Practical Concurrent and Parallel Programming III
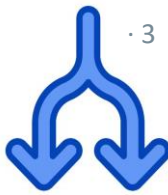
Shared Memory II

Raúl Pardo

Assignment workload

- We would like to get an estimation on the amount of hours you spend on assignments

- Please go to the following mentimeter poll

  https://www.menti.com/ale2q4ottxor

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- Readers and Writers Problem
- Monitors
- Fairness
- Java Intrinsic Locks (**synchronized**)
- Hardware and Programming Language Concurrency Issues

  - Visibility

  - Reordering
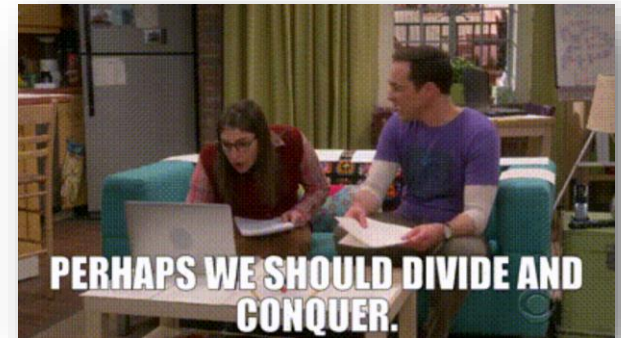- Volatile variables (**volatile**)

- Definitions of thread-safety
  - Classes
  - Programs
- Safe publication
- Immutability
- Instance confinement
- Synchronization primitives (synchronizers)
  - Semaphores
  - Barriers
- Producer-consumer problem

- We have already covered the basic concepts to analyse concurrent programs

- Analysing concurrent programs is tricky
  - You have experienced this already in the assignments where you work with programs consisting in a few lines of code

- Imagine having to reason about applications with hundreds of lines of code and many classes
  - Server applications
  - Operating Systems
  - GUIs
  - …

Thread safety

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  - …

PERHAPS WE SHOULD DIVIDE AND CONQUER.

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- It is more manageable to separately analyse parts of the code and then combine them in safe ways

- In Object Oriented languages (such as Java) we can focus on analysing thread-safety for classes

- This reduces the analysis to concurrent method calls and field accesses

Thread-safe classes

*A **class** is said to be **thread-safe** if and only if
no concurrent execution of
method calls or field accesses* <mark>*(read/write)*</mark>
<mark>*result in race conditions*</mark>

PCPP teaching team

*A **class** is said to be **thread-safe** if and only if
no concurrent execution of
method calls or field accesses (read/write)
result in race conditions*

Note that this definition is <u>independent of class invariants</u> as opposed to Goetz Chapter 4. This definition is more <u>similar to Goetz Chapter 2, page 18</u>.

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Thread-safe classes

WARNING: Note that, in this course, *thread-safety* is not an umbrella term for code that seem to behave correctly in concurrent environments.

*A **class** is said to be **thread-safe** if and only if*
no concurrent execution of
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*A concurrent **program** is said to be **thread-safe**
if and only if it is race condition free*

Do not confuse thread-safe classes with thread-safe programs.
Thread-safe programs are not defined in Goetz. But it is aligned
with the definition of correctly synchronized programs in JLS

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It is very important to note that:

For any program p,

p only accesses thread-safe <u>classes</u>
⇏
p is a thread-safe <u>program</u>

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For any program p,

$$p \text{ only accesses thread-safe } \underline{classes}$$
$$\nRightarrow$$
$$p \text{ is a thread-safe } \underline{program}$$

Programs using thread-safe classes may contain race conditions.

Thread-safety

It is very importa...

For any progr...

Does this hold?

p is a thread-safe <u>program</u>

$\not\Rightarrow$

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$\not\Rightarrow$

p is a thread-safe <u>program</u>

Programs using thread-safe classes
may contain race conditions.

Thread-safe classes

- To analyse whether a class is thread-safe, we must identify/consider:

  - Class state

  - Escaping

  - (Safe) publication

  - Immutability

  - Mutual exclusion

Class state

- As we have seen, (uncontrolled) concurrent access to the shared state (variables) may lead to race conditions

- So, the first thing we need to do is to identify the fields that may be shared by several threads

- The state of a class involves the fields defined in the class
  - In a nutshell, our goal is to ensure that concurrent manipulation of the class state is race condition free

```
class C {
    // class state (variables)
    T s1;
    T s2;
    T s3;
    T s4;
    …

    // class methods
    T m1(…) {…}
    T m2(…) {…}
    T m3(…) {…}
    …
}
```

Class state

If a class has no state (variables),
is it thread-safe?

- As we have seen, (uncontrolled) concurrent access to the shared state (variables) may lead to race conditions

- So, the first thing we need to do is to identify the fields that may be shared by several threads

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    …

    // class methods
    T m1(…) {…}
    T m2(…) {…}
    T m3(…) {…}
    …
}
```

```
class Counter {
     // class state (variables)
     int i=0;

     // class methods
     public synchronized void inc(){i++;}
}
```

Is the class `Counter` thread-safe?

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}
```

```
// program using Counter

Counter c = new Counter();
new Thread(() -> {
    c.inc();
}).start();


new Thread(() -> {
    c.i++; // escaped the lock in inc()
}).start();
```

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- It is important to not expose shared state variables

- Otherwise, threads may use them without proper locking
  - Thus, we allow several threads in the critical section

```
class Counter {
    // class state (variables)
    int i=0;

    // class methods
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- It is important to not expose shared state variables

- Otherwise, threads may use them without proper locking
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- Defining all (shared) class state (primitive) variables as private ensures that these variables will only be accessed through public methods.
  - Thus, it is easier to control and reason about concurrent access

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class Counter {
    // class state (variables)
    int i=0;

    // class methods
    public synchronized void inc(){i++;}
}
```

```
// program using Counter

Counter c = new Counter();
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```

```
class IntArrayList {
    // class state
    private List<Integer> a = new ArrayList<Integer>();

    public synchronized void set(Integer index, Integer elem)
        {  a.set(index,elem); }

    public synchronized List<Integer> get() { return a; }
}
```

Is the class `IntArrayList` thread-safe?

```java
class IntArrayList {
    // class state
    private List<Integer> a = new ArrayList<Integer>();

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}
```

```
IntArrayList array = new IntArrayList();
new Thread(() -> {
    array.set(0,1); // access state with lock
}).start();
new Thread(() -> {
    array.get().set(0,42); // access state without locks
}).start();
```

- Remember that when a method returns an object, we get a *reference* to that object

```
class IntArrayList {
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    private List<Integer> a = new ArrayList<Integer>();

    public synchronized void set(Integer index, Integer elem)
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- Therefore, even if obtain the reference using locks, later we can modify the content of the object without locks

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Is this *program* thread-safe?

- It is important to ensure that <u>initialization *happens-before* publication</u>
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public class UnsafeLazyInitialization {
    private static Resource resource;

    public static Resource getInstance() {
        if (resource == null)
            resource = new Resource();
        return resource;
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```

Is this class thread-safe?

- Visibility issues may appear during initialization of objects

```java
public class UnsafeInitialization {
    private int x;
    private Object o;
    public UnsafeInitialization() {
        x = 42;
        o = new Object();
    }
}
```

- Visibility issues may appear during initialization of objects


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```

- For the thread executing the constructor, there are no visibility issues, but if a reference to an instance of UnsafeInitialization object is accessible to another thread, it might not see **x==42** or **o** completely initialized

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- We can address visibility issues during initialization as follows

```java
public class UnsafeInitialization {
    private volatile int x;
    private final Object o;
    public UnsafeInitialization() {
        x = 42;
        o = new Object();
    }
}
```

- We can address visibility issues during initialization as follows

For primitive types, we can:
- Declare them as **volatile**
- Declare them as **final** (only works if the content is never modified)
- Initialize as the default value: 0. (only works if the default value is acceptable)
- Use corresponding atomic class from Java standard library: **AtomicInteger**

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For complex objects, we can:
- Declare them as **final**
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Object initialization & visibility

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Why do these solutions solve visibility issues?

- The previous suggestions ensure safe publication because:

  - They established a *happens-before* relation between initialization and access the object's reference (publication)
    - *A write to a volatile field happens-before every subsequent read of that field.*
    - *The default initialization (zero, false, or null) of any object happens-before any other actions of a program.*
    - *The initialization of a final field happens-before any other actions of a program (after the constructor has finished its execution)*

  - At the JVM level, the reason is that
    - `final` fields cannot be cached or reordered during initialization
    - All fields are initialized with default values during class loading
    - writes on `volatile` are flushed to main memory and reordered (during initialization)

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Defined by us from the JLS explanation. You can use for exercises in this course.

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If the constructor of the class leaks a reference of the object being constructed before it has completed its execution, then there is no happen-before relation with the accesses to final field

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Object initialization & visibility

NOTE: For clarity and simplicity, up to now, we did not take initialization concerns into account. But from now on we will.

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  - *A write to a volatile field happens-before every subsequent read of that field.*
  - *The default initialization (zero, false, or null) of any object happens-before any other actions of a program.*
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- An immutable object is one whose state cannot be changed after initialization

    - You can think of it as a constant
    - The **`final`** keyword in Java prevents modification of fields
        - Remember that variables assigned to an object only hold a reference to the object

- A immutable class is one whose instances are immutable objects

Immutability

- An immutable object is one whose state cannot be changed after initialization

  - You can think of it as a constant
  - The **`final`** keyword in Java prevents modification of fields
    - Remember that variables assigned to an object only hold a reference to the object

- A immutable class is one whose instances are immutable objects

Are immutable classes thread-safe?

Immutable class & `final`

Does defining all fields as `final` ensure that the class is immutable?

Does defining all fields as `final` ensure that the class is immutable?

If in a class, no fields are defined as `final`, is it possible to make it immutable?

Immutability

- To ensure thread-safety of immutable classes you simply need to make sure:
  - No fields can be modified after publication
  - Objects are safely published
  - Access to inner mutable object do not escape

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  - No fields can be modified after publication

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```java
public final class ThreeStooges {
  private final Set<String> stooges = new HashSet<String>();

  public ThreeStooges () {
    stooges.add("Moe");
    stooges.add("Larry");
    stooges.add("Curly");
  }

  public Boolean isStooge(String name) {
    return stooges.contains(name)
  }
}
```

Goetz p. 47

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  - No fields can be modified after publication

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  public Boolean isStooge(String name) {
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  }
}
```

Why is this class thread-safe?
(tip: there are 3 main reasons)

Goetz p. 47

- Whenever shared <u>mutable</u> state is accessed by several threads is must be protected by locks

Mutual exclusion

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> **Are Monitors a thread-safe class?**
> (when implemented as a class in OO languages)

- Whenever shared <u>mutable</u> state is accessed by several threads is must be protected by locks

> Are Monitors a thread-safe class?
> (when implemented as a class in OO languages)

> Is it always necessary to use locks in the methods of thread-safe classes?

- To analyse thread-safe in a class, we must identify/consider:
  - Identify the <u>class state</u>
  - Make sure that mutable class state does not <u>escape</u>
  - Ensure <u>safe publication</u>
  - Whenever possible define class state as <u>immutable</u>
  - If class <u>state</u> must be <u>mutable</u>, ensure <u>mutual exclusion</u>

Interesting section (4.5) on documenting synchronization in Goetz. Unfortunately, not widespread.

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- *Instance confinement* refers to encapsulating access to a thread-unsafe object into a thread-safe class

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```java
public class PersonSet {
  private final Set<Person> mySet = new HashSet<Person>();

  public synchronized void addPerson (Person p) {
    mySet.add(p);
  }

  public synchronized boolean contains(Person p) {
    return mySet.contains(p);
  }
}
```

Goetz p. 59

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Goetz p. 59

Why is this class thread-safe?

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Synchronized collections

- Java's standard library provides a method to convert ordinary collections in to "synchronized" collections
  - `synchronizedCollection(Collection<T> c)`, `synchronizedList(List<T> l)`, `synchronizedSet(Set<T> s)`, …, `synchronizedXXX(XXX<T> x)` with **XXX** a Java collection.

  - Internally, these methods turn all the methods in the collection into synchronized
  – That is, they use the instance lock

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Are synchronized collections thread-safe?

Let's look at the Javadoc
(https://docs.oracle.com/javase/8/docs/api/java/util/Collections.html#synchronizedList-java.util.List-)

p only accesses thread-safe <u>classes</u> ⇏ p is a thread-safe <u>program</u>

```
List<Integer> l = new ArrayList<Integer>();
List<Integer> lSync = Collections.synchronizedList(l);

…

new Thread(() -> { addIfAbsent(lSync,1); }).start();
new Thread(() -> { addIfAbsent(lSync,1); }).start();

…

public void addIfAbsent(List l, Integer e) {
  if (!l.contains(e))
    l.add(e);
}
```

Is this <u>program</u> thread-safe?

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Extending thread-safe classes

- Thread-safe classes may be extended to include compound actions
  - Intuitively, compound actions can be seen multiple method calls or field accesses within a critical section
  - A common examples are: *check-and-set,* iteration, navigation (*contains*)

```
public void addIfAbsent(List l, Integer e) {
  synchronized (l) {
    if (!l.contains(e))
      l.add(e);
  }
}
```

```
class ThreadSafeList {
  …
  public void synchronized addIfAbsent(T e) {
    if (!l.contains(e))
        l.add(e);
  }
  …
}
```

Thread uses the intrinsic lock of a synchronized collection

Thread-safe class is extended with a custom method to perform the action

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Other synchronization primitives (synchronizers)

Semaphores

- Semaphores are synchronization primitives that allow at most *c* number of threads in the critical section where *c* is called the *capacity*
  - First introduced by Dijkstra

- A semaphore consists of:
  - An integer capacity (*c*), permits in Java
    – Initial number of threads allowed in the critical section
  - A method **acquire()**
    – Checks if $c > 0$, if so, it decrements capacity by one (c--) and allows the calling thread to make progress, otherwise it blocks the thread
    – It is a blocking call
  - A method **release()**
    – It checks whether there are waiting threads, if so, it wakes up one of them, otherwise it increases the capacity by one (c++)
    – It is non-blocking

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> Semaphores (1968) appear before Monitors (1972)

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Semaphores

If we set the capacity of a semaphore to 1, does it behave like a lock?

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  - First introduced by Dijkstra

Semaphores (1968) appear before Monitors (1972)

- A semaphore consists of:
  - An integer capacity (*c*), permits in Java
    - Initial number of threads allowed in the critical section
  - A method `acquire()`
    - Checks if *c* > 0, if so, it decrements capacity by one (c--) and allows the calling thread to make progress, otherwise it blocks the thread
    - It is a blocking call
  - A method `release()`
    - It checks whether there are waiting threads, if so, it wakes up one of them, otherwise it increases the capacity by one (c++)
    - It is non-blocking

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Semaphores

> If we set the capacity of a semaphore to 1, does it behave like a lock?

- Semaphores are synchronization primitives that allow at most *c* number of threads in the critical section where *c* is called the
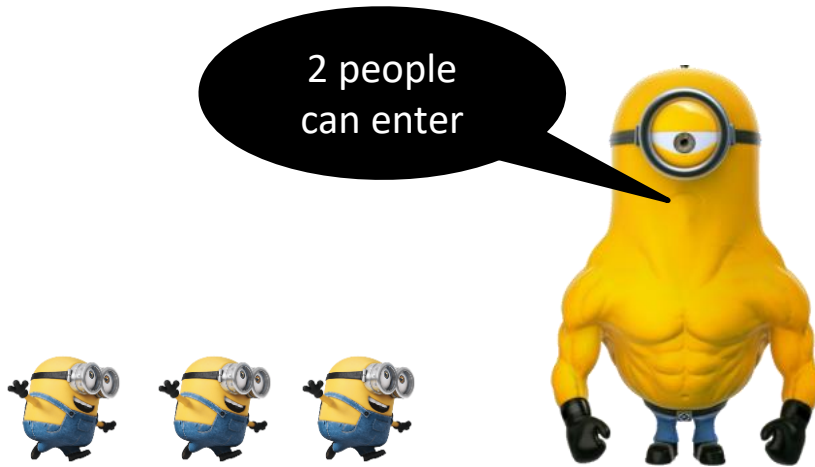
> Synchronization primitives that only allow one thread in the critical section are called **_mutex_** (which is short for mutual exclusion)

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- You can think of a semaphore as a "bouncer" to enter a critical section or to be allowed to used a shared resource

2 people can enter

CLUB BANANA

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Semaphores | Intuition

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1 people can enter

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0 people can enter

Semaphores | Example

- Semaphores are typically used to control the number of threads accessing a resource (here we fix a maximum 5 readers and writers)

```
ReadWriteMonitor m = new ReadWriteMonitor();
Semaphore semReaders = new Semaphore(5,true);
Semaphore semWriters = new Semaphore(5,true);
for (int i = 0; i < 10; i++) {
    // start a reader
    new Thread(() -> {
        m.readLock();
        semReaders.acquire();
        // read
        semReaders.release();
        m.readUnlock();
    }).start();

    // start a writer
    new Thread(() -> {
        m.writeLock();
        semWriters.acquire();
        // write
        semWriters.acquire();
        m.writeUnlock();
    }).start();
}
```

Java semaphores have a fair flag so that their entry queue prioritizes the longest waiting thread

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Does the semaphore make any difference for writers?

See **ReadersWritersSemaphore.java**

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Java semaphores have a fair flag so that their entry queue prioritizes the longest waiting thread

Do we need a semaphore to impose this constraint or can we implement it in the monitor?
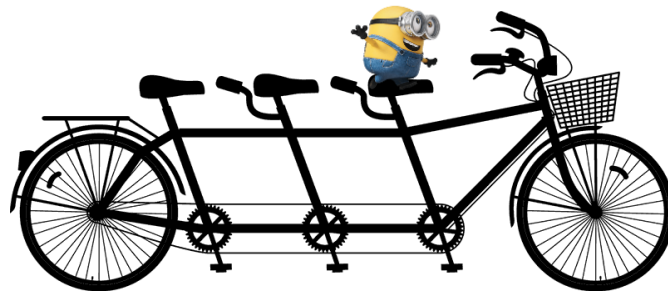
Does the semaphore make any difference for writers?

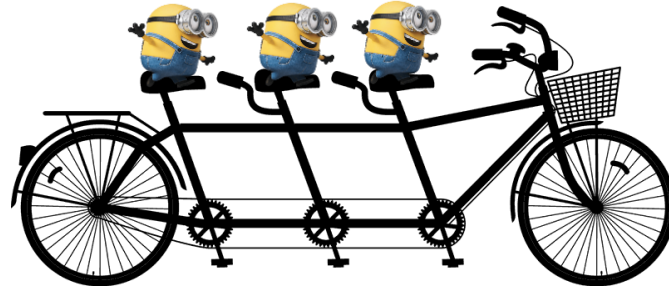See `ReadersWritersSemaphore.java`

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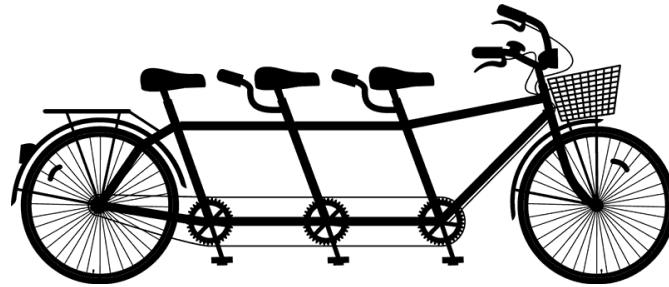
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- Barriers consists of
  - A number *parties* to wait for
  - A method `await()`
    – If the number of waiting threads is less than *parties*, then the calling thread blocks, otherwise all waiting threads wake up and the calling thread is allowed to make progress

- Java includes the class `CyclicBarrier`
  - After *parties* called `await()`, then the state is reset and the barrier behaves as initially

- Several threads are used to initialize an array (each a different position), the barrier is used for threads to know when the initialization is finished
    - This example is a bit artificial, but it illustrates the use of barriers.

```java
int parties       = 10;
CyclicBarrier cb   = new CyclicBarrier(parties);
int[] shared_array = new int[parties];
…
for (int i = 0; i < parties; i++) {
  new SetterClass(i).start();
}
…
public class SetterClass extends Thread {
  int index;
  public SetterClass(int index) {this.index = index;}

  public void run() {
    shared_array[index] = index+1;
    cb.await();
    // After this point the array is initialized and it is safe to read it
  }
}
```

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See **BarrierExample.java**

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  }
}
```

- Consider a shared data structure of fixed size from which threads may add and remove elements

- *Producer* threads may add elements to the structure as long as it is not full
  - If the structure is full and a producer tries to add an element, it must block until there an element is removed

- *Consumer* threads remove elements to the structure as long as it is not empty
  - If the structure is empty and a consumer tries to remove an element, then it must block until an element is added

- A good solution to the problem must be deadlock free and (possibly) starvation free

- Perhaps more intuitive example

Producers

Consumers

Shared data structure of fixed size

Producer-consumer problem

- The producer-consumer problem appears in many multi-threaded situates

  - Handling access to a shared bounded data structure

  - Controlling access to limited computational resources

  - E.g., thread pools

  - Asynchronous I/O operations

  - External devices may at as producers providing data to the system (keyboard, mouse, etc…), or consumer obtaining tasks to perform (IoT devices)

- Definitions of thread-safety

  - Classes

  - Programs

- Safe publication
- Immutability
- Instance confinement
- Synchronization primitives (synchronizers)

  - Semaphores

  - Barriers

- Producer-consumer problem