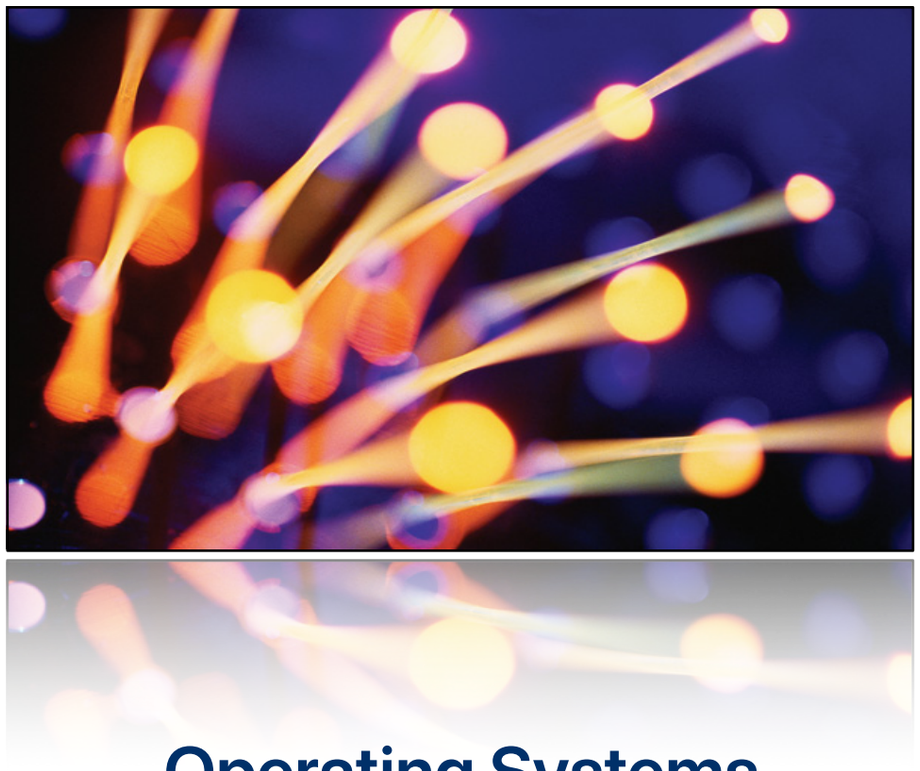
Monitors & Condition Variables



Operating Systems

Baochun Li
University of Toronto

Producer-consumer using semaphores

```
semaphore mutex = 1, empty = N, full = 0
send(message msg)
  down(empty)
  down(mutex)
  buffer[in modulo N] = msg
  in = in + 1
  up(mutex)
  up(full)
message receive()
  down(full)
  down(mutex)
  msg = buffer[out modulo N]
  out = out + 1
  up(mutex)
  up(empty)
  return msg
```

Monitors: the motivation

It is difficult to produce correct programs using semaphores

- correct ordering of down is tricky
- avoiding race conditions and deadlocks is tricky

Is it possible to ask a compiler to generate the correct semaphore code for us?

- If so, what are the suitable higher level abstraction?

Monitors: one thread at a time

Monitors are like objects in object-oriented programs

Compiler enforces encapsulation and mutual exclusion

Encapsulation

Local data variables are accessible only via the monitor's entry methods

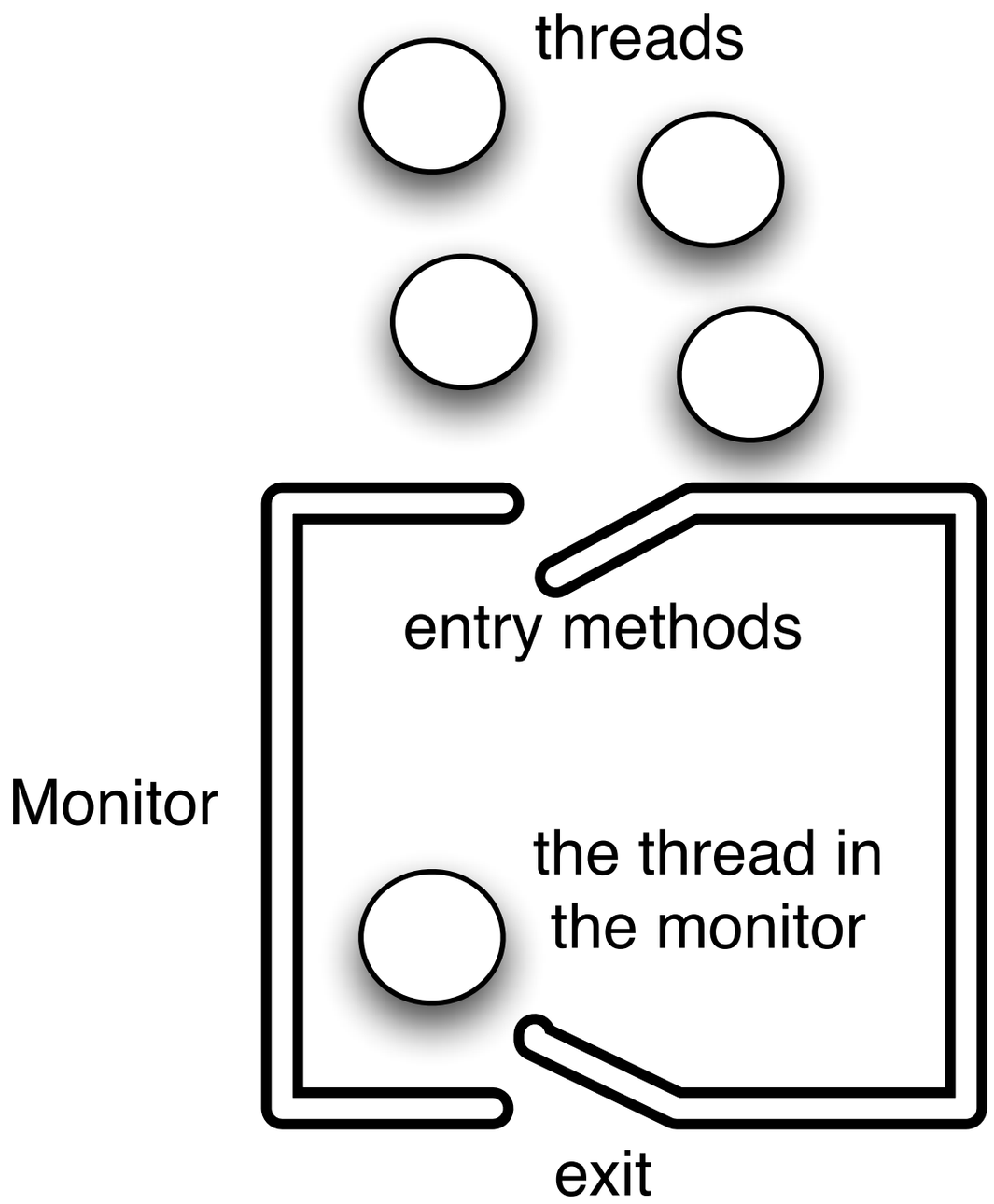
Mutual exclusion

Each monitor has an associated mutex lock

Threads must acquire the lock when invoking any of the **entry methods**

Automatically, only **one thread** can be active in a monitor at any time

A monitor illustrated



How BLITZ implements a monitor

```
class AMonitor
  fields
  monitorLock: Mutex

method MyEntryMethod
  monitorLock.Lock()
  ...
    if ...
      monitorLock.Unlock()
      return
    endIf
  ...
  monitorLock.Unlock()
endMethod
```

Implementing producer-consumer with monitors

```
monitor ProducerConsumer
  send(message msg)
    while in - out == N do
      sleep()
    buffer[in modulo N] = msg
    if in == out then
      in = in + 1
      wakeup(receiverThread)
    else
      in = in + 1
  message receive()
    while in == out do
      sleep()
    msg = buffer[out modulo N]
    if in - out == N then
      out = out + 1
      wakeup(senderThread)
    else
      out = out + 1
     return msg
```

Problems with using a monitor

When the sender thread sleeps and blocks itself when it finds the buffer full, no one else will be able to wake it up

Why?

The sender thread goes to sleep inside a monitor

No other threads are able to enter the monitor to wake it up!

The root of the problem

We have two concurrency problems to solve

The need for mutual exclusion

Only one at a time in the critical section

Handled by the definition of a monitor: one thread in the monitor at any time

The need for synchronization

Wait (sleep) until a certain condition holds

Signal (wake up) waiting threads when the condition holds

Revisiting a previous idea without monitors

```
send(message msg)
  acquire(buffer_lock)
  while in - out == N do
    release(buffer_lock)
    sleep()
    acquire(buffer_lock)
  buffer[in modulo N] = msg
  if in == out then
    in = in + 1
    wakeup(receiverThread)
  else in = in + 1
  release(buffer_lock)
```

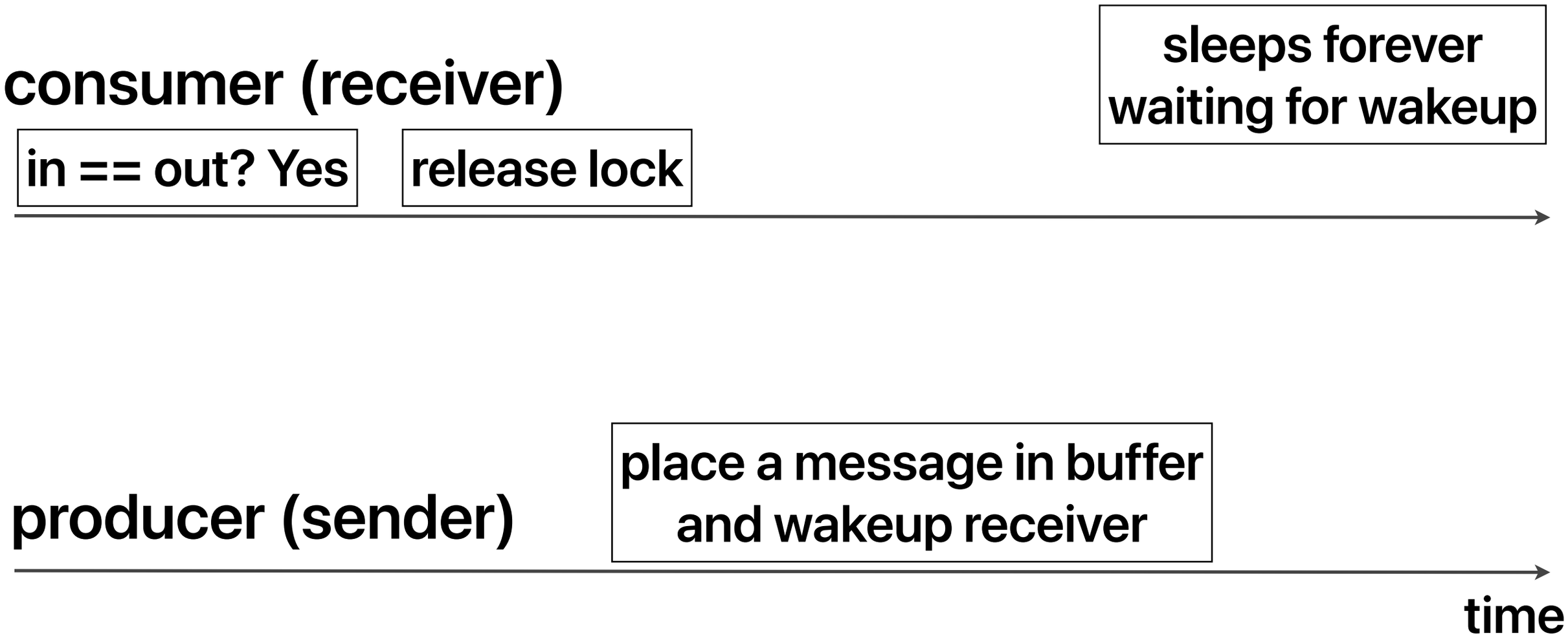
```
message receive()
  acquire(buffer_lock)
  while in == out do
    release(buffer_lock)
    sleep()
    acquire(buffer_lock)
  msg = buffer[out modulo N]
  if in - out == N then
    out = out + 1
    wakeup(senderThread)
  else out = out + 1
  release(buffer_lock)
  return msg
```

The problem in this idea

In the first try of solving the problem of synchronization in producer-consumer, the solution suffers from the lost wakeup problem

```
while in == out do
  release(buffer_lock)
  sleep()
  acquire(buffer_lock)
```

Revisiting the lost wakeup problem



Solving this in the context of monitors

It will be good to make the release()/sleep()/acquire() trio before-or-after atomic

In the context of a monitor, the thread exits the monitor, blocks itself to wait for an event to occur, and enter the monitor when it wakes up

No interruption between it exits the monitor and blocks itself

No interruption between it wakes up and re-enters the monitor

Condition variables

A condition variable represents a condition that a thread is waiting for and signaling

It supports three operations —

condition.**wait**(): a thread exits the monitor, waits for the condition variable condition to hold, and enters the monitor again when it does

condition.**signal**(): signals (wakes up) a waiting thread on the condition variable condition, so that it can try to enter the monitor

condition.**broadcast**(): signals (wakes up) **all** waiting threads on the condition variable condition, so that they can **all** try to enter the monitor

wait(), signal(), and broadcast() are made before-or-after atomic actions in order to avoid the lost wakeup problem

Revisiting the producer-consumer problem

```
monitor ProducerConsumer
  Condition full    // Sender threads wait when buffer is full
  Condition empty   // Receiver threads wait when buffer is empty

  send(message msg)
     if in - out == N then
       full.wait()  // buffer is full, let me wait outside monitor
     buffer[in modulo N] = msg
     if in == out then
       in = in + 1
       empty.signal() // wake up a receiver waiting outside
     else in = in + 1

  message receive()
     if in == out then
       empty.wait() // buffer is empty, let me wait outside monitor
     msg = buffer[out modulo N]
     if in - out == N then
       out = out + 1
       full.signal() // wake up a sender waiting outside
     else out = out + 1
     return msg
```

How BLITZ implements condition variables

```
class Condition
  fields
    waitingThreads: List [Thread]
method Init()
  waitingThreads = new List [Thread]
endMethod

method Wait(mutex: ptr to Mutex)
  disable interrupts
  mutex.Unlock()
  waitingThreads.AddToEnd(currentThread)
  currentThread.Sleep()
  mutex.Lock()
  restore interrupts
endMethod
```

How BLITZ implements condition variables

```
method Signal(mutex: ptr to Mutex)
   disable interrupts
   t = waitingThreads.Remove()
   if t
      t.status = READY
      readyList.AddToEnd(t)
   endIf
   restore interrupts
endMethod
```

How BLITZ implements condition variables

```
method Broadcast(mutex: ptr to Mutex)
    disable interrupts
    while true
        t = waitingThreads.Remove()
        if t == null
            break
        endIf
        t.status = READY
        readyList.AddToEnd(t)
    endWhile
    restore interrupts
endMethod
```

Revisiting the producer-consumer problem

```
monitor ProducerConsumer
  Condition full    // Sender threads wait when buffer is full
  Condition empty   // Receiver threads wait when buffer is empty

  send(message msg)
     if in - out == N then
       full.wait()  // buffer is full, let me wait outside monitor
     buffer[in modulo N] = msg
     if in == out then
       in = in + 1
       empty.signal() // wake up a receiver waiting outside
     else in = in + 1

  message receive()
     if in == out then
       empty.wait() // buffer is empty, let me wait outside monitor
     msg = buffer[out modulo N]
     if in - out == N then
       out = out + 1
       full.signal() // wake up a sender waiting outside
     else out = out + 1
     return msg
```

One more (last) problem

The sender thread is running in the monitor

It adds a message to an empty shared buffer

It signals a waiting receiver thread, waking it up

At this time, the sender and receiver thread cannot both run inside the monitor

Which one runs (in the monitor), and which one blocks (outside of the monitor)?

Revisiting the producer-consumer problem

```
monitor ProducerConsumer
  Condition full    // Sender threads wait when buffer is full
  Condition empty   // Receiver threads wait when buffer is empty

  send(message msg)
     if in - out == N then
       full.wait()  // buffer is full, let me wait outside monitor
     buffer[in modulo N] = msg
     if in == out then
       in = in + 1
       empty.signal() // wake up a receiver waiting outside
     else in = in + 1

  message receive()
     if in == out then
       empty.wait() // buffer is empty, let me wait outside monitor
     msg = buffer[out modulo N]
     if in - out == N then
       out = out + 1
       full.signal() // wake up a sender waiting outside
     else out = out + 1
     return msg
```

Design choices of monitors

Only one thread is active in the monitor at a time, so what do we do when a thread is unblocked on signal?

Choices when thread A signals a condition unblocking thread B —

1. B enters the monitor, A waits for B to exit the monitor
2. A remains in the monitor, B waits for A to exit the monitor

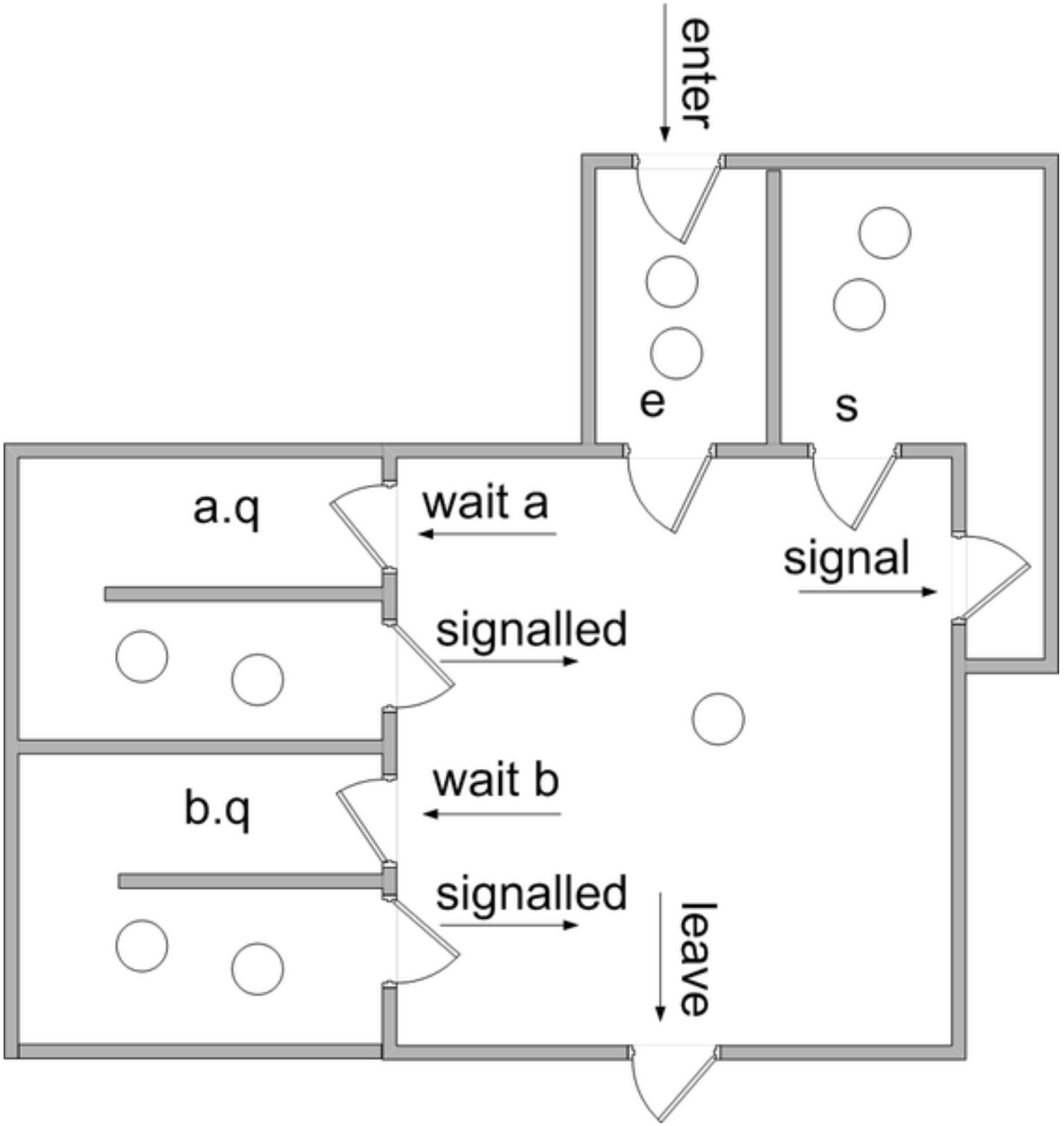
Option 1: Hoare Semantics

Tony Hoare, who invented the monitor, proposed Hoare Semantics

- The signaling thread, **A**, always leaves and waits
- The signaled thread, **B**, enters the monitor immediately
- No other threads can enter the monitor between the execution of the signal operation by the signaling thread **A**, and the acquisition of the lock by the signaled thread **B**

Now the signaled thread B can have a guarantee that the condition holds when it enters the monitor

Option 1: Hoare Semantics



Option 2: MESA Semantics

MESA Semantics is more relaxed

The only guarantee: the signaled thread is awakened

It will have to compete against all other threads for the monitor lock

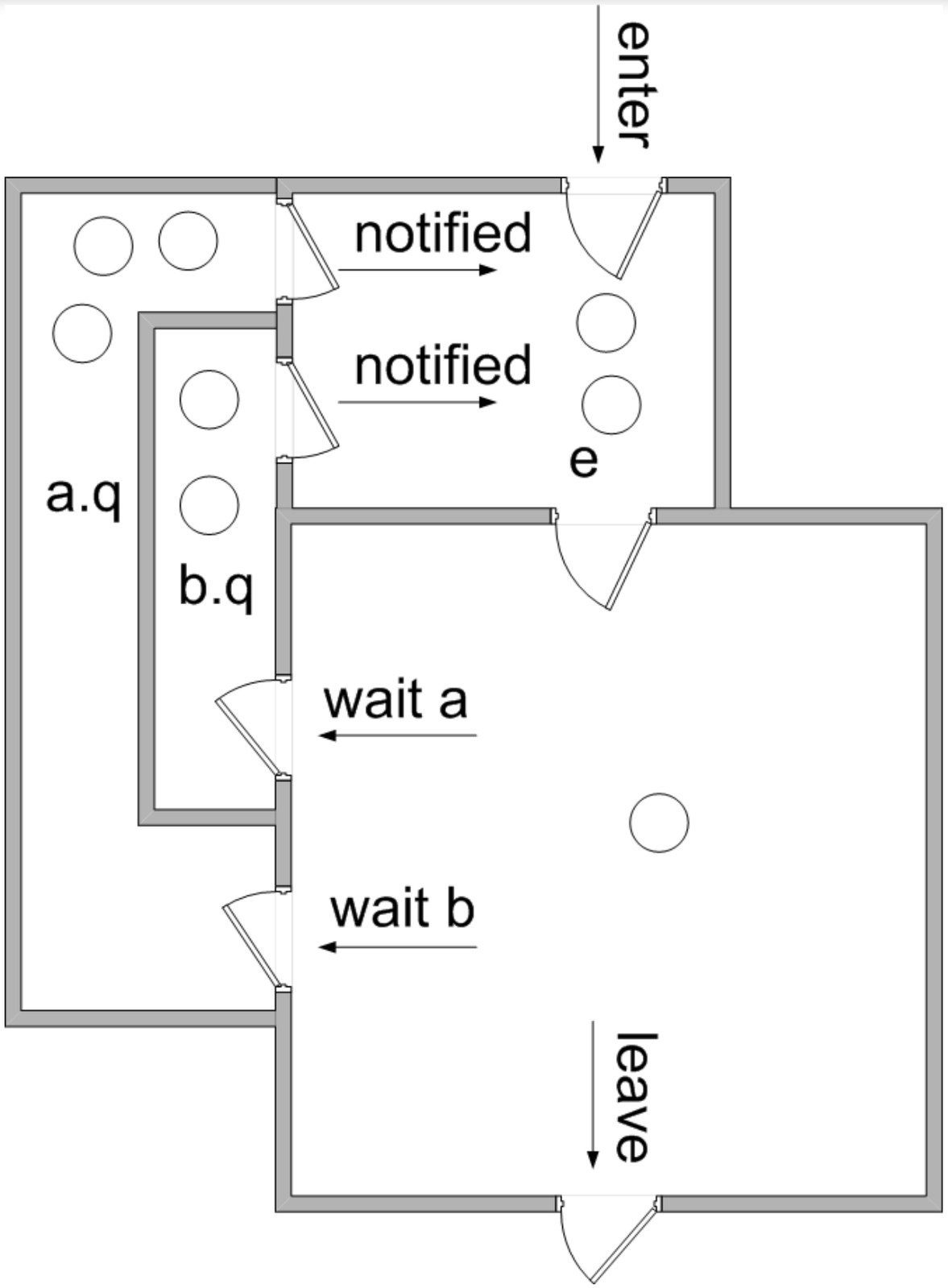
The signaling thread is allowed to continue its execution

When it leaves the monitor, the awakened thread, and perhaps other threads, will try to acquire the monitor lock

The signaled thread will eventually enter the monitor

but there are no guarantee that the condition still holds!

Option 2: MESA Semantics



How BLITZ implements condition variables

```
method Wait(mutex: ptr to Mutex)
   disable interrupts
   mutex.Unlock()
   waitingThreads.AddToEnd(currentThread)
   currentThread.Sleep()
   mutex.Lock()
   enable interrupts
endMethod
```

What semantics does BLITZ implement?

```
method Signal(mutex: ptr to Mutex)
   disable interrupts
   t = waitingThreads.Remove()
   if t
      t.status = READY
      readyList.AddToEnd(t)
   endIf
   enable interrupts
endMethod
```

What semantics does BLITZ implement?

MESA Semantics

Revisiting the producer-consumer problem

```
monitor ProducerConsumer
  Condition full    // Sender threads wait when buffer is full
  Condition empty   // Receiver threads wait when buffer is empty

  send(message msg)
     if in - out == N then
       full.wait()  // buffer is full, let me wait outside monitor
     buffer[in modulo N] = msg
     if in == out then
       in = in + 1
       empty.signal() // wake up a receiver waiting outside
     else in = in + 1

  message receive()
     if in == out then
       empty.wait() // buffer is empty, let me wait outside monitor
     msg = buffer[out modulo N]
     if in - out == N then
       out = out + 1
       full.signal() // wake up a sender waiting outside
     else out = out + 1
     return msg
```

Producer-consumer with MESA Semantics

```
monitor ProducerConsumer
  Condition full    // Sender threads wait when buffer is full
  Condition empty   // Receiver threads wait when buffer is empty

  send(message msg)
     while in - out == N do
       full.wait()  // buffer is full, let me wait outside monitor
     buffer[in modulo N] = msg
     if in == out then
       in = in + 1
       empty.signal() // wake up a receiver waiting outside
     else in = in + 1

  message receive()
     while in == out do
       empty.wait() // buffer is empty, let me wait outside monitor
     msg = buffer[out modulo N]
     if in - out == N then
       out = out + 1
       full.signal() // wake up a sender waiting outside
     else out = out + 1
     return msg
```

A simplified monitor in Java

Each object may be used as a monitor

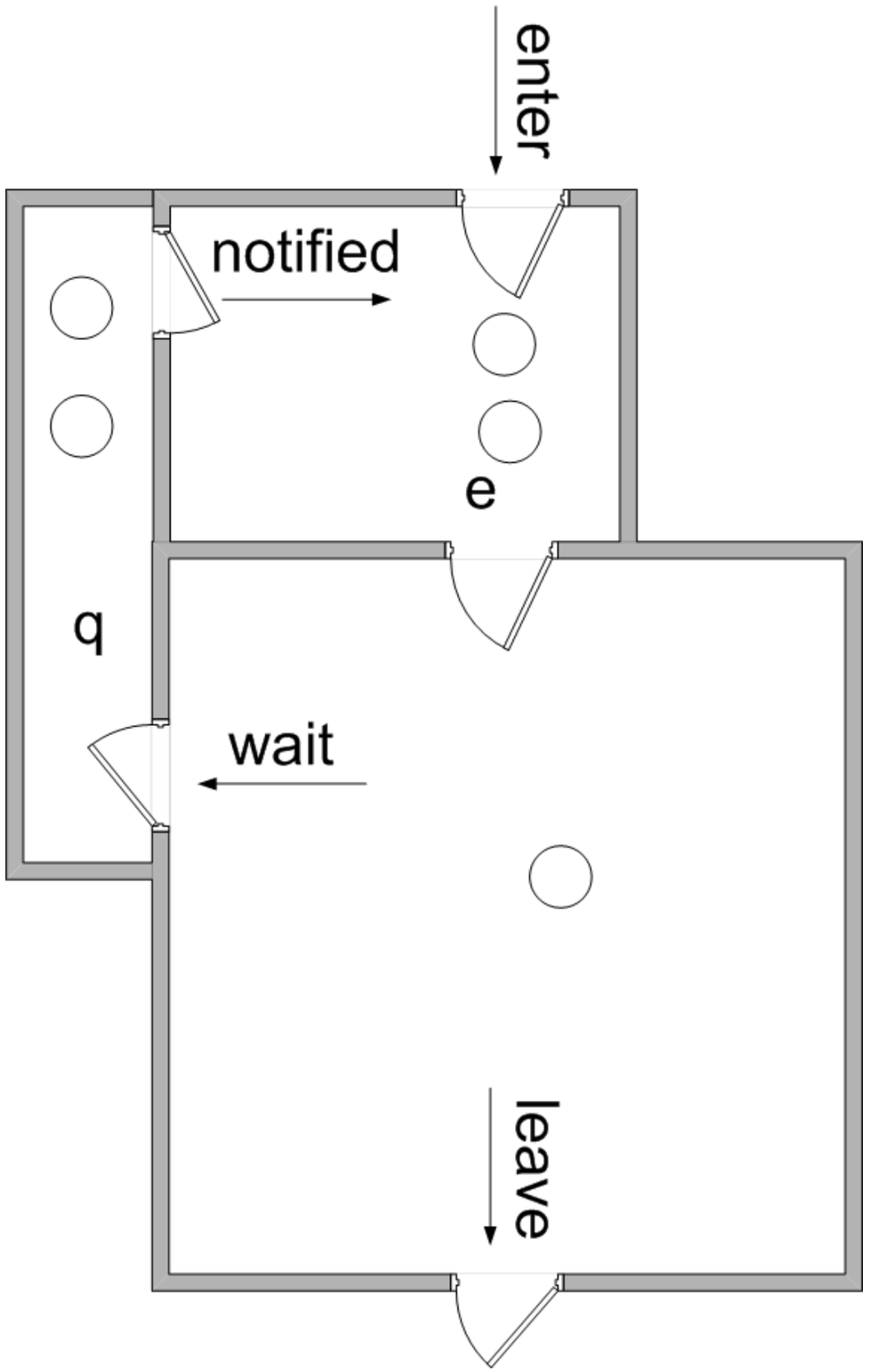
Entry methods requiring mutual exclusion must be explicitly marked as **synchronized**

Rather than having explicit condition variables, each monitor (i.e., object) is equipped with a single wait queue, in addition to its entrance queue

All waiting is done on this single wait queue, by calling **wait()**

All **notify()** and **notifyAll()** operations apply to this queue

A Java-style monitor



What we've covered so far

Three Easy Pieces

Chapter 30: Condition Variables

BLITZ Documentation: "The Thread Scheduler and Concurrency Control Primitives," pages 35-41