Synchronization problems with semaphores

Lecture 4 of TDA384/DIT391

Principles of Concurrent Programming

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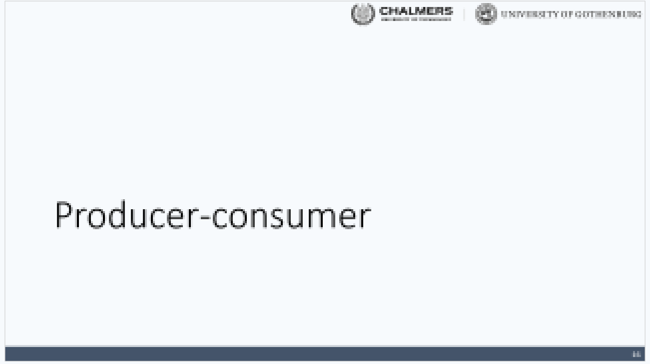
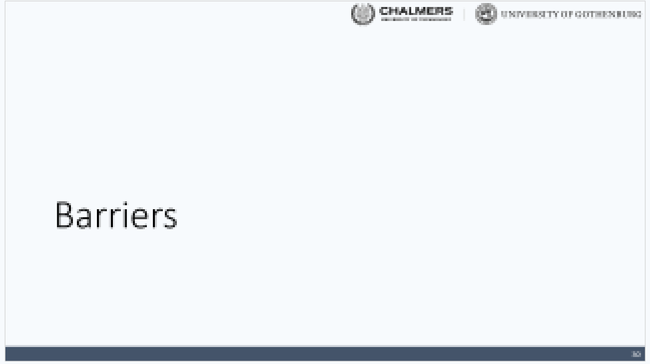
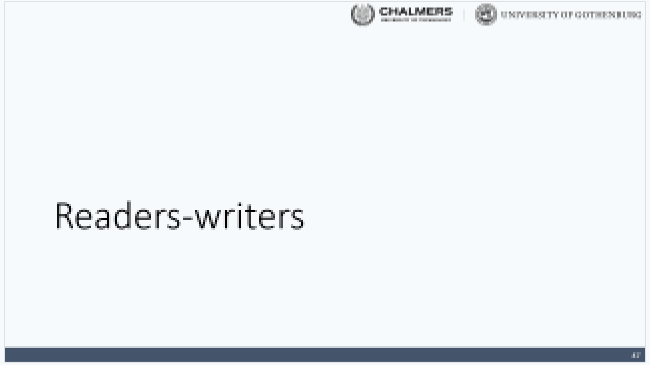
Lesson's menu



- Dining philosophers
- Producer-consumer
- Barriers
- Readers-writers





Lesson's menu

- Dining philosophers
- Producer-consumer
- Barriers
- Readers-writers
  - Identify problems of synchronization
  - What issues and problems can arise
  - Patterns for introducing synchronization

Learning outcomes

Knowledge and understanding:

- demonstrate knowledge of the issues and problems that arise in writing correct concurrent programs;
- identify the problems of synchronization typical of concurrent programs, such as race conditions and mutual exclusion

Skills and abilities:

- apply common patterns, such as lock, semaphores, and message-passing synchronization for solving concurrent program problems;
- apply practical knowledge of the programming constructs and techniques offered by modern concurrent programming languages;
- implement solutions using common patterns in modern programming languages

Judgment and approach:

- evaluate the correctness, clarity, and efficiency of different solutions to concurrent programming problems;
- judge whether a program, a library, or a data structure is safe for usage in a concurrent setting;
- pick the right language constructs for solving synchronization and communication problems between computational units.

A gallery of synchronization problems

- Today we go through several classical synchronization problems and solve them using threads and semaphores
- If you want to learn about many other synchronization problems and their solutions
  - "The little book of semaphores" by A. B. Downey: http://greenteapress.com/semaphores/
- We use pseudo-code to simplify the details of Java syntax and libraries but which can be turned into fully functioning code by adding boilerplate
  - On the course website: can download fully working implementations of some of the problems
- Recall that we occasionally annotate classes with *invariants* using the pseudo-code keyword `invariant`
  - **Not** a valid Java keyword – that is why we highlight it in a different color – but we will use it to help make more explicit the behavior of classes
  - We also use `at(i)` or `at(i,j)` to indicate the number of threads that are at location `i` or between locations `i,j`. (That's not Java either)

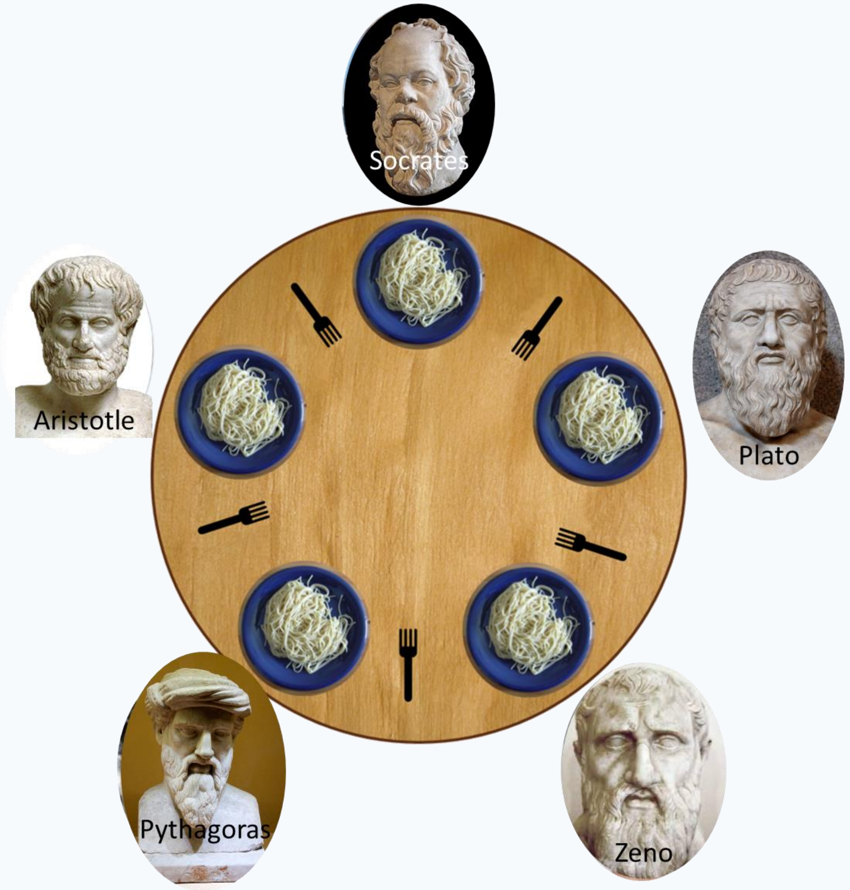
Dining philosophers

The dining philosophers (reminder)

The dining philosophers is a classic synchronization problem introduced by Dijkstra

It illustrates the problem of deadlocks using a colorful metaphor (by Hoare)

- Five philosophers are sitting around a dinner table, with a fork in between each pair of adjacent philosophers
- Each philosopher alternates between thinking (non-critical section) and eating (critical section)
- In order to eat, a philosopher needs to pick up the two forks that lie to the philopher's left and right
- Since the forks are shared, there is a synchronization problem between philosophers (threads)



Dining philosophers: the problem

```
interface Table {
    // philosopher k picks up forks
    void getForks(int k);
    // philosopher k releases forks
    void putForks(int k);
}
```

Properties of a good solution:

- support an *arbitrary number* of philosophers
- *deadlock* freedom
- *starvation* freedom
- reasonable *efficiency*: eating in parallel still possible

Dining philosophers' problem: implement `Table` such that:

- forks are held exclusively by one philosopher at a time
- each philosopher only accesses adjacent forks

The philosophers

Each philosopher continuously alternate between thinking and eating; the table must **guarantee** proper synchronization when eating

```
Table table; // table shared by all philosophers
```

philosopher$_k$

```
while (true) {
  think();             // think
  table.getForks(k);   // wait for forks
  eat();               // eat
  table.putForks(k);   // release forks
}
```

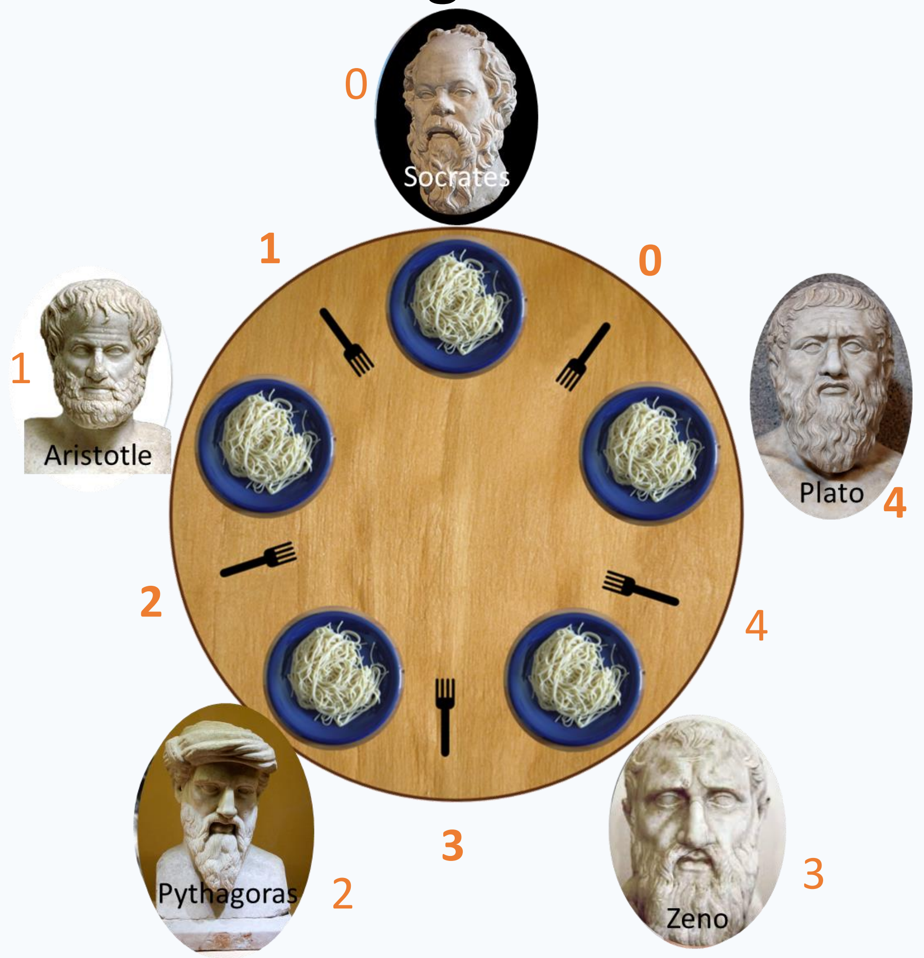
Left and right

For convenience, we introduce a consistent numbering scheme for forks and philosophers, in a way that it is easy to refer to the left or right fork of each philosopher.

```java
// in classes implementing Table:

// fork to the left of philosopher k
public int left(int k) {
  return k;
}


// fork to the right of philosopher k
public int right(int k) {
  // N is the number of philosophers
  return (k + 1) % N;
}
```



Dining philosophers with locks and semaphores

- We use semaphores to enforce mutual exclusion when philosophers access the forks

First solution needs only locks:

```
Lock[] forks = new Lock[N]; // array of locks
```

- One lock per fork
- `forks[i].lock()` to pick up fork `i`:
  `forks[i]` is held if fork `i` is held
- `forks[i].unlock()` to put down fork `i`:
  `forks[i]` is available if fork `i` is available

Dining philosophers with semaphores: first attempt

In the first attempt, every philosopher picks up the left fork and then the right fork:

```
public class DeadTable implements Table {
  Lock[] forks = new Lock[N];
```

All forks initially avaliable

```
public void getForks(int k) {
  // pick up left fork
  forks[left(k)].lock();
  // pick up right fork
  forks[right(k)].lock();
}
```

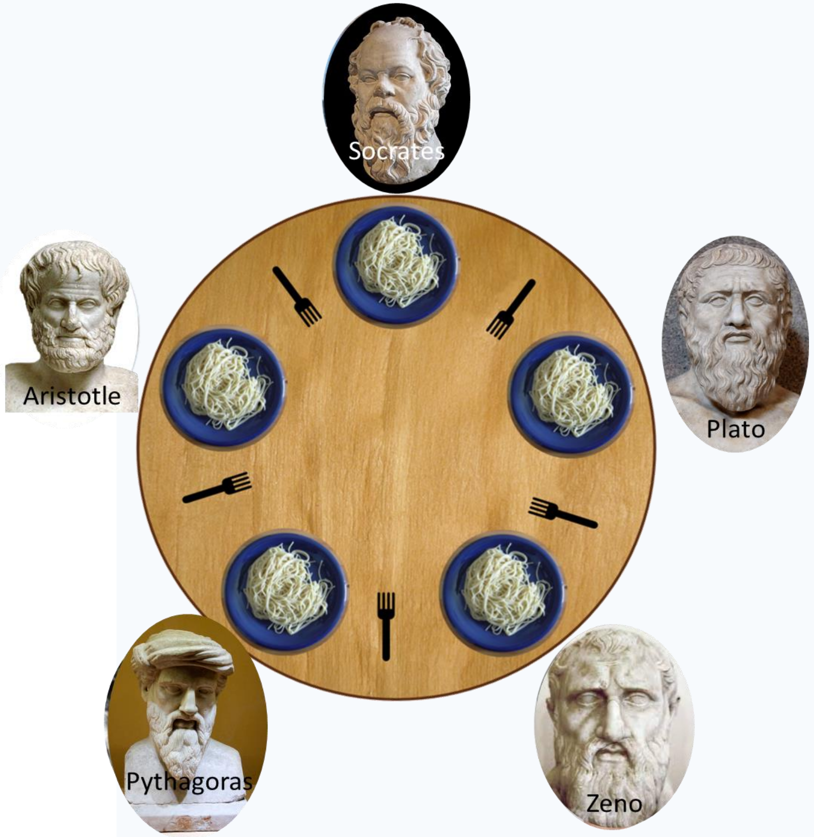
```
public void putForks(int k) {
  // put down left fork
  forks[left(k)].unlock();
  // put down right fork
  forks[right(k)].unlock();
}
```

Dining philosophers with semaphores: first attempt

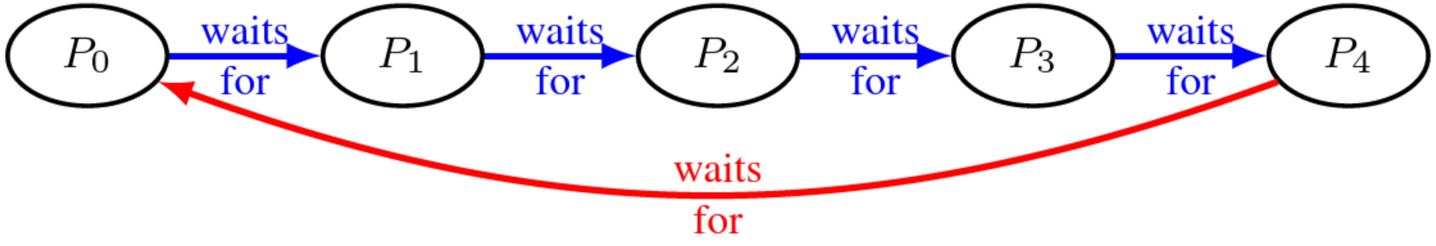
```
public class DeadTable implements Table
{       Lock[] forks = new Lock[N];

public void getForks(int k) {
        // pick up left fork
        forks[left(k)].lock();
        // pick up right fork
        forks[right(k)].lock();
        }
```

if all philosophers hold left fork: deadlock!



A deadlock may occur because of circular waiting:

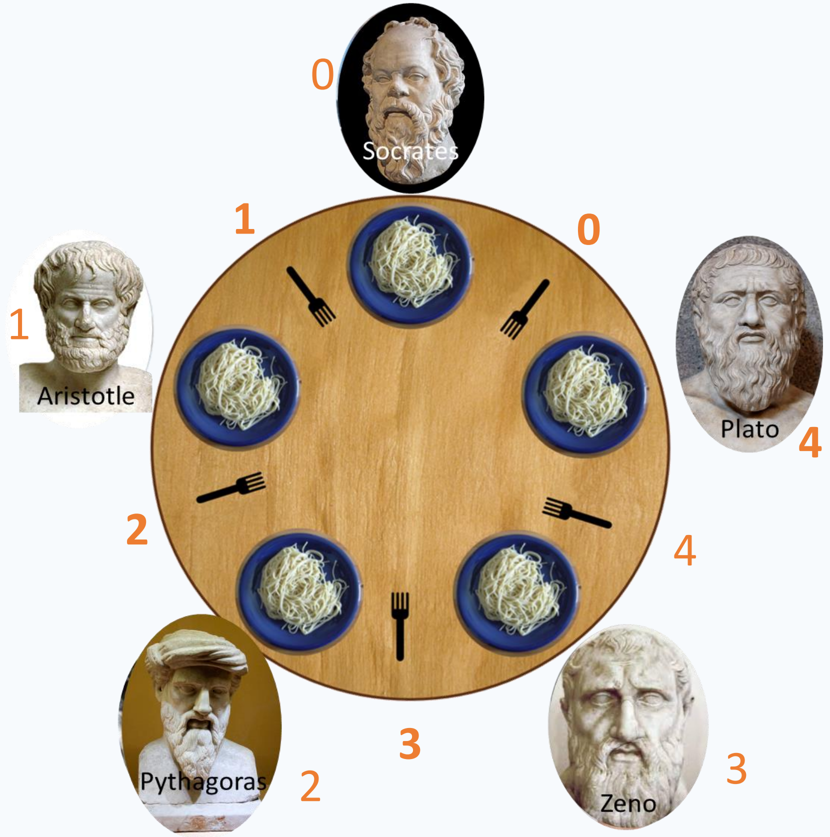


Dining philosophers solution 1: breaking the symmetry

Having one philosopher pick up forks in a different order than the others is sufficient to break the symmetry, and thus to avoid deadlock

```
public class AsymetricTable implements Table {
  Lock[] forks = new Lock[N];

 public void getForks(int k) {
        if (k == N) { // right before left
                forks[right(k)].lock();
                forks[left(k)].lock();
        } else {        // left before right
                forks[left(k)].lock();
                forks[right(k)].lock();
        }
 }
 // putForks as in DeadTable
```



Breaking symmetry to avoid deadlock

Breaking the symmetry is a general strategy to avoid deadlock when acquiring multiple shared resources:

- assign a total order between the shared resources $R_0 < R_1 < \cdots < R_M$
- a thread can try to obtain resource R_i, with $i > j$, only after it has successfully obtained resource R_j

Recall the *Coffman conditions* from Lecture 2…:

1. mutual exclusion: exclusive access to the shared resources
2. hold and wait: request one resource while holding another
3. no preemption: resources cannot forcibly be released
4. circular wait: threads form a circular chain, each waiting for a resource the next is holding

Circular wait is a necessary condition for a deadlock to occur

Dining philosophers solution 2: bounding resources

Limiting the number of philosophers active at the table to $M < N$ ensures that there are enough resources for everyone at the table, thus **avoiding deadlock**

```
public class SeatingTable implements Table {
  Lock[] forks = new Lock[N];
  Semaphore seats = new Semaphore(M); // # available seats
```

```
public void getForks(int k) {
  // get a seat
  seats.down();
  // pick up left fork
  forks[left(k)].lock();
  // pick up right fork
  forks[right(k)].lock();
}
```

```
public void putForks(int k) {
  // put down left fork
  forks[left(k)].unlock();
  // put down right fork
  forks[right(k)].unlock();
  // leave seat
  seats.up();
}
```

Starvation-free philosophers

The two solutions to the dining philosophers problem also guarantee freedom from starvation, under the assumption that locks/semaphores (and scheduling) are fair

In the asymmetric solution (`AsymmetricTable`):

- if a philosopher P waits for a fork k, P gets the fork as soon as P's neighbor holding fork k releases it,
- P's neighbor eventually releases fork k because there are no deadlocks.

In the bounded-resource solution (`SeatingTable`):

- at most `M` philosophers are active at the table,
- the other `N−M` philosophers are waiting on `seats.down()`,
- the first of the `M` philosophers that finishes eating releases a seat,
- the philosopher P that has been waiting on `seats.down()` proceeds,
- similarly to the asymmetric solution, P also eventually gets the forks.

Producer-consumer

Producer-consumer: overview

Producers and consumer exchange items through a shared buffer:

- producers asynchronously produce items and store them in buffer
- consumers asynchronously consume items after removing them from buffer

Producer-consumer: The problem

Producer-consumer problem: implement Buffer such that:

- producers and consumers access the buffer in mutual exclusion
- consumers block when the buffer is empty
- producers block when the buffer is full (bounded buffer variant)

```
interface Buffer<T> {
    // add item to buffer; block if full
    void put(T item);

    // remove item from buffer; block if empty
    T get();

    // number of items in buffer
    int count();
}
```

Producer-consumer: Desired properties

Producer-consumer problem: implement Buffer such that:

- producers and consumers access the buffer in mutual exclusion
- consumers block when the buffer is empty
- producers block when the buffer is full (bounded buffer variant)

Other properties that a good solution should have:

- support an arbitrary number of producers and consumers
- deadlock freedom
- starvation freedom

Producers and consumers

Producers and consumers continuously and asynchronously access the buffer, which must **guarantee** proper synchronization

```
Buffer<Item> buffer;
```

producer$_n$	consumer$_m$

`while (true) {`
`  // create a new item`
`  Item item = produce();`
`  buffer.put(item);`
`}`
	`while (true) {`
	`  Item item = buffer.get();`
	`  // do something with 'item'`
	`  consume(item);`
	`}`

Unbounded shared buffer

Solution based on one lock and one semaphore

```
public class UnboundedBuffer<T> implements Buffer<T> {
  Lock lock = new Lock(); // for exclusive access to buffer
  Semaphore nItems = new Semaphore(0); // number of items in buffer
  Collection storage = ...; // any collection (list, set, ...)
  invariant { storage.count() == nItems.count() + at(5,15-17); }
}
```

```
1  public void put(T item) {
2    lock.lock(); // lock
3    // store item
4    storage.add(item);
5    nItems.up();    // update nItems
6    lock.unlock(); // release
7  }
8
9  public int count() {
10   return nItems.count(); // locking here?
11 }
```

Signals to consumers waiting in **get** that they can proceed

```
12 public T get() {
13   // wait until nItems > 0
14   nItems.down();
15   lock.lock(); // lock
16   // retrieve item
17   T item =storage.remove();
18   lock.unlock(); // release
19   return item;
20 }
```

Buffer: method `put`

Can we execute **`up`** after **`unlock`**?

```java
public void put(T item) {
  lock.lock(); // lock
  // store item
  storage.add(item);
  nItems.up();    // update nItems
  lock.unlock(); // release
}

public int count() {
  return nItems.count(); // locking here?
}
```

Executing `up` after `unlock`:

- No effects on other threads executing `put`: they only wait for `lock`
- If a thread is waiting for `nItems > 0` in `get`: it does not have to wait again for `lock` just after it has been signaled to continue
- If a thread is waiting for the lock in `get`: it may return with the buffer in a (temporarily) inconsistent state (broken invariant, but <u>benign</u> because temporary)

Executing `up` after `unlock`

```
1  public void put(T item) {
2        lock.lock();
3        storage.add(item);
4        lock.unlock();
5        nItems.up();
6  }
```

```
7  public T get() {
8   nItems.down();
9   lock.lock();
10  T item =storage.remove();
11  lock.unlock();
12  return item;
13 }
```

Different numbers than original program

Temporary breaking of the invariant

Old invariant needs rewriting

OLD: `invariant { storage.count() == nItems.count() + at(5,15-17); }`

```
invariant {
storage.count() ==
nItems.count() + at(4,9-10);
}
```

\# elements in *buffer*

Value of *nItem* (semaphore counter)

\# threads in these locations

#	producer put	consumer get	SHARED
+1	pc_t : 3	pc_u : 8	nItems : 1 buffer : $\langle x \rangle$
+2	pc_t : 3	pc_u : 9	nItems : 0 buffer : $\langle x \rangle$
+3	pc_t : 4	pc_u : 9	nItems : 0 buffer : $\langle x, y \rangle$
+4	pc_t : 5	pc_u : 9	nItems : 0 buffer : $\langle x, y \rangle$
+5	pc_t : 5	pc_u : 10	nItems : 0 buffer : $\langle x, y \rangle$
+6	pc_t : 5	pc_u : 11	nItems : 0 buffer : $\langle y \rangle$
+7	pc_t : 5	pc_u : 12	nItems : 0 buffer : $\langle y \rangle$
+8	pc_t : 5	done	nItems : 0 buffer : $\langle y \rangle$
+9	done	done	nItems : 1 buffer : $\langle y \rangle$

Unbounded shared buffer

```
public class UnboundedBuffer<T> implements Buffer<T> {
  Lock lock = new Lock(); // for exclusive access to buffer
  Semaphore nItems = new Semaphore(0); // number of items in buffer
  Collection storage = ...; // any collection (list, set, ...)
  invariant { storage.count() == nItems.count() + at(5,15-17); }
}
```

```
1  public void put(T item) {
2    lock.lock(); // lock
3    // store item
4    storage.add(item);
5    nItems.up();    // update nItems
6    lock.unlock(); // release
7  }
8
9  public int count() {
10   return nItems.count(); // locking here?
11 }
```

```
12 public T get() {
13   // wait until nItems > 0
14   nItems.down();
15   lock.lock(); // lock
16   // retrieve item
17   T item =storage.remove();
18   lock.unlock(); // release
19   return item;
20 }
```

Buffer: method `get`

What happens if another thread gets the lock just after the current threads has decremented the semaphore `nItems`?

- If the other thread is a producer, it doesn't matter: as soon as `get` resumes execution, there will be one element in storage to remove

- If the other thread is a consumer, it must have synchronized with the current thread on `nItems.down()`, and the order of removal of elements from the buffer doesn't matter

Can we execute **`down`** after **`lock`**?

```
public T get() {
  // wait until nItems > 0
  nItems.down();
  lock.lock(); // lock
  // retrieve item
  T item =storage.remove();
  lock.unlock(); // release
  return item;
}
```

Buffer: method `get`

Executing `down` after `lock`:

- If the buffer is empty when locking, there is a deadlock!
  - Will not succeed executing `down()` since the buffer is empty: it blocks!

```java
public T get() {
   // wait until nItems > 0
   lock.lock(); // lock
   nItems.down();
   // retrieve item
   T item =storage.remove();
   lock.unlock(); // release
   return item;
}
```

Bounded shared buffer

Size of buffer

Two semaphores

```
public class BoundedBuffer<T> implements Buffer<T> {
  Lock lock = new Lock(); // for exclusive access to buffer
  Semaphore nItems = new Semaphore(0); // # items in buffer
  Semaphore nFree = new Semaphore(N);  // # free slots in buffer
  Collection storage = ...; // any collection (list, set, ...)
  invariant { storage.count() == nItems.count() +
              + at(6,13-15) == N - nFree.count() - at(4-6,16) ; }
```

```
1  public void put(T item) {
2   // wait until nFree > 0
3   nFree.down();
4   lock.lock(); // lock
5   // store item
6   storage.add(item);
7   nItems.up();    // update nItems
8   lock.unlock(); // release
9  }
```

May deadlock if swapped

OK to swap

```
10 public T get() {
11  // wait until nItems > 0
12  nItems.down();
13  lock.lock(); // lock
14  // retrieve item
15  T item = storage.remove();
16  nFree.up(); // update nFree
17  lock.unlock(); // release
18  return item;
19 }
```

May deadlock if swapped

OK to swap

Waiting on multiple conditions?

The operations offered by semaphores **do not support** waiting on multiple conditions (not empty and not full in our case) using **only** one semaphore

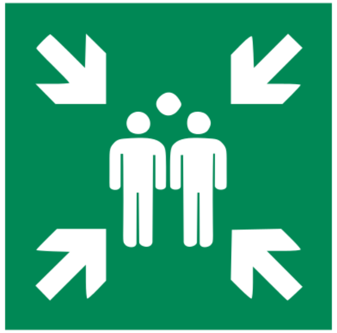
- Busy-waiting on the semaphore will **not** work:

```
  // wait until there is space in the buffer
  while (!(nItems.count() < N)) {};
  // the buffer may be full again when locking!
  lock.lock(); // lock
  // store item
  storage.add(item);
  nItems.up();    // update nItems
  lock.unlock(); // release
}
```

Barriers

Barriers (also called rendezvous)

A barrier is a form of synchronization where there is a point (the barrier) in a program's execution that all threads in a group have to reach **before** any of them is allowed to continue



A **solution** to the barrier synchronization problem for 2 threads with binary semaphores

```
Semaphore[] done = {new Semaphore(0), new Semaphore(0)};
```

t_0	t_1
`// code before barrier`	`// code before barrier`
`done[`t_0`].up();    // t done`	`done[`t_1`].up();    // u done`
`done[`t_1`].down(); // wait u`	`done[`t_0`].down(); // wait t`
`// code after barrier`	`// code after barrier`

Capacity 0 forces **up** before first **down**

up done unconditionally

down waits until the other tread has reaches the barrier

Barriers: variant 1

The solution still works if t_0 performs `down` before `up` – or, symmetrically, if t_1 does the same

```
Semaphore[] done = new Semaphore(0), new Semaphore(0);
```

t_0	t_1
`// code before barrier`	`// code before barrier`
`done[t1].down(); // wait u`	`done[t1].up();   // u done`
`done[t0].up();   // t done`	`done[t0].down(); // wait t`
`// code after barrier`	`// code after barrier`

This is, however, a bit <u>less efficient</u>: the last thread to reach the barrier has to stop and yield to the other (one more context switch)

Barriers: variant 2

Deadlock

The solution deadlocks if both t_0 and t_1 perform `down` before `up`

```
Semaphore[] done = new Semaphore(0), new Semaphore(0);
```

t_0	t_1
`// code before barrier`	`// code before barrier`
`done[`t_1`].down(); // wait u`	`done[`t_0`].down(); // wait t`
`done[`t_0`].up();   // t done`	`done[`t_1`].up();   // u done`
`// code after barrier`	`// code after barrier`

There is a circular waiting, because no thread has a chance to signal to the other that it has reached the barrier

Barriers with n threads (single use)

Keeping track of n threads reaching the barrier:

- `nDone`: number of threads that have reached the barrier
- `lock`: to update `nDone` atomically
- `open`: to release the waiting threads ("opening the barrier")

```
int nDone = 0; // number of done threads
Lock lock = new Lock(); // mutual exclusion for nDone
Semaphore open = new Semaphore(0); // 1 iff barrier is open
```

thread t_k

```
// code before barrier
lock.lock();                      // lock nDone
nDone = nDone + 1;                // I'm done
if (nDone == n) open.up();        // I'm the last: we can go!
lock.unlock();                    // unlock nDone
open.down();                      // proceed when possible
open.up();                        // let the next one go
// code after barrier
```

Total number of expected threads

Can we switch these?

Barriers with *n* threads (single use): variant

```
int nDone = 0; // number of done threads
Lock lock = new Lock(); // mutual exclusion for nDone
Semaphore open = new Semaphore(0); // 1 iff barrier is open
```

thread t_k

```
// code before barrier
lock.lock();                      // lock nDone
nDone = nDone + 1;                // I'm done
lock.unlock();                    // unlock nDone
if (nDone == n) open.up();        // I'm the last: we can go!
open.down();                      // proceed when possible
open.up();                        // let the next one go
// code after barrier
```

Can we open the barrier after `unlock`?

Such pairs of wait/signal are called **turnstiles**

- **In general**, reading a shared variable outside a lock may give an inconsistent value
- **In this case**, however, only after the last thread has arrived can any thread read `nDone == n`, because `nDone` is only incremented

Reusable barriers

```
interface Barrier {
  // block until expect() threads have reached barrier
  void wait();

  // number of threads expected at the barrier
  int expect();
}
```

Returned from

Reusable barrier: implement `Barrier` such that:

- a thread blocks on `wait()` until all threads have reached the barrier
- after `expect()` threads have executed `wait()`, the barrier is closed again

Threads at a reusable barrier

Threads continuously approach the barrier, and all synchronize their access at the barrier

```
Barrier barrier = new Barrier(n); // barrier for n threads
```

thread_k

```
while (true) {
  // code before barrier
  barrier.wait();   // synchronize at barrier
  // code after barrier
}
```

Reusable barriers: first attempt


```java
public class NonBarrier1 implements Barrier {
  int nDone = 0; // number of done threads
  Semaphore open = new Semaphore(0);
  final int n;

  // initialize barrier for `n' threads
  NonBarrier1(int n) {
    this.n = n;
  }

  // number of threads expected at the barrier
  int expect() {
    return n;
  }

  public void wait() {
    synchronized(this) {
      nDone += 1;           // I'm done
    }
    if (nDone == n)
      open.up();            // I'm the last arrived: All can go!

    open.down()             // proceed when possible
    open.up()               // let the next one go
    synchronized(this) {
      nDone -= 1;           // I've gone through
    }
    if (nDone == 0)
      open.down();          // I'm the last through: Close barrier!
  }
}
```

What if n threads "wait" here until `nDone` == n?

More than one thread may open the barrier (the first `open.up()`): this was not a problem in the non-reusable version, but now some threads may be executing `wait` again before the barrier is closed again!

What if n threads "wait" here until `nDone` == 0?

More than one thread may try to close the barrier (last `open.down()`): Deadlock!

Reusable barriers: second attempt

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```
public class NonBarrier2 implements Barrier {
  int nDone = 0; // number of done threads
  Semaphore open = new Semaphore(0);
  final int n;

  // initialize barrier for `n' threads
  NonBarrier2(int n) {
    this.n = n;
  }

  // number of threads expected at the barrier
  int expect() {
    return n;
  }

  public void wait() {
    synchronized(this) {
      nDone += 1;                             // I'm done
      if (nDone == n) open.up();              // open barrier
    }
    open.down()                               // proceed when possible
    open.up()                                 // let the next one go
    synchronized(this) {
      nDone -= 1;                             // I've gone through
      if (nDone == 0) open.down();            // close barrier
    }
  }
}
```

Is multiple signalling possible? No!

Anything else going wrong?

A fast thread may race through the whole method, and re-enter it before the barrier has been closed, thus getting ahead of the slower threads (still in the previous iteration of the barrier)

This is not prevented by strong semaphores: it occurs because the last thread through leaves the gate open (calls `open.up()`)

Reusable barriers: second attempt (cont'd)

```
1  public class NonBarrier2 {
2   public void wait() {
3     synchronized(this)
4     {nDone += 1;
5      if (nDone == n) open.up();}
6     open.down()
7     open.up()
8     synchronized(this)
9     {nDone -= 1;
10     if (nDone == 0) open.down();}
11 }
```

(a) All n threads are at 8, with `open.count() == 1`

(b) The fastest thread t_f completes `wait` and re-enters it with `nDone == n - 1`

(c) Thread t_f reaches 6 with `nDone == n`, which it can execute because `open.count() > 0`

(d) Thread t_f reaches 8 again, but it is one iteration ahead of all other threads!

Reusable barriers: Correct solution

Photo by Photnart: Heidelberg Lock, Germany

Reusable barriers: Correct solution

gate1 closed

gate2 open

```
public class SemaphoreBarrier implements Barrier {
  int nDone = 0; // number of done threads
  Semaphore gate1 = new Semaphore(0);// first gate
  Semaphore gate2 = new Semaphore(1);// second gate
  final int n;

  // initialize barrier for `n' threads
  SemaphoreBarrier(int n) {
    this.n = n;
  }

  // number of threads expected at the barrier
  int expect() {
    return n;
  }

  public void wait() { approach(); leave(); }
```

```
void approach() {
  synchronized (this) {
   nDone += 1;          // arrived
   if (nDone == n) {  // if last in:
     gate1.up();        // open gate1
     gate2.down();      // close gate2
   }
  }
  gate1.down(); // pass gate1
  gate1.up();   // let next pass
}

void leave() {
  synchronized (this) {
   nDone -= 1;          // going out
   if (nDone == 0) {  // if last out:
     gate2.up();        // open gate2
     gate1.down();      // close gate1
   }
  }
  gate2.down(); // pass gate2
  gate2.up();   // let next pass
}
```

Reusable barriers: improved solution

If the semaphores support adding n to the counter at once, we can write a barrier with fewer semaphore accesses

Both gates initially closed

```
public class NSemaphoreBarrier extends SemaphoreBarrier {
   Semaphore gate1 = new Semaphore(0);   // first gate
   Semaphore gate2 = new Semaphore(0);   // second gate

   void approach() {
     synchronized (this) {
      nDone += 1;
      if (nDone == n)
        gate1.up(n);
     }
     gate1.down(); // pass gate1
     // last thread here closes gate1
   }
```

Open gate1 for n threads

```
   void leave() {
     synchronized (this) {
      nDone -= 1;
      if (nDone == 0)
        gate2.up(n);
     }
     gate2.down();
     // last thread here closes gate2
   }
```

Open gate2 for n threads

Java semaphores support adding n to counter (`release(n)`)

Anyway, `up(n)` need not be uninterruptible, so we can also implement it with a loop

Readers-writers

Readers-writers: overview

Readers and writers concurrently access shared data:

- readers may execute concurrently with other readers, but need to exclude writers
- writers need to exclude both readers and other writers

The problem captures situations common in databases, filesystems, and other situations where accesses to shared data may be inconsistent

Readers-writers: The problem

```
interface Board<T> {
    // write message `msg' to board
    void write(T msg);
    // read current message on board
    T read();
}
```

Readers-writers problem: implement Board data structure such that:

- multiple reader can operate concurrently
- each writer has exclusive access

Invariant: #WRITERS = 0 ∨ (#WRITERS = 1 ∧ #READERS = 0)

Other properties that a good solution should have:

- support an arbitrary number of readers and writers
- no starvation of readers or writers

Readers and writers

Readers and writers continuously and asynchronously try to access the board, which must guarantee proper synchronization

```
Board<Message> board;
```

reader_n	writer_m

`while (true) {`
`  // read message from board`
`  Message msg = board.read();`
`  // do something with 'msg'`
`  process(msg);`
`}`
	`while (true) {`
	`  // create a new message`
	`  Message msg = create();`
	`  // write 'msg' to board`
	`  board.write(msg);`
	`}`

Readers-writers board: `write`

Solution based on one lock and one semaphore

```
public class SyncBoard<T> implements Board<T> {
  int nReaders = 0; // # readers on board
  Lock lock = new Lock(); // for exclusive access to nReaders
  Semaphore empty = new Semaphore(1); // 1 iff no active threads
  T message; // current message

  public T read() {
    lock.lock();          // lock to update nReaders
    if (nReaders == 0)    // if first reader,
      empty.down();       //              set not empty
    nReaders += 1;        // update active readers
    lock.unlock();        // release lock to nReaders

    T msg = message;      // read (critical section)

    lock.lock();          // lock to update nReaders
    nReaders -= 1;        // update active readers
    if (nReaders == 0)    // if last reader
      empty.up();         //              set empty
    lock.unlock();        // release lock to nReaders
    return msg;
  }
```

```
public void write(T msg) {
  // get exclusive access
  empty.down();
  message = msg; // write (cs)
  // release board
  empty.up();
}
```

invariant { nReaders == 0 ⟸ empty.count() == 1 }

`count()` becomes 1 after executing `empty.up()` and it happens that `nReaders = 0`

Properties of the readers-writers solution

We can check the following properties of the solution:

- `empty` is a binary semaphore
- when a writer is running, no reader can run
- one reader waiting for a writer to finish also locks out other readers
- a reader signals “empty” only when it is the last reader to leave the board
- deadlock is not possible (no circular waiting)

However, writers can starve: as long as readers come and go with at least one reader always active, writers are shut out of the board.

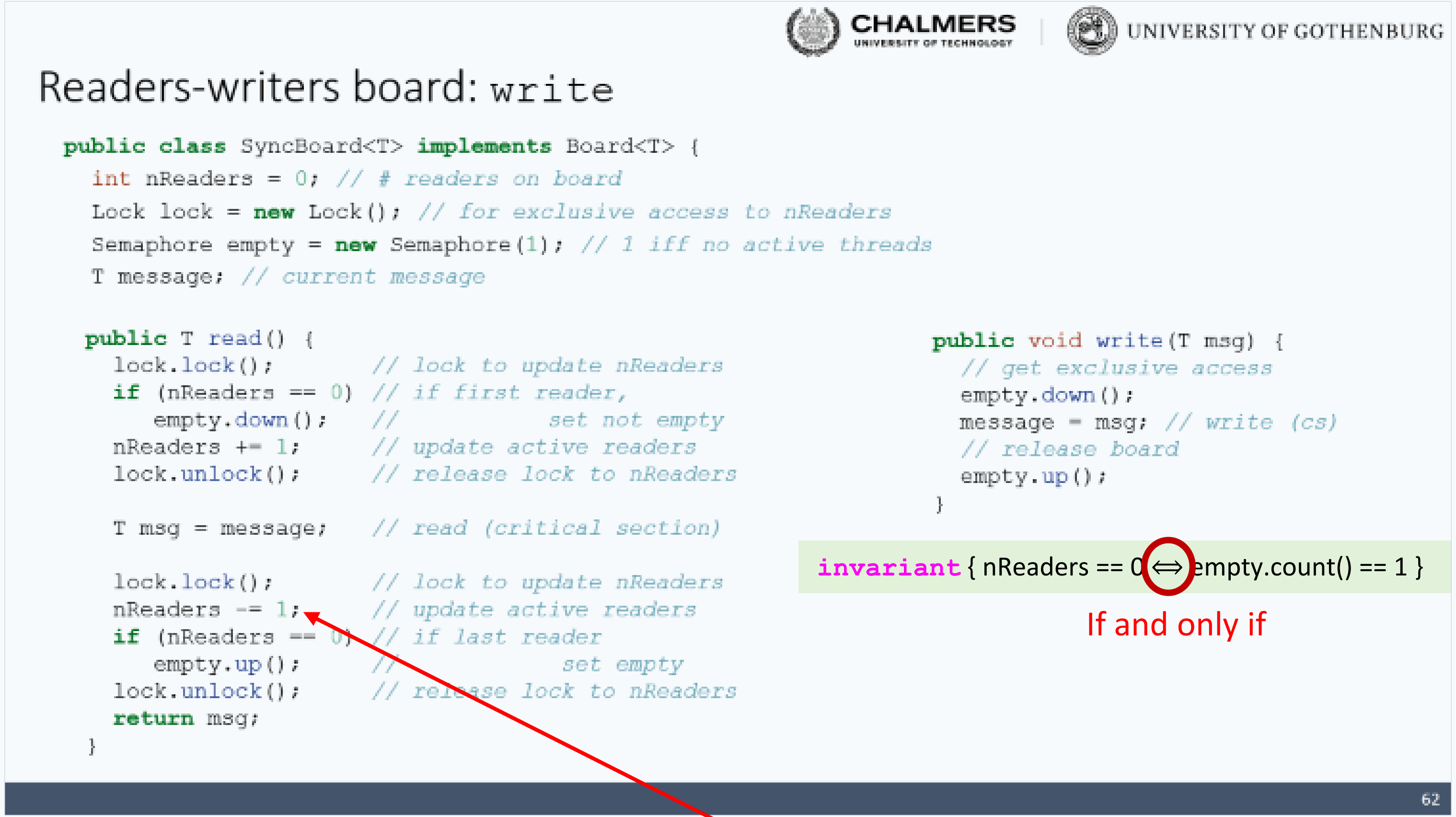
Readers-writers board without starvation

One additional semaphore

```
public class FairBoard<T> extends SyncBoard<T> {
  // held by the next thread to go
  Semaphore baton = new Semaphore(1, true); // fair binary sem.

  public T read() {
    // wait for my turn
    baton.down();
    // release a waiting thread
    baton.up();
    // read() as in SyncBoard
    return super.read();
  }

  public void write(T msg) {
    // wait for my turn
    baton.down();
    // write() as in SyncBoard
    super.write(msg);
    // release a waiting thread
    baton.up();
  }
```



Readers-writers board: `write`

```
public class SyncBoard<T> implements Board<T> {
  int nReaders = 0; // # readers on board
  Lock lock = new Lock(); // for exclusive access to nReaders
  Semaphore empty = new Semaphore(1); // 1 iff no active threads
  T message; // current message

  public T read() {
    lock.lock();           // lock to update nReaders
    if (nReaders == 0)     // if first reader,
      empty.down();        //          set not empty
    nReaders += 1;         // update active readers
    lock.unlock();         // release lock to nReaders

    T msg = message;       // read (critical section)

    lock.lock();           // lock to update nReaders
    nReaders -= 1;         // update active readers
    if (nReaders == 0)     // if last reader
      empty.up();          //          set empty
    lock.unlock();         // release lock to nReaders
    return msg;
  }

  public void write(T msg) {
    // get exclusive access
    empty.down();
    message = msg; // write (cs)
    // release board
    empty.up();
  }
```

invariant { nReaders == 0 ⟺ empty.count() == 1 }

If and only if

invariant breaks temporary here when `nReaders = 0`; just before calling `empty.up()`

Readers-writers board without starvation

```java
public class FairBoard<T> extends SyncBoard<T> {
  // held by the next thread to go
  Semaphore baton = new Semaphore(1, true); // fair binary sem.

  public T read() {
    // wait for my turn
    baton.down();
    // release a waiting thread
    baton.up();
    // read() as in SyncBoard
    return super.read();
  }

  public void write(T msg) {
    // wait for my turn
    baton.down();
    // write() as in SyncBoard
    super.write(msg);
    // release a waiting thread
    baton.up();
  }
```

Now writers do not starve:

- Suppose a writer is waiting that all active readers leave: it waits on `empty.down()` while holding the `baton`
- If new readers arrive, they are shut out waiting for the `baton`
- As soon as the active readers terminate and leave, the writer is signaled `empty`, and thus it gets exclusive access to the board

Readers-writers with priorities

The starvation free solution we have presented gives all threads the same priority: assuming a fair scheduler, writers and readers take turn as they try to access the board

In some applications it might be preferable to enforce difference priorities:

- $R = W$: readers and writers have the same priority (as in `FairBoard`)
- $R > W$: readers have higher priority than writers (as in `SyncBoard`)
- $W > R$: writers have higher priority than readers