CS3211 Tutorial 7

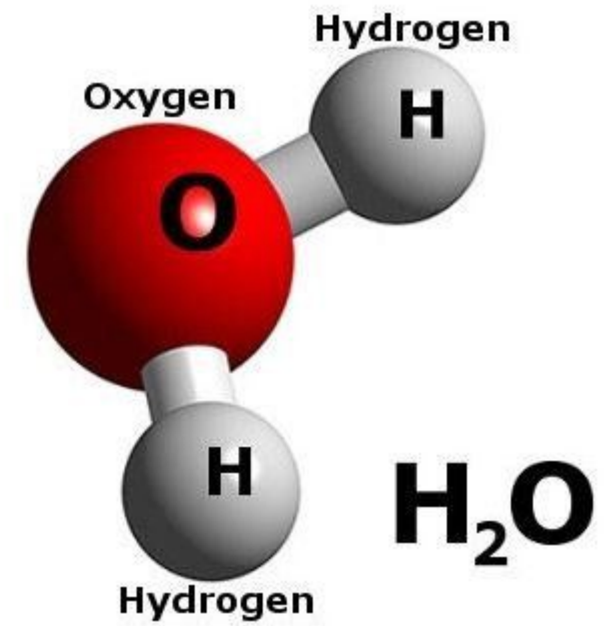
Classic Concurrency Problems in C++ & Go

H2O Problem

i.e. resource management

1. H2O Problem

- Hydrogen and oxygen atoms arrive at the factory.
- We **only** want to bond 2 H with 1 O.
- Atoms only start bonding when 2 H and 1 O arrives.
- Other atoms block.
- Only 1 bonding can occur at a time.



Models allocation of specific resources to a process.

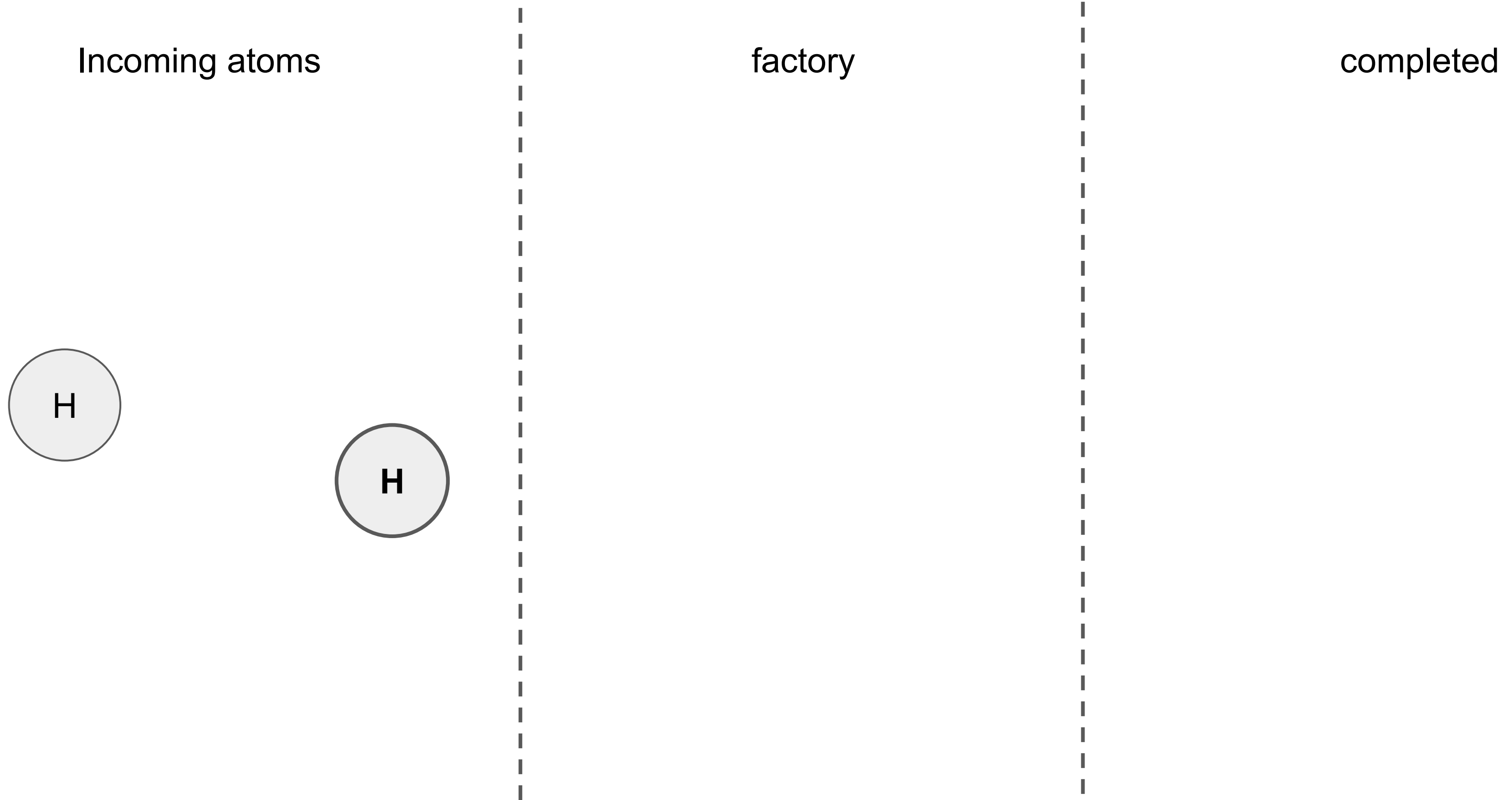
Models distributed transactions.

1. H2O Problem

Incoming atoms | factory | completed

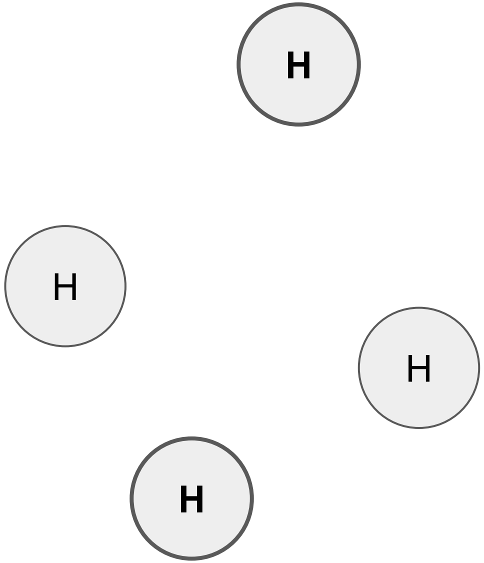
H

1. H2O Problem



1. H2O Problem

Incoming atoms | factory | completed

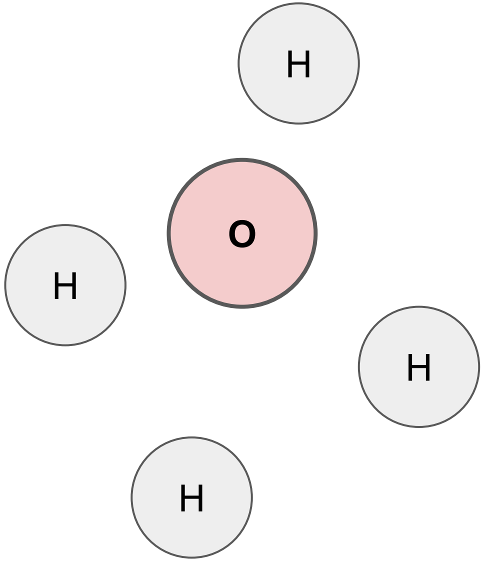


1. H2O Problem

Incoming atoms

factory

completed



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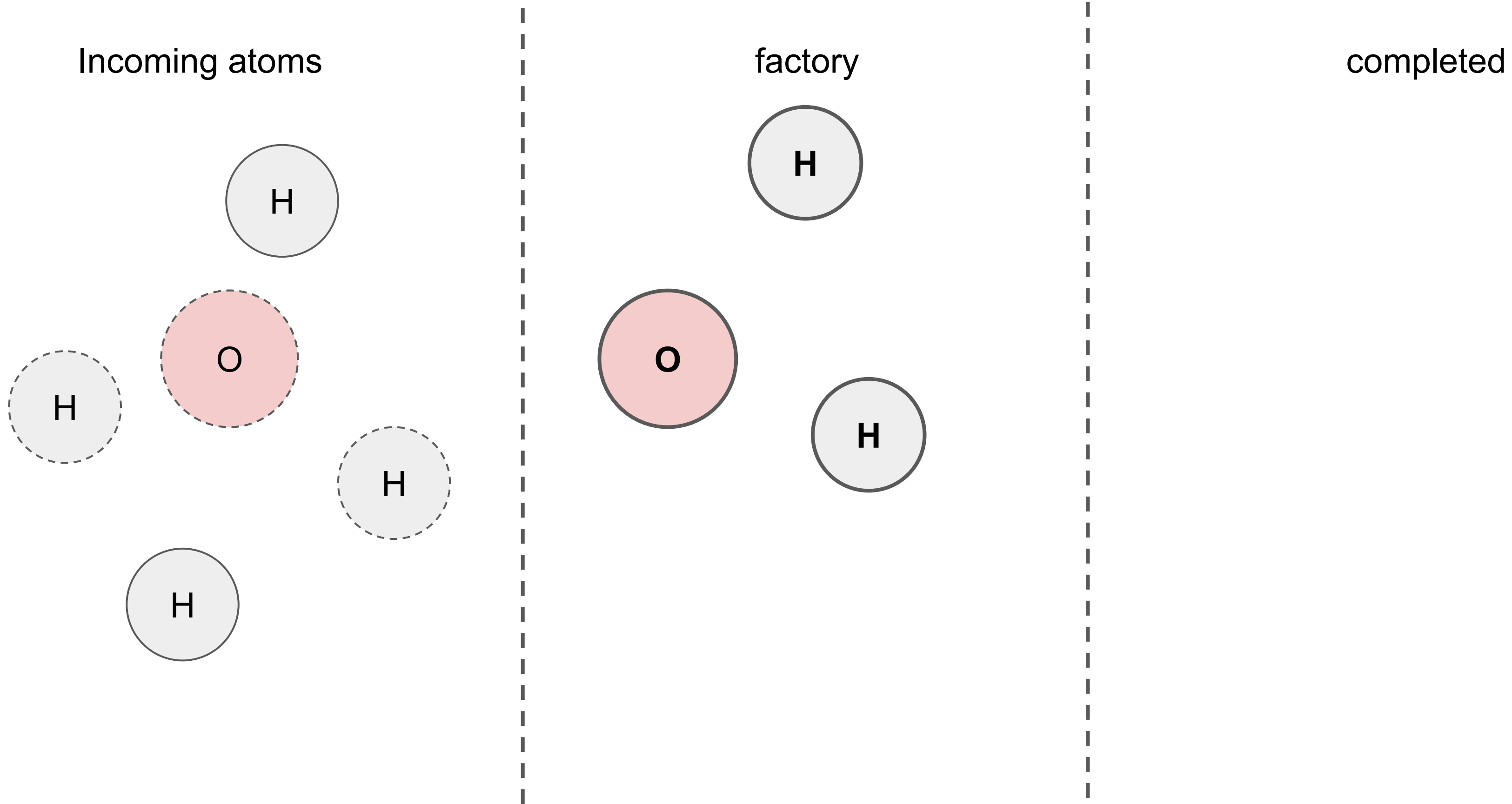

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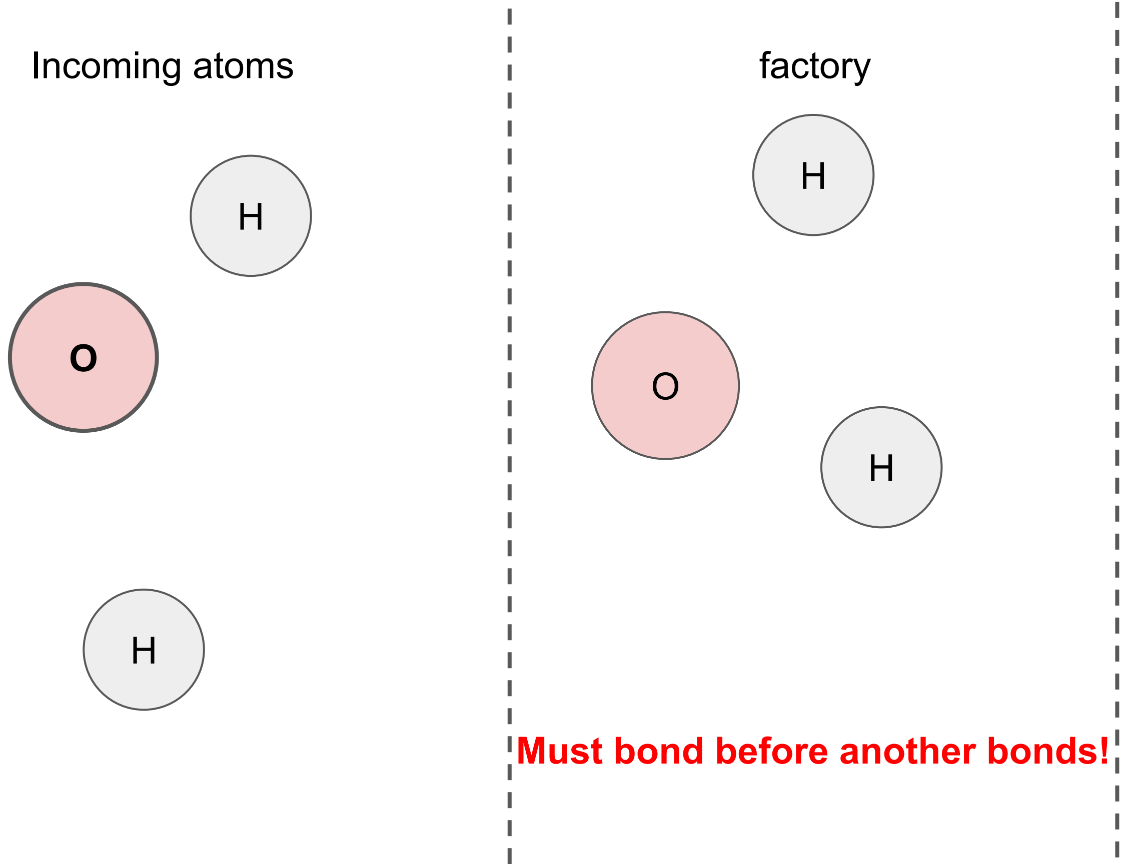
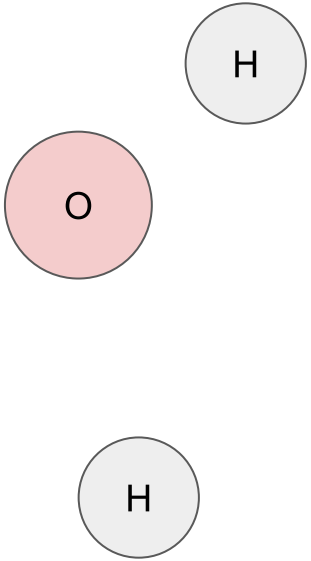


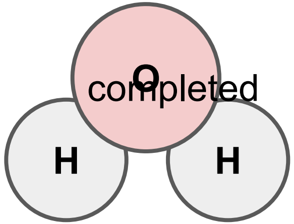
1. H2O Problem

Incoming atoms



factory

completed



Solution 1: Using a Barrier

Any problem here?

```
struct WaterFactory {
  std::barrier<> barrier;
  WaterFactory() : barrier{3} {}

  void oxygen(void (*bond)()) {
    barrier.arrive_and_wait();
    bond();
  }

  void hydrogen(void (*bond)()) {
    barrier.arrive_and_wait();
    bond();
  }
};
```

Solution 1: Using a Barrier

```
auto oxygen_bond = []() {
  print("Bonding oxygen\n");
  std::this_thread::sleep_for(std::chrono::milliseconds{5});
  print("Done\n");
};
std::thread t1{[&]() { factory.oxygen(oxygen_bond); }};
std::thread t2{[&]() { factory.oxygen(oxygen_bond); }};
std::thread t3{[&]() { factory.oxygen(oxygen_bond); }};
// Bonding oxygen
// Bonding oxygen
// Bonding oxygen
// Done
// Done
// Done
```

Does not ensure correct types! Here we form ozone rather than water

```
struct WaterFactory {
  std::barrier<> barrier;
  WaterFactory() : barrier{3} {}

  void oxygen(void (*bond)()) {
    barrier.arrive_and_wait();
    bond();
  }

  void hydrogen(void (*bond)()) {
    barrier.arrive_and_wait();
    bond();
  }
};
```

Solution 2: Using Semaphores

Any problem here?

```
struct WaterFactory {
  std::counting_semaphore oSem{1}, hSem{2};
  WaterFactory() : barrier{3} {}

  void oxygen(void (*bond)()) {
    oSem.acquire(); -> 0
    bond();
    oSem.release();
  }

  void hydrogen(void (*bond)()) {
    hSem.acquire();
    bond();
    hSem.release();
  }
};
```

Solution 2: Using Semaphores

Any problem here? **Yes!**

Case 1: 1 or 2 H atoms call bond() -> we get H2 or H

Case 2: 1 O atom call bond() -> We get O

```
struct WaterFactory {
  std::counting_semaphore oSem{1}, hSem{2};
  WaterFactory() : barrier{3} {}

  void oxygen(void (*bond)()) {
    oSem.acquire();
    bond();
    oSem.release();
  }

  void hydrogen(void (*bond)()) {
    hSem.acquire();
    bond();
    hSem.release();
  }
};
```

Solution 3: Using Barrier + Semaphores

Any problem here?

```
struct WaterFactory {
  std::counting_semaphore oSem{1}, hSem{2};
  std::barrier<> barrier;
  WaterFactory() : barrier{3} {}

  void oxygen(void (*bond)()) {
    oSem.acquire();->0
    barrier.arrive_and_wait();
    bond();
    oSem.release();
  }

  void hydrogen(void (*bond)()) {
    hSem.acquire();->1->0
    barrier.arrive_and_wait();
    bond();
    hSem.release();
  }
};
```

Solution 3: Using Barrier + Semaphores

Any problem here? NO!

Case 1: there are less than 3 atoms -> atoms will block on barrier

Case 2: There are 3+ H atoms -> extra H will block on hSem

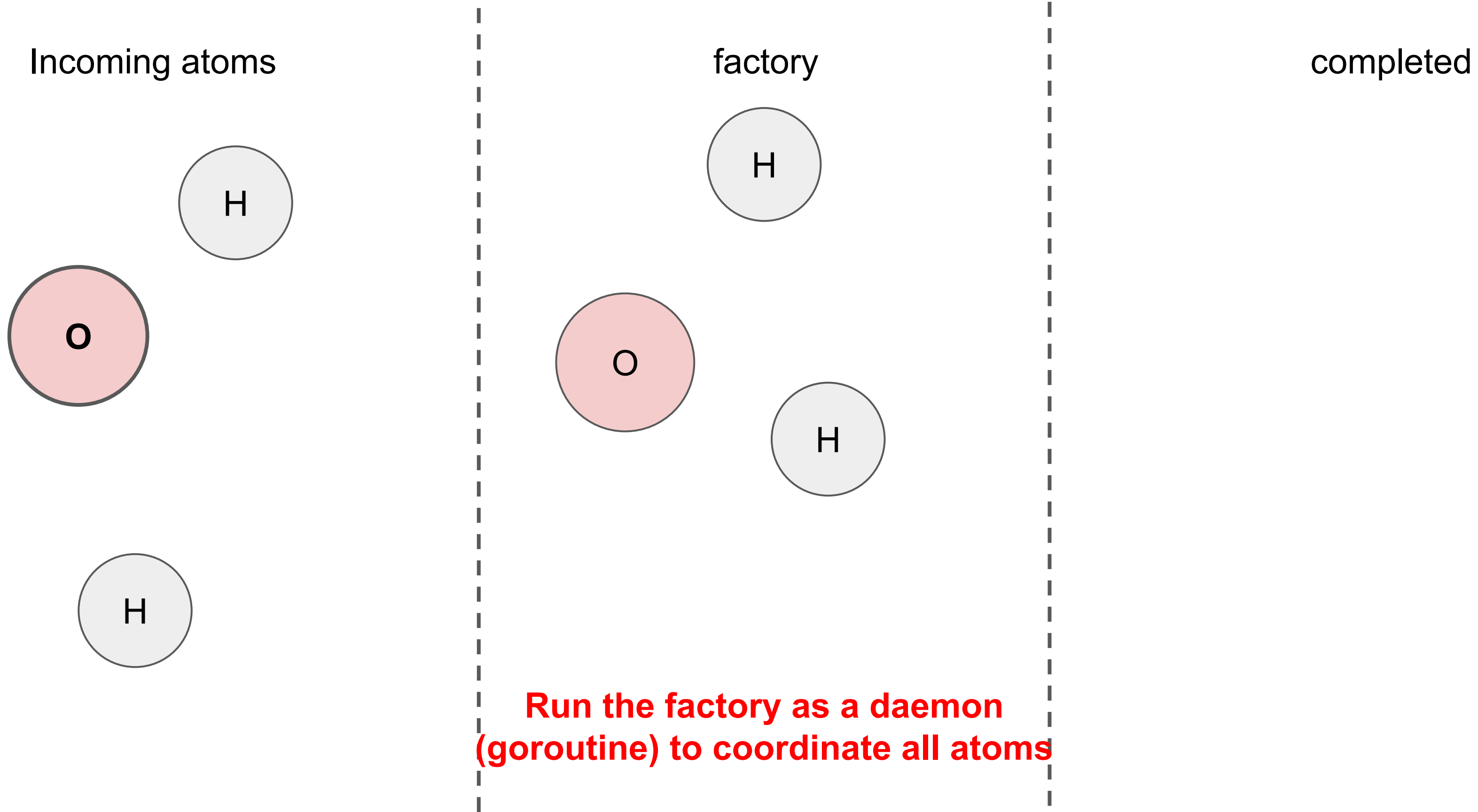
Case 3: There are 2+ O atoms -> extra O will block on oSem

```
struct WaterFactory {
  std::barrier<> oBarrier{1}, hSem{2};
  std::barrier<> barrier;
  WaterFactory() : barrier{3} {}

  void oxygen(void (*bond)()) {
    Obarrier.arrive_and_wait();
    barrier.arrive_and_wait(); waitgroup
    bond();
    oSem.release();
  }

  void hydrogen(void (*bond)()) {
    barrier.arrive_and_wait();
    bond();
    hSem.release();
  }
};
```

Go Solution 1:



Go Solution 1:

```go
// Step 1: (Precommit)
//         Receive arrival requets from 2 hydrogen and 1 oxygen atoms
h1 := <-wfd.precomH
h2 := <-wfd.precomH
o := <-wfd.precomO

// Step 2: (Commit)
//         Tell the 3 atoms to start bonding
h1 <- struct{}{}
h2 <- struct{}{}
o <- struct{}{}

// Step 3: (Postcommit)
//         Wait until the 3 atoms have finished before looping
// We re-use the same communication channel as (Commit)
<-h1
<-h2
<-o
```

```go
type WaterFactoryWithDaemon struct {
    // Channels for atoms to send their arrival requests
    precomH chan chan struct{}
    precomO chan chan struct{}
}
```

```go
func (wfd *WaterFactoryWithDaemon) hydrogen(bond func()) {
    commit := make(chan struct{}) // Step 1: Create private communication channel
    wfd.precomH <- commit         // Step 2: (Precommit)
    <-commit                      // Step 3: (Commit)
    bond()                        // Step 4: Bond
    commit <- struct{}{}          // Step 5: (Postcommit)
}
```

Go Solution 1:

Issues:

- daemon thread is a single point of failure
- potential performance bottleneck due to scheduling decisions

Go Solution 1:

Issues:

- daemon thread is a single point of failure

- potential performance bottleneck due to scheduling decisions

Recall: 1 oxygen per H2O, why not make oxygen the coordinator?

Go Solution 2:

```go
func (wf *WaterFactoryWithLeader) oxygen(bond func()) {
    // Step 1: Become leader
    <-wf.oxygenMutex // For fun, we can use a channel as a mutex

    // Step 2: (Precommit)
    //         Receive arrival requets from 2 hydrogen atoms
    h1 := <-wf.precomH
    h2 := <-wf.precomH

    // Step 3: (Commit)
    //         Tell the 2 hydrogen atoms to start bonding
    h1 <- struct{}{}
    h2 <- struct{}{}

    // Step 4: Bond
    bond()

    // Step 5: (Postcommit)
    //         Wait until the 2 hydrogen atoms to finish
    // We re-use the same communication channel as (Commit)
    <-h1
    <-h2

    // Step 6: Step down from being leader
    wf.oxygenMutex <- struct{}{}
}
```

```go
type WaterFactoryWithLeader struct {
    oxygenMutex chan struct{}
    precomH     chan chan struct{}
}
```

```go
func (wf *WaterFactoryWithLeader) hydrogen(bond func()) {
    commit := make(chan struct{}) // Step 1: Create private communication channel
    wf.precomH <- commit          // Step 2: (Precommit)
    <-commit                      // Step 3: (Commit)
    bond()                        // Step 4: Bond
    commit <- struct{}{}          // Step 5: (Postcommit)
}
```

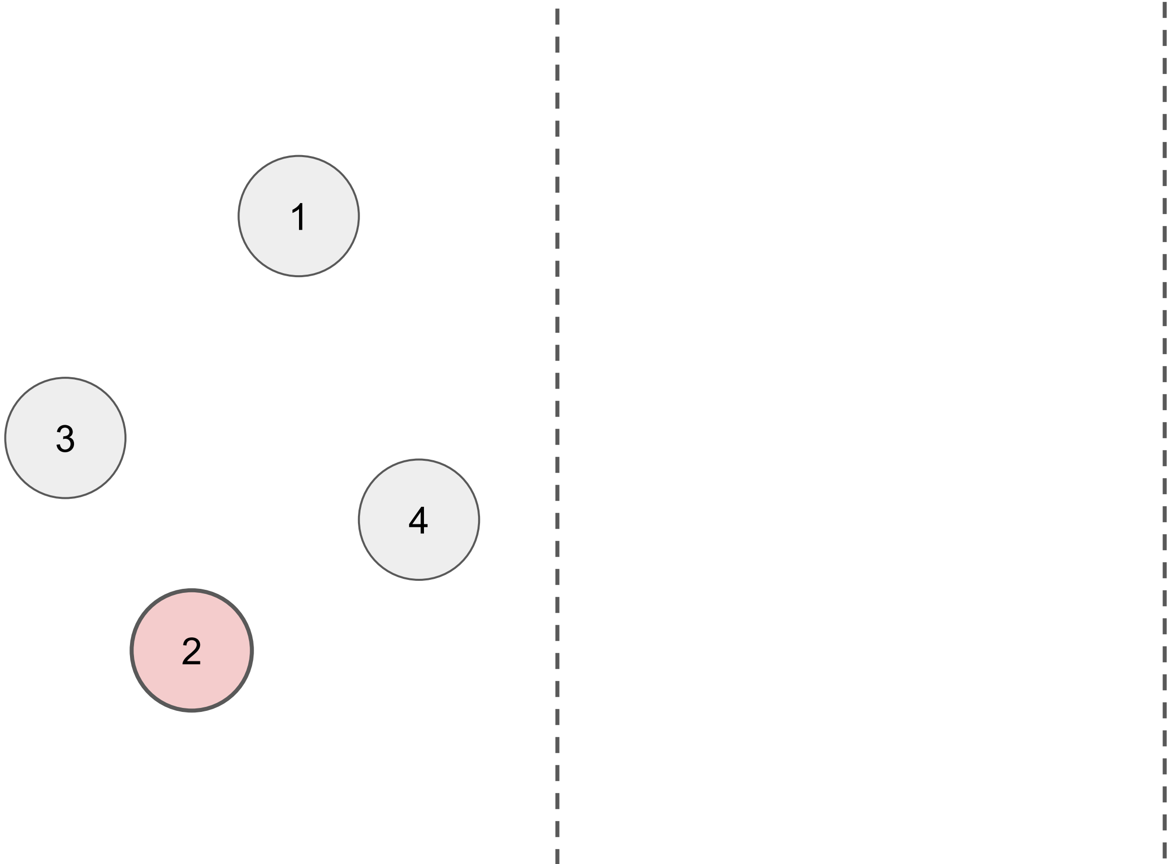
Can still have issues if oxygen holding the “mutex” dies but the probability is lower

FIFO Semaphore

i.e. starvation-free

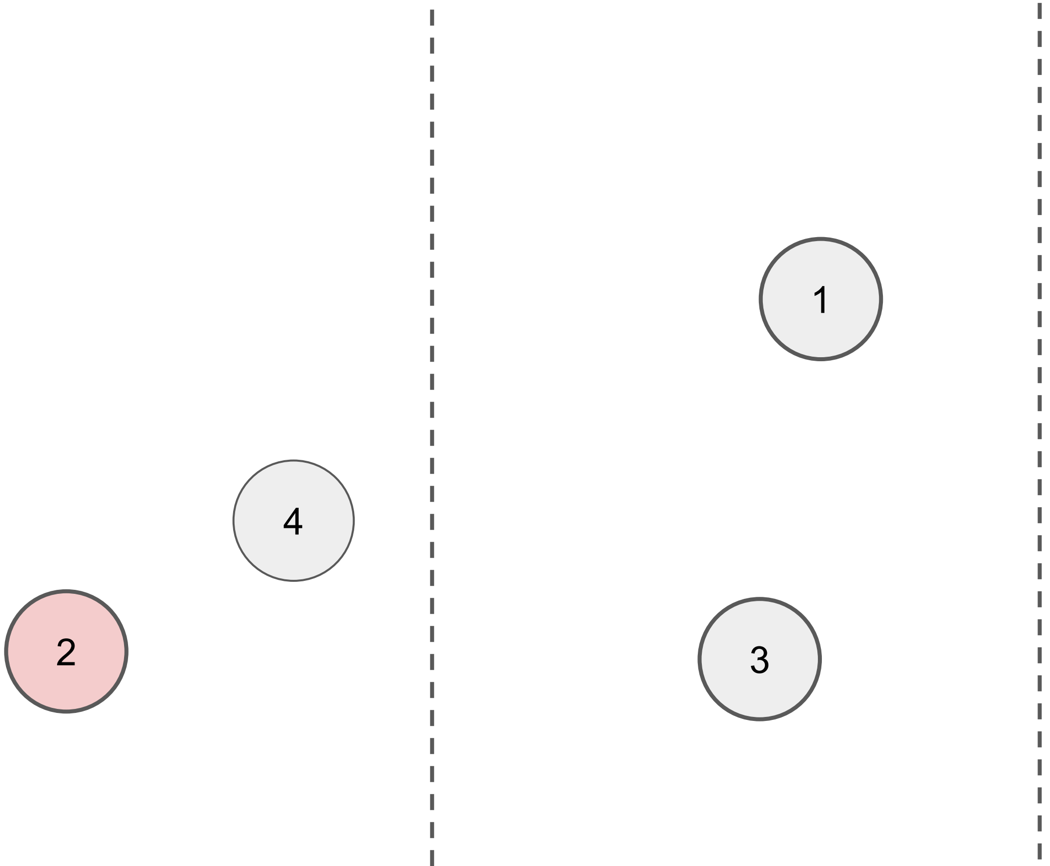
4 threads on sem of 2: 2->1->0(thread 3 and 4 blocked)->1

FIFO Semaphore(=2) Problem Statement



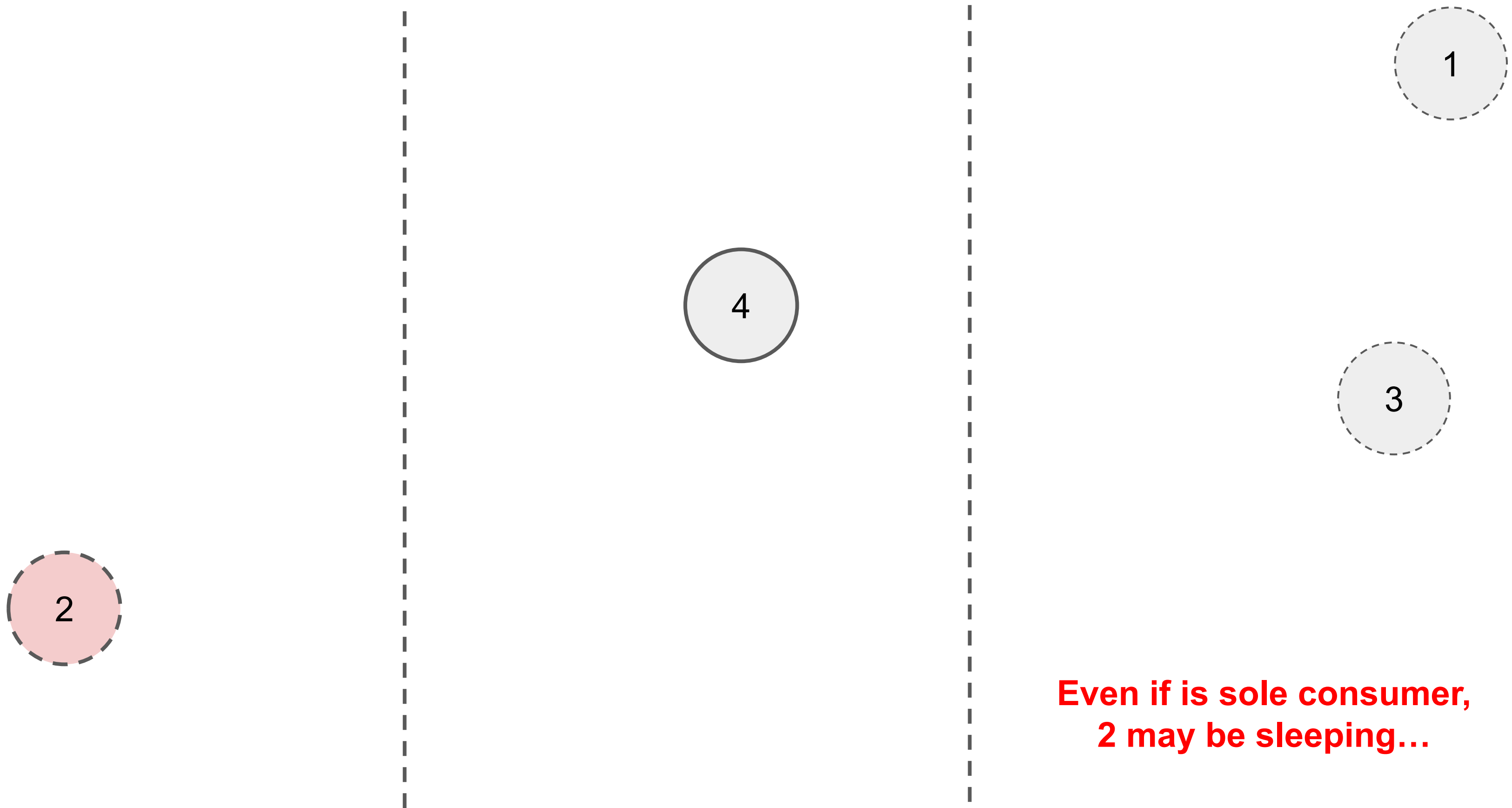
E.g. Oxygen atoms waiting to bond()

FIFO Semaphore(=2) Problem Statement



Semaphores don't guarantee order!

FIFO Semaphore(=2) Problem Statement



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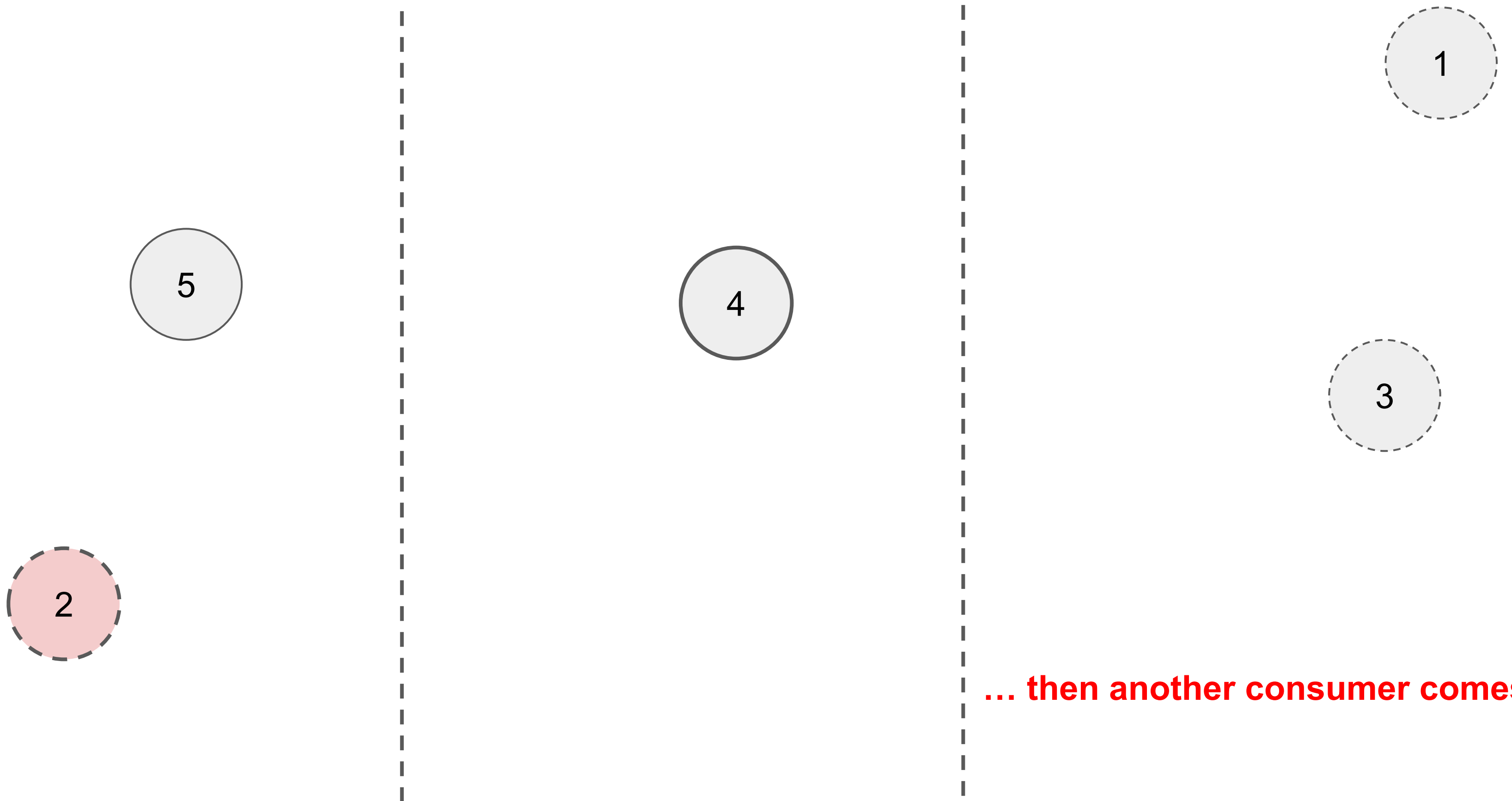
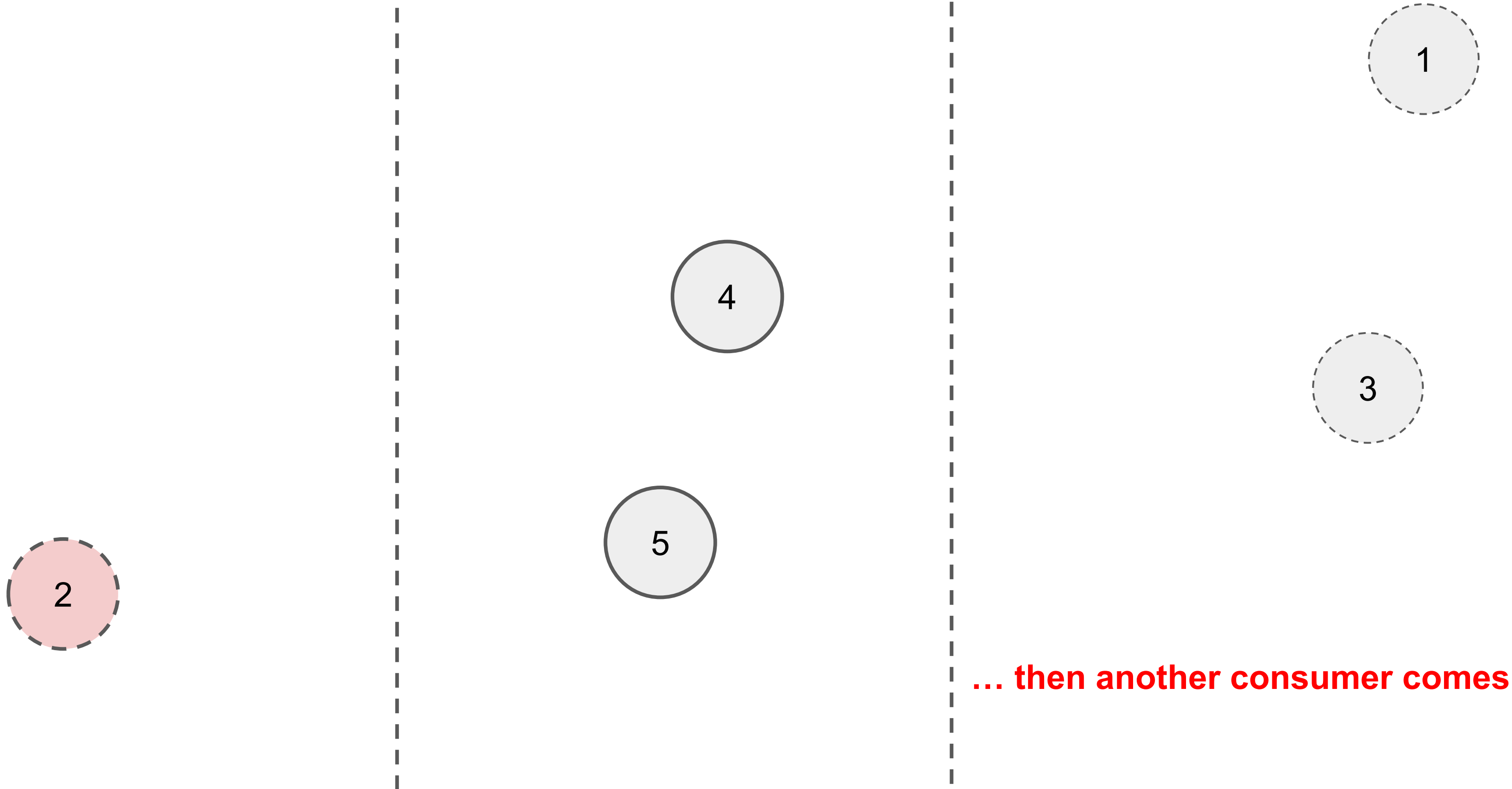


… then another consumer comes

FIFO Semaphore(=2) Problem Statement



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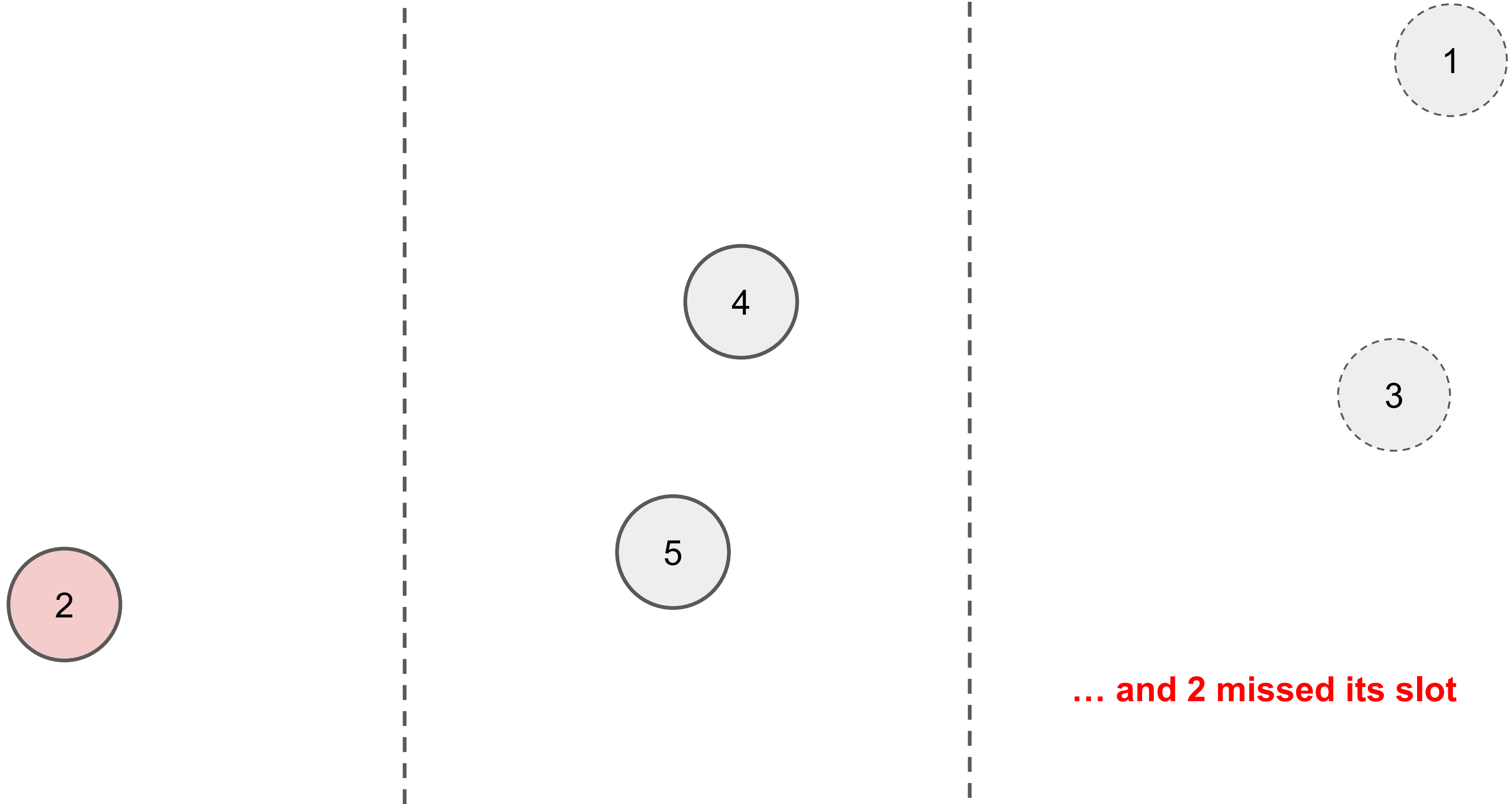
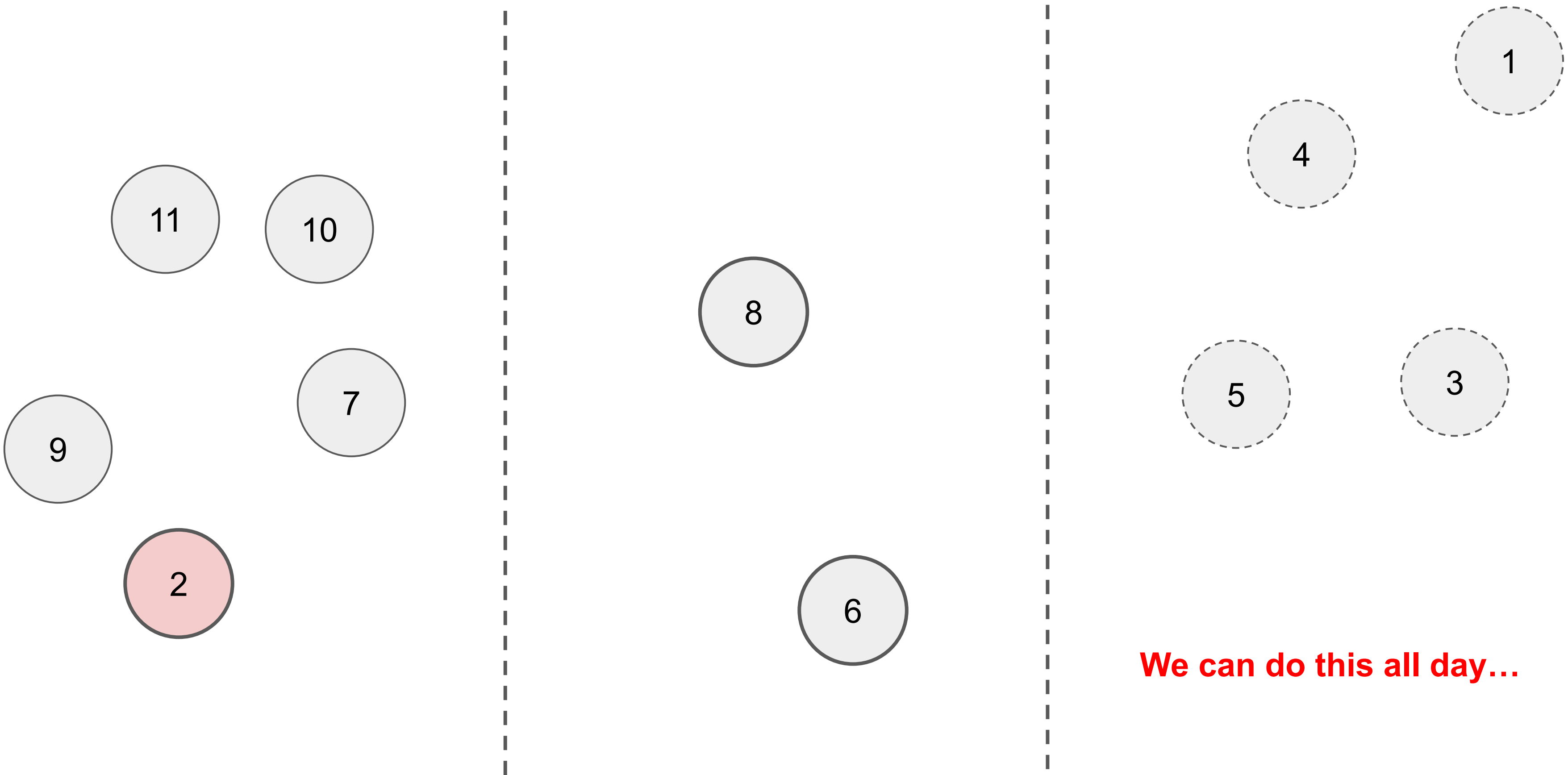


FIFO Semaphore(=2) Problem Statement



We can do this all day…

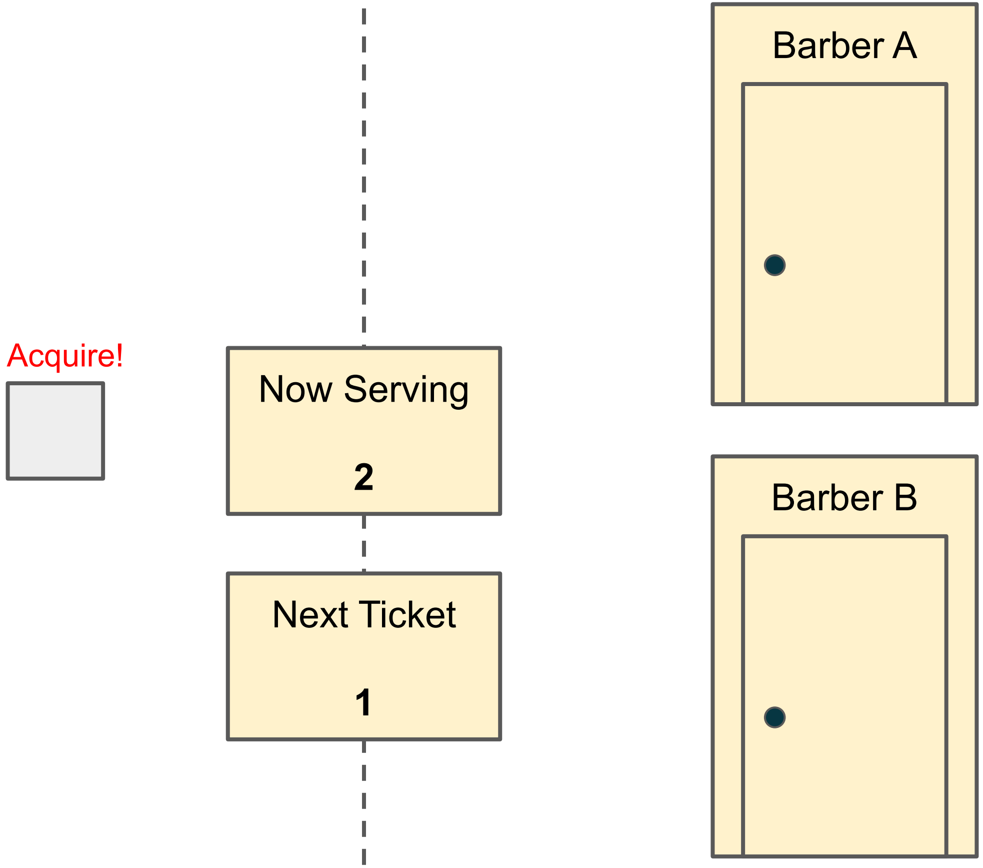
FIFO using ticket queue

Demo 4

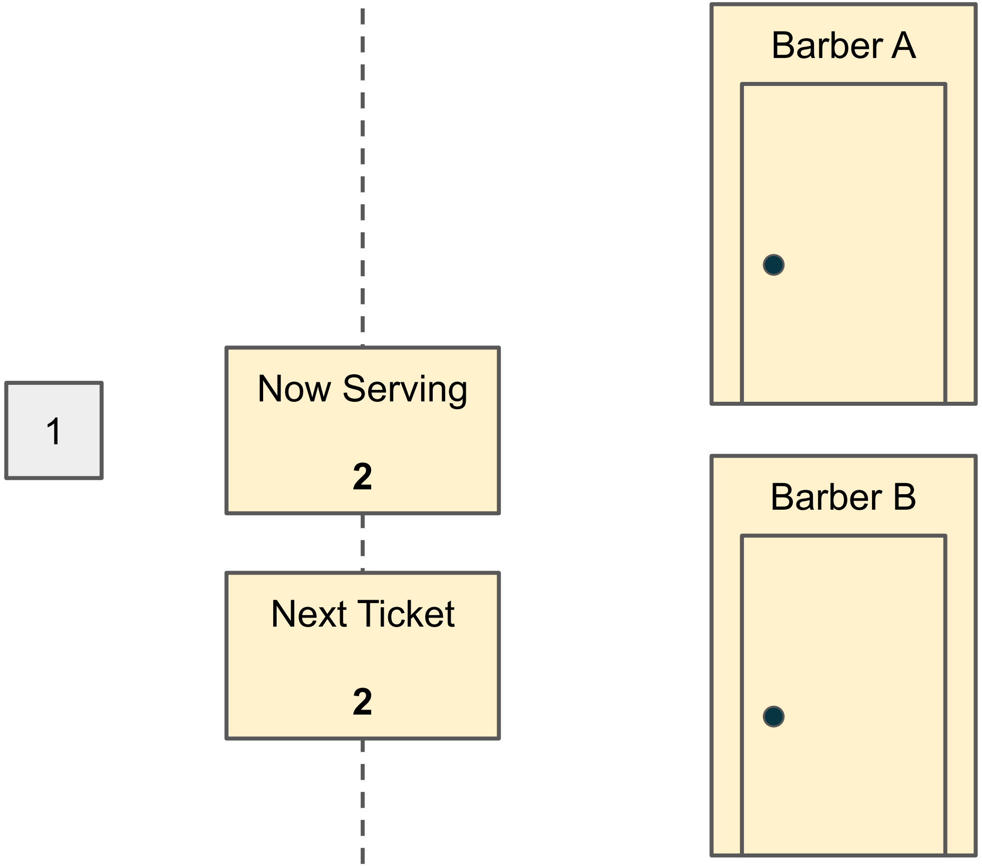
Demo 4: ticket queue

```
struct FIFOSemaphore {
  std::atomic<std::ptrdiff_t> next_ticket{1};
  std::atomic<std::ptrdiff_t> now_serving;

  FIFOSemaphore(std::ptrdiff_t initial_count) : now_serving{initial_count}
{}

  void acquire() {
    auto my_ticket = next_ticket.fetch_add(1);
    while (now_serving.load() < my_ticket) {}
  }

  void release() {
    now_serving.fetch_add(1);
  }
};
```

Demo 4: ticket queue (initial_count = 2)



Demo 4: ticket queue (initial_count = 2)



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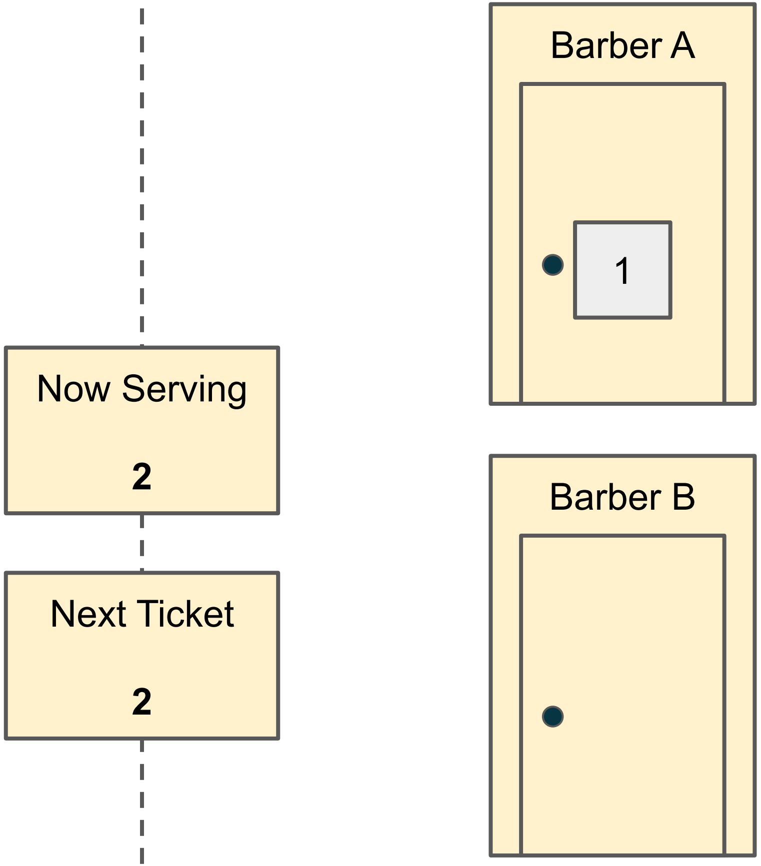

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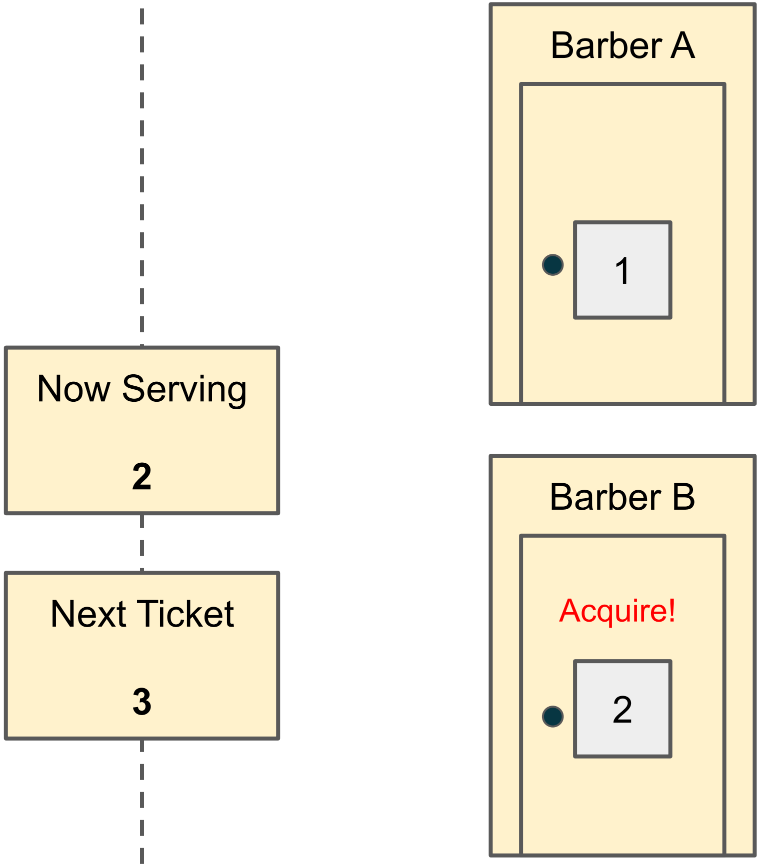

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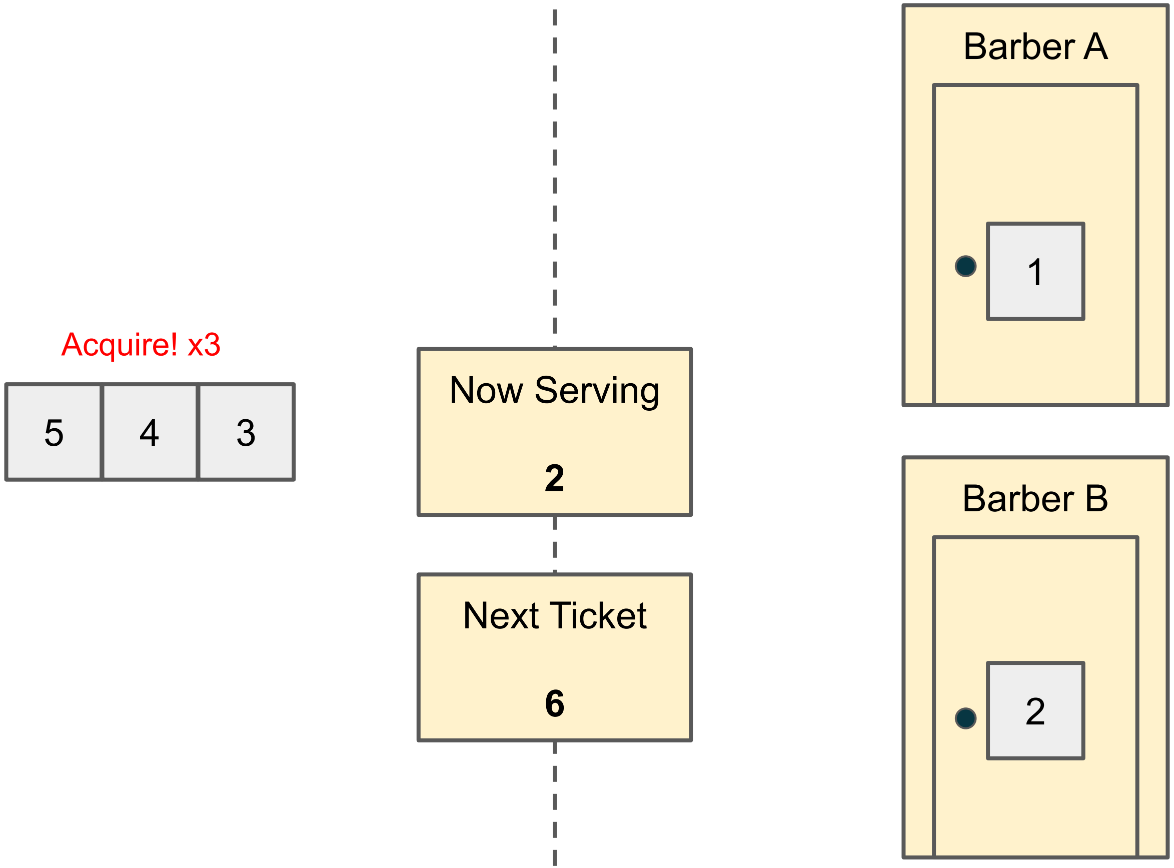

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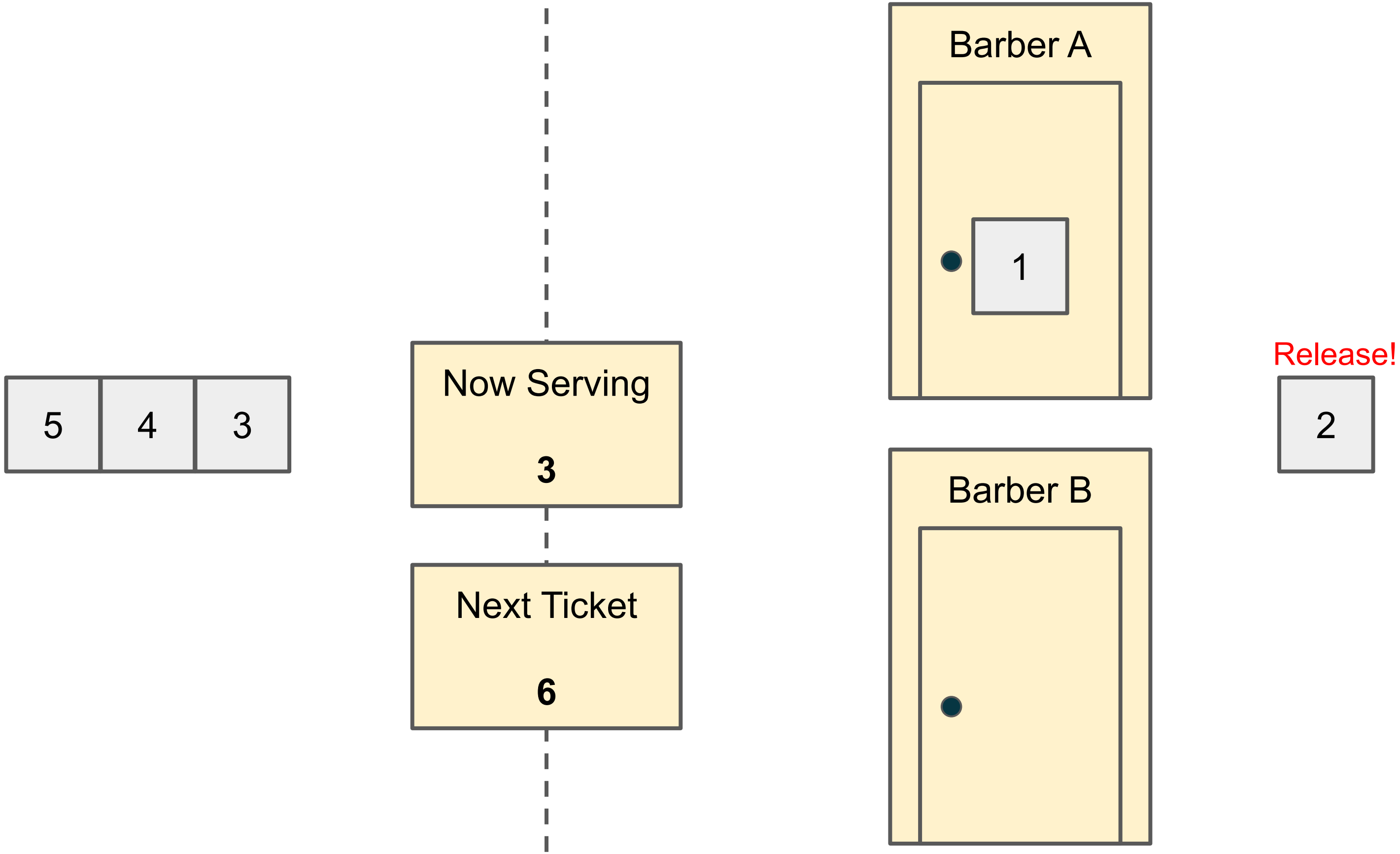

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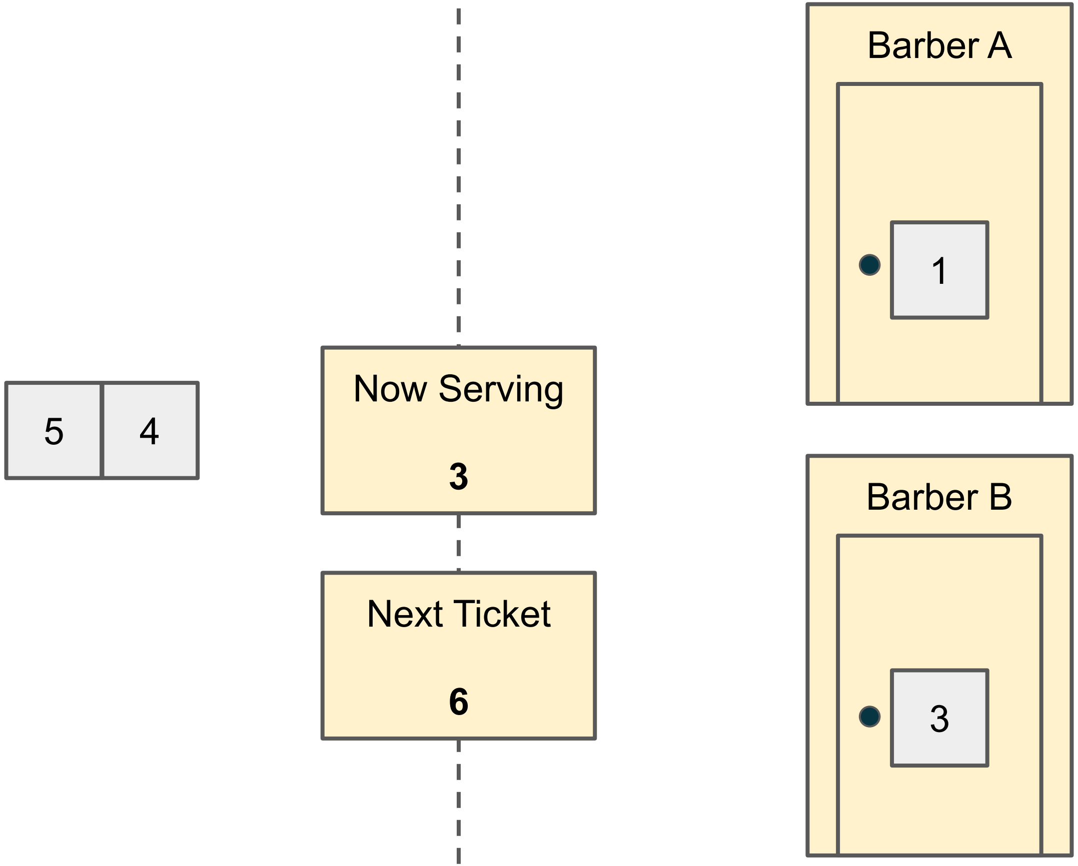


Task 1: Replace spinwait

Try it yourself!

Use

condition_variable

or

atomic<T>::wait

```
struct FIFOSemaphore {
  std::atomic<std::ptrdiff_t> next_ticket{1};
  std::atomic<std::ptrdiff_t> now_serving;

  FIFOSemaphore(std::ptrdiff_t initial_count) : now_
{}

  void acquire() {
    auto my_ticket = next_ticket.fetch_add(1);
    while(now_serving.load() < my_ticket) {}
  }

  void release() {
    now_serving.fetch_add(1);
  }
};
```

Task 1: Replace spinwait

```
struct FIFOSemaphore {
  std::atomic<std::ptrdiff_t> next_ticket{1};
  std::atomic<std::ptrdiff_t> now_serving;

  FIFOSemaphore(std::ptrdiff_t initial_count) : now_serving{initial_count}
{}

  void acquire() {
    auto my_ticket = next_ticket.fetch_add(1);
    auto old_now_serving = now_serving.load();
    if(old_now_serving < my_ticket)
        now_serving.wait(old_now_serving); // 6 oh its different unblock
  } old == new

  void release() {
    now_serving.fetch_add(1);
    now_serving.notify_one();// 8
  }
};
```

Any problems?

Task 1: Replace spinwait

Performs atomic waiting operations. Behaves as if it repeatedly performs the following steps:

- Compare the value representation of `this->load(order)` with that of `old`.
  - If those are equal, then blocks until `*this` is notified by `notify_one()` or `notify_all()`, or the thread is unblocked spuriously.
  - Otherwise, returns.

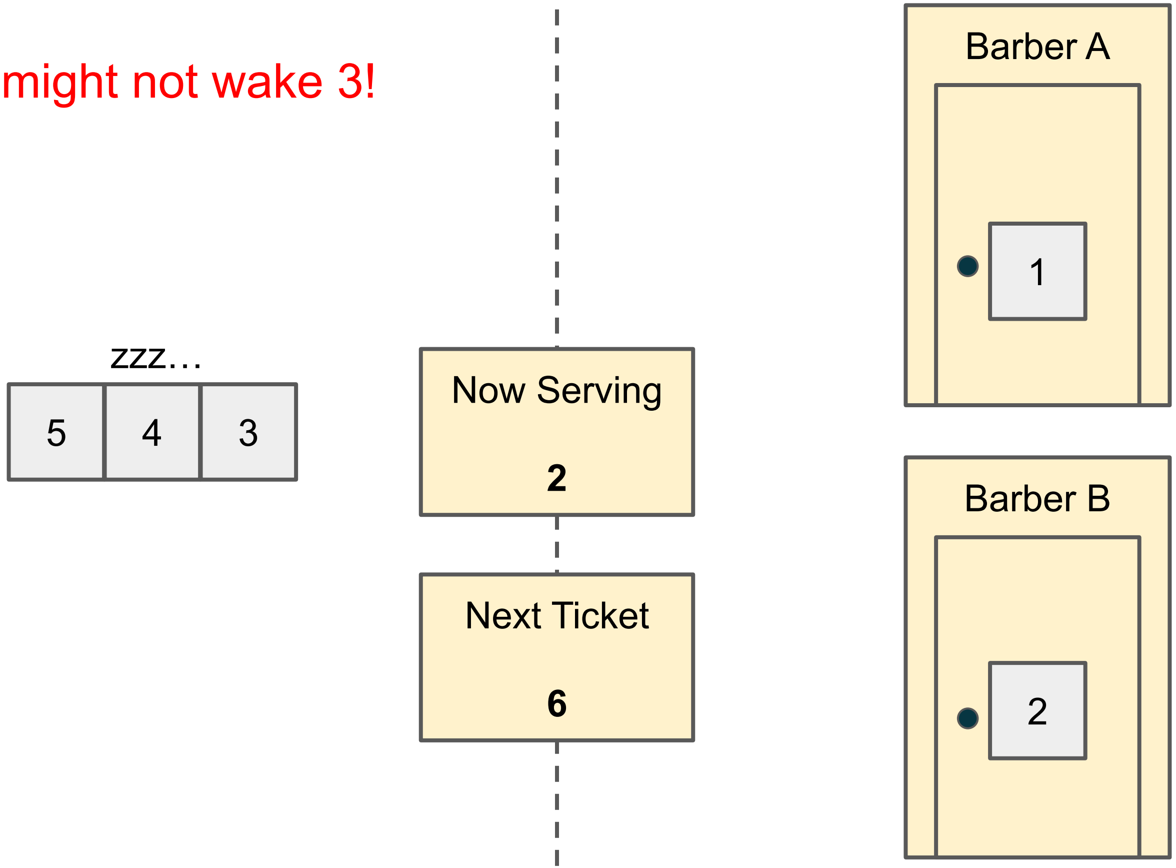
These functions are guaranteed to return only if value has changed, even if underlying implementation unblocks spuriously.

```
    if(old_now_serving < my_ticket)
      now_serving.wait(old_now_serving, my_ticket);
  }

  void release() {
    now_serving.fetch_add(1);
    now_serving.notify_one();
  }
};
```

Just because old changed doesn't mean the condition is true

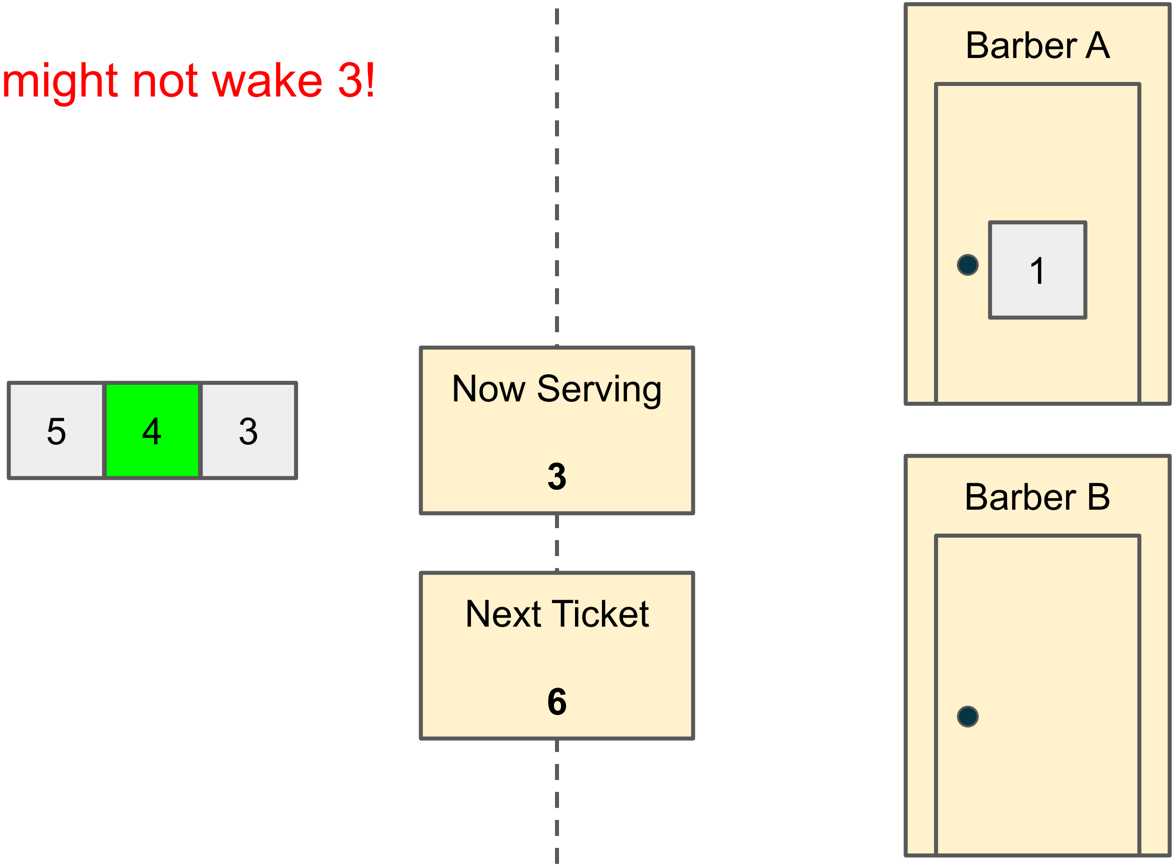
Task 1: Replace spinwait

`notify_one()` might not wake 3!



Task 1: Replace spinwait

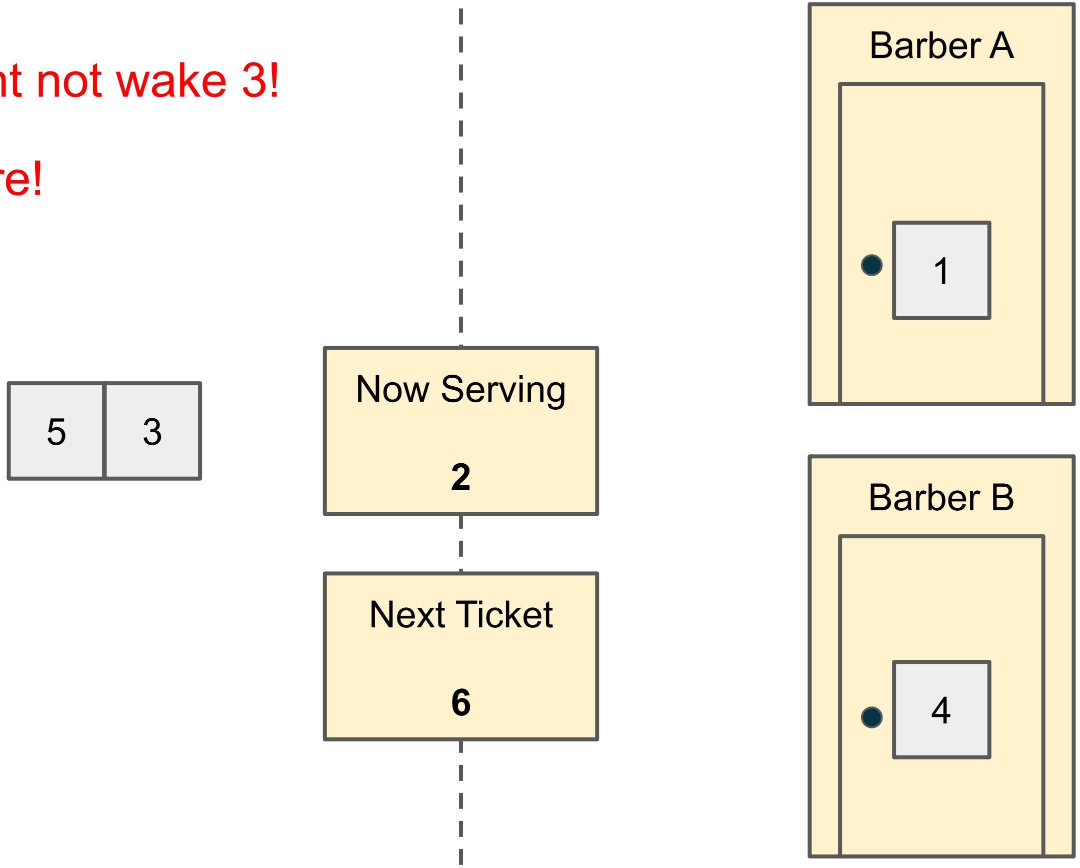
`notify_one()` might not wake 3!



Task 1: Replace spinwait

`notify_one()` might not wake 3!

-> not FIFO anymore!



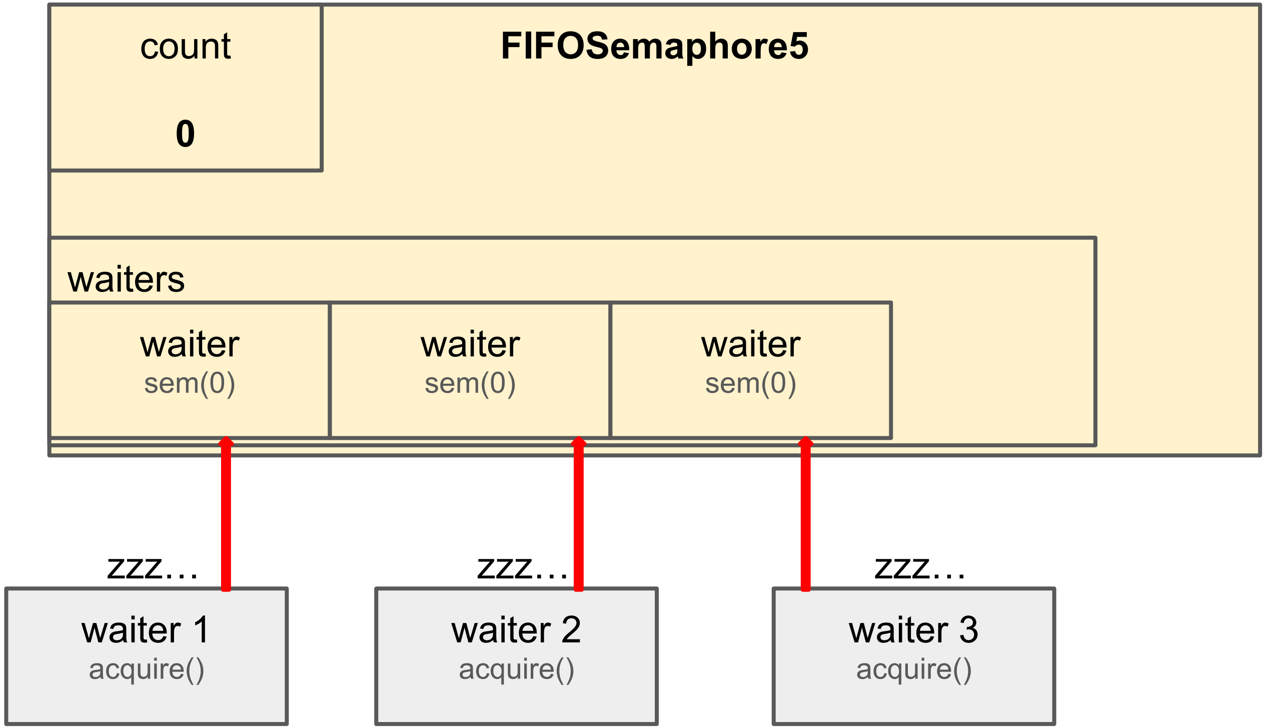
Demo 5: Queue of semaphores

```cpp
struct FIFOSemaphore5 {
  struct Waiter {
    std::binary_semaphore sem{0};
  };

  std::mutex mut;
  std::queue<std::shared_ptr<Waiter>> waiters;
  std::ptrdiff_t count;

  FIFOSemaphore5(std::ptrdiff_t initial_count)
      : mut{}, waiters{}, count{initial_count} {}
```

```cpp
void acquire() {
  auto waiter = std::make_shared<Waiter>();
  {
    std::scoped_lock lock{mut};
    if (count > 0) {
      count--;  // Positive count,
      return;   // simply decrement without blocking
    }
    waiters.push(waiter);  // Zero count, add to waiters
  }
  waiter->sem.acquire();  // and block on the semaphore
}
```

```cpp
void release() {
  std::shared_ptr<Waiter> waiter;
  {
    std::scoped_lock lock{mut};
    if (waiters.empty()) {
      count++;  // No waiters, simply increment count
      return;
    }

    waiter = waiters.front();  // Pop a waiter
    waiters.pop();
  }
  waiter->sem.release();  // and signal it
}
```

Demo 5: Queue of semaphores



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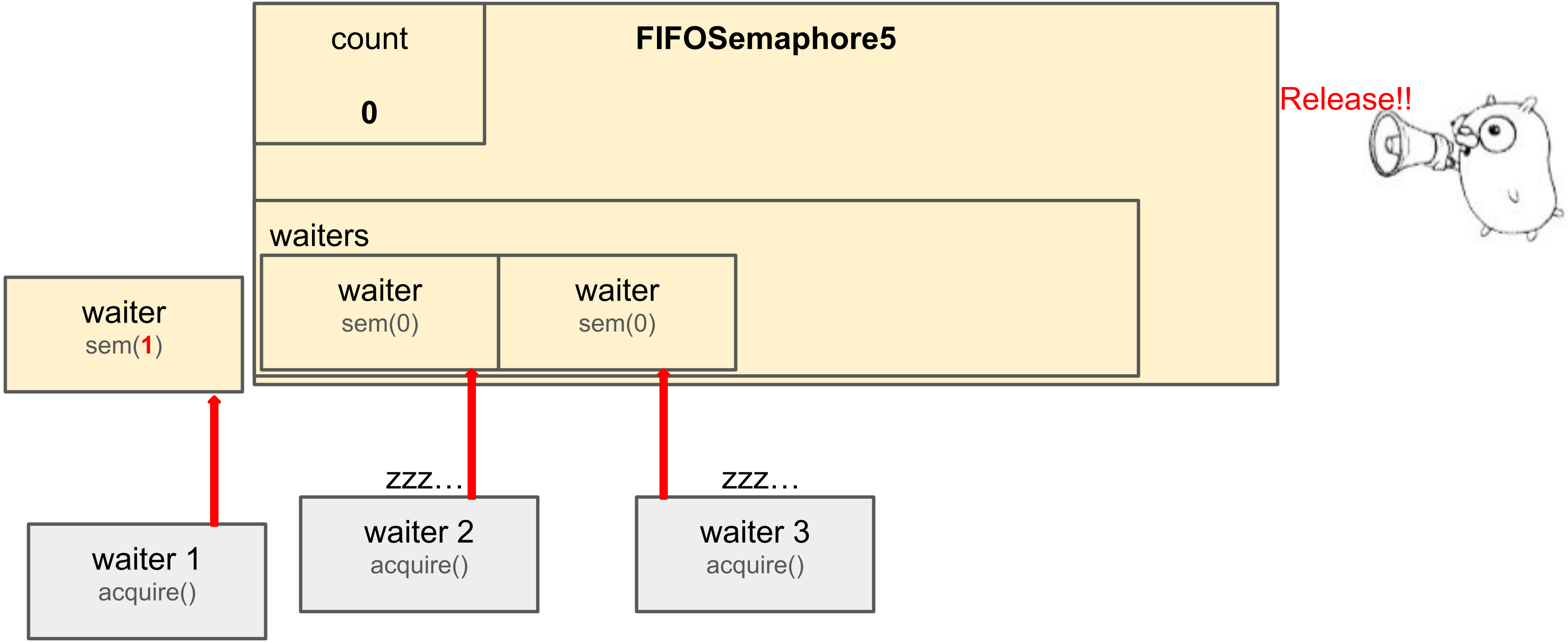

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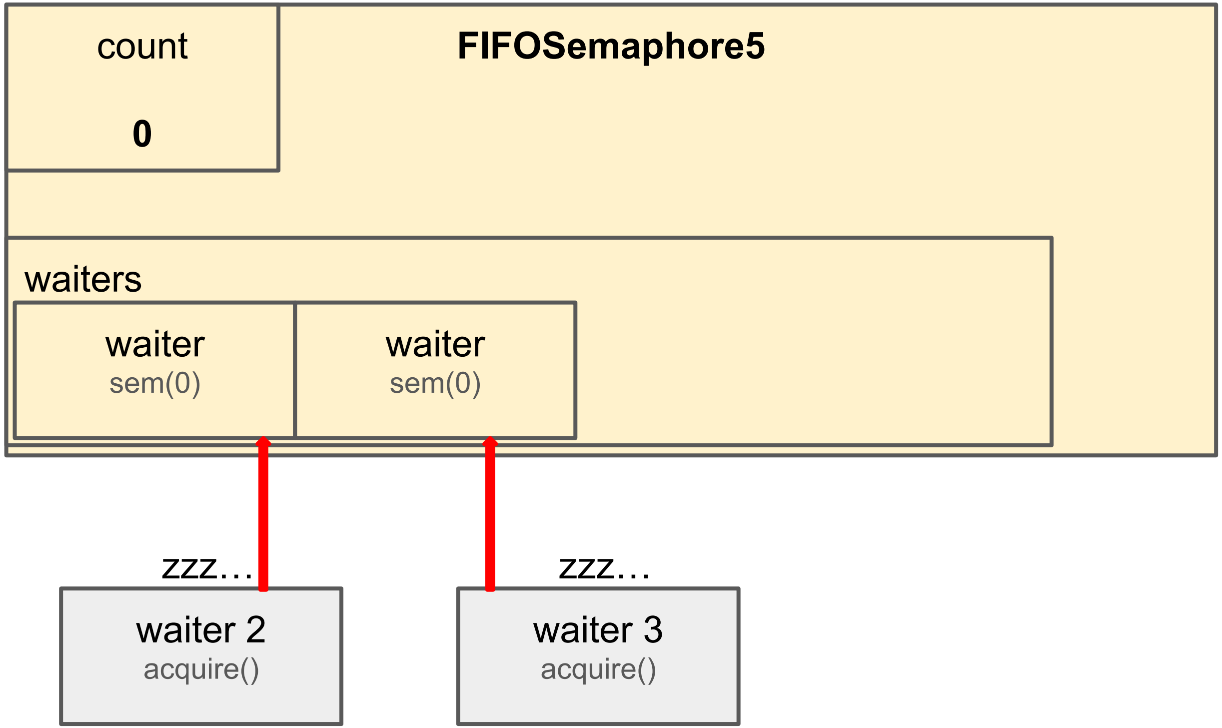

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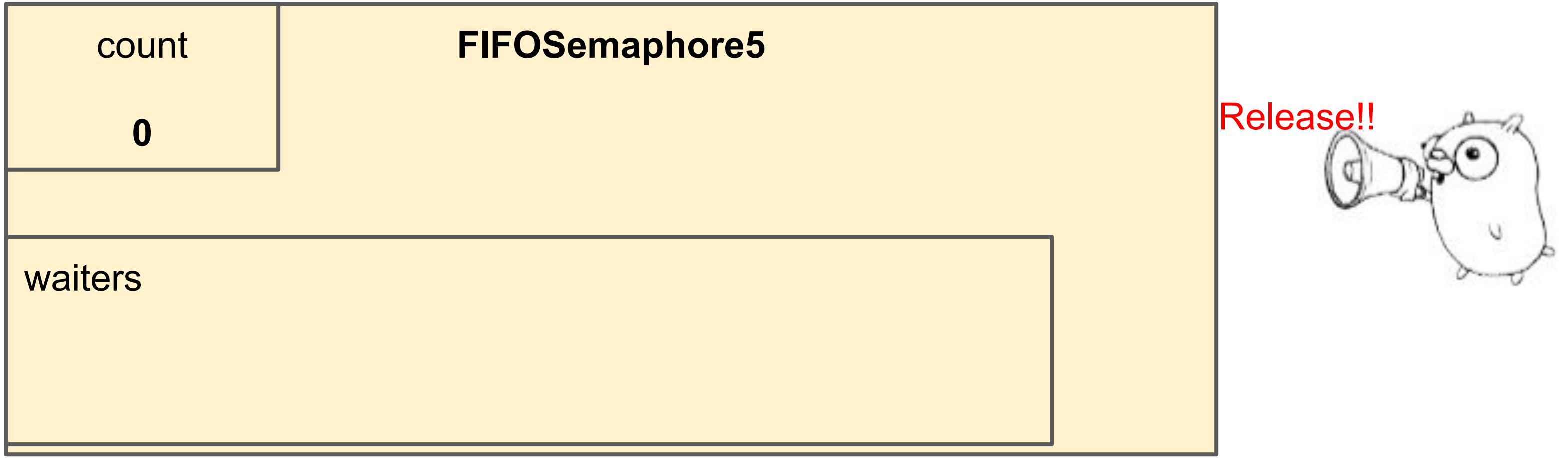
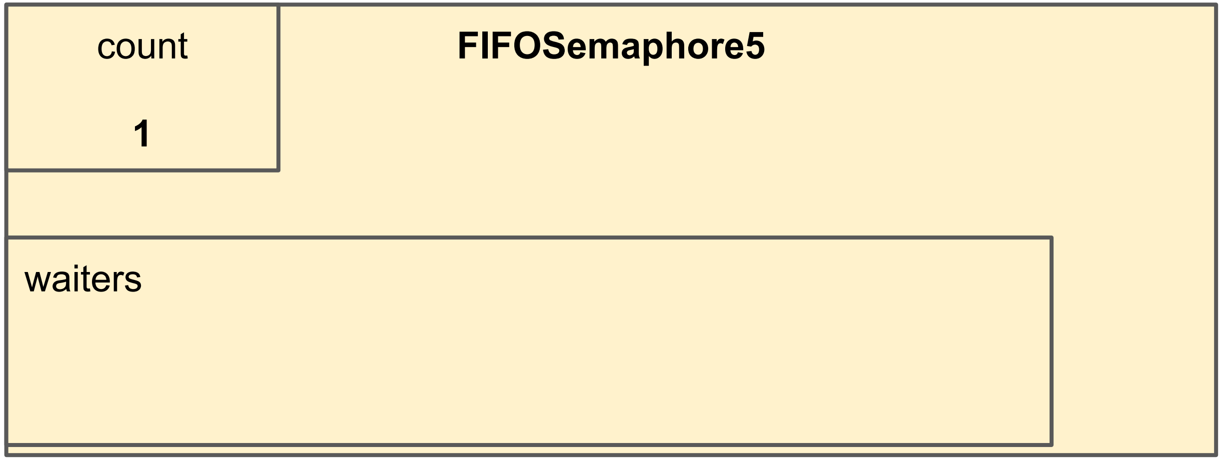


Demo 5: Queue of semaphores



Demo 5: extras

Issues:

- 2 allocations each time waiter is added to queue

How about we do only 1 allocation?

Demo 5: extras

```
void acquire() {
  Waiter waiter;

  {
    std::scoped_lock lock{mut};
    if (count > 0) {
      count--;
      return;
    }

    if (back == nullptr) {
      front = back = &waiter;
    } else {
      back->next = &waiter;
      back = &waiter;
    }
  }
  waiter.sem.acquire();
}
```

Since destruction of waiter is after all “external” accesses to it, no invalid memory access.
tldr; no lifetime issues

```
struct FIFOSemaphore7 {
  struct Waiter {
    std::binary_semaphore sem{0};
    Waiter *next{nullptr};
  };

  std::mutex mut;
  Waiter *front;
  Waiter *back;
  std::ptrdiff_t count;

  FIFOSemaphore7(std::ptrdiff_t initial_count)
      : mut{}, front{nullptr}, back{nullptr}, count{initial_count} {}
```

```
void release() {
  Waiter *head;
  {
    std::scoped_lock lock{mut};
    if (front == nullptr) {
      count++;
      return;
    }
    head = front;
    front = front->next;
    if (front == nullptr) {
      back = nullptr;
    }
  }
  head->sem.release();
}
```

Demo 6: Using a buffered channel

- Sending on a full/unbuffered channel -> block

- Suppose initial_count = N
  - Make a buffered channel of size N.
  - If M > N goroutines arrive at the same time, (M - N) goroutines block.
  - release -> send to channel
  - acquire -> recv from channel

Basically a semaphore!

Demo 6: Using a buffered channel

```
type hchan struct {
        qcount   uint           // total data in the queue
        dataqsiz uint           // size of the circular queue
        buf      unsafe.Pointer // points to an array of dataqsiz elements
        elemsize uint16
        closed   uint32
        elemtype *_type // element type
        sendx    uint   // send index
        recvx    uint   // receive index
        recvq    waitq  // list of recv waiters
        sendq    waitq  // list of send waiters
```

```
type waitq struct {
        first *sudog
        last  *sudog
}
```

```
type sudog struct {
        // The following fields are protected by the hchan.lock of the
        // channel this sudog is blocking on. shrinkstack depends on
        // this for sudogs involved in channel ops.

        g *g

        next *sudog
        prev *sudog
```

current impl is fifo, but not guaranteed by the standard.

Demo 7: Using a daemon goroutine

Bad idea to rely on implementation-defined behaviour.

How about we have a goroutine manage others!

Demo 7: Using a daemon goroutine

```go
type Semaphore2 struct {
    acquireCh chan chan struct{}
    releaseCh chan struct{}
}
```

```go
func (s *Semaphore2) Acquire() {
    ch := make(chan struct{})
    // Send daemon a channel that can be used to unblock us
    s.acquireCh <- ch
    // Block until daemon decides to unblock us
    <-ch
}

func (s *Semaphore2) Release() {
    s.releaseCh <- struct{}{}
}
```

```go
func NewSemaphore2(initial_count int) *Semaphore2 {
    sem := new(Semaphore2)
    sem.acquireCh = make(chan chan struct{}, 100)
    sem.releaseCh = make(chan struct{}, 100)

    go func() {
        count := initial_count
        // The FIFO queue that stores the channels used to unblock waiters
        waiters := NewChanQueue()
```

Demo 7: Using a daemon goroutine

```
for {
        select {
        case <-sem.releaseCh:
            // …

        case ch := <-sem.acquireCh:
            // …
    }
```

Either process a release or acquire request

Demo 7: Using a daemon goroutine

```go
        case ch := <-sem.acquireCh: // Decrement or add a waiter
            if count > 0 {
                count--
                ch <- struct{}{} // Since count is +ve, don’t block the waiter
            } else {
                waiters.PushBack(ch) // Add waiter to back of the wait queue
            }
        }
```

Either process a release or acquire request

Demo 7: Using a daemon goroutine

```go
case <-sem.releaseCh: // Increment or unblock a waiter
    if waiters.Len() > 0 {
        ch := waiters.Pop()
        ch <- struct{}{} // Unblocks the oldest waiter
    } else {
        count++
    }
```

Either process a release or acquire request

Demo 7: Using a daemon goroutine

Why a buffer of 100?

```go
func NewSemaphore2(initial_count int) *Semaphore2 {
    sem := new(Semaphore2)
    sem.acquireCh = make(chan chan struct{}, 100)
    sem.releaseCh = make(chan struct{}, 100)

    go func() {
        count := initial_count
        // The FIFO queue that stores the channels used to unblock waiters
        waiters := NewChanQueue()
```

Demo 7: Using a daemon goroutine

Why a buffer of 100?

If goroutine blocks on

```
func (s *Semaphore2) Acquire() {

   ch := make(chan struct{})
   // Send daemon a channel that can be used to unblock us
   s.acquireCh <- ch
   // Block until daemon decides to unblock us
   <-ch
}
```

for a long time (wakeups not in FIFO), no guarantees of FIFO.

BUT, if send succeeds (buffered in channel), we get FIFO behavior.

```
type hchan struct {
        qcount   uint           // total data in the queue
        dataqsiz uint           // size of the circular queue
        buf      unsafe.Pointer // points to an array of dataqsiz elements
        elemsize uint16
        closed   uint32
        elemtype *_type // element type
        sendx    uint   // send index
        recvx    uint   // receive index
        recvq    waitq  // list of recv waiters
        sendq    waitq  // list of send waiters

        // lock protects all fields in hchan, as well as several
        // fields in sudogs blocked on this channel.
        //
        // Do not change another G's status while holding this lock
        // (in particular, do not ready a G), as this can deadlock
        // with stack shrinking.
        lock mutex
}
```

Pls scan for attendance

See you next week!