# Parallel Programming
# Exercise Session 3

Spring 2025

# Today

Post-Discussion Exercise 2

Theory Recap

Quiz

Pre-Discussion Exercise 3

# Post-Discussion Exercise 2

# Task A

```
public static void taskA() {
    Thread t = new Thread(new Runnable() {
      @Override
      public void run() {
        System.out.println("Hello Thread!");
        System.out.println("Its printed from "+Thread.currentThread().getName());
      }
    });

    t.start();

    try {
      t.join();
    } catch (InterruptedException e) {
      e.printStackTrace();
    }
  }
```

# Task A

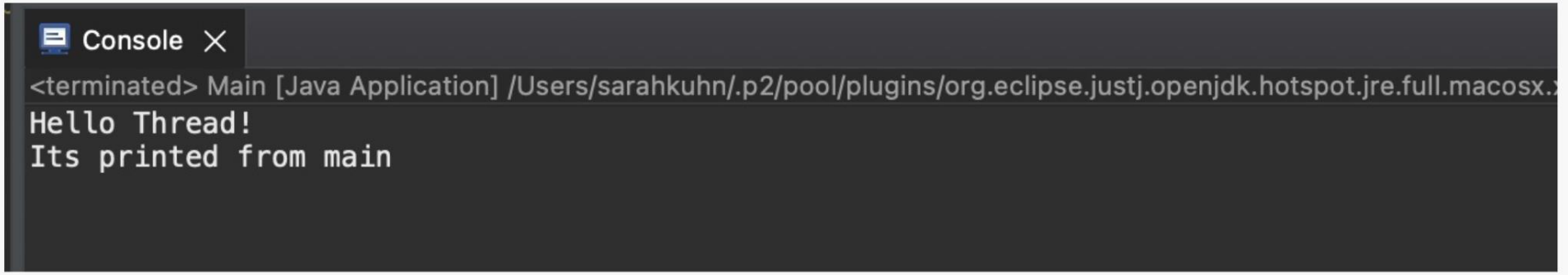
```
public static void taskA() {
    Thread t = new Thread(new Runnable() {
      @Override
      public void run() {
        System.out.println("Hello Thread!");
        System.out.println("Its printed from "+Thread.currentThread().getName());
      }
    });

    t.start();

    try {
      t.join();
    } catch (InterruptedException e) {
      e.printStackTrace();
    }
  }
```

What happens if we change t.start() to t.run()?

# Task A

t.start();


t.run();



# Task B

Run computePrimeFactors: main thread vs. single other thread

- There should not be any noticeable difference

What about Overhead?

- Overhead of a single Thread is not significant
- Use a lot of threads → Overhead sums up → Overhead takes up noticeable amount

# Task C: Thread with no Task

```java
public static class EmptyTask implements Runnable{

  @Override
  public void run() {}

}

public static long taskC() {
  long start = System.nanoTime();
  Thread t = new Thread(new EmptyTask());
  t.start();
  long end = System.nanoTime();
  return (end-start);
 }
```

# Task C: Thread with no Task

```
public static long taskC() {
  long start = System.nanoTime();
  Thread t = new Thread(); //no Task!
  t.start();
  long end = System.nanoTime();
  return (end-start);
 }
```

# Task D

```
public static class ArraySplit {
    public final int startIndex;
    public final int length;

    ArraySplit(int startIndex, int length) {
        this.startIndex = startIndex;
        this.length = length;
    }
}
```

# Task D

```java
public static ArraySplit[] PartitionData(int length, int numPartitions) {
    ArraySplit[] partitions = new ArraySplit[numPartitions];

    int chunkSize = Math.max(a:1, length / numPartitions);
    int assignedInput = 0;
    for (int i = 0; i < numPartitions; i++) {
        int reimainingInput = length - assignedInput;
        int inputSize = Math.min(chunkSize, reimainingInput);
        if (i == numPartitions - 1) {
            inputSize = reimainingInput;
        }
        partitions[i] = new ArraySplit(assignedInput, inputSize);

        assignedInput += inputSize;
    }

    return partitions;
}
```

# Task D: PartitionData

In real world: use existing libraries. well tested, concise, fast (e.g. parallel streams for Java)

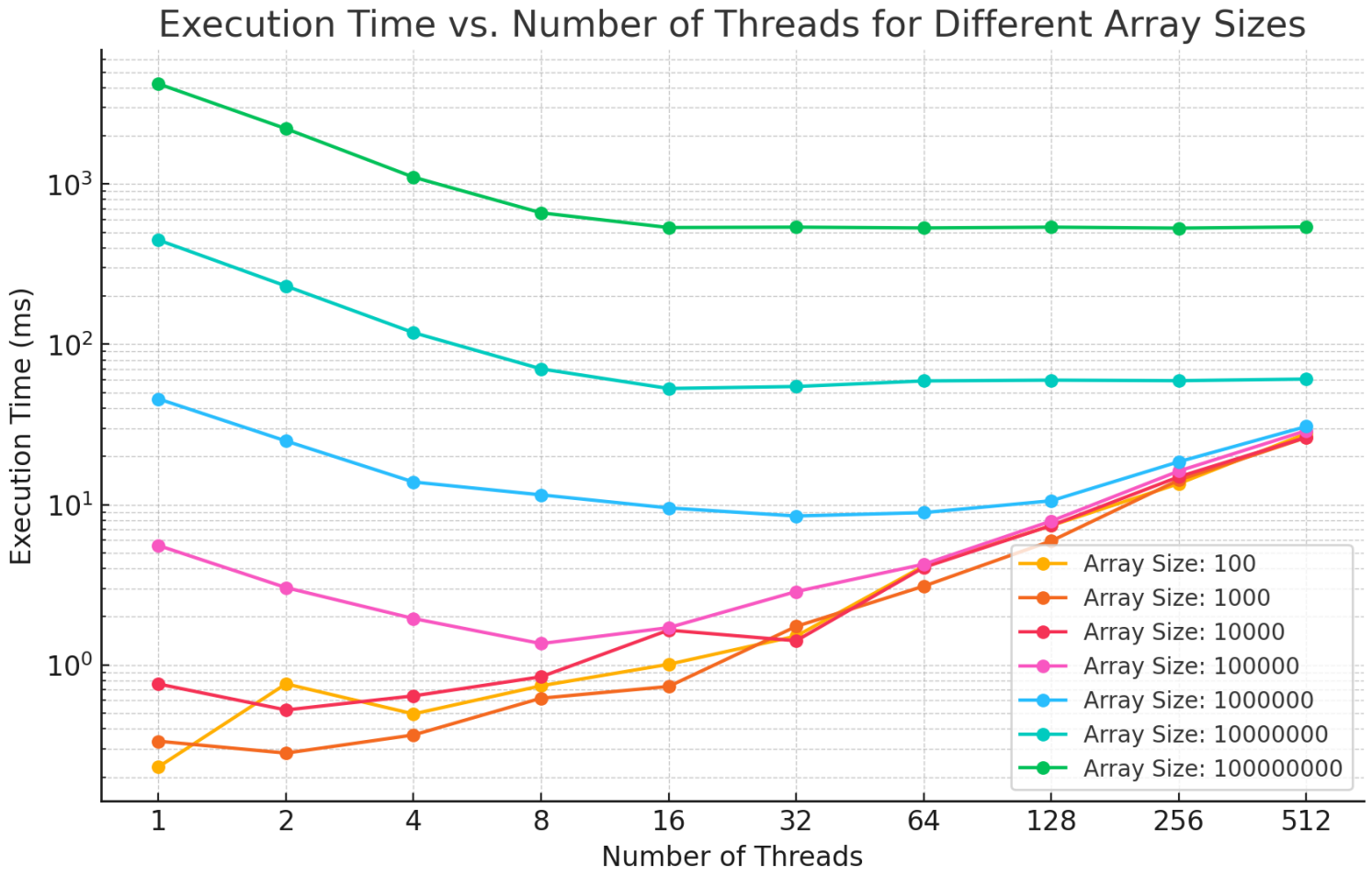
Think about edge cases: What if more Threads than values?

# Task E: Sharing Data Across Threads

demo `SharedData`

(need this for E)

# Task F: Execution Speed-Up




Experiment done on CPU with 16 cores available.

# Task F: Execution Speed-Up

**Small arrays**: increasing number of threads does not improve performance due to thread management overhead.

**Large arrays**: speed-up converges with a certain number of threads.

At very high thread counts, overhead dominates, causing execution time to increase.

# Theory Recap

# Counter

Let’s count the number of times a given event occurs

```
public interface Counter {
  public void increment();
  public int value();
}
```

# Counter

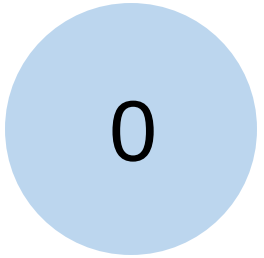
Let’s count the number of times a given event occurs

```
public interface Counter {
  public void increment();
  public int value();
}
```

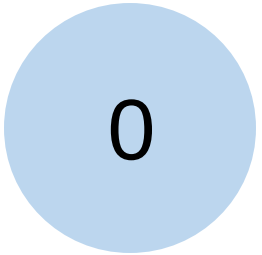
```
// background threads
for (int i = 0; i < numIterations; i++) {
  // perform some work

  counter.increment();
}

// progress thread
while (isWorking) {
  System.out.println(counter.value());
}
```

10 iterations each

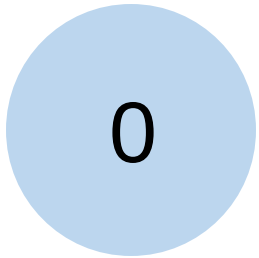
Thread 1



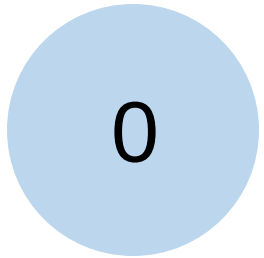

Counter




Thread 2



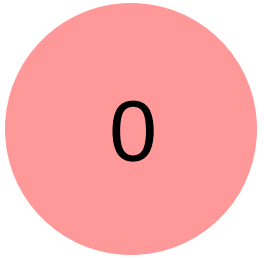

Thread 3



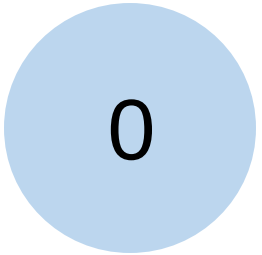

value of the
shared Counter

number of times
`increment()` is called

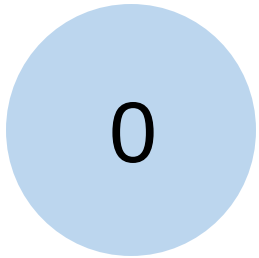
Thread 1



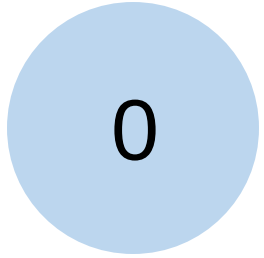

Counter




Thread 2

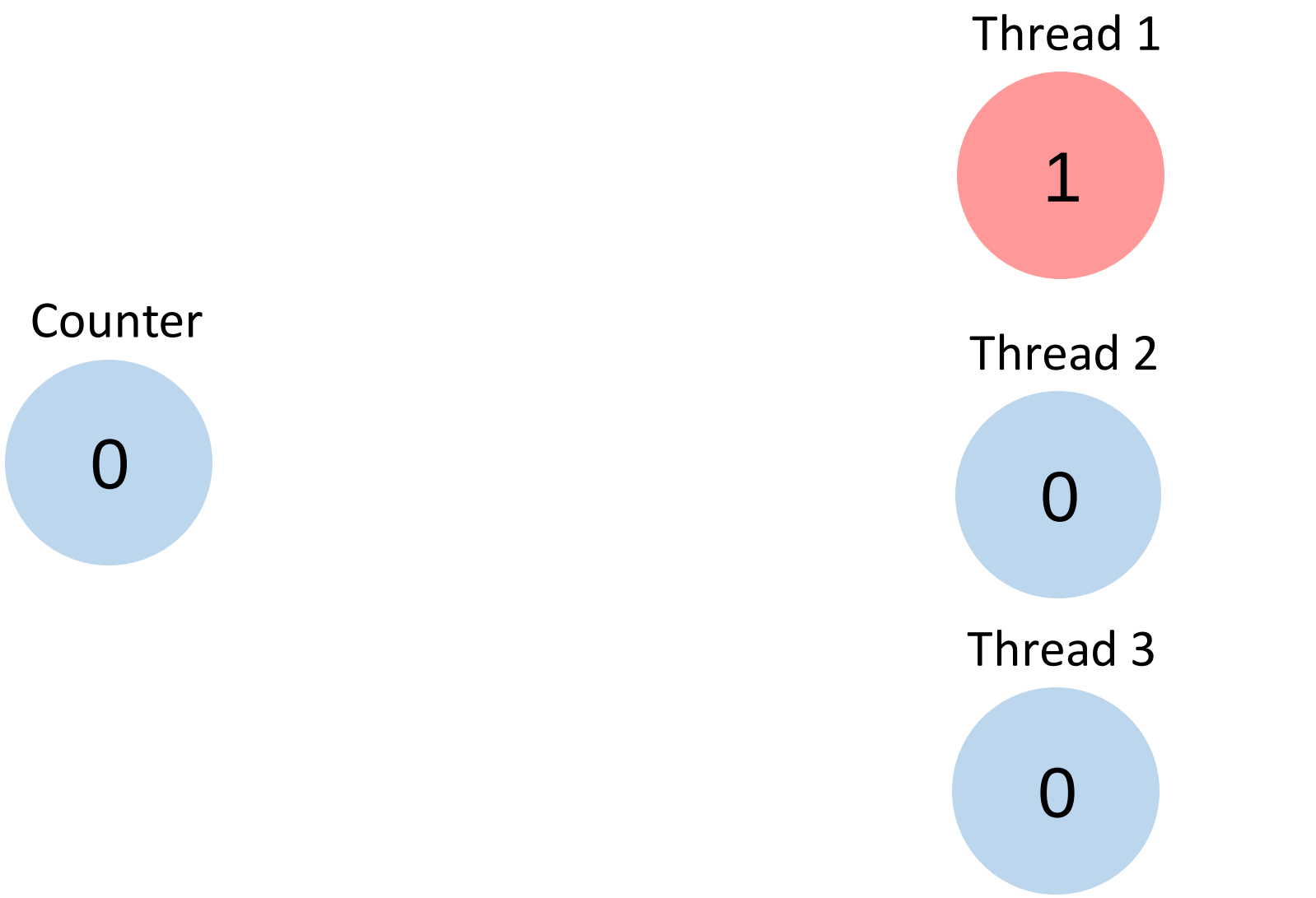


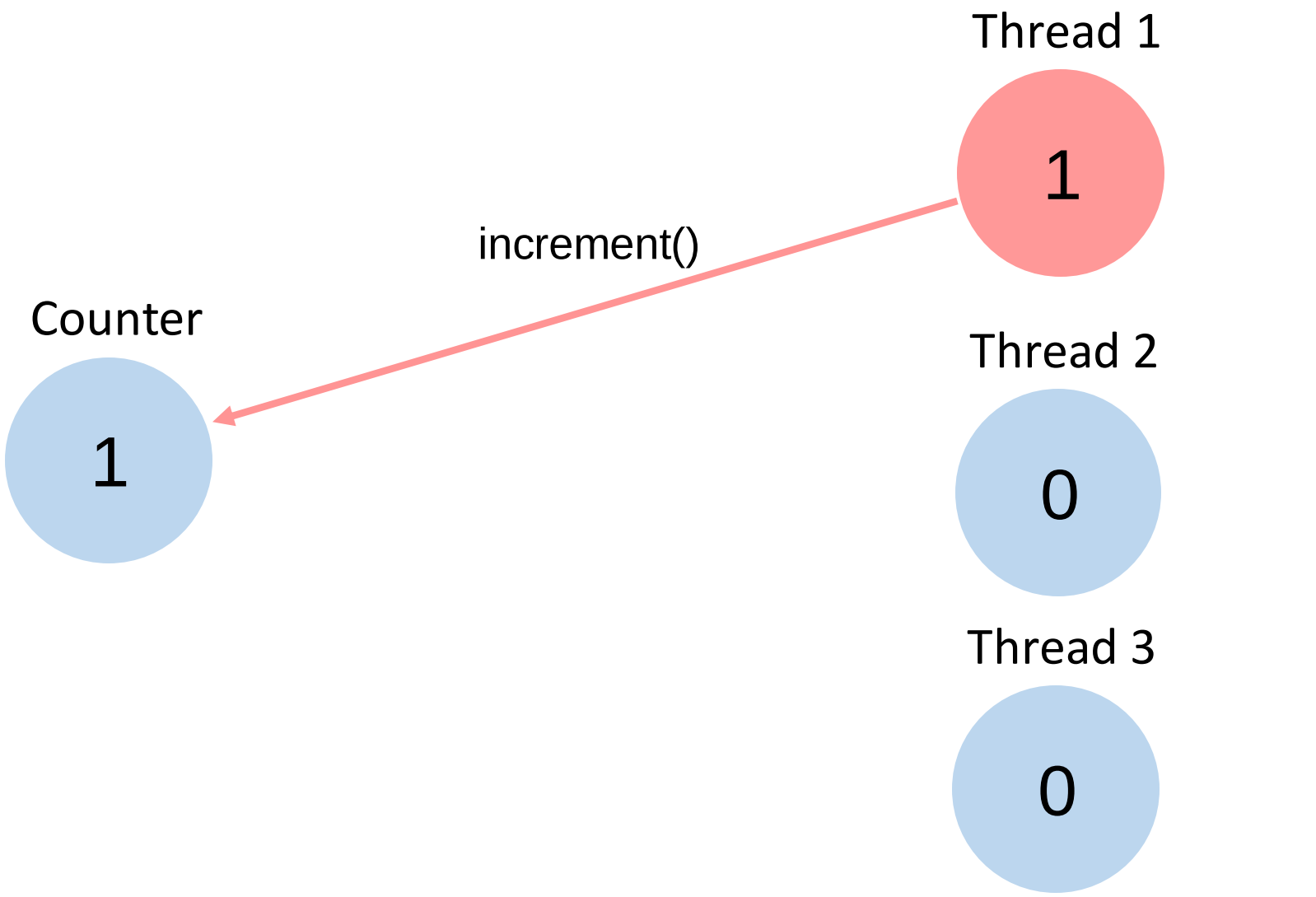

Thread 3

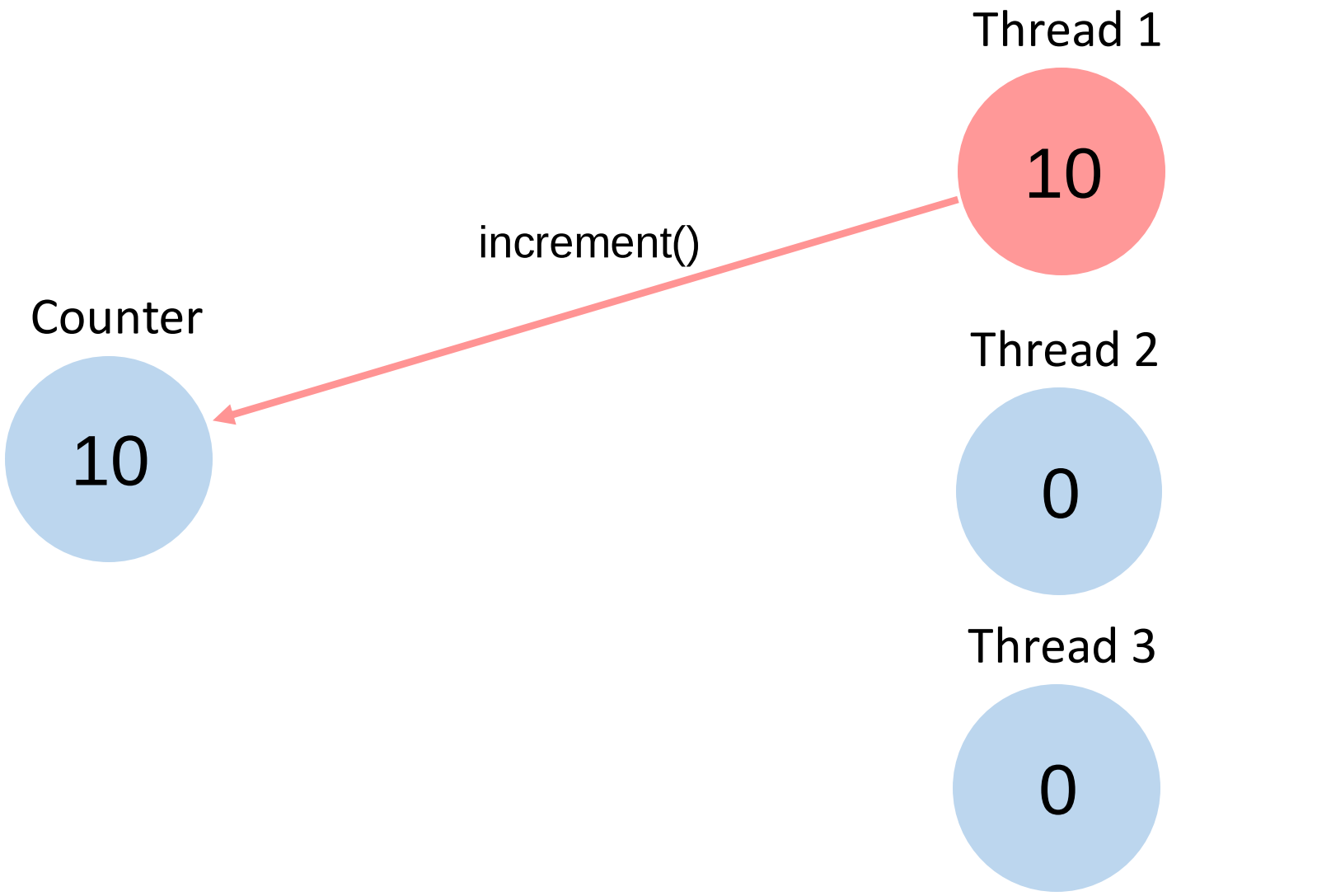


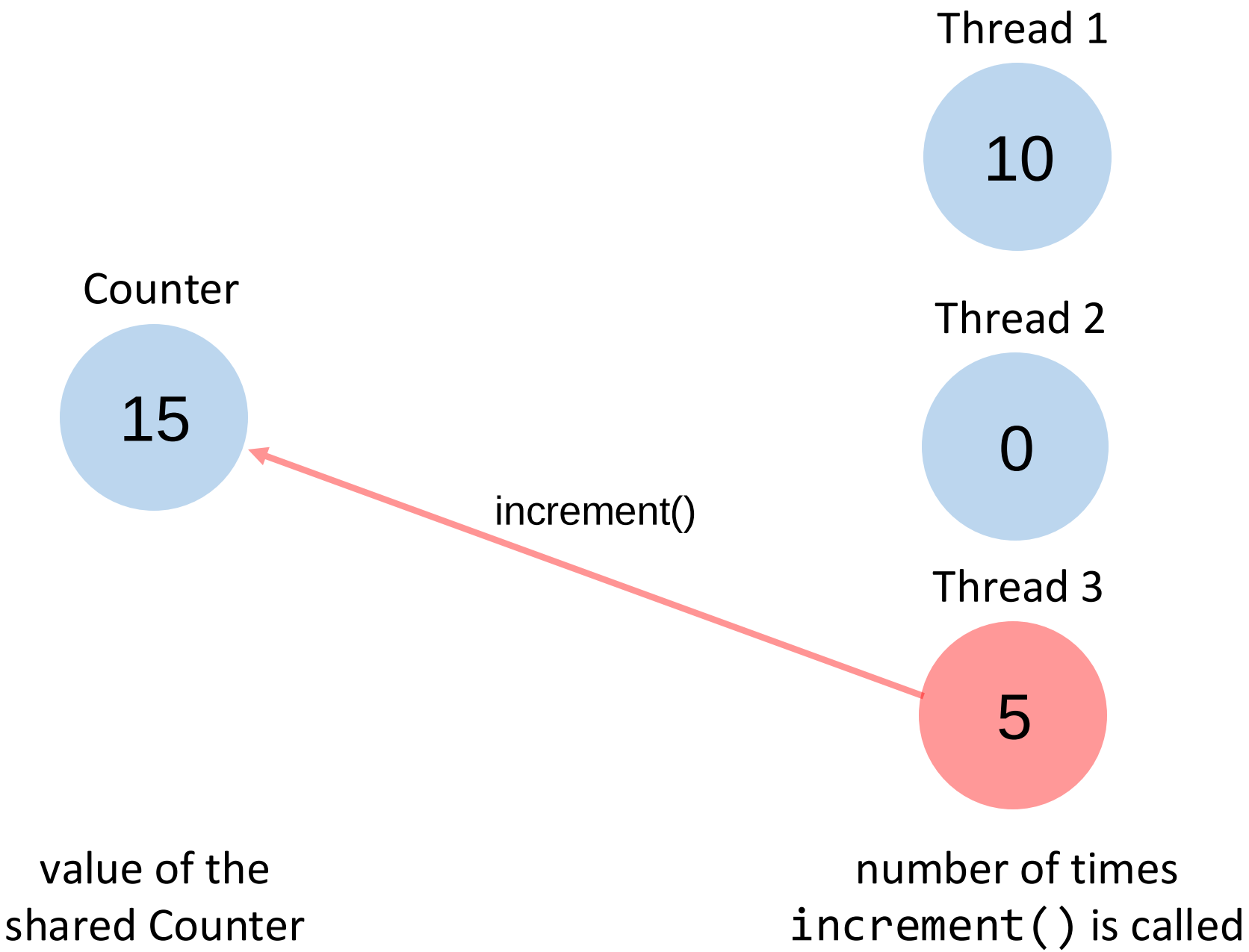

value of the
shared Counter

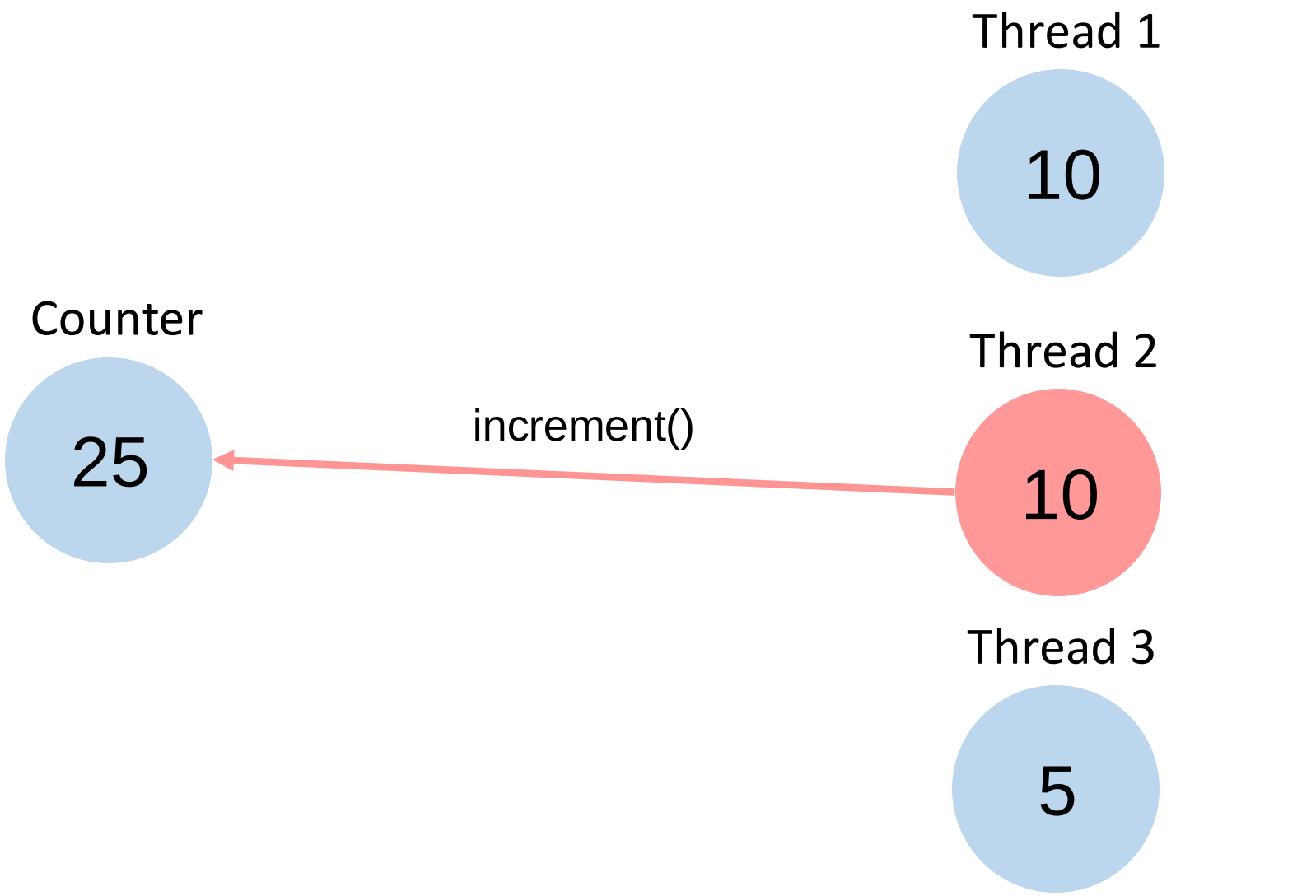
number of times
`increment()` is called

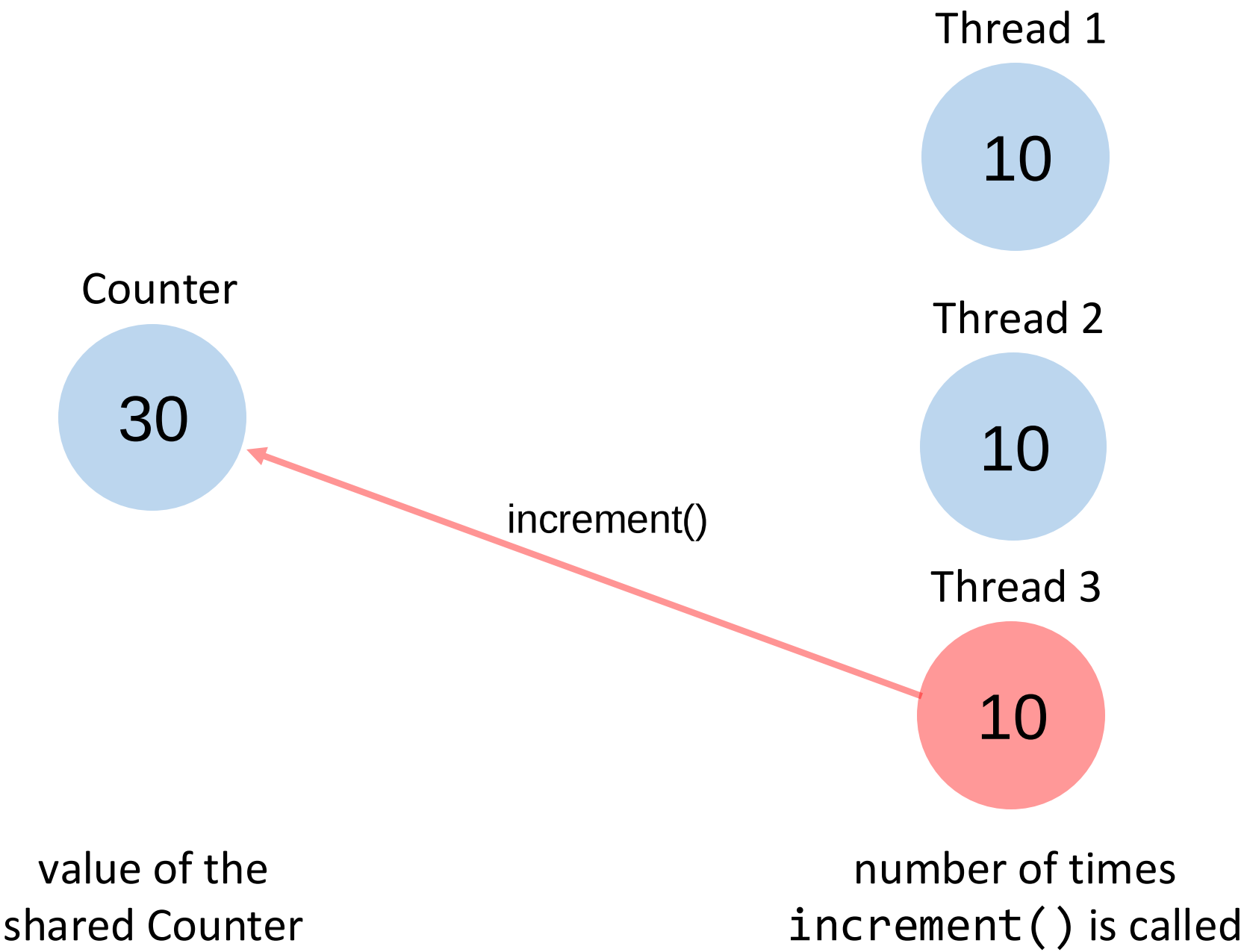

Thread 1
1
Counter
0
Thread 2
0
Thread 3
0
value of the
shared Counter
number of times
increment() is called

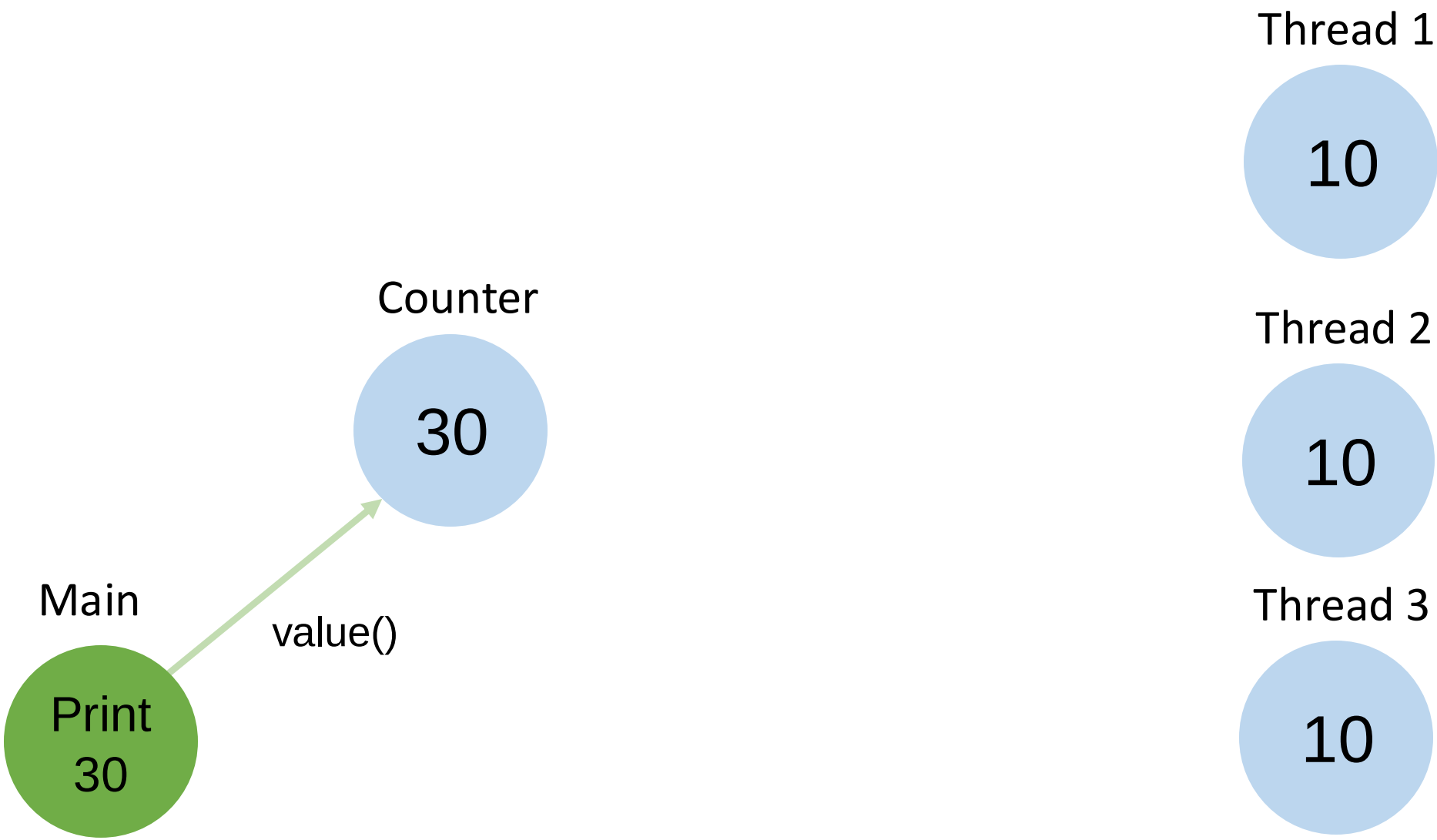

Thread 1
1
increment()
Counter
1
Thread 2
0
Thread 3
0
value of the
shared Counter
number of times
increment() is called


Thread 1
10
increment()
Counter
10
Thread 2
0
Thread 3
0
value of the
shared Counter
number of times
increment() is called


Thread 1
10
Counter
15
Thread 2
0
increment()
Thread 3
5
value of the
shared Counter
number of times
increment() is called


Thread 1
10
Counter
25
increment()
Thread 2
10
Thread 3
5
value of the
shared Counter
number of times
increment() is called


Thread 1
10
Counter
30
Thread 2
10
increment()
Thread 3
10
value of the
shared Counter
number of times
increment() is called




read the Counter value

value of the shared Counter

number of times `increment()` is called

# Counter

Why will what we just saw probably not work?

# Remember: Data Races

Assume we have two threads executing increment() n-times concurrently.

```
public class Counter {
  int count = 0;

  public void increment() {
     count++;
  }
}
```

# Data Race

count == 0

| **Thread A** | **Thread B** |
| --- | --- |
| Read count == 0 | |
| tmp = count + 1 | |
| | Read count == 0 |
| count = tmp | |
| | tmp = count + 1 |
| | count = tmp |

count == 1

# Synchronization

- ➔ Every reference type contains a lock inherited from the Object class
- ➔ Primitive fields can be locked only via their enclosing objects
- ➔ Locking arrays does not lock their elements
- ➔ A lock is *automatically* acquired when entering and released when exiting a synchronized block
- ➔ ***Locks will be covered in more detail later in the course***

# Synchronization

```
public synchronized void xMethod() {
  // method body
}
```

```
public void xMethod() {
  synchronized (this) {
    // method body
  }
}
```

➔ Synchronized method locks the object owning the method

`foo.xMethod() //lock on foo`

➔ Synchronized keyword obtains a lock on the parameter object

`synchronized (bar) { … } //lock on bar`

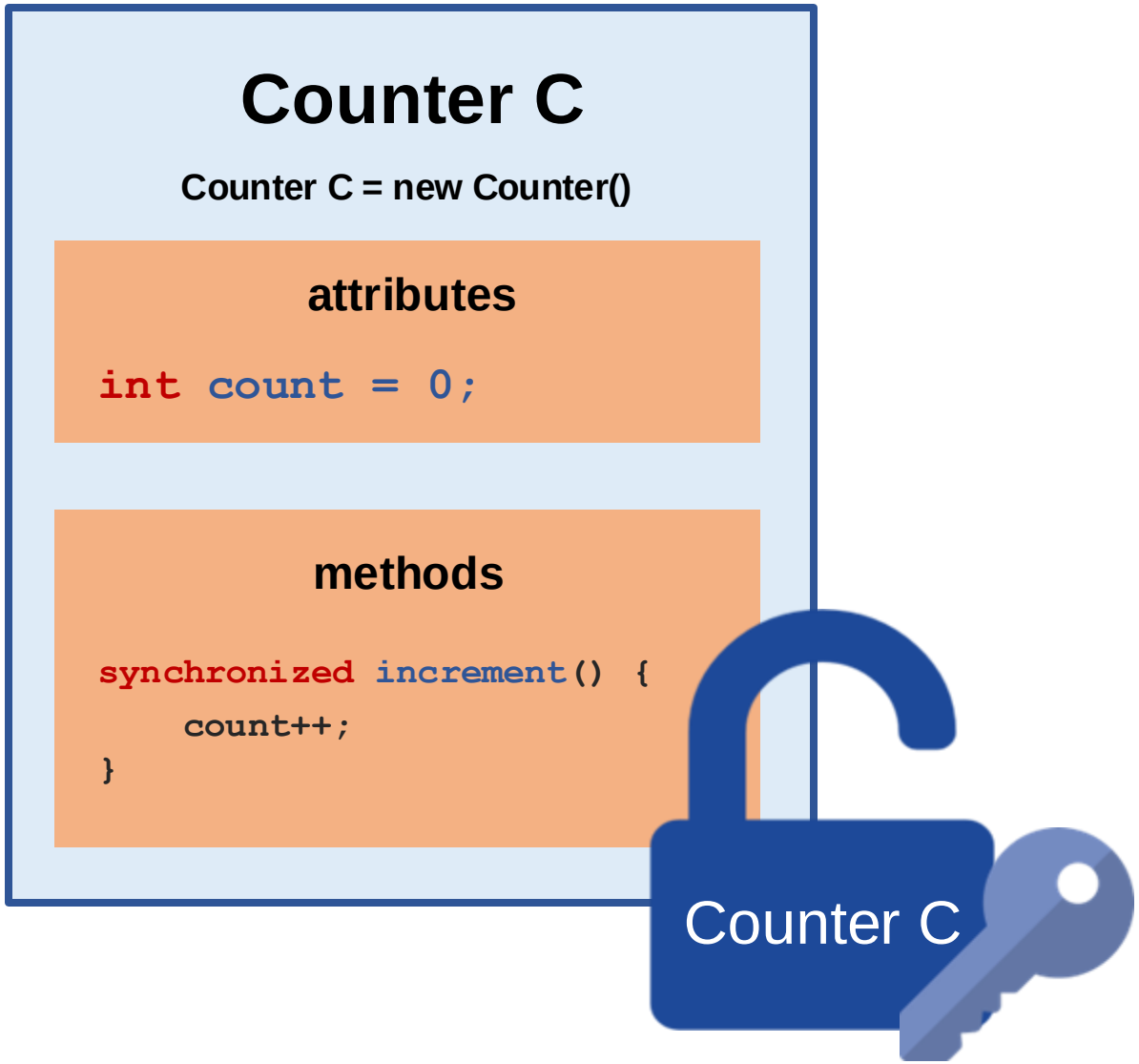
➔ A thread can obtain multiple locks (by nesting the synchronized blocks)

# Using `synchronized`

Now only one thread at a time can enter the increment() method ☺

```
public class Counter {
  int count = 0;

  public synchronized void increment() {
     count++;
  }
}
```

# What exactly is a lock/monitor?

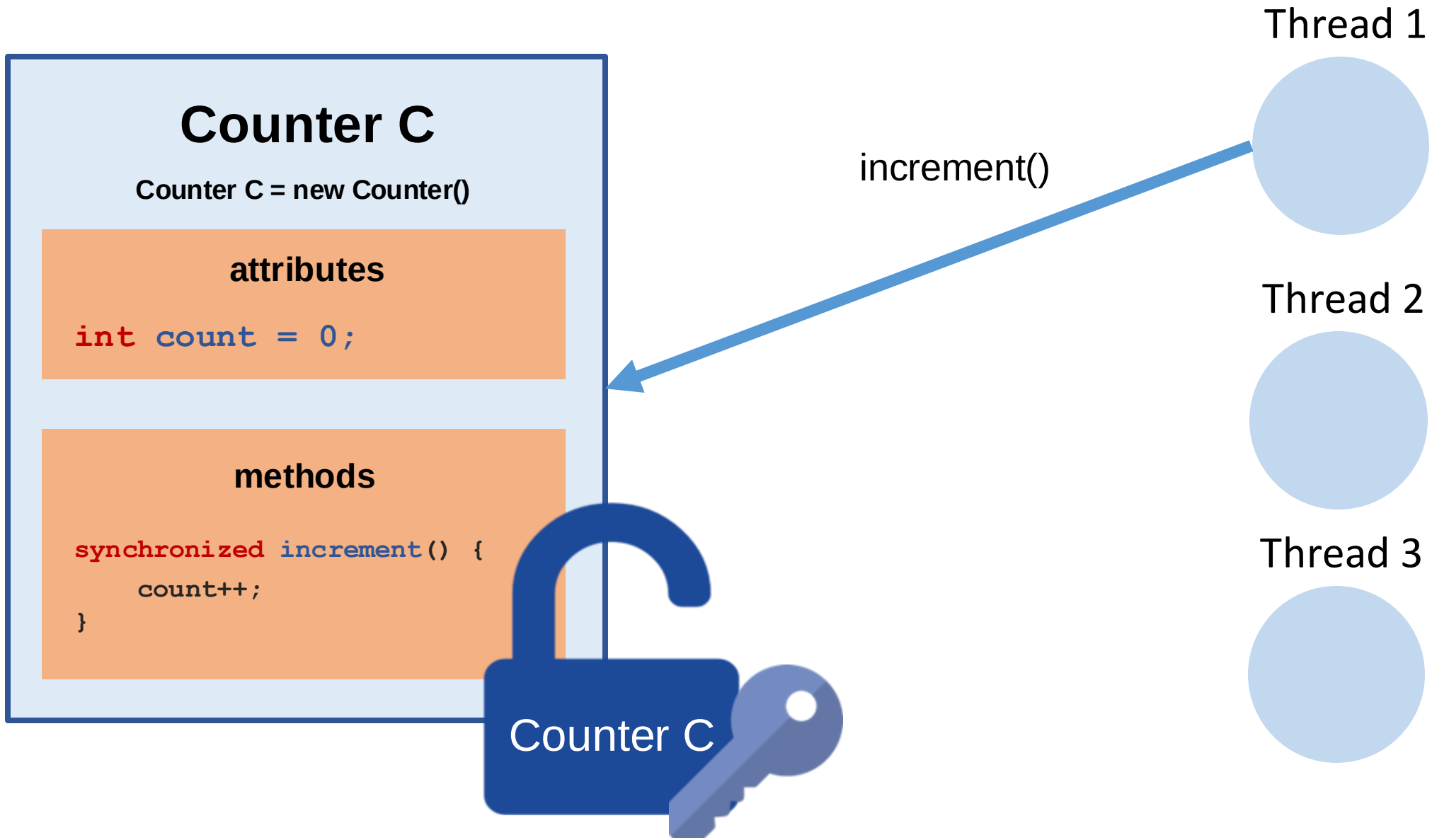



Thread 1

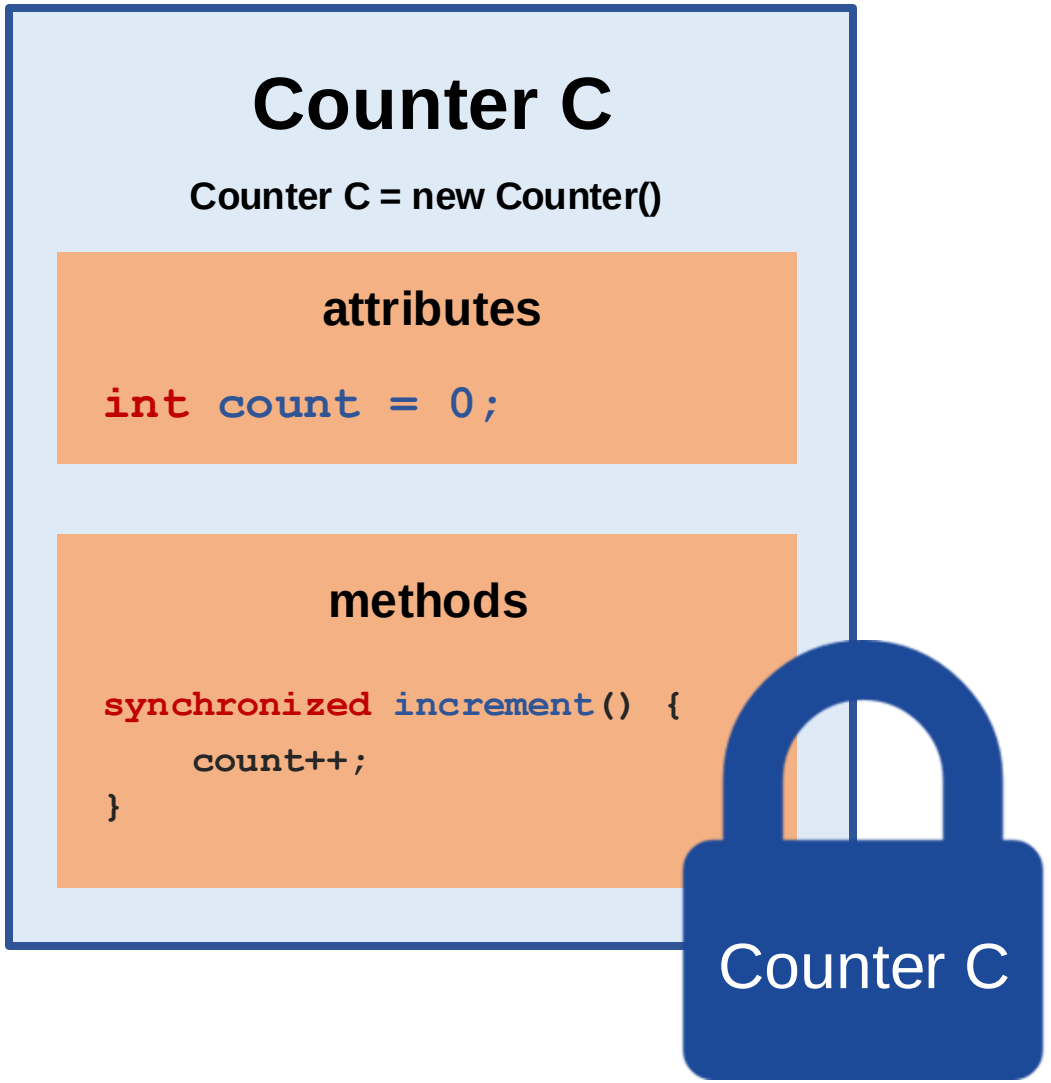
Thread 2

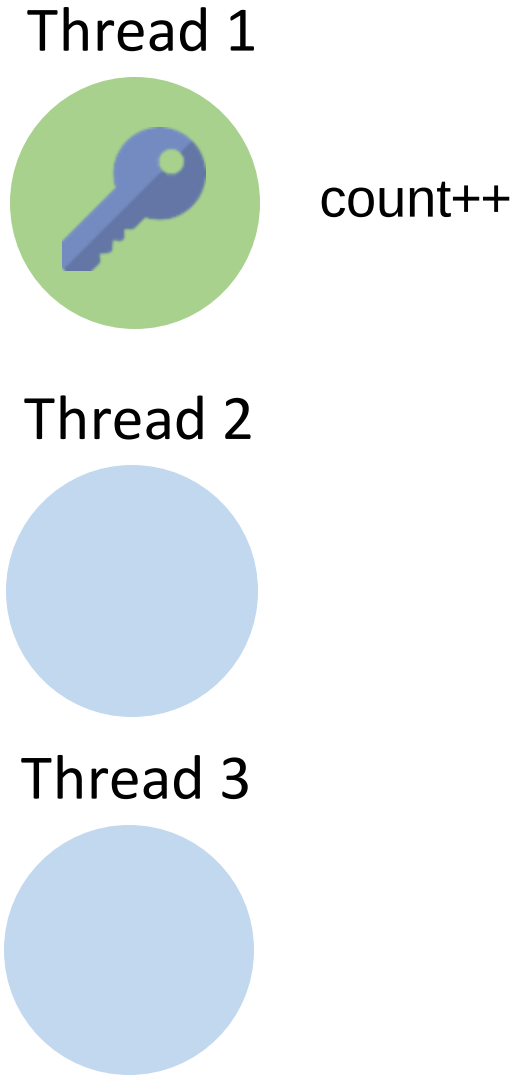
Thread 3

# What exactly is a lock/monitor?

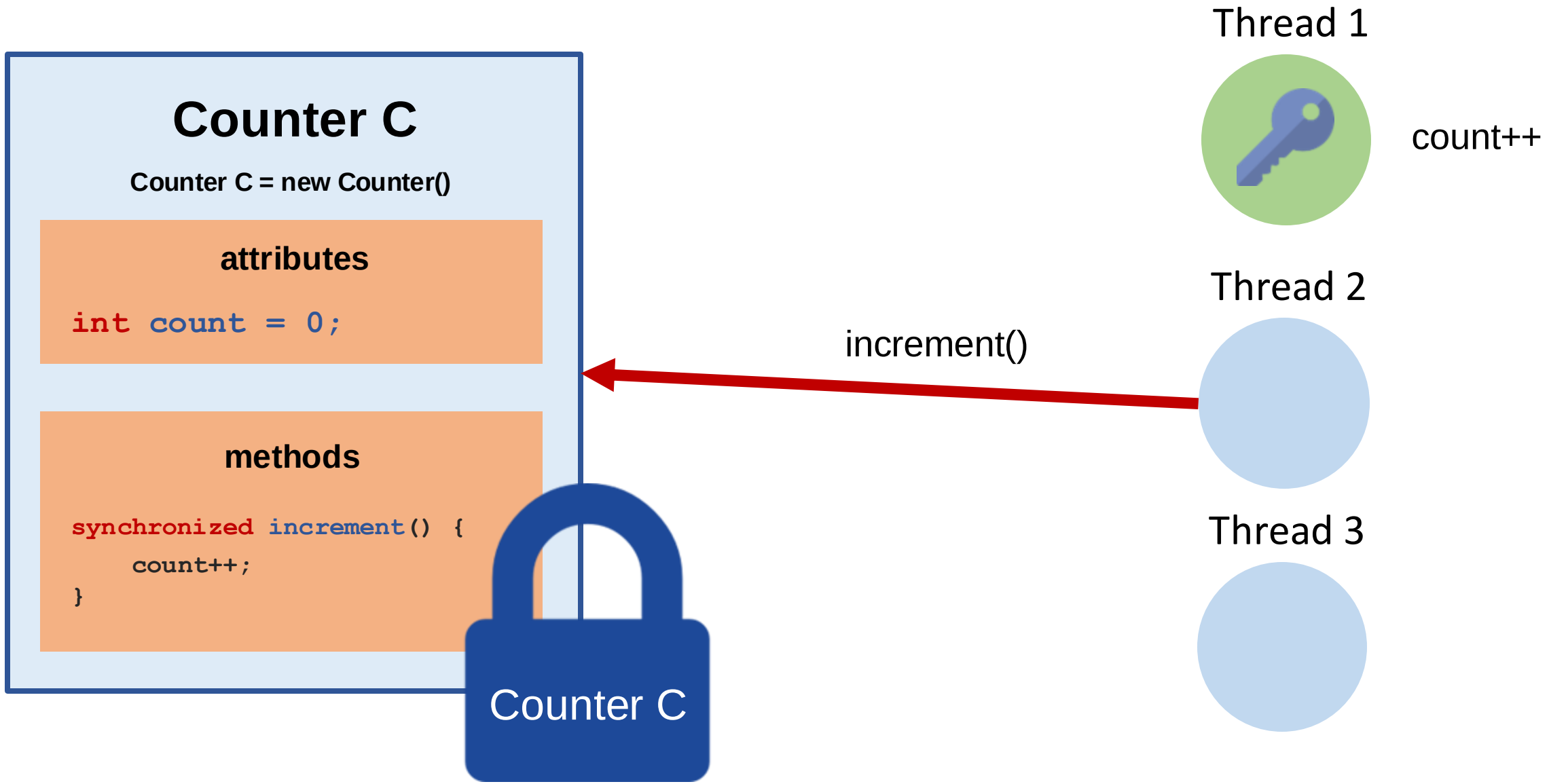


# What exactly is a lock/monitor?

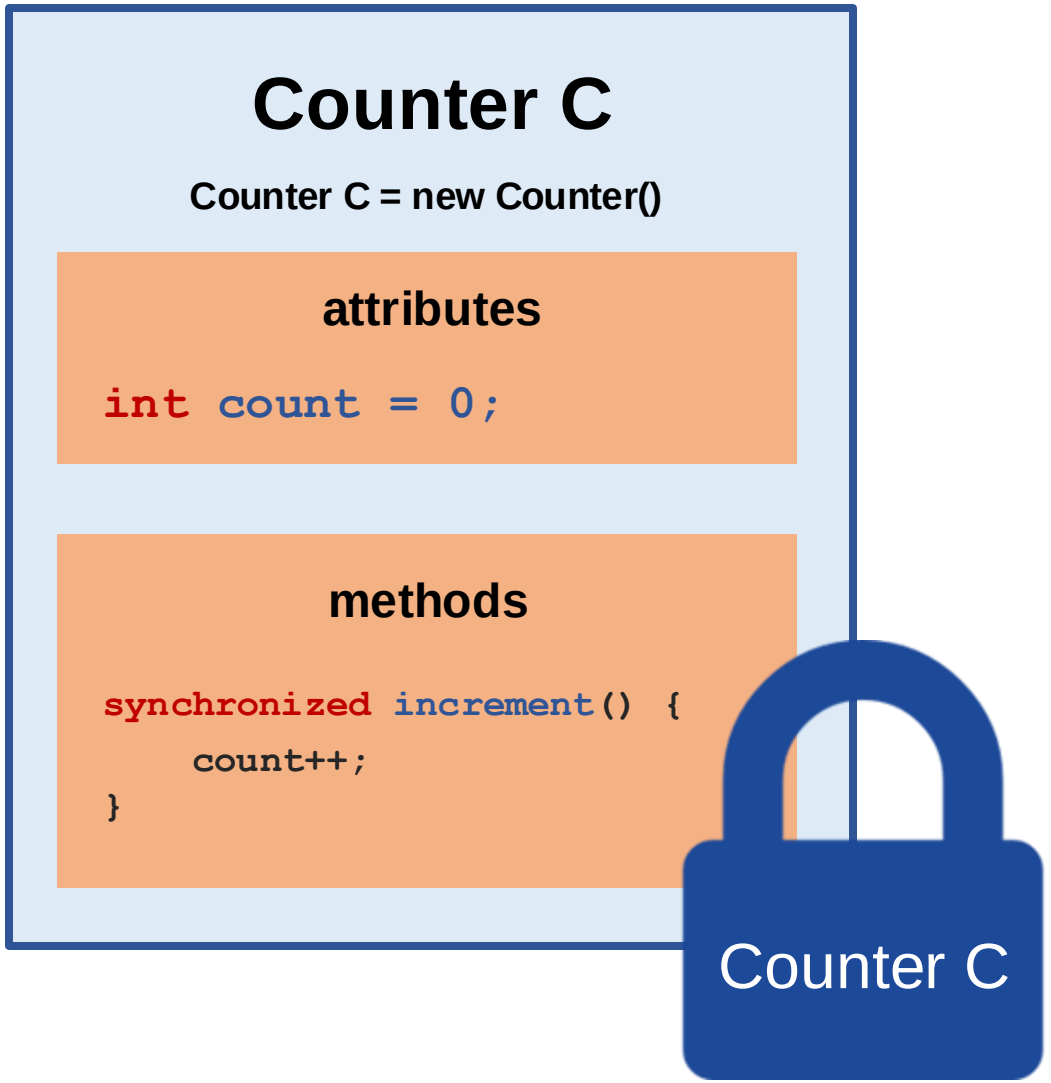


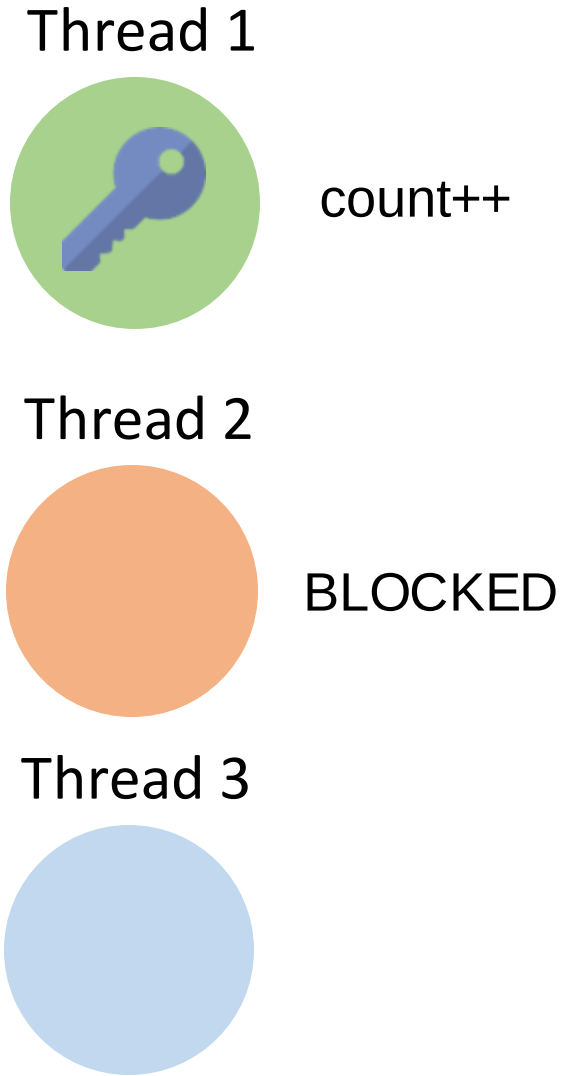



# What exactly is a lock/monitor?

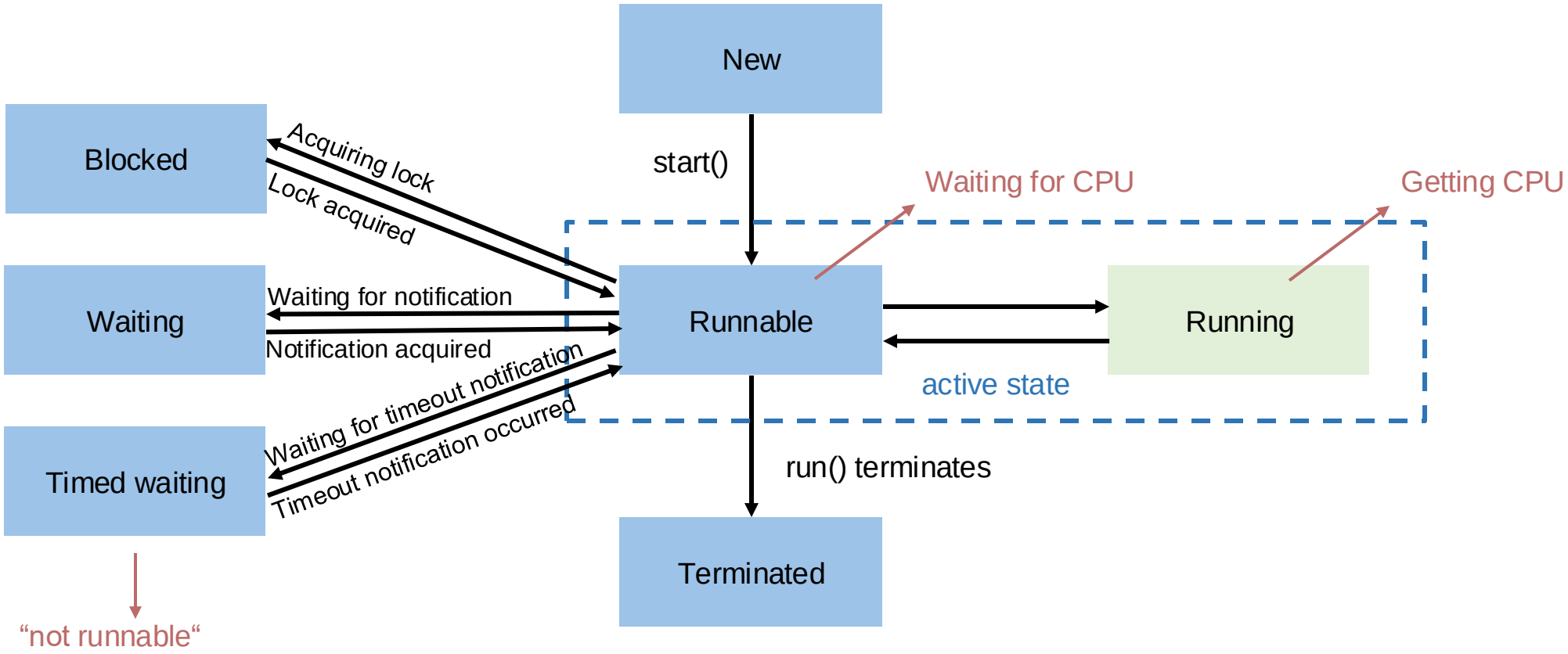


# What exactly is a lock/monitor?

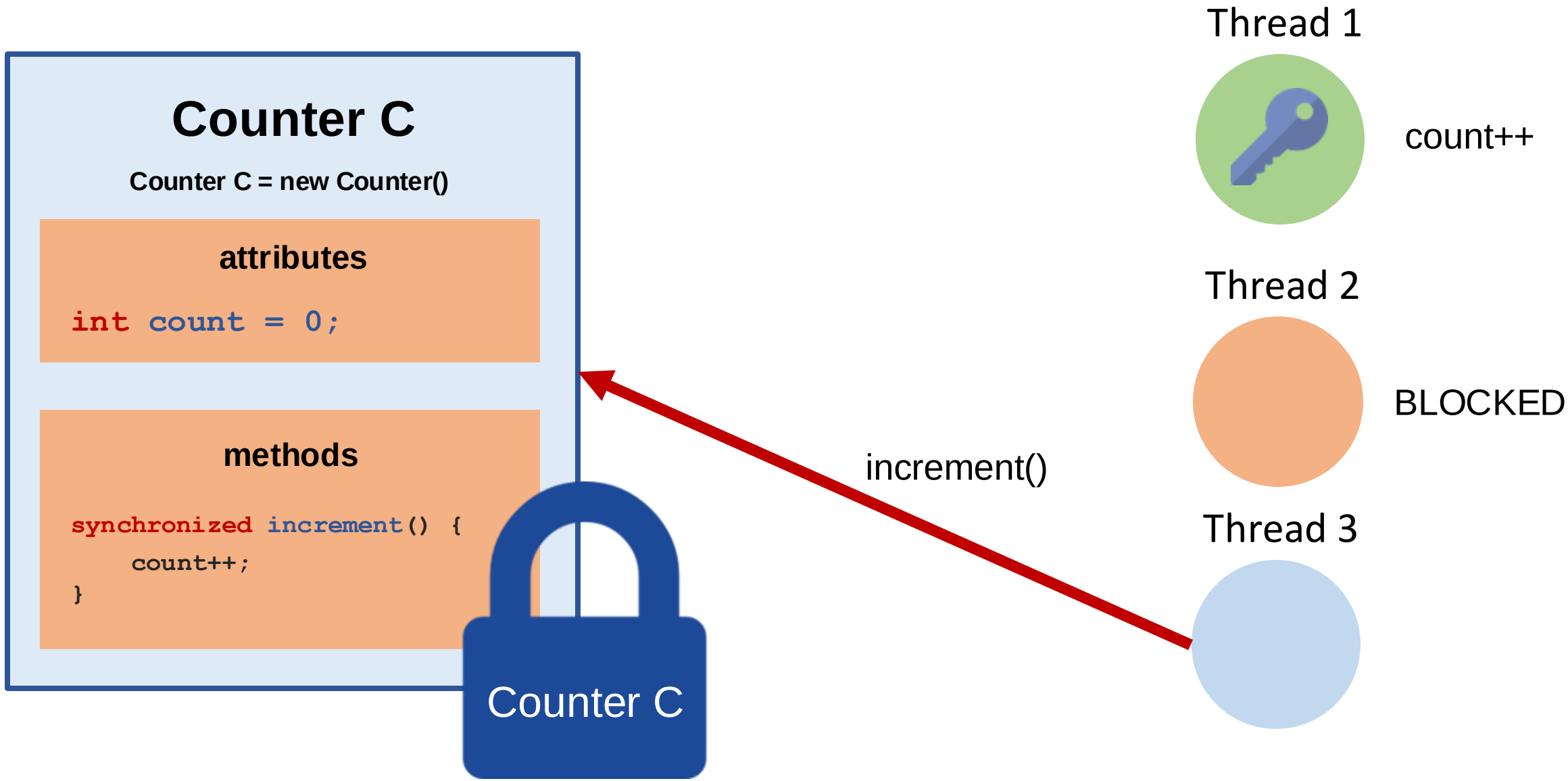


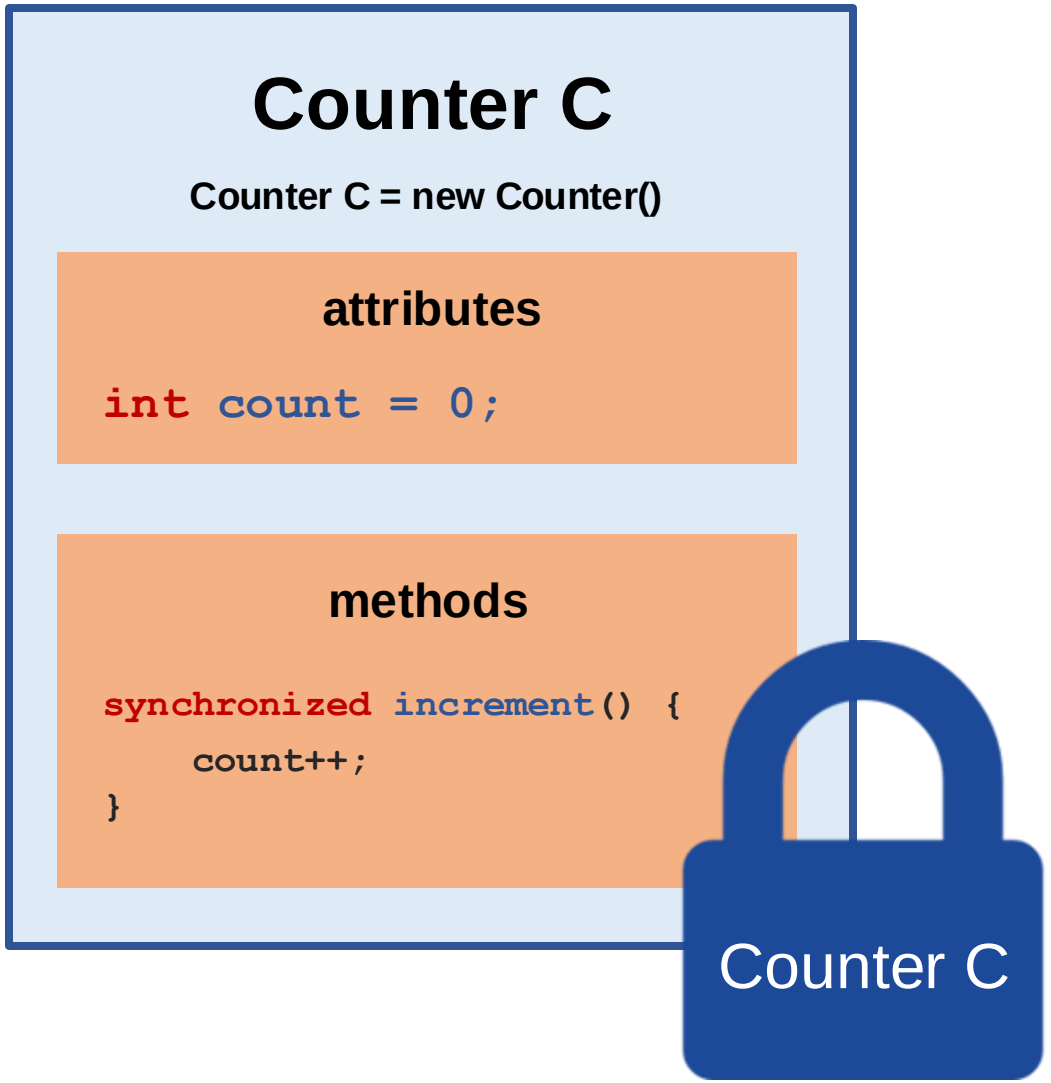
# Remember: Java Thread State Model

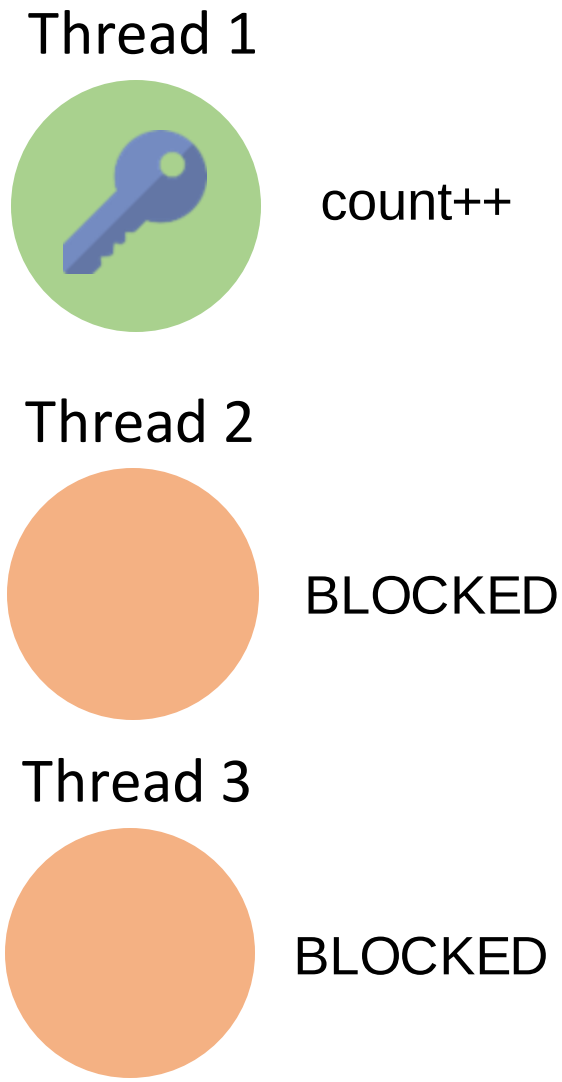


# What exactly is a lock/monitor?

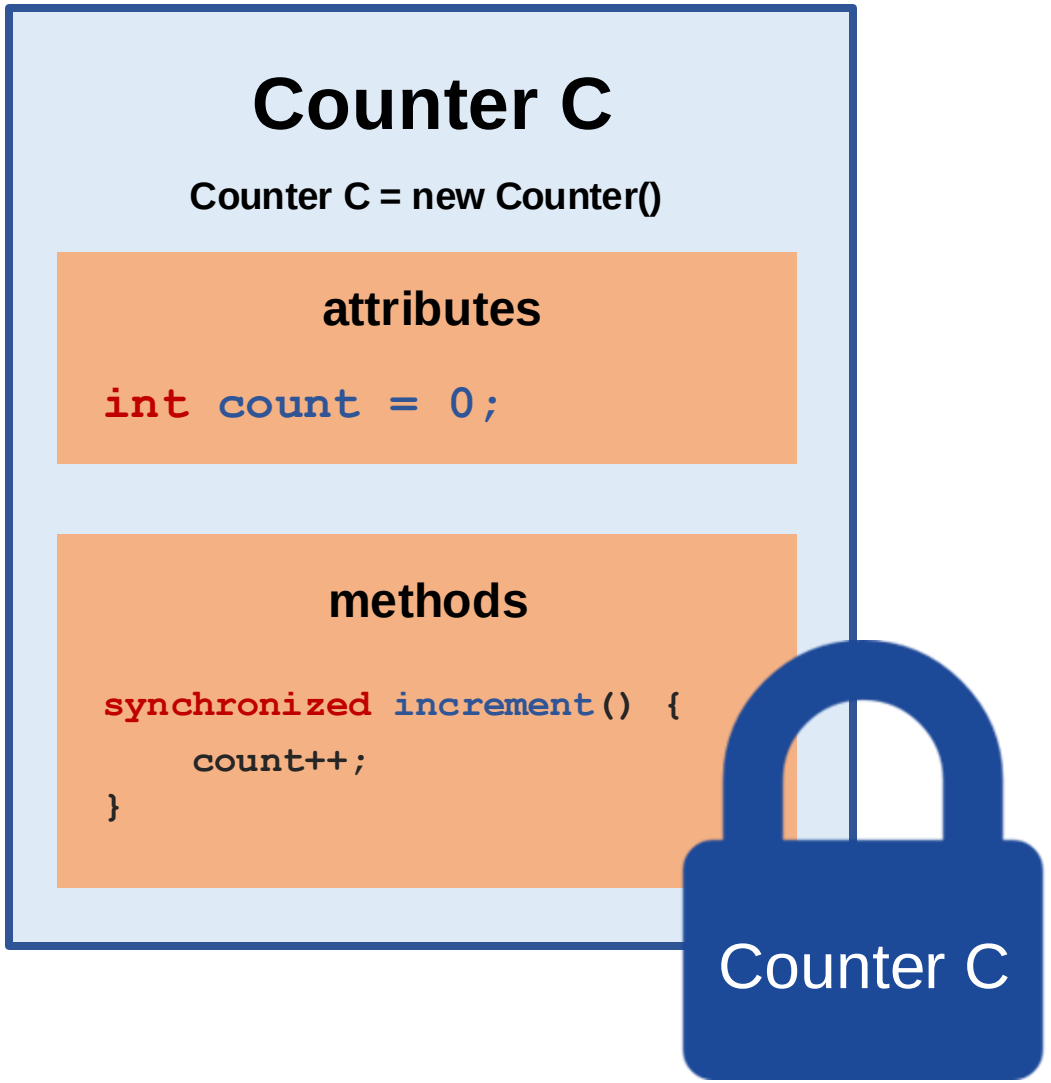


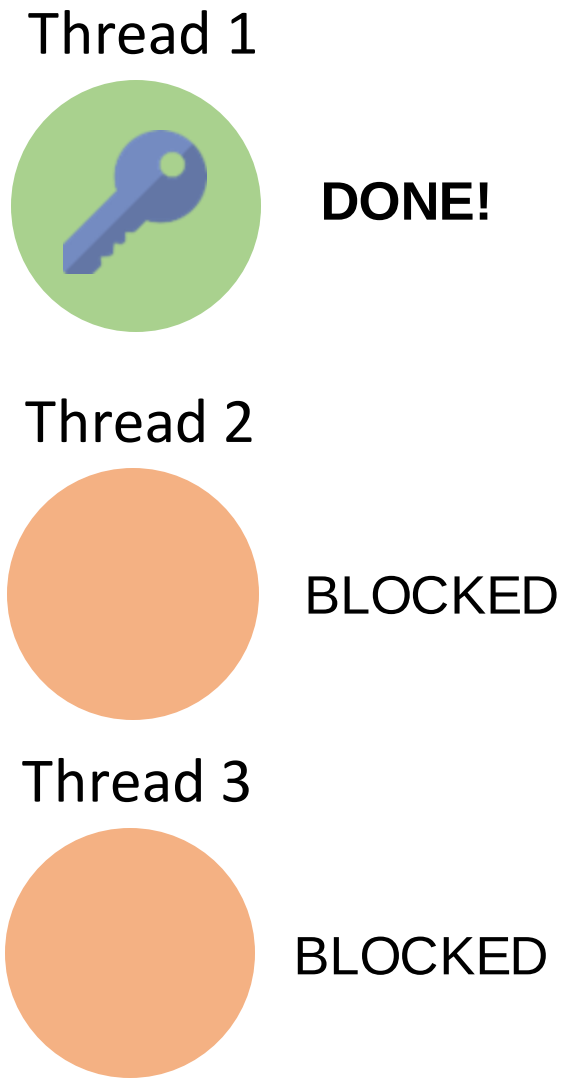
# What exactly is a lock/monitor?



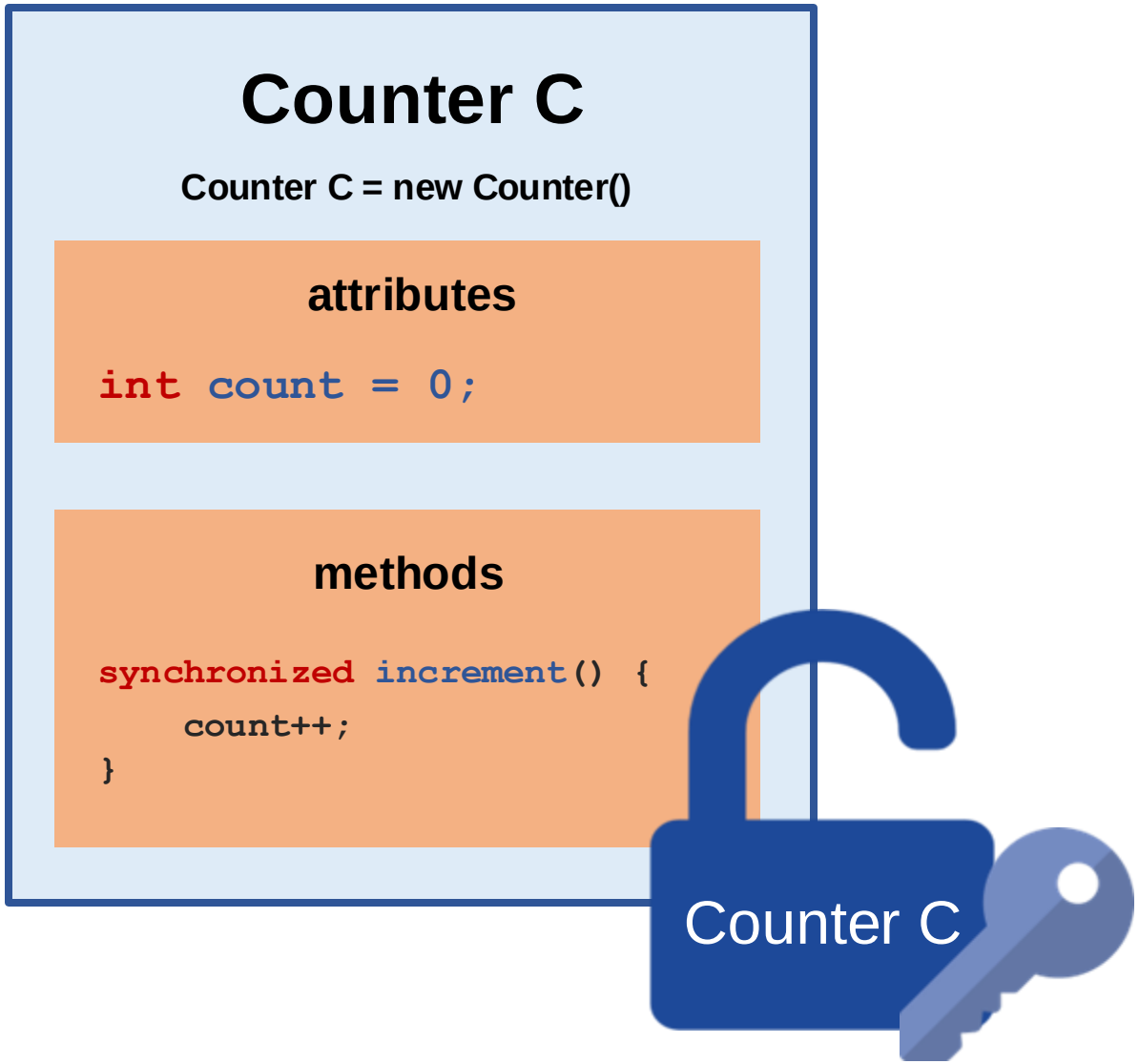



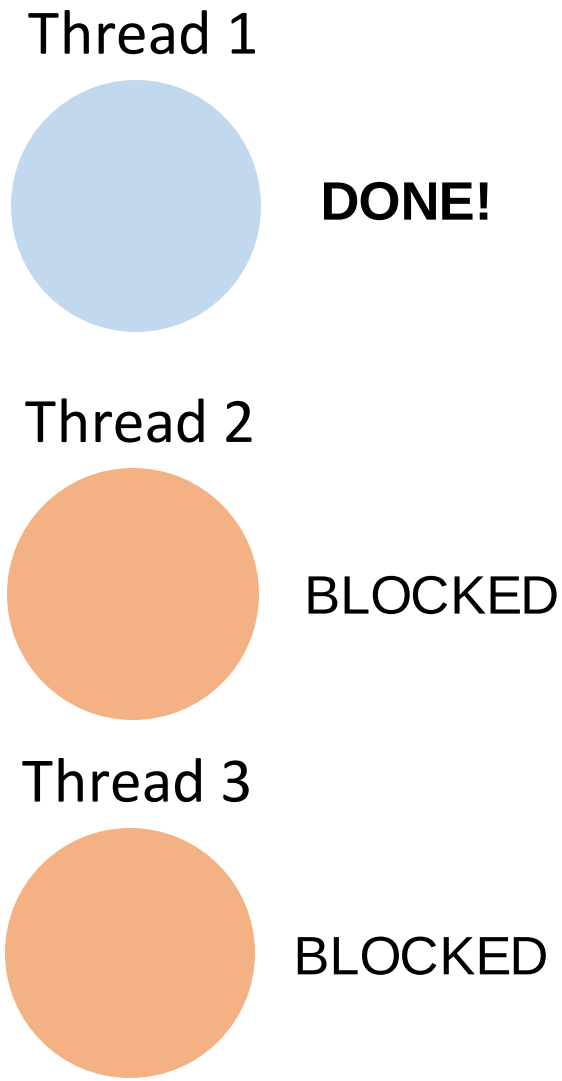
# What exactly is a lock/monitor?



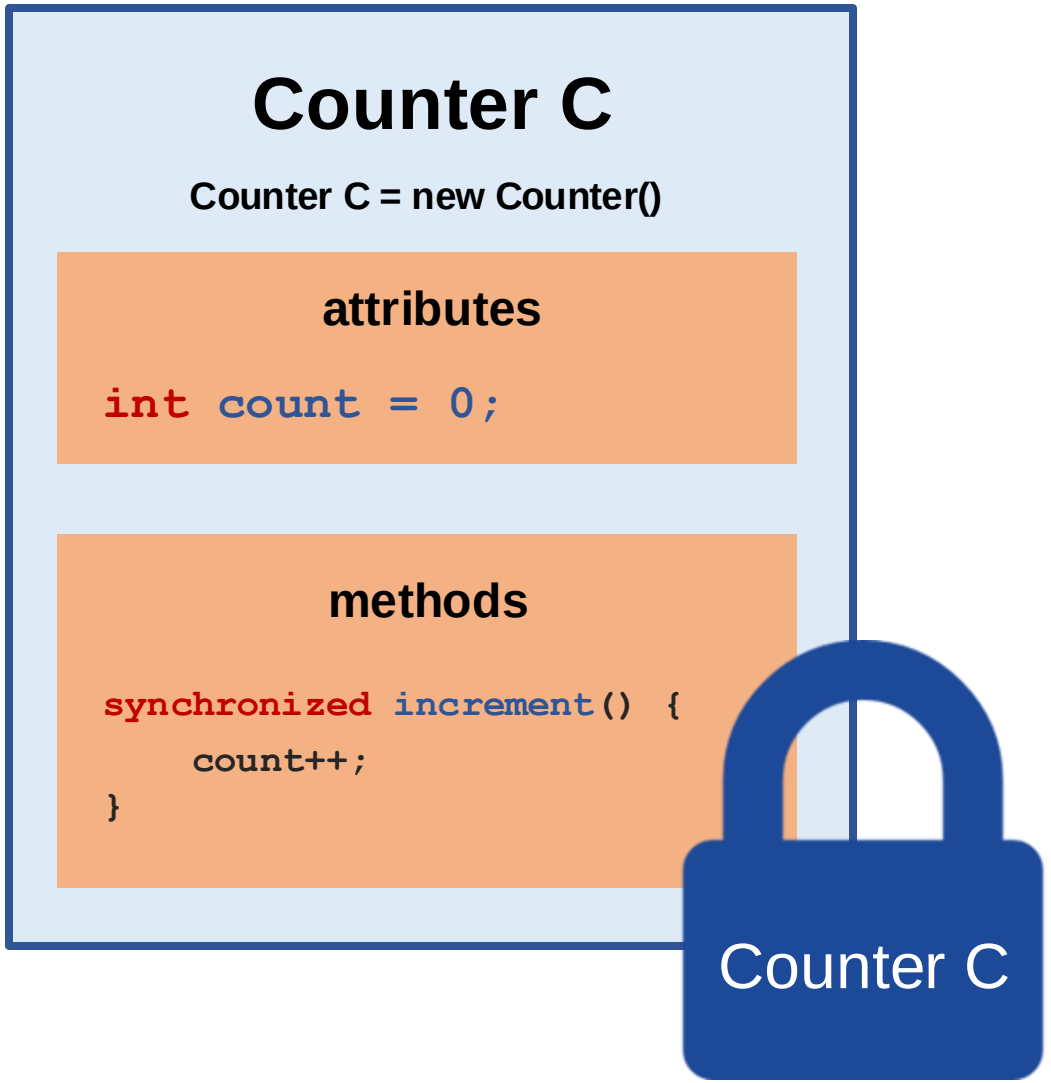
# What exactly is a lock/monitor?

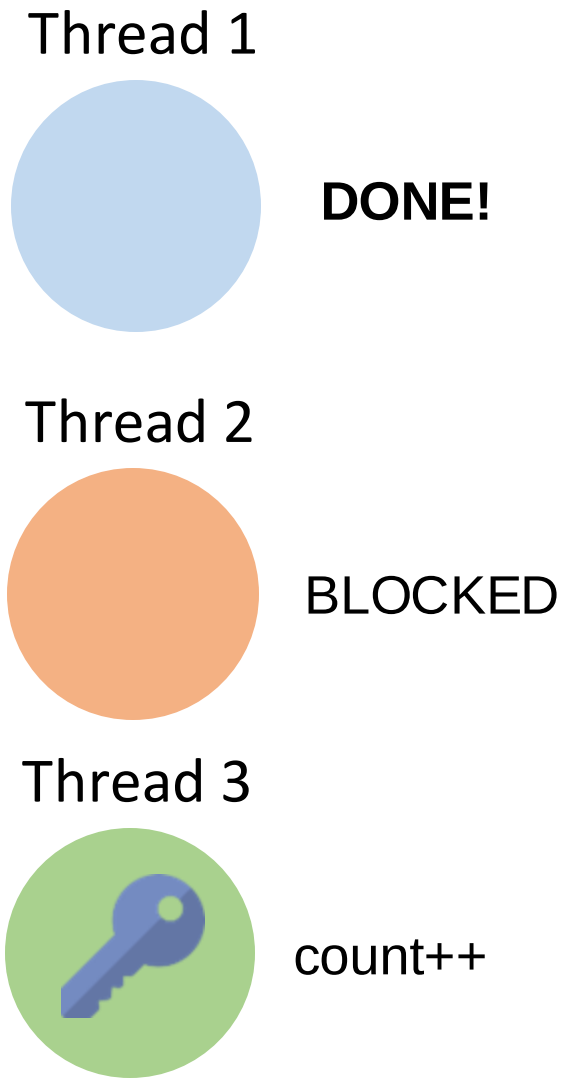


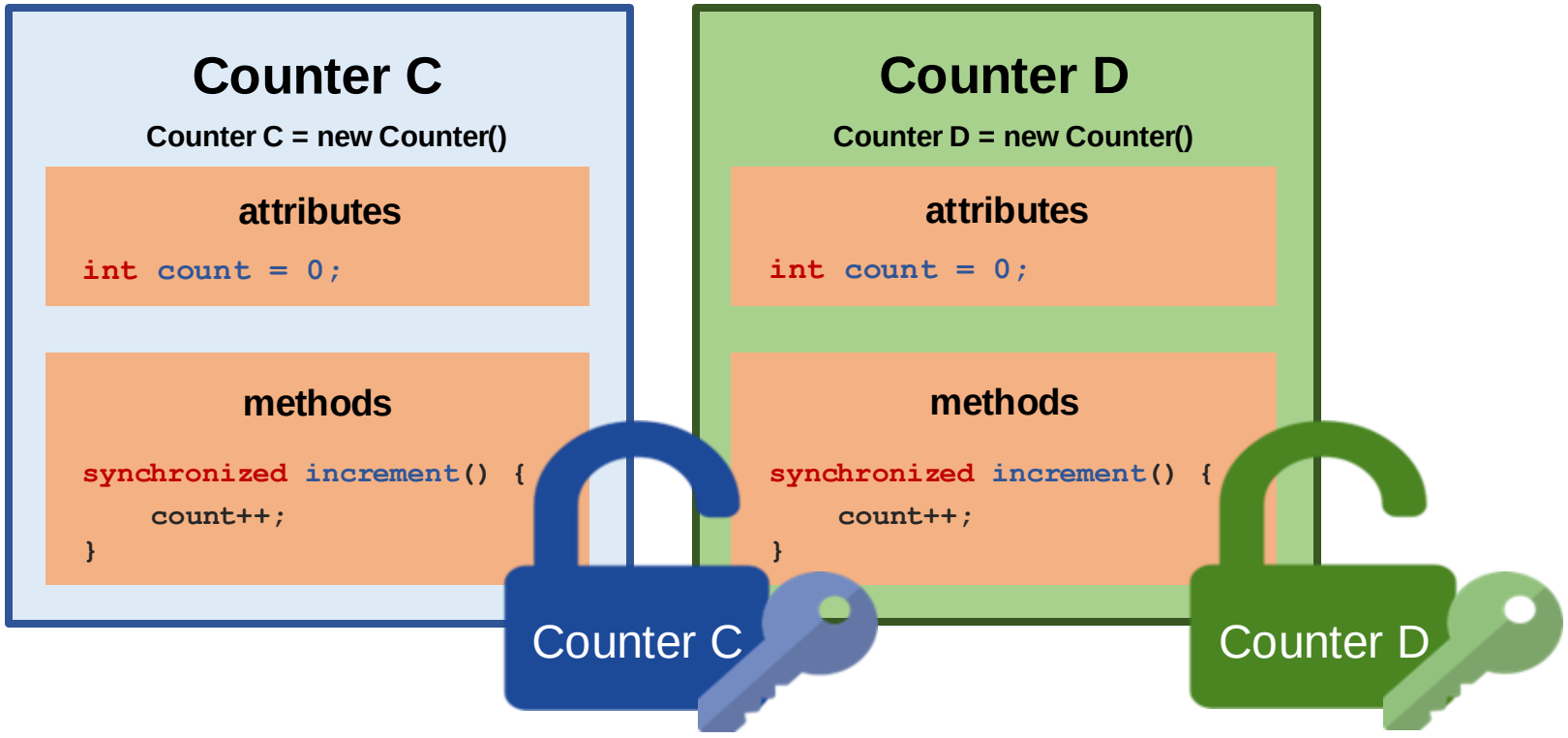
# What exactly is a lock/monitor?

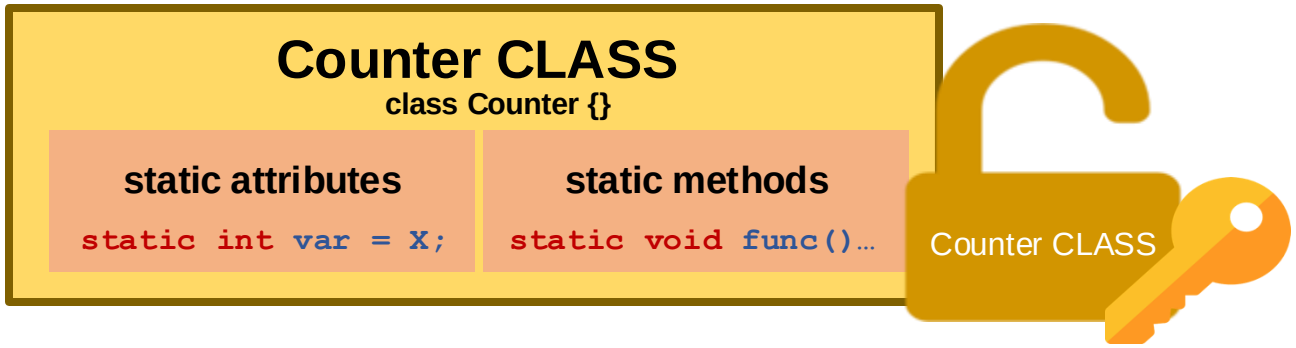
**THIS LOCK IS SPECIFIC TO THE OBJECT!**

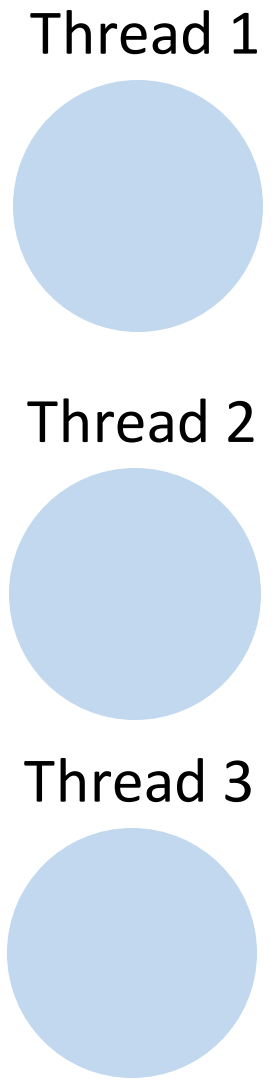


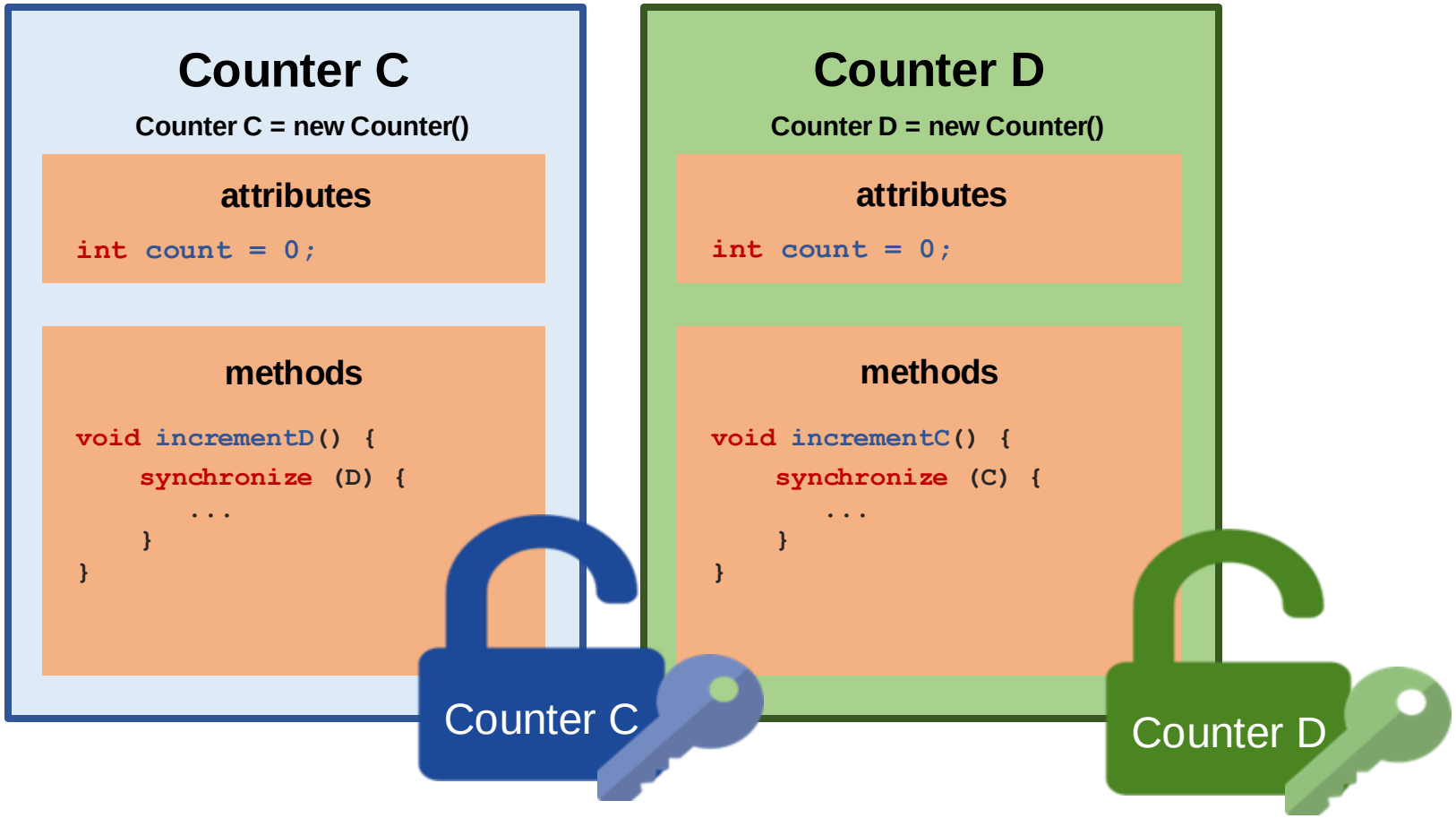
# Locks are specific to Object/Class



# Locks are specific to Object/Class

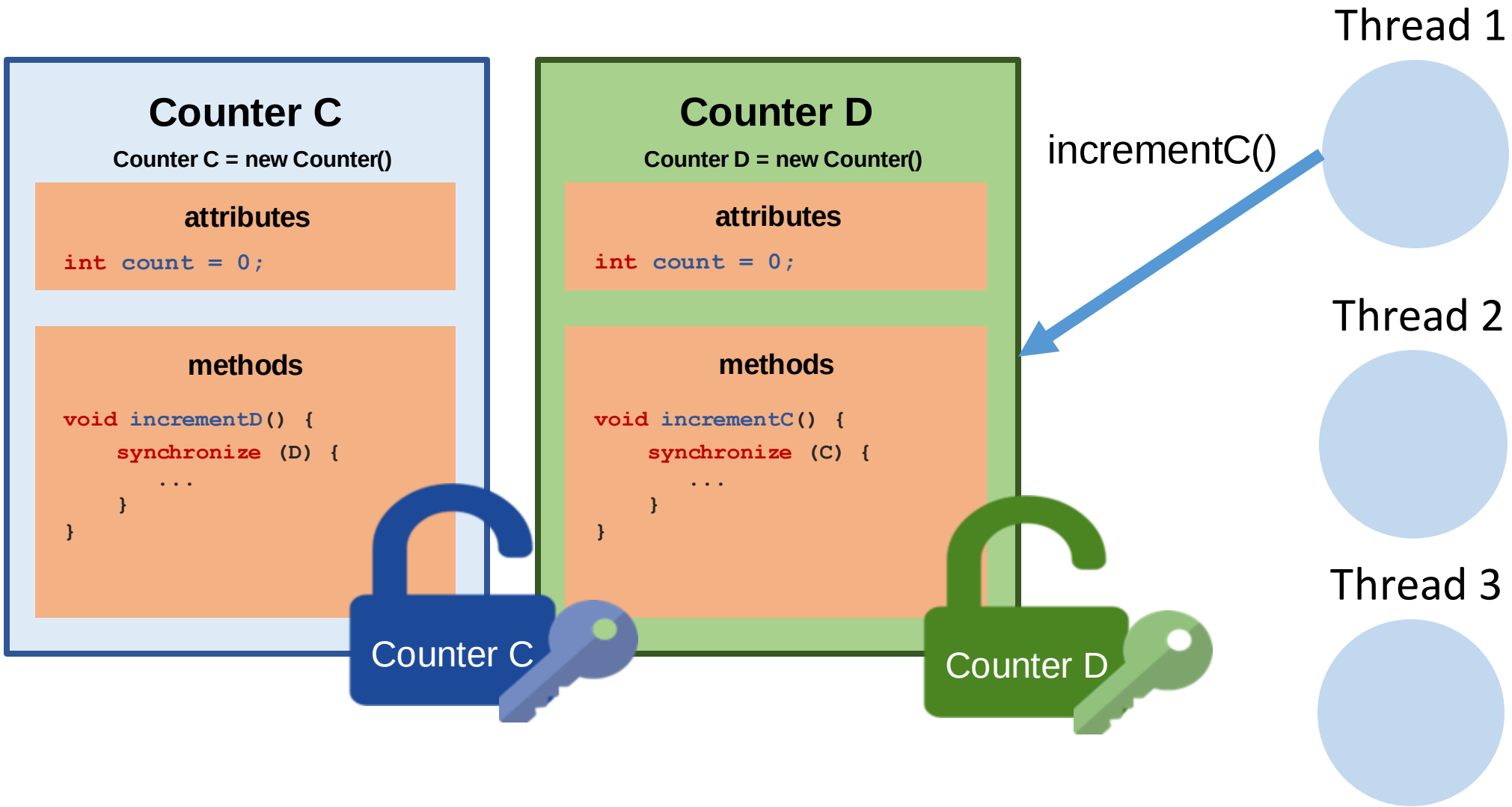



Thread 1

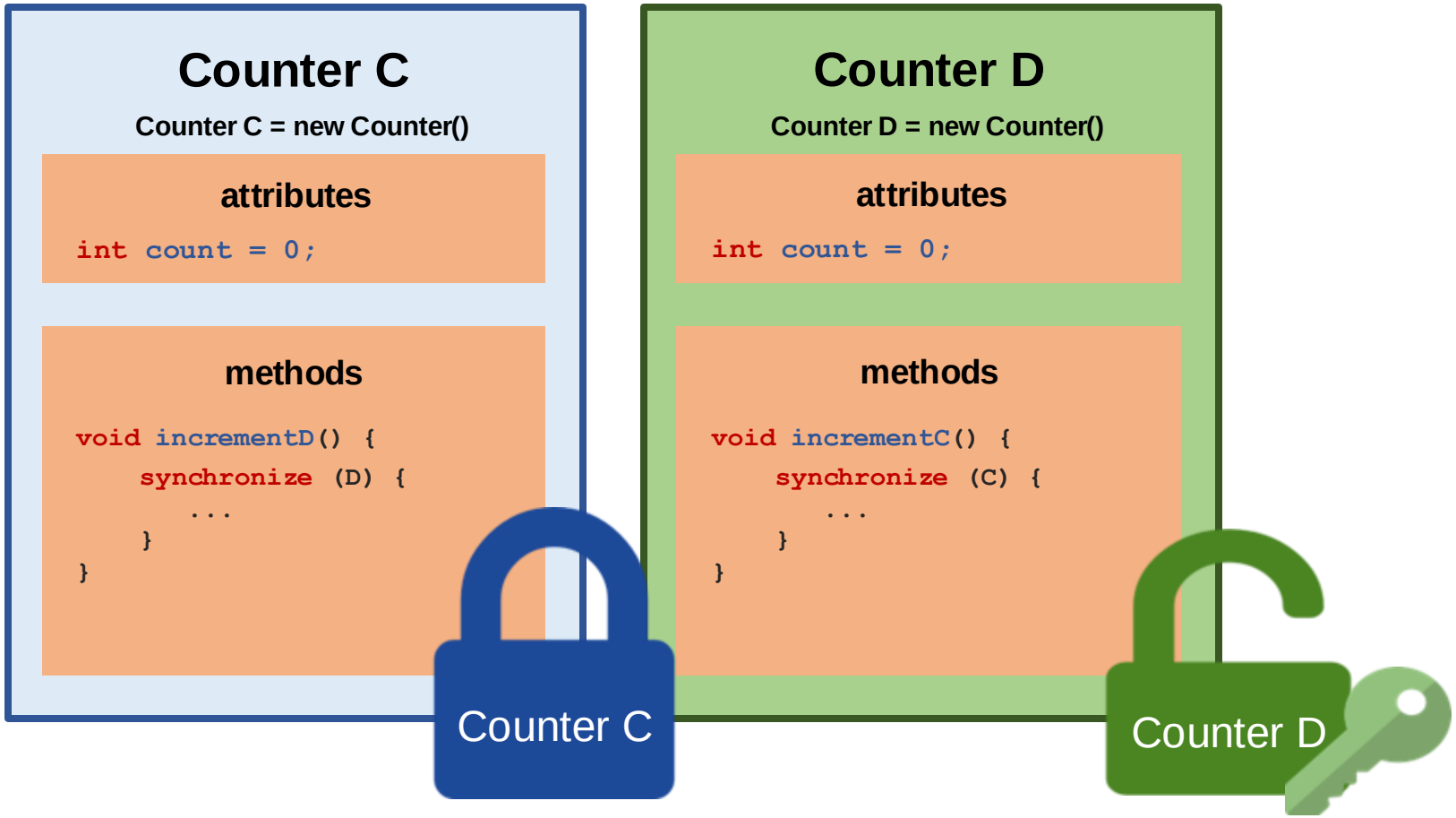
Thread 2

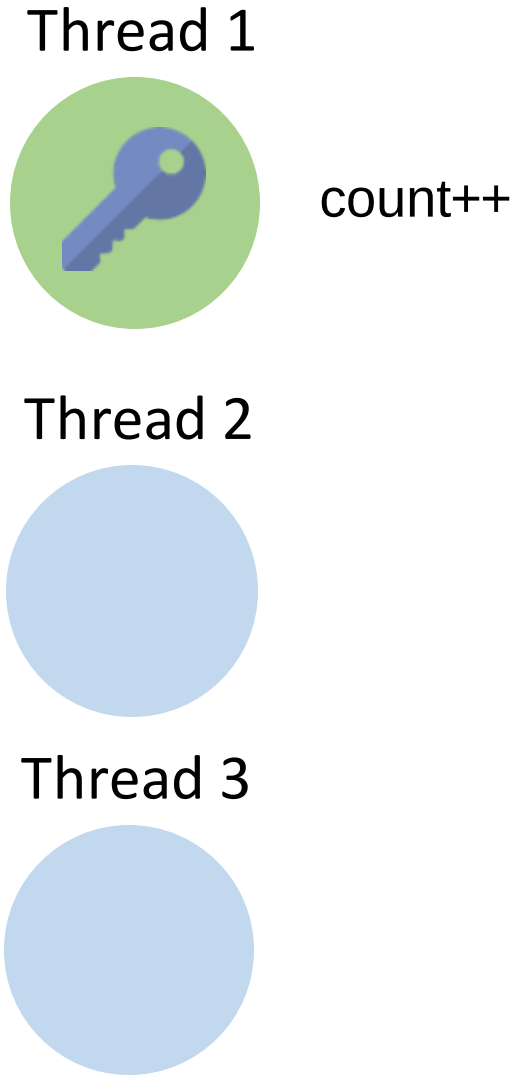
Thread 3

# Locks are specific to Object/Class



# Locks are specific to Object/Class



# Bad Practices With Synchronization

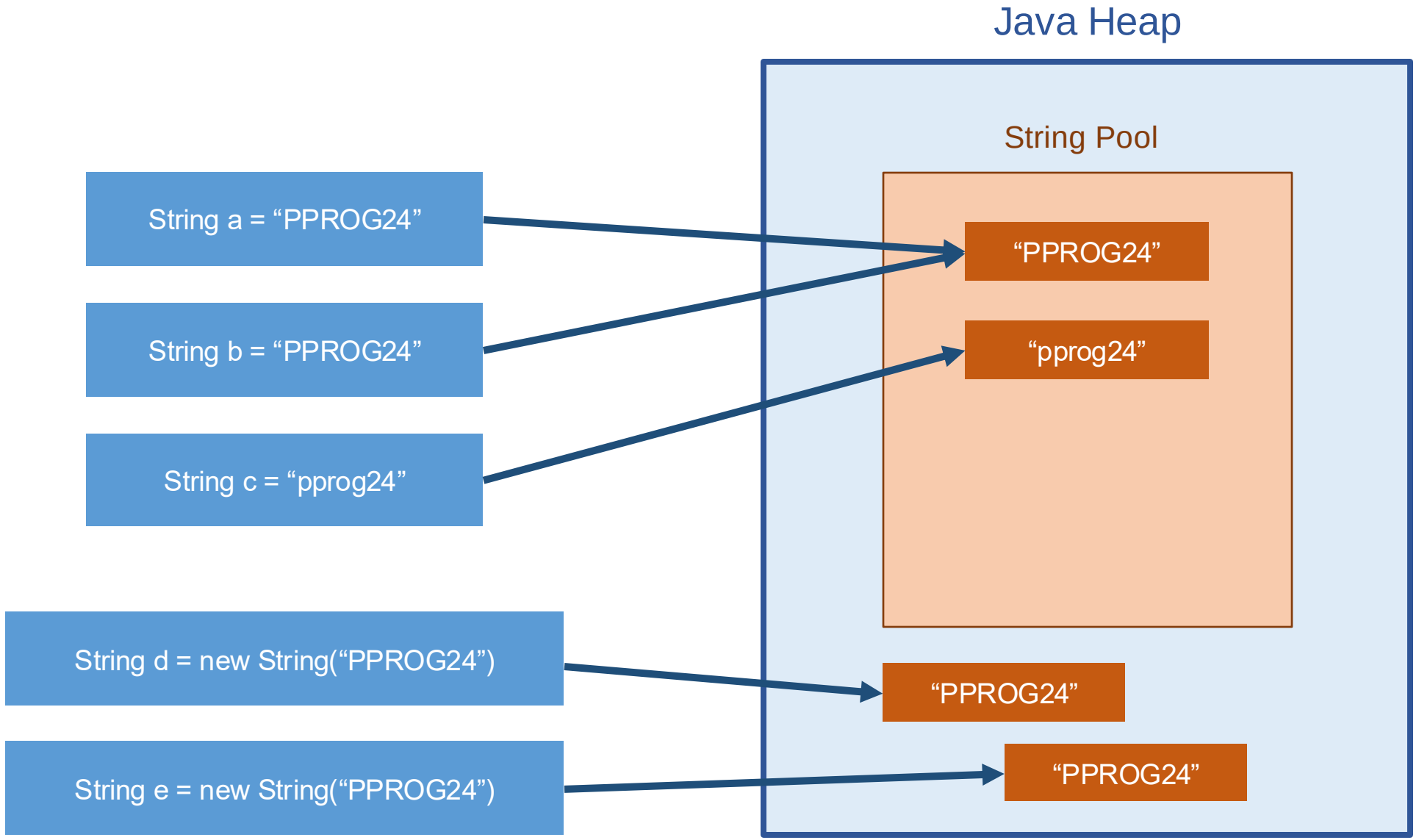
Do NOT synchronize on:

- Literals
- Boxed Primitives

# Good or not good?

```
String stringLock = "LOCK_STRING";

public void badOrGood() {
    synchronized (stringLock) {
        // ...
    }
}
```

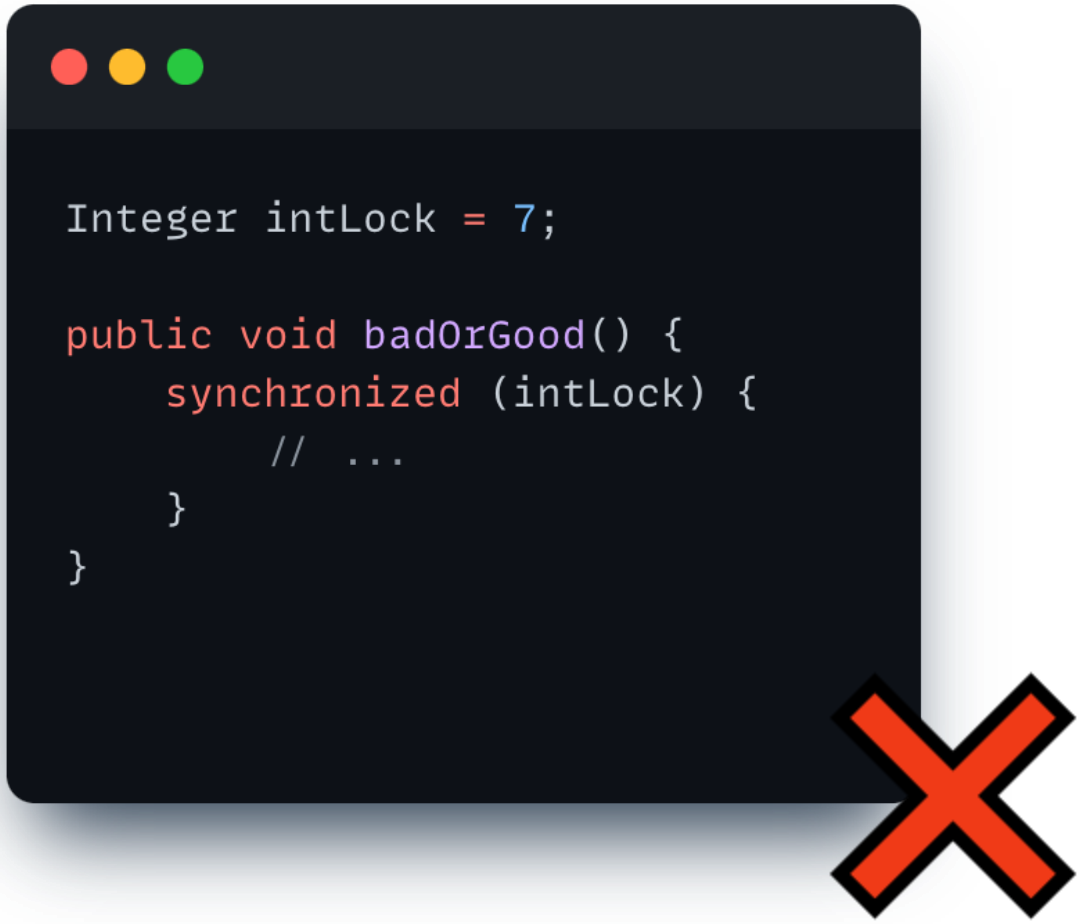
# Java String Pool



# Good or not good?

```
String stringLock = new String("LOCK_STRING");

public void badOrGood() {
    synchronized (stringLock) {
        // ...
    }
}
```

# Good or not good?

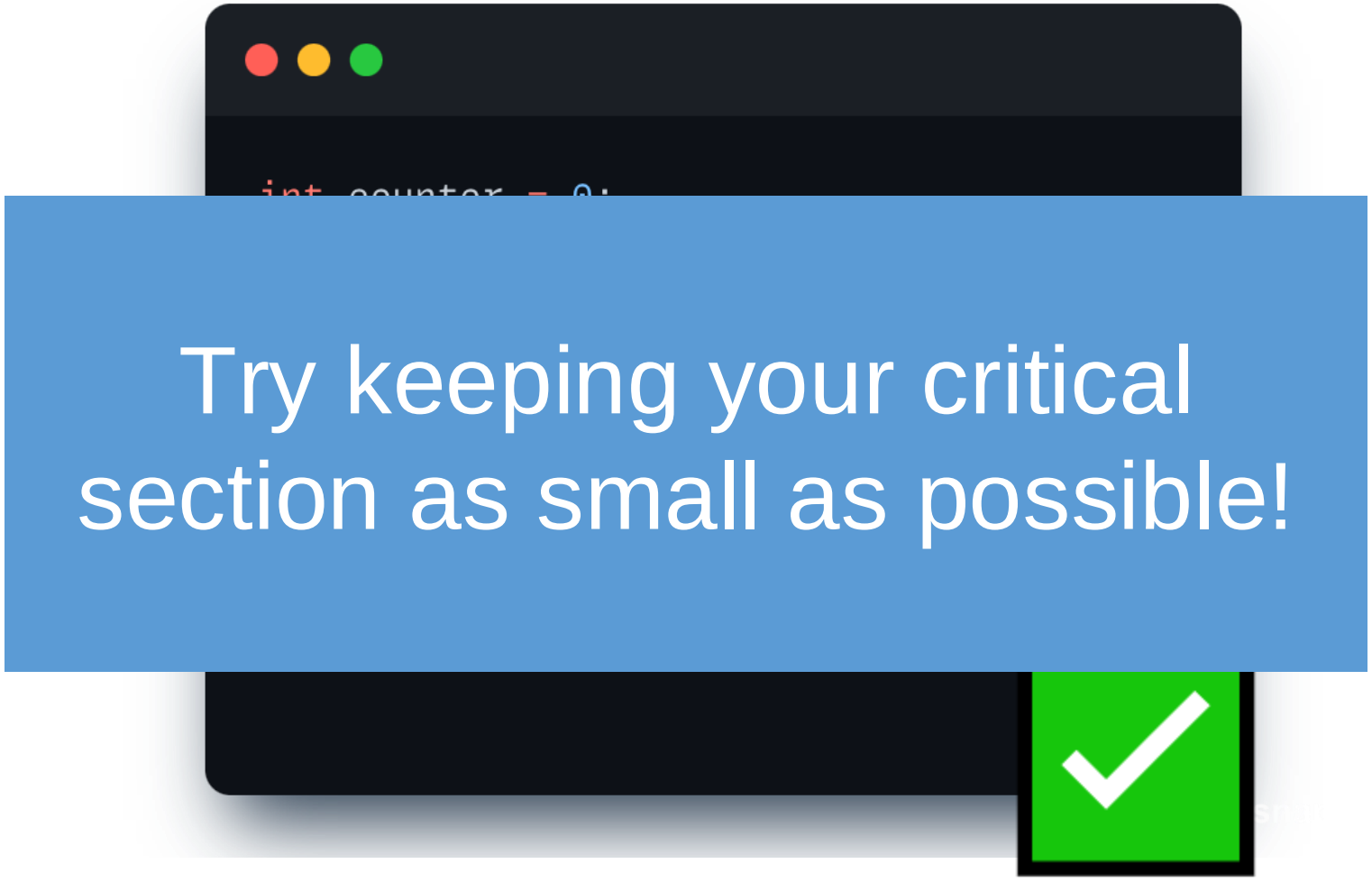


# Good or not good?

```
int counter = 0;

public void badOrGood() {
    synchronized (this) {
        Result r = someHeavyComputation();
        counter += r.value();
    }
}
```

Assume this computation takes *a lot* of time

# Good or not good?



# Wait and Notify Recap

Object (lock) provides `wait` and `notify` methods

(any object is a lock)

`wait`: Thread must own object's lock to call `wait`
thread releases lock and is added to "waiting list" for that object
thread waits until `notify` is called on the object

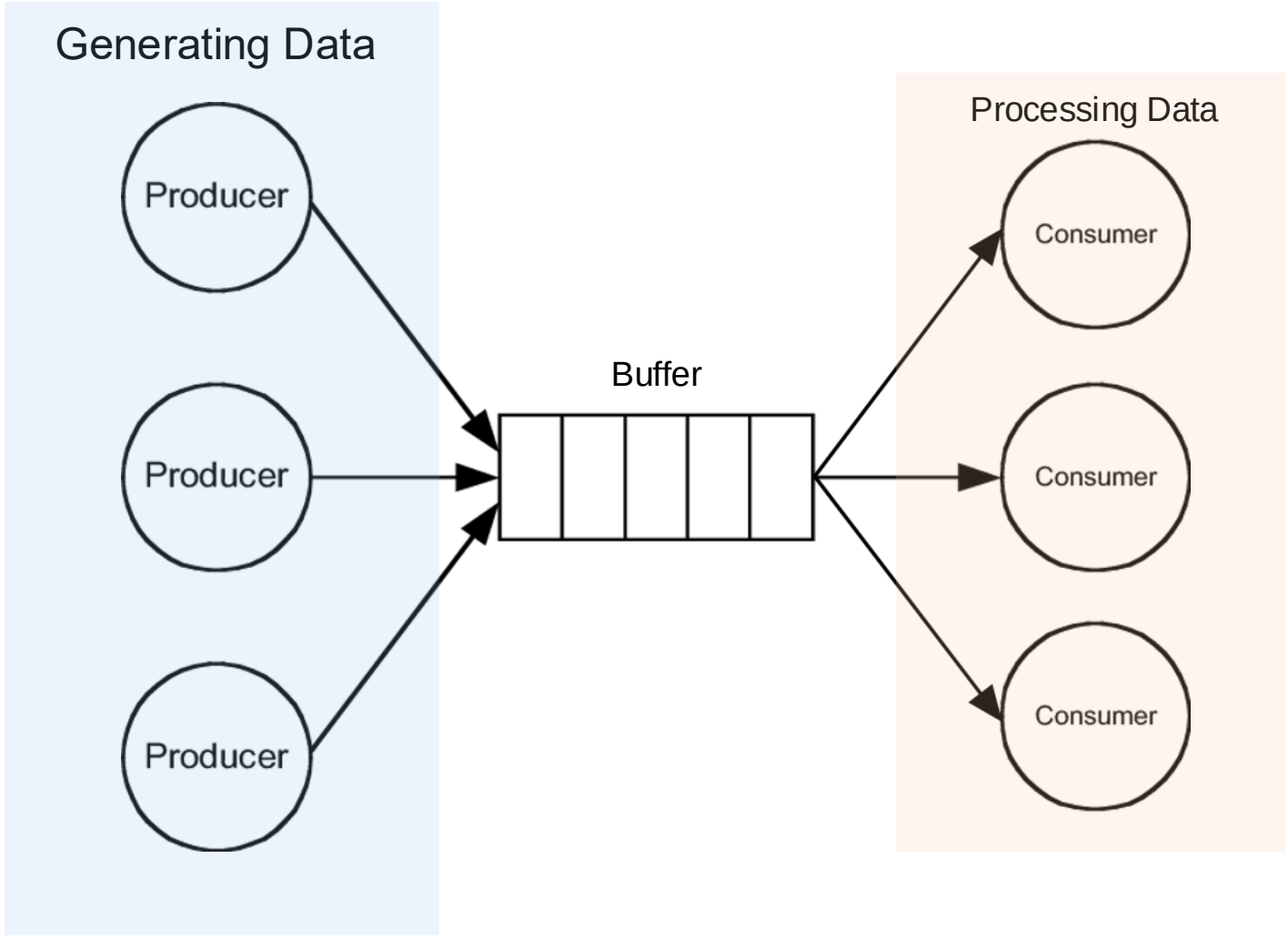
`notify`: Thread must own object's lock to call `notify`

`notify`: Wake one **(arbitrary)** thread from object's "waiting list"

`notifyAll`: Wake all threads

# But… why?

# Producer-Consumer Problem



# The Buffer

```
public class UnboundedBuffer {
  // Internal implementation could be a standard collection,
  // or a manually-maintained array or linked-list

  public boolean isEmpty() { ... }
  public void add(long value) { ... }
  public long remove() { ... }
}
```

# The Producer

```
public class Producer extends Thread {
  private final UnboundedBuffer buffer;
  ...

  public void run() {
    ...

    while (true) {
      prime = computeNextPrime(prime);
      buffer.add(prime);
    }
  }
}
```

# The Consumer

```
public class Consumer extends Thread {
  private final UnboundedBuffer buffer;
  ...

  public void run() {
    while (true) {
      while (buffer.isEmpty()); // Spin until item available
      performLongRunningComputation(buffer.remove());
    }
  }
}
```

Where is the problem?

# The Consumer

```
public class Consumer extends Thread {
  private final UnboundedBuffer buffer;
  ...

  public void run() {
    while (true) {
      while (buffer.isEmpty()); // Spin until item available
      performLongRunningComputation(buffer.remove());
    }
  }
}
```

Bad Interleaving!

# How about now?

```
public class Consumer extends Thread {
  ...

  public void run() {
    long prime;
    while (true) {
      synchronize (buffer) {
        while (buffer.isEmpty());
        prime = buffer.remove();
      }
      performLongRunningComputation(prime);
    }
  }
}
```

```
public class Producer extends Thread {
  ...

  public void run() {
    ...

    while (true) {
      prime = computeNextPrime(prime);
      synchronize (buffer) {
        buffer.add(prime);
      }
    }
  }
}
```

# How about now?

```
public class Consumer extends Thread {
  ...

  public void run() {
    long prime;
    while (true) {
      synchronize (buffer) {
        while (buffer.isEmpty());
        prime = buffer.remove();
      }
      performLongRunningComputation(prime);
    }
  }
}
```

```
public class Producer extends Thread {
  ...

  public void run() {
    ...

    while (true) {
      prime = computeNextPrime(prime);
      synchronize (buffer) {
        buffer.add(prime);
      }
    }
  }
}
```

Problem:

1. Consumer locks buffer (`synchronize (buffer)`)
2. Consumer spins on `isEmpty()`, i.e. waits for producer to add item
3. Producer waits for lock to become available (`synchronize (buffer)`)
4. → Deadlock! Consumer and producer wait for each other; no progress

# Solution? Use wait/notify!

```
public class Consumer extends Thread {
  ...

  public void run() {
    long prime;
    while (true) {
      synchronize (buffer) {
        while (buffer.isEmpty())
          buffer.wait();
        prime = buffer.remove();
      }
      performLongRunningComputation(prime);
    }
  }
}
```

`buffer.wait()`:

1. Consumer thread goes to sleep (status NOT RUNNABLE) …
2. … and gives up buffer's lock

```
public class Producer extends Thread {
  ...

  public void run() {
    ...

    while (true) {
      prime = computeNextPrime(prime);
      synchronize (buffer) {
        buffer.add(prime);
        buffer.notifyAll();
      }
    }
  }
}
```

`buffer.notifyAll()`:

1. All threads waiting for buffer's lock are woken up (status RUNNABLE)

# Wait and Notify Recap

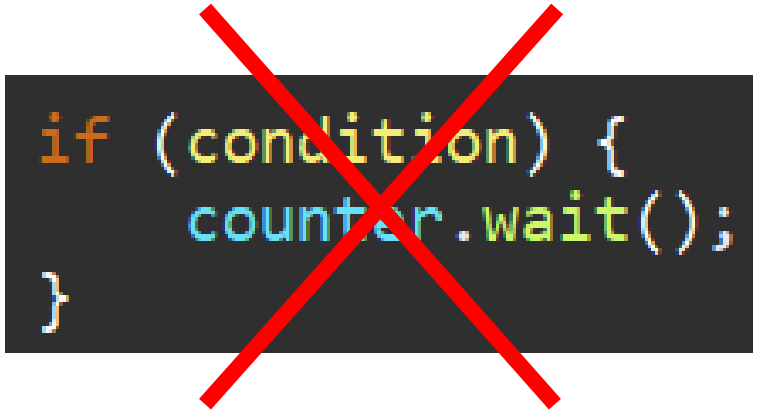
```
while (condition) {
    counter.wait();
}
```

```
if (condition) {
    counter.wait();
}
```

What is the difference? Issues?

# Wait and Notify Recap

```
while (condition) {
    counter.wait();
}
```




Spurious wake-ups and notifyAll()
→ `wait` has to be in a `while` loop

# Wait and Notify Recap

```
public class Object {
      ...
      public final native void notify();
      public final native void notifyAll();

      public final native void wait(long timeout) throws InterruptedException;
      public final void wait() throws InterruptedException { wait(0); }
      public final void wait(long timeout, int nanos)
         throws InterruptedException { ... }
}
```

wait() releases object lock, thread waits on internal queue

notify() wakes the highest-priority thread closest to front of object's internal queue

notifyAll() wakes up all waiting threads

- Threads non-deterministically compete for access to object
- May not be fair (low-priority threads may never get access)

May only be called when object is locked (e.g. inside `synchronize`)

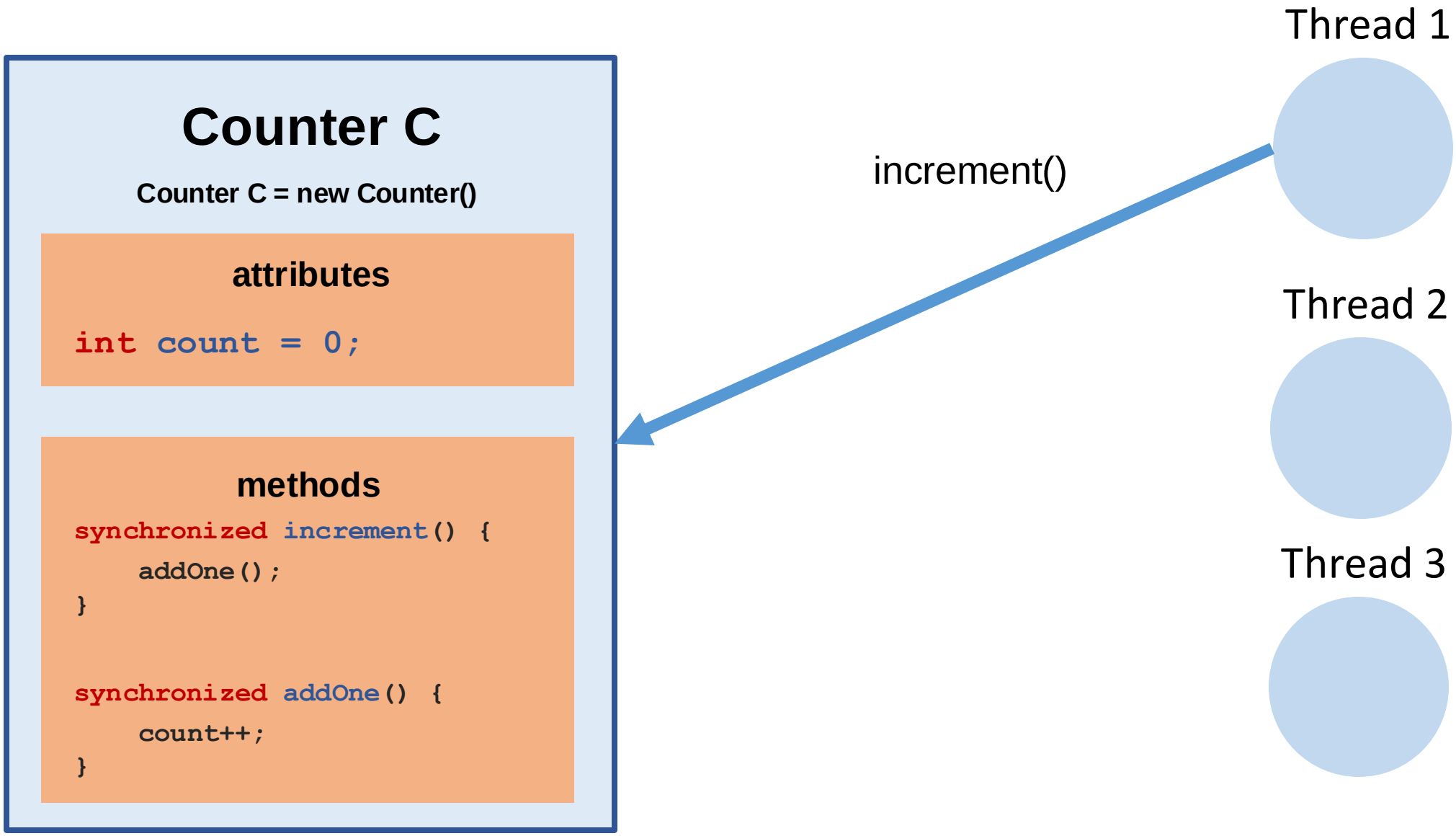
# Reentrant

Java locks are reentrant

A thread can hold a lock more than once

Also have to release multiple times

# Reentrant


Counter C
Counter C = new Counter()
attributes
int count = 0;
methods
synchronized increment() {
addOne();
}
synchronized addOne() {
count++;
}
increment()
Thread 1
Thread 2
Thread 3

# Past Exam Task

Kreuzen Sie alle korrekten Aussagen über die Ausführung von Java `Threads` an.

*Mark all correct statements regarding the execution of Java `Threads`.*

- ○ Die start() Methode in `t = new Thread(); t.start()` ruft automatisch auch die run() methode auf.

  *The start() method in `t = new Thread(); t.start()` automatically also calls the run() method.*

- ○ Die run() Methode in `t = new Thread(); t.run()` erzeugt einen neuen Thread und führt diesen aus.

  *The run() method in `t = new Thread(); t.run()` creates a new thread and executes the thread.*

- ○ Ein Codeblock mit mehreren Threads wird immer deterministisch ausgeführt. D.h. der Output ist immer exakt der gleiche.

  *A codeblock with several threads is always executed deterministically. That means the output is always the same.*

- ○ Ein komplett serieller Codeblock kann zur Beschleunigung auf mehreren Prozessoren ausgeführt werden.

  *A fully serial block of code can be run on multiple processors to speedup execution.*

Rep. Exam, FS 2023

# Past Exam Task

Kreuzen Sie alle korrekten Aussagen über die Ausführung von Java `Threads` an.

*Mark all correct statements regarding the execution of Java `Threads`.*

√ **Die start() Methode in `t = new Thread(); t.start()` ruft automatisch auch die run() methode auf.**

*The start() method in `t = new Thread(); t.start()` automatically also calls the run() method.*

○ Die run() Methode in `t = new Thread(); t.run()` erzeugt einen neuen Thread und führt diesen aus.

*The run() method in `t = new Thread(); t.run()` creates a new thread and executes the thread.*

○ Ein Codeblock mit mehreren Threads wird immer deterministisch ausgeführt. D.h. der Output ist immer exakt der gleiche.

*A codeblock with several threads is always executed deterministically. That means the output is always the same.*

○ Ein komplett serieller Codeblock kann zur Beschleunigung auf mehreren Prozessoren ausgeführt werden.

*A fully serial block of code can be run on multiple processors to speedup execution.*

Rep. Exam, FS 2023

# Past Exam Task

(c) Wozu dient die `join()` Methode in Java `Threads`? *What is the purpose of the `join()` method in Java `Threads`?.* (2)

- ◯ Um eine Prioritätenreihenfolge zwischen mehreren Threads zu erzwingen. *To enforce a priority order among multiple threads.*
- ◯ Um das von dem aktuellen Thread gehaltene `Lock` freizugeben. *To release the lock held by the current thread.*
- ◯ Um die Ausführung des aktuellen Threads anzuhalten, bis der Thread, den er `joined`, abgeschlossen ist. *To pause the current thread's execution until the thread it `joins` completes.*
- ◯ Um die Kontrolle an einen anderen Thread zu übergeben, ohne auf dessen Abschluss zu warten. *To transfer control to another thread without waiting for its completion.*

Rep. Exam, FS 2023

# Past Exam Task

(c) Wozu dient die `join()` Methode in Java `Threads`?

*What is the purpose of the `join()` method in Java `Threads`?.*

(2)

- ○ Um eine Prioritätenreihenfolge zwischen mehreren Threads zu erzwingen.
  *To enforce a priority order among multiple threads.*
- ○ Um das von dem aktuellen Thread gehaltene `Lock` freizugeben.
  *To release the lock held by the current thread.*
- √ **Um die Ausführung des aktuellen Threads anzuhalten, bis der Thread, den er `joined`, abgeschlossen ist.**
  *To pause the current thread's execution until the thread it `joins` completes.*
- ○ Um die Kontrolle an einen anderen Thread zu übergeben, ohne auf dessen Abschluss zu warten.
  *To transfer control to another thread without waiting for its completion.*

Rep. Exam, FS 2023


QUIZ

# Pre-Discussion Exercise 3

# Counter

There are many threads accessing the counter at the same time.
How should we implement it such that there are no conflicts?
You will try different solutions including:

- ➔*Task A: SequentialCounter*
- ➔*Task B: SynchronizedCounter*
- ➔*Task E (optional): AtomicCounter*

# Task A – Sequential counter

- ➔ Implement a sequential version of the Counter in SequentialCounter class that does not use any synchronization.
- ➔ In taskASequential we provide a method that runs a single thread which increments the counter. Inspect the code and understand how it works.
- ➔ Verify that the SequentialCounter works properly when used with a single thread (the test testSequentialCounter should pass).

# Task A – Parallel counter

- ➔ Run the code in taskAParallel which creates several threads that all try to increment the counter at the same time.
- ➔ Will this work? What will happen?

# Task B – Synchronized counter

- ➔ Implement a different thread safe version of the Counter in SynchronizedCounter. In this version use the standard primitive type int but synchronize the access to the variable by inserting synchronized blocks.
- ➔ Run the code in taskB.

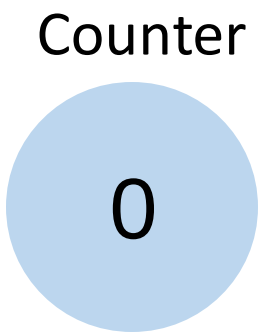
# Task C

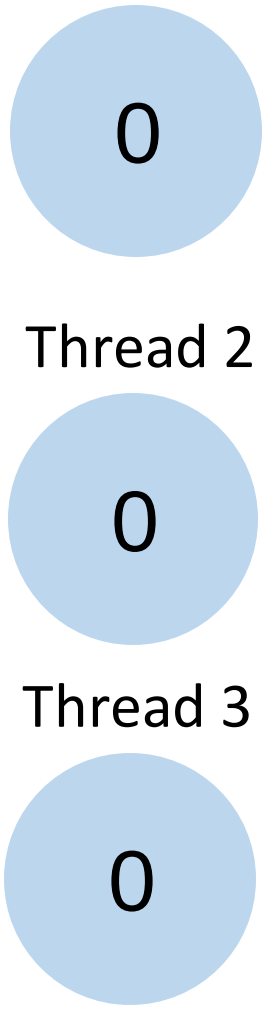
Whenever the Counter is incremented, keep track which thread performed the increment (you can print out the thread-id to the console). Observe how the threads are scheduled and discuss the factors that might influence this behavior.

# Task D

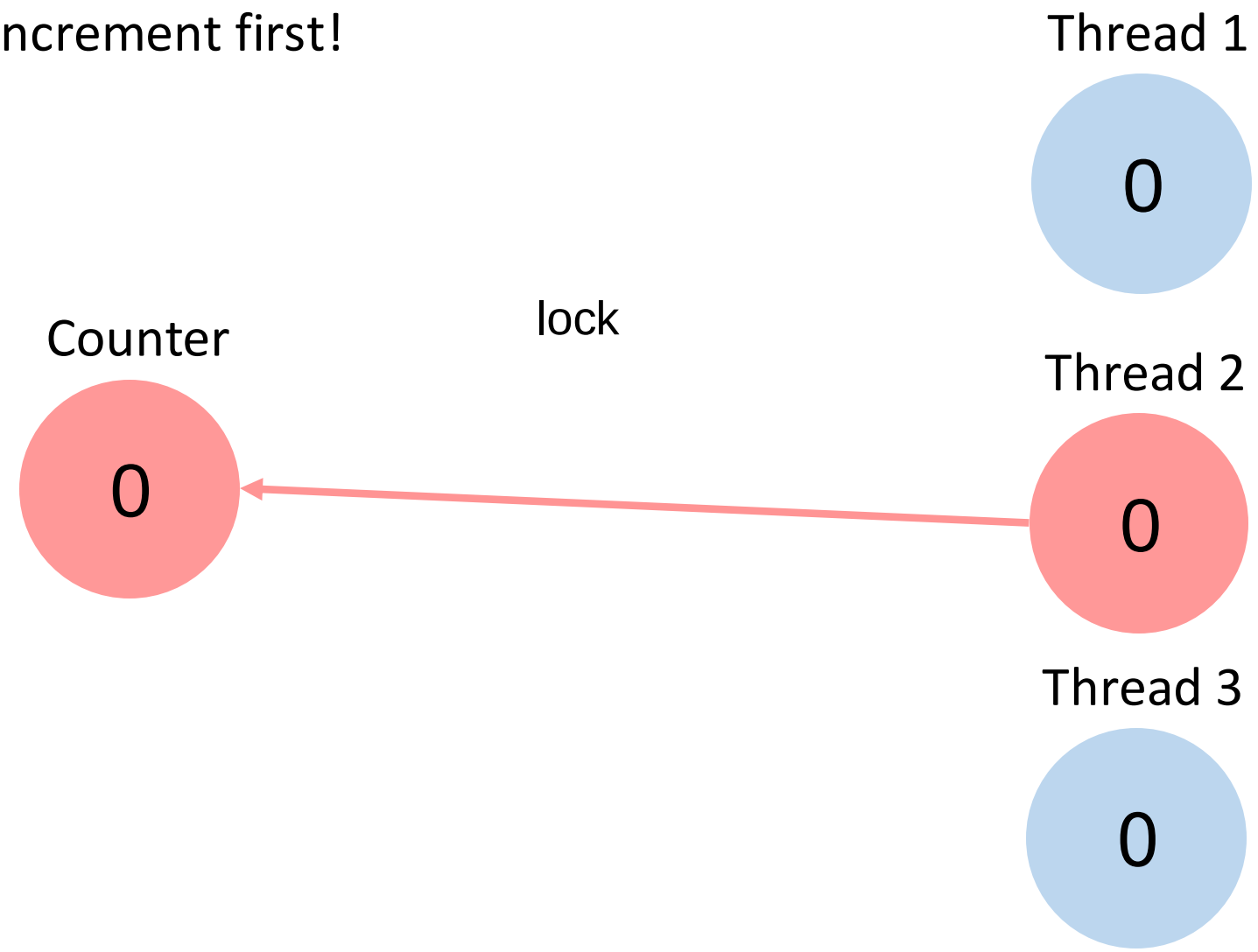
- ➔ Implement a FairThreadCounter that ensures that different threads increment the Counter in a round-robin fashion. In round-robin scheduling the threads perform the increments in circular order. That is, two threads with ids 1 and 2 would increment the value in the following order 1, 2, 1, 2, 1, 2, etc.
- ➔ You should implement the scheduling using the **wait** and **notify** methods.
- ➔ Can you think of implementation that does not use wait and notify methods?

Thread 1 must increment first!

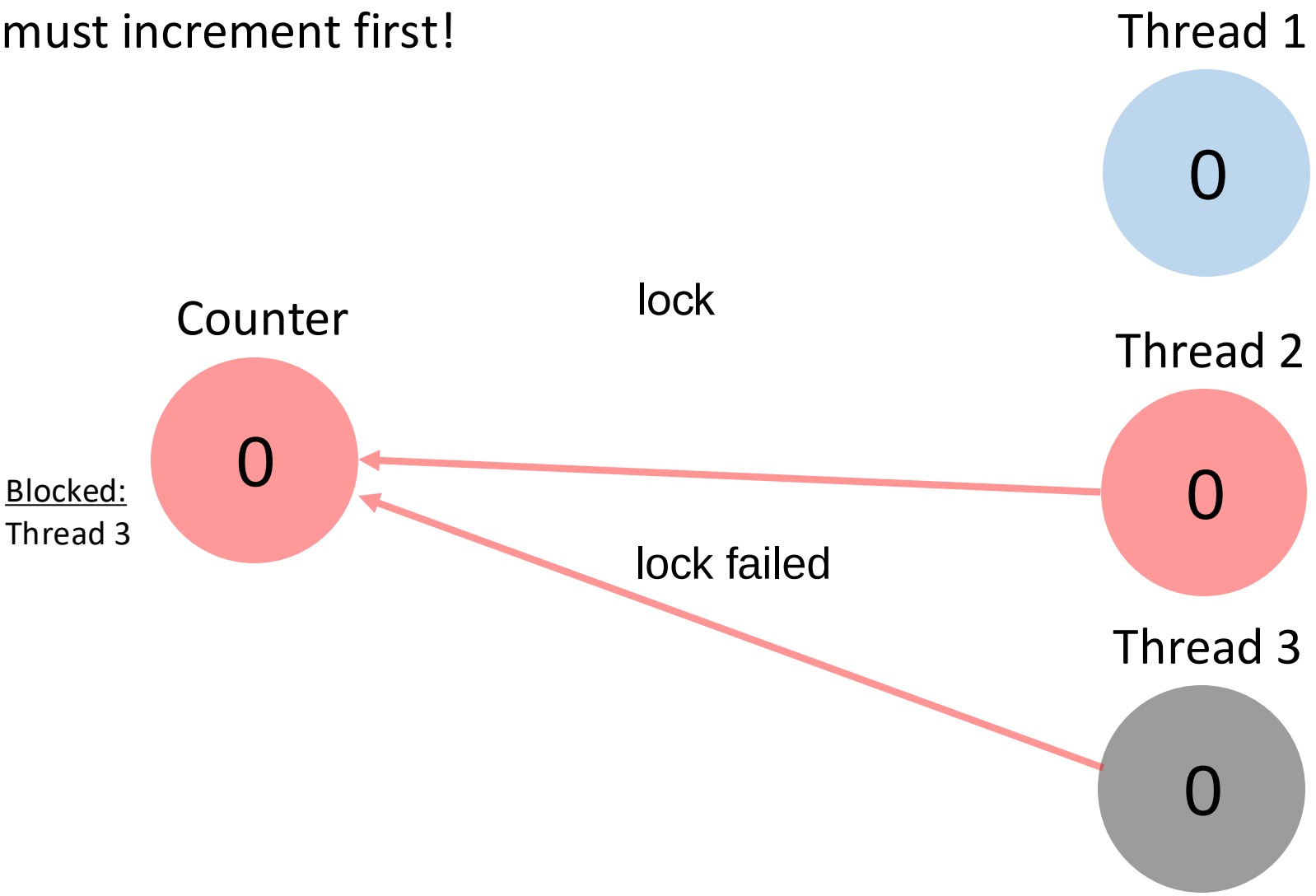


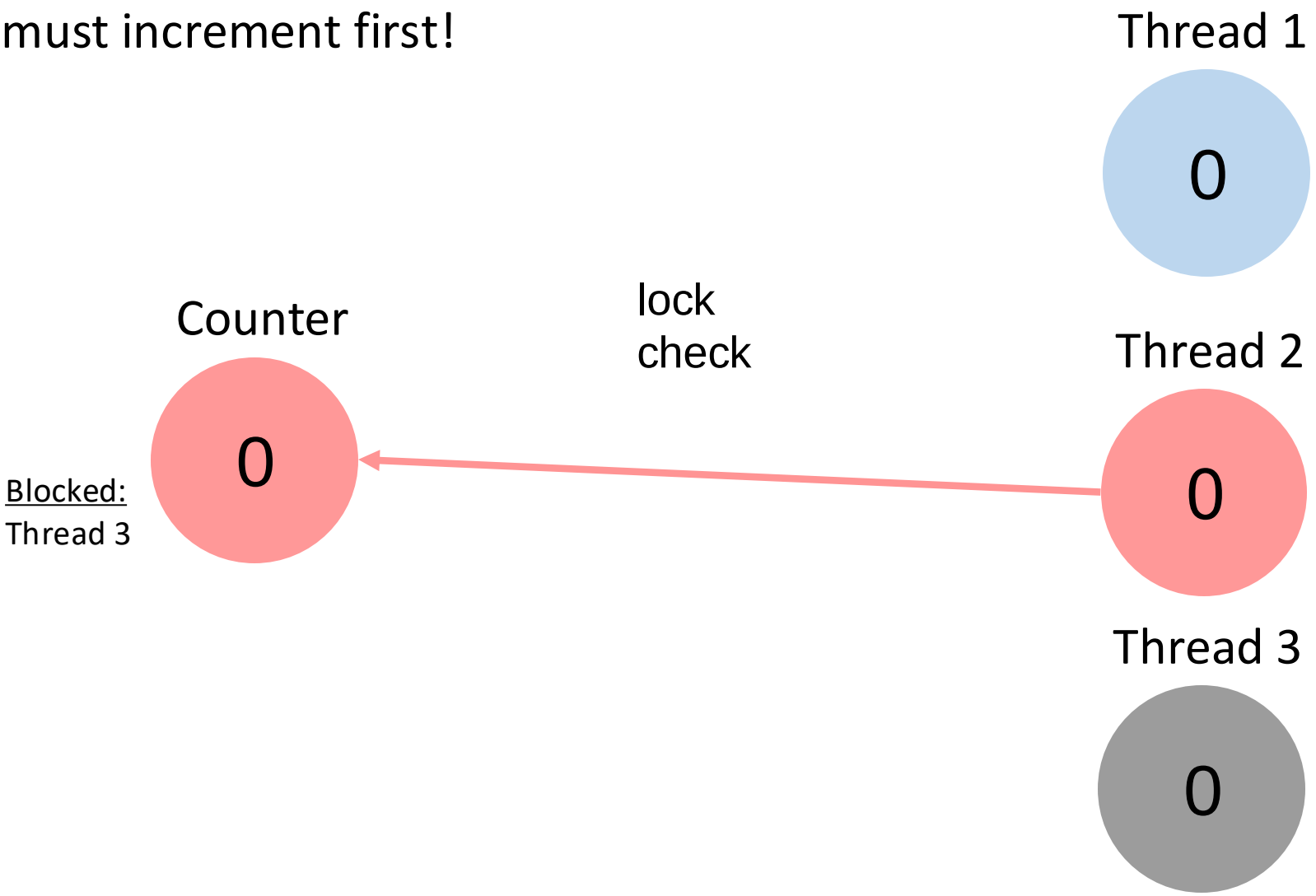
Thread 1 must increment first!



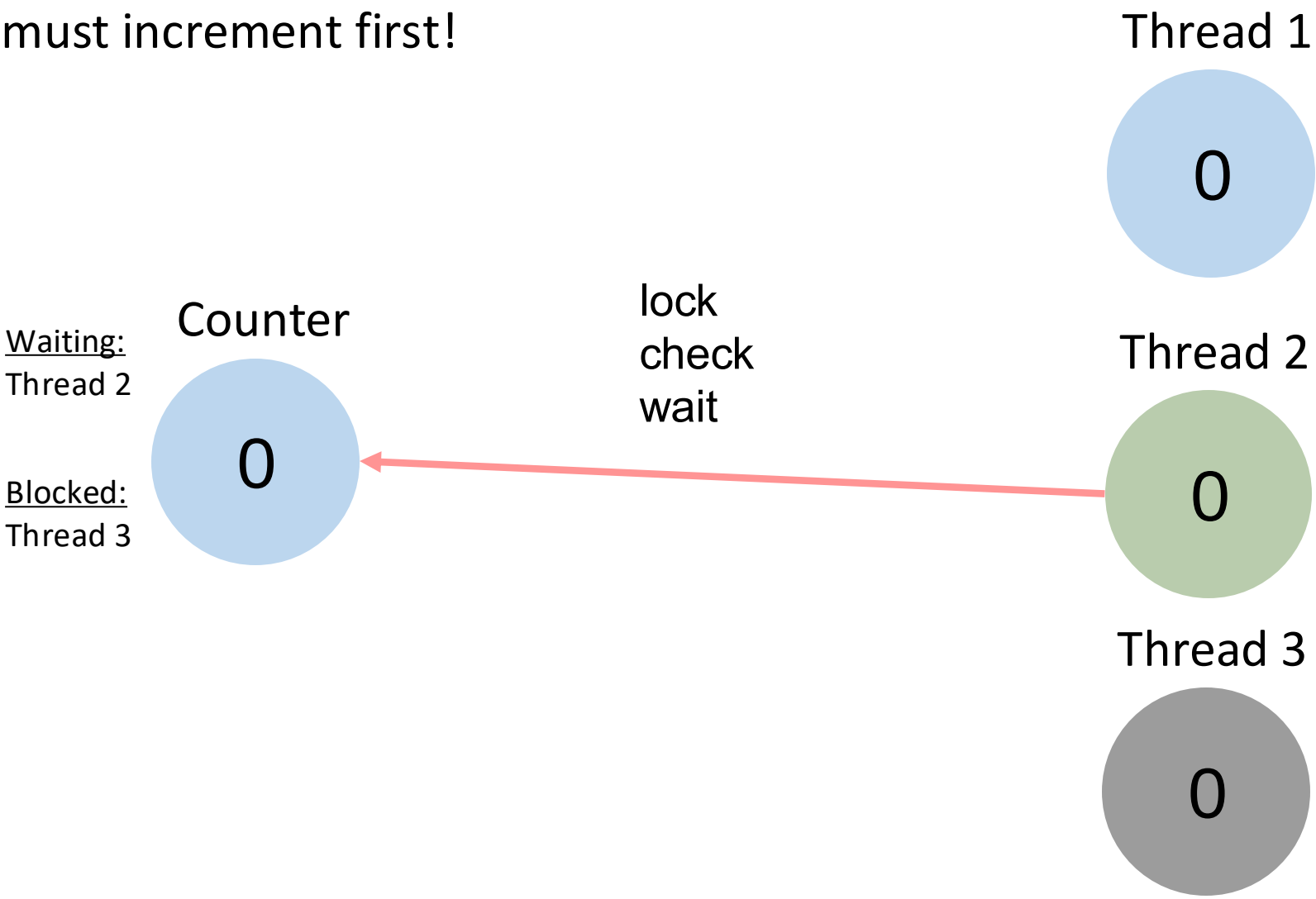
Thread 1 must increment first!



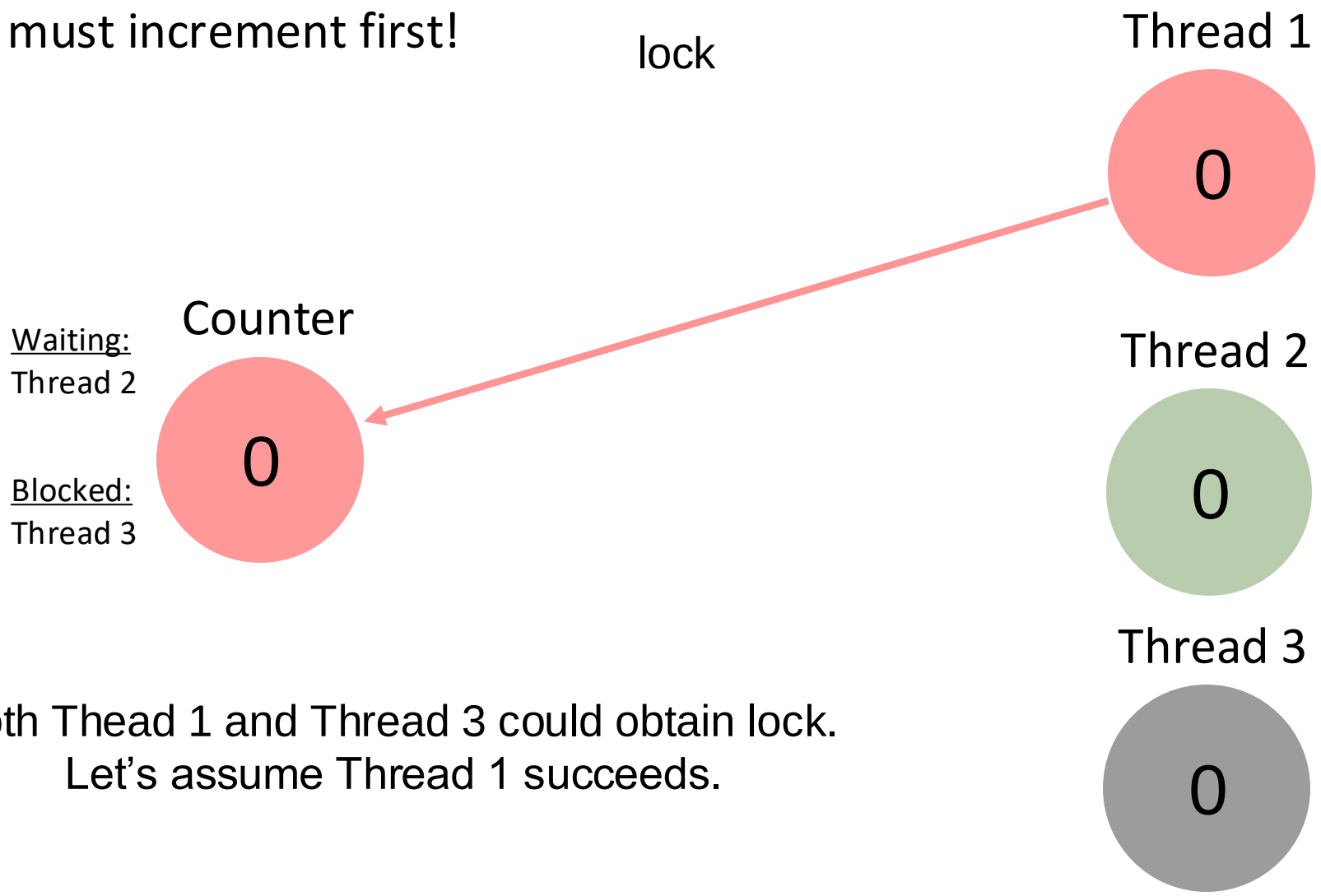
Thread 1 must increment first!



Thread 1 must increment first!

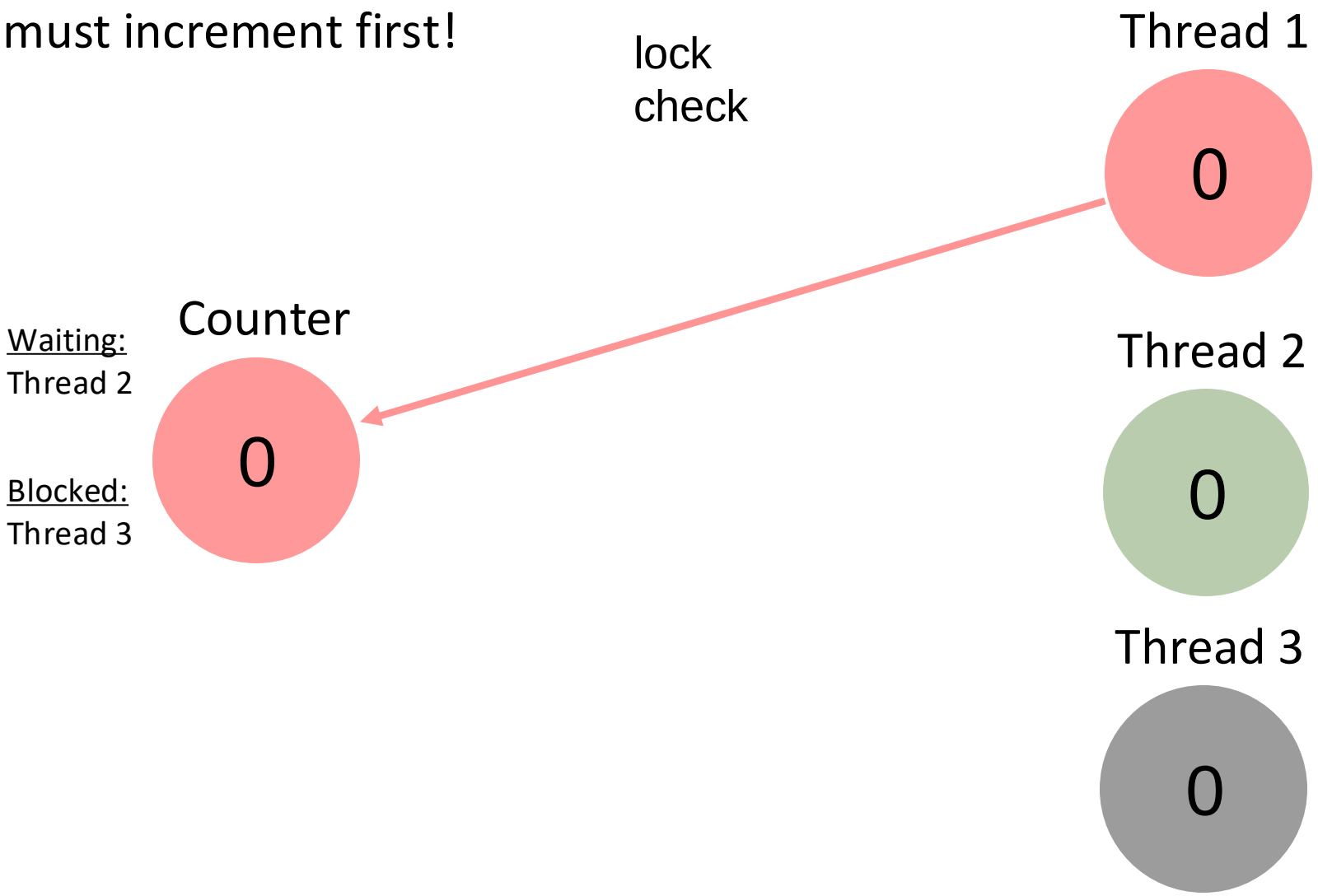


Thread 1 must increment first!

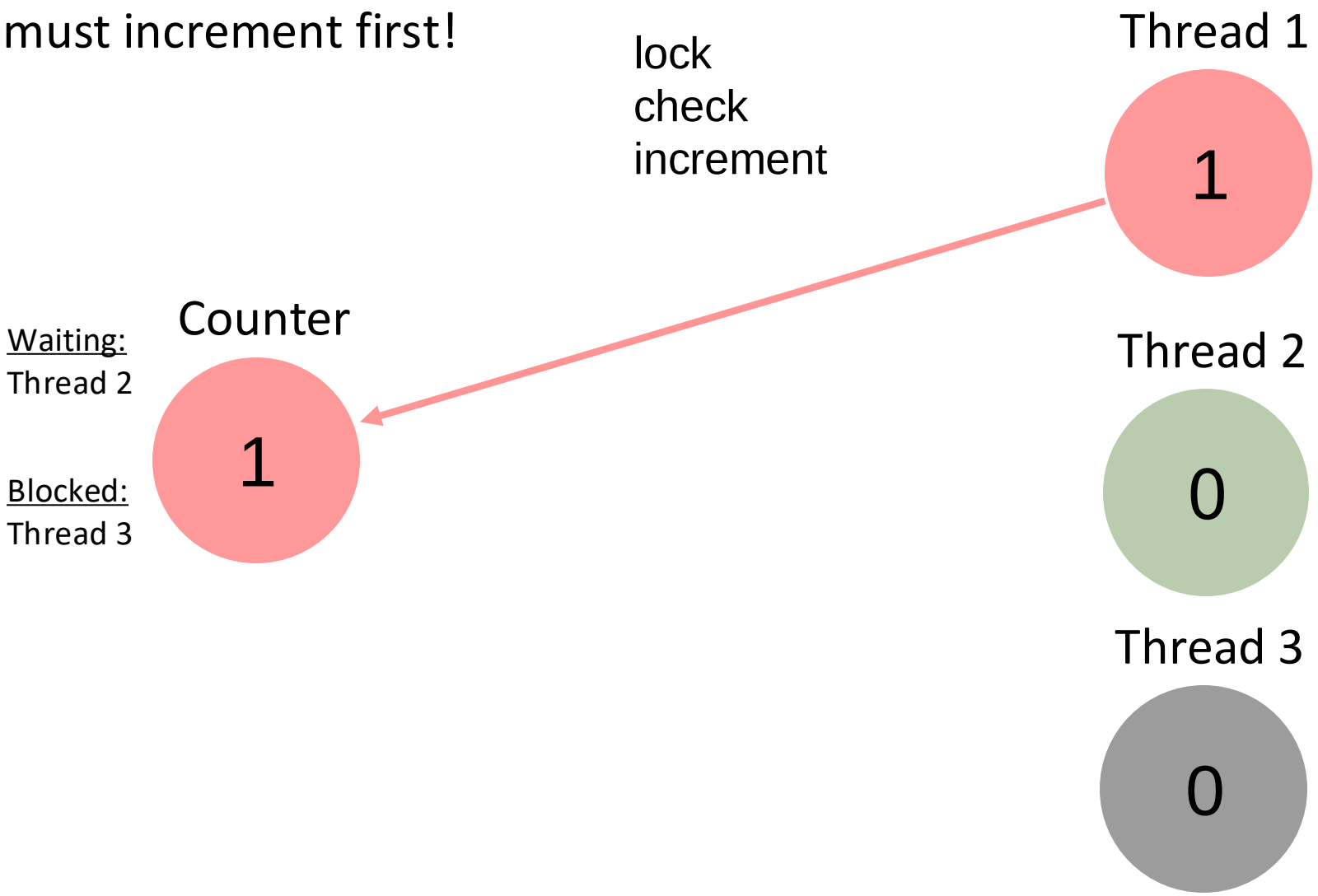



Both Thead 1 and Thread 3 could obtain lock.
Let's assume Thread 1 succeeds.

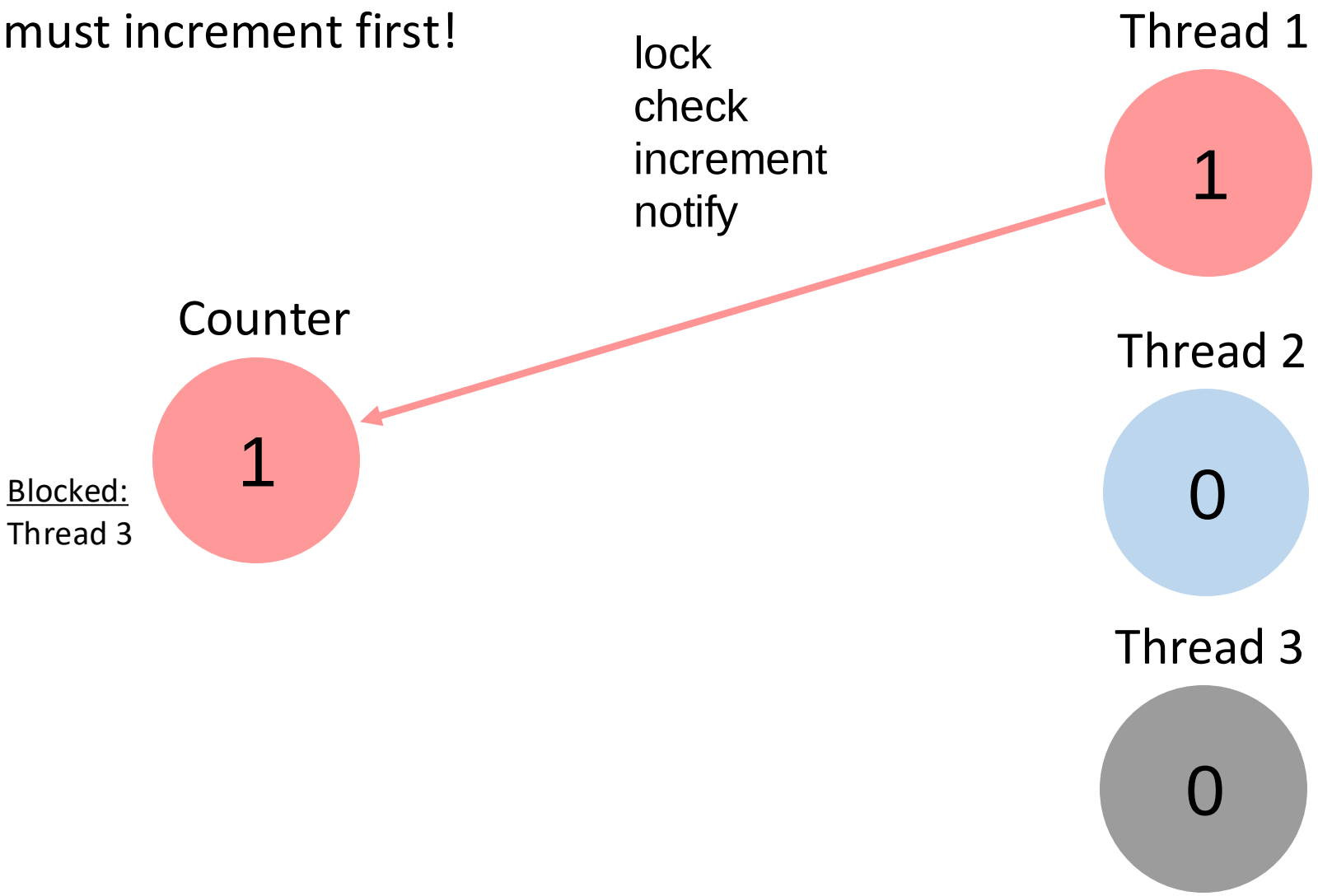
Thread 1 must increment first!



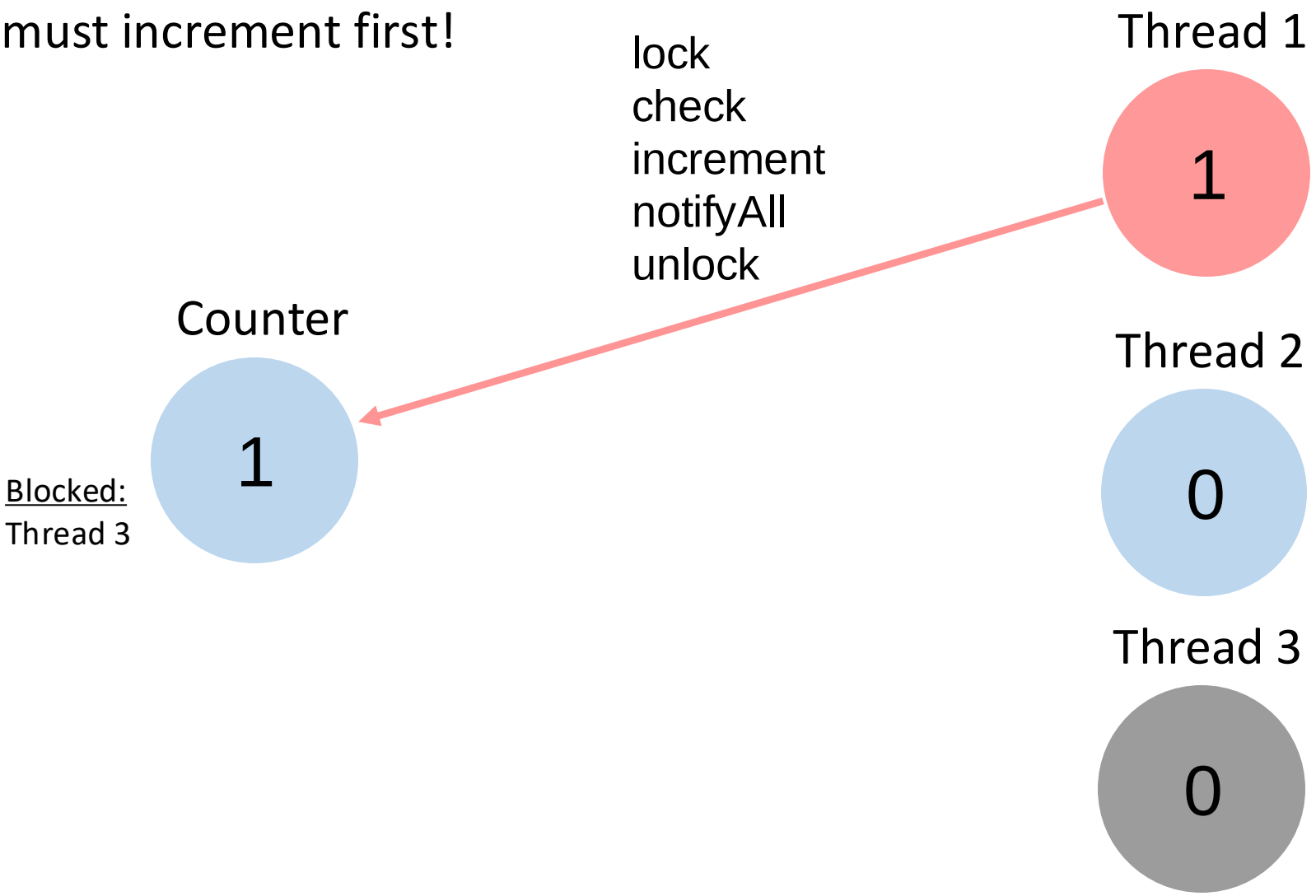
Thread 1 must increment first!



Thread 1 must increment first!



Thread 1 must increment first!



# Task E – Atomic counter

Implement a thread safe version of the Counter in AtomicCounter. In this version we will use an implementation of the int primitive value, called AtomicInteger, that can be safely used from multiple threads.

# Atomic Variables

- ➔ Set of classes providing implementation of atomic variables in Java, e.g., AtomicInteger, AtomicLong, ...
- ➔ An operation is atomic if no other thread can see it partially executed. Atomic as in “appears indivisible”.
- ➔ Implemented using special hardware primitives (instructions) for concurrency. ***Will be covered in detail later in the course.***

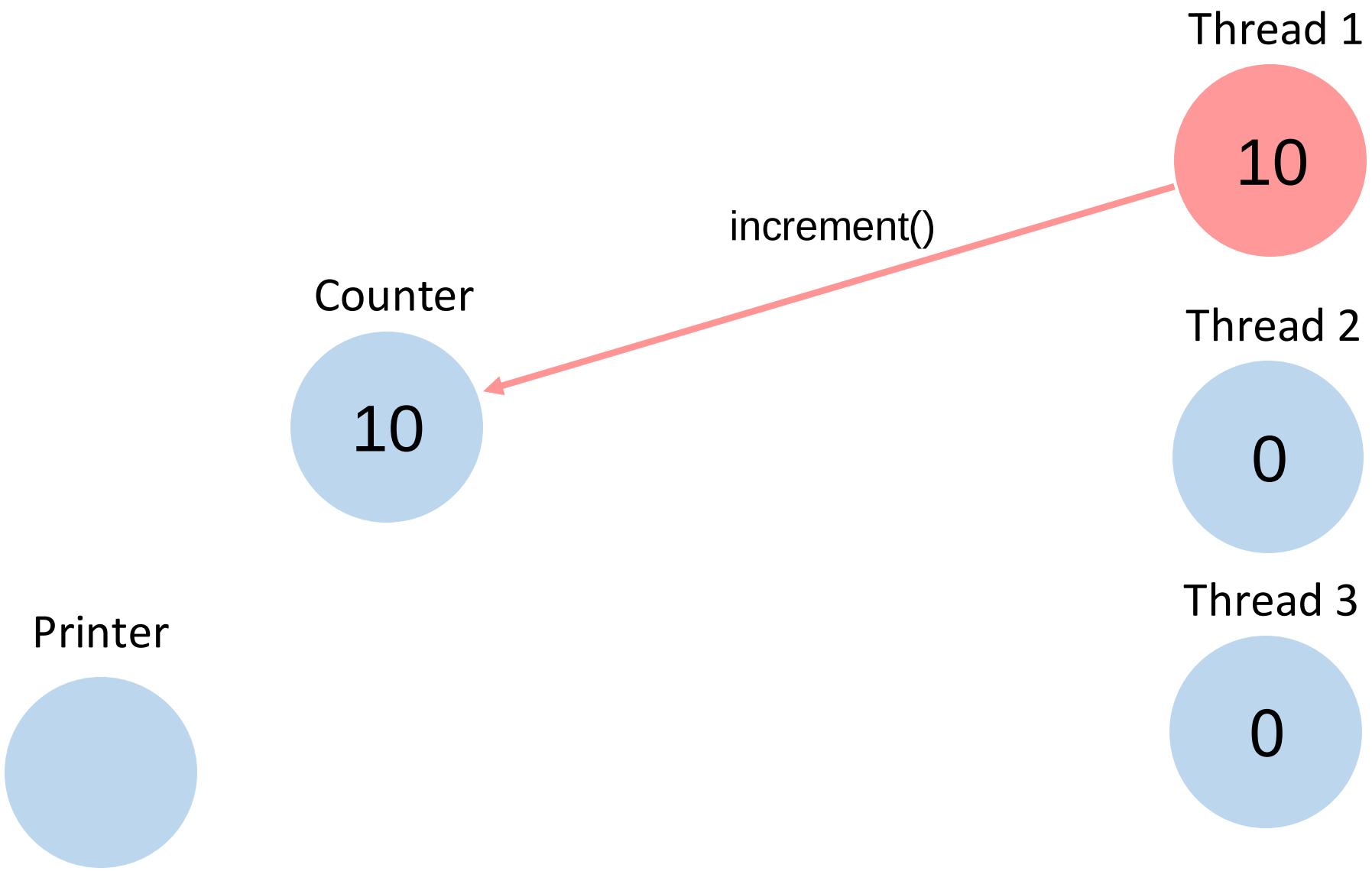
# Task F – Atomic vs Synchronized counter

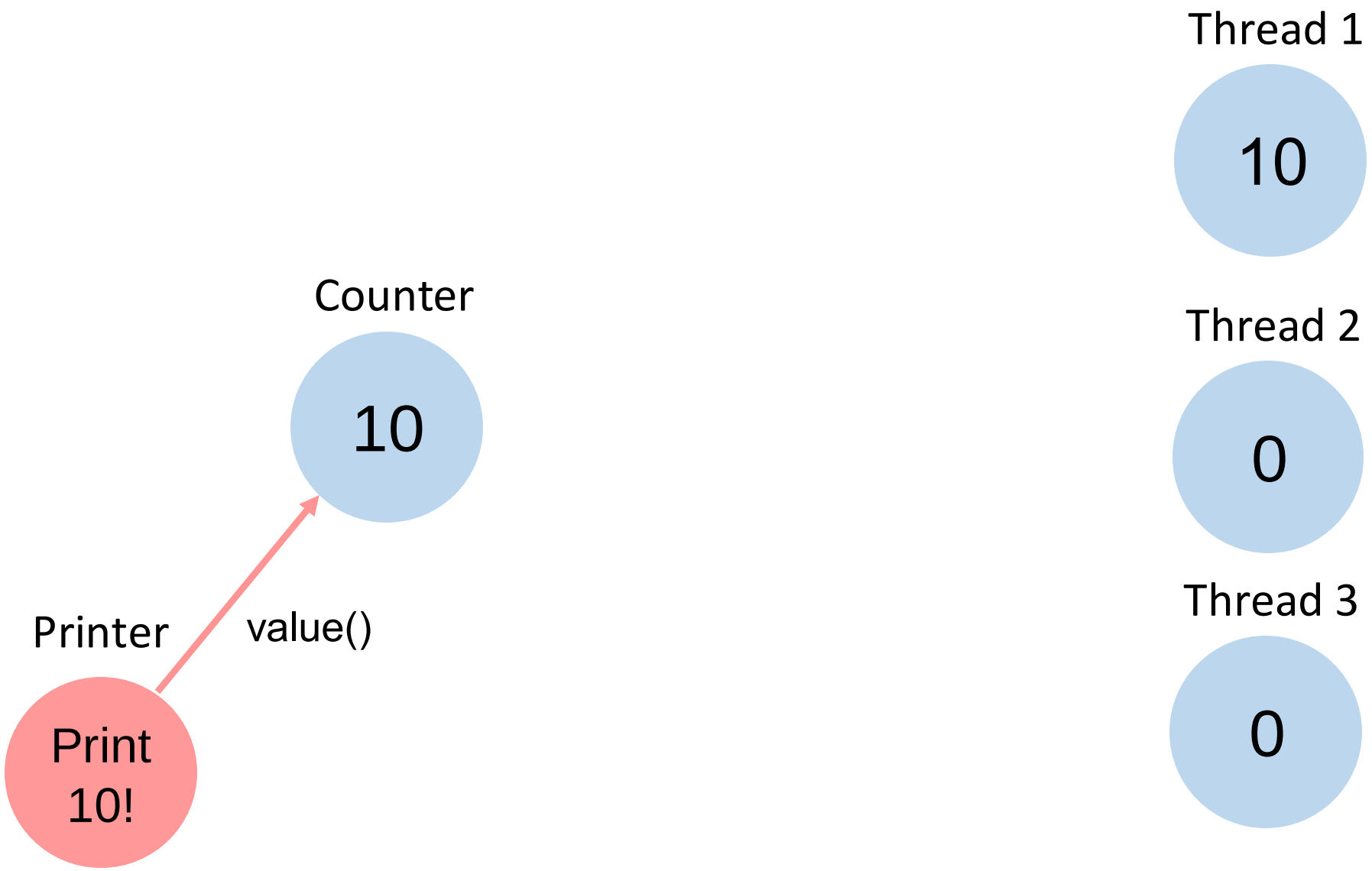
Experimentally compare the AtomicCounter and SynchronizedCounter implementations by measuring which one is faster. Observe the differences in the CPU load between the two versions. Can you explain what is the cause of different performance characteristics?

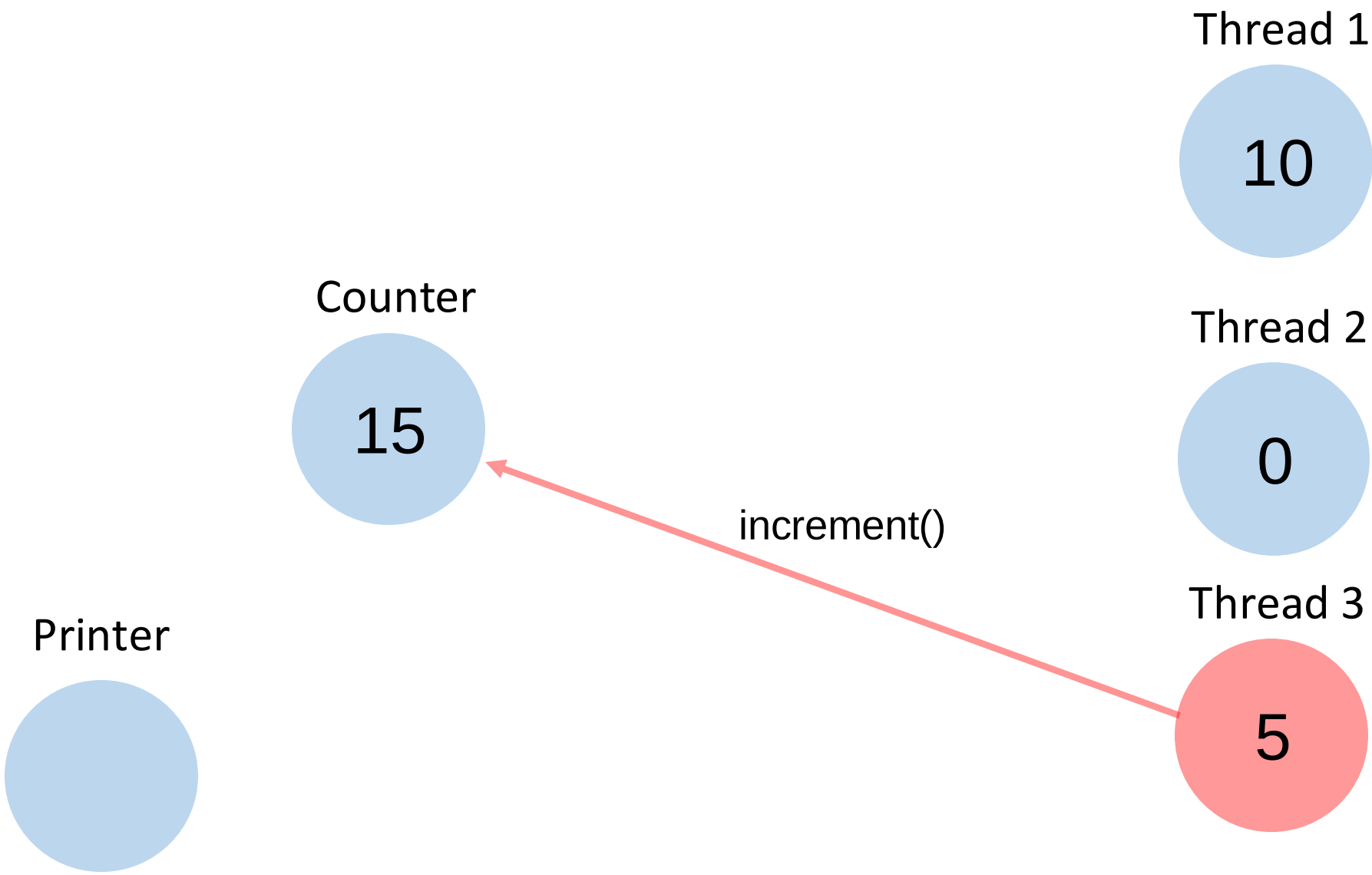
- Vary the load per thread
- Vary the number of threads

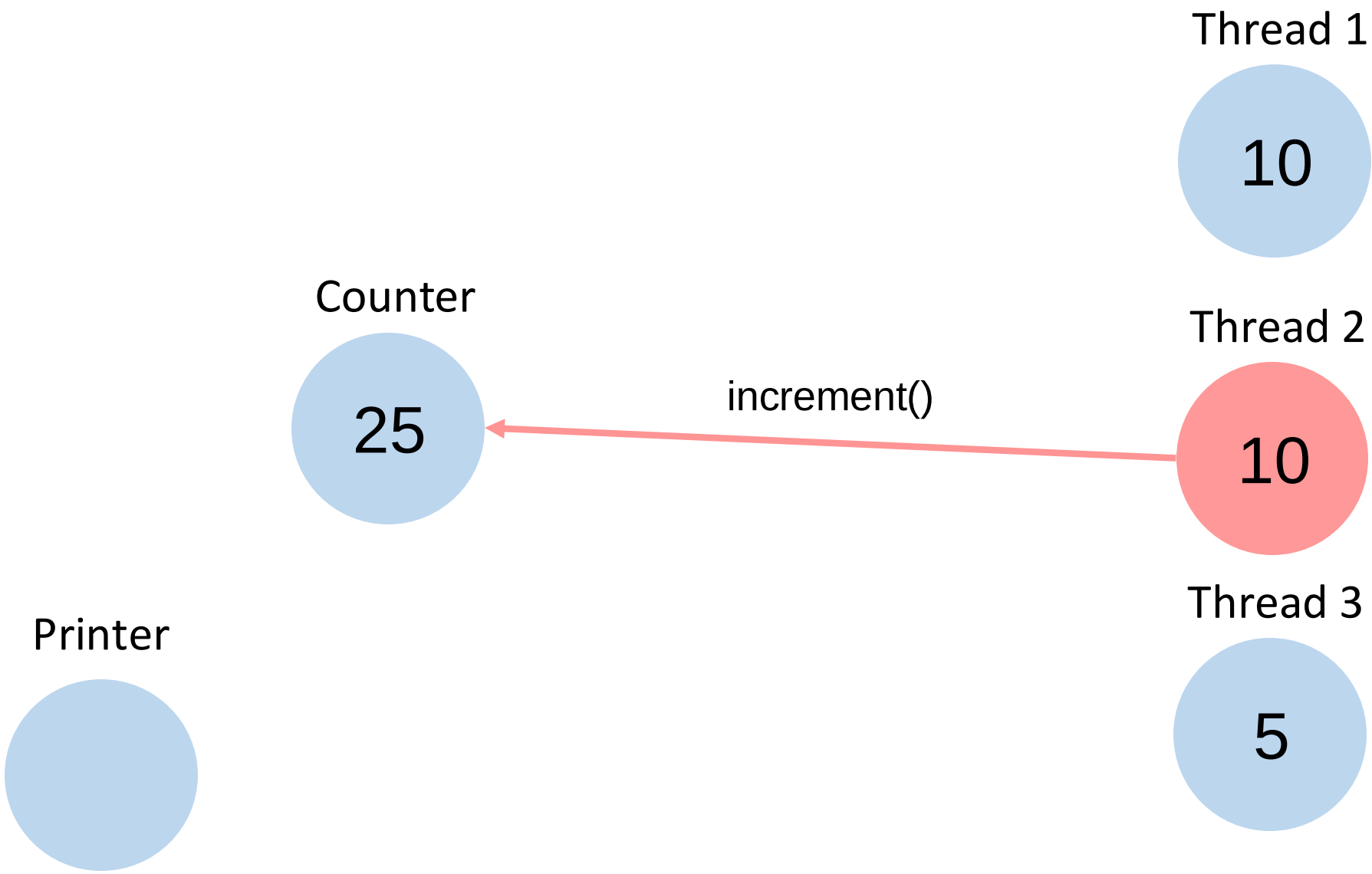
# Task G

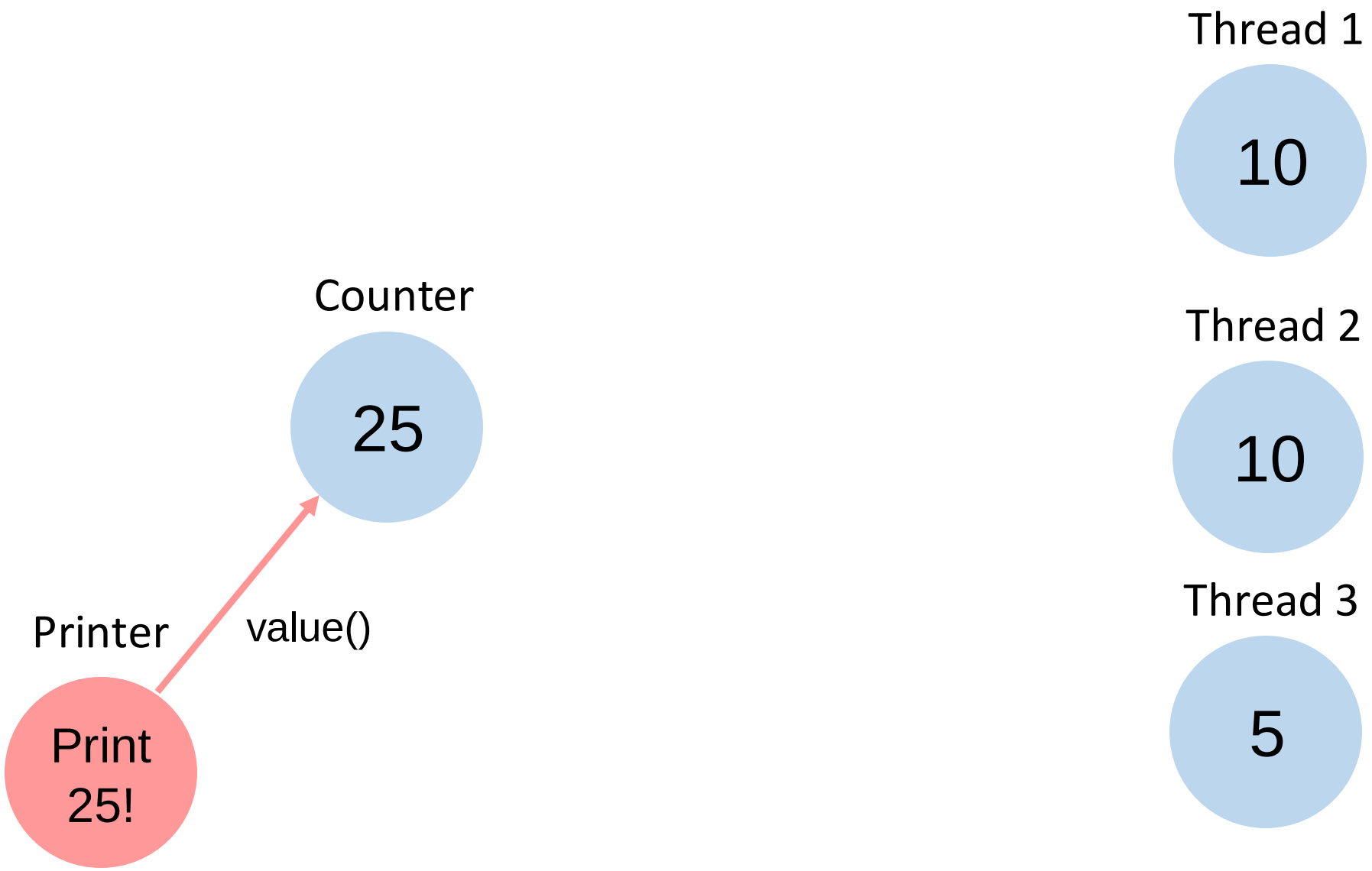
Implement a thread that measures execution progress. That is, create a thread that observes the values of the Counter during the execution and prints them to the console. Make sure that the thread is properly terminated once all the work is done [thread.interrupt()].

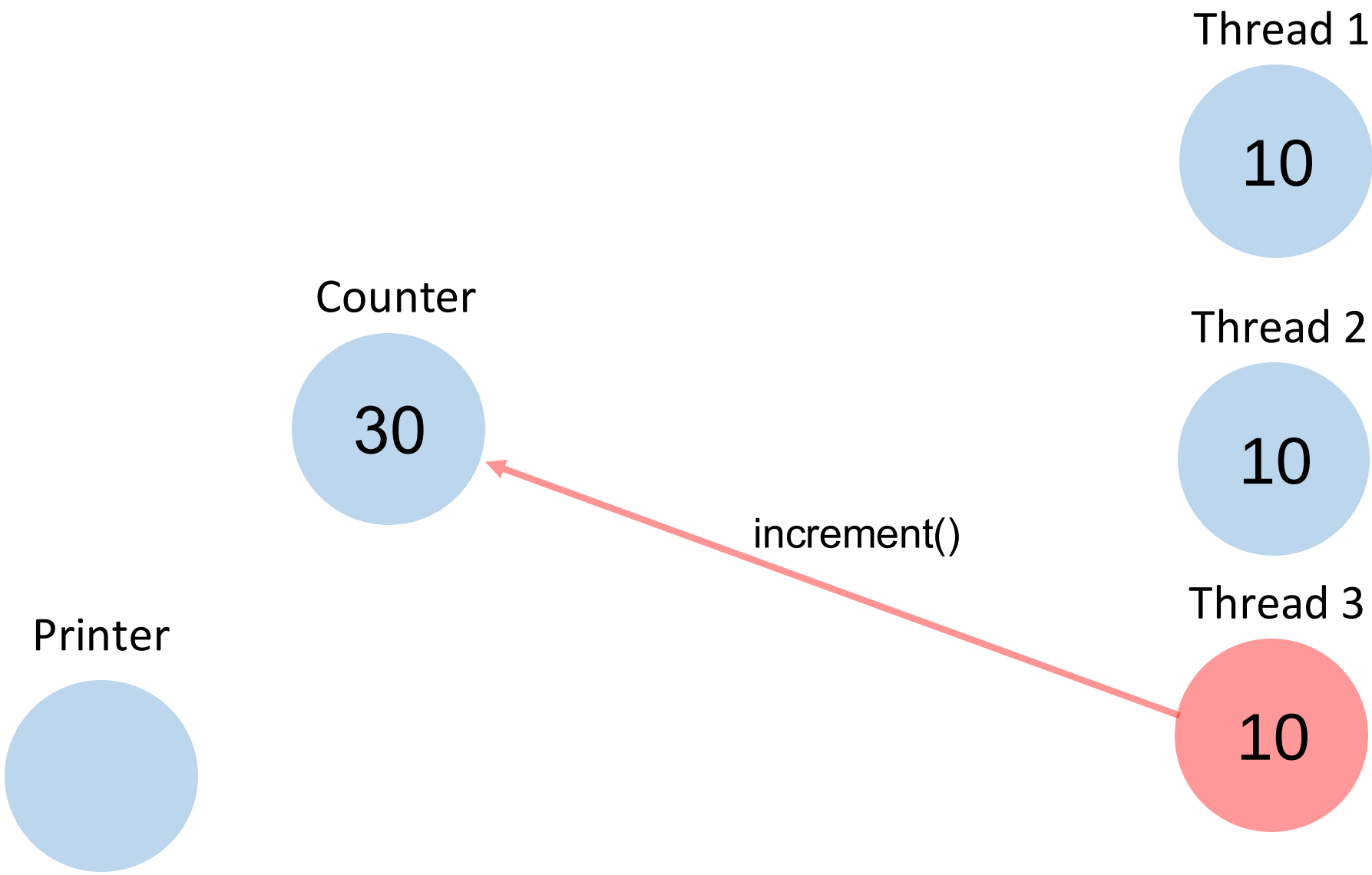

Thread 1
10
increment()
Counter
10
Thread 2
0
Thread 3
0
Printer

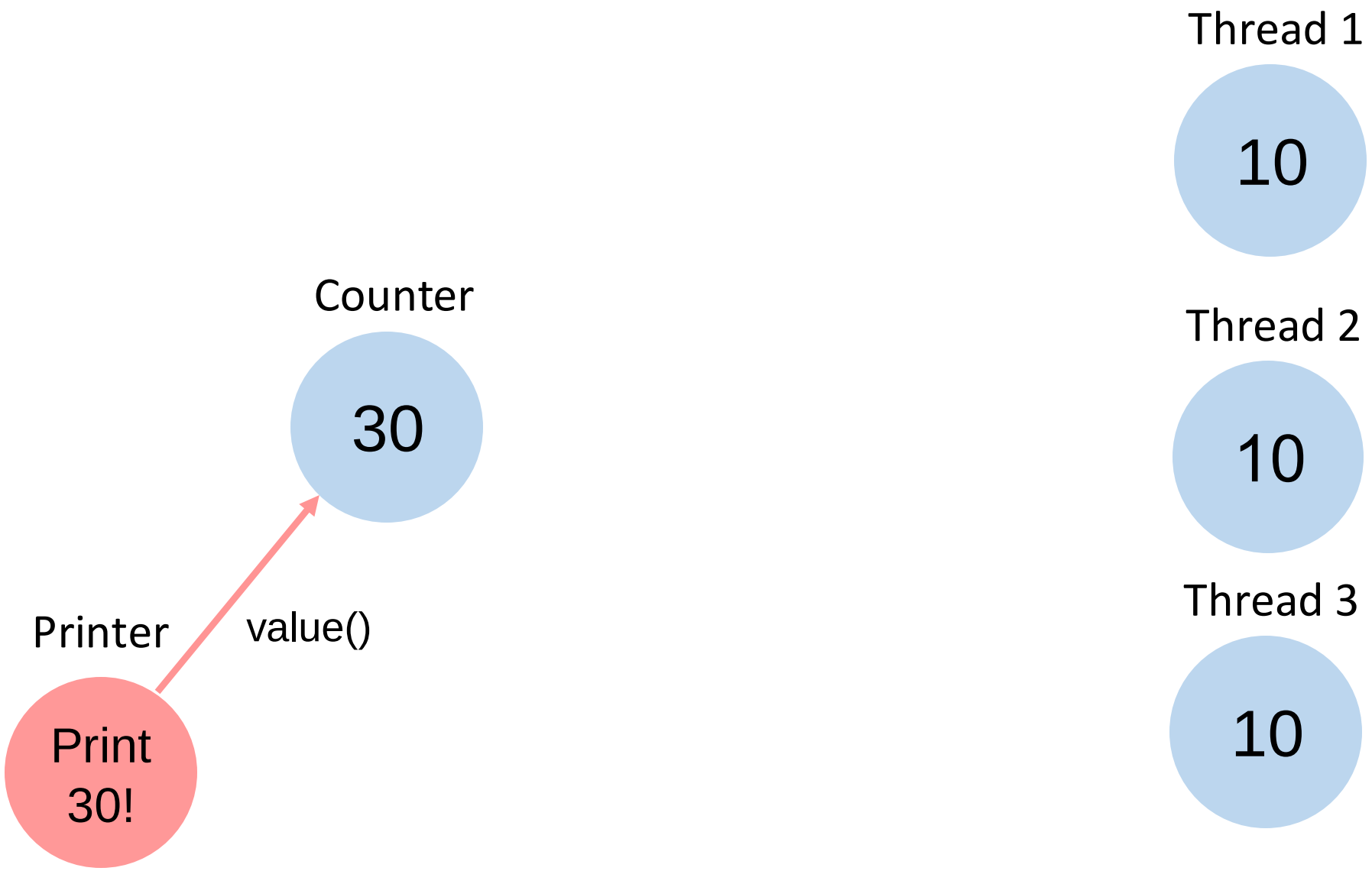

Thread 1
10
Thread 2
0
Thread 3
0
Counter
10
Printer
value()
Print
10!


Thread 1
10
Counter
15
Thread 2
0
increment()
Thread 3
5
Printer


Thread 1
10
Counter
25
increment()
Thread 2
10
Printer
Thread 3
5


Thread 1
10
Thread 2
10
Thread 3
5
Counter
25
Printer
value()
Print
25!


Thread 1
10
Counter
30
Thread 2
10
increment()
Thread 3
10
Printer


Thread 1
10
Thread 2
10
Thread 3
10
Counter
30
Printer
value()
Print
30!

# Homework Assignments

I highly recommend doing the homework assignments

- → Check and deepen your knowledge
- → Feedback: Push to GitLab and then message me