Little Book of Semaphores, Chapter 4

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Producers and Consumers

Producer i
```
event[i] = waitForEvent()
buffer.add(event[i])
```

Consumer j
```
event[j] = buffer.get()
event[j].process()
```

- Threads must have exclusive access to the buffer. No adding and getting at the same time.
- If a consumer thread arrives when the buffer is empty, it blocks until a producer adds an item.
- `waitForEvent` and `process` can happen simultaneously, but not buffer access.
- `event` is a local variable for each thread—not shared.
- We could use an array, as above, with all producers and consumers having different indices.

Producers and Consumers Hint

```
mutex = Semaphore(1)
items = Semaphore(0)
local event
```

- Local events can be handled several ways:
  - Each thread has its own run-time stack. (We use this in scheme and python, where threads are functions.)
  - Threads could be objects, with local private variables.
  - Threads can use unique IDs as indices into an array.

Producer-consumer solution

Producer

```
event = waitForEvent()
mutex.wait()
  buffer.add(event)
  items.signal()
mutex.signal()
```

Consumer

```
items.wait()
mutex.wait()
  event = buffer.get()
mutex.signal()
event.process()
```

Producer-consumer solution

Producer

```
event = waitForEvent()
mutex.wait()
  buffer.add(event)
  items.signal()
mutex.signal()
```

Consumer

```
items.wait()
mutex.wait()
  event = buffer.get()
mutex.signal()
event.process()
```

- Could the `items.signal()` be taken out of the mutex?
- What would be the advantage?

Producer-consumer solution (slight improvement)

Producer

```
event = waitForEvent()
mutex.wait()
  buffer.add(event)
mutex.signal()
items.signal()
```

Consumer

```
items.wait()
mutex.wait()
  event = buffer.get()
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Producer-consumer solution (slight improvement)

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```
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mutex.wait()
  buffer.add(event)
mutex.signal()
items.signal()
```

Consumer

```
items.wait()
mutex.wait()
  event = buffer.get()
mutex.signal()
event.process()
```

- `items` could at times not accurately reflect the actual number of waiting consumers.

Producer-consumer solution (broken)

Producer

```
event = waitForEvent()
mutex.wait()
  buffer.add(event)
mutex.signal()
items.signal()
```

Consumer

```
mutex.wait()
  items.wait()
  event = buffer.get()
mutex.signal()
event.process()
```

- Why is this broken?

Producer-consumer solution (broken)

Producer

```
event = waitForEvent()
mutex.wait()
  buffer.add(event)
mutex.signal()
items.signal()
```

Consumer

```
mutex.wait()
  items.wait()
  event = buffer.get()
mutex.signal()
event.process()
```

- Why is this broken?
- Don't wait for a semaphore after grabbing a mutex!

Producer-consumer with finite buffer

Broken finite buffer solution

```
if items >= bufferSize:
  block()
```

- `items` is a semaphore, we can't check its size
- Even if we could, we could be interrupted between checking and blocking.
- We *don't* want to block inside a mutex!
- What to do?

Producer-consumer with finite buffer

Broken finite buffer solution

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if items >= bufferSize:
  block()
```

- `items` is a semaphore, we can't check its size
- Even if we could, we could be interrupted between checking and blocking.
- We *don't* want to block inside a mutex!
- What to do?
- How can we use a semaphore to count?

Producer-consumer with finite buffer

Broken finite buffer solution

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if items >= bufferSize:
  block()
```

- `items` is a semaphore, we can't check its size
- Even if we could, we could be interrupted between checking and blocking.
- We *don't* want to block inside a mutex!
- What to do?
- How can we use a semaphore to count?
- We can *only* "check" if a semaphore is zero.
- (For this problem, think of semaphores as ≥ 0.)

Finite buffer producer-consumer hint

```
mutex = Semaphore(1)
items = Semaphore(0)
spaces = Semaphore(bufferSize)
```

- `items + spaces = bufferSize`
- (only considering positive semaphore values)

Finite buffer producer-consumer solution

```
mutex = Semaphore(1)
items = Semaphore(0)
spaces = Semaphore(bufferSize)
```

Producer

```
event = waitForEvent()

spaces.wait()
mutex.wait()
  buffer.add(event)
mutex.signal()
items.signal()
```

Consumer

```
items.wait()
mutex.wait()
  event = buffer.get()
mutex.signal()
spaces.signal()

event.process()
```

Finite buffer producer-consumer solution

```
mutex = Semaphore(1)
items = Semaphore(0)
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Producer

```
event = waitForEvent()
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```

Consumer

```
items.wait()
mutex.wait()
  event = buffer.get()
mutex.signal()
spaces.signal()
event.process()
```

- Note that `items + spaces` is a constant.
- This is an *invariant*
- Using invariants is a good way to design programs and help prove properties.

Readers-writers problem

- Suppose a number of processes all access the same data.
- Any number of readers can be in the critical section simultaneously.
- Writers must have exclusive access to the critical section.
- This might be called **categorical mutual exclusion**.
- Ideas?

Readers-writers problem

- Suppose a number of processes all access the same data.
- Any number of readers can be in the critical section simultaneously.
- Writers must have exclusive access to the critical section.
- This might be called **categorical mutual exclusion**.
- Ideas?
- Remember the barrier, where the last one in opened the turnstyle?

Readers-writers hint

```
readers = 0
mutex = Semaphore(1)
roomEmpty = Semaphore(1)
```

- "wait" means "wait for the condition to be true"
- "signal" means "signal that the condition is true"

Readers-writers solution

Writers

```
roomEmpty.wait()
# critical section for writer
roomEmpty.signal()
```

- A **Lightswitch**
- Note that Readers wait while holding a mutex.
- Can we prove that this is never deadlocks?

Readers

```
mutex.wait()
  readers += 1
  if readers == 1:
    # first in locks:
    roomEmpty.wait()
mutex.signal()

# critical section for reader

mutex.wait()
  readers -= 1
  if readers == 0:
    # last out unlocks
    roomEmpty.signal()
mutex.signal()
```

Claims useful in a proof of correctness

Writers

```
roomEmpty.wait()
# critical section for writer
roomEmpty.signal()
```

- Only one reader can queue on `roomEmpty`
- Several writers might be queued on `roomEmpty`
- When a reader signals `roomEmpty` the room is empty

Readers

```
mutex.wait()
  readers += 1
  if readers == 1:
    # first in locks:
    roomEmpty.wait()
mutex.signal()
# critical section for reader
mutex.wait()
  readers -= 1
  if readers == 0:
    # last out unlocks
    roomEmpty.signal()
mutex.signal()
```

A lightswitch object

```
class Lightswitch:
  def __init__(self):
    self.counter = 0
    self.mutex = Semaphore(1)

  def lock(self, semaphore):
    self.mutex.wait()
      self.counter += 1
      if self.counter == 1:
        semaphore.wait()
    self.mutex.signal()

  def unlock(self, semaphore):
    self.mutex.wait()
      self.counter -= 1
      if self.counter == 0:
        semaphore.signal()
        self.mutex.signal()
```

Initialization

```
readswitch = Lightswitch()
roomEmpty = Semaphore(1)
```

Readers

```
readswitch.lock(roomEmpty)
# critical section
readwitch.unlock(roomEmpty)
```

Writers

```
roomEmpty.wait()
# critical section for writer
roomEmpty.signal()
```

- Note that lock takes the semaphore to lock as an argument.

Rewritten Readers-Writers Solution

Initialization

```
readSwitch = Lightswitch()
roomEmpty = Semaphore(1)
```

Writers

```
roomEmpty.wait()
# critical section for writer
roomEmpty.signal()
```

Readers

```
readSwitch.lock(roomEmpty)
# critical section for reader
readSwitch.unlock(roomEmpty)
```

Starvation

- No deadlock in the above readers-writers solution.
- However, it is possible for a writer to **starve**.
- While a writer is blocked, readers can come and go, and the writer never progresses.
- (In the buffer problem, readers eventually empty the buffer, but we can imagine readers who simply examine the buffer without removing an item.)

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- Puzzle: extend the solution so that when a writer arrives, the existing readers can finish, but no additional readers may enter.

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- Puzzle: extend the solution so that when a writer arrives, the existing readers can finish, but no additional readers may enter.
- Hint: Add a turnstyle and allow the writers to lock it.

No-starve readers-writers hint

```
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roomEmpty = Semaphore(1)
turnstile = Semaphore(1)
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No-starve readers-writers hint

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```

- `turnstile` is a turnstile for readers and a mutex for writers

No-starve readers-writers solution

Writers

```
turnstile.wait()
  roomEmpty.wait()
  # critical section
turnstile.signal()
roomEmpty.signal()
```

Readers

```
turnstile.wait()
turnstile.signal()
readSwitch.lock(roomEmpty)
  # critical section
readSwitch.unlock(roomEmpty)
```

- `turnstile` is a turnstile for readers and a mutex for writers

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Writers

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turnstile.signal()

readSwitch.lock(roomEmpty)
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readSwitch.unlock(roomEmpty)
```

- `turnstile` is a turnstile for readers and a mutex for writers
- It is now possible for *readers* to starve!

Priority Scheduling

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- Some schedulers allow priority scheduling.
- Puzzle: Write a solution to readers-writers that gives priority to writers. In other words, once a writer arrives, no readers are allowed in the critical section until *all* writers have left the system.

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- Hint: use two lightswitches

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- Puzzle: Write a solution to readers-writers that gives priority to writers. In other words, once a writer arrives, no readers are allowed in the critical section until *all* writers have left the system.
- Hint: use two lightswitches
- One lightswitch controls access to the *VIP waiting area*.

Writer-priority readers-writers hint

```
readSwitch = Lightswitch()
writeSwitch = Lightswitch()
mutex = Semaphore(1)
noReaders = Semaphore(1)
noWriters = Semaphore(1)
```

Writer-priority readers-writers solution

Writers

```
writeSwitch.lock(noReaders)
  noWriters.wait()

    # critical section

  noWriters.signal()
writeSwitch.unlock(noReaders)
```

Readers

```
noReaders.wait()
  readSwitch.lock(noWriters)
noReaders.signal()

# critical section

readSwitch.unlock(noWriters)
```

- Writers in critical section hold *both* `noReaders` and `noWriters`.
- `writeSwitch` allows writers to queue on `noWriters`, but keeps `noReaders` locked
- The last writer signals `noReaders`

Writer-priority readers-writers solution

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```

- Writers in critical section hold *both* `noReaders` and `noWriters`.
- `writeSwitch` allows writers to queue on `noWriters`, but keeps `noReaders` locked
- The last writer signals `noReaders`
- Readers in critical section hold `noWriters` but don't hold `noReaders`, so a writer can lock `noReaders`
- The last reader signals `noWriters` so writers can go

Thread starvation

- We just addressed **categorical starvation**: one category of threads makes another category starve.
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Thread starvation

- We just addressed **categorical starvation**: one category of threads makes another category starve.
- **Thread starvation** is the more general possibility of a thread waiting indefinitely while other threads proceed.
- Part of the problem is the responsibility of the scheduler. If a thread is never scheduled, it is starved.
- Some schedulers use algorithms that guarantee bounded waiting.

Thread starvation

- If we don't want to assume too much about the scheduler, can we assume:
- **Property 1:** if there is only one thread that is ready to run, the scheduler has to let it run.
- This would be sufficient for the barrier problem.
- In general we need a stronger assumption.

Thread starvation

- **Property 2:** if a thread is ready to run, then the time it waits until it runs is bounded.
- We use this assumption in all our work.
- Some schedulers in the real world do not guarantee this strictly.
- Property 2 is not strong enough if we use semaphores. Why?

Thread starvation

- **Property 2:** if a thread is ready to run, then the time it waits until it runs is bounded.
- We use this assumption in all our work.
- Some schedulers in the real world do not guarantee this strictly.
- Property 2 is not strong enough if we use semaphores. Why?
- We never said *which* thread is woken up.
- A thread might never be ready to run.

Semaphore starvation

- The weakest assumption about semaphores that makes it possible to avoid starvation is:
- **Property 3:** if there are threads waiting on a semaphore when a thread executes `signal`, then one of the waiting threads has to be woken.

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- **Property 3:** if there are threads waiting on a semaphore when a thread executes `signal`, then one of the waiting threads has to be woken.
- Prevents a thread from signalling a semaphore, racing around a loop and catching its own signal!

Thread i

```
while True:
  mutex.wait()
  # critical section
  mutex.signal()
```

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- Prevents a thread from signalling a semaphore, racing around a loop and catching its own signal!

Thread i

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while True:
  mutex.wait()
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  mutex.signal()
```

- However, if A, B, and C are using a mutex in a loop, A and B could race around and around, starving C.
- A semaphore with Property 3 is called a **weak semaphore**.

Semaphore starvation

- **Property 4:** if a thread is waiting at a semaphore, then the number of threads that will be woken before it is bounded.

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- A semaphore with Property 4 is called a **strong semaphore**.

Semaphore starvation

- **Property 4:** if a thread is waiting at a semaphore, then the number of threads that will be woken before it is bounded.
- FIFO queues satisfy this property.
- A semaphore with Property 4 is called a **strong semaphore**.
- Dijkstra (inventor of semaphores) conjectured in 1965 that it was impossible to solve the mutex problem without starvation with weak semaphores.

Semaphore starvation

- **Property 4:** if a thread is waiting at a semaphore, then the number of threads that will be woken before it is bounded.
- FIFO queues satisfy this property.
- A semaphore with Property 4 is called a **strong semaphore**.
- Dijkstra (inventor of semaphores) conjectured in 1965 that it was impossible to solve the mutex problem without starvation with weak semaphores.
- Morris showed you could do it in 1979.

Morris's algorithm

Initialization

```
room1 = room2 = 0
mutex = Semaphore(1)
t1 = Semaphore(1)
t2 = Semaphore(0)
```

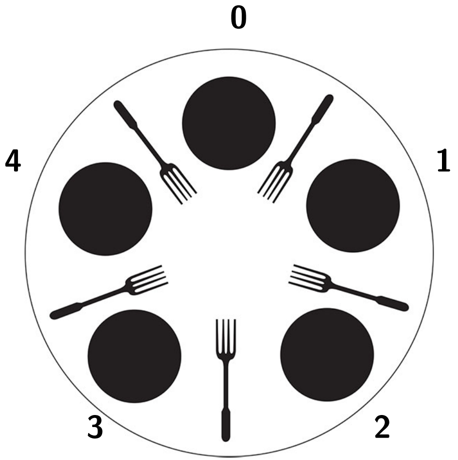
```
mutex.wait()
  room1 += 1
mutex.signal()
t1.wait()
  room2 += 1
  mutex.wait()
  room1 -= 1
  if room1 == 0:
    mutex.signal()
    t2.signal()
  else:
    mutex.signal()
    t1.signal()
t2.wait()
  room2 -= 1
  # critical section
  if room2 == 0:
    t1.signal()
  else:
    t2.signal()
```

The Dining Philosophers

- Five philosophers are eating spaghetti.
- There are five forks.
- Eating spaghetti requires two forks.
- More than one philosopher can eat at a time.

Philosopher i

```
while True:
    think()
    get_forks()
    eat()
    put_forks()
```



The Dining Philosophers: a Non-solution

Which fork?

```
def left(i) = return i
def right(i) = return (i+1)%5
```

Initialization

```
forks =
  [Semaphore(1)
    for i in range(5)]
```

Non-solution

```
def get_forks(i):
  fork[right(i)].wait()
  fork[left(i)].wait()

def put_forks(i):
  fork[right(i)].signal()
  fork[left(i)].signal()
```

- Why does this not work?

The Dining Philosophers: a Non-solution

Which fork?

```
def left(i) = return i
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```

Initialization

```
forks =
  [Semaphore(1)
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Non-solution

```
def get_forks(i):
  fork[right(i)].wait()
  fork[left(i)].wait()

def put_forks(i):
  fork[right(i)].signal()
  fork[left(i)].signal()
```

- Why does this not work?
- Deadlock is possible. How?
- Can you think of a symmetric solution?

The Dining Philosophers: Solution #1

Initialization

```
footman = Semaphore(4)
```

Solution #1

```
def get_forks(i):
  footman.wait()
  fork[right(i)].wait()
  fork[left(i)].wait()

def put_forks(i):
  fork[right(i)].signal()
  fork[left(i)].signal()
  footman.signal()
```

- Only allow 4 philosophers at a time.
- Can you prove deadlock is impossible?

The Dining Philosophers: Solution #1

Initialization

```
footman = Semaphore(4)
```

Solution #1

```
def get_forks(i):
  footman.wait()
  fork[right(i)].wait()
  fork[left(i)].wait()

def put_forks(i):
  fork[right(i)].signal()
  fork[left(i)].signal()
  footman.signal()
```

- Only allow 4 philosophers at a time.
- Can you prove deadlock is impossible?
- Can you think of an asymmetric solution with no footman?

The Dining Philosophers: Solution #2

- Have at least one leftie and at least one rightie.
- How can you prove deadlock is impossible?

The Dining Philosophers: Tanenbaum's solution

Initialization

```
state = ['thinking'] * 5
sem = [Semaphore(0) for i in range(5)]
mutex = Semaphore(1)
```

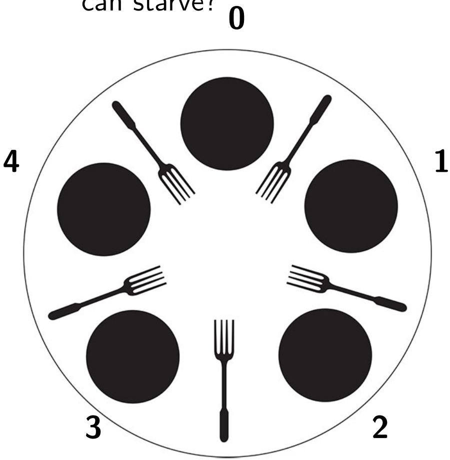
```
def get_fork(i):
  mutex.wait()
  state[i] = 'hungry'
  test(i)
  mutex.signal()
  sem[i].wait()

def put_fork(i):
  mutex.wait()
  state[i] = 'thinking'
  test(right(i))
  test(left(i))
  mutex.signal()
```

```
def test(i):
if (
  state[i] == 'hungry'
  and
  state(left(i)) != 'eating'
  and
  state(right(i)) != 'eating'
  ) :
    state[i] = 'eating'
    sem[i].signal()
```

Tanenbaum's solution not starvation-free

- Can you think of a situation where a Tanenbaum philosopher can starve?



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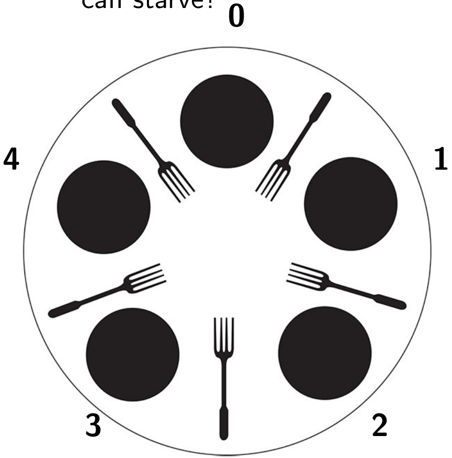

- Imagine trying to starve 0.
- Initially 1 and 3 are eating
- 3 swaps with 4
- 1 swaps with 2
- Now 2 and 4 are eating
- Repeat

Cigarette smokers problem

- To smoke you need: paper, tobacco, and a match.
- Four threads: an agent and three smokers.
- One smoker already has lots of paper.
- One smoker already has lots of tobacco.
- One smoker already has lots of matches.
- The agent repeatedly obtains two ingredients at random.
- The agent should wake up the smoker who needs those ingredients.

Cigarette smokers problem: agent code

- Interesting problem assumes we cannot change agent code.

Initialization

```
agentSem = Semaphore(1)
tabacco = Semaphore(0)
paper = Semaphore(0)
match = Semaphore(0)
```

Agent A

```
agentSem.wait()
tabacco.signal()
paper.signal()
```

Agent B

```
agentSem.wait()
paper.signal()
match.signal()
```

Agent C

```
agentSem.wait()
tabacco.signal()
match.signal()
```

Cigarette smokers problem: Non-solution

Agent A
```
agentSem.wait()
tabacco.signal()
paper.signal()
```

Agent B
```
agentSem.wait()
paper.signal()
match.signal()
```

Agent C
```
agentSem.wait()
tabacco.signal()
match.signal()
```

Smoker with matches
```
tabacco.wait()
paper.signal()
agentSem.signal()
```

Smoker with tobacco
```
paper.wait()
match.wait()
agentSem.signal()
```

Smoker with paper
```
tabacco.wait()
match.wait()
agentSem.signal()
```

- Why doesn't this work?

Smokers problem: Parnas solution

Initialization

```
isTobacco = isPaper =
    isMatch = False
tobaccoSem = Semaphore(0)
paperSem = Semaphore(0)
matchSem = Semaphore(0)
```

Smoker with tobacco

```
tobaccoSem.wait()
makeCigarette()
agentSem.signal()
smoke()
```

Pusher A

```
tobacco.wait()
mutex.wait()
  if isPaper:
    isPaper = False
    matchSem.signal()
  elif isMatch:
    isMatch = False
    paperSem.signal()
  else:
    isTobacco = True
mutex.signal()
```

Generalized smokers problem

Initialization

```
numTobacco = numPaper =
    numMatch = 1
tobaccoSem = Semaphore(0)
paperSem = Semaphore(0)
matchSem = Semaphore(0)
```

Smoker with tobacco

```
tobaccoSem.wait()
makeCigarette()
agentSem.signal()
smoke()
```

Pusher A

```
tobacco.wait()
mutex.wait()
  if numPaper:
    isPaper -= 1
    matchSem.signal()
  elif numMatch:
    isMatch -= 1
    paperSem.signal()
  else:
    isTobacco += 1
mutex.signal()
```

- Keep a **scoreboard**:
  variables describing the state of the system.
- Each agent checks the scoreboard to see if it can proceed.