



# Practical Concurrent and Parallel Programming III

## Shared Memory II

Raúl Pardo

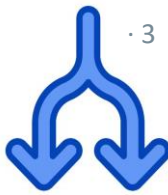
# Assignment workload



- 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>



# Previously on PCPP...



- Readers and Writers Problem
- Monitors
- Fairness
- Java Intrinsic Locks (**synchronized**)
- Hardware and Programming Language Concurrency Issues
  - Visibility
  - Reordering
- Volatile variables (**volatile**)

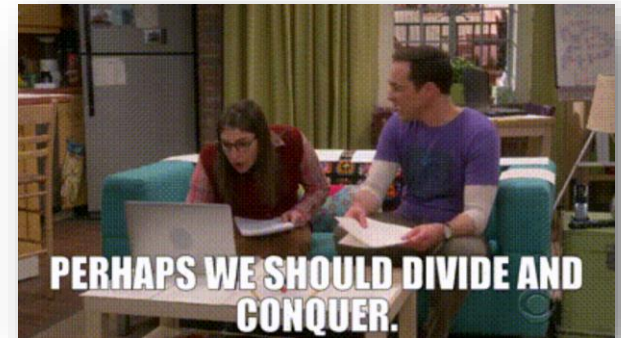


- Definitions of thread-safety
  - Classes
  - Programs
- Safe publication
- Immutability
- Instance confinement
- Synchronization primitives (synchronizers)
  - Semaphores
  - Barriers
- Producer-consumer problem



- 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
  - ...

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**PERHAPS WE SHOULD DIVIDE AND CONQUER.**

# Thread-safe classes



- 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



*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*

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no concurrent execution of  
method calls or field accesses (read/write)  
result in race conditions*

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

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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 method calls or field accesses (read/write) result in race conditions*

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

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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 classes*

$\Rightarrow$

*$p$  is a thread-safe program*

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Programs using thread-safe classes  
may contain race conditions.

# Thread-safety

.9

It is very important

For any program

Does this hold?

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Programs using thread-safe classes  
may contain race conditions.

- To analyse whether a class is thread-safe, we must identify/consider:
  - Class state
  - Escaping
  - (Safe) publication
  - Immutability
  - Mutual exclusion



- 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 (...) {...}  
    ...  
}
```



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
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    // class state (variables)  
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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?



```
class Counter {  
    // class state (variables)  
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## Is the class `Counter` thread-safe?



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class Counter {  
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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();
```



- 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

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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
- 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 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?



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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
- Therefore, even if obtain the reference using locks, later we can modify the content of the object without locks

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class IntArrayList {  
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Is this program thread-safe?



- It is important to ensure that initialization *happens-before* publication
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public class UnsafeLazyInitialization {  
    private static Resource resource;  
  
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Is this class thread-safe?

- Visibility issues may appear during initialization of objects

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

# Object initialization & visibility



- 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



- We can address visibility issues during initialization as follows

```
public class UnsafeInitialization {  
    private volatile int x;  
    private final Object o;  
    public UnsafeInitialization() {  
        x = 42;  
        o = new Object();  
    }  
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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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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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If the constructor of the class leaks a reference of the object being constructed before it has completed its execution, then there is no happens-before relation with the accesses to final field



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

- 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

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  - You can think of it as a constant
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    - Remember that variables assigned to an object only hold a reference to the object
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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?

- 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
  - Objects are safely published
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```
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
  - Objects are safely published
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    }  
  
    public Boolean isStooge(String name) {  
        return stooges.contains(name)  
    }  
}
```

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

Goetz p. 47

# Mutual exclusion



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- Whenever shared mutable state is accessed by several threads is must be protected by locks



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



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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 class state
  - Make sure that mutable class state does not escape
  - Ensure safe publication
  - Whenever possible define class state as immutable
  - If class state must be mutable, ensure mutual exclusion

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

# Instance confinement



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



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```
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



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

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public class PersonSet {  
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}
```

Goetz p. 59

Why is this class thread-safe?





- 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?



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

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 classes  $\nRightarrow p$  is a thread-safe program*



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*p only accesses thread-safe classes  $\nRightarrow$  p is a thread-safe program*



```
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);  
}
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*p only accesses thread-safe classes  $\nRightarrow$  p is a thread-safe program*



Is this program thread-safe?

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List<Integer> l = new ArrayList<Integer>();  
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new Thread(() -> { addIfAbsent(lSync, l); }).start();  
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```



- 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);  
    }  
}
```

Thread uses the intrinsic lock of a  
synchronized collection

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

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

## Other synchronization primitives (synchronizers)





- 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)



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

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    - 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

Semaphores (1968) appear before Monitors (1972)



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

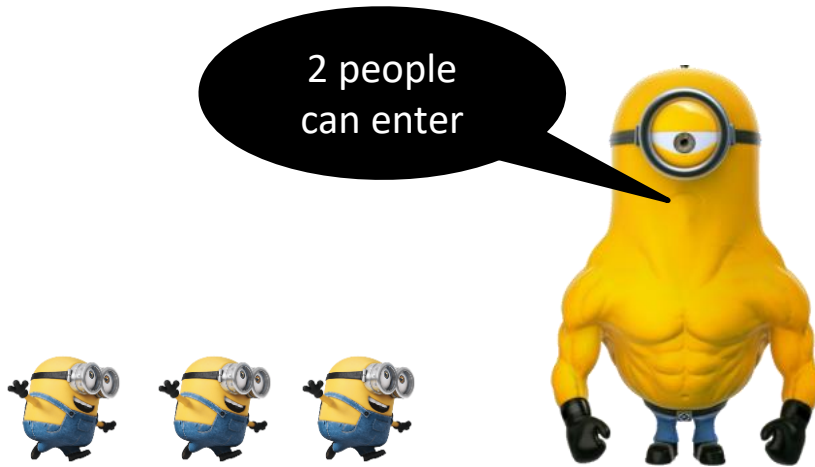
Synchronization primitives that only allow one thread in the critical section are called **mutex** (which is short for mutual exclusion)

Semaphores (1968) appear before Monitors (1972)

- 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 ( $c++$ )
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- You can think of a semaphore as a “bouncer” to enter a critical section or to be allowed to use a shared resource





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

Does the semaphore make any difference for writers?

See `ReadersWritersSemaphore.java`



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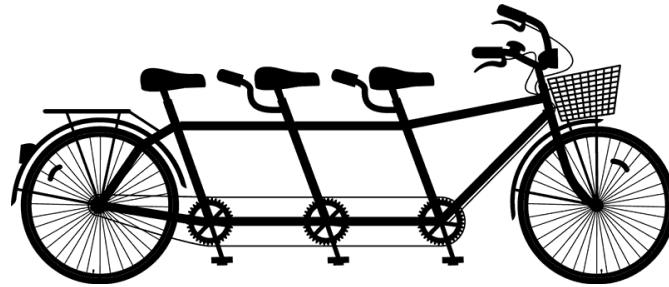
Do we need a semaphore to impose this constraint or can we implement it in the monitor?

Does the semaphore make any difference for writers?

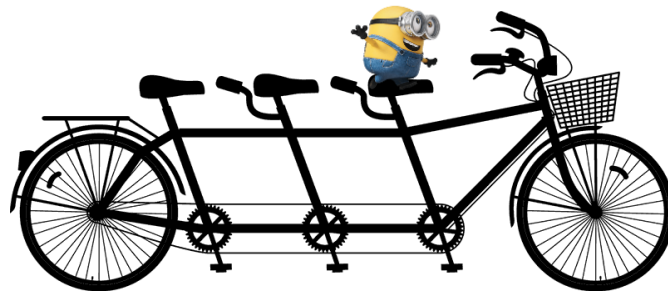
See `ReadersWritersSemaphore.java`

- *Barriers* are synchronization primitives used to wait until several threads reach some point in their computation

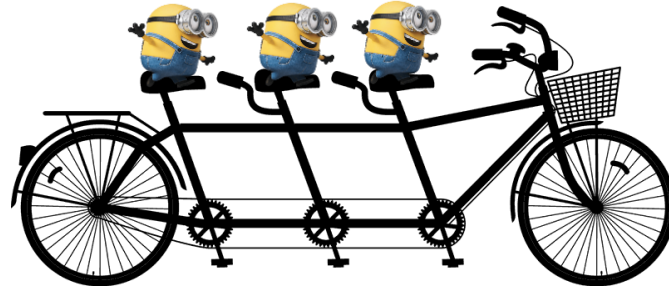
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- *Barriers* are synchronization primitives used to wait until several thread reach some point in their computation
- Barriers consists of
  - A number *parties* to wait for
  - A method **await()**
    - If the number of waiting threads is less than *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.

```
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`

# Producer-consumer problem



- 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

# Producer-consumer problem | Intuition



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- Perhaps more intuitive example

Consumers

Producers



Shared data structure of fixed size

- The producer-consumer problem appears in many multi-threaded situations
  - 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 act 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