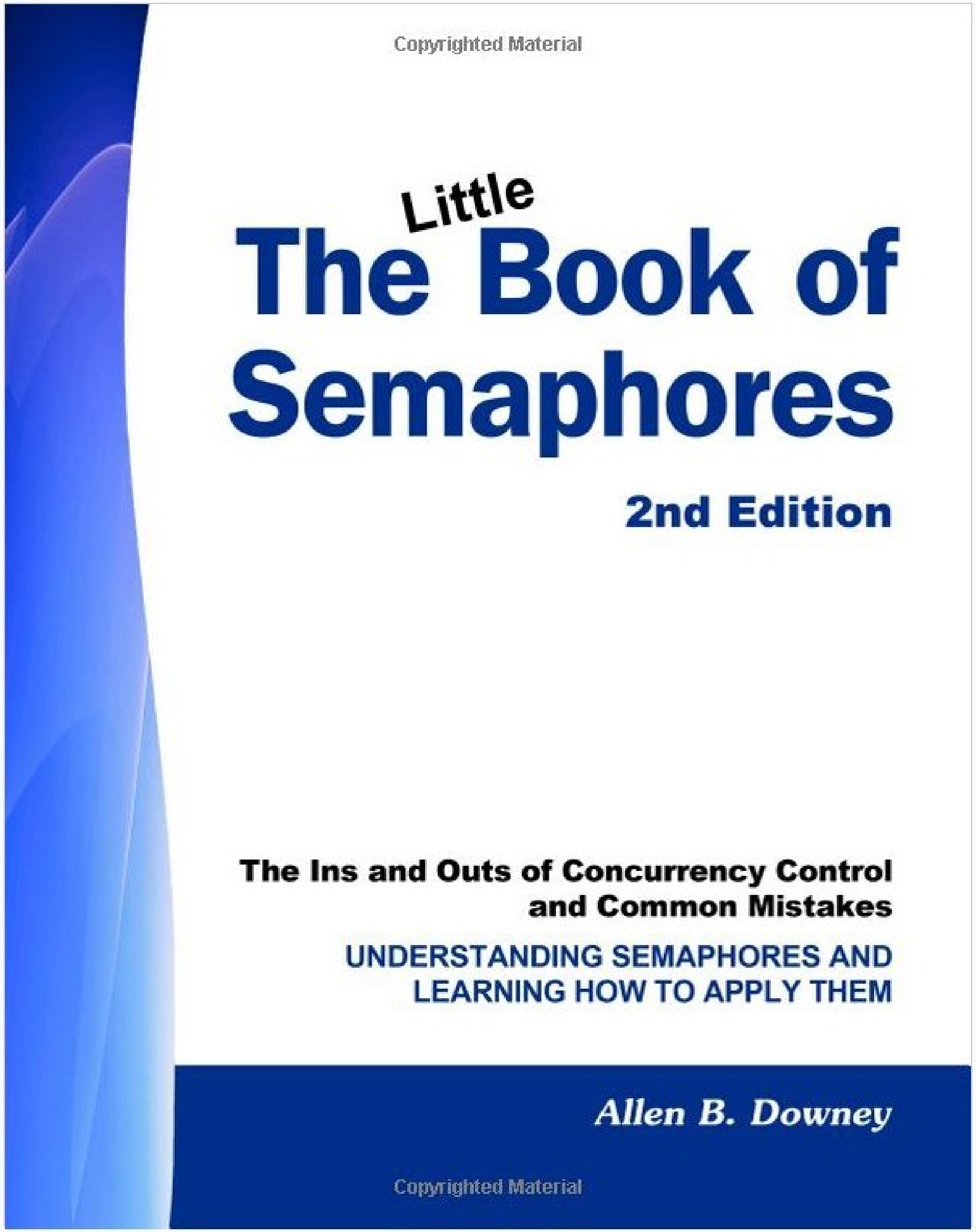

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The Little Book of Semaphores

2nd Edition

The Ins and Outs of Concurrency Control and Common Mistakes

UNDERSTANDING SEMAPHORES AND LEARNING HOW TO APPLY THEM

Allen B. Downey

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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)

```
#define wait(sem)   atomic { sem > 0; sem-- }
#define signal(sem) sem++

byte sem = 0
byte x = 0

proctype A() {
  x = 1
  signal(sem)
}

proctype B() {
  wait(sem)
  x = 2
}

init {
  atomic { run A(); run B() }
  _nr_pr == 1
  assert( x == 2 )
}
```

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
...
```

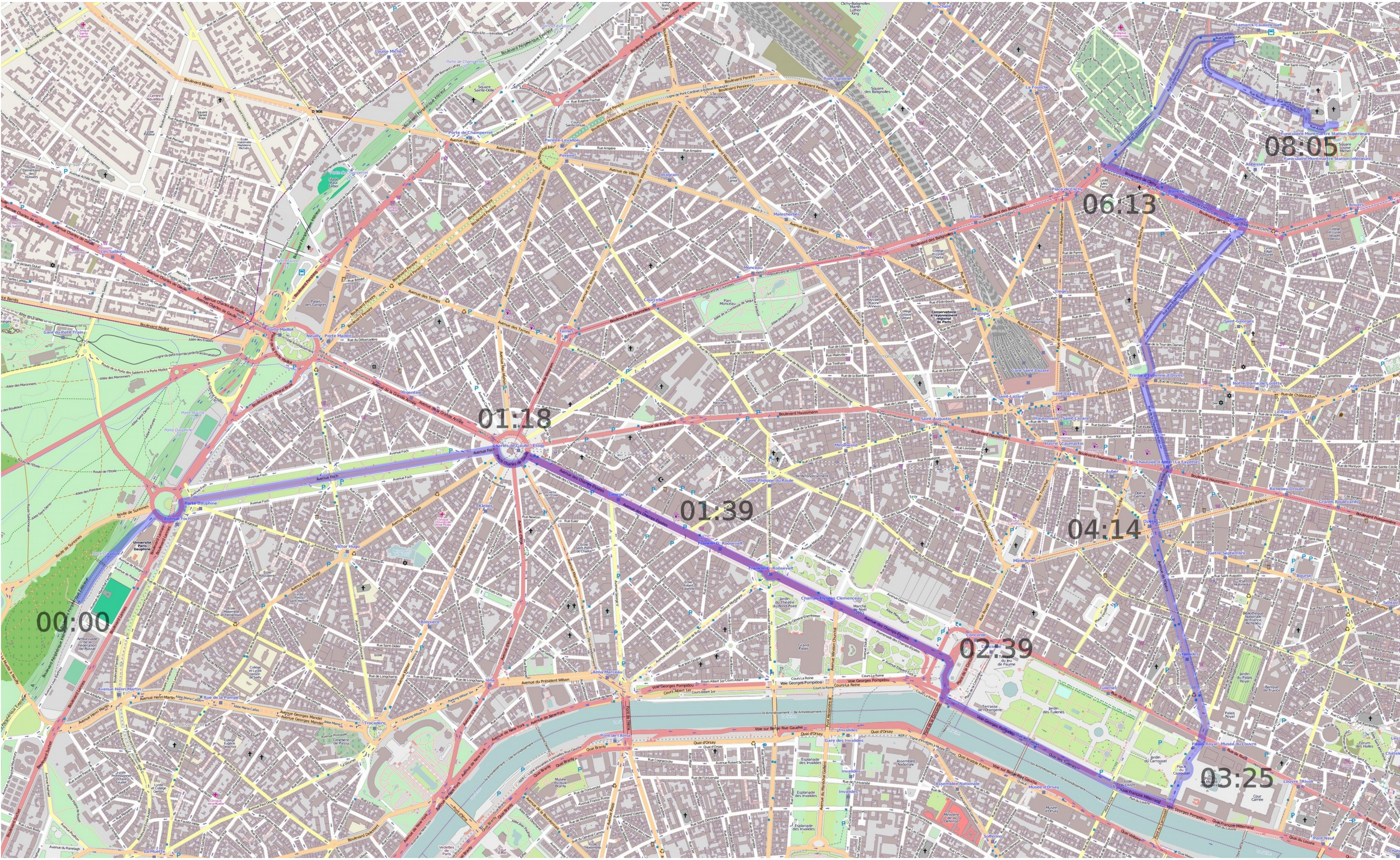
TLBOS, Chapter 3

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


00:00
01:18
01:39
02:39
03:25
04:14
06:13
08:05

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)

```
...
int x = 0

proctype A() {
  x = 10*x + 1
  x = 10*x + 2
}

proctype B() {
  x = 10*x + 3
  x = 10*x + 4
}

init {
  atomic { run A(); run B() }
  _nr_pr == 1
  printf("x = %d\n", x)
  assert(x==1234 || x==1324 || x==1342 || x==3412 || x==3142 || x==3124)
/* must be prohibited: 3412 and 1234 */
}
```

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)

```
...
#define wait(sem)   atomic { sem > 0; sem-- }
#define signal(sem) sem++

byte aArrived = 0, bArrived = 0
int x = 0

proctype A() {
  x = 10*x + 1
  signal(aArrived)   # a) "llegaré en 10 minutos"
  wait(bArrived)     # b) llega en 8, debe esperar (context switch)
  x = 10*x + 2
}

proctype B() {
  x = 10*x + 3
  signal(bArrived)   # c) "ya llegué"
  wait(aArrived)     # d) puede seguir sin cambio del contexto (1342)
  x = 10*x + 4
}

...
```

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

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

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`)

```
...
#define wait(sem)   atomic { sem > 0; sem-- }
#define signal(sem) sem++

byte aArrived = 0, bArrived = 0
int x = 0

proctype A() {
  x = 10*x + 1
  wait(bArrived)      # a) "¿cuándo llegaras?" (context switch)
  signal(aArrived)    # d) "pardon, ya estoy" (1324 o 1342)
  x = 10*x + 2
}

proctype B() {
  x = 10*x + 3
  signal(bArrived)    # b) "ya llegué"
  wait(aArrived)      # c) "pero tú no estás" (context switch extra)
  x = 10*x + 4
}

...
```

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

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

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`)

```
...
#define wait(sem)   atomic { sem > 0; sem-- }
#define signal(sem) sem++

byte aArrived = 0, bArrived = 0;
int x = 0

proctype A() {
  x = 10*x + 1
  wait(bArrived)
  signal(aArrived)
  x = 10*x + 2
}

proctype B() {
  x = 10*x + 3
  wait(aArrived)
  signal(bArrived)
  x = 10*x + 4
}

...
```

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

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

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`)

```
...
byte count = 0

proctype Th(byte i) {
  byte temp

  temp = count
  count = temp + 1
  printf("%c: count=%d\n",i,count)
}

init {
  atomic { run Th('A'); run Th('B') }
  _nr_pr == 1
  assert(count==2)
}
```

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)

```
...
#define wait(sem)   atomic { sem > 0; sem-- }
#define signal(sem) sem++

byte mutex = 1
byte count = 0

proctype Th(byte i) {
  byte temp

  wait(mutex)
    temp = count
    count = temp + 1
  signal(mutex)
}

init {
  atomic { run Th('A'); run Th('B') }
  _nr_pr == 1
  assert(count==2)
}
```

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`)

```
...
#define wait(sem)   atomic { sem > 0; sem-- }
#define signal(sem) sem++

#define LIMIT 3

byte multiplex=LIMIT, cs=0

proctype Th(byte i) {
  wait(multiplex)
    cs++   /* atomic inc by Promela */
    assert(cs <= LIMIT)
    cs--   /* atomic dec by Promela */
  signal(multiplex)
}

init {
  byte i

  atomic {
    for (i : 1 .. 9) {
      run Th(i)
    }
  }
}
```

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`)

```
...
byte count=0, mutex=1, barrier=0

proctype Th(byte i) {
    byte temp

    do
    ::  wait(mutex)
            temp=count
            count=temp+1
        signal(mutex)
        if
        :: count == N ->
                         signal(barrier)
        :: else
        fi
        wait(barrier)
        printf("Th(%d): count = %d\n",i,count)
        break
    od
}

```

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

```
...
init {
    byte i

    atomic {
        for (i: 1 .. THREADS) {
            run Th(i)
        }
    }
}
```

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)

```
...
byte count=0, mutex=1, barrier=0
bit  bar[THREADS+1]

proctype Th(byte i) {
    byte temp

    do
    ::  wait(mutex)
            temp=count
            count=temp+1
        signal(mutex)
        bar[i]=false
        if
        :: count == N ->
            bar[i]=true
            assert(!bar[1]||!bar[2]||!bar[3]||!bar[4]||!bar[5])
            signal(barrier)
        :: else
        fi
        wait(barrier)
        printf("Th(%d): count = %d\n",i,count)
        break
    od
}
```

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

```
...

init {
    byte i

    atomic {
        for (i: 1 .. THREADS) {
            run Th(i)
        }
    }
}
```

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)

```
...
byte count=0, mutex=1, barrier=0    /* barrier is locked */

proctype Th(byte i) {
    byte temp

    do
    ::  wait(mutex)
            temp=count
            count=temp+1
        signal(mutex)
        if
        :: count == N ->
            signal(barrier)
        :: else
        fi
        wait(barrier)
        printf("Th(%d): count = %d\n",i,count)
        signal(barrier)
        break    /* one only iteration */
    od
}

...
```

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

```
...
init {
    byte i

    atomic {
        for (i: 1 .. THREADS) {
            run Th(i)
        }
    }
    _nr_pr == 1 ->
        assert(barrier != 0)    /* barrier (turnstile) is open! */
        printf("barrier = %d\n",barrier)
}
...
```

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)

```
...
init {
    byte i

    atomic {
        for (i: 1 .. THREADS) {
            run Th(i)
        }
    }
    _nr_pr == 1 ->
        assert(0 < barrier && barrier < 5)
        printf("barrier = %d\n",barrier)
}
...
```

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)

```
...
proctype Th(byte i) {
    byte temp

rendezvous:
    do
    ::  wait(mutex)
            temp=count
            count=temp+1
            if
            :: count == N ->
                signal(barrier)
            :: else
            fi
            wait(barrier)
            printf("Th(%d): count = %d\n",i,count)
            signal(barrier)
        signal(mutex)
        break    /* one only iteration */
    od
critical_point:
}
...
```

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
```