Semaphores: A First Cut

Operating Systems
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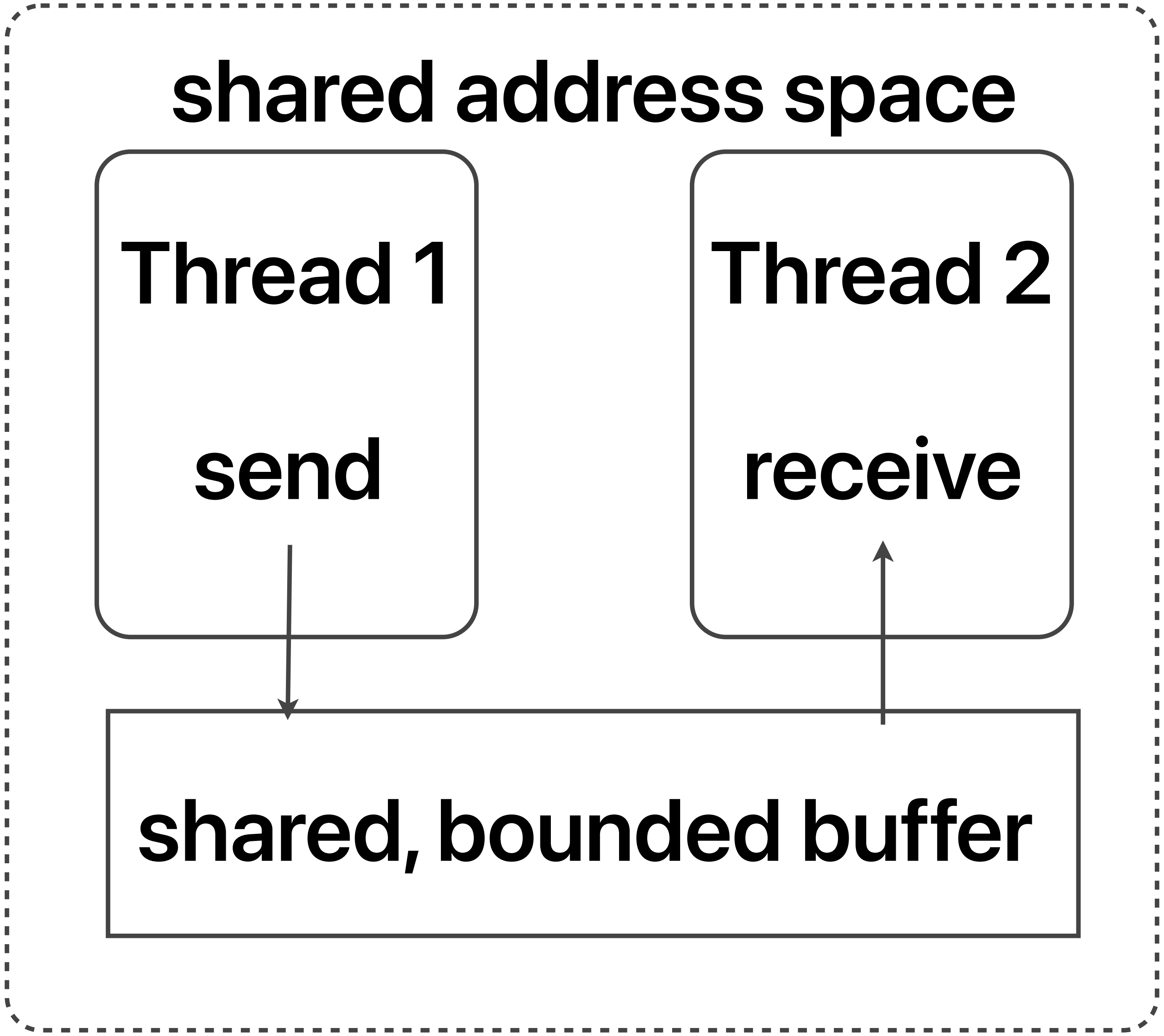
Recall: communicating across threads

The Producer-Consumer Problem

Race Condition: solved using mutual exclusion locks



Synchronization between Producer/Consumer

Mutual exclusion only solves part of the concurrency problem

Synchronization: With two or more communicating threads, one thread needs to wait for another thread until some condition is true

Our previous implementation: producer

```
send(message msg)
  acquire(buffer_lock)
  while in – out == N do
    release(buffer_lock)
    acquire(buffer_lock)
  buffer[in modulo N] = msg
  in = in + 1
  release(buffer_lock)
  return
```

Our previous implementation: polling

Our previous implementation uses a loop (polling) on buffer conditions, in both send() and receive() — not desirable

Intuitively, it will be nice to have something like —

- sleep(): suspends a thread by changing its state to BLOCKED, until another wakes it up
- wakeup(thread_id): wake up another thread, by changing its state to READY

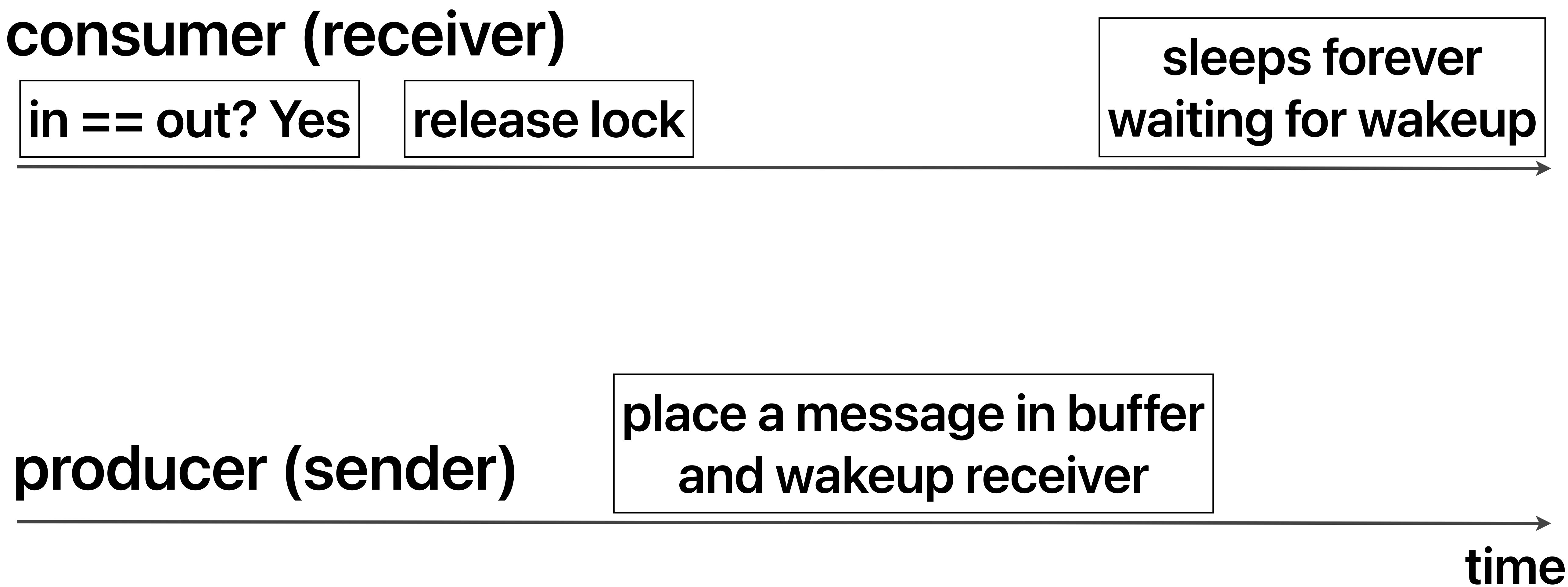
Solving the problem: first try — receive()

```
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
```

Solving the problem: first try — send()

```
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)
```

The Lost Wakeup Problem



What's causing the problem?

What causes the problem?

The problem is we need to make two actions before-or-after atomic:

- Releases the lock
- Calls sleep(), which changes the thread state from RUNNING to BLOCKED

We need better synchronization primitives

Intuitively, we need to design a better set of thread synchronization primitives

- **sleep()** and **wakeup(thread_id)** does not work well since they do not maintain a "state" or "memory" about past wakeups

Semaphores: maintaining a "table count"

Analogy: the person at the entrance of a restaurant who oversees table assignments

- She needs to maintain a count of unoccupied tables
- When guests arrive, she decrements the table count for each table taken
- When there is no table left, guests will have to wait in a queue
- As tables are freed up, waiting guests are allowed into the restaurant

Semaphores: maintaining a "table count"

Edsger Dijkstra, a 1972 Turing Award winner, proposed Semaphore primitives, down() and up(), in 1965

Defining semaphores: the first alternative

A semaphore is a non-negative integer that remembers past wakeups

down(semaphore): if semaphore > 0, decrement semaphore. Otherwise, wait until another thread increments semaphore, then try to decrement again

up(semaphore): increment semaphore, and wake up all threads waiting on semaphore

A binary semaphore: takes on only values of 0 and 1

a binary semaphore can be used as a mutex lock **without the need for polling**: down() corresponds to acquire(), up() corresponds to release()

Defining semaphores: second alternative

The previous definition does not allow a negative count

We can instead allow the count to go negative

- A positive value: it is the number of resources available
- A negative value: its absolute value is the number of threads waiting on available resources
- Just like in a restaurant!

Semantics of Down() and Up()

- down(semaphore): decrement semaphore, then add itself to the waiting queue and change the thread state to BLOCKED, if its value is negative
- up(semaphore): increment semaphore, and wake up **one** of the threads waiting on semaphore

BLITZ semaphores use the second alternative

```
class semaphore
  int count
  waitingThreads: List [Thread]
up()
  disable interrupts
  count = count + 1
  if count <= 0
    t = waitingThreads.Remove()
    t.status = READY
    readyList.addToEnd(t)
  endIf
  enable interrupts
down()
  disable interrupts
  count = count – 1
  if count < 0
    waitingThreads.AddToEnd(currentThread)
    currentThread.Sleep()
  endIf
  enable interrupts
```

Binary semaphores

A **binary** semaphore: takes on only values of 0 and 1

a binary semaphore can be used as a mutex lock **without the need for polling ("spin lock")**: down() corresponds to acquire(), up() corresponds to release()

Solving the P-C problem with semaphores

full: counting the number of slots that are occupied

- initialized to 0

empty: counting the number of slots that are empty

- initialized to the size of the buffer

mutex: make sure the sending and receiving threads do not access the shared buffer at the same time

- initialized to 1
- **a binary semaphore**

Thread synchronization and mutual exclusion

- mutex used to solve the mutual exclusion problem
- full and empty used for thread synchronization

Solving the problem with binary semaphores

First try

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

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

Potential for deadlocks

mutex was decremented before empty instead of after it

If the buffer were completely full, the sender thread will block on empty, with mutex set to 0 already

The next time the receiver thread tried to access the buffer, it would do a down on mutex

mutex is now 0, so the receiver thread will block, too

Both threads will be blocked forever

Solving the problem with binary 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
```

Improving acquire() and release()

acquire() have been implemented using a TSL instruction in a spin loop

Spin loops consume processor cycles and should be avoided

If acquire() finds that the lock is LOCKED, a better idea is to put the thread itself to BLOCKED, waiting for another thread to release the lock

You were asked to implement this improvement in Lab 2 in BLITZ

- waitingThreads: a list of threads suspended and waiting on the lock
- heldBy: the current state of the lock — which thread is holding the lock
- Think about race conditions and correctness carefully

What We've Covered So Far

Three Easy Pieces

Chapter 31: "Semaphores", 31.1-31.4, 31.7

Principles of Computer Systems Design

Section 5.6.1: The Lost Notification Problem

Sidebar 5.7

BLITZ Documentation: "The Thread Scheduler and Concurrency Control Primitives," pages 31-35