Operating Systems: Synchronization

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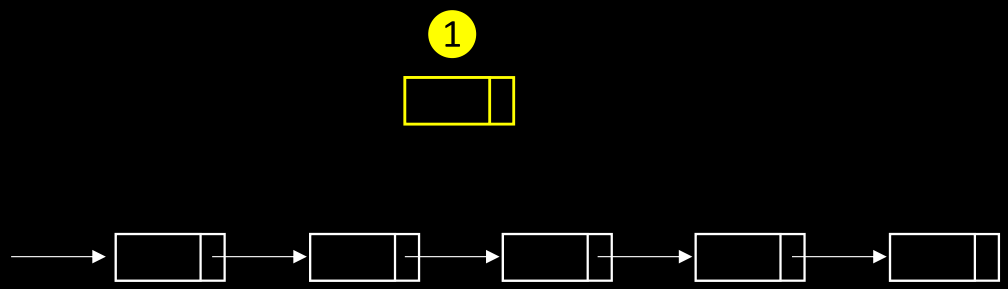
https://gforgeron.gitlab.io/se/

Why do we need synchronization?

- To protect data structures from being corrupted by concurrent execution of non-reentrant code
  - Mutual exclusion of critical sections
  - Reader/Writer
  - Producer/consumer
- To enforce dependencies between code regions
  - Blocking a process until an event has occurred
  - Joining a synchronization point

Race conditions

- Example with linked lists
  - Insertion of a new element
    - 3 steps
      1. Allocate
      2. Set next
      3. Modify previous



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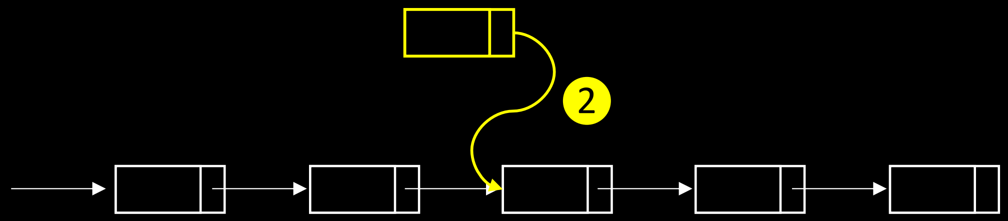

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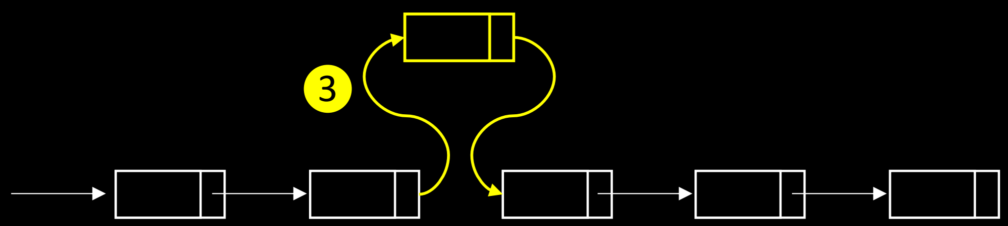

Race conditions

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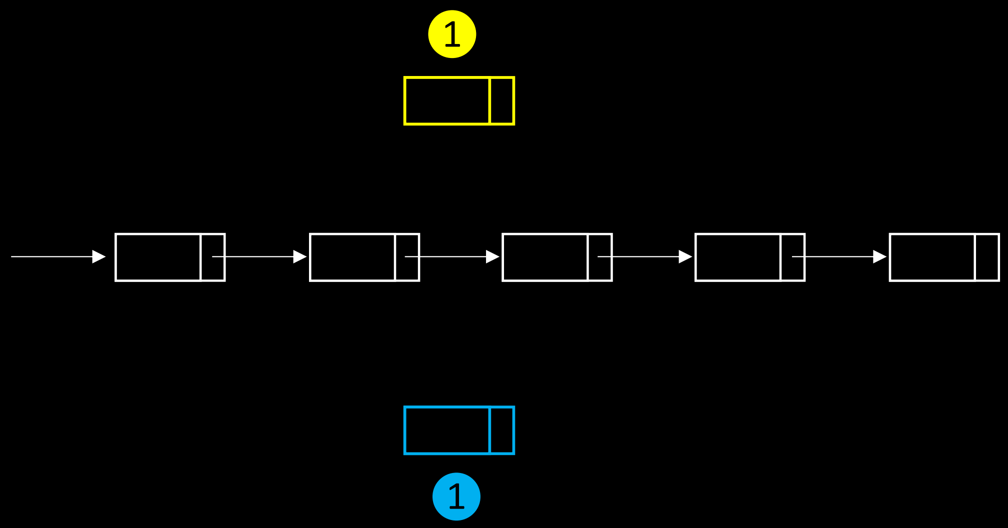
  - What if two threads perform an insert simultaneously, at the same position?



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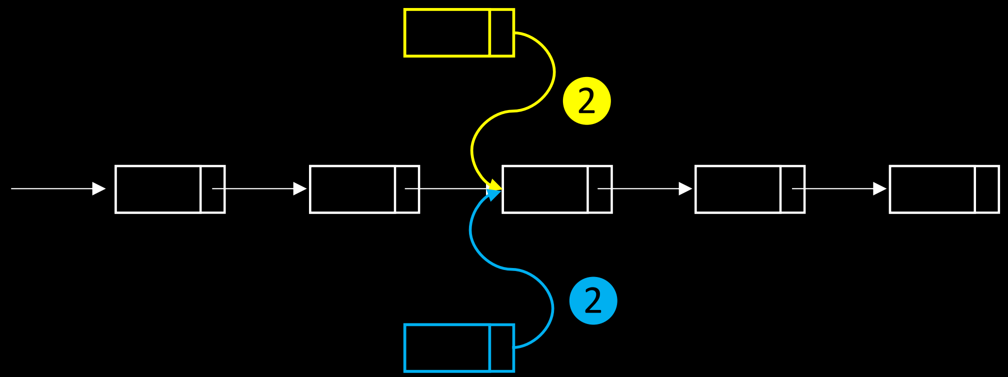

Race conditions

- Example with linked lists
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      1. Allocate
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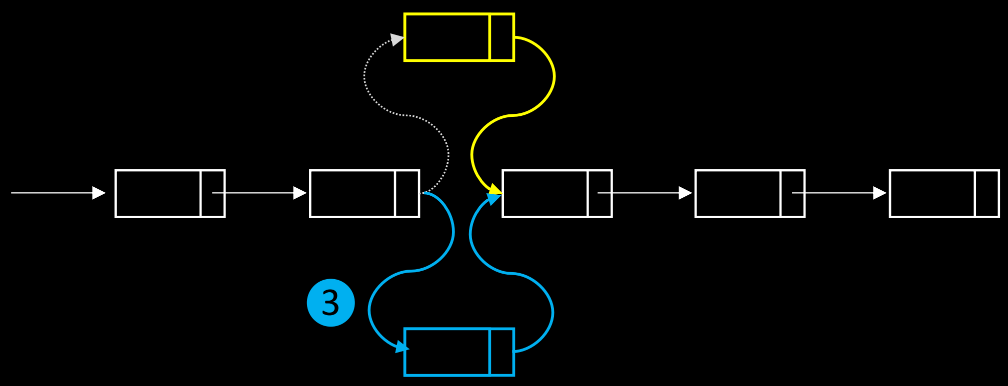
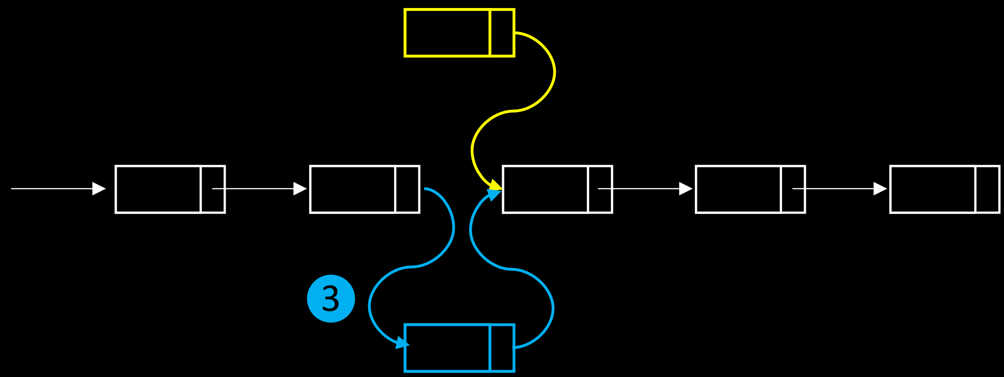


Race conditions

- Example with linked lists
  - Insertion of a new element
    - 3 steps
      1. Allocate
      2. Set next
      3. Modify previous
  - What if two threads perform an insert simultaneously, at the same position?
    - We may end up with a corrupted list



Enforcing mutual exclusion

- Let’s say we want to wrap our critical section this way

```
enter_cs ()
<critical section>
exit_cs ()
```

- How make sure that *at most 1 thread at a time* can run in the critical section?

- Possible using read/write operations?
  - Reading or writing a word (64 bits) is atomic on modern computers

Enforcing mutual exclusion

- Let's say we want to wrap our critical section this way

```
enter_cs ()
<critical section>
exit_cs ()
```

- Think about shower cabins
  - Red flag = busy
  - Green flag = free

```
bool busy = FALSE;

void enter_sc ()
{
  while (busy)
    /* wait */ ;
  busy = TRUE;
}

void exit_sc ()
{
  busy = FALSE;
}
```

Enforcing mutual exclusion

- Let’s say we want to wrap our critical section this way

```
enter_cs ()
<critical section>
exit_cs ()
```

- Think about shower cabins
  - Red flag = busy
  - Green flag = free

```
bool busy = FALSE;

void enter_sc ()
{
}

void exit_sc ()
{
  busy = FALSE;
}
```

Fail!

Enforcing mutual exclusion

```
//  Gary L. Peterson, 1981. Works with two processes : #0 and #1
bool flag [2] = { FALSE, FALSE };
unsigned turn = 0;

void enter_sc ()
{
  flag[me] = TRUE;
  turn = me;
  wait (flag[1 – me] == FALSE  or  turn != me);
}

void exit_sc ()
{
  flag[me] = FALSE;
}
```

Enforcing mutual exclusion

```
bool flag [2] = { FALSE, FALSE };
unsigned turn = 0;
```

```
// Thread #0

void enter_sc ()
{

}
```

```
// Thread #1

void enter_sc ()
{

}
```

Enforcing mutual exclusion

```
bool flag [2] = { FALSE, TRUE };
unsigned turn = 0;
```

```
// Thread #0

void enter_sc ()
{



}
```

```
// Thread #1

void enter_sc ()
{
  flag[1] = TRUE;

}
```

Enforcing mutual exclusion

```
bool flag [2] = { FALSE, TRUE };
unsigned turn = 1;
```

```
// Thread #0

void enter_sc ()
{





}
```

```
// Thread #1

void enter_sc ()
{
  flag[1] = TRUE;
  turn = 1;

}
```

Enforcing mutual exclusion

```
bool flag [2] = { FALSE, TRUE };
unsigned turn = 1;
```

```
// Thread #0

void enter_sc ()
{



}
```

```
// Thread #1

void enter_sc ()
{
  flag[1] = TRUE;
  turn = 1;
  wait (flag[0] == FALSE  or  turn != 1);
}
```

Enforcing mutual exclusion

```
bool flag [2] = { FALSE, TRUE };
unsigned turn = 1;
```

```
// Thread #0

void enter_sc ()
{

}
```

```
// Thread #1

void enter_sc ()
{
  flag[1] = TRUE;
  turn = 1;
  // Not blocked…
}
```

Enforcing mutual exclusion

```
bool flag [2] = { TRUE, TRUE };
unsigned turn = 1;
```

```
// Thread #0

void enter_sc ()
{



  flag[0] = TRUE;


}
```

```
// Thread #1

void enter_sc ()
{
  flag[1] = TRUE;
  turn = 1;
  // Not blocked…
}
```

Enforcing mutual exclusion

```
bool flag [2] = { TRUE, TRUE };
unsigned turn = 0;
```

```
// Thread #0

void enter_sc ()
{

  flag[0] = TRUE;
  turn = 0;

}
```

```
// Thread #1

void enter_sc ()
{
  flag[1] = TRUE;
  turn = 1;
  // Not blocked…
}
```

Enforcing mutual exclusion

```
bool flag [2] = { TRUE, TRUE };
unsigned turn = 0;
```

```
// Thread #0

void enter_sc ()
{




  flag[0] = TRUE;
  turn = 0;
  wait (flag[1] == FALSE  or  turn != 0);
}
```

```
// Thread #1

void enter_sc ()
{
  flag[1] = TRUE;
  turn = 1;
  // Not blocked…
}
```

Enforcing mutual exclusion

```
bool flag [2] = { TRUE, TRUE };
unsigned turn = 0;
```

```
// Thread #0

void enter_sc ()
{




  flag[0] = TRUE;
  turn = 0;
  wait (flag[1] == FALSE  or  turn != 0);
  // Blocked
}
```

```
// Thread #1

void enter_sc ()
{
  flag[1] = TRUE;
  turn = 1;
  // Not blocked…
}
```

Enforcing mutual exclusion

```
bool flag [2] = { TRUE, TRUE };
unsigned turn = ?;
```

```
// Thread #0

void enter_sc ()
{
  flag[0] = TRUE;
  turn = 0;


  wait (flag[1] == FALSE  or  turn != 0);
}
```

```
// Thread #1

void enter_sc ()
{
  flag[1] = TRUE;
  turn = 1;


  wait (flag[0] == FALSE  or  turn != 1);
}
```

Enforcing mutual exclusion

```
bool flag [2] = { TRUE, TRUE };
unsigned turn = 1;
```

```
// Thread #0

void enter_sc ()
{
  flag[0] = TRUE;
  turn = 0;


  wait (flag[1] == FALSE  or  turn != 0);
}
```

```
// Thread #1

void enter_sc ()
{
  flag[1] = TRUE;

  turn = 1;

  wait (flag[0] == FALSE  or  turn != 1);
}
```

Enforcing mutual exclusion

- Peterson's algorithm limitations
  - Only works with two processes
  - Introduces busy waiting
- Extending Peterson's algorithm to work with N processes
  - Idea:
    - Imagine a stairway to ~~heaven~~ critical section
    - At each step, a modified version of Peterson lets only N-1 processes access to the upper step
    - Eventually, only one process reaches the top (= critical section)

Enforcing mutual exclusion

- Coping with N processes is undoubtedly better…
  - But in a real kernel, we don’t know how many processes will participate!

- We need a mechanism which works with an arbitrary number of processes/threads
  - Maybe computer architects can help us?

Enforcing mutual exclusion

- Processor atomic instructions
  - Execution cannot be interleaved with the execution of another instruction
  - Modern processors feature a large set of atomic operations

- To enforce mutual exclusion, we only need one
  - *“Test-and-Set”* (TAS)

Enforcing mutual exclusion

```
int test_and_set (int *address)
{
  int old = *address;
  *address = 1;
  return old;
}
```

- *test-and-set* is a hardware processor instruction
  - This C code should be considered for illustrative purposes only
    - memory side effects
    - returned value
  - Its execution wouldn’t guarantee atomicity!

test-and-set

- How does it work?

```
int i = 0;
test_and_set (&i) ➔ ?
```

test-and-set

- How does it work?

```
int i = 1;
test_and_set (&i) ➔ 0
```

test-and-set

- How does it work?

```
int i = 1;
test_and_set (&i) → 0
test_and_set (&i) → ?
```

test-and-set

- How does it work?

```
int i = 1;
test_and_set (&i) → 0
test_and_set (&i) → 1
```

test-and-set

- How does it work?

```
int i = 1;
test_and_set (&i) → 0
test_and_set (&i) → 1
test_and_set (&i) → ?
```

test-and-set

- How does it work?

```
int i = 1;
test_and_set (&i) → 0
test_and_set (&i) → 1
test_and_set (&i) → 1
```

test-and-set

- How does it work?
  - Well… straightforward

- What happens when multiple threads use it simultaneously?

```
int i = 1;
test_and_set (&i) → 0
test_and_set (&i) → 1
test_and_set (&i) → 1
test_and_set (&i) → 1
…
```

test-and-set

```
volatile int i = 0;
```

`test_and_set (&i) ➔ ?`

`test_and_set (&i) ➔ ?`

`test_and_set (&i) ➔ ?`

test-and-set

```
volatile int i = 1;
```

`test_and_set (&i)` ➔ 1

`test_and_set (&i)` ➔ 0

`test_and_set (&i)` ➔ 1

Because *test-and-set* is atomic, only ONE thread gets 0

test-and-set

```
volatile int i = 1;
```

```
test_and_set (&i) ➔ 1
test_and_set (&i) ➔ 1
…
```

```
test_and_set (&i) ➔ 0
```

```
test_and_set (&i) ➔ 1
test_and_set (&i) ➔ 1
…
```

test-and-set

```
volatile int i = 0;
```

```
test_and_set (&i) ➔ 1
test_and_set (&i) ➔ 1
…
```

```
test_and_set (&i) ➔ 0

i = 0
```

```
test_and_set (&i) ➔ 1
test_and_set (&i) ➔ 1
…
```

test-and-set

```
volatile int i = 0;
```

```
test_and_set (&i) → 1          test_and_set (&i) → 0          test_and_set (&i) → 1
test_and_set (&i) → 1                                         test_and_set (&i) → 1
        …                                                             …
                                       i = 0
test_and_set (&i) → 1                                         test_and_set (&i) → 0
```

It seems we've found a simple protocol to enter/exit critical sections!

Enforcing mutual exclusion

- Let's say we want to wrap our critical section this way

```
enter_cs ()
<critical section>
exit_cs ()
```

- Think about shower cabins
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```
int lock = 0;

void enter_sc ()
{


}

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```

Enforcing mutual exclusion

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```
enter_cs ()
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```

- Think about shower cabins
  - Red flag = busy
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```
int lock = 0;

void enter_sc ()
{
  while (test_and_set(&lock) == 1)
    /* wait */ ;
}

void exit_sc ()
{

}
```

Enforcing mutual exclusion

- Let's say we want to wrap our critical section this way

```
enter_cs ()
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  lock = 0;
}
```

Enforcing mutual exclusion

- Note: the following variant is usually preferred
  - Less pressure
    on the memory bus

```
int lock = 0;

void enter_sc ()
{
  while (test_and_set(&lock) == 1)
    while (lock)
      /* wait */ ;
}

void exit_sc ()
{
  lock = 0;
}
```

Enforcing mutual exclusion

- Note: the following variant is usually preferred
  - Less pressure
    on the memory bus

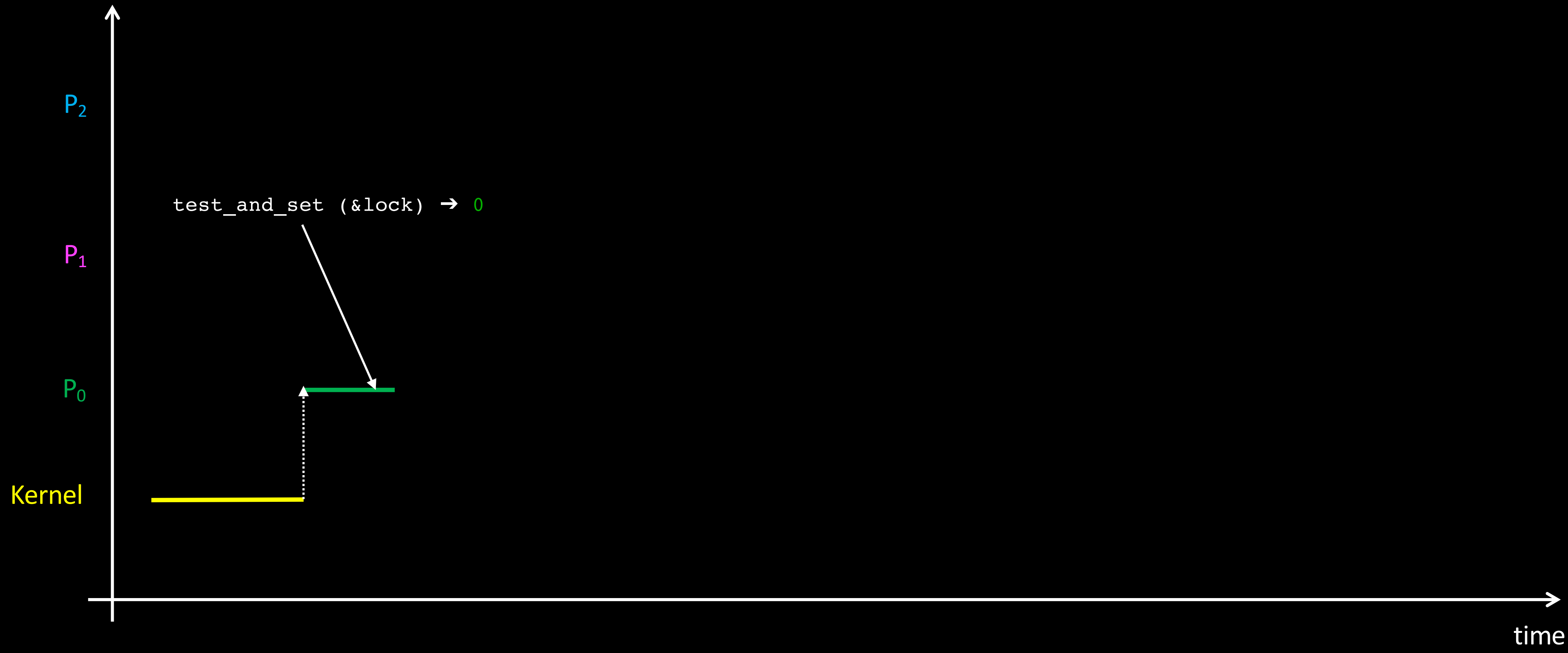
- Still one (major ?) issue:
  - Busy waiting

```
int lock = 0;

void enter_sc ()
{
  while (test_and_set(&lock) == 1)
    while (lock)
      /* wait */ ;
}

void exit_sc ()
{
  lock = 0;
}
```

Is *busy waiting* a major issue?



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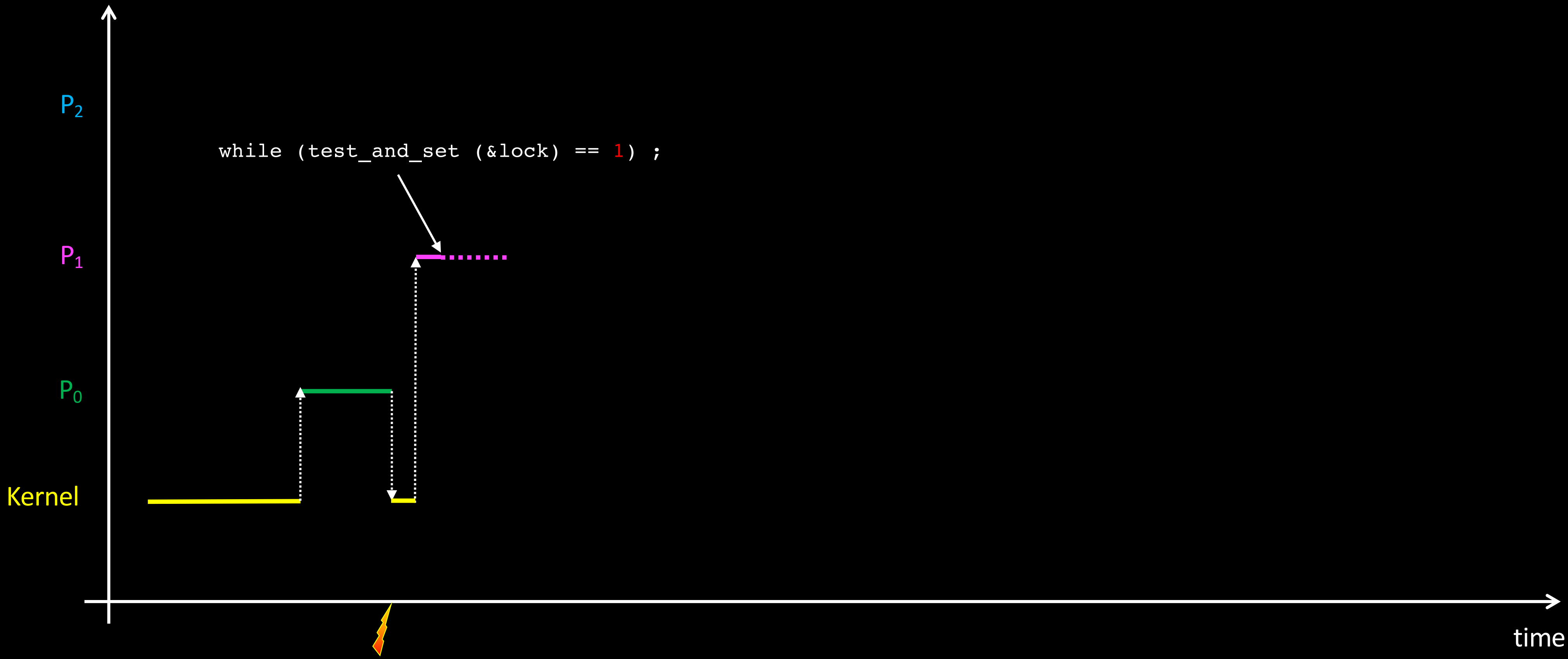

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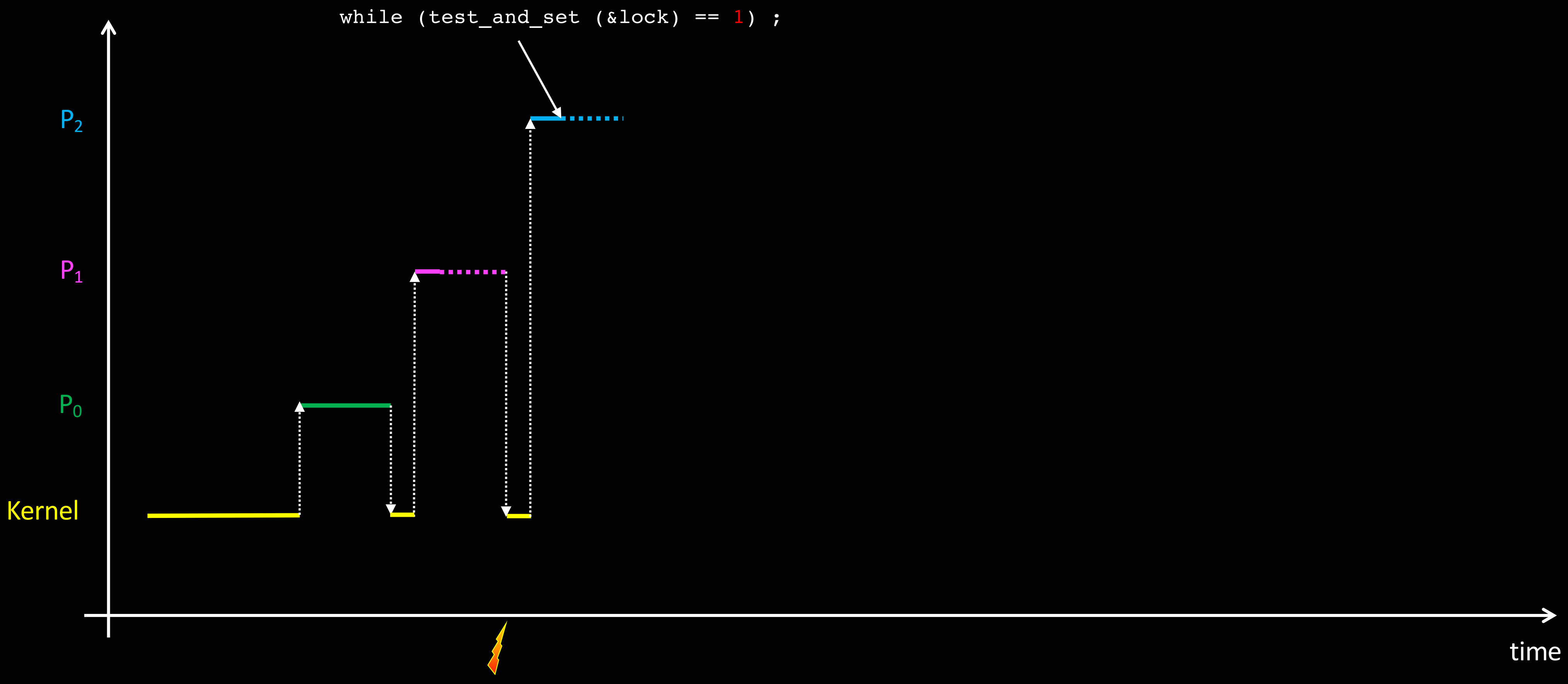

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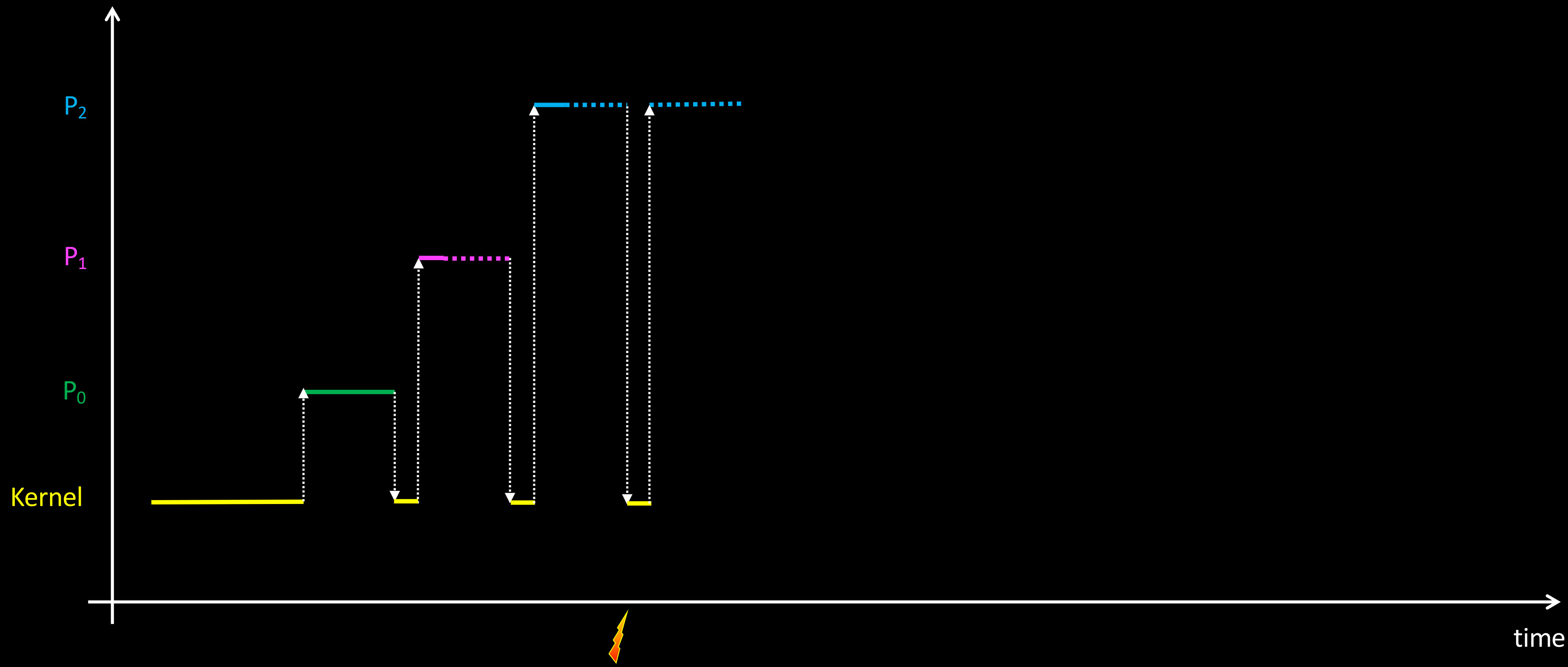

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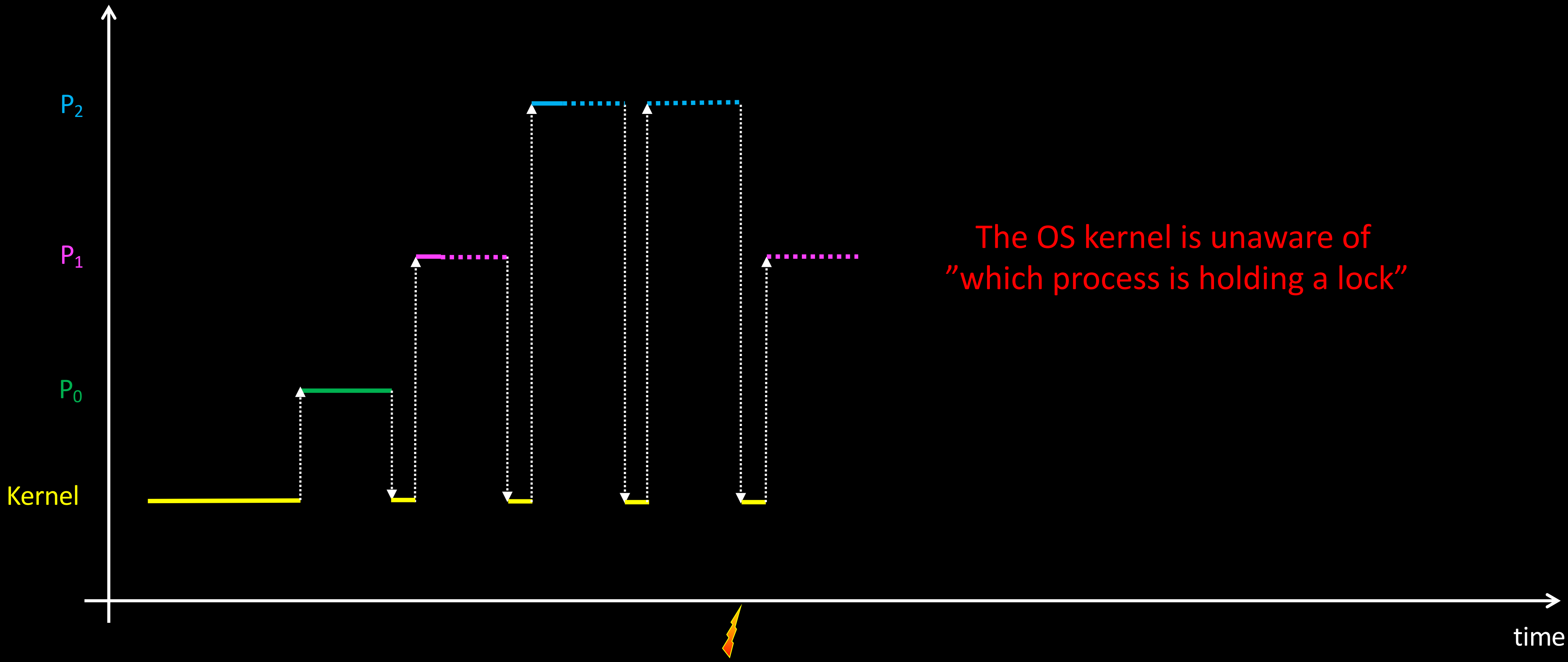

The OS kernel is unaware of
"which process is holding a lock"

Enforcing mutual exclusion

- Atomic instructions solve the problem at the lowest level
  - But *busy waiting* is a waste of CPU cycles

- We need to block processes which cannot enter critical section
  - Blocking processes can only be done inside the kernel

Enforcing mutual exclusion

- Atomic instructions solve the problem at the lowest level
    - But *busy waiting* is a waste of CPU cycles
- We need to block processes which cannot enter critical section
    - Blocking processes can only be done inside the kernel

```
int lock = 0;

void enter_sc ()
{
  while (test_and_set (&lock) == 1)
    syscall_enter_block_state ();
}

void exit_sc ()
{
  lock = 0;
  if (processes_are_waiting ())
    wake_up_one_process ();
}
```

Enforcing mutual exclusion

- Atomic instructions solve the problem at the lowest level
  - But *busy waiting* is a waste of CPU cycles

- We need to block processes which cannot enter critical section
  - Blocking processes can only be done inside the kernel

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{
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    wake_up_one_process ();
}
```

Semaphores [E. Dijsktra, 1962]

- Semaphores are high-level (*are you kidding me?*) synchronization objects
  - Implemented in the kernel
- A Semaphore is a structure containing private information
  - An integer value (initially ≥ 0)
  - A list of waiting processes (initially = NULL)
- Only 2 available operations. Both are atomic:
  - P (*probeer te verlagen*)
  - V (*vrijgave*)

Semaphores [E. Dijsktra, 1962]

```
// P is atomic
P(s)
{
  s->value--;
  if (s->value < 0)
    go_sleep_in (s->list);
}
```

Semaphores [E. Dijsktra, 1962]

```
// P is atomic
P(s)
{
  s->value--;
  if (s->value < 0)
    go_sleep_in (s->list);
}
```

```
// V is atomic
V(s)
{
  s->value++;
  if (s->value <= 0)
    wake_one_from (s->list);
}
```

Semaphores [E. Dijsktra, 1962]

```
// P is atomic
P(s)
{
  s->value--;
  if (s->value < 0)
    go_sleep_in (s->list);
}
```

```
// V is atomic
V(s)
{
  s->value++;
  if (s->value <= 0)
    wake_one_from (s->list);
}
```

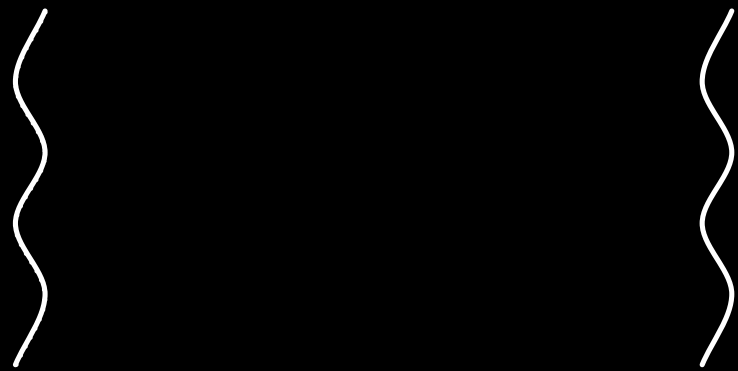
Semaphores can be seen as boxes containing tokens:

- P() == wait for a token in the box, take it and continue
- V() == throw a token into the box

Semaphore initialized to zero

- Let's see how it works on a simple example
  - Two threads
    - One calls P()
    - The other calls V()

```
Semaphore s(0);
```



Semaphore initialized to zero

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  - Two threads
    - One calls P()
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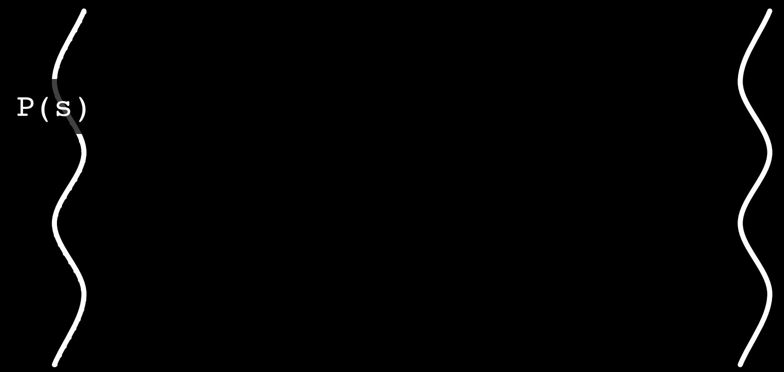
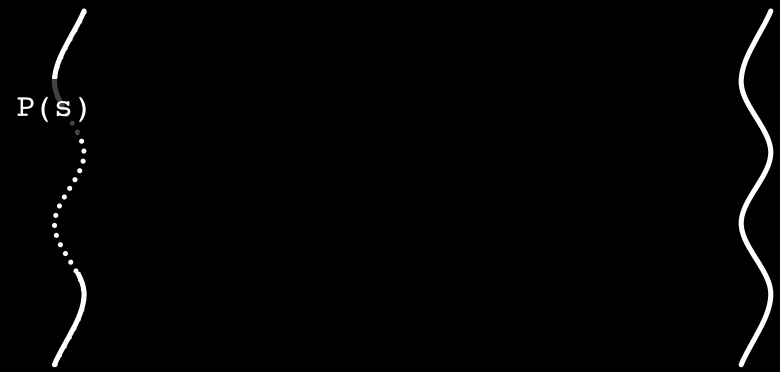
`Semaphore s(0);`



Semaphore initialized to zero

- Let’s see how it works on a simple example
  - Two threads
    - One calls P()
    - The other calls V()

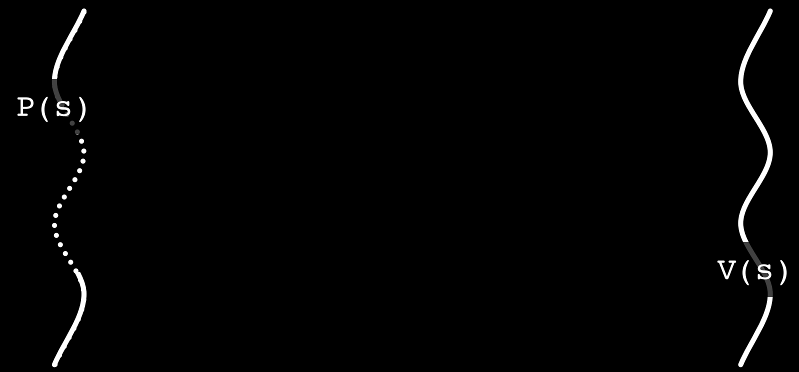
```
Semaphore s(−1);
```



Semaphore initialized to zero

- Let's see how it works on a simple example
  - Two threads
    - One calls P()
    - The other calls V()

```
Semaphore s(-1);
```



Semaphore initialized to zero

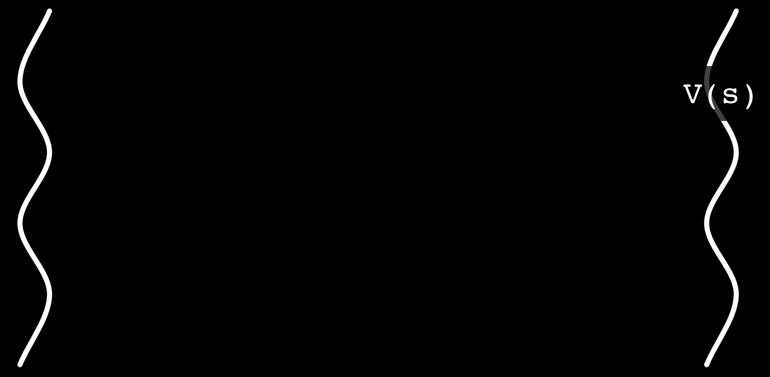
- Let's see how it works on a simple example
  - Two threads
    - One calls P()
    - The other calls V()

- When P is called first, it blocks the caller until… someone else calls V

Semaphore initialized to zero

- Let's see how it works on a simple example
  - Two threads
    - One calls P()
    - The other calls V()

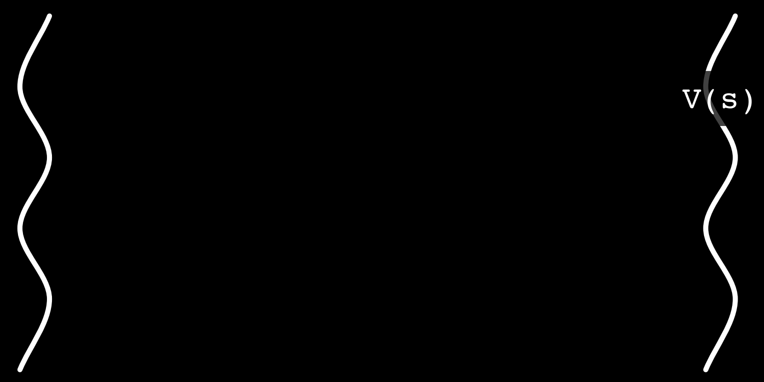
```
Semaphore s(0);
```



Semaphore initialized to zero

- Let's see how it works on a simple example
  - Two threads
    - One calls P()
    - The other calls V()

```
Semaphore s(1);
```



Semaphore initialized to zero

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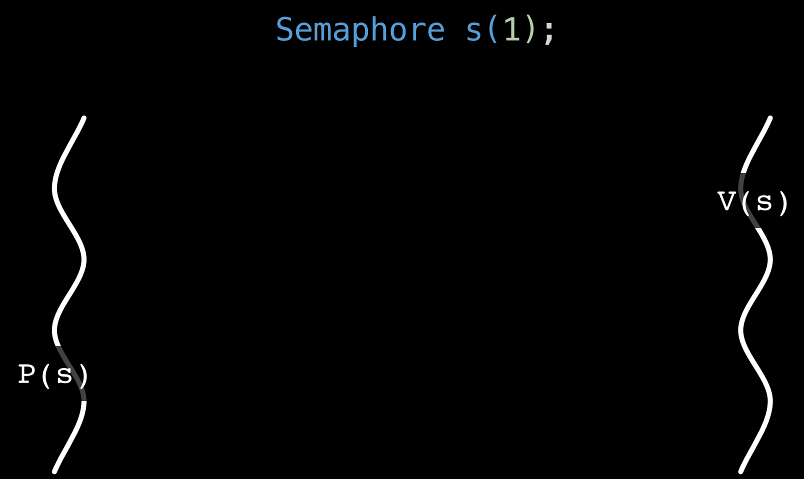
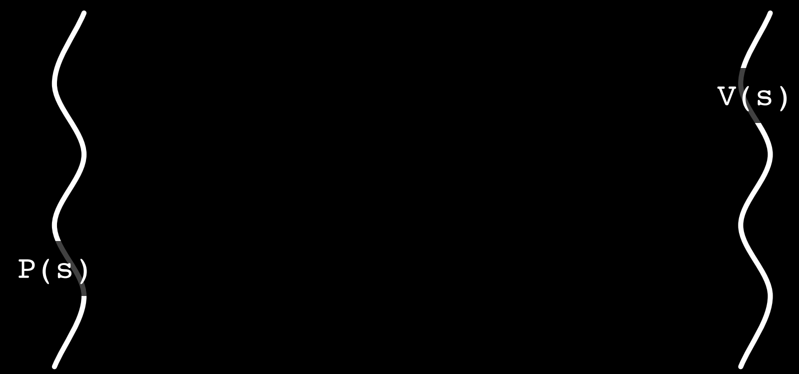


Semaphore initialized to zero

- Let’s see how it works on a simple example
  - Two threads
    - One calls P()
    - The other calls V()

- When V is called ahead of P, P is non-blocking

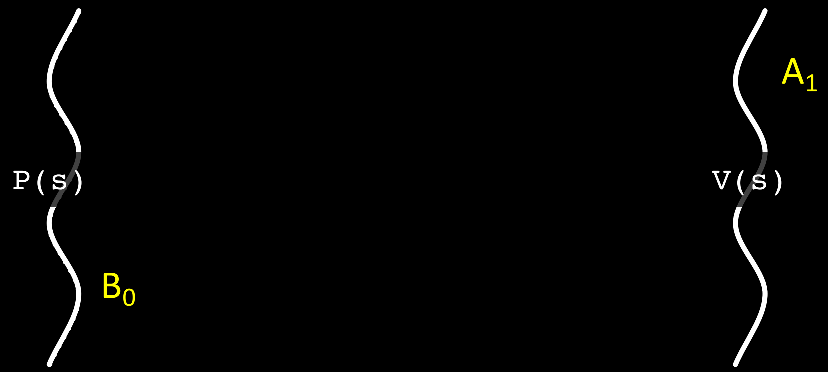
```
Semaphore s(0);
```



Semaphore initialized to zero

- In either case, it enforces a code dependency:
  - B_0 can only start when A_1 has completed

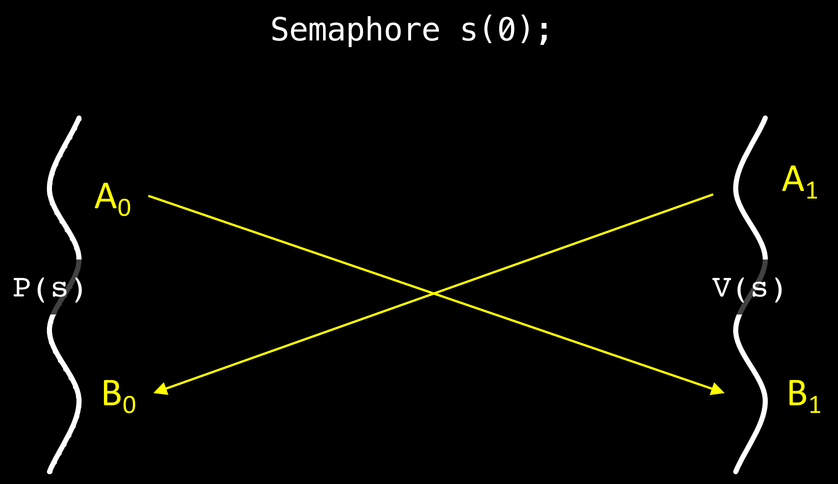
```
Semaphore s(0);
```



Semaphore initialized to zero

- Let us enforce:
  - B_0 can only start when A_1 has completed

  AND
  - B_1 can only start when A_0 has completed

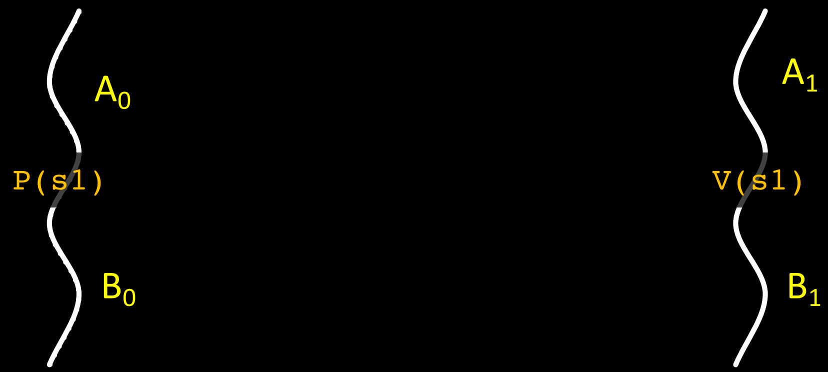


Semaphore initialized to zero

- Let us enforce:
  - B_0 can only start when A_1 has completed

  AND
  - B_1 can only start when A_0 has completed

```
Semaphore s1(0), s2(0);
```



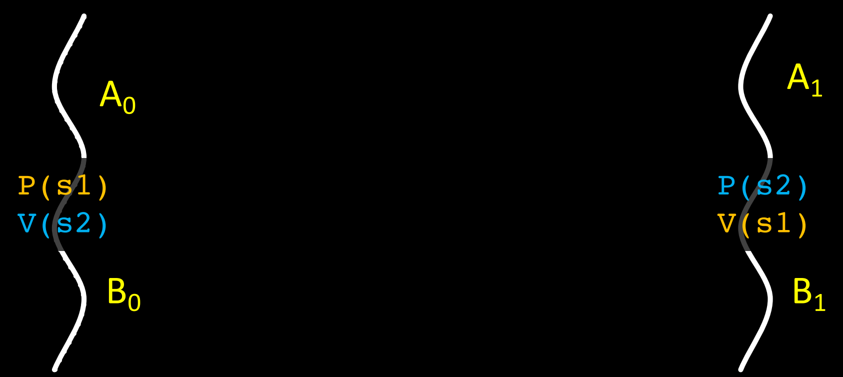
Semaphore initialized to zero

- Let us enforce:
  - B_0 can only start when A_1 has completed

  AND

  - B_1 can only start when A_0 has completed

```
Semaphore s1(0), s2(0);
```



Semaphore initialized to zero

- Let us enforce:
  - B_0 can only start when A_1 has completed

  AND
  - B_1 can only start when A_0 has completed

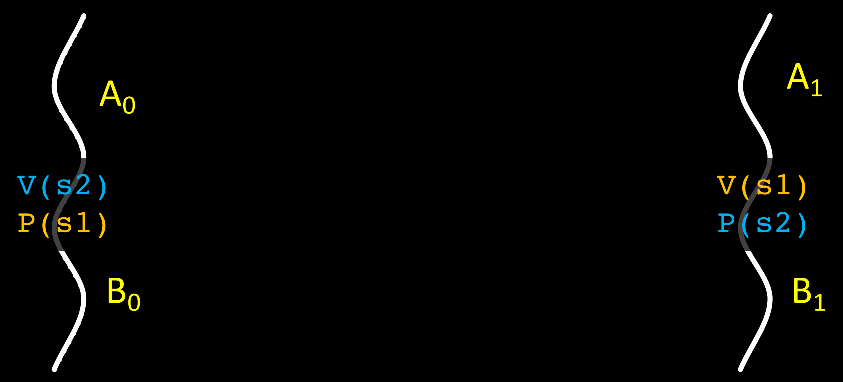
```
Semaphore s1(0), s2(0);
```

Semaphore initialized to zero

- Let us enforce:
  - B_0 can only start when A_1 has completed

  AND
  - B_1 can only start when A_0 has completed

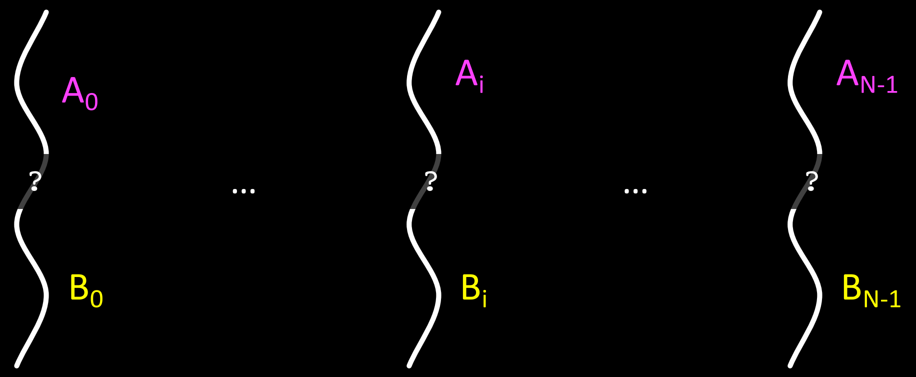
```
Semaphore s1(0), s2(0);
```



Semaphore initialized to zero

- Generalization to N processes
  - B_i can only start when all A_j have completed

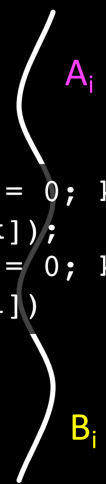
```
Semaphore s[N](0);
```



Semaphore initialized to zero

- Generalization to N processes
  - B_i can only start
    when all A_j have completed

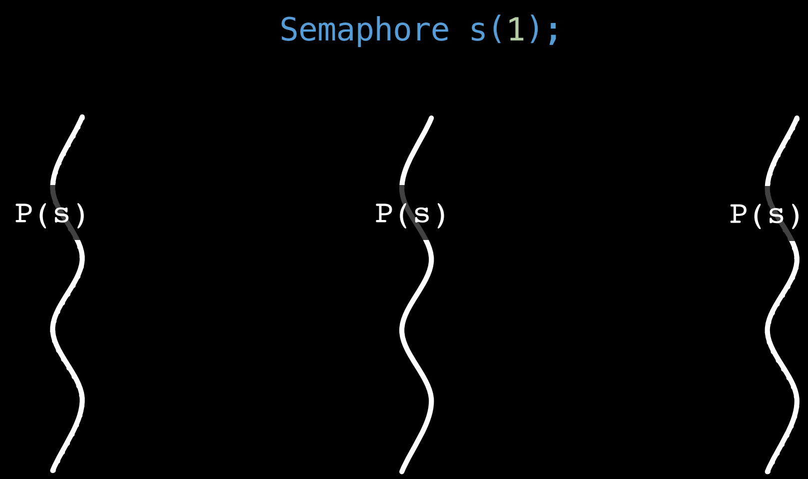
```
Semaphore s[N](0);
```




```
For (k = 0; k < N; k++)
  V(s[k]);
For (k = 0; k < N; k++)
  P(s[i])
```

Semaphore initialized to one

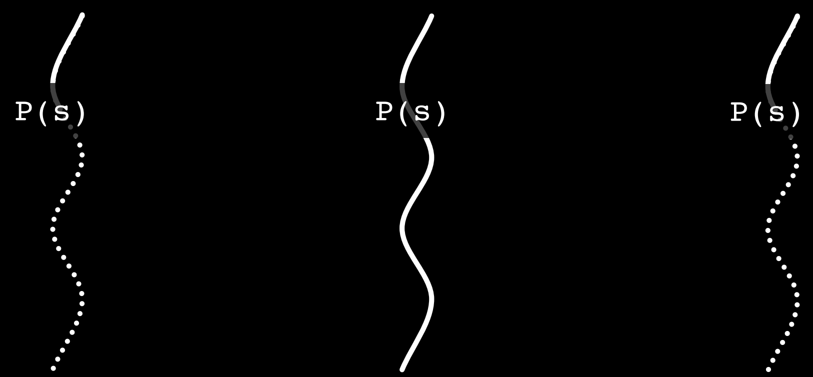
- Let's see how it works on a simple example
  - Three threads
    - Each one calls P(), then V()



Semaphore initialized to one

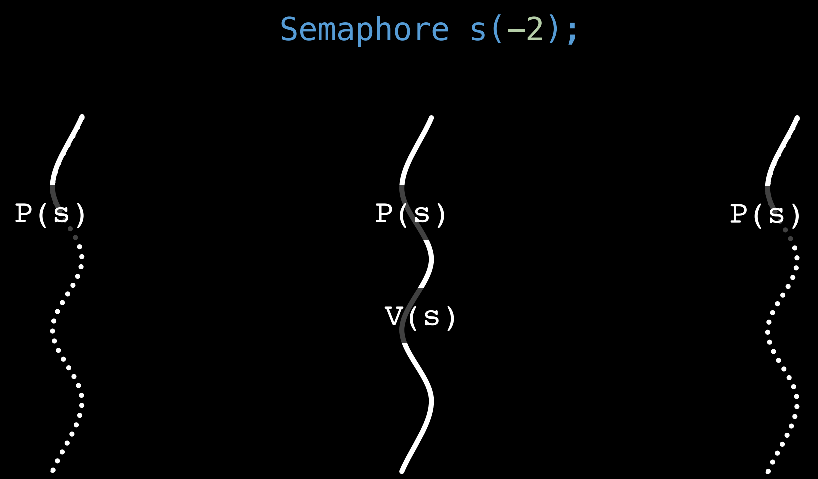
- Let’s see how it works on a simple example
  - Three threads
    - Each one calls P(), then V()

```
Semaphore s(-2);
```



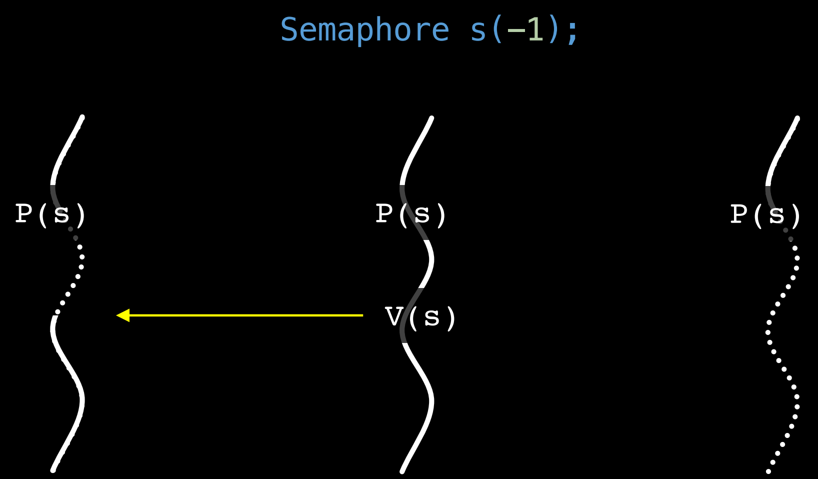
Semaphore initialized to one

- Let's see how it works on a simple example
  - Three threads
    - Each one calls P(), then V()



Semaphore initialized to one

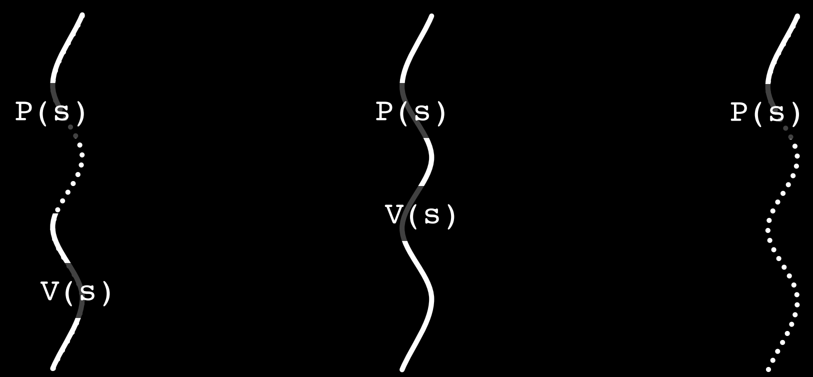
- Let's see how it works on a simple example
  - Three threads
    - Each one calls P(), then V()



Semaphore initialized to one

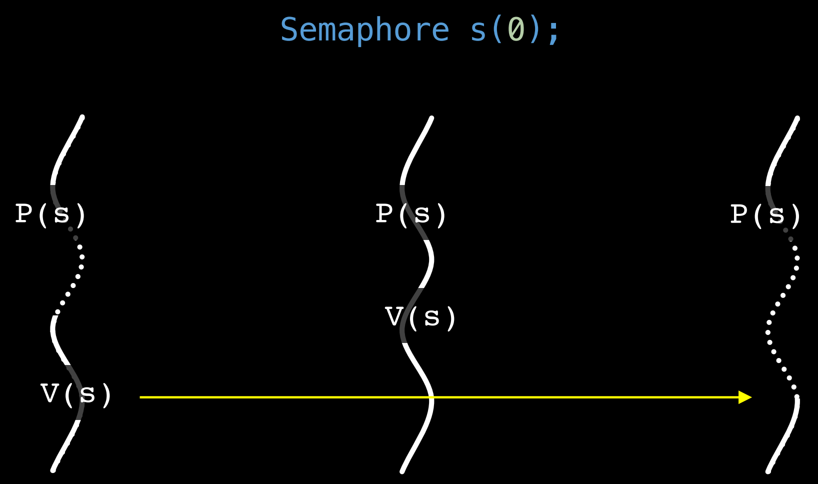
- Let's see how it works on a simple example
  - Three threads
    - Each one calls P(), then V()

```
Semaphore s(-1);
```



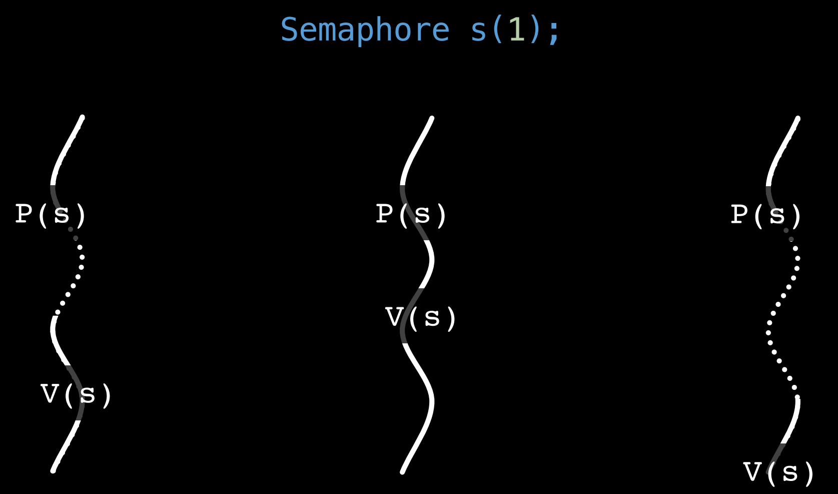
Semaphore initialized to one

- Let's see how it works on a simple example
  - Three threads
    - Each one calls P(), then V()



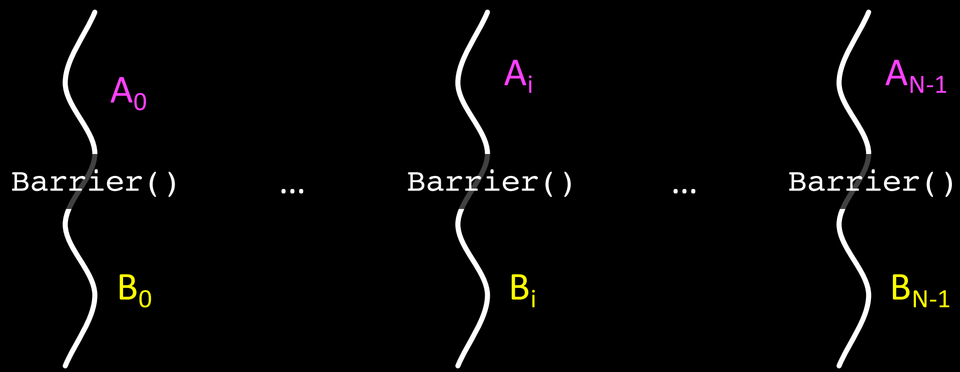
Semaphore initialized to one

- Let's see how it works on a simple example
  - Three threads
    - Each one calls P(), then V()
- That solves the mutual exclusion problem
  - `enter_sc = P(s)`
  - `exit_sc = V(s)`



Back to our *rendez-vous* problem

- Can we design a solution involving less than N semaphores?



Back to our *rendez-vous* problem

- Can we design a solution involving less than N semaphores?

- Ideas
  - Block the N-1 first processes joining the barrier
  - The last process wakes everyone

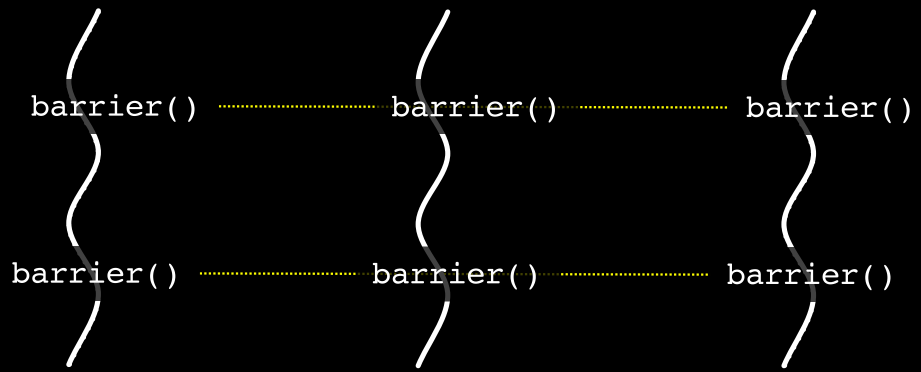
```
Semaphore wait(0), mutex(1);
int count = 0;

void barrier ()
{
  P(mutex);
  count++;
  if (count < N) {
    V(mutex);
    P(wait);
  } else {
    count = 0;
    V(mutex);
    for (k = 0; k < N-1; k++)
      V(wait);
  }
}
```

Back to our *rendez-vous* problem

- Ok, we now have a nice barrier that should be re-usable multiple times

- Is it?

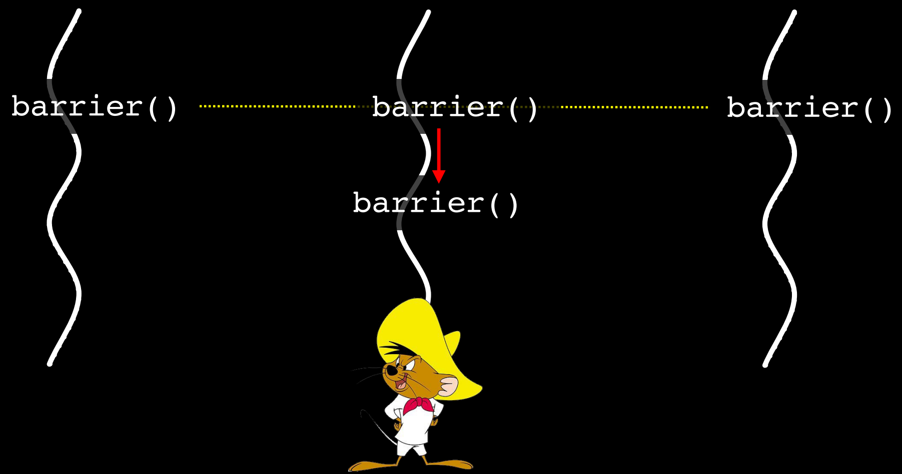



```
Semaphore wait(0), mutex(1);
int count = 0;

void barrier ()
{
  P(mutex);
  count++;
  if (count < N) {
    V(mutex);
    P(wait);
  } else {
    count = 0;
    V(mutex);
    for (int k=0; k < N-1; k++)
      V(wait);
  }
}
```

Back to our *rendez-vous* problem

- What if a thread quickly jumps from the first barrier to the second?




```
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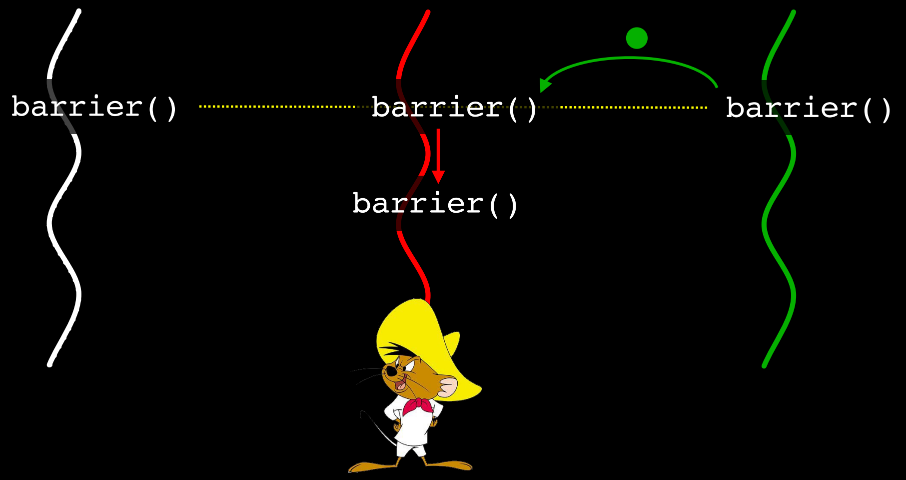
int count = 0;

void barrier ()
{
  P(mutex);
  count++;
  if (count < N) {
    V(mutex);
    P(wait);
  } else {
    count = 0;
    V(mutex);
    for (int k=0; k < N-1; k++)
      V(wait);
  }
}
```

Back to our *rendez-vous* problem

- What if a thread quickly jumps from the first barrier to the second?

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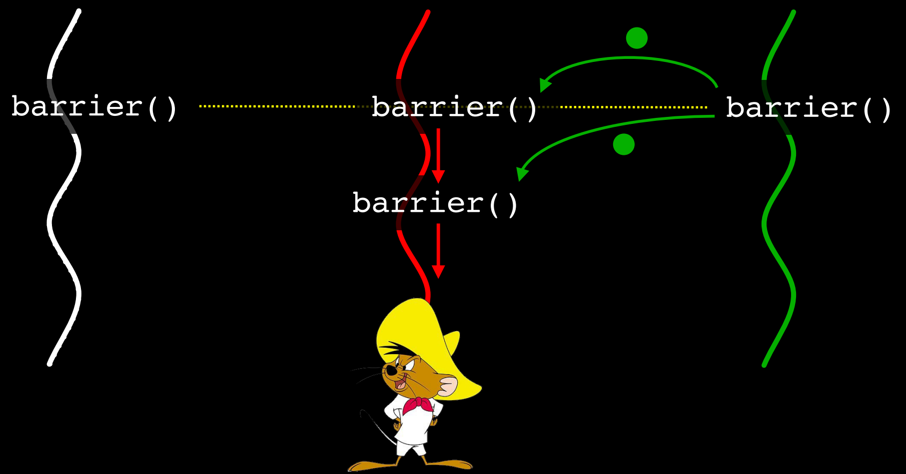
Semaphore wait(0), mutex(1);
int count = 0;

void barrier ()
{
  P(mutex);
  count++;
  if (count < N) {
    V(mutex);
    P(wait);
  } else {
    count = 0;
    V(mutex);
    for (int k=0; k < N-1; k++)
      V(wait);
  }
}
```

Back to our *rendez-vous* problem

- What if a thread quickly jumps from the first barrier to the second?




```
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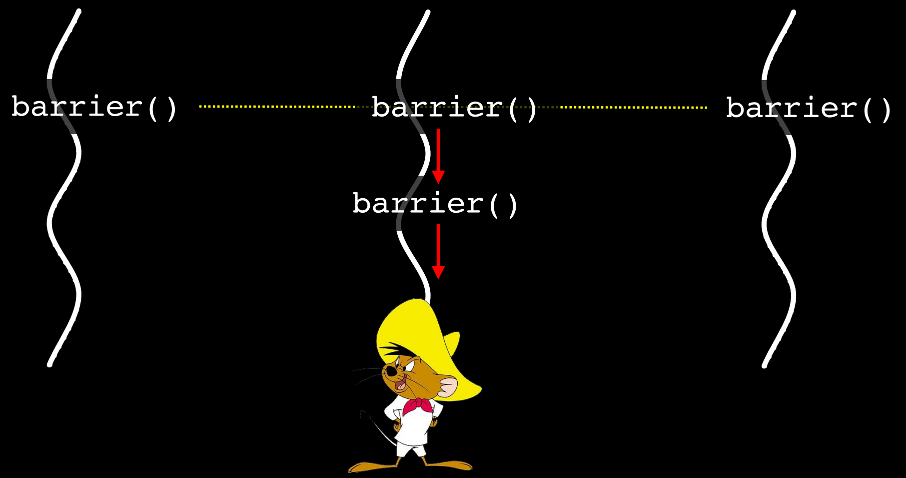
int count = 0;

void barrier ()
{
  P(mutex);
  count++;
  if (count < N) {
    V(mutex);
    P(wait);
  } else {
    count = 0;
    V(mutex);
    for (int k=0; k < N-1; k++)
      V(wait);
  }
}
```

Back to our *rendez-vous* problem

- What if a thread quickly jumps from the first barrier to the second?

  Damn!! This speedy thread can eat someone else's token… and go ahead!




```
Semaphore wait(0), mutex(1);
int count = 0;

void barrier ()
{
  P(mutex);
  count++;
  if (count < N) {
    V(mutex);
    P(wait);
  } else {
    count = 0;
    V(mutex);
    for (int k=0; k < N-1; k++)
      V(wait);
  }
}
```

Back to our rendez-vous problem

- What if a thread quickly jumps from the first barrier to the second?
  - Damn!! This speedy thread can eat someone else’s token… and go ahead!

- We should probably release the mutex at the latest…

```
Semaphore wait(0), mutex(1);
int count = 0;

void barrier ()
{
  P(mutex);
  count++;
  if (count < N) {
    V(mutex);
    P(wait);
  } else {
    count = 0;
    for (int k=0; k < N-1; k++)
      V(wait);
    V(mutex);
  }
}
```

Back to our rendez-vous problem

- What if a thread quickly jumps from the first barrier to the second?

  Damn!! This speedy thread can eat someone else's token… and go ahead!

- We should probably release the mutex at the latest…
  - Happy folks? ☺

```
Semaphore wait(0), mutex(1);
int count = 0;

void barrier ()
{
  P(mutex);
  count++;
  if (count < N) {
    V(mutex);
    P(wait);
  } else {
    count = 0;
    for (int k=0; k < N-1; k++)
      V(wait);
    V(mutex);
  }
}
```

Back to our rendez-vous problem

- Hmmm… Unfortunately, it doesn't solve the problem ☹

```
Semaphore wait(0), mutex(1);
int count = 0;

void barrier ()
{
  P(mutex);
  count++;
  if (count < N) {
    V(mutex);
    P(wait);
  } else {
    count = 0;
    for (int k=0; k < N-1; k++)
      V(wait);
    V(mutex);
  }
}
```

Back to our rendez-vous problem

- Hmmm… Unfortunately, it doesn't solve the problem ☹

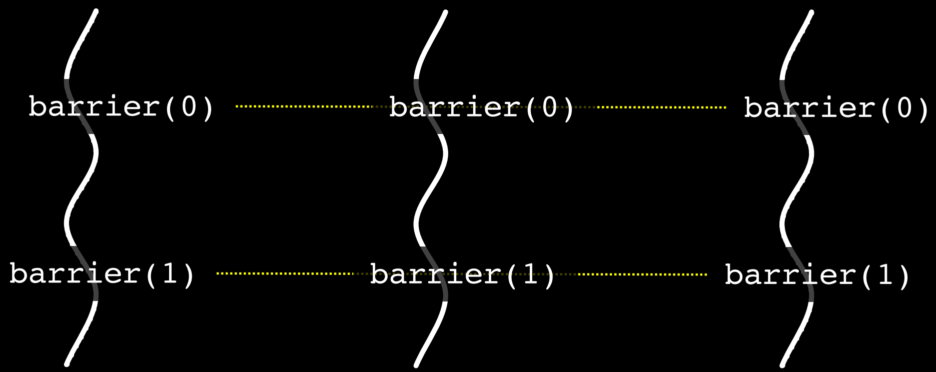
- A process can have some rest before entering P(wait)
    - So we don't know WHEN he will call P(wait)…
    - The solution IS NOT to postpone V(mutex)

```
Semaphore wait(0), mutex(1);
int count = 0;

void barrier ()
{
  P(mutex);
  count++;
  if (count < N) {
    V(mutex);
    P(wait);
  } else {
    count = 0;
    for (int k=0; k < N-1; k++)
      V(wait);
    V(mutex);
  }
}
```

Back to our *rendez-vous* problem

- Say we want to use *barrier()* only twice
  - We could duplicate all data to separate tokens
    - Two separate phases (0 and 1)

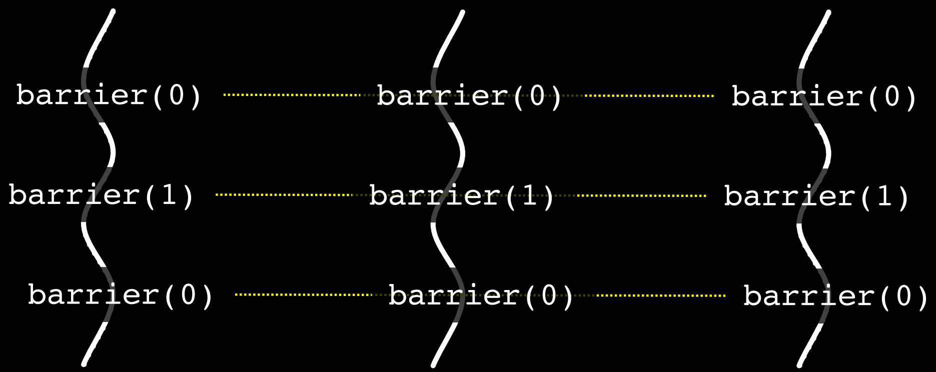



```
Semaphore wait[2](0), mutex[2](1);
int count[2] = { 0, 0 };

void barrier (int i)
{
  P(mutex[i]);
  count[i]++;
  if (count[i] < N) {
    V(mutex[i]);
    P(wait[i]);
  } else {
    count[i] = 0;
    V(mutex[i]);
    for (int k=0; k < N-1; k++)
      V(wait[i]);
  }
}
```

Back to our *rendez-vous* problem

- Need to use *barrier()* more than twice?
  - We just need to alternate between *even* and *odd* phases

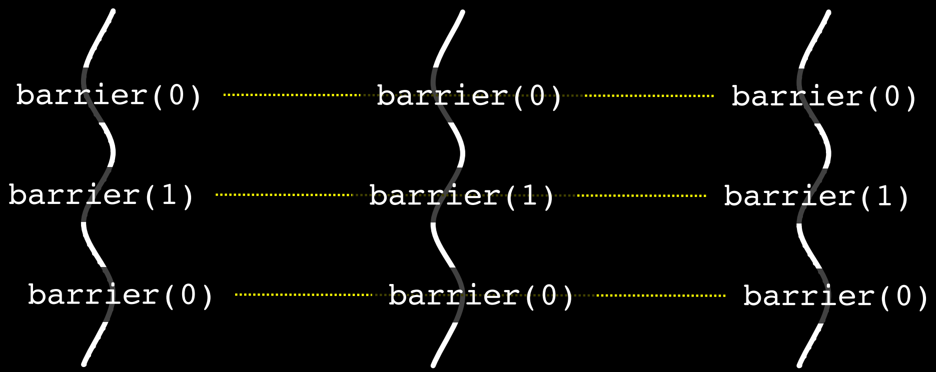



```
Semaphore wait[2](0), mutex[2](1);
int count[2] = { 0, 0 };

void barrier (int i)
{
  P(mutex[i]);
  count[i]++;
  if (count[i] < N) {
    V(mutex[i]);
    P(wait[i]);
  } else {
    count[i] = 0;
    V(mutex[i]);
    for (int k=0; k < N-1; k++)
      V(wait[i]);
  }
}
```

Back to our *rendez-vous* problem

- Need to use *barrier()* more than twice?
  - We just need to alternate between *even* and *odd* phases



- Threads must maintain the phase number in a “local” variable
  - Thread Local Storage (TLS)

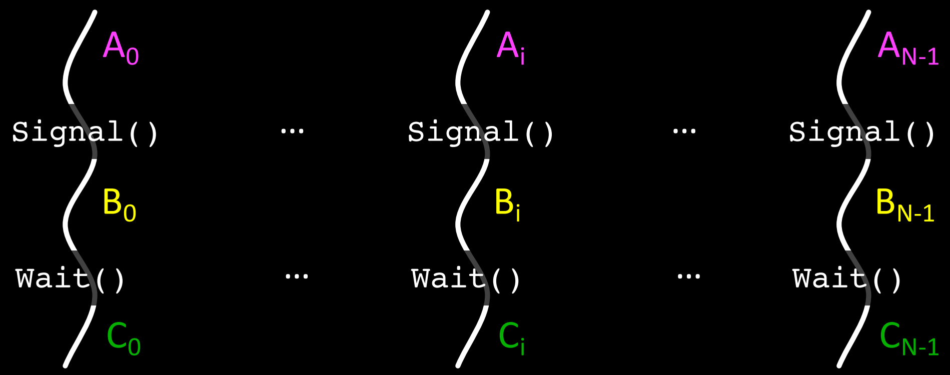
```
__thread int phase = 0;

barrier()
{
…
   phase = 1 – phase;
}
```

Back to our *rendez-vous* problem

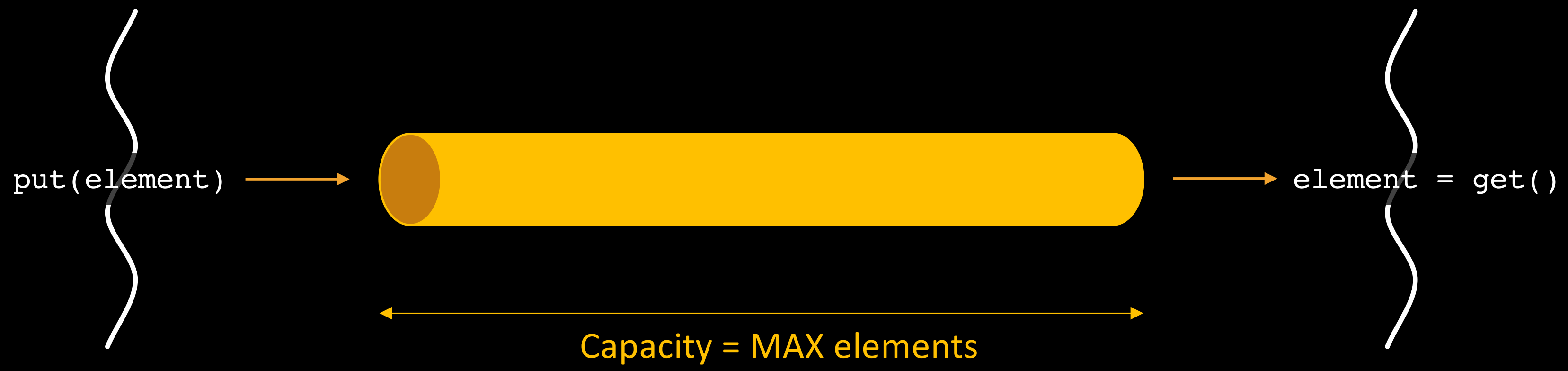
- Okay, now we have a classy barrier we can be proud of!

- In some applications, two-phase barriers are more useful
  - C_k must start after A_i
  - B_j has no dependency on A_i and C_k
  - Signal() is non-blocking
  - Wait() blocks until all A_i have completed



Producers/Consumers problem

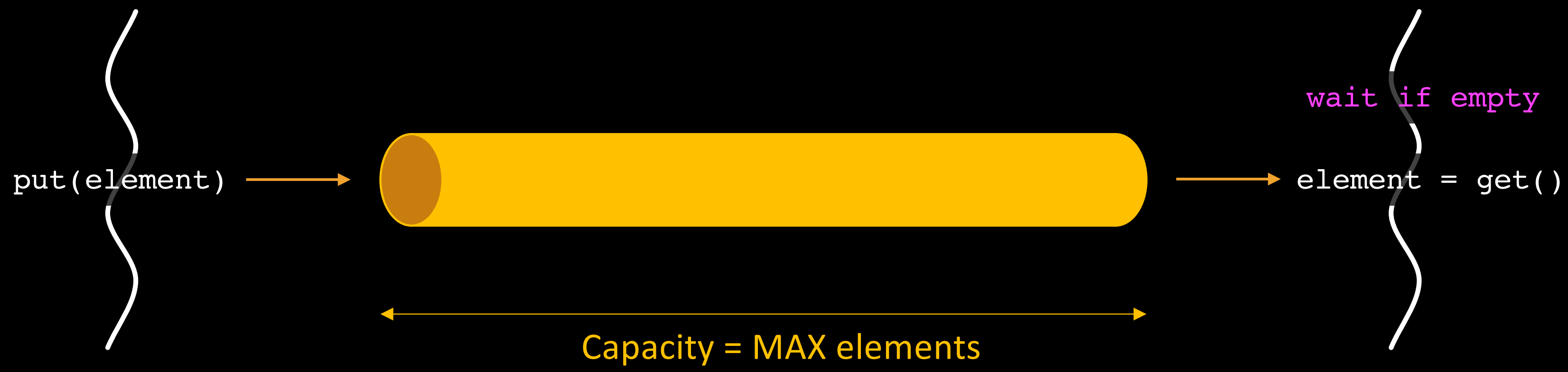
- Shared FIFO structure (initially empty)
  - put() and get() are not synchronized
    - When FIFO is full, put raises an error / when FIFO is empty, get raises an error
    - We assume put() and get() can be performed simultaneously



Producers/Consumers problem

- Let's look at the Consumers side first
  - Do we need to count elements?

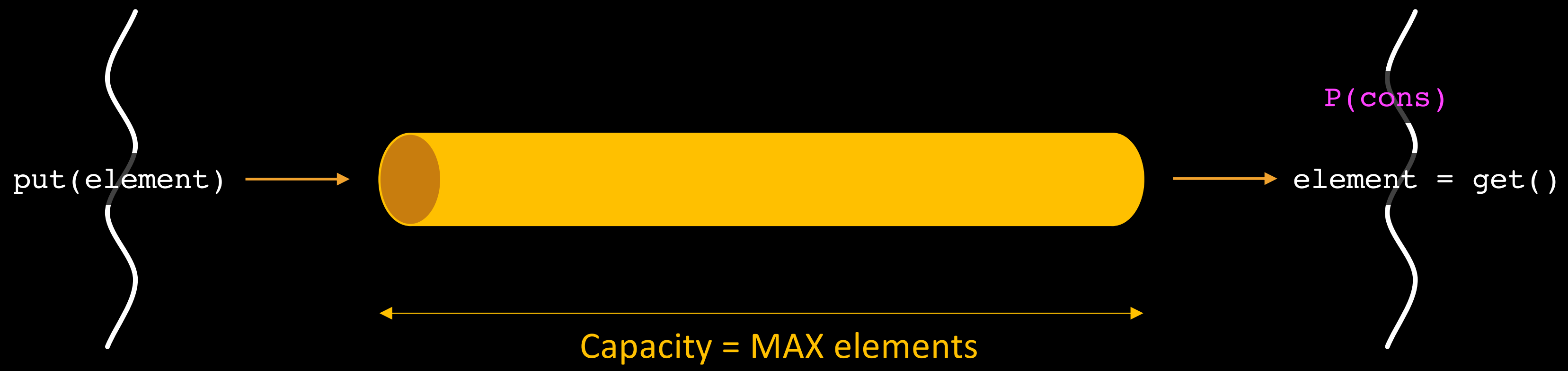
```
semaphore cons(?);
```



Producers/Consumers problem

- Let's look at the Consumers side first
  - Do we need to count elements?

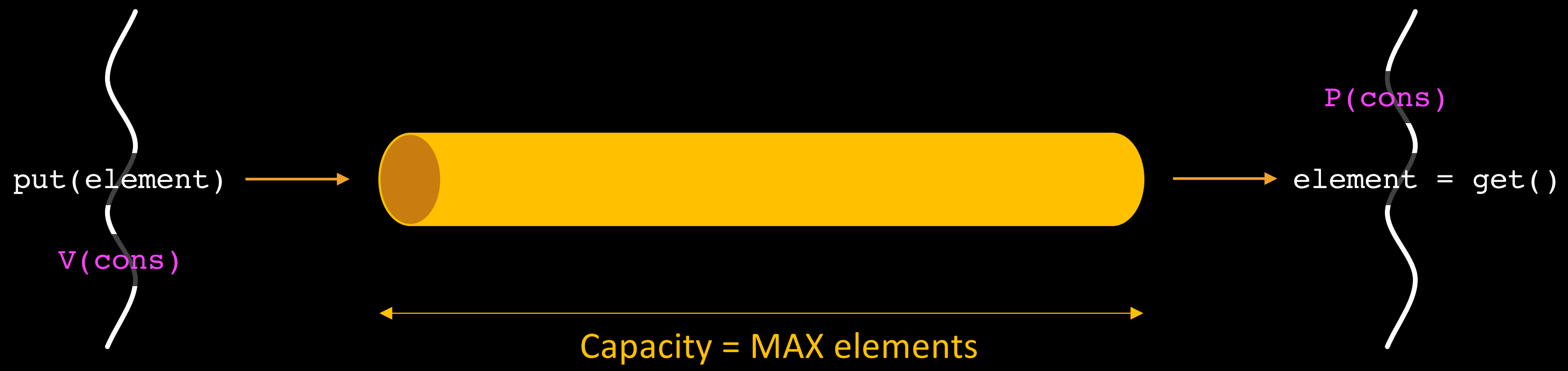
```
semaphore cons(0);
```



Producers/Consumers problem

- Let's look at the Consumers side first
  - N elements in FIFO
    => N tokens in cons

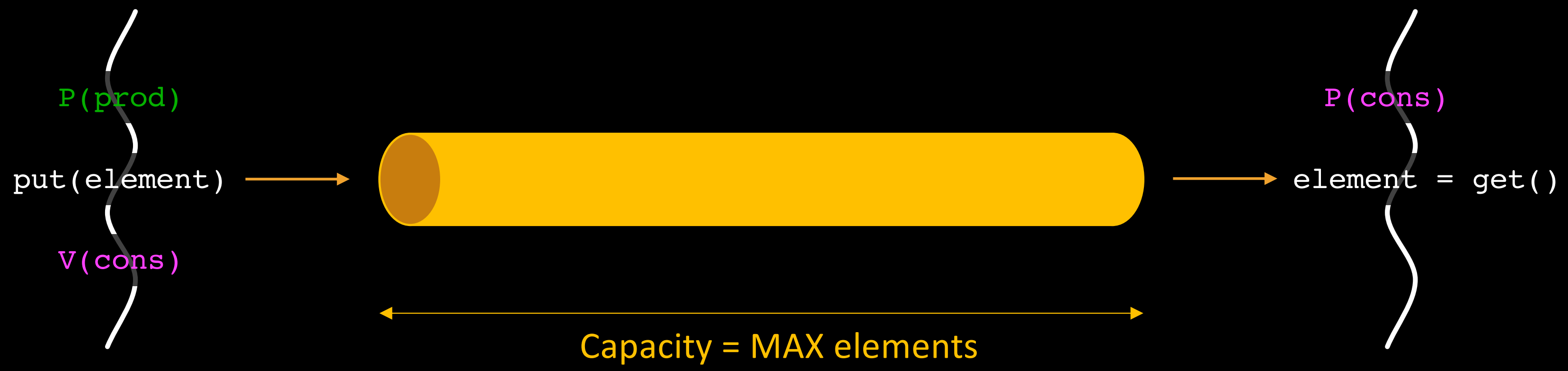
```
semaphore cons(0);
```



Producers/Consumers problem

- Let’s look at the Consumers side first
  - N elements in FIFO
    => N tokens in cons

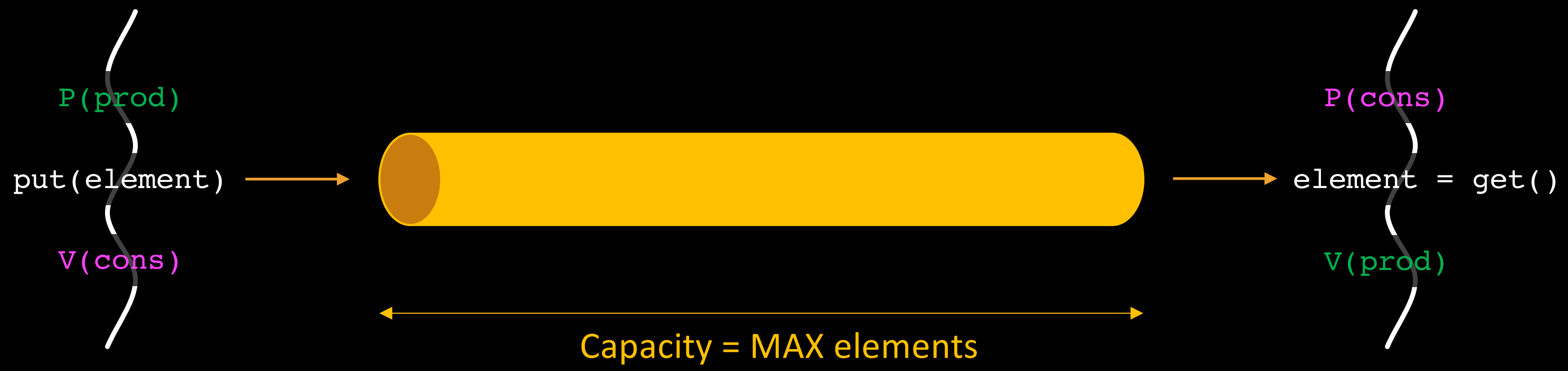
```
semaphore cons(0), prod(?);
```



Producers/Consumers problem

- Let's look at the Consumers side first
  - N free slots in FIFO
    => N tokens in prod

```
semaphore cons(0), prod(MAX);
```



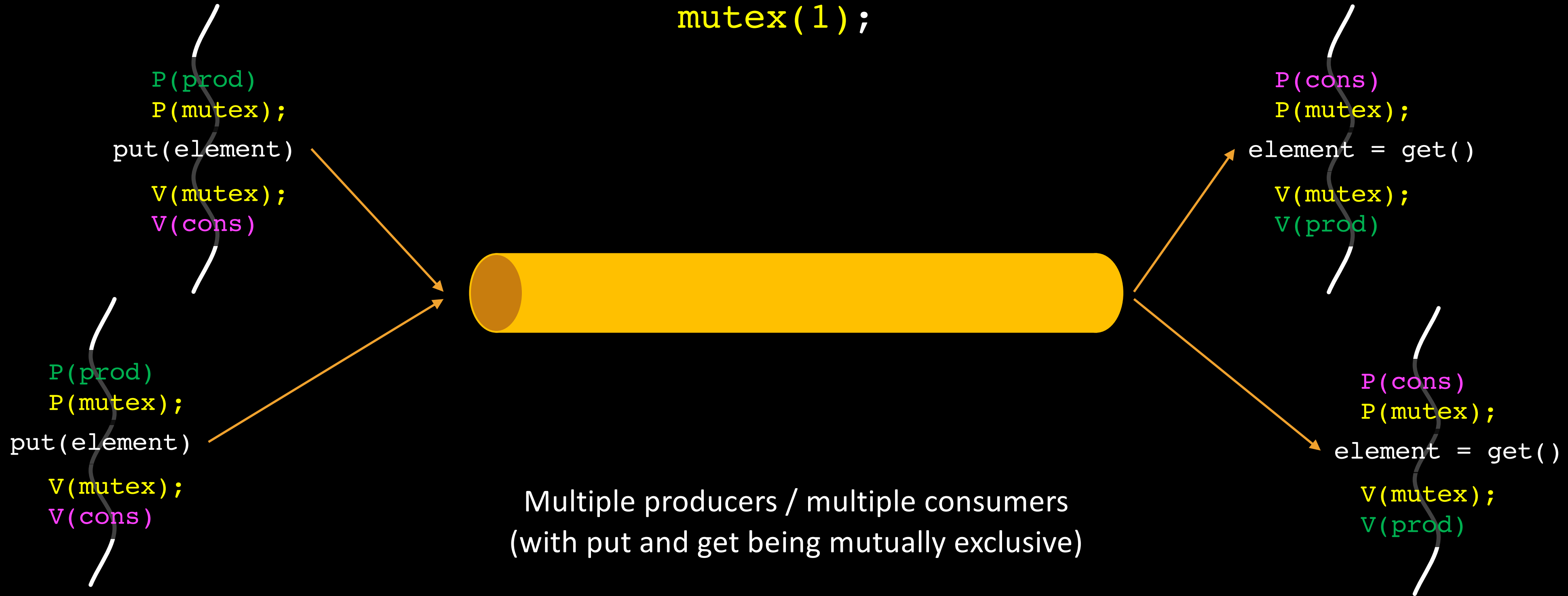
Producers/Consumers problem

```
semaphore cons(0), prod(MAX);
```

Multiple producers / multiple consumers

Producers/Consumers problem

```
semaphore cons(0), prod(MAX)
          mutex(1);
```



Multiple producers / multiple consumers
(with put and get being mutually exclusive)

Producers/Consumers problem

```
semaphore cons(0), prod(MAX)
          mutexC(1), mutexP(1);
```

```
P(prod)
P(mutexP)
put(element)
V(mutexP)
V(cons)
```

```
P(prod)
P(mutexP)
put(element)
V(mutexP)
V(cons)
```

```
P(cons)
P(mutexC)
element = get()
V(mutexC)
V(prod)
```

```
P(cons)
P(mutexC)
element = get()
V(mutexC)
V(prod)
```

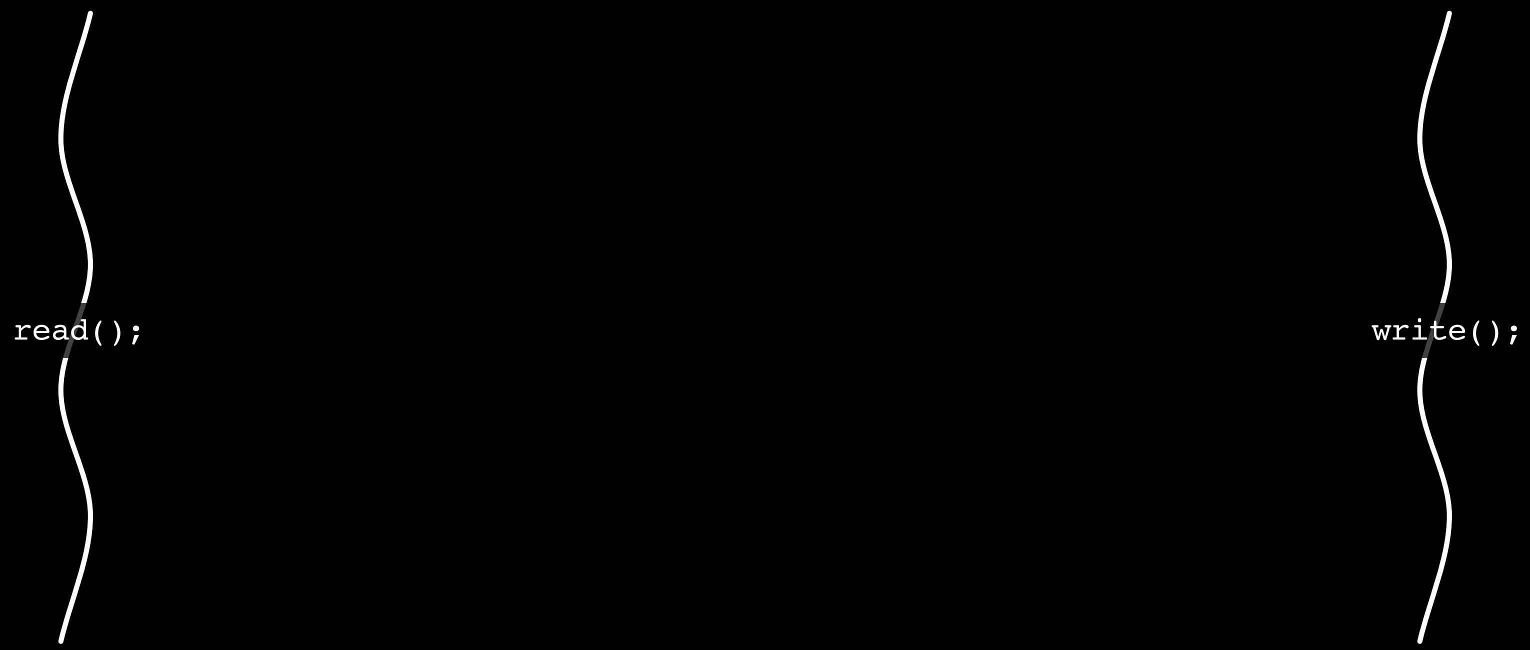
Multiple producers / multiple consumers

Reader/Writer problem

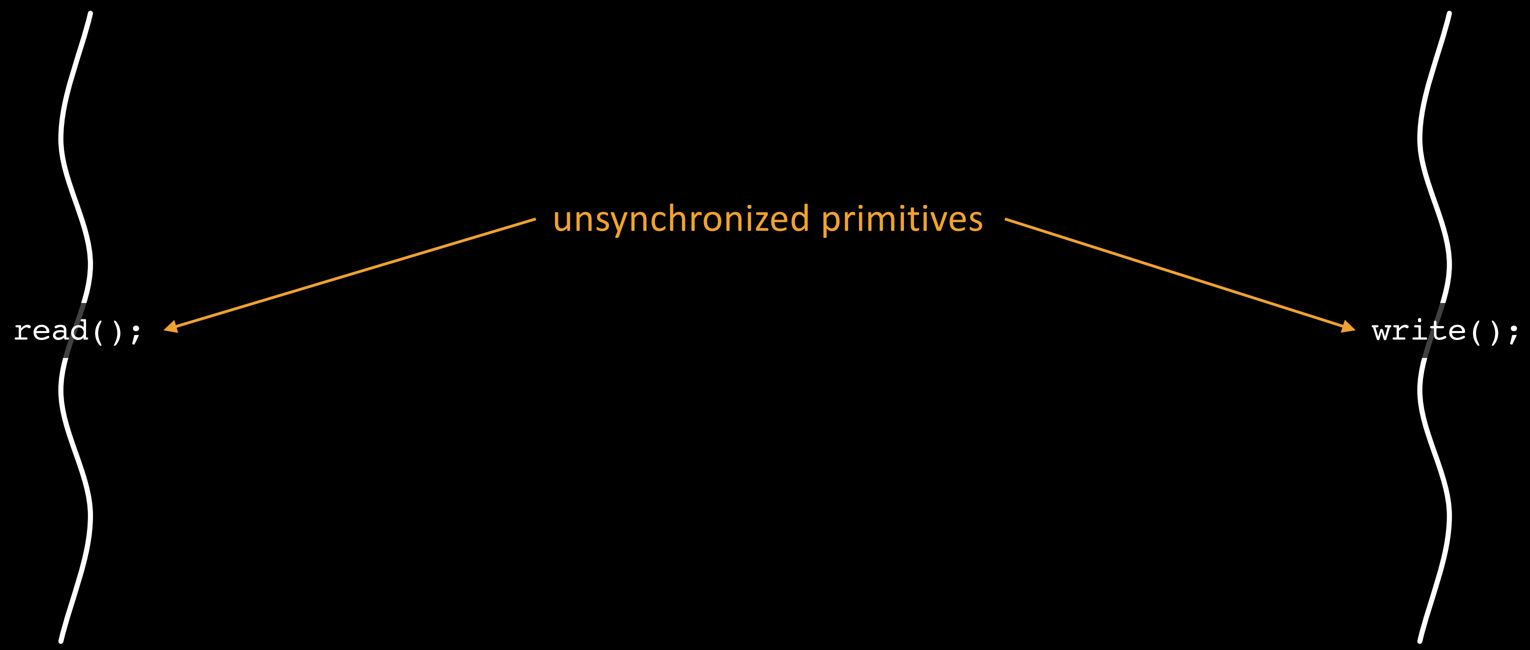
- A shared data structure is accessed by two types of processes
  - Readers
    - These processes only read the data
  - Writers
    - These processes can modify the data

- Consequently, we want to enforce the following rules
  - Multiple Readers can access data concurrently (R // R // R // ... is ok)
  - Writers are mutually exclusive (no W // W)
  - Writers and Readers are mutually exclusive (no W // R)

Reader/Writer problem



Reader/Writer problem



Reader/Writer problem

Semaphore writeToken(?);

```
read();
```

```
?
write();
?
```

Reader/Writer problem

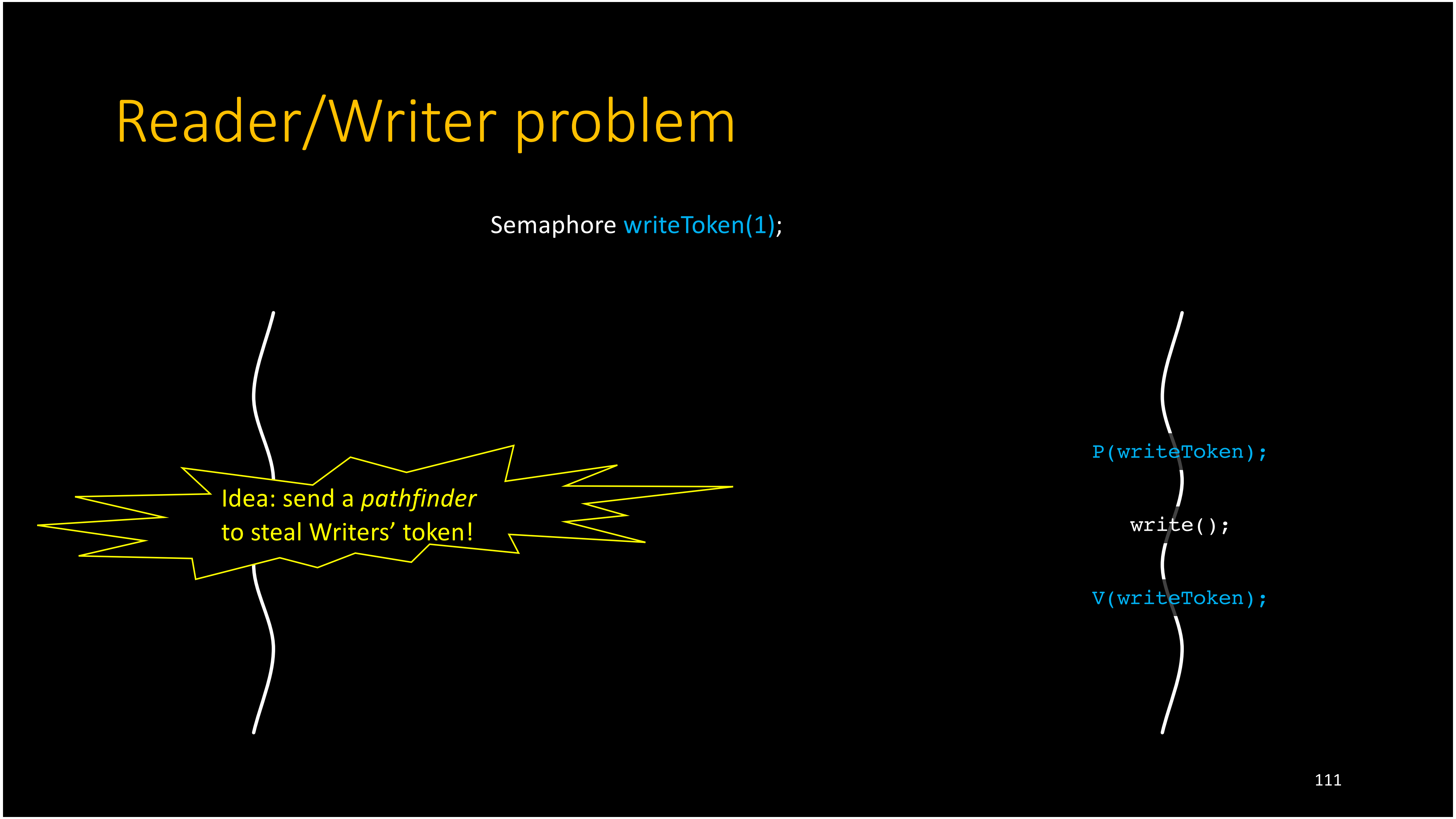
Semaphore writeToken(1);

```
read();
```

```
P(writeToken);

write();

V(writeToken);
```


Reader/Writer problem
Semaphore writeToken(1);
Idea: send a pathfinder
to steal Writers' token!
P(writeToken);
write();
V(writeToken);
111

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;

```
Nbr++;
If (nbr == 1)
  P(writeToken);

read();

Nbr--;
If (nbr == 0)
  V(writeToken);
```

```
P(writeToken);

write();

V(writeToken);
```

Reader/Writer problem

```
Semaphore writeToken(1);
int nbr = 0;
```

```
if(++nbr == 1)
  P(writeToken);

read();

if(--nbr == 0)
  V(writeToken);
```

```
P(writeToken);

write();

V(writeToken);
```

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;

```
if(++nbr == 1)
  P(writeToken);

read();

if(--nbr == 0)
  V(writeToken);
```

"Oulala!"

```
P(writeToken);

write();

V(writeToken);
```

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);

```
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);

 read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

```
P(writeToken);

   write();

V(writeToken);
```

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);

```
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);

  read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

Re-“Oulala!”

```
P(writeToken);

  write();

V(writeToken);
```

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);

```
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);

  read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

For once, it's ok

```
P(writeToken);

  write();

V(writeToken);
```

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);

```
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);

  read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

```
P(writeToken);

  write();

V(writeToken);
```

Can we guarantee this won't block forever?

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);

```
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);

  read();

 P(mutexR);
 if(--nbr == 0) // last to leave
   V(writeToken);
 V(mutexR);
```

Is this algorithm fair?

```
P(writeToken);

  write();

V(writeToken);
```

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);

```
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);

 read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

This algorithm is totally **unfair**!

Readers and Writers do not accumulate on the same semaphores…

```
P(writeToken);

  write();

V(writeToken);
```

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

 read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

Reader/Writer problem

R

W

R

R

R

```
Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);
```

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

 read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

  write();

V(writeToken);
```

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);

R

W

R

R

R

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

 read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

Reader/Writer problem

R

W

R

R

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

 read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

R

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

Reader/Writer problem

R

W

R

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

 read();

 P(mutexR);
 if(--nbr == 0) // last to leave
   V(writeToken);
 V(mutexR);
```

R

R

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

Reader/Writer problem

R

W

R

```
Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);
```

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

  read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

R

R

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

Reader/Writer problem

R

W

R

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

  read();

 P(mutexR);
 if(--nbr == 0) // last to leave
   V(writeToken);
 V(mutexR);
```

R

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

Reader/Writer problem

R

W

```
Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);
```

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

  read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

R

R

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

Reader/Writer problem

R

W

```
Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);
```

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

  read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

R R

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

  write();

V(writeToken);
```

Reader/Writer problem

R

```
Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);
```

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

  read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

W

R R

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

Reader/Writer problem

R

Semaphore writeToken(1);
int nbr = 0;
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Semaphore waitingRoom(1);

```
P(waitingRoom);
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if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

 read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

W

R

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
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Reader/Writer problem

R

Semaphore writeToken(1);
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P(waitingRoom);
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if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

 read();

 P(mutexR);
 if(--nbr == 0) // last to leave
   V(writeToken);
 V(mutexR);
```

W

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

Reader/Writer problem

R

```
Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);
```

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

 read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

W

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

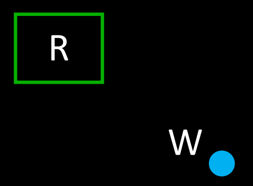
Reader/Writer problem

```
Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);
```

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

 read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```




```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

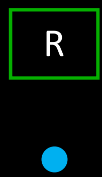
Reader/Writer problem

```
Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
Semaphore waitingRoom(1);
```

```
P(waitingRoom);
P(mutexR);
if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

 read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```




```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

V(writeToken);
```

Reader/Writer problem

Semaphore writeToken(1);
int nbr = 0;
Semaphore mutexR(1);
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```
P(waitingRoom);
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if (++nbr == 1) // pathfinder
  P(writeToken);
V(mutexR);
V(waitingRoom);

  read();

P(mutexR);
if(--nbr == 0) // last to leave
  V(writeToken);
V(mutexR);
```

R

```
P(waitingRoom);
P(writeToken);
V(waitingRoom);

   write();

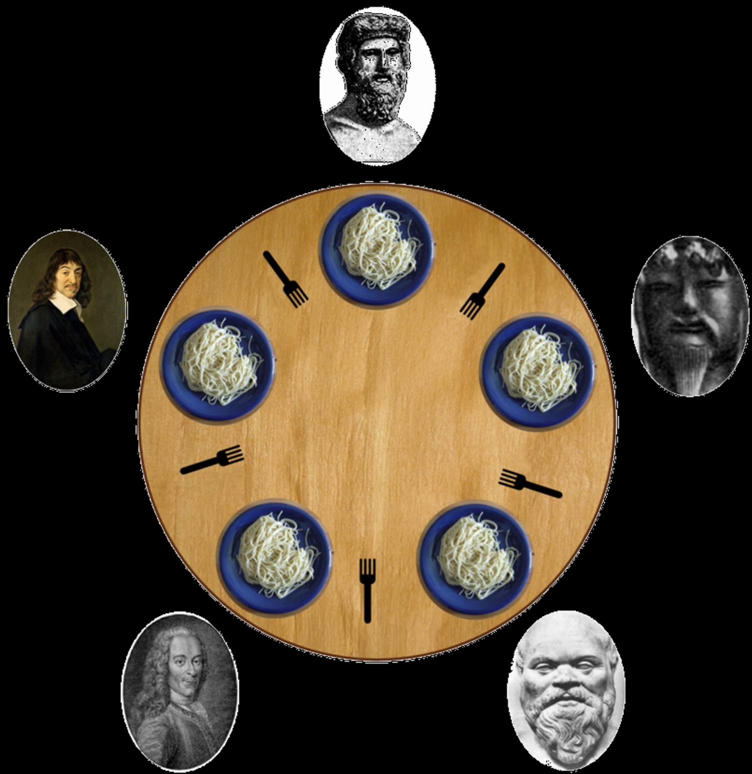
V(writeToken);
```

Recap

- Most popular synchronization schemes
  - Mutual Exclusion
  - Execution Dependencies
  - Barriers
  - Producers-Consumers
  - Readers-Writers

- You'll find many, many other (theoretical) problems in OS books

The Dining Philosophers problem



Hoare Monitors (1973)

- Synchronization construct initially proposed in the context of OO Languages
  - Simula67
  - Concurrent Pascal
- Later used in
  - Ada
  - Java
  - Operating Systems

```
Monitor class m {
  private int i = …;

  public method f() {
    … i++; …
  }

  public method g() {
    … i--; …
  }
}
```

Hoare Monitors (1973)

- Principles
  - Implicit *lock* associated to a monitor
    - Methods are mutually exclusive

```
Monitor class m {
  private int i = …;

  public method f() {
    … i++; …
  }

  public method g() {
    … i--; …
  }
}
```

≈ P(mutex)

≈ V(mutex)

Hoare Monitors (1973)

- Principles
  - Implicit *lock* associated to a monitor
    - Methods are mutually exclusive
  - *Conditions* are synchronizing objects
    - Think about a list of waiting processes
    - Wait
      - Unconditionally blocks
    - Signal / Bcast
      - Wakes up one (all) process, or do nothing

```
Monitor class m {
  private int i = …;
  private condition c;

  public method f() {
    if (…)
      wait (c);
    …
  }

  public method g() {
    …
    signal (c);
    …
  }
}
```

Hoare Monitors (1973)

- Conditions ≠ Semaphores
  - No tokens saved
    - Signal does nothing if no process is waiting
  - The wait operation is subtle
    - Sleep in the condition list

```
Monitor class m {
  private int i = …;
  private condition c;

  public method f() {
    if (…)
      wait (c);
    …
  }

  public method g() {
    …
    signal (c);
    …
  }
}
```

Hoare Monitors (1973)

- Conditions ≠ Semaphores
  - No tokens saved
    - Signal does nothing if no process is waiting
  - The wait operation is subtle
    - Release the implicit lock
    - Sleep in the condition list

```
Monitor class m {
  private int i = …;
  private condition c;

  public method f() {
    if (…)
      wait (c);
    …
  }

  public method g() {
    …
    signal (c);
    …
  }
}
```

Hoare Monitors (1973)

- Conditions ≠ Semaphores
  - No tokens saved
    - Signal does nothing if no process is waiting
  - The wait operation is subtle
    - Release the implicit lock
    - Sleep in the condition list
    - Re-acquire the implicit lock upon wake up

```
Monitor class m {
  private int i = …;
  private condition c;

  public method f() {
    if (…)
      wait (c);
    …
  }

  public method g() {
    …
    signal (c);
    …
  }
}
```

Hoare Monitors (1973)

- Conditions ≠ Semaphores
  - No tokens saved
    - Signal does nothing if no process is waiting
  - The wait operation is subtle
    - Release the implicit lock
    - Sleep in the condition list
    - Re-acquire the implicit lock upon wake up

atomic

```
Monitor class m {
  private int i = …;
  private condition c;

  public method f() {
    if (…)
      wait (c);
    …
  }

  public method g() {
    …
    signal (c);
    …
  }
}
```

Hoare Monitors (1973)

- Monitors and conditions were initially introduced as language constructs

- In operating systems or applications, the API is slightly different
  - `mutex_t` type
    - `mutex_lock (mutex_t *m)`
    - `mutex_unlock (mutex_t *m)`
  - `cond_t` type
    - `cond_wait (cond_t *c, mutex_t *m)`
    - `cond_signal (cond_t *c)`
    - `cond_bcast (cond_t *c)`

Hoare Monitors (1973)

```
Monitor class m {
  private int i = …;
  private condition c;

  public method f() {
    if (…)
      wait (c);
    …
  }

  public method g() {
    …
    signal (c);
    …
  }
}
```

```
mutex_t m;
cond_t c;

void f() {
  mutex_lock (&m);
  if (…)
    cond_wait (&c, &m);
  mutex_unlock (&m);
}

void g() {
  mutex_lock (&m);
  …
  cond_signal (&c);
  …
  mutex_unlock (&m);
}
```

Hoare Monitors (1973)

- Caveats
  - No cond_wait outside monitor (i.e. [lock – unlock] block)
    - "No cond_signal/bcast" is also a good idea
  - Mutexes have an *owner*
    - mutex_unlock can only be done by the owner
- Recommendation
  - Since conditions are "token-less", more variables are usually needed (in comparison to using semaphores)

Back to our *rendez-vous* problem

- Solution with Hoare Monitors

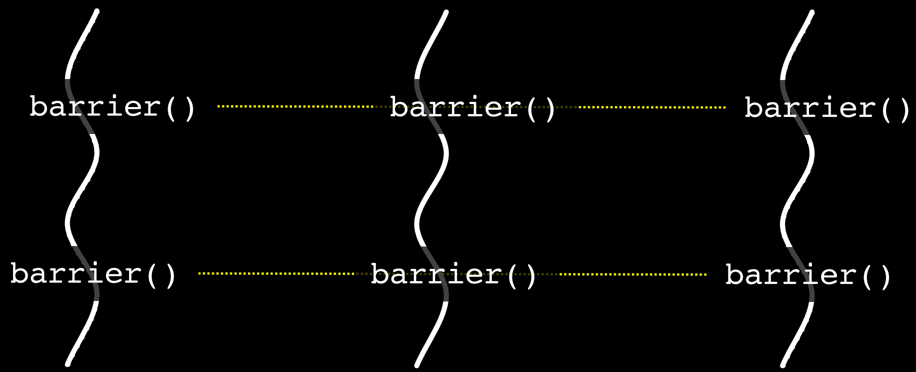
- Ideas
  - Block the N-1 first processes joining the barrier
  - The last process wakes everyone

```
mutex_t m;
cond_t wait;
int count = 0;

void barrier ()
{
  mutex_lock (&m);
  count++
  if (count < N)
    cond_wait (&wait, &m);
  } else {
    cond_bcast (&wait);
  }
  mutex_unlock (&m);
}
```

Back to our *rendez-vous* problem

- Is it re-usable multiple times?

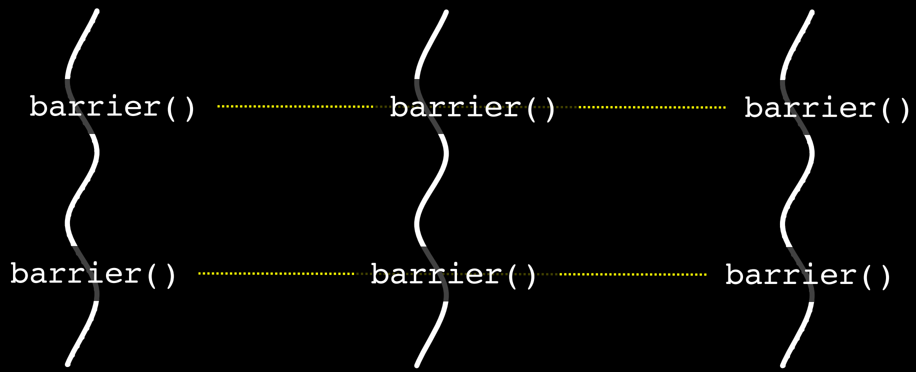



```
mutex_t m;
cond_t wait;
int count = 0;

void barrier ()
{
  mutex_lock(&m);
  count++
  if (count < N)
    cond_wait (&wait, &m);
  else {
    cond_bcast (&wait);
    count = 0;
  }
  mutex_unlock(&m);
}
```

Back to our *rendez-vous* problem

- Is it re-usable multiple times?
  - Yes! ☺




```
mutex_t m;
cond_t wait;
int count = 0;

void barrier ()
{
  mutex_lock(&m);
  count++
  if (count < N)
    cond_wait (&wait, &m);
  else {
    cond_bcast (&wait);
    count = 0;
  }
  mutex_unlock(&m);
}
```

Producers/Consumers

```
mutex_t m;
cond_t cons, prod;
int nbe = 0;
```

```
mutex_lock (&m);
If (nbe == MAX)
  cond_wait (&prod, &m);

put(element)

Nbe++;
Cond_signal (&cons);
mutex_unlock (&m);
```

Capacity = MAX elements

```
mutex_lock (&m);
If (nbe == 0)
  cond_wait (cons, &m);

element = get()

Nbe--;
Cond_signal (&prod);
mutex_unlock (&m);
```

Producers/Consumers

```
mutex_t m;
cond_t cons, prod;
int nbe = 0;
```

Does it work well?

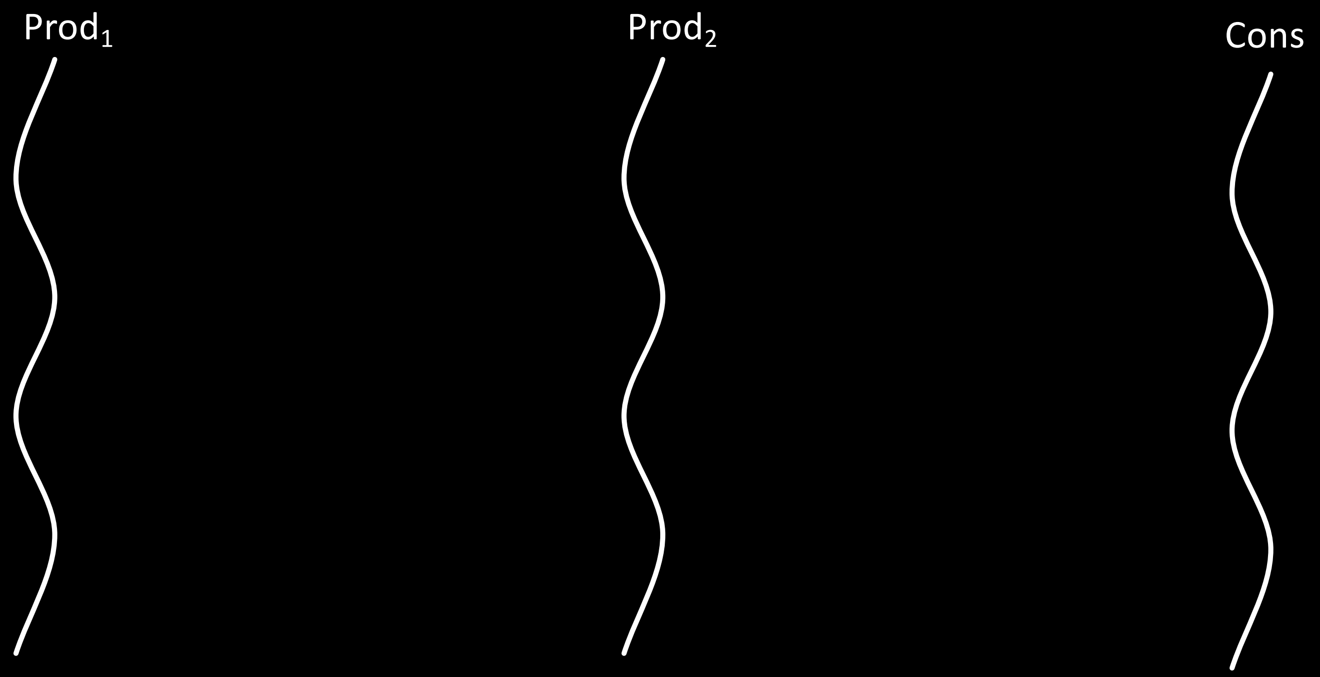
```
mutex_lock (&m);
if (nbe == MAX)
  cond_wait(&prod, &m);
put(element)
nbe++;
cond_signal(&cons);
mutex_unlock (&m);
```

Capacity = MAX elements

```
mutex_lock (&m);
if (nbe == 0)
  cond_wait(&cons);
element = get()
nbe--;
cond_signal(&prod);
mutex_unlock (&m);
```

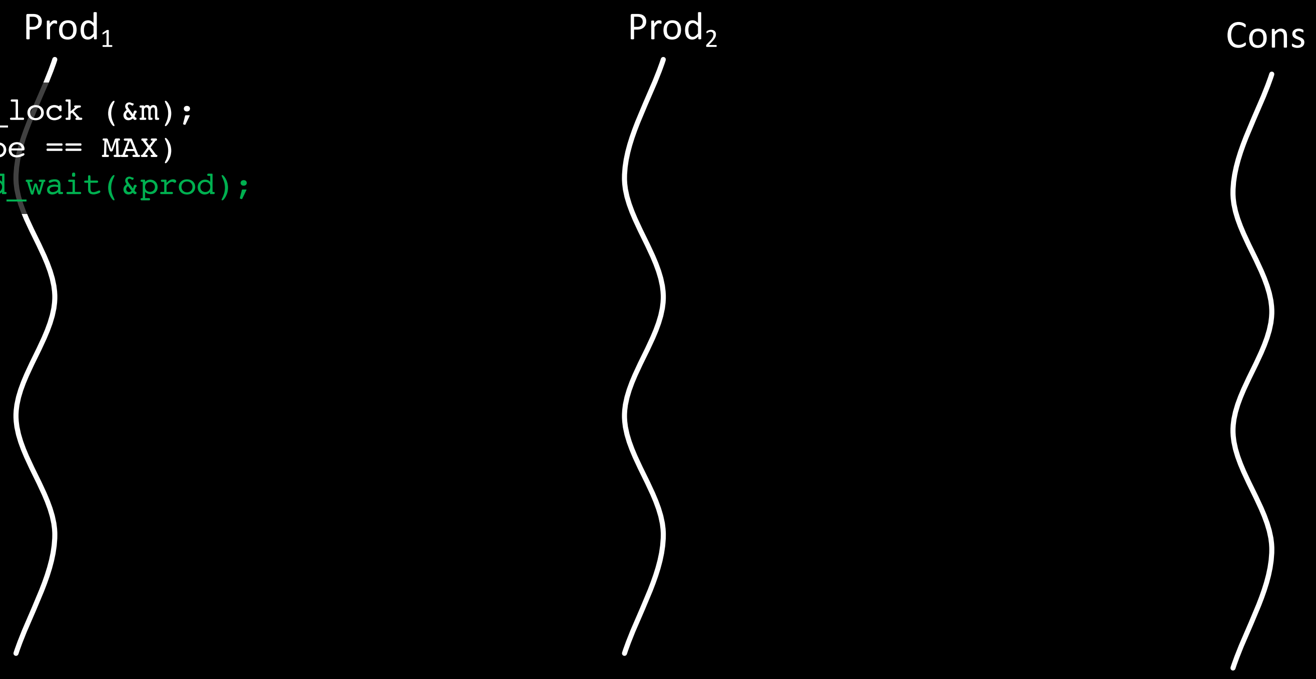
Producers/Consumers

Assuming nbe == MAX...



Producers/Consumers

Assuming nbe == MAX...




```
mutex_lock (&m);
if (nbe == MAX)
  cond_wait(&prod);
```

Producers/Consumers

Assuming nbe == MAX…

Prod$_1$

```
mutex_lock (&m);
if (nbe == MAX)
  cond_wait(&prod);
```

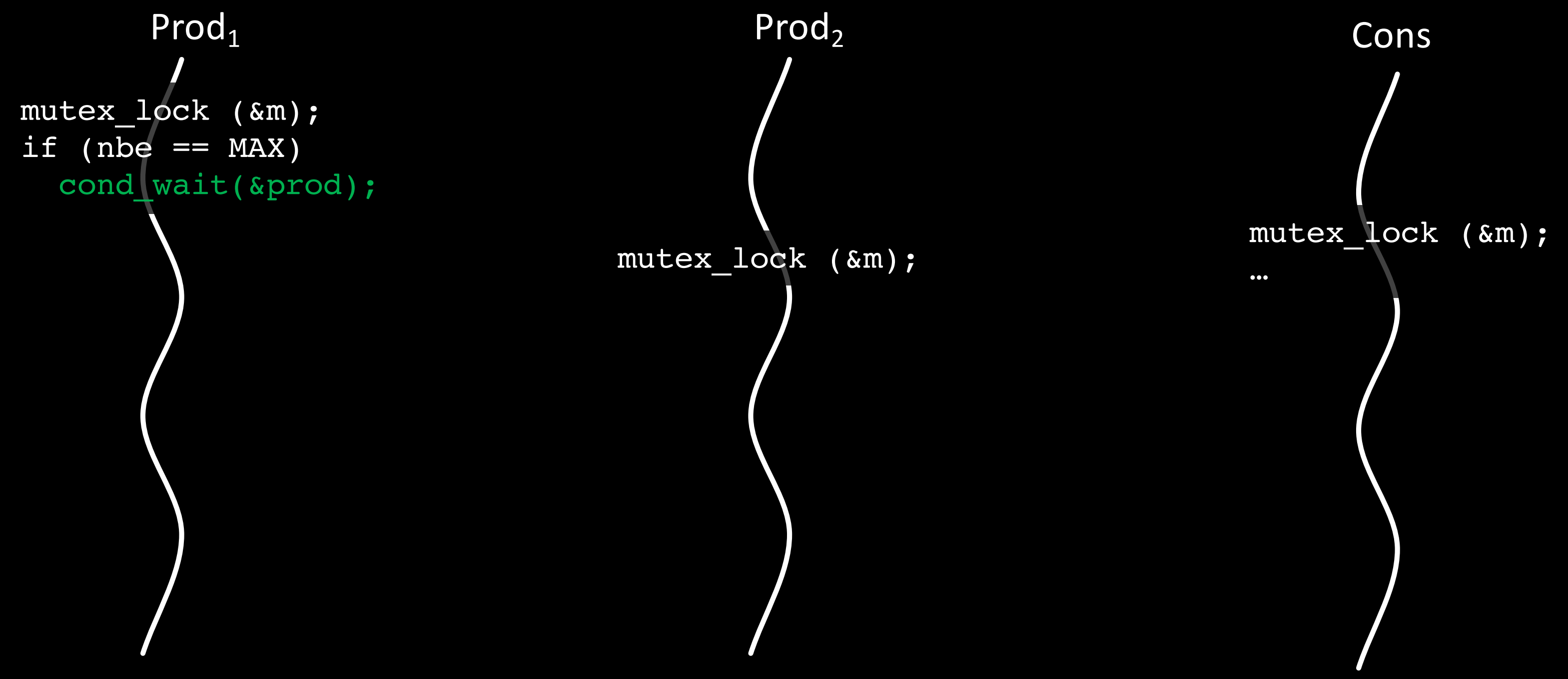
Prod$_2$

Cons

```
mutex_lock (&m);
…
```

Producers/Consumers

Assuming nbe == MAX...



Producers/Consumers

Prod$_1$

```
mutex_lock (&m);
if (nbe == MAX)
  cond_wait(&prod);
```

Prod$_2$

```
mutex_lock (&m);
```

Cons

```
mutex_lock (&m);
…
element = get()
nbe--;
cond_signal(&prod);
mutex_unlock (&m);
```

Producers/Consumers

Prod$_1$

```
mutex_lock (&m);
if (nbe == MAX)
  cond_wait(&prod);
```

Prod$_2$

```
mutex_lock (&m);

put(element)
nbe++;
cond_signal(&cons);
mutex_unlock (&m);
```

Cons

```
mutex_lock (&m);
…
element = get()
nbe--;
cond_signal(&prod);
mutex_unlock (&m);
```

Producers/Consumers

Prod$_1$

```
mutex_lock (&m);
if (nbe == MAX)
  cond_wait(&prod);

put(element)
```

Prod$_2$

```
mutex_lock (&m);

put(element)
nbe++;
cond_signal(&cons);
mutex_unlock (&m);
```

Cons

```
mutex_lock (&m);
…
element = get()
nbe--;
cond_signal(&prod);
mutex_unlock (&m);
```

Producers/Consumers

Prod$_1$

```
mutex_lock (&m);
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  cond_wait(&prod);

put(element)
```

Prod$_2$

```
mutex_lock (&m);

put(element)
nbe++;
cond_signal(&cons);
mutex_unlock (&m);
```

Cons

```
mutex_lock (&m);
…
element = get()
nbe--;
cond_signal(&prod);
mutex_unlock (&m);
```

Producers/Consumers

```
mutex_t m;
cond_t cons, prod;
int nbe = 0;
```

```
mutex_lock (&m);
if (nbe == MAX)
  cond_wait(&prod);

put(element)

nbe++;
cond_signal(&cons);
mutex_unlock (&m);
```

Capacity = MAX elements

```
mutex_lock (&m);
if (nbe == 0)
  cond_wait(&cons);

element = get()

nbe--;
cond_signal(&prod);
mutex_unlock (&m);
```

Producers/Consumers

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mutex_t m;
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mutex_lock (&m);
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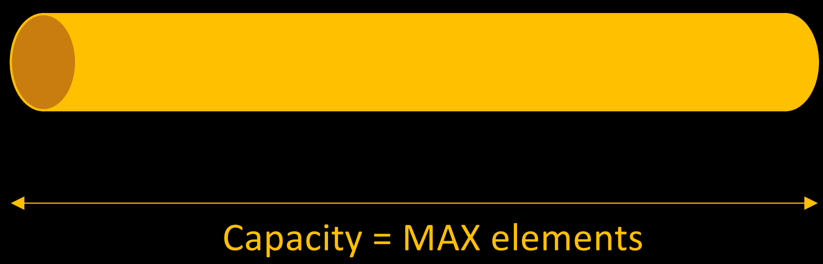
put(element)

nbe++;
cond_signal(&cons);
mutex_unlock (&m);
```




```
mutex_lock (&m);
if (nbe == 0)
  cond_wait(&cons);

element = get()

nbe--;
cond_signal(&prod);
mutex_unlock (&m);
```

Producers/Consumers

```
mutex_t m;
cond_t cons, prod;
int nbe = 0;
```

```
mutex_lock (&m);
while (nbe == MAX)
  cond_wait(&prod);

put(element)

nbe++;
cond_signal(&cons);
mutex_unlock (&m);
```


```
mutex_lock (&m);
while (nbe == 0)
  cond_wait(&cons);

element = get()

nbe--;
cond_signal(&prod);
mutex_unlock (&m);
```

Readers/Writers

On souhaite disposer de verrous similaires aux « *Mutex* », mais permettant d'établir facilement une synchronisation de type « lecteurs/rédacteurs » au sein des applications. L'idée est donc de fournir un type **rwlock_t** et des primitives associées (**rwl_readlock()**, **rwl_readunlock()**, etc.) qui permettent à un processus lecteur (resp. rédacteur) d'encadrer la zone de code critique où il accèdera aux données partagées en lecture (resp. écriture).

Donnez le code associé à la gestion des verrous en lecture-écriture, en utilisant des primitives fournissant la sémantique des moniteurs de Hoare. On ne demande pas d'implementer une version équitable du problème.

```
/* code à écrire */
typedef ... rwlock_t ;

void rwl_readlock(rwlock_t *l) ;
void rwl_readunlock(rwlock_t *l) ;
void rwl_writelock(rwlock_t *l) ;
void rwl_writeunlock(rwlock_t *l) ;
```

```
/* code disponible */
typedef ... mutex_t ;
typedef ... cond_t ;
void mutex_lock(mutex_t *m) ;
void mutex_unlock(mutex_t *m) ;
void cond_wait(cond_t *c, mutex_t *m) ;
void cond_signal(cond_t *c) ;
```

Readers/Writers

```
typedef struct {
  mutex_t m;
  cond_t cr, cw;
  int nbr = 0;
  int nbw = 0;
} rwlock_t;

rwlock_t cool_lock;
```

```
rwl_readlock (&cool_lock);

read();

rwl_readunlock (&cool_lock);
```

```
rwl_writelock (&cool_lock);

write();

rwl_writeunlock (&cool_lock);
```

Readers’ side

```
typedef struct {
  unsigned nbr = 0;
  unsigned nbw = 0;
  mutex_t m;
  cond_t cr, cw;
} rwlock_t;

rwlock_t cool_lock;
```

```
rwl_readlock (&cool_lock);

    read();

rwl_readunlock (&cool_lock);
```

```
void rwl_readlock(rwlock_t *l)
{
  mutex_lock (&l->m);
  while (l->nbw > 0)
    cond_wait (&l->cr, &l->m);
  l->nbr++;
  mutex_unlock (&l->m);
}

void rwl_readunlock(rwlock_t *l)
{
  mutex_lock (&l->m);
  l->nbr--;
  if (l->nbr == 0)
    cond_signal (&l->cw);
  mutex_unlock (&l->m);
}
```

Writers' side

```
void rwl_writelock(rwlock_t *l)
{
  mutex_lock (&l->m);
  while (l->nbr + l->nbw > 0)
    cond_wait (&l->cw, &l->m);
  l->nbw++;
  mutex_unlock (&l->m);
}

void rwl_writeunlock(rwlock_t *l)
{
  mutex_lock (&l->m);
  l->nbw--;
  cond_signal (&l->cw); cond_bcast (&l->cr);
  mutex_unlock (&l->m);
}
```

```
typedef struct {
  unsigned nbr = 0;
  unsigned nbw = 0;
  mutex_t m;
  cond_t cr, cw;
} rwlock_t;

rwlock_t cool_lock;
```

```
rwl_writelock (&cool_lock);

write();

rwl_writeunlock (&cool_lock);
```

Final words

- Like Semaphores, Hoare monitors are implemented on top of atomic processor instructions

- User space implementations often mix polling and blocking calls
  - i.e. poll during a few iterations and then block if lock not available

- Hoare monitors are preferred by most programmers
  - For the sake of minimizing headaches…

Final words

- FUTEXes (Fast User-Level Mutex) were introduced in Linux 2.6.x in 2003
  - Introduced in Microsoft Windows 8 under the name “WaitOnAddress”
    - Patented in 2013 ☺
- Idea
  - Use atomic operations on 32bits integer variables in user space
  - If blocking or waking is needed, use
    - sys_futex(&var, FUTEX_WAIT…) or sys_futex (&var, FUTEX_WAKE…)
  - Kernel queues are associated to physical addresses using hash tables

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  - Use atomic operations on 32bits integer variables in user space
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    - sys_futex (&var, FUTEX_WAIT…) / sys_futex (&var, FUTEX_WAKE…)
  - Kernel queues are associated to physical addresses using hash tables
- Hmm… Isn’t this what we were looking for on slide 53? 😇

Additional resources available on http://gforgeron.gitlab.io/se/