

CS206 Concurrency and Parallelism

Martin Odersky and Sanidhya Kashyap

EPFL, Spring 2022

- Building blocks of concurrency:
 - Memory model
 - Atomics
 - Volatile variable

- A memory model is a contract about data access and visibility.
 - Memory models are non-deterministic, to allow some freedom of implementation in compiler and hardware.
- Java follows happens-before relation-based memory model.
 - Program order, monitor locking, volatile, thread start, thread termination.
- Execution context uses threads to multiplex tasks and task creation overhead.

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*.

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

- Atomic increment/decrement
- Atomic exchange
- Atomic compare and swap

Example: Generating unique ID (getUniqueId)

```
object GetUID extends Monitor:
  var uidCount = 0
  def getUniqueId() = synchronized {
    val freshUID = uidCount + 1
    uidCount = freshUID
    freshUID
  }
  ...
```

- This code is slow due to:
 - Possibility of a deadlock if the lock monitor is used at several places.
 - Possibility of arbitrary delay
 - More instructions are being issued in this case.

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()}")
```

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.

- All this occurs in one instruction

No intermediate result can be observed by other threads.

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.

- All this occurs in one instruction

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.

Complex atomic Operations often rely 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.

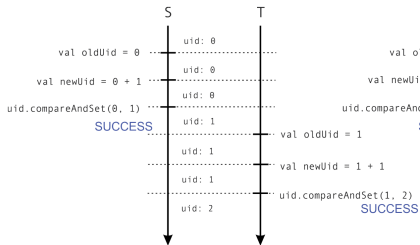
Let's implement `getUniqueId` using CAS directly:

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

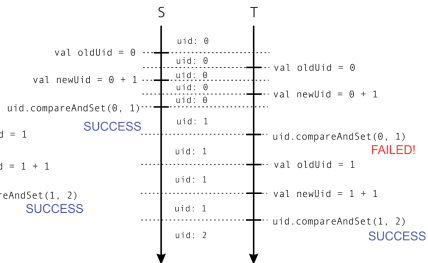
This uses the following general schema:

- ❶ Read the old value from the atomic variable
- ❷ Compute the new value
- ❸ 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

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.

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.

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.

Is this operation lock-free?

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

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

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.

One last synchronization primitive that we examine are *volatile variables*.

Sometimes we need only safe publication instead of atomic execution. In these cases, `synchronized` can be too heavyweight.

One last synchronization primitive that we examine are *volatile variables*.

Sometimes we need only safe publication instead of atomic execution. In these cases, `synchronized` can be too heavyweight.

There's a cheaper solution than using `synchronized` – we can use a *volatile field*.

Making a variable `@volatile` has several effects.

First, reads and writes to volatile variables are never reordered by the compiler.

Making a variable `@volatile` has several effects.

First, reads and writes to volatile variables are never reordered by the compiler.

Second, volatile reads and writes are never cached in CPU registers – they go directly to the main memory.

Making a variable `@volatile` has several effects.

First, reads and writes to volatile variables are never reordered by the compiler.

Second, volatile reads and writes are never cached in CPU registers – they go directly to the main memory.

Third, writes to normal variables that in the program precede a volatile write `W` cannot be moved by the compiler after `W`.

Making a variable `@volatile` has several effects.

First, reads and writes to volatile variables are never reordered by the compiler.

Second, volatile reads and writes are never cached in CPU registers – they go directly to the main memory.

Third, writes to normal variables that in the program precede a volatile write `W` cannot be moved by the compiler after `W`.

Fourth, reads from normal variables that in the program appear after a volatile read `R` cannot be moved by the compiler before `R`.

Making a variable `@volatile` has several effects.

First, reads and writes to volatile variables are never reordered by the compiler.

Second, volatile reads and writes are never cached in CPU registers – they go directly to the main memory.

Third, writes to normal variables that in the program precede a volatile write `W` cannot be moved by the compiler after `W`.

Fourth, reads from normal variables that in the program appear after a volatile read `R` cannot be moved by the compiler before `R`.

Fifth, before a volatile write, values cached in registers must be written back to main memory.

Making a variable `@volatile` has several effects.

First, reads and writes to volatile variables are never reordered by the compiler.

Second, volatile reads and writes are never cached in CPU registers – they go directly to the main memory.

Third, writes to normal variables that in the program precede a volatile write `W` cannot be moved by the compiler after `W`.

Fourth, reads from normal variables that in the program appear after a volatile read `R` cannot be moved by the compiler before `R`.

Fifth, before a volatile write, values cached in registers must be written back to main memory.

Sixth, after a volatile read, values cached in registers must be re-read from the main memory.

For almost all practical purposes, you should keep your programs simple, and avoid using `@volatile` variables.

For almost all practical purposes, you should keep your programs simple, and avoid using `@volatile` variables.

Instead, as a rule of the thumb, stick with `synchronized` when you need to make your writes visible to other threads.

Scala provides lazy values to compute only once.

- Writing efficient functional data structures
- Avoid allocating and initializing expensive resources
- Achieve the correct “initialize only once” semantic

```
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.

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?

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).

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
}
```

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?

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?

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.

The previous implementation of lazy values is what *scala* 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:                                object B:
  lazy val x = B.y                        lazy val y = A.x
```

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

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
```

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
```

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.

Check out the following link to further consider more issues:

- <https://docs.scala-lang.org/sips/improved-lazy-val-initialization.html>

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.

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")
  }
}
```

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

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

```
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
```

```
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)
```

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`.

```
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)
```



```
@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.

```
@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.

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.

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()
```

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*

The Scala library also provides implementations of concurrent sets and maps. These make use of the underlying data structure for efficiency. Hashmaps are use hashtable with chaining.

A memory model is a contract about data access and visibility.

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.

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.

Consider:

```
var x = 0; var y = 0;
val t1 = thread {
  x = 1
  lock.synchronized {
    y = 2
  }
}

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

What we discussed in the last class does not follow the Java memory model. We learned about the weaker memory model.

If we think about the Java's memory model, is 0, 2, 0 a possibility, remember program order and monitor locking?