 #define signal(sem) sem++
    18
    19 byte mutex = 1
    20 byte count = 0
    21
    22 proctype Th(byte i) {
    23   byte temp
    24
    25   wait(mutex)
    26     temp = count
    27     count = temp + 1
    28   signal(mutex)
    29 }
    30
    31 init {
    32   atomic { run Th('A'); run Th('B') }
    33   _nr_pr == 1
    34   assert(count==2)
    35 }
```



## 3.4.2 Mutex (3.4.2.mutex.pml)

```
$ spin -run 3.4.2.mutex.pml

(Spin Version 6.4.8 -- 2 March 2018)
        + Partial Order Reduction

Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      +

State-vector 28 byte, depth reached 15, errors: 0

...
```

## 3.5.1 Multiplex (3.5.1.multiplex.pml)

```
$ cat -n 3.5.1.multiplex.pml | expand

     1  /*  The Little Book of Semaphores (2.2.1)
     2      by A. Downey
     3
     4      Chapter 3. Basic synchronization patterns
     5
     6      3.4 Multiplex
     7                  Thread i
     8                  1  multiplex.wait()
     9                  2    # critical section
    10                  3  multiplex.signal()
    11
    12      3.5.1.multiplex.pml
    13  */
    14
...
```



## 3.5.1 Multiplex (3.5.1.multiplex.pml)

```
...
    15  #define wait(sem)   atomic { sem > 0; sem-- }
    16  #define signal(sem) sem++
    17
    18  #define LIMIT 3
    19
    20  byte multiplex=LIMIT, cs=0
    21
    22  proctype Th(byte i) {
    23    wait(multiplex)
    24      cs++   /* atomic inc by Promela */
    25      assert(cs <= LIMIT)
    26      cs--   /* atomic dec by Promela */
    27    signal(multiplex)
    28  }
    29
    30  init {
    31    byte i
    32
    33    atomic {
    34      for (i : 1 .. 9) {
    35        run Th(i)
    36      }
    37    }
    38  }
```



## 3.5.1 Multiplex (3.5.1.multiplex.pml)

```
$ spin -run 3.5.1.multiplex.pml | expand

(Spin Version 6.4.8 -- 2 March 2018)
        + Partial Order Reduction

Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      +

State-vector 84 byte, depth reached 86, errors: 0

...

unreached in proctype Th
        (0 of 8 states)
unreached in init
        (0 of 11 states)

pan: elapsed time 0.35 seconds
pan: rate 1372128.6 states/second
```



## 3.6.2 Barrier non-solution (3.6.2a.barrier_nonsol.pml)

```
$ cat -n 3.6.2a.barrier_nonsol.pml | expand

     1  /*  The Little Book of Semaphores (2.2.1)
     2      by A. Downey
     3
     4      Chapter 3. Basic synchronization patterns
     5
     6      3.6 Barrier
     7      3.6.2 Barrier non-solution
     8
     9      vk, 2017
    10  */
    11
    12  #define THREADS 10   /* value for threads number */
    13  #define N       5    /* value for barrier limit */
    14
    15  #define wait(sem)   atomic { sem > 0; sem-- }
    16  #define signal(sem) sem++
    17
...
```

## 3.6.2 Barrier non-solution (3.6.2a.barrier_nonsol.pml)

```
...
    18  byte count=0, mutex=1, barrier=0
    19
    20  proctype Th(byte i) {
    21      byte temp
    22
    23      do
    24      ::  wait(mutex)
    25              temp=count
    26              count=temp+1
    27          signal(mutex)
    28          if
    29          :: count == N ->
    30                          signal(barrier)
    31          :: else
    32          fi
    33          wait(barrier)
    34          printf("Th(%d): count = %d\n",i,count)
    35          break
    36      od
    37  }
    38
```



## 3.6.2 Barrier non-solution (3.6.2a.barrier_nonsol.pml)

```
...
    39  init {
    40      byte i
    41
    42      atomic {
    43          for (i: 1 .. THREADS) {
    44              run Th(i)
    45          }
    46      }
    47  }
```



## 3.6.2 Barrier non-solution (3.6.2a.barrier_nonsol.pml)

```
$ spin 3.6.2a.barrier_nonsol.pml | expand

                                    Th(8): count = 5
     timeout
#processes: 11
                count = 10
                mutex = 1
                barrier = 0
109:    proc 10 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  9 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  8 (Th:1) 3.6.2a.barrier_nonsol.pml:37 (state 20) <valid end
state>
109:    proc  7 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  6 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  5 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  4 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  3 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  2 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  1 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  0 (:init::1) 3.6.2a.barrier_nonsol.pml:47 (state 11) <valid end
state>
11 processes created
```



## 3.6.2 Barrier non-solution (3.6.2a.barrier_nonsol.pml)

```
$ spin 3.6.2a.barrier_nonsol.pml | expand

          Th(1): count = 7
     timeout
#processes: 11
                count = 10
                mutex = 1
                barrier = 0
109:    proc 10 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  9 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  8 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  7 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  6 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  5 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  4 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  3 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  2 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
109:    proc  1 (Th:1) 3.6.2a.barrier_nonsol.pml:37 (state 20) <valid end
state>
109:    proc  0 (:init::1) 3.6.2a.barrier_nonsol.pml:47 (state 11) <valid end
state>
11 processes created
```

## 3.6.2 Barrier non-solution (3.6.2a.barrier_nonsol.pml)

```
$ spin 3.6.2a.barrier_nonsol.pml | expand

      timeout
#processes: 11
                count = 10
                mutex = 1
                barrier = 0
104:    proc 10 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
104:    proc  9 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
104:    proc  8 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
104:    proc  7 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
104:    proc  6 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
104:    proc  5 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
104:    proc  4 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
104:    proc  3 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
104:    proc  2 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
104:    proc  1 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
104:    proc  0 (:init::1) 3.6.2a.barrier_nonsol.pml:47 (state 11) <valid end
state>
11 processes created
```



## 3.6.2 Barrier non-solution (3.6.2a.barrier_nonsol.pml)

```
$ spin 3.6.2a.barrier_nonsol.pml | expand
                                        Th(8): count = 5
                          Th(5): count = 5
      timeout
#processes: 11
                count = 10
                mutex = 1
                barrier = 0
114:    proc 10 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
114:    proc  9 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
114:    proc  8 (Th:1) 3.6.2a.barrier_nonsol.pml:37 (state 20) <valid end
state>
114:    proc  7 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
114:    proc  6 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
114:    proc  5 (Th:1) 3.6.2a.barrier_nonsol.pml:37 (state 20) <valid end
state>
114:    proc  4 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
114:    proc  3 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
114:    proc  2 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
114:    proc  1 (Th:1) 3.6.2a.barrier_nonsol.pml:33 (state 14)
114:    proc  0 (:init::1) 3.6.2a.barrier_nonsol.pml:47 (state 11) <valid end
state>
11 processes created
```



## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
$ cat -n 3.6.3.barrier_nonsol.pml | expand

     1  /*  The Little Book of Semaphores (2.2.1)
     2      by A. Downey
     3
     4      Chapter 3. Basic synchronization patterns
     5
     6      3.6 Barrier
     7      3.6.2 Barrier non-solution
     8
     9      vk, 2017
    10  */
    11
    12  #define THREADS 5    /* value for threads number */
    13  #define N       5    /* value for barrier limit */
    14
    15  #define wait(sem)   atomic { sem > 0; sem-- }
    16  #define signal(sem) sem++
    17
...
```



## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
...
    18  byte count=0, mutex=1, barrier=0
    19  bit  bar[THREADS+1]
    20
    21  proctype Th(byte i) {
    22      byte temp
    23
    24      do
    25      ::  wait(mutex)
    26              temp=count
    27              count=temp+1
    28          signal(mutex)
    29          bar[i]=false
    30          if
    31          :: count == N ->
    32              bar[i]=true
    33              assert(!bar[1]||!bar[2]||!bar[3]||!bar[4]||!bar[5])
    34              signal(barrier)
    35          :: else
    36          fi
    37          wait(barrier)
    38          printf("Th(%d): count = %d\n",i,count)
    39          break
    40      od
    41  }
```

## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
...
    42
    43  init {
    44      byte i
    45
    46      atomic {
    47          for (i: 1 .. THREADS) {
    48              run Th(i)
    49          }
    50      }
    51  }
```



## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
$ spin -run -E 3.6.3.barrier_nonsol.pml | expand

pan:1: assertion violated (((( !(bar[1])|| !(bar[2]))|| !(bar[3]))|| !
(bar[4]))|| !(bar[5])) (at depth 74)
pan: wrote 3.6.3.barrier_nonsol.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    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      - (disabled by -E flag)

State-vector 64 byte, depth reached 74, errors: 1
...
```



## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
$ spin -t -p -g -l 3.6.3.barrier_nonsol.pml | expand
using statement merging
  1:    proc  0 (:init::1) 3.6.3.barrier_nonsol.pml:47 (state 1)       [i = 1]
              :init:(0):i = 1
  2:    proc  0 (:init::1) 3.6.3.barrier_nonsol.pml:47 (state 2)       [((i<=5))]
Starting Th with pid 1
  3:    proc  0 (:init::1) 3.6.3.barrier_nonsol.pml:48 (state 3)       [(run Th(i))]
  4:    proc  0 (:init::1) 3.6.3.barrier_nonsol.pml:47 (state 4)       [i = (i+1)]
              :init:(0):i = 2
...
              :init:(0):i = 6
 17:    proc  0 (:init::1) 3.6.3.barrier_nonsol.pml:49 (state 5)       [else]
 18:    proc  0 (:init::1) 3.6.3.barrier_nonsol.pml:49 (state 6)       [goto :b1]
 19:    proc  0 (:init::1) 3.6.3.barrier_nonsol.pml:49 (state 9)       [break]

 20:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:25 (state 1)   [((mutex>0))]
 20:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:25 (state 2)   [mutex = (mutex-1)]
              mutex = 0
 21:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:26 (state 4)   [temp = count]
              Th(5):temp = 0
 22:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:27 (state 5)   [count = (temp+1)]
              count = 1
 23:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:28 (state 6)   [mutex = (mutex+1)]
              mutex = 1
 24:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:29 (state 7)   [bar[i] = 0]
...
```



## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
...
 25:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:25 (state 1)   [((mutex>0))]
 25:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:25 (state 2)   [mutex = (mutex-1)]
              mutex = 0
 26:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:26 (state 4)   [temp = count]
              Th(4):temp = 1
 27:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:27 (state 5)   [count = (temp+1)]
              count = 2
 28:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:28 (state 6)   [mutex = (mutex+1)]
              mutex = 1
 29:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:29 (state 7)   [bar[i] = 0]


 30:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:25 (state 1)   [((mutex>0))]
 30:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:25 (state 2)   [mutex = (mutex-1)]
              mutex = 0
 31:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:26 (state 4)   [temp = count]
              Th(3):temp = 2
 32:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:27 (state 5)   [count = (temp+1)]
              count = 3
 33:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:28 (state 6)   [mutex = (mutex+1)]
              mutex = 1
 34:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:29 (state 7)   [bar[i] = 0]

...
```

## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
...

 35:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:25 (state 1)   [((mutex>0))]
 35:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:25 (state 2)   [mutex = (mutex-1)]
                mutex = 0
 36:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:26 (state 4)   [temp = count]
                Th(2):temp = 3
 37:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:27 (state 5)   [count = (temp+1)]
                count = 4
 38:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:28 (state 6)   [mutex = (mutex+1)]
                mutex = 1
 39:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:29 (state 7)   [bar[i] = 0]


 40:    proc  1 (Th:1) 3.6.3.barrier_nonsol.pml:25 (state 1)   [((mutex>0))]
 40:    proc  1 (Th:1) 3.6.3.barrier_nonsol.pml:25 (state 2)   [mutex = (mutex-1)]
                mutex = 0
 41:    proc  1 (Th:1) 3.6.3.barrier_nonsol.pml:26 (state 4)   [temp = count]
                Th(1):temp = 4
 42:    proc  1 (Th:1) 3.6.3.barrier_nonsol.pml:27 (state 5)   [count = (temp+1)]
                count = 5

...
```



## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
...

 43:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:31 (state 8)   [((count==5))]
 44:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:32 (state 9)   [bar[i] = 1]
                bar[0] = 0
                bar[1] = 0
                bar[2] = 0
                bar[3] = 0
                bar[4] = 0
                bar[5] = 1
 45:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:33 (state 10)  [assert(((((!(bar[1])||!
(bar[2]))||!(bar[3]))||!(bar[4]))||!(bar[5])))]
 46:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:34 (state 11)  [barrier = (barrier+1)]
                barrier = 1
 47:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:37 (state 15)  [((barrier>0))]
 47:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:37 (state 16)  [barrier = (barrier-1)]
                barrier = 0
                          Th(5): count = 5
 48:    proc  5 (Th:1) 3.6.3.barrier_nonsol.pml:38 (state 18)  [printf('Th(%d): count = %d\\
n',i,count)]
 49: proc 5 terminates

...
```



## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
...

 50:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:31 (state 8)   [((count==5))]
 51:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:32 (state 9)   [bar[i] = 1]
                bar[0] = 0
                bar[1] = 0
                bar[2] = 0
                bar[3] = 0
                bar[4] = 1
                bar[5] = 1
 52:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:33 (state 10)  [assert(((((!(bar[1])||!
(bar[2]))||!(bar[3]))||!(bar[4]))||!(bar[5])))]
 53:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:34 (state 11)  [barrier = (barrier+1)]
                barrier = 1
 54:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:37 (state 15)  [((barrier>0))]
 54:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:37 (state 16)  [barrier = (barrier-1)]
                barrier = 0
                          Th(4): count = 5
 55:    proc  4 (Th:1) 3.6.3.barrier_nonsol.pml:38 (state 18)  [printf('Th(%d): count = %d\\
n',i,count)]
 56: proc 4 terminates
...
```



## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
...

 57:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:31 (state 8)   [((count==5))]
 58:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:32 (state 9)   [bar[i] = 1]
                bar[0] = 0
                bar[1] = 0
                bar[2] = 0
                bar[3] = 1
                bar[4] = 1
                bar[5] = 1
 59:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:33 (state 10)  [assert(((((!(bar[1])||!
(bar[2]))||!(bar[3]))||!(bar[4]))||!(bar[5])))]
 60:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:34 (state 11)  [barrier = (barrier+1)]
                barrier = 1
 61:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:37 (state 15)  [((barrier>0))]
 61:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:37 (state 16)  [barrier = (barrier-1)]
                barrier = 0
                          Th(3): count = 5
 62:    proc  3 (Th:1) 3.6.3.barrier_nonsol.pml:38 (state 18)  [printf('Th(%d): count = %d\\
n',i,count)]
 63: proc 3 terminates

...
```

## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
...
 64:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:31 (state 8)   [((count==5))]
 65:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:32 (state 9)   [bar[i] = 1]
                bar[0] = 0
                bar[1] = 0
                bar[2] = 1
                bar[3] = 1
                bar[4] = 1
                bar[5] = 1
 66:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:33 (state 10)  [assert(((((!(bar[1])||!
(bar[2]))||!(bar[3]))||!(bar[4]))||!(bar[5])))]
 67:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:34 (state 11)  [barrier = (barrier+1)]
                barrier = 1
 68:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:37 (state 15)  [((barrier>0))]
 68:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:37 (state 16)  [barrier = (barrier-1)]
                barrier = 0
              Th(2): count = 5
 69:    proc  2 (Th:1) 3.6.3.barrier_nonsol.pml:38 (state 18)  [printf('Th(%d): count = %d\\
n',i,count)]
 70: proc 2 terminates

...
```



## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
...
 71:    proc  1 (Th:1) 3.6.3.barrier_nonsol.pml:28 (state 6)   [mutex = (mutex+1)]
                mutex = 1
 72:    proc  1 (Th:1) 3.6.3.barrier_nonsol.pml:29 (state 7)   [bar[i] = 0]
 73:    proc  1 (Th:1) 3.6.3.barrier_nonsol.pml:31 (state 8)   [((count==5))]
 74:    proc  1 (Th:1) 3.6.3.barrier_nonsol.pml:32 (state 9)   [bar[i] = 1]
                bar[0] = 0
                bar[1] = 1
                bar[2] = 1
                bar[3] = 1
                bar[4] = 1
                bar[5] = 1
spin: 3.6.3.barrier_nonsol.pml:33, Error: assertion violated
spin: text of failed assertion: assert(((((!(bar[1])||!(bar[2]))||!(bar[3]))||!(bar[4]))||!
(bar[5])))
 75:    proc  1 (Th:1) 3.6.3.barrier_nonsol.pml:33 (state 10)  [assert(((((!(bar[1])||!
(bar[2]))||!(bar[3]))||!(bar[4]))||!(bar[5])))]
spin: trail ends after 75 steps

...
```



## 3.6.2 Barrier non-solution (3.6.3.barrier_nonsol.pml)

```
...

#processes: 2
                count = 5
                mutex = 1
                barrier = 0
                bar[0] = 0
                bar[1] = 1
                bar[2] = 1
                bar[3] = 1
                bar[4] = 1
                bar[5] = 1
 75:    proc  1 (Th:1) 3.6.3.barrier_nonsol.pml:34 (state 11)
 75:    proc  0 (:init::1) 3.6.3.barrier_nonsol.pml:51 (state 11) <valid end state>
6 processes created
```



## 3.6.4 Barrier solution (3.6.4a.barrier_sol.pml)

```
$ cat -n 3.6.4a.barrier_sol.pml | expand

     1  /*  The Little Book of Semaphores (2.2.1)
     2      by A. Downey
     3
     4      Chapter 3. Basic synchronization patterns
     5
     6      3.6 Barrier
     7      3.6.4 Barrier solution
     8
     9      vk, 2017
    10  */
    11
    12  #define THREADS 5    /* value for threads number */
    13  #define N       5    /* value for barrier limit */
    14
    15  #define wait(sem)   atomic { sem > 0; sem-- }
    16  #define signal(sem) sem++
    17
...
```

## 3.6.4 Barrier solution (3.6.4a.barrier_sol.pml)

```
...
    18  byte count=0, mutex=1, barrier=0    /* barrier is locked */
    19
    20  proctype Th(byte i) {
    21      byte temp
    22
    23      do
    24      ::  wait(mutex)
    25              temp=count
    26              count=temp+1
    27          signal(mutex)
    28          if
    29          :: count == N ->
    30              signal(barrier)
    31          :: else
    32          fi
    33          wait(barrier)
    34          printf("Th(%d): count = %d\n",i,count)
    35          signal(barrier)
    36          break    /* one only iteration */
    37      od
    38  }
    39
...
```



## 3.6.4 Barrier solution (3.6.4a.barrier_sol.pml)

```
...
    40  init {
    41      byte i
    42
    43      atomic {
    44          for (i: 1 .. THREADS) {
    45              run Th(i)
    46          }
    47      }
    48      _nr_pr == 1 ->
    49          assert(barrier != 0)    /* barrier (turnstile) is open! */
    50          printf("barrier = %d\n",barrier)
    51  }
...
```



## 3.6.4 Barrier solution (3.6.4a.barrier_sol.pml)

```
$ spin 3.6.4a.barrier_sol.pml | expand
                  Th(3): count = 5
                      Th(4): count = 5
              Th(2): count = 5
                          Th(5): count = 5
          Th(1): count = 5
      barrier = 1
6 processes created


$ spin 3.6.4a.barrier_sol.pml | expand
                      Th(4): count = 5
                  Th(3): count = 5
          Th(1): count = 5
              Th(2): count = 5
                          Th(5): count = 5
      barrier = 1
6 processes created
```



## 3.6.4 Barrier solution (3.6.4a.barrier_sol.pml)

```
$ spin 3.6.4a.barrier_sol.pml | expand
                      Th(4): count = 5
                  Th(3): count = 5
              Th(2): count = 5
                          Th(5): count = 5
          Th(1): count = 5
      barrier = 2
6 processes created
```

## 3.6.4 Barrier solution (3.6.4b.barrier_sol.pml)

```
...
    40  init {
    41      byte i
    42
    43      atomic {
    44          for (i: 1 .. THREADS) {
    45              run Th(i)
    46          }
    47      }
    48      _nr_pr == 1 ->
    49          assert(0 < barrier && barrier < 5)
    50          printf("barrier = %d\n",barrier)
    51  }
...
```



## 3.6.4 Barrier solution (3.6.4b.barrier_sol.pml)

```
$ spin -run 3.6.4b.barrier_sol.pml | expand
pan:1: assertion violated ((0<barrier)&&(barrier<5)) (at depth 70)
pan: wrote 3.6.4b.barrier_sol.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    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      +

State-vector 64 byte, depth reached 72, errors: 1
...
```



## 3.6.4 Barrier solution (3.6.4b.barrier_sol.pml)

```
$ spin -t -p -g -l 3.6.4b.barrier_sol.pml | expand
using statement merging
  1:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:44 (state 1)  [i = 1]
              :init:(0):i = 1
  2:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:44 (state 2)  [((i<=5))]
Starting Th with pid 1
  3:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:45 (state 3)  [(run Th(i))]
  4:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:44 (state 4)  [i = (i+1)]
              :init:(0):i = 2
  5:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:44 (state 2)  [((i<=5))]
Starting Th with pid 2
...
              :init:(0):i = 6
 17:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:46 (state 5)  [else]
 18:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:46 (state 6)  [goto :b1]
 19:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:46 (state 9)  [break]

 20:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:24 (state 1)      [((mutex>0))]
 20:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:24 (state 2)      [mutex = (mutex-1)]
              mutex = 0
 21:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:25 (state 4)      [temp = count]
              Th(5):temp = 0
 22:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:26 (state 5)      [count = (temp+1)]
              count = 1
 23:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:27 (state 6)      [mutex = (mutex+1)]
              mutex = 1

...
```



## 3.6.4 Barrier solution (3.6.4b.barrier_sol.pml)

```
...
 24:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:24 (state 1)      [((mutex>0))]
 24:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:24 (state 2)      [mutex = (mutex-1)]
              mutex = 0
 25:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:25 (state 4)      [temp = count]
              Th(4):temp = 1
 26:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:26 (state 5)      [count = (temp+1)]
              count = 2
 27:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:27 (state 6)      [mutex = (mutex+1)]
              mutex = 1

 28:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:24 (state 1)      [((mutex>0))]
 28:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:24 (state 2)      [mutex = (mutex-1)]
              mutex = 0
 29:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:25 (state 4)      [temp = count]
              Th(3):temp = 2
 30:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:26 (state 5)      [count = (temp+1)]
              count = 3
 31:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:27 (state 6)      [mutex = (mutex+1)]
              mutex = 1

 32:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:24 (state 1)      [((mutex>0))]
 32:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:24 (state 2)      [mutex = (mutex-1)]
              mutex = 0
 33:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:25 (state 4)      [temp = count]
              Th(2):temp = 3
 34:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:26 (state 5)      [count = (temp+1)]
              count = 4
 35:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:27 (state 6)      [mutex = (mutex+1)]
              mutex = 1
...
```

## 3.6.4 Barrier solution (3.6.4b.barrier_sol.pml)

```
...
 36:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:24 (state 1)      [((mutex>0))]
 36:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:24 (state 2)      [mutex = (mutex-1)]
               mutex = 0
 37:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:25 (state 4)      [temp = count]
               Th(1):temp = 4
 38:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:26 (state 5)      [count = (temp+1)]
               count = 5

 39:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:29 (state 7)      [((count==5))]
 40:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:30 (state 8)      [barrier = (barrier+1)]
               barrier = 1
 41:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:33 (state 12)     [((barrier>0))]
 41:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:33 (state 13)     [barrier = (barrier-1)]
               barrier = 0
                        Th(5): count = 5
 42:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:34 (state 15)     [printf('Th(%d): count = %d\\
n',i,count)]
 43:    proc  5 (Th:1) 3.6.4b.barrier_sol.pml:35 (state 16)     [barrier = (barrier+1)]
               barrier = 1
 44: proc 5 terminates

...
```



## 3.6.4 Barrier solution (3.6.4b.barrier_sol.pml)

```
...
 45:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:29 (state 7)      [((count==5))]
 46:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:30 (state 8)      [barrier = (barrier+1)]
               barrier = 2
 47:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:33 (state 12)     [((barrier>0))]
 47:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:33 (state 13)     [barrier = (barrier-1)]
               barrier = 1
                     Th(4): count = 5
 48:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:34 (state 15)     [printf('Th(%d): count = %d\\
n',i,count)]
 49:    proc  4 (Th:1) 3.6.4b.barrier_sol.pml:35 (state 16)     [barrier = (barrier+1)]
               barrier = 2
 50: proc 4 terminates


 51:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:29 (state 7)      [((count==5))]
 52:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:30 (state 8)      [barrier = (barrier+1)]
               barrier = 3
 53:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:33 (state 12)     [((barrier>0))]
 53:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:33 (state 13)     [barrier = (barrier-1)]
               barrier = 2
                 Th(3): count = 5
 54:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:34 (state 15)     [printf('Th(%d): count = %d\\
n',i,count)]
 55:    proc  3 (Th:1) 3.6.4b.barrier_sol.pml:35 (state 16)     [barrier = (barrier+1)]
               barrier = 3
 56: proc 3 terminates

...
```



## 3.6.4 Barrier solution (3.6.4b.barrier_sol.pml)

```
...
 57:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:29 (state 7)      [((count==5))]
 58:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:30 (state 8)      [barrier = (barrier+1)]
               barrier = 4
 59:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:33 (state 12)     [((barrier>0))]
 59:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:33 (state 13)     [barrier = (barrier-1)]
               barrier = 3
             Th(2): count = 5
 60:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:34 (state 15)     [printf('Th(%d): count = %d\\
n',i,count)]
 61:    proc  2 (Th:1) 3.6.4b.barrier_sol.pml:35 (state 16)     [barrier = (barrier+1)]
               barrier = 4
 62: proc 2 terminates


 63:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:27 (state 6)      [mutex = (mutex+1)]
               mutex = 1
 64:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:29 (state 7)      [((count==5))]
 65:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:30 (state 8)      [barrier = (barrier+1)]
               barrier = 5
 66:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:33 (state 12)     [((barrier>0))]
 66:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:33 (state 13)     [barrier = (barrier-1)]
               barrier = 4
           Th(1): count = 5
 67:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:34 (state 15)     [printf('Th(%d): count = %d\\
n',i,count)]
 68:    proc  1 (Th:1) 3.6.4b.barrier_sol.pml:35 (state 16)     [barrier = (barrier+1)]
               barrier = 5
 69: proc 1 terminates
...
```



## 3.6.4 Barrier solution (3.6.4b.barrier_sol.pml)

```
...
 70:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:48 (state 11) [((_nr_pr==1))]
spin: 3.6.4b.barrier_sol.pml:49, Error: assertion violated
spin: text of failed assertion: assert(((0<barrier)&&(barrier<5)))
 71:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:49 (state 12)
[assert(((0<barrier)&&(barrier<5)))]
spin: trail ends after 71 steps
#processes: 1
               count = 5
               mutex = 1
               barrier = 5
 71:    proc  0 (:init::1) 3.6.4b.barrier_sol.pml:50 (state 13)
6 processes created
```

## 3.6.5 Bad barrier solution (3.6.5.bad_barrier.pml)

```
$ cat -n 3.6.5.bad_barrier.pml | expand

     1  /*  The Little Book of Semaphores (2.2.1)
     2      by A. Downey
     3
     4      Chapter 3. Basic synchronization patterns
     5
     6      3.6 Barrier
     7      3.6.5 Bad barrier solution (deadlock)
     8
     9      vk, 2017
    10  */
    11
    12  #define THREADS 3    /* value for threads number */
    13  #define N       3    /* value for barrier limit */
    14
    15  #define wait(sem)   atomic { sem > 0; sem-- }
    16  #define signal(sem) sem++
    17
    18  byte count=0, mutex=1, barrier=0    /* barrier is locked */
    19
...
```



## 3.6.5 Bad barrier solution (3.6.5.bad_barrier.pml)

```
...
    20  proctype Th(byte i) {
    21      byte temp
    22
    23  rendezvous:
    24      do
    25      ::  wait(mutex)
    26              temp=count
    27              count=temp+1
    28              if
    29              :: count == N ->
    30                  signal(barrier)
    31              :: else
    32              fi
    33              wait(barrier)
    34              printf("Th(%d): count = %d\n",i,count)
    35              signal(barrier)
    36          signal(mutex)
    37          break    /* one only iteration */
    38      od
    39  critical_point:
    40  }
...
```



## 3.6.5 Bad barrier solution (3.6.5.bad_barrier.pml)

```
...
    41
    42  init {
    43      byte i
    44
    45      atomic {
    46          for (i: 1 .. THREADS) {
    47              run Th(i)
    48          }
    49      }
    50  }

$ spin 3.6.5.bad_barrier.pml | expand
      timeout
#processes: 4
                count = 1
                mutex = 0
                barrier = 0
 19:    proc  3 (Th:1) 3.6.5.bad_barrier.pml:24 (state 18)
 19:    proc  2 (Th:1) 3.6.5.bad_barrier.pml:24 (state 18)
 19:    proc  1 (Th:1) 3.6.5.bad_barrier.pml:33 (state 13)
 19:    proc  0 (:init::1) 3.6.5.bad_barrier.pml:50 (state 11) <valid end
state>
4 processes created
```