Java concurrency (multi-threading) - Tutorial

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Java concurrency (multi-threading). This article describes how to do concurrent programming with Java. It covers the concepts of parallel programming, immutability, threads, the executor framework (thread pools), futures, callables CompletableFuture and the fork-join framework.

1. Concurrency

1.1. What is concurrency?

Concurrency is the ability to run several programs or several parts of a program in parallel. If a time consuming task can be performed asynchronously or in parallel, this improves the throughput and the interactivity of the program.

A modern computer has several CPU's or several cores within one CPU. The ability to leverage these multi-cores can be the key for a successful high-volume application.

1.2. Process vs. threads

A *process* runs independently and isolated of other processes. It cannot directly access shared data in other processes. The resources of the process, e.g. memory and CPU time, are allocated to it via the operating system.

A *thread* is a so called lightweight process. It has its own call stack, but can access shared data of other threads in the same process. Every thread has its own memory cache. If a thread reads shared data, it stores this data in its own memory cache.

A thread can re-read the shared data.

A Java application runs by default in one process. Within a Java application you work with several threads to achieve parallel processing or asynchronous behavior.

2. Improvements and issues with concurrency

2.1. Limits of concurrency gains

Within a Java application you work with several threads to achieve parallel processing or asynchronous behavior. Concurrency promises to perform certain task faster as these tasks can be divided into subtasks and these subtasks can be executed in parallel. Of course the runtime is limited by parts of the task which can be performed in parallel.

The theoretical possible performance gain can be calculated by the following rule which is referred to as *Amdahl's Law*.

If F is the percentage of the program which can not run in parallel and N is the number of processes, then the maximum performance gain is 1 / (F+ ((1-F)/N)).

2.2. Concurrency issues

Threads have their own call stack, but can also access shared data. Therefore you have two basic problems, visibility and access problems.

A visibility problem occurs if thread A reads shared data which is later changed by thread B and thread A is unaware of this change.

An access problem can occur if several threads access and change the same shared data at the same time.

Visibility and access problem can lead to:

- Liveness failure: The program does not react anymore due to problems in the concurrent access of data, e.g. deadlocks.
- Safety failure: The program creates incorrect data.

3. Concurrency in Java

3.1. Processes and Threads

A Java program runs in its own process and by default in one thread. Java supports threads as part of the Java language via the `Thread` code. The Java application can create new threads via this class.

Java 1.5 also provides improved support for concurrency with the `java.util.concurrent` package.

3.2. Locks and thread synchronization

Java provides *locks* to protect certain parts of the code to be executed by several threads at the same time. The simplest way of locking a certain method or Java class is to define the method or class with the `synchronized` keyword.

The *synchronized* keyword in Java ensures:

- that only a single thread can execute a block of code at the same time
- that each thread entering a synchronized block of code sees the effects of all previous modifications that were guarded by the same lock

Synchronization is necessary for mutually exclusive access to blocks of and for reliable communication between threads.

You can use the *synchronized* keyword for the definition of a method. This would ensure that only one thread can enter this method at the same time. Another thread which is calling this method would wait until the first thread leaves this method.

JAVA

```
public synchronized void critial() {
    // some thread critical stuff
    // here
}
```

You can also use the `synchronized` keyword to protect blocks of code within a method. This block is guarded by a key, which can be either a string or an object. This key is called the *lock*.

All code which is protected by the same lock can only be executed by one thread at the same time.

For example the following data structure will ensure that only one thread can access the inner block of the `add()` and `next()` methods.

```
import java.util.List;
/**
 * Data structure for a web crawler. Keeps track of the visited sites and keeps
 * a list of sites which needs still to be crawled.
 *
 * @author Lars Vogel
 *
 */
public class CrawledSites {
    private List<String> crawledSites = new ArrayList<String>();
    private List<String> linkedSites = new ArrayList<String>();

    public void add(String site) {
        synchronized (this) {
            if (!crawledSites.contains(site)) {
                linkedSites.add(site);
            }
        }
    }

    /**
     * Get next site to crawl. Can return null (if nothing to crawl)
     */
    public String next() {
        if (linkedSites.size() == 0) {
            return null;
        }
        synchronized (this) {
            // Need to check again if size has changed
            if (linkedSites.size() > 0) {
                String s = linkedSites.get(0);
                linkedSites.remove(0);
                crawledSites.add(s);
                return s;
            }
            return null;
        }
    }

}
```


3.3. Volatile

If a variable is declared with the *volatile* keyword then it is guaranteed that any thread that reads the field will see the most recently written value. The *volatile* keyword will not perform any mutual exclusive lock on the variable.

As of Java 5, write access to a *volatile* variable will also update non-volatile variables which were modified by the same thread. This can also be used to update values within a reference variable, e.g. for a *volatile* variable person. In this case you must use a temporary variable person and use the setter to initialize the variable and then assign the temporary variable to the final variable. This will then make the address changes of this variable and the values visible to other threads.

4. The Java memory model

4.1. Overview

The *Java memory model* describes the communication between the memory of the threads and the main memory of the application.

It defines the rules how changes in the memory done by threads are propagated to other threads.

The *Java memory model* also defines the situations in which a thread re-freshes its own memory from the main memory.

It also describes which operations are atomic and the ordering of the operations.

4.2. Atomic operation

An atomic operation is an operation which is performed as a single unit of work without the possibility of interference from other operations.

The Java language specification guarantees that reading or writing a variable is an atomic operation (unless the variable is of type `long` or `double`). Operations variables of type `long` or `double` are only atomic if they are declared with the `volatile` keyword.

The `i++` operation first reads the value which is currently stored in i (atomic operations) and then it adds one to it (atomic operation). But between the read and the write the value of i might have changed.

Since Java 1.5 the java language provides atomic variables, e.g. AtomicInteger or AtomicLong which provide methods like `getAndDecrement()`, `getAndIncrement()` and `getAndSet()` which are atomic.

4.3. Memory updates in synchronized code

The Java memory model guarantees that each thread entering a synchronized block of code sees the effects of all previous modifications that were guarded by the same lock.

5. Immutability and defensive Copies

5.1. Immutability

The simplest way to avoid problems with concurrency is to share only immutable data between threads. Immutable data is data which cannot be changed.

To make a class immutable define the class and all its fields as final.

Also ensure that no reference to fields escape during construction. Therefore any field must:

- be private
- have no setter method
- be copied in the constructor if it is a mutable object to avoid changes of this data from outside
- never be directly returned or otherwise exposed to a caller
- not change or if a change happens this change must not be visible outside

An immutable class may have some mutable data which is used to manage its state but from the outside neither this class nor any attribute of this class can get changed.

For all mutable fields, e.g. Arrays, that are passed from the outside to the class during the construction phase, the class needs to make a defensive-copy of the elements to make sure that no other object from the outside can change the data

5.2. Defensive Copies

You must protect your classes from calling code. Assume that calling code will do its best to change your data in a way you didn't expect it. While this is especially true in the case of immutable data, it is also true for non-immutable data which you don't expect to be changed from outside your class.

To protect your class against that, you should copy data which you receive and only return copies of data to calling code.

The following example creates a copy of a list (ArrayList) and returns only the copy of the list. This way the client of this class cannot remove elements from the list.

```
import java.util.Collections;
import java.util.List;

public class MyDataStructure {
    List<String> list = new ArrayList<String>();

    public void add(String s) {
        list.add(s);
    }

    /**
     * Makes a defensive copy of the List and return it
     * This way cannot modify the list itself
     *
     * @return List<String>
     */
    public List<String> getList() {
        return Collections.unmodifiableList(list);
    }
}
```


6. Threads in Java

The base means for concurrency is the `java.lang.Threads` class. A `Thread` executes an object of type `java.lang.Runnable`.

`Runnable` is an interface with defines the `run()` method. This method is called by the `Thread` object and contains the work which should be done. Therefore the `Runnable` is the task to perform. The `Thread` is the worker who is doing this task.

The following demonstrates a task (Runnable) which counts the sum of a given range of numbers. Create a new Java project called `de.vogella.concurrency.threads` for the example code of this section.

```
 * MyRunnable will count the sum of the number from 1 to the parameter
 * countUntil (inclusive).
 * <p>
 * MyRunnable is the task which will be performed
 *
 * @author Lars Vogel
 *
 */
public class MyRunnable implements Runnable {
    private final long countUntil;

    MyRunnable(long countUntil) {
        this.countUntil = countUntil;
    }

    @Override
    public void run() {
        long sum = 0;
        for (long i = 1; i < countUntil; i++) {
            sum += i;
        }
        System.out.println(sum);
    }
}
```


The following example demonstrates the usage of the `Thread` and the `Runnable` class.

JAVA

```
package de.vogella.concurrency.threads;

import java.util.ArrayList;
import java.util.List;

public class Main {

    public static void main(String[] args) {
        // We will store the threads so that we can check if they are done
        List<Thread> threads = new ArrayList<Thread>();
        // We will create 500 threads
        for (int i = 0; i < 500; i++) {
            Runnable task = new MyRunnable(10000000L + i);
            Thread worker = new Thread(task);
            // We can set the name of the thread
            worker.setName(String.valueOf(i));
            // Start the thread, never call method run() direct
            worker.start();
            // Remember the thread for later usage
            threads.add(worker);
        }
        int running = 0;
        do {
            running = 0;
            for (Thread thread : threads) {
                if (thread.isAlive()) {
                    running++;
                }
            }
            System.out.println("We have " + running + " running threads. ");
        } while (running > 0);

    }
}
```

Using the `Thread` class directly has the following disadvantages:

- Creating a new thread causes some performance overhead.
- Too many threads can lead to reduced performance, as the CPU needs to switch between these threads.
- You cannot easily control the number of threads, therefore you may run into out of memory errors due to too many threads.

```
The `java.util.concurrent` package offers improved support for concurrency compared to the direct
usage of `Threads`.
This package is described in the next section.
```

7. Threads pools with the Executor Framework

You find this examples in the source section in Java project called *de.vogella.concurrency.threadpools*.

Thread pools manage a pool of worker threads. The thread pools contain a work queue which holds tasks waiting to get executed.

A thread pool can be described as a collection of `Runnable` objects (work queue) and a connection of running threads.

These threads are constantly running and are checking the work query for new work. If there is new work to be done they execute this Runnable. The Thread class itself provides a method, e.g. execute(Runnable r) to add a new `Runnable` object to the work queue.

The Executor framework provides example implementation of the java.util.concurrent.Executor interface, e.g. Executors.newFixedThreadPool(int n) which will create n worker threads. The ExecutorService adds life cycle methods to the Executor, which allows to shutdown the Executor and to wait for termination.

If you want to use one thread pool with one thread which executes several runnables you can use the `Executors.newSingleThreadExecutor()` method.

Create again the Runnable.

JAVA

```
package de.vogella.concurrency.threadpools;

/**
 * MyRunnable will count the sum of the number from 1 to the parameter
 * countUntil and then write the result to the console.
 * <p>
 * MyRunnable is the task which will be performed
 *
 * @author Lars Vogel
 *
 */
public class MyRunnable implements Runnable {
    private final long countUntil;

    MyRunnable(long countUntil) {
        this.countUntil = countUntil;
    }

    @Override
    public void run() {
        long sum = 0;
        for (long i = 1; i < countUntil; i++) {
            sum += i;
        }
        System.out.println(sum);
    }
}
```

Now you run your runnables with the executor framework.

```
import java.util.concurrent.Executors;
public class Main {
    private static final int NTHREDS = 10;

    public static void main(String[] args) {
        ExecutorService executor = Executors.newFixedThreadPool(NTHREDS);
        for (int i = 0; i < 500; i++) {
            Runnable worker = new MyRunnable(10000000L + i);
            executor.execute(worker);
        }
        // This will make the executor accept no new threads
        // and finish all existing threads in the queue
        executor.shutdown();
        // Wait until all threads are finish
        executor.awaitTermination();
        System.out.println("Finished all threads");
    }
}
```


In case the threads should return some value (result-bearing threads) then you can use the `java.util.concurrent.Callable` class.

8. CompletableFuture

Any time consuming task should be preferable done asynchronously. Two basic approaches to asynchronous task handling are available to a Java application:

- application logic blocks until a task completes
- application logic is called once the task completes, this is called a nonblocking approach.

`CompletableFuture` which extends the `Future` interface supports asynchronous calls. It implements the `CompletionStage` interface. `CompletionStage` offers methods, that let you attach callbacks that will be executed on completion.

It adds standard techniques for executing application code when a task completes, including various ways to combine tasks. `CompletableFuture` support both blocking and nonblocking approaches, including regular callbacks.

This callback can be executed in another thread as the thread in which the `CompletableFuture` is executed.

The following example demonstrates how to create a basic CompletableFuture.

```
CompletableFuture.supplyAsync(this::doSomething);
```
JAVA

`CompletableFuture.supplyAsync` runs the task asynchronously on the default thread pool of Java. It has the option to supply your custom executor to define the `ThreadPool` .

```
import java.util.concurrent.ExecutionException;
public class CompletableFutureSimpleSnippet {
    public static void main(String[] args) {
        long started = System.currentTimeMillis();

        // configure CompletableFuture
        CompletableFuture<Integer> futureCount = createCompletableFuture();

            // continue to do other work
            System.out.println("Took " + (started - System.currentTimeMillis()) + " milliseconds" );

            // now its time to get the result
            try {
              int count = futureCount.get();
                System.out.println("CompletableFuture took " + (started - System.currentTimeMillis())
+ " milliseconds" );

               System.out.println("Result " + count);
             } catch (InterruptedException | ExecutionException ex) {
                // Exceptions from the future should be handled here
            }
    }

    private static CompletableFuture<Integer> createCompletableFuture() {
        CompletableFuture<Integer> futureCount = CompletableFuture.supplyAsync(
                () -> {
                    try {
                        // simulate long running task
                        Thread.sleep(5000);
                    } catch (InterruptedException e) { }
                    return 20;
                });
        return futureCount;
    }

}
```

The `thenApply` can be used to define a callback which is executed once the `CompletableFuture.supplyAsync` finishes. The usage of the `thenApply` method is demonstrated by the following code snippet.

JAVA

```
package snippet;

import java.util.concurrent.CompletableFuture;
import java.util.concurrent.ExecutionException;

public class CompletableFutureCallback {
    public static void main(String[] args) {
        long started = System.currentTimeMillis();

        CompletableFuture<String>  data = createCompletableFuture()
                .thenApply((Integer count) -> {
                    int transformedValue = count * 10;
                    return transformedValue;
                }).thenApply(transformed -> "Finally creates a string: " + transformed);

            try {
                System.out.println(data.get());
            } catch (InterruptedException | ExecutionException e) {

            }
    }

    public static CompletableFuture<Integer> createCompletableFuture() {
        CompletableFuture<Integer>  result = CompletableFuture.supplyAsync(() -> {
            try {
                // simulate long running task
                Thread.sleep(5000);
            } catch (InterruptedException e) { }
            return 20;
        });
        return result;
    }

}
```

You can also start a `CompletableFuture` delayed as of Java 9.

JAVA

```
CompletableFuture<Integer> future = new CompletableFuture<>();
 future.completeAsync(() -> {
       System.out.println("inside future: processing data...");
       return 1;
 }, CompletableFuture.delayedExecutor(3, TimeUnit.SECONDS))
 .thenAccept(result -> System.out.println("accept: " + result));
```

9. Nonblocking algorithms

Java 5.0 provides support for additional atomic operations. This allows to develop algorithms which are non-blocking algorithms, e.g. which do not require synchronization, but are based on low-level atomic hardware primitives such as compare-and-swap (CAS). A compare-and-swap operation checks if a variable has a certain value and if it has that value it will perform an operation.

Non-blocking algorithms are typically faster than blocking algorithms, as the synchronization of threads appears on a much finer level (hardware).

For example this creates a non-blocking counter which always increases. This example is contained in the project called *de.vogella.concurrency.nonblocking.counter*.

```
package de.vogella.concurrency.nonblocking.counter;

import java.util.concurrent.atomic.AtomicInteger;

public class Counter {
    private AtomicInteger value = new AtomicInteger();
    public int getValue(){
        return value.get();
    }
    public int increment(){
        return value.incrementAndGet();
    }

    // Alternative implementation as increment but just make the
    // implementation explicit
    public int incrementLongVersion(){
        int oldValue = value.get();
        while (!value.compareAndSet(oldValue, oldValue+1)){
             oldValue = value.get();
        }
        return oldValue+1;
    }

}
```

And a test.

```
import java.util.HashSet;
import java.util.List;
import java.util.Set;
import java.util.concurrent.Callable;
import java.util.concurrent.ExecutionException;
import java.util.concurrent.ExecutorService;
import java.util.concurrent.Executors;
import java.util.concurrent.Future;

public class Test {
        private static final int NTHREDS = 10;

        public static void main(String[] args) {
            final Counter counter = new Counter();
            List<Future<Integer>> list = new ArrayList<Future<Integer>>();

            ExecutorService executor = Executors.newFixedThreadPool(NTHREDS);
            for (int i = 0; i < 500; i++) {
                Callable<Integer> worker = new  Callable<Integer>() {
                    @Override
                    public Integer call() throws Exception {
                        int number = counter.increment();
                        System.out.println(number );
                        return number ;
                    }
                };
                Future<Integer> submit= executor.submit(worker);
                list.add(submit);

            }


            // This will make the executor accept no new threads
            // and finish all existing threads in the queue
            executor.shutdown();
            // Wait until all threads are finish
            while (!executor.isTerminated()) {
            }
            Set<Integer> set = new HashSet<Integer>();
            for (Future<Integer> future : list) {
                try {
                    set.add(future.get());
                } catch (InterruptedException e) {
                    e.printStackTrace();
                } catch (ExecutionException e) {
                    e.printStackTrace();
                }
            }
            if (list.size()!=set.size()){
                throw new RuntimeException("Double-entries!!!");
            }

        }


}
```

The interesting part is how the `incrementAndGet()` method is implemented. It uses a CAS operation.

JAVA

```
public final int incrementAndGet() {
        for (;;) {
            int current = get();
            int next = current + 1;
            if (compareAndSet(current, next))
                return next;
        }
    }
```

The JDK itself makes more and more use of non-blocking algorithms to increase performance for every developer. Developing correct non-blocking algorithms is not a trivial task.

For more information on non-blocking algorithms, e.g. examples for a non-blocking Stack and non-blocking LinkedList, please see http://www.ibm.com/developerworks/java/library/j-jtp04186/index.html .

10. Fork-Join in Java 7

Java 7 introduced a new parallel mechanism for compute intensive tasks, the fork-join framework. The fork-join framework allows you to distribute a certain task on several workers and then wait for the result.

For Java 6.0 you can download the package (jsr166y) from the Download site (http://gee.cs.oswego.edu/dl/concurrency-interest/index.html).

Create first an `algorithm` package and then the following class.

```
package algorithm;

import java.util.Random;

/**
 *
 * This class defines a long list of integers which defines the problem we will
 * later try to solve
 *
 */
public class Problem {
    private final int[] list = new int[2000000];

    public Problem() {
        Random generator = new Random(19580427);
        for (int i = 0; i < list.length; i++) {
            list[i] = generator.nextInt(500000);
        }
    }

    public int[] getList() {
        return list;
    }

}
```

Define now the `Solver` class as shown in the following example coding.

The API defines other top classes, e.g. RecursiveAction, AsyncAction. Check the Javadoc for details.

```
package algorithm;

import java.util.Arrays;

import jsr166y.forkjoin.RecursiveAction;

public class Solver extends RecursiveAction {
    private int[] list;
    public long result;

    public Solver(int[] array) {
        this.list = array;
    }

    @Override
    protected void compute() {
        if (list.length == 1) {
            result = list[0];
        } else {
            int midpoint = list.length / 2;
            int[] l1 = Arrays.copyOfRange(list, 0, midpoint);
            int[] l2 = Arrays.copyOfRange(list, midpoint, list.length);
            Solver s1 = new Solver(l1);
            Solver s2 = new Solver(l2);
            forkJoin(s1, s2);
            result = s1.result + s2.result;
        }
    }
}
```

Now define a small test class for testing it efficiently.

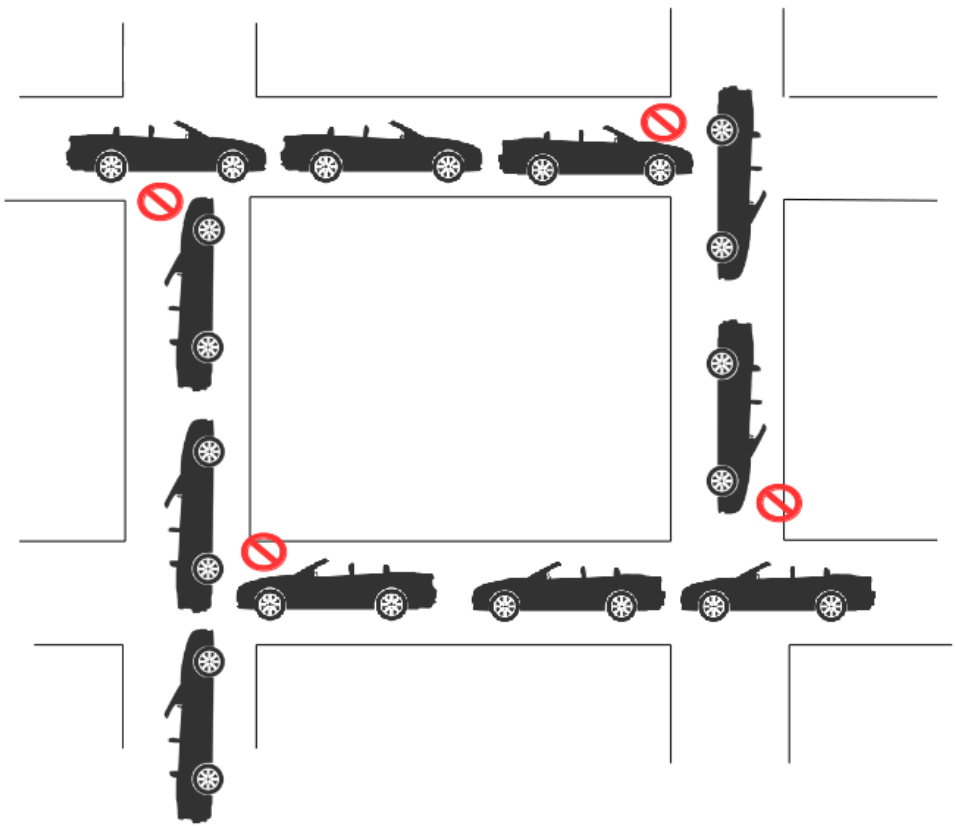
```
import jsr166y.forkjoin.ForkJoinPool;
import algorithm.Solver;

public class Test {

    public static void main(String[] args) {
        Problem test = new Problem();
        // check the number of available processors
        int nThreads = Runtime.getRuntime().availableProcessors();
        System.out.println(nThreads);
        Solver mfj = new Solver(test.getList());
        ForkJoinExecutor pool = new ForkJoinPool(nThreads);
        pool.invoke(mfj);
        long result = mfj.getResult();
        System.out.println("Done. Result: " + result);
        long sum = 0;
        // check if the result was ok
        for (int i = 0; i < test.getList().length; i++) {
            sum += test.getList()[i];
        }
        System.out.println("Done. Result: " + sum);
    }
}
```


11. Deadlock

A concurrent application has the risk of a *deadlock*. A set of processes are deadlocked if all processes are waiting for an event which another process in the same set has to cause.

For example if thread A waits for a lock on object Z which thread B holds and thread B waits for a lock on object Y which is hold by process A, then these two processes are locked and cannot continue in their processing.

This can be compared to a traffic jam, where cars(threads) require the access to a certain street(resource), which is currently blocked by another car(lock).



12. Links and Literature

12.1. Concurrency Resources

JVM concurrency: Java 8 concurrency basics (http://www.ibm.com/developerworks/java/library/j-jvmc2/index.html)

Functional-Style Callbacks Using Java 8's CompletableFuture (http://www.infoq.com/articles/Functional-Style-Callbacks-Using-CompletableFuture)

Thread pools and work queues by Brian Goetz (http://www.ibm.com/developerworks/library/j-jtp0730.html)

Introduction to nonblocking algorithms by Brian Goetz (http://www.ibm.com/developerworks/java/library/j-jtp04186/index.html)

Java theory and practice: Stick a fork in it, Part 1 by Brian Goetz (http://www.ibm.com/developerworks/java/library/j-jtp11137.html)

Java theory and practice: Stick a fork in it, Part 2 by Brian Goetz (http://www.ibm.com/developerworks/java/library/j-jtp03048.html)

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