



# Concurrency Building Blocks

Principles of Functional Programming

Martin Odersky and Viktor Kuncak

## Recap: Concurrency Operations

- ▶ `thread(...)` to spawn a thread
- ▶ `t.join()` to wait for `t` to finish
- ▶ `synchronized(...)` for atomic execution
- ▶ `wait`, `notify`, `notifyAll` for signalling inside monitors
- ▶ `@volatile` for safe publishing of fields

## Memory Models in General

A memory model is an abstraction of the hardware capabilities of different computer systems.

It essentially abstracts over the underlying systems *cache coherence protocol*.

Memory models are non-deterministic, to allow some freedom of implementation in compiler and hardware.

Every memory model is a compromise, since it has to trade off between:

- ▶ more guarantees = easier to write concurrent programs,
- ▶ fewer guarantees = more capabilities for optimizations.

## Recap: Sequential Consistency

*The result of any execution is the same as if the operations of all threads were executed in some sequential order, and the operations of each individual thread appear in this sequence in the order specified by its program.*

This is a relatively strong guarantee

- + Simple to reason about
- Inefficient to implement

## Recap: The Java Memory Model

Define a “*happens-before*” relationship as follows.

- ▶ **Program order:** Each action in a thread *happens-before* every subsequent action in the same thread.
- ▶ **Monitor locking:** Unlocking a monitor *happens-before* every subsequent locking of that monitor
- ▶ **Volatile fields:** A write to a volatile field *happens-before* every subsequent read of that field.
- ▶ **Thread start:** A call to `start()` on a thread *happens-before* all actions of that thread.
- ▶ **Thread termination.** An action in a thread *happens-before* another thread completes a `join` on that thread.
- ▶ **Transitivity.** If A happens before B and B *happens-before* C, then A *happens-before* C.

## Ctd: The Java Memory Model

Now,

- ▶ A program point of a thread  $t$  is *guaranteed* to see all actions that *happen\_before* it.
- ▶ It *may* also see actions that can occur before it in the sequential consistency (interleaving) model.

The second point is the source of non-determinism of the model.

## Example: The Java Memory Model

Consider:

```
val x = 0; val y = 0;
```

```
val t1 = thread {  
    x = 1  
    lock.synchronized {  
        y = 2  
    }  
}
```

```
val t2 = thread {  
    println(x)  
    lock.synchronized { println(y) }  
    println(x)  
}
```

Then we have:

# Executors

Thread creation is expensive.

Therefore, one often multiplexes threads to perform different tasks.

The JVM offers abstractions for that: ThreadPools and Executors.

- ▶ Threads become in essence the workhorses that perform various tasks presented to them.
- ▶ The number of available threads in a pool is typically some polynomial of the number of cores  $N$ . (e.g.,  $N^2$ )
- ▶ That number is independent of the number of concurrent activities to perform.



# Runnables

A task presented to an executor is encapsulated in a Runnable object.

Its signature is as follows.

```
trait Runnable:  
  def run(): Unit // actions to be performed by the task
```

## Forking a Task

Here's how a task gets passed to the ForkJoinPool executor:

```
import java.util.concurrent.ForkJoinPool
@main def ExecutorsCreate =
  val executor = new ForkJoinPool
  executor.execute(new Runnable:
    def run() = log("This task is run asynchronously.")
  )
  Thread.sleep(500)
```

ForkJoinPool is a system provided thread-pool which also handles tasks spawned by Scala's implementation of parallel collections (and Java 8's implementation of streams).

## Notes

1. Tasks are run by passing Runnable objects to an executor.
2. There is no way to await the end of a task, as we did with `t.join()` for threads.
3. Instead, we pause the main thread to give the executor threads time to finish.
4. Alternatively, we could do the following

```
import java.util.concurrent.TimeUnit  
executor.shutdown()  
executor.awaitTermination(60, TimeUnit.SECONDS)
```

Methods `awaitTermination` and `shutdown` are defined in the Java interface `ExecutorService`, which is also inherited by `ForkJoinPool`.

## Execution Contexts

The `scala.concurrent` package defines the `ExecutionContext` trait and object which is similar to `Executor` but more specific to Scala.

Execution contexts are passed as implicit parameters to many of Scala's concurrency abstractions.

Here's how one runs a task using the default execution context:

```
import scala.concurrent
@main def ExecutionContextCreate =
  val ectx = ExecutionContext.global
  ectx.execute(new Runnable:
    def run() = log("This task is run asynchronously.")
  )
  Thread.sleep(500)
```

## Hiding Boilerplate

To hide the boilerplate around executing tasks we define this utility method in the package object of the package where examples are run (i.e. in file `concurrent/package.scala`).

```
package object concurrent:
  ...
  def execute(body: => Unit) =
    scala.concurrent.ExecutionContext.global.execute(
      new Runnable { def run() = body })
```

## Simplified Task Execution

With the helper method, we can spawn tasks as follows:

```
package concurrent
import scala.concurrent._
@main def SimpleExecute =
  execute{ log("This task is run asynchronously." ) }
  Thread.sleep(500)
```

## Atomic Primitives

So far, we have based concurrent operations on `synchronized`, `wait`, `notify` and `notifyAll`.

These are all complex operations which require support from the OS scheduler.

We now look at the primitives in terms of which these higher-level operations are implemented.

On the JVM these primitives are based on the notion of an *atomic variable*.

# Atomic Variables

An atomic variable is a memory location that supports **linearizable** operations.

A **linearizable** operation is one that appears instantaneously with the rest of the system. We also say the operation is performed **atomically**.

Classes that create atomic variables are defined in package

```
java.util.concurrent.atomic
```

They include

```
AtomicInteger, AtomicLong, AtomicBoolean, AtomicReference
```



## Using Atomic Variables

Here's how `getUniqueId` can be defined without `synchronized`:

```
import java.util.concurrent.atomic._

@main def AtomicUid =
  private val uid = new AtomicLong(0L)
  def getUniqueId(): Long = uid.incrementAndGet()
  execute {
    log(s"Got a unique id asynchronously: ${getUniqueId()}")
  }
  log(s"Got a unique id: ${getUniqueId()}")
```

# Atomic Operations

The `incrementAndGet` method is a complex, linearizable operation.

It reads the value `x` of `uid`, computes `x + 1`, stores the result back in `uid` and returns it.

No intermediate result can be observed by other threads.

Other linearizable method offered by `AtomicLong`:

```
def getAndSet(newValue: Long)
```

This reads the current value of the atomic variable, sets the new value, and returns the previous value.

## Compare and Swap

Atomic Operations are usually all based on the **compare-and-swap (CAS)** primitive.

CAS is available as a `compareAndSet` method on atomic variables.

It is usually implemented by the underlying hardware as a machine instruction, but we can think of its implementation as follows:

```
class AtomicLong {  
    ...  
    def compareAndSet(expect: Long, update: Long) = this.synchronized {  
        if this.get == expect then { this.set(update); true }  
        else false  
    }  
}
```

That is, `compareAndSet` atomically sets the value to the given updated value if the current value equals the expected value.

## Using CAS

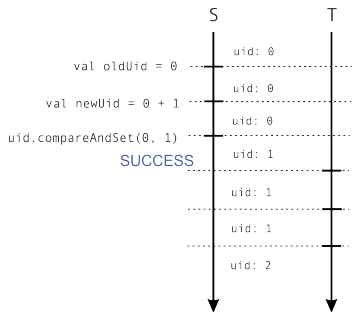
Let's implement `getUniqueId` using CAS directly:

```
@tailrec def getUniqueId(): Long =  
    val oldUid = uid.get  
    val newUid = oldUid + 1  
    if uid.compareAndSet(oldUid, newUid) then newUid  
    else getUniqueId()
```

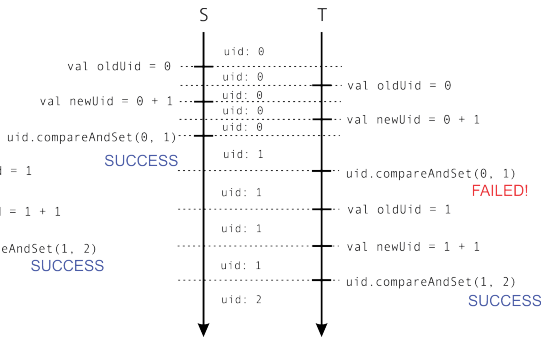
This uses the following general schema:

1. Read the old value from the atomic variable
2. Compute the new value
3. Try to do a CAS.
  - ▶ If successful, the value was updated, and we are done.
  - ▶ If unsuccessful, some other thread had stored a new value in the meantime. In that case, try the same operation again.

# Execution Diagram



Execution without retries



Execution with retries

# Programming Without Locks

Locks as implemented by `synchronized` are a convenient concurrency mechanism.

But they are also problematic

- ▶ possibility of deadlock
- ▶ possibility to arbitrarily delay other threads if a thread executes a long-running operation in a `synchronized`, or if it gets pre-empted by the OS.

With atomic variables and their **lock-free operations**, we can avoid these problems.

A thread executing a lock-free operation cannot be pre-empted by the OS, so it cannot temporarily block other threads.

## Simulating Locks

However, not all operations composed from atomic primitives are lock-free.

In fact, we can implement synchronized only from atomic operations:

```
private val lock = new AtomicBoolean(false)
def mySynchronized(body: => Unit): Unit =
  while !lock.compareAndSet(false, true) do {}
  try body
  finally lock.set(false)
```

So, atomic operations can be used to model locks and locking operations.

## Lock-Free Operations

Here is a way to define lock-freedom without looking at implementation primitives:

*An operation  $op$  is lock-free if whenever there is a set of threads executing  $op$  at least one thread completes the operation after a finite number of steps, regardless of the speed in which the different threads progress.*



## Example

Is this operation lock-free?

```
@tailrec def getId(): Long =  
    val oldUid = uid.get  
    val newUid = oldUid + 1  
    if uid.compareAndSet(oldUid, newUid) then newUid  
    else getId()
```

Problem: It is (tail-)recursive, so could take arbitrarily long.

## Example

Is this operation lock-free?

```
@tailrec def getId(): Long =  
    val oldId = uid.get  
    val newId = oldId + 1  
    if uid.compareAndSet(oldId, newId) then newId  
    else getId()
```

Problem: It is (tail-)recursive, so could take arbitrarily long.

However, the recursive call is made only if *some other thread* completed the operation (in a finite number of steps).

This observation proves lock-freedom.

In general, lock-freedom is quite hard to reason about.

# Lazy Values

You know about lazy values in Scala.

```
lazy val x: T = E
```

We now look at how to implement them so that several threads can use a lazy value.

Would like to achieve the following:

- ▶ The first thread that demands a lazy value computes it.
- ▶ Other threads will block until the value is computed by the first thread.
- ▶ That way, every lazy value initializer is executed at most once.

## Lazy Values (1)

Here is a first, naive implementation of the definition of `x` above:

```
import compiletime.uninitialized
private var x_defined = false
private var x_cached: T = uninitialized

def x: T =
  if !x_defined then
    x_cached = E
    x_defined = true
  x_cached
```

What is wrong with this implementation?

## Lazy Values (2)

The previous implementation of `x` is not thread-safe.

- ▶ `E` might be evaluated several times
- ▶ We might access `x` without a value (possible reordering between `x_defined` and `x_cached` assignments).

## Lazy Values (3)

Here's a safer implementation:

```
private var x_defined = false
private var x_cached: T = uninitialized

def x: T = this.synchronized {
  if !x_defined then
    x_cached = E
    x_defined = true
  x_cached
}
```

What are potential problems with this implementation?

## Lazy Values (4)

The synchronized call on every access is quite costly. Here is a faster implementation:

```
@volatile private var x_defined = false
private var x_cached: T = uninitialized
def x: T =
  if !x_defined then this.synchronized {
    if !x_defined then { x_cached = E; x_defined = true }
  }
  x_cached
```

This pattern is called *double locking*. How does it work?

## Lazy Values (4)

The synchronized call on every access is quite costly. Here is a faster implementation:

```
@volatile private var x_defined = false
private var x_cached: T = uninitialized
def x: T =
  if !x_defined then this.synchronized {
    if !x_defined then { x_cached = E; x_defined = true }
  }
  x_cached
```

This pattern is called *double locking*. How does it work?

If `x_defined` is set, some thread must have completed the synchronized to do this.



## Lazy Values (5)

The previous implementation of lazy values is what *scalac* currently implements in version 2.13.

It's not without problems though:

- ▶ it is not lock free
- ▶ it uses the current object as a lock, which might conflict with application-defined locking.
- ▶ it is prone to deadlocks.

Consider:

```
object A:  
  lazy val x = B.y
```

```
object B:  
  lazy val y = A.x
```

What does this do in a sequential setting? What can it do in a concurrent one?

## Better Lazy Values

An alternative implementation of lazy values uses two flag bits per lazy value:

```
private var x_evaluating = false  
private var x_defined = false  
private var x_cached = uninitialized
```

## Better Lazy Values (2)

The implementation of the getter `x` is as follows:

```
def x: T =  
  if !x_defined then  
    this.synchronized {  
      if x_evaluating then wait() else x_evaluating = true  
    }  
  if !x_defined then  
    x_cached = E  
    this.synchronized {  
      x_evaluating = false; x_defined = true; notifyAll()  
    }  
  x_cached
```

## Better Lazy Values (3)

This is essentially the implementation scheme used in the new Scala 3 compiler, dotc, developed at LAMP/EPFL.

Notes:

- ▶ The evaluation of expression E happens outside a monitor, therefore no arbitrary slowdowns.
- ▶ Two short synchronized blocks instead of one arbitrary long one.
- ▶ No interference with user-defined locks.
- ▶ lazy val/lazy val deadlocks are still possible with the new implementation, but only in cases where sequential execution would give an infinite loop.

**Exercise:** Implement the new getter implementation using only atomic operations.

## Using Collections Concurrently

Operations on mutable collections are usually not thread-safe.

Example:

```
import scala.collection._
@main def CollectionBad =
  val buffer = mutable.ArrayBuffer[Int]()
  def add(numbers: Seq[Int]) = execute {
    buffer += numbers
    log(s"buffer = $buffer")
  }
  add(0 until 10)
  add(10 until 20)
  Thread.sleep(1000)
```

This can give arbitrary interleavings of elements in buffer and it can also crash.

## Using Synchronization

A safe way to deal with this is to use synchronized:

```
val buffer = mutable.ArrayBuffer[Int]()  
def add(numbers: Seq[Int]) = execute {  
  buffer.synchronized {  
    buffer += numbers  
    log(s"buffer = $buffer")  
  }  
}
```

## Concurrent Collections

Using synchronized often leads to too much blocking because of *coarse-grained locking*.

To gain speed, we can use or implement special *concurrent collection* implementations.

Example: Concurrent queues, with operations append, remove.

- ▶ Append needs access to the end of the queue
- ▶ Remove needs access to the beginning of the queue

# Concurrent Queues

We now develop a lock-free concurrent queues implementation.

First step: A sequential implementation.

A queue has two fields:

- ▶ head points to a dummy node *before* the first element
- ▶ last points to the last element (or the dummy node if the queue is empty).

head last

Empty Queue

head last

Non-empty queue



# Sequential Queue Implementation

```
object SeqQueue:  
  private class Node[T](var next: Node[T]):  
    var elem: T = uninitialized
```

```
class SeqQueue[T]:  
  import SeqQueue._  
  private var last = new Node[T](null)  
  private var head = last
```

## Sequential Queue Implementation (ctd)

```
final def append(elem: T): Unit =  
    val last1 = new Node[T](null)  
    last1.elem = elem  
    val prev = last  
    last = last1  
    prev.next = last1
```

```
final def remove(): Option[T] =  
    if head eq last then None  
    else  
        val first = head.next  
        head = first  
        Some(first.elem)
```

# Concurrent Queue Implementation

**Idea:** make head and last atomic (reference) variables.

**Problem:** append needs to atomically update *two* variables:

```
last = last1  
prev.next = last1
```

But CAS can only work on one variable at a time!

**Solution:**

- ▶ Use one CAS (for `last = last1`) and fix the other assignment when successful.
- ▶ This leaves a window of vulnerability where `prev.next == null` instead of `prev.next == last1`.
- ▶ We need to detect and compensate for this in `remove`.

## Concurrent Queue: Setup

```
import java.util.concurrent.atomic._
import scala.annotation.tailrec

object ConcQueue:
  private class Node[T](@volatile var next: Node[T]):
    var elem: T = uninitialized

class ConcQueue[T]:
  import ConcQueue._
  private var last = new AtomicReference(new Node[T](null))
  private var head = new AtomicReference(last.get)
```

## Concurrent Queue: Append

```
@tailrec final def append(elem: T): Unit =  
  val last1 = new Node[T](null)  
  last1.elem = elem  
  val prev = last.get  
  if last.compareAndSet(prev, last1)  
  then prev.next = last1  
  else append(elem)
```

Only last two lines are substantially different from the sequential implementation.

## Concurrent Queue: Remove

```
@tailrec final def remove(): Option[T] =  
  if head eq last then None  
  else  
    val hd = head.get  
    val first = hd.next  
    if first != null && head.compareAndSet(hd, first)  
    then Some(first.elem)  
    else remove()
```

Again, only the last two lines are substantially different from the sequential implementation.

## Question

Are append and remove of ConcQueue lock-free operations?

Recall the definition:

*An operation  $op$  is lock-free if whenever there is a set of threads executing  $op$  at least one thread completes the operation after a finite number of steps, regardless of the speed in which the different threads progress.*

## Question (2)

What about if we change remove to the following implementation?

```
@tailrec final def remove(): Option[T] =  
  val hd = head.get  
  val first = hd.next  
  if first == null then None  
  else if head.compareAndSet(hd, first)  
  then Some(first.elem)  
  else remove()
```



## Concurrent Queues in the Standard Library

Multiple implementations in package `java.util.concurrent` implement interface `BlockingQueue`:

`ArrayBlockingQueue`    `// bounded queue, similar to exercise last week`

`LinkedBlockingQueue`   `// unbounded queue, similar to implementation here`

## Concurrent Sets and Maps

The Scala library also provides implementations of concurrent sets and maps.

These make use of the underlying data structure for efficiency.

For instance for Hashmaps: