

Project 1 - Build a thread system for kernel processes

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1 URL of git Repository

<https://github.com/bcip/nachos>

2 Implementation of KThread.join()

2.1 Overview

In this task, we need to implement `KThread.join()`, and the method should

- if this is finished return immediately
- be called only once
- store `currentThread` and wake it later
- assure that the thread finish executing normally

2.2 Correctness Constraints

- Corner cases: when this equals to `currentThread` or this is already finished, return immediately
- Need to be atomic by disable interruption and restore interruption at last
- When this thread finish, it should wake the stored thread

2.3 Declaration

- Add new state variable `waitQueue` which is a `ThreadQueue(true)` into `KThread`.

- Modification of `join()`: Firstly, disable interruption to make the operation atomic and restore it at last; secondly, prevent joining itself and prevent a finished thread from joining others, otherwise, let the current-Thread sleep to wait this method finish.
- Modification of `finish()`: Assure that once this method is finished, wake the thread join it to let the joining thread normally continue executing.

2.4 Description

Shown in pseudocode.

```

procedure JOIN()
    Disable Interruption
    if currentThread == this or this.status == statusFinished then
        Restore Interruption
        return
    else
        add currentThread into waitQueue
        currentThread sleep
    end if
    Restore Interruption
end procedure
procedure FINISH()
    ...
    currentThread.status = statusFinished
    Ready thread in waitQueue
    sleep()
end procedure

```

2.5 Test

Using `selfTest()` method in `KThread`, the main thought is making some join example, so we have those tests below.

```

private static void test1(){
    //Test Case 1
    System.out.println("\n*** Test Case 1 for join ***");
    ToJoin toJoin = new ToJoin();
    KThread toJoinThread = new
        KThread(toJoin).setName("ToJoin Thread");
    KThread toBeJoinedThread = new KThread(new
        ToBeJoined(toJoinThread)).setName("ToBeJoined
        Thread");
    toBeJoinedThread.fork();
    toJoinThread.fork();
}

```

```

        ThreadedKernel.alarm.waitUntil(100000);
    }
    private static void test2(){
        //Test Case 2
        System.out.println("\n*** Test Case 2 for join ***");
        ToJoin toJoin = new ToJoin();
        KThread toJoinThread = new
            KThread(toJoin).setName("ToJoin Thread");
        KThread toBeJoinedThread = new KThread(new
            ToBeJoined(toJoinThread)).setName("ToBeJoined
            Thread");
        toJoinThread.fork();
        toBeJoinedThread.fork();
        ThreadedKernel.alarm.waitUntil(100000);
    }
    private static void test3(){
        //Test Case 3
        System.out.println("\n*** Test Case 3 for join ***");
        ToJoin toJoin = new ToJoin();
        KThread toJoinThread = new
            KThread(toJoin).setName("ToJoin Thread");
        KThread toBeJoined1 = new KThread(new
            ToBeJoined(toJoinThread)).setName("ToBeJoined1
            Thread");
        KThread toBeJoined2 = new KThread(new
            ToBeJoined(toJoinThread)).setName("ToBeJoined2
            Thread");
        toBeJoined1.fork();
        toBeJoined2.fork();
        toJoinThread.fork();
        ThreadedKernel.alarm.waitUntil(100000);
    }
    private static void test4(){
        //Test Case 4
        System.out.println("\n*** Test Case 4 for join ***");
        ToJoin toJoin1 = new ToJoin();
        ToJoin toJoin2 = new ToJoin();
        KThread t1 = new KThread(toJoin1).setName("ToJoin Thread
            1");
        KThread t2 = new KThread(toJoin2).setName("ToJoin Thread
            2");
        KThread toBeJoined = new KThread(new
            ToBeJoinedCouple(t1,t2)).setName("ToBeJoined Thread");
        toBeJoined.fork();
        t1.fork();
        t2.fork();
        ThreadedKernel.alarm.waitUntil(100000);
    }
}

```

And the results of tests are as follows.

```
*** Test Case 1 for join ***
* ToBeJoined starts running
* ToJoin joins
* ToJoin starts running
* ToJoin ends running
* ToBeJoined continues running after ToJoin Thread finishes

*** Test Case 2 for join ***
* ToJoin starts running
* ToJoin ends running
* ToBeJoined starts running
* ToJoin joins
* ToBeJoined continues running after ToJoin Thread finishes

*** Test Case 3 for join ***
* ToBeJoined starts running
* ToJoin joins
* ToBeJoined starts running
* ToJoin joins
* ToJoin starts running
* ToJoin ends running
* ToBeJoined continues running after ToJoin Thread finishes
* ToBeJoined continues running after ToJoin Thread finishes

*** Test Case 4 for join ***
* ToBeJoinedCouple starts running
* ToJoin Thread 1 joins
* ToJoin starts running
* ToJoin ends running
* ToJoin starts running
* ToJoin ends running
* ToJoin Thread 2 joins
* ToBeJoinedCouple continues running after two joining threads
```

1. For `test1`, we have the thread being joined run first, and have the other thread join the former run later;
2. For `test2`, just change the running order of the threads in the first test;
3. For `test3`, we have a thread join two different threads;
4. For `test4`, we have a thread be joined by two different threads;

And all the results shows that the joining thread finished before the threads being joined continue which is the expected results.

3 Implementation of Condition2

3.1 Overview

Implement `Condition2` without using semaphore and `Condition2` must be equivalent implementation as `Condition`.

3.2 Correctness Constraints

- `sleep` method:
 - Atomically release the associated lock and put the current thread to sleep until be waken
 - The associated lock must be held by current thread before the method and re-required after this method.
- `wake` method:
 - Atomically wake up a thread which called `sleep`
 - The associated lock must be held by current thread before the method.
- `wakeAll` method:
 - Atomically wake up all thread which called `sleep` on this condition
 - The associated lock must be held by current thread before the method.

3.3 Declaration

- Add new state variable `waitQueue` which is a `ThreadQueue` into `Condition2`.
- `sleep` method: place `currentThread` into `ThreadQueue` and release the lock, then sleep the `currentThread` and then re-acquire the lock when it return from `sleep`
- `wake` method: remove the thread from the `waitQueue` and put it on the ready Queue
- `wakeAll` method: remove all threads from the `waitQueue` and put them on the ready Queue

3.4 Description

3.5 Test

Using `selfTest()` in `Condition2`,

In this session, the test is using `Condition` and `Condition2` to do the same job, and compare their results, and then we finish the test. Here are the codes.

```

procedure SLEEP()
    Lib.assertTrue conditionLock.isHeldByCurrentThread
    Disable Interruption
    Add currentThread into waitQueue
    Release the conditionLock
    currentThread sleep
    Acquire the conditionLock
    Restore Interruption
end procedure

procedure WAKE()
    Lib.assertTrue conditionLock.isHeldByCurrentThread
    Disable Interruption
    if waitQueue is not empty then
        Remove and wake the first thread in waitQueue
    end if
    Restore Interruption
end procedure

procedure WAKEALL()
    Lib.assertTrue conditionLock.isHeldByCurrentThread
    Disable Interruption
    while waitQueue is not empty do
        Remove and wake the first thread in waitQueue
    end while
    Restore Interruption
end procedure

```

```

private static class Int {
    int value;
    Int(int _value){
        value = _value;
    }
    public void inc(){
        value++;
    }
    public void dec(){
        value--;
    }
    public int val(){
        return value;
    }
}

private static class Producer implements Runnable {
    private Int goods;
    private Condition2 condition;
    private Lock lock;
    private int index;

    Producer(int _index, Int _goods, Condition2 _condition,
        Lock _lock){
        index = _index;
        goods = _goods;
        condition = _condition;
        lock = _lock;
    }

    public void run() {
        lock.acquire();
        System.out.println("Producer " + index + " starts
            running");
        goods.inc();
        System.out.println("Producer " + index + "
            produces 1 item (" + goods.val() + " items)");
        condition.wakeAll();
        System.out.println("Producer " + index + " ends
            running");
        lock.release();
    }
}

private static class Consumer implements Runnable {
    private Int goods;
    private Condition2 condition;
    private Lock lock;
    private int index;

    Consumer(int _index, Int _goods, Condition2 _condition,

```



```

        Lock _lock) {
            index = _index;
            goods = _goods;
            condition = _condition;
            lock = _lock;
        }

        public void run() {
            lock.acquire();
            System.out.println("Consumer " + index + " starts
                                running");
            while(goods.val() < 1){
                System.out.println("Consumer " + index + "
                                    sleeps " + "(" + goods.val() + "
                                    items)");
                condition.sleep();
            }
            goods.dec();
            System.out.println("Consumer " + index + "
                                consumes " + "(" + 1 + " item (" + goods.val()
                                + " items)");
            System.out.println("Consumer " + index + " ends
                                running");
            lock.release();
        }
    }

    public static void selfTest(){
        Int goods = new Int(0);
        Lock lock = new Lock();
        Condition2 condition = new Condition2(lock);
        KThread consumer1 = new KThread(new Consumer(1, goods,
            condition, lock));
        KThread consumer2 = new KThread(new Consumer(2, goods,
            condition, lock));
        KThread producer1 = new KThread(new Producer(1, goods,
            condition, lock));
        KThread producer2 = new KThread(new Producer(2, goods,
            condition, lock));
        KThread producer3 = new KThread(new Producer(3, goods,
            condition, lock));
        KThread consumer3 = new KThread(new Consumer(3, goods,
            condition, lock));
        consumer1.fork();
        consumer2.fork();
        producer1.fork();
        producer2.fork();
        producer3.fork();
        consumer3.fork();
        ThreadedKernel.alarm.waitUntil(100000);
    }
}

```

And for Condition, we just change the test code above. And here are the results.

```
using condition2:
Consumer 1 starts running
Consumer 1 sleeps (0 items)
Consumer 2 starts running
Consumer 2 sleeps (0 items)
Producer 1 starts running
Producer 1 produces 1 item (1 items)
Producer 1 ends running
Producer 2 starts running
Producer 2 produces 1 item (2 items)
Producer 2 ends running
Producer 3 starts running
Producer 3 produces 1 item (3 items)
Producer 3 ends running
Consumer 3 starts running
Consumer 3 consumes 1 item (2 items)
Consumer 3 ends running
Consumer 1 consumes 1 item (1 items)
Consumer 1 ends running
Consumer 2 consumes 1 item (0 items)
Consumer 2 ends running

using condition:
Consumer 1 starts running
Consumer 1 sleeps (0 items)
Consumer 2 starts running
Consumer 2 sleeps (0 items)
Producer 1 starts running
Producer 1 produces 1 item (1 items)
Producer 1 ends running
Producer 2 starts running
Producer 2 produces 1 item (2 items)
Producer 2 ends running
Producer 3 starts running
Producer 3 produces 1 item (3 items)
Producer 3 ends running
Consumer 3 starts running
Consumer 3 consumes 1 item (2 items)
Consumer 3 ends running
Consumer 1 consumes 1 item (1 items)
Consumer 1 ends running
Consumer 2 consumes 1 item (0 items)
Consumer 2 ends running
```

In this test result, Consumer waits for Producer rightly when there is no good

and `Consumer`, `Producer` consumes and produces good rightly. And `Condition2` works the same as `Condition`.

4 Implementation of Alarm

4.1 Overview

Implementation of `Alarm` class, such that after the thread called `waitUttill(x)` at time `t` then `timerInterrupt` wake the thread after time `x+t`.

4.2 Correctness Constraints

- `waitUttill` method: Move the calling thread into `waitQueue` and block the thread.
- `timerInterrupt` method: The thread should be woken when the interval on the call is over.

4.3 Declaration

- Create a new class `WaitThread` which contains a thread and its wake time. Add a new instance variable `waitQueue` of `WaitThread` which is a `PriorityQueue` with wake time as priority.
- `waitUttill` method: Calculate the wake time by adding `x` to current time and the `WaitThread` of the thread should be store in `waitQueue` which is a priority queue(hence is efficient).
- `timerInterrupt` method: use a while loop to wake threads whose wake time is less than current time.

4.4 Description

4.5 Test

Call `waitUttill` by several threads and print the calling time and the wake time. Find out whether the threads are waken after wake time.

So the codes are as follows.

```
public static void selfTest(){
    KThread[] t = new KThread[10];
    for(int i = 0; i < 10; i++){
        t[i] = new KThread(new AlarmTest((long)((i+1) * 100)));
        t[i].fork();
    }
    ThreadedKernel.alarm.waitUntil(100000);
}
```

```

procedure WAITUNTIL(x)
    Disable Interruption
    Calculate the wake time( $x + \text{currentTime}$ ) and create a waitThread
    Put waitThread into waitQueue
    sleep this thread
    Restore Interruption
end procedure
procedure TIMERINTERRUPT()
    Disable Interruption
    while waitQueue is not empty AND wake time of first thread in waitQueue
    < currentTime do
        wake first thread in waitQueue
    end while
    Restore Interruption
end procedure

```

And the result is as follows.

```

Thread starts at 120
Thread calls waitUtime with delay 100
Thread starts at 130
Thread calls waitUtime with delay 200
Thread starts at 140
Thread calls waitUtime with delay 300
Thread starts at 150
Thread calls waitUtime with delay 400
Thread starts at 160
Thread calls waitUtime with delay 500
Thread starts at 170
Thread calls waitUtime with delay 600
Thread starts at 180
Thread calls waitUtime with delay 700
Thread starts at 190
Thread calls waitUtime with delay 800
Thread starts at 200
Thread calls waitUtime with delay 900
Thread starts at 210
Thread calls waitUtime with delay 1000
Thread recovers at 500 ( $500 \geq 120+100$ )
Thread recovers at 510 ( $510 \geq 130+200$ )
Thread recovers at 520 ( $520 \geq 140+300$ )
Thread recovers at 1030 ( $1030 \geq 150+400$ )
Thread recovers at 1040 ( $1040 \geq 160+500$ )
Thread recovers at 1050 ( $1050 \geq 170+600$ )
Thread recovers at 1060 ( $1060 \geq 180+700$ )
Thread recovers at 1070 ( $1070 \geq 190+800$ )
Thread recovers at 1540 ( $1540 \geq 200+900$ )

```

Thread recovers at 1550 (1550>=210+1000)

And the test accurately meet the needs, since all threads continues after the delay time.

5 Implementation of Communicator

5.1 Overview

Implementat `Communicator` class. Two methods `speak` and `listener` to implement. The message is passed from exactly one speaker to exactly one listener.

5.2 Correctness Constraints

- Listeners wait when there is no speaker
- Speakers wait when there is no listener

5.3 Declaration

- Add a state variable `lock` which is a `Lock` into `Communicator`. Add four counters `AS`, `WS`, `AL`, `WL` initially as 0. Add three `conditions` for speaker, listener and return with the same lock. Add a state variable `word` to store words from speakers.
- Note that the first speaker or listener is what we call active speaker or listener and is exchanging message and sleep on condition until other one wakes it up and both return.
- A speaker speaks to only one listener and a listener listens to only one speaker, so the waiting speaker(listener) will be blocked by active speaker(listener).

5.4 Description

5.5 Test

Test a sequence of speakers and listeners in different orders and check the output.

And the test code as follows.

```
public static void selfTest() {
    Communicator com = new Communicator();
    /* case 1
    (new KThread(new Listener(1, com))).fork();
    (new KThread(new Listener(2, com))).fork();
    (new KThread(new Speaker(1, com, 1))).fork();
    (new KThread(new Speaker(2, com, 2))).fork();
    (new KThread(new Speaker(3, com, 3))).fork();
```

```

procedure COMMUNICATOR()
    initialize lock
    initialize AS WS AL WL to 0
    initialize conditions with same lock
end procedure

procedure SPEAK(word)
    Acquire the lock
    while AS != 0 do
        WS++
        // sleep on condition speaker
        sleep
        WS--
    end while
    AS++
    set word
    if AL != 0 then
        Wake active listener
    else
        if WL != 0 then
            wake one listener
        end if
        // in case that the later speaker runs too fast and cover the word
        // sleep on condition return
        sleep till the wait listener to return
        AS-
        AL-
        if WS != 0 then
            wake the wait speaker
        end if
    end if
    Release the lock
    return
end procedure

```

```

procedure LISTENER()
  Acquire the lock
  while AL != 0 do
    WL++
    // sleep on condition listener
    sleep
    WL--
  end while
  AL++
  if AS != 0 then
    Wake active speaker
  else
    if WS != 0 then
      wake one speaker
    end if
    // in case that the later listener runs too fast and retrieve the word
    // sleep on condition return
    sleep till the wait speaker to return
    AL-
    AS-
    if WL != 0 then
      wake the wait listener
    end if
  end if
  retrieve word
  Release the lock
  return
end procedure

```

```

        (new KThread(new Listener(3, com))).fork();
    */
    /** case 2
    for(int i = 1; i < 6; i++){
        (new KThread(new Listener(i, com))).fork();
    }
    for(int i = 5; i > 0; i--){
        (new KThread(new Speaker(i, com, i))).fork();
    }
    /**/
    ThreadedKernel.alarm.waitUntil(100000);
}

```

And the results is as follows.

```

case 1
Listener 1 starts listening
Listener 2 starts listening
Speaker 1 starts speaking
Speaker 1 speaks 1
Speaker 1 ends speaking
Speaker 2 starts speaking
Speaker 3 starts speaking
Listener 3 starts listening
Listener 1 hears 1 from speaker 1
Listener 1 ends listening
Speaker 2 speaks 2
Speaker 2 ends speaking
Listener 2 hears 2 from speaker 2
Listener 2 ends listening
Speaker 3 speaks 3
Speaker 3 ends speaking
Listener 3 hears 3 from speaker 3
Listener 3 ends listening

case 2
Listener 1 starts listening
Listener 2 starts listening
Listener 3 starts listening
Listener 4 starts listening
Listener 5 starts listening
Speaker 5 starts speaking
Speaker 5 speaks 5
Speaker 5 ends speaking
Speaker 4 starts speaking
Speaker 3 starts speaking
Speaker 2 starts speaking
Speaker 1 starts speaking
Listener 1 hears 5 from speaker 5
Listener 1 ends listening

```



```

Speaker 4 speaks 4
Speaker 4 ends speaking
Listener 2 hears 4 from speaker 4
Listener 2 ends listening
Listener 3 hears 3 from speaker 3
Listener 3 ends listening
Speaker 3 speaks 3
Speaker 3 ends speaking
Speaker 2 speaks 2
Speaker 2 ends speaking
Listener 4 hears 2 from speaker 2
Listener 4 ends listening
Speaker 1 speaks 1
Speaker 1 ends speaking
Listener 5 hears 1 from speaker 1
Listener 5 ends listening

```

And According the results, each **Listener** listens to exactly one **Speaker** and each **Speaker** speaks to exactly one **Listener** which meets the requirements.

6 Implementation of PriorityScheduler

6.1 Overview

Implement **PriorityScheduler** class so that the scheduler can properly schedule the threads by its priority and by priority donation we can avoid priority inversion.

6.2 Correctness Constraints

- Waiting thread donates its priority to the thread which is holding the resource to avoid priority inversion.
- Scheduler always retrieve the thread with highest priority from the waitingQueue.

6.3 Declaration

- Here we only consider the case **transferPriority** is true, since when it's false, we only have to sort the threads by their original priority and don't need to calculate EP.
- In **PriorityQueue**:
Add **waitingList**: a priority-queue(realized by maximal heap or red-black tree) by EP of **ThreadState** waiting for this resource. Add a **maxEP** denotes maximal EP in the **waitingQueue**. Add a **boolean changed** denotes whether **maxEP** should be updated. Add a **ThreadState master** which is occupying the resource.

- In `ThreadState`:
Add a list by EP of `PriorityQueue occupiedResources` collects the resources which is now occupied by this thread. Add a list by EP of `PriorityQueue acquiredResources` collects the resources which is being acquired (but not yet) by this thread. Add a `boolean changed` denotes whether EP should be updated. Add a `EP` denotes EP of this thread.
- The EP should be recursively updated when a new waiting thread enters or when a thread quits holding resources. And updated by rules: Waiting thread donates its priority to the thread which is holding the resource to avoid priority inversion.

6.4 Description

6.5 Test

1. Set up several threads with random priorities associated with one condition. And test whether they execute in decreasing order.
2. Set up several threads with random priorities associated with multiple conditions. And test whether they execute in decreasing order. And Test by printing that whether the waiting thread properly donates its priority and whether the quit-holding thread recovers its priority.

The following are test codes.

```
private static void test1() {
    System.out.println("PriorityScheduler.test1() begins.");
    KThread thread0 = new KThread(new PTest(0));
    KThread thread1 = new KThread(new PTest(1));

    thread0.fork();
    thread1.fork();

    thread0.join();
    thread1.join();
    System.out.println("PriorityScheduler.test1() ends.");
}

private static void test2() {
    System.out.println("PriorityScheduler.test2() begins.");
    KThread thread0 = new KThread(new PTest(0));
    KThread thread1 = new KThread(new PTest(1));

    boolean intStatus = Machine.interrupt().disable();

    ThreadedKernel.scheduler.setPriority(thread0, 2);

    Machine.interrupt().restore(intStatus);
}
```

Algorithm 1 PriorityQueue

```
procedure GETMAXEP()  
  if !transferPriority then  
    return minimum priority  
  end if  
  if changed then  
    maxEP  $\leftarrow$  minimum priority  
    for each ThreadState ts in waitingQueue do  
      temp  $\leftarrow$  MAX(maxEP, ts.getEP())  
    end for changed  $\leftarrow$  false  
  end if  
  return maxEP  
end procedure  
procedure WAITFORACCESS(KThread thread)  
  Lib.assertTrue(Machine.interrupt.disable())  
  Add (ts  $\leftarrow$  getThreadState(thread)) into waitingQueue  
  ts.waitForAccess(this)  
end procedure  
procedure ACQUIRE(KThread thread)  
  Lib.assertTrue(Machine.interrupt.disable())  
  if master != null then  
    Remove this from master.occupiedResource  
  end if  
  getThreadState(thread).acquire(this)  
end procedure  
procedure NEXTTHREAD()  
  Lib.assertTrue(Machine.interrupt.disable())  
  if master != null then  
    Remove this from master.occupiedResource  
  end if  
  thread  $\leftarrow$  null  
  if waitingQueue is not empty then  
    thread  $\leftarrow$  pickNextThread()  
    Remove thread from waitingQueue  
    thread.acquire(this)  
  end if  
  return thread  
end procedure
```

```

procedure PICKNEXTTHREAD()
  if waitingQueue is not empty then
    threadState  $\leftarrow$  first element of waitingQueue
    for each ThreadState ts in waitingQueue do
      if ts has higher priority than threadState then
        threadState  $\leftarrow$  ts
      end if
    end for
  else
    thread  $\leftarrow$  null
  end if
  return thread
end procedure

```

Algorithm 2 ThreadState

```

// once new thread enter, all the EP should change
procedure CHANGE()
  if !changed then
    changed  $\leftarrow$  true
    EP  $\leftarrow$  getEP()
    for each PriorityQueue pq in acquiredResource do
      if pq.master != null && transferPriority then
        pq.changed  $\leftarrow$  true
        pq.master.change()
      end if
    end for
  end if
end procedure

procedure GETEP()
  if changed then
    EP  $\leftarrow$  priority
    for each PriorityQueue pq in occupiedQueue do
      EP  $\leftarrow$  MAX(EP, pq.getMaxEP)
    end for
  end if
  return EP
end procedure

```

```

procedure SETPRIORITY(int Priority)
    if priority != Priority then
        priority ← Priority
        change()
    end if
end procedure
procedure WAITFORACCESS(PriorityQueue waitQueue)
    Add waitQueue into acquiredResource
    if waitQueue is in occupiedResource then
        Remove waitQueue from occupiedResource
        waitQueue.master ← null
    end if
    if waitQueue.master != null then
        // new thread wait hence EP should change
        if transferPriority then
            waitQueue.changed ← true
            waitQueue.master.change()
        end if
    end if
end procedure
procedure ACQUIRE(PriorityQueue waitQueue)
    Add waitQueue into occupiedResource
    if waitQueue is in acquiredResource then
        Remove waitQueue from acquiredResource
        waitQueue.master ← this
    end if
    change()
end procedure

```

```

        thread0.fork();
        thread1.fork();

        thread0.join();
        thread1.join();
        System.out.println("PriorityScheduler.test2() ends.");
    }

    private static void test3() {
        System.out.println("PriorityScheduler.test3() begins.");

        KThread thread0 = new KThread(new PStest(0));
        KThread thread1 = new KThread(new PStest(1));

        thread0.setName("thread0");
        thread1.setName("thread1");

        boolean intStatus = Machine.interrupt().disable();

        ThreadedKernel.scheduler.setPriority(thread0, 2);

        Machine.interrupt().restore(intStatus);

        thread0.fork();
        thread1.fork();

        /*
         * The main thread which has increased its priority is
         * waiting for
         * thread1.
         */
        ThreadedKernel.scheduler.increasePriority();
        thread1.join();
        thread0.join();
        ThreadedKernel.scheduler.decreasePriority();

        System.out.println("PriorityScheduler.test3() ends.");
    }

    private static void test4() {
        System.out.println("PriorityScheduler.test4() begins.");

        KThread thread0 = new KThread(new PStest(0));
        KThread thread1 = new KThread(new PStest(1));

        thread0.setName("thread0");
        thread1.setName("thread1");

        boolean intStatus = Machine.interrupt().disable();

```

```

ThreadedKernel.scheduler.setPriority(thread0, 2);

Machine.interrupt().restore(intStatus);

thread0.fork();
thread1.fork();

/*
 * The main thread which has increased its priority is
 * waiting for
 * thread1.
 */
ThreadedKernel.scheduler.increasePriority();
ThreadedKernel.scheduler.increasePriority();
thread1.join();
thread0.join();
ThreadedKernel.scheduler.decreasePriority();
ThreadedKernel.scheduler.decreasePriority();

System.out.println("PriorityScheduler.test4() ends.");
}

private static void test5() {
    System.out.println("PriorityScheduler.test5() begins.");

    KThread thread0 = new KThread(new PTest(0));
    KThread thread1 = new KThread(new PTest(1));
    KThread thread2 = new KThread(new PTest(2));

    thread0.setName("thread0");
    thread1.setName("thread1");
    thread2.setName("thread2");

    /* Disable interrupt for convenience. */
    boolean intStatus = Machine.interrupt().disable();

    ThreadedKernel.scheduler.setPriority(thread0, 2);
    ThreadedKernel.scheduler.setPriority(thread1, 2);
    ThreadedKernel.scheduler.setPriority(thread2, 1);

    thread0.fork();
    thread1.fork();
    thread2.fork();

    /* Priority of thread1 is changed later than thread2, but
     * that thread is enqueued earlier. */
    ThreadedKernel.scheduler.setPriority(thread1, 1);

    /* Wait until all the threads ends. */

```

```

        thread0.join();
        thread1.join();
        thread2.join();

        Machine.interrupt().restore(intStatus);

        System.out.println("PriorityScheduler.test5() ends.");
    }

    private static class Competitor implements Runnable {
        private int index;
        private Communicator pubCom;
        private Communicator priCom;

        Competitor(int _index, Communicator _pubCom, Communicator
            _priCom) {
            index = _index;
            pubCom = _pubCom;
            priCom = _priCom;
        }

        public void run() {
            if(pubCom.listen() > 0)
                priCom.speak(index);
        }
    }

    private static class Referee implements Runnable {
        private int capacity;
        private Communicator pubCom;
        private Communicator priCom;

        Referee(int _capacity, Communicator _pubCom, Communicator
            _priCom){
            capacity = _capacity;
            pubCom = _pubCom;
            priCom = _priCom;
        }

        public void run() {
            while(capacity>0){
                pubCom.speak(capacity);
                int temp = priCom.listen();
                for(int i = 0; i < 5; i++){
                    System.out.println("Competitor " +
                        temp + " loop " + i);
                }
                capacity--;
            }
        }
    }
}

```



```

private static void test6() {
    Communicator pubCom = new Communicator();
    Communicator priCom = new Communicator();
    int capacity = 7;
    KThread[] competitors = new KThread[10];
    for(int i = 0; i < capacity; i++){
        competitors[i] = new KThread(new Competitor(i,
            pubCom, priCom));
    }
    KThread referee = new KThread(new Referee(capacity,
        pubCom, priCom));
    boolean intStatus = Machine.interrupt().disable();
    for(int i = 0; i < capacity; i++){
        int priority = (int)(Math.random()*7);
        ThreadedKernel.scheduler.setPriority(competitors[i],
            priority);
        System.out.println("Competitor " + i + " with
            priority " + priority);
    }
    for(int i = 0; i < capacity; i++)
        competitors[i].fork();
    referee.fork();
    for(int i = 0; i < capacity; i++)
        competitors[i].join();
    referee.join();
    Machine.interrupt().restore(intStatus);
}

private static class Joiner implements Runnable {
    int length;
    String name;
    Joiner(int _length, String _name){
        length = _length;
        name = _name;
    }
    public void run(){
        for(int i = 0; i < length; i++)
            System.out.println(name + " loop " + i);
    }
}

private static class Joinee implements Runnable {
    private KThread joiner;
    int length;
    String name;
    Joinee(int _length, String _name, KThread _joiner){
        length = _length;
        joiner = _joiner;
        name = _name;
    }
    public void run(){
        joiner.join();
    }
}

```

```

        for(int i = 0; i < length; i++)
            System.out.println(name + " loop " + i);
    }
}

private static void test7() {
    KThread thread0 = new KThread(new Joiner(2, "thread0"));
    KThread threadL = new KThread(new Joinee(2, "threadL",
        thread0));
    KThread threadM = new KThread(new Joinee(10, "threadM",
        thread0));
    KThread threadH = new KThread(new Joinee(2, "threadH",
        threadL));

    threadH.setName("threadH");
    threadM.setName("threadM");
    threadL.setName("threadL");
    thread0.setName("thread0");

    boolean intStatus = Machine.interrupt().disable();

    ThreadedKernel.scheduler.setPriority(thread0, 7);
    ThreadedKernel.scheduler.setPriority(threadH, 7);
    ThreadedKernel.scheduler.setPriority(threadM, 4);
    ThreadedKernel.scheduler.setPriority(threadL, 1);

    threadM.fork();
    threadL.fork();
    threadH.fork();
    thread0.fork();
    thread0.join();
    threadM.join();
    threadL.join();
    threadH.join();

    Machine.interrupt().restore(intStatus);
}

public static void selfTest() {
    test1();
    test2();
    test3();
    test4();
    test5();
}

private static class PSTest implements Runnable {
    private int index;

```

```

PSTest(int _index) {
    index = _index;
}

public void run() {
    int i;
    boolean intStatus = Machine.interrupt().disable();
    System.out.println("EffectivePriority of thread" +
        index + " is "
            + ThreadedKernel.scheduler.getEffectivePriority());
    Machine.interrupt().restore(intStatus);
    for (i = 0; i < 5; i++) {
        System.out.println("PSTest " + index + "
            loop " + i);
        KThread.yield();
    }
}
}

```

The results go as follows:

```

PriorityScheduler.test1() begins.
EffectivePriority of thread0 is 1
PSTest 0 loop 0
EffectivePriority of thread1 is 1
PSTest 1 loop 0
PSTest 0 loop 1
PSTest 1 loop 1
PSTest 0 loop 2
PSTest 1 loop 2
PSTest 0 loop 3
PSTest 1 loop 3
PSTest 0 loop 4
PSTest 1 loop 4
PriorityScheduler.test1() ends.
PriorityScheduler.test2() begins.
EffectivePriority of thread0 is 2
PSTest 0 loop 0
PSTest 0 loop 1
PSTest 0 loop 2
PSTest 0 loop 3
PSTest 0 loop 4
EffectivePriority of thread1 is 1
PSTest 1 loop 0
PSTest 1 loop 1
PSTest 1 loop 2
PSTest 1 loop 3
PSTest 1 loop 4
PriorityScheduler.test2() ends.

```

```
PriorityScheduler.test3() begins.  
EffectivePriority of thread1 is 2  
PSTest 1 loop 0  
EffectivePriority of thread0 is 2  
PSTest 0 loop 0  
PSTest 1 loop 1  
PSTest 0 loop 1  
PSTest 1 loop 2  
PSTest 0 loop 2  
PSTest 1 loop 3  
PSTest 0 loop 3  
PSTest 1 loop 4  
PSTest 0 loop 4  
PriorityScheduler.test3() ends.  
PriorityScheduler.test4() begins.  
EffectivePriority of thread1 is 3  
PSTest 1 loop 0  
PSTest 1 loop 1  
PSTest 1 loop 2  
PSTest 1 loop 3  
PSTest 1 loop 4  
EffectivePriority of thread0 is 3  
PSTest 0 loop 0  
PSTest 0 loop 1  
PSTest 0 loop 2  
PSTest 0 loop 3  
PSTest 0 loop 4  
PriorityScheduler.test4() ends.  
PriorityScheduler.test5() begins.  
EffectivePriority of thread0 is 2  
Competitor 0 with priority 1  
Competitor 1 with priority 6  
Competitor 2 with priority 6  
Competitor 3 with priority 0  
Competitor 4 with priority 4  
Competitor 5 with priority 1  
Competitor 6 with priority 0  
Competitor 0 loop 0  
Competitor 0 loop 1  
Competitor 0 loop 2  
Competitor 0 loop 3  
Competitor 0 loop 4  
Competitor 1 loop 0  
Competitor 1 loop 1  
Competitor 1 loop 2  
Competitor 1 loop 3  
Competitor 1 loop 4  
Competitor 2 loop 0  
Competitor 2 loop 1  
Competitor 2 loop 2
```

```
Competitor 2 loop 3
Competitor 2 loop 4
Competitor 4 loop 0
Competitor 4 loop 1
Competitor 4 loop 2
Competitor 4 loop 3
Competitor 4 loop 4
Competitor 3 loop 0
Competitor 3 loop 1
Competitor 3 loop 2
Competitor 3 loop 3
Competitor 3 loop 4
Competitor 5 loop 0
Competitor 5 loop 1
Competitor 5 loop 2
Competitor 5 loop 3
Competitor 5 loop 4
Competitor 6 loop 0
Competitor 6 loop 1
Competitor 6 loop 2
Competitor 6 loop 3
Competitor 6 loop 4
PSTest 0 loop 0
PSTest 0 loop 1
PSTest 0 loop 2
PSTest 0 loop 3
PSTest 0 loop 4
EffectivePriority of thread1 is 1
EffectivePriority of thread2 is 1
PSTest 2 loop 0
PSTest 1 loop 0
PSTest 2 loop 1
PSTest 1 loop 1
PSTest 2 loop 2
PSTest 1 loop 2
PSTest 2 loop 3
PSTest 1 loop 3
PSTest 2 loop 4
PSTest 1 loop 4
PriorityScheduler.test5() ends.
thread0 loop 0
thread0 loop 1
threadL loop 0
threadL loop 1
threadH loop 0
threadH loop 1
threadM loop 0
threadM loop 1
threadM loop 2
threadM loop 3
```

```
threadM loop 4
threadM loop 5
threadM loop 6
threadM loop 7
threadM loop 8
threadM loop 9
```

Note in the last second test, scheduler schedules the threads in the decreasing order of priorities and in the last test, we test **Priority Inversion**, eventually, `threadL` executes before `threadM` by priority donation.

7 Solution to Boat Problem

7.1 Overview

Implement Boat class to solve the boat problem.

7.2 Correctness Constraints

- The boat can only hold one or two children or one adult.
- Each time the location of the boat changes, the number of passengers in boat cannot be zero.
- `begin` method finished with both of children and adults is on Molokai.

7.3 Declaration

- In Boat class, add `locationOfBoat`, `numOfChildOahu`, `numOfAdultOahu`, `numOfChildMolokai`, `numOfAdultMolokai`, `numOfChildBoat`, `boatLock`, `waitOnOahuCondition`, `waitBoardingCondition`, `waitOnMolokaiCondition`, and message a `Communicator`.
- In `begin`, what we need to do is for each children and adults create a thread, and we also use message to see whether we have move all people to Molokai.
- In `AdultItinerary`, the adult can move to Molokai when the boat is at Oahu and empty with child on Molokai can't be zero. Then we move this adult to Molokai and wake waiting on Molokai.
- In `ChildItinerary`, add `location` to show the location of this child. For child move to Molokai, the condition is boat is at Oahu and empty or with one child, and also the child can't be himself. If the child is the first in the boat, then it wait for another to board. If the location of the boat is on Molokai, then it must have one child back to Oahu.

```

procedure BEGIN(int adults, int children, BoatGrader b)
    bg  $\leftarrow$  b
    for each childs, create a thread of ChildItinerary
    for each adults, create a thread of AdultItinerary
    while message.listen() is not the total of children and adults do
    end while
end procedure
procedure ADULTITINERARY
    numOfAdultOahu++
    boatLock.acquire()
    while locationOfBoat is not Oahu or numOfChildBoat  $\leq$  0 or num-
    mOfChildOahu  $\leq$  1 do
        if locationOfBoat is on Oahu then
            waitOnOahuCondition.wakeAll()
        end if
        waitOnOahuCondition.sleep()
    end while
    bg.AdultRowToMolokai()
    numOfAdultOahu-, numOfAdultMolokai++
    locationOfBoat is Molokai
    message.speak(numOfAdultMolokai + numOfChildMolokai)
    waitOnMolokaiCondition.wakeAll()
    boat.release()
end procedure

```

```

procedure CHILDITINERARY
  location is Oahu
  numOfChildOahu++
  while true do
    boat.acquire()
    if location is Oahu then
      while locationOfBoat is not Oahu or numOfChildBoat is 2 or numOfChildOahu is 1 do
        if locationOfBoat is Oahu then
          waitOnOahuCondition.wakeAll()
        end if
        waitOnOahuCondition.sleep()
      end while
      numOfChildBoat++
      if numOfChildBoat == 1 then
        waitOnOahuCondition.wakeAll()
        waitBoardingCondition.sleep()
        numOfChildOahu--
        bg.ChildRideToMolokai()
        location is Molokai
        numOfChildBoat ← 0
        numOfChildMolokai++
        message.speak(numOfAdultMolokai + numOfChildMolokai)
        waitOnMolokaiCondition.wakeAll()
        waitOnMolokaiCondition.sleep()
      else
        waitBoardingCondition.wake()
        numOfChildOahu--
        bg.ChildRowToMolokai()
        location is Molokai
        numOfChildMolokai++
        waitOnMolokaiCondition.sleep()
      end if
    else
      while locationOfBoat is not Molokai do
        waitOnMolokaiCondition.sleep()
      end while
      numOfChildMolokai--
      bg.ChildRowToOahu()
      location is Oahu
      locationOfBoat is Oahu
      numOfChildOahu++
      waitOnOahuCondition.wakeAll()
      waitOnOahuCondition.sleep()
    end if
    boat.release()
  end while
end procedure

```

7.4 Description

7.5 Test

```
public static void selfTest() {  
    BoatGrader b = new BoatGrader();  
  
    begin(4, 3, b);  
}
```

We test the case start with 4 adults and 3 childs and here is the result:

```
A child has forked.  
A child has forked.  
A child has forked.  
An adult as forked.  
An adult as forked.  
An adult as forked.  
An adult as forked.  
**Child rowing to Molokai.  
**Child arrived on Molokai as a passenger.  
**Child rowing to Oahu.  
**Child rowing to Molokai.  
**Child arrived on Molokai as a passenger.  
**Child rowing to Oahu.  
**Adult rowing to Molokai.  
**Child rowing to Oahu.  
**Child rowing to Molokai.  
**Child arrived on Molokai as a passenger.  
**Child rowing to Oahu.  
**Adult rowing to Molokai.  
**Child rowing to Oahu.  
**Child rowing to Molokai.  
**Child arrived on Molokai as a passenger.  
**Child rowing to Oahu.  
**Adult rowing to Molokai.  
**Child rowing to Oahu.  
**Child rowing to Molokai.  
**Child arrived on Molokai as a passenger.  
**Child rowing to Oahu.  
**Adult rowing to Molokai.  
**Child rowing to Oahu.  
**Child rowing to Molokai.  
**Child arrived on Molokai as a passenger.
```

As we can easily check, the question is solved properly.