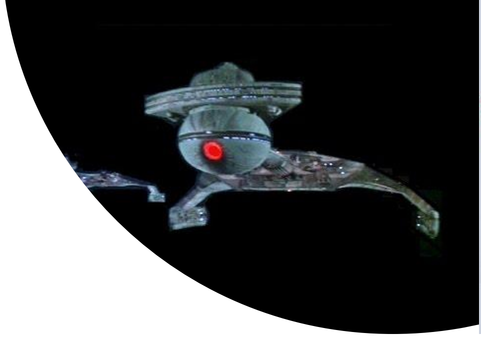
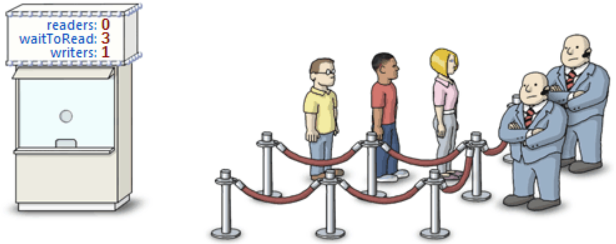
Synchronization: Semaphores, Mutex, Futex, Monitors, Barriers

Chris Rossbach

Today



- Questions?
- Administrivia
  - Start looking at Lab 2, esp if you’re done with Lab 1
- Material for the day
  - Coherence redux
  - Monitors
  - Barriers



- Acknowledgements
  - Thanks to Gadi Taubenfield: I borrowed and modified some of his slides on barriers
- Image credits
  - https://www.google.com/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=2ahUKEwjxi4uip8LdAhWFq1MKHbBeD4sQjRx6BAgBEAU&url=http%3A%2F%2Fpreshing.com%2F20150316%2Fsemaphores-are-surprisingly-versatile&psig=AOvVaw20Zw2eU9WAmbX8qxDSLSRd&ust=1537282884760655
  - https://images-na.ssl-images-amazon.com/images/I/31EcIPmMniL.jpg
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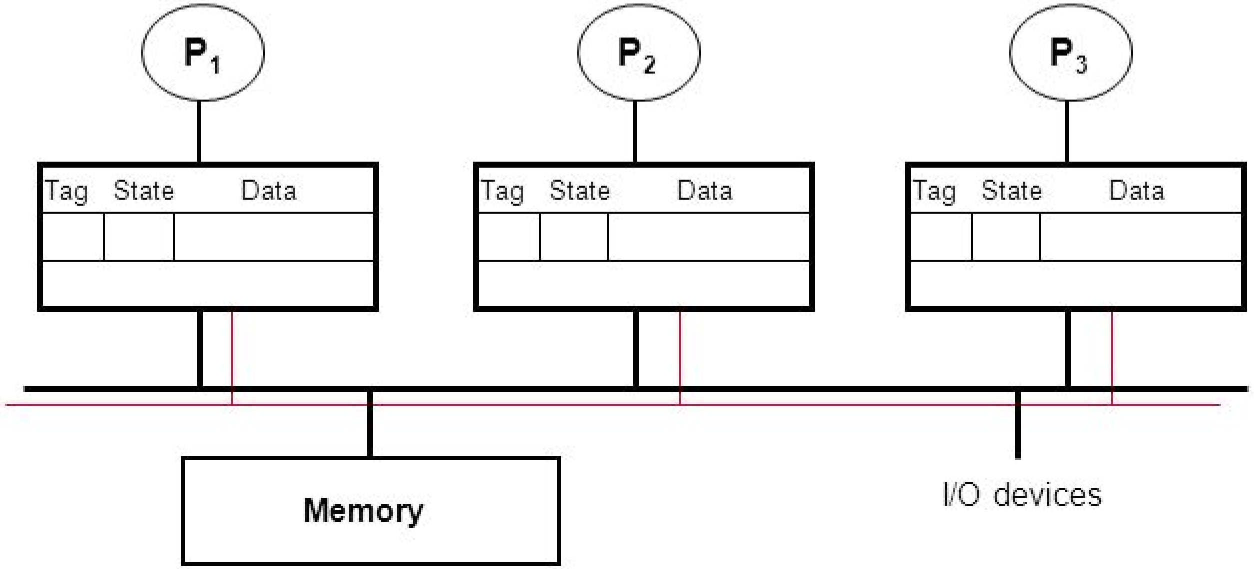
Faux Quiz (answer any 2, 5 min)

- What is the difference between Mesa and Hoare monitors?
- Why recheck the condition on wakeup from a monitor wait?
- How can you build a barrier with spinlocks?
- How can you build a barrier with monitors?
- How can you build a barrier without spinlocks or monitors?
- What is the difference between mutex and semaphores?
- How are monitors and semaphores related?
- Why does pthread_cond_init accept a pthread_mutex_t parameter? Could it use a pthread_spinlock_t? Why [not]?
- Why do modern CPUs have both coherence and HW-supported RMW instructions? Why not just one or the other?
- What is priority inheritance?

Review: Basic MESI Cache Coherence



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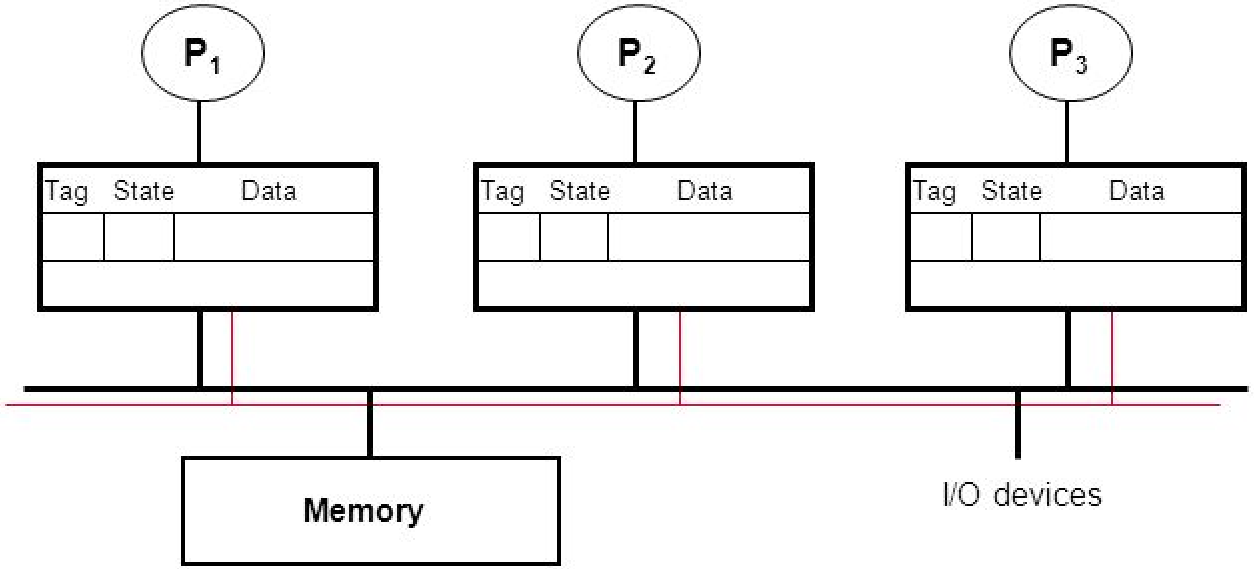

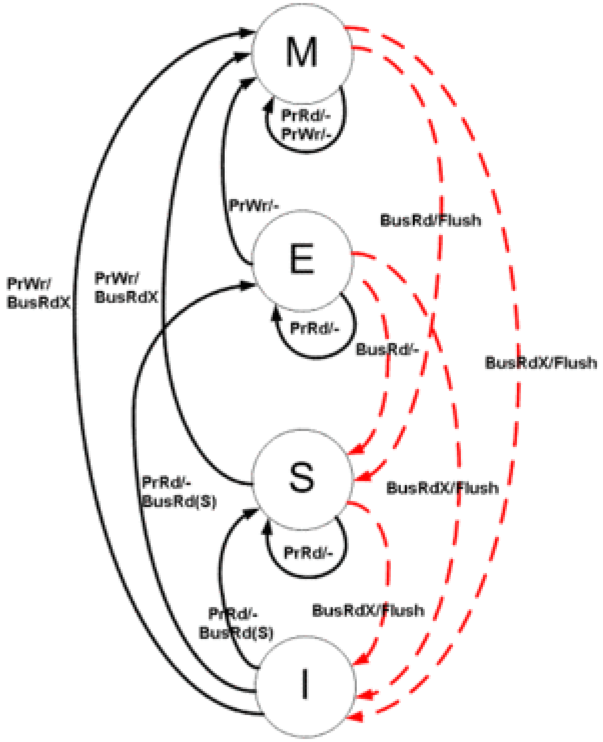

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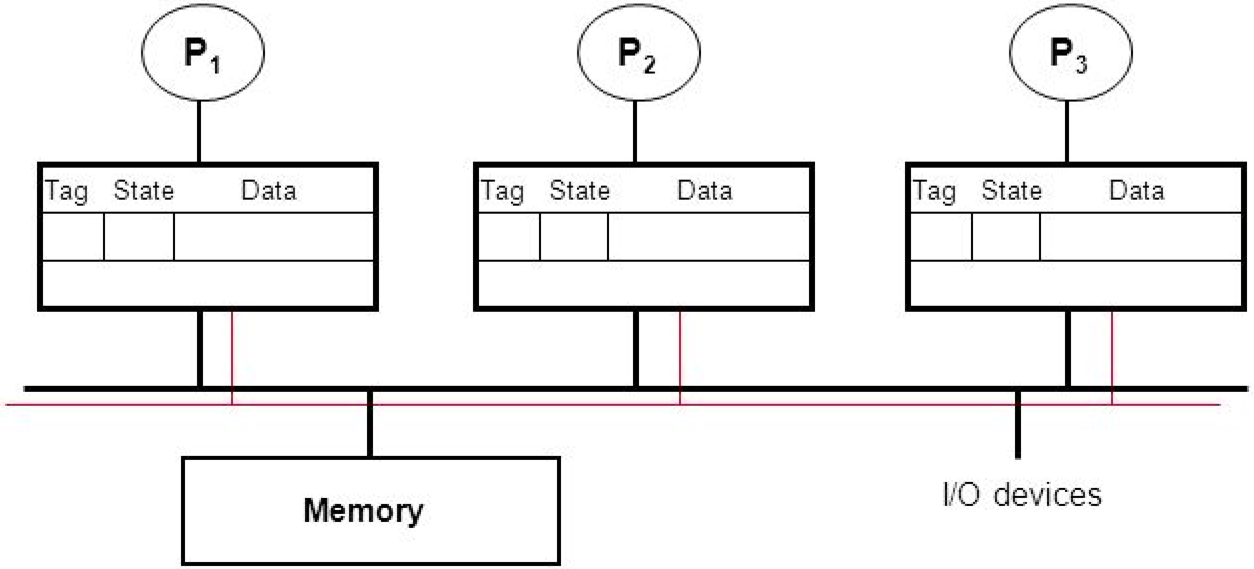
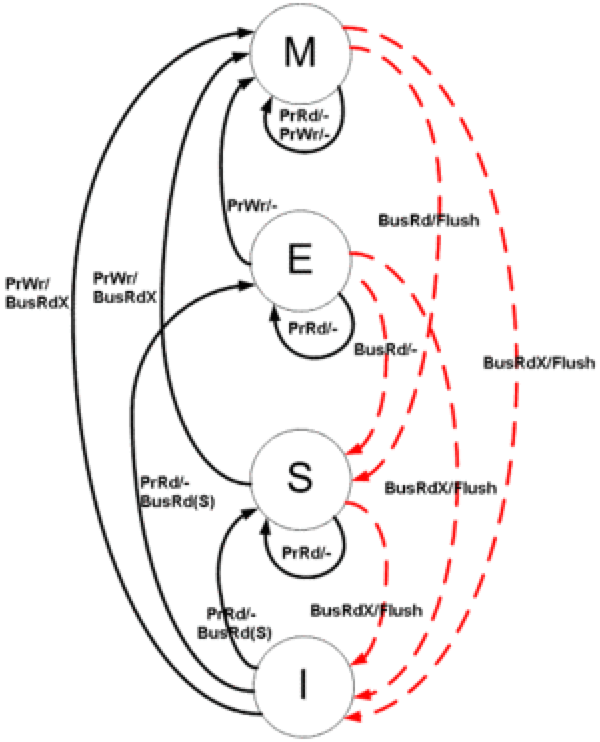


Each cache line has a state (M, E, S, I)



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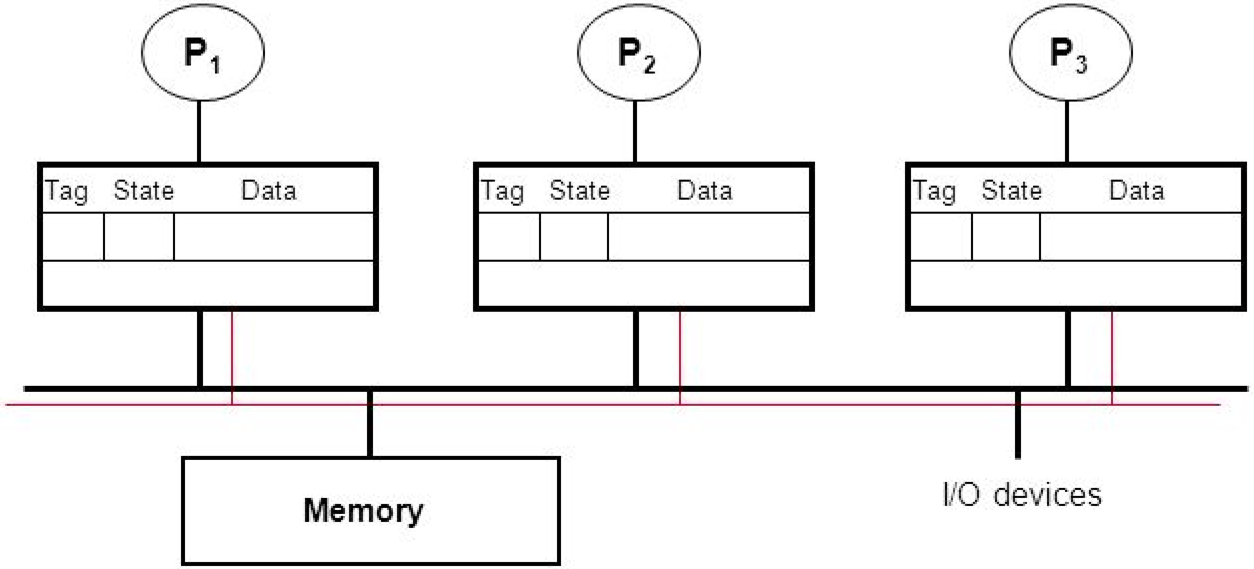

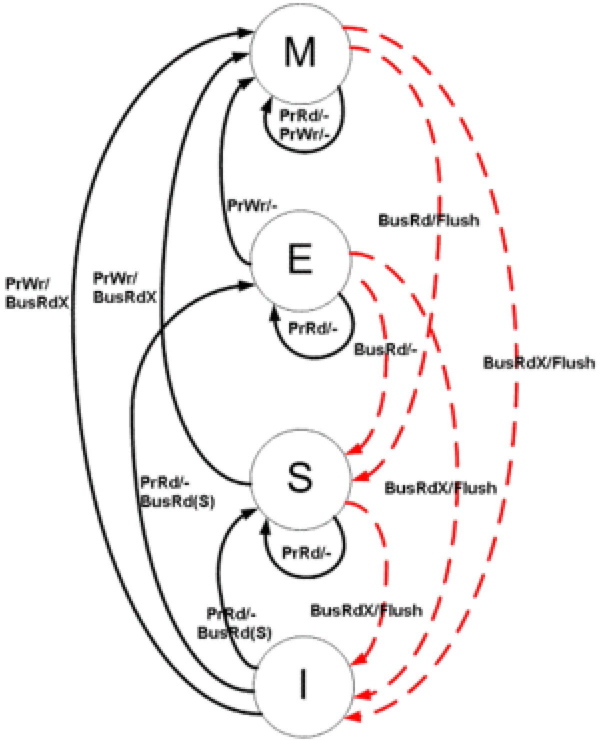

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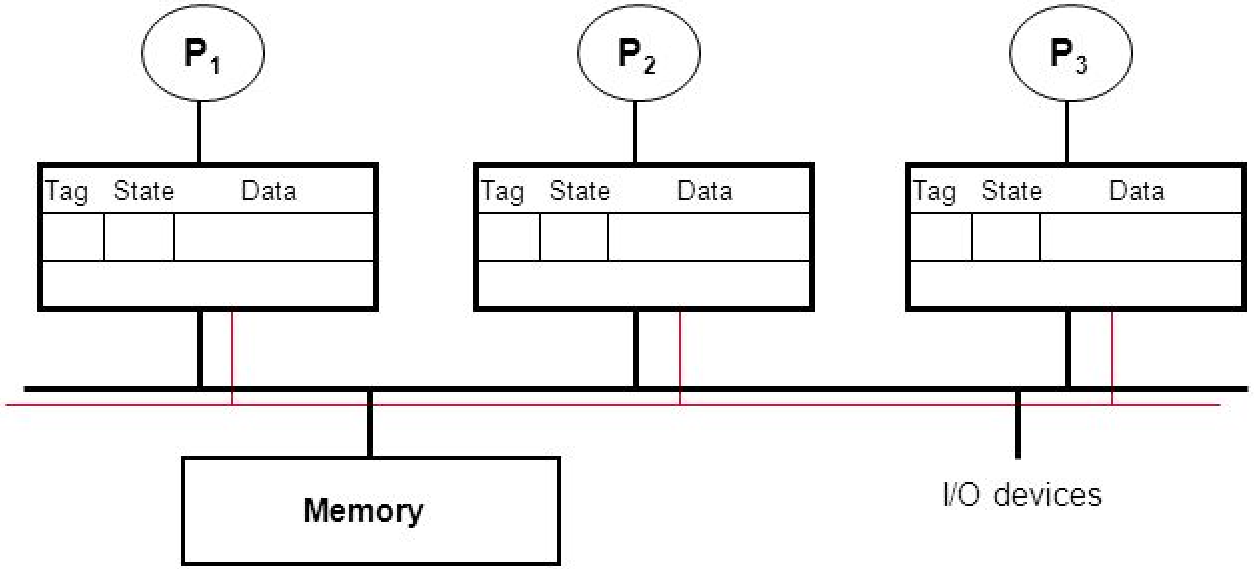

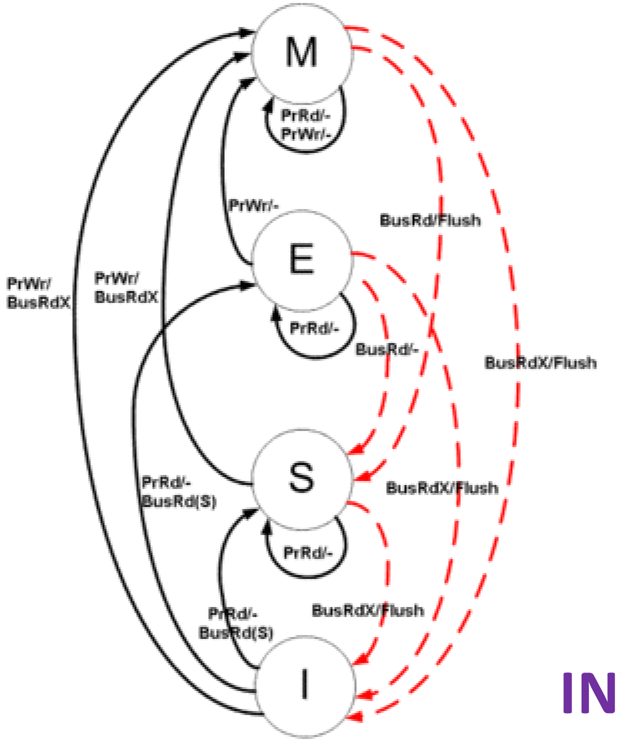

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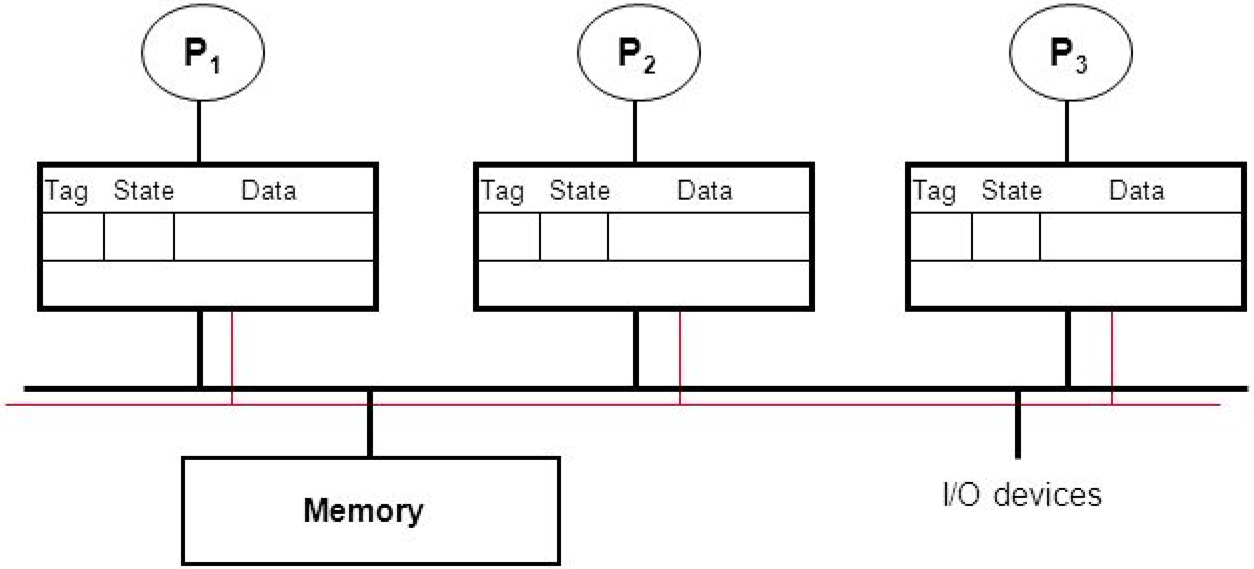

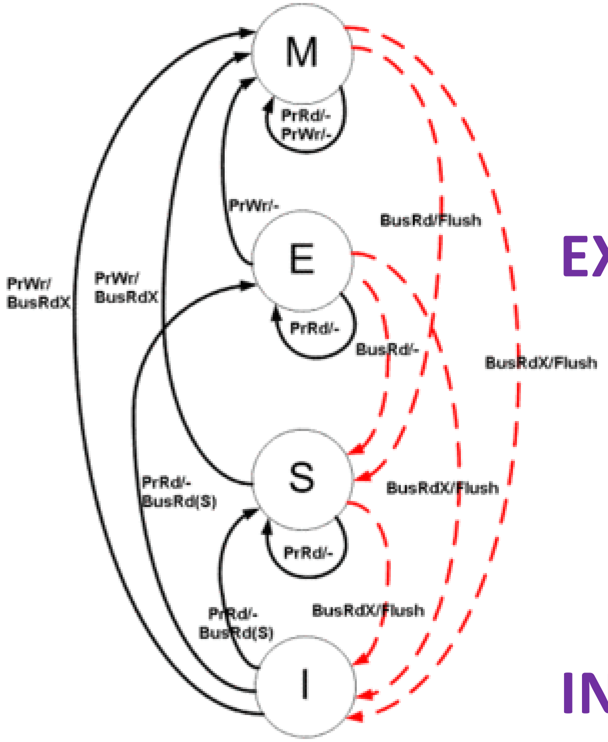

EXCLUSIVE

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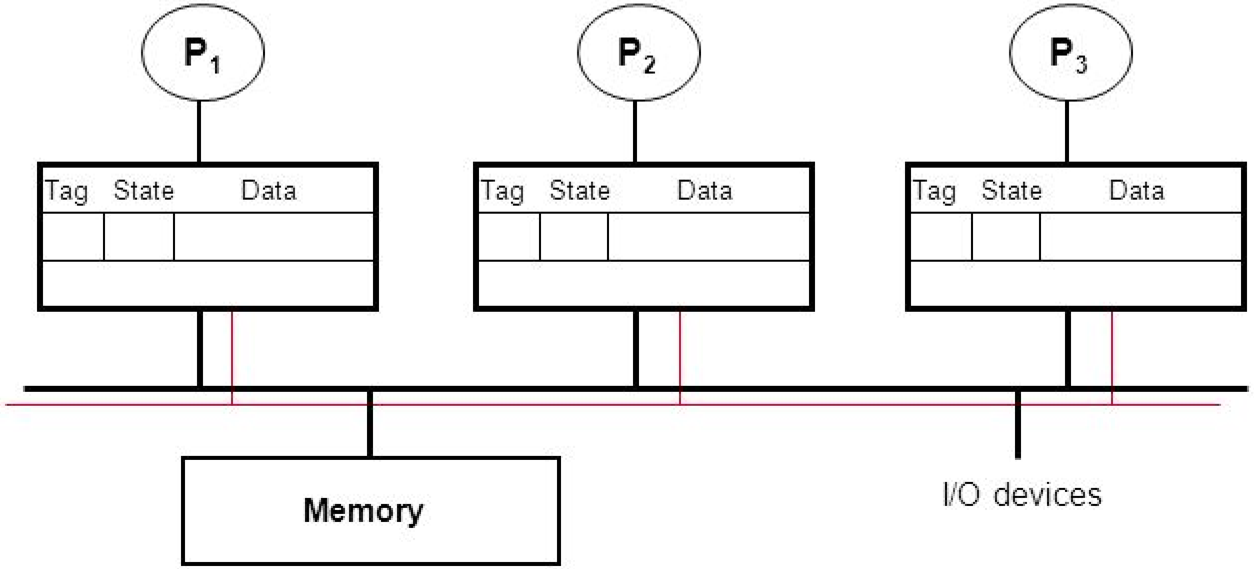

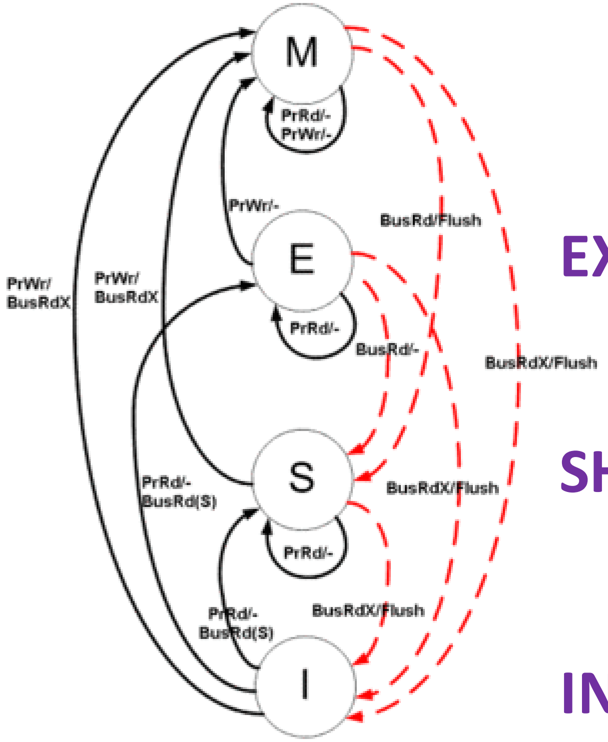

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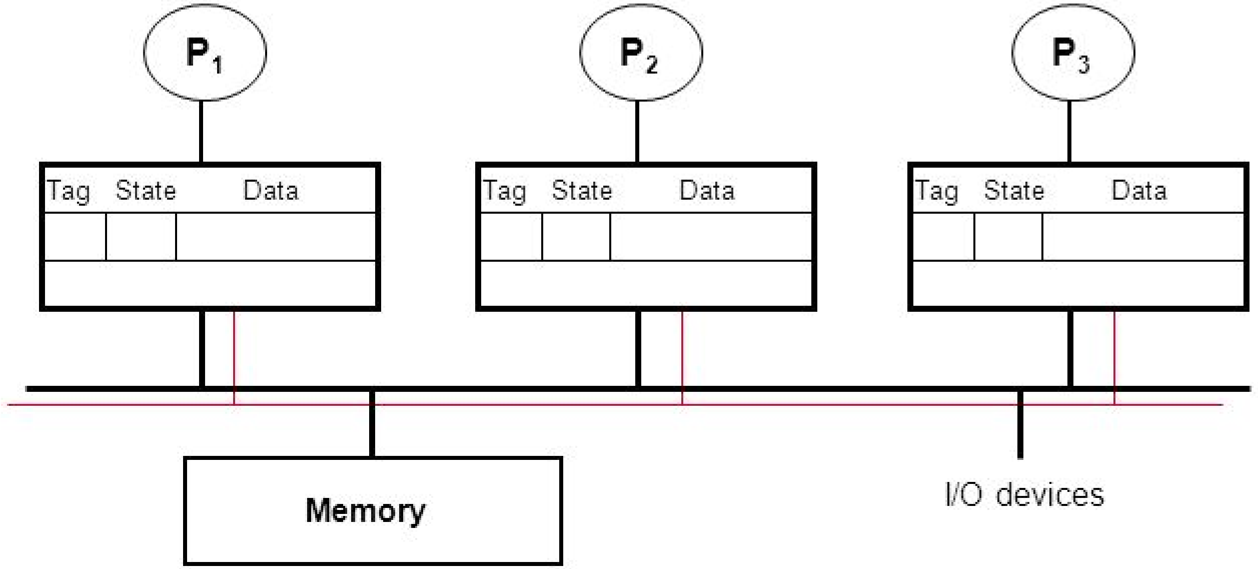

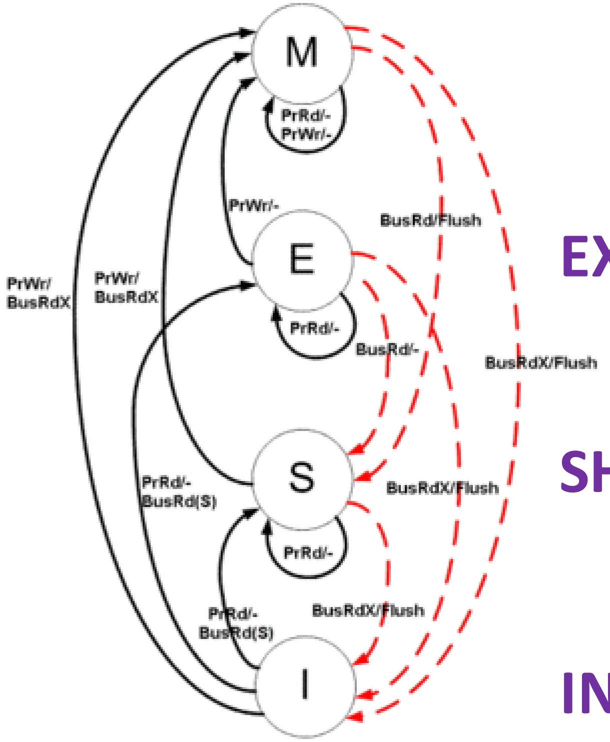

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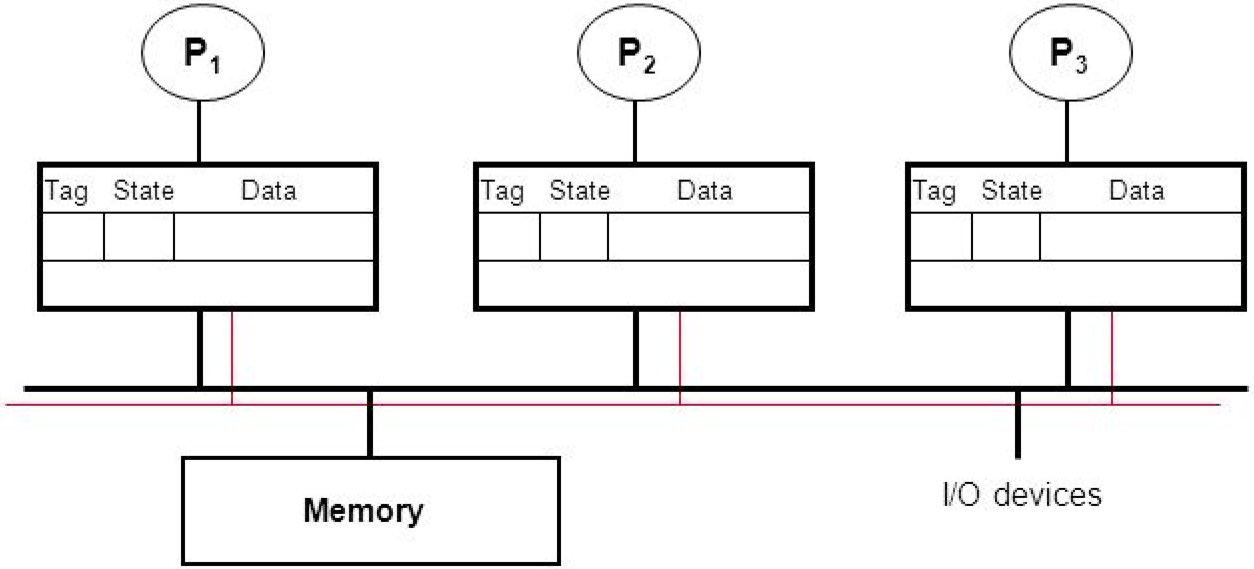

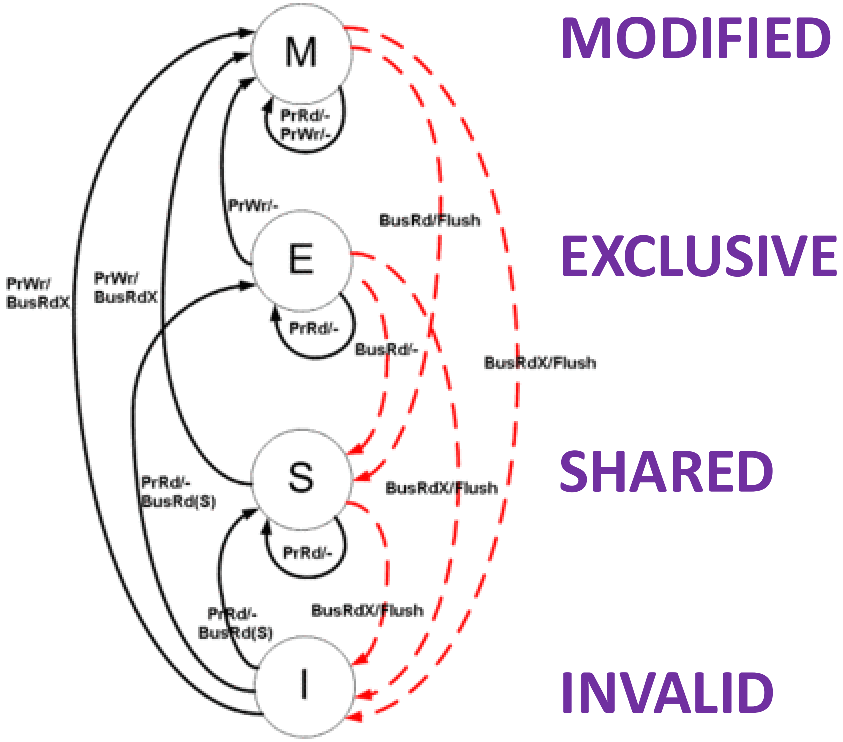

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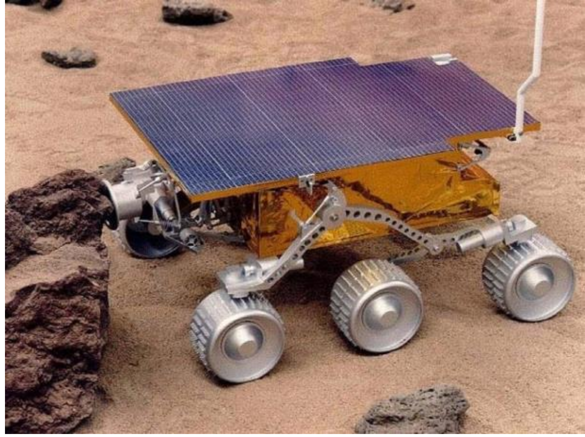
Lock Pitfalls…



A(prio-0) → `lock(my_lock);`

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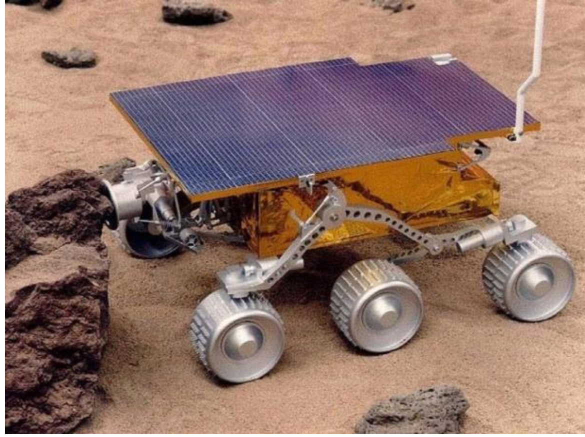

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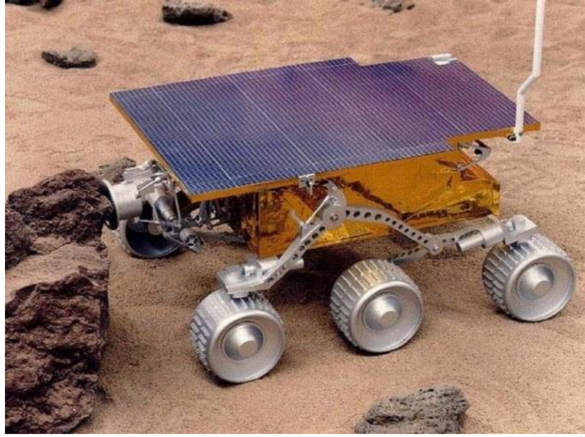

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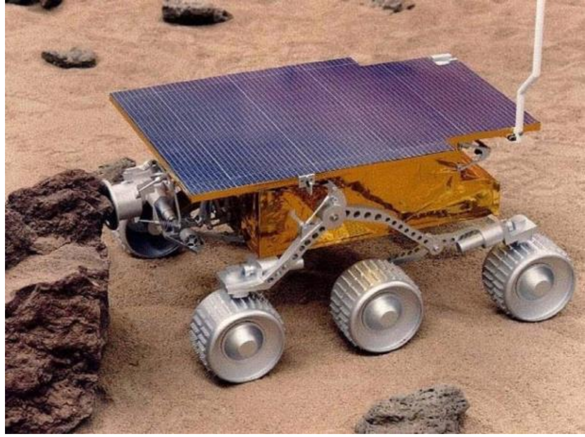

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Solution?

Priority inheritance: A runs at B's priority

MARS pathfinder failure:

http://wiki.csie.ncku.edu.tw/embedded/priority-inversion-on-Mars.pdf

Other ideas?

Can you build a lock without HW RMW?

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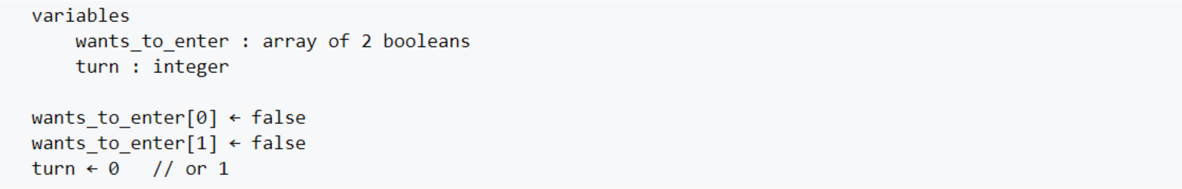
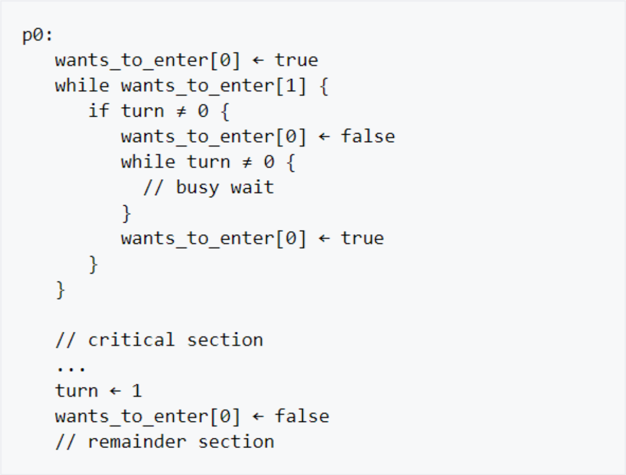
Dekker's Algorithm



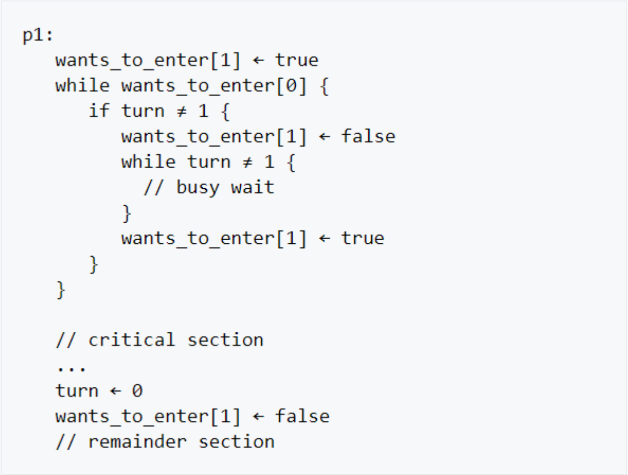
```
variables
    wants_to_enter : array of 2 booleans
    turn : integer

wants_to_enter[0] ← false
wants_to_enter[1] ← false
turn ← 0   // or 1
```



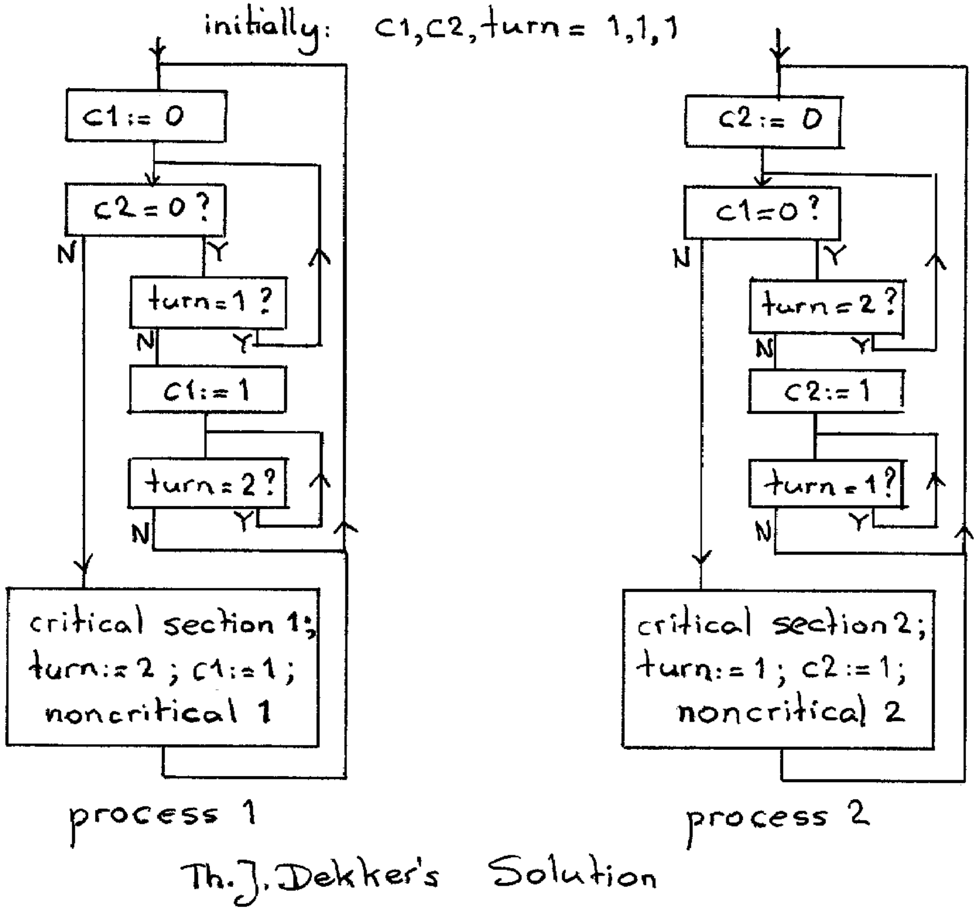
```
p0:
   wants_to_enter[0] ← true
   while wants_to_enter[1] {
      if turn ≠ 0 {
         wants_to_enter[0] ← false
         while turn ≠ 0 {
           // busy wait
         }
         wants_to_enter[0] ← true
      }
   }

   // critical section
   ...
   turn ← 1
   wants_to_enter[0] ← false
   // remainder section
```



```
p1:
   wants_to_enter[1] ← true
   while wants_to_enter[0] {
      if turn ≠ 1 {
         wants_to_enter[1] ← false
         while turn ≠ 1 {
           // busy wait
         }
         wants_to_enter[1] ← true
      }
   }

   // critical section
   ...
   turn ← 0
   wants_to_enter[1] ← false
   // remainder section
```



How can we improve over busy-wait?

```
Lock::Acquire() {
while(1) {
  while (*lock == 1) ; // spin just reading
  if (test&set(lock) == 0)  break;
}
```

Producer-Consumer (Bounded-Buffer) Problem

- Bounded buffer: size ‘N’
  - Access entry 0… N-1, then “wrap around” to 0 again
- Producer process writes data to buffer
  - Must not write more than ‘N’ items more than consumer “consumes”
- Consumer process reads data from buffer
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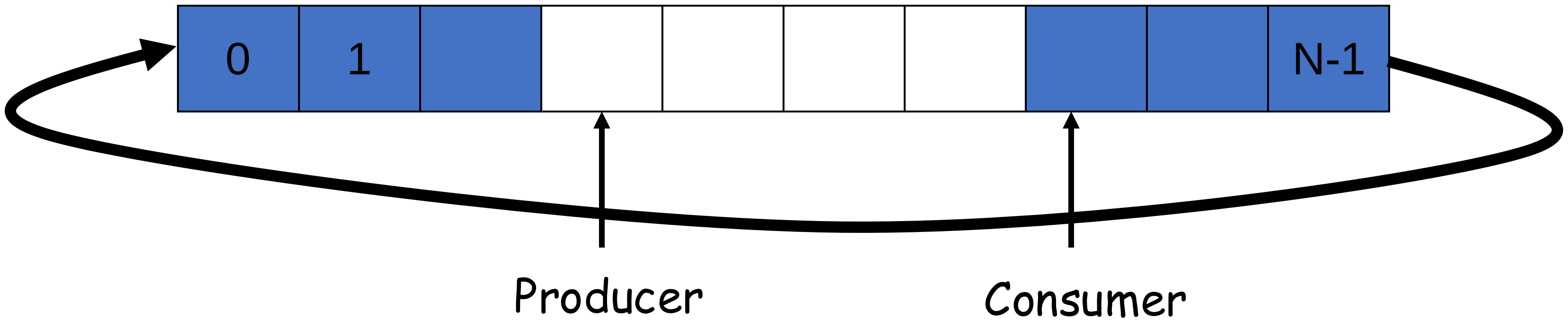

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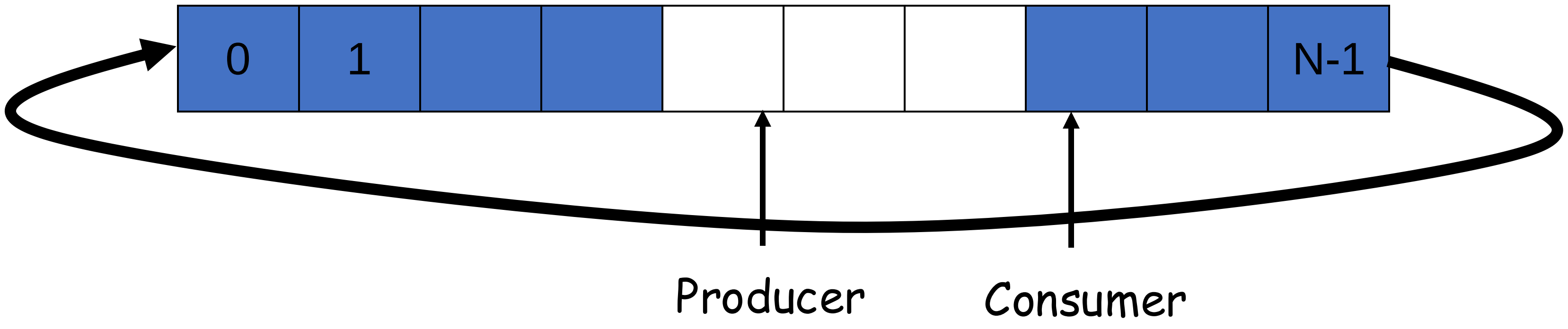

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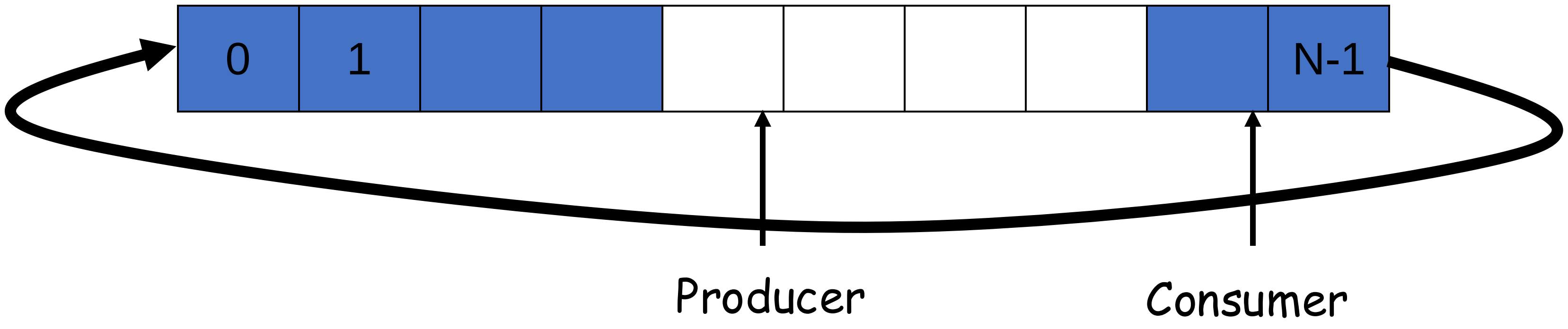

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OK, let’s write some code for this
(using locks only)

```
object array[N]
void enqueue(object x);
object dequeue();
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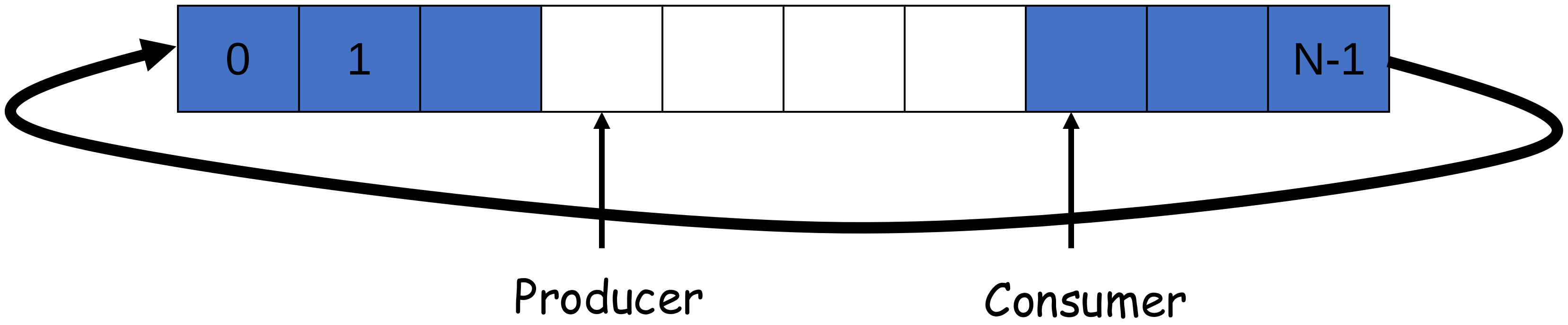

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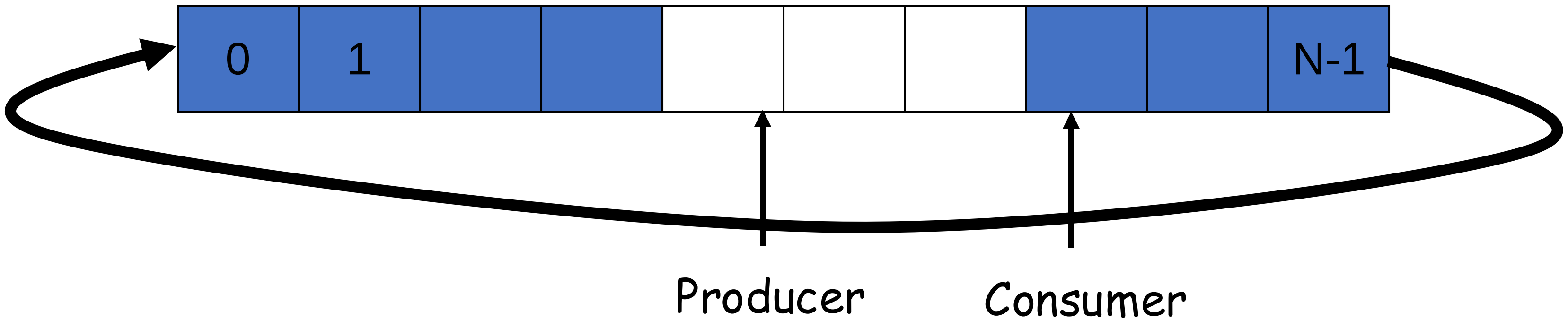

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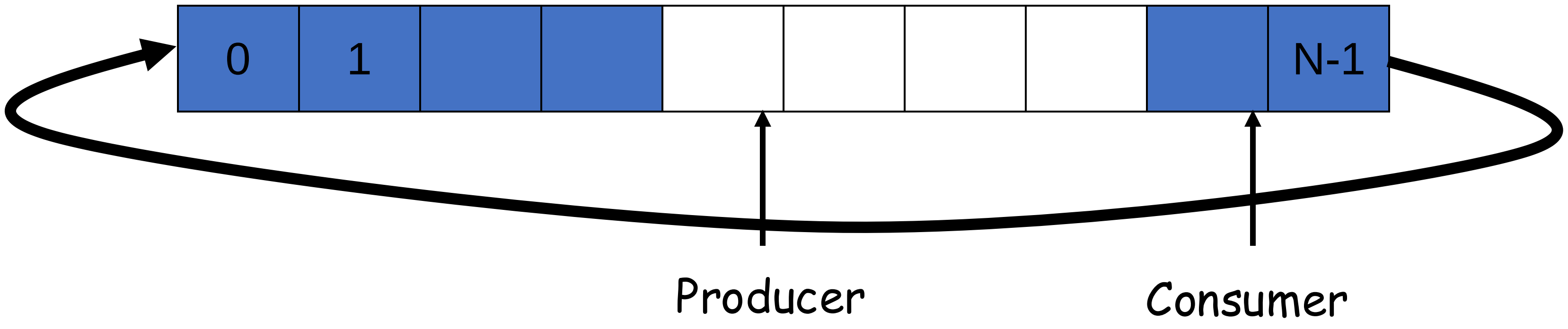
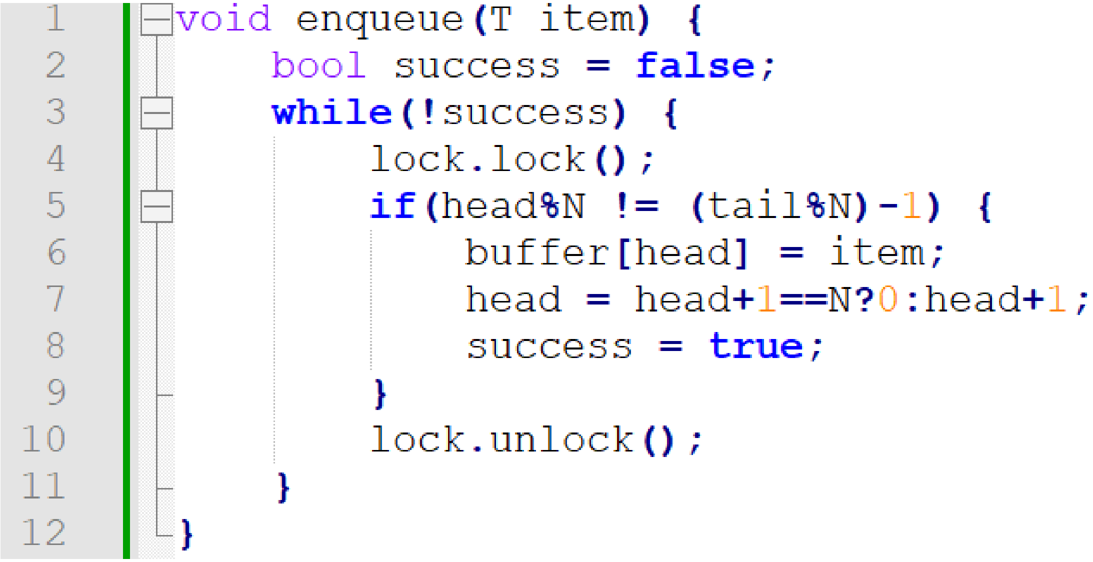


Last Class' Solution: Bounded Buffer



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void enqueue(T item) {
    bool success = false;
    while(!success) {
        lock.lock();
        if(head%N != (tail%N)-1) {
            buffer[head] = item;
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        lock.unlock();
    }
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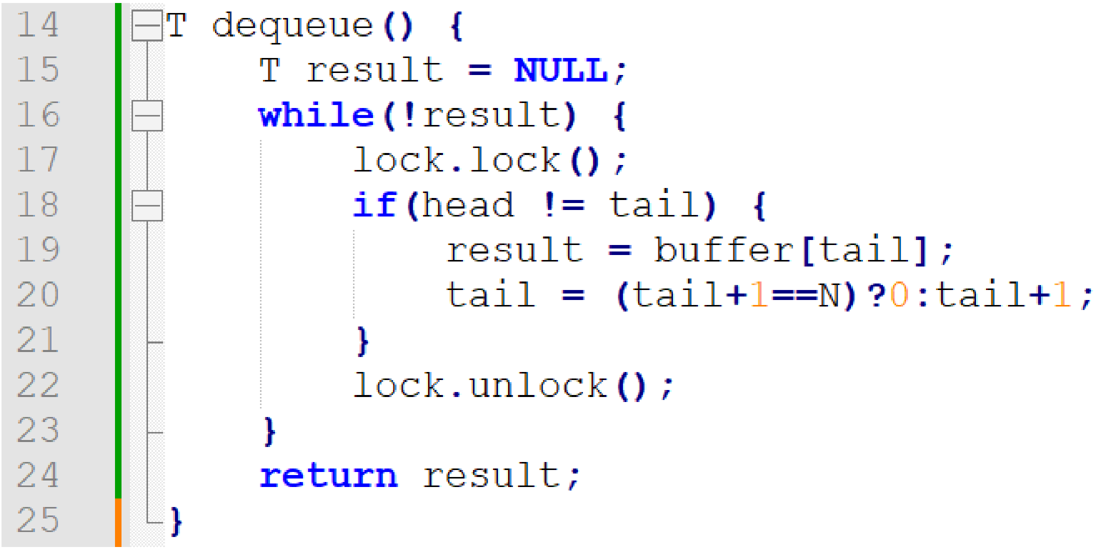

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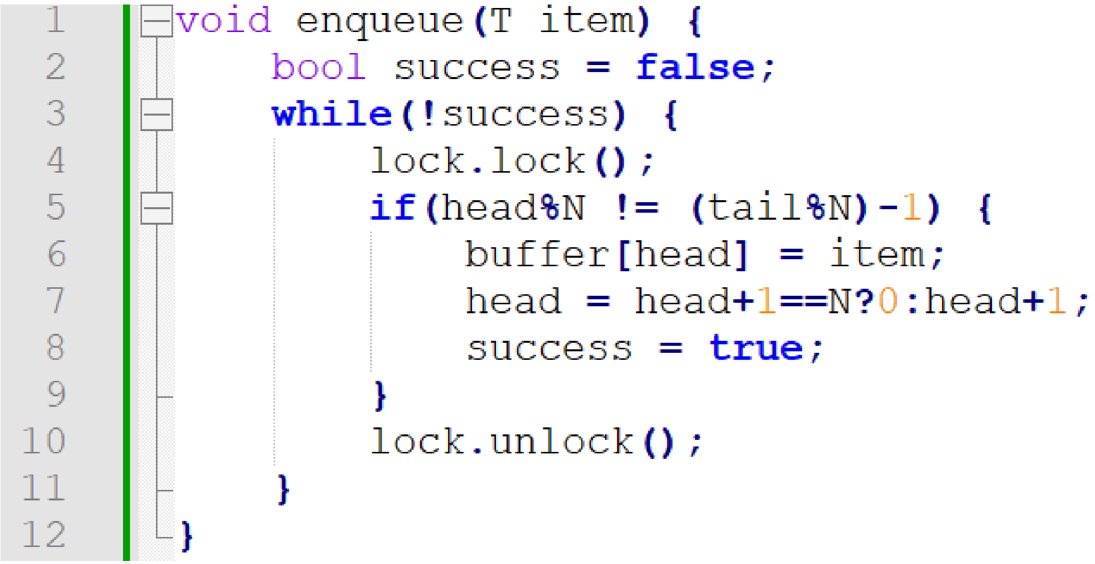

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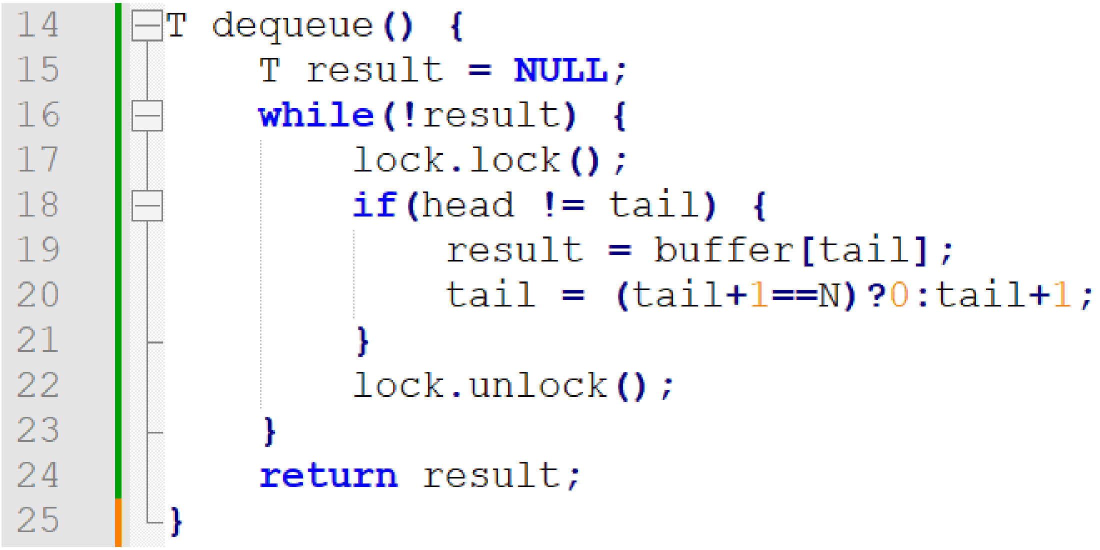

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Pros/Cons?

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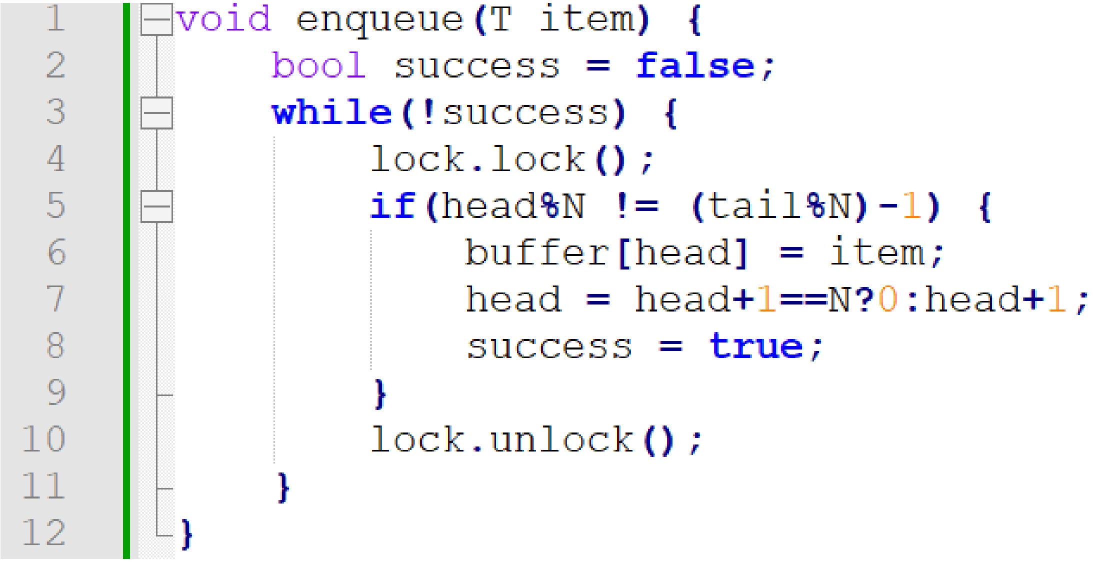

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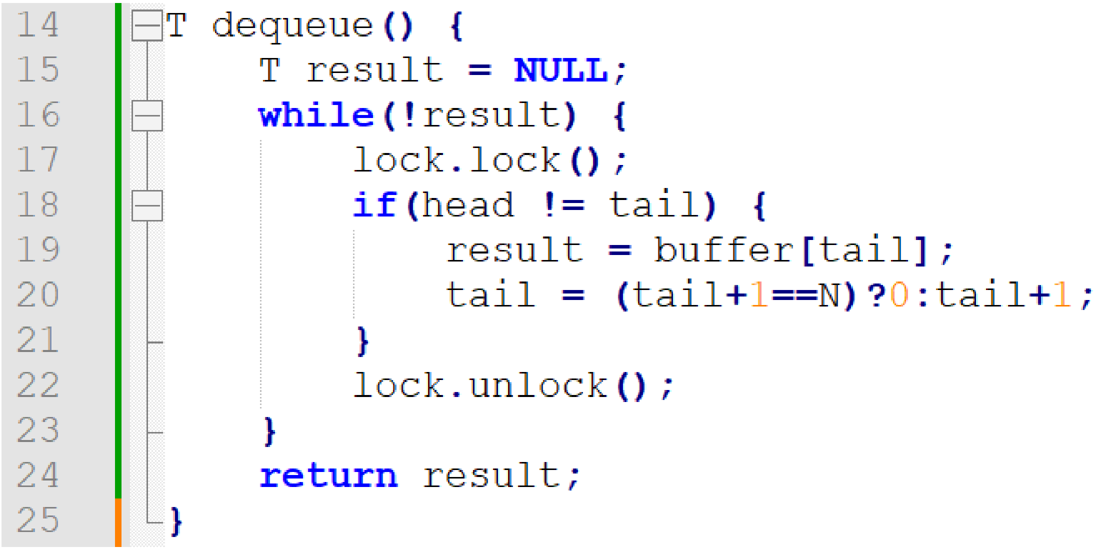

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Semaphore Motivation

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- Problem with locks: mutual exclusion, but *no ordering*
- Inefficient for producer-consumer (and lots of other things)
  - Producer: creates a resource
  - Consumer: uses a resource
  - bounded buffer between them
  - You need synchronization for correctness, *and…*
  - Scheduling order:
    - producer waits if buffer full, consumer waits if buffer empty

Semaphores

- Synchronization variable
  - Integer value
    - Can’t access value directly
    - Must initialize to some value
      - sem_init(sem_t *s, int pshared, unsigned int value)
  - Two operations
    - sem_wait, or down(), P()
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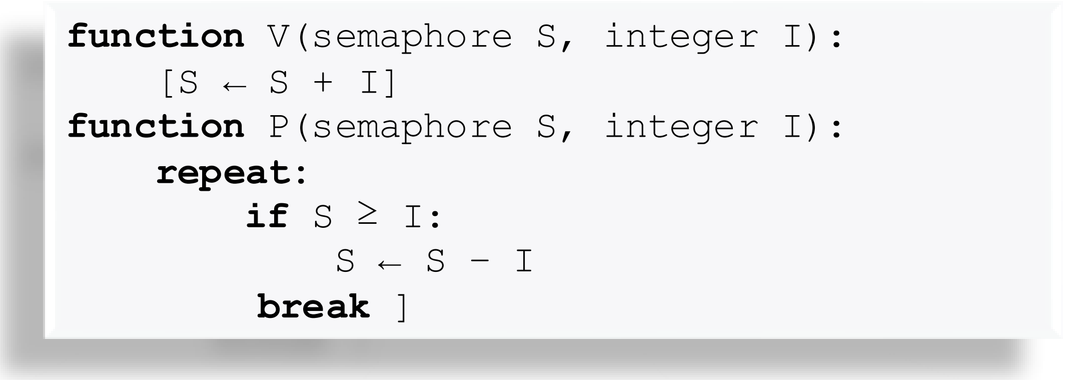
```
int sem_wait(sem_t *s) {
    wait until value of semaphore s
          is greater than 0
    decrement the value of
          semaphore s by 1
}
```

```
int sem_post(sem_t *s) {
    increment the value of
          semaphore s by 1
    if there are 1 or more
            threads waiting, wake 1
}
```

Semaphores



```
function V(semaphore S, integer I):
    [S ← S + I]
function P(semaphore S, integer I):
    repeat:
        if S ≥ I:
            S ← S − I
         break ]
```

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Semaphore Uses

- Mutual exclusion
    - Semaphore as mutex
    - What should initial value be?

```
// initialize to X
sem_init(s, 0, X)

sem_wait(s);
// critical section
sem_post(s);
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    - Binary semaphore: X=1
    - (Counting semaphore: X>1)

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Semaphore Uses

- Mutual exclusion
  - Semaphore as mutex
  - What should initial value be?
    - Binary semaphore: X=1
    - (Counting semaphore: X>1)
- Scheduling order
  - One thread waits for another

```
// initialize to X
sem_init(s, 0, X)

sem_wait(s);
// critical section
sem_post(s);
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//thread 0
… // 1st half of computation
sem_post(s);
```

```
// thread 1

sem_wait(s);
… //2nd half of computation
```

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Producer-Consumer with semaphores

- Two semaphores
  - sem_t full; // # of filled slots
  - sem_t empty; // # of empty slots

Producer-Consumer with semaphores

- Two semaphores
  - sem_t full; // # of filled slots
  - sem_t empty; // # of empty slots

```
sem_init(&full, 0, 0);
sem_init(&empty, 0, N);
```

```
producer() {
    sem_wait(empty);
    … // fill a slot
    sem_post(full);
}
```

```
consumer() {
    sem_wait(full);
    … // empty a slot
    sem_post(empty);
}
```

Producer-Consumer with semaphores

- Two semaphores
  - sem_t full; // # of filled slots
  - sem_t empty; // # of empty slots

Is this correct?

```
sem_init(&full, 0, 0);
sem_init(&empty, 0, N);
```

```
producer() {
    sem_wait(empty);
    … // fill a slot
    sem_post(full);
}
```

```
consumer() {
    sem_wait(full);
    … // empty a slot
    sem_post(empty);
}
```

Producer-Consumer with semaphores

- Two semaphores
  - sem_t full; // # of filled slots
  - sem_t empty; // # of empty slots

```
sem_init(&full, 0, 0);
sem_init(&empty, 0, N);
```

```
producer() {
    sem_wait(empty);
    … // fill a slot
    sem_post(full);
}
```

```
consumer() {
    sem_wait(full);
    … // empty a slot
    sem_post(empty);
}
```

Producer-Consumer with semaphores

- Two semaphores
  - sem_t full; // # of filled slots
  - sem_t empty; // # of empty slots

- Problem: mutual exclusion?

```
sem_init(&full, 0, 0);
sem_init(&empty, 0, N);
```

```
producer() {
    sem_wait(empty);
    … // fill a slot
    sem_post(full);
}
```

```
consumer() {
    sem_wait(full);
    … // empty a slot
    sem_post(empty);
}
```

Producer-Consumer with semaphores

- Three semaphores
  - sem_t full; // # of filled slots
  - sem_t empty; // # of empty slots
  - sem_t mutex; // mutual exclusion

```
sem_init(&full, 0, 0);
sem_init(&empty, 0, N);
sem_init(&mutex, 0, 1);
```

```
producer() {
    sem_wait(empty);
    sem_wait(&mutex);
    … // fill a slot
    sem_post(&mutex);
    sem_post(full);
}
```

```
consumer() {
    sem_wait(full);
    sem_wait(&mutex);
    … // empty a slot
    sem_post(&mutex);
    sem_post(empty);
}
```

Pthreads and Semaphores

- Type: `pthread_semaphore_t`

```
int pthread_semaphore_init(pthread_spinlock_t *lock);
int pthread_semaphore_destroy(pthread_spinlock_t *lock);
…
```

- ?????

Pthreads and Semaphores

Pthreads and Semaphores

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Pthreads and Semaphores

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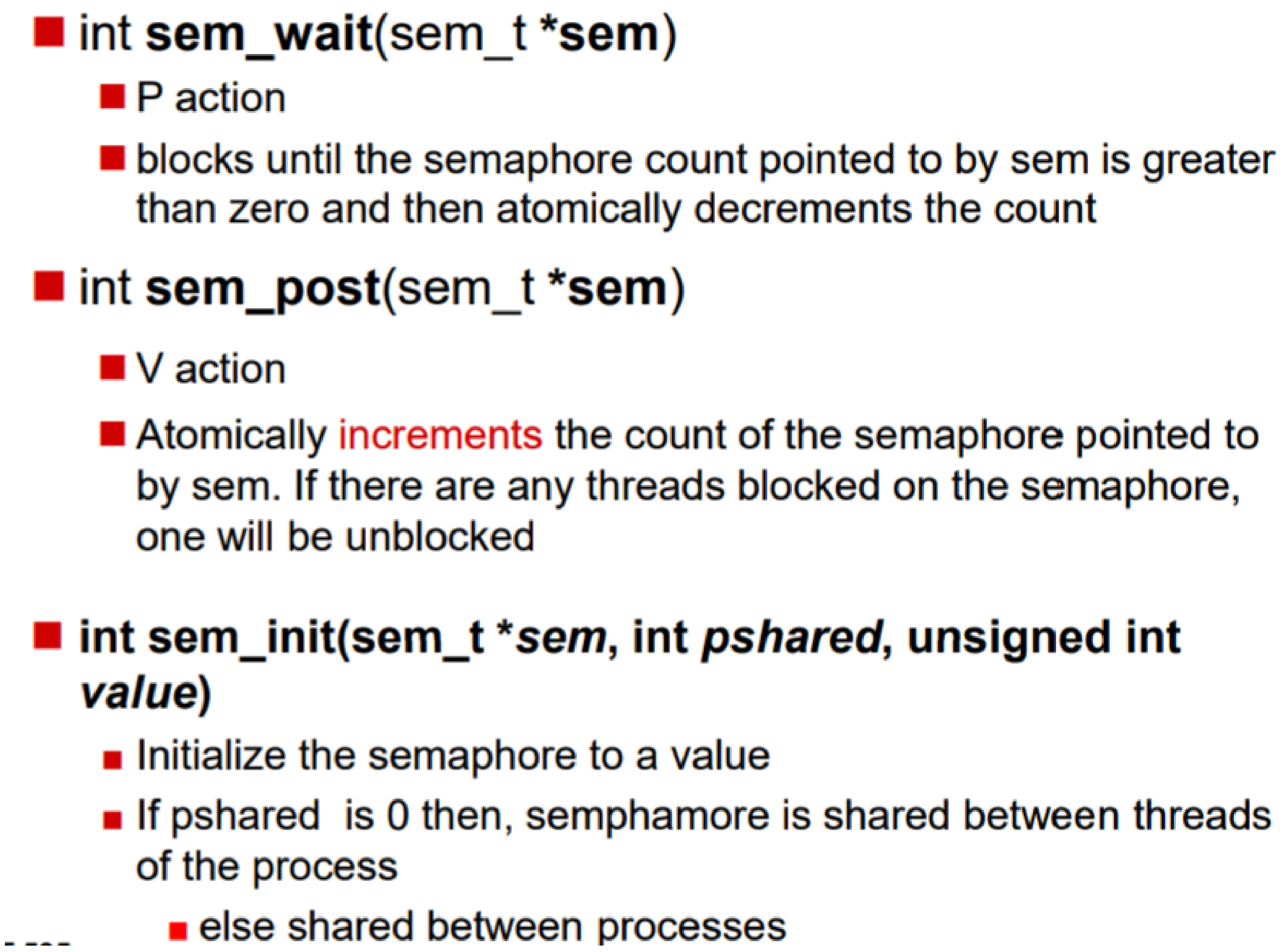
- POSIX does define standard
- #include <semaphore.h>



- int **sem_wait**(sem_t ***sem**)
  - P action
  - blocks until the semaphore count pointed to by sem is greater than zero and then atomically decrements the count
- int **sem_post**(sem_t ***sem**)
  - V action
  - Atomically increments the count of the semaphore pointed to by sem. If there are any threads blocked on the semaphore, one will be unblocked
- **int sem_init(sem_t *_sem_, int _pshared_, unsigned int _value_)**
  - Initialize the semaphore to a value
  - If pshared is 0 then, semphamore is shared between threads of the process
    - else shared between processes

Semaphore Drawbacks?

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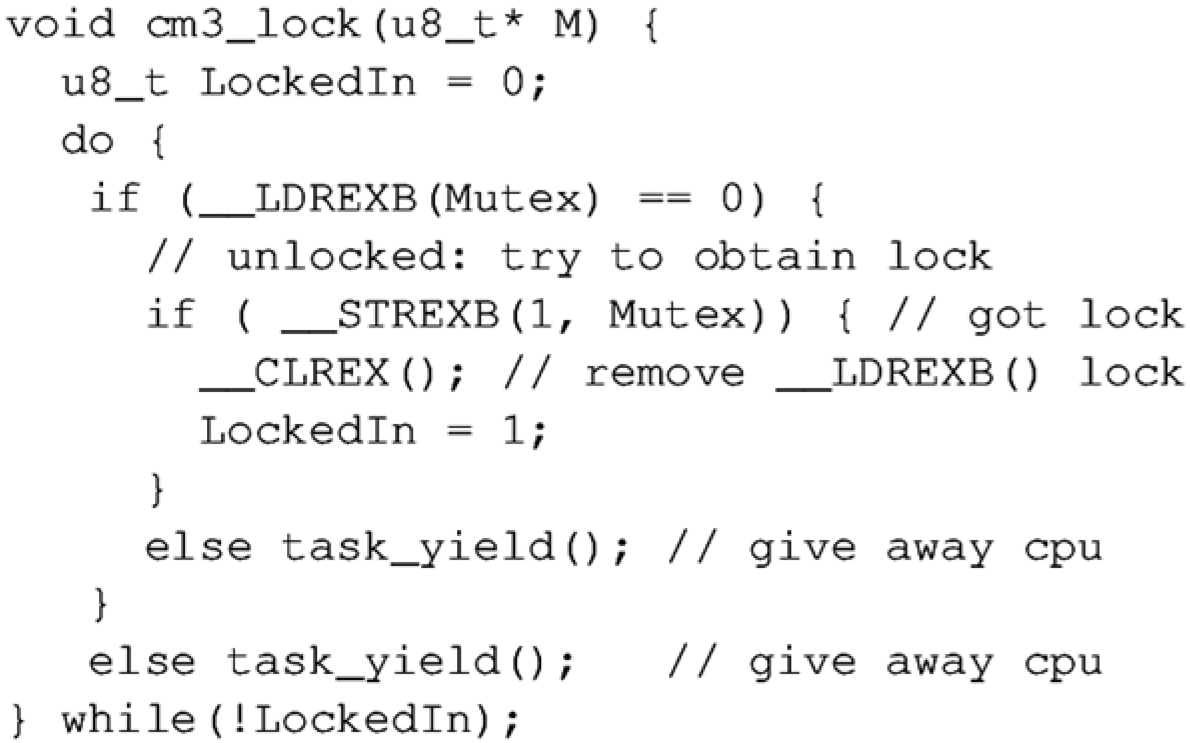
- Heavy-weight object

Semaphore Drawbacks?

- Heavy-weight object
- Insufficiently expressive

Mutex

- Same abstraction as spinlock
- But is a “blocking” primitive
  - Lock available → same behavior
  - Lock held → yield/block
- Many ways to yield
- Simplest case of semaphore



```
void cm3_lock(u8_t* M) {
  u8_t LockedIn = 0;
  do {
   if (__LDREXB(Mutex) == 0) {
     // unlocked: try to obtain lock
     if ( __STREXB(1, Mutex)) { // got lock
       __CLREX(); // remove __LDREXB() lock
       LockedIn = 1;
     }
     else task_yield(); // give away cpu
   }
   else task_yield();   // give away cpu
} while(!LockedIn);
```

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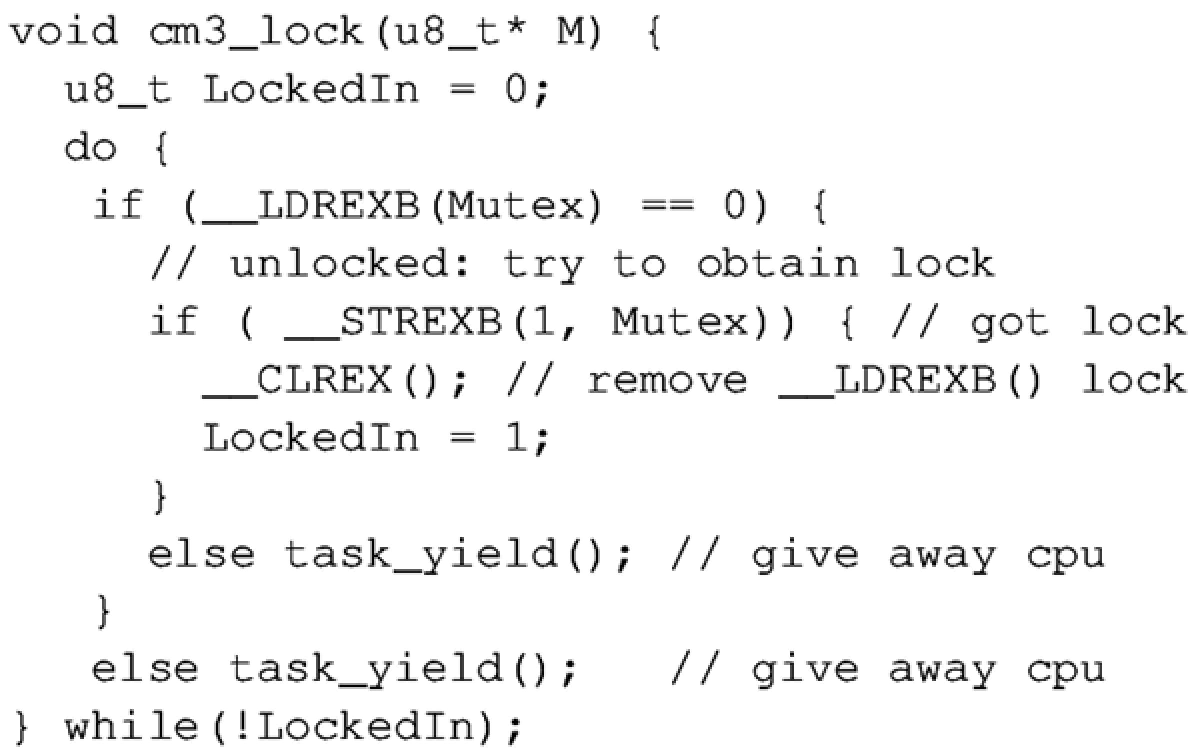

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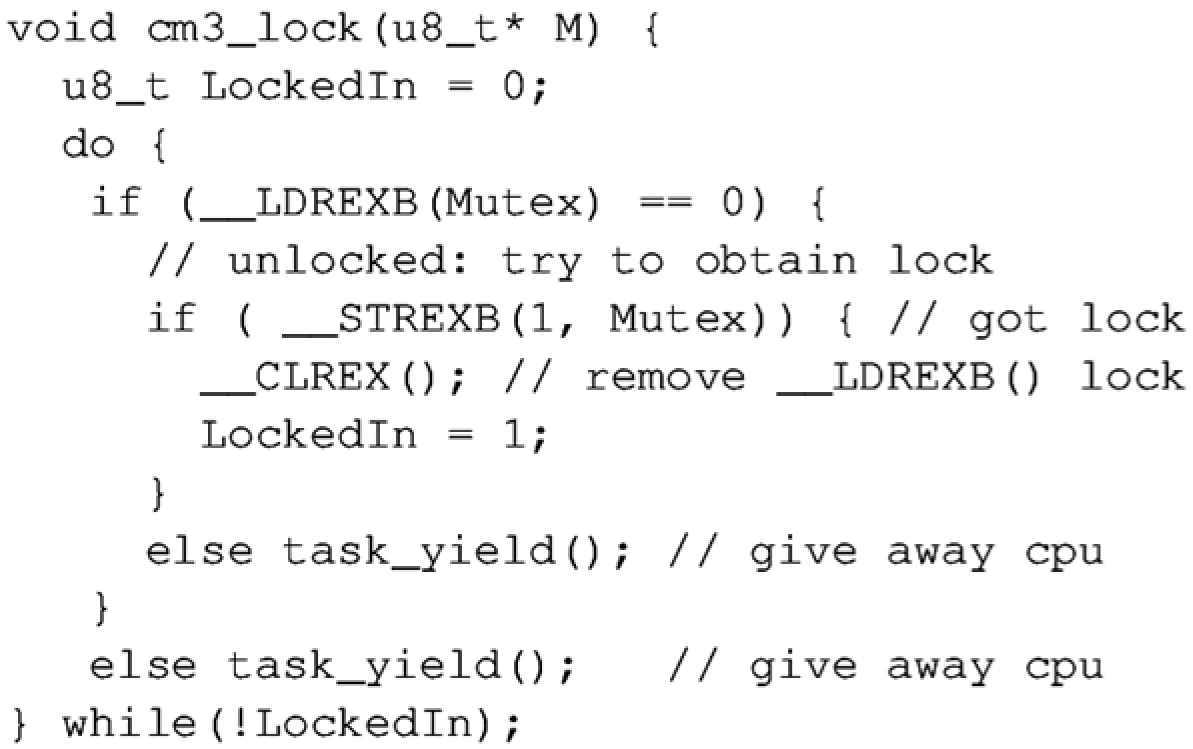

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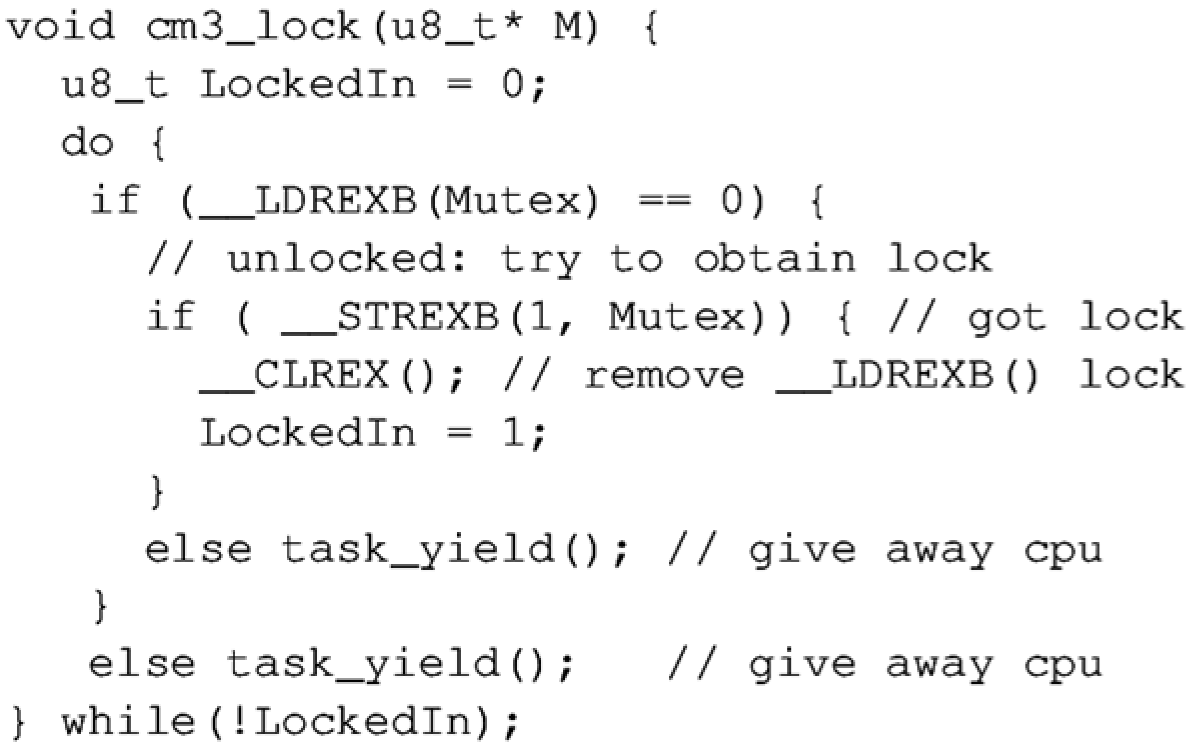

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- Is it better to use a spinlock or mutex on a uni-processor?
- Is it better to use a spinlock or mutex on a multi-processor?
- How do you choose between spinlock/mutex on a multi-processor?

futex: Fast Userspace Mutex

```
int futex(int *uaddr, int futex_op, int val,
          const struct timespec *timeout );
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- Interface to the kernel sleep()
- Let thread deschedule itself – conditionally!
- Can be used to implement locks, semaphores, monitors, etc…

Test&Set and `futex`

Test&Set and futex

```
int mylock = 0; // Interface: acquire(&mylock);
                //            release(&mylock);

acquire(int *thelock) {
  while (test&set(thelock)) {
     futex(thelock, FUTEX_WAIT, 1);
  }
}
```

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release(int *thelock) {
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   futex(&thelock, FUTEX_WAKE, 1);

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    - Sleep interface by using futex – no busywaiting

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  - Ideally, we have no-kernel crossings when uncontended

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Improved Test&Set with futex

```
bool maybe_waiters = false;
int mylock = 0; // Interface: acquire(&mylock,&maybe_waiters);
                //            release(&mylock,&maybe_waiters);
```

```
acquire(int *thelock, bool *maybe) {
   while (test&set(thelock)) {
      // Sleep, since lock busy!
      *maybe = true;
      futex(thelock, FUTEX_WAIT, 1);

      // Make sure other sleepers not stuck
      *maybe = true;
   }
}
```

```
release(int*thelock, bool *maybe) {
   thelock = 0;
   if (*maybe) {
      *maybe = false;
      // Try to wake up someone
      futex(&value, FUTEX_WAKE, 1);
   }
}
```

- Pros: syscall-free in the uncontended case
  - Uses syscalls if multiple waiters, or concurrent acquire/release
- But it can be considerably optimized!
  - See “Futexes are Tricky” by Ulrich Drepper

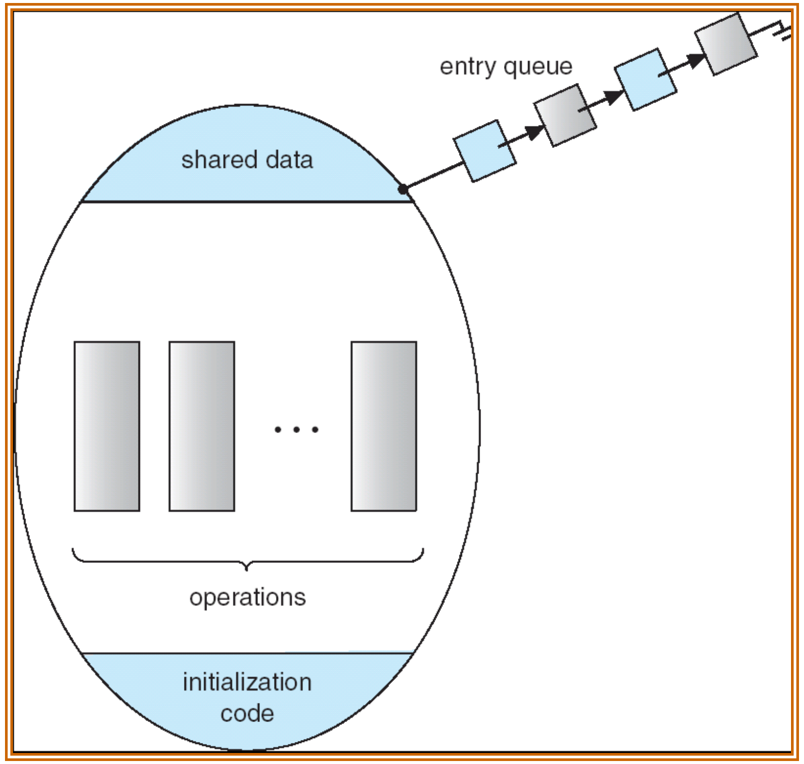
What is a monitor?

What is a monitor?

- ❑ Monitor: one big lock for set of operations/ methods
- ❑ Language-level implementation of mutex

- Entry procedure: called from outside
- Internal procedure: called within monitor
- Wait within monitor releases lock

Many variants…



Pthreads and conditions/monitors

- Type `pthread_cond_t`

```
int pthread_cond_init(pthread_cond_t *cond,
                      const pthread_condattr_t *attr);
int pthread_cond_destroy(pthread_cond_t *cond);
int pthread_cond_wait(pthread_cond_t *cond,
                      pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
```

Pthreads and conditions/monitors

Why the pthread_mutex_t parameter for pthread_cond_wait?

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Java:

`synchronized` keyword

`wait()/notify()/notifyAll()`

C#: Monitor class

`Enter()/Exit()/`

`Pulse()/PulseAll()`

Does this code work?

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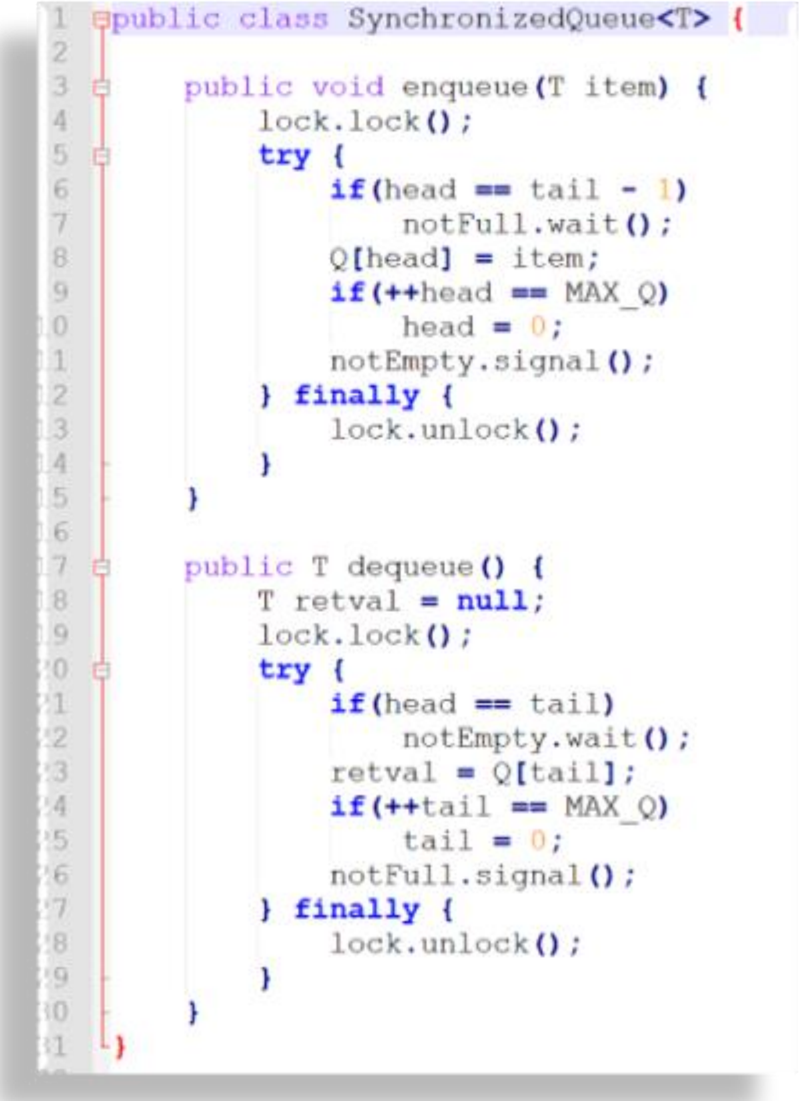

```java
public class SynchronizedQueue<T> {

    public void enqueue(T item) {
        lock.lock();
        try {
            if(head == tail - 1)
                notFull.wait();
            Q[head] = item;
            if(++head == MAX_Q)
                head = 0;
            notEmpty.signal();
        } finally {
            lock.unlock();
        }
    }

    public T dequeue() {
        T retval = null;
        lock.lock();
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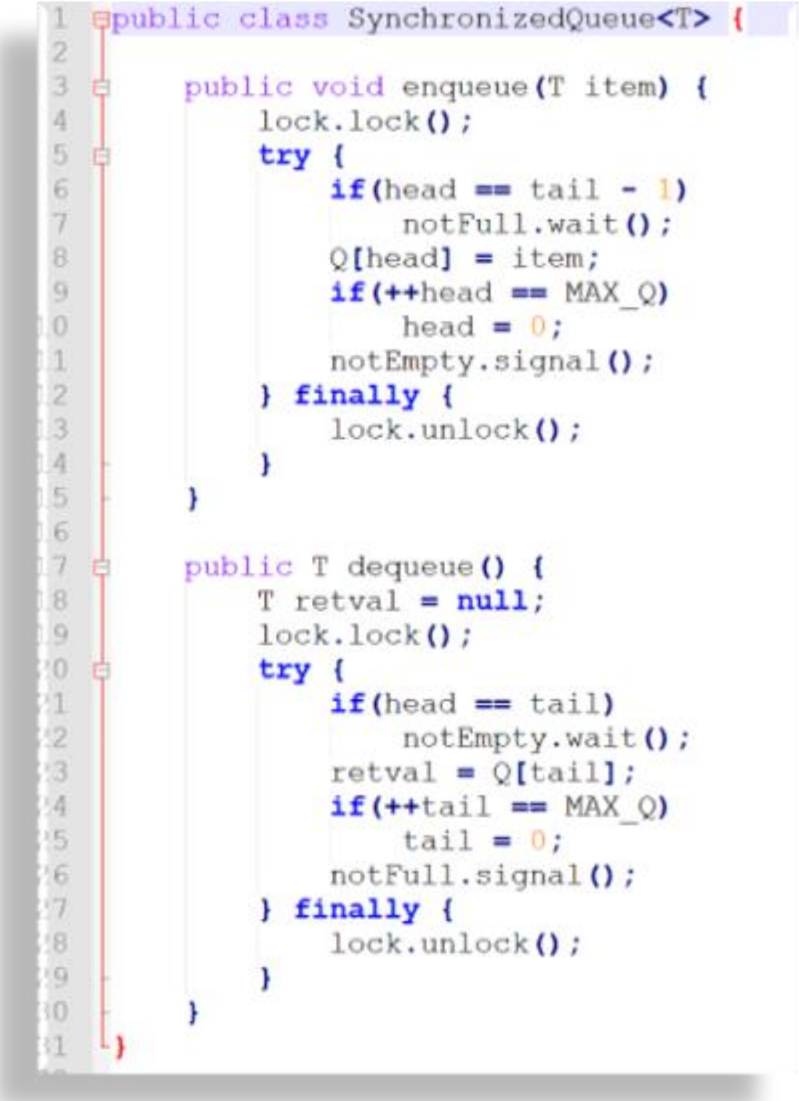

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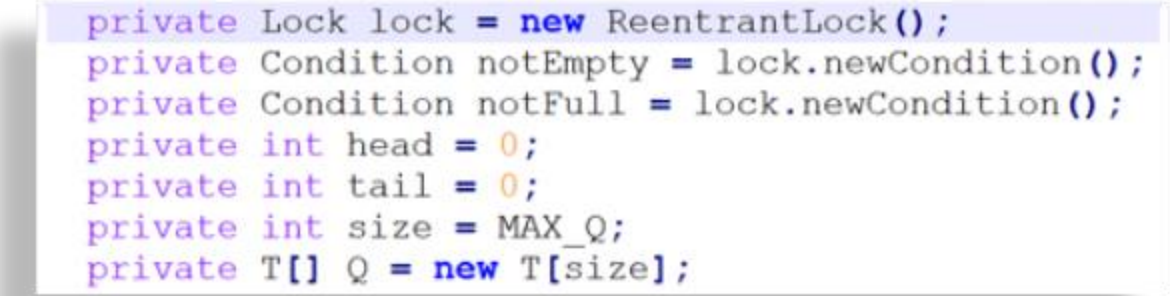

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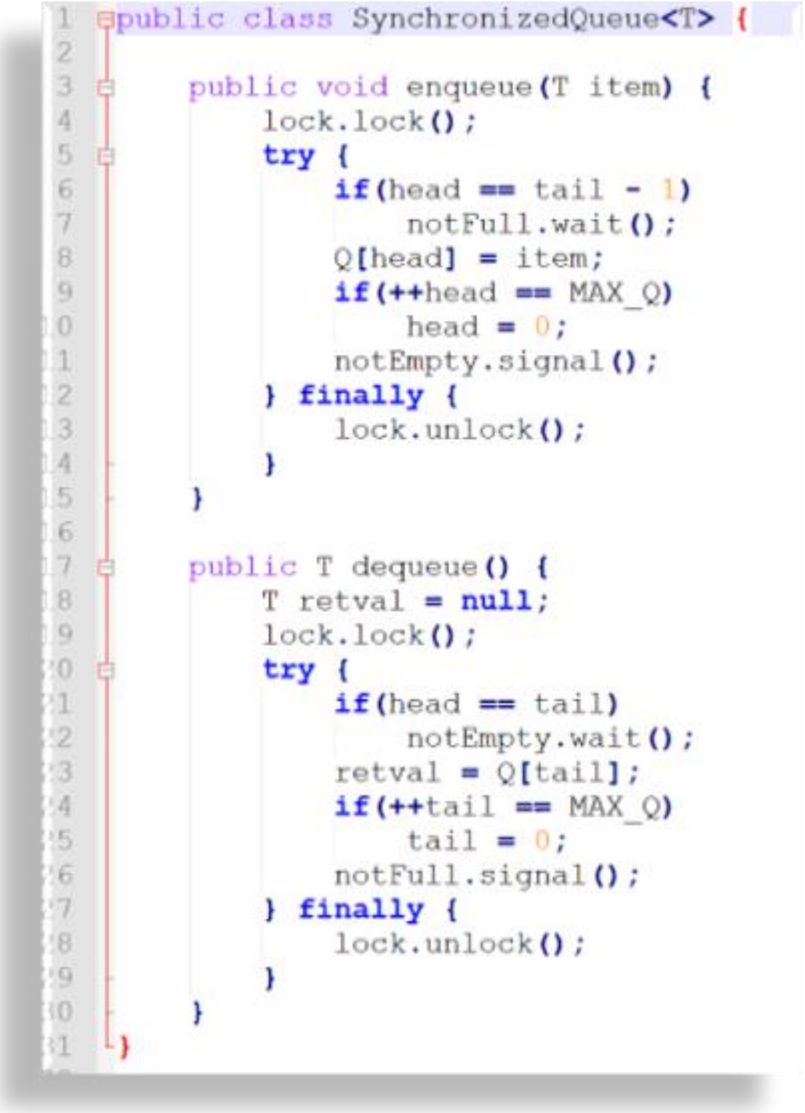

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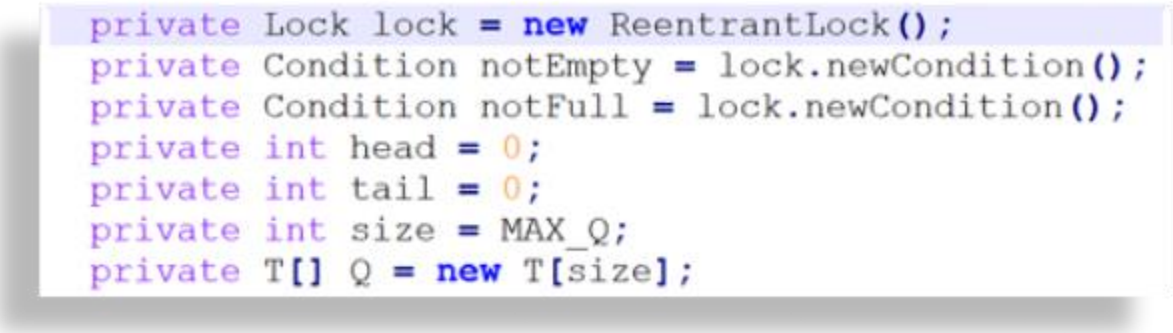

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- Uses “if” to check invariants.

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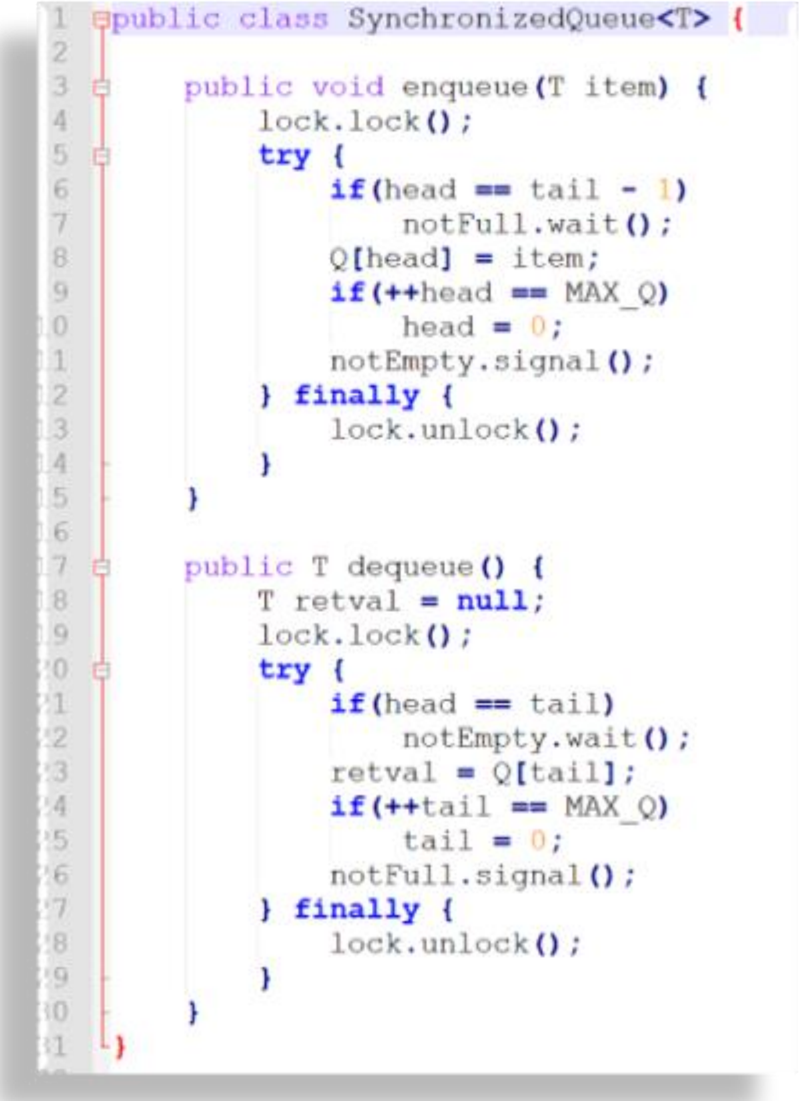

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                tail = 0;
            notFull.signal();
        } finally {
            lock.unlock();
        }
    }
}
```
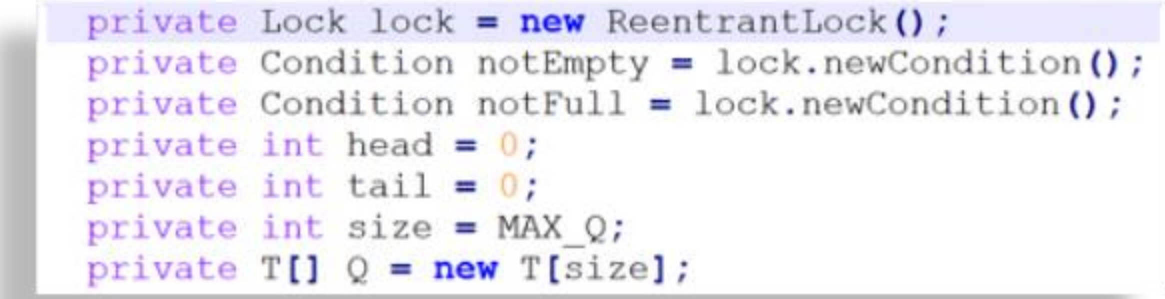
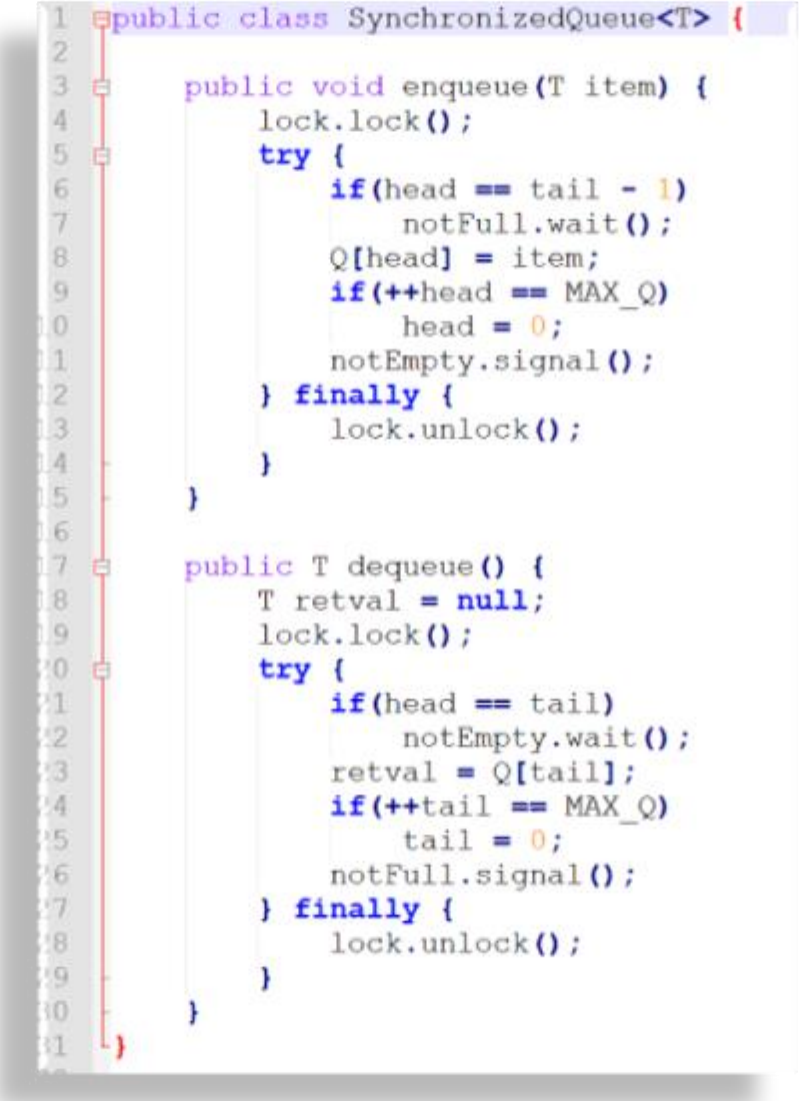



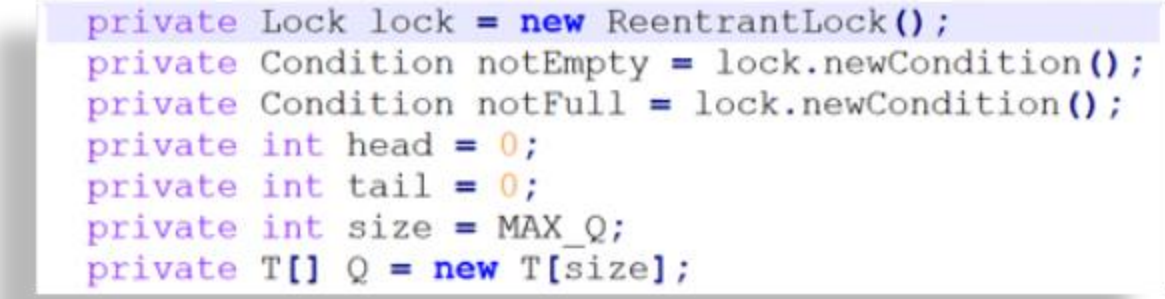
```java
private Lock lock = new ReentrantLock();
private Condition notEmpty = lock.newCondition();
private Condition notFull = lock.newCondition();
private int head = 0;
private int tail = 0;
private int size = MAX_Q;
private T[] Q = new T[size];
```

- Uses “if” to check invariants.
- Why doesn’t **if** work?

Does this code work?



```
public class SynchronizedQueue<T> {

    public void enqueue(T item) {
        lock.lock();
        try {
            if(head == tail - 1)
                notFull.wait();
            Q[head] = item;
            if(++head == MAX_Q)
                head = 0;
            notEmpty.signal();
        } finally {
            lock.unlock();
        }
    }

    public T dequeue() {
        T retval = null;
        lock.lock();
        try {
            if(head == tail)
                notEmpty.wait();
            retval = Q[tail];
            if(++tail == MAX_Q)
                tail = 0;
            notFull.signal();
        } finally {
            lock.unlock();
        }
    }
}
```



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- Uses “if” to check invariants.
- Why doesn’t **if** work?
- How could we MAKE it work?

Hoare-style Monitors

(aka blocking condition variables)

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Given entrance queue ‘e’, signal queue ‘s’, condition var ‘c’

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schedule:
    if s.any()
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        unlock // monitor unoccupied
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- Pros/Cons?

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Options for signaler:

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- Switch out (go on s queue)

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Must run signaled thread immediately
Options for signaler:
- Switch out (go on s queue)
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- Signaler must wait, but gets priority over threads on entrance queue
- Lock only released by
  - Schedule (if no waiters)
  - Application
- Pros/Cons?

Must run signaled thread immediately
Options for signaler:

- Switch out (go on s queue)
- Exit (Hansen monitors)
- Continue executing?

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(aka non-blocking condition variables)

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```
notify C:

    if C.q.any()

         t ← C.q.pop_front() // t is "notified “
         e.push_back(t)
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- Leave still calls schedule

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- Extendable with more queues for priority

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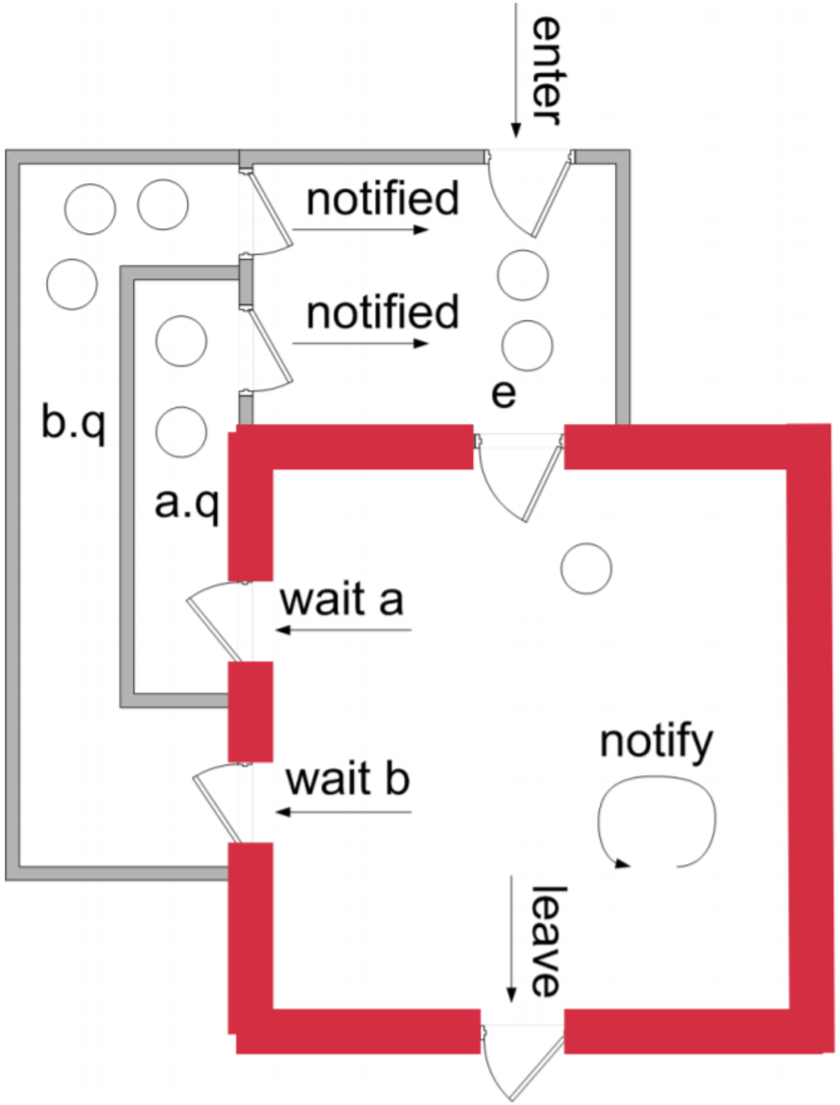
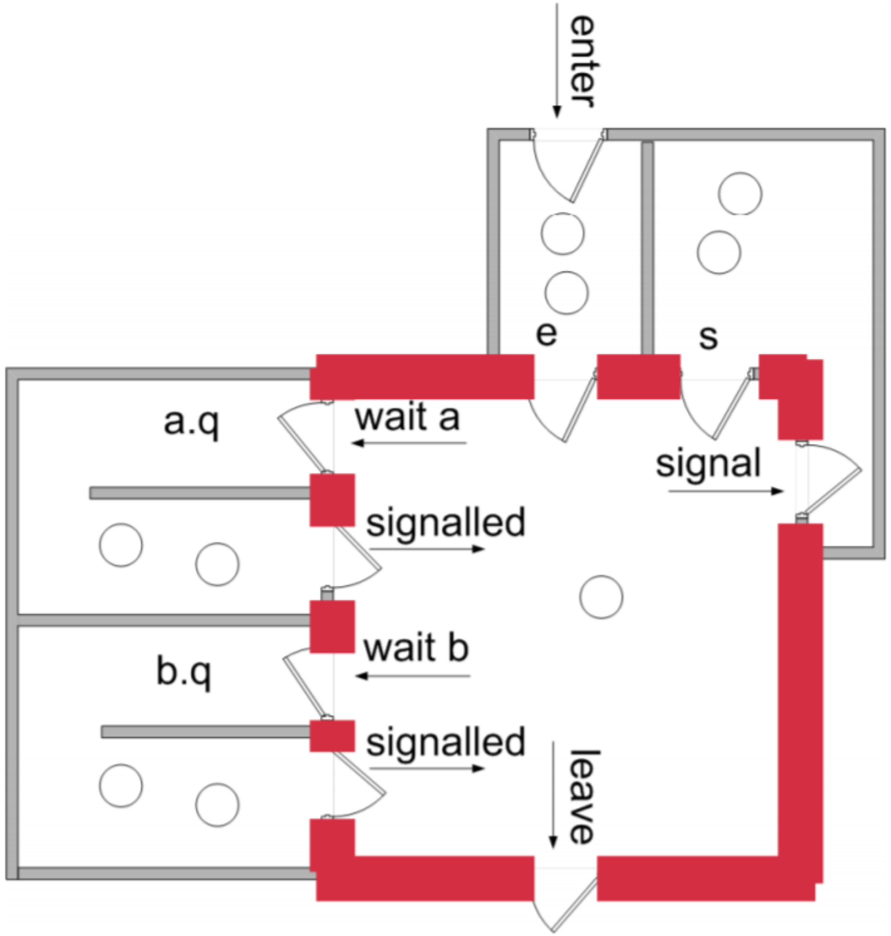
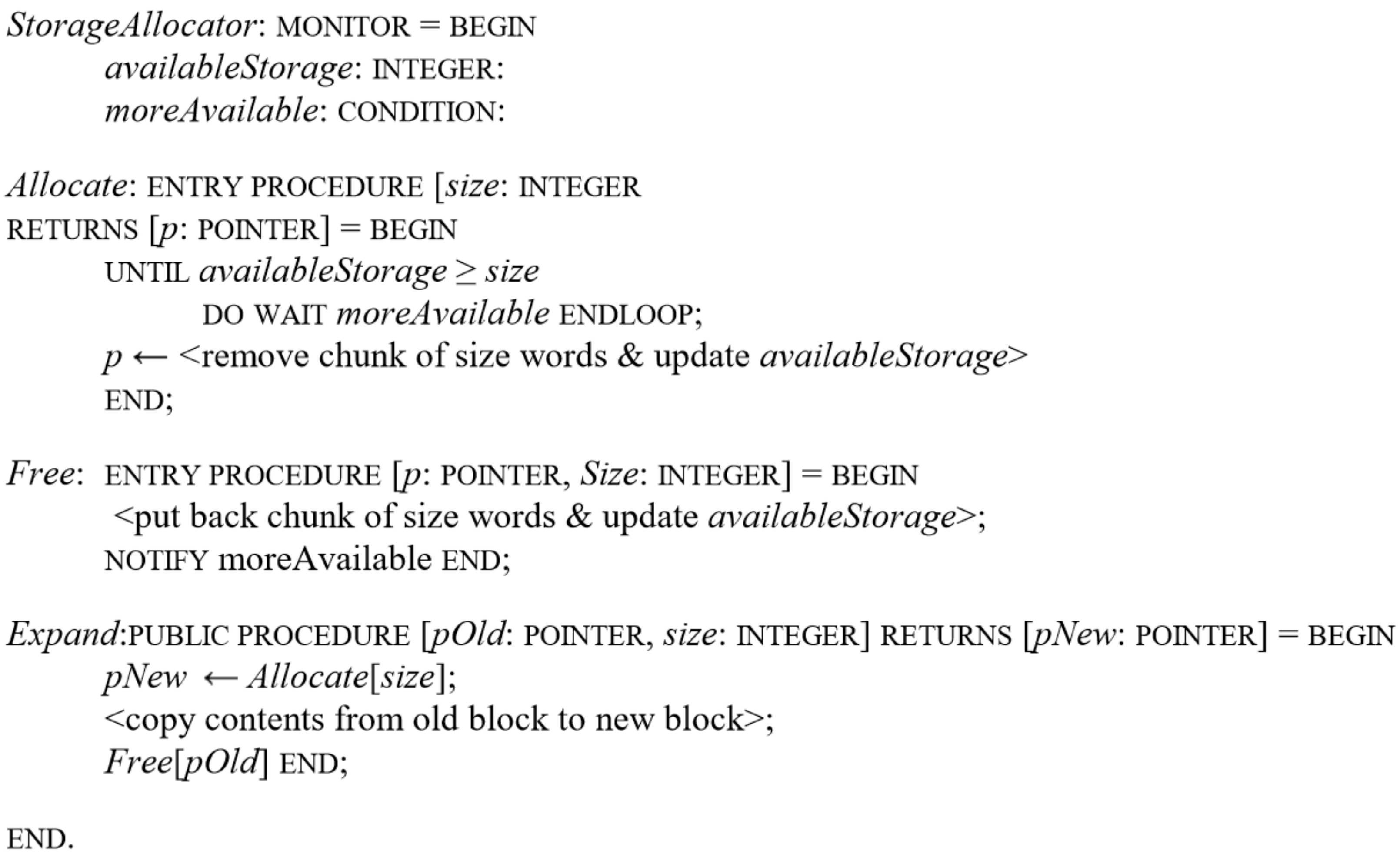
- Leave still calls schedule
- No signal queue
- Extendable with more queues for priority
- What are the differences/pros/cons?

Mesa, Hansen, Hoare





Example: anyone see a bug?



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StorageAllocator: MONITOR = BEGIN
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Allocate: ENTRY PROCEDURE [size: INTEGER
RETURNS [p: POINTER] = BEGIN
        UNTIL availableStorage ≥ size
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Expand:PUBLIC PROCEDURE [pOld: POINTER, size: INTEGER] RETURNS [pNew: POINTER] = BEGIN
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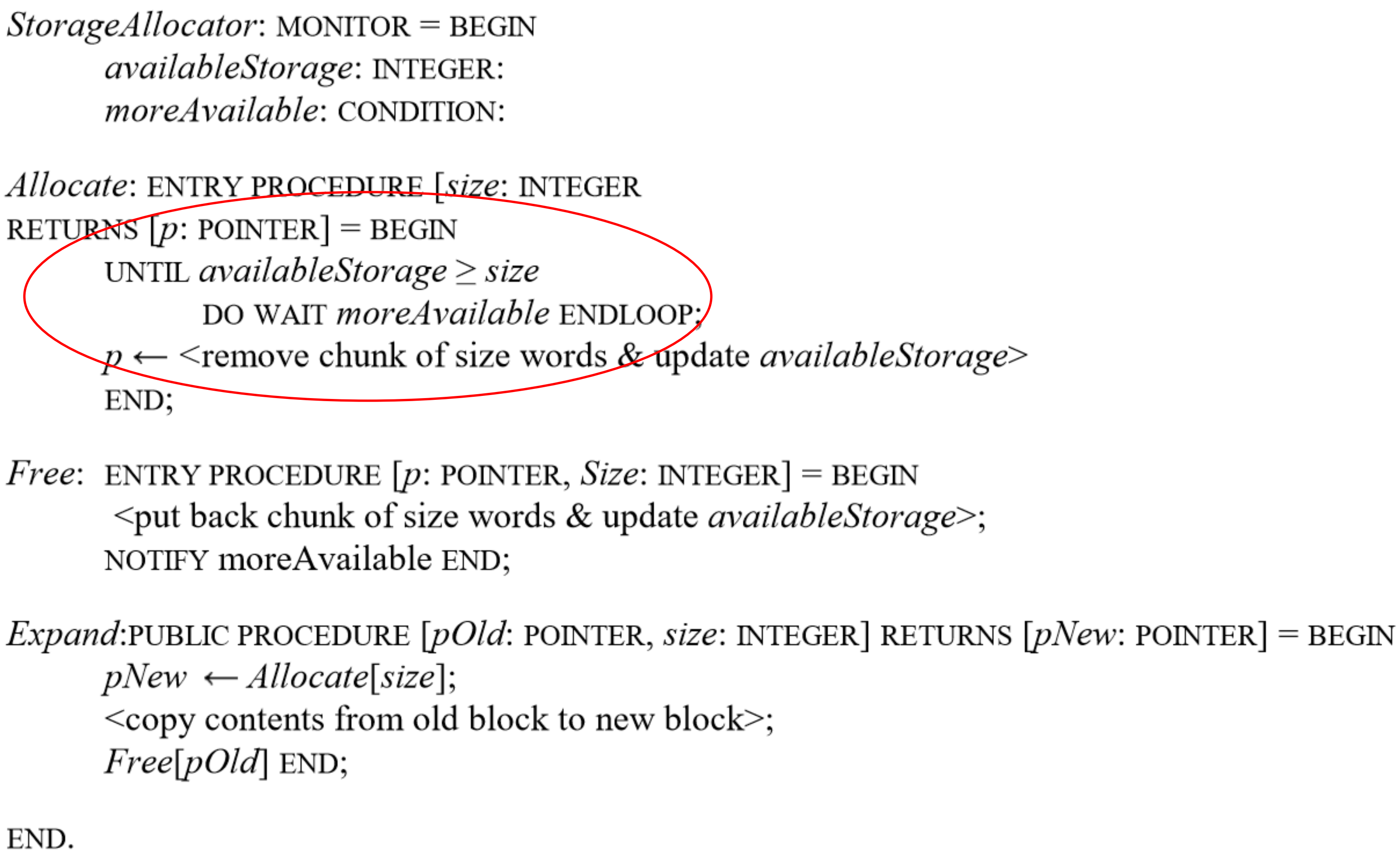

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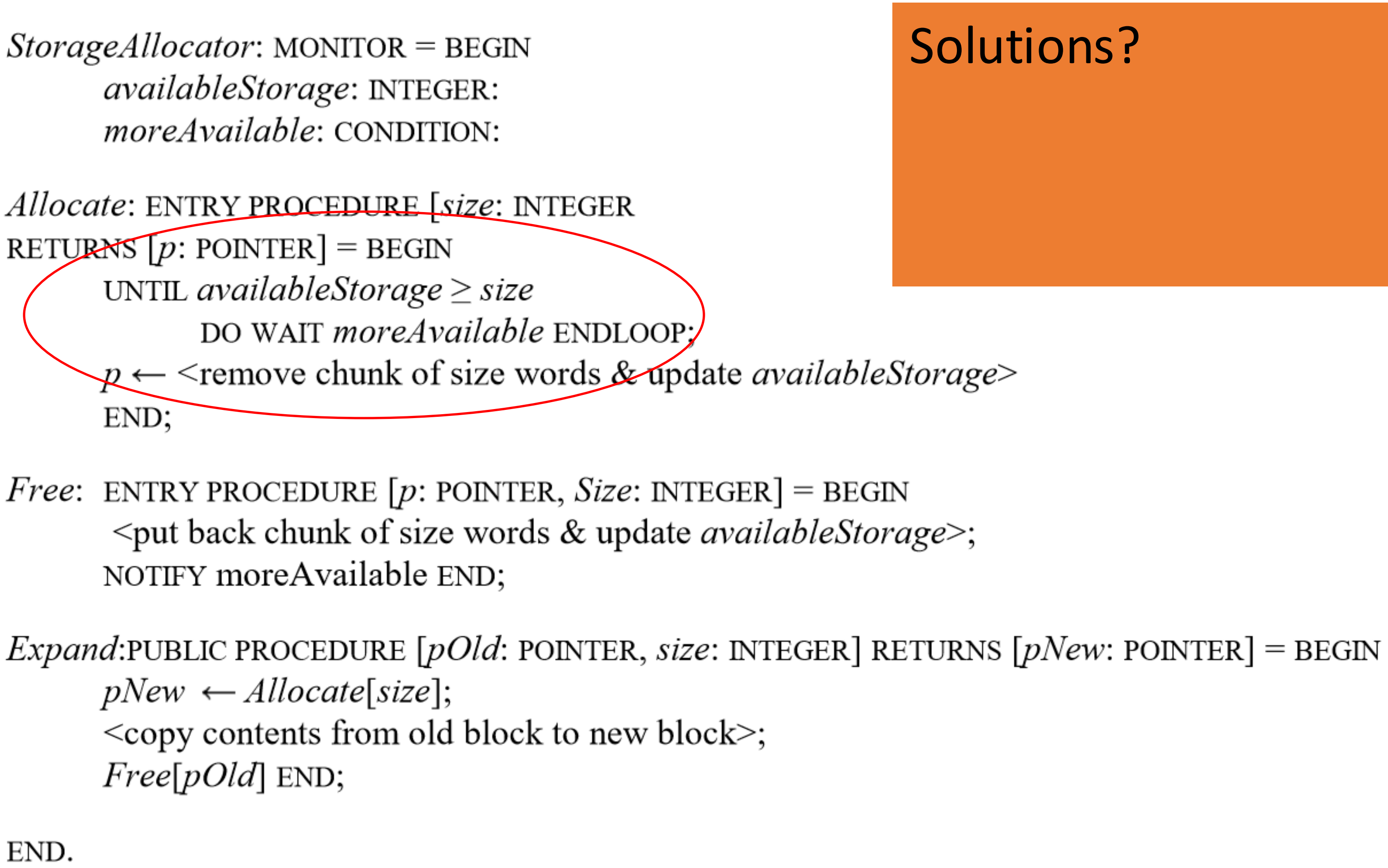

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Solutions?

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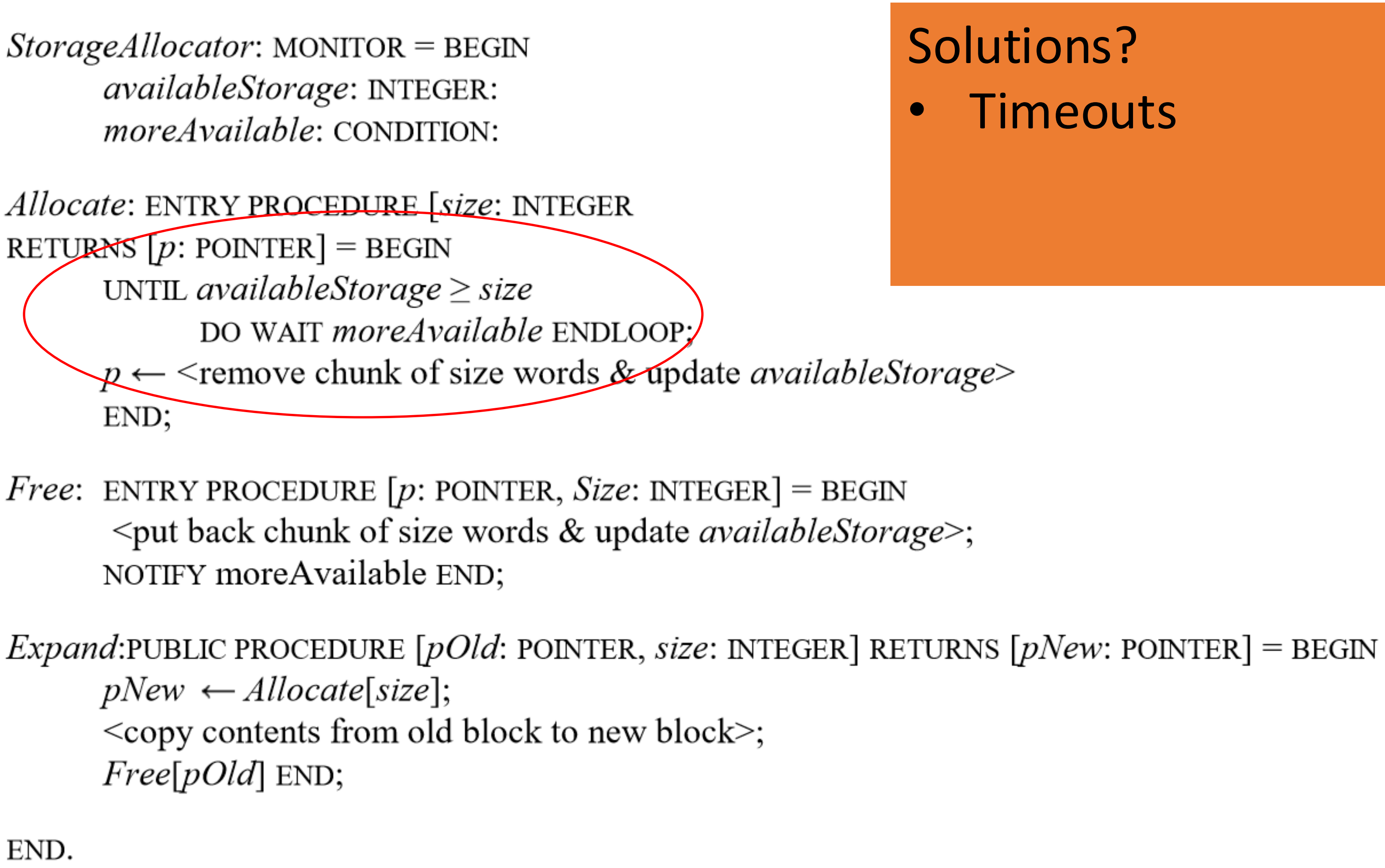

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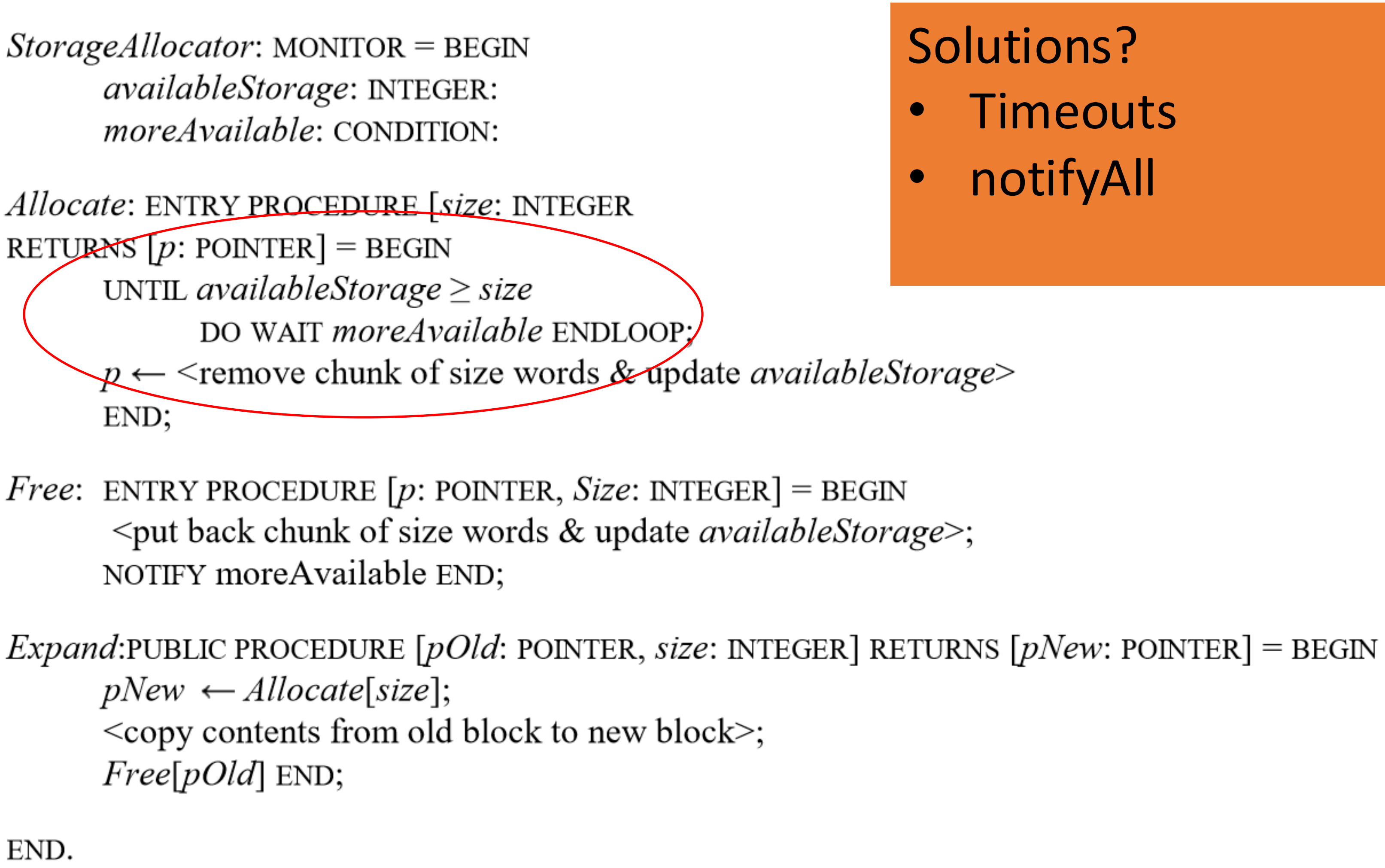
Solutions?

- Timeouts

Example: anyone see a bug?

Solutions?

- Timeouts
- notifyAll



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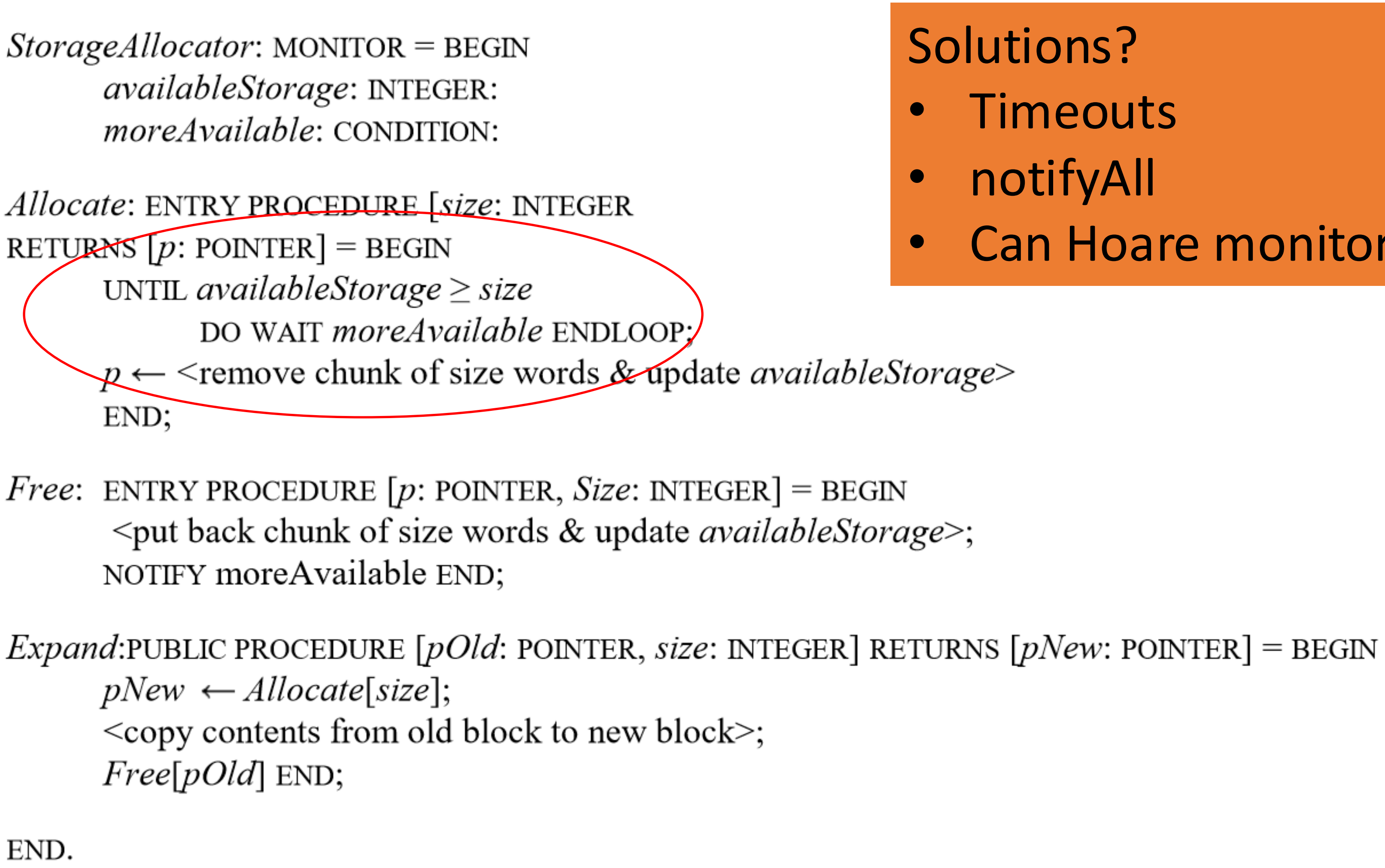

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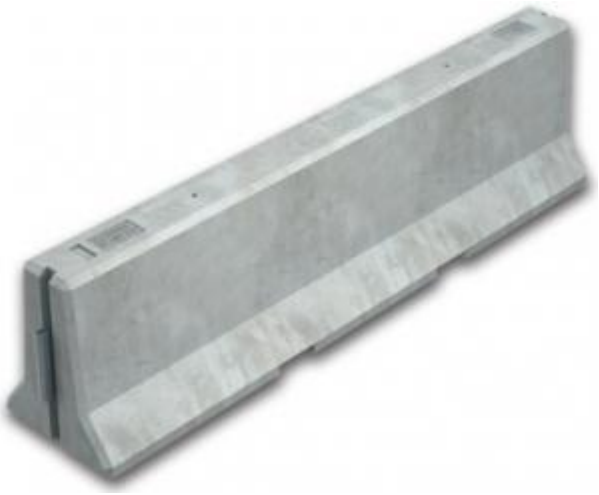
Solutions?
- Timeouts
- notifyAll
- Can Hoare monitors support notifyAll?

Barriers

Barriers



Prefix Sum

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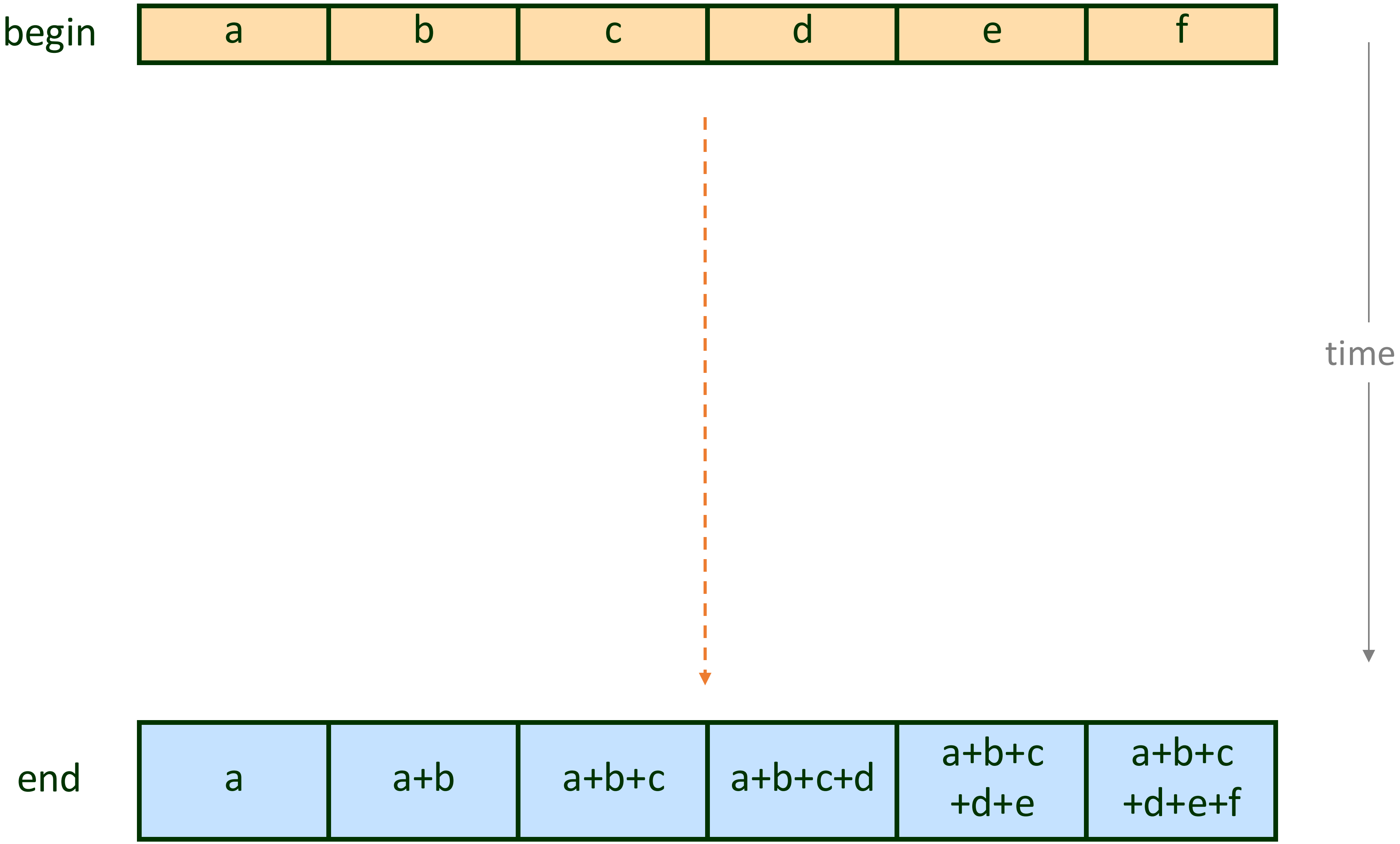
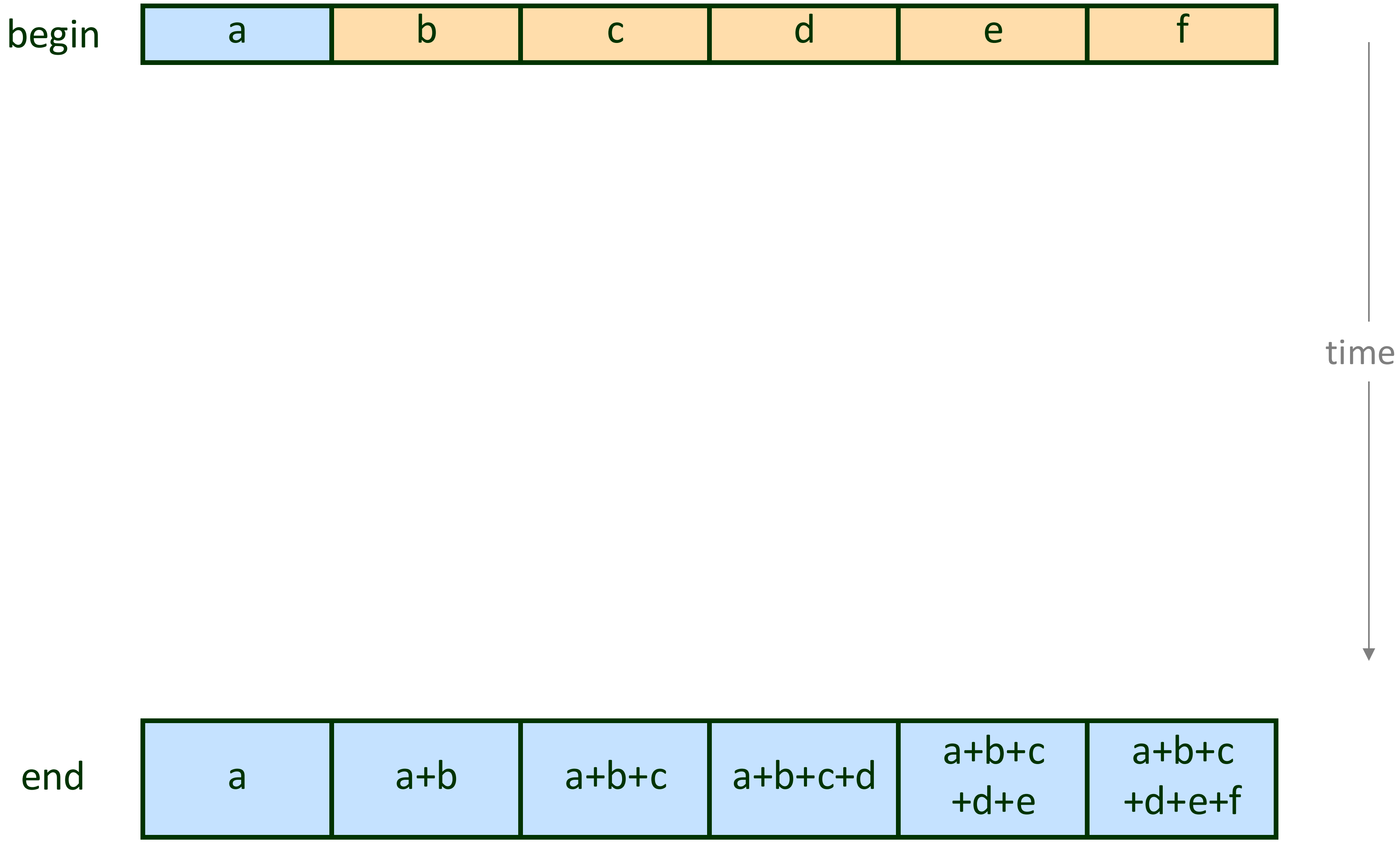
begin	a	b	c	d	e	f

Prefix Sum



begin	a	b	c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



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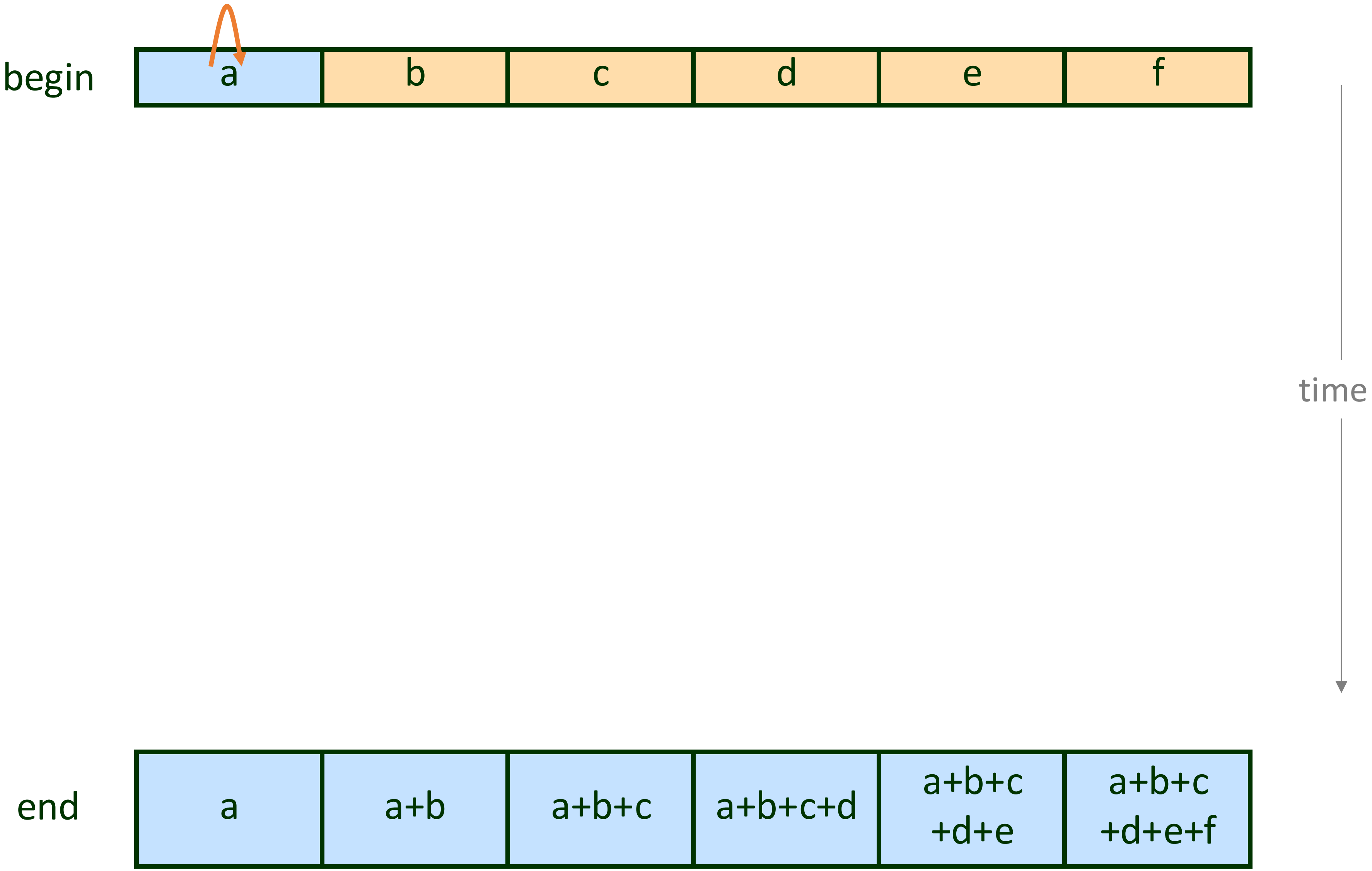
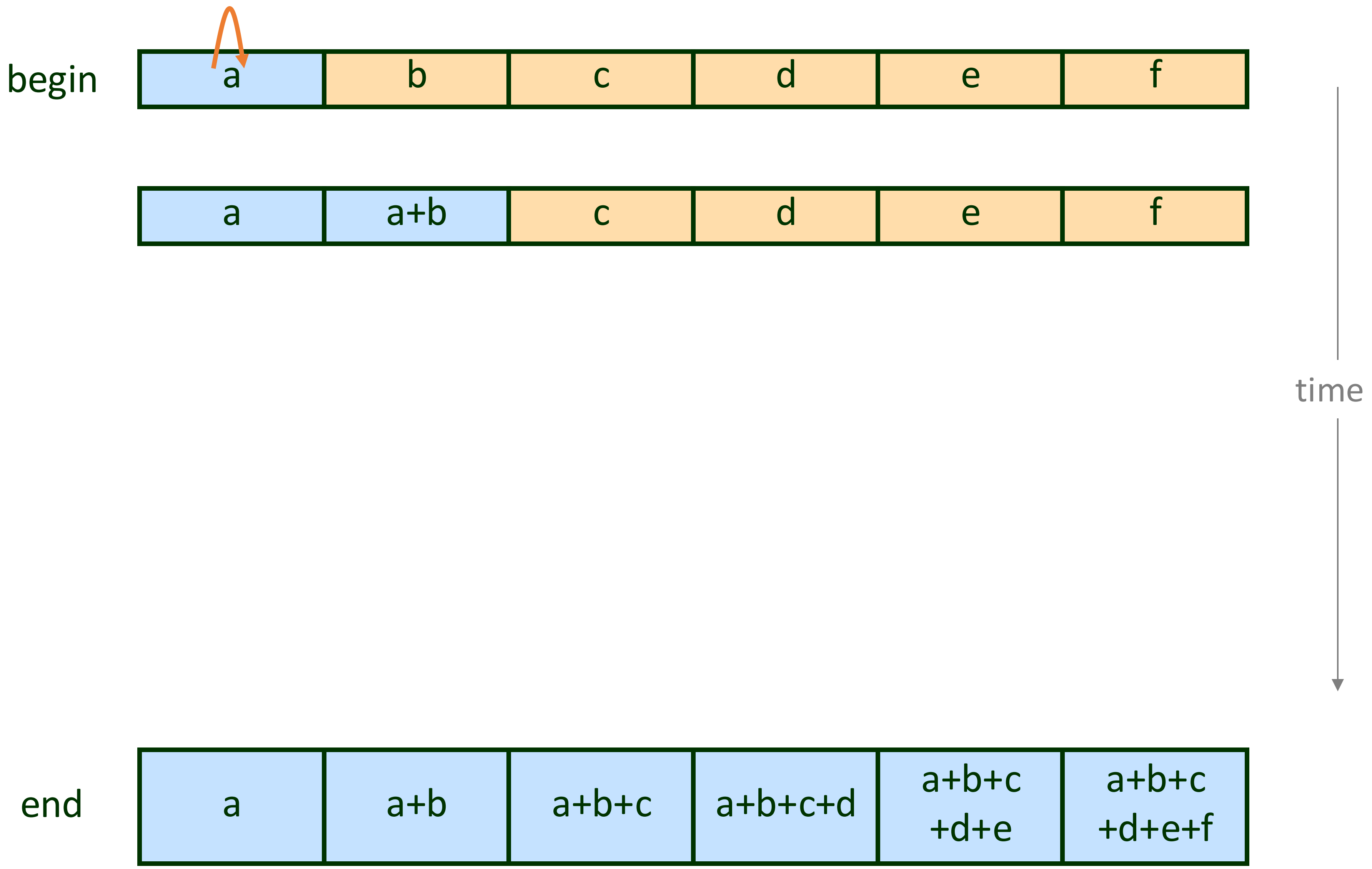


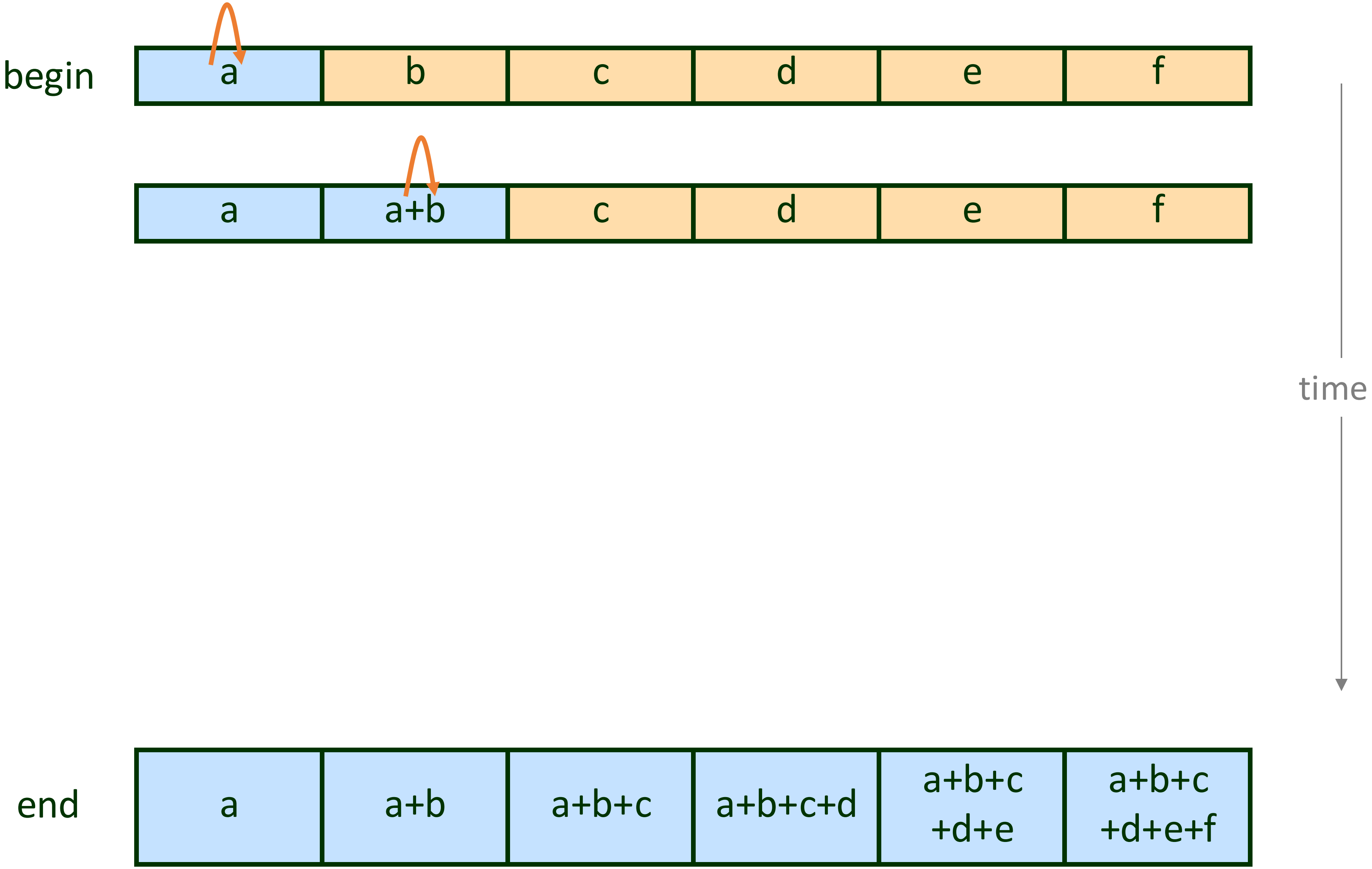
begin	a	b	c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



begin

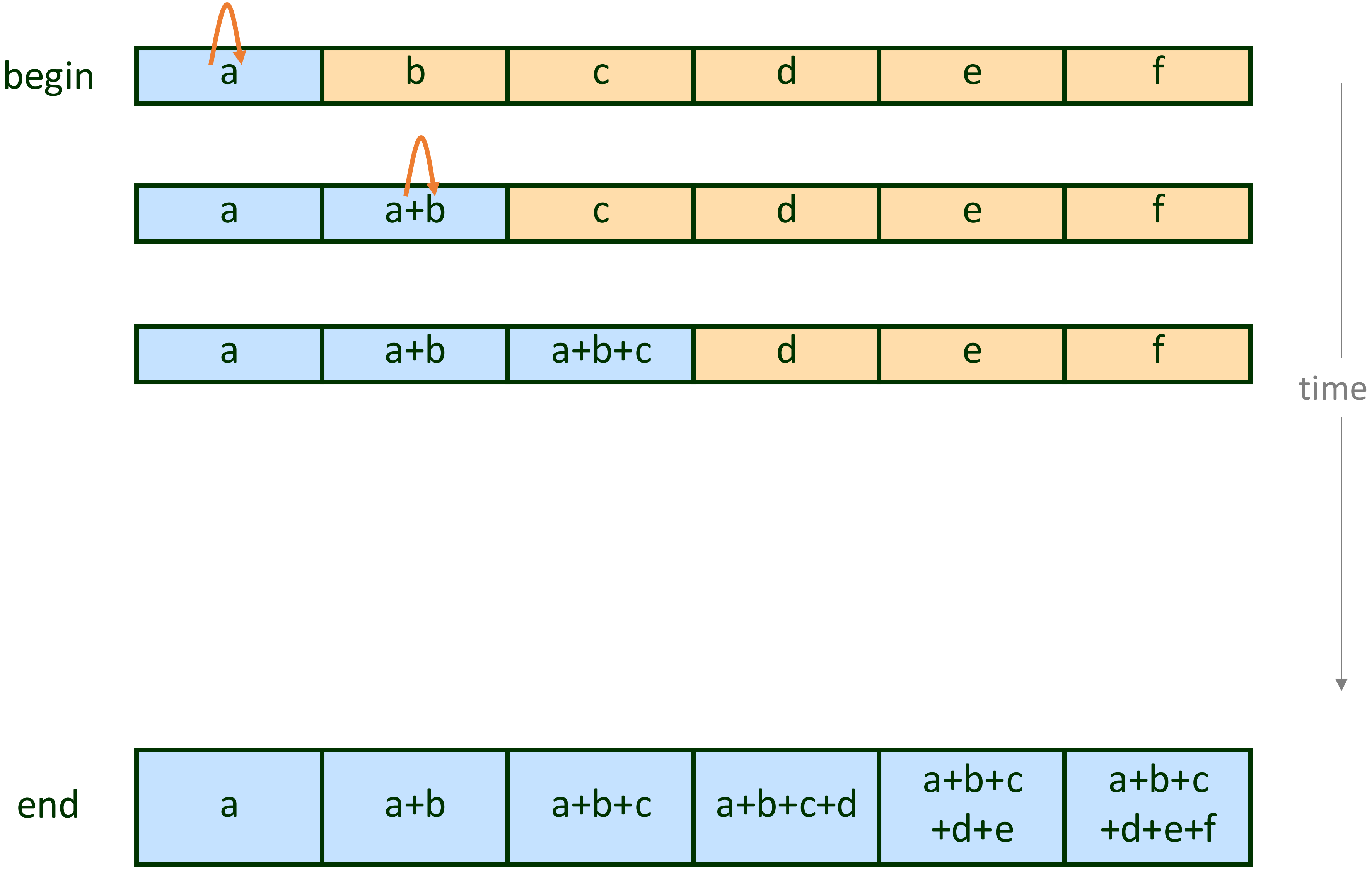
a	b	c	d	e	f

a	a+b	c	d	e	f

end

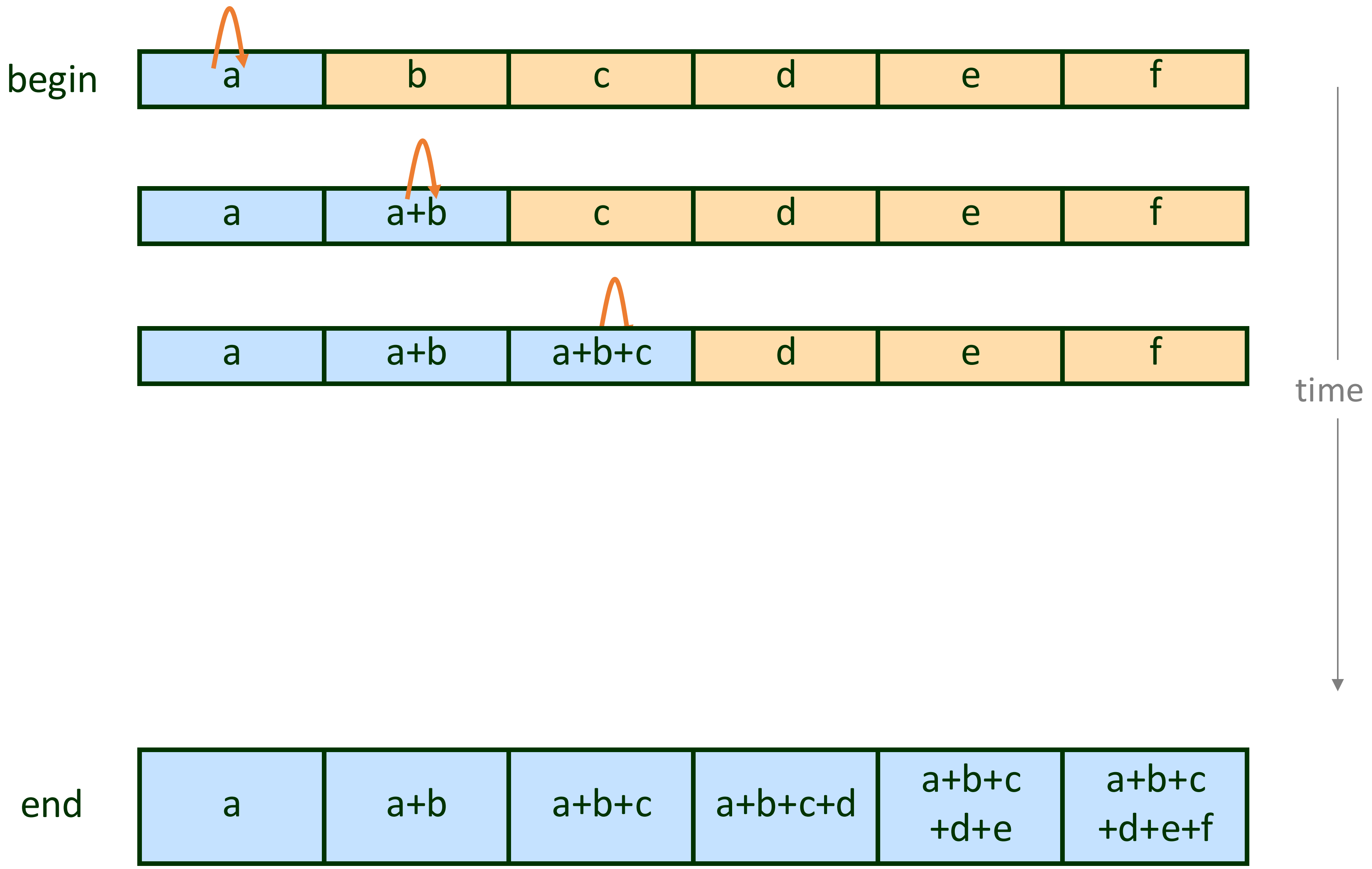
a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

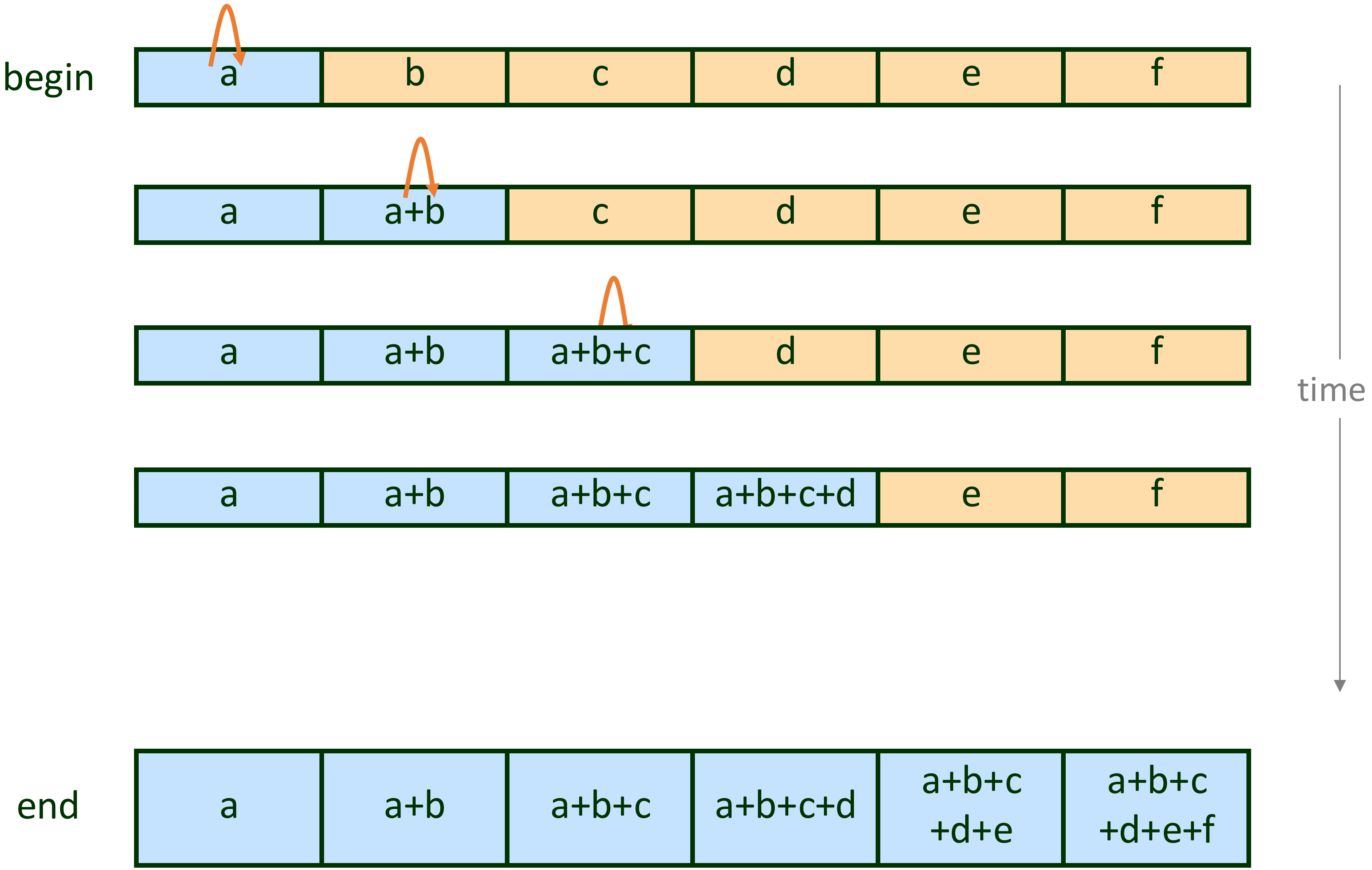
Prefix Sum



begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

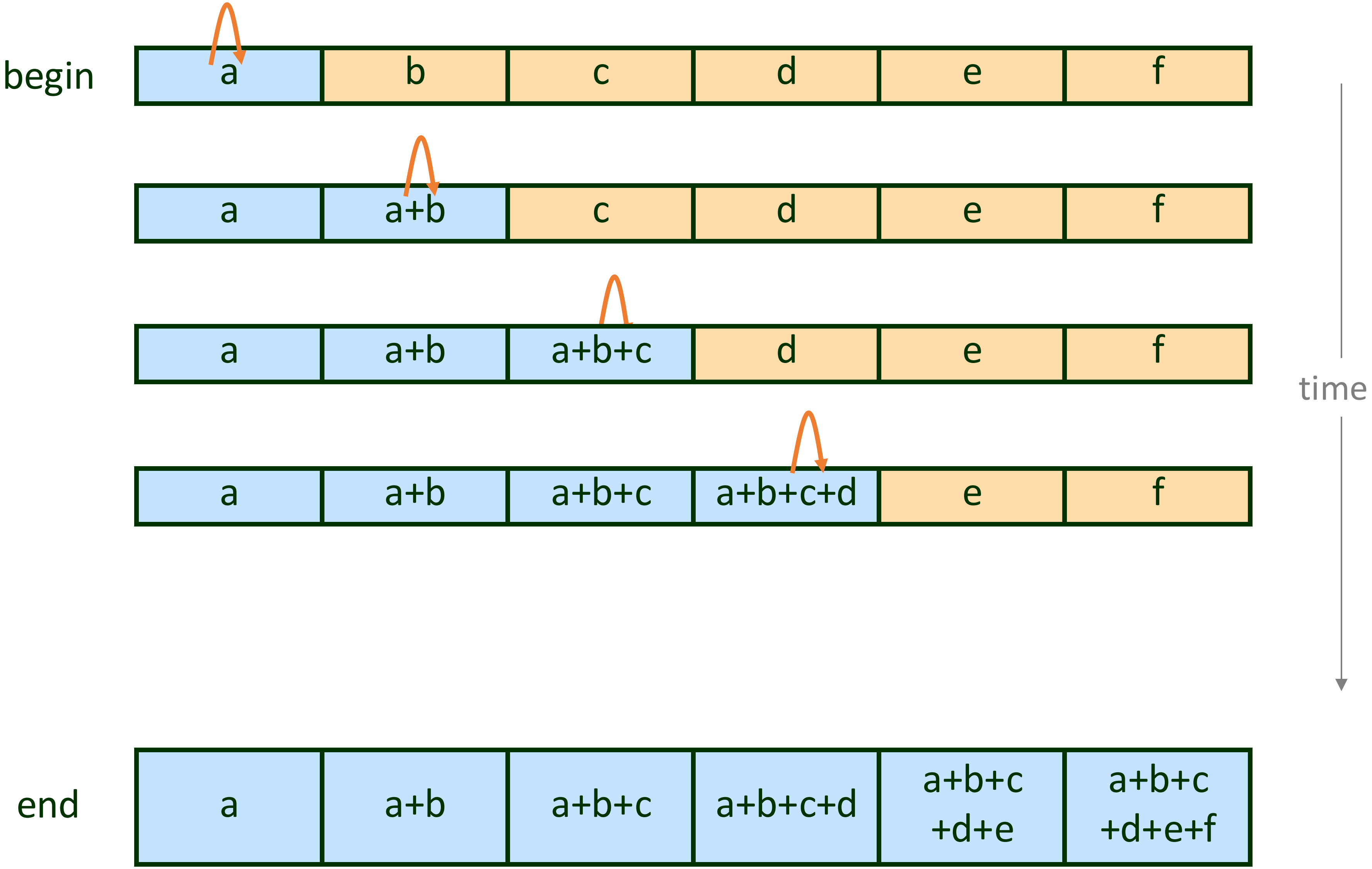
time

Prefix Sum



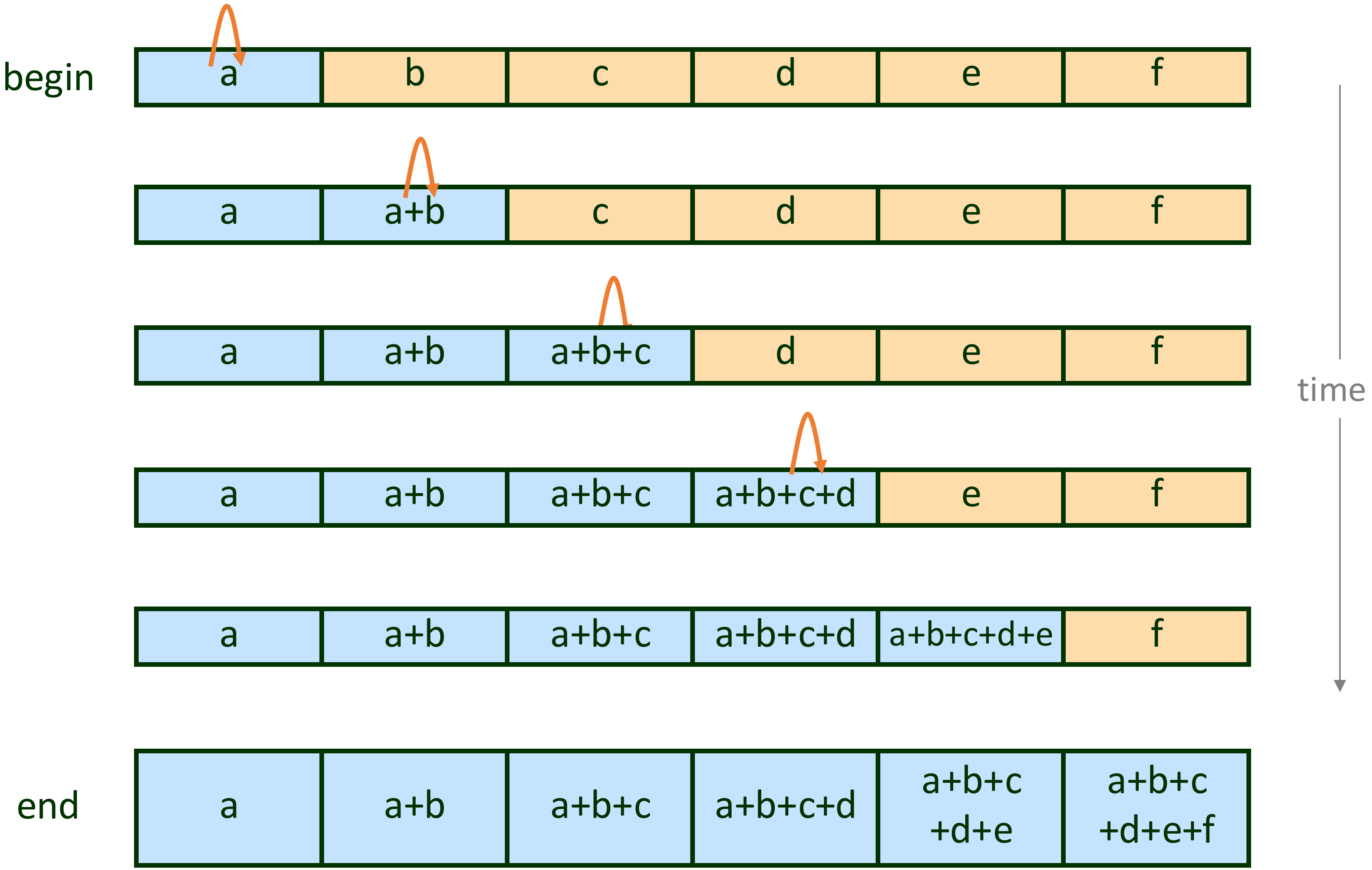
begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
	a	a+b	a+b+c	a+b+c+d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



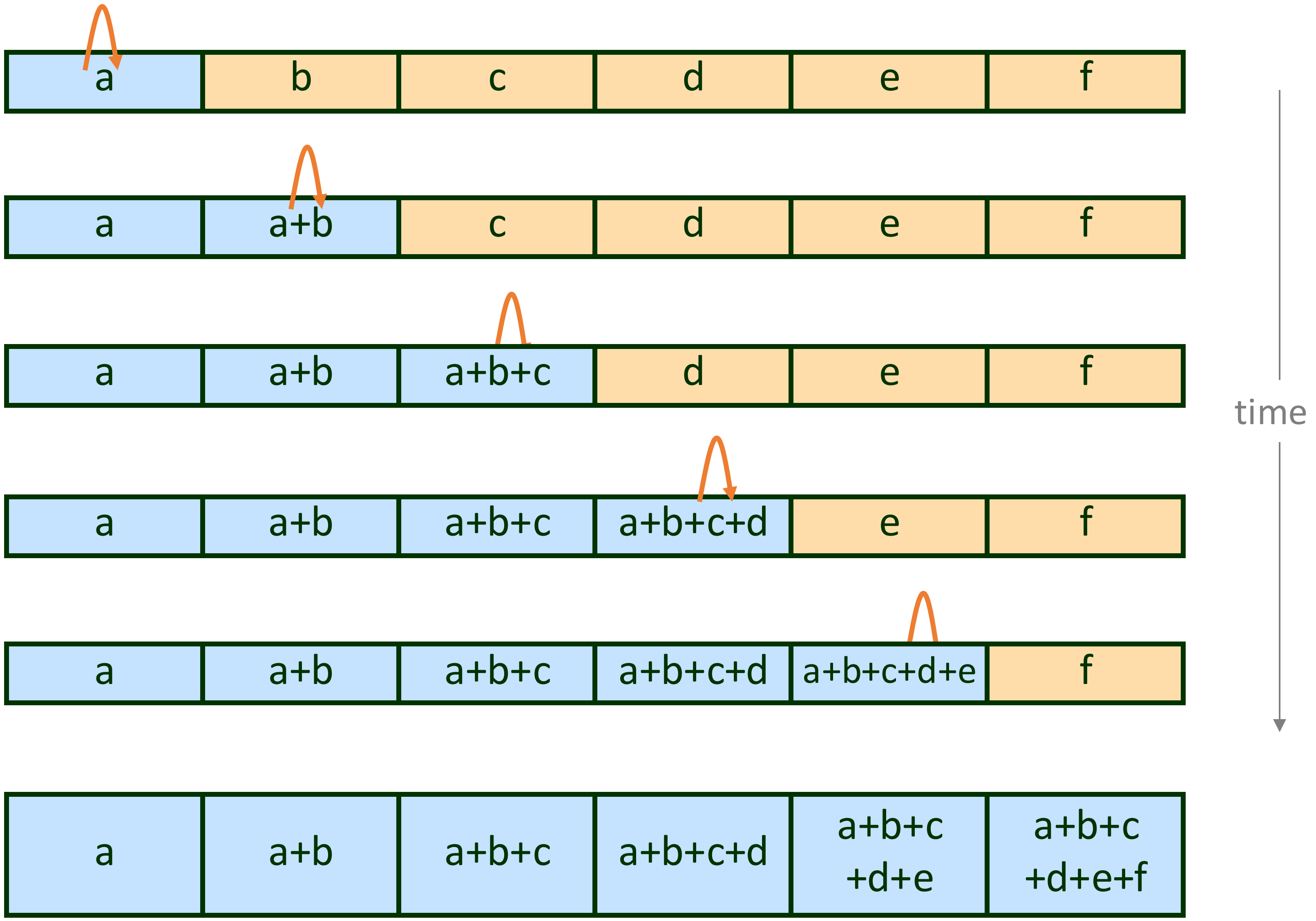
begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
	a	a+b	a+b+c	a+b+c+d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



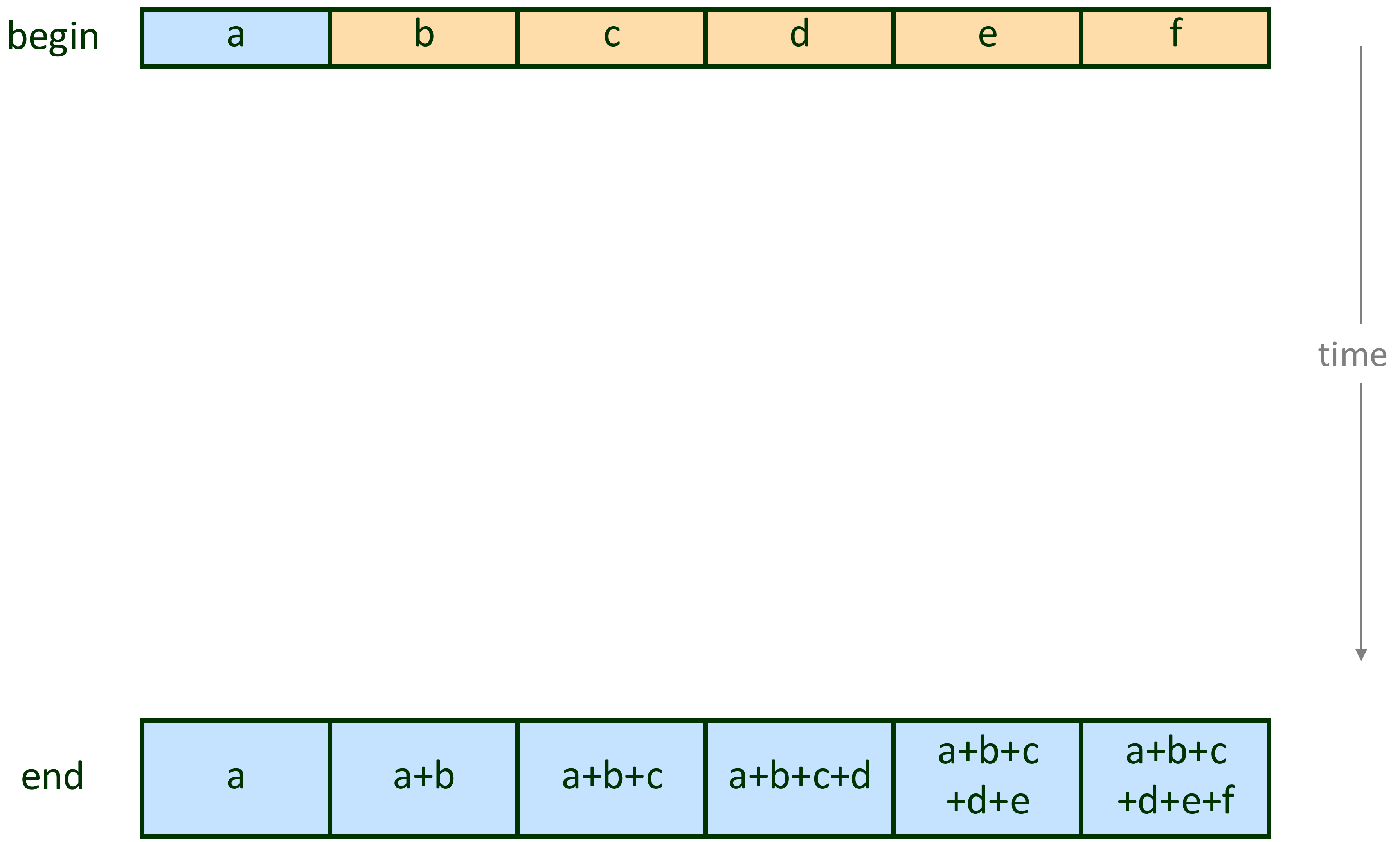
begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
	a	a+b	a+b+c	a+b+c+d	e	f
	a	a+b	a+b+c	a+b+c+d	a+b+c+d+e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Prefix Sum



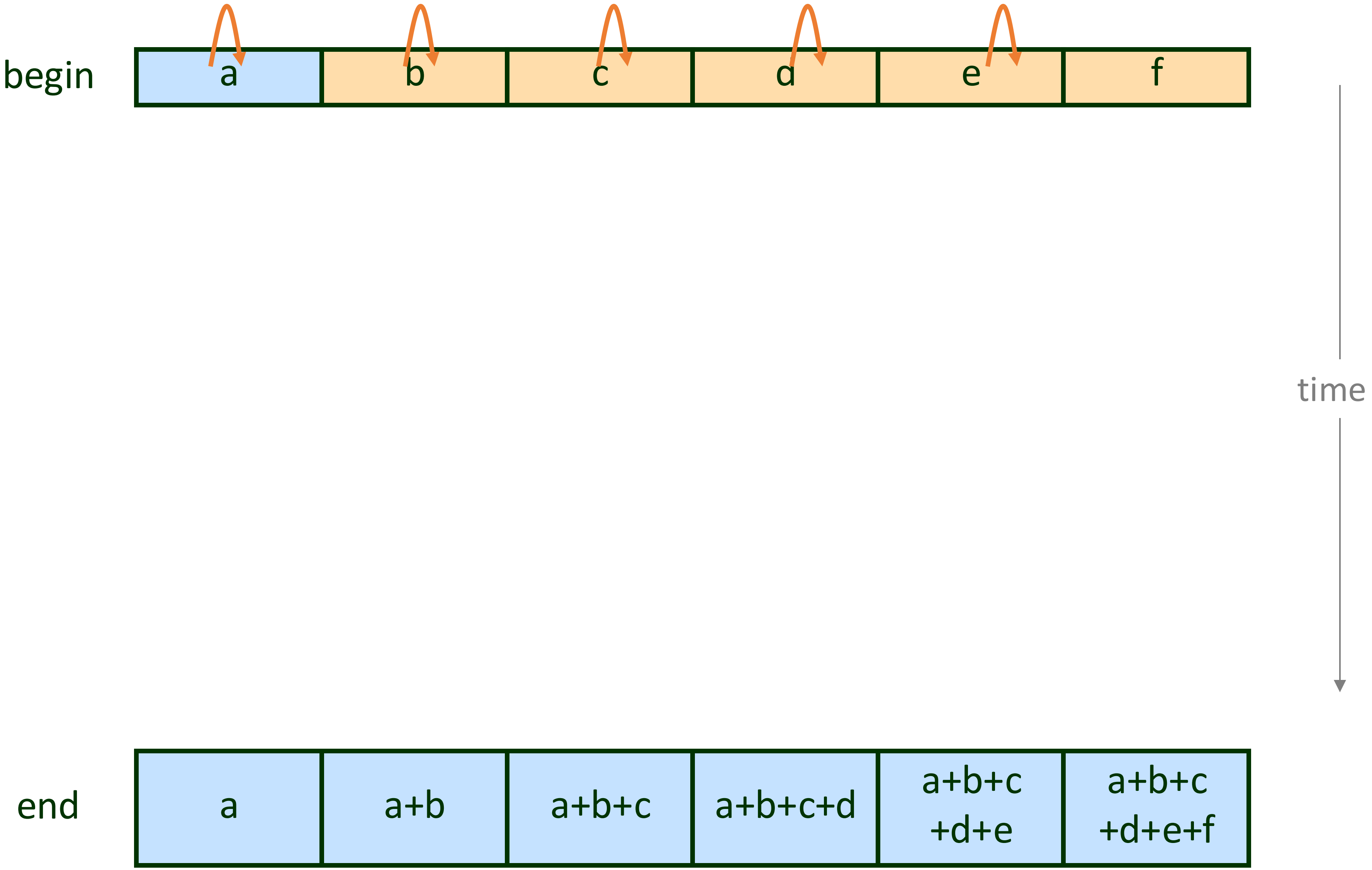
begin	a	b	c	d	e	f
	a	a+b	c	d	e	f
	a	a+b	a+b+c	d	e	f
	a	a+b	a+b+c	a+b+c+d	e	f
	a	a+b	a+b+c	a+b+c+d	a+b+c+d+e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Parallel Prefix Sum



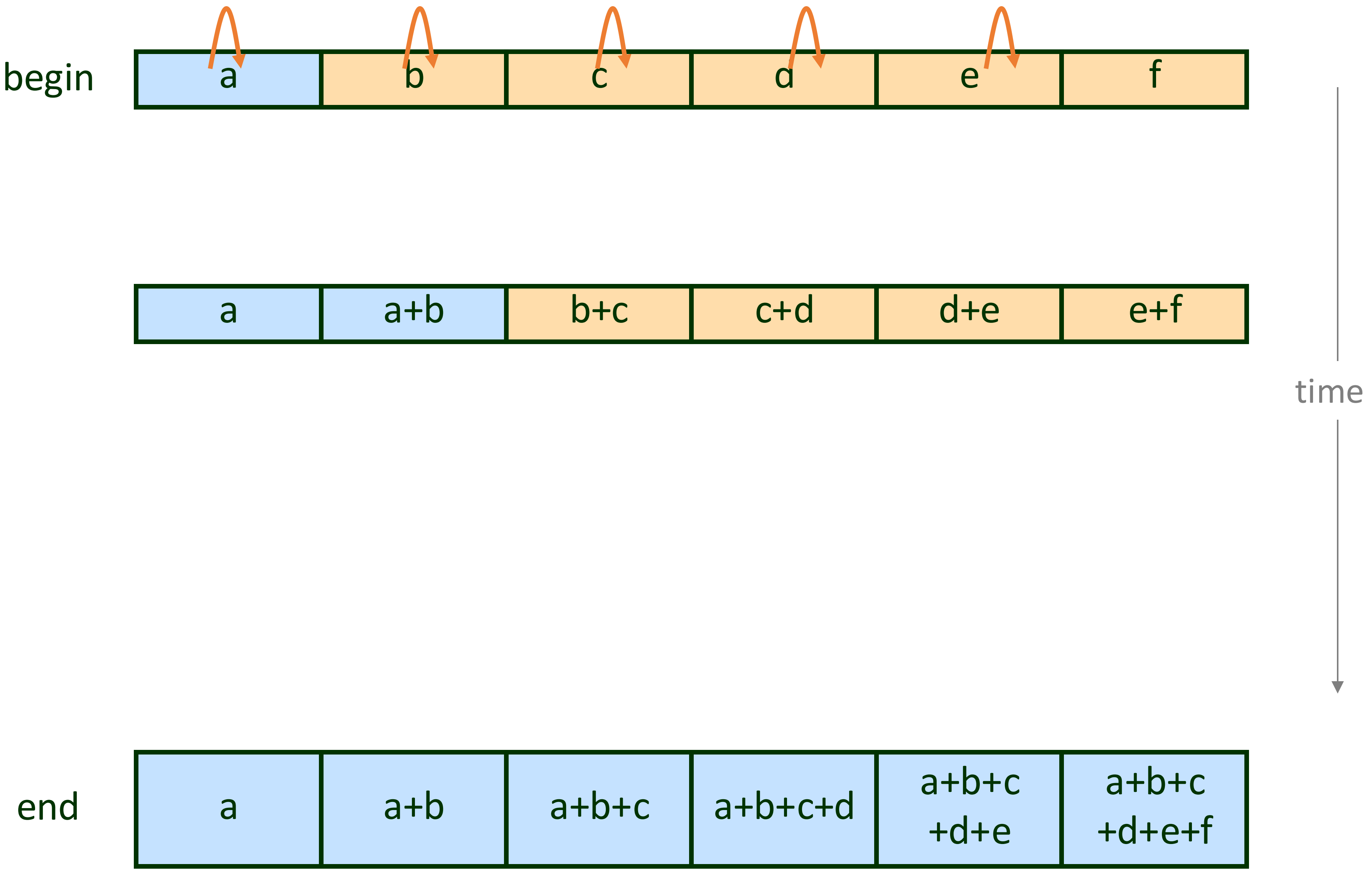
begin	a	b	c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Parallel Prefix Sum



begin	a	b	c	d	e	f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Parallel Prefix Sum



begin

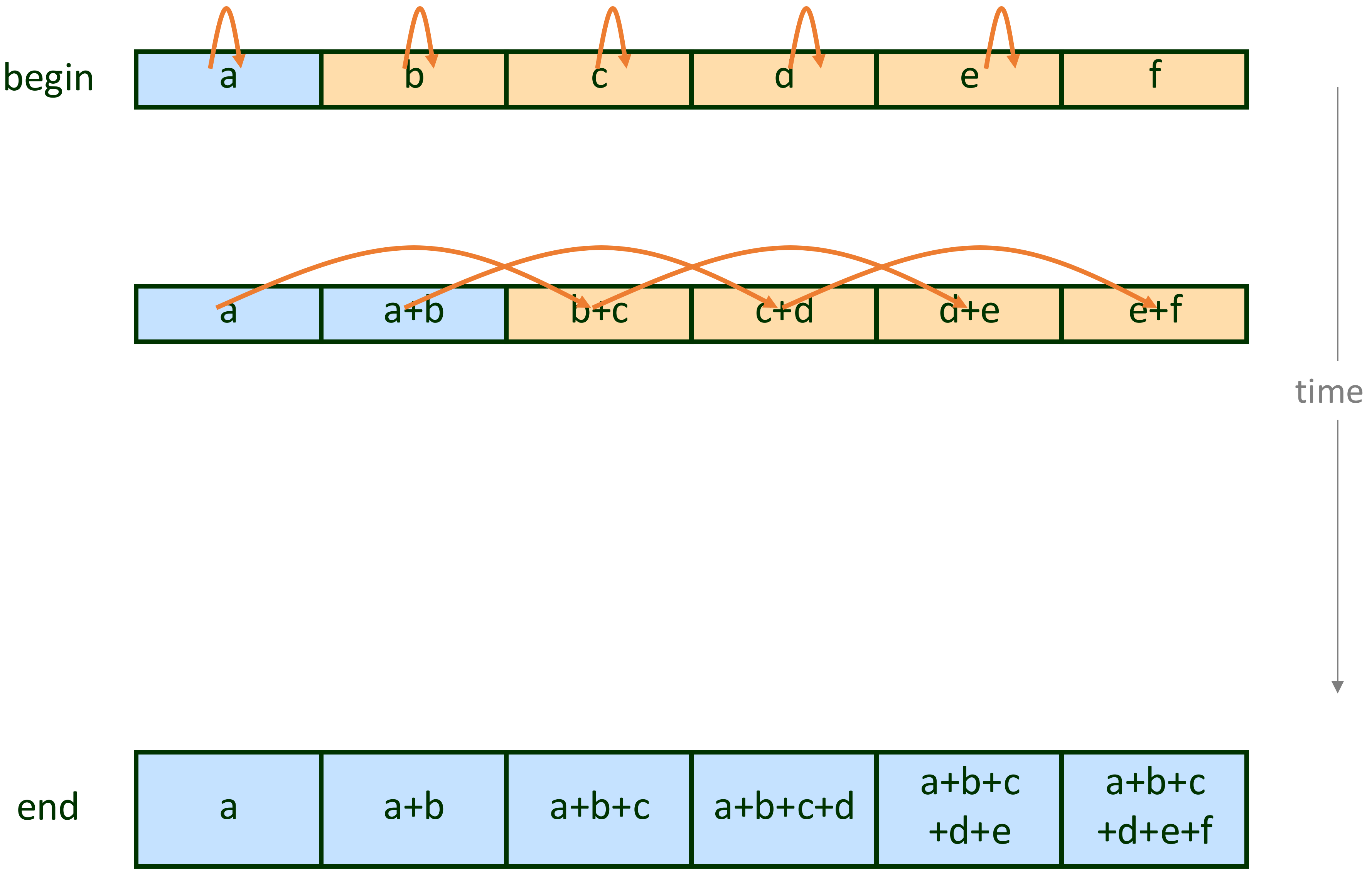
a	b	c	d	e	f

a	a+b	b+c	c+d	d+e	e+f

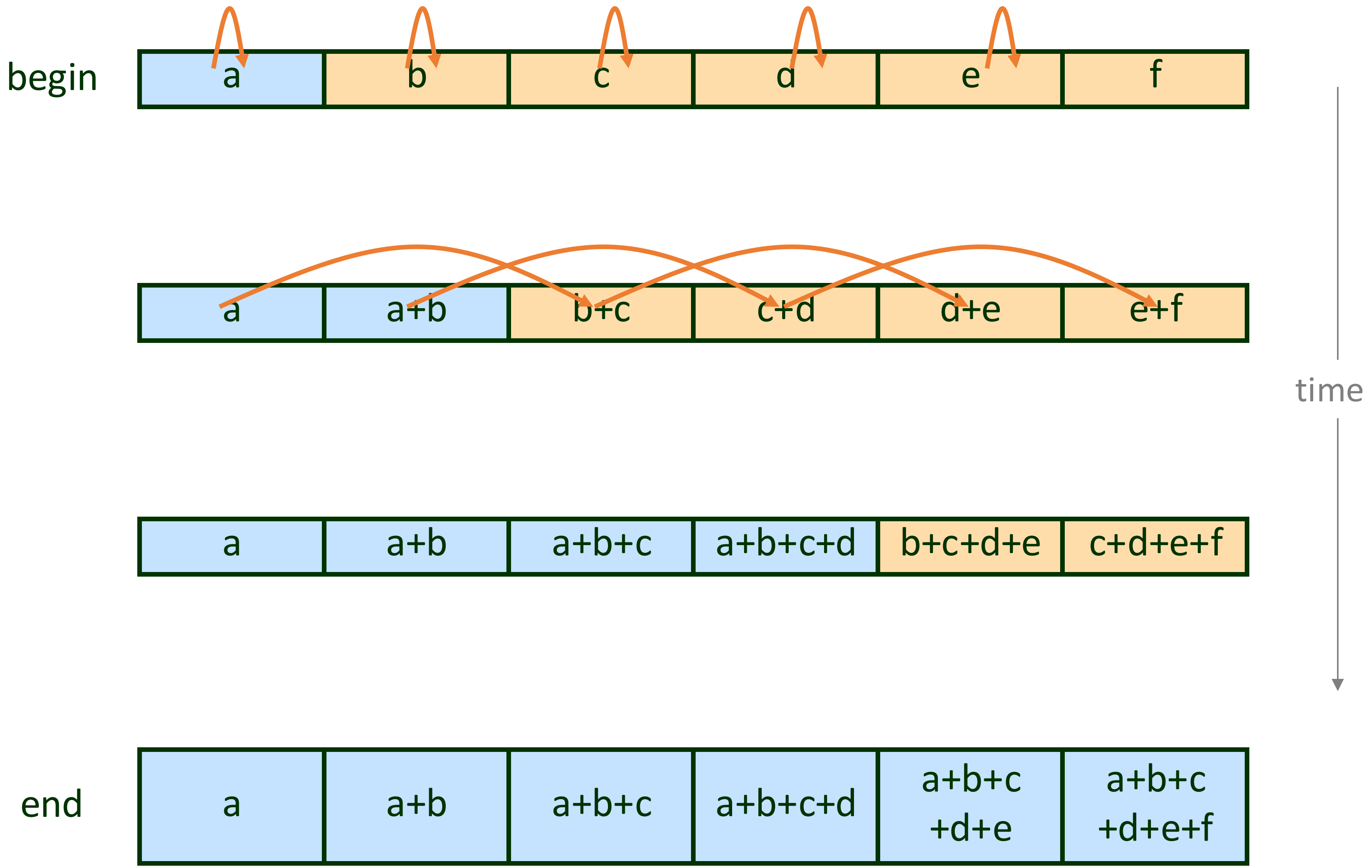
end

a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Parallel Prefix Sum

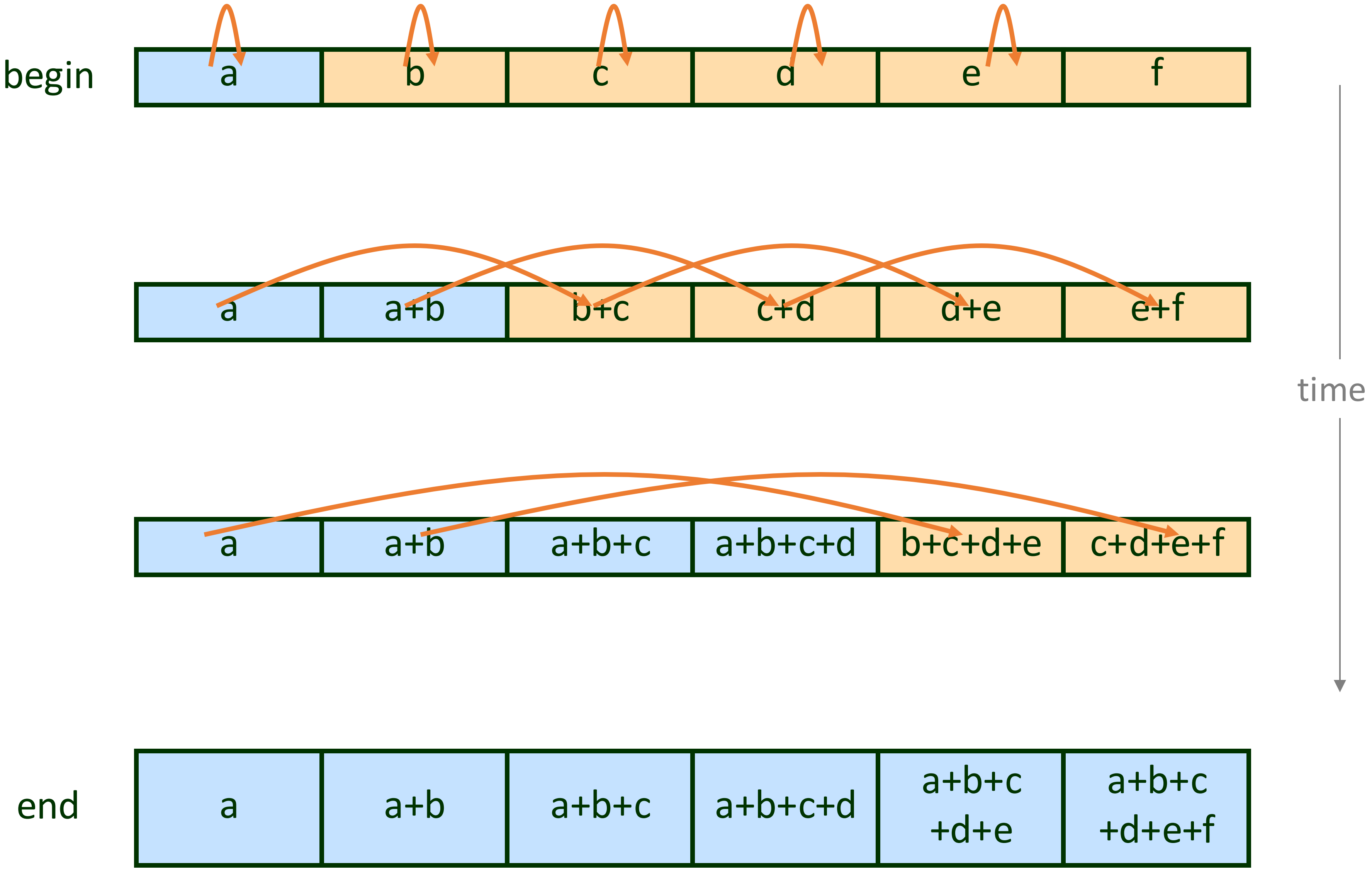


Parallel Prefix Sum



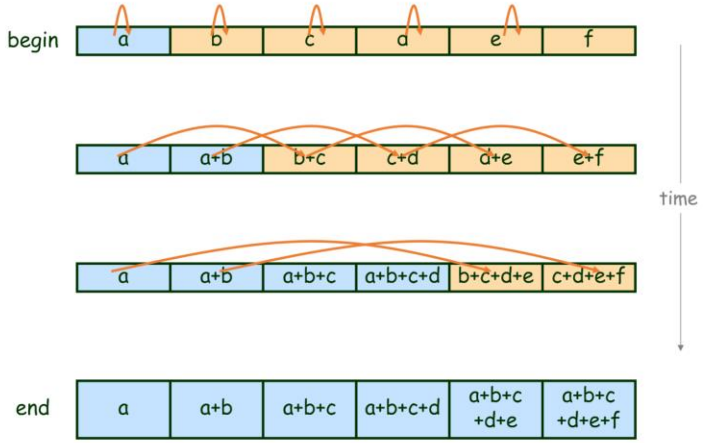
begin	a	b	c	d	e	f
	a	a+b	b+c	c+d	d+e	e+f
	a	a+b	a+b+c	a+b+c+d	b+c+d+e	c+d+e+f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Parallel Prefix Sum



begin	a	b	c	d	e	f
	a	a+b	b+c	c+d	d+e	e+f
	a	a+b	a+b+c	a+b+c+d	b+c+d+e	c+d+e+f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Pthreads Parallel Prefix Sum



begin: a | b | c | d | e | f

a | a+b | b+c | c+d | d+e | e+f

a | a+b | a+b+c | a+b+c+d | b+c+d+e | c+d+e+f

end: a | a+b | a+b+c | a+b+c+d | a+b+c +d+e | a+b+c +d+e+f

```
int g_values[N] = { a, b, c, d, e, f };

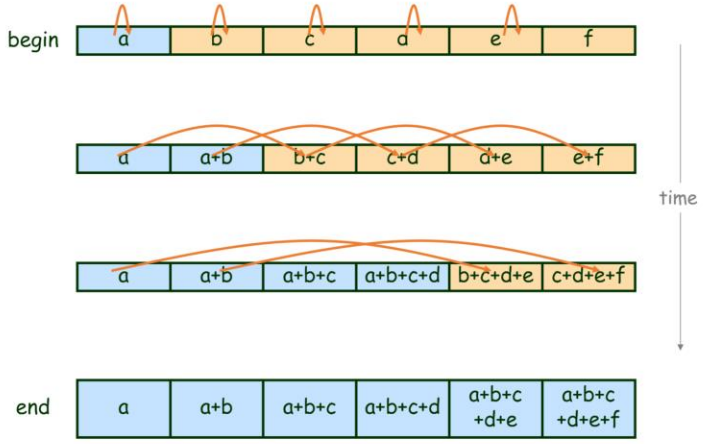
void prefix_sum_thread(void * param) {

  int i;
  int id = *((int*)param);
  int stride = 0;

  for(stride=1; stride<=N/2; stride:<<1) {
    g_values[id+stride] += g_values[id];
  }

}
```

Pthreads Parallel Prefix Sum



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int g_values[N] = { a, b, c, d, e, f };

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  int id = *((int*)param);
  int stride = 0;

  for(stride=1; stride<=N/2; stride<<1) {
    g_values[id+stride] += g_values[id];
  }

}
```
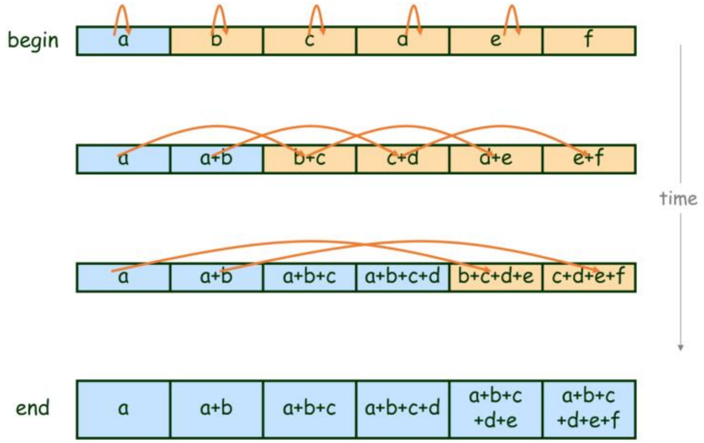
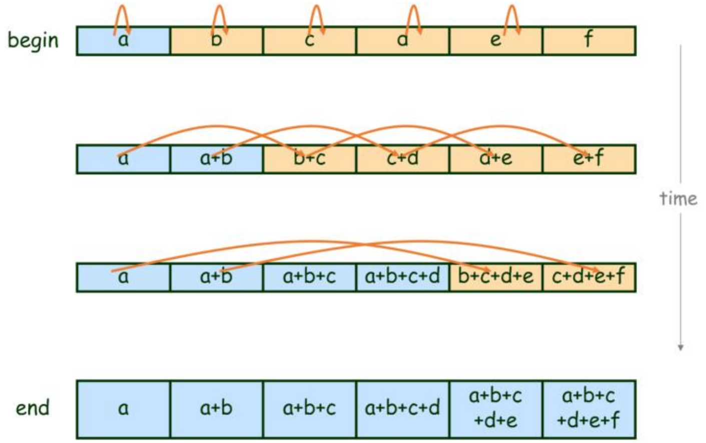

Will this work?

Pthreads Parallel Prefix Sum



```
pthread_mutex_t g_locks[N] = { MUTEX_INITIALIZER, ...};
int g_values[N] = { a, b, c, d, e, f };

void prefix_sum_thread(void * param) {

  int i;
  int id = *((int*)param);
  int stride = 0;

  for(stride=1; stride<=N/2; stride<<1) {
    pthread_mutex_lock(&g_locks[id]);
    pthread_mutex_lock(&g_locks[id+stride]);
    g_values[id+stride] += g_values[id];
    pthread_mutex_unlock(&g_locks[id]);
    pthread_mutex_unlock(&g_locks[id+stride]);
  }

}
```

Pthreads Parallel Prefix Sum



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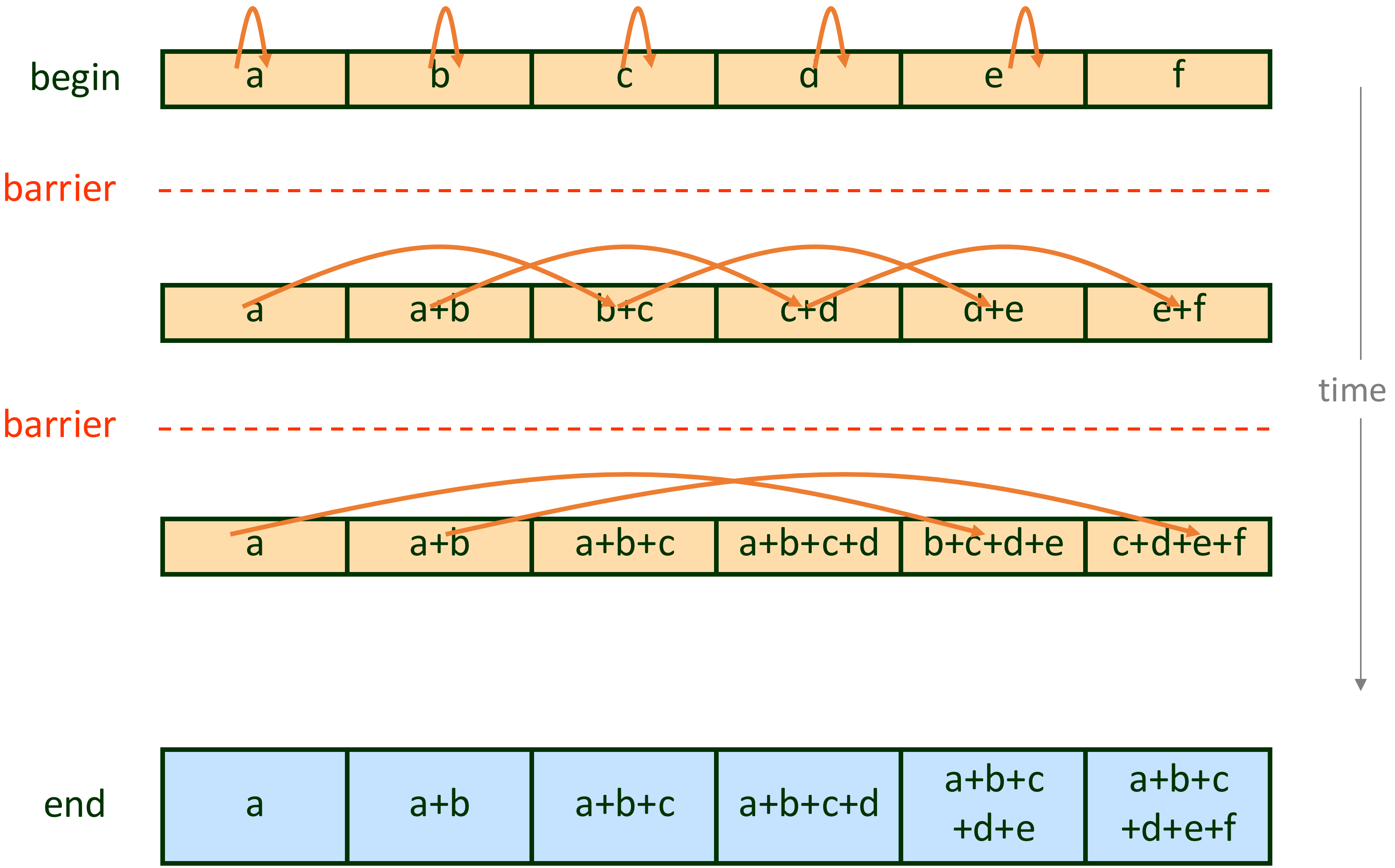
    g_values[id+stride] += g_values[id];
    pthread_mutex_unlock(&g_locks[id]);
    pthread_mutex_unlock(&g_locks[id+stride]);
  }

}
```

fixed?

Parallel Prefix Sum



begin

a	b	c	d	e	f

barrier

a	a+b	b+c	c+d	d+e	e+f

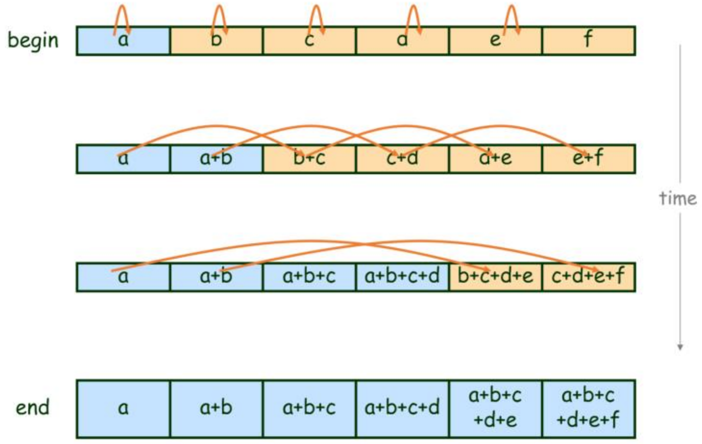
barrier

a	a+b	a+b+c	a+b+c+d	b+c+d+e	c+d+e+f

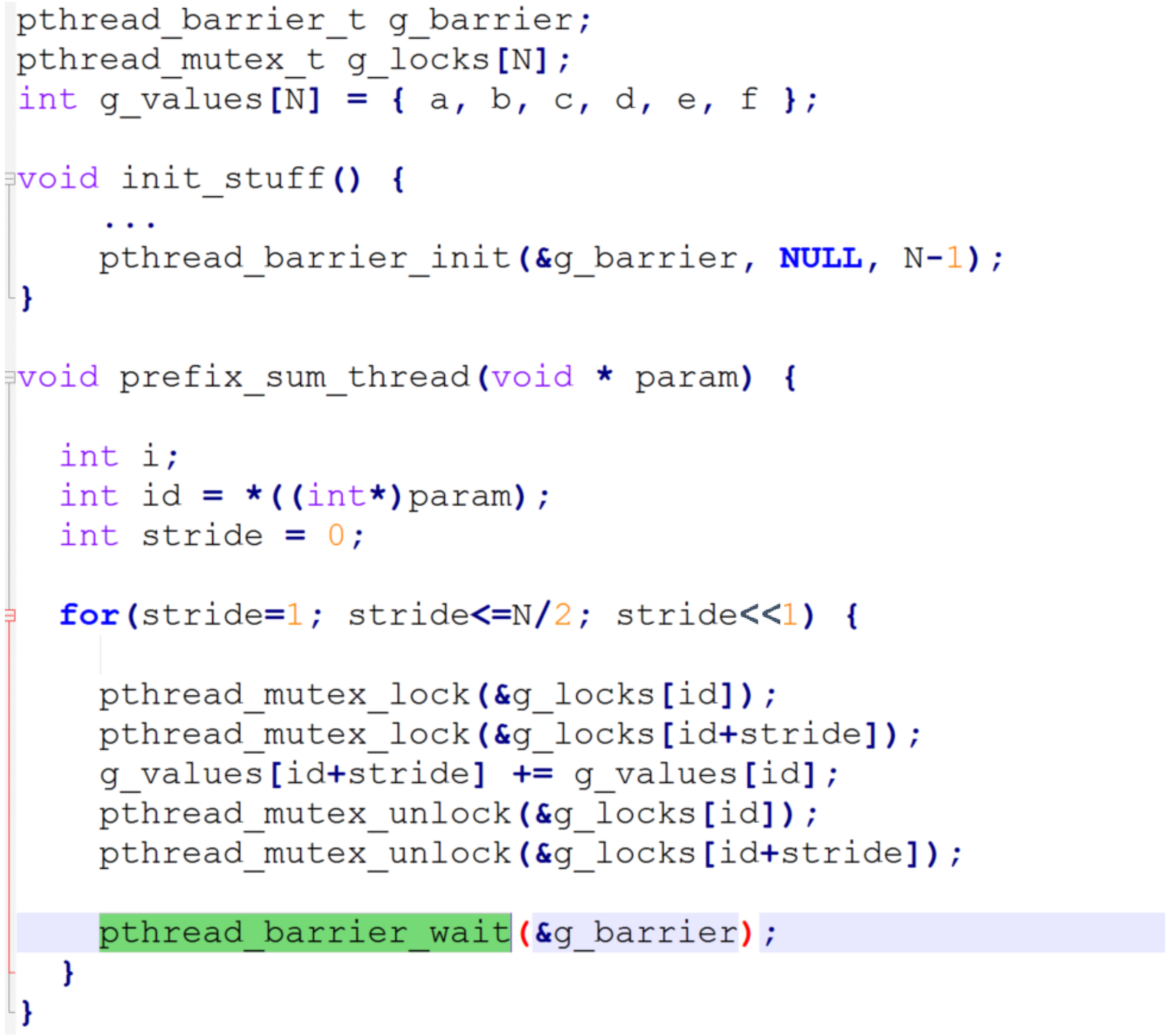
end

a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f

Pthreads Parallel Prefix Sum



begin	a	b	c	d	e	f
	a	a+b	b+c	c+d	d+e	e+f
	a	a+b	a+b+c	a+b+c+d	b+c+d+e	c+d+e+f
end	a	a+b	a+b+c	a+b+c+d	a+b+c +d+e	a+b+c +d+e+f



```
pthread_barrier_t g_barrier;
pthread_mutex_t g_locks[N];
int g_values[N] = { a, b, c, d, e, f };

void init_stuff() {
    ...
    pthread_barrier_init(&g_barrier, NULL, N-1);
}

void prefix_sum_thread(void * param) {

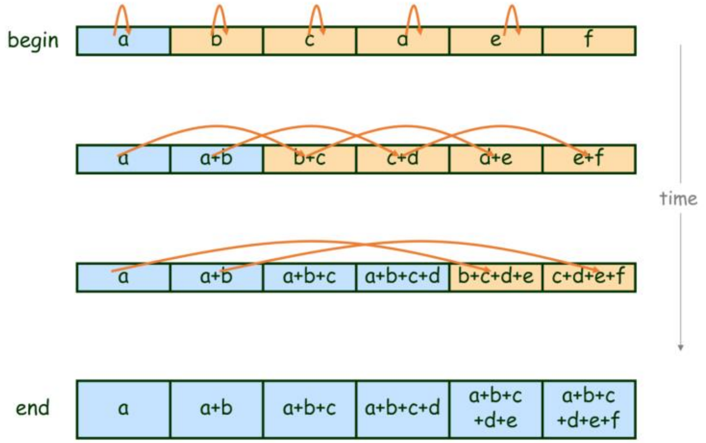
  int i;
  int id = *((int*)param);
  int stride = 0;

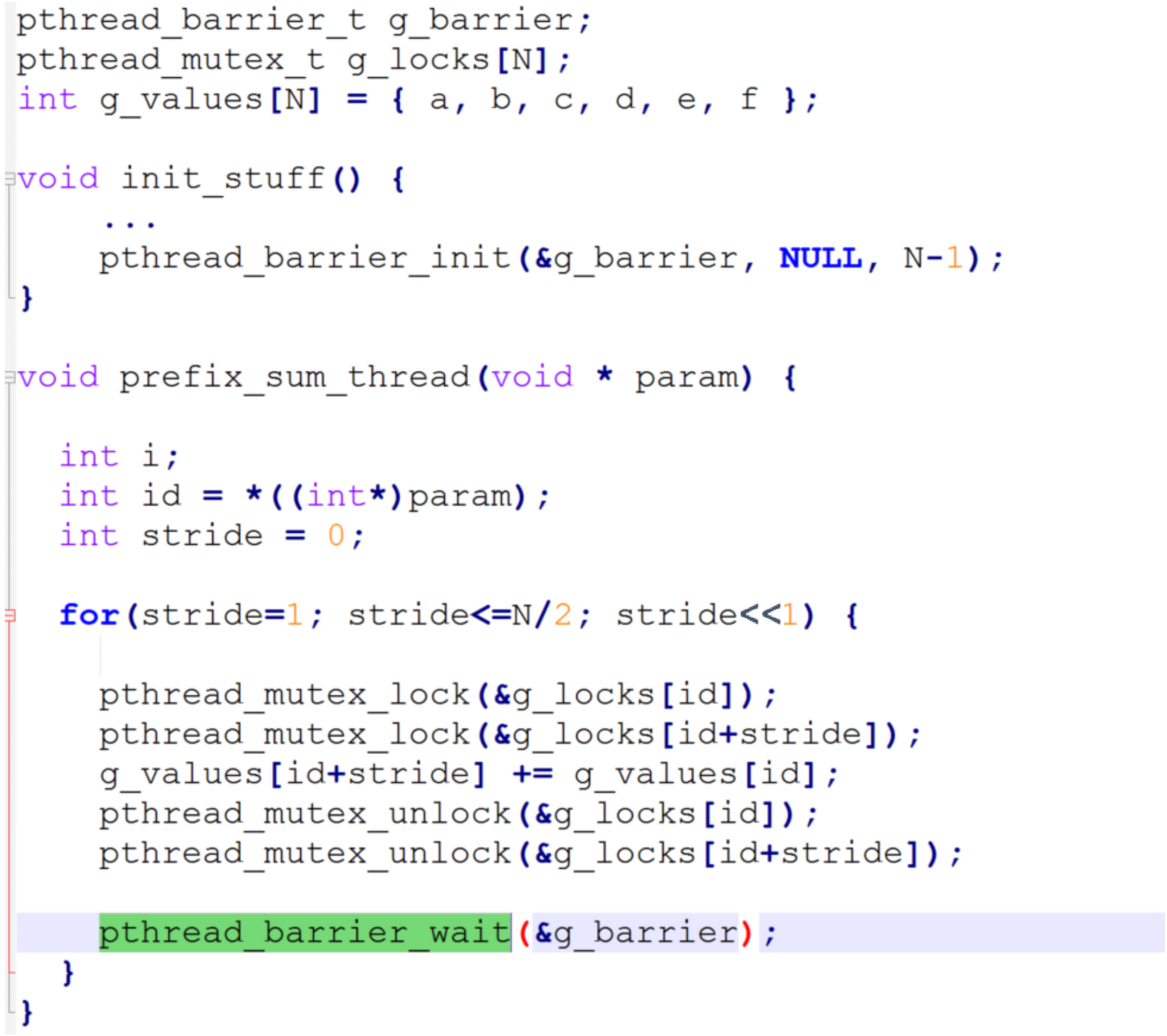
  for(stride=1; stride<=N/2; stride<<1) {

    pthread_mutex_lock(&g_locks[id]);
    pthread_mutex_lock(&g_locks[id+stride]);
    g_values[id+stride] += g_values[id];
    pthread_mutex_unlock(&g_locks[id]);
    pthread_mutex_unlock(&g_locks[id+stride]);

    pthread_barrier_wait(&g_barrier);
  }
}
```

Pthreads Parallel Prefix Sum





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void prefix_sum_thread(void * param) {

  int i;
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  int stride = 0;

  for(stride=1; stride<=N/2; stride<<1) {

    pthread_mutex_lock(&g_locks[id]);
    pthread_mutex_lock(&g_locks[id+stride]);
    g_values[id+stride] += g_values[id];
    pthread_mutex_unlock(&g_locks[id]);
    pthread_mutex_unlock(&g_locks[id+stride]);

    pthread_barrier_wait(&g_barrier);
  }
}
```

fixed?

Barrier Goals

Desirable barrier properties:

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- Low shared memory space complexity

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- Minimal propagation time

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Desirable barrier properties:

- Low shared memory space complexity
- Low contention on shared objects
- Low shared memory references per process
- No need for shared memory initialization
- Symmetric: same amount of work for all processes
- Algorithm simplicity
- Simple basic primitive
- Minimal propagation time
- Reusability of the barrier (must!)

Barrier Building Blocks

- Conditions
- Semaphores
- Atomic Bit
- Atomic Register
- Fetch-and-increment register
- Test and set bits
- Read-Modify-Write register

Barrier with Semaphores

Barrier using Semaphores

Algorithm for N threads

Barrier using Semaphores

Algorithm for N threads

Barrier using Semaphores

Algorithm for N threads

```
shared      sem_t arrival = 1;            // sem_init(&arrival, NULL, 1)
            sem_t departure = 0;          // sem_init(&departure, NULL, 0)
            atomic int counter = 0;       // (gcc intrinsics are verbose)
```

Barrier using Semaphores

Algorithm for N threads

```
shared   sem_t arrival = 1;          // sem_init(&arrival, NULL, 1)
         sem_t departure = 0;        // sem_init(&departure, NULL, 0)
         atomic int counter = 0;     // (gcc intrinsics are verbose)
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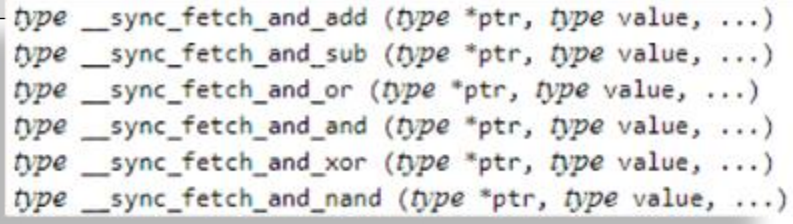

```
type __sync_fetch_and_add (type *ptr, type value, ...)
type __sync_fetch_and_sub (type *ptr, type value, ...)
type __sync_fetch_and_or (type *ptr, type value, ...)
type __sync_fetch_and_and (type *ptr, type value, ...)
type __sync_fetch_and_xor (type *ptr, type value, ...)
type __sync_fetch_and_nand (type *ptr, type value, ...)
```

Barrier using Semaphores

Algorithm for N threads

```
shared      sem_t arrival = 1;           // sem_init(&arrival, NULL, 1)
            sem_t departure = 0;         // sem_init(&departure, NULL, 0)
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          sem_t departure = 0;         // sem_init(&departure, NULL, 0)
          atomic int counter = 0;      // (gcc intrinsics are verbose)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Barrier using Semaphores

Algorithm for N threads

```
shared    sem_t arrival = 1;          // sem_init(&arrival, NULL, 1)
          sem_t departure = 0;        // sem_init(&departure, NULL, 0)
          atomic int counter = 0;     // (gcc intrinsics are verbose)
```

Phase I

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
```

Phase II

```
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Barrier using Semaphores

Algorithm for N threads

```
shared      sem_t arrival = 1;            // sem_init(&arrival, NULL, 1)
            sem_t departure = 0;          // sem_init(&departure, NULL, 0)
            atomic int counter = 0;       // (gcc intrinsics are verbose)
```

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```
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if(++counter < N)
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else
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```

Phase II

```
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

First N-1 threads post on arrival, wait on departure

Barrier using Semaphores

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```
shared     sem_t arrival = 1;            // sem_init(&arrival, NULL, 1)
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```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
```

Phase II

```
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

First N-1 threads post on arrival, wait on departure

Nth thread post on departure, releasing threads into phase II (what is value of arrival?)

Barrier using Semaphores

Algorithm for N threads

```
shared    sem_t arrival = 1;           // sem_init(&arrival, NULL, 1)
          sem_t departure = 0;         // sem_init(&departure, NULL, 0)
          atomic int counter = 0;      // (gcc intrinsics are verbose)
```

Phase I

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
```

Phase II

```
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

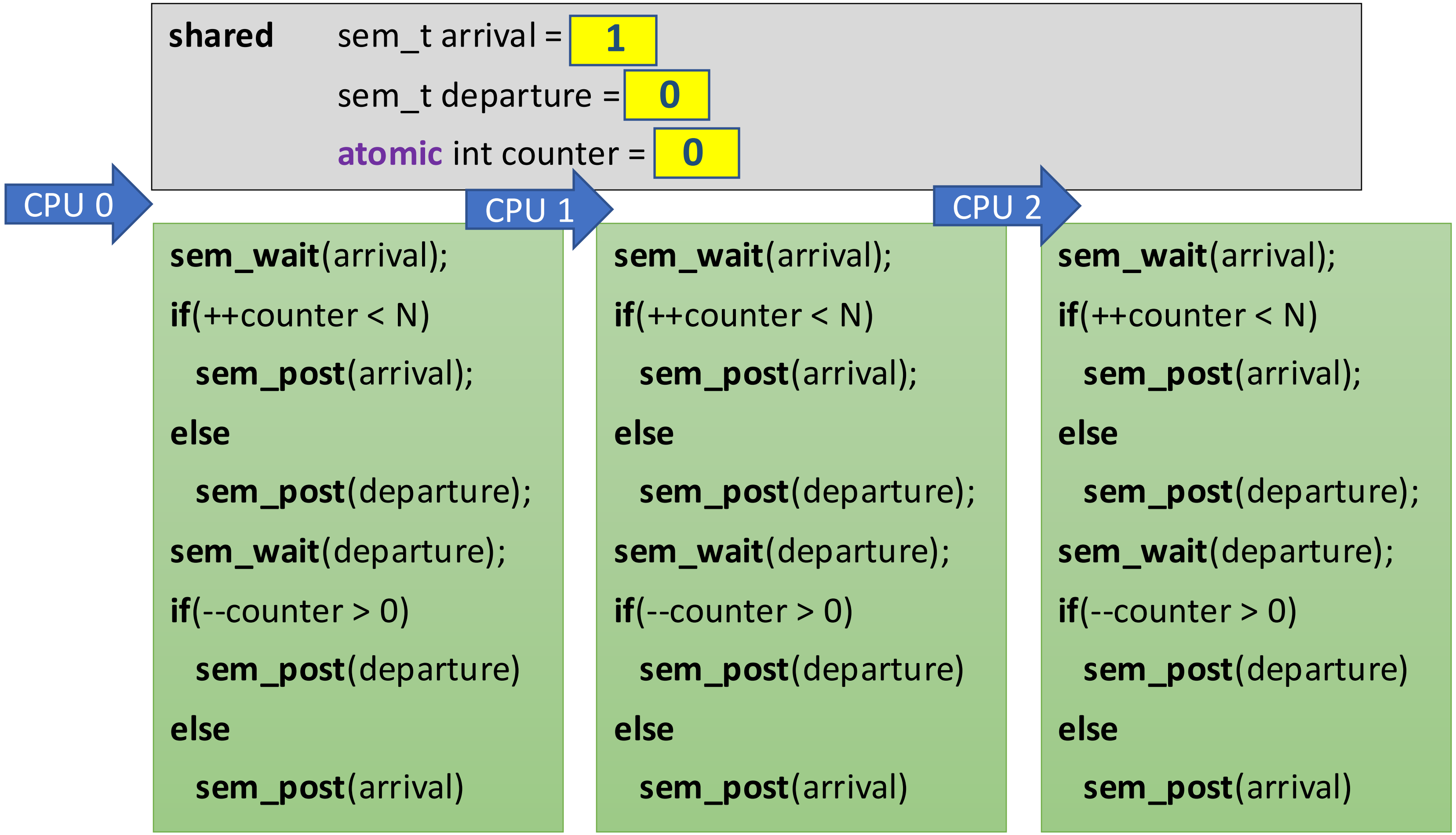
First N-1 threads post on arrival, wait on departure

Nth thread post on departure, releasing threads into phase II (what is value of arrival?)

First N-1 threads post on departure, last posts arrival

Semaphore Barrier Action Zone

N == 3



shared sem_t arrival = **1**

sem_t departure = **0**

atomic int counter = **0**

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
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  sem_post(arrival);
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  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
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```
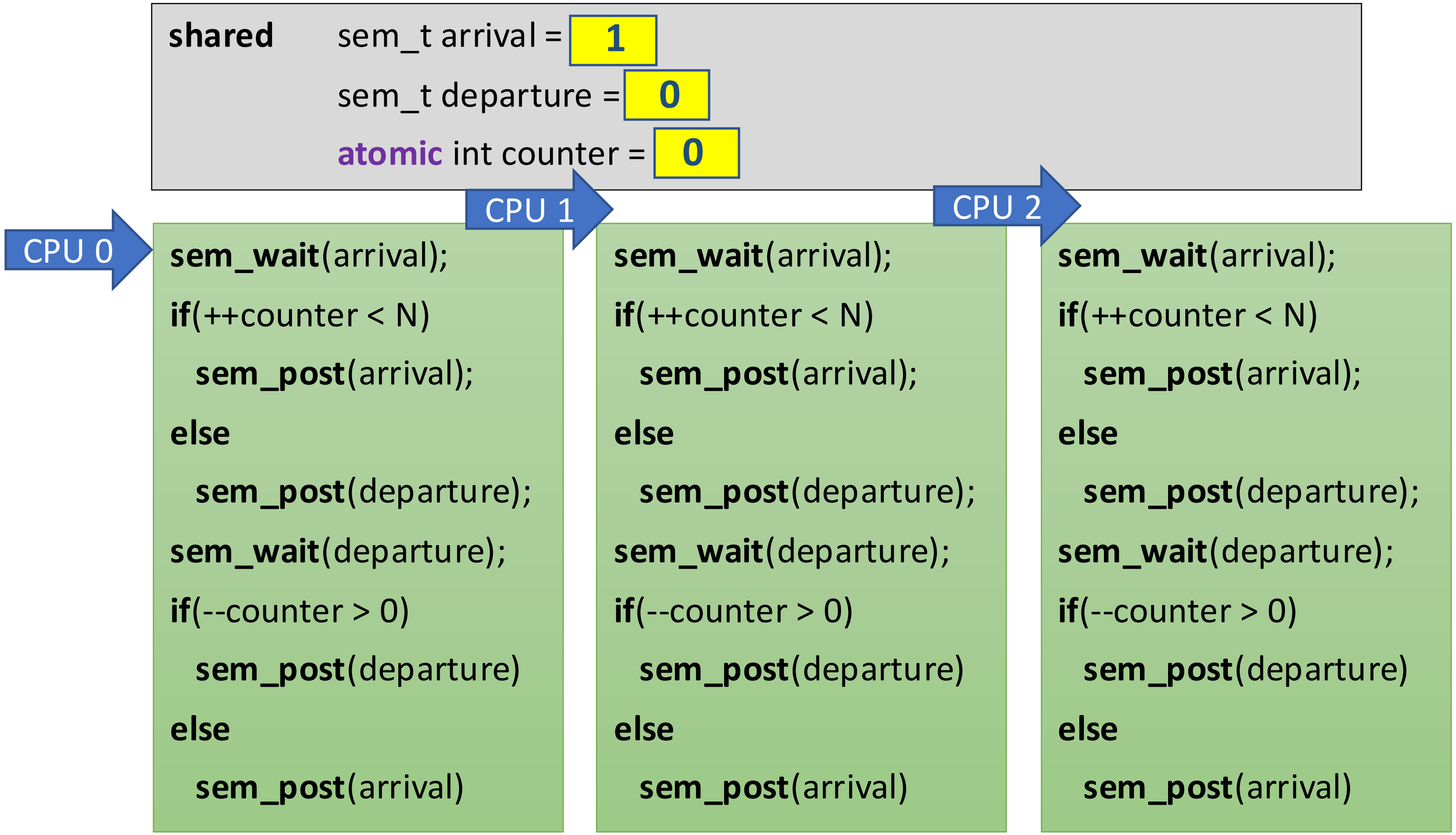

1

Semaphore Barrier Action Zone

N == 3



```
shared      sem_t arrival = 1
            sem_t departure = 0
            atomic int counter = 0
```

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

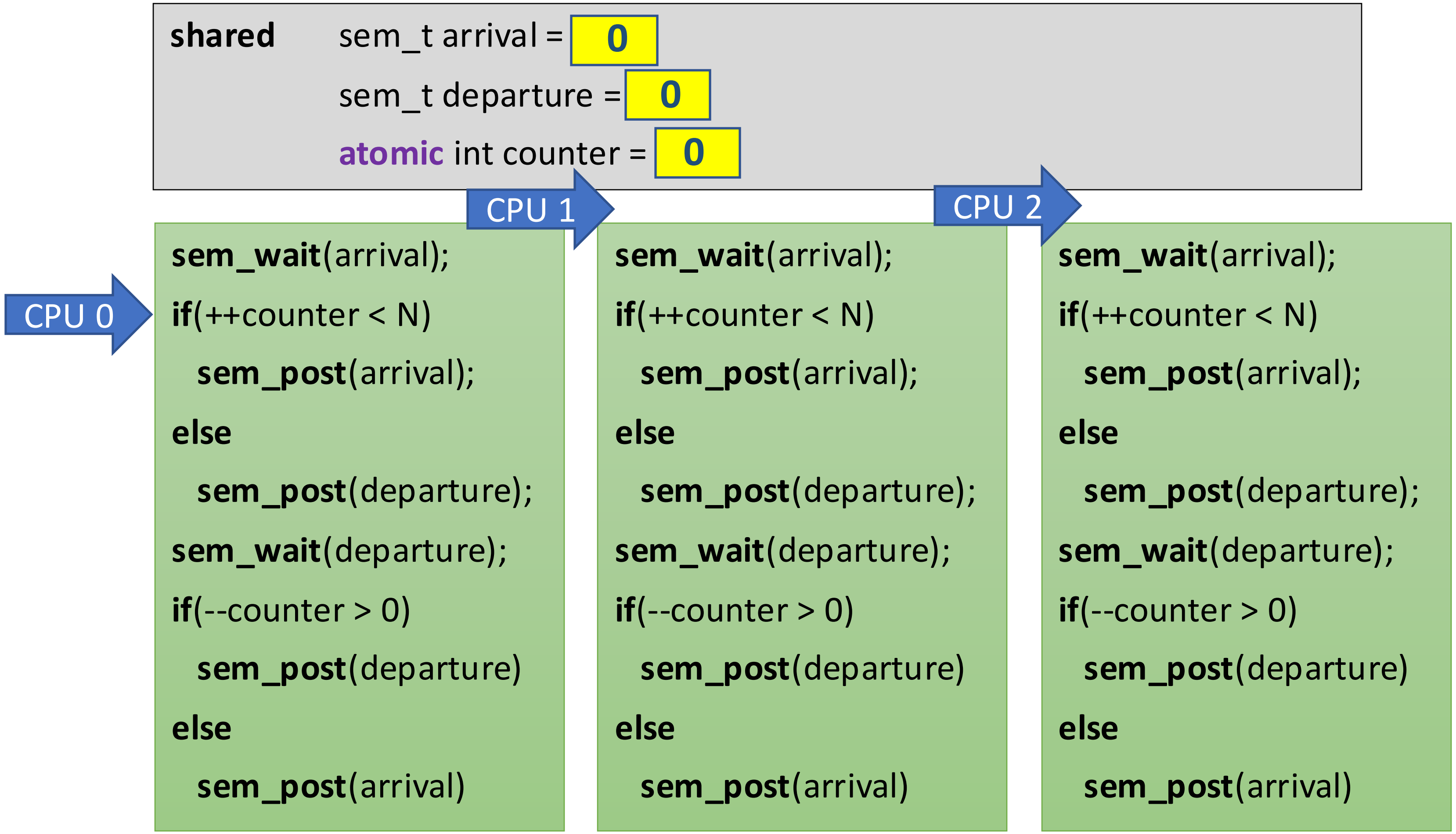
CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

1

Semaphore Barrier Action Zone

N == 3



```
shared      sem_t arrival = 0
            sem_t departure = 0
            atomic int counter = 0
```

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

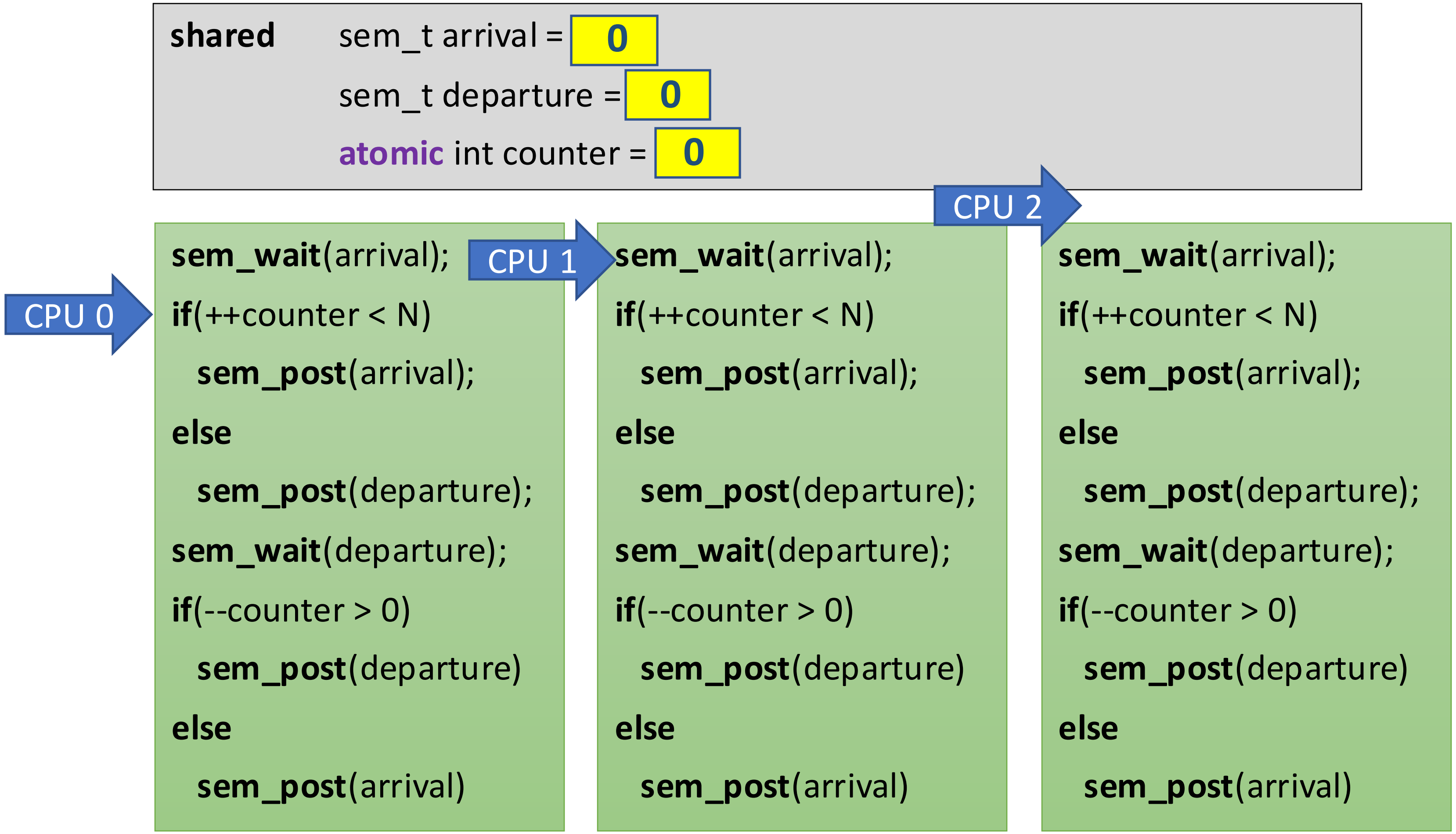
CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

1

Semaphore Barrier Action Zone

N == 3



```
shared    sem_t arrival = 0
          sem_t departure = 0
          atomic int counter = 0
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

1

Semaphore Barrier Action Zone

N == 3

```
shared     sem_t arrival = 0
           sem_t departure = 0
           atomic int counter = 0
```

1

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

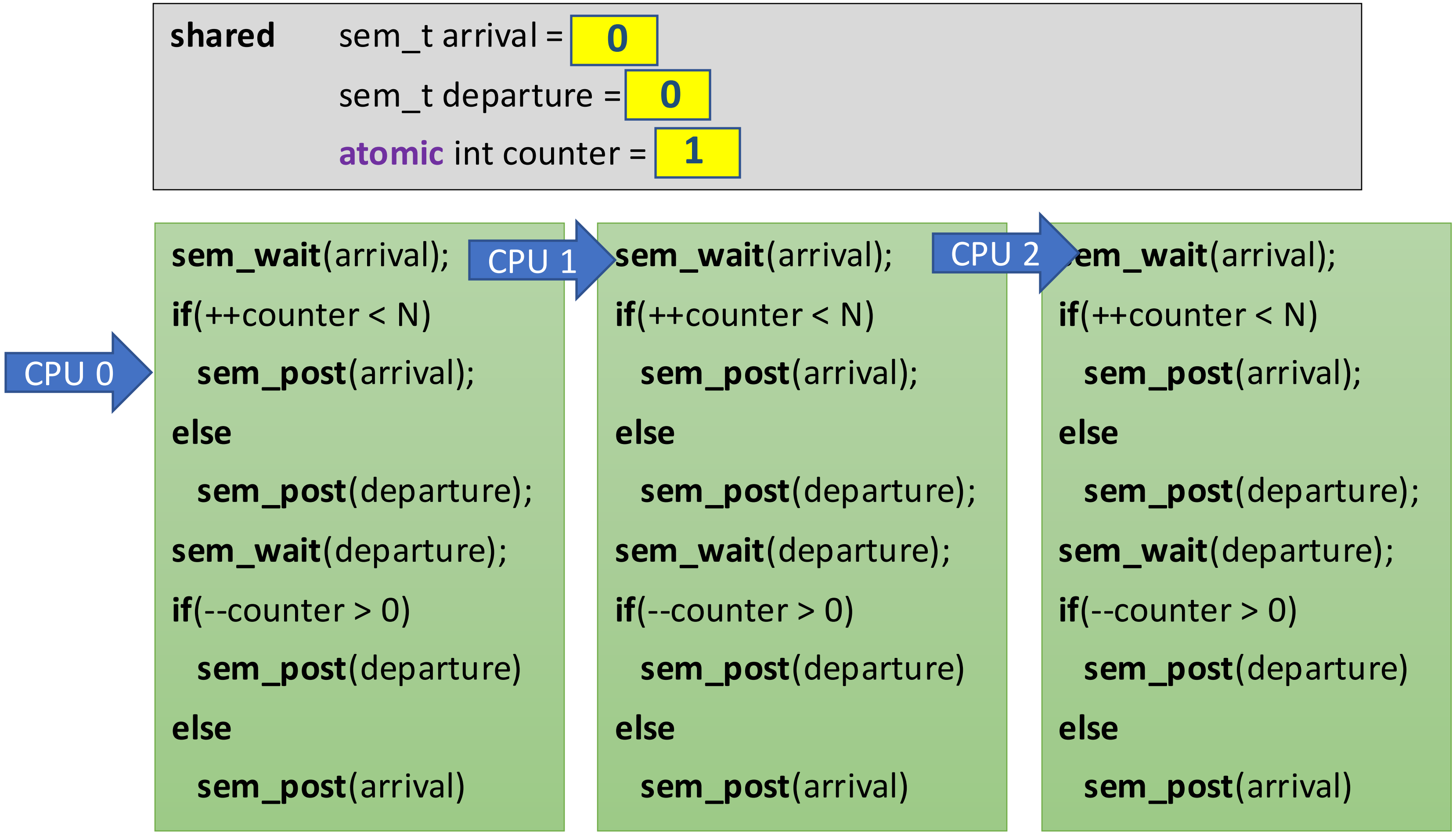
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3



```
shared     sem_t arrival = 0
           sem_t departure = 0
           atomic int counter = 1
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

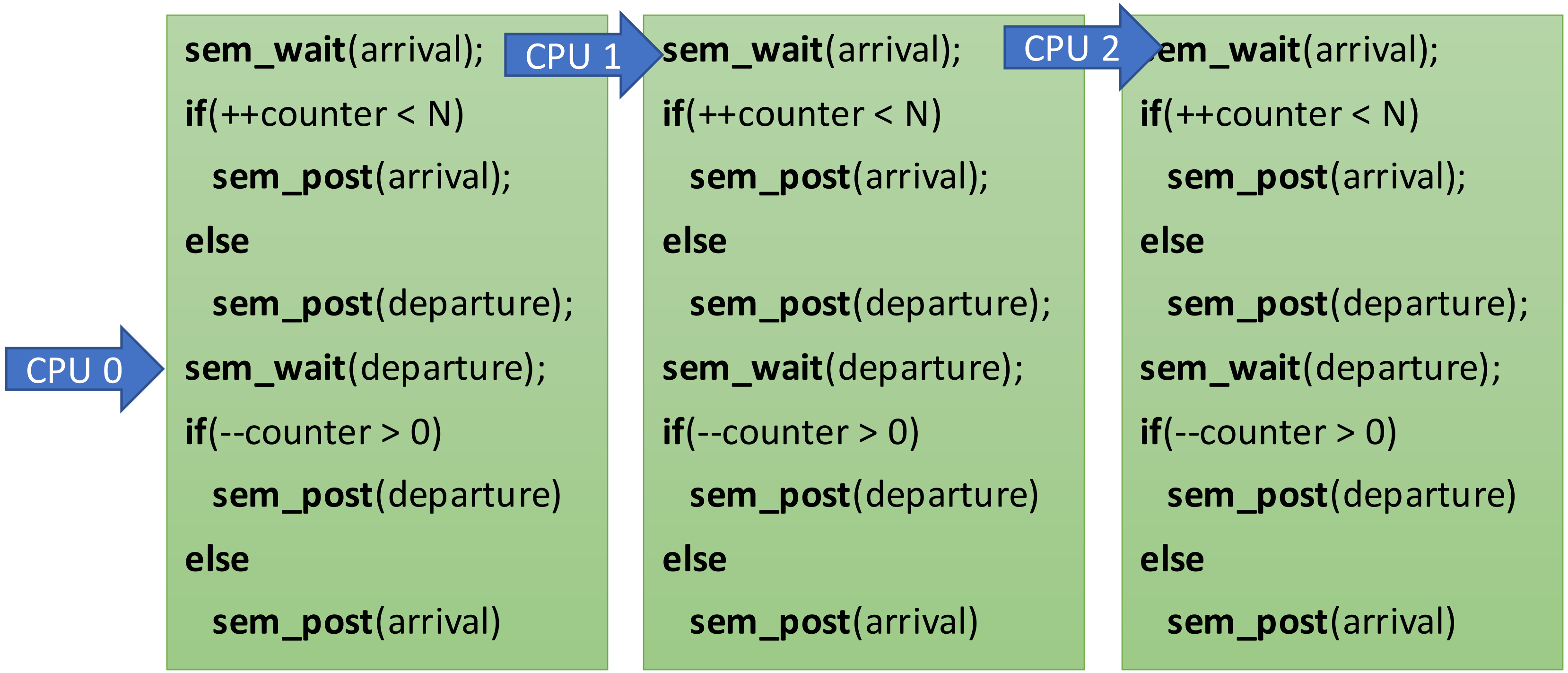
1

Semaphore Barrier Action Zone

N == 3

```
shared    sem_t arrival = 1
          sem_t departure = 0
          atomic int counter = 1
```

1



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

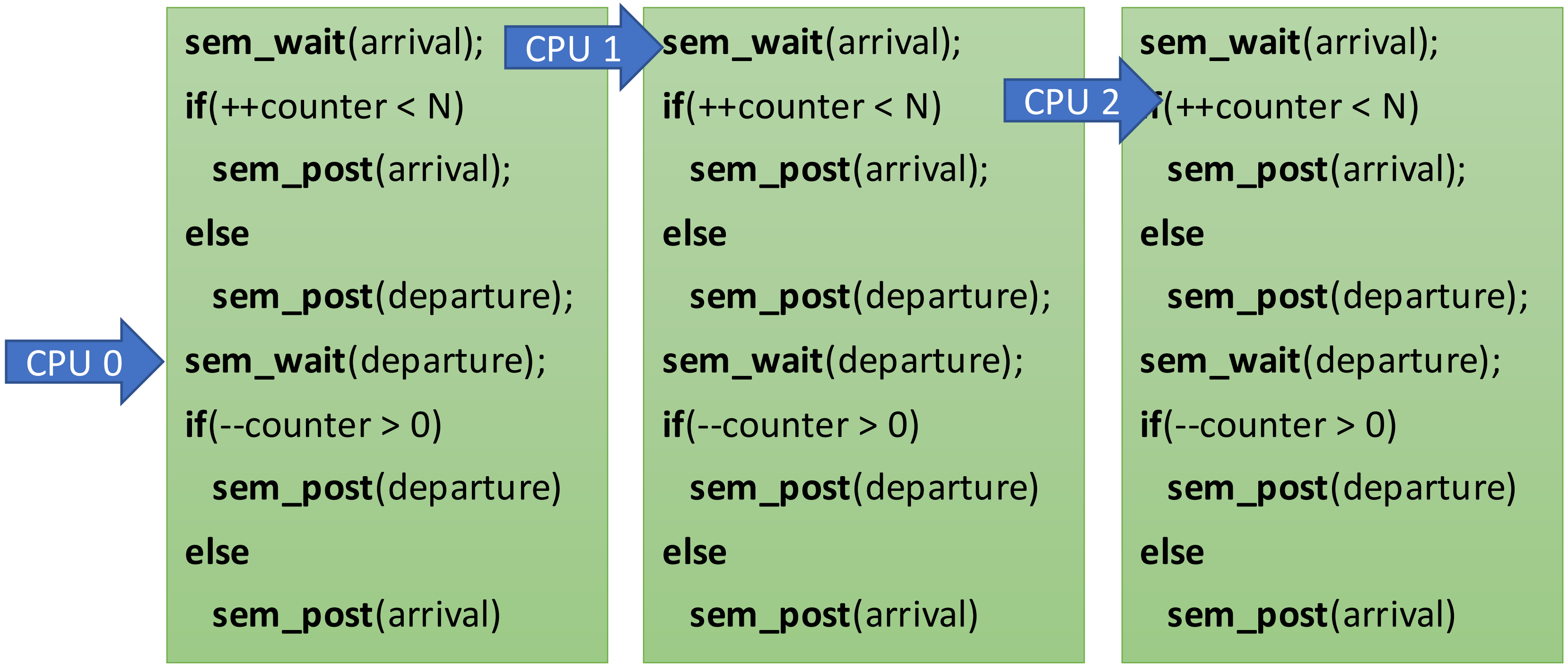
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

```
shared      sem_t arrival = 0
            sem_t departure = 0
            atomic int counter = 1
```

1



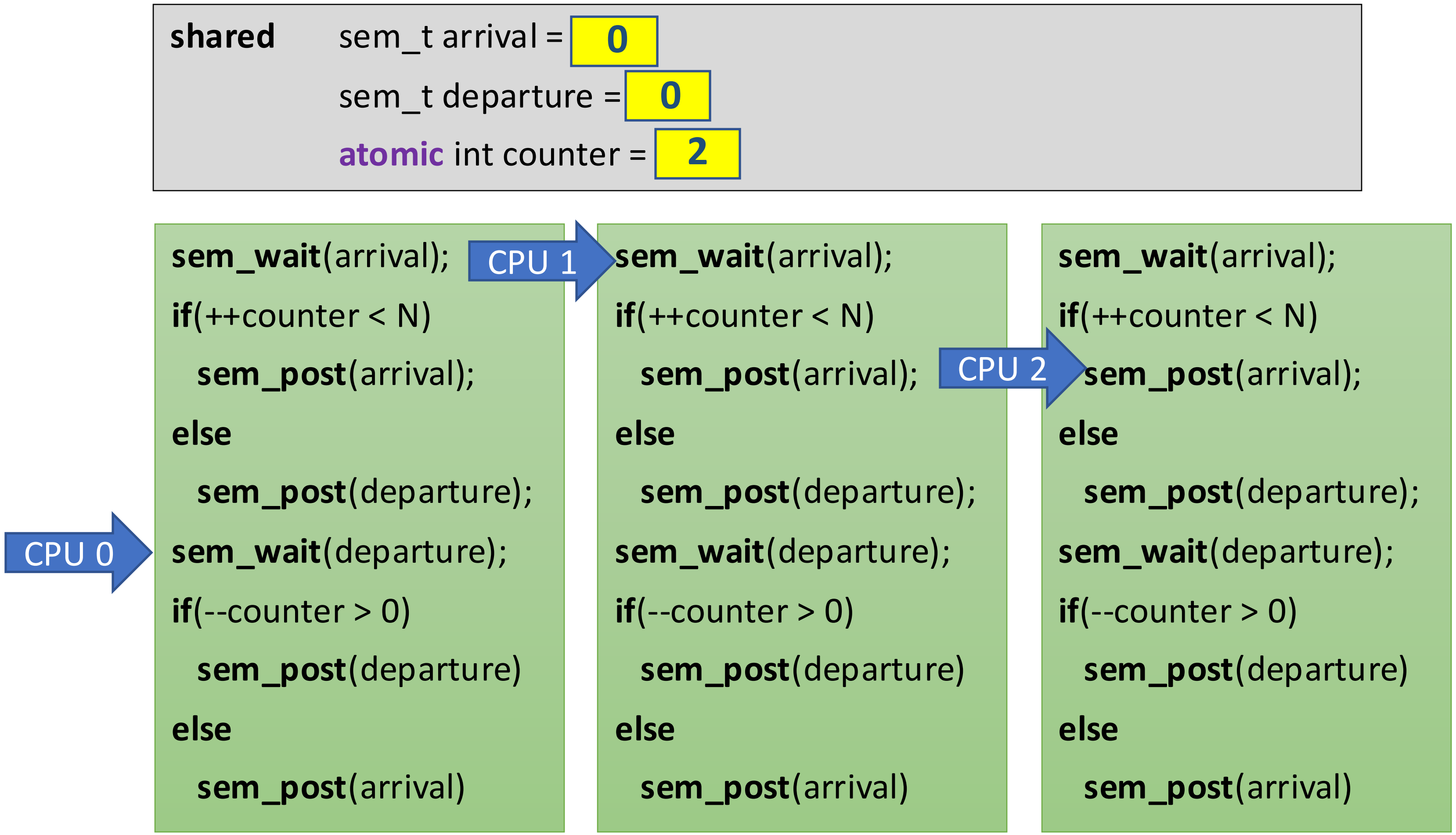
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3



```
shared    sem_t arrival = 0
          sem_t departure = 0
          atomic int counter = 2
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

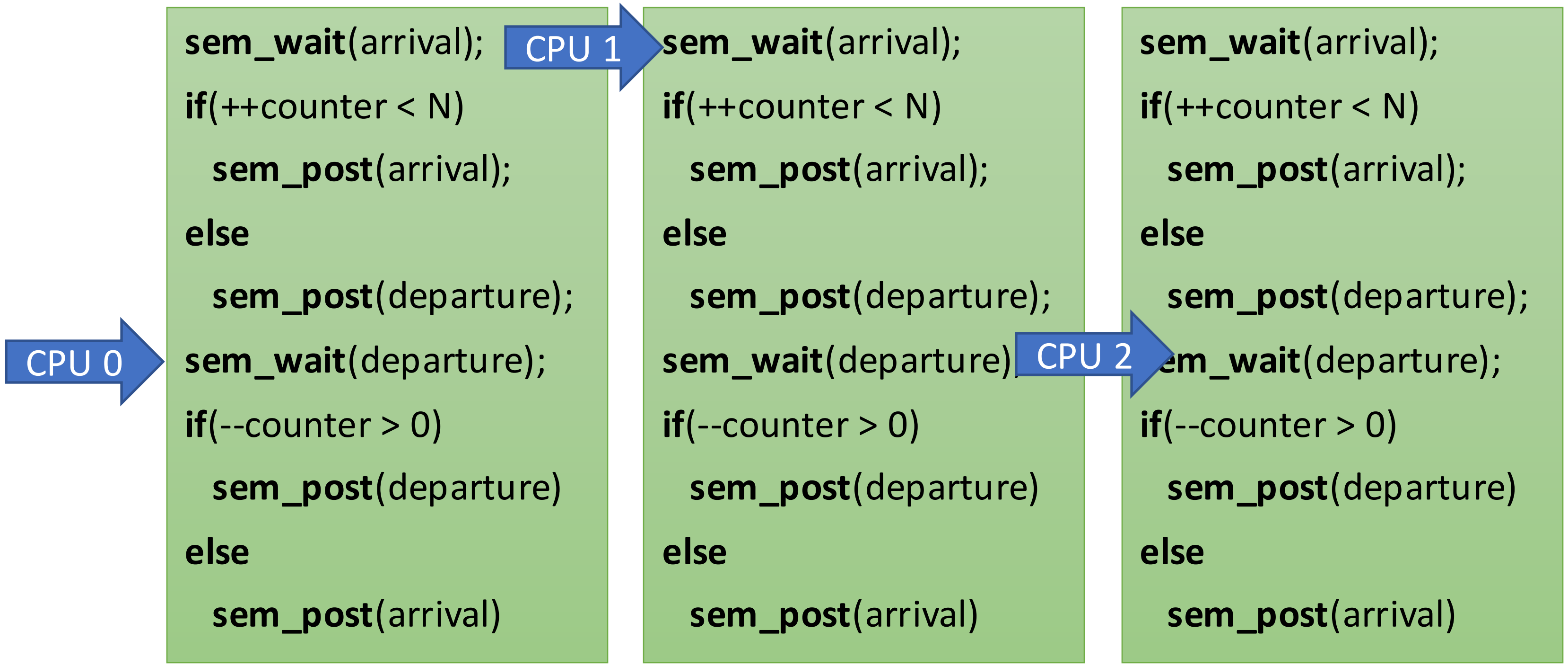
1

Semaphore Barrier Action Zone

N == 3

```
shared    sem_t arrival = 1
          sem_t departure = 0
          atomic int counter = 2
```

1



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

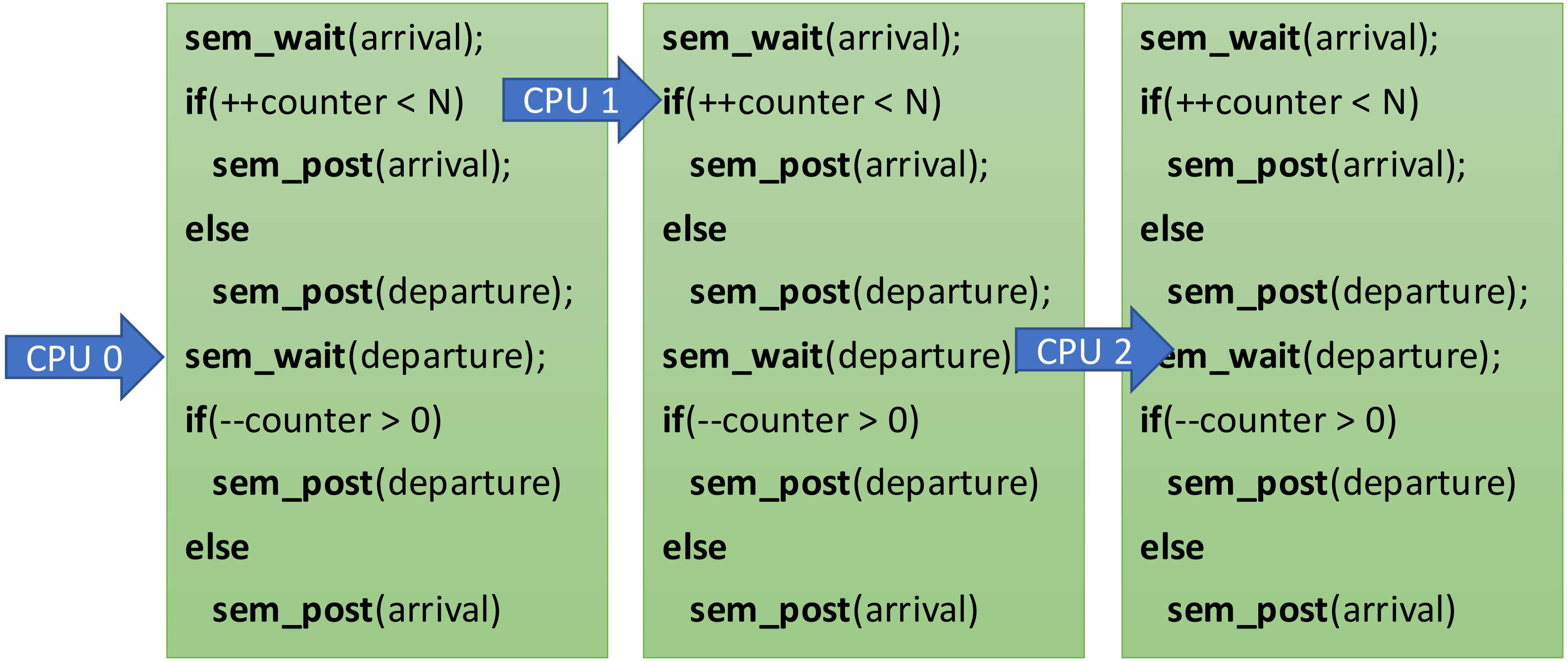
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

```
shared    sem_t arrival = 0
          sem_t departure = 0
          atomic int counter = 2
```

1



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

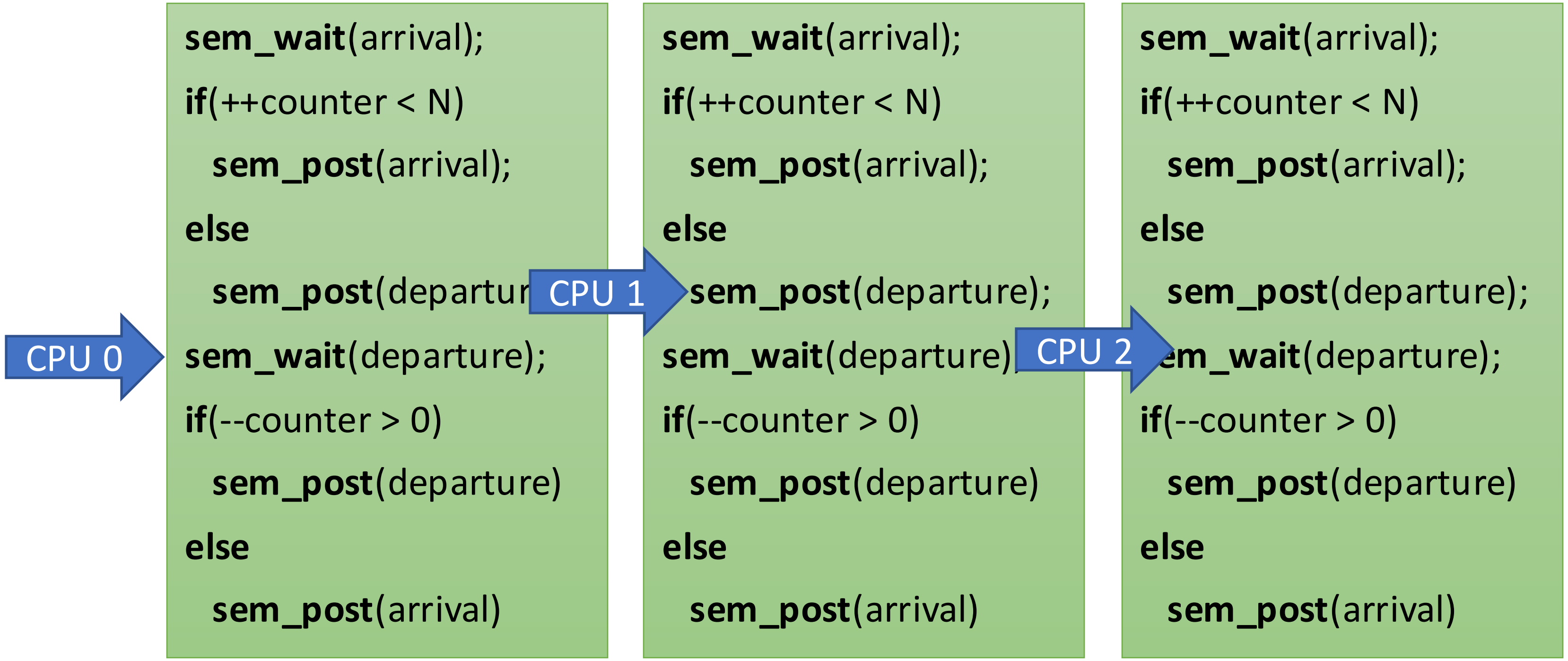
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

```
shared    sem_t arrival = 0
          sem_t departure = 0
          atomic int counter = 3
```

1



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departur
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure)
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
 em_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

shared sem_t arrival = **0**

sem_t departure = **1**

atomic int counter = **3**

1

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departur
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

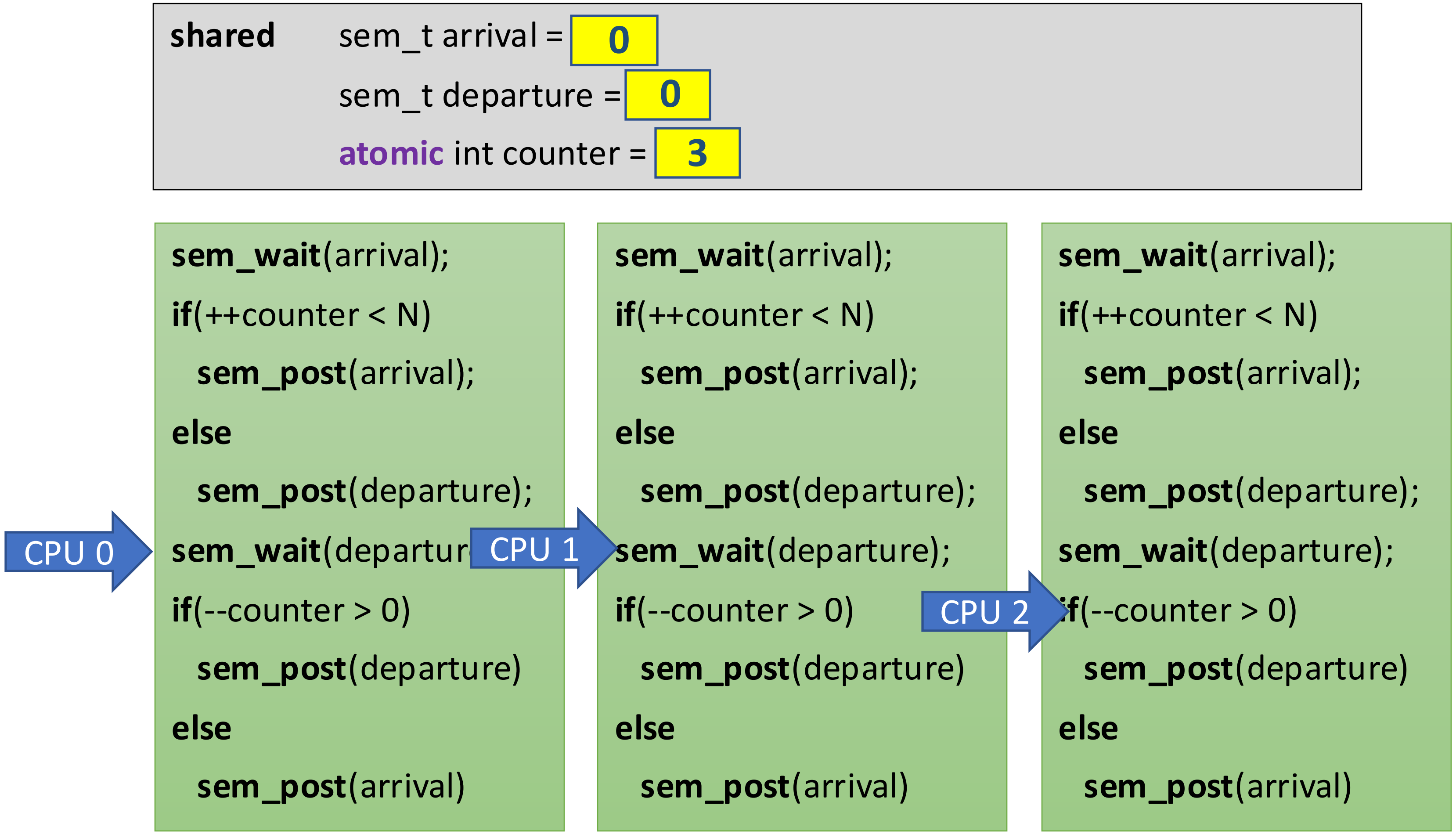
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure)
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
em_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3



```
shared    sem_t arrival = 0
          sem_t departure = 0
          atomic int counter = 3
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

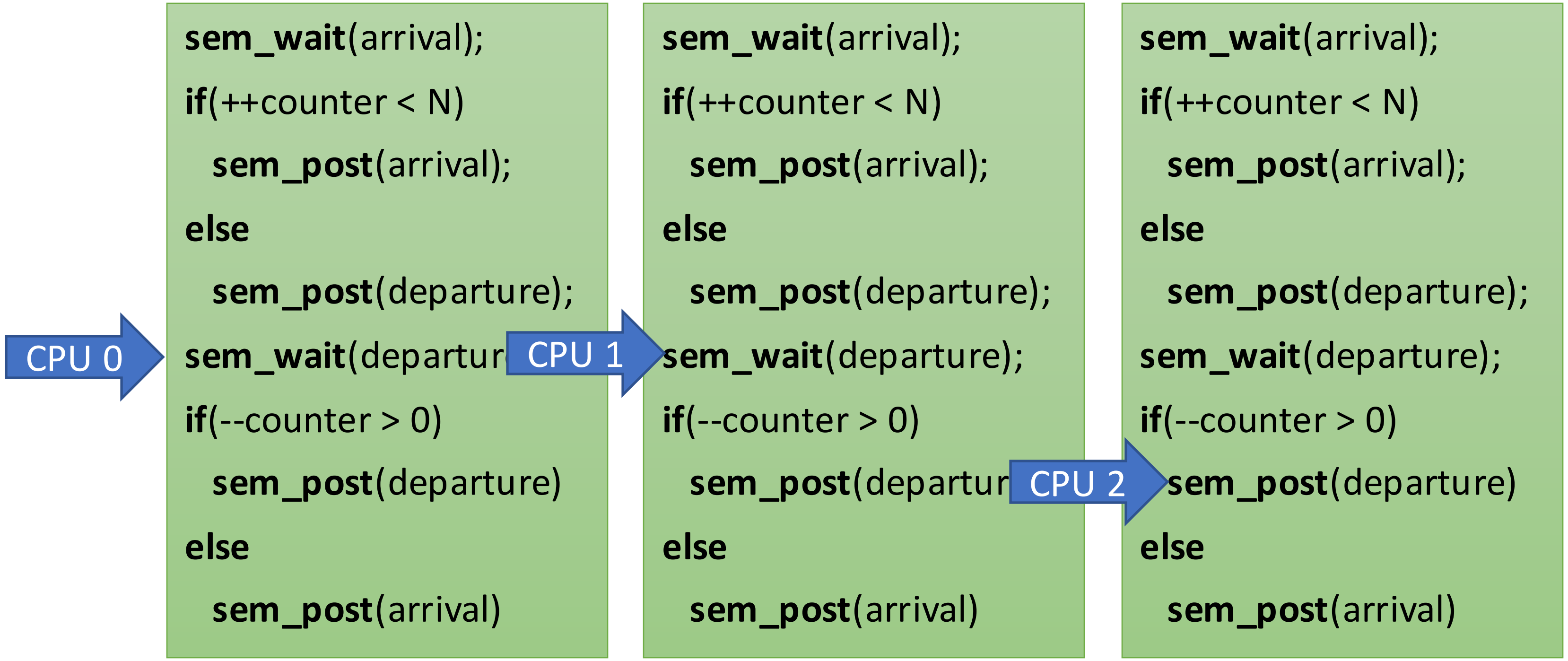
1

Semaphore Barrier Action Zone

N == 3

```
shared     sem_t arrival = 0
           sem_t departure = 0
           atomic int counter = 2
```

1



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

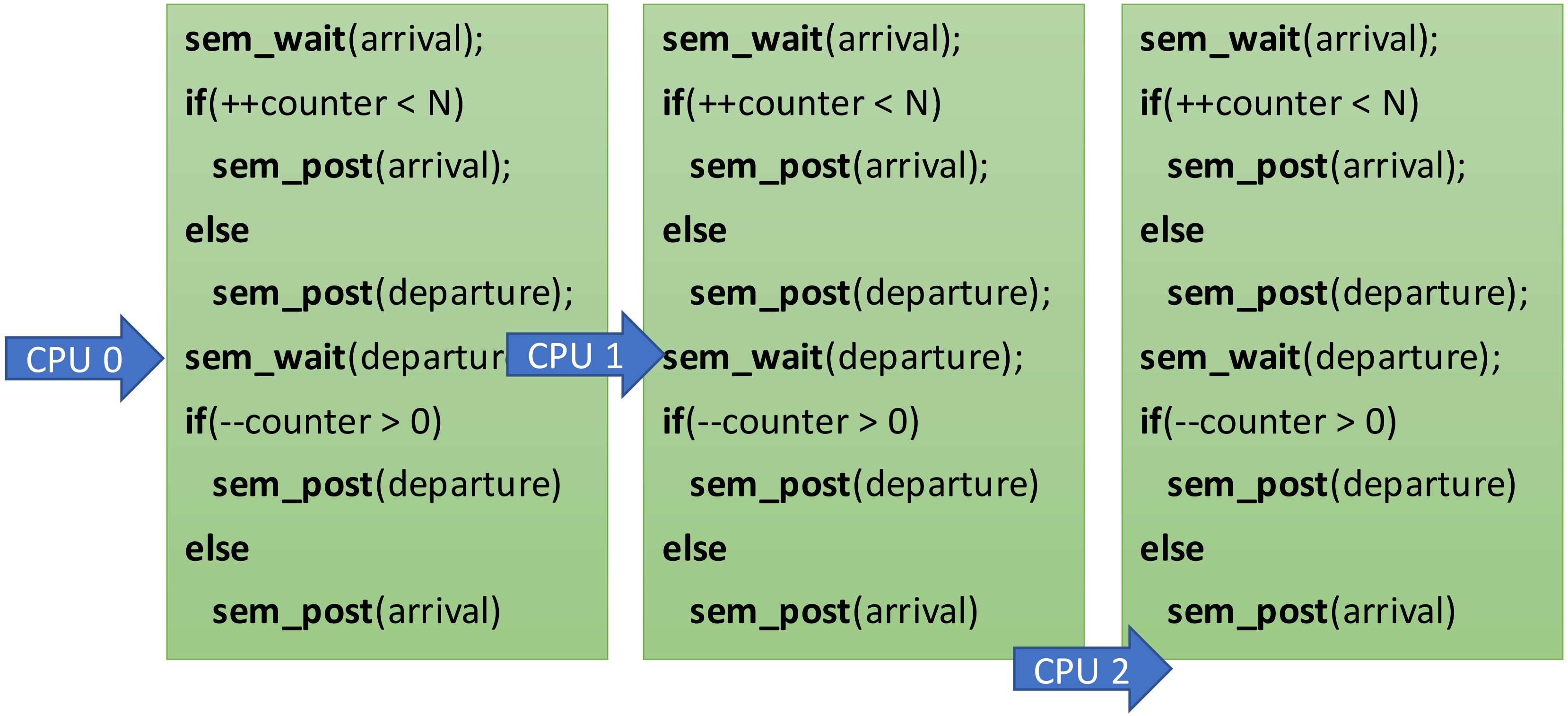
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3

```
shared    sem_t arrival = 0
          sem_t departure = 1
          atomic int counter = 2
```

1



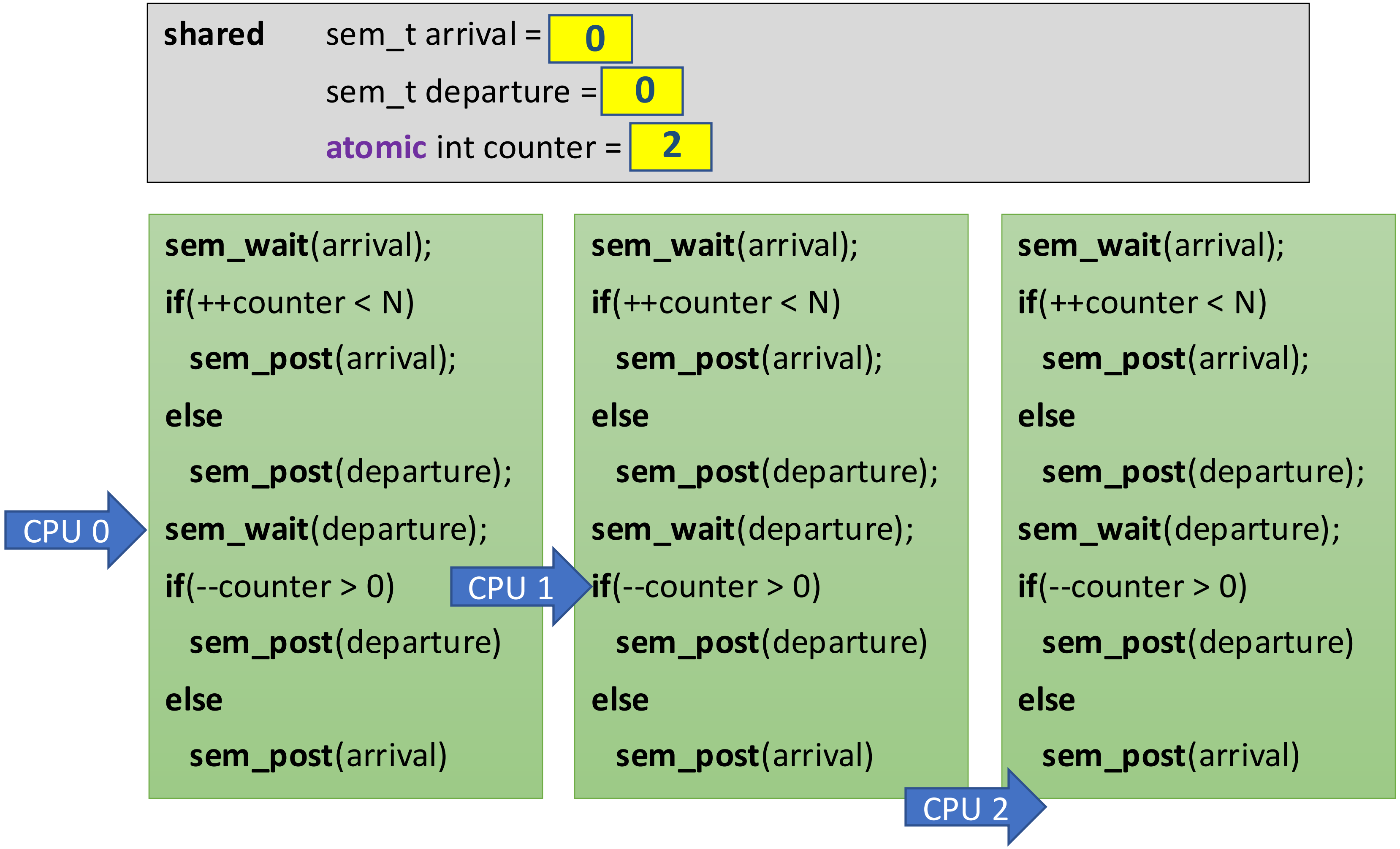
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3



```
shared   sem_t arrival = 0
         sem_t departure = 0
         atomic int counter = 2
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

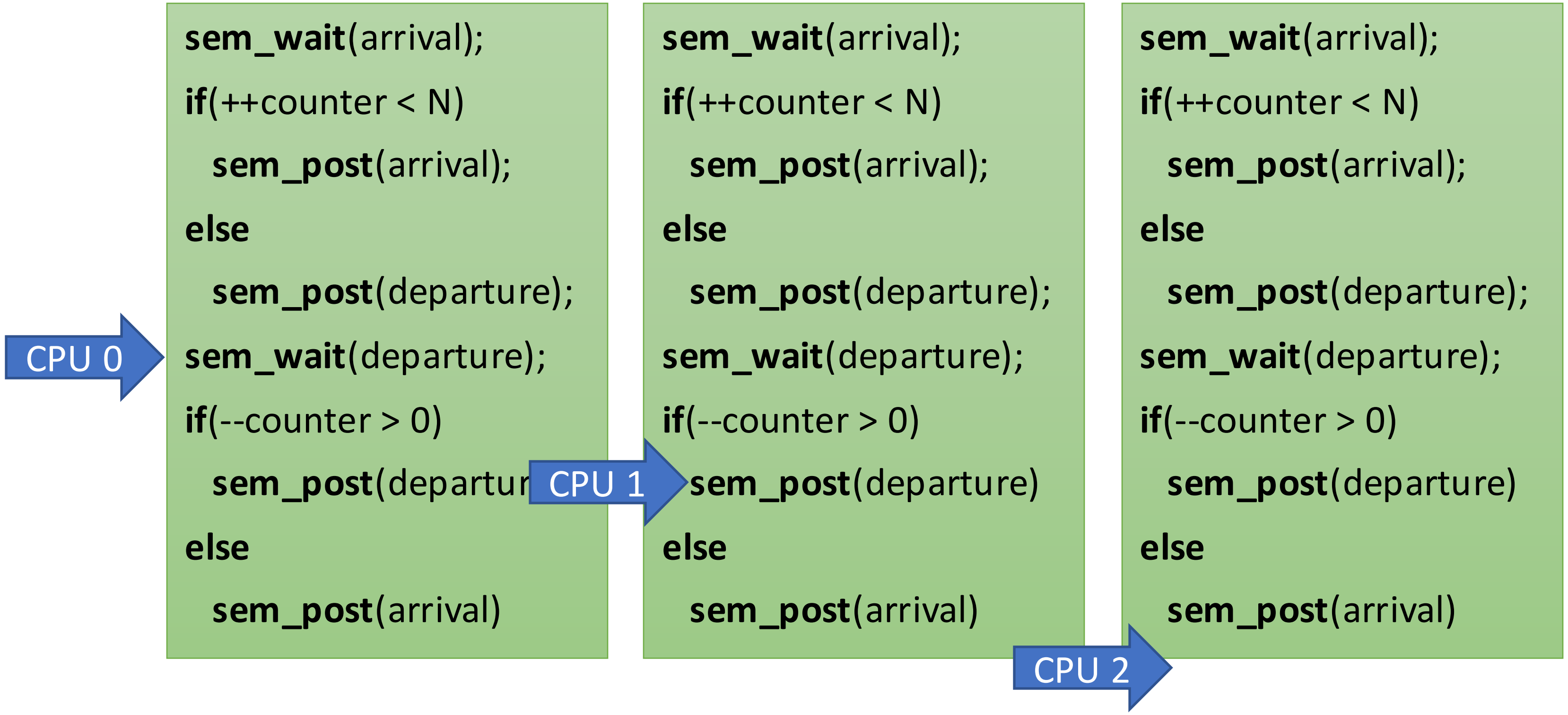
1

Semaphore Barrier Action Zone

N == 3

```
shared      sem_t arrival = 0
            sem_t departure = 0
            atomic int counter = 1
```

1



```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

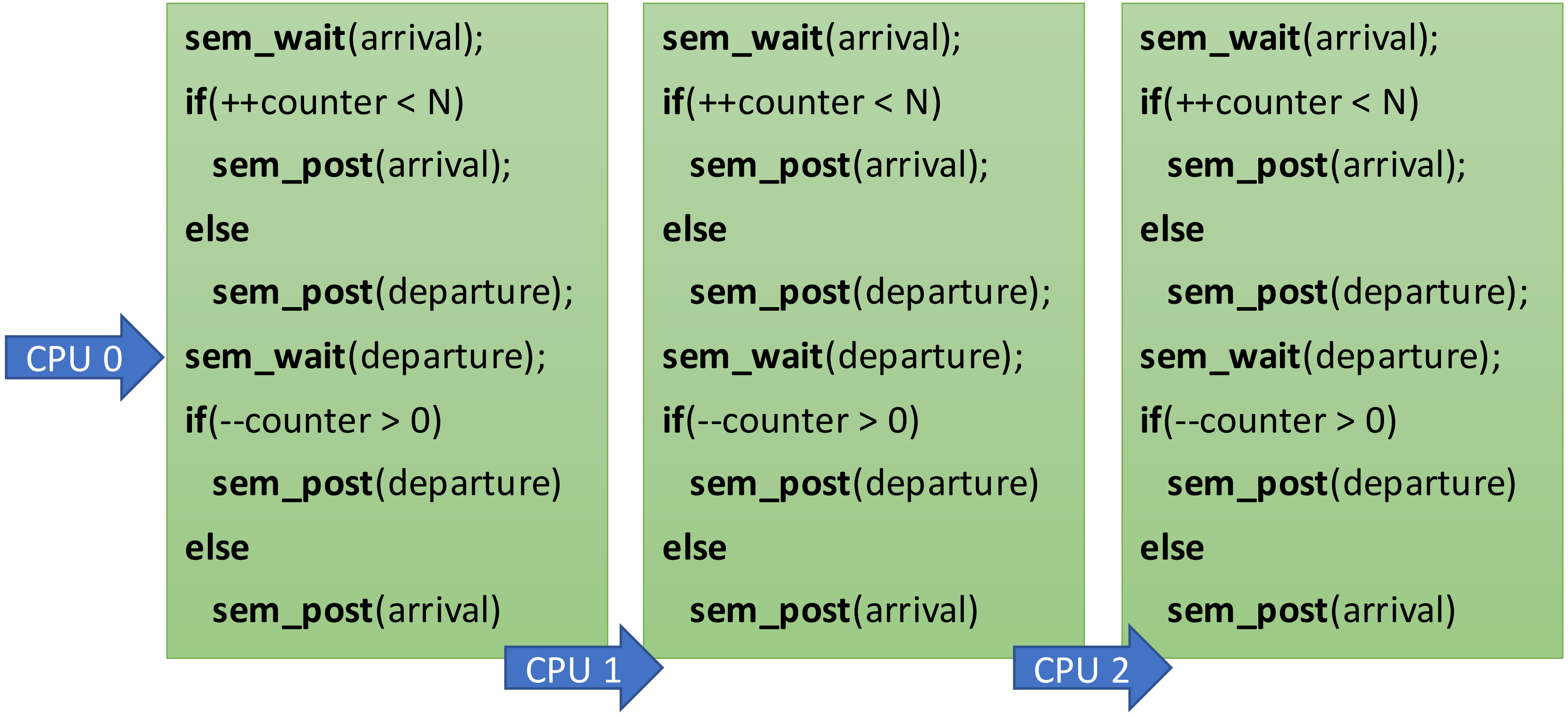
N == 3

shared sem_t arrival = **0**

sem_t departure = **1**

atomic int counter = **1**

1



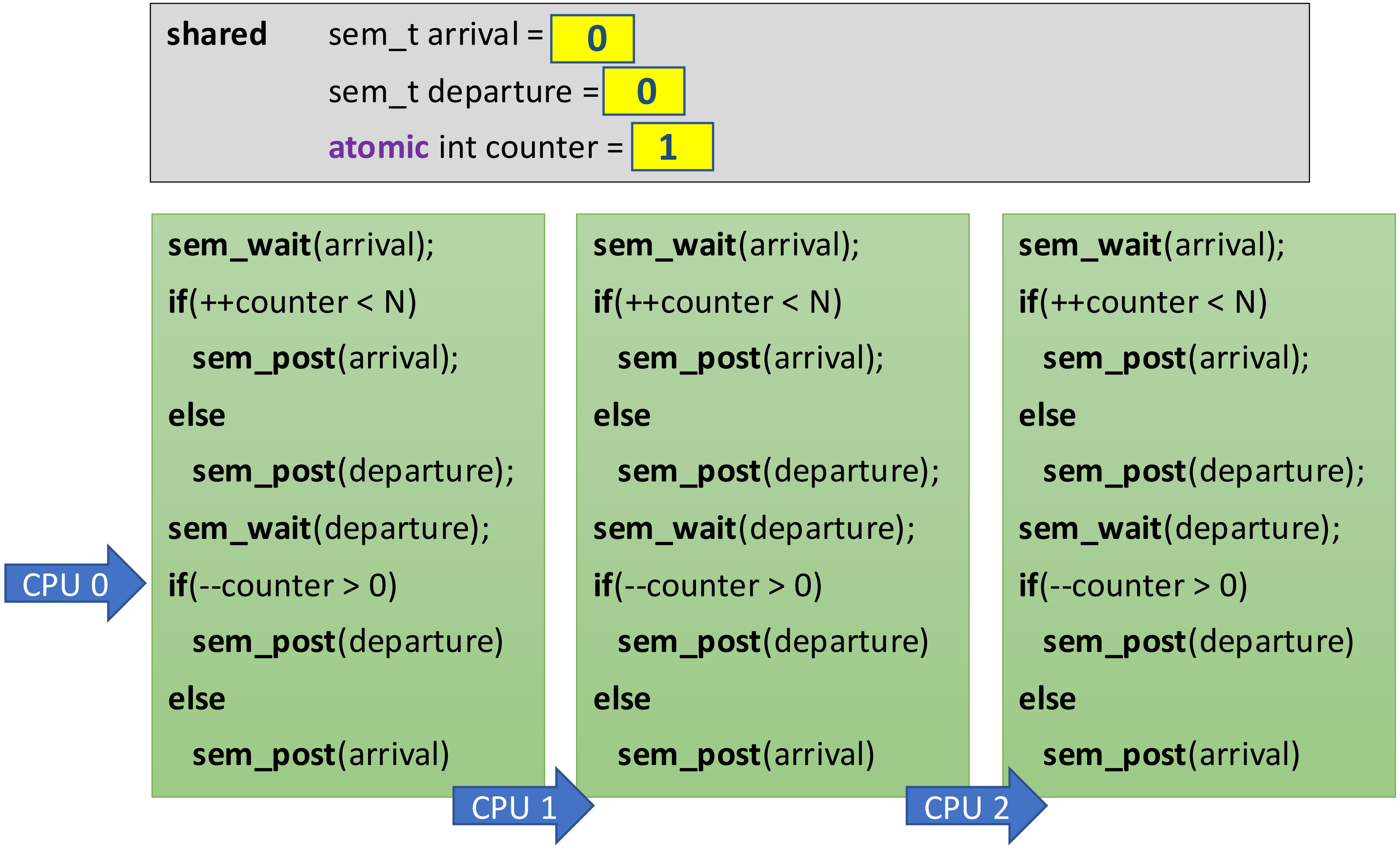
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3



```
shared    sem_t arrival = 0
          sem_t departure = 0
          atomic int counter = 1
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

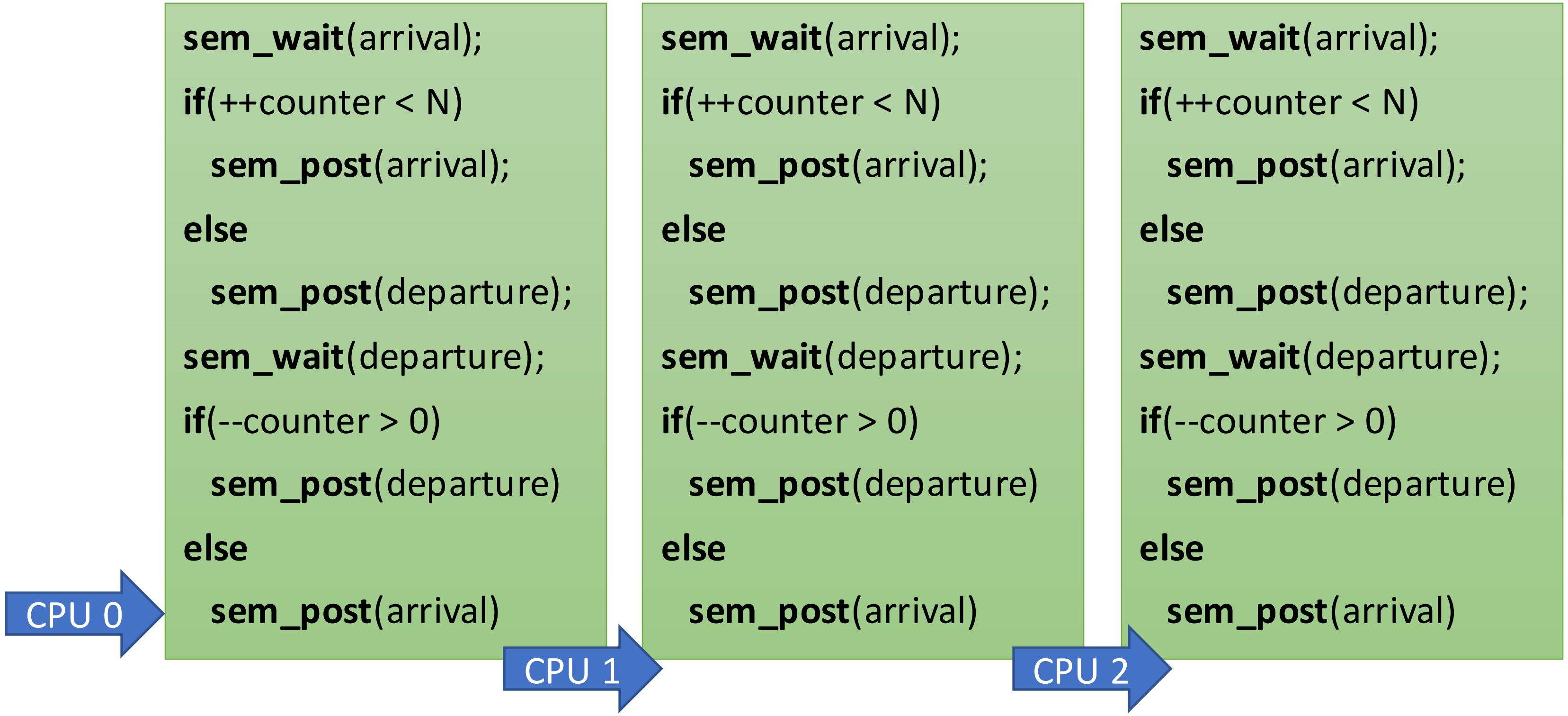
1

Semaphore Barrier Action Zone

N == 3

```
shared    sem_t arrival = 0
          sem_t departure = 0
          atomic int counter = 0
```

1



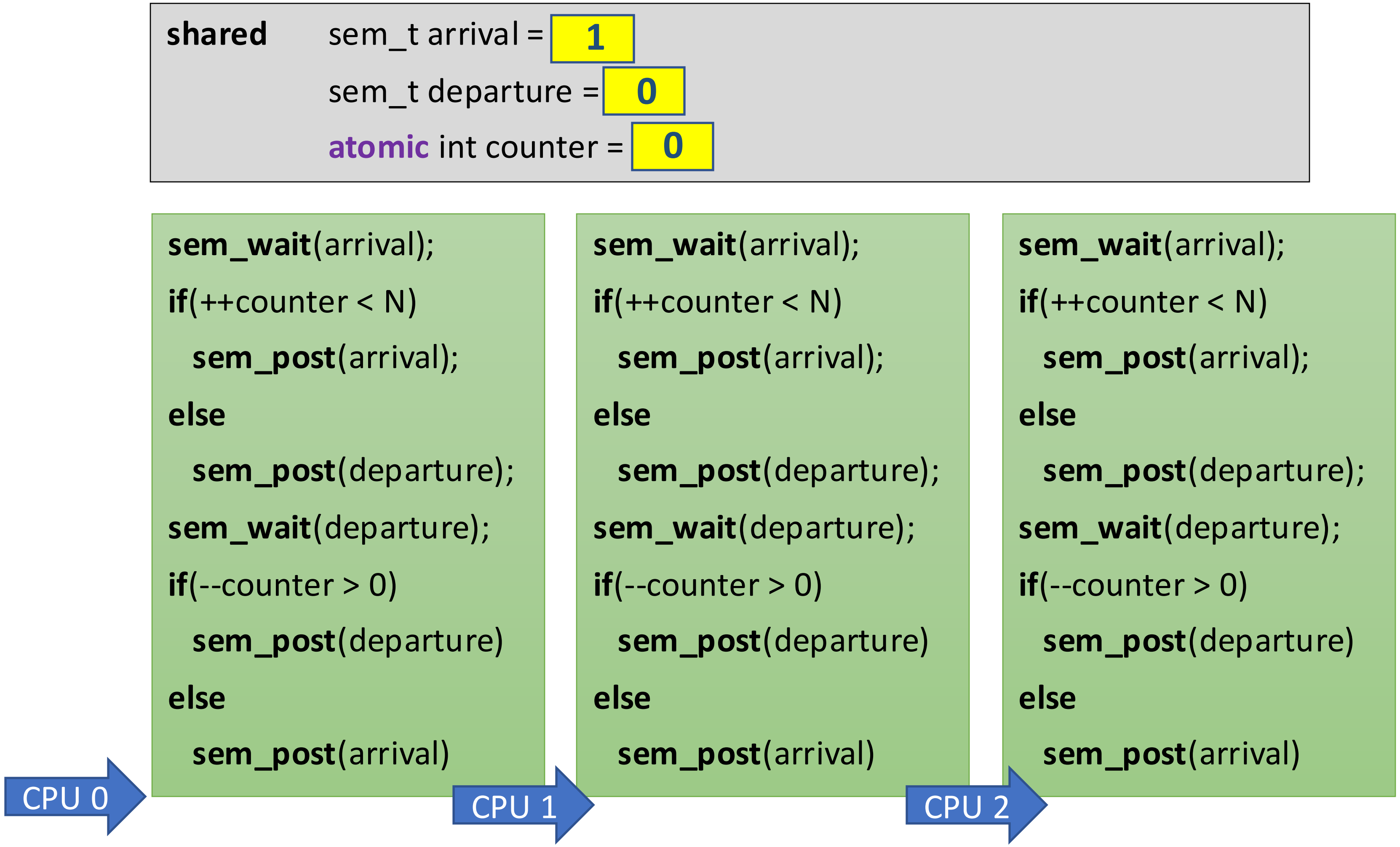
```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Semaphore Barrier Action Zone

N == 3



```
shared    sem_t arrival = 1
          sem_t departure = 0
          atomic int counter = 0
```

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

1

Semaphore Barrier Action Zone

N == 3

```
shared    sem_t arrival = 1
          sem_t departure = 0
          atomic int counter = 0
```

1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

Still correct if counter is not atomic?

Semaphore Barrier Action Zone

N == 3

```
shared      sem_t arrival = 1
            sem_t departure = 0
            atomic int counter = 0
```

1

CPU 0

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 1

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

CPU 2

```
sem_wait(arrival);
if(++counter < N)
  sem_post(arrival);
else
  sem_post(departure);
sem_wait(departure);
if(--counter > 0)
  sem_post(departure)
else
  sem_post(arrival)
```

Do we need two phases?

Still correct if counter is not atomic?

Barrier using Semaphores

Properties

- Pros:

- Cons:

Barrier using Semaphores

Properties

- Pros:
  - Very Simple
  - Space complexity O(1)
  - Symmetric
- Cons:

Barrier using Semaphores

Properties

- Pros:
  - Very Simple
  - Space complexity O(1)
  - Symmetric
- Cons:
  - Required a strong object
    - Requires some central manager
    - High contention on the semaphores
  - Propagation delay O(n)

Barriers based on counters

Counter Barrier Ingredients

Fetch-and-Increment register

- A shared register that supports a F&I operation:
- Input: register *r*
- Atomic operation:
  - *r* is incremented by 1
  - the old value of r is returned

```
function fetch-and-increment (r : register)
    orig_r := r;
    r:= r + 1;
    return (orig_r);
end-function
```

Await

- For brevity, we use the **await** macro
- Not an operation of an object
- This is also called: “spinning”

```
macro await (condition : boolean condition)
    repeat
        cond = eval(condition);
    until (cond)
end-macro
```

Simple Barrier Using an Atomic Counter

```
shared   counter: fetch and increment reg. – {0,..n}, initially = 0
         go: atomic bit, initial value is immaterial
local    local.go: a bit, initial value is immaterial
         local.counter: register
```

Simple Barrier Using an Atomic Counter

shared counter: fetch and increment reg. – {0,..n}, initially = 0

go: atomic bit, initial value is immaterial

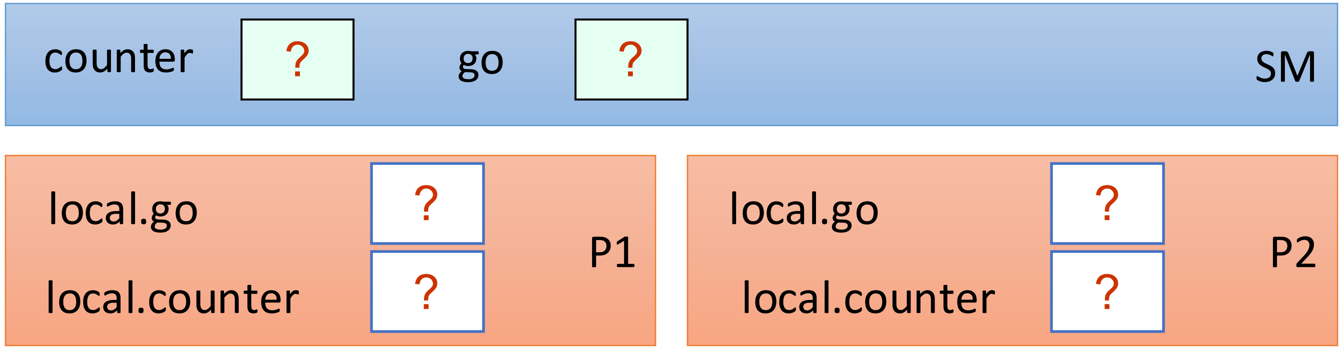
local local.go: a bit, initial value is immaterial

local.counter: register

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

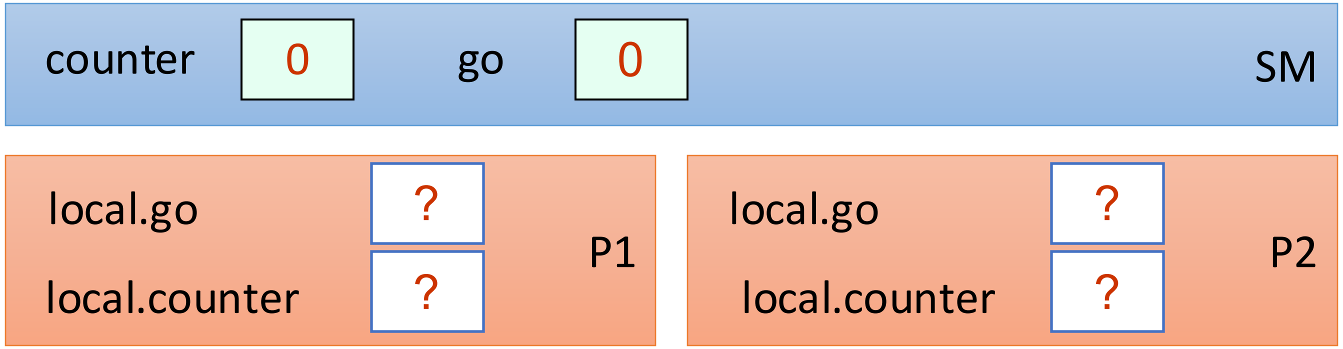
Run for n=2 Threads



```
local.go := go
local.counter := fetch-and-increment (counter)
**if** local.counter + 1 = n **then**
    counter := 0
    go := 1 - go
**else await**(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



counter 0 go 0 SM

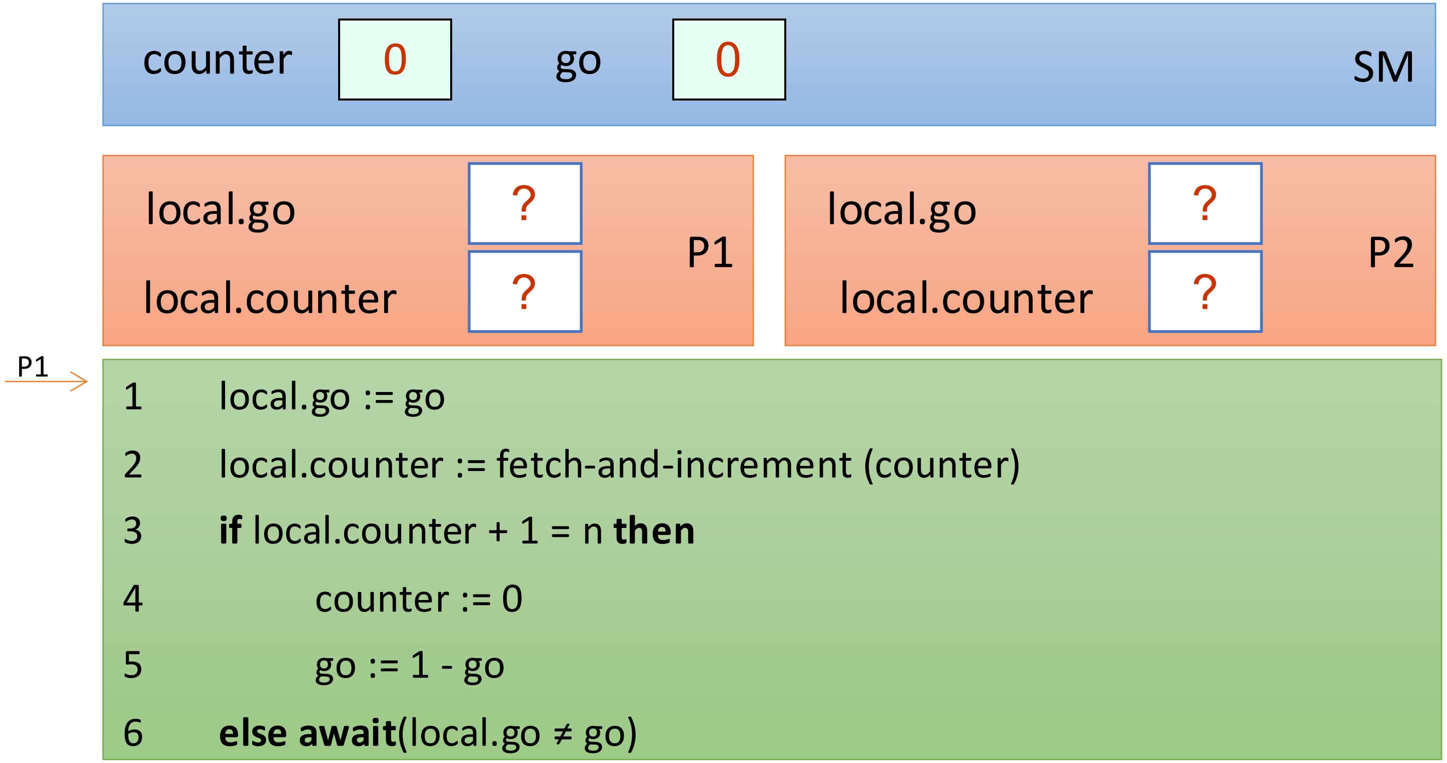
local.go ? local.counter ? P1

local.go ? local.counter ? P2

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



counter 0 go 0 SM

local.go ? local.counter ? P1

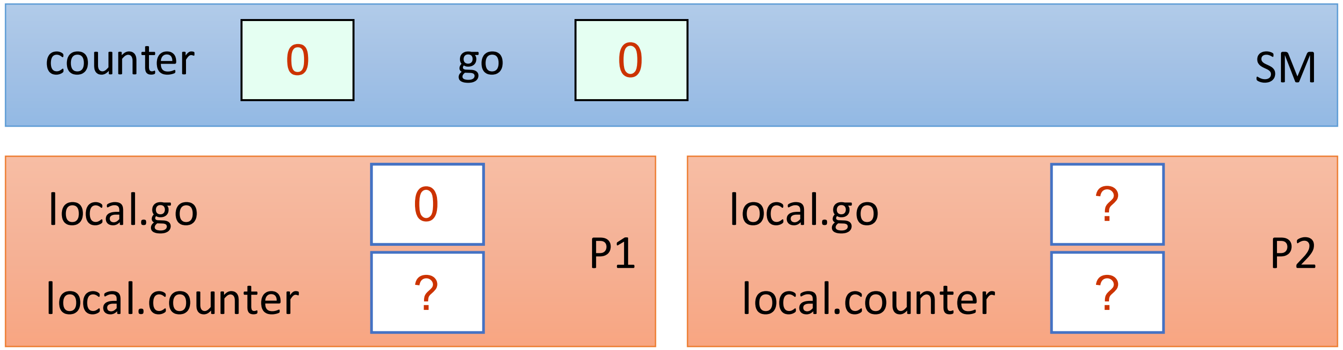
local.go ? local.counter ? P2

P1

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



counter 0 go 0 SM

local.go 0
local.counter ? P1

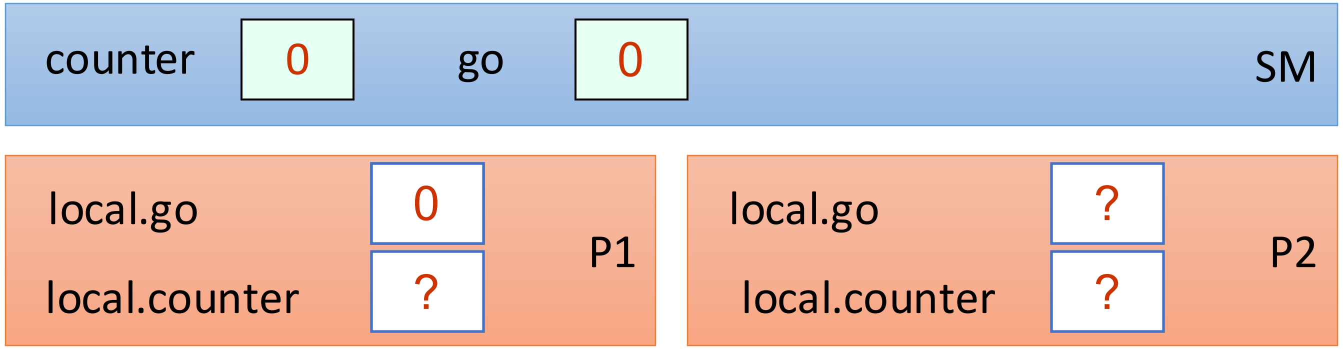
local.go ?
local.counter ? P2

P1 →

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

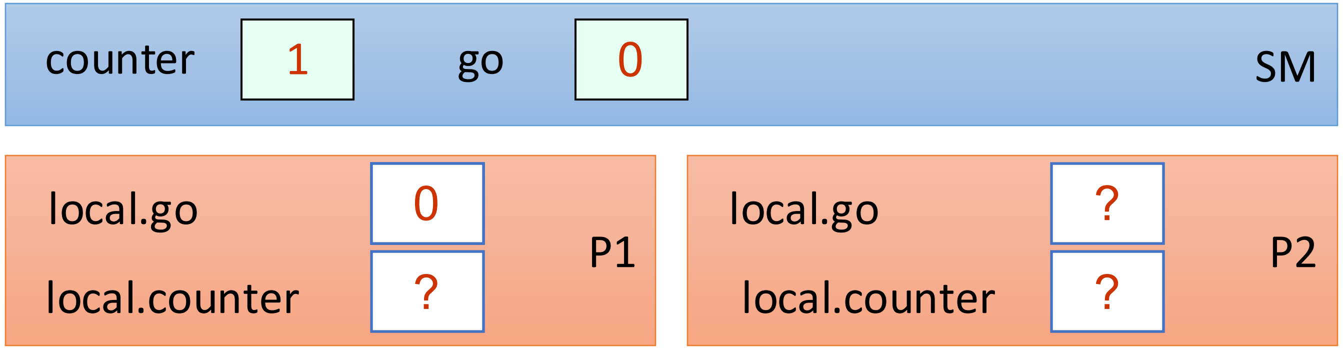
Run for n=2 Threads



```
     local.go := go
P1 → local.counter := fetch-and-increment (counter)
     if local.counter + 1 = n then
          counter := 0
          go := 1 - go
     else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



SM

counter 1 go 0

P1

local.go 0

local.counter ?

P2

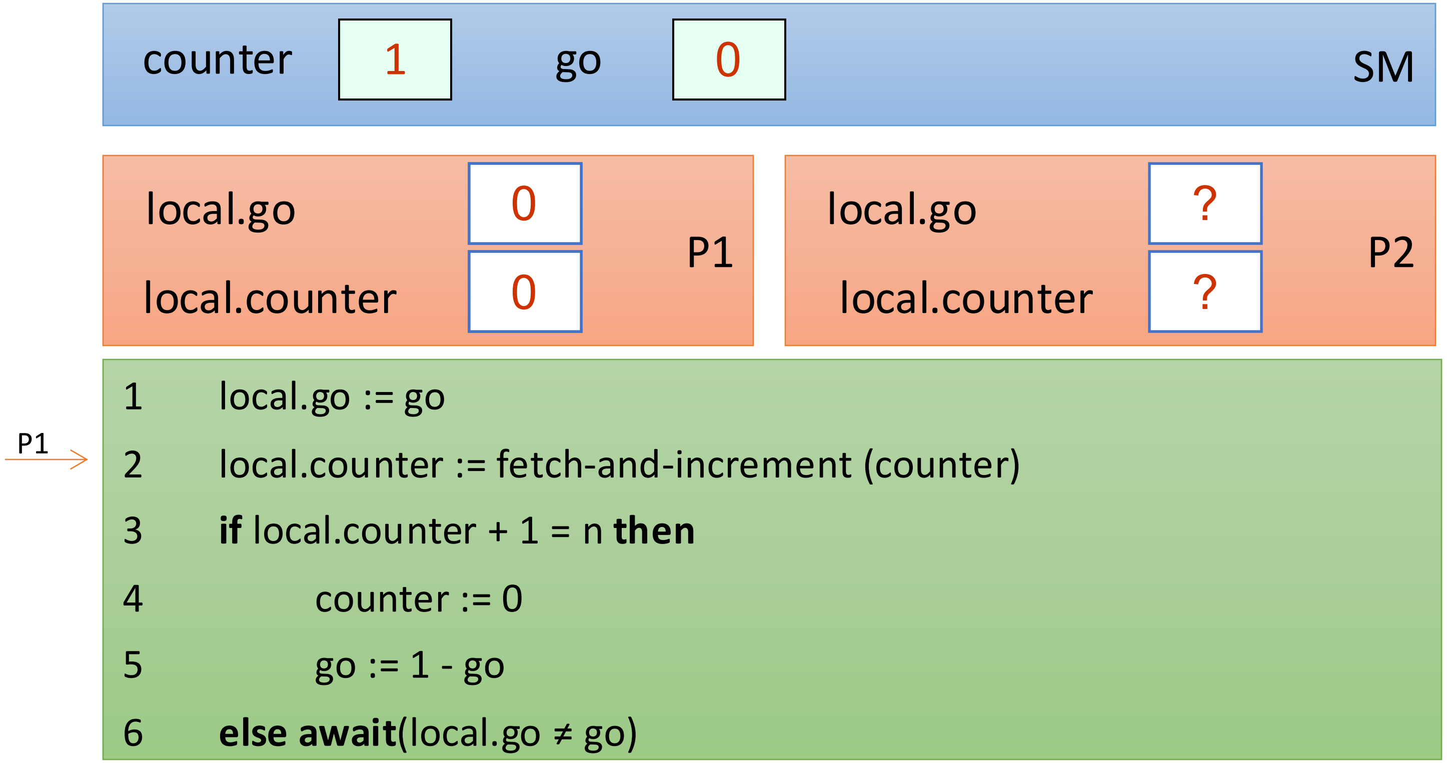
local.go ?

local.counter ?

```
   1    local.go := go
P1 → 2    local.counter := fetch-and-increment (counter)
   3    if local.counter + 1 = n then
   4        counter := 0
   5        go := 1 - go
   6    else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



counter 1 go 0 SM

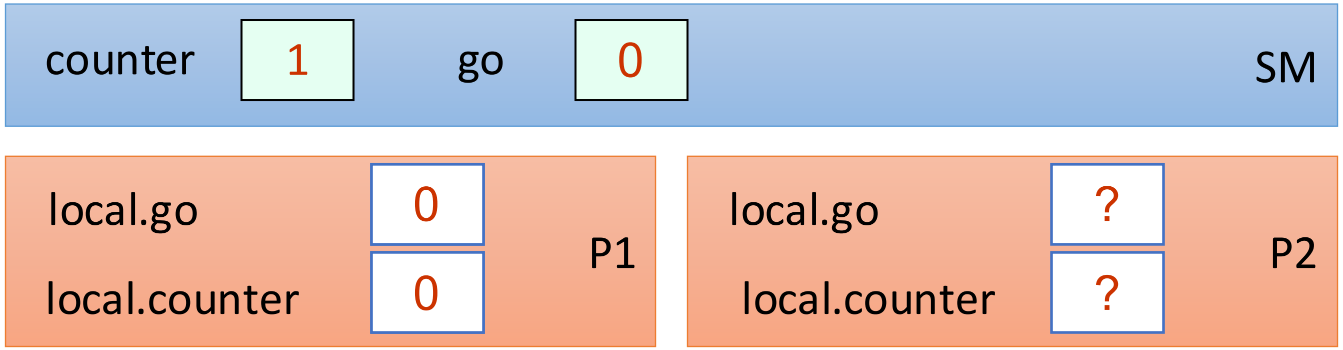
local.go 0
local.counter 0
P1

local.go ?
local.counter ?
P2

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



counter 1 go 0 SM

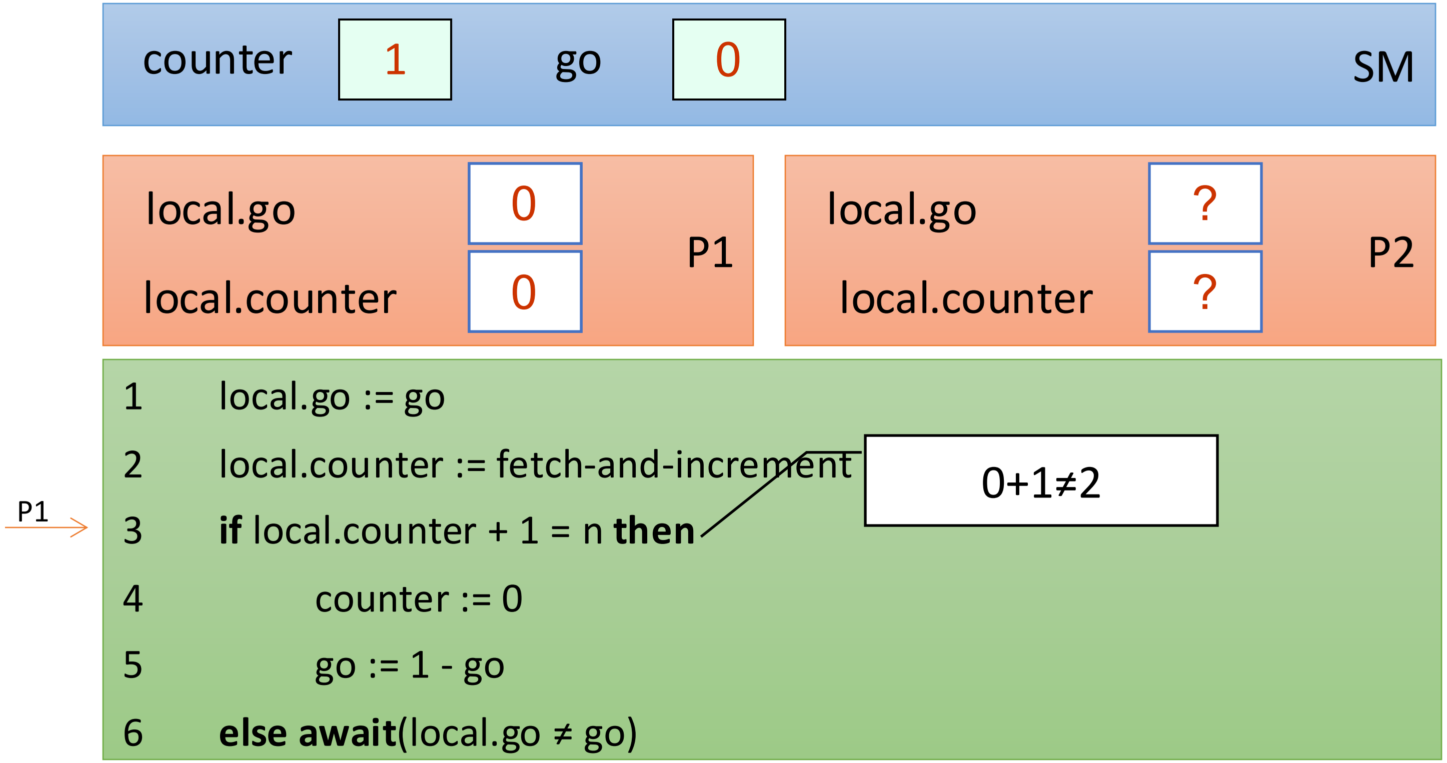
local.go 0
local.counter 0
P1

local.go ?
local.counter ?
P2

```
      1   local.go := go
      2   local.counter := fetch-and-increment (counter)
P1 →  3   if local.counter + 1 = n then
      4       counter := 0
      5       go := 1 - go
      6   else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



SM

counter 1

go 0

P1

local.go 0

local.counter 0

P2

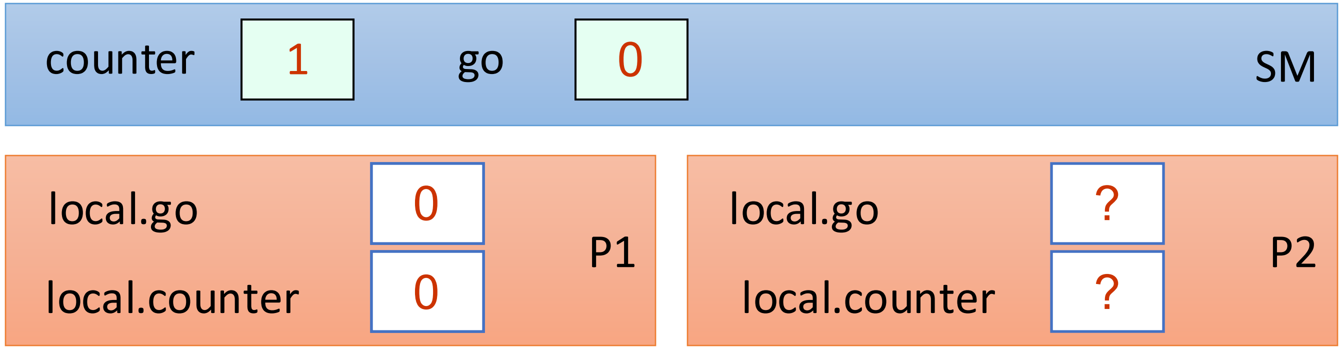
local.go ?

local.counter ?

```
local.go := go
local.counter := fetch-and-increment
if local.counter + 1 = n then
        counter := 0
        go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

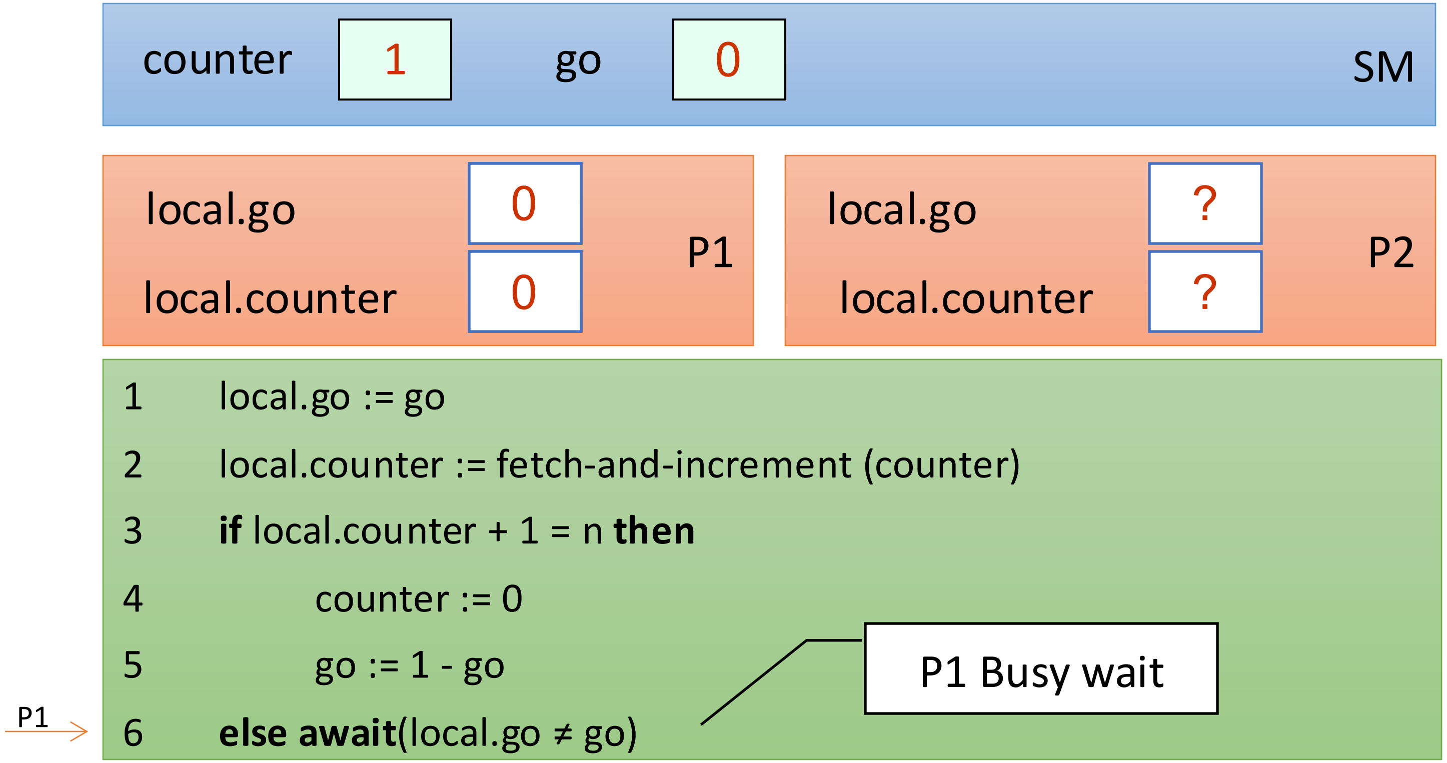
Run for n=2 Threads



```
      1    local.go := go
      2    local.counter := fetch-and-increment (counter)
      3    if local.counter + 1 = n then
      4         counter := 0
      5         go := 1 - go
P1 →  6    else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

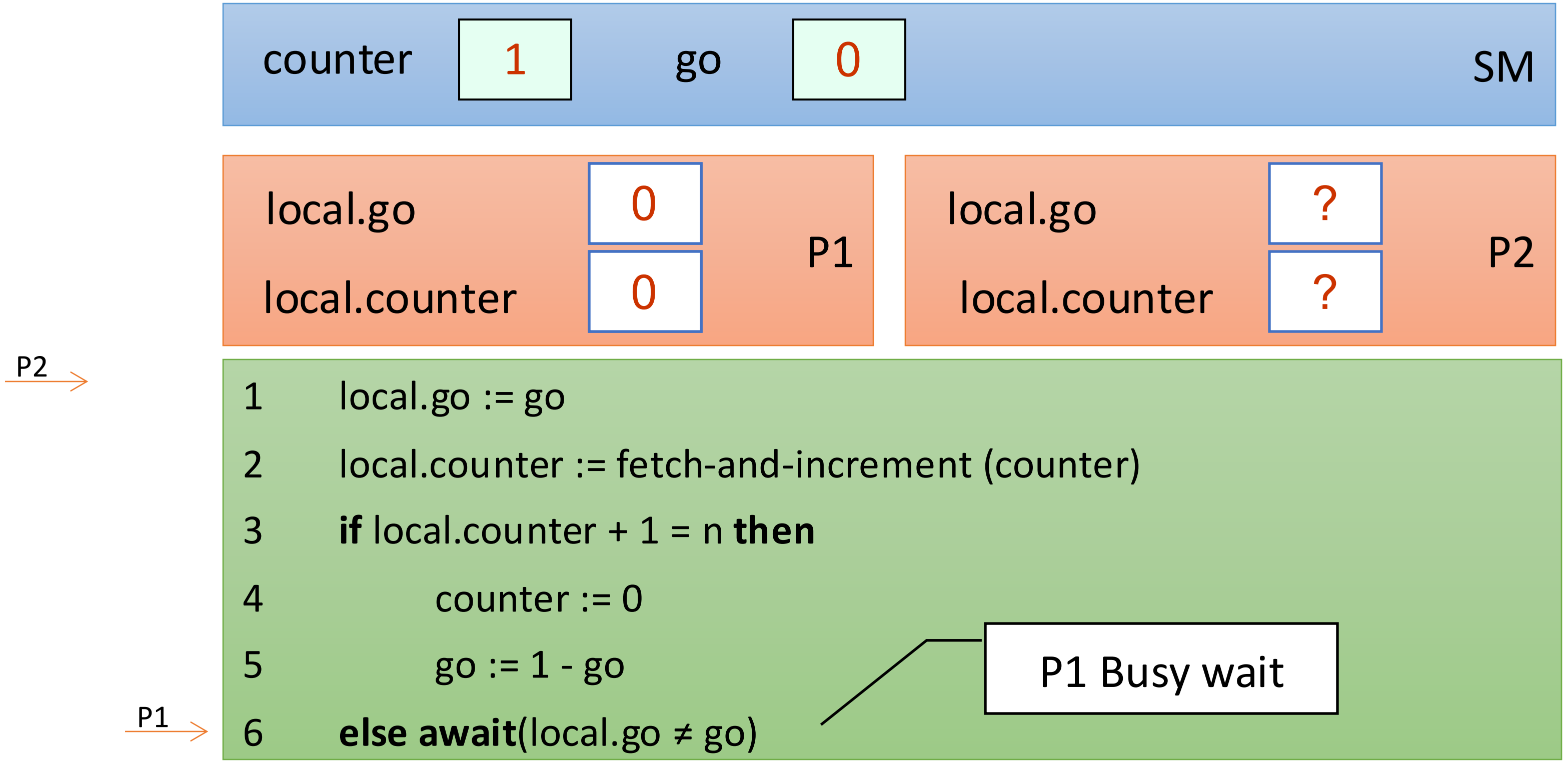
Run for n=2 Threads



```
local.go := go
local.counter := fetch-and-increment (counter)
**if** local.counter + 1 = n **then**
    counter := 0
    go := 1 - go
**else await**(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

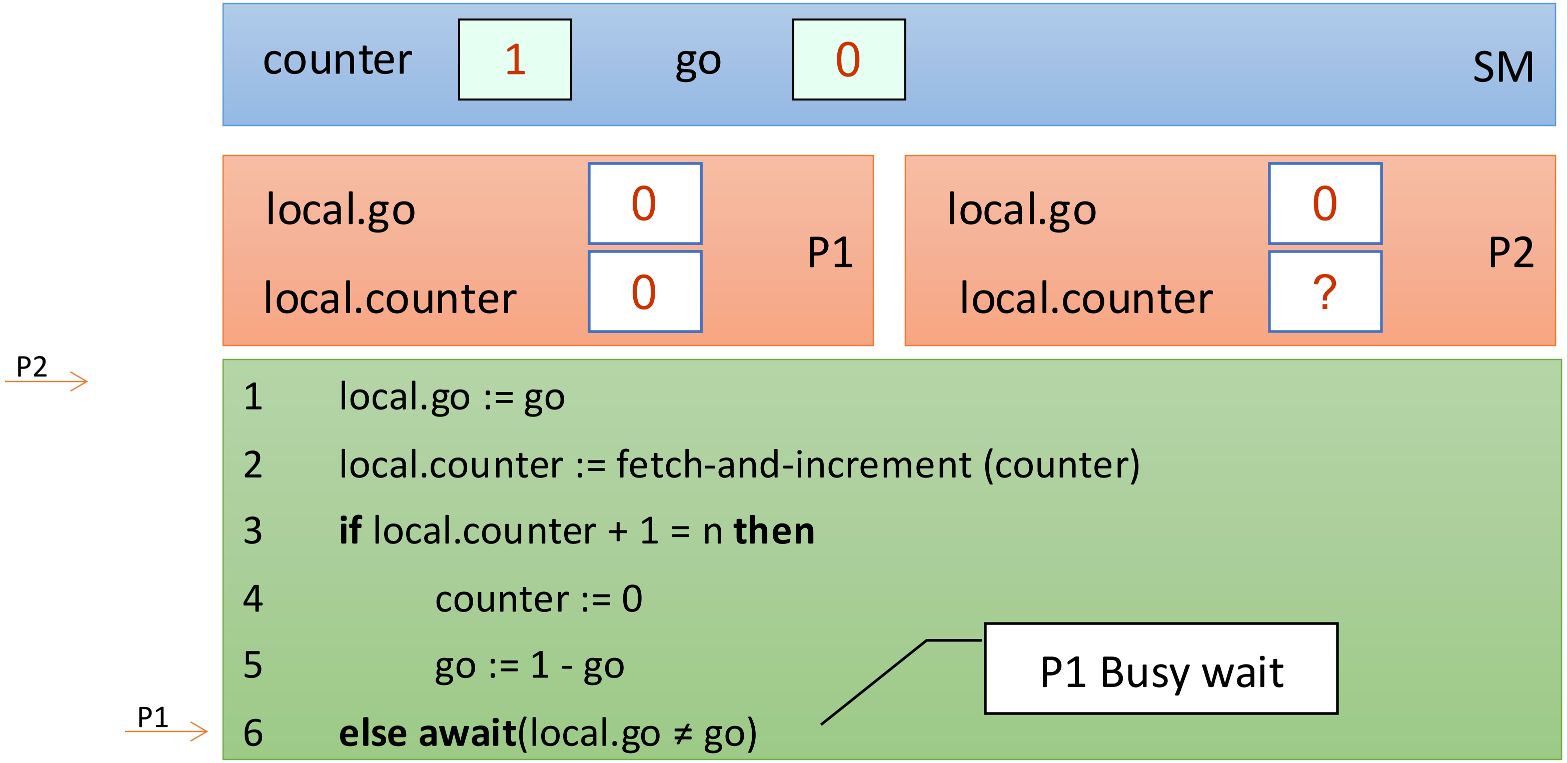
Run for n=2 Threads



```
local.go := go
local.counter := fetch-and-increment (counter)
**if** local.counter + 1 = n **then**
        counter := 0
        go := 1 - go
**else await**(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

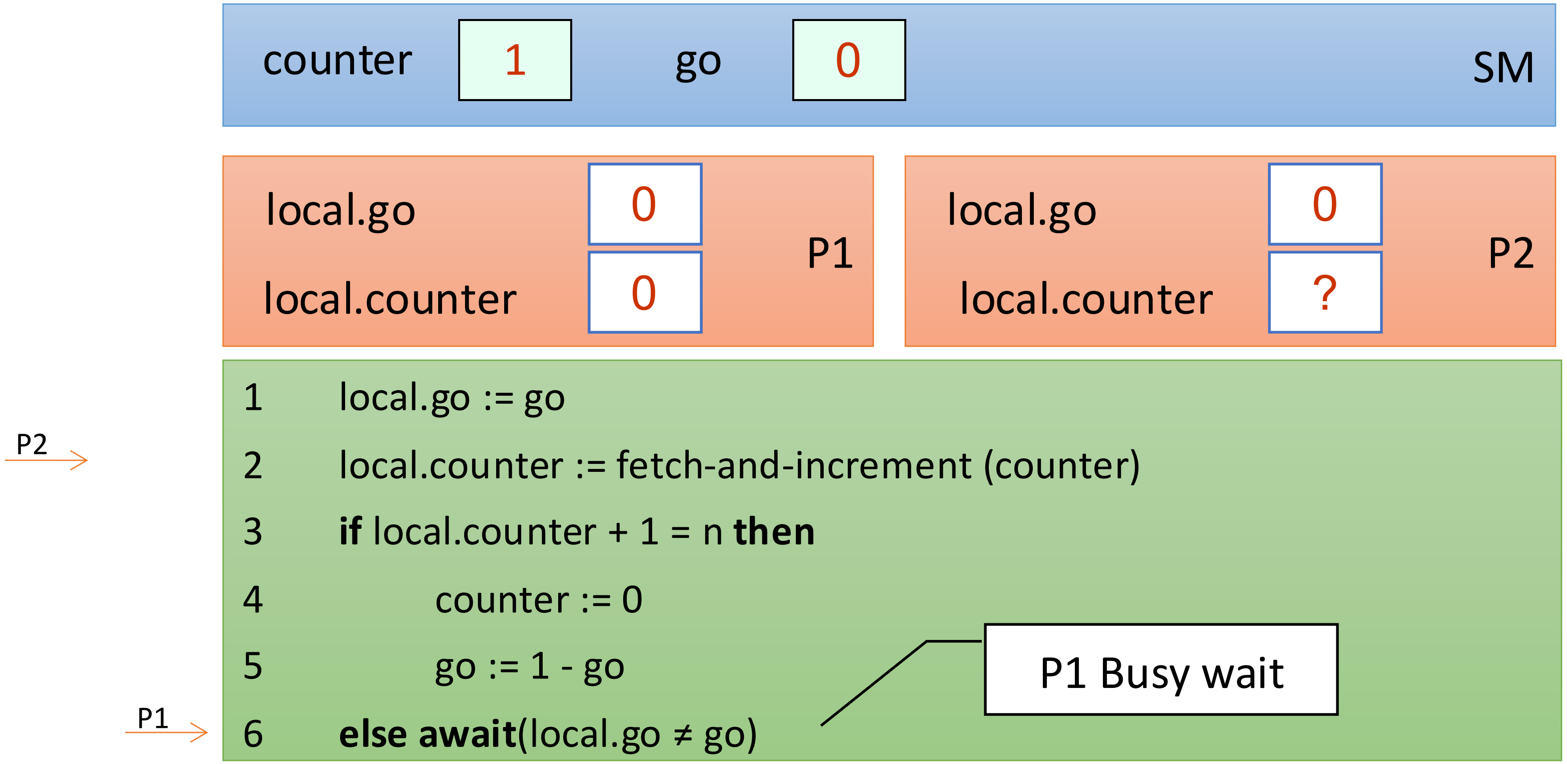
Run for n=2 Threads



```
local.go := go
local.counter := fetch-and-increment (counter)
**if** local.counter + 1 = n **then**
    counter := 0
    go := 1 - go
**else await**(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



SM

counter 1

go 0

P1

local.go 0

local.counter 0

P2

local.go 0

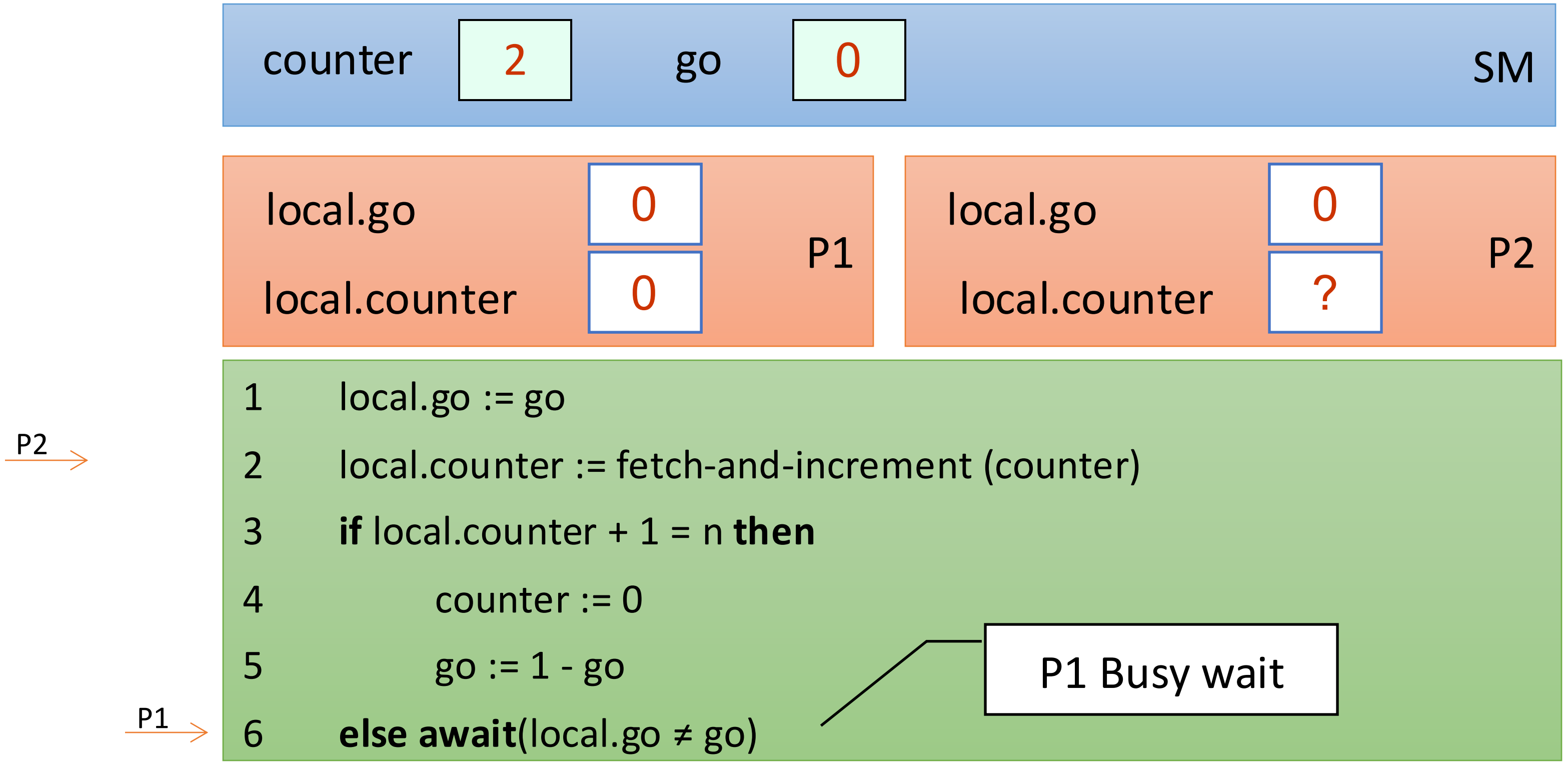
local.counter ?

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

P1 Busy wait

Simple Barrier Using an Atomic Counter

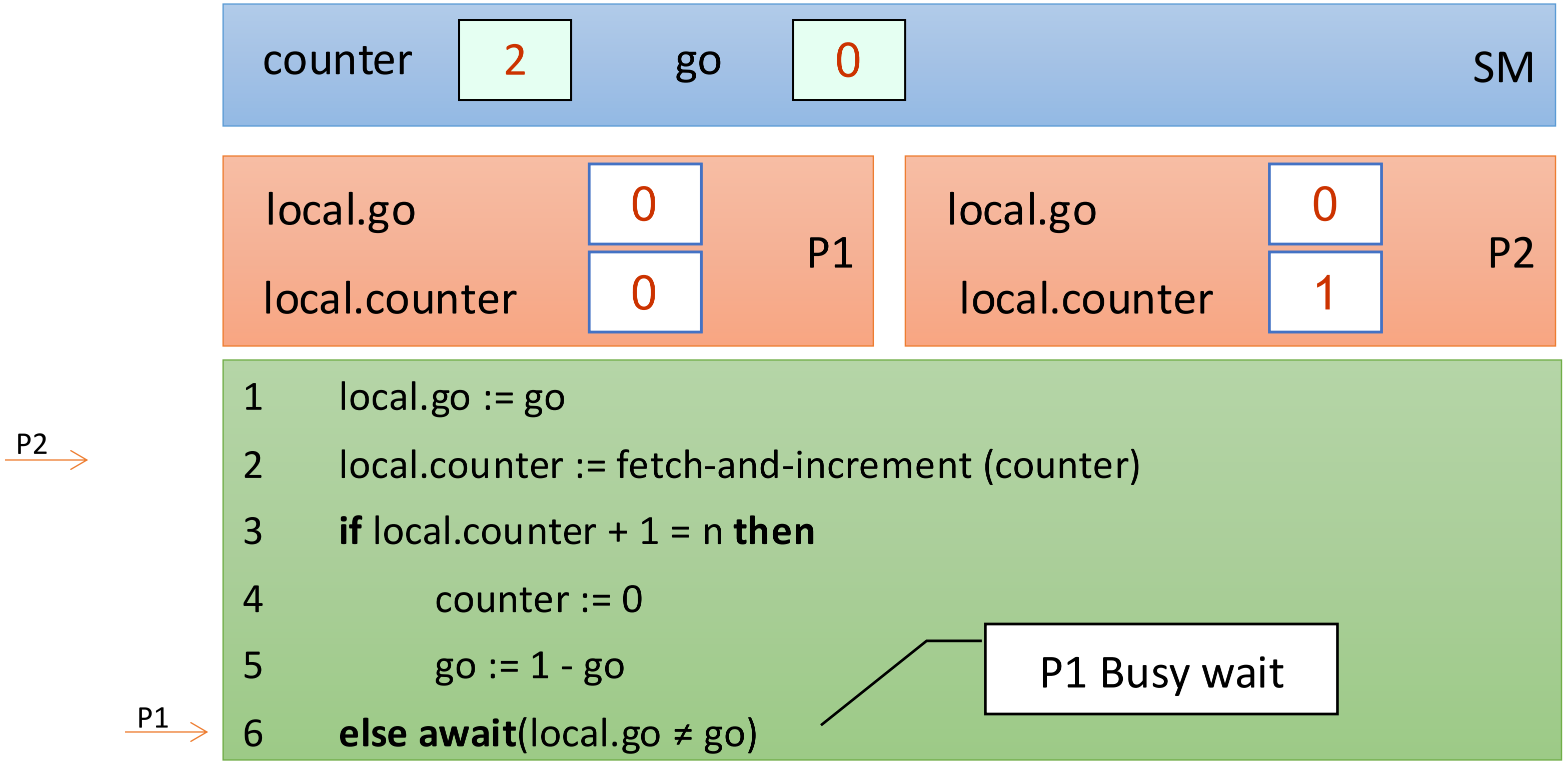
Run for n=2 Threads



```
1    local.go := go
2    local.counter := fetch-and-increment (counter)
3    if local.counter + 1 = n then
4            counter := 0
5            go := 1 - go
6    else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

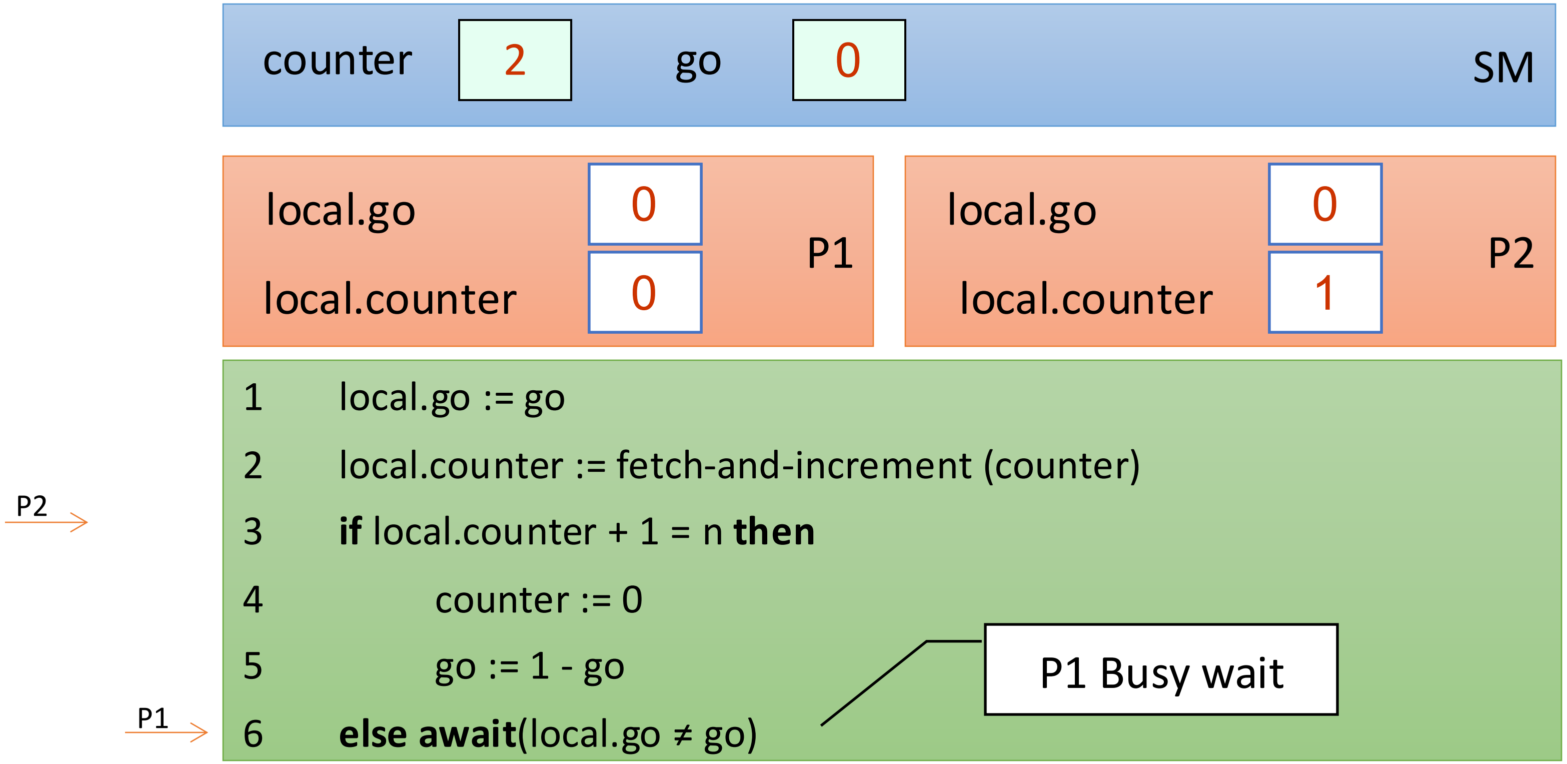
Run for n=2 Threads



```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

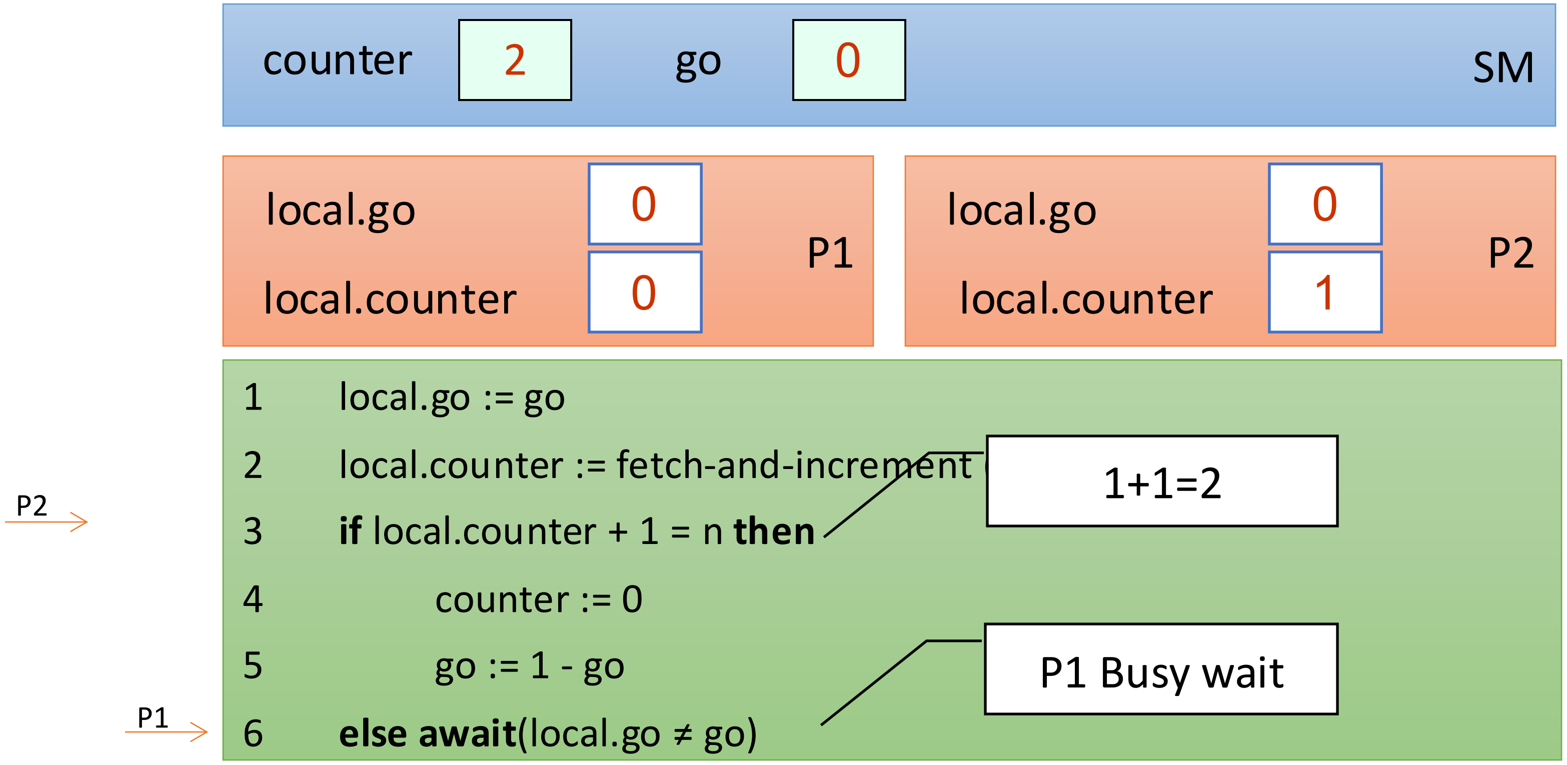
Run for n=2 Threads



```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

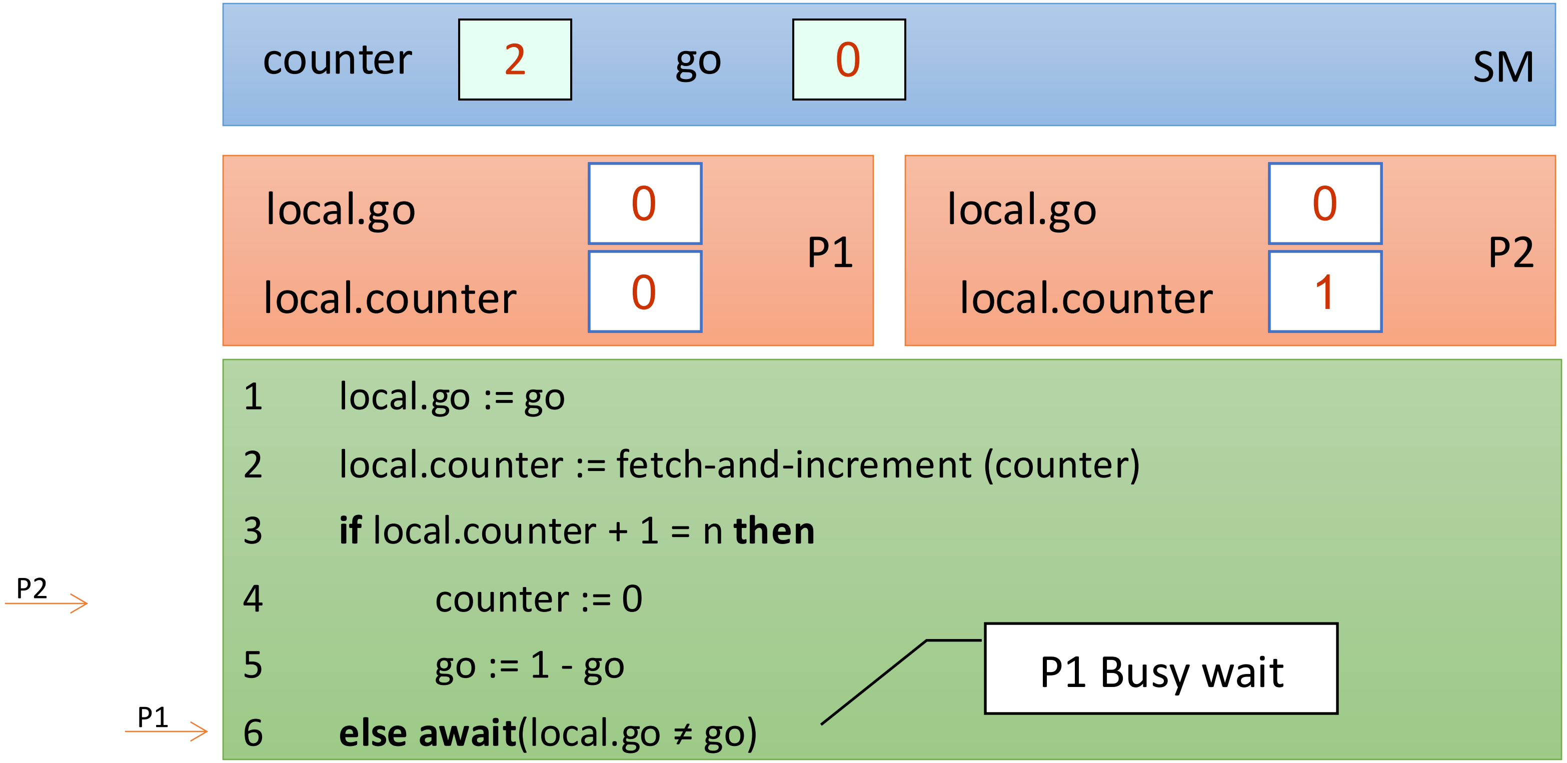
Run for n=2 Threads



```
1    local.go := go
2    local.counter := fetch-and-increment
3    **if** local.counter + 1 = n **then**
4        counter := 0
5        go := 1 - go
6    **else await**(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

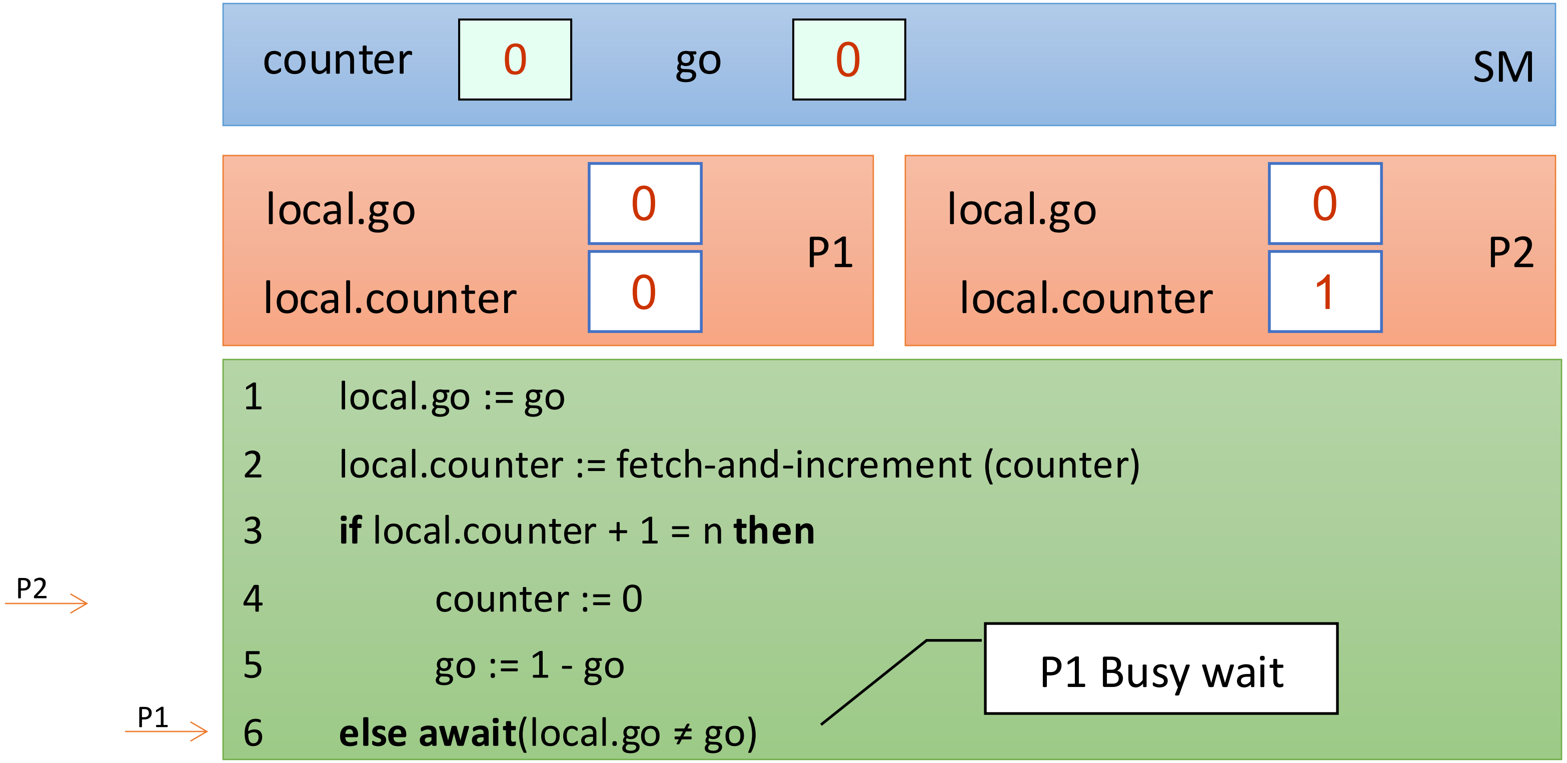
Run for n=2 Threads



```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

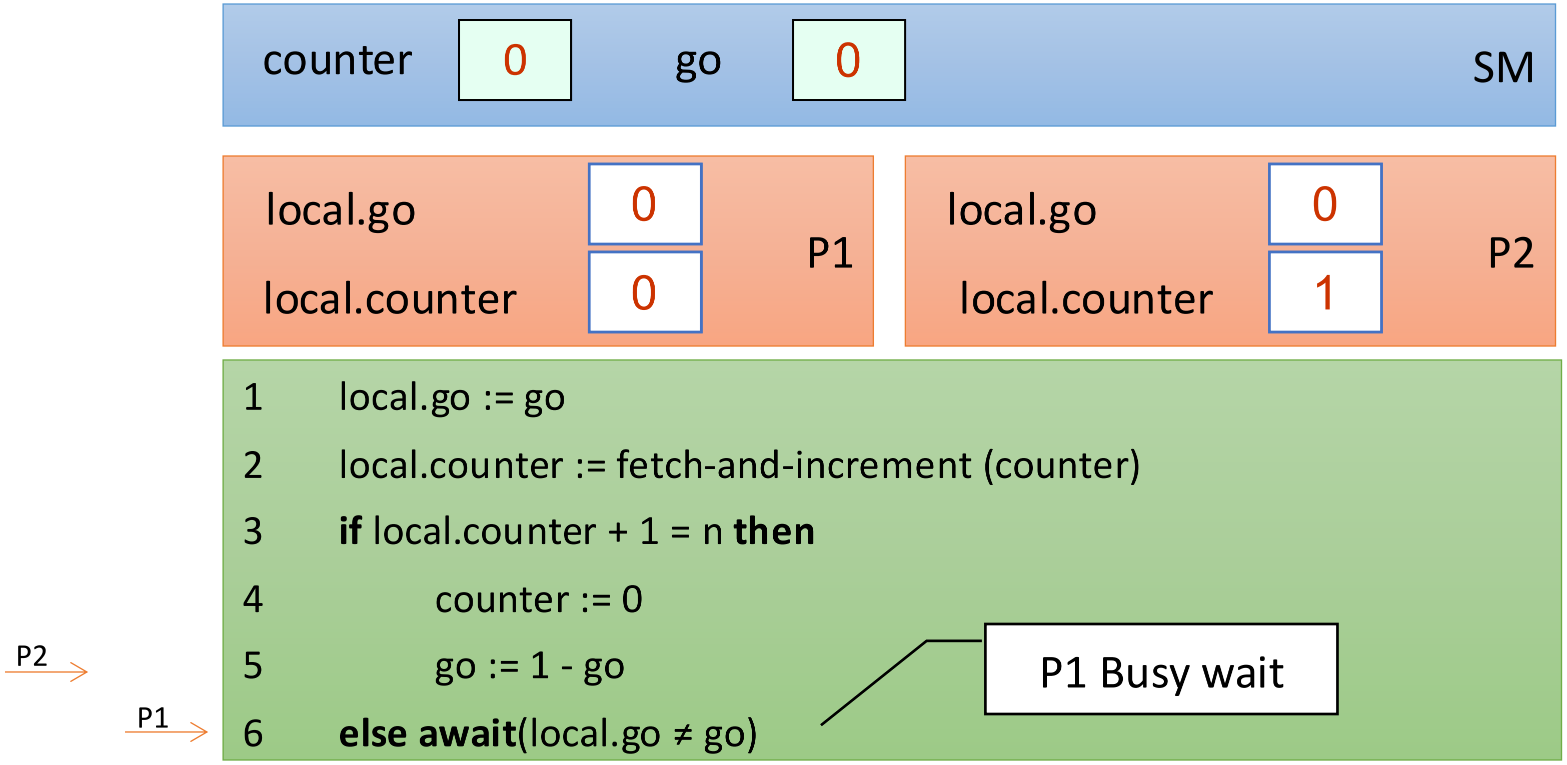
Run for n=2 Threads



```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        go := 1 - go
else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



SM

counter 0

go 0

P1

local.go 0

local.counter 0

P2

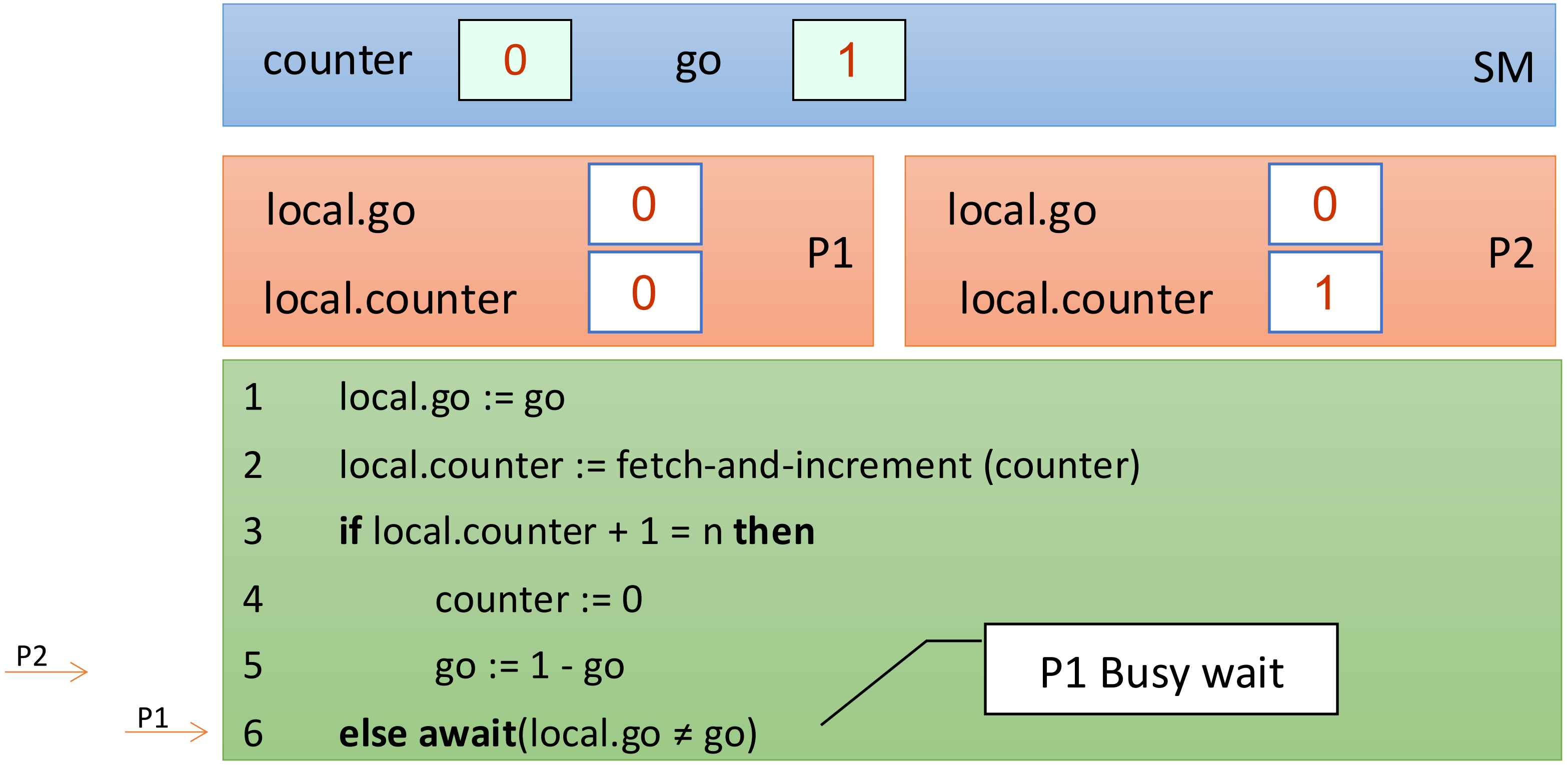
local.go 0

local.counter 1

```
1   local.go := go
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4           counter := 0
5           go := 1 - go
6   else await(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

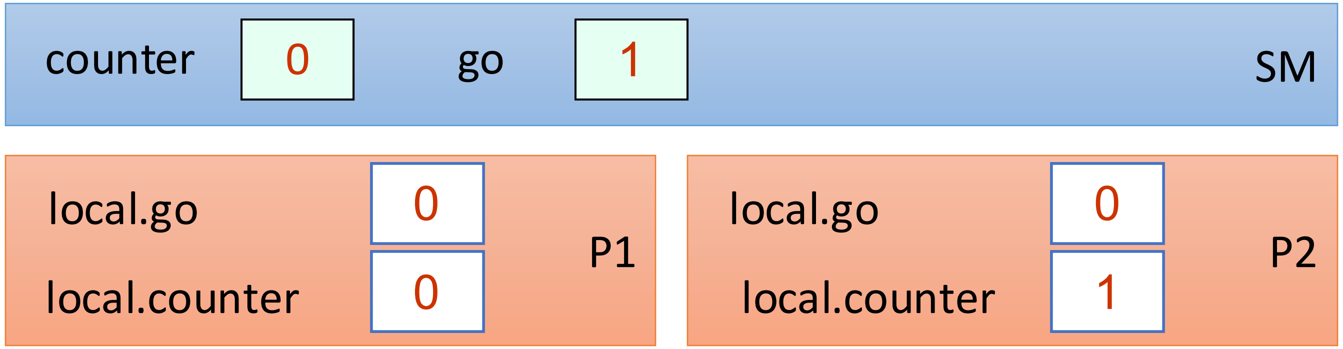
Run for n=2 Threads



```
local.go := go
local.counter := fetch-and-increment (counter)
**if** local.counter + 1 = n **then**
        counter := 0
        go := 1 - go
**else await**(local.go ≠ go)
```

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



counter 0 go 1 SM

local.go 0 local.counter 0 P1

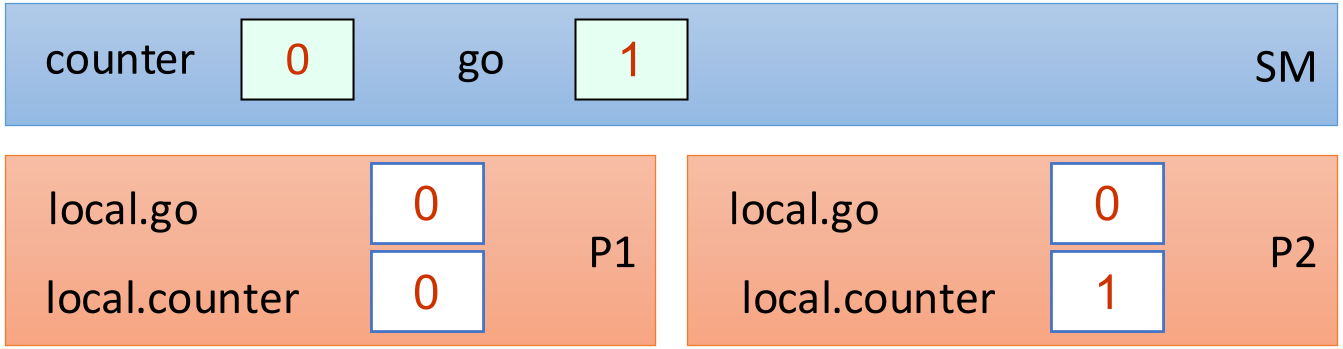
local.go 0 local.counter 1 P2

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

P2 → P1 →

Simple Barrier Using an Atomic Counter

Run for n=2 Threads

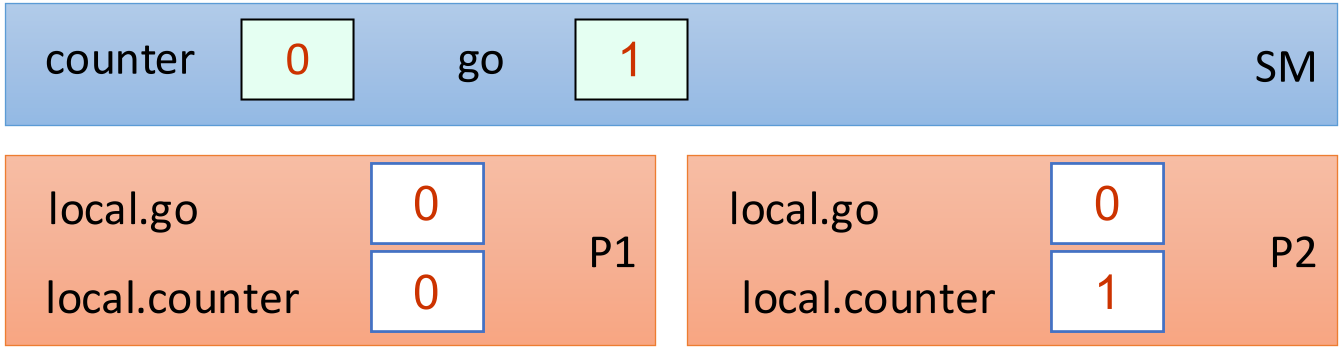


```
local.go := go
local.counter := fetch-and-increment (counter)
**if** local.counter + 1 = n **then**
        counter := 0
        go := 1 - go
**else await**(local.go ≠ go)
```

Pros/Cons?

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



counter 0 go 1 SM

local.go 0

local.counter 0

P1

local.go 0

local.counter 1

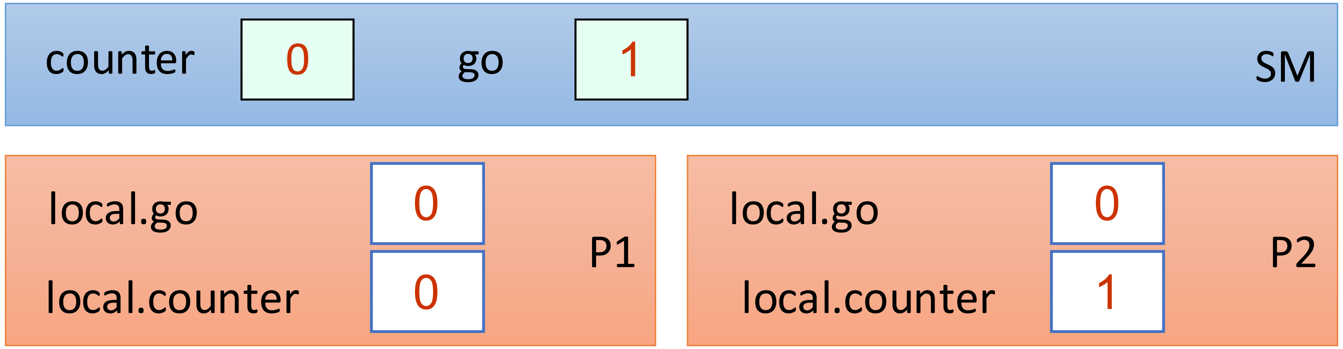
P2

```
local.go := go
local.counter := fetch-and-increment (counter)
**if** local.counter + 1 = n **then**
        counter := 0
        go := 1 - go
**else await**(local.go ≠ go)
```

Pros/Cons?

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



counter 0 go 1 SM

local.go 0

local.counter 0

P1

local.go 0

local.counter 1

P2

```
local.go := go
local.counter := fetch-and-increment (counter)
**if** local.counter + 1 = n **then**
        counter := 0
        go := 1 - go
**else await**(local.go ≠ go)
```

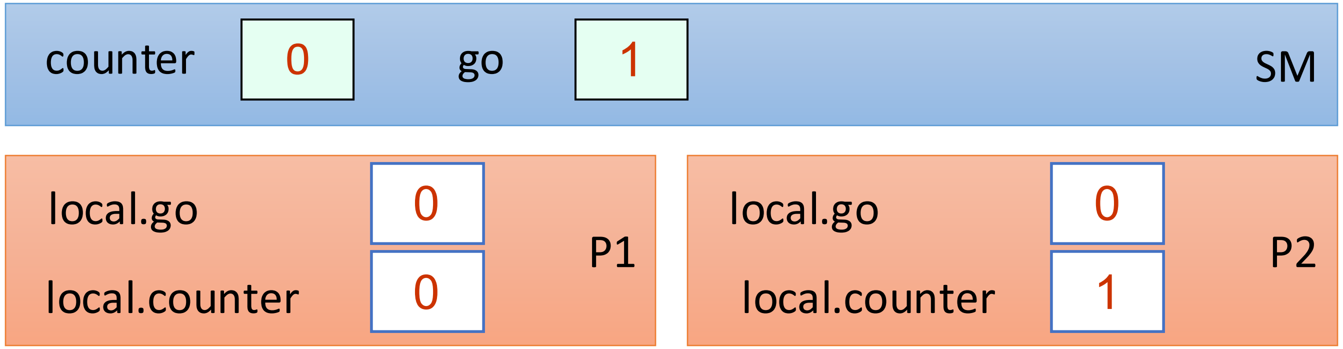
P2 → P1 →

Pros/Cons?

- There is high memory contention on *go* bit

Simple Barrier Using an Atomic Counter

Run for n=2 Threads



counter 0 go 1 SM

local.go 0 local.counter 0 P1

local.go 0 local.counter 1 P2

```
local.go := go
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    go := 1 - go
else await(local.go ≠ go)
```

P2 → P1 →

Pros/Cons?

- There is high memory contention on *go* bit
- Reducing the contention:
    - Replace the *go* bit with *n* bits: *go*[1],…,*go*[*n*]
    - Process p_i may spin only on the bit *go*[*i*]

A Local Spinning Counter Barrier

Program of a Thread i

```
shared   counter: fetch and increment reg. – {0,..n}, initially = 0
         go[1..n]: array of atomic bits, initial values are immaterial
local    local.go: a bit, initial value is immaterial
         local.counter: register
```

A Local Spinning Counter Barrier

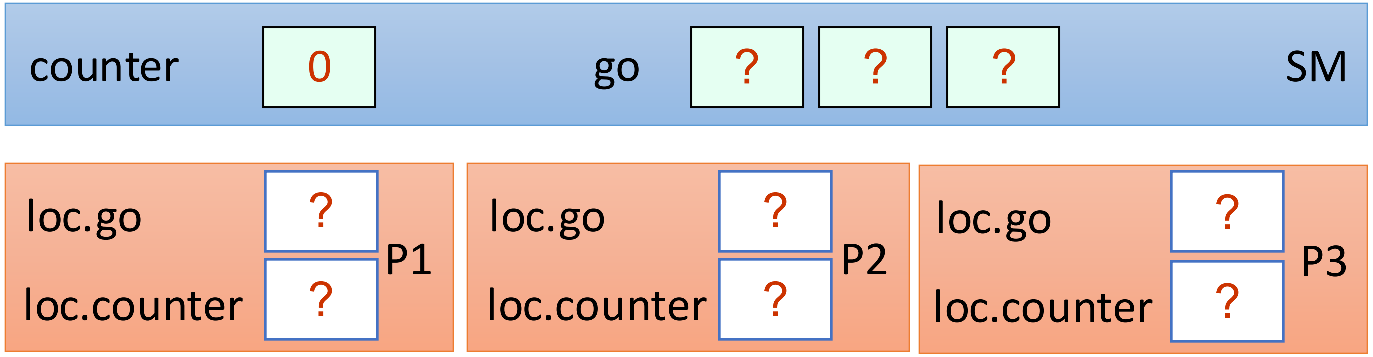
Program of a Thread i

```
shared    counter: fetch and increment reg. – {0,..n}, initially = 0
          go[1..n]: array of atomic bits, initial values are immaterial
local     local.go: a bit, initial value is immaterial
          local.counter: register
```

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0 go ? ? ? SM

loc.go ? loc.counter ? P1

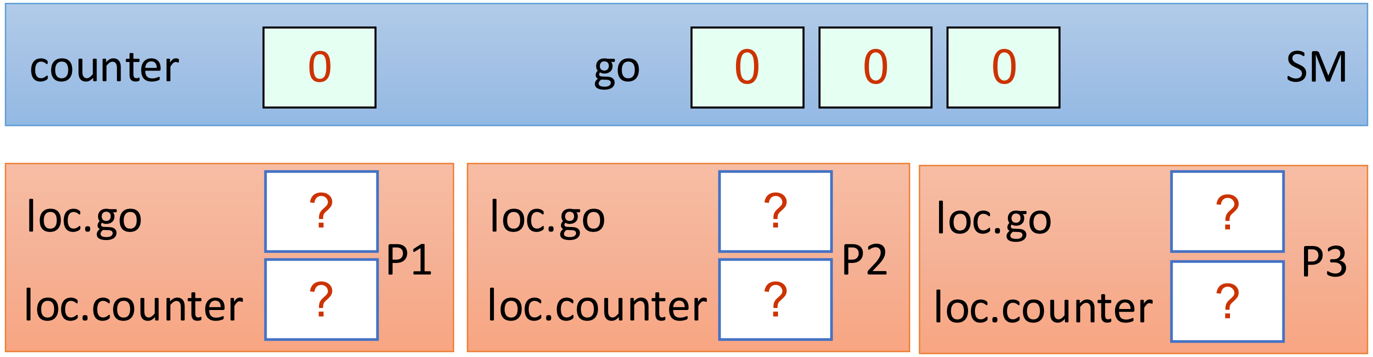
loc.go ? loc.counter ? P2

loc.go ? loc.counter ? P3

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0 go 0 0 0 SM

loc.go ? loc.counter ? P1

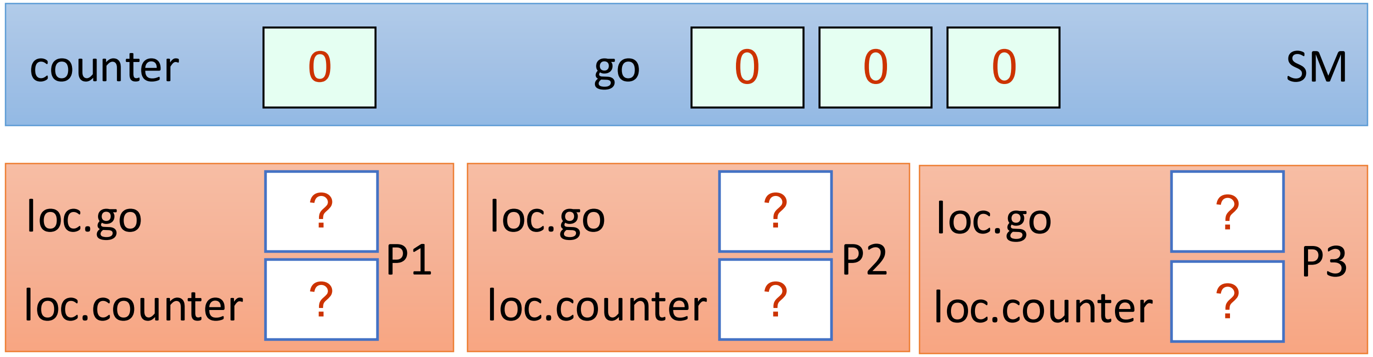
loc.go ? loc.counter ? P2

loc.go ? loc.counter ? P3

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads

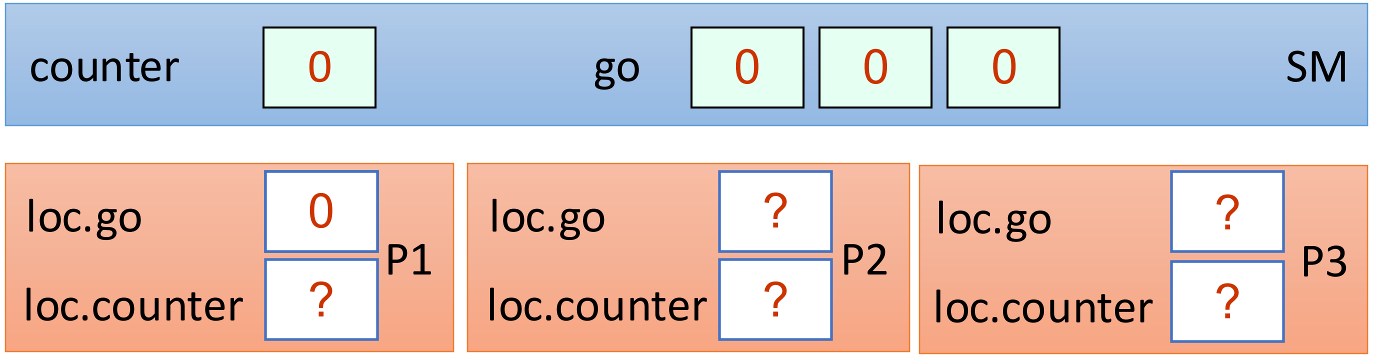


P1 →

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0 go 0 0 0 SM

loc.go 0 loc.counter ? P1

loc.go ? loc.counter ? P2

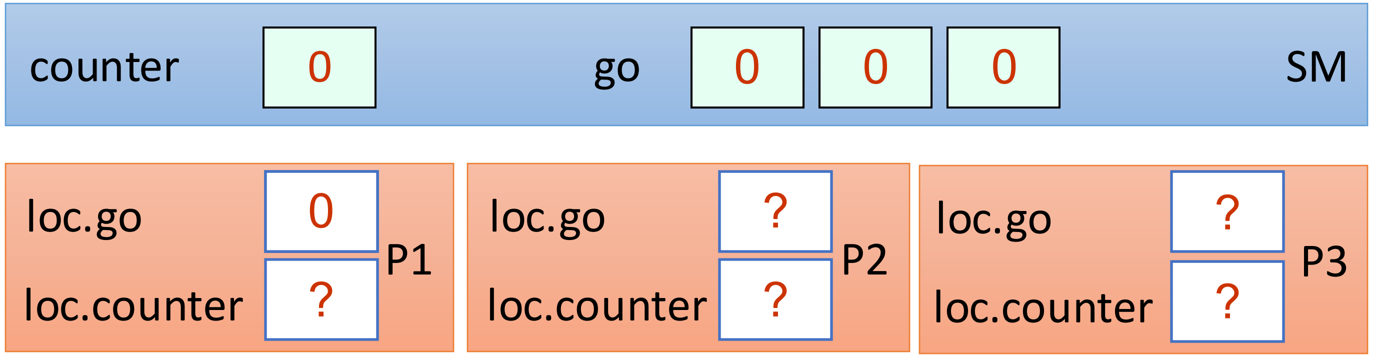
loc.go ? loc.counter ? P3

P1 →

```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4           counter := 0
5           for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0

go 0 0 0

SM

loc.go 0

loc.counter ?

P1

loc.go ?

loc.counter ?

P2

loc.go ?

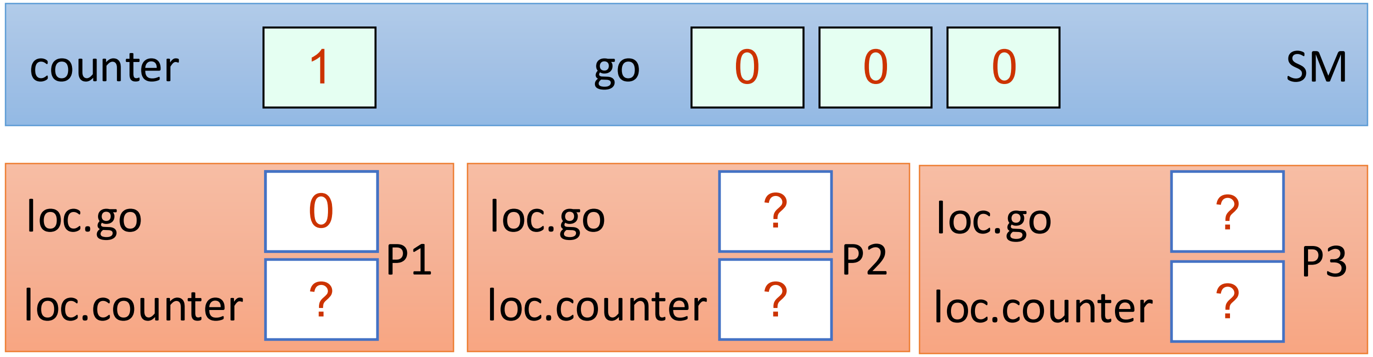
loc.counter ?

P3

```
      local.go := go[i]
P1 →  local.counter := fetch-and-increment (counter)
      if local.counter + 1 = n then
          counter := 0
          for j=1 to n { go[j] := 1 – go[j] }
      else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 1

go 0 0 0

SM

loc.go 0

loc.counter ?

P1

loc.go ?

loc.counter ?

P2

loc.go ?

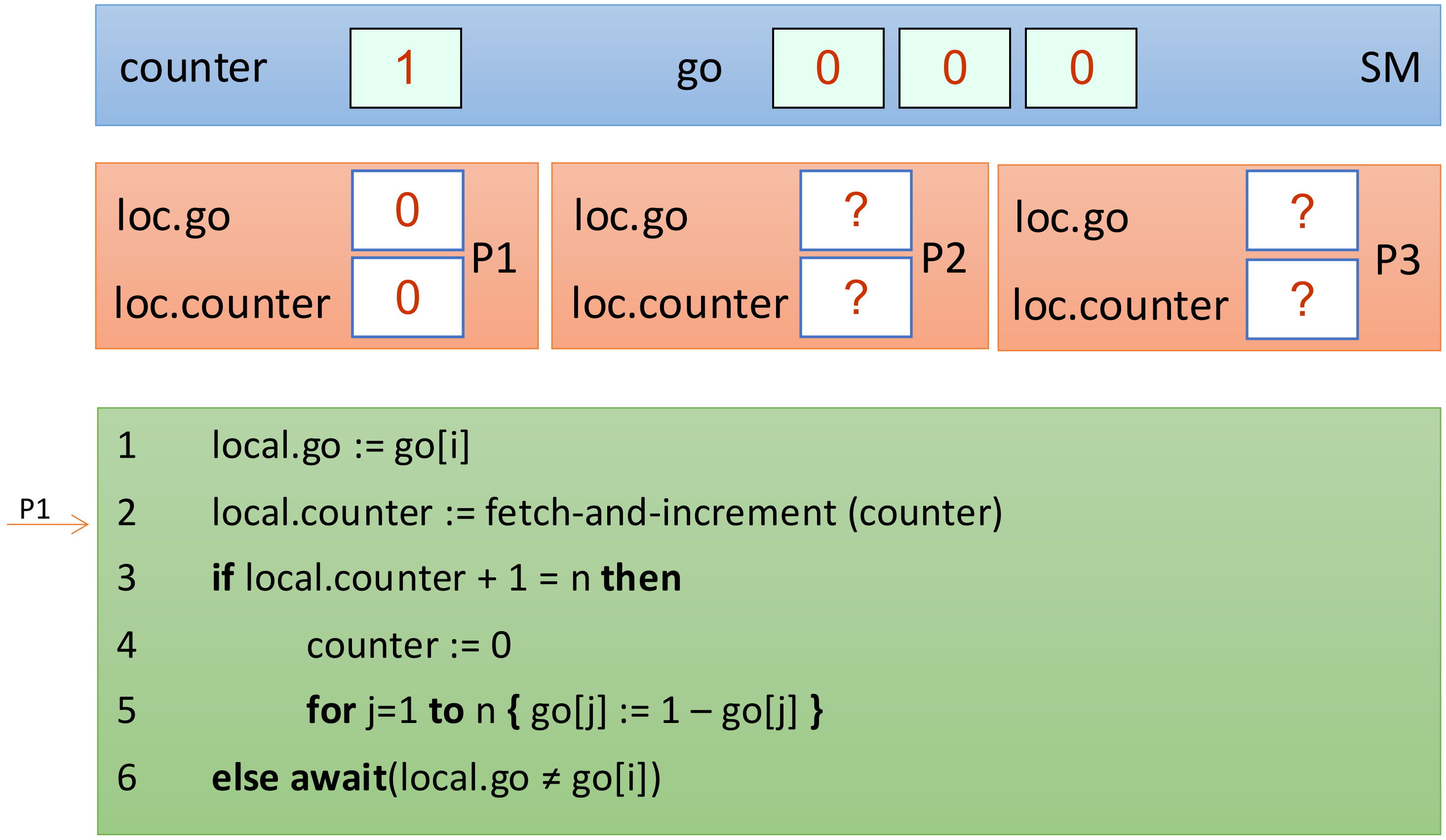
loc.counter ?

P3

```
      1    local.go := go[i]
P1 →  2    local.counter := fetch-and-increment (counter)
      3    if local.counter + 1 = n then
      4        counter := 0
      5        for j=1 to n { go[j] := 1 – go[j] }
      6    else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



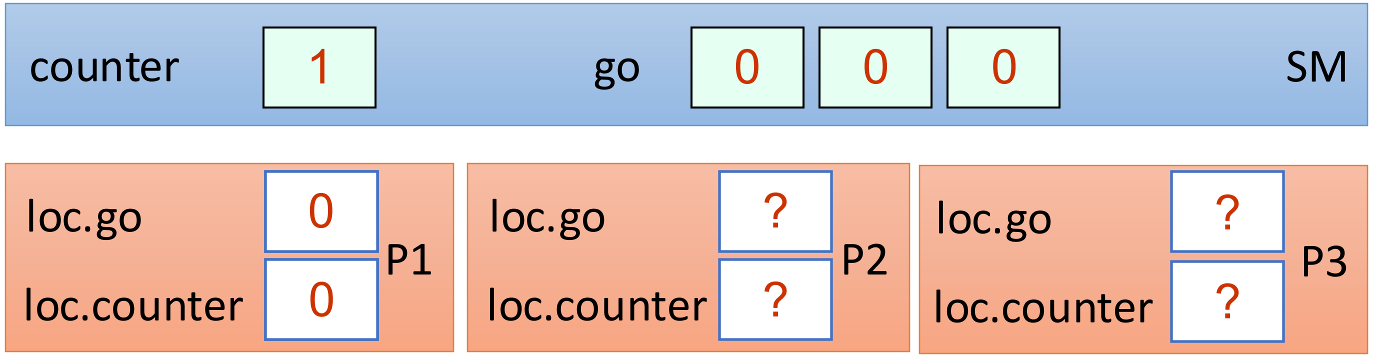
SM				
counter	1	go	0	0	0

	P1	P2	P3
loc.go	0	?	?
loc.counter	0	?	?

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
**if** local.counter + 1 = n **then**
        counter := 0
        **for** j=1 **to** n **{** go[j] := 1 – go[j] **}**
**else await**(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



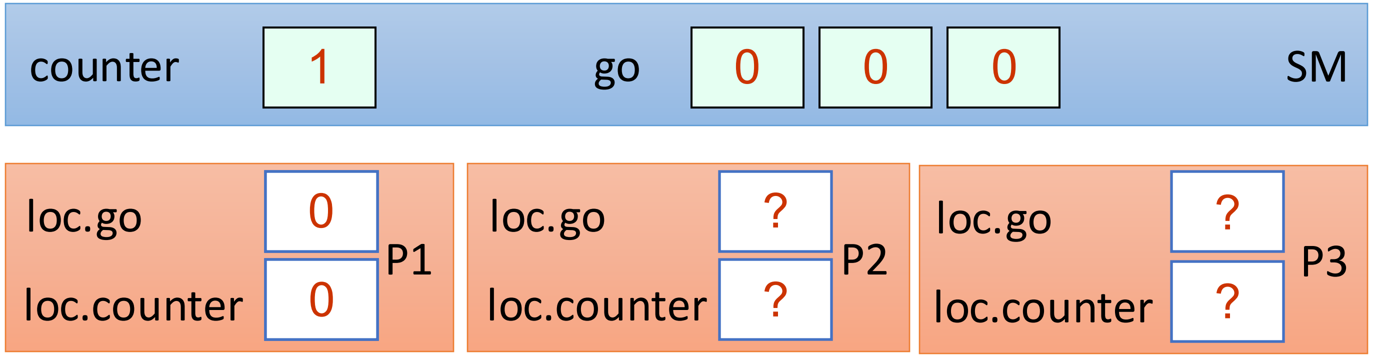
counter	1	go	0	0	0	SM

loc.go	0	loc.go	?	loc.go	?		
loc.counter	0	loc.counter	?	loc.counter	?		
P1		P2		P3			

```
     1   local.go := go[i]
     2   local.counter := fetch-and-increment (counter)
P1 → 3   if local.counter + 1 = n then
     4       counter := 0
     5       for j=1 to n { go[j] := 1 – go[j] }
     6   else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 1 go 0 0 0 SM

P1: loc.go 0, loc.counter 0

P2: loc.go ?, loc.counter ?

P3: loc.go ?, loc.counter ?

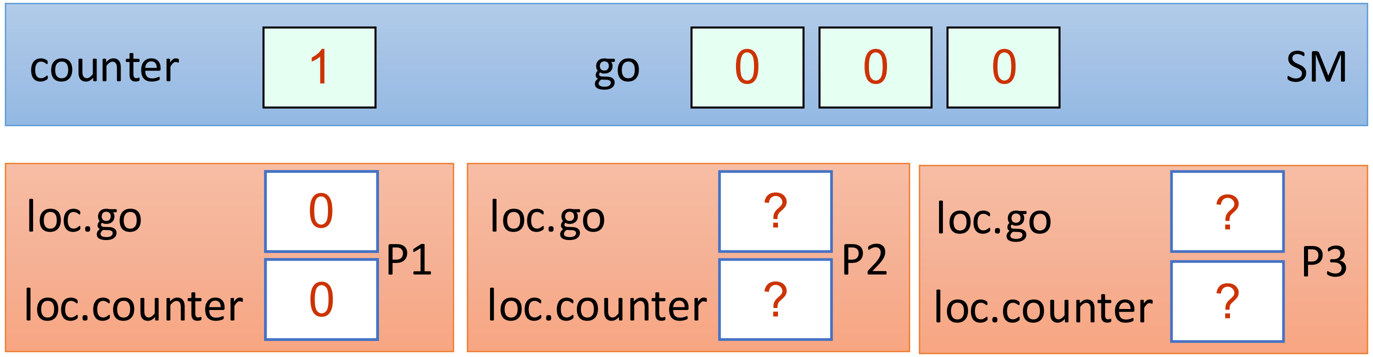
```
local.go := go[i]
local.counter := fetch-and-increment(
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1 → **if** local.counter + 1 = n **then**

0+1≠3

A Local Spinning Counter Barrier

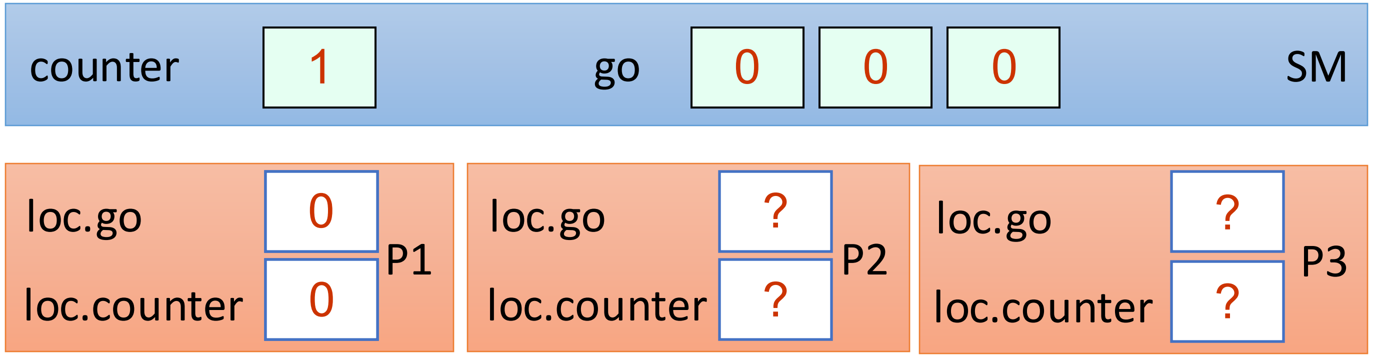
Example Run for n=3 Threads



```
       local.go := go[i]
       local.counter := fetch-and-increment (counter)
       if local.counter + 1 = n then
           counter := 0
           for j=1 to n { go[j] := 1 – go[j] }
P1 →   else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 1 go 0 0 0 SM

loc.go 0 loc.counter 0 P1

loc.go ? loc.counter ? P2

loc.go ? loc.counter ? P3

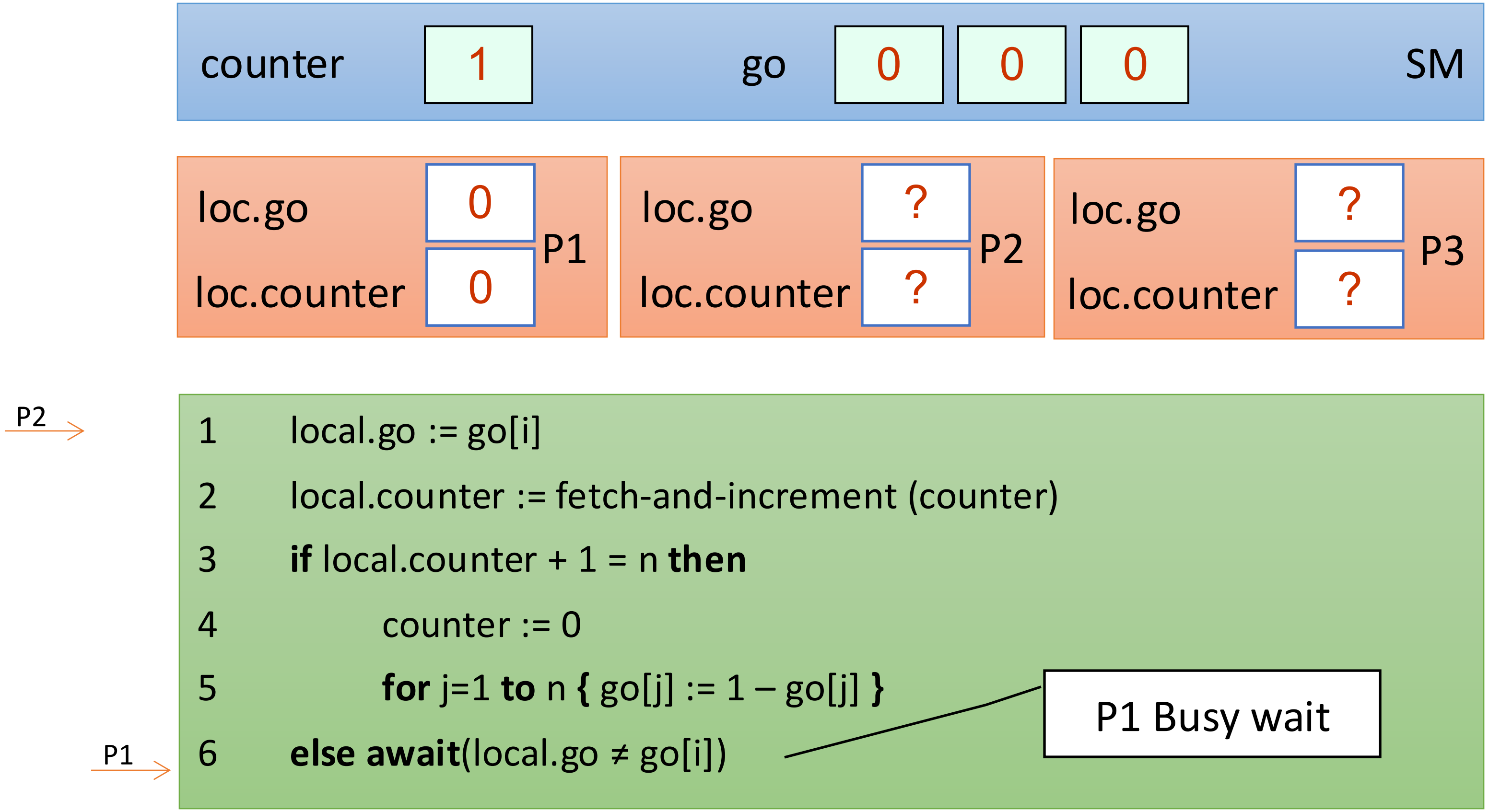
```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 1 go 0 0 0 SM

P1: loc.go 0, loc.counter 0

P2: loc.go ?, loc.counter ?

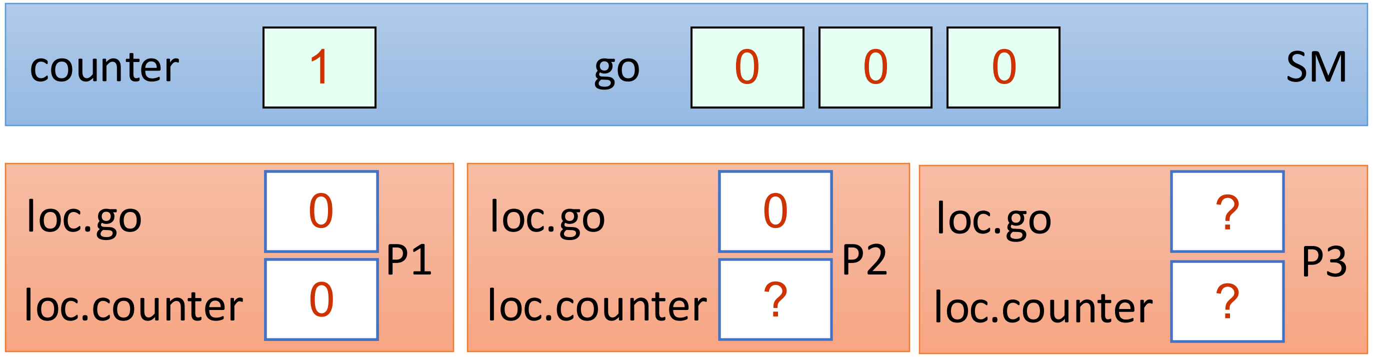
P3: loc.go ?, loc.counter ?

```
P2 →  local.go := go[i]
      local.counter := fetch-and-increment (counter)
      if local.counter + 1 = n then
          counter := 0
          for j=1 to n { go[j] := 1 – go[j] }
P1 →  else await(local.go ≠ go[i])
```

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter	1	go	0	0	0	SM

loc.go	0	P1
loc.counter	0	

loc.go	0	P2
loc.counter	?	

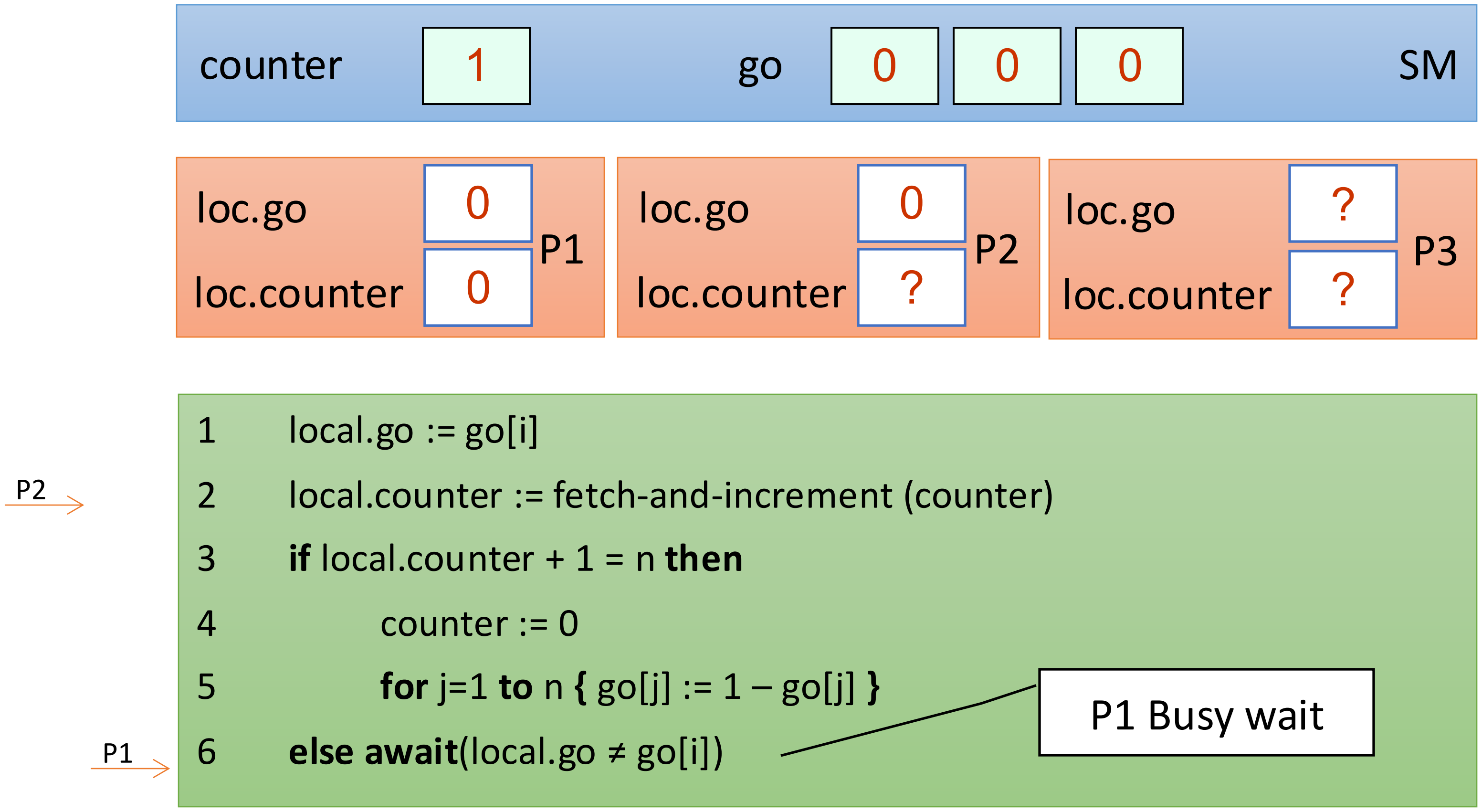
loc.go	?	P3
loc.counter	?	

```
P2 →  1    local.go := go[i]
      2    local.counter := fetch-and-increment (counter)
      3    if local.counter + 1 = n then
      4        counter := 0
      5        for j=1 to n { go[j] := 1 – go[j] }
P1 →  6    else await(local.go ≠ go[i])
```

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



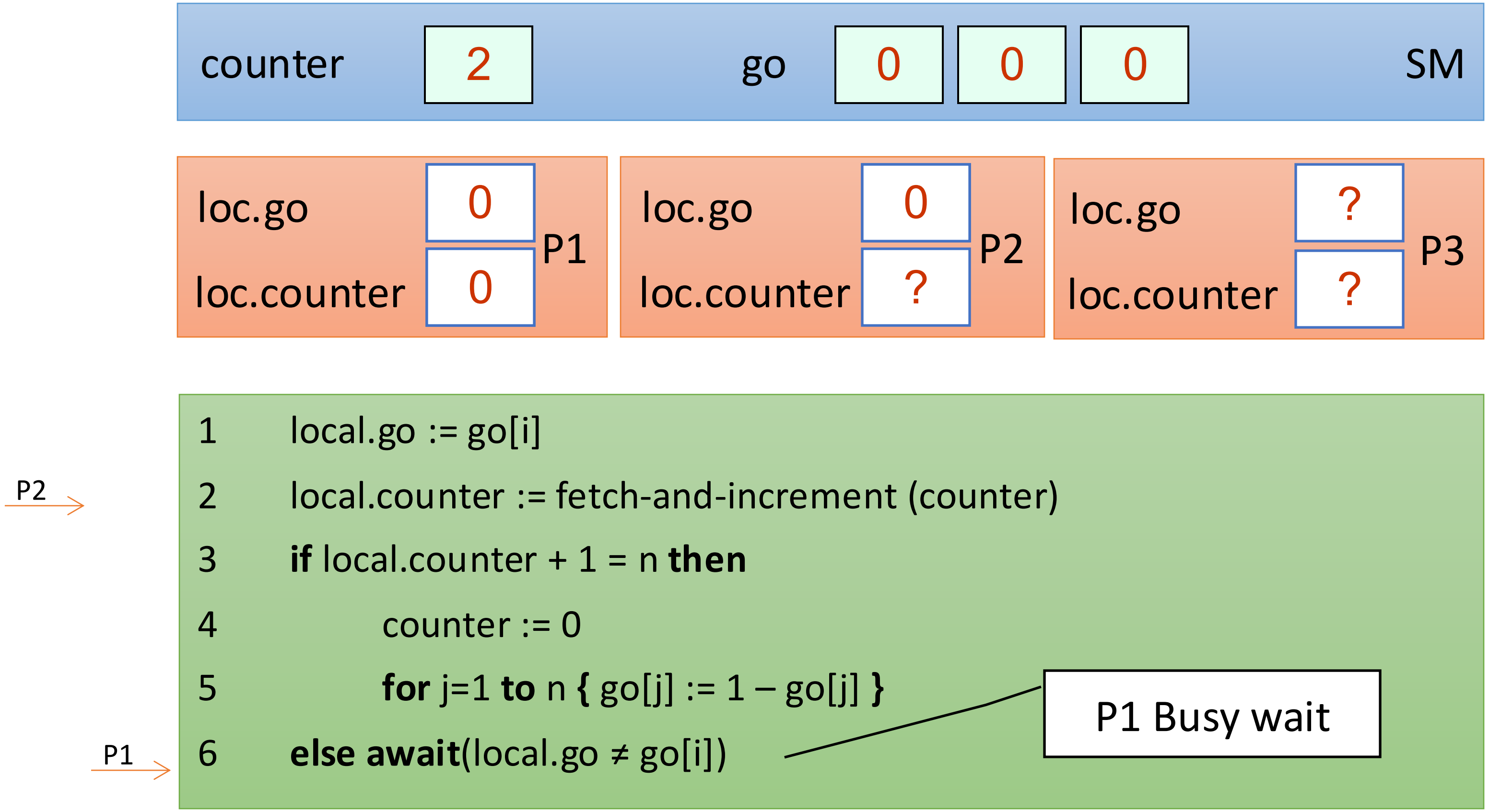
SM				
counter	1			
go	0	0	0	

	loc.go	loc.counter
P1	0	0
P2	0	?
P3	?	?

```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 2 go 0 0 0 SM

P1: loc.go 0, loc.counter 0

P2: loc.go 0, loc.counter ?

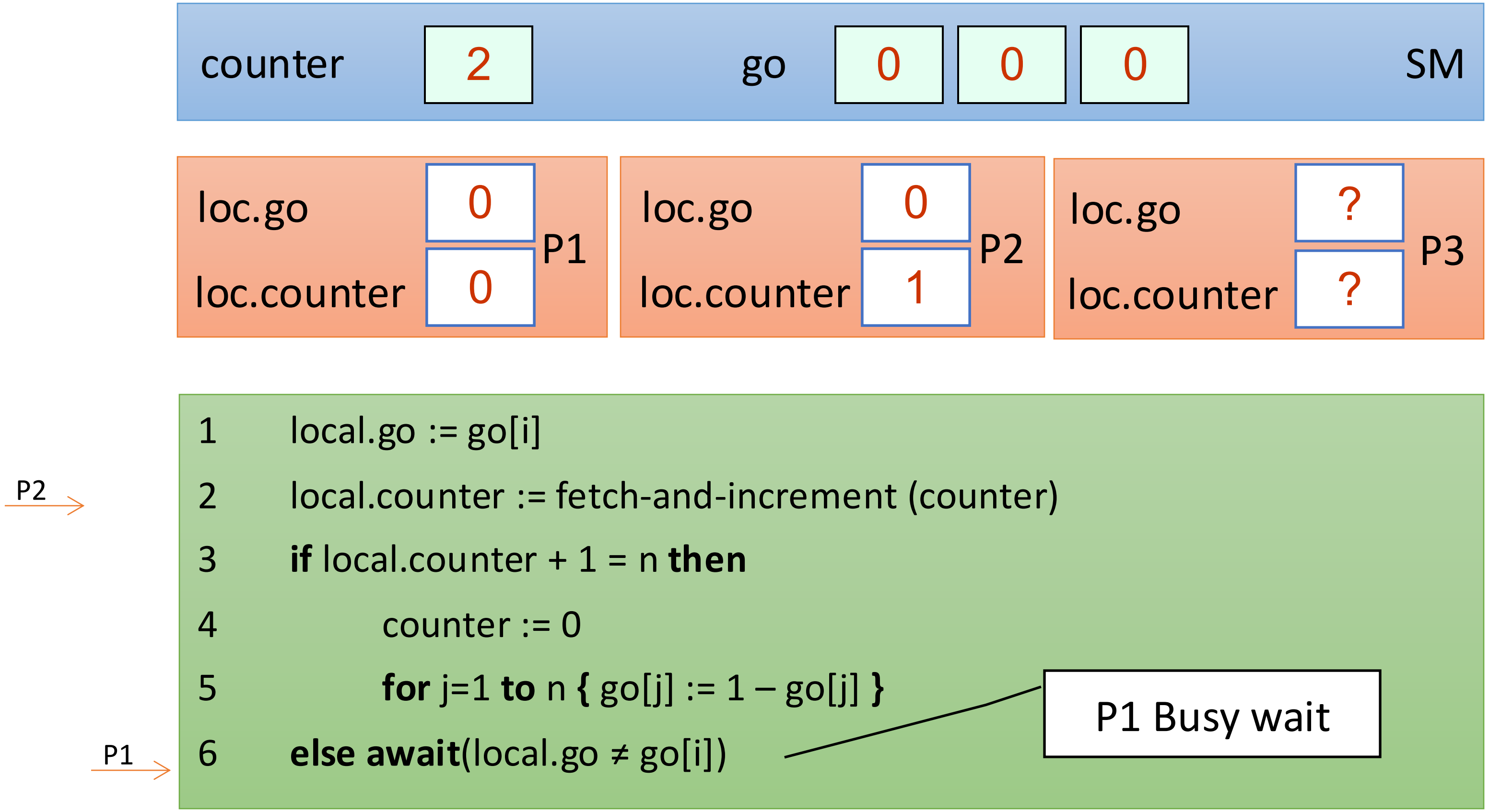
P3: loc.go ?, loc.counter ?

```
   local.go := go[i]
P2 → local.counter := fetch-and-increment (counter)
   if local.counter + 1 = n then
       counter := 0
       for j=1 to n { go[j] := 1 – go[j] }
P1 → else await(local.go ≠ go[i])
```

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



SM

counter 2

go 0 0 0

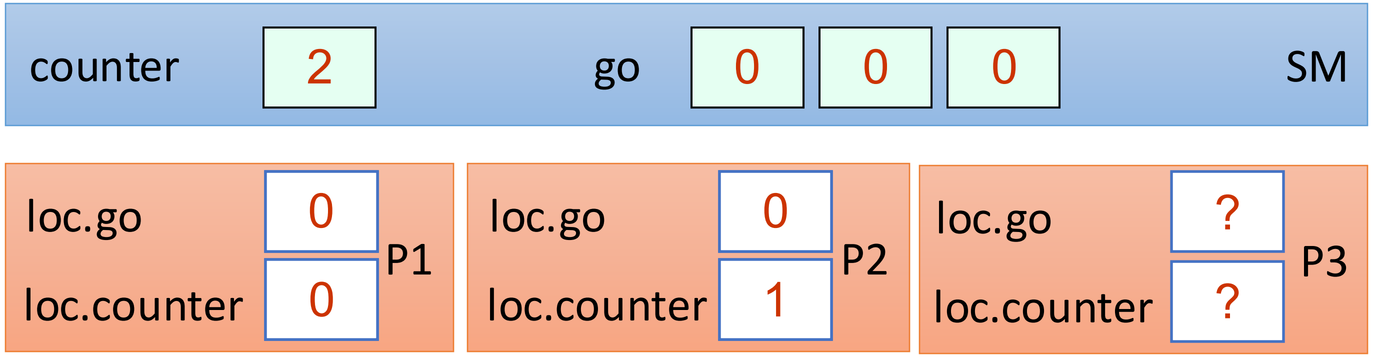
	P1	P2	P3
loc.go	0	0	?
loc.counter	0	1	?

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter	2	go	0	0	0	SM

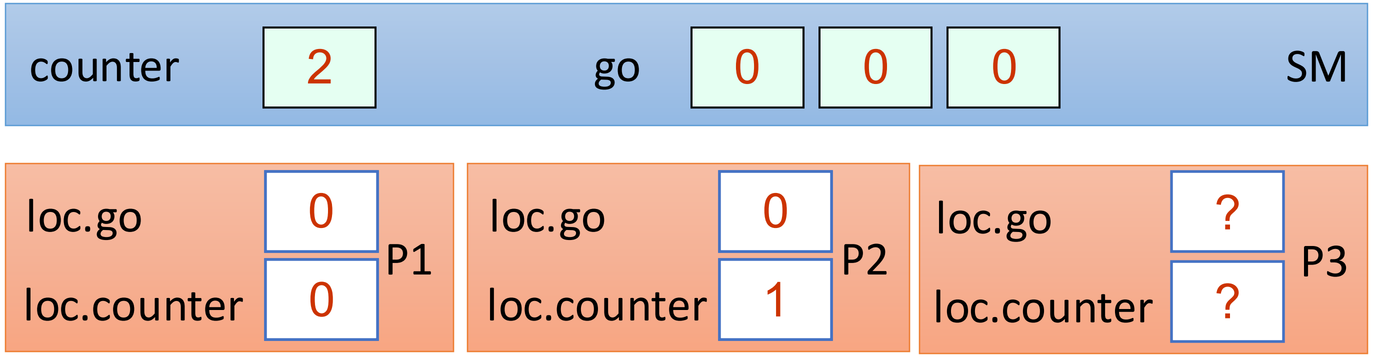
loc.go	0	P1
loc.counter	0	
loc.go	0	P2
loc.counter	1	
loc.go	?	P3
loc.counter	?	

```
      1   local.go := go[i]
      2   local.counter := fetch-and-increment (counter)
P2 →  3   if local.counter + 1 = n then
      4       counter := 0
      5       for j=1 to n { go[j] := 1 – go[j] }
P1 →  6   else await(local.go ≠ go[i])
```

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



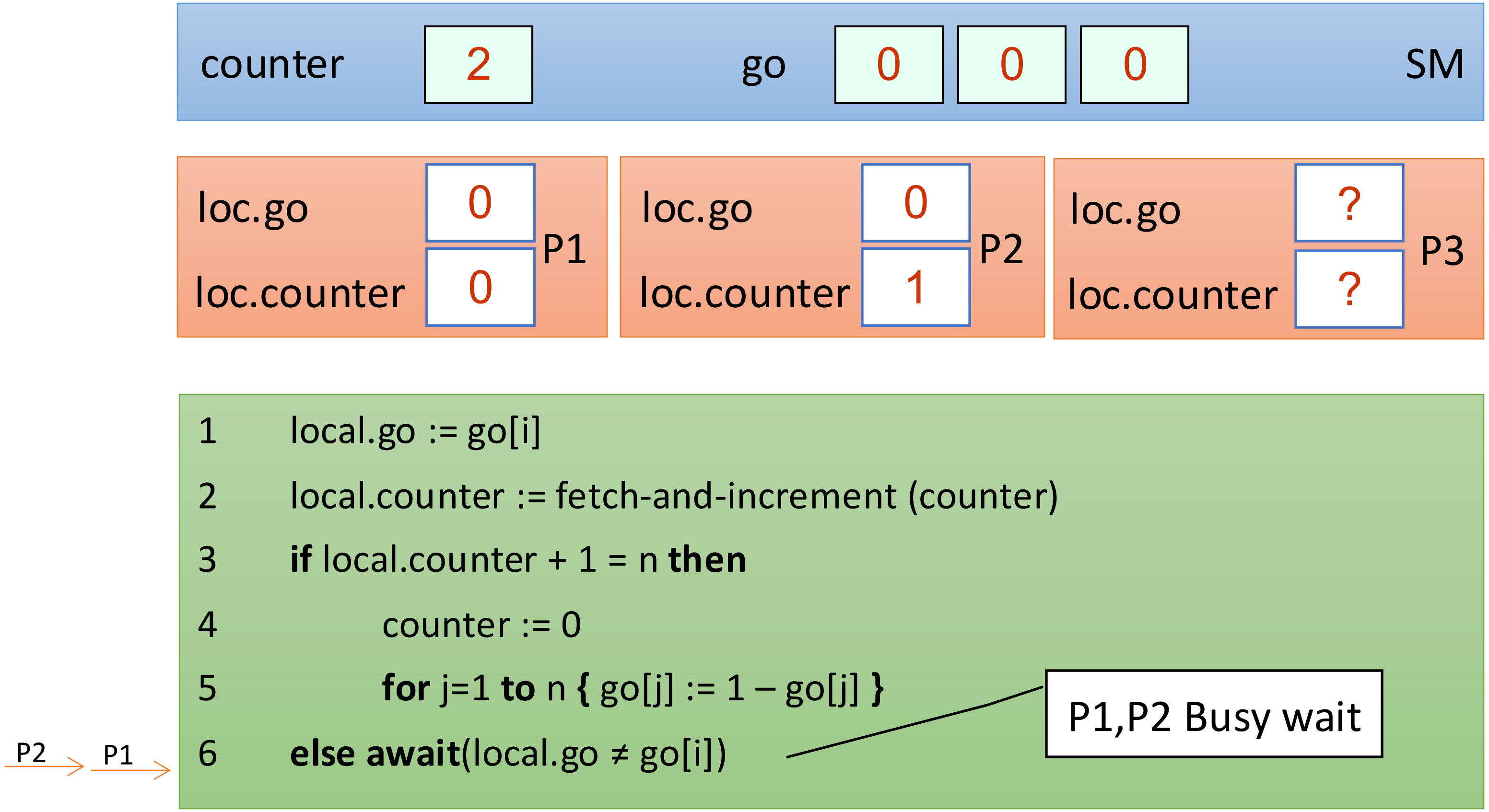
```
   1   local.go := go[i]
   2   local.counter := fetch-and-increment
P2 → 3   if local.counter + 1 = n then
   4         counter := 0
   5         for j=1 to n { go[j] := 1 – go[j] }
P1 → 6   else await(local.go ≠ go[i])
```

1+1≠3

P1 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



SM				
counter	2	go	0	0	0

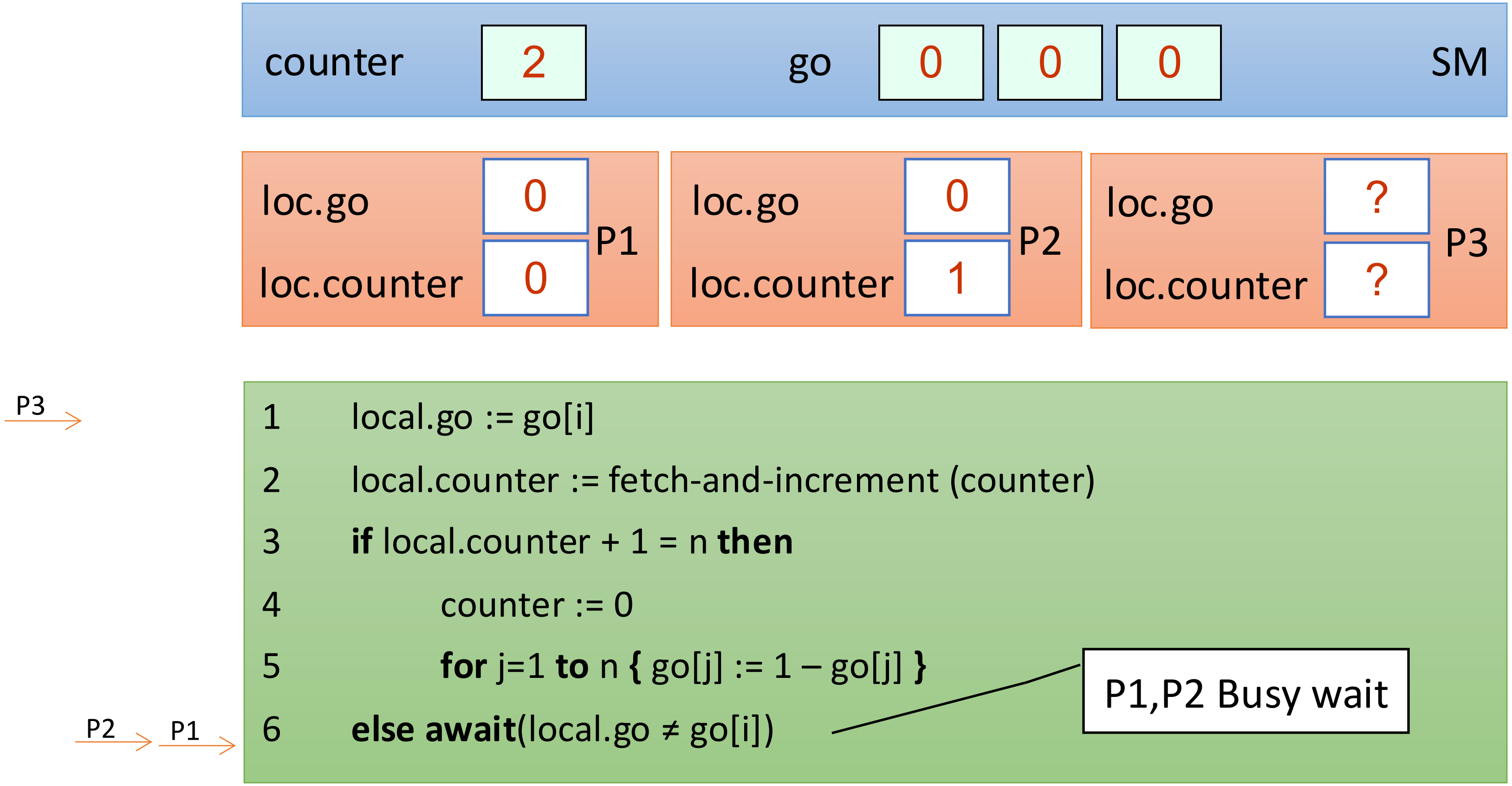
	P1	P2	P3
loc.go	0	0	?
loc.counter	0	1	?

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



SM				
counter	2	go	0	0	0

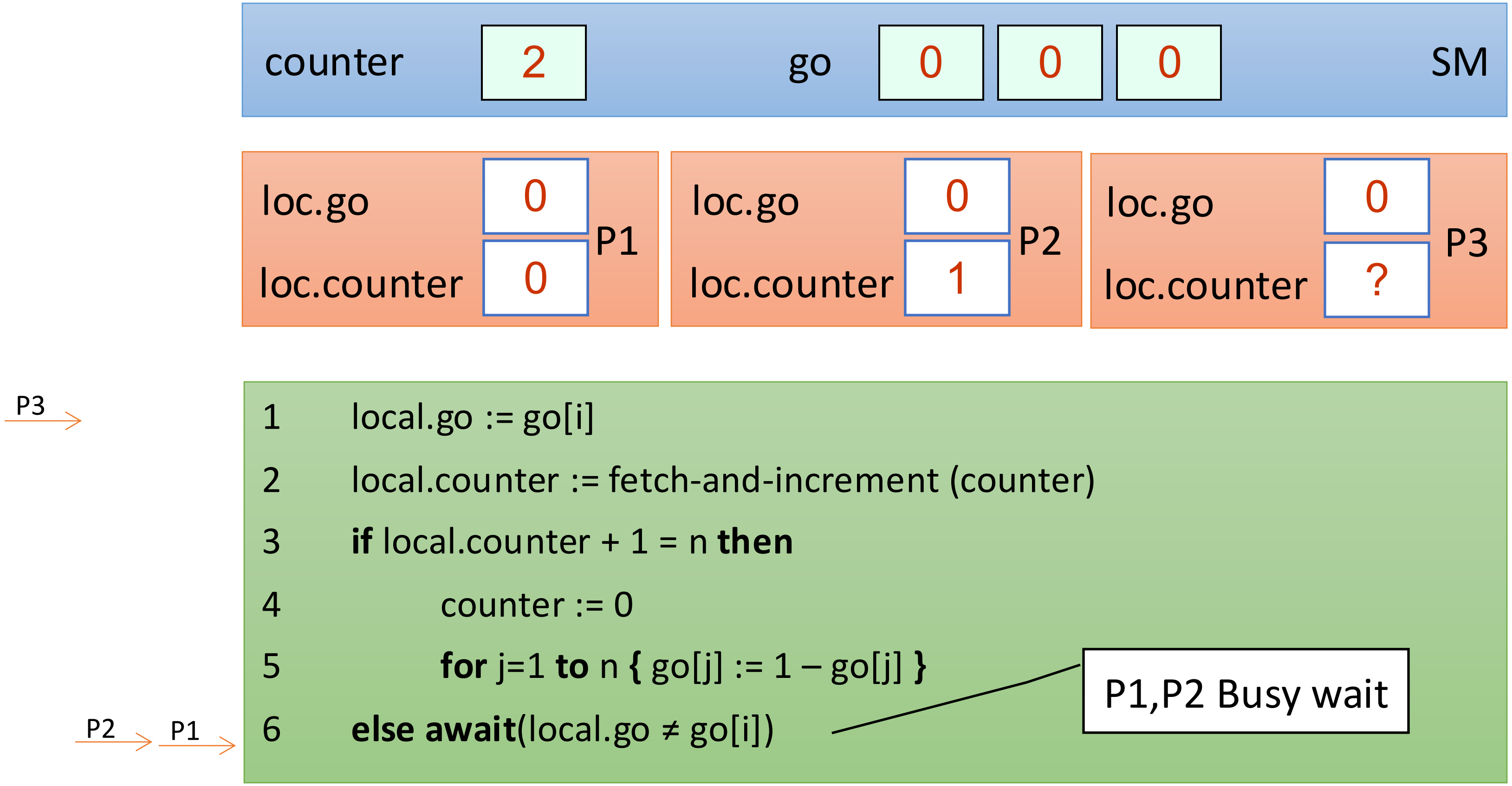
	P1	P2	P3
loc.go	0	0	?
loc.counter	0	1	?

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
**if** local.counter + 1 = n **then**
        counter := 0
        **for** j=1 **to** n **{** go[j] := 1 – go[j] **}**
**else await**(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



SM: counter 2; go 0 0 0

P1: loc.go 0; loc.counter 0

P2: loc.go 0; loc.counter 1

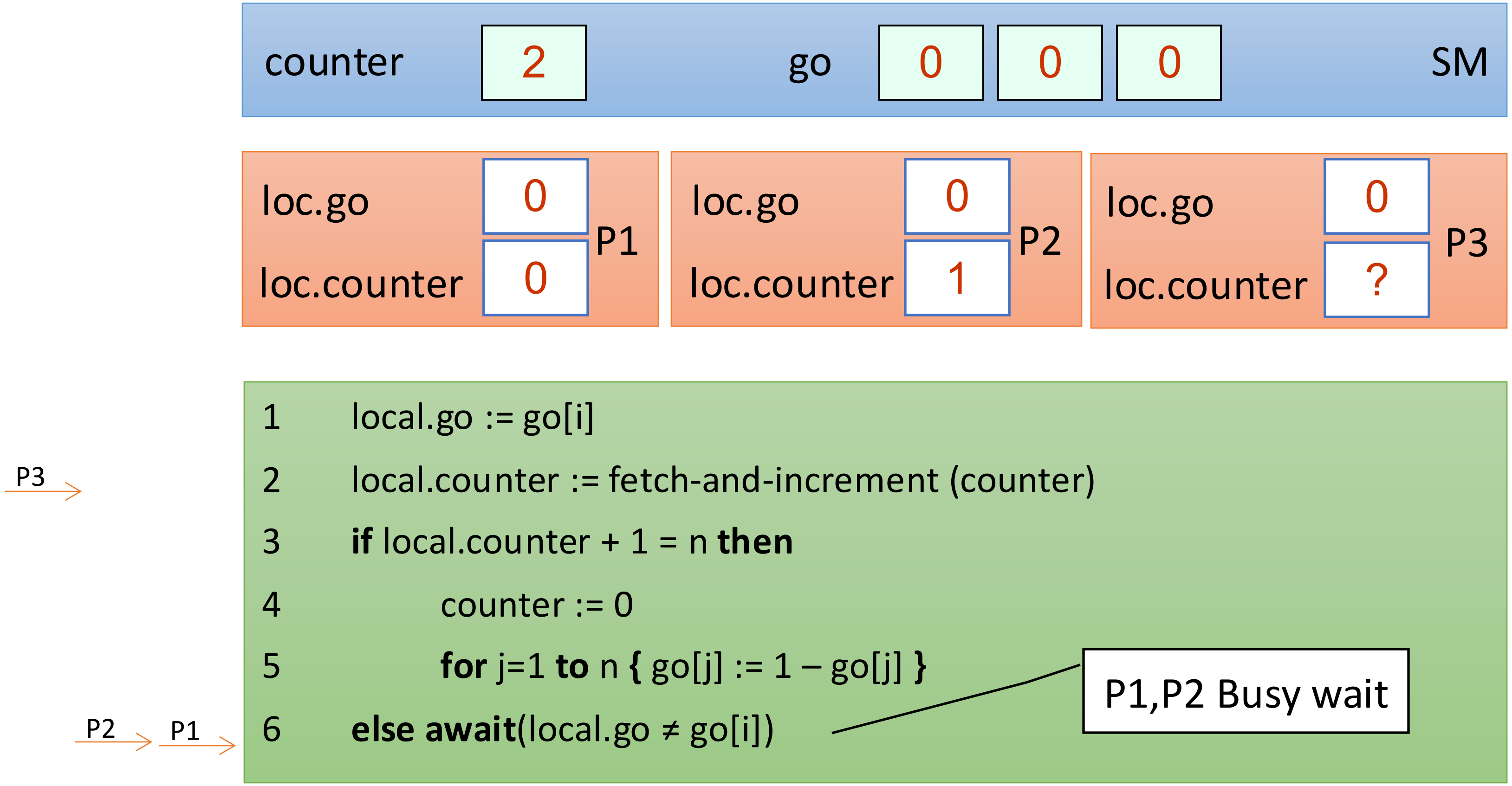
P3: loc.go 0; loc.counter ?

```
1    local.go := go[i]                                    ← P3
2    local.counter := fetch-and-increment (counter)
3    if local.counter + 1 = n then
4        counter := 0
5        for j=1 to n { go[j] := 1 – go[j] }
6    else await(local.go ≠ go[i])                         ← P2, P1
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

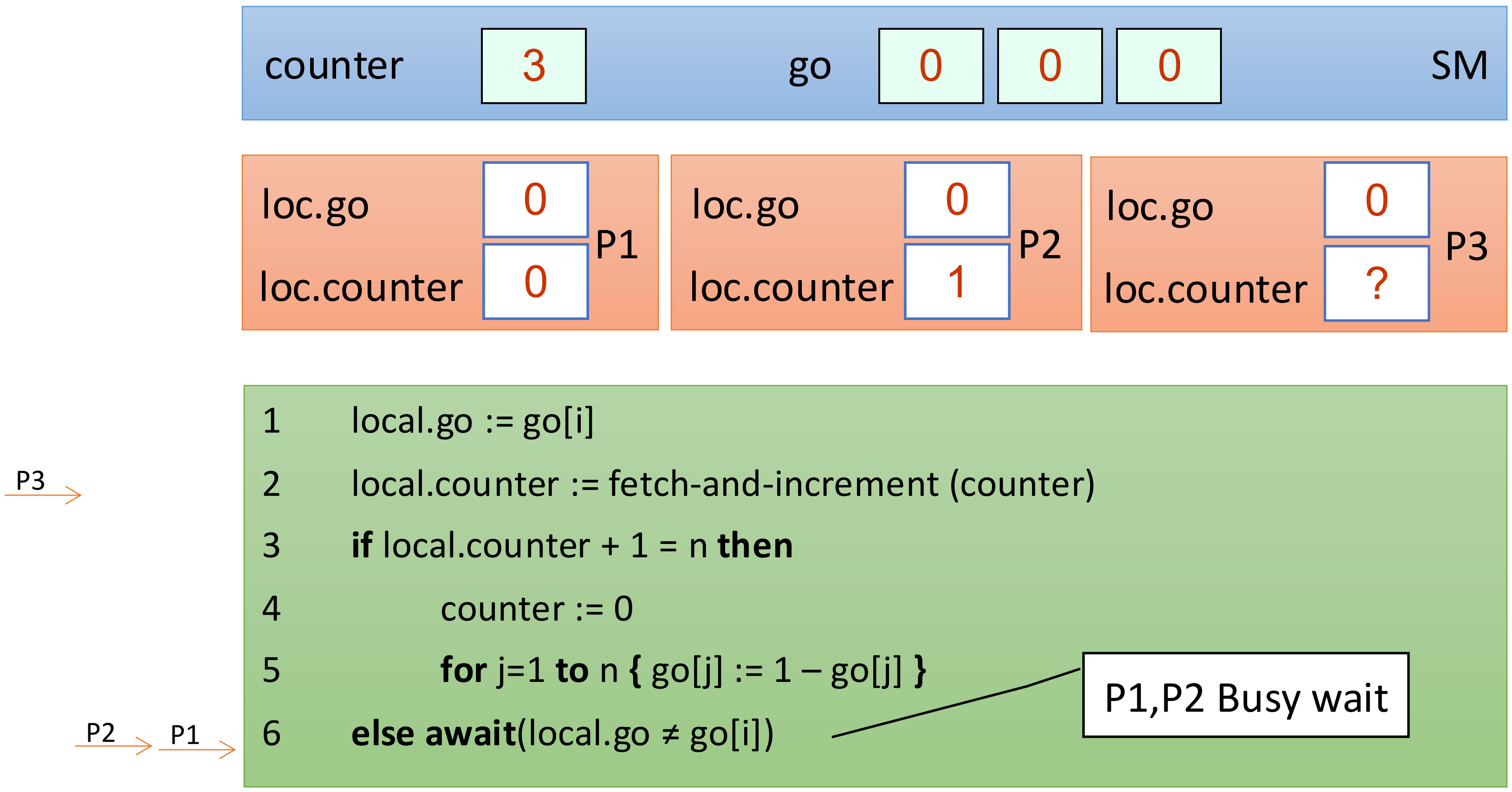
Example Run for n=3 Threads



```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   **if** local.counter + 1 = n **then**
4           counter := 0
5           **for** j=1 **to** n **{** go[j] := 1 – go[j] **}**
6   **else await**(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter	3	go	0	0	0	SM

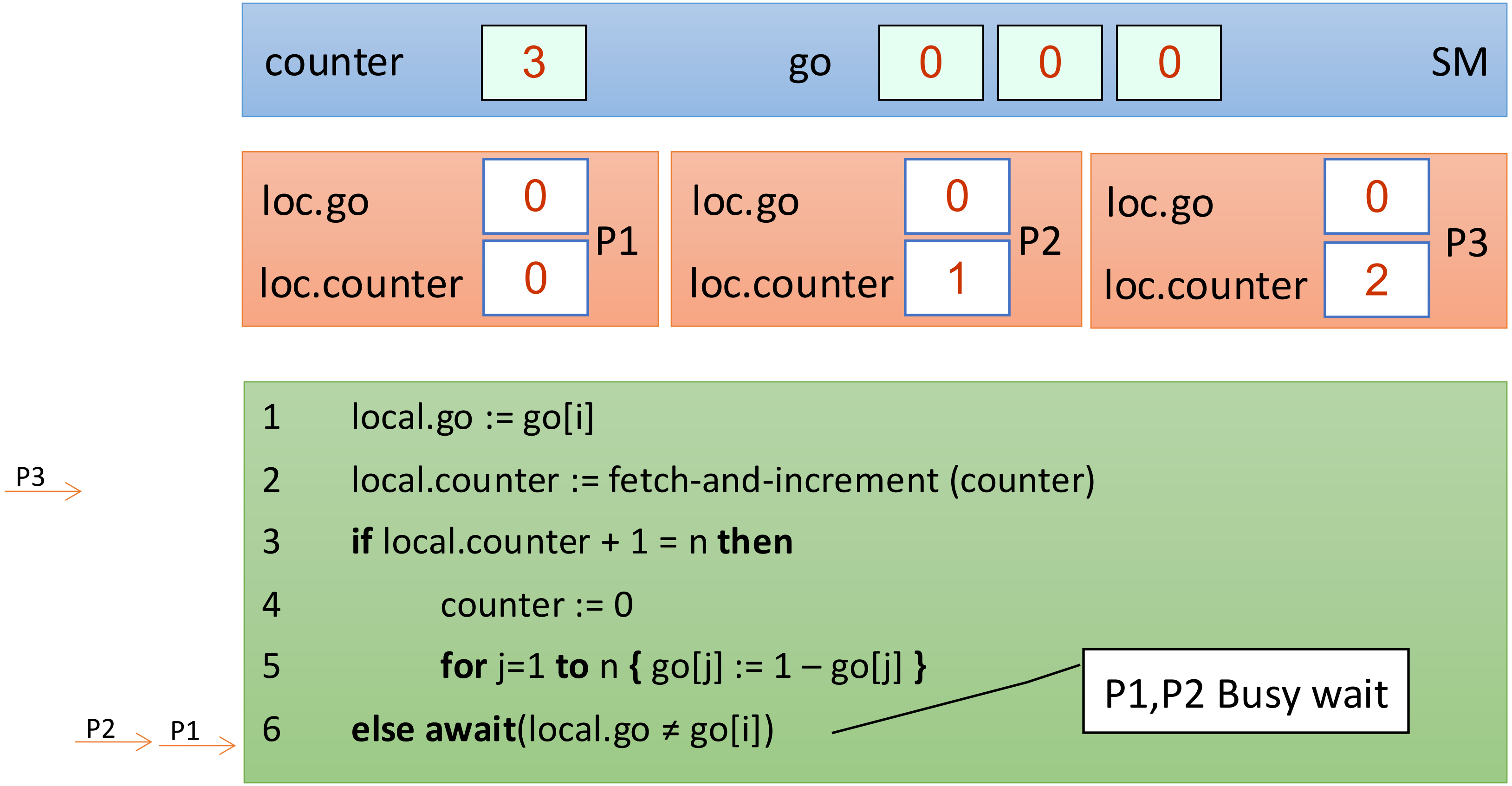
loc.go	0	P1	loc.go	0	P2	loc.go	0	P3
loc.counter	0		loc.counter	1		loc.counter	?	

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads

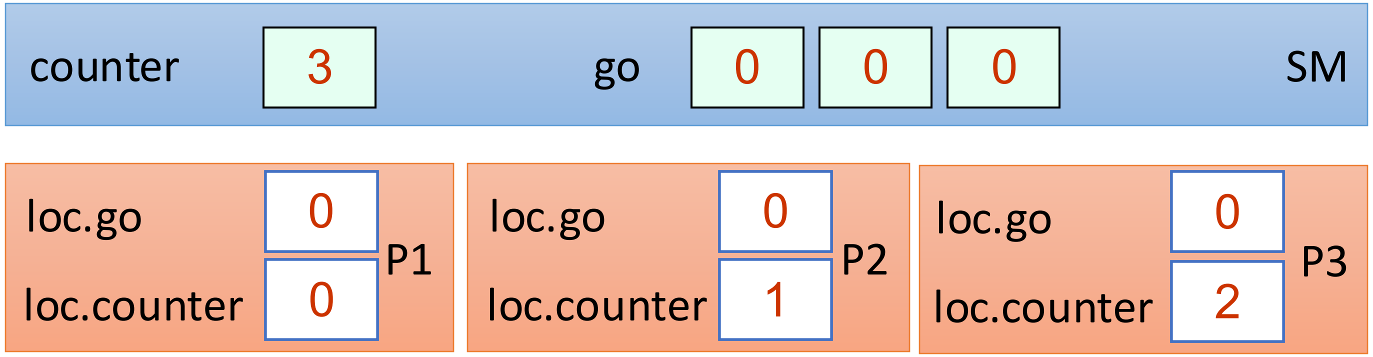


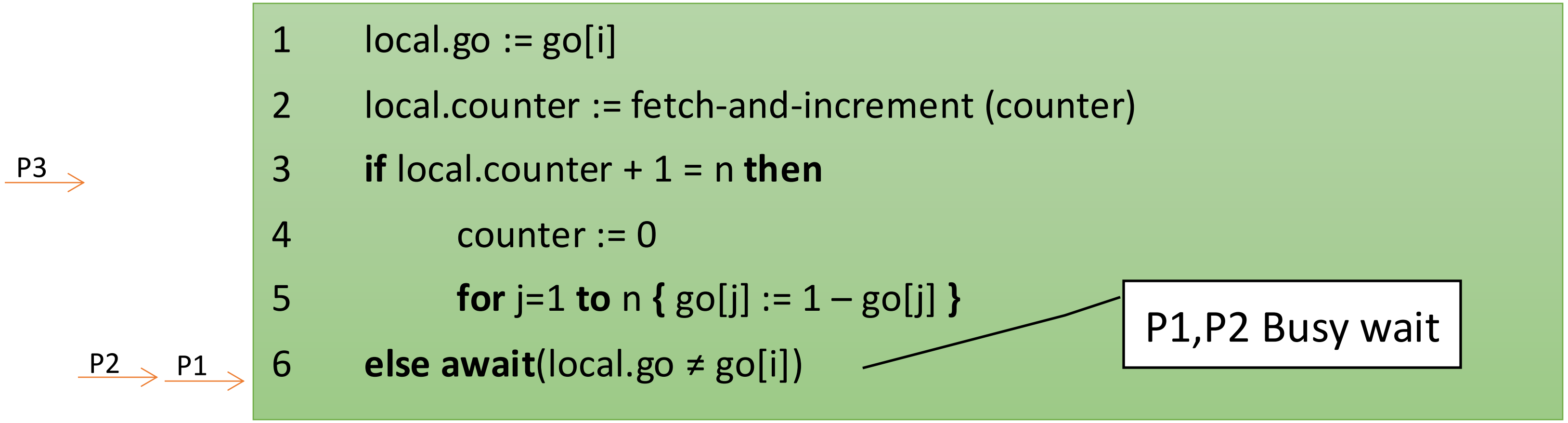
```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads

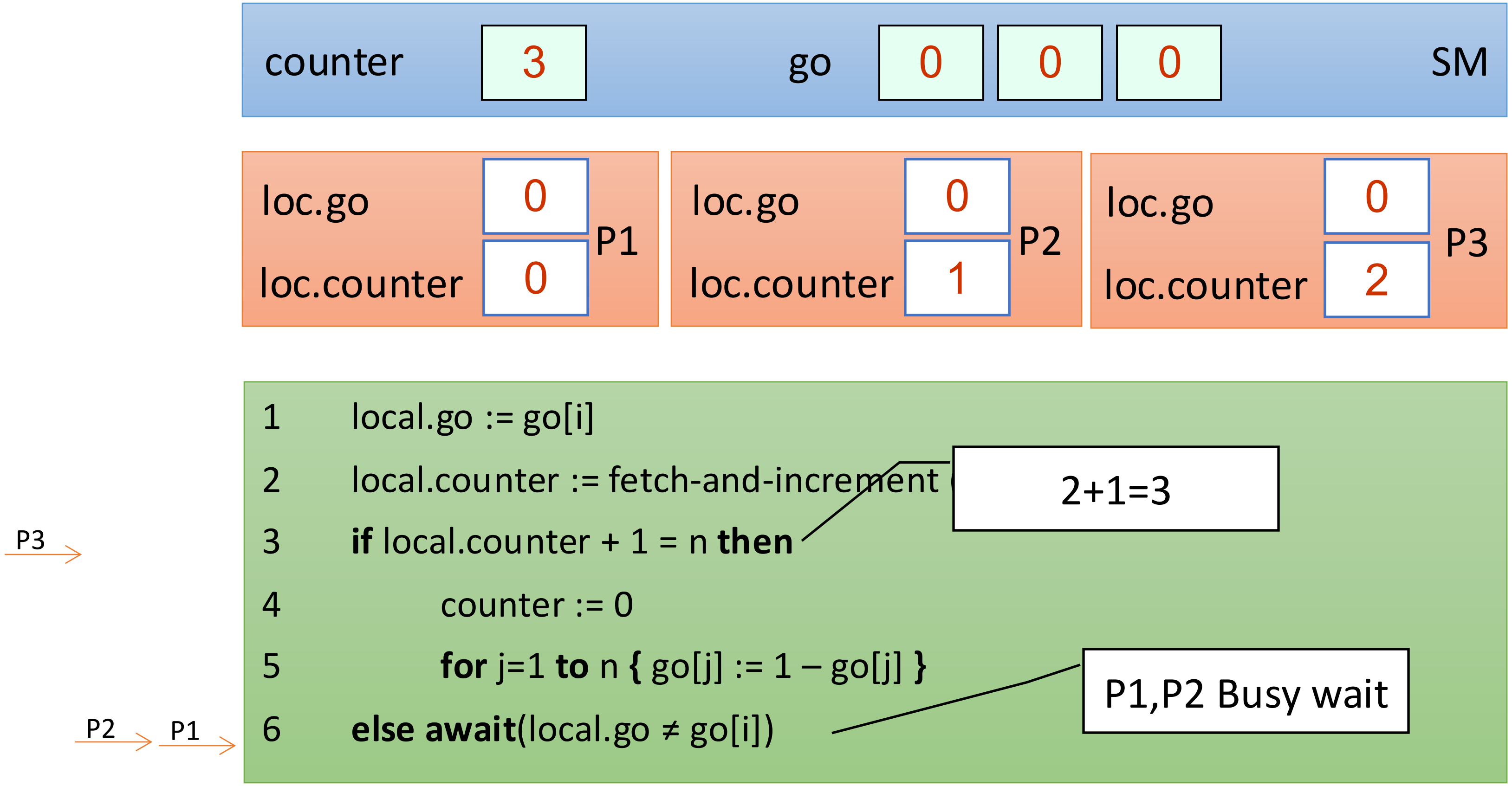




```
1    local.go := go[i]
2    local.counter := fetch-and-increment (counter)
3    if local.counter + 1 = n then
4        counter := 0
5        for j=1 to n { go[j] := 1 – go[j] }
6    else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



SM				
counter	3	go	0	0	0

	P1	P2	P3
loc.go	0	0	0
loc.counter	0	1	2

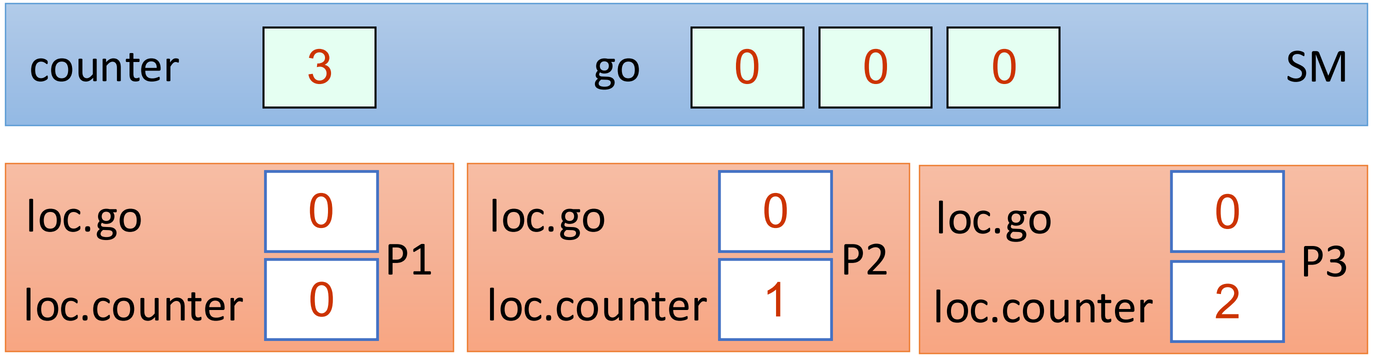
```
1   local.go := go[i]
2   local.counter := fetch-and-increment
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

2+1=3

P1,P2 Busy wait

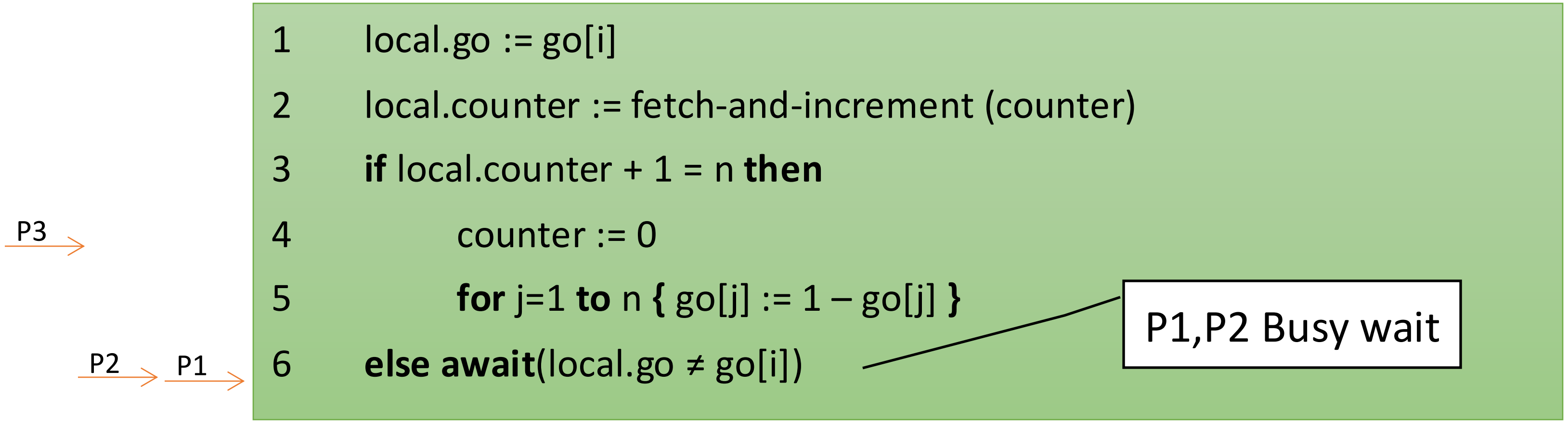
A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 3 go 0 0 0 SM

P1		P2		P3	
loc.go	0	loc.go	0	loc.go	0
loc.counter	0	loc.counter	1	loc.counter	2

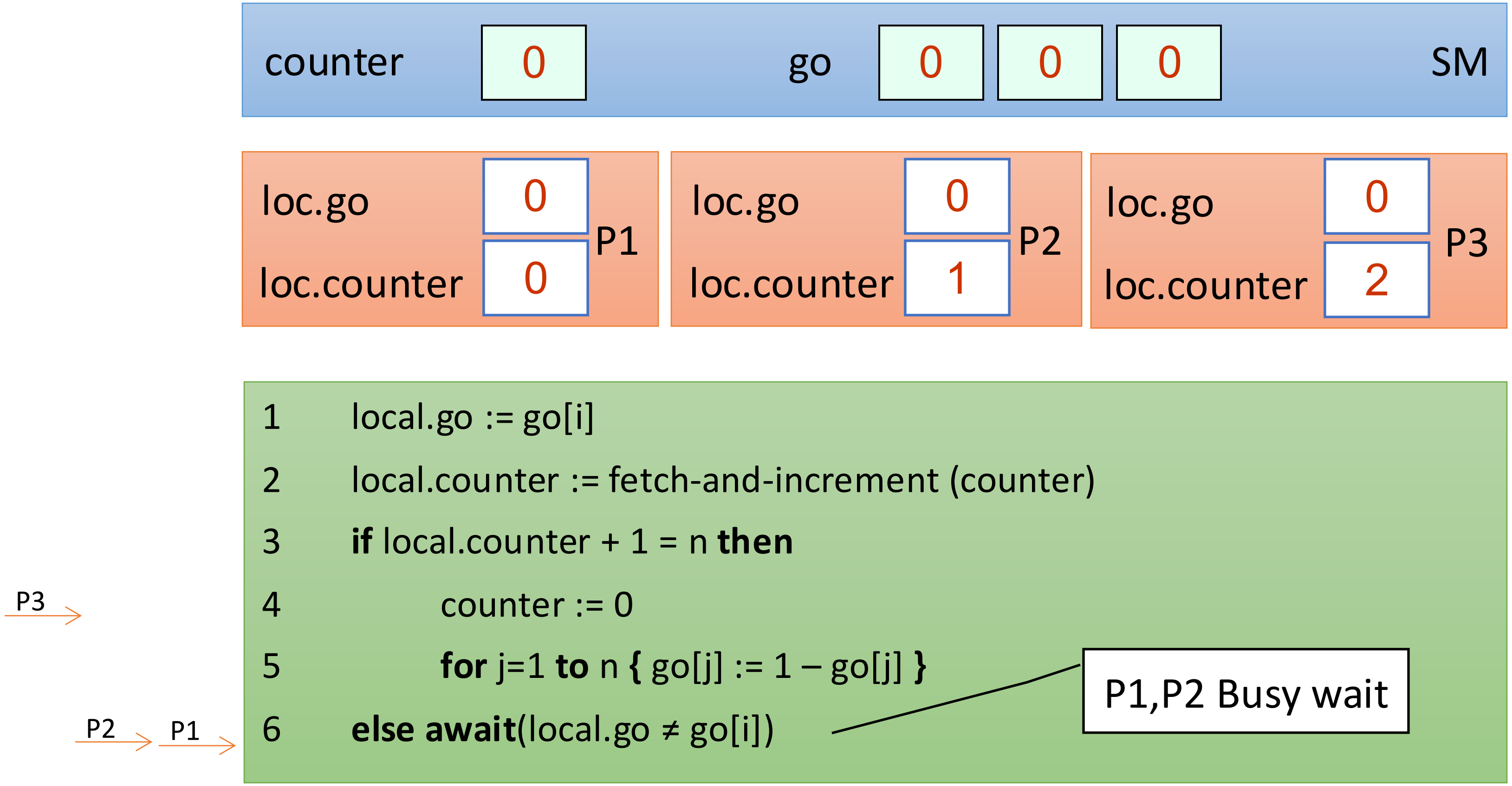


```
1      local.go := go[i]
2      local.counter := fetch-and-increment (counter)
3      if local.counter + 1 = n then
4              counter := 0
5              for j=1 to n { go[j] := 1 – go[j] }
6      else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads

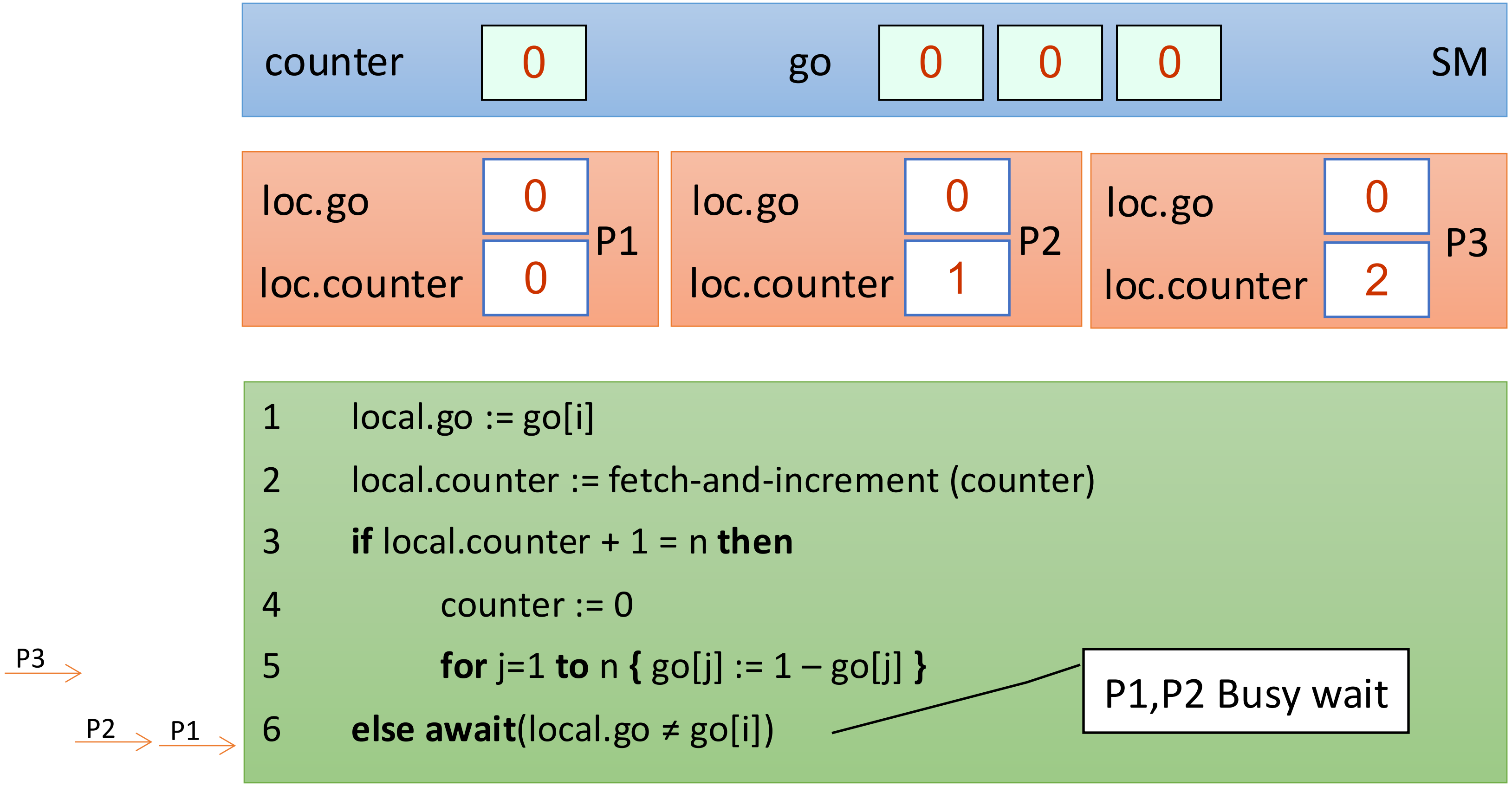


```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



SM				
counter	0	go	0	0	0

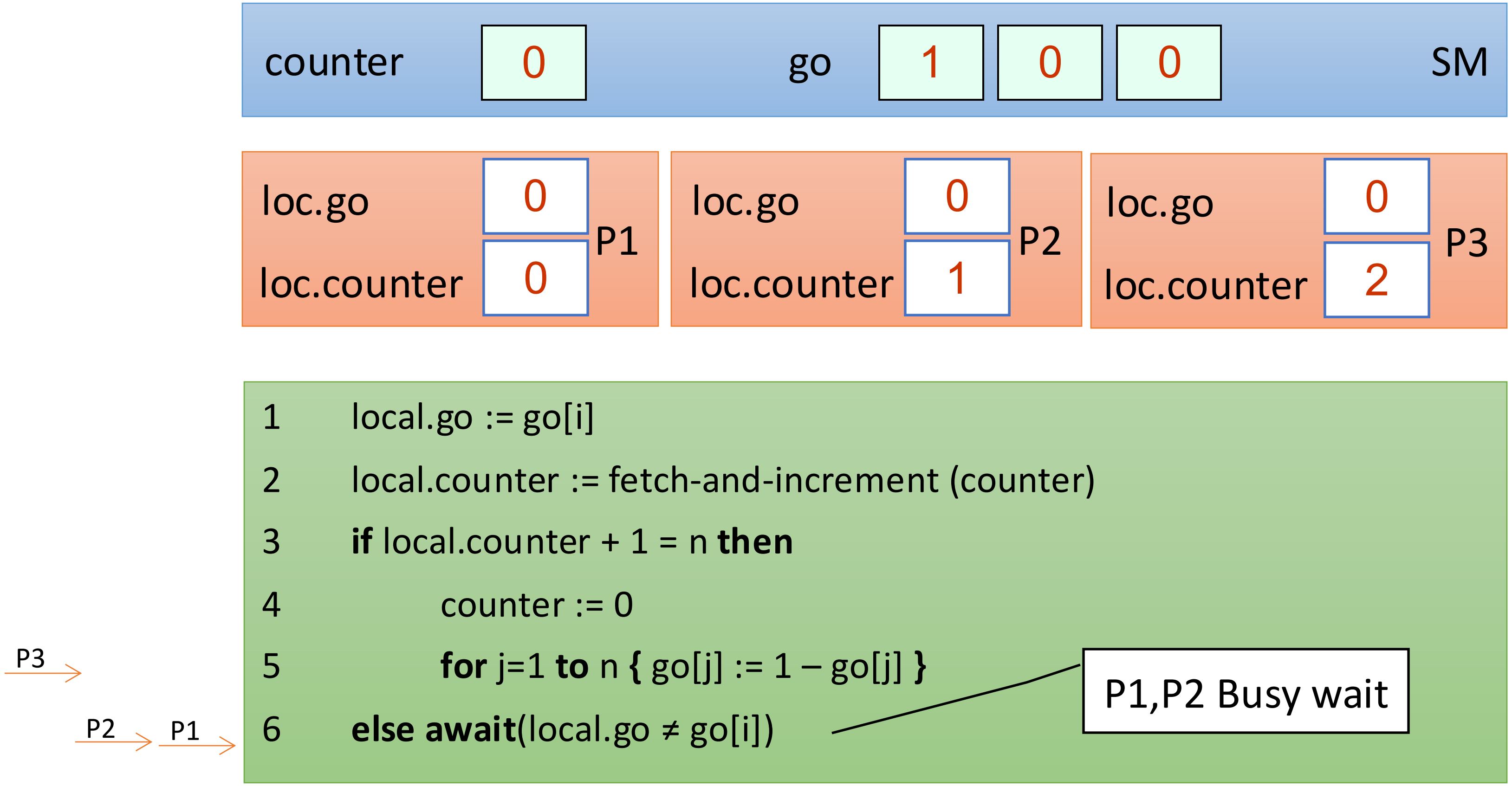
	P1	P2	P3
loc.go	0	0	0
loc.counter	0	1	2

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
        counter := 0
        for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0 go 1 0 0 SM

P1: loc.go 0, loc.counter 0

P2: loc.go 0, loc.counter 1

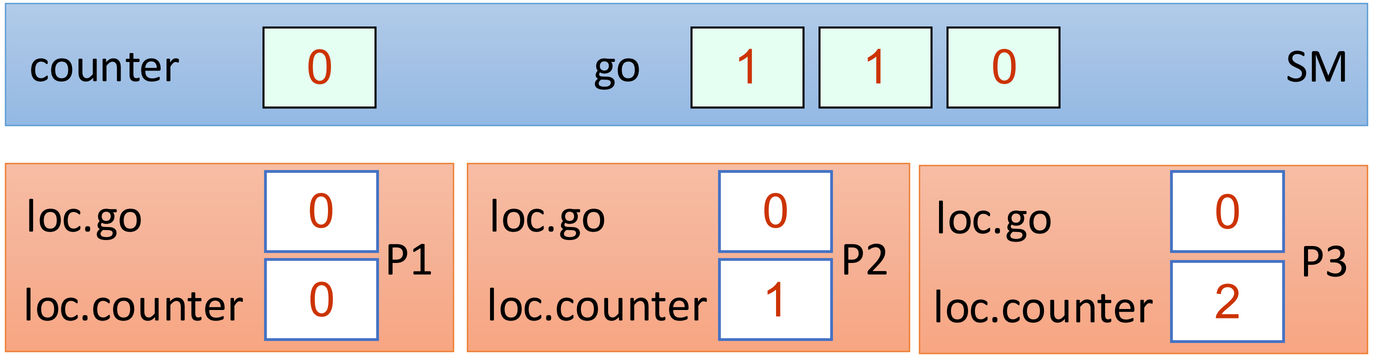
P3: loc.go 0, loc.counter 2

```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

P1,P2 Busy wait

A Local Spinning Counter Barrier

Example Run for n=3 Threads



```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

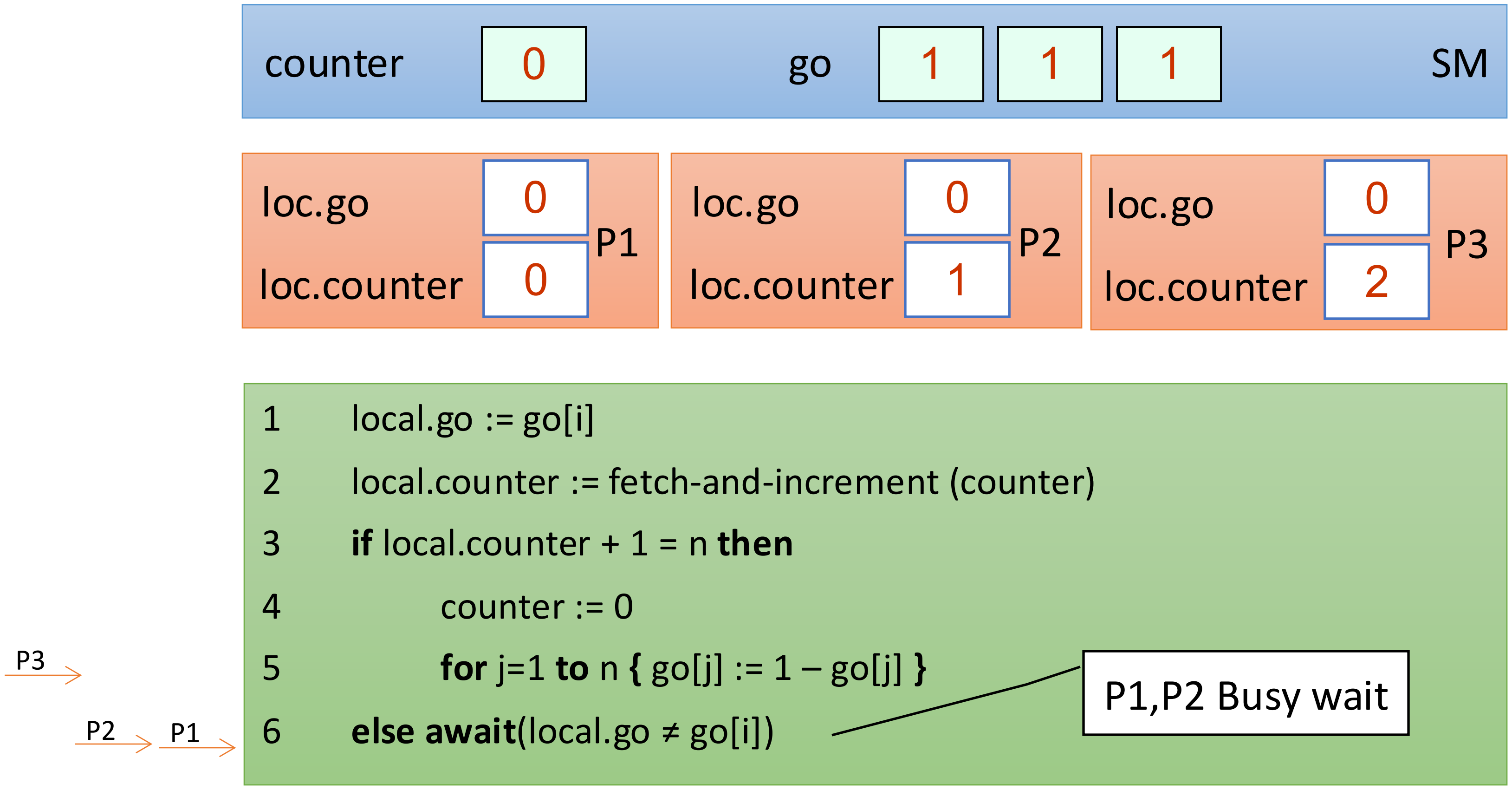
P3 → 5

P2 → P1 → 6

P1,P2 Busy wait

A Local Spinning Counter Barrier

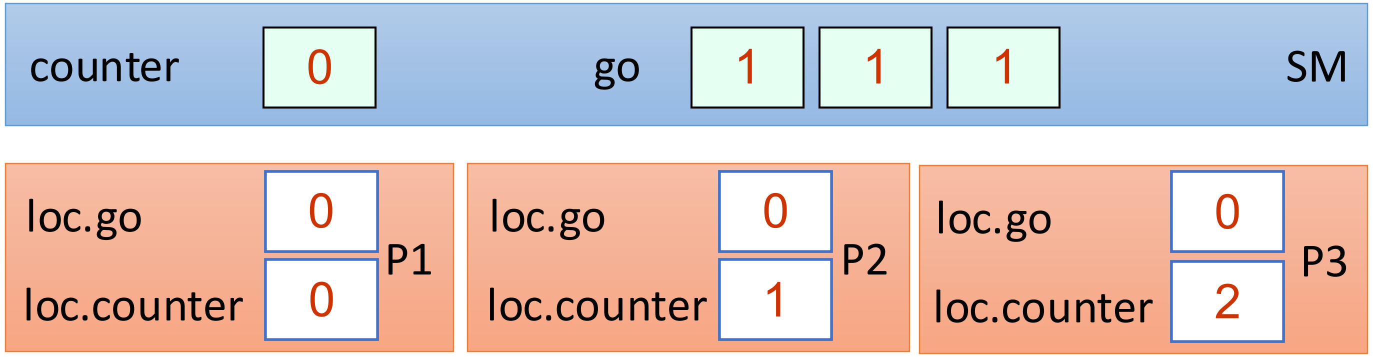
Example Run for n=3 Threads



```
1   local.go := go[i]
2   local.counter := fetch-and-increment (counter)
3   if local.counter + 1 = n then
4       counter := 0
5       for j=1 to n { go[j] := 1 – go[j] }
6   else await(local.go ≠ go[i])
```

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0

go 1 1 1

SM

P1: loc.go 0, loc.counter 0

P2: loc.go 0, loc.counter 1

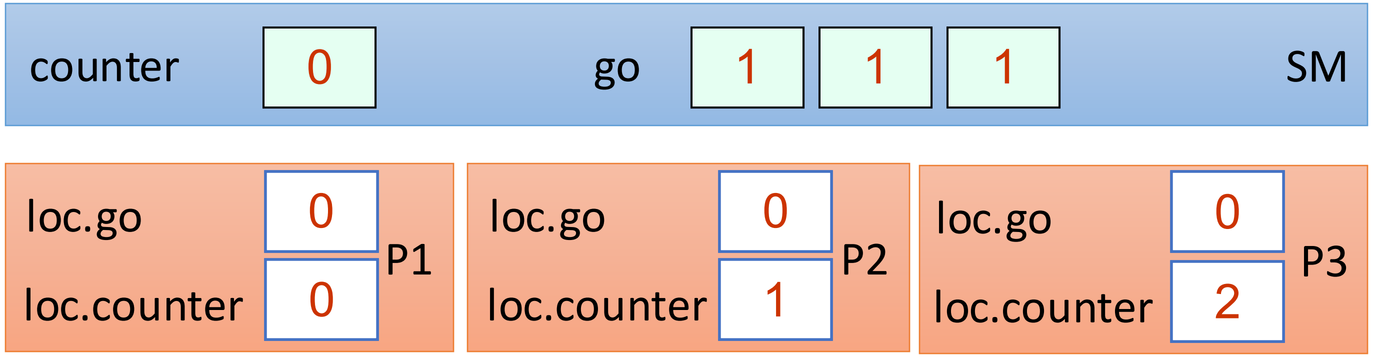
P3: loc.go 0, loc.counter 2

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P3 → P2 → P1

A Local Spinning Counter Barrier

Example Run for n=3 Threads



counter 0 go 1 1 1 SM

loc.go 0 loc.counter 0 P1

loc.go 0 loc.counter 1 P2

loc.go 0 loc.counter 2 P3

```
local.go := go[i]
local.counter := fetch-and-increment (counter)
if local.counter + 1 = n then
    counter := 0
    for j=1 to n { go[j] := 1 – go[j] }
else await(local.go ≠ go[i])
```

P3 → P2 → P1 →

Pros/Cons?

Does this actually reduce contention?

Comparison of counter-based Barriers

Simple Barrier

- Pros:

- Cons:

Simple Barrier with go array

- Pros:

- Cons:

Comparison of counter-based Barriers

Simple Barrier

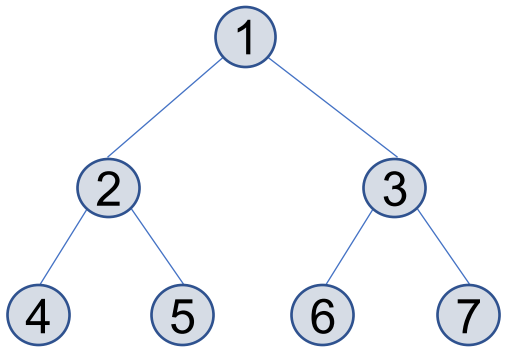
- Pros:
  - Very Simple
  - Shared memory: O(log n) ***bits***
  - Takes O(1) until last waiting p is awaken
- Cons:
  - High contention on the go bit
  - Contention on the counter register (*)

Simple Barrier with go array

- Pros:
  - Low contention on the go array
  - In some models:
    - spinning is done on local memory
    - remote mem. ref.: O(1)
- Cons:
  - Shared memory: O(n)
  - Still contention on the counter register (*)
  - Takes O(n) until last waiting p is awaken

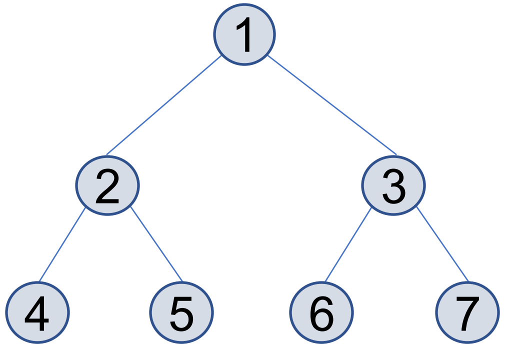
Tree Barriers

A Tree-based Barrier



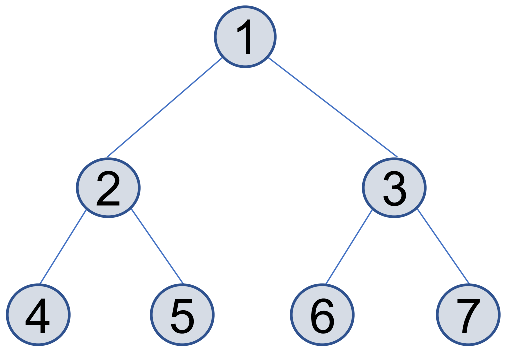
A Tree-based Barrier

- Threads are organized in a binary tree
- Each node is owned by a predetermined thread



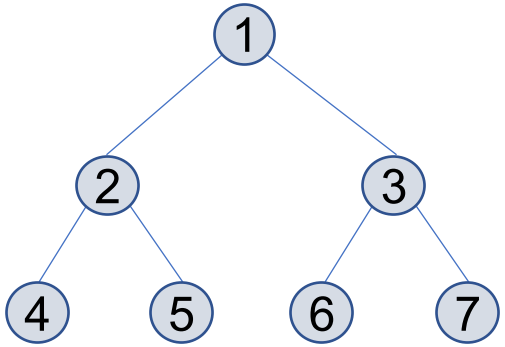
A Tree-based Barrier

- Threads are organized in a binary tree
- Each node is owned by a predetermined thread
- Each thread waits until its 2 children arrive
  - combines results
  - passes them on to its parent

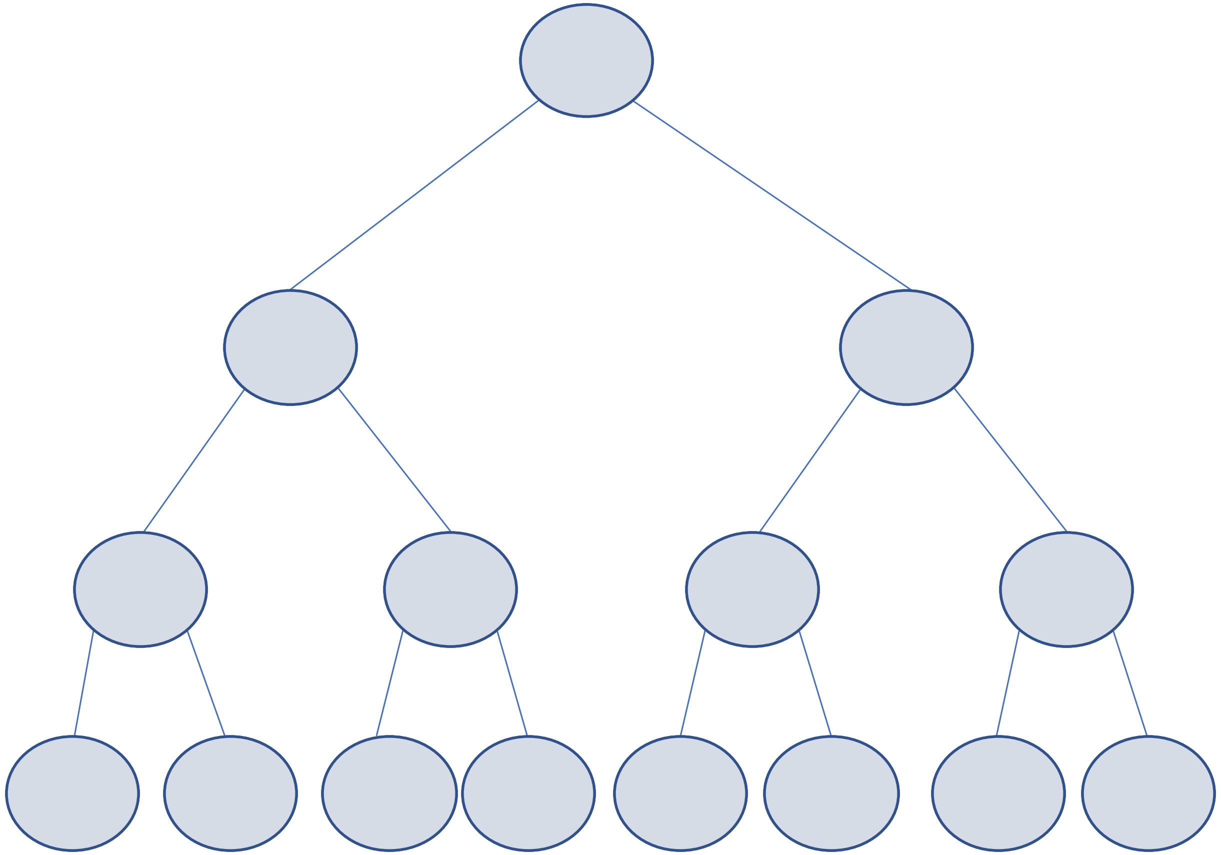


A Tree-based Barrier

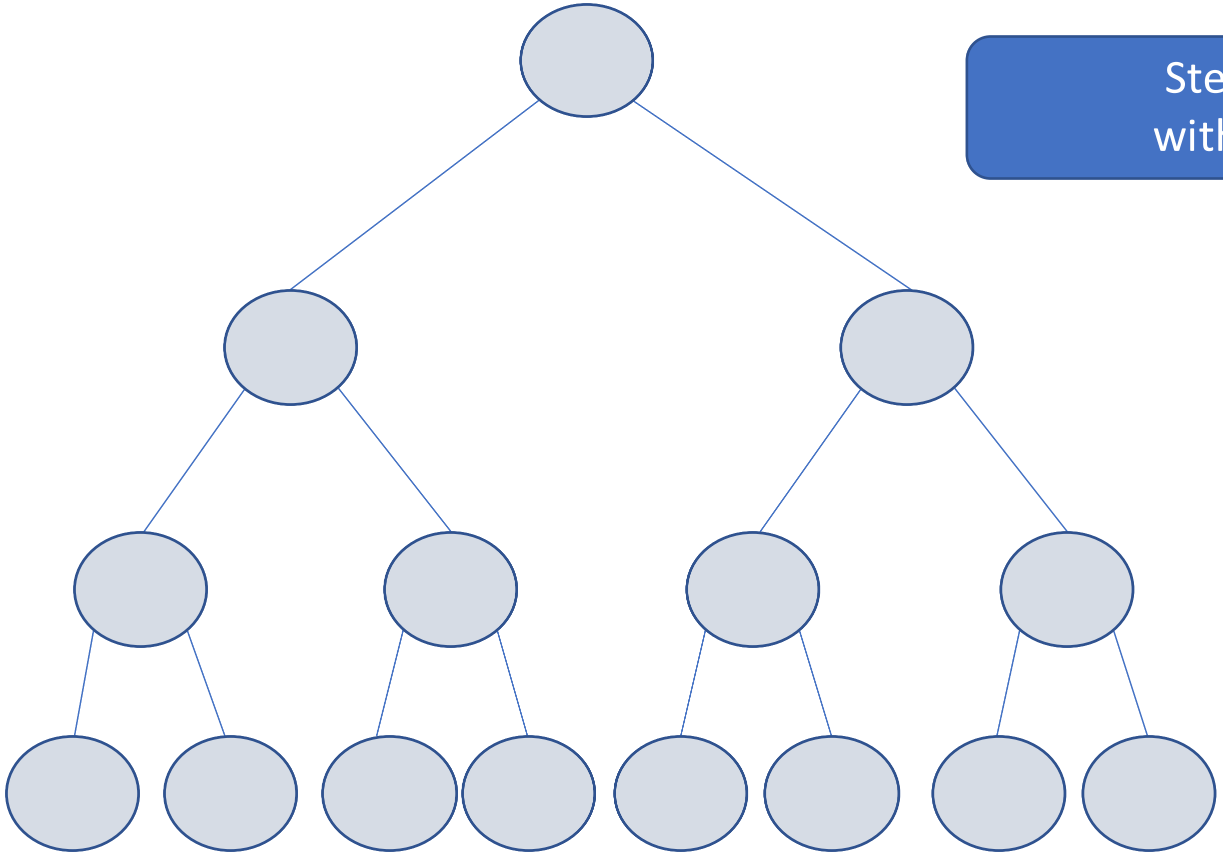
- Threads are organized in a binary tree
- Each node is owned by a predetermined thread
- Each thread waits until its 2 children arrive
    - combines results
    - passes them on to its parent
- Root learns that its 2 children have arrived→tells children they can go
- The signal propagates down the tree until all the threads get the message



A Tree-based Barrier: indexing

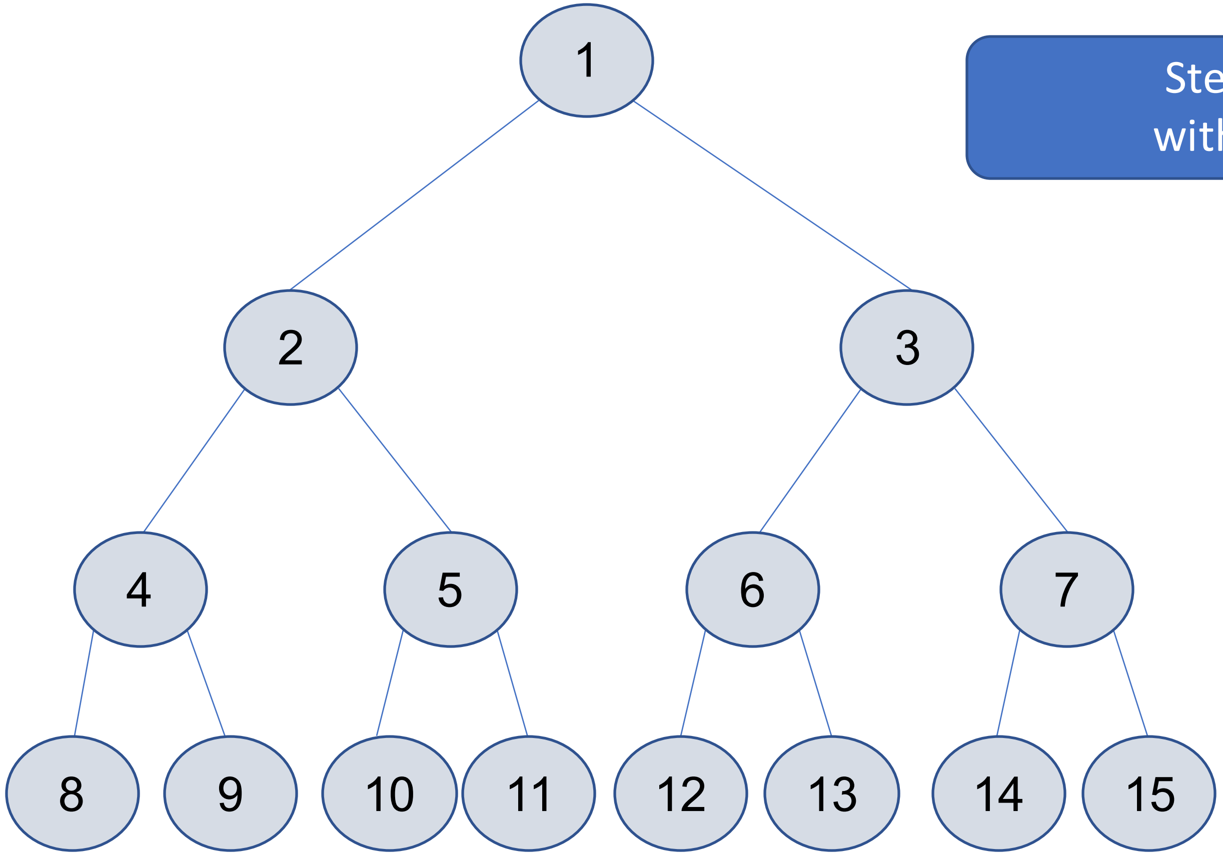


A Tree-based Barrier: indexing



Step 1: label numerically
with breadth-first traveral

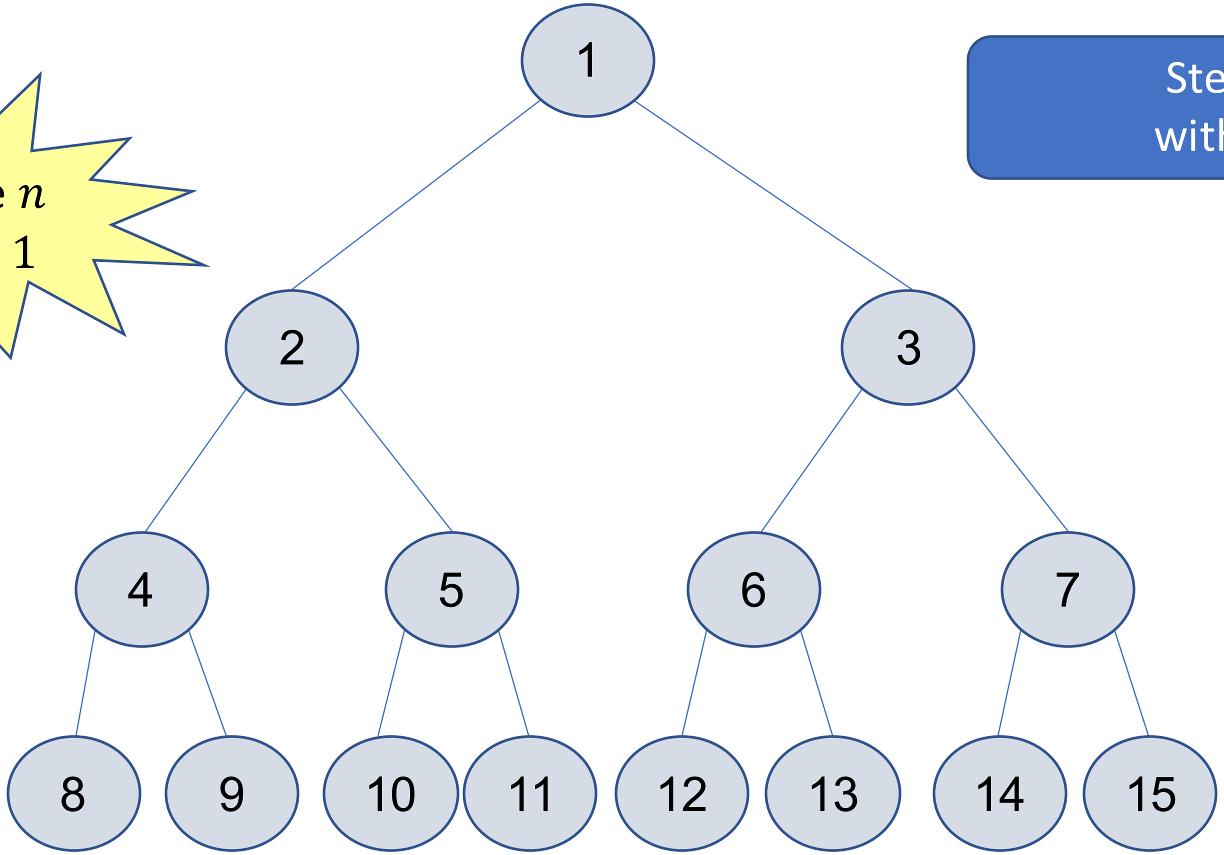
A Tree-based Barrier: indexing



Step 1: label numerically
with breadth-first traveral

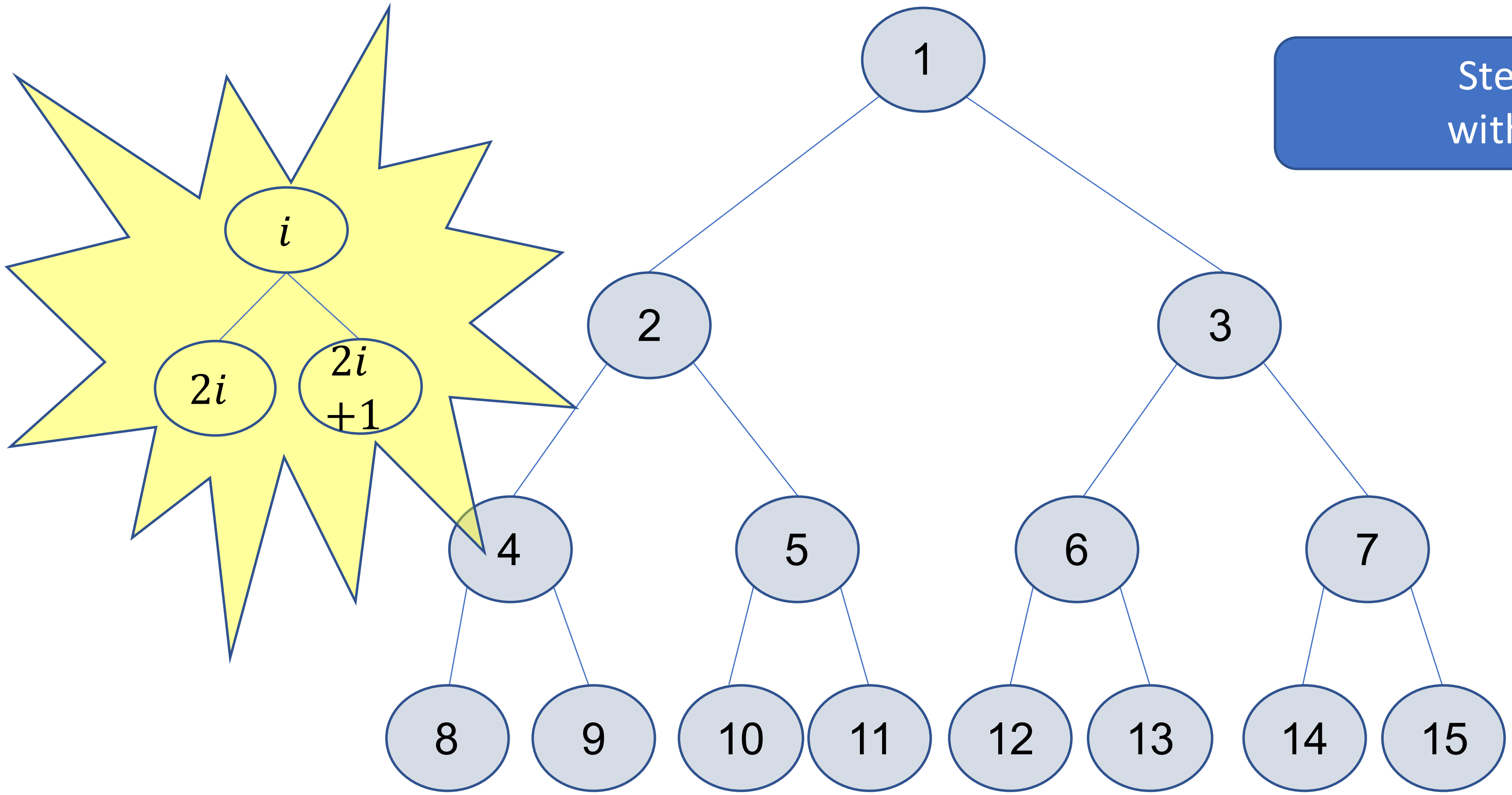
A Tree-based Barrier: indexing

Assume $n = 2^k - 1$



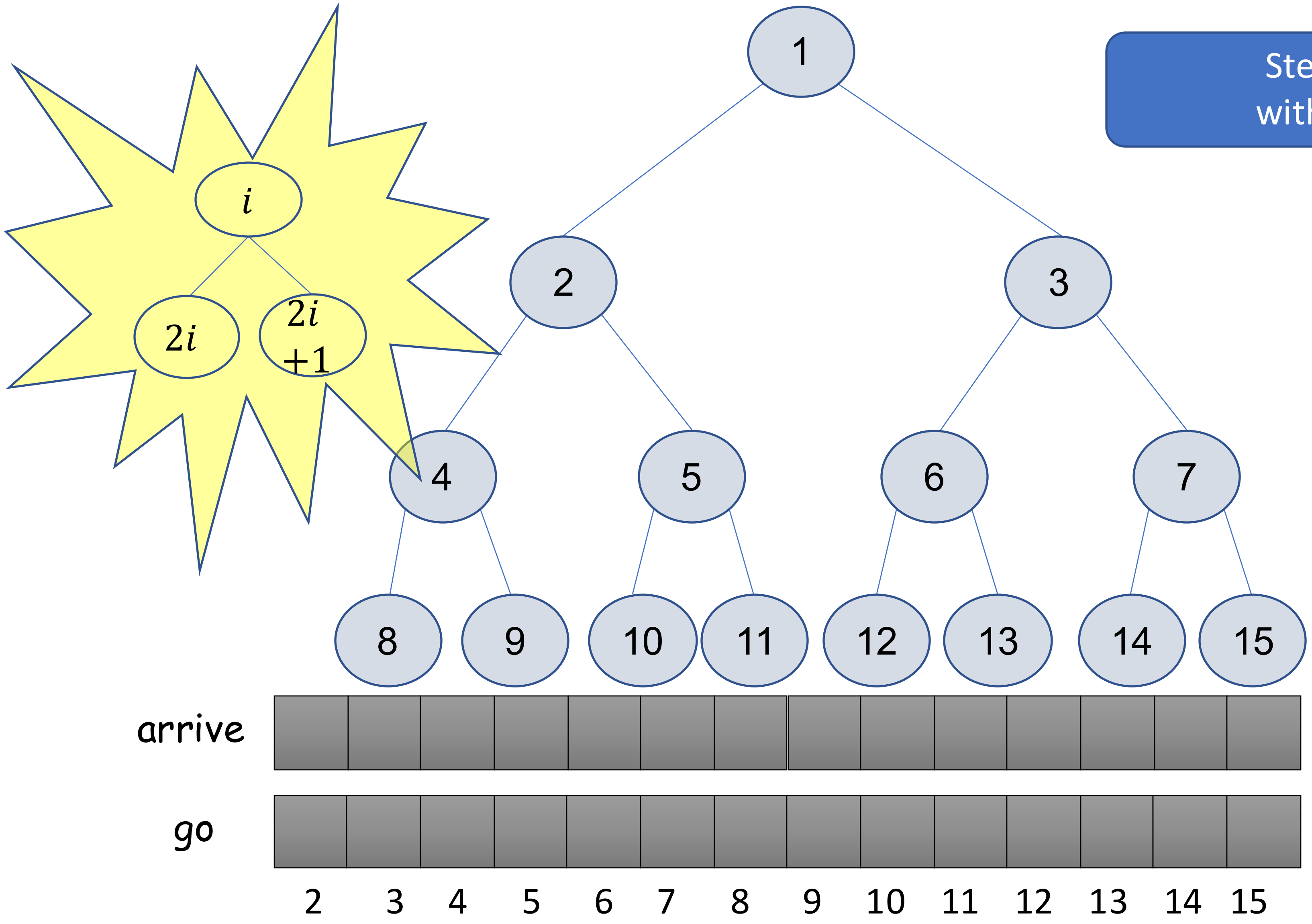
Step 1: label numerically with breadth-first traveral

A Tree-based Barrier: indexing



Step 1: label numerically
with breadth-first traveral

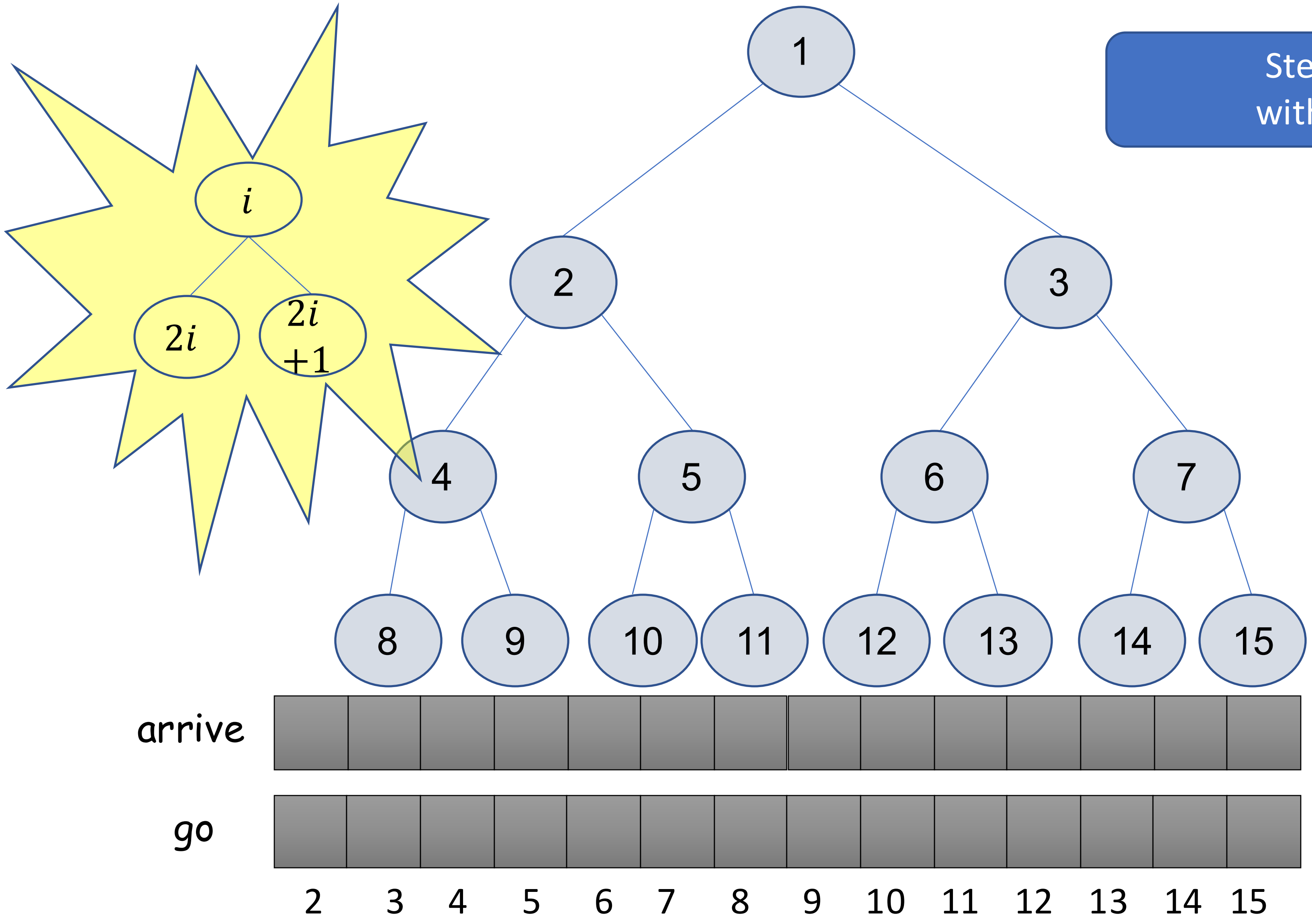
A Tree-based Barrier: indexing



Step 1: label numerically
with breadth-first traveral

A Tree-based Barrier: indexing

Step 1: label numerically
with breadth-first traveral



Indexing starts from 2
Root → 1, doesn't need wait objects

A Tree-based Barrier

program of thread i

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
program of thread i

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

Root

Internal

Leaf

```
if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier

program of thread i

```
shared  arrive[2..n]: array of atomic bits, initial values = 0
        go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

Root

Internal

Leaf

Root:
- Wait for arriving children
- Tell children to go

A Tree-based Barrier
program of thread i

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                              // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                                 // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                     // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

Root

Internal

Leaf

Root:
- Wait for arriving children
- Tell children to go

Internal:
- Wait for arriving children
- Wait for parent go signal
- Tell children to go

A Tree-based Barrier

program of thread i

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

Root

```
if i=1 then                                              // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
```

Internal

```
else if i ≤ (n-1)/2 then                                 // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
```

Leaf

```
else                                                     // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

Root:
- Wait for arriving children
- Tell children to go

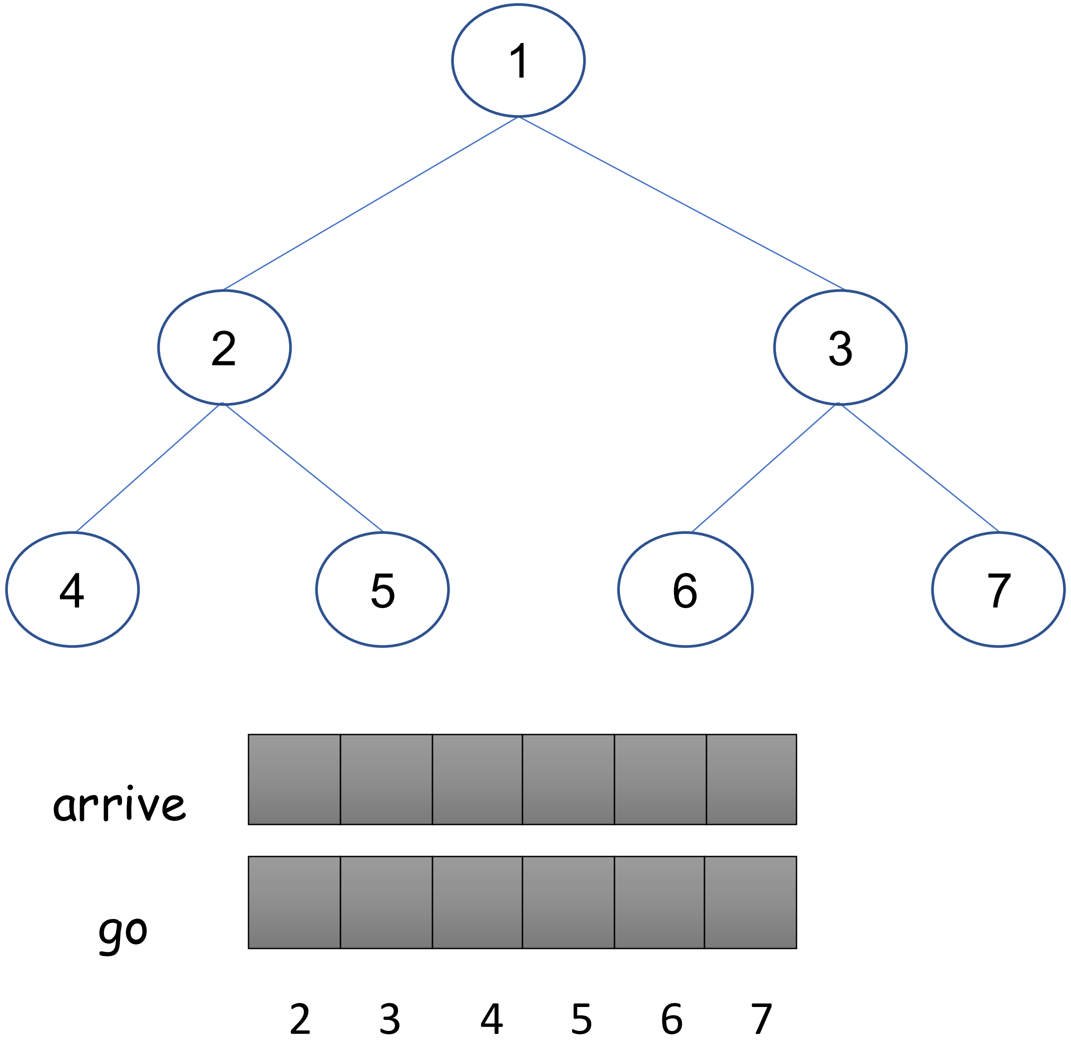
Internal:
- Wait for arriving children
- Wait for parent go signal
- Tell children to go

Child:
- arrive
- Wait for parent go signal

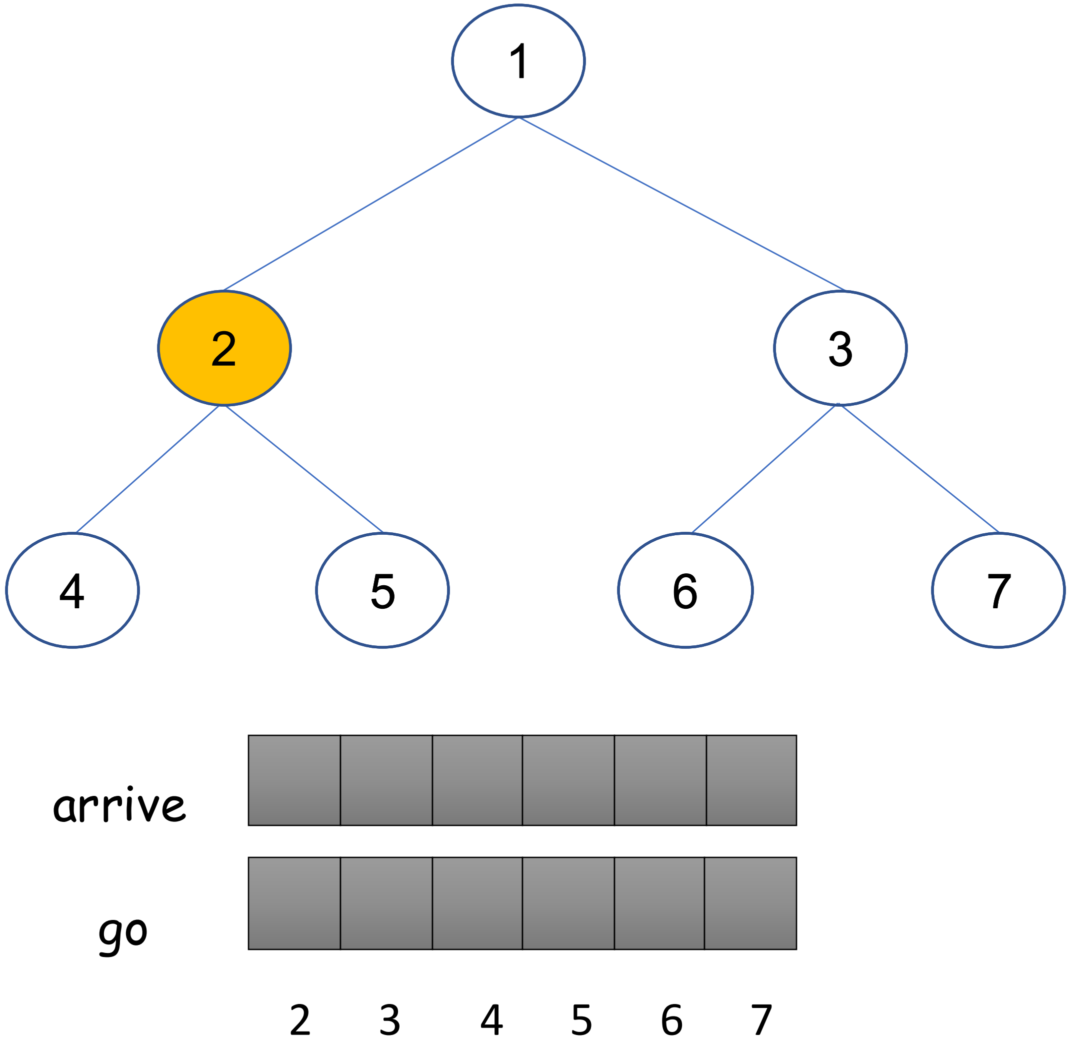
A Tree-based Barrier
Example Run for n=7 threads

```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0 fi
fi
```



A Tree-based Barrier
Example Run for n=7 threads

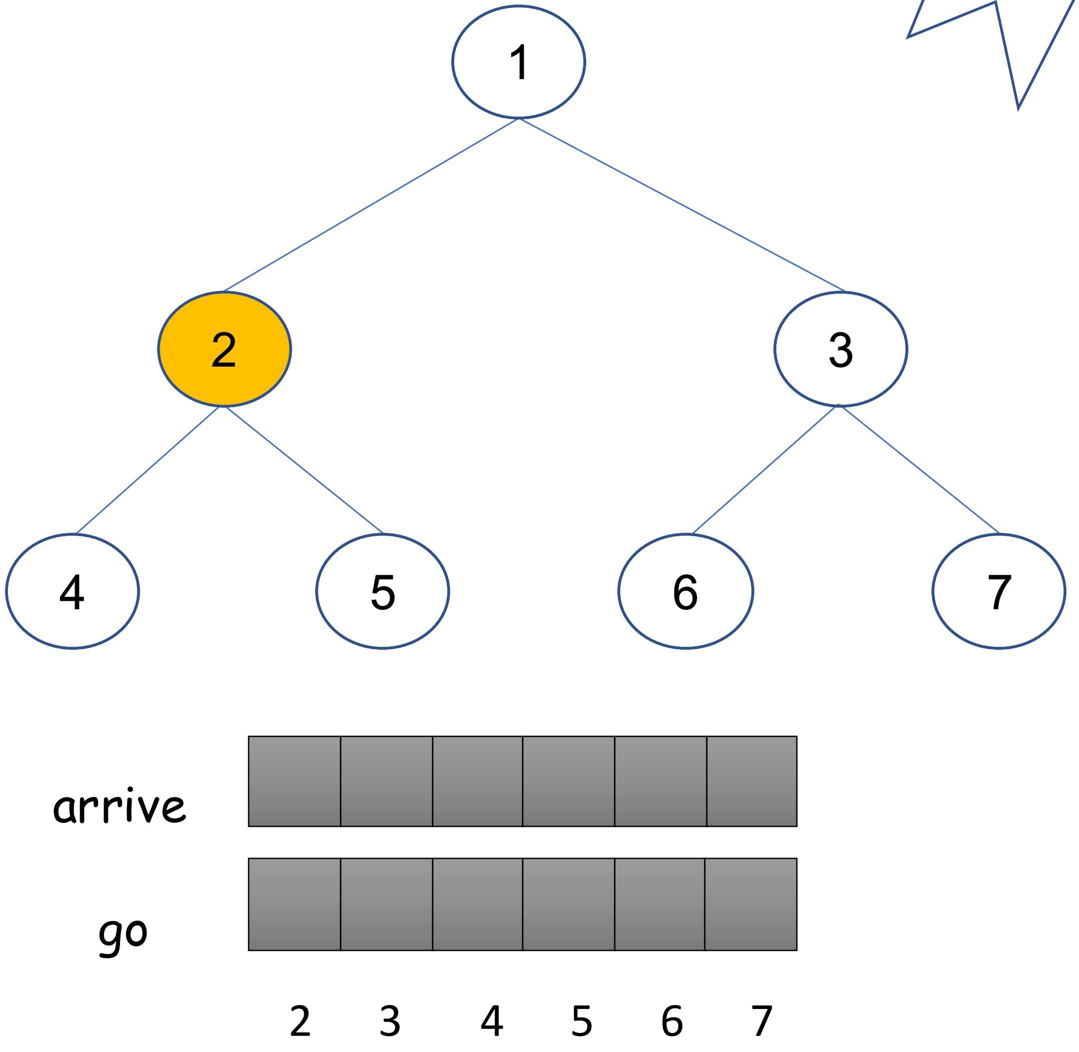


```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2]  = 1); arrive[2]  := 0
    await(arrive[3]  = 1); arrive[3]  := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

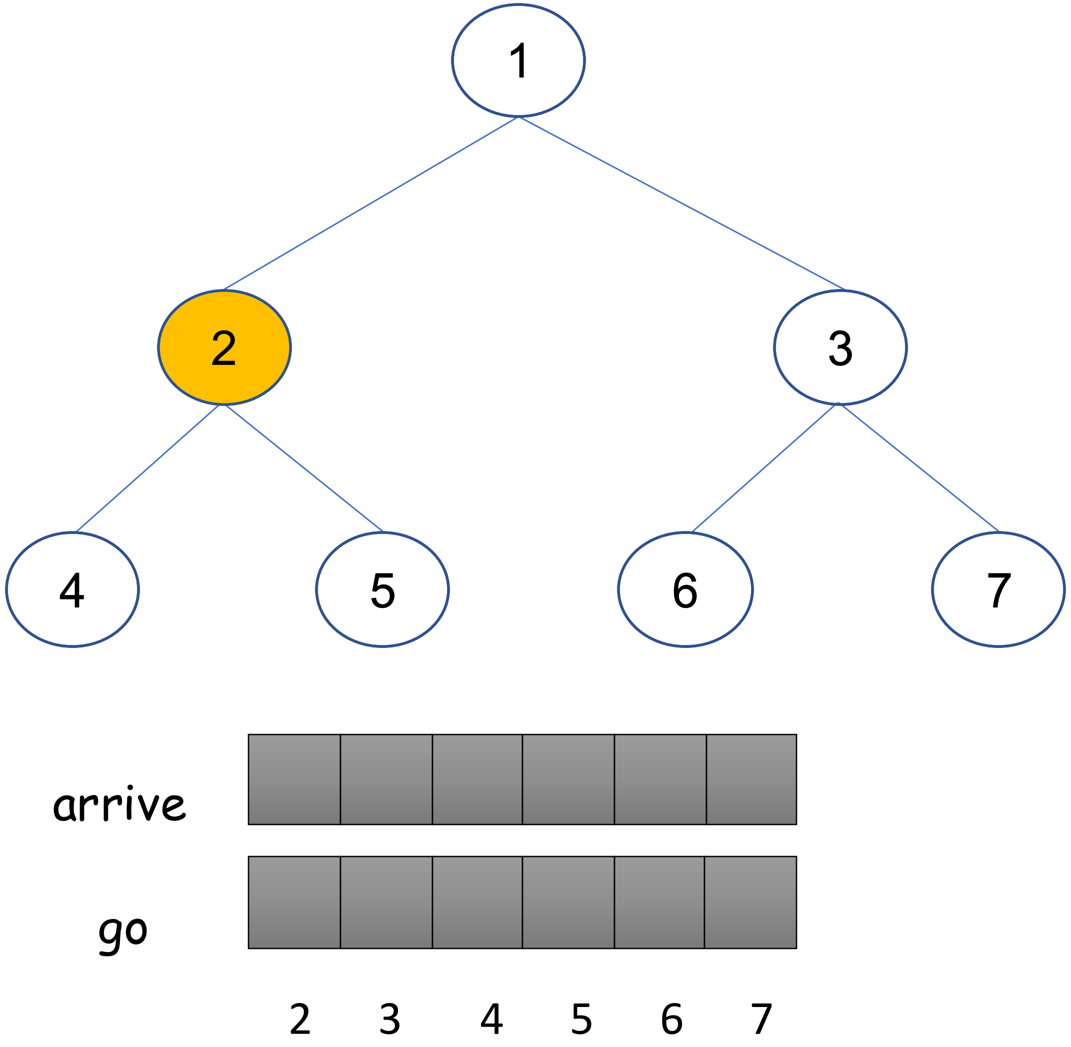
arrive[2]=1
?



```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
      await(arrive[2]  = 1); arrive[2]  := 0
      await(arrive[3]  = 1); arrive[3]  := 0
      go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
      await(arrive[2i]  = 1); arrive[2i]  := 0
      await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
      arrive[i]  := 1
      await(go[i] = 1); go[i] := 0
      go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
      arrive[i]  := 1
      await(go[i] = 1); go[i] := 0 fi
fi
```

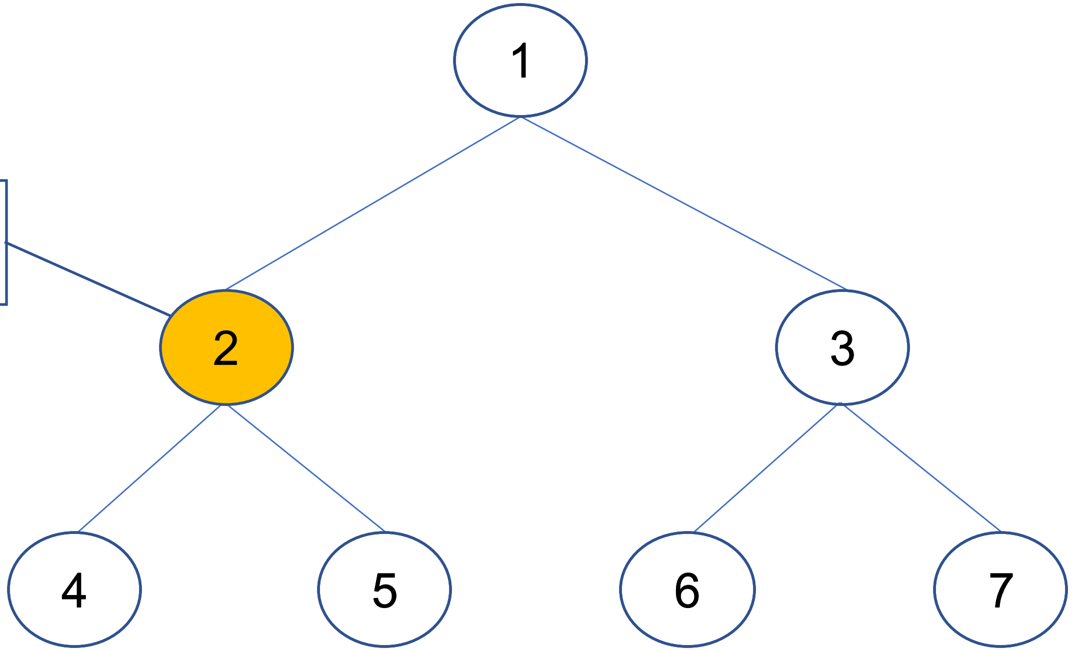
A Tree-based Barrier
Example Run for n=7 threads



```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

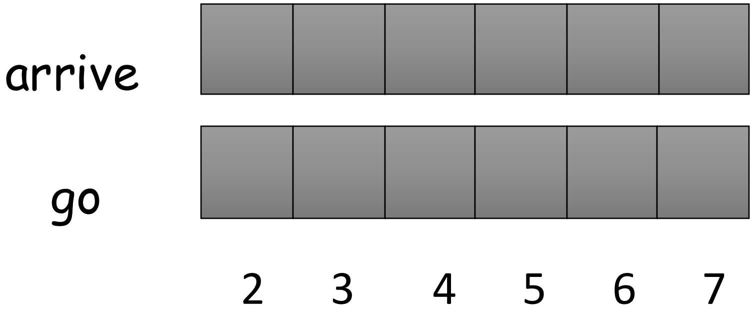
```
if i=1 then                                        // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                               // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

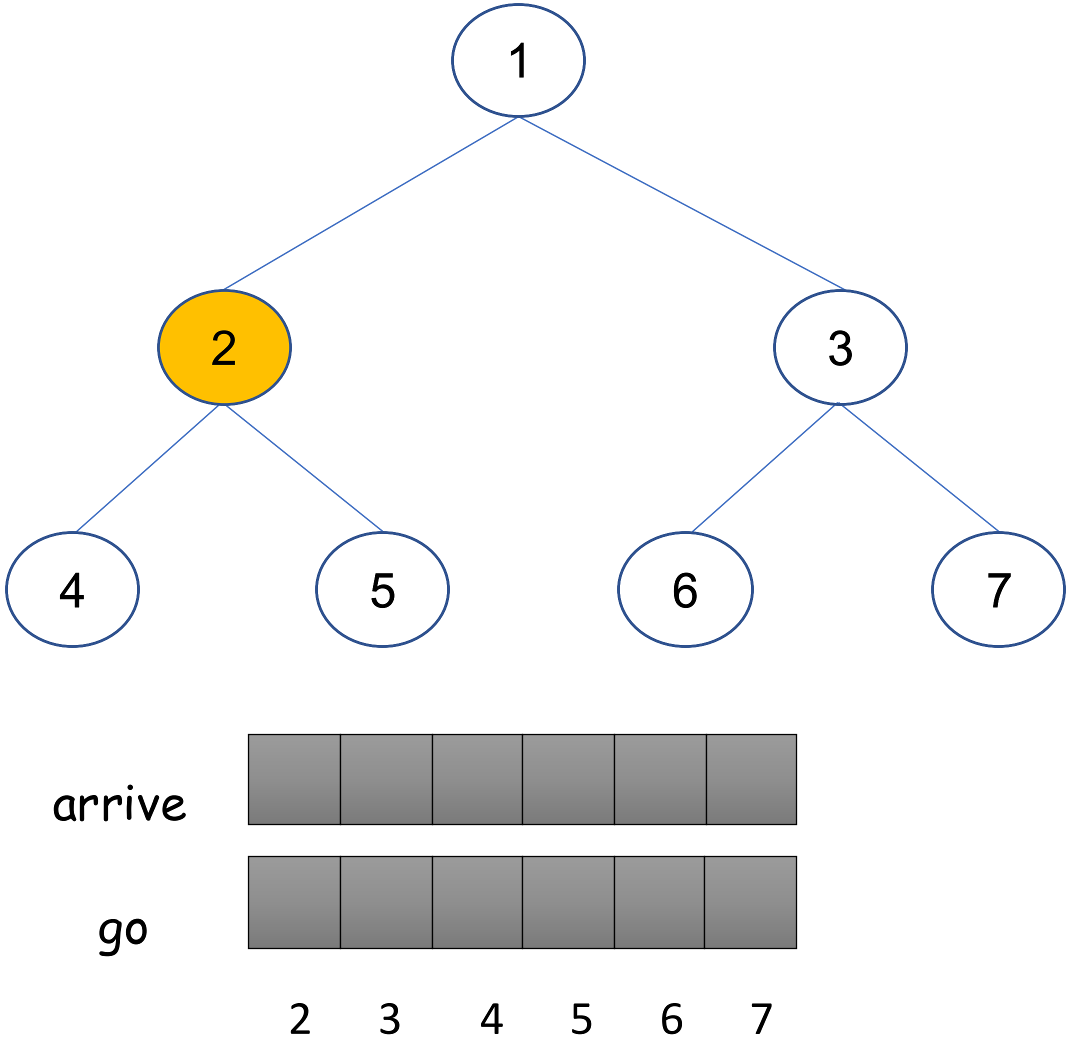


Waiting for p_4 to arrive

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                        // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                               // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```



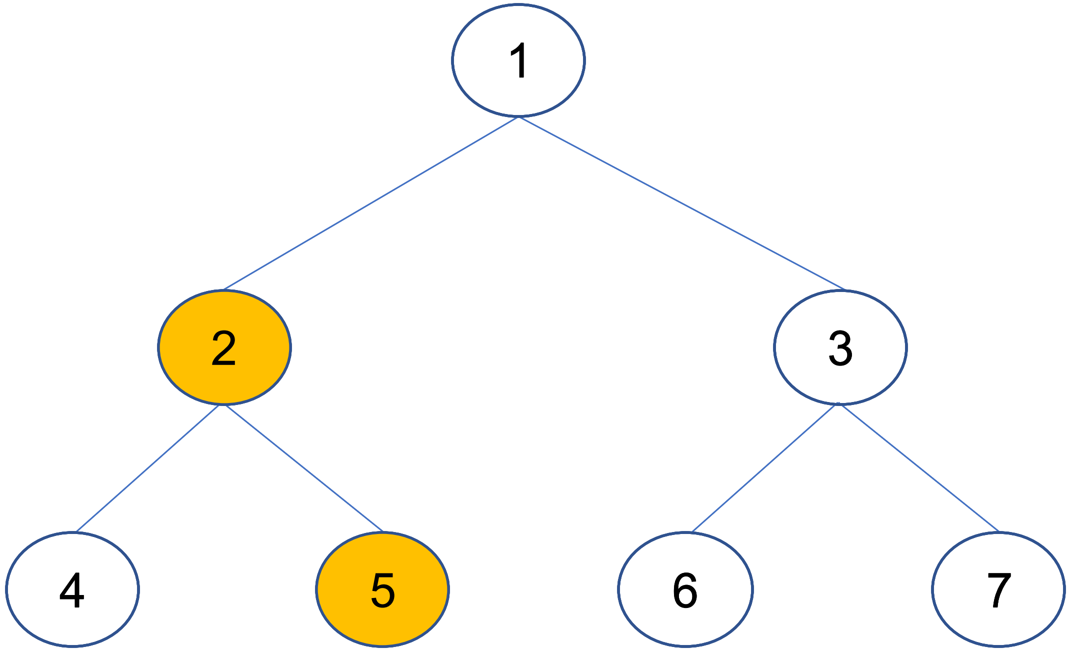
A Tree-based Barrier
Example Run for n=7 threads



```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
    await(arrive[2]  = 1); arrive[2]  := 0
    await(arrive[3]  = 1); arrive[3]  := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                               // leaf
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

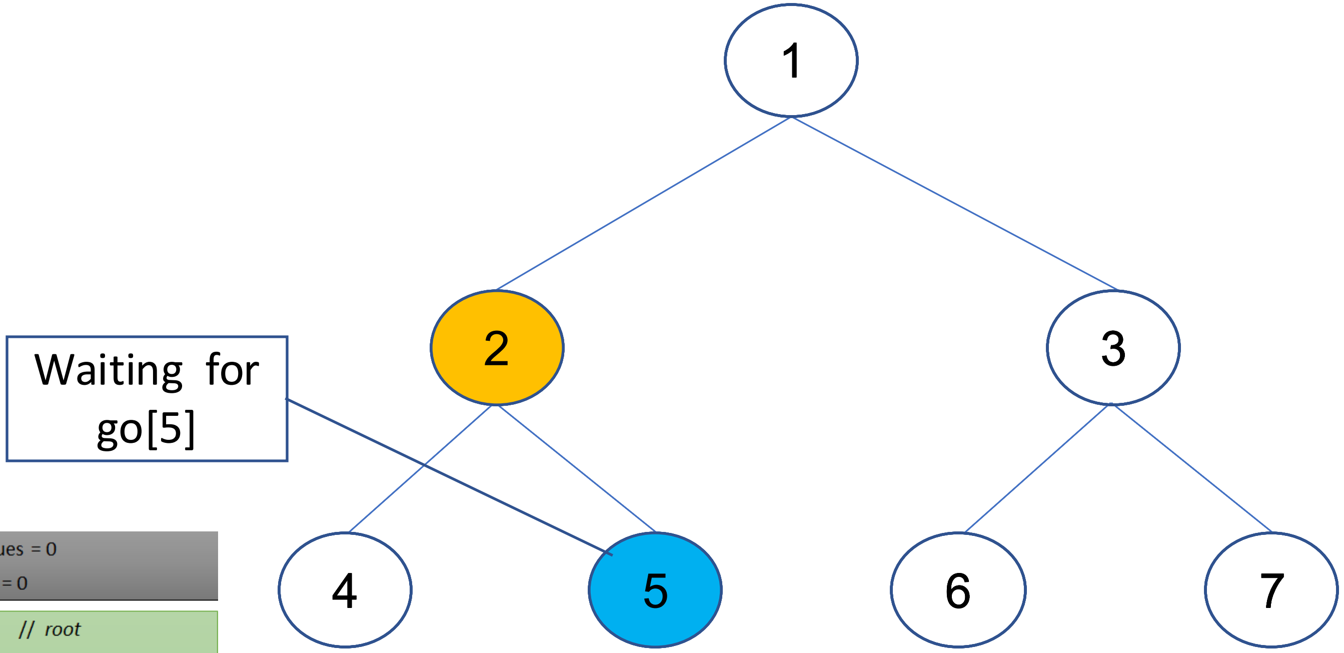


```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                               // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

arrive				1		
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads



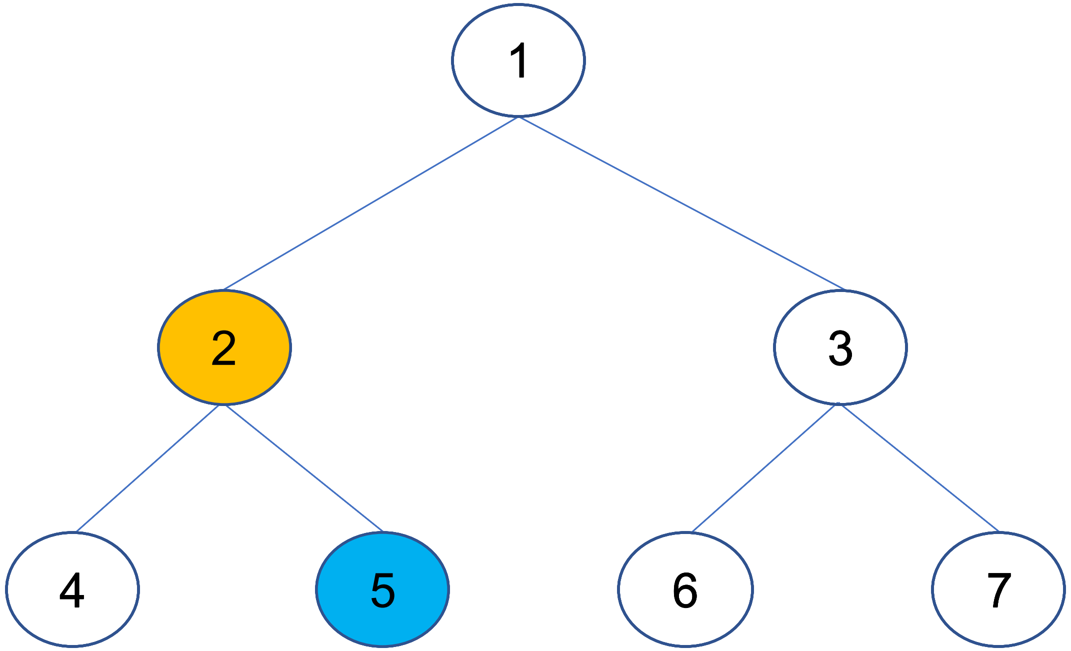
Waiting for go[5]

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                              // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                                 // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                     // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive				1		
go						
	2	3	4	5	6	7

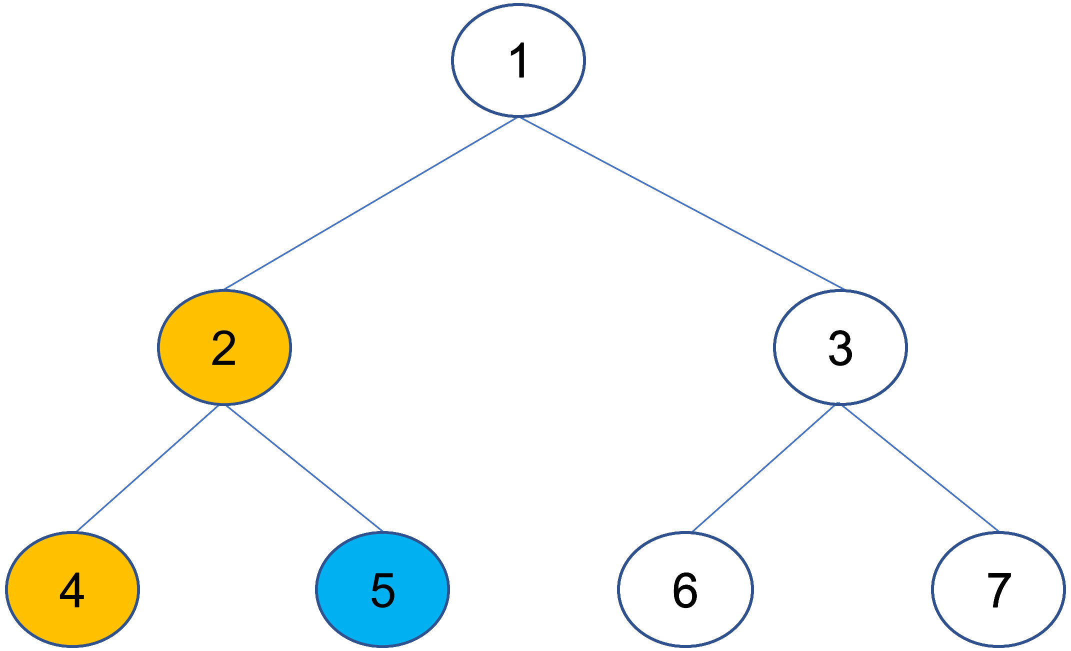
A Tree-based Barrier
Example Run for n=7 threads



```
shared    arrive[2..n]:  array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                          // root
    await(arrive[2]  = 1); arrive[2]  := 0
    await(arrive[3]  = 1); arrive[3]  := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

	2	3	4	5	6	7
arrive				1		
go						

A Tree-based Barrier
Example Run for n=7 threads

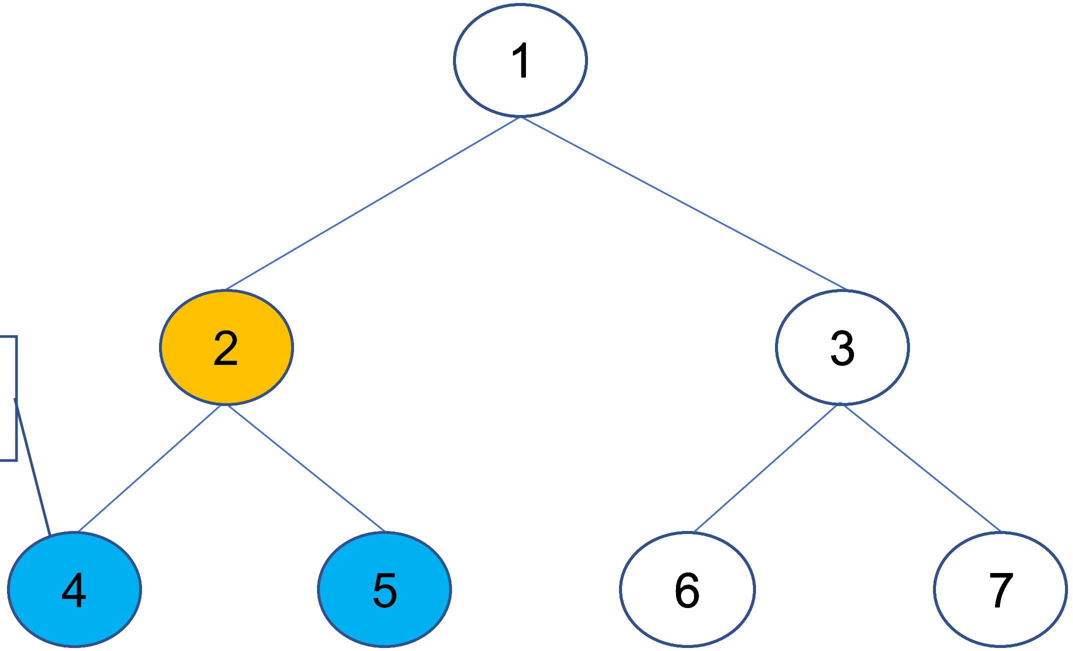


	2	3	4	5	6	7
arrive			1	1		
go						

```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



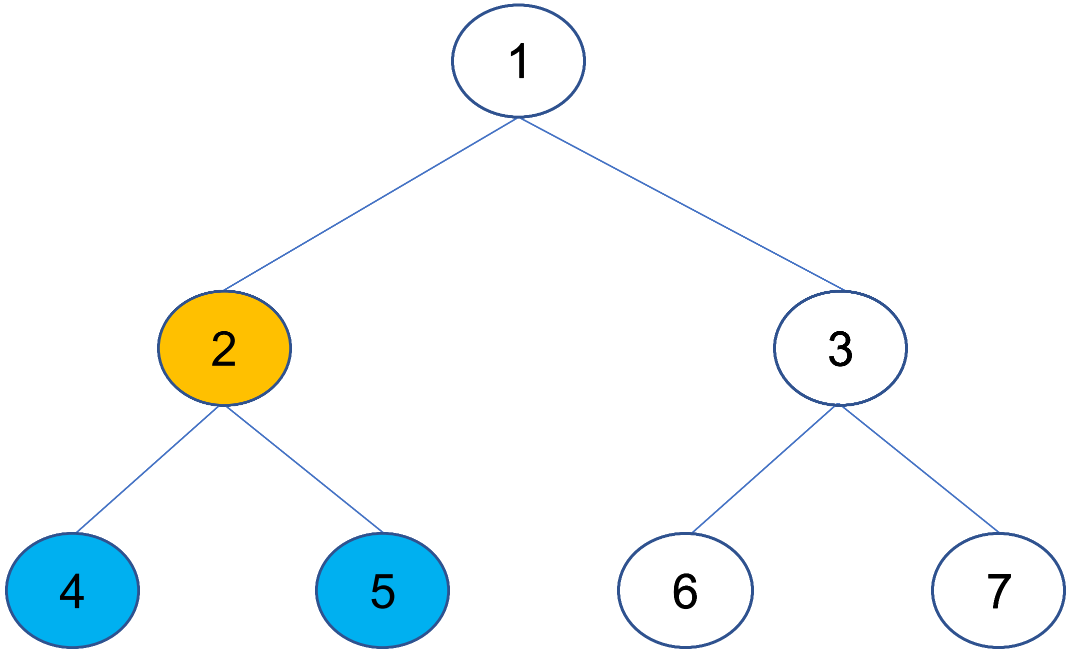
Waiting for go[4]

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

	2	3	4	5	6	7
arrive			1	1		
go						

A Tree-based Barrier
Example Run for n=7 threads



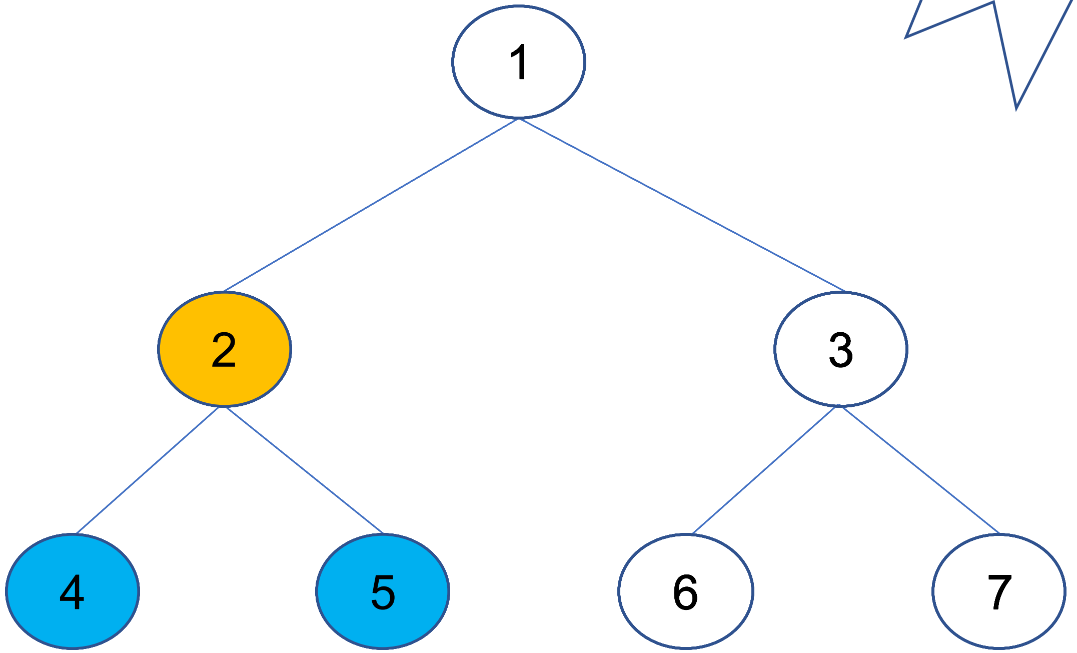
```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2] := 0
        await(arrive[3]  = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

	2	3	4	5	6	7
arrive			1	1		
go						

A Tree-based Barrier
Example Run for n=7 threads

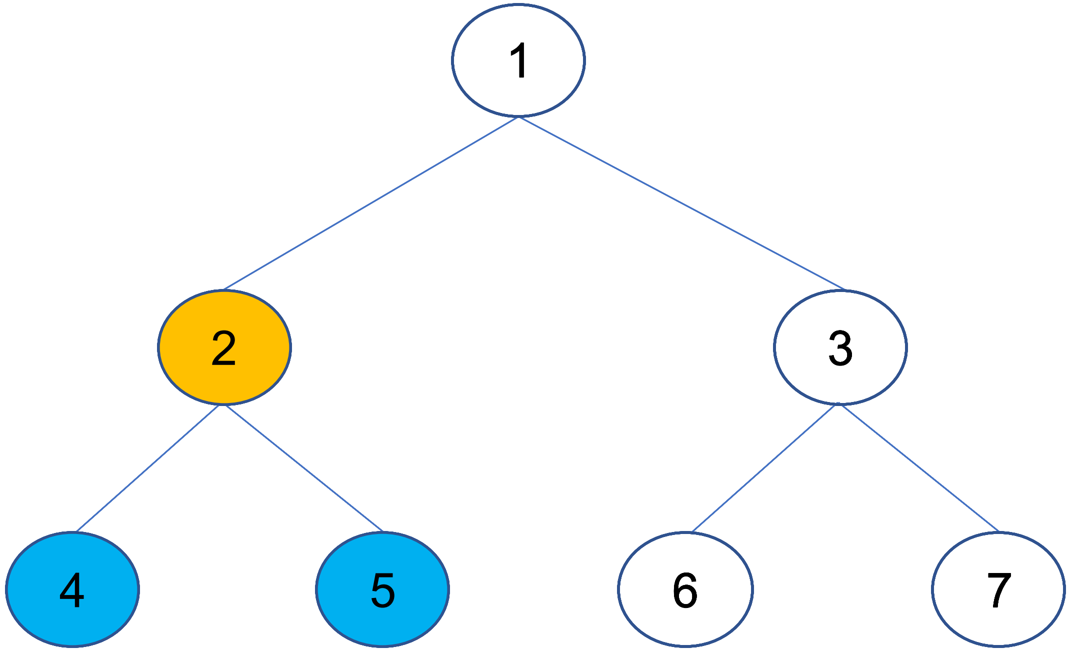
P_2 zeros arrive[4,5]



	2	3	4	5	6	7
arrive			0	0		
go						

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                        // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                               // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

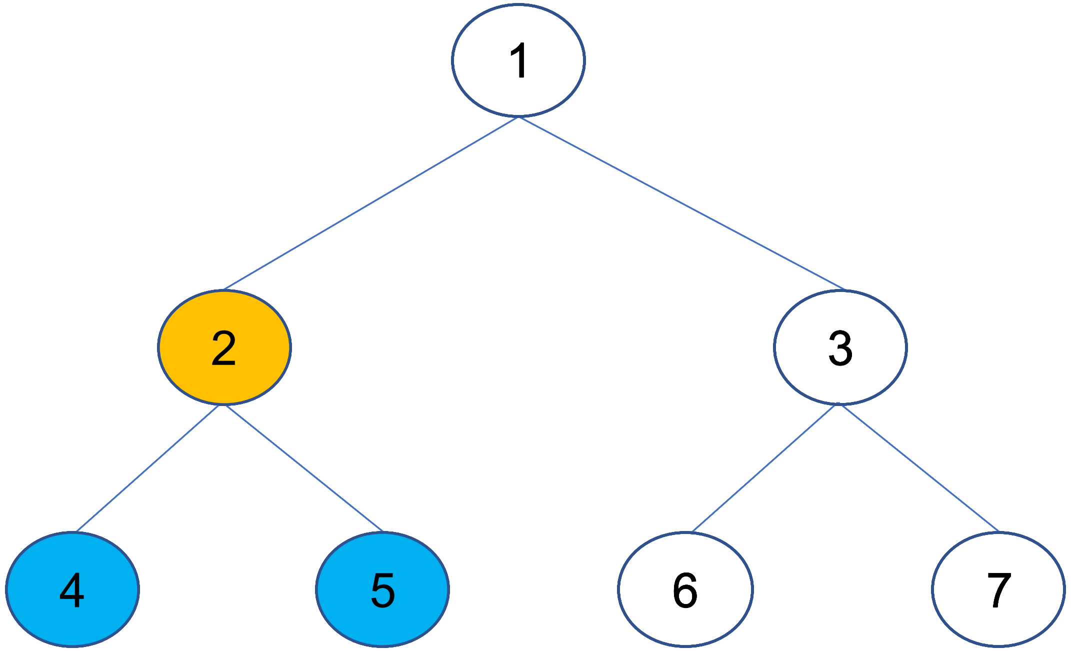
A Tree-based Barrier
Example Run for n=7 threads



```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

	2	3	4	5	6	7
arrive			0	0		
go						

A Tree-based Barrier
Example Run for n=7 threads

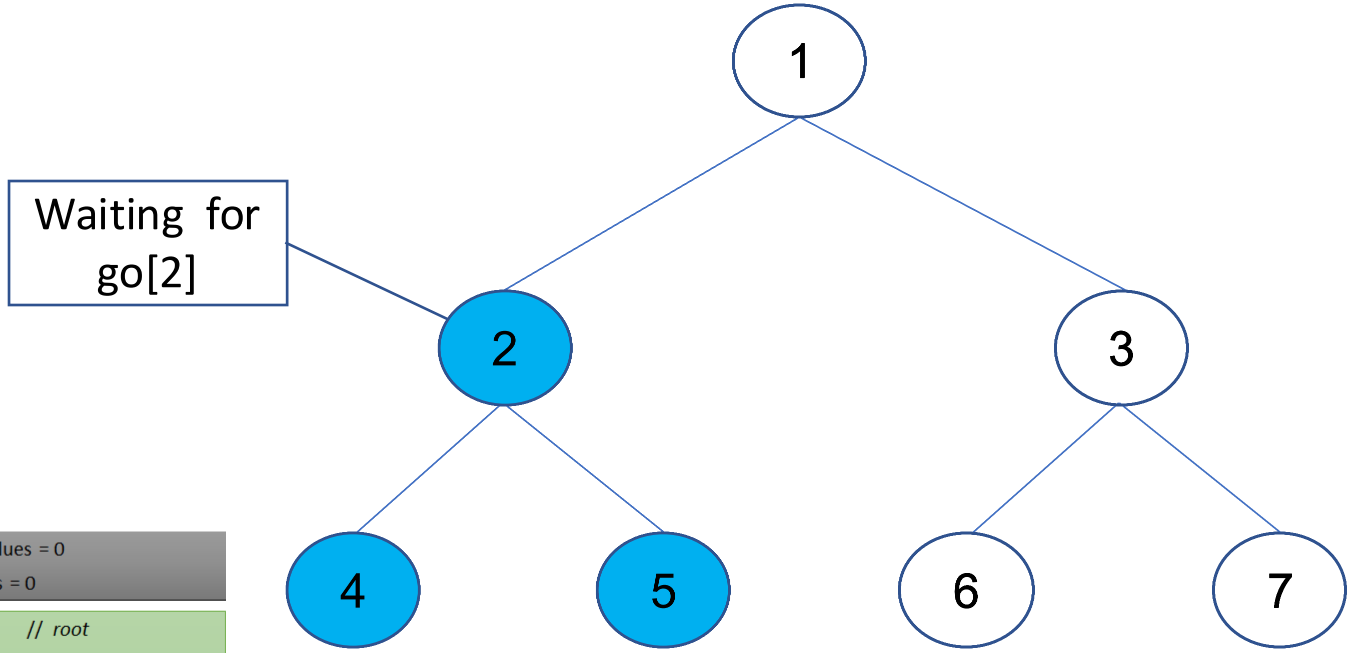


```
shared      arrive[2..n]:  array of atomic bits, initial values = 0
            go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                              // root
      await(arrive[2]  = 1); arrive[2]  := 0
      await(arrive[3]  = 1); arrive[3]  := 0
      go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                                 // internal node
      await(arrive[2i]  = 1); arrive[2i]  := 0
      await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
      arrive[i]  := 1
      await(go[i] = 1); go[i] := 0
      go[2i] = 1; go[2i+1] := 1
else                                                     // leaf
      arrive[i]  := 1
      await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	1		0	0		
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads



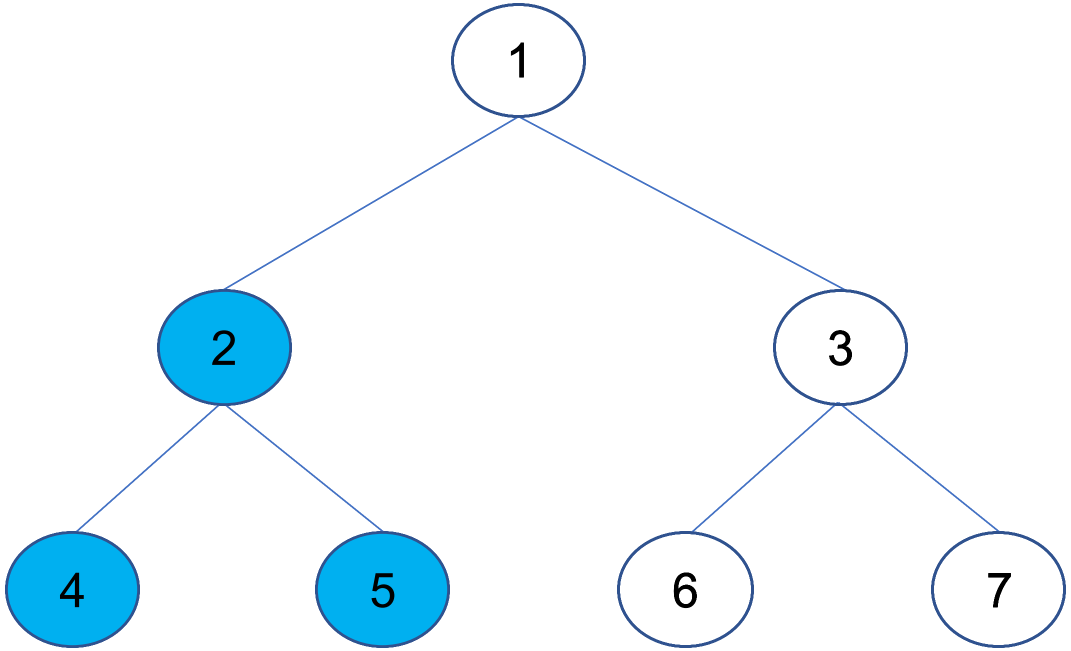
Waiting for go[2]

```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	1		0	0		
go						
	2	3	4	5	6	7

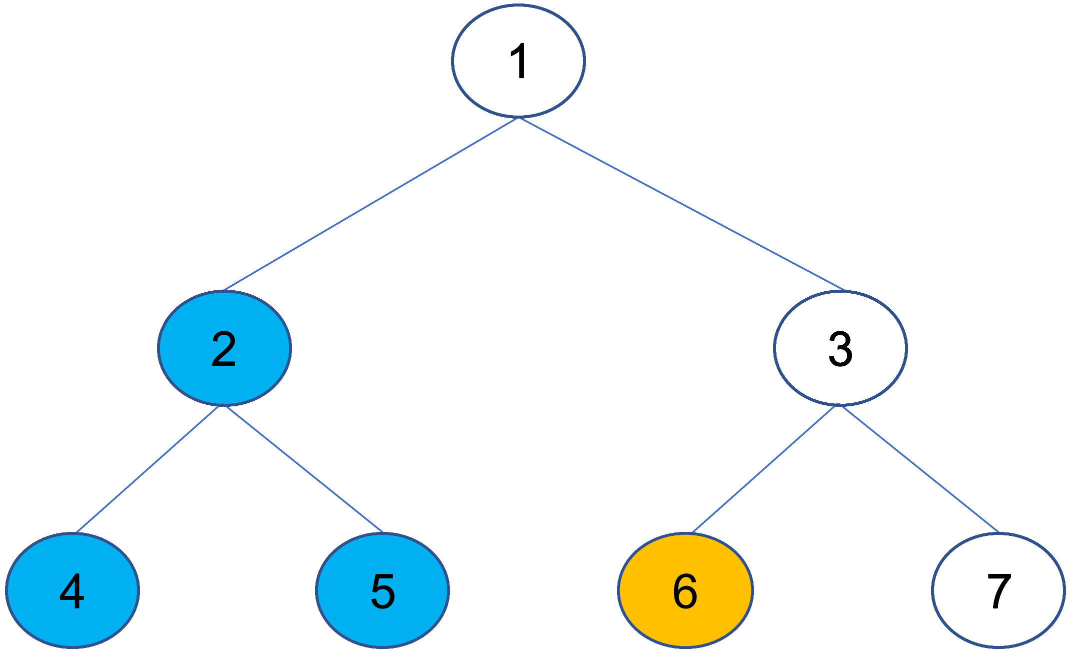
A Tree-based Barrier
Example Run for n=7 threads



```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                          // root
      await(arrive[2]  = 1); arrive[2]  := 0
      await(arrive[3]  = 1); arrive[3]  := 0
      go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
      await(arrive[2i]  = 1); arrive[2i]  := 0
      await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
      arrive[i]  := 1
      await(go[i]  = 1); go[i] := 0
      go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
      arrive[i]  := 1
      await(go[i]  = 1); go[i] := 0 fi
fi
```

arrive	1		0	0		
go						
	2	3	4	5	6	7

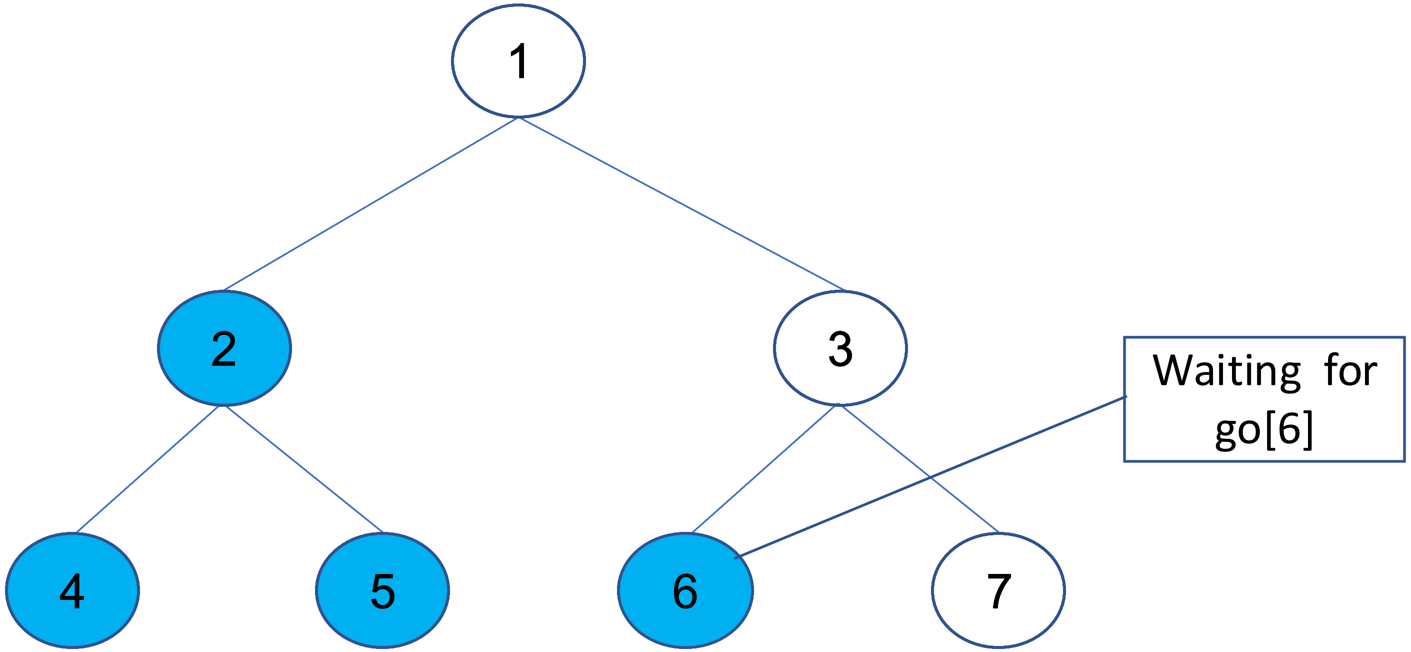
A Tree-based Barrier
Example Run for n=7 threads



	2	3	4	5	6	7
arrive	1		0	0	1	
go						

```
shared      arrive[2..n]:  array of atomic bits, initial values = 0
            go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                             // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                                // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                    // leaf
        arrive[i]  := 1
        await(go[i]  = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



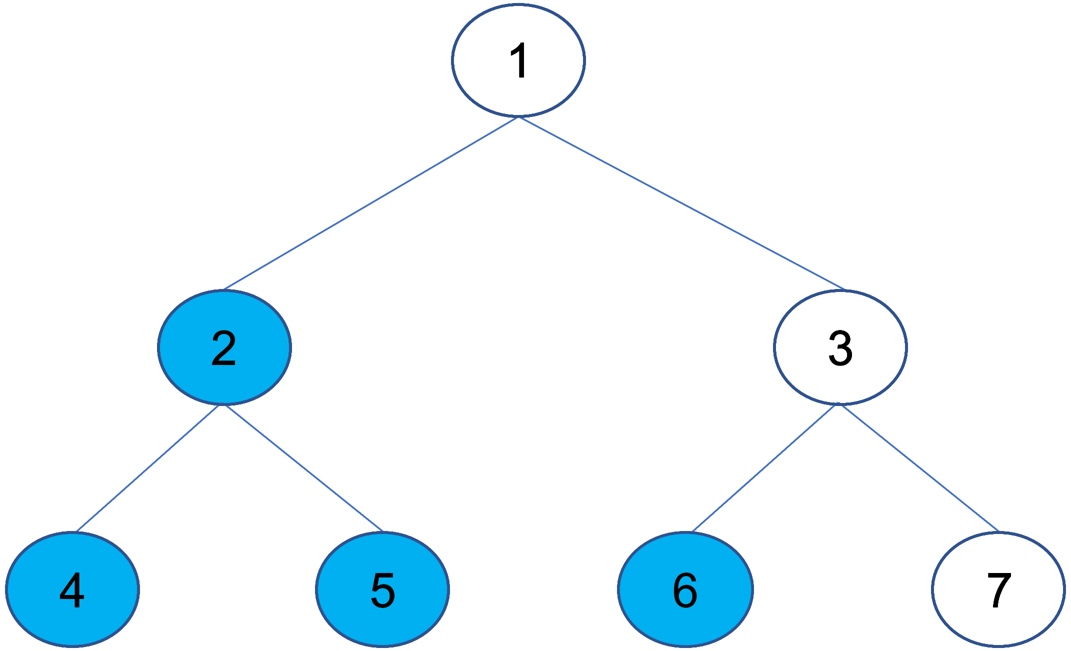
Waiting for go[6]

	2	3	4	5	6	7
arrive	1		0	0	1	
go						

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
    await(arrive[2]  = 1); arrive[2] := 0
    await(arrive[3]  = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                               // leaf
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

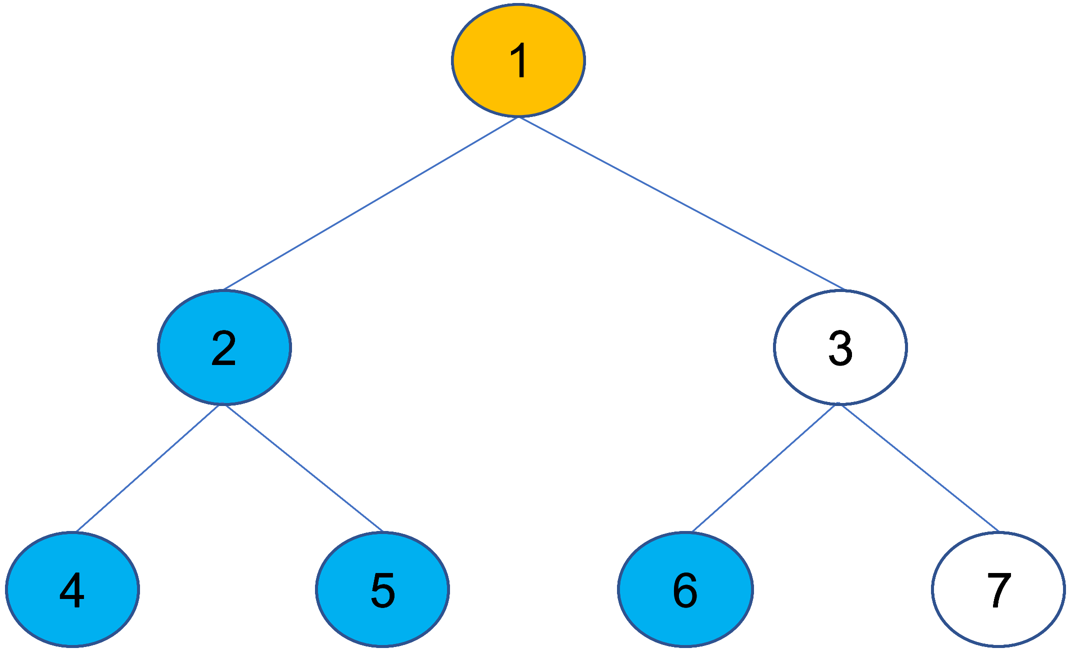


	2	3	4	5	6	7
arrive	1		0	0	1	
go						

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



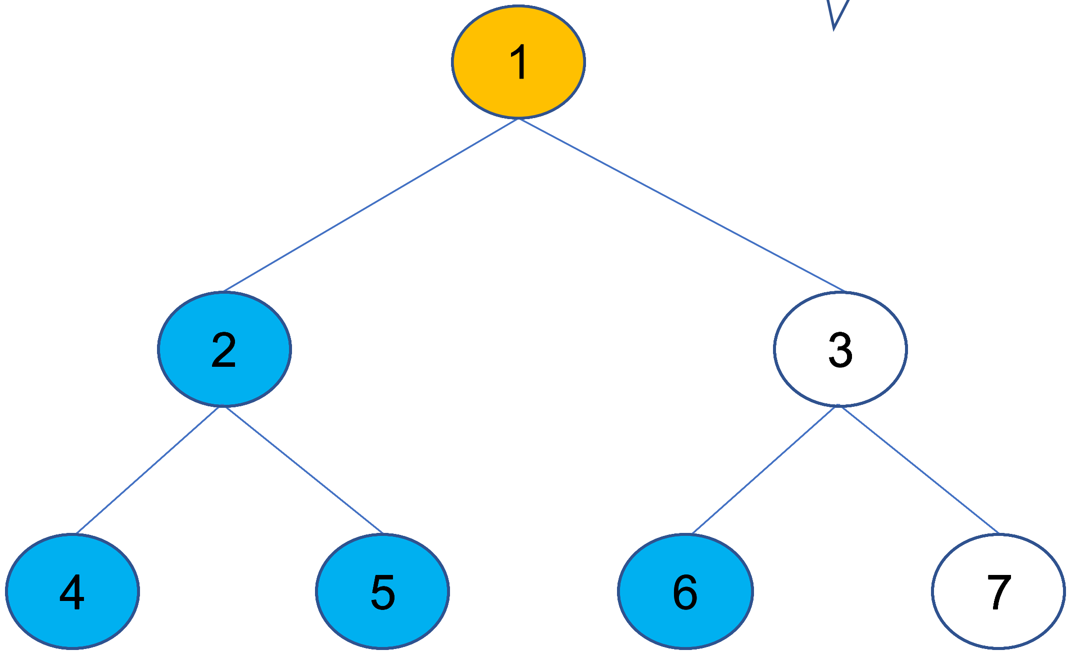
```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
      await(arrive[2] = 1); arrive[2] := 0
      await(arrive[3] = 1); arrive[3] := 0
      go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
      await(arrive[2i] = 1); arrive[2i] := 0
      await(arrive[2i+1] = 1); arrive[2i+1] := 0
      arrive[i] := 1
      await(go[i] = 1); go[i] := 0
      go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
      arrive[i] := 1
      await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	1		0	0	1	
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

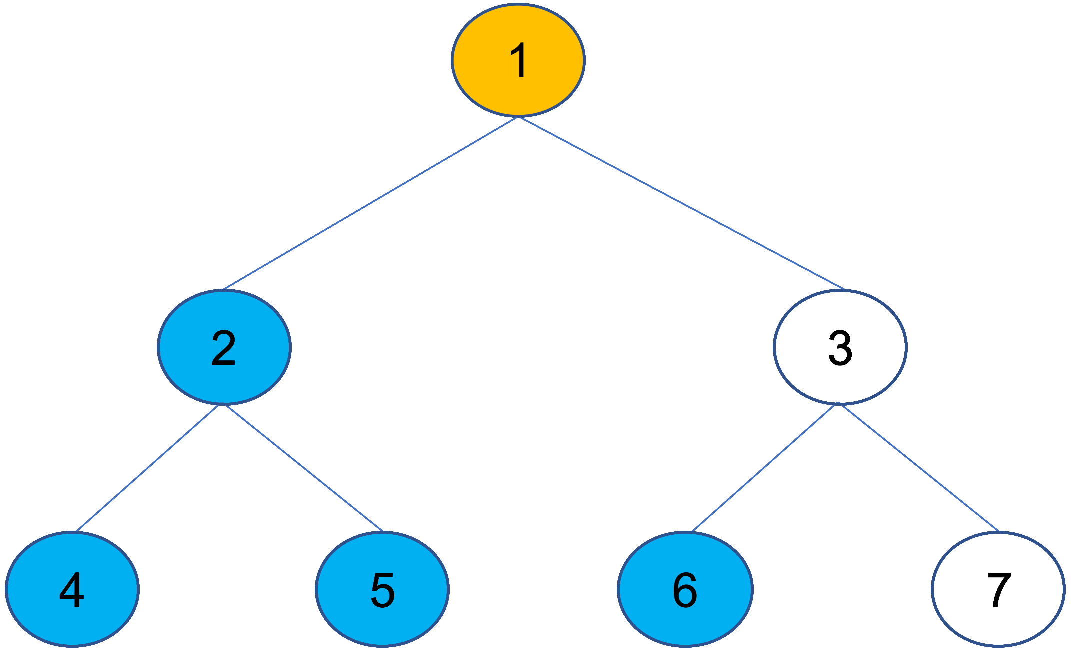
Arrive[2]=1
?



```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	1		0	0	1	
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

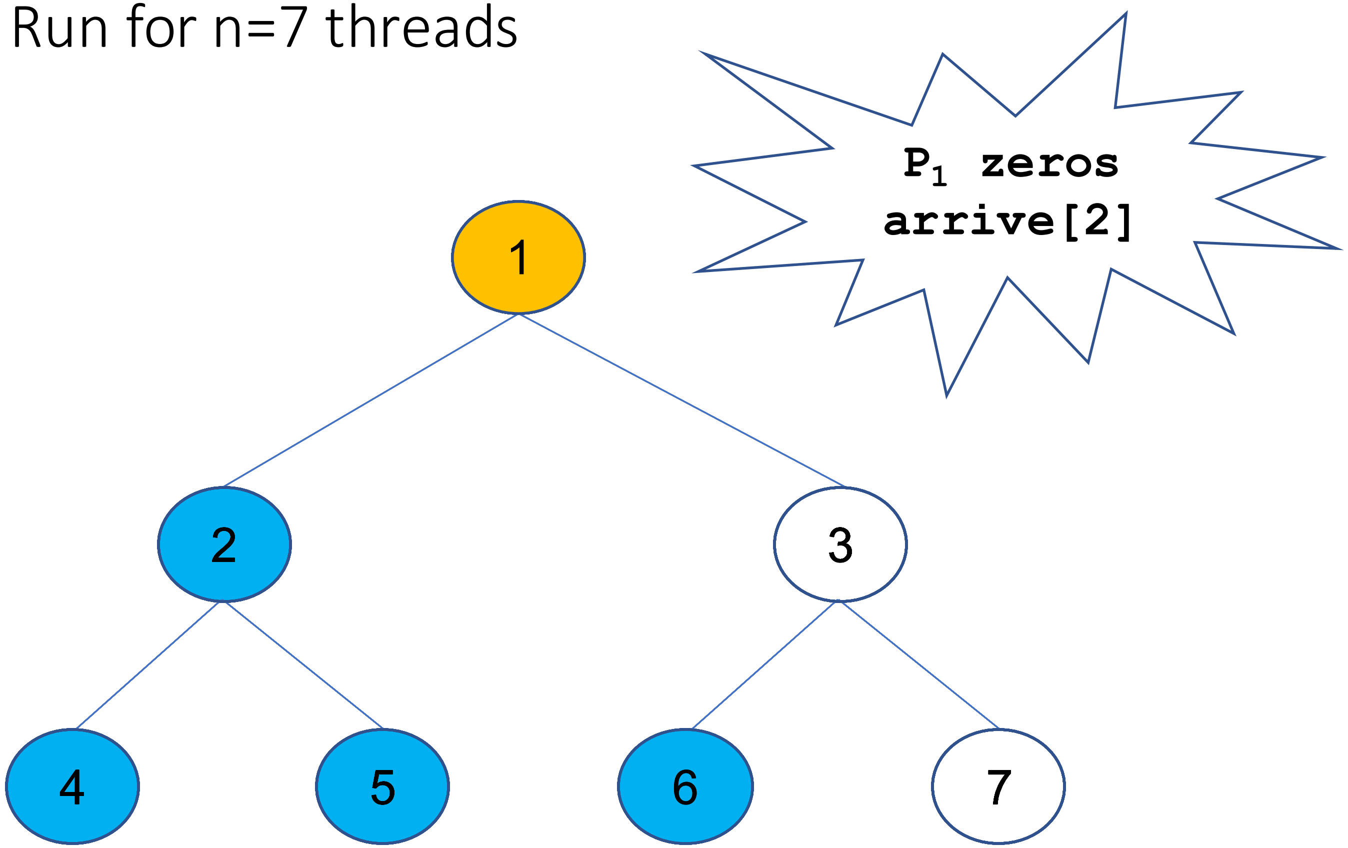


	2	3	4	5	6	7
arrive	1		0	0	1	
go						

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



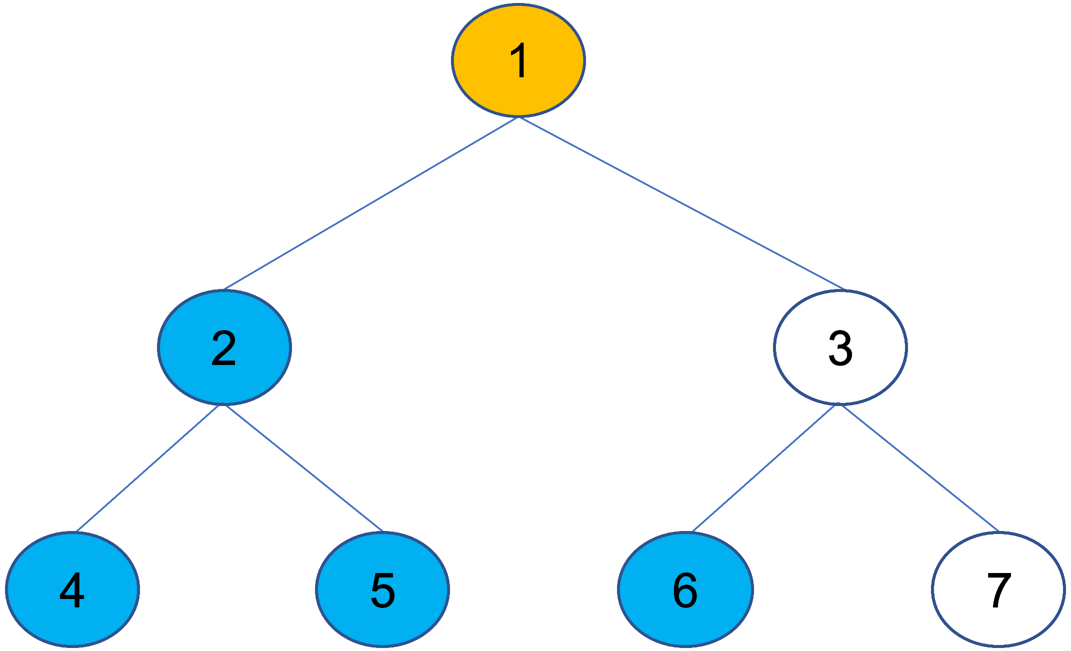
P_1 **zeros arrive[2]**

shared arrive[2..n]: array of atomic bits, initial values = 0
go[2..n]: array of atomic bits, initial values = 0

```
if i=1 then                                  // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                     // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                         // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

	2	3	4	5	6	7
arrive	0		0	0	1	
go						

A Tree-based Barrier
Example Run for n=7 threads

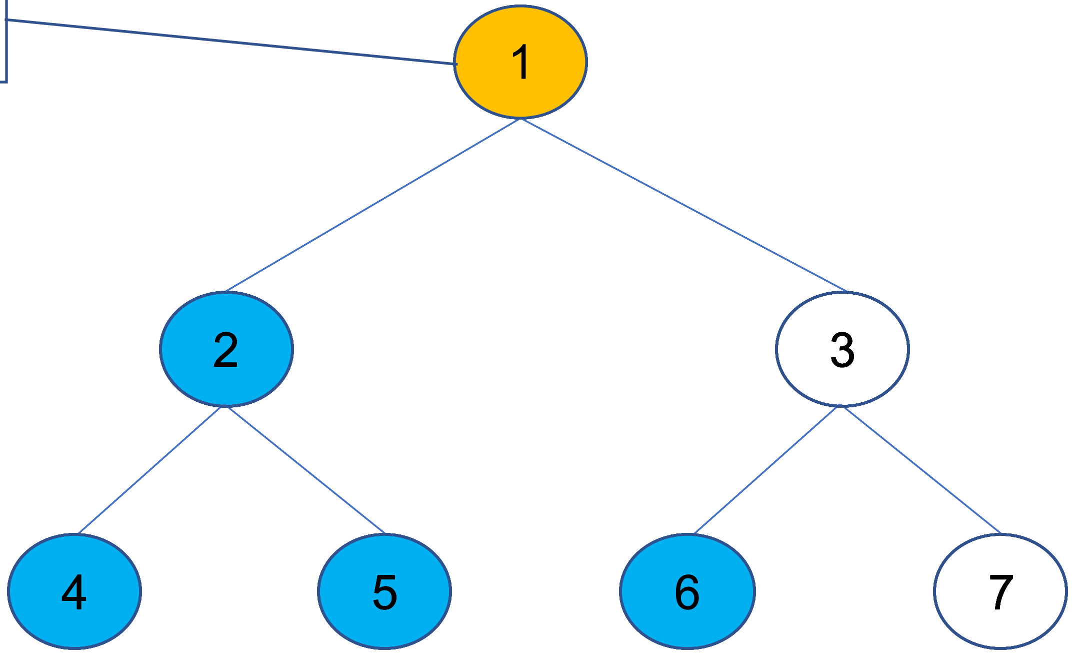


```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                           // root
    await(arrive[2]  = 1); arrive[2] := 0
    await(arrive[3]  = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                              // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                  // leaf
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0		0	0	1	
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads



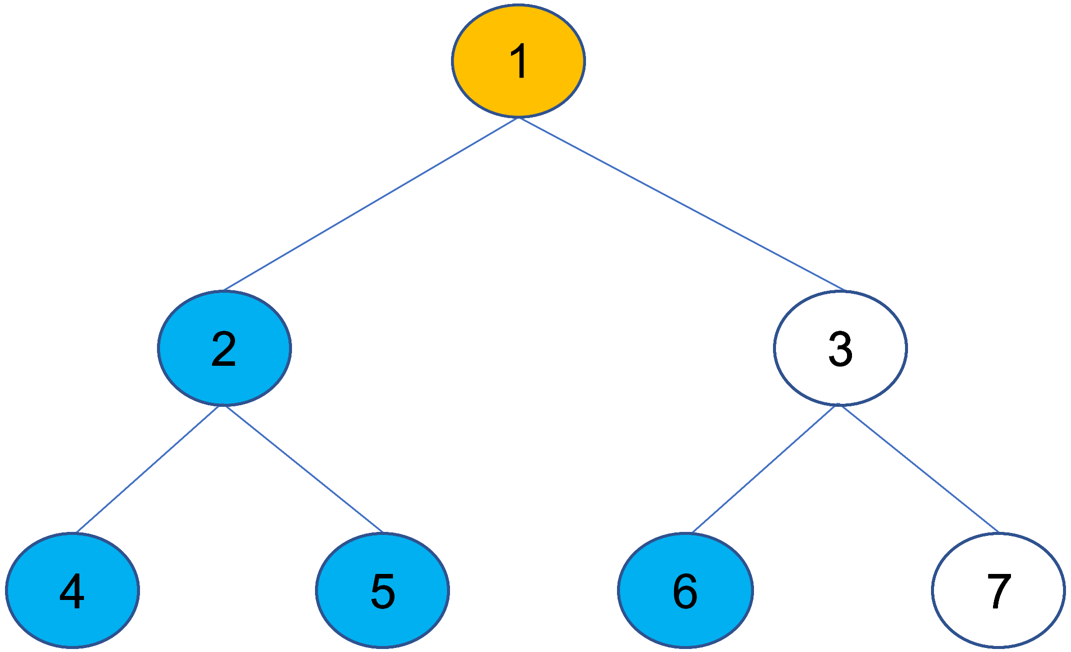
Waiting for p_3 to arrive

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                               // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

	2	3	4	5	6	7
arrive	0		0	0	1	
go						

A Tree-based Barrier
Example Run for n=7 threads

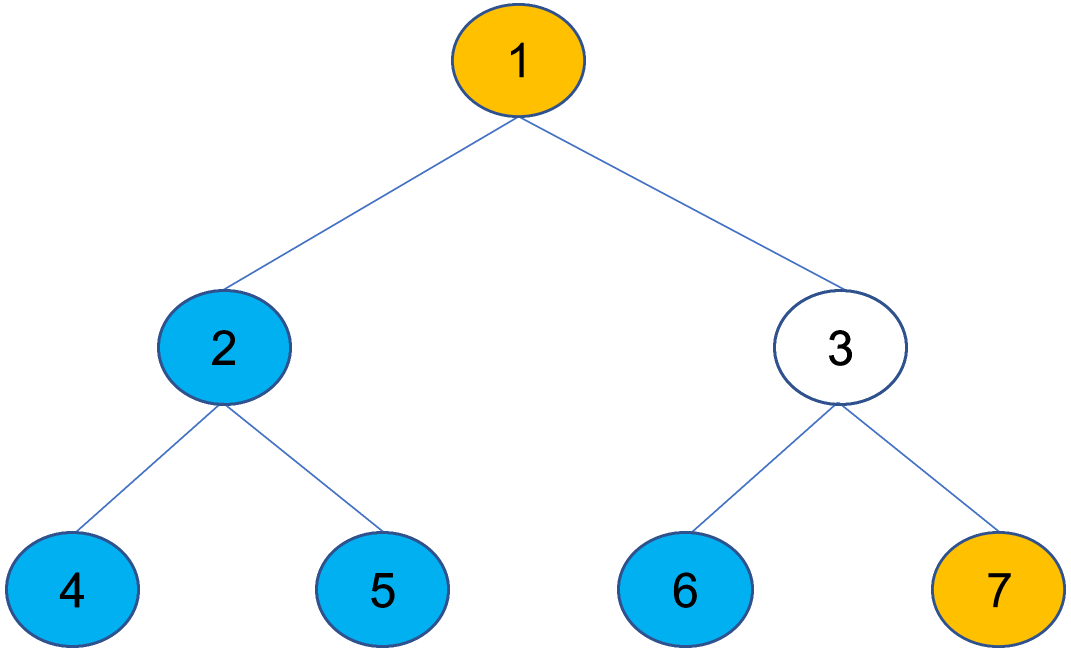


```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                               // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0		0	0	1	
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

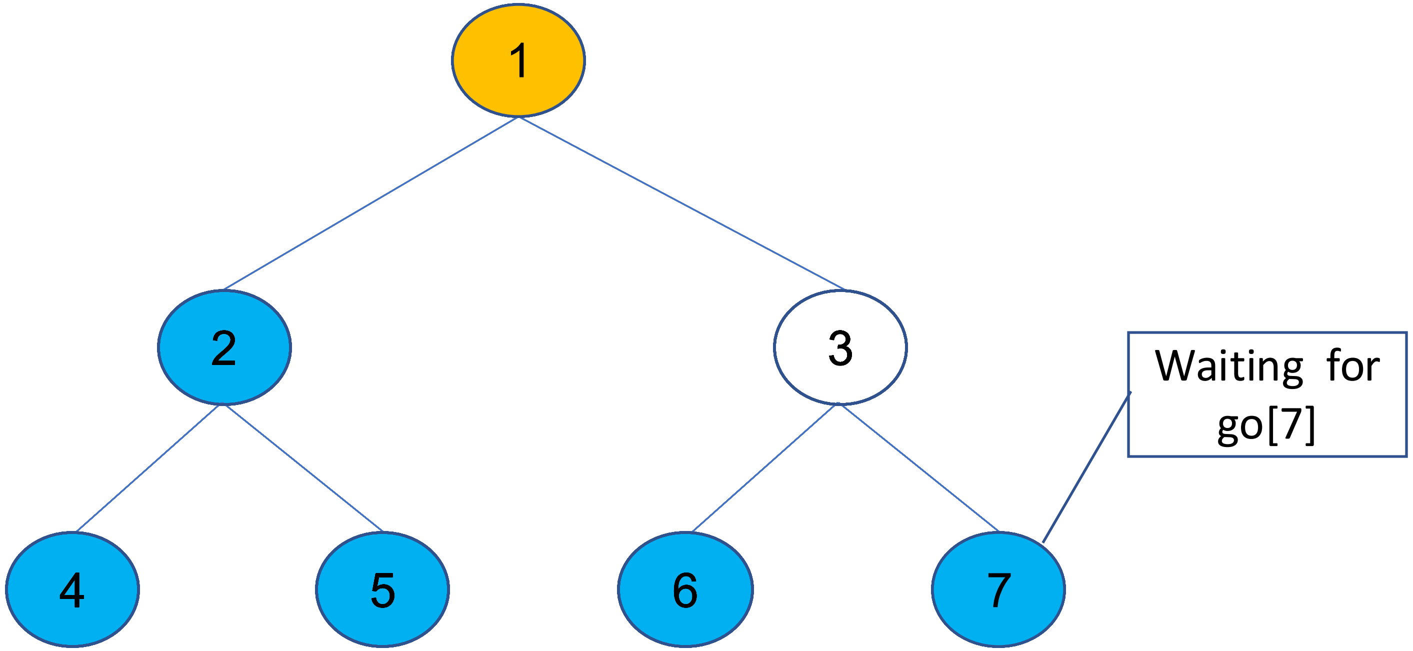


	2	3	4	5	6	7
arrive	0		0	0	1	1
go						

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                           // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                              // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                  // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads



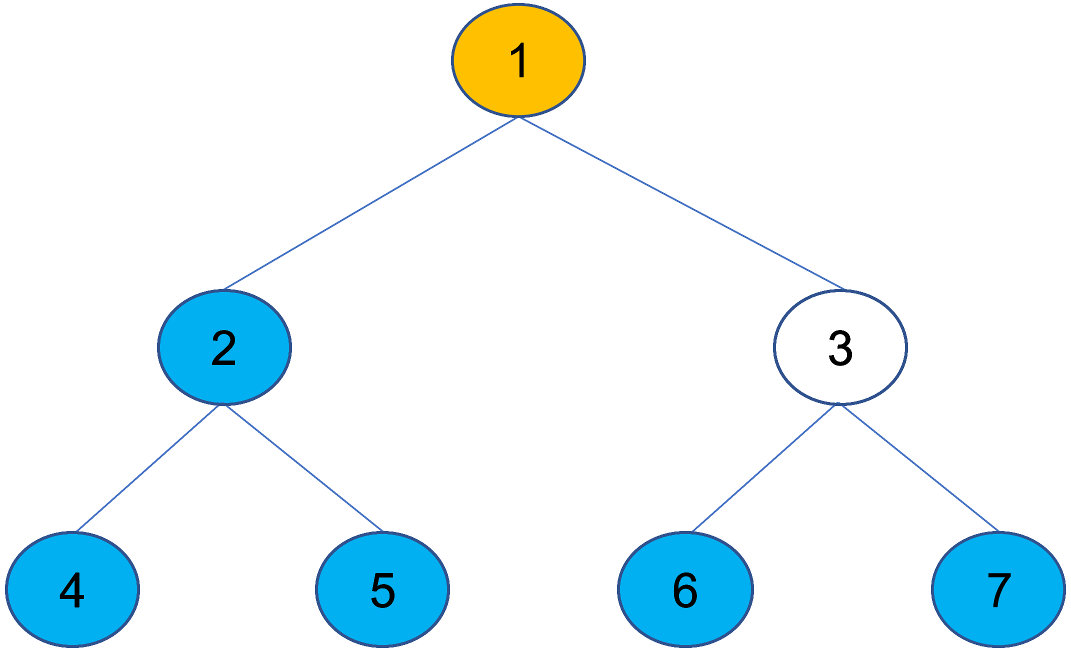
Waiting for go[7]

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                               // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0		0	0	1	1
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

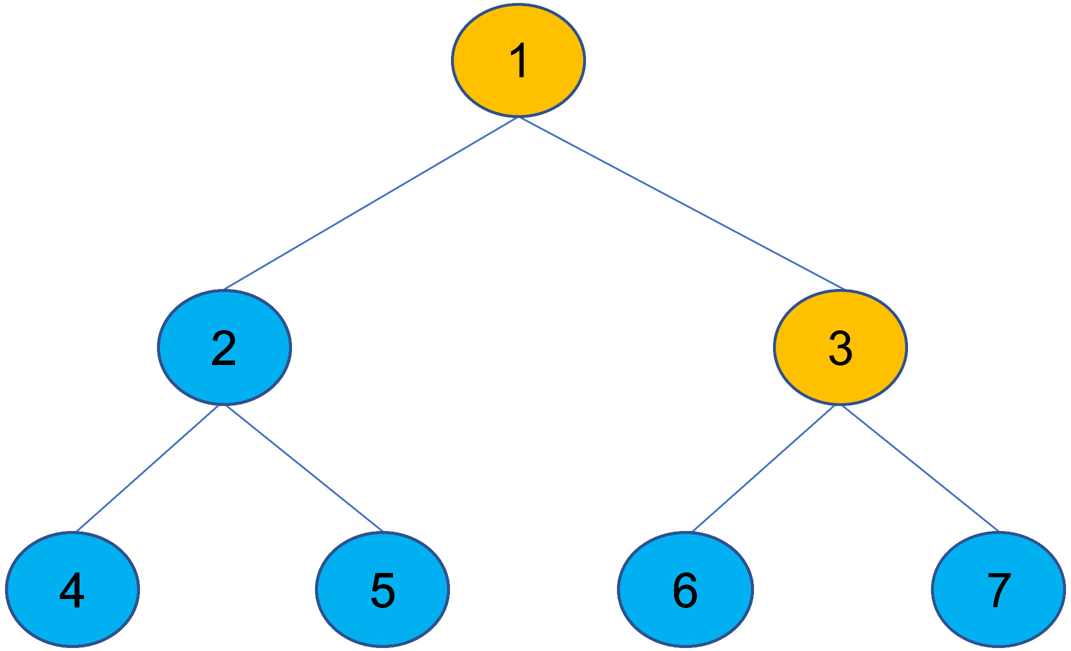


```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                   // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                      // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                          // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0		0	0	1	1
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads



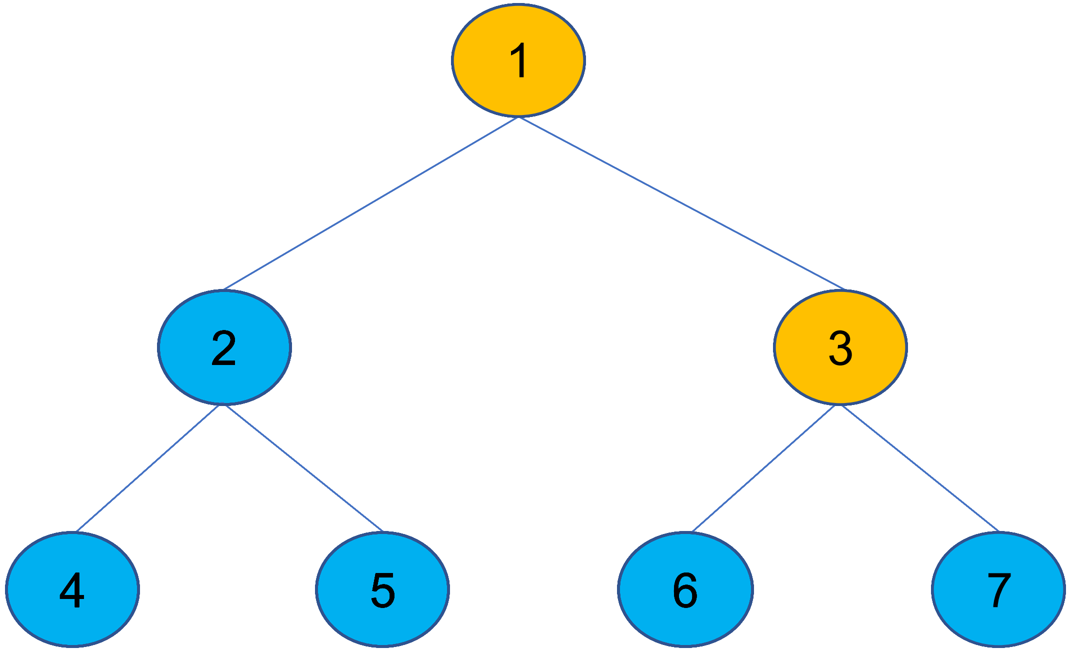
	2	3	4	5	6	7
arrive	0		0	0	1	1
go						

```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

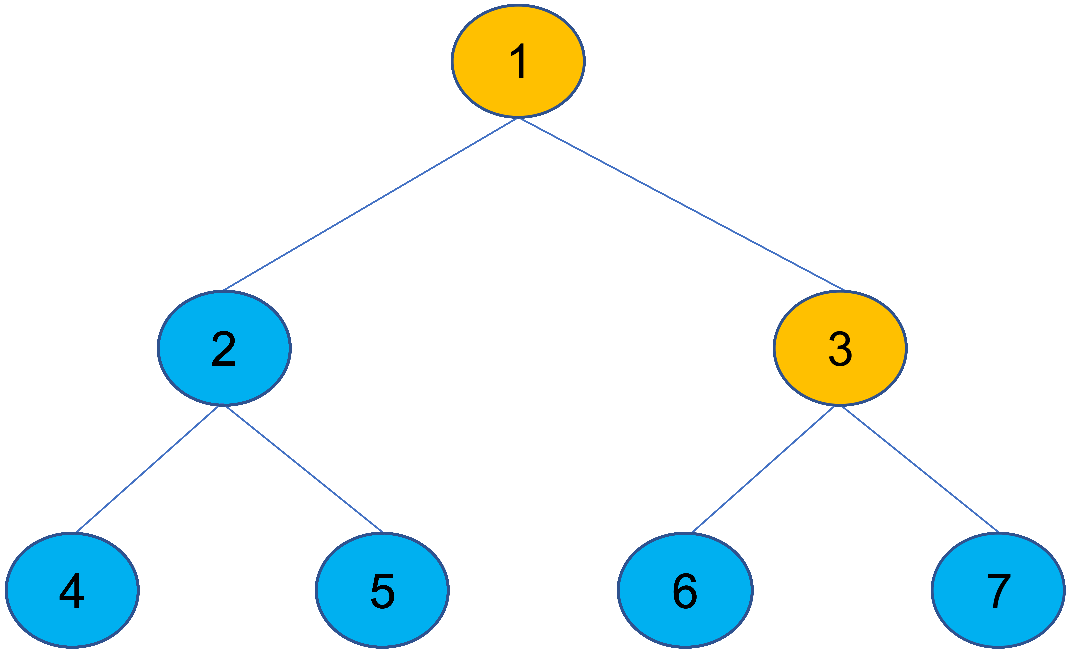
P_3 zeros arrive[6,7]



	2	3	4	5	6	7
arrive	0		0	0	0	0
go						

```
shared  arrive[2..n]: array of atomic bits, initial values = 0
        go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                        // root
    await(arrive[2] = 1); arrive[2] := 0
    await(arrive[3] = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
    await(arrive[2i] = 1); arrive[2i] := 0
    await(arrive[2i+1] = 1); arrive[2i+1] := 0
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                               // leaf
    arrive[i] := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

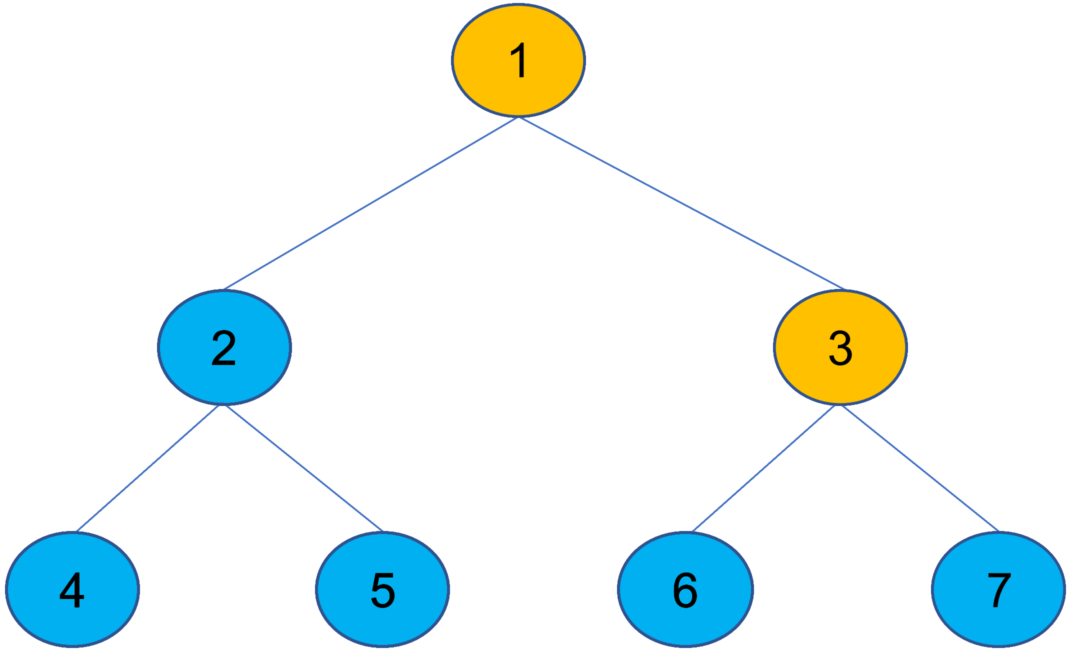


```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0		0	0	0	0
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

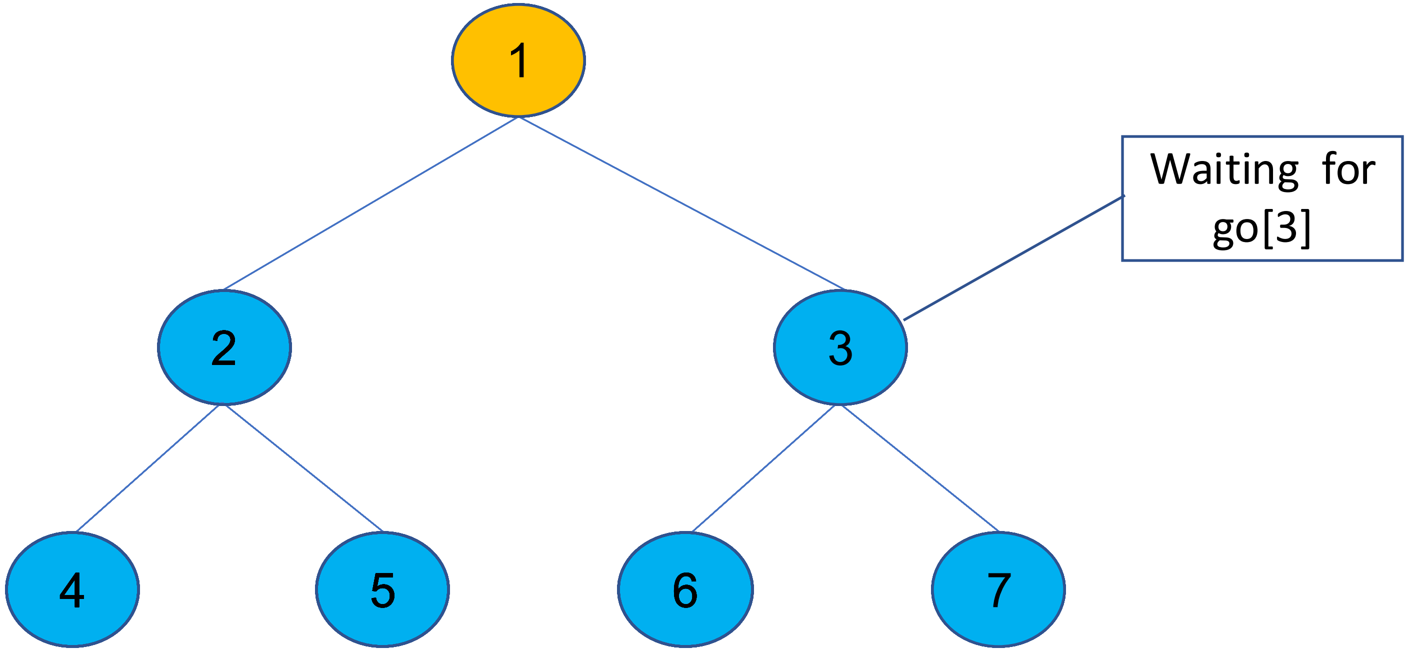


arrive	0	1	0	0	0	0
go						
	2	3	4	5	6	7

```
shared      arrive[2..n]:  array of atomic bits, initial values = 0
            go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
    await(arrive[2]  = 1); arrive[2] := 0
    await(arrive[3]  = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

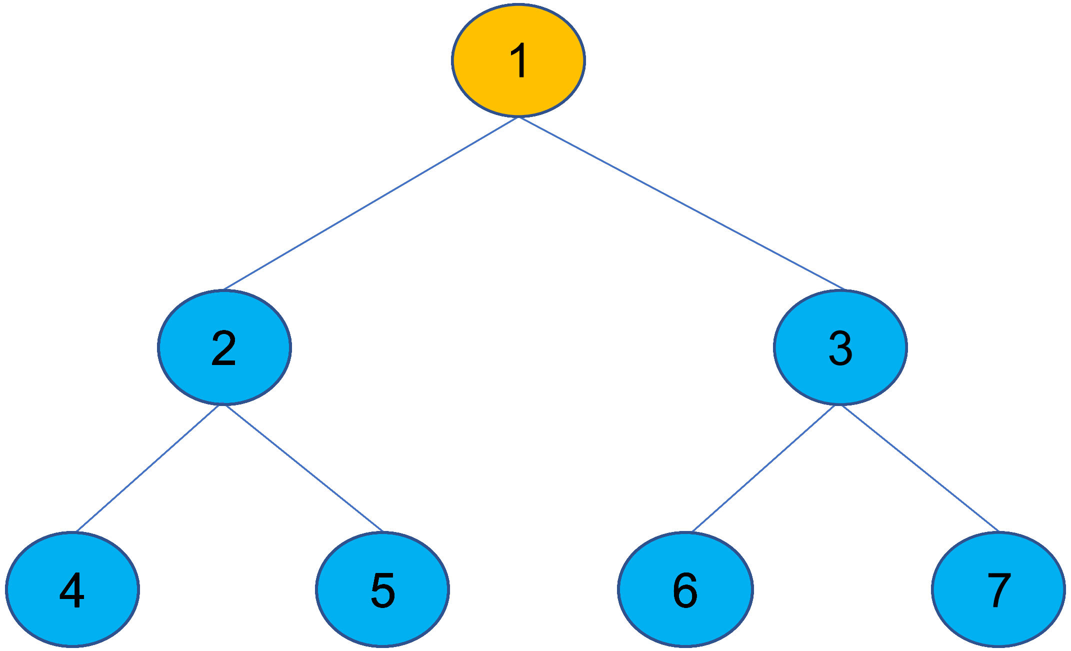


Waiting for go[3]

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0

if i=1 then                                          // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

	2	3	4	5	6	7
arrive	0	1	0	0	0	0
go						

A Tree-based Barrier
Example Run for n=7 threads



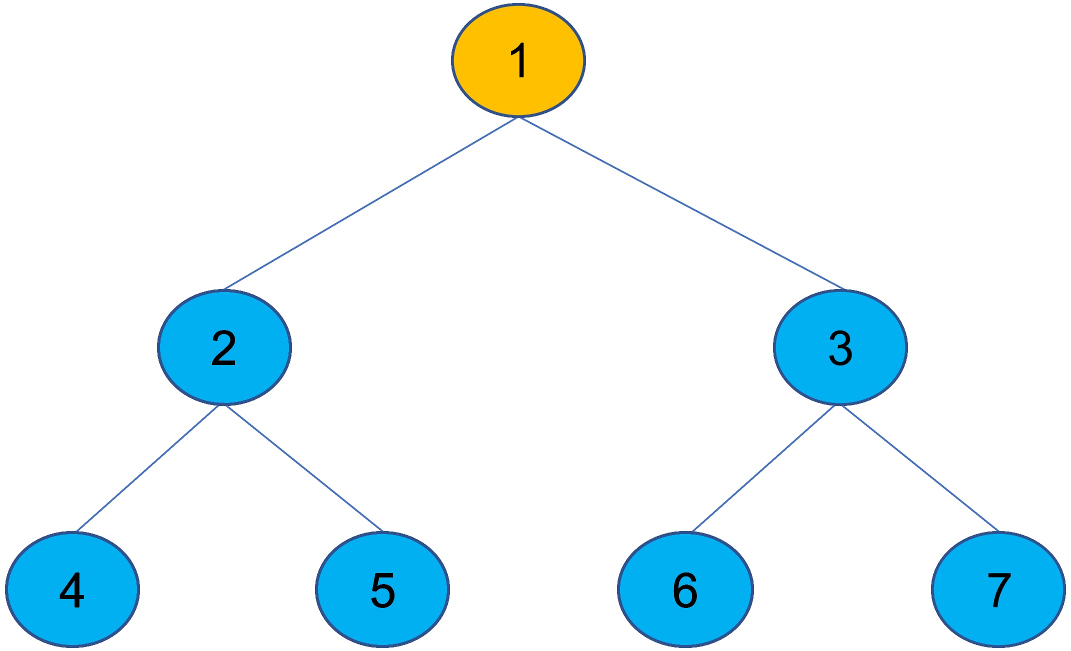
```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2] := 0
        await(arrive[3]  = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0	1	0	0	0	0
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

P_1 zeros arrive[3]



arrive	0	0	0	0	0	0
go						
	2	3	4	5	6	7

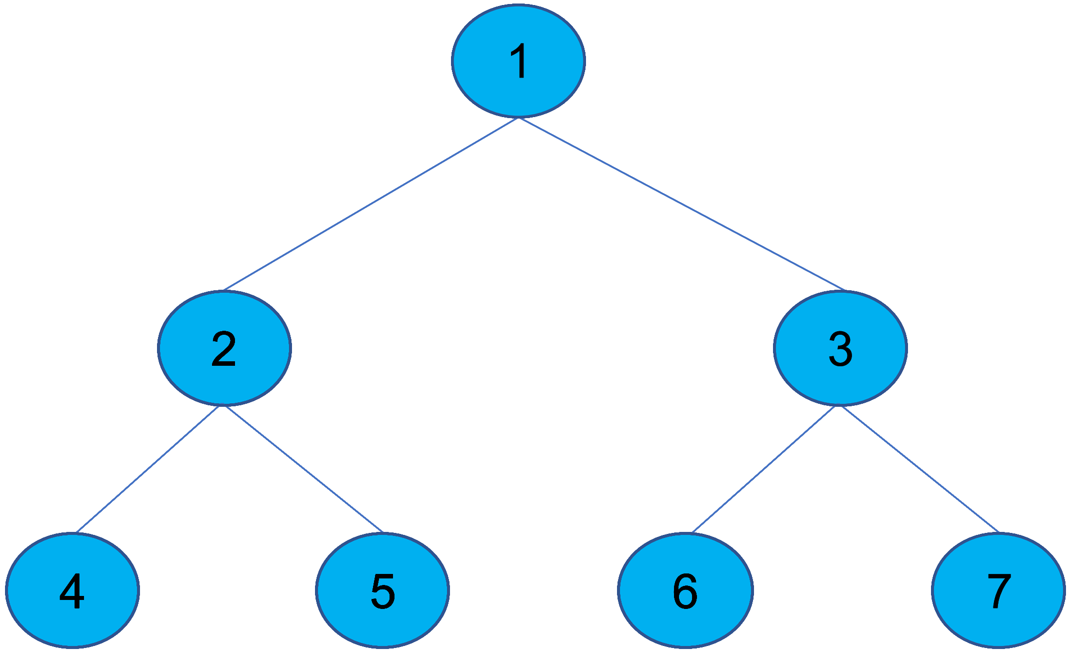
```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                            // root
      await(arrive[2] = 1); arrive[2] := 0
      await(arrive[3] = 1); arrive[3] := 0
      go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                               // internal node
      await(arrive[2i] = 1); arrive[2i] := 0
      await(arrive[2i+1] = 1); arrive[2i+1] := 0
      arrive[i] := 1
      await(go[i] = 1); go[i] := 0
      go[2i] = 1; go[2i+1] := 1
else                                                   // leaf
      arrive[i] := 1
      await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

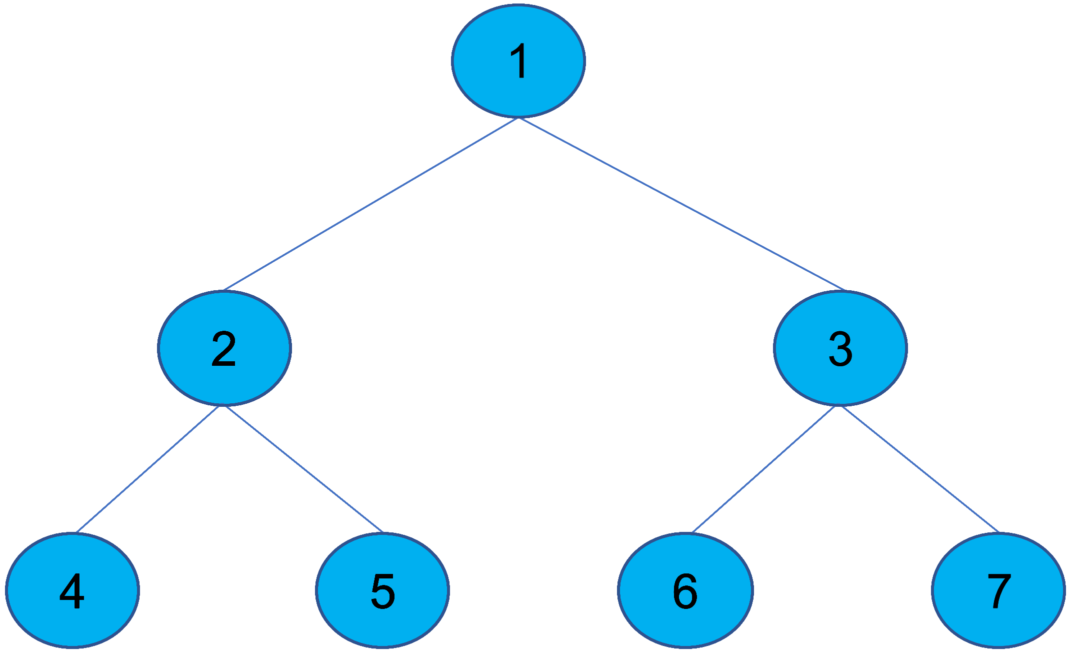
```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                            // root
        await(arrive[2] = 1); arrive[2] := 0
        await(arrive[3] = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                               // internal node
        await(arrive[2i] = 1); arrive[2i] := 0
        await(arrive[2i+1] = 1); arrive[2i+1] := 0
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                   // leaf
        arrive[i] := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```



	2	3	4	5	6	7
arrive	0	0	0	0	0	0
go						

A Tree-based Barrier
Example Run for n=7 threads



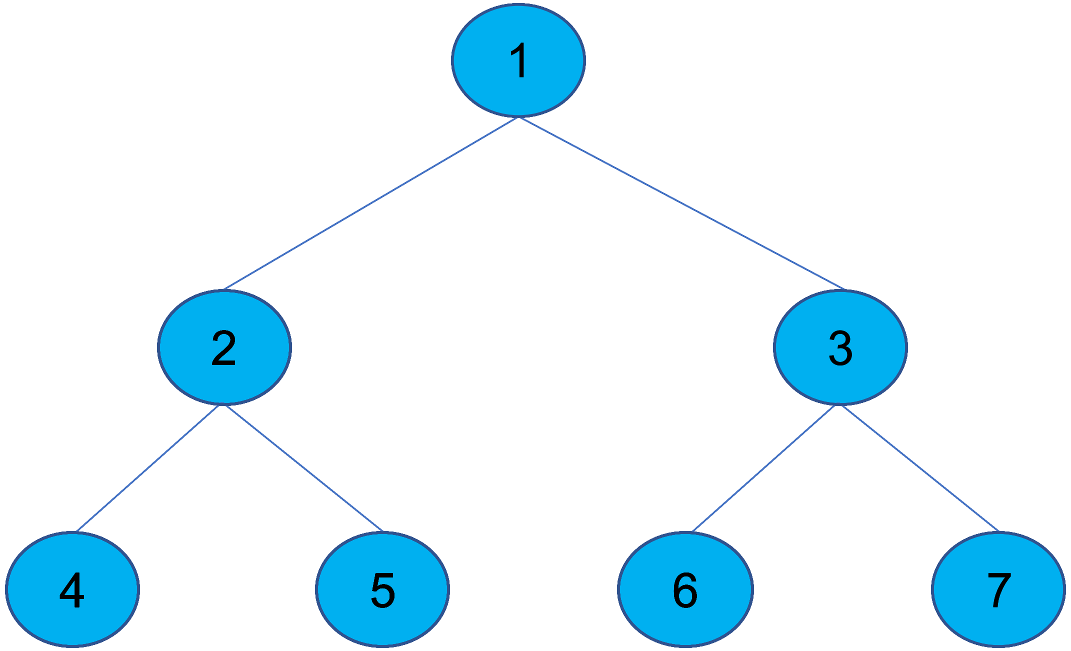
```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                        // root
        await(arrive[2]  = 1); arrive[2]  := 0
        await(arrive[3]  = 1); arrive[3]  := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                           // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                               // leaf
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

	2	3	4	5	6	7
arrive	0	0	0	0	0	0
go						

At this point all non-root threads in some await(go) case

A Tree-based Barrier
Example Run for n=7 threads

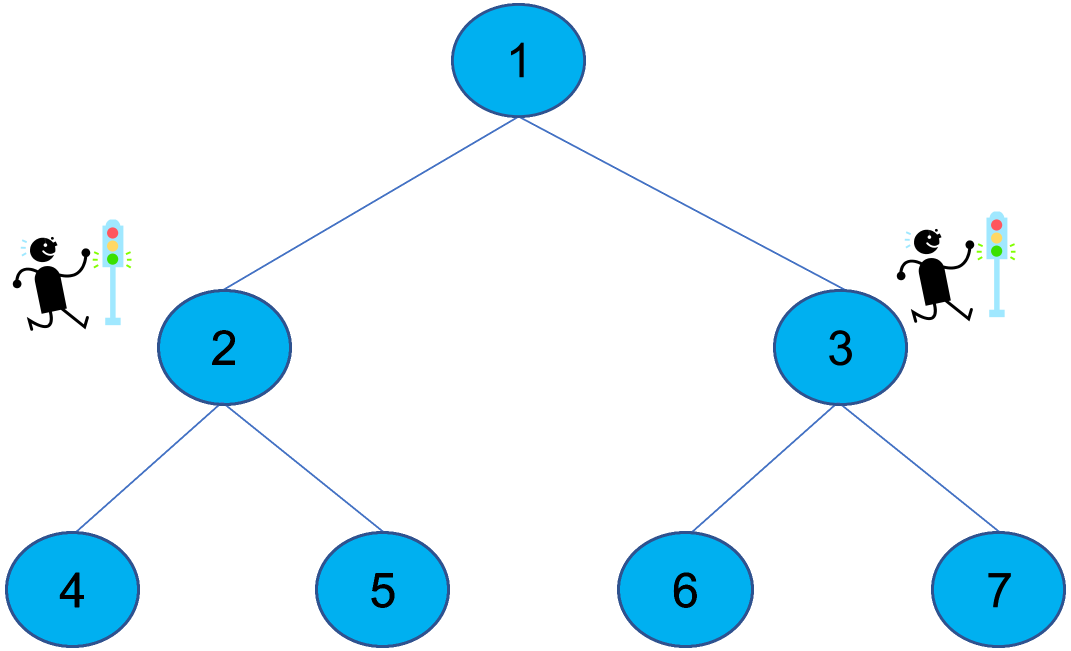


```
shared   arrive[2..n]:  array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
      await(arrive[2]  = 1); arrive[2]  := 0
      await(arrive[3]  = 1); arrive[3]  := 0
      go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                              // internal node
      await(arrive[2i]  = 1); arrive[2i]  := 0
      await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
      arrive[i]  := 1
      await(go[i]  = 1); go[i] := 0
      go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
      arrive[i]  := 1
      await(go[i]  = 1); go[i] := 0 fi
fi
```

arrive	0	0	0	0	0	0
go						
	2	3	4	5	6	7

A Tree-based Barrier
Example Run for n=7 threads

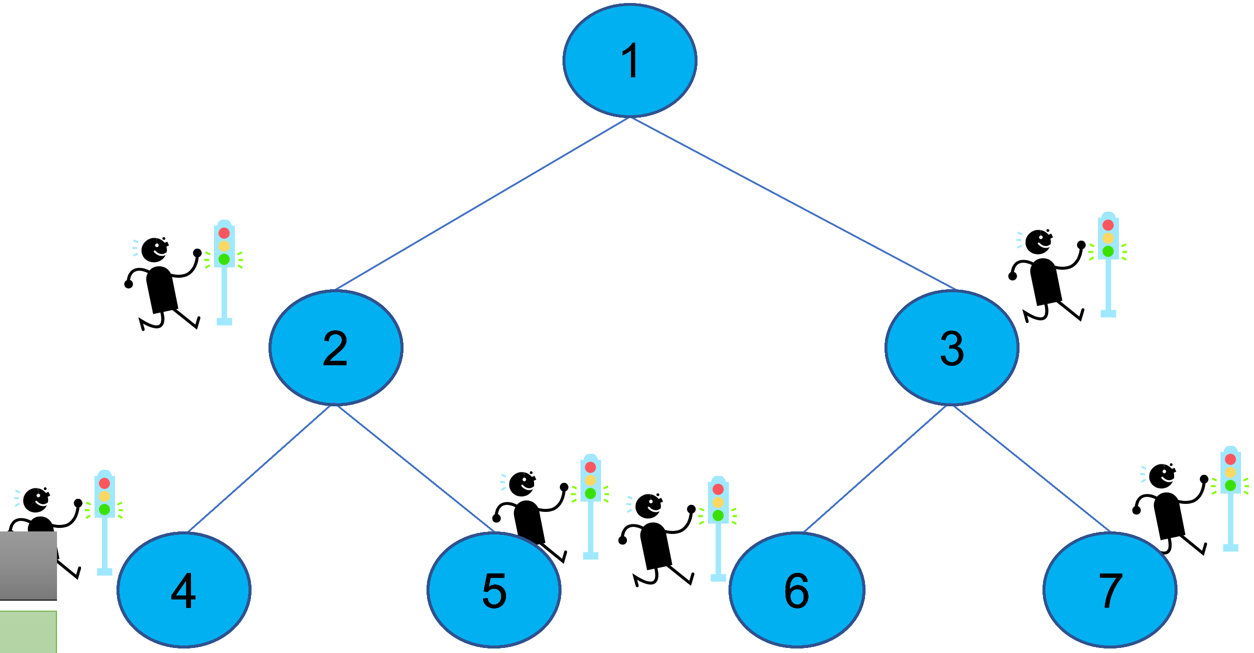


arrive	0	0	0	0	0	0
go	1	1				
	2	3	4	5	6	7

```
shared   arrive[2..n]: array of atomic bits, initial values = 0
         go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                         // root
    await(arrive[2]  = 1); arrive[2] := 0
    await(arrive[3]  = 1); arrive[3] := 0
    go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                            // internal node
    await(arrive[2i]  = 1); arrive[2i]  := 0
    await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0
    go[2i] = 1; go[2i+1] := 1
else                                                // leaf
    arrive[i]  := 1
    await(go[i] = 1); go[i] := 0 fi
fi
```

A Tree-based Barrier
Example Run for n=7 threads

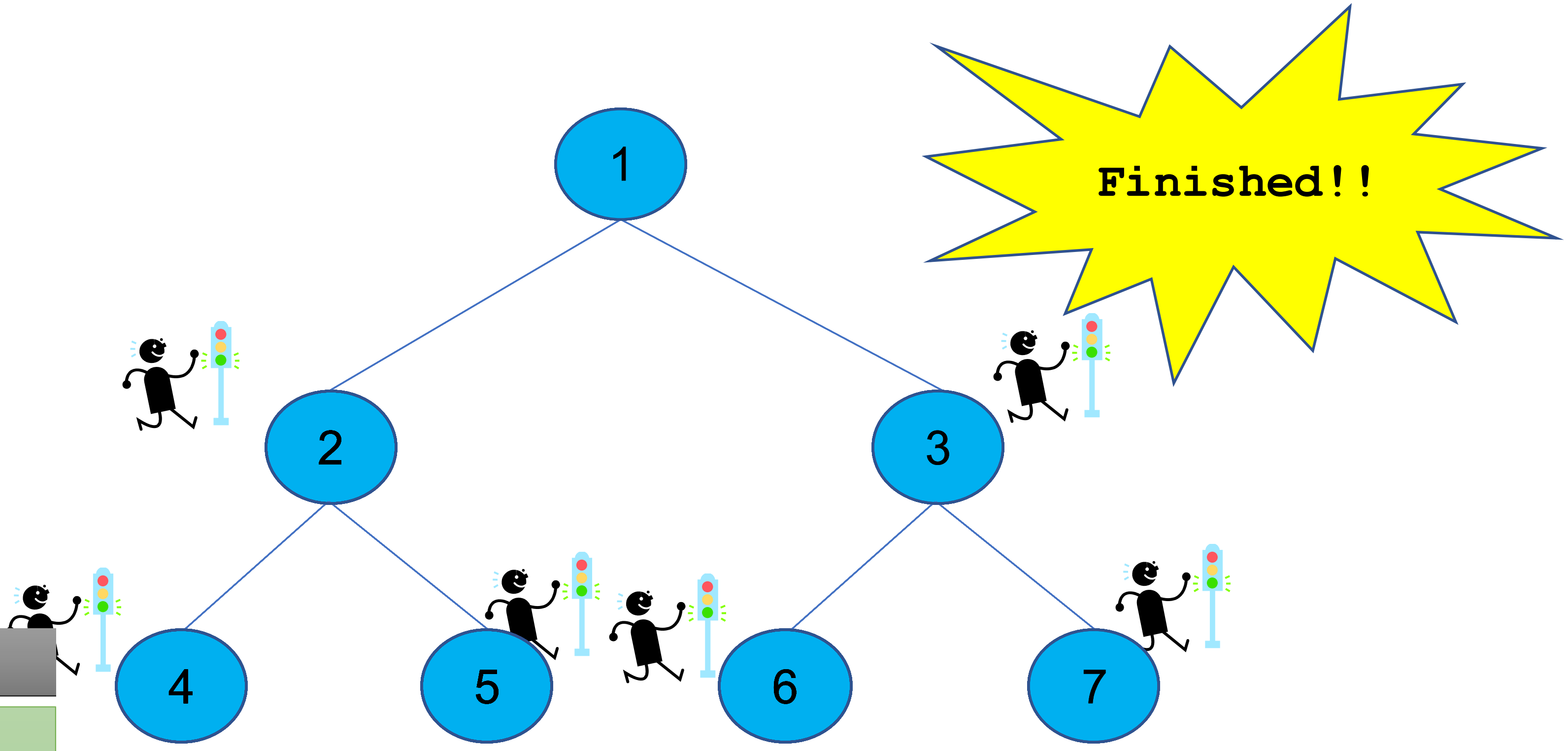


```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                          // root
        await(arrive[2]  = 1); arrive[2] := 0
        await(arrive[3]  = 1); arrive[3] := 0
        go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                             // internal node
        await(arrive[2i]  = 1); arrive[2i]  := 0
        await(arrive[2i+1]  = 1); arrive[2i+1]  := 0
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0
        go[2i] = 1; go[2i+1] := 1
else                                                 // leaf
        arrive[i]  := 1
        await(go[i] = 1); go[i] := 0 fi
fi
```

	2	3	4	5	6	7
arrive	0	0	0	0	0	0
go	1	1	1	1	1	1

A Tree-based Barrier
Example Run for n=7 threads



```
shared    arrive[2..n]: array of atomic bits, initial values = 0
          go[2..n]: array of atomic bits, initial values = 0
```

```
if i=1 then                                         // root
      await(arrive[2] = 1); arrive[2] := 0
      await(arrive[3] = 1); arrive[3] := 0
      go[2] = 1; go[3] = 1
else if i ≤ (n-1)/2 then                            // internal node
      await(arrive[2i] = 1); arrive[2i] := 0
      await(arrive[2i+1] = 1); arrive[2i+1] := 0
      arrive[i] := 1
      await(go[i] = 1); go[i] := 0
      go[2i] = 1; go[2i+1] := 1
else                                                // leaf
      arrive[i] := 1
      await(go[i] = 1); go[i] := 0 fi
fi
```

arrive	0	0	0	0	0	0
go	1	1	1	1	1	1
	2	3	4	5	6	7

Tree Barrier Tradeoffs

- Pros:

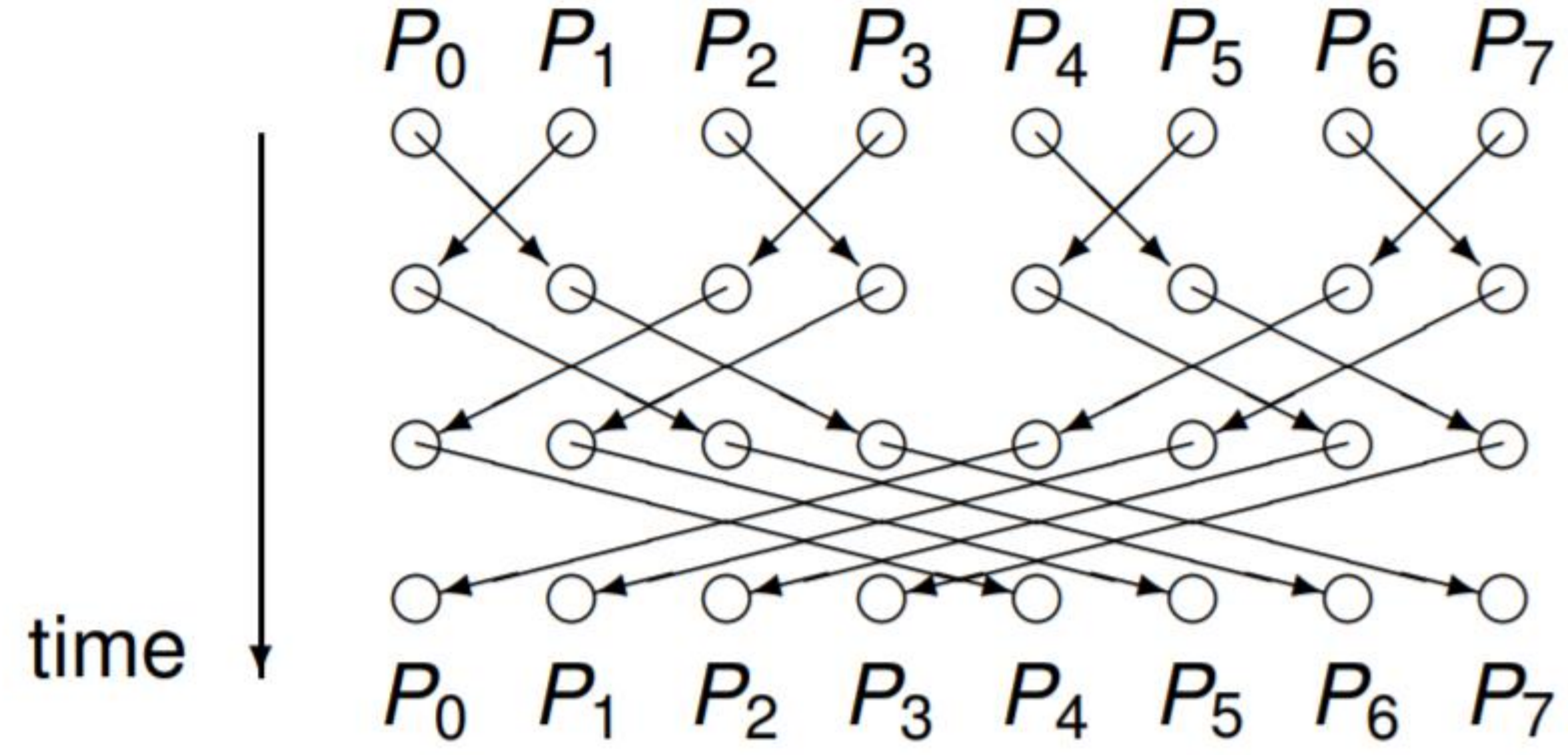
- Cons:

Tree Barrier Tradeoffs

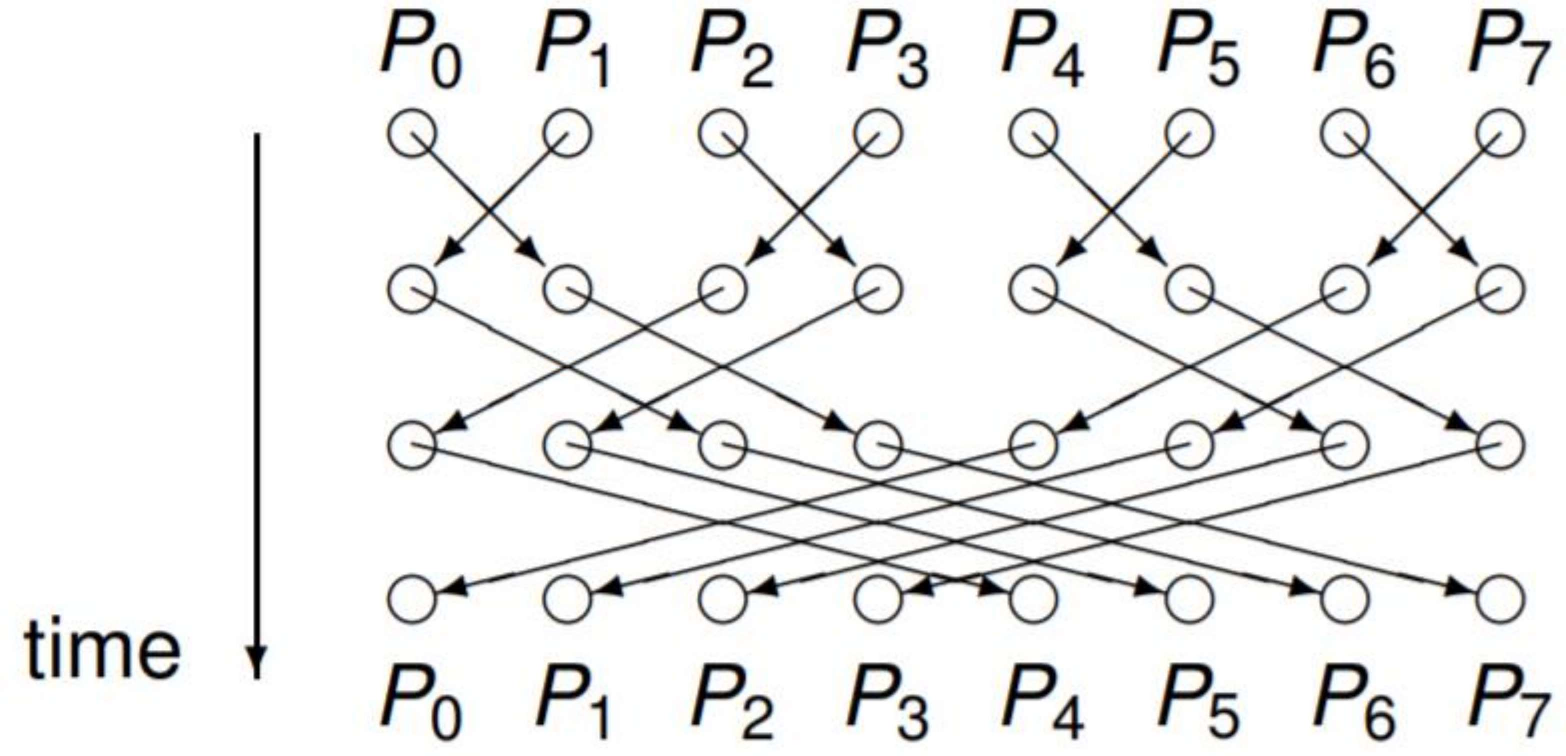
- Pros:
  - Low shared memory contention
    - No wait object is shared by more than 2 processes
    - Good for larger n
  - Fast – information from the root propagates after log(n) steps
  - Can use only atomic primitives (no special objects)
  - On some models:
    - each process spins on a locally accessible bit
    - # (remote memory ref.) = O(1) per process
- Cons:
  - Shared memory space complexity – O(n)
  - Asymmetric –all the processes don’t do the same amount of work

Butterfly Barrier

Butterfly Barrier

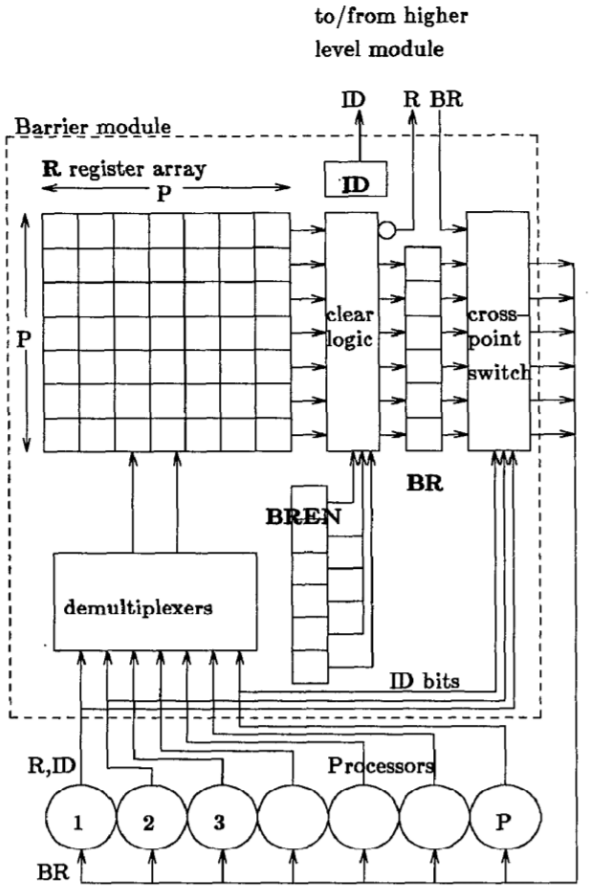

P_0 P_1 P_2 P_3 P_4 P_5 P_6 P_7
time
P_0 P_1 P_2 P_3 P_4 P_5 P_6 P_7

Butterfly Barrier

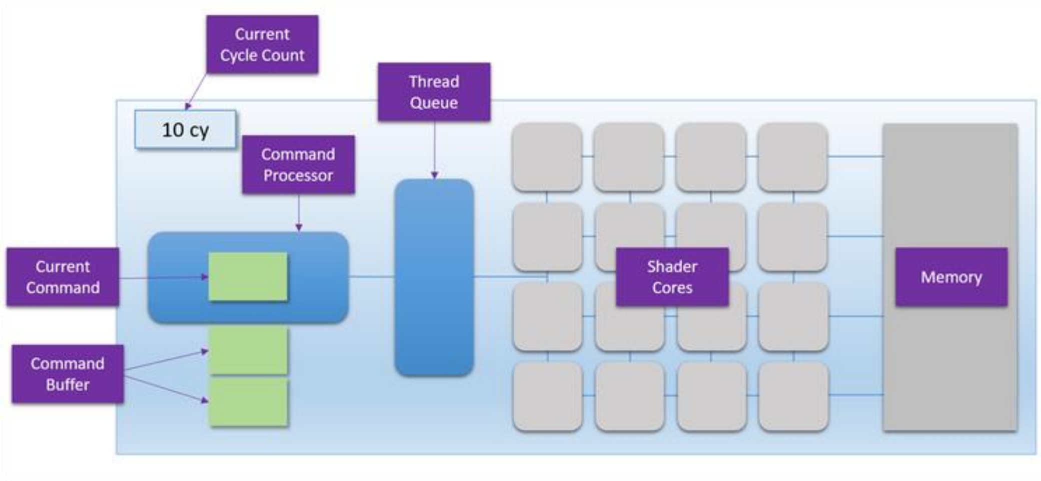

P_0 P_1 P_2 P_3 P_4 P_5 P_6 P_7
time
P_0 P_1 P_2 P_3 P_4 P_5 P_6 P_7

- When would this be preferable?

Hardware Supported Barriers



CPU



GPU

Barriers Summary

Seen:

- Semaphore-based barrier
- Simple barrier
    - Based on atomic fetch-and-increment counter
- Local spinning barrier
    - Based on atomic fetch-and-increment counter and go array
- Tree-based barrier

Not seen:

- Test-and-Set barriers
    - Based on test-and-test-and-set objects
    - One version without memory initialization
- See-Saw barrier

Questions?