

# Practical Concurrent and Parallel Programming

Martin Rønning Bech (mrob@itu.dk)

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**I hereby declare that I have answered these exam questions myself without any outside help.**

Martin Rønning Bech - 2015-01-08

## Introduction

The following report is Martin Rønning Bech's answer to the Programs as Data (PRCPP) E2014 examination. It is split into sections for each of the question.

The code snippets for each of the questions can be found in the corresponding question section, the code have been cut out of the Quicksorts.java file. The complete source code can be found in Appendix but should not be needed to read this report. The code have been compiled and run on Arch Linux using OpenJDK 1.8.0\_25

## Question 1:

In this question we have to make the given *SimpleDeque* thread safe using locks. To make the *SimpleDeque* thread safe we can apply the Java Monitor Pattern, that is to make sure that any mutable state that is put in private fields are guarded by the *SimpleDeque* object lock.

So in our *SimpleDeque* we ensure that *items*, *bottom* and *top* are private and are *GuardedBy*("this"). We then make the public method's *push*, *pop* and *steal* *synchronized*. These changes makes the *SimpleDeque* objects thread safe by ensuring that only a single thread will ever be allowed to make updates to their individual internal mutable state.

The *GuardedBy*("this") annotations are added to all internal state that needs to be guarded by the objects lock, this is to communicate to others that any

updates made to these fields must only be done when the *this* lock is taken, it is also useful in combination with tools that can be used to detect if the correct lock is always taken when access are made to the fields.

```
@GuardedBy("this")
private long bottom = 0;
@GuardedBy("this")
private long top = 0;
@GuardedBy("this")
private final T[] items;

public synchronized void push(T item) {...}
public synchronized T pop() {...}
public synchronized T steal() {...}
```

## Question 2

The *SortTask* is an immutable object, this is done by making all the fields *final*. By being immutable we ensure that after its creation no one can update the instance, so we can safely pass it around in different threads. Any thread that needs to do an “update” of the *SortTask* will instead have to create a new instance with the updated values.

## Question 3

In this question we implement a multi threaded Quicksort that uses a single shared queue to communicate sorting tasks. I have broken my code into three functions: *singleQueueMultiThread* that runs a small test case and prints it to the console, *sqmtWorkers* that starts the worker threads, *sqmtWorker* that contains the code for a single worker thread. Below I will explain how each function works, afterwards I will show a tests run and finally I will explain why the implementation is thread safe.

The *singleQueueMultiThread* implementation found below is quite simple, it creates a *SimpleDeque* instance and an array with random integers we want to sort (using the *randomIntArray* method given with the assignment). It then prints the array before sorting using the *IntArrayUtil.printout* method given with the assignment, runs the *sqmtWorkers* sorting method and finally prints the resulting array and the result of running *isSorted* helper method given with the assignment.

```
private static void singleQueueMultiThread(final int threadCount) {
    System.out.println("Running singleQueueMultiThread");
```

```

SimpleDeque<SortTask> queue = new SimpleDeque<SortTask>(100000);
//int[] arr = IntArrayUtil.randomIntArray(size);
System.out.println("Before:");
int[] arr = IntArrayUtil.randomIntArray(20);

IntArrayUtil.printout(arr, 20);

queue.push(new SortTask(arr, 0, arr.length-1));
sqmtWorkers(queue, threadCount);

System.out.println("After:");
IntArrayUtil.printout(arr, 20);

System.out.println("Sorted:");
System.out.println(IntArrayUtil.isSorted(arr));
}

```

The *sqmtWorkers* implementation takes a *Deque* and a *threadCount*. It then creates a *LongAdder* instance for keeping track of the amount of ongoing work. It then spawn *threadCount* amount of *sqmtWorker* threads and finally waits for them all to finish.

```

/**
 * Function for starting singleQueueMultiThread workers
 */
private static void sqmtWorkers(Deque<SortTask> queue, int threadCount) {
    //Initialize ongoing counter with the size of the queue
    //We assume the queue only has a single task
    LongAdder ongoing = new LongAdder();
    ongoing.increment();

    //Creating threads:
    Thread[] threads = new Thread[threadCount];
    for(int t = 0; t < threadCount; t++){
        //Start the thread
        threads[t] = new Thread(()-> sqmtWorker(queue, ongoing));
        threads[t].start();
    }

    //Wait for the threads to finish
    for(int t = 0; t < threadCount; t++){
        try{
            threads[t].join();
        }catch(InterruptedException e){}
    }
}

```

The *sqmtWorker* implementation works by first getting a new task (using the helper *SortTask* helper method given by the assignment, that first tries to take a task from the queue, if there are none left it will see if there is any ongoing worker, if there is it yield the thread to wait for more work to appear in the queue, if there isn't any ongoing work it will return null).

If the worker gets a task it will take the information from the task, if the array needs to be partitioned ( $a < b$ ) it will do so and finally add two new sorting tasks to the queue, as well as increment the ongoing counter after each task has been added. Finally when so work have been done (partitioned or not) it will decrement the ongoing counter.

We are ensured that the entire thing will terminate because by the end all tasks should no longer need to be partitioned and the ongoing counter will therefore be decremented to zero.

```
/**
 * Function for a singleQueueMultiThread worker
 */
private static void sqmtWorker(Deque<SortTask> queue, LongAdder ongoing){
    SortTask task;
    while (null != (task = getTask(queue, ongoing))) {
        //We have a task now partition!
        final int[] arr = task.arr;
        final int a = task.a, b = task.b;
        if (a < b) {
            int i = a, j = b;
            int x = arr[(i+j) / 2];
            do {
                while (arr[i] < x) i++;
                while (arr[j] > x) j--;
                if (i <= j) {
                    swap(arr, i, j);
                    i++; j--;
                }
            } while (i <= j);

            //Increment the counter when pushing
            queue.push(new SortTask(arr, a, j));
            ongoing.increment();
            queue.push(new SortTask(arr, i, b));
            ongoing.increment();
        }
        //We have sorted something, time to decrement
        ongoing.decrement();
    }
}
```

Below output from running the *singleQueueMultiThread* method with 8 threads can be seen. As expected the array is sorted.

```
Running singleQueueMultiThread
Before:
38 1 12 30 27 19 15 18 33 6 13 11 28 25 12 4 38 33 29 7
After:
1 4 6 7 11 12 12 13 15 18 19 25 27 28 29 30 33 33 38 38
Sorted:
true
```

So the array gets sorted, the implementation is thread safe because (1) the queue object we are using is thread safe a task will never be delegated to more than one thread and multiple accesses to the queue will never break the queue, and (2) the worker threads will never access the same part of the array at the same time this is due to the nature of the quick sort algorithm, notice that at any given time there will only ever exist a task (recursive step in the normal algorithm) going from some *a* to some *b* and there will be no overlap.

## Question 4

In this question we write tests for the *SimpleDeque* implementation implemented in Question 1. First we write a sequential test that tests that the *SimpleDeque* works as expected using only a single thread. Then we write parallel tests that try to test if the implementation works when accessed by multiple threads. For the tests I have used the *assertEquals* and *assertTrue* methods given in the course material from week 9 as well as introduced two new helper methods *assertNull* and *awaitBarrier* all the helper methods can be found in appendix .

In the *sequentialDequeTest* we test that the general functionality of the given *Deque* works. First we test that *pop* and *steal* will return *null* when the *Deque* is empty. We then test that putting a single element into the queue will make *pop* return it again and again testing that using *pop* now will yield *null* we do this for *steal* as well. Finally we fill the queue with 3 elements and test that *steal* will give the element first inserted and *pop* will give the element last inserted. These tests should cover the general functionality of the *Deque*.

```
static void sequentialDequeTest(Deque<Integer> queue) throws Exception{
    //Check that it only returns null
    assertNull(queue.pop());
    assertNull(queue.steal());

    //Check that pop/push works on single insert
    queue.push(42);
```

```

    assertEquals(42, queue.pop());
    assertNull(queue.pop());

    //Check that steal work on single insert
    queue.push(43);
    assertEquals(43, queue.steal());
    assertNull(queue.pop());

    queue.push(44);
    queue.push(45);
    queue.push(46);

    //Check that steal takes from the back
    assertEquals(44, queue.steal());

    //Check that pop takes from the front
    assertEquals(46, queue.pop());
}

```

Now comes the *parallelDequeTest*. In this tests we start 4 kind of threads:

- Pushing threads that will *push* one million random integers between 0-9999 into the *Deque*
- Popping threads that will *pop* one million integers from the *Deque*
- Stealing threads that will *steal* one million integers from the *Deque*
- Main thread that starts all the threads, waits and checks the result.

Each of the different kind of threads will have local *long* sum counter that they will continuously update when they have pushed, popped or stolen a value from the *Deque*. When they have completed their work they will add their local *long* sum value to a shared *LongAdder* between the threads. The threads are synchronized using a *CyclicBarrier* so they wait for all threads to have started and completed. The idea here is to try and force the test to go through as many different code interleavings as possible.

The main thread starts all the threads, it then waits first for all of them to start then for all of them to finish. After all threads have completed it empties the *Deque* and sums the remaining values. The implementation then sums the sum of the remaining values, the sum of the values popped and the sum of the values stolen and compares the result with the sum of the values pushed.

```

static void parallelDequeTest(Deque<Integer> queue,
    int threadCount) throws Exception {
    CyclicBarrier barrier = new CyclicBarrier((threadCount*3)+1);

```

```

int pushedSum = 0;

//Start pushing threads
LongAdder pushed = new LongAdder();
for(int t = 0; t < threadCount; t++){
    final int lt = t;
    new Thread()->{
        awaitBarrier(barrier);
        long p = 0;
        for(int i = 0; i < 1_000_000; i++){
            Random random = new Random();
            int r = random.nextInt() % 1000;
            p += r;
            queue.push(r);
        }
        pushed.add(p);
        awaitBarrier(barrier);
    }.start();
}

//Start pop threads
LongAdder popped = new LongAdder();
for(int t = 0; t < threadCount; t++){
    final int lt = t;
    new Thread()->{
        awaitBarrier(barrier);
        long pop = 0;
        for(int i = 0; i < 1_000_000; i++){
            Integer p = queue.pop();
            if(p != null){
                pop += p;
            }
        }
        popped.add(pop);
        awaitBarrier(barrier);
    }.start();
}

//Start stealing threads
LongAdder stolen = new LongAdder();
for(int t = 0; t < threadCount; t++){
    final int lt = t;
    new Thread()->{
        awaitBarrier(barrier);
        long s = 0;
        for(int i = 0; i < 1_000_000; i++){
            Integer p = queue.steal();

```

```

        if(p != null){
            s += p;
        }
    }
    stolen.add(s);
    awaitBarrier(barrier);
}).start();
}

//Start test
awaitBarrier(barrier);
//Wait for the test to stop
awaitBarrier(barrier);

//Get the remaining sum
long remaining = 0;
Integer p = queue.pop();
while(p != null){
    remaining += p;
    p = queue.pop();
}

//Get the sum of the threads
long pushedsum = pushed.sum();
long retrievedsum = remaining + popped.sum() + stolen.sum();

//Check that sum matches
assertEquals(retrievedsum, pushedsum);
}

```

I have run the tests on my *SimpleDeque* implementation multiple times using different amount of threads and it seems to pass every time.

To see if these tests will actually be able to find errors in my implementation I have done the following mutations of my implementation:

- Removed the statement that adds the *item* to the *items* list in the *push* method, this gets caught by the sequential test.
- Removed the decrement of *bottom* in the *pop* method, this gets caught by the sequential test.
- Removed the increment of *top* in *steal*, this gets caught by the sequential test.
- Different permutations of removing the *synchronized* keyword from *push*, *pop* and *steal*. All permutations was found by the parallel test.



## Question 5

In this question we measure the wall clock time of the sorting process in the single-queue multi-threaded Quicksort from Question 3. First we show the implementation of the measurement code and then what execution time it produces.

The *benchmarkSingleQueueMultiThread* method is a simple method that calls the benchmarking method with threadcount 1...8 as well as printing the result to the console in a table like format.

```
public static void benchmarkSingleQueueMultiThread(){
    System.out.println("Threads\tTime");
    for(int i = 1; i<9; i++){
        double time = sqmtBenchMarkVersion(i);
        System.out.println(i + "\t" + time);
    }
}
```

The *sqmtBenchMarkVersion* is the actual benchmark methods. This method takes a thread count, creates an instance of the SimpleDeque, an array of 50 million random integers, the ongoing counter and then starts all of the *sqmtWorker* threads. It uses a *CyclicBarrier* to ensure that all of the threads starts at the same time and to start the timer after the threads have started execution and stopping after all threads are done, this is to avoid measuring the thread startup time. In the main thread we therefore wait for all threads to start, start the timer, wait for the threads to finish and stop the timer returning the resulting time.

```
public static double sqmtBenchMarkVersion(int threadCount){
    SimpleDeque<SortTask> queue = new SimpleDeque<SortTask>(100000);
    int[] array = IntArrayUtil.randomIntArray(50_000_000);
    queue.push(new SortTask(array, 0, array.length-1));
    CyclicBarrier barrier = new CyclicBarrier(threadCount+1);

    //Initialize ongoing counter with the size of the queue
    //We assume the queue only has a single task
    LongAdder ongoing = new LongAdder();
    ongoing.increment();

    //Creating threads:
    Thread[] threads = new Thread[threadCount];
    for(int t = 0; t < threadCount; t++){
        threads[t] = new Thread()->{
            awaitBarrier(barrier);
            sqmtWorker(queue, ongoing);
        };
    }
}
```

```

        awaitBarrier(barrier);
    });
    //Start the thread
    threads[t].start();
}

//Waiting for threads
awaitBarrier(barrier);
//Threads started
Timer t = new Timer();
awaitBarrier(barrier);
//Threads done
return t.check();
}

```

I have run the tests on a Linux machine with 2 cores (4 hyper-threaded), compiled and run with OpenJDK Java 8. Below is the resulting table of sorting 50 million integers using 1 to 8 threads. The measurements shows first a decrease in performance and then a slight increase, the extra overhead of all threads accessing the same queue does seem to some degree hinder the execution time of this implementation.

Threads	Time (Seconds)
1	12.340515302
2	16.846127914
3	17.464326595
4	17.812679099
5	12.014321464
6	12.175678324
7	12.185204746
8	12.476405772

The test is obviously no completely accurate, but it does show something about the performance of the implementation. There are however a few things to note:

- Its only a single sorting run. We do not repeat and average.
- Its only shows the execution time on my specific machine.
- It might be influenced by the software running on my machine.
- It might be influenced by JVM optimizations, especially in the later runs.

## Question 6

In this question we create a multi-threaded multi-queue Quicksort. I will first show my implementation and explain why it works. I will then show the output of running the implementation.

The *multiQueueMultiThread* is very similar to the *singleQueueMultiThread* (see Question 3) method, but instead it creates a list of SimpleDequeues.

```
private static void multiQueueMultiThread(final int threadCount) {
    System.out.println("Running multiQueueMultiThread");
    SimpleDeque<SortTask>[] queues = new SimpleDeque[threadCount];
    for(int i = 0; i < threadCount; i++){
        queues[i] = new SimpleDeque<SortTask>(100000);
    }
    //int[] arr = IntArrayUtil.randomIntArray(size);
    System.out.println("Before:");
    int[] arr = IntArrayUtil.randomIntArray(20);
    IntArrayUtil.printout(arr, 20);

    queues[0].push(new SortTask(arr, 0, arr.length-1));
    mqmtWorkers(queues, threadCount);

    System.out.println("After:");
    IntArrayUtil.printout(arr, 20);

    System.out.println("Sorted:");
    System.out.println(IntArrayUtil.isSorted(arr));
}
```

The *mqmtWorkers* is similar to *sqmtWorkers* (see Question 3). It now takes a list of *Deque* and assigns each thread worker a number thereby assigning each worker a *Deque* from the list. An interesting point here is that the first thread will initially be the only thread gets a task, it will then partition and the other threads will be able to steal the new tasks from it.

```
“java private static void mqmtWorkers(Deque[] queues, int threadCount)
{ //Initialize ongoing counter with the size of the queue //We assume
the queue only has a single task LongAdder ongoing = new LongAdder();
ongoing.increment();
```

```
//Creating threads:
Thread[] threads = new Thread[threadCount];
for(int t = 0; t < threadCount; t++){
    //Start worker thread
```

```

        final int myNumber = t;
        threads[t] = new Thread(()-> mqmtWorker(queues, myNumber, ongoing));
        threads[t].start();
    }

    //Wait for the threads to finish
    for(int t = 0; t < threadCount; t++){
        try{
            threads[t].join();
        }catch(InterruptedException e){}
    }

}

```

The *mqmtWorker* method is almost identical to the *sqmtWorker* (see Question 3). It however uses the overloaded *getTask* method and pushes tasks to its assigned *Deque*.

```

private static void mqmtWorker(Deque<SortTask>[] queues, int myNumber,
    LongAdder ongoing){
    SortTask task;
    while (null != (task = getTask(myNumber, queues, ongoing))) {
        //We have a task now partition!
        final int[] arr = task.arr;
        final int a = task.a, b = task.b;
        if (a < b) {
            int i = a, j = b;
            int x = arr[(i+j) / 2];
            do {
                while (arr[i] < x) i++;
                while (arr[j] > x) j--;
                if (i <= j) {
                    swap(arr, i, j);
                    i++; j--;
                }
            } while (i <= j);

            //Increment the counter when pushing
            queues[myNumber].push(new SortTask(arr, a, j));
            ongoing.increment();
            queues[myNumber].push(new SortTask(arr, i, b));
            ongoing.increment();
        }
        //We have sorted something, time to decrement
        ongoing.decrement();
    }
}

```

```
    }
}
```

The new *getTask* method now first tries to *pop* a task from the threads own queue, if this returns empty it will try to steal from all the other queues if it fails it will yield, finally it will check the ongoing value and if this is zero it will return null otherwise it will try to steal again.

The reason why this will terminate at some point is that a worker will only ever push to it's own queue and we can therefore assume that we will have to try to stealing until we find something or there is not more work and then we can conclude that we are finished, because when we are in the stealing loop that directly means there are no tasks in our queue. Other than that the points from Question 3 still applies.

```
private static SortTask getTask(final int myNumber, final Deque<SortTask>[] queues,
    LongAdder ongoing) {
    final int threadCount = queues.length;
    SortTask task = queues[myNumber].pop();
    if (null != task)
        return task;
    else {
        do {
            //Lets try to steal a task from someone...
            for(int i = 0; i < queues.length; i++){
                if(i != myNumber){
                    task = queues[i].steal();
                    if(task != null){
                        return task;
                    }
                }
            }
            Thread.yield();
        } while (ongoing.longValue() > 0);
        return null;
    }
}
```

Below output from running the *multiQueueMultiThread* method with 8 threads can be seen. As expected the array is sorted.

Running multiQueueMultiThread

Before:

23 39 3 21 30 16 6 5 13 19 34 36 14 14 29 33 31 14 1 31

After:

```

1 3 5 6 13 14 14 14 16 19 21 23 29 30 31 31 33 34 36 39
Sorted:
true

```

## Question 7

In this question we have to measure the wall clock running time of the multi-queue multi-threaded Quicksort implementation from Question 6. First I show my measurement code I then show the result of running the measurement code on my machine and finally I comment on the differences between the execution time of the multi-queue multi-threaded Quicksort with results of running the single-queue multi-threaded Quicksort in Question 5.

The *benchmarkMultiQueueMultiThread* method simply creates the list of *SimpleQueues* and calls the benchmarking method with thread count from 1 to 8 and prints the result to the console in a table like format.

```

private static void benchMarkMultiQueueMultiThread() {
    System.out.println("Threads\tTime");
    for(int i = 1; i<9; i++){
        SimpleDeque<SortTask>[] queues = new SimpleDeque[i];
        for(int t = 0; t < i; t++){
            queues[t] = new SimpleDeque<SortTask>(100000);
        }
        double time = mqmtBenchMarkVersion(i, queues);
        System.out.println(i + "\t" + time);
    }
}

```

The *mqmtBenchMarkVersion* method is similar to the *sqmtBenchMarkVersion* method from Question 5. It uses a *CyclicBarrier* to synchronize the execution start the threads and only starts the timer when all the threads have been started to avoid measuring the thread start overhead. It waits for all the threads to finish and then returns the resulting time.

```

private static double mqmtBenchMarkVersion(int threadCount,
    Deque<SortTask>[] queues) {
    int[] array = IntArrayUtil.randomIntArray(50_000_000);
    queues[0].push(new SortTask(array, 0, array.length-1));
    CyclicBarrier barrier = new CyclicBarrier(threadCount+1);

    //Initialize ongoing counter with the size of the queue
    //We assume the queue only has a single task
    LongAdder ongoing = new LongAdder();

```

```

ongoing.increment();

//Creating threads:
Thread[] threads = new Thread[threadCount];
for(int t = 0; t < threadCount; t++){
    final int myNumber = t;
    threads[t] = new Thread()->{
        awaitBarrier(barrier);
        mqmtWorker(queues, myNumber, ongoing);
        awaitBarrier(barrier);
    };
    //Start the thread
    threads[t].start();
}

//Waiting for threads
awaitBarrier(barrier);
//Threads started
Timer t = new Timer();
awaitBarrier(barrier);
//Threads done
return t.check();
}

```

I have run the tests on Linux machine with 2 cores (4 hyper-threaded), compiled and run with OpenJDK Java 8 (Same as in Question 5). Below is the resulting table of sorting 50 million integers using 1 to 8 threads. The table shows a decent performance gain from adding multiple threads until 4 threads are added it then stays around the same execution time.

Threads	Time
1	12.465767929
2	6.606346842
3	6.595644916
4	7.033794127
5	5.883259311
6	6.057786901
7	5.285766619
8	5.159242964

For a short discussion of reasons why these tests is not accurate see Question 5. From this benchmark we see a clear benefit from adding more threads to the multi-threaded multi-queued Quicksort in comparison to the single-queued multi-threaded approach. The reason for this is most likely that we have re-

duced the actual overhead from the threads having to access the same queue all the time, with this implementation we mostly access our own queue and then sometimes when we run out of work steal from someone else.

I will also note that this implementation shows better performance on a single thread, but this is most likely purely by chance.

## Question 8

```
class ChaseLevDeque<T> implements Deque<T> {
    volatile long bottom = 0;
    final AtomicLong top = new AtomicLong(0);
    final T[] items;

    public ChaseLevDeque(int size) {
        this.items = makeArray(size);
    }

    @SuppressWarnings("unchecked")
    private static <T> T[] makeArray(int size) {
        // Java's @$#@?! type system requires this unsafe cast
        return (T[])new Object[size];
    }

    private static int index(long i, int n) {
        return (int)(i % (long)n);
    }

    public void push(T item) { // at bottom
        final long b = bottom, t = top.get(), size = b - t;
        if (size == items.length)
            throw new RuntimeException("queue overflow");
        items[index(b, items.length)] = item;
        bottom = b+1;
    }

    public T pop() { // from bottom
        final long b = bottom - 1;
        bottom = b;
        final long t = top.get(), afterSize = b - t;

        if (afterSize < 0) { // empty before call
            bottom = t;
            return null;
        } else {
```



```

        T result = items[index(b, items.length)];
        if (afterSize > 0) // non-empty after call
            return result;
        else { // became empty, update both top and bottom
            if (!top.compareAndSet(t, t+1)) // somebody stole result
                result = null;
            bottom = t+1;
            return result;
        }
    }
}

public T steal() { // from top
    final long t = top.get(), b = bottom, size = b - t;
    if (size <= 0)
        return null;
    else {
        T result = items[index(t, items.length)];
        if (top.compareAndSet(t, t+1))
            return result;
        else
            return null;
    }
}
}

```

## Question 9

In this question we write tests for the *ChaseLevDeque* implemented in Question 8. First we write a parallel test that only pop/pushes in one thread and steals in multiple threads. We then run the sequential test from Question 4 and our new parallel test on the *ChaseLevDeque*.

First we have the *runTestChaseLevDeque* method that sets up and runs the *sequentialDequeTest* from Question 4 and our new *parallelCLDequeTest* test on the *ChaseLevDeque*.

```

static void runTestChaseLevDeque() throws Exception {
    System.out.println("Running ChaseLevDeque Tests");
    ChaseLevDeque<Integer> c1 = new ChaseLevDeque<Integer>(100_000_000);
    sequentialDequeTest(c1);
    ChaseLevDeque<Integer> c12 = new ChaseLevDeque<Integer>(100_000_000);
    parallelCLDequeTest(c12, 10);
    System.out.println("ChaseLevDeque Tests Completed");
}

```

The *parallelCLDDequeTest* is a modified version of the *parallelDequeTest* from Question 4. This test still uses *CyclicBarrier* to synchronize the thread starts, and it still compares the sum on values push on the queue with the sum of the values popped, stolen and remaining in the queue after the test run.

The big differences between this test and the test in Question 4 is that we now only have a single thread that pushes and pops. So to try and force as many different code interleavings between the stealing threads and the push/pop thread I have introduced some randomness to the execution. So in the push/pop threads we randomly either do push or pop.

```
static void parallelCLDequeTest(Deque<Integer> queue,
    int threadCount) throws Exception {
    CyclicBarrier barrier = new CyclicBarrier(threadCount+2);
    int pushedSum = 0;

    //Start pushing and popping thread
    LongAdder pushed = new LongAdder();
    LongAdder popped = new LongAdder();
    new Thread()->{
        awaitBarrier(barrier);
        long p = 0;
        long pop = 0;
        for(int i = 0; i < 10_000_000; i++){
            Random random = new Random();
            if((random.nextInt() % 2) == 0){
                int r = random.nextInt() % 100;
                p += r;
                queue.push(r);
            }else{
                Integer pp = queue.pop();
                if(pp != null){
                    pop += pp;
                }
            }
        }

        pushed.add(p);
        popped.add(pop);
        awaitBarrier(barrier);
    }).start();

    //Start stealing threads
    LongAdder stolen = new LongAdder();
    for(int t = 0; t < threadCount; t++){
        final int lt = t;
```

```

        new Thread()->{
            awaitBarrier(barrier);
            long s = 0;
            for(int i = 0; i < 10_000_000; i++){
                Integer p = queue.steal();
                if(p != null){
                    s += p;
                }
            }
            stolen.add(s);
            awaitBarrier(barrier);
        }).start();;
    }

    //Start test
    awaitBarrier(barrier);
    //Wait for the test to stop
    awaitBarrier(barrier);

    //Get the remaining sum
    long remaining = 0;
    Integer p = queue.pop();
    while(p != null){
        remaining += p;
        p = queue.pop();
    }

    //Get the sum of the threads
    long pushedsum = pushed.sum();
    long retrievedsum = remaining + popped.sum() + stolen.sum();

    //Check that sum matches
    assertEquals(retrievedsum, pushedsum);
}

```

Running the sequential test on the *ChaseLevDeque* passed without errors. Running the parallel test with different numbers of threads and different numbers of push/pop and steal operations have all passed without errors on the current implementation of the *ChaseLevDeque*.

To see if these tests will actually be able to find errors in the implementation I have done the following mutations of the implementation:

- Removed the statement that adds the *item* to the *items* list in the *push* method, this gets caught by the sequential test.

- Made the *top.compareAndSwap* if statment in *pop* into a *top.set(t+1)*, was caught by the parallel test.
- Made the *top.compareAndSwap* in *steal* into a *top.set(t+1)*, was caught by the parallel test.

## Question 10

In this question we must used the *ChaseLevDeque* from Question 8 with the multi-threaded multi-queue Quicksort from Question 6. We will first show the code and then the output of running the code.

Below is the code used to run the *ChaseLevDeque* with the multi-threaded multi-queue Quicksort. It is also identical to the code from *multiQueueMultiThread* from Question 6, except it now creates a list of *ChaseLevDeque*.

```
private static void multiQueueMultiThreadCL(final int threadCount) {
    System.out.println("Running multiQueueMultiThreadCL");
    ChaseLevDeque<SortTask>[] queues = new ChaseLevDeque[threadCount];
    for(int i = 0; i < threadCount; i++){
        queues[i] = new ChaseLevDeque<SortTask>(100000);
    }
    //int[] arr = IntArrayUtil.randomIntArray(size);
    System.out.println("Before:");
    int[] arr = IntArrayUtil.randomIntArray(20);
    IntArrayUtil.printout(arr, 20);

    queues[0].push(new SortTask(arr, 0, arr.length-1));
    mqmtWorkers(queues, threadCount);

    System.out.println("After:");
    IntArrayUtil.printout(arr, 20);

    System.out.println("Sorted:");
    System.out.println(IntArrayUtil.isSorted(arr));
}
```

Below is the output of running the code above, sorting the list as expected.

```
Running multiQueueMultiThreadCL
Before:
15 0 15 31 6 26 38 29 12 38 38 16 27 20 7 20 23 13 10 24
After:
0 6 7 10 12 13 15 15 16 20 20 23 24 26 27 29 31 38 38 38
```

Sorted:  
true

## Question 11

In this question we have to measure the wall clock running time of the multi-queue multi-threaded Quicksort using the *ChaseLevDeque* implemented in Question 8. First we show the implementation used, then we show the measurements made and finally we compare the measurements with the measurements of the other implementations.

The measurements code found in *benchmarkMultiCLQueueMultiThread* method is very similar to the code found in *benchMarkMultiQueueMultiThread* method from Question 7 and uses the *mqmtBenchMarkVersion* method from Question 7. It creates a list of *ChaseLevDeque* and calls the benchmarking method with thread count from 1 to 8.

```
private static void benchMarkMultiCLQueueMultiThread() {
    System.out.println("Threads\tTime");
    for(int i = 1; i<9; i++){
        ChaseLevDeque<SortTask>[] queues = new ChaseLevDeque[i];
        for(int t = 0; t < i; t++){
            queues[t] = new ChaseLevDeque<SortTask>(100000);
        }
        double time = mqmtBenchMarkVersion(i, queues);
        System.out.println(i + "\t" + time);
    }
}
```

I have run the tests on Linux machine with 2 cores (4 hyper-threaded), compiled and run with OpenJDK Java 8 (Same as in Question 5). Below is the resulting table of sorting 20 million integers using 1 to 8 threads. The table shows a decent performance gain from adding multiple threads until 4 threads are added it then stays around the same execution time.

Threads	Time
1	11.295220809
2	6.124706902
3	5.452502169
4	5.026470204
5	5.349917083
6	4.809790837
7	5.006808109
8	4.948741356

For a short discussion of reasons why these tests is not accurate see Question 5.

Comparing with the benchmarks performed in Question 5 and Question 7, there is no doubt that this solution still provides better performance over the single-queued multi-threaded solution. It also seems to provide slightly better performance than using the *SimpleDeque* not by a lot but enough to make it significant and it will probably even scale better on machines with more cores. The downside to using this queue is obviously how easy it is to make mistakes. As described in Question 8 even the pseudo implementation given with this exam had subtle small errors in the code.

## Helper methods

```
public static void assertNull(Object o) throws Exception {
    if(o != null)
        throw new Exception(String.format("ERROR: assertNull"));
}

public static void awaitBarrier(CyclicBarrier c){
    //What is up with this checked exception madness
    try{
        c.await();
    }catch(Exception e){
        throw new RuntimeException(e);
    }
}

static void assertEquals(long x, long y) throws Exception {
    if (x != y)
        throw new Exception(String.format("ERROR: %d not equal to %d%n", x, y));
}

public static void assertTrue(boolean b) throws Exception {
    if (!b)
        throw new Exception(String.format("ERROR: assertTrue"));
}
```

## Chase-Lev Before Fix Output

Failed: java.lang.Exception: ERROR: -182875 not equal to -182817  
Failed: java.lang.Exception: ERROR: 155085 not equal to 155018  
Failed: java.lang.Exception: ERROR: 227353 not equal to 227306  
Failed: java.lang.Exception: ERROR: -668438 not equal to -668421  
Failed: java.lang.Exception: ERROR: -573121 not equal to -573045  
Failed: java.lang.Exception: ERROR: -552821 not equal to -552897  
Failed: java.lang.Exception: ERROR: 663331 not equal to 663407  
Failed: java.lang.Exception: ERROR: 847382 not equal to 847403  
Failed: java.lang.Exception: ERROR: -368363 not equal to -368236  
Failed: java.lang.Exception: ERROR: -531851 not equal to -531807

## Quicksorts.java Source code

Notice that the source code has been formatted by Latex listing, weird newlines can occur.

```
// For PCPP exam January 2015
// sestoft@itu.dk * 2015-01-03

// Several versions of sequential and parallel quicksort:
// A: sequential recursive
// B: sequential using work a deque as a stack

// To do by students:
// C: single-queue multi-threaded with shared lock-based
   queue
// D: multi-queue multi-threaded with thread-local lock-
   based queues and stealing
// E: as D but with thread-local lock-free queues and
   stealing

import java.util.concurrent.CyclicBarrier;
import java.util.concurrent.atomic.AtomicInteger;
import java.util.concurrent.atomic.AtomicLong;
import java.util.concurrent.atomic.LongAdder;
import javax.annotation.concurrent.GuardedBy;
import java.util.Random;

public class Quicksorts {
    final static int size = 1_000_000; // Number of
        integers to sort

    public static void main(String[] args) throws
        Exception {
        //sequentialRecursive();
        //singleQueueSingleThread();
        //singleQueueMultiThread(8);
        //multiQueueMultiThread(8);
        //multiQueueMultiThreadCL(8);
        Tests.benchmarkSingleQueueMultiThread();
        Tests.benchMarkMultiQueueMultiThread();
        Tests.benchMarkMultiCLQueueMultiThread();
        Tests.runTests();
    }
}
```



```

// Testing

static class Tests {
    // Question 6
    private static void
    benchMarkMultiQueueMultiThread() {
        System.out.println("Threads\tTime");
        for(int i = 1; i < 9; i++){
            SimpleDeque<SortTask>[] queues = new
                SimpleDeque[i];
            for(int t = 0; t < i; t++){
                queues[t] = new SimpleDeque<SortTask>
                    (100000);
            }
            double time = mqmtBenchMarkVersion(i,
                queues);
            System.out.println(i + "\t" + time);
        }
    }
    // Question 11
    private static void
    benchMarkMultiCLQueueMultiThread() {
        System.out.println("Threads\tTime");
        for(int i = 1; i < 9; i++){
            ChaseLevDeque<SortTask>[] queues = new
                ChaseLevDeque[i];
            for(int t = 0; t < i; t++){
                queues[t] = new ChaseLevDeque<
                    SortTask>(100000);
            }
            double time = mqmtBenchMarkVersion(i,
                queues);
            System.out.println(i + "\t" + time);
        }
    }

    private static double mqmtBenchMarkVersion(int
        threadCount, Deque<SortTask>[] queues) {
        int[] array = IntArrayUtil.randomIntArray(50
            _000_000);
        queues[0].push(new SortTask(array, 0, array.
            length-1));
        CyclicBarrier barrier = new CyclicBarrier(
            threadCount+1);
    }
}

```

```

        //Initialize ongoing counter with the size of
        the queue
        //We assume the queue only has a single task
        LongAdder ongoing = new LongAdder();
        ongoing.increment();

        //Creating threads:
        Thread[] threads = new Thread[threadCount];
        for(int t = 0; t < threadCount; t++){
            final int myNumber = t;
            threads[t] = new Thread()->{
                awaitBarrier(barrier);
                mqmtWorker(queues, myNumber, ongoing)
                ;
                awaitBarrier(barrier);
            };
            //Start the thread
            threads[t].start();
        }

        //Waiting for threads
        awaitBarrier(barrier);
        //Threads started
        Timer t = new Timer();
        awaitBarrier(barrier);
        //Threads done
        return t.check();
    }

    // Question 5
    public static void
    benchmarkSingleQueueMultiThread(){
        System.out.println("Threads\tTime");
        for(int i = 1; i<9; i++){
            double time = sqmtBenchMarkVersion(i);
            System.out.println(i + "\t" + time);
        }
    }

    public static double sqmtBenchMarkVersion(int
    threadCount){
        SimpleDeque<SortTask> queue = new SimpleDeque
        <SortTask>(100000);
        int[] array = IntArrayUtil.randomIntArray(50
        _000_000);
        queue.push(new SortTask(array, 0, array.

```

```

        length-1));
    CyclicBarrier barrier = new CyclicBarrier(
        threadCount+1);

    //Initialize ongoing counter with the size of
    //the queue
    //We assume the queue only has a single task
    LongAdder ongoing = new LongAdder();
    ongoing.increment();

    //Creating threads:
    Thread[] threads = new Thread[threadCount];
    for(int t = 0; t < threadCount; t++){
        threads[t] = new Thread()->{
            awaitBarrier(barrier);
            sqmtWorker(queue, ongoing);
            awaitBarrier(barrier);
        };
        //Start the thread
        threads[t].start();
    }

    //Waiting for threads
    awaitBarrier(barrier);
    //Threads started
    Timer t = new Timer();
    awaitBarrier(barrier);
    //Threads done
    return t.check();
}

static void runTests() throws Exception{
    //runTestsSimpleDeque();
    runTestChaseLevDeque();
}

// Question 9
static void runTestChaseLevDeque() throws
Exception {
    System.out.println("Running ChaseLevDeque
        Tests");
    ChaseLevDeque<Integer> cl = new ChaseLevDeque
        <Integer>(100_000_000);
    sequentialDequeTest(cl);
    ChaseLevDeque<Integer> cl2 = new
        ChaseLevDeque<Integer>(100_000_000);

```

```

        parallelCLDequeTest(cl2, 10);
        System.out.println("ChaseLevDeque Tests Completed");
    }

    static void parallelCLDequeTest(Deque<Integer>
        queue, int threadCount) throws Exception {
        CyclicBarrier barrier = new CyclicBarrier(
            threadCount+2);
        int pushedSum = 0;

        //Start pushing and popping thread
        LongAdder pushed = new LongAdder();
        LongAdder popped = new LongAdder();
        new Thread()->{
            awaitBarrier(barrier);
            long p = 0;
            long pop = 0;
            for(int i = 0; i < 10_000_000; i++){
                Random random = new Random();
                if((random.nextInt() % 2) == 0){
                    int r = random.nextInt() % 100;
                    p += r;
                    queue.push(r);
                }else{
                    Integer pp = queue.pop();
                    if(pp != null){
                        pop += pp;
                    }
                }
            }

            }
        pushed.add(p);
        popped.add(pop);
        awaitBarrier(barrier);
    }).start();

    //Start stealing threads
    LongAdder stolen = new LongAdder();
    for(int t = 0; t < threadCount; t++){
        final int lt = t;
        new Thread()->{
            awaitBarrier(barrier);
            long s = 0;
            for(int i = 0; i < 10_000_000; i++){
                Integer p = queue.steal();

```

```

        if(p != null){
            s += p;
        }
    }
    stolen.add(s);
    awaitBarrier(barrier);
}).start();
}

//Start test
awaitBarrier(barrier);
//Wait for the test to stop
awaitBarrier(barrier);

//Get the remaining sum
long remaining = 0;
Integer p = queue.pop();
while(p != null){
    remaining += p;
    p = queue.pop();
}

//Get the sum of the threads
long pushedsum = pushed.sum();
long retrievedsum = remaining + popped.sum()
    + stolen.sum();

//Check that sum matches
assertEquals(retrievedsum, pushedsum);
}

// Question 4
static void runTestsSimpleDeque() throws
Exception {
    //Test SimpleDeque
    System.out.println("Running SimpleDeque Tests");
    SimpleDeque<Integer> simple = new SimpleDeque
        <Integer>(100_000_000);
    sequentialDequeTest(simple);
    SimpleDeque<Integer> simple2 = new
        SimpleDeque<Integer>(100_000_000);
    parallelDequeTest(simple2, 10);
    System.out.println("SimpleDeque Tests
        Completed");
}

```

```

static void sequentialDequeTest (Deque<Integer>
queue) throws Exception{
    //Check that it only returns null
    assertNull(queue.pop());
    assertNull(queue.steal());

    //Check that pop/push works on single insert
    queue.push(42);
    assertEquals(42, queue.pop());
    assertNull(queue.pop());

    //Check that steal work on single insert
    queue.push(43);
    assertEquals(43, queue.steal());
    assertNull(queue.pop());

    queue.push(44);
    queue.push(45);
    queue.push(46);

    //Check that steal takes from the back
    assertEquals(44, queue.steal());

    //Check that pop takes from the front
    assertEquals(46, queue.pop());
}

static void parallelDequeTest (Deque<Integer>
queue, int threadCount) throws Exception {
    CyclicBarrier barrier = new CyclicBarrier((
        threadCount*3)+1);
    int pushedSum = 0;

    //Start pushing threads
    LongAdder pushed = new LongAdder();
    for(int t = 0; t < threadCount; t++){
        final int lt = t;
        new Thread(()->{
            awaitBarrier(barrier);
            long p = 0;
            for(int i = 0; i < 1_000_000; i++){
                Random random = new Random();
                int r = random.nextInt() % 1000;
                p += r;
            }
        })
    }
}

```

```

        queue.push(r);
    }
    pushed.add(p);
    awaitBarrier(barrier);
}).start();
}

//Start pop threads
LongAdder popped = new LongAdder();
for(int t = 0; t < threadCount; t++){
    final int lt = t;
    new Thread(()->{
        awaitBarrier(barrier);
        long pop = 0;
        for(int i = 0; i < 1_000_000; i++){
            Integer p = queue.pop();
            if(p != null){
                pop += p;
            }
        }
        popped.add(pop);
        awaitBarrier(barrier);
    }).start();
}

//Start stealing threads
LongAdder stolen = new LongAdder();
for(int t = 0; t < threadCount; t++){
    final int lt = t;
    new Thread(()->{
        awaitBarrier(barrier);
        long s = 0;
        for(int i = 0; i < 1_000_000; i++){
            Integer p = queue.steal();
            if(p != null){
                s += p;
            }
        }
        stolen.add(s);
        awaitBarrier(barrier);
    }).start();
}

//Start test
awaitBarrier(barrier);
//Wait for the test to stop
awaitBarrier(barrier);

```

```

        //Get the remaining sum
        long remaining = 0;
        Integer p = queue.pop();
        while(p != null){
            remaining += p;
            p = queue.pop();
        }

        //Get the sum of the threads
        long pushedsum = pushed.sum();
        long retrievedsum = remaining + popped.sum()
            + stolen.sum();

        //Check that sum matches
        assertEquals(retrievedsum, pushedsum);
    }

    static void assertEquals(long x, long y) throws
        Exception {
        if (x != y)
            throw new Exception(String.format("ERROR:
                %d not equal to %d\n", x, y));
    }

    public static void assertTrue(boolean b) throws
        Exception {
        if (!b)
            throw new Exception(String.format("ERROR:
                assertTrue"));
    }

    public static void assertNull(Object o) throws
        Exception {
        if(o != null)
            throw new Exception(String.format("ERROR:
                assertNull"));
    }

    /**
     * What is up with this checked exception madness
     */
    public static void awaitBarrier(CyclicBarrier c){
        try{
            c.await();
        }catch(Exception e){

```



```

        throw new RuntimeException(e);
    }
}

// Version A: Standard sequential quicksort using
// recursion

private static void sequentialRecursive() {
    int[] arr = IntArrayUtil.randomIntArray(size);
    qsort(arr, 0, arr.length-1);
    System.out.println(IntArrayUtil.isSorted(arr));
}

// Sort arr[a..b] endpoints inclusive
private static void qsort(int[] arr, int a, int b) {
    if (a < b) {
        int i = a, j = b;
        int x = arr[(i+j) / 2];
        do {
            while (arr[i] < x) i++;
            while (arr[j] > x) j--;
            if (i <= j) {
                swap(arr, i, j);
                i++; j--;
            }
        } while (i <= j);
        qsort(arr, a, j);
        qsort(arr, i, b);
    }
}

// Swap arr[s] and arr[t]
private static void swap(int[] arr, int s, int t) {
    int tmp = arr[s]; arr[s] = arr[t]; arr[t] = tmp;
}

// Version B: Single-queue single-thread setup;
// sequential quicksort using queue

private static void singleQueueSingleThread() {
    SimpleDeque<SortTask> queue = new SimpleDeque<
        SortTask>(100000);
    int[] arr = IntArrayUtil.randomIntArray(size);

```

```

        queue.push(new SortTask(arr, 0, arr.length-1));
        sqstWorker(queue);
        System.out.println(IntArrayUtil.isSorted(arr));
    }

    private static void sqstWorker(Deque<SortTask> queue)
    {
        SortTask task;
        while (null != (task = queue.pop())) {
            final int[] arr = task.arr;
            final int a = task.a, b = task.b;
            if (a < b) {
                int i = a, j = b;
                int x = arr[(i+j) / 2];
                do {
                    while (arr[i] < x) i++;
                    while (arr[j] > x) j--;
                    if (i <= j) {
                        swap(arr, i, j);
                        i++; j--;
                    }
                } while (i <= j);
                queue.push(new SortTask(arr, a, j));
                queue.push(new SortTask(arr, i, b));
            }
        }
    }

    // Version C: Single-queue multi-thread setup

    private static void singleQueueMultiThread(final int
        threadCount) {
        System.out.println("Running_
            singleQueueMultiThread");
        SimpleDeque<SortTask> queue = new SimpleDeque<
            SortTask>(100000);
        //int[] arr = IntArrayUtil.randomIntArray(size);
        System.out.println("Before:");
        int[] arr = IntArrayUtil.randomIntArray(20);

        IntArrayUtil.printout(arr, 20);

        queue.push(new SortTask(arr, 0, arr.length-1));
        sqmtWorkers(queue, threadCount);

        System.out.println("After:");
    }

```

```

        IntArrayUtil.printout(arr, 20);

        System.out.println("Sorted:");
        System.out.println(IntArrayUtil.isSorted(arr));
    }

    /**
     * Function for starting singleQueueMultiThread
     * workers
     */
    private static void sqmtWorkers(Deque<SortTask> queue
        , int threadCount) {
        //Initialize ongoing counter with the size of the
        queue
        //We assume the queue only has a single task
        LongAdder ongoing = new LongAdder();
        ongoing.increment();

        //Creating threads:
        Thread[] threads = new Thread[threadCount];
        for(int t = 0; t < threadCount; t++){
            //Start the thread
            threads[t] = new Thread(()-> sqmtWorker(queue
                , ongoing));
            threads[t].start();
        }

        //Wait for the threads to finish
        for(int t = 0; t < threadCount; t++){
            try{
                threads[t].join();
            }catch(InterruptedException e){}
        }
    }

    /**
     * Function for a singleQueueMultiThread worker
     */
    private static void sqmtWorker(Deque<SortTask> queue,
        LongAdder ongoing){
        SortTask task;
        while (null != (task = getTask(queue, ongoing)))
        {
            //We have a task now partition!
            final int[] arr = task.arr;
            final int a = task.a, b = task.b;

```

```

        if (a < b) {
            int i = a, j = b;
            int x = arr[(i+j) / 2];
            do {
                while (arr[i] < x) i++;
                while (arr[j] > x) j--;
                if (i <= j) {
                    swap(arr, i, j);
                    i++; j--;
                }
            } while (i <= j);

            //Increment the counter when pushing
            queue.push(new SortTask(arr, a, j));
            ongoing.increment();
            queue.push(new SortTask(arr, i, b));
            ongoing.increment();
        }
        //We have sorted something, time to decrement
        ongoing.decrement();
    }
}

// Tries to get a sorting task. If task queue is
// empty but some
// tasks are not yet processed, yield and then try
// again.

private static SortTask getTask(final Deque<SortTask>
    queue, LongAdder ongoing) {
    SortTask task;
    while (null == (task = queue.pop())) {
        if (ongoing.longValue() > 0)
            Thread.yield();
        else
            return null;
    }
    return task;
}

// Version D: Multi-queue multi-thread setup, thread-
// local queues

private static void multiQueueMultiThread(final int
    threadCount) {

```

```

        System.out.println("Running multiQueueMultiThread
        ");
        SimpleDeque<SortTask>[] queues = new SimpleDeque[
            threadCount];
        for(int i = 0; i < threadCount; i++){
            queues[i] = new SimpleDeque<SortTask>(100000)
                ;
        }
        //int[] arr = IntArrayUtil.randomIntArray(size);
        System.out.println("Before:");
        int[] arr = IntArrayUtil.randomIntArray(20);
        IntArrayUtil.printout(arr, 20);

        queues[0].push(new SortTask(arr, 0, arr.length-1)
            );
        mqmtWorkers(queues, threadCount);

        System.out.println("After:");
        IntArrayUtil.printout(arr, 20);

        System.out.println("Sorted:");
        System.out.println(IntArrayUtil.isSorted(arr));
    }

    // Version E: Multi-queue multi-thread setup, thread-
    // local queues

    private static void multiQueueMultiThreadCL(final int
        threadCount) {
        System.out.println("Running multiQueueMultiThreadCL");
        ChaseLevDeque<SortTask>[] queues = new
            ChaseLevDeque[threadCount];
        for(int i = 0; i < threadCount; i++){
            queues[i] = new ChaseLevDeque<SortTask>
                >(100000);
        }
        //int[] arr = IntArrayUtil.randomIntArray(size);
        System.out.println("Before:");
        int[] arr = IntArrayUtil.randomIntArray(20);
        IntArrayUtil.printout(arr, 20);

        queues[0].push(new SortTask(arr, 0, arr.length-1)
            );
    }

```

```

        mqmtWorkers(queues, threadCount);

        System.out.println("After:");
        IntArrayUtil.printout(arr, 20);

        System.out.println("Sorted:");
        System.out.println(IntArrayUtil.isSorted(arr));
    }

    private static void mqmtWorkers(Deque<SortTask>[]
        queues, int threadCount) {
        //Initialize ongoing counter with the size of the
        queue
        //We assume the queue only has a single task
        LongAdder ongoing = new LongAdder();
        ongoing.increment();

        //Creating threads:
        Thread[] threads = new Thread[threadCount];
        for(int t = 0; t < threadCount; t++){
            //Start worker thread
            final int myNumber = t;
            threads[t] = new Thread(()-> mqmtWorker(
                queues, myNumber, ongoing));
            threads[t].start();
        }

        //Wait for the threads to finish
        for(int t = 0; t < threadCount; t++){
            try{
                threads[t].join();
            }catch(InterruptedException e){}
        }
    }

    private static void mqmtWorker(Deque<SortTask>[]
        queues, int myNumber,
        LongAdder ongoing){
        SortTask task;
        while (null != (task = getTask(myNumber,
            queues, ongoing))) {
            //We have a task now partition!
            final int[] arr = task.arr;
            final int a = task.a, b = task.b;
            if (a < b) {
                int i = a, j = b;

```

```

        int x = arr[(i+j) / 2];
        do {
            while (arr[i] < x) i++;
            while (arr[j] > x) j--;
            if (i <= j) {
                swap(arr, i, j);
                i++; j--;
            }
        } while (i <= j);

        //Increment the counter when pushing
        queues[myNumber].push(new SortTask(
            arr, a, j));
        ongoing.increment();
        queues[myNumber].push(new SortTask(
            arr, i, b));
        ongoing.increment();
    }
    //We have sorted something, time to
    decrement
    ongoing.decrement();
}

// Tries to get a sorting task. If task queue is
// empty, repeatedly
// try to steal, cyclically, from other threads and
// if that fails,
// yield and then try again, while some sort tasks
// are not processed.

private static SortTask getTask(final int myNumber,
    final Deque<SortTask>[] queues,
    LongAdder ongoing) {
    final int threadCount = queues.length;
    SortTask task = queues[myNumber].pop();
    if (null != task)
        return task;
    else {
        do {
            //Lets try to steal a task from someone
            ...
            for(int i = 0; i < queues.length; i++){
                if(i != myNumber){
                    task = queues[i].steal();
                    if(task != null){

```

```

        return task;
    }
}

Thread.yield();
} while (ongoing.longValue() > 0);
return null;
}
}

// SortTask class, Deque<T> interface, SimpleDeque<T>
// Represents the task of sorting arr[a..b]
class SortTask {
    public final int[] arr;
    public final int a, b;

    public SortTask(int[] arr, int a, int b) {
        this.arr = arr;
        this.a = a;
        this.b = b;
    }
}

interface Deque<T> {
    void push(T item);    // at bottom
    T pop();              // from bottom
    T steal();            // from top
}

class SimpleDeque<T> implements Deque<T> {
    // The queue's items are in items[top%S...(bottom-1)%S], where S ==
    // items.length; items[bottom%S] is where the next
    // push will happen;
    // items[(bottom-1)%S] is where the next pop will
    // happen;
    // items[top%S] is where the next steal will happen;
    // the queue is
    // empty if top == bottom, non-empty if top < bottom,
    // and full if
    // bottom - top == items.length. The top field can
    // only increase.
    @GuardedBy("this")
    private long bottom = 0, top = 0;

```



```

    @GuardedBy("this")
    private final T[] items;

    public SimpleDeque(int size) {
        this.items = makeArray(size);
    }

    @SuppressWarnings("unchecked")
    private static <T> T[] makeArray(int size) {
        // Java's @$#@?! type system requires this
        // unsafe cast
        return (T[])new Object[size];
    }

    private static int index(long i, int n) {
        return (int)(i % (long)n);
    }

    public synchronized void push(T item) { // at bottom
        final long size = bottom - top;
        if (size == items.length)
            throw new RuntimeException("queue overflow");
        items[index(bottom++, items.length)] = item;
    }

    public synchronized T pop() { // from bottom
        final long afterSize = bottom - 1 - top;
        if (afterSize < 0)
            return null;
        else
            return items[index(--bottom, items.length)];
    }

    public synchronized T steal() { // from top
        final long size = bottom - top;
        if (size <= 0)
            return null;
        else
            return items[index(top++, items.length)];
    }
}

// A lock-free queue simplified from Chase and Lev:
//   Dynamic circular
//   work-stealing queue, SPAA 2005. We simplify it by not

```

```

    reallocating
// the array; hence this queue may overflow. This is
// close in spirit
// to the original ABP work-stealing queue (Arora,
// Blumofe, Plaxton:
// Thread scheduling for multiprogrammed multiprocessors,
// 2000,
// section 3) but in that paper an "age" tag needs to be
// added to the
// top pointer to avoid the ABA problem (see ABP section
// 3.3). This
// is not necessary in the Chase-Lev deque design,
// where the top
// index never assumes the same value twice.

// PSEUDOCODE for ChaseLevDeque class:

class ChaseLevDeque<T> implements Deque<T> {
    volatile long bottom = 0;
    final AtomicLong top = new AtomicLong(0);
    final T[] items;

    public ChaseLevDeque(int size) {
        this.items = makeArray(size);
    }

    @SuppressWarnings("unchecked")
    private static <T> T[] makeArray(int size) {
        // Java's @$#@?! type system requires this
        // unsafe cast
        return (T[])new Object[size];
    }

    private static int index(long i, int n) {
        return (int)(i % (long)n);
    }

    public void push(T item) { // at bottom
        final long b = bottom, t = top.get(), size = b -
            t;
        if (size == items.length)
            throw new RuntimeException("queue overflow");
        items[index(b, items.length)] = item;
        bottom = b+1;
    }
}

```

```

    public T pop() { // from bottom
        final long b = bottom - 1;
        bottom = b;
        final long t = top.get(), afterSize = b - t;

        if (afterSize < 0) { // empty before call
            bottom = t;
            return null;
        } else {
            T result = items[index(b, items.length)];
            if (afterSize > 0) // non-empty after call
                return result;
            else { // became empty, update
                both top and bottom
                if (!top.compareAndSet(t, t+1)) //
                    somebody stole result
                    result = null;
                bottom = t+1;
                return result;
            }
        }
    }

    public T steal() { // from top
        final long t = top.get(), b = bottom, size = b -
            t;
        if (size <= 0)
            return null;
        else {
            T result = items[index(t, items.length)];
            if (top.compareAndSet(t, t+1))
                return result;
            else
                return null;
        }
    }
}

class IntArrayUtil {
    public static int[] randomIntArray(final int n) {
        int[] arr = new int[n];
        for (int i = 0; i < n; i++)
            arr[i] = (int) (Math.random() * n * 2);
        return arr;
    }
}

```

```
public static void printout(final int[] arr, final
    int n) {
    for (int i=0; i < n; i++)
        System.out.print(arr[i] + " ");
    System.out.println("");
}

public static boolean isSorted(final int[] arr) {
    for (int i=1; i<arr.length; i++)
        if (arr[i-1] > arr[i])
            return false;
    return true;
}
}
```