

Discrete-Event Simulation  
of Queueing Systems in Java:  
The JSimulation and JQueues Libraries

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Release 5



*This book is dedicated to Dick Epema and Graham Birtwistle.*



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# Chapter 1

## Preface

Queueing systems deal with the general notion of *waiting* for (the completion of) something. They are ubiquitously and often annoyingly present in our everyday lives. If there is anything we do most, it is probably *waiting* for something to happen (finally winning a non-trivial prize in the State Lottery after paying monthly tickets over the past thirty years), arrive (the breath-taking dress we ordered from that webshop against warnings in the seller's reputation blog), change (the reception of many severely bad hands in the poker game we just happened to ran into), stop (the constant flipping into red of traffic lights while we are just within breaking distance in our urban environment), or resume (the heater that regularly happens to have a mind of its own during winter months).

**XXX**



# Chapter 2

## Introduction



# Chapter 3

## Guided Tour

### 3.1 Getting Started

### 3.2 Creating and Running Queueing-System Simulations

In order to perform a simulation study in `jqueues`, the following four actions need to be taken:

- The creation of an event list;
- The creation of one or more queues, and their attachment to the event list;
- The selection of the method for listening to the queue(s), and/or the event list;
- The creation of a workload consisting of jobs;
- Running the event list.

Without much further ado, here's an example:

Listing 3.1: A simple simulation with a single FCFS\_B queue and ten jobs.

```
final SimEventList el = new DefaultSimEventList ();
final int bufferSize = 2;
final FCFS_B queue = new FCFS_B (el, bufferSize);
queue.registerStdOutSimQueueListener ();
for (int j = 0; j < 10; j++)
{
    final double jobServiceTime = (double) 2.2 * j;
    final double jobArrivalTime = (double) j;
    final String jobName = Integer.toString (j);
    final SimJob job = new DefaultSimJob (null, jobName, jobServiceTime);
    SimEntityEventScheduler.scheduleJobArrival (job, queue, jobArrivalTime);
}
```

```
}
el.run ();
```

In Listing 3.1, we first create a single event list of type `DefaultSimEventList` and a `FCFS_B` queue. On the queue, we invoke its default "listener", issuing notification to the standard output. Subsequently, we create ten jobs named "0", "1", "2", ..., scheduled for arrival at the queue at  $t = 0$ ,  $t = 1$ ,  $t = 2$ , ..., respectively. Finally, we "run" the event list, i.e., let it process the arrivals.

The event list type `DefaultSimEventList` will suffice for almost all practical cases, but it is essential to note already that a *single* event-list instance is typically used throughout *any* simulation program. Its purpose of the event list is to hold scheduled *events* in non-decreasing order of *schedule time*, and, upon request (in this case through `el.run`), starts processing the scheduled events in sequence, invoking their associated *actions*. In this case, the use of events remains hidden, because jobs are scheduled through the use of utility method `scheduleJobArrival`.

The queue of choice is the First-Come First-Served queue with limited buffer size, `FCFS_B`, described in more detail in Section 6.4.2. The constructor takes two arguments, the event list `el` and the buffer size. The queueing system consists of a queue with only `B` places to hold jobs, and a single server that "serves" the jobs in the queue in order of their arrival. If a job arrives at the `FCFS_B` system while all places in the queue are occupied by other jobs, the arriving job is denied access to the system, and is *dropped*. Once a queue has finished serving the (single) job, the job *departs* from the system.

So how long does it take to serve a job? Well, in `jqueues`, the default behavior is that a queue requests the job for its *required service time*, and we set a fixed service time (at *any* queue) for each job upon creation as the third argument of the constructor. The first argument of the `DefaultSimJob` is the event list to which it is to be attached. For jobs (well, at least the ones derived from `DefaultSimJob`), it is often safe to set this to `null`, although we could have equally well set it to `el`. However, queues must always be attached to the event list; a `null` value upon construction will throw an exception.

The (approximate) output of the code fragment of Listing 3.1 is shown in Listing 3.2 below.

Listing 3.2: Example output of Listing 3.1.

```
StdOutSimQueueListener t=0.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=0.0, entity=FCFS_B[2]: STATE CHANGED:
=> ARRIVAL [Arr[0]@FCFS_B[2]]
=> START [Start[0]@FCFS_B[2]]
=> DEPARTURE [Dep[0]@FCFS_B[2]]
StdOutSimQueueListener t=0.0, queue=FCFS_B[2]: ARRIVAL of job 0.
StdOutSimQueueListener t=0.0, queue=FCFS_B[2]: START of job 0.
StdOutSimQueueListener t=0.0, queue=FCFS_B[2]: DEPARTURE of job 0.
```



```

StdOutSimQueueListener t=1.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=1.0, entity=FCFS_B[2]: STATE CHANGED:
=> ARRIVAL [Arr[1]@FCFS_B[2]]
=> START [Start[1]@FCFS_B[2]]
=> STA_FALSE [StartArmed[false]@FCFS_B[2]]
StdOutSimQueueListener t=1.0, queue=FCFS_B[2]: ARRIVAL of job 1.
StdOutSimQueueListener t=1.0, queue=FCFS_B[2]: START of job 1.
StdOutSimQueueListener t=1.0, queue=FCFS_B[2]: START-ARMED -> false.
StdOutSimQueueListener t=2.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=2.0, entity=FCFS_B[2]: STATE CHANGED:
=> ARRIVAL [Arr[2]@FCFS_B[2]]
StdOutSimQueueListener t=2.0, queue=FCFS_B[2]: ARRIVAL of job 2.
StdOutSimQueueListener t=3.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=3.0, entity=FCFS_B[2]: STATE CHANGED:
=> ARRIVAL [Arr[3]@FCFS_B[2]]
StdOutSimQueueListener t=3.0, queue=FCFS_B[2]: ARRIVAL of job 3.
StdOutSimQueueListener t=3.2, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=3.2, entity=FCFS_B[2]: STATE CHANGED:
=> DEPARTURE [Dep[1]@FCFS_B[2]]
=> START [Start[2]@FCFS_B[2]]
StdOutSimQueueListener t=3.2, queue=FCFS_B[2]: DEPARTURE of job 1.
StdOutSimQueueListener t=3.2, queue=FCFS_B[2]: START of job 2.
StdOutSimQueueListener t=4.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=4.0, entity=FCFS_B[2]: STATE CHANGED:
=> ARRIVAL [Arr[4]@FCFS_B[2]]
StdOutSimQueueListener t=4.0, queue=FCFS_B[2]: ARRIVAL of job 4.
StdOutSimQueueListener t=5.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=5.0, entity=FCFS_B[2]: STATE CHANGED:
=> ARRIVAL [Arr[5]@FCFS_B[2]]
=> DROP [Drop[5]@FCFS_B[2]]
StdOutSimQueueListener t=5.0, queue=FCFS_B[2]: ARRIVAL of job 5.
StdOutSimQueueListener t=5.0, queue=FCFS_B[2]: DROP of job 5.
StdOutSimQueueListener t=6.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=6.0, entity=FCFS_B[2]: STATE CHANGED:
=> ARRIVAL [Arr[6]@FCFS_B[2]]
=> DROP [Drop[6]@FCFS_B[2]]
StdOutSimQueueListener t=6.0, queue=FCFS_B[2]: ARRIVAL of job 6.
StdOutSimQueueListener t=6.0, queue=FCFS_B[2]: DROP of job 6.
StdOutSimQueueListener t=7.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=7.0, entity=FCFS_B[2]: STATE CHANGED:
=> ARRIVAL [Arr[7]@FCFS_B[2]]
=> DROP [Drop[7]@FCFS_B[2]]
StdOutSimQueueListener t=7.0, queue=FCFS_B[2]: ARRIVAL of job 7.
StdOutSimQueueListener t=7.0, queue=FCFS_B[2]: DROP of job 7.
StdOutSimQueueListener t=7.6000000000000005, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=7.6000000000000005, entity=FCFS_B[2]: STATE CHANGED:
=> DEPARTURE [Dep[2]@FCFS_B[2]]
=> START [Start[3]@FCFS_B[2]]
StdOutSimQueueListener t=7.6000000000000005, queue=FCFS_B[2]: DEPARTURE of job 2.
StdOutSimQueueListener t=7.6000000000000005, queue=FCFS_B[2]: START of job 3.
StdOutSimQueueListener t=8.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=8.0, entity=FCFS_B[2]: STATE CHANGED:
=> ARRIVAL [Arr[8]@FCFS_B[2]]
StdOutSimQueueListener t=8.0, queue=FCFS_B[2]: ARRIVAL of job 8.
StdOutSimQueueListener t=9.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=9.0, entity=FCFS_B[2]: STATE CHANGED:
=> ARRIVAL [Arr[9]@FCFS_B[2]]
=> DROP [Drop[9]@FCFS_B[2]]
StdOutSimQueueListener t=9.0, queue=FCFS_B[2]: ARRIVAL of job 9.
StdOutSimQueueListener t=9.0, queue=FCFS_B[2]: DROP of job 9.
StdOutSimQueueListener t=14.200000000000001, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=14.200000000000001, entity=FCFS_B[2]: STATE CHANGED:
=> DEPARTURE [Dep[3]@FCFS_B[2]]
=> START [Start[4]@FCFS_B[2]]
StdOutSimQueueListener t=14.200000000000001, queue=FCFS_B[2]: DEPARTURE of job 3.
StdOutSimQueueListener t=14.200000000000001, queue=FCFS_B[2]: START of job 4.
StdOutSimQueueListener t=23.0, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=23.0, entity=FCFS_B[2]: STATE CHANGED:
=> DEPARTURE [Dep[4]@FCFS_B[2]]
=> START [Start[8]@FCFS_B[2]]
StdOutSimQueueListener t=23.0, queue=FCFS_B[2]: DEPARTURE of job 4.
StdOutSimQueueListener t=23.0, queue=FCFS_B[2]: START of job 8.
StdOutSimQueueListener t=40.6, entity=FCFS_B[2]: UPDATE.
StdOutSimQueueListener t=40.6, entity=FCFS_B[2]: STATE CHANGED:
=> DEPARTURE [Dep[8]@FCFS_B[2]]
=> STA_TRUE [StartArmed[true]@FCFS_B[2]]
StdOutSimQueueListener t=40.6, queue=FCFS_B[2]: DEPARTURE of job 8.
StdOutSimQueueListener t=40.6, queue=FCFS_B[2]: START-ARMED -> true.

```

Apart from the `STATE CHANGED`, `UPDATE` and `START_ARMED` lines in the output, the notifications pretty much speak for themselves. We even get notified when jobs start service (`START`), and when they are dropped (jobs 5, 6, and 7) by the queue (`DROP`). The `START_ARMED` notifications refer to state changes in a special boolean attribute of a queue named its `StartArmed` property. It is explained in detail in Section 5.3.2 but since you will hardly need it in practical applications, we will not delve into it. Suffice it to say that `StartArmed` property reveals in some strange way whether the queue *would* start a hypothetical arriving job if several additional conditions are also met. It is crucial for the implementation of more complex queueing systems.

The remaining two notification types, `UPDATE` and `STATE CHANGED` are essential, however, and require special attention. As you may have spotted, events are actually reported twice, once as part of a `STATE CHANGED` notification, followed by a separate notification specific to the event type (`ARRIVAL`, `DEPARTURE`, etc.). As a matter of fact, these separate notifications are merely a courtesy of the queue as it is only required to issue `UPDATE`, `STATE CHANGED` and `RESET` notifications.

In order to understand this, we realize that in *any* discrete-event simulation, the entities (like queues) involved possess an individual *state* that can only change at discrete moments in time (the *epochs*), and as a result of an *operation* on the entity at that time.

# Chapter 4

## Events, Event Lists and Actions

This chapter describes the event and event-list features that are available from the `jsimulation` package. Note that `jsimulation` is a dependency of `jqueues`.

### 4.1 Creating the Event List and Events

At the very heart of every simulation experiment in `jqueues` is the so-called *event list*. The event list obviously holds the events, keeps them ordered, and maintains a notion of "where we are" in a simulation run. Together, an event list and the events it contains define the precise sequence of actions taken in a simulation. The following code snippet shows how to create an event list and schedule two (empty) events, one at  $t_1 = 5.0$  and one at  $t_2 = 10$ , and print the resulting event list on `System.out`:

```
final SimEventList el = new DefaultSimEventList ();
final SimEvent e1 = new DefaultSimEvent (5.0);
final SimEvent e2 = new DefaultSimEvent (10.0);
el.add (e1);
el.add (e2);
el.print ();
```

In `jsimulation`, the event list is of type `SimEventList`; events are of type `SimEvent`, respectively. Since both of them are Java *interfaces*, you need implementing classes to instantiate them: `DefaultSimEventList` for an event list; `DefaultSimEvent` for an event. Typically, you instantiate a single event list for a simulation experiment, and numerous events.

The `double` argument in the `DefaultSimEvent` constructor (of which there are several) is the *schedule time* of the event on the event list. Perhaps surprisingly,

in `jsimulation`, the schedule time is actually held on the event, *not* on the event list. Also, a `SimEventList` is inheriting from `SortedSet` from the Java Collections Framework. These choices have the following consequences:

- Each `SimEvent` can be present *at most once* in a `SimEventList`. You cannot reuse a single event instance (like a job creation and arrival event) by scheduling it multiple times on the event list. Instead, you must either use separate event instances, or reschedule the event the moment it leaves the event list.
- You cannot (more precisely, *should not*) modify the time on the event while it is scheduled on an event list.
- You always have access to the (intended) schedule time of the event, without having to refer to an event list (if the event is scheduled at all) or use a separate variable to keep and maintain that time.
- The events must be equipped with a *total ordering* (imposed by `SortedSet`) and distinct events should not be equal (imposed by us). This means that for each pair of (distinct) events scheduled on a `SimEventList`, one of them is always strictly larger than the other (in the ordering, they cannot be "equal").

The output of the code snippet is something like<sup>1</sup>:

```
SimEventList {X}.DefaultSimEventList@{Y}, class=DefaultSimEventList, time=-Infinity:
t=5.0, name=No Name, object=null, action=null.
t=10.0, name=No Name, object=null, action=null.
```

The output shows the name of the event list (as obtained from its `toString` method) and the current time ( $-\infty$ ) in the first row, and then the events in the list in the proper order. By the way, we modified the output; the markers `{X}` and `{Y}` represents strings that most likely deviate on your system.

The output also shows the four properties of an event: its time, name, user object, and action. These will be described in more detail in the next section.

## 4.2 Event Properties and Event Constructors

A `SimEvent` has the following properties:

- Time: The (intended) schedule time of the event (default  $-\infty$ ).
- Name: The name of the event, which is only used for logging and output (default "No Name").

---

<sup>1</sup>We may have improved the layout in the meantime.

- Object: A general-purpose object available for storing information associated with the event (`jsimulation` nor `jqueues` uses this field; its default value is `null`).
- Action: The action to take, a `SimEventAction` (default `null`), described in the next section.

Each property has corresponding getter and setter methods:

Properties of <code>SimEvent</code>
<code>double</code> <code>getTime ()</code> <code>void</code> <code>setTime (double)</code>
<code>String</code> <code>getName ()</code> <code>void</code> <code>setName (String)</code>
<code>T</code> <code>getObject ()</code> <code>void</code> <code>setObject (T)</code>
<code>SimEventAction</code> <code>getEventAction ()</code> <code>void</code> <code>setEventAction (SimEventAction)</code>

Note that `T` refers to the so-called *generic-type argument* of `SimEvent` (and also of `DefaultSimEvent`). The prototype is `SimEvent<T>`, so `T` can be any object type. The use of generic types is explained in some more details in the "Advanced Topics" section, but for now `T` can be simply read as a `Object`.

The next section describes the actions in more detail, but we first provide a list of constructors for `DefaultSimEvent`:

Constructors of <code>DefaultSimEvent</code>
<code>DefaultSimEvent (String, double, T, SimEventAction)</code>
<code>DefaultSimEvent (double, T, SimEventAction)</code>
<code>DefaultSimEvent (double, SimEventAction)</code>
<code>DefaultSimEvent (double)</code>
<code>DefaultSimEvent ()</code>

Any non-listed property in a constructor will obtain its default value.

## 4.3 Actions

A `SimEventAction` defined what needs to be done by the time an event is *executed* or *processed*. In Java terms, a `SimEventAction` is an interface with a single abstract method which is invoked when the event is processed. Below we show the declaration of the interface:

```
@FunctionalInterface
public interface SimEventAction<T>
```

```

{
    /** Invokes the action for supplied {@link SimEvent}.
     * @param event The event.
     * @throws IllegalArgumentException If <code>event</code> is <code>null</code>.
     */
    public void action (SimEvent<T> event);
}

```

There are several ways to create actions for events. The first and most often used way in our own code is to use anonymous inner classes:

```

final SimEventList el = new DefaultSimEventList ();
final SimEvent e =
    new DefaultSimEvent ("My_First_Real_Event", 5.0, null, new SimEventAction ()
    {
        @Override
        public final void action (final SimEvent event)
        {
            System.out.println ("Event=" + event + ",_time=" + event.getTime () + ".");
        }
        @Override
        public String toString ()
        {
            return "My_First_Action";
        }
    });
el.add (e);
el.print ();
el.run ();
el.print ();

```

Note that we are now using the full `DefaultSimEvent` constructor, passing a name, and supplying a `SimEventAction` as an anonymous inner class. In the inner class, we define the `action` method, and in the meantime override the `toString` method (to be honest, this was merely to keep the generated text within bounds). The generated output is:

```

SimEventList {X}.DefaultSimEventList@{Y}, class=DefaultSimEventList, time=-Infinity:
t=5.0, name=My First Real Event, object=null, action=My First Action.
Event=My First Real Event, time=5.0.
SimEventList {X}.DefaultSimEventList@{Y}, class=DefaultSimEventList, time=5.0:
EMPTY!

```

Clearly, as expected! However, note that after "running" the event list, it turns out to be empty, and its time is now  $t = 5.0$ , the schedule time of our event. This is as intended, and will be explained in the next section. But first we look at an alternative way of attaching actions to events:

```

final SimEventList el = new DefaultSimEventList ()
{
    @Override
    public final String toString ()
    {
        return "My_Renamed_Event_List";
    }
};
final SimEventAction action = new SimEventAction ()
{
    @Override
    public final void action (final SimEvent event)
    {

```

```

        System.out.println ("Event=" + event + ",_time=" + event.getTime () + ".");
    }
    @Override
    public final String toString ()
    {
        return "A_Shared_Action";
    }
}
};
for (int i = 1; i <= 10; i++)
{
    final SimEvent e = new DefaultSimEvent ("Our_Event", (double) i, null, action);
    el.add (e);
}
el.print ();
el.run ();
el.print ();

```

In this example, we created a single action object (again using an anonymous inner class), and reuse it among ten distinct events we schedule (we cannot reuse those). We also took the opportunity give our event list a friendlier name by overriding its `toString` method. The output is as follows:

```

SimEventList My Renamed Event List, class=, time=-Infinity:
t=1.0, name=Our Event, object=null, action=A Shared Action.
t=2.0, name=Our Event, object=null, action=A Shared Action.
t=3.0, name=Our Event, object=null, action=A Shared Action.
t=4.0, name=Our Event, object=null, action=A Shared Action.
t=5.0, name=Our Event, object=null, action=A Shared Action.
t=6.0, name=Our Event, object=null, action=A Shared Action.
t=7.0, name=Our Event, object=null, action=A Shared Action.
t=8.0, name=Our Event, object=null, action=A Shared Action.
t=9.0, name=Our Event, object=null, action=A Shared Action.
t=10.0, name=Our Event, object=null, action=A Shared Action.
Event=Our Event, time=1.0.
Event=Our Event, time=2.0.
Event=Our Event, time=3.0.
Event=Our Event, time=4.0.
Event=Our Event, time=5.0.
Event=Our Event, time=6.0.
Event=Our Event, time=7.0.
Event=Our Event, time=8.0.
Event=Our Event, time=9.0.
Event=Our Event, time=10.0.
SimEventList My Renamed Event List, class=, time=10.0:
EMPTY!

```

Again note that the time on the event list after running it is the time of the last event we scheduled on it. In the output, funny enough, the `class` of the event list is now reported as empty. This is because we used an anonymous class to construct it!

So, there are different ways of attaching a `SimEventAction` to a `DefaultSimEvent`. The abundant use of anonymous inner classes as shown here is certainly not to everyone's taste, but it results in relatively compact code (even more through the use of lambda expressions, see **XXX**).

## 4.4 Processing the Event List

Once the events of your liking are scheduled on the event list, you can start the simulation by *processing* or *running* the event lists. Processing the event list will cause the

event list to equentially invoke the actions attached to the events in increasing-time order. There are several ways to process a `SimEventList`:

- You can process the event list until it is empty with the `run` method.
- You can process the event list until some specified (simulation) time with the `runUntil` method.
- You can *single-step* through the event list with the `runSingleStep` method.

You can check whether an event list is being processed through its `isRunning` method.

While processing, the event list maintains a *clock* holding the (simulation) time of the current event. You can get the time from the event list through `getTime` method, although you can obtain it more easily from the event itself. You can insert new events while it is being processed, *but these events must not be in the past*. Once the event list detects insertion of events in the past, it will throw an exception.

Note that processing the event list is thread-safe in the sense that all methods involved need to obtain a *lock* before being able to process the list. Trying to process an event list that is already being processed from another thread, or from the thread that currently processes the list, will lead to an exception. Note that currently there is no safe, atomic, way to process an event list on the condition that it is not being processed already. Though you can check with `isRunning` whether the list is being processed or not, the answer from this method has zero validity lifetime.

The example below shows how to schedule new events from event actions; it also shows what happens if you schedule events in the past.

```
final SimEventList el = new DefaultSimEventList ()
{
    @Override
    public final String toString ()
    {
        return "The_Event_List";
    }
};

final SimEventAction schedulingAction = new SimEventAction ()
{
    private int counter = 0;
    @Override
    public final void action (final SimEvent event)
    {
        System.out.println ("Event=" + event + ",_time=" + event.getTime () + ".");
        counter++;
        if (counter < 10)
            // Schedule 1 second from now.
            // Use utility method on SimEventList.
            el.schedule (event.getTime () + 1, this);
        else if (counter == 10)
        {
            // Schedule now.
            el.schedule (event.getTime (), this);
            System.out.println ("Scheduled_event_now.");
        }
    }
}
```



```

        else
        {
            // Schedule 1 second in the past -> throws exception.
            el.schedule (event.getTime () - 1, this);
            // Never reached.
            System.out.println ("Scheduled_event_in_the_past.");
        }
    }
    @Override
    public final String toString ()
    {
        return "Scheduling_Action";
    }
};

el.schedule (0, schedulingAction);
el.print ();
el.run ();
el.print ();

```

The code begins to look familiar. First, we create the event list, then a single action. The action is a bit more complicated than before; it has an internal **counter** in the anonymous class. Using the counter, it reschedules itself ten times, the first nine times one second in the future, the tenth time at exactly the same time. As mentioned before, this is perfectly legal (and, in fact, often used in our own code). The final attempt to reschedule the action results in an exception, because the event is scheduled in the past. Note that the example also showcases a utility method in `SimEventList`, viz., `schedule (double, SimEventAction)`, which directly schedules the action on the event list at given time, creating a new `SimEvent` on the fly. In a later section we will look in more detail at more utility methods on event lists.

The output of the example is shown below<sup>2</sup>.

```

SimEventList The Event List, class=, time=-Infinity:
  t=0.0, name=No Name, object=null, action=Scheduling Action.
Event=No Name, time=0.0.
Event=No Name, time=1.0.
Event=No Name, time=2.0.
Event=No Name, time=3.0.
Event=No Name, time=4.0.
Event=No Name, time=5.0.
Event=No Name, time=6.0.
Event=No Name, time=7.0.
Event=No Name, time=8.0.
Event=No Name, time=9.0.
Scheduled event now.
Event=No Name, time=9.0.
Exception in thread "main" java.lang.IllegalArgumentException:
Schedule time is in the past: 8.0 < 9.0!

```

Note that in this particular case, the exception thrown actually comes with an instructive message as to what caused it (you tried to schedule something on the event list at  $t = 8.0$ , whereas the current time is beyond that,  $t = 9.0$ ). However, in all honesty, such messages are not present for the majority of exceptions thrown as a result of incorrect arguments from user code. We are currently working on improving this.

---

<sup>2</sup>For improved reading, we have left out the full stack-trace of the exception, and rearranged the mixed outputs from `System.out` and `System.err`. We will do that without notice in the sequel.

The output also shows the expected result from the first `el.print` statement: Only a single event is scheduled! The others are created and scheduled while the event list is being processed. It is important to realize that the contents of a `SimEventList` can always change, as long as these are changes *now or in the future*. By the way, the second invocation of `el.print` does not stand a chance; it is unreachable because of the exception thrown in `el.run`.

## 4.5 Utility Methods for Scheduling Events

A `SimEventList` supports various methods for directly scheduling events and actions without the need to generate both the `SimEvent` *and* the `SimEventAction`. In most cases, the availability of one of the object suffices. Below we show the most common utility methods for scheduling on a `SimEventList`.

Utility methods for scheduling	
<b>void</b> schedule (E)	Schedules the event at its own time.
<b>void</b> schedule ( <b>double</b> , E)	Schedules the event at given time.
reschedule ( <b>double</b> , E)	Reschedules (if present, else schedules) the event at given new time.
E schedule ( <b>double</b> , SimEventAction, String)	Schedules the action at given time with given event name.
<b>void</b> scheduleNow (E)	Schedules the event now.
E schedule ( <b>double</b> , SimEventAction)	Schedules the action at given time with default event name.
E scheduleNow (SimEventAction, String)	Schedules the action now with given event name.
E scheduleNow (SimEventAction)	Schedules the action now with default event name.

Note that `E` refers to the so-called *generic-type argument* of `SimEventList`. The prototype is `SimEventList<E extends SimEvent>`. The use of generic types is explained in some more details in the "Advanced Topics" section, but for now `E` can be simply read as a `SimEvent`.

For any of the utility methods that take a `SimEventAction` as argument, a new `SimEvent` is created on the fly, and returned from the method. Upon return from these methods, the newly created event has already been scheduled, and you *really*

should not schedule it again.

You may wonder how to *remove* events and actions from the event list. Well, since `SimEventList` implements the `Set` interface for `SimEvent` members, removing an event `e` from an event list `el` is as simple as `el.remove (e)`. Currently, there is no support to remove an action from an event list. Because actions can be reused, it would require iterating over all scheduled events, and remove all events with the given action. It is not hard to implement at all, we just did not do it<sup>3</sup>:

```
public static void removeAction
(final SimEventList eventList, final SimAction action)
{
    if (eventList != null)
    {
        final Iterator it = eventList.iterator();
        while (it.hasNext ())
            if (it.next ().getEventAction () == action)
                it.remove ();
    }
}
```

The code fragment silently assumes the absence of `null` events in the event list, which is indeed guaranteed, and works perfectly for `null` actions. Note the somewhat unexpected method name on `SimEvent` to get its action, viz., `getEventAction`. This name was chosen in order to avoid potential name clashes. At the risk of sounding pedantic, the explicit use of the iterator looks old-fashioned, yet allows for the safe removal of elements from a collection in a loop (contrary to a much fancier `for` construction).

We conclude with an overview of non-scheduling related utility methods of `SimEventList`:

Method	Description
<code>void print ()</code>	Prints the event list to <code>System.out</code> .
<code>void print (PrintStream)</code>	Prints the event list to the stream.

## 4.6 Simultaneous Events

While reading through the previous sections, you may have wondered what would happen if two events are scheduled on exactly the same time. Well, why not just give it a try? First, we create an action class with an index number as argument; when invoked, the action merely prints its index number to `System.out`:

```
private static class IndexedSimEventAction
implements SimEventAction
{
    final int index;

    public IndexedSimEventAction (final int index)
    {
        this.index = index;
    }
}
```

<sup>3</sup>This code fragment has not been tested.

```

@Override
public void action (SimEvent event)
{
    System.out.println ("Hello, _I_am_action_number_" + this.index + "!");
}

@Override
public String toString ()
{
    return "Action_" + index;
}
}

```

So, let us schedule some of these at  $t = 0$  in order of increasing index:

```

final SimEventList el = new DefaultSimEventList ();
for (int i = 1; i <= 10; i++)
    el.schedule (0, new IndexedSimEventAction (i), "Event_" + i);
el.print ();
el.run ();

```

The potential result of this code may be a bit surprising<sup>4</sup>:

```

SimEventList {X}@{Y}, class=DefaultSimEventList, time=-Infinity:
t=0.0, name=Event 3, object=null, action=Action 3.
t=0.0, name=Event 8, object=null, action=Action 8.
t=0.0, name=Event 9, object=null, action=Action 9.
t=0.0, name=Event 5, object=null, action=Action 5.
t=0.0, name=Event 1, object=null, action=Action 1.
t=0.0, name=Event 4, object=null, action=Action 4.
t=0.0, name=Event 7, object=null, action=Action 7.
t=0.0, name=Event 2, object=null, action=Action 2.
t=0.0, name=Event 6, object=null, action=Action 6.
t=0.0, name=Event 10, object=null, action=Action 10.
Hello, I am action number 3!
Hello, I am action number 8!
Hello, I am action number 9!
Hello, I am action number 5!
Hello, I am action number 1!
Hello, I am action number 4!
Hello, I am action number 7!
Hello, I am action number 2!
Hello, I am action number 6!
Hello, I am action number 10!

```

Well, it looks like all our scheduled events were indeed processed, *but not in the order we inserted them into the list!* It was even clear *before* processing the event list that there was something "wrong" with the sequence of events. Why? Well, because we explicitly instructed the `SimEventList` *not* to do process simultaneous events in so-called *insertion order*, but instead to break ties *at random* for simultaneously scheduled events. The exact reasoning for doing this is a bit involved, and deferred until the "Advanced Topics" section, but for now it is important to realize that a `DefaultSimEventList`

- processes its scheduled events in random order should they have equal schedule times;

---

<sup>4</sup>The probability of you seeing the same result is  $1/(10!)$ , which equals the probability of you being *not* surprised at all about your own output.

- will *never* preempt or interrupt the current event it is processing in favor of another event that is scheduled at the same time from within the action of the current event.

Since there is absolutely nothing wrong with maintaining insertion order, you can switch to a different event-list implementation, viz., `DefaultEventList_IOEL`:

```
final SimEventList el = new DefaultSimEventList_IOEL ();
for (int i = 1; i <= 10; i++)
    el.schedule (0, new IndexedSimEventAction (i), "Event_" + i);
el.print ();
el.run ();
```

Now the output looks mores structured:

```
SimEventList {X}.DefaultSimEventList_IOEL@{Y}, class=DefaultSimEventList_IOEL,
time=-Infinity:
t=0.0, name=Event 1, object=null, action=Action 1.
t=0.0, name=Event 2, object=null, action=Action 2.
t=0.0, name=Event 3, object=null, action=Action 3.
t=0.0, name=Event 4, object=null, action=Action 4.
t=0.0, name=Event 5, object=null, action=Action 5.
t=0.0, name=Event 6, object=null, action=Action 6.
t=0.0, name=Event 7, object=null, action=Action 7.
t=0.0, name=Event 8, object=null, action=Action 8.
t=0.0, name=Event 9, object=null, action=Action 9.
t=0.0, name=Event 10, object=null, action=Action 10.
Hello, I am action number 1!
Hello, I am action number 2!
Hello, I am action number 3!
Hello, I am action number 4!
Hello, I am action number 5!
Hello, I am action number 6!
Hello, I am action number 7!
Hello, I am action number 8!
Hello, I am action number 9!
Hello, I am action number 10!
```

Just in case you are curious: we use the abbreviations ROEL for Random-Order Event List and IOEL for Insertion-Order Event List. The `DefaultSimEventList` is obviously a ROEL; actually it subclasses `DefaultSimEventList_ROEL` without changes, hence you can also use `SimEventList_ROEL` as your event-list implementation (perhaps making more explicit the nature of the event list):

```
// Be very careful: this event-list does not respect insertion
// order for simultaneous events!
// ROEL = Random-Order Event List.
final SimEventList el = new DefaultSimEventList_ROEL ();
```

We want to stress that just because our default event-list implementation is a ROEL, it is by no means because ROEL "is just better" than IOEL, or the software in `jsimulation` and/or `jqueues` "works better" or even "works only" with a ROEL. Far from it, the current implementations will probably work slightly faster with an IOEL; maintaining insertion order is likely to be faster than drawing random number upon each insertion. So, by all means, use the IOEL implementation if you want to as a replacement to the default ROEL.

## 4.7 Resetting an Event List

By resetting an event list, through `reset`, we remove all the events it contains, and set the time to  $t = -\infty$ , or to a user-specified time through `reset (double)`. Resetting an event list is typically done before repeating a simulation experiment, for instance with a different seed value for random-number generation.

Despite the simplicity of the concept, we cannot stress enough the importance and consequences of resetting an event list. Although not mandated by `jsimulation`, the general convention we follow is that an event-list reset puts the event list itself, but also all "entities" (like queues) that use it *in a well-known, default, often "empty", state*. Partially to that purpose, an event list informs its so-called *reset listeners* when it is reset. The concept of listeners is described in the next section.

For reasons that will become clear later, in particular when discussing obtaining statistics on queueing systems in **XXX**, it is *highly recommended* to always reset the event list to a *finite* time, even before running it for the first time.

One may wonder why we chose  $-\infty$  as the default new time upon a reset, instead of a finite value (zero comes to mind here...). Well, first, we wanted a "fresh" event list to accept all events scheduled at *arbitrary* time. (Recall that even without running an event list, it will throw an exception if events are scheduled "in the past".) Second, we wanted to avoid the ubiquitous "a simulation starts at  $t = 0$ " assumption, at least in our own code. For instance, it would be very hard to debug the case in which a statistics-gathering object (e.g., measuring the average number of jobs in a queue) silently assumes that all simulations start at  $t = 0$ , and the user decides to run a simulation at (for whatever reason)  $t = +100$ .

On the other hand, having to remember to pass a finite time upon every reset is, admittedly, far from ideal. The `setDefaultResetTime (double)` therefore allow for changing the default event-list start time used by `reset ()`. Note though, that this still requires explicit resets of the event list, even before using it for the first time. We are still seeking to improve the reset semantics, in particular related to the new time on the event list and its effect on statistics gathering.

**ADD AN EXAMPLE OR TWO HERE!**

## 4.8 Listening to an Event List

You can listen to changes to a `SimEventList` by registering a *listener* of type `SimEventListListener` to it. At the present time, there is only support for notifications for an event list reset, and for event-list processing so there is not general "event list changed" notification.

A listener gets notifications for:

- A *reset* of the event list. This notification is always sent while the list is *not* begin processed. In fact, if you are only interested in receiving reset notifications, you can use a `SimEventListResetListener` instead of (the full) `SimEventListListener`.
- An *update* of the event list. An update is defined as a *strictly positive jump in time during processing*.
- An *empty* event list during processing (this effectively ends processing the event list).
- A *next event* while processing the event list. These notifications, however, are only sent to listeners that implement `SimEventListListener.Fine`.

The following table summarizes the listener-related methods on a `SimEventList`.

Method	Description
<code>void</code> <code>addListener (SimEventListResetListener)</code>	Adds a listener.
<code>void</code> <code>removeListener (SimEventListResetListener)</code>	Removes a listener.

The table below list the various notification methods on a listener per listener type; the types are shown in increasing richness.

Method	Description
<b>SimEventListResetListener</b>	
<code>void</code> <code>notifyEventListReset (SimEventList)</code>	Reset of given event list.
<b>SimEventListListener</b>	
<code>void</code> <code>notifyEventListUpdate (SimEventList, <b>double</b>)</code>	Event list update; <i>new</i> time.
<code>void</code> <code>notifyEventListEmpty (SimEventList, <b>double</b>)</code>	Event list empty at given time.
<b>SimEventListListener.Fine</b>	
<code>void</code> <code>notifyNextEvent (SimEventList, <b>double</b>)</code>	Process next event; <i>old</i> time.

## 4.9 Advanced Topics

In this section we take a closer look at some more advanced topics `jsimulation`. The sections can be skipped at first reading.

### 4.9.1 Using Generic-Type Arguments

Interface	Type	Description
<code>SimEvent&lt;T&gt;</code>	<code>T</code>	The type of user object.
<code>SimEventList&lt;E extends SimEvent&gt;</code>	<code>E</code>	The type of events.
<code>SimEventAction&lt;T&gt;</code>	<code>T</code>	The type of user object.

The (partial) implementations in `jsimulation` follow the same convention as the interface they belong to:

Class
<code>DefaultSimEvent&lt;T&gt;</code>
<code>AbstractSimEventList&lt;E extends SimEvent&gt;</code>
<code>DefaultSimEventList_IOEL&lt;E extends SimEvent&gt;</code>
<code>DefaultSimEventList_ROEL&lt;E extends SimEvent&gt;</code>
<code>DefaultSimEventList&lt;E extends SimEvent&gt;</code>

### 4.9.2 Event Factories

An *event factory* has a sole purpose: generating new event instances. The use of factories is very common in Java, especially if one needs to create a "default" instance for a given interface, in our case for `SimEvent`.

The `SimEventFactory` interface is as follows:

```
@FunctionalInterface
public interface SimEventFactory<E extends SimEvent>
{
    E newInstance
      (String name, double time, SimEventAction eventAction);
}
```

The generic type argument `E` is the (base) type of the generated `SimEvents`. The argument list for `newInstance` allows for setting all `SimEvent` properties except the user object (because we believe it is rarely of use).

One particular use for this is to set the event factory on an arbitrary `SimEventList` through its `setSimEventFactory` method. This is a safe way of using an interface (or event multiple ones) as type argument to `SimEventList`:

```
interface MySimEvent
extends SimEvent
{
    BigInteger getSeqNumber ();
}
```



```

}

static class DefaultMySimEvent
extends DefaultSimEvent
implements MySimEvent
{

    private static BigInteger
        NEXT_SEQUENCE_NUMBER = BigInteger.ZERO;

    private final BigInteger seqNumber;

    @Override
    public final BigInteger getSeqNumber ()
    {
        return this.seqNumber;
    }

    public DefaultMySimEvent
        (final String name,
         final double time,
         final SimEventAction action)
    {
        super (name, time, null, action);
        this.seqNumber = NEXT_SEQUENCE_NUMBER;
        NEXT_SEQUENCE_NUMBER =
            NEXT_SEQUENCE_NUMBER.add (BigInteger.ONE);
    }
}

public static void main (final String[] args)
{
    final SimEventList<MySimEvent> el =
        new DefaultSimEventList (MySimEvent.class);
    el.add (new DefaultMySimEvent
        ("MySimEvent_instance", 5.0, null));
    el.print ();
}

```

In the code fragment, we extended the basic `SimEvent` interface with a method to maintain a global instance counter of type `BigInteger` (ignoring the total lack of usefulness), and created a default implementation for it in `DefaultMySimEvent`. Subsequently, we created an event list, using the generic-type argument and the `class` argument in the constructor to make sure that the `DefaultSimEventList`

only accepts `MyEventType` as events. Note that we use the *interface* here, not the *default implementation*. The program runs fine and prints the event scheduled on the event list.

However, if we try to schedule an action (`null` in this case):

```
el.schedule (10.0, (SimEventAction) null);
```

we are treated with an exception:

```
... IllegalStateException: Cannot instantiate MySimEvent!
```

It is more or less immediately clear what the problem is: the event list has to generate a `SimEvent` in order to schedule the action, but it tries to instantiate `MySimEvent`, which is an *interface*. (By the way, it also assumes that the event class supports a parameterless constructor!)

We need to tell the event list how to create the events for the various utility methods, and we do that by creating and registering a `SimEventFactory` for `MySimEvent`<sup>5</sup>:

```
final SimEventList<MySimEvent> el =
    new DefaultSimEventList (MySimEvent.class);
el.setSimEventFactory
(
    (final String name,
     final double time,
     final SimEventAction eventAction)
    -> new DefaultMySimEvent (name, time, eventAction)
);
el.add (new DefaultMySimEvent
    ("MySimEvent_instance", 5.0, null));
el.schedule (10.0, (SimEventAction) null);
el.print ();
```

Now we are out of trouble:

```
...
t=5.0, name=MySimEvent_instance, object=null, action=null.
t=10.0, name=null, object=null, action=null.
```

This section and the previous one on generic-type arguments hopefully showed the maturity of support the generic and runtime type arguments. However, we do not recommend their use unless for very specific use cases that require extending the `SimEvent` and/or `SimEventList` interfaces. The problem is that by restricting the allowable compile-time and runtime `SimEvent` types, the generated objects become

<sup>5</sup>Using a *lambda expression* this time, see **XXX**.

unusable for libraries using "bare" `SimEvents`. For instance, the `jqueues` library will not work with event-lists not supporting "plain" `SimEvents`.

### 4.9.3 Simultaneous Events: Random-Order and Insertion-Order Event Lists

In previous sections in this book, we explained that event-list implementations, at least the *non-preemptive* types, come in two natural variants: the ROEL processes simultaneous events in random order, and the IOEL does that in insertion order. We also declared that the default implementation is a ROEL, and that you can easily switch to an IOEL, possibly even gaining some performance. This section is dedicated to motivating the use of, or even the consideration of ROEL as an event list implementation, let alone making it the default! It does not introduce any new software. We already want to stress that ROEL is by no means "better" than IOEL from a user point of view. We do not intend to avocate ROEL over IOEL!

The distinction between ROEL and IOEL is all about *simultaneous* events, and we look at this phenomena from three different viewpoint:

- The *physical* viewpoint: In physics, we are rarely concerned with occurrence of simultaneous events, because physical models (to our knowledge) rarely exhibit a strong behavioral dependence on "things happening at the same time".
- The *mathematical* viewpoint: In mathematical models, we *are* nearly always dealing with the possibility of "things being equal". For instance, it is "undone" to specify a function on two real variables (say, a "maximum indicator") without exactly specifying the result for equal inputs. However, in applications of probability theory, like queueing theory, we often deal with continuous distributions and the probability of simultaneous events is often zero. Although simultaneous events still require attention, one can usually get away with noting that "ties are broken at random (with equal probabilities)". Almost always, this solution approach is preferred over trying to impose an additional ordering on the events, as in "Jobs A and B both arrived at  $t = 0$ , but job A was first."
- The *software-engineering* viewpoint: In software-engineering, we are not that used to simultaneous events. Sure, there are cases of *concurrency* but the problems that arise are usually fixed by imposing some *order* into which statements, programs, expressions, etc. are to be processed. As a result, software engineering is very much concerned with "doing the right thing given a strict order of

input”. A prime example of this are Finite-State Machines supporting state transitions upon external events. Rarely, if ever, does this take into account the possibility of simultaneous events.

Needless to say, our argument is that *the occurrence of simultaneous events is very natural in mathematics, yet the concept of “insertion order” is purely relevant to software-engineering*. In other words, there is no equivalence in this context for “insertion order” in mathematics, nor is there in physics.

The reasons for choosing a Random-Order Event List are primarily motivated by its use in `jqueues`:

- We do not want to *specify* queueing systems with the notion of insertion order, and we probably cannot. Such a specification would be overly complicated, and, as mentioned before, in the mathematical context we rather break ties at random.
- We do not want to *imply* to users the conservation of insertion order in the implementations.
- We do not want to *rely* on insertion order of events in our tests.

Admittedly, for simple queueing systems like FCFS, it seems simple enough to maintain the order of arrival of jobs in the output process. But as soon as queueing systems become more complicated, especially if multiple queues are involved or feedback, the specification becomes just unnecessarily difficult. To give an example: Suppose we have a feedback FCFS queue with feedback probability  $1/4$  and two jobs arriving at  $t = 0$ ; jobs A and B having required service times (for each visit) of zero and unity, respectively. Suppose with an insertion-order event list, job A’s first arrival is before job B’s. So, trusting the conservation of insertion order, the queue starts processing job A, which is fed back to the queue’s input immediately with probability  $1/4$ . If so, we are in trouble because we now have to specify whether to first serve job A reappearing at the input or job B. Of course we can find a solution by indeed specifying that a job that is fed back is always inserted *after* jobs already there, but the real problem is that *we have to specify all cases of simultaneous events through insertion-order arguments*. And this is just a simple example.

#### 4.9.4 Event Comparators

In order to obtain the required total order on the `SimEvents` in a `SimEventList`, the latter uses a `Comparator`, which by default is an instance of `DefaultSimEventComparator`, both for ROEL (the default) and IOEL event lists. Its core implementation is

```

@Override
public int compare (E e1 , E e2)
{
    int c = Double.compare (e1.getTime (), e2.getTime ());
    if (c == 0)
    {
        c = e1.getSimEventListDeconflictValue ()
            .compareTo
            (e2.getSimEventListDeconflictValue ());
    }
    if ((e1 == e2 && c != 0)
        || (e1 != e2 && c == 0))
        throw new RuntimeException
            ("Error attempting to order events.");
    return c;
}

```

Not surprisingly, the comparator uses the time property on the events to make a first comparison. In case of a tie, it uses the so-called *deconflict value* on the events, throwing an exception if this still yields a tie. What is interesting to note is that the deconflict value on an event is generated when an event is *added* to an event list by overriding the `add` and `addAll` methods from the super class (i.e., `TreeSet`), e.g., in case of ROEL:

```

@Override
public final boolean add (final E e)
{
    if (e == null)
        throw new NullPointerException
            ("Attempt to add null event to event list!");
    if (! contains (e))
    {
        e.setSimEventListDeconflictValue
            (this.rngDeconflict_ROEL.nextLong ());
        return super.add (e);
    }
    return false;
}

```

In ROEL, the deconflict value is, as expected drawn from a random-number generator (RNG) `rngDeconflict_ROEL`. Using this approach has the major advantage that even though events with equal times will be ordered at random, their ordering remains fixed as long as they are in the event list. So, the random ordering in ROEL is *not* implemented by drawing from a RNG the moment it is needed from the event

list (which would, actually, be substantially more difficult), but it is already fixed upon insertion. This, for instance, has the nice feature that consecutive iterators over the (same) event set will always return the events in the same order. By the way, you can set an alternative `Comparator` by using one of `AbstractSimEventList` constructors. You cannot change it on the default implementations.

### 4.9.5 Action is a Functional Interface

Because a `SimEventAction` is an interface with exactly one abstract method, it can be used in so-called *lambda expressions* in Java 8. So, instead of

```
final SimEventAction action = new SimEventAction ()
{
    @Override
    public final void action (final SimEvent event)
    {
        // Do something with event...
    }
};
```

you can also write:

```
final SimEventAction action =
    (SimEventAction) (final SimEvent event) ->
    {
        // Do something with event...
    };
```

or even make it a one-liner.

The `SimEventAction` interface has been marked a `@FunctionalInterface`.

## 4.10 Timers

The abstract `AbstractSimTimer` class is a small utility class for scheduling a timer on a `SimEventList`. In view of the classes and methods described before it is not all that useful, but it has been kept in the library for support of legacy code. An `AbstractSimTimer` features a `schedule (double, SimEventList)` method that schedules an appropriate event after a delay (the `double` argument). When the event is processed, the (abstract) method `expireAction` is invoked, which needs to be defined in a subclass. Also, a pending timer can be (safely) cancelled through its `cancel` method.

Below is a small, naive example of its use:

```
private static class MyTimer
extends AbstractSimTimer
{
    @Override
    public final void expireAction
    (final double time)
    {
        System.out.println ("t=" + time + ": _Timer_expired!");
    }
}

public static void main (final String [] args)
{
    final SimEventList el = new DefaultSimEventList ();
    final MyTimer myTimer = new MyTimer ();
    // Progress event list until t=10.
    // Note that AbstractSimTimer does not support t=-\infty.
    el.runUntil (10.0, true, true);
    myTimer.schedule (5, el);
    el.print ();
    el.run ();
}
```

The result of which is:

```
SimEventList {X}@{Y}, class=DefaultSimEventList, time=10.0:
  t=15.0, name=_expire, object=null, action={...}.
t=15.0: Timer expired!
```

Note that you cannot easily *reschedule* the timer from within the action, because there is no access to the `SimEventList`, and that you cannot schedule the timer when the time on the event list is infinite (hence the `runUntil` in the example!).

## 4.11 Summary and Conclusions

This chapter introduced `jsimulation`, a small Java library for discrete-event simulation. An overview of the main interfaces and classes is given below:

Interface	Class	Description
SimEvent<T>	DefaultSimEvent<T>	Event Default Event
SimEventList<E>	AbstractSimEventList<E> DefaultSimEventList_ROEL<E> DefaultSimEventList_IOEL<E> DefaultSimEventList<E>	Event List (partial) Random-Order Event List Insertion-Order Event List Default Event List
SimEventAction<T>		Action
SimEventListResetListener SimEventListListener SimEventListResetListener		Reset Listener Normal Listener Detailed Listener
SimEventFactory<E>	DefaultSimEventFactory	Event Factory Default Event Factory

The remainder of this book is about **jqueues**, a library for discrete-event simulation of queueing systems. The **jqueues** library depends on **jsimulation** for scheduling and processing events and actions.



# Chapter 5

## Queueing Systems; Entities, Queues, and Jobs

This chapter introduces the concepts behind and implementation of the `jqueues` package. Together with the underlying `jsimulation` package, this package allows for discrete-event simulation of a very broad range of queueing systems.

### 5.1 Introduction and Definitions

Despite the fact that we deal with queueing, waiting, being served (or not), and being denied service on a daily basis, it is, unfortunately, not that easy at all to precisely define a system that captures these "facts of life". In our, admittedly unsatisfactory, definition, a *queue* or *queueing system* is an entity that can be visited by other entities called *jobs*; each visit being initiated by a so-called *arrival* of a specific job at that queue. A job can only visit only a single queue at a time, yet it can hop to another (or the same) queue once its visit to a particular queue has ended. A queue, on the other hand, can be visited by multiple jobs.

In *queueing theory*, a branch of mathematics, one attempts to predict the behavior of queues and jobs without being (too) concerned about the particular *reasons* of a job visit. A very common setting is that jobs visit a queue in order to get a particular *service* from that queue taking a non-trivial amount of time to complete, the *required service time* associated with the visit. In other words, visiting jobs have to *wait* for the completion of their service request. Even worse, the queue is often limited in providing the required services to multiple jobs simultaneously, so jobs have to *compete* for the *service capacity* of the server. The outcome of this competition is determined by the so-called *service discipline* or *queue discipline* of the queueing

system: the way in which it distributes its limited (finite) service *capacity* among its currently visiting jobs.

Unfortunately, the view of a queueing system as consisting of a waiting area in which jobs wait before being served by one or more servers (i.e., a finite number of them) for a given required service time is too narrow in many interesting applications. For instance, in Medium-Access Control systems, the required "service" to waiting jobs (i.e., *frames to be transmitted*) is largely determined by external events, viz., the availability of the *medium* for transmissions. In such cases, jobs are not staying in the queue because of an *intrinsic* requirement of service from that queue, but merely because they are waiting for an event *external* to that queue. In other words, the notion of "servers" in a queueing system providing "service" works for many cases, but not for all. And from (theoretical) examples like the Processor-Sharing<sup>1</sup> queueing discipline, it is clear that the notion of servers serving at any time a single job exclusively, needs refinement as well. So, a single server is not constrained, in the general case, to serving only a single job. In Infinite-Server (IS), on the other hand, each job present is served by its own server (of which there are infinitely many), meaning that the "total service capacity" is not a fixed constant, let alone be known in advance. The capacity may not even be finite.

In our conceptual model of a queueing system, we include explicitly the notions of waiting and of being served, but we do not impose *any* structure on the service. In our implementation, queues and jobs are named `SimQueues` and `SimJobs`, respectively. Their common features are implemented in an abstract base class `SimEntity`; for simulation entity.

## 5.2 Simulation Entities

A `SimEntity` is an entity relevant to event-list scheduling in a queueing system simulation. Presently, it is either a queue (`SimQueue`) or a job (`SimJob`). A queue is an object capable of holding *visiting* jobs, providing (generic) service to these jobs, and deciding when (or if) they will leave the queue, and end the visit. A `SimEntity` is the common part of queues and jobs. What they share in common is the event list (`SimEventList`) they are attached to, the fact that they have a name, and their obligation to propagate state changes (including the currently visited queue of a job, and the jobs currently visiting a queue) to registered *listeners*. In addition, they must notify such listeners of a reset of the event list. In the table below, we summarize

---

<sup>1</sup>In Processor-Sharing (PS), a server equally distributes its service capacity among jobs present, see **XXX**.

the `SimEntity` methods.

Method	Description
<code>SimEventList getEventList ()</code>	Gets the non- <code>null</code> event list.
<code>void registerSimEntityListener (SimEntityListener&lt;J, Q&gt; listener)</code>	Adds a listener.
<code>void unregisterSimEntityListener (SimEntityListener&lt;J, Q&gt; listener)</code>	Removes a listener.
<code>Set&lt;SimEntityListener&lt;J, Q&gt;&gt; getSimEntityListeners ()</code>	Gets a set of current listeners.
<code>String toStringDefault ()</code>	Returns a default, type-specific name of the entity.
<code>setName (String name)</code>	Sets the name of the entity.
<code>void resetEntity ()</code>	Puts the entity in its known initial state.

## 5.3 Queues

### 5.3.1 Structure of a `SimQueue`

A `SimQueue` consists of two areas, and while a `SimJob` visits a queue, it is present in either one of them:

- The *waiting area*: After a successful arrival at the queue, the visiting job always enters the waiting area; in the waiting area, jobs wait before they can be "served", or until they leave the queue otherwise.
- The *service area*: In the service area, jobs receive some sort of (otherwise irrelevant) service from the queue. A job can only enter the service area *from the waiting area*; it cannot directly enter the service area.

Method	Description
Set<J> getJobs ()	The current visitor jobs.
<b>int</b> getNumberOfJobs ()	The number of current visitor jobs.
Set<J> getJobsInWaitingArea ()	The current visitor jobs in the waiting area.
<b>int</b> getNumberOfJobsInWaitingArea ()	The number of current visitor jobs in the waiting area.
Set<J> getJobsInServiceArea ()	The current visitor jobs in the service area.
<b>int</b> getNumberOfJobsInServiceArea ()	The number of current visitor jobs in the service area.

### 5.3.2 The SimQueue-Visit Lifecycle

#### Job Arrival

A queue visit starts with the arrival of a job through `arrive(double, J)`. The first argument of `arrive` is the arrival time; typically an arrival is scheduled as the result of processing a `SimEvent` on the event list, and the time argument is taken from the event. The second argument is the `SimJob` that arrives; note the use of the generic type `J` restricting the type of jobs (at compile time) allowed at the `SimQueue`.

Method	Description
<b>void</b> arrive ( <b>double</b> , J)	Arrival of a job at the queue.

#### Job Drop

At the discretion of the `SimQueue`, a job can be forced to leave the queue; this is referred to as a *job drop*. Implementations of the `SimQueue` interface must specify under which conditions they decide to drop jobs. Typical examples are the unavailability of buffer space, or exceeding a maximum allowed service time. Note that job drops cannot be requested by the user of the queue. A job can be dropped from the waiting area as well as from the service area. (For completeness, we note that a job can also be dropped immediately upon arrival due to queue-access vacations; see next section.)

### Queue-Access Vacation

During a queue-access vacation, access to the `SimQueue` is prohibited and all jobs are dropped immediately upon arrival. A queue-access vacation affects the queue's behavior only upon arrivals; it has no effects whatsoever on jobs that are already present at the queue. Note that formally, a job arrival at a queue with queue-access vacation is *not* a visit, because the job is never actually present at the queue.

Method	Description
<b>void</b> <code>setQueueAccessVacation (double, boolean)</code>	Starts or stops a QAV at given time.
<b>boolean</b> <code>isQueueAccessVacation ()</code>	Checks for an ongoing QAV.

### Job Start

At the discretion of the `SimQueue`, a visiting `SimJob` can be moved from the waiting area to the service area. This is referred to as a *job start*. The start of a job cannot be (directly) controlled by the user. In our interface, it is important to note that 'started jobs' do not necessarily have exclusive access to the server(s). Between arrival and start, a job is said to be *waiting*. After its start, a job is said to be *started*.

### Job Revocation

Once a job has been offered, `revoke(double, J, boolean)` tries to revoke the job, if (still) possible and if supported by the queue discipline at all. The return value indicates if the revocation succeeded. The first argument is the time of the revocation attempt, the second is the job to be revoked. The third argument indicates whether it is allowed to revoke the job from the service area. If `false`, the revocation attempt will always fail if the job is already in the service area. Note the difference between a revocation (at the caller's discretion) and a drop (at the queue's discretion).

Method	Description
<b>boolean</b> <code>revoke (double, J, boolean)</code>	Revocation attempt of a job at the queue.

### Server-Access Credits

During a *server-access vacation*, jobs are prohibited to start, i.e., there is no access to the service area for jobs in the waiting area. It does not affect jobs that have already started. Server-access vacations are actually somewhat more flexible through the notion of *server-access credits*, denoting the number of jobs still admissible to the service

area, see `getServerAccessCredits()`. A server-access vacation starts when there are no more server-access credits (due to jobs starting), and ends when credits are explicitly granted to the interface through `setServerAccessCredits(double, int)`. Note that by default, each `SimQueue` has infinite server-access credits.

Method	Description
<b>void</b> <code>setServerAccessCredits (double, int)</code>	Sets the remaining SACs at given time.
<b>int</b> <code>getServerAccessCredits ()</code>	Gets the actual SACs.

Note that the value `Integer.MAX_VALUE` is interpreted as  $+\infty$ .

### Job Departure

At the discretion of the `SimQueue`, a visiting job may leave the queue because it "got what it came for", i.e., its visit comes to an end according to the queueing discipline in place. This is referred to a *job departure*; and it cannot be enforced by the user. We want to stress that jobs do not necessarily depart from the service area, but can depart from the waiting area as well, or even immediately upon arrival (in which case we formally do not speak of a visit).

### The StartArmed Property of a SimQueue

Every `SimQueue` (implementation) supports the notion of the `StartArmed` property. The property is a bit difficult to grasp at first sight and has little use in simulations, but it is essential in so-called *compressed tandem queues*, see **XXX**. Nonetheless, since it is part of the `SimQueue` interface, we state its formal definition: A `SimQueue` is in `StartArmed` state, if and only if any (hypothetical) arriving job *would* start service immediately (i.e., enter the service area upon arrival immediately), *if* the following conditions *would* hold:

- the absence of a queue access vacation,
- at least one server-access credit, and
- an empty waiting area.

The actual values of these three state properties is irrelevant, which, admittedly, makes the definition quite hard to understand. If a `SimQueue` is in `StartArmed` state, changing its state such that it meets the three conditions above, would lead to the immediate start of a hypothetical arriving job (irrespective of the type and properties of that job).

As an example, consider an instance of the (single-server) FCFS queueing system which has no queue-access vacation, and suppose that it is out of server-access credits, has a single job in the waiting area and no jobs in the service area. In this case, `StartArmed == true` because an arriving job would be taken into service if we apply the state transformation rules: (1) remove any queue-access vacation (check), (2) give it a single (or more) server-access credit, and (3) remove the job from the waiting area. This leaves a FCFS queueing system without queue-access-vacation, no jobs in the waiting area, and at least one server-access credits, and surely, such a queue would immediately start an arriving job. If initially, however, a job would be in service at the queue, we have `StartArmed == false`, because the transformed state of the queueing system has a job in service, and FCFS cannot guarantee at all that an arriving job would be taken into service. If on the other side, in the latter case the queue is of type PS, we would have `StartArmed == true`, because the presence of jobs in the service area in PS, does not inhibit it from immediately starting newly arrived jobs.

Informally, the `StartArmed` state of a queue reflects the fact *as far as the service area is concerned*, at least one more job can be added to it.

Method	Description
<code>boolean isStartArmed ()</code>	Gets the <code>StartArmed</code> property value.

### Copying a SimQueue

Every `SimQueue` (implementation) supports the creation of a copy of itself.

## 5.4 The SimJob Interface

Compared to the `SimQueue` interface, the `SimJob` interface is remarkably simple. Apart from the internal maintenance of the `SimQueue` being visited, a `SimJob` only needs to provide information on the so-called *requested service time* for a queue visit, through implementation of `getServiceTime (Q)`. This method is used by a @link `SimQueue` to query the requested service time, and appropriately schedule a departure event for the job, but it can be called anytime. However, the returned value should not change during a visit to a `SimQueue`, and it is not manipulated by the queue being visited, in other words, it cannot be used to query the remaining service time of a job at a queue. It is safe though to change the return value in-between queue visits. However, the convention is that the method then returns the required service time at the *next* visit to the queue. For instance, many test and job-

factory classes depend on this, as they often directly probe a non-visiting job for its required service time at a queue. Obviously, implementations must be prepared for invocations of this method while not visiting a queue. If `null`,s passed as argument the service time at the current queue is used, or zero if the job is not currently visiting a queue.

Method	Description
Q <code>getQueue ()</code>	The queue currently visiting.
<b>void</b> <code>setQueue (Q)</code>	Sets the queue currently visiting.
<b>double</b> <code>getServiceTime (Q)</code>	Gets the service time for a visit.

## 5.5 Invariants and Constraints

Despite the large number of freedom degrees for `SimQueues`, there is also a number of (obvious) restrictions on the behavior of a queue. For instance,

- a job cannot start, be dropped or be revoked before having arrived;
- a job can start at most once during a queue visit;
- a job can only leave the queueing system through departure (with or without being served), successful revocation or drop;
- a job may not leave the queue at all (a *sticky* job).

Note that with the current interface, a `SimJob` cannot visit multiple `SimQueues` simultaneously. The `SimQueue` currently being visited by a `SimJob` can be obtained from `SimJob.getQueue ()`; this must be maintained by implementations of `arrive (J, double)`.

## 5.6 Listening to a SimEntity

One can listen to relevant events at a `SimEntity` by registering with the entity as a `SimEntityListener`, the methods of which are summarized in the table below.



Method	Description
<b>void</b> notifyResetEntity (SimEntity)	Notification of the reset of an entity
<b>void</b> notifyUpdate ( <b>double</b> , SimEntity)	Notification of an update at an entity
<b>void</b> notifyStateChanged ( <b>double</b> , SimEntity)	Notification of a state change at an entity
<b>void</b> notifyArrival ( <b>double</b> , J, Q)	Notification of the arrival of a job at a queue
<b>void</b> notifyStart ( <b>double</b> , J, Q)	Notification of the start of a job at a queue
<b>void</b> notifyDrop ( <b>double</b> , J, Q)	Notification of the drop of a job at a queue
<b>void</b> notifyRevocation ( <b>double</b> , J, Q)	Notification of the successful revocation of a job at a queue
<b>void</b> notifyDeparture ( <b>double</b> , J, Q)	Notification of the departure of a job at a queue

It is important to realize that most notifications are fired at the time the **SimEntity** has processed the corresponding event, and attained its new state. However, there are the following exceptions:

- Update notifications are, by their nature, fired *before* any state change;
- Arrival notifications are fired *before* the job enters the queue (or before it is dropped);
- Unsuccessful revocations are *not* reported as notification.

Notifications can have tricky semantics, and one should be careful at making assumptions of the **SimEntity** upon receiving a notification. This is because with notifications, we attempt to achieve two potentially conflicting objectives:

- Each state change is reported as notification;
- Notification listeners always find the **SimEntity** in a valid state.

So, for instance, one should not assume that during an arrival notification, the job is actually present at the queue, because a queue-access vacation may be active. In that case, the queue will report an arrival of the job, immediately followed by a notification of the job having been dropped. However, upon reception of the arrival notification, the job will not be present at the **SimQueue**, because that would exhibit an illegal state

of that queue. What we would actually like here, is a notification of a *sequence* of events at the queue, all happening at the same time, yet in a particular order. In this particular example, a notification of the sequence  $(\text{ARRIVAL}(\mathbf{t}, \mathbf{j}, \mathbf{q}), \text{DROP}(\mathbf{t}, \mathbf{j}, \mathbf{q}))$  would be required, where  $\mathbf{t}$  is the time,  $\mathbf{j}$  is the job and  $\mathbf{q}$  is the queue. And even though this may not seem important right now, realize that certain queue types depend on maintaining the validity of invariants throughout their lifetime. For instance, the **DROP** queue drops jobs immediately upon arrival, irrespective of the state of the queue-access vacation. An important sensible invariant for the **DROP** queue, is that the set of jobs visiting it *is always empty*. Analogous invariants exist for other queue types, and we take great care to enforce these invariants to listeners as well as to independently scheduled events.

For **SimQueues**, one can obtain additional information by registering as a **SimQueueListener**, the methods of which are summarized in the table below.

Method	Description
<b>void</b> notifyNewNoWaitArmed ( <b>double</b> , Q, <b>boolean</b> )	Notification of a change of the <b>noWaitArmed</b> state
<b>void</b> notifyStartQueueAccessVacation ( <b>double</b> , Q)	Notification of the start of a queue-access vacation
<b>void</b> notifyStopQueueAccessVacation ( <b>double</b> , Q)	Notification of the end of a queue-access vacation
<b>void</b> notifyOutOfServerAccessCredits ( <b>double</b> , Q)	Notification that a queue has run out of server-access credits
<b>void</b> notifyRegainedServerAccessCredits ( <b>double</b> , Q)	Notification that a queue has regained server-access credits

## 5.7 Formal Treatment of Simulation Entities

Whereas the previous sections introduced **SimEntity**, **SimQueue**, and **SimJob** objects from a use-case perspective, the current section tightens the rope a bit, and treats these objects more formally.

### 5.7.1 Properties of an Entity

#### Operational Properties

An *operational* property of an entity is a property that can be changed at any time by the user without effects on the entity's behavior in a simulation. In addition, these properties are never affected by a simulation (i.e., by *operations* on the entity).

Examples include:

- The *name* of an entity;
- The *listeners* to the entity.

### Essential Properties

An *essential* property of an entity is a property that can be only be changed before and after a simulation (i.e., immediately after a **reset** or construction, but before the start of the simulation). Like operational properties, however, essential properties are never affected by operations on the entity. Essential properties impact the behavior of the queueing system during simulations, but should remain constant while simulating. Examples include:

- The *buffer size* of a FCFS\_B queue;
- The *number of servers* of a FCFS\_c queue;
- The *waiting time* of a DELAY queue.

### State Properties

Unlike operational and essential properties, *state* properties cannot be directly set by the user; they can only be read. State properties are those properties that change as a result of a simulation running, and the entity being subject to scheduled operations from the event list. State properties can be further subdivided into

- **Event** properties: State properties that can only change due to an operation (either internal or external) on the entity.
- **Continuous** properties: State properties that (potentially) change continuously over time, even in the absence of operations on the entity.

Some examples of event properties:

- The *set of jobs (in the waiting/service) area* present at a SimQueue;
- The queue-access vacation state of a SimQueue;
- The **StartArmed** state of a SimQueue.

Some examples of continuous properties:

- The *remaining service time* of the job in the service area in PS queue;
- The *total remaining work* in a FCFS queue;
- The *elapsed time since the start of the current busy period* for a SimQueue.

Note that changes to event properties are always reported to listeners of the entity; whereas changes to continuous properties are *never* reported.

Orthogonal to distinction between state and continuous properties, a state property may be

- **Exposed:** The property value is accessible to callers.
- **Hidden:** The property value is hidden from callers.

### 5.7.2 The State of a Simulation Entity

### 5.7.3 External Operations on a Simulation Entity

### 5.7.4 Internal Operations on a Simulation Entity

### 5.7.5 Notifications of a Simulation Entity

### 5.7.6 Extensions

State Extensions

Operation Extensions

Notification Extensions

# Chapter 6

## Fundamental Queues

In this chapter we describe implementations of `SimQueue` corresponding to well-known queueing disciplines.

### 6.1 Introduction

### 6.2 The Generic `SimQueue`

#### 6.2.1 Introduction

#### 6.2.2 Essential Properties

SimQueue		
Essential Properties		
EventList	SimEventList	The event list; non- <a href="#">null</a> .
AutoRevocationPolicy	AutoRevocationPolicy	The auto-revocation policy.
RegisteredOperations	Set<SimEntityOperation>	The registered operations.
RegisteredNotificationTypes	Set<Member>	The registered notification types.

### 6.2.3 State Properties

SimQueue			
State Properties			
LastUpdateTime	EE	double	Last update (or reset) time.
QueueAccessVacation	EE	boolean	Queue-Access Vacation state.
StartArmed	EE	boolean	The StartArmed state.
Jobs	EE	Set<J>	Jobs present (default: arrival order).
JobsInWaitingArea	EE	Set<J>	Jobs waiting (default: arrival order).
JobsInServiceArea	EE	Set<J>	Jobs in service (default: start order).
ServerAccessCredits	EE	int $\geq 0$	Number of server-access credits.

### 6.2.4 Operations

SimQueue			
Operations			
Update	E	double	Update at time.
DoOperation	E	double, Request	Perform operation at time.
SetQueueAccessVacation	E	double, boolean	Starts/ends a QAV at time.
Arrive	E	J	Arrival of job at time.
Drop	I	J	Drop of job at time.
Revoke	E	J, boolean	Revocation attempt of job at time.
SetServerAccessCredits	E	int $\geq 0$	Set the SACs at time.
Start	I	J, double	Starts job at time.
Depart	I	J	Lets job depart at time.

### 6.2.5 State Invariants

SimQueue
<b>State Invariants</b>
$\text{JobsInWaitingArea} \cap \text{JobsInServiceArea} = \emptyset.$ $\text{Jobs} = \text{JobsInWaitingArea} \cup \text{JobsInServiceArea}.$

### 6.2.6 Notification Types

SimQueue		
<b>Notification Types</b>		
RESET	double	Reset notification with new time.
UPDATE	double	Update notification with new time.
STATE_CHANGED	double, Set<Notification>	State-changed notification with new time and sub-notifications.

### 6.2.7 Internal Schedulable Events

SimQueue	
<b>Internal Schedulable Events</b>	
DepartureEvent	The scheduled departure of a job.

### 6.2.8 Operational Properties

SimQueue		
Operational Properties		
Name	String	The name, default depends on sub-class.
SimEntityListeners	Set<SimEntityListener>	The registered listeners.

## 6.3 Serverless Queues

The *serverless* queueing systems in `jqueues` have no servers and (effectively) no service area. All state operations and state changes concentrate at the waiting area of the queue, and typically upon arrivals. Note that just because the serverless queues have no service area does not mean that visiting jobs cannot depart from it.

### 6.3.1 The DROP SimQueue

DROP	
<i>Drops jobs immediately upon arrival.</i>	
Super	
SimQueue	See Section 6.2.
State Invariants	
StartArmed = <code>false</code> . Jobs = $\emptyset$ .	
Operational Properties	
Name	The name, default "DROP".



**6.3.2 The SINK SimQueue**

SINK	
<i>Lets jobs wait indefinitely.</i>	
<b>Super</b>	
SimQueue	See Section 6.2.
<b>State Invariants</b>	
StartArmed = <code>false</code> . Jobs = JobInWaitingArea.	
<b>Operational Properties</b>	
Name	The name, default "SINK".

**6.3.3 The ZERO SimQueue**

ZERO	
<i>Lets jobs depart immediately upon arrival.</i>	
<b>Super</b>	
SimQueue	See Section 6.2.
<b>State Invariants</b>	
StartArmed = <code>false</code> . Jobs = $\emptyset$ .	
<b>Operational Properties</b>	
Name	The name, default "ZERO".

### 6.3.4 The DELAY SimQueue

DELAY	
<i>Lets jobs depart after a fixed wait time.</i>	
Super	
SimQueue	See Section 6.2.
Essential Properties	
WaitTime	The wait time, non-negative.
State Invariants	
StartArmed = <code>false</code> . Jobs = JobsInWaitingArea. WaitTime = 0 $\Rightarrow$ Jobs = $\emptyset$ .	
Operational Properties	
Name	The name, default "DELAY[WaitTime]".
Equivalences	
DELAY[0] = ZERO. DELAY[ $\infty$ ] = SINK.	

### 6.3.5 The GATE SimQueue

GATE			
<i>Lets jobs depart in arrival order while its "gate" is open; lets jobs wait otherwise.</i>			
Super			
SimQueue	See Section 6.2.		
State Properties			
GatePassageCredits	EE	<code>int</code> $\geq 0$	Remaining allowed departures.
Operations			
SetGatePassageCredits	E	<code>int</code> $\geq 0$	Sets the remaining number of GPCs. <code>Integer.MAX_VALUE</code> is treated as $+\infty$ .
State Invariants			
StartArmed = <code>false</code> . GatePassageCredits $> 0 \Rightarrow$ Jobs = $\emptyset$ .			
Operational Properties			
Name	The name, default "GATE".		

### 6.3.6 The ALIMIT SimQueue

ALIMIT			
Arrival-Rate Limiter			
<i>Lets jobs depart immediately but drops jobs whose arrival exceeds a given arrival-rate limit.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
RateLimit	double	The rate limit, $\geq 0$ ; $\leq +\infty$ .	
State Properties			
RateLimited	HE	boolean	Whether currently (arrival) rate-limited.
Internal Schedulable Events			
RateLimitExpirationEvent		The expiration of the rate-limit period.	
Operational Properties			
Name		The name, default "ALIMIT[RateLimit]".	
Equivalences			
ALIMIT[0] = DROP. ALIMIT[ $\infty$ ] = ZERO.			

### 6.3.7 The DLIMIT SimQueue

DLIMIT			
Departure-Rate Limiter			
<i>Lets jobs depart immediately but respects a given departure-rate limit.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
RateLimit	double	The rate limit, $\geq 0$ ; $\leq +\infty$ .	
State Properties			
RateLimited	HE	boolean	Whether currently (departure) rate-limited.
Internal Schedulable Events			
RateLimitExpirationEvent		The expiration of the rate-limit period.	
Operational Properties			
Name		The name, default "DLIMIT[RateLimit]".	
Equivalences			
DLIMIT[0] = SINK. DLIMIT[ $\infty$ ] = ZERO.			

### 6.3.8 The LeakyBucket SimQueue

LeakyBucket			
<i>Lets jobs depart immediately but respects a given departure-rate limit, and drops arriving jobs that need to wait but find the waiting area full.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	<code>int</code> $\geq 0$	The buffer size; <code>Integer.MAX_VALUE</code> is treated as $+\infty$ .	
RateLimit	<code>double</code>	The rate limit, $\geq 0$ ; $\leq +\infty$ .	
State Properties			
RateLimited	HE	<code>boolean</code>	Whether currently (departure) rate-limited.
Internal Schedulable Events			
RateLimitExpirationEvent		The expiration of the rate-limit period.	
Operational Properties			
Name		The name, default "LeakyBucket[BufferSize,RateLimit]".	
Equivalences			
LeakyBucket $[\infty, L]$ = DLIMIT $[L]$ . LeakyBucket $[0, L]$ = ALIMIT $[L]$ .			

**6.3.9 The WUR SimQueue**

<p style="text-align: center;"><b>WUR</b></p> <p style="text-align: center;">Wait Until Relieved</p>	
<i>Lets arriving jobs wait for their departure until the next arrival.</i>	
<p style="text-align: center;"><b>Super</b></p>	
<b>SimQueue</b>	See Section 6.2.
<p style="text-align: center;"><b>State Invariants</b></p>	
$ \text{Jobs}  = 0$ or $1$ .	
<p style="text-align: center;"><b>Operational Properties</b></p>	
<b>Name</b>	The name, default "WUR".

## 6.4 Nonpreemptive Queues

### 6.4.1 The FCFS SimQueue

FCFS			
First-Come First-Served			
<i>Serves jobs in arrival order until completion with a single server and infinite buffer size.</i>			
<i>The server can serve at most one job at a time.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
State Invariants			
StartArmed = (JobsInServiceArea = $\emptyset$ ).			
$ \text{JobsInServiceArea}  \leq 1$ .			
ServerAccessCredits > 0, JobsInWaitingArea $\neq \emptyset \Rightarrow$ JobsInServiceArea $\neq \emptyset$ .			
Operational Properties			
Name	The name, default "FCFS".		



**6.4.2 The FCFS\_B SimQueue**

FCFS_B			
First-Come First-Served with given buffer size			
<i>Serves jobs in arrival order until completion with a single server and given (possibly finite) buffer size (BufferSize).</i> <i>The server can serve at most one job at a time.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	C	<code>int</code> $\geq 0$	The buffer size; <code>Integer.MAX_VALUE</code> is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
State Invariants			
StartArmed = (JobsInServiceArea = $\emptyset$ ). $ \text{JobsInWaitingArea}  \leq \text{BufferSize}$ . $ \text{JobsInServiceArea}  \leq 1$ . $\text{ServerAccessCredits} > 0, \text{JobsInWaitingArea} \neq \emptyset \Rightarrow \text{JobsInServiceArea} \neq \emptyset$ .			
Operational Properties			
Name	The name, default "FCFS_B[BufferSize]".		
Equivalences			
<code>FCFS_B[Integer.MAX_VALUE]</code> = FCFS.			

### 6.4.3 The FCFS\_c SimQueue

FCFS_c			
First-Come First-Served with given number of servers			
<i>Serves jobs in arrival order until completion with a given number (NumberOfServers) of equal servers and infinite buffer size. Each server can serve at most one job at a time. Jobs do not prefer one server over another; there are no server affinities.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	C	<code>int</code> $\geq 0$	The number of servers; Integer.MAX_VALUE is treated as $+\infty$ .
State Invariants			
StartArmed = ( $ \text{JobsInServiceArea}  < \text{NumberOfServers}$ ). $ \text{JobsInServiceArea}  \leq \text{NumberOfServers}$ . $\text{ServerAccessCredits} > 0, \text{JobsInWaitingArea} \neq \emptyset$ $\Rightarrow  \text{JobsInServiceArea}  = \text{NumberOfServers}$ .			
Operational Properties			
Name	The name, default "FCFS_NumberOfServers".		
Equivalences			
FCFS_0 = DROP. FCFS_1 = FCFS.			

### 6.4.4 The FCFS\_B\_c SimQueue

FCFS_B_c			
First-Come First-Served with given buffer size and number of servers			
<i>Serves jobs in arrival order until completion with a given number (NumberOfServers) of equal servers and given (possibly finite) buffer size (BufferSize). Each server can serve at most one job at a time. Jobs do not prefer one server over another; there are no server affinities.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	C	<code>int</code> $\geq 0$	The buffer size; <code>Integer.MAX_VALUE</code> is treated as $+\infty$ .
NumberOfServers	C	<code>int</code> $\geq 0$	The number of servers; <code>Integer.MAX_VALUE</code> is treated as $+\infty$ .
State Invariants			
StartArmed = ( $ \text{JobsInServiceArea}  < \text{NumberOfServers}$ ). $ \text{JobsInWaitingArea}  \leq \text{BufferSize}$ . $ \text{JobsInServiceArea}  \leq \text{NumberOfServers}$ . $\text{ServerAccessCredits} > 0, \text{JobsInWaitingArea} \neq \emptyset$ $\Rightarrow  \text{JobsInServiceArea}  = \text{NumberOfServers}$ .			
Operational Properties			
Name	The name, default "FCFS_NumberOfServers[BufferSize]".		
Equivalences			
FCFS_1[Integer.MAX_VALUE] = FCFS. FCFS_1[B] = FCFS_B[B]. FCFS_c[Integer.MAX_VALUE] = FCFS_c. FCFS_0[0] = DROP. FCFS_0[Integer.MAX_VALUE] = SINK.			

### 6.4.5 The IS SimQueue

IS			
Infinite Servers			
<i>Serves jobs in arrival order until completion with an infinite number of servers and infinite buffer size.</i>			
<i>Each server can serve at most one job at a time.</i>			
<i>Jobs do not prefer one server over another; there are no server affinities.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	Integer.MAX_VALUE	The number of servers; Integer.MAX_VALUE is treated as $+\infty$ .
State Invariants			
StartArmed = true.			
ServerAccessCredits > 0 $\Rightarrow$ JobsInWaitingArea = $\emptyset$ .			
Operational Properties			
Name	The name, default "IS".		
Equivalences			
IS = FCFS_Integer.MAX_VALUE.			
IS = FCFS_Integer.MAX_VALUE[Integer.MAX_VALUE].			

### 6.4.6 The IS\_CST SimQueue

IS_CST			
Infinite Servers with Constant Service Time			
<i>Serves jobs in arrival order until completion with an infinite number of servers and infinite buffer size.</i> <i>Each job is served for a queue-determined fixed service time (ServiceTime).</i> <i>Each server can serve at most one job at a time.</i> <i>Jobs do not prefer one server over another; there are no server affinities.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	Integer.MAX_VALUE	The number of servers; Integer.MAX_VALUE is treated as $+\infty$ .
ServiceTime	C	double $\geq 0$	The service time for each job.
State Invariants			
StartArmed = true. ServerAccessCredits $> 0 \Rightarrow$ JobsInWaitingArea = $\emptyset$ . ServiceTime = 0 $\Rightarrow$ JobsInServiceArea = $\emptyset$ .			
Operational Properties			
Name	The name, default "IS_CST[ServiceTime]".		

### 6.4.7 The IC SimQueue

IC			
Infinite Capacity			
<i>Serves jobs in arrival order until completion with an infinite number of infinite-capacity servers and infinite buffer size. Each job is served in zero time. Each server can serve at most one job at a time. Jobs do not prefer one server over another; there are no server affinities.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	Integer.MAX_VALUE	The number of servers; Integer.MAX_VALUE is treated as $+\infty$ .
State Invariants			
StartArmed = true. ServerAccessCredits > 0 $\Rightarrow$ Jobs = $\emptyset$ . JobsInServiceArea = $\emptyset$ .			
Operational Properties			
Name	The name, default "IC".		
Equivalences			
IC = IS_CST[0].			

## 6.4.8 The NoBuffer\_c SimQueue

NoBuffer_c			
<i>Serves jobs in arrival order until completion with a given number (NumberOfServers) of equal servers and zero buffer size. Each server can serve at most one job at a time. Jobs do not prefer one server over another; there are no server affinities.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	0	The buffer size;
NumberOfServers	C	<code>int</code> $\geq 0$	The number of servers; <code>Integer.MAX_VALUE</code> is treated as $+\infty$ .
State Invariants			
StartArmed = ( <code> JobsInServiceArea </code> < NumberOfServers). JobsInWaitingArea= $\emptyset$ . <code> JobsInServiceArea </code> $\leq$ NumberOfServers.			
Operational Properties			
Name	The name, default "NoBuffer_NumberOfServers".		
Equivalences			
NoBuffer_c = FCFS_c[0]. NoBuffer_1 = FCFS[0]. NoBuffer_0 = DROP.			

### 6.4.9 The LCFS SimQueue

LCFS			
Last-Come First-Served			
<i>Serves jobs in reverse arrival order until completion with a single server and infinite buffer size.</i> <i>The server can serve at most one job at a time.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
State Properties			
JobsInWaitingArea	EE	Set<J>	Jobs waiting in <i>reverse-arrival</i> order.
State Invariants			
StartArmed = (JobsInServiceArea = $\emptyset$ ). $ \text{JobsInServiceArea}  \leq 1$ . ServerAccessCredits > 0, JobsInWaitingArea $\neq \emptyset \Rightarrow$ JobsInServiceArea $\neq \emptyset$ .			
Operational Properties			
Name	The name, default "LCFS".		



## 6.4.10 The SJF SimQueue

SJF			
Shortest-Job First			
<i>Serves jobs in increasing service-time order until completion with a single server and infinite buffer size.</i> <i>The server can serve at most one job at a time.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
State Properties			
JobsInWaitingArea	EE	Set<J>	Jobs waiting in <i>increasing service-time</i> order.
State Invariants			
StartArmed = (JobsInServiceArea = $\emptyset$ ). $ \text{JobsInServiceArea}  \leq 1$ . ServerAccessCredits > 0, JobsInWaitingArea $\neq \emptyset \Rightarrow$ JobsInServiceArea $\neq \emptyset$ .			
Operational Properties			
Name	The name, default "SJF".		

### 6.4.11 The LJF SimQueue

LJF			
Longest-Job First			
Serves jobs in decreasing service-time order until completion with a single server and infinite buffer size. The server can serve at most one job at a time.			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
State Properties			
JobsInWaitingArea	EE	Set<J>	Jobs waiting in <i>decreasing service-time</i> order.
State Invariants			
StartArmed = (JobsInServiceArea = $\emptyset$ ). $ \text{JobsInServiceArea}  \leq 1$ . ServerAccessCredits > 0, JobsInWaitingArea $\neq \emptyset \Rightarrow$ JobsInServiceArea $\neq \emptyset$ .			
Operational Properties			
Name	The name, default "LJF".		

## 6.4.12 The RANDOM SimQueue

RANDOM			
<i>Serves jobs in random order until completion with a single server and infinite buffer size. The server can serve at most one job at a time.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
State Properties			
JobsInWaitingArea	EE	Set<J>	Jobs waiting in <i>random</i> order.
State Invariants			
StartArmed = (JobsInServiceArea = $\emptyset$ ). $ \text{JobsInServiceArea}  \leq 1$ . ServerAccessCredits > 0, JobsInWaitingArea $\neq \emptyset \Rightarrow$ JobsInServiceArea $\neq \emptyset$ .			
Operational Properties			
Name	The name, default "RANDOM".		

### 6.4.13 The SUR SimQueue

<div>SUR</div> <div>Serve Until Relieved</div>			
<i>Serves jobs in arrival order until the start of the next job with a single server and infinite buffer size.</i> <i>The server can serve at most one job at a time.</i>			
<div>Super</div>			
SimQueue		See Section 6.2.	
<div>Essential Properties</div>			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
<div>State Invariants</div>			
StartArmed = true. $ \text{JobsInServiceArea}  \leq 1$ . $\text{ServerAccessCredits} > 0 \Rightarrow \text{JobsInWaitingArea} = \emptyset$ .			
<div>Operational Properties</div>			
Name		The name, default "SUR".	

## 6.5 Preemptive Queues

In preemptive queues, the service area consists of a countable number of servers, each capable of serving a single job at a time, yet this service to a job can be *preempted* in favor of another job.

### 6.5.1 Preemption Strategies; the PreemptionStrategy Class

At the moment a job is preempted at a server, one of several things can happen, as determined by the *preemption strategy*. In `jqueues`, the preemption strategy is implemented in an `enum` name `PreemptionStrategy`, and it can take the following values:

- **DROP**: The preempted job is dropped.
- **RESUME**: The preempted job is put on hold, after calculating the remaining service time. Future service resumption continues at the point where the previous service was interrupted.
- **RESTART**: The preempted job is put on hold. Future service resumption requires the job to be served from scratch.
- **REDRAW**: The preempted job is put on hold. Future service resumption requires the job to be served from scratch with a new required service time.
- **DEPART**: The preempted job departs, even though it may not have finished its service requirements.
- **CUSTOM**: A different strategy that those mentioned above is applied to preempted jobs. The strategy needs to be specified in the concrete `SimQueue` implementation.

Not all preemptive-queue implementations support all preemption strategies. For instance, the **REDRAW** strategy is not supported by any implementation, because it conflicts with the contract the the service time of a `SimJob` has to remain constant during a (single) `SimQueue` visit.

The preemption strategy is a parameter that can be passed upon construction by all implemented preemptive queues in `jqueues`. Its default value is **RESUME**. If you pass an unsupported preemption strategy, the queue will throw an `UnsupportedOperationException`.

### 6.5.2 The P\_LCFS SimQueue

P_LCFS			
Preemptive Last-Come First-Served			
<i>Serves jobs in reverse arrival order until completion or preemption with a single server and infinite buffer size.</i> <i>A job in service is preempted upon the start of a new job.</i> <i>The server can execute at most one job at a time, but an arbitrary number of jobs may be in service.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
PreemptionStrategy	C	PreemptionStrategy	The preemption strategy.
State Properties			
JobsInWaitingArea	EE	Set<J>	Jobs waiting in <i>reverse-arrival</i> order.
Operations			
Preempt	I	double, J	Job preemption at time.
StartServiceChunk	I	double, J	Start service chunk for job at time.
State Invariants			
StartArmed = true. ServerAccessCredits > 0 $\Rightarrow$ JobsInWaitingArea = $\emptyset$ .			
Operational Properties			
Name	The name, default "P_LCFS[PreemptionStrategy]".		

### 6.5.3 The SRTF SimQueue

SRTF			
Shortest Remaining-Time First			
<i>Serves jobs in reverse order of remaining service time until completion or preemption with a single server and infinite buffer size.</i> <i>A job in service is preempted upon the start of a new job with a strictly smaller remaining service time.</i> <i>Jobs are started in reverse required service-time order at the earliest opportunity (i.e., independent of the state of the service area).</i> <i>The server can execute at most one job at a time, but an arbitrary number of jobs may be in service.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
PreemptionStrategy	C	PreemptionStrategy	The preemption strategy.
State Properties			
JobsInWaitingArea	EE	Set<J>	Jobs waiting in (1) <i>service-time</i> and (2) <i>arrival</i> order.
Operations			
Preempt	I	double, J	Job preemption at time.
StartServiceChunk	I	double, J	Start service chunk for job at time.
State Invariants			
StartArmed = true. ServerAccessCredits > 0 $\Rightarrow$ JobsInWaitingArea = $\emptyset$ .			
Operational Properties			
Name	The name, default "SRTF[PreemptionStrategy]".		

## 6.6 Processor-Sharing Queues

In Processor-Sharing (PS) queues, the service area consists of a countable number of servers, each capable of serving multiple jobs at a time, sharing its capacity among those jobs.

### 6.6.1 The PS SimQueue

PS			
Processor Sharing			
<i>Serves all started jobs simultaneously at equal rates until completion with a single server and infinite buffer size.</i> <i>Jobs are started in arrival order at the earliest opportunity.</i> <i>The server can execute an arbitrary number of jobs simultaneously.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
State Invariants			
StartArmed = true. ServerAccessCredits > 0 $\Rightarrow$ JobsInWaitingArea = $\emptyset$ .			
Operational Properties			
Name	The name, default "PS".		



**6.6.2 The CUPS SimQueue**

CUPS			
Catch-Up Processor-Sharing			
<i>Serves all started jobs with least obtained service times simultaneously at equal rates until (1) completion, or (2) another job starts or (3) the jobs in execution "catch-up" in terms of obtained service time with another set of jobs in service, with a single server and infinite buffer size.</i> <i>Jobs are started in arrival order at the earliest opportunity.</i> <i>The server can execute an arbitrary number of jobs simultaneously.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
Operations			
CatchUp	I	double	Catch-up at time.
State Invariants			
StartArmed = true. ServerAccessCredits > 0 $\Rightarrow$ JobsInWaitingArea = $\emptyset$ .			
Internal Schedulable Events			
CatchUpEvent	A "catch-up" event.		
Operational Properties			
Name	The name, default "CUPS".		

### 6.6.3 The SocPS SimQueue

SocPS			
Social Processor-Sharing			
<i>Serves all started jobs simultaneously such that their departures times are equal, distributing its service capacity among those job to that effect, with a single server and infinite buffer size.</i> <i>The service rate of a job in the service area is linearly proportional to its remaining service time.</i> <i>Jobs are started in arrival order at the earliest opportunity.</i> <i>The server can execute an arbitrary number of jobs simultaneously.</i>			
Super			
SimQueue	See Section 6.2.		
Essential Properties			
BufferSize	F	Integer.MAX_VALUE	The buffer size; Integer.MAX_VALUE is treated as $+\infty$ .
NumberOfServers	F	1	The number of servers.
State Invariants			
StartArmed = true. ServerAccessCredits > 0 $\Rightarrow$ JobsInWaitingArea = $\emptyset$ .			
Operational Properties			
Name	The name, default "SocPS".		

# Chapter 7

## Multiclass Queues and Jobs

### 7.1 Introduction

### 7.2 Nonpreemptive Multiclass Queues

#### 7.2.1 The HOL SimQueue

### 7.3 Preemptive Multiclass Queues

#### 7.3.1 The PQ SimQueue

### 7.4 Processor-Sharing Multiclass Queues

#### 7.4.1 The HOL-PS SimQueue



# Chapter 8

## Composite Queues

### 8.1 Introduction

Composite queues consist of zero or more other queues named *subqueues* or *embedded queues*, and a visit of a job to the composite queue is equivalent to a sequence of visits to the subqueues, the order of which is determined by the composite queue. The most prominent example of a composite queue is called a *tandem queue*, consisting of a finite sequence of (distinct) queues that a job must visit in order before leaving the composite queue. If we number the subqueues  $1, 2, \dots, K$ , a job visiting the tandem queue, must first complete a visit to queue 1, and upon departure from queue 1, it immediately arrives at queue 2, and so forth, until it departs from queue  $K$ , at which time it leaves the tandem queue. Using the previous chapters, it is actually rather easy to construct a tandem queue, e.g., a tandem queue consisting of two P\_LCFS queues, as we have shown in Listing 8.1 below. The output of the program is shown in Listing 8.2.

Listing 8.1: A tandem queue consisting of two P\_LCFS queues (using SimJob).

```
private static final class TandemJob
extends DefaultSelfListeningSimJob
{
    final List<SimQueue> queues;

    public TandemJob (final SimEventList eventList,
        final String name,
        final double requestedServiceTime,
        final List<SimQueue> queues)
    {
        super (eventList, name, requestedServiceTime);
        this.queues = queues;
        this.registerSimEntityListener (new StdOutSimEntityListener ());
    }

    @Override
    public void notifyDeparture (final double time,
        final DefaultSelfListeningSimJob job,
```

```

    final SimQueue queue)
{
    if (this.queues.indexOf (queue) < this.queues.size () - 1)
        getEventList ().schedule (time, (SimEventAction) (SimEvent event) ->
        {
            queues.get (queues.indexOf (queue) + 1).arrive (time, job);
        });
}

}

public static void main (final String[] args)
{
    final SimEventList el = new DefaultSimEventList ();
    el.reset (0);
    final P_LCFS lcfs_1 = new P_LCFS (el, null);
    lcfs_1.setName ("Q1");
    final P_LCFS lcfs_2 = new P_LCFS (el, null);
    lcfs_2.setName ("Q2");
    final List<SimQueue> queueSequence = new ArrayList<> ();
    queueSequence.add (lcfs_1);
    queueSequence.add (lcfs_2);
    for (int j = 1; j <= 5; j++)
        lcfs_1.scheduleJobArrival (j, new TandemJob (el, "J" + j, 10 * j, queueSequence));
    el.run ();
}

```

Listing 8.2: Output of the program in Listing 8.1.

```

StdOutSimEntityListener t=1.0, queue=Q1: ARRIVAL of job J1.
StdOutSimEntityListener t=1.0, queue=Q1: START of job J1.
StdOutSimEntityListener t=2.0, queue=Q1: ARRIVAL of job J2.
StdOutSimEntityListener t=2.0, queue=Q1: START of job J2.
StdOutSimEntityListener t=3.0, queue=Q1: ARRIVAL of job J3.
StdOutSimEntityListener t=3.0, queue=Q1: START of job J3.
StdOutSimEntityListener t=4.0, queue=Q1: ARRIVAL of job J4.
StdOutSimEntityListener t=4.0, queue=Q1: START of job J4.
StdOutSimEntityListener t=5.0, queue=Q1: ARRIVAL of job J5.
StdOutSimEntityListener t=5.0, queue=Q1: START of job J5.
StdOutSimEntityListener t=55.0, queue=Q1: DEPARTURE of job J5.
StdOutSimEntityListener t=55.0, queue=Q2: ARRIVAL of job J5.
StdOutSimEntityListener t=55.0, queue=Q2: START of job J5.
StdOutSimEntityListener t=94.0, queue=Q1: DEPARTURE of job J4.
StdOutSimEntityListener t=94.0, queue=Q2: ARRIVAL of job J4.
StdOutSimEntityListener t=94.0, queue=Q2: START of job J4.
StdOutSimEntityListener t=123.0, queue=Q1: DEPARTURE of job J3.
StdOutSimEntityListener t=123.0, queue=Q2: ARRIVAL of job J3.
StdOutSimEntityListener t=123.0, queue=Q2: START of job J3.
StdOutSimEntityListener t=142.0, queue=Q1: DEPARTURE of job J2.
StdOutSimEntityListener t=142.0, queue=Q2: ARRIVAL of job J2.
StdOutSimEntityListener t=142.0, queue=Q2: START of job J2.
StdOutSimEntityListener t=151.0, queue=Q1: DEPARTURE of job J1.
StdOutSimEntityListener t=151.0, queue=Q2: ARRIVAL of job J1.
StdOutSimEntityListener t=151.0, queue=Q2: START of job J1.
StdOutSimEntityListener t=161.0, queue=Q2: DEPARTURE of job J1.
StdOutSimEntityListener t=172.0, queue=Q2: DEPARTURE of job J2.
StdOutSimEntityListener t=183.0, queue=Q2: DEPARTURE of job J3.
StdOutSimEntityListener t=194.0, queue=Q2: DEPARTURE of job J4.
StdOutSimEntityListener t=205.0, queue=Q2: DEPARTURE of job J5.

```

In the example, 5 jobs are scheduled to arrive at a tandem queueing system consisting of the sequence of two P\_LCFS queues named Q1 and Q2. The jobs arrive at  $t = 1, 2, \dots, 5$ , and require service times at *each* of the P\_LCFS queues of 10, 20,  $\dots$ , 50, respectively. Given the high required service times compared to the interarrival times, the jobs leave Q1, in reverse order of arrival. However, again because of the relatively high required service times, no job can depart from Q2 before the next arrival at that queue. As a result, Q2 again reverses the order of arriving job in its departure process, and jobs depart from Q2 in order of arrival at the first queue (and

at the virtual tandem queue).

Despite the intriguing result that a tandem queue consisting of two P\_LCFS queues *can* behaves like a FCFS queue with modified service-time requirement, and the fact that the tandem queue was so easy to realize, we want to focus at the implementation of the tandem queue, because there are some issues with it. Most important, we explained in the beginning of this section, that a composite queue behaves like the equivalent of its subqueues equipped with some *routing* of jobs between these subqueues. However, in the example, there is no notion of a composite `SimQueue` at all! The job-arrival process "somehow know" that Q1 is the first queue at which jobs must arrive, and the jobs *themselves* route themselves to the "next queue". In other words, all the "logic" related to routing jobs in a tandem queue is implemented in the arrival process and in the job implementation, whereas we really want these to be part of the tandem queue, the `SimQueue`. This, for instance, would allow *any* to properly visit the composite `SimQueue` without knowledge on its (internal) structure.

Well, allowing *any* `SimJob` to visit the tandem queue is not that difficult, as is shown in Listing 8.3 below. All we have to do is listen to departure events on Q1 and then schedule an arrival event at Q2.

Listing 8.3: A tandem queue consisting of two P\_LCFS queues (using `SimQueue`).

```
public static void main (final String[] args)
{
    final SimEventList el = new DefaultSimEventList ();
    el.reset (0);
    final P_LCFS lcfs_1 = new P_LCFS (el, null);
    lcfs_1.setName ("Q1");
    final P_LCFS lcfs_2 = new P_LCFS (el, null);
    lcfs_2.setName ("Q2");
    lcfs_1.registerSimEntityListener (new DefaultSimEntityListener ()
    {
        @Override
        public void notifyDeparture (final double time, final SimJob job, final SimQueue queue)
        {
            el.schedule (time, (SimEventAction) (SimEvent event) ->
            {
                lcfs_2.arrive (time, job);
            });
        }
    });
    for (int j = 1; j <= 5; j++)
    {
        final SimJob job = new DefaultSimJob (el, "J" + j, 10 * j);
        lcfs_1.scheduleJobArrival (j, job);
        job.registerSimEntityListener (new StdOutSimEntityListener ());
    }
    el.run ();
}
```

The result of the program is identical to that shown in 8.2, and the program itself is surprisingly short (we no longer have to create a dedicated `SimJob` for the tandem queue). This suggests (luckily) that the `jqueues` package has sufficient means to model composite queues manually. However, we are still faced with the problems that there is not really a notion of a composite queue, and we have not tackled the more generic problem of putting `SimQueues` in tandem:

- What if any of the subqueues *drops* the job?
- How to revoke a jobs from a composite queue?
- How to obtain statistics on the composite queue?

In other words, what we really want is an implementation of a `SimQueue` that behaves as the concatenation of visits to its subqueues. In Listing 8.4 we show this approach using a `BlackTandemSimQueue` described in this chapter, with its output in 8.5.

Listing 8.4: A tandem queue consisting of two P\_LCFS queues (using `BlackTandemSimQueue`).

```
public static void main (final String[] args)
{
    final SimEventList el = new DefaultSimEventList ();
    el.reset (0);
    final P_LCFS lcfs_1 = new P_LCFS (el, null);
    lcfs_1.setName ("Q1");
    final P_LCFS lcfs_2 = new P_LCFS (el, null);
    lcfs_2.setName ("Q2");
    final Set<SimQueue> subQueues = new LinkedHashSet<> ();
    subQueues.add (lcfs_1);
    subQueues.add (lcfs_2);
    final BlackTandemSimQueue compositeQueue = new BlackTandemSimQueue (el, subQueues, null);
    for (int j = 1; j <= 5; j++)
    {
        final SimJob job = new DefaultSimJob (el, "J" + j, 10 * j);
        compositeQueue.scheduleJobArrival (j, job);
        job.registerSimEntityListener (new StdOutSimEntityListener ());
    }
    el.run ();
}
```

Listing 8.5: Output of the program in Listing 8.4.

```
StdOutSimEntityListener t=1.0, queue=Tandem[Q1,Q2]: ARRIVAL of job J1.
StdOutSimEntityListener t=1.0, queue=Tandem[Q1,Q2]: START of job J1.
StdOutSimEntityListener t=2.0, queue=Tandem[Q1,Q2]: ARRIVAL of job J2.
StdOutSimEntityListener t=2.0, queue=Tandem[Q1,Q2]: START of job J2.
StdOutSimEntityListener t=3.0, queue=Tandem[Q1,Q2]: ARRIVAL of job J3.
StdOutSimEntityListener t=3.0, queue=Tandem[Q1,Q2]: START of job J3.
StdOutSimEntityListener t=4.0, queue=Tandem[Q1,Q2]: ARRIVAL of job J4.
StdOutSimEntityListener t=4.0, queue=Tandem[Q1,Q2]: START of job J4.
StdOutSimEntityListener t=5.0, queue=Tandem[Q1,Q2]: ARRIVAL of job J5.
StdOutSimEntityListener t=5.0, queue=Tandem[Q1,Q2]: START of job J5.
StdOutSimEntityListener t=161.0, queue=Tandem[Q1,Q2]: DEPARTURE of job J1.
StdOutSimEntityListener t=172.0, queue=Tandem[Q1,Q2]: DEPARTURE of job J2.
StdOutSimEntityListener t=183.0, queue=Tandem[Q1,Q2]: DEPARTURE of job J3.
StdOutSimEntityListener t=194.0, queue=Tandem[Q1,Q2]: DEPARTURE of job J4.
StdOutSimEntityListener t=205.0, queue=Tandem[Q1,Q2]: DEPARTURE of job J5.
```

The latter example shows exactly what we want: The creation of a new `SimQueue` that behaves exactly like a tandem configuration of two other queues. Admittedly, the code in the example is not particularly smaller than that of the previous examples, and the latter examples can certainly be used as a starting point for the study of tandem (and other composite) queues. However, if, for instance, you want to create a new `SimQueue` type that is the equivalent of other queues that are somehow interconnected, or if you want to study nested composite queues, then constructing a composite queue is a much faster (and more reliable) approach.



The extensive support for composite queues is one of the most distinguishing features of `jqueues`. Next to tandem queues, there is support for various types of *feedback* queues, *encapsulated* queues and *parallel* queues. In the next chapter we describe these composite queues in detail. In the remainder of the present chapter, we introduce some important concepts that apply to *any* composite queue.

## 8.2 The SimQueueComposite Interface

In the `jqueues` implementation, composite queues implement the `SimQueueComposite` interface, which, in turn, inherits from `SimQueue`.

### 8.2.1 The 'Queues' Property

The value of the 'Queues' property of a `SimQueueComposite` is a `Set` holding the subqueues of the composite queue. The property can only be set upon construction of the composite queue; and cannot be changed thereafter, but the subqueues can be accessed through `getQueues ()`. (Note that the `Set` returned should *not* be modified.) Since the order of the subqueues is important to most composite-queue types, the implementation of `getQueues ()` *must* maintain a deterministic ordering of the subqueues.

### 8.2.2 The 'StartModel' Property

## 8.3 Tandem Queues

### 8.3.1 The Tandem SimQueue

In tandem queues, visiting jobs must visit each subqueue one in a predetermined (and fixed) sequence. The list of (distinct) subqueues is passed upon construction, and cannot be changed afterwards.

Tandem	
Description	Serves jobs by letting their delegate jobs visit the sequence of subqueues $\mathcal{Q}$ exactly once.
State	
QAV	Drops arriving jobs during QAVs.
NoWaitArmed	Always <b>true</b> .
Waiting Area	Infinite waiting area, FIFO discipline.
SAC	The remaining number of arriving jobs that can have a delegate job arrive at the tandem queue. If zero, arriving jobs wait in the waiting area. <b>Integer.MAX_VALUE</b> is treated as $+\infty$ .
Service Area	Holds the jobs whose delegate job have arrived <i>anywhere</i> .
State Operations	
Set QAV	Ends/starts a QAV.
Arrival	The queue accepts arrivals.
Drop	Drops arriving jobs during QAVs. Drops a visiting job if its delegate job is dropped on any subqueue.
Revocation	Jobs can be revoked while waiting and while being served.
Set SAC	Sets/overwrites SAC; <b>Integer.MAX_VALUE</b> == $+\infty$ . Starts waiting jobs if $SAC > 0$ .
Start	Starts a job if its delegate job arrives <i>anywhere</i> .
Departure	Jobs depart if its delegate job departs from the last subqueue.
State Invariants	
$ J(t)  =  J_w(t)  + \sum_{q \in \mathcal{Q}}  J_q(t) .$	
Properties	
EventList	The event list; non- <b>null</b> ; RO.
Name	The name, default "LJF"; non- <b>null</b> ; RW.
Queues	The set (and list) of subqueues $\mathcal{Q}$ ; ordered; RO.

### 8.3.2 The CTandem2 SimQueue

## 8.4 Parallel Queues

### 8.4.1 The JSQ SimQueue

### 8.4.2 The JRQ SimQueue

### 8.4.3 The Pattern SimQueue

### 8.4.4 The Parallel SimQueue

## 8.5 Feedback Queues

### 8.5.1 The FB\_v SimQueue

### 8.5.2 The FB\_p SimQueue

### 8.5.3 The FB SimQueue

## 8.6 Jackson Queues

### 8.6.1 The Jackson SimQueue

## 8.7 Encapsulator Queues

An *encapsulator* queue has exactly one subqueue.

**8.7.1** The Enc SimQueue

**8.7.2** The EncHS SimQueue

**8.7.3** The EncTL SimQueue

**8.7.4** The EncJL SimQueue

**8.7.5** The EncXM SimQueue

## **8.8 Special Composite Queues**

**8.8.1** The Drop-Collector Queue

## **8.9 Generic Composite Queues**

**8.9.1** The Comp SimQueue

# Chapter 9

## Queue and Job Statistics

### 9.1 Introduction

If you have read this book linearly up to this point, we hope you are wondering by now how to compute statistics like average job sojourn time at a queue, or average server utilization (just to name a few). Actually, this is somewhat on purpose: None of the interfaces and concrete implementations of jobs and queues provide direct support for maintaining and calculating statistics. This has three important reasons:

- It relieves the concrete `SimQueue` and `SimJob` implementations of the tedious and error-prone responsibility of maintaining and calculating statistics; their basis functionality in terms of e.g. implementing the proper queueing discipline is complicated enough as it is.
- It forces the implementation of statistics in a generic way, e.g., applicable to *any* queue type.
- It allows for easy replacement of *all* statistics-gathering and maintenance code with that of a professional third-party statistics package like **XXX**.

Needless to say, `jqueues` has full support for the implementation of statistics, and actually, provides a few basic, but highly effective and extensible classes for statistics gathering itself. The starting point for gathering statistics of a `SimEntity` is to register as a suitable `SimEntityListener` to it, and update statistics upon notifications from the entity, in particular update notifications and visit-related notifications like arrivals, drops and departures. Recall that a `SimEntity` is required to notify registered listeners *just before* it state changes through an update notification, allowing for easy maintenance of "time-average-type" statistics like the average number

of jobs present at a queue. In addition (and often requiring a bit more work) the visit-related notifications allow for maintenance of "visit-related" statistics, like the average job sojourn time at a queue.

In the following section, we will first explain how to obtain statistics for a `SimQueue` or `SimJob` manually, following the approach outline above. Subsequently, we will introduce a few statistics-related class that intend to make it easier to obtain such statistics.

### 9.1.1 Example: The Average Number of Jobs at a Queue

In this statistics-related example, we create a `SimQueue` and a workload consisting of arriving `SimJobs`. Our objective is to run the simulation, and calculate the average number of jobs at the queue. To make the example more interesting, we create two queues, a FCFS queue and a Preemptive (Resume) LCFS queue. We equip each with a listener that maintains the number of jobs at the queue over time. As shown in Listing 9.1 below, we use a `DefaultSimEntityListener` as base class, making it easier to ignore all the notifications we are not interested in. Note that we are silently assuming that the listener is registered at a `SimQueue`, and not at some other `SimEntity` type. In addition, we left out some sanity checking, e.g., on the `time` parameter (should not be in the past).

Listing 9.1: Simple listener for maintaining and calculating the average number of jobs at a `SimQueue`.

```
private final static class AvgJStatListener
extends DefaultSimEntityListener
{
    public AvgJStatListener (SimQueue queue)
    {
        notifyResetEntity (queue);
        queue.registerSimEntityListener (this);
    }

    private double tStart = Double.NEGATIVE_INFINITY;
    private double tLast = Double.NEGATIVE_INFINITY;
    private double cumJ = 0;

    @Override
    public void notifyResetEntity (SimEntity entity)
    {
        tStart = entity.getEventList ().getTime ();
        tLast = tStart;
        cumJ = 0;
    }

    @Override
    public void notifyUpdate (double time, SimEntity entity)
    {
        cumJ += ((SimQueue) entity).getNumberOfJobs () * (time - tLast);
        tLast = time;
    }

    public final double getStartTime ()
    {
        return this.tStart;
    }
}
```

```

    }

    public final double getEndTime ()
    {
        return this.tLast;
    }

    public final double calculate ()
    {
        if (tLast > tStart)
        {
            if (! Double.isInfinite (tLast - tStart))
                return cumJ / (tLast - tStart);
            else
                return 0;
        }
        else
            return 0;
    }
}

```

Note that we are only interested in two notifications from the **SimQueue**, *reset* and *update* notifications. Because the number of jobs at a **SimQueue** is a *simple function*, we can easily integrate it over time by considering all points in time at which the function value *can* change, and cumulating the product of the interval since the last update with the current value. By definition, such points in time are the *updates* of a **SimQueue** and the contract of the latter mandates that each update results in a notification at its listeners *before* any changes have been applied to the queue. Needless to say, this requires substantial discipline for implementations of **SimQueue**, but we use it here to our advantage. In the end, all we need to do is divide the cumulated value with the total time interval, taking special care of the possibility that the interval is  $+\infty$ .

For the start of the interval, we use the reset notification from the queue. At each reset, we take the start time from the current time of the event list (note that we cannot take the time from the **SimQueue** directly), and reset our internal statistics. Note that we call **notifyResetEntity** directly from the constructor as well, because we cannot rely on receiving a reset between construction of the object and starting the simulation. Also note that we may assume that the number of jobs at a reset, as well as upon construction of a **SimQueue** is zero, conform the contract of a **SimQueue**. However, unless the event list or the **SimQueue** attached to it is reset to a finite time value, we must use **Double.NEGATIVE\_INFINITY** as time value. This explains the default values used in **AvgJStatListener**.

We list the example program using the **AvgJStatListener** and its output in Listings 9.2 and 9.3 below. Note the very important **el.reset (0)** line in the main program. We will later show the effect of leaving out or forgetting this statement. The correctness of the calculated values in the output can be assessed easily as is shown in the comments of the main program. For **P\_LCFS**, the program outputs one of two distinct values for the average, both of which are actually correct, due to

an ambiguity in the event scheduling. (Which we, in all honesty, overlooked while constructing the example.) This is also explained in the comments of the program.

Listing 9.2: Example program for calculating the average number of jobs at two queues.

```
public static void main (final String[] args)
{
    final SimEventList el = new DefaultSimEventList ();
    el.reset (0);
    // Schedule 5 jobs, 0 through 4 at t = 0, 1, 2, 3, 4
    // and service times 0, 1, 2, 3, 4, respectively.
    //
    // Departure times with FCFS: 0, 2, 4, 7, 11.
    // cumJ = 0 + 1 + 1 + 2 + 2 + 2 + 2 + 1 + 1 + 1 + 1 = 14.
    // avgJ = 14 / 11 = 1.2727.
    //
    // WITH P-LCFS: AMBIGUITY!
    //
    // Departure times with P-LCFS [2 arrives after departure of 1]: 0, 2, 8, 10, 11.
    // cumJ = 0 + 1 + 1 + 2 + 3 + 3 + 3 + 3 + 2 + 2 + 1 = 21.
    // avgJ = 21 / 11 = 1.9090.
    //
    // Departure times with P-LCFS [2 arrives before departure of 1]: 0, 8, 10, 11, 11.
    // cumJ = 0 + 1 + 2 + 3 + 4 + 4 + 4 + 4 + 3 + 3 + 2 = 30.
    // avgJ = 30 / 11 = 2.7272.
    //
    final FCFS fcfs = new FCFS (el);
    final P-LCFS lcfs = new P-LCFS (el, null);
    for (int j = 0; j <= 4; j++)
    {
        fcfs.scheduleJobArrival (j, new DefaultSimJob (el, "JobF_" + j, j));
        lcfs.scheduleJobArrival (j, new DefaultSimJob (el, "JobL_" + j, j));
    }
    final AvgJStatListener avgJStatListener_fcfs = new AvgJStatListener (fcfs);
    final AvgJStatListener avgJStatListener_lcfs = new AvgJStatListener (lcfs);
    el.run ();
    System.out.println ("FCFS:");
    System.out.println ("  _Start_time_:_" + avgJStatListener_fcfs.getStartTime () + ".");
    System.out.println ("  _End_time_:_" + avgJStatListener_fcfs.getEndTime () + ".");
    System.out.println ("  _Average_number_of_jobs_:_" + avgJStatListener_fcfs.calculate () + ".");
    System.out.println ("P-LCFS:");
    System.out.println ("  _Start_time_:_" + avgJStatListener_lcfs.getStartTime () + ".");
    System.out.println ("  _End_time_:_" + avgJStatListener_lcfs.getEndTime () + ".");
    System.out.println ("  _Average_number_of_jobs_:_" + avgJStatListener_lcfs.calculate () + ".");
}
```

Listing 9.3: Output from the example program in Listing 9.2.

```
FCFS:
  Start time: 0.0.
  End Time : 11.0.
  Average number of jobs: 1.2727272727272727.
P-LCFS:
  Start time: 0.0.
  End Time : 11.0.
  Average number of jobs: 1.9090909090909092 [OR 2.727272727272727, see comments].
```

As mentioned earlier, it is essential to reset the event list to a finite time value before use. Below in Listing 9.4 we show the output of the program if we leave out the `el.reset (0)` statement, essentially starting the simulation and, more importantly, gathering the statistics at  $t = -\infty$ . The result is zero, because we are taking the average value of a function over an infinite interval, knowing that it is only non-zero over a finite interval. Despite that fact that for this particular case, we seem to get away with the infinite interval, and are able to return a sensible value for the



average, this does not hold for the general case. (For instance, suppose we would have scheduled an arrival at  $t = -\infty$ , the program would still return the incorrect zero value for the average.) As a rule of thumb, the use of statistics involving infinite values should be avoided at all times, again stressing the importance of resetting the event list to a finite value before its use.

Listing 9.4: Output from the example program in Listing 9.2 without resetting the event list to zero (i.e., starting at  $t = -\infty$ ).

```
FCFS:
  Start time: -Infinity.
  End Time   : 11.0.
  Average number of jobs: 0.0.
P_LCFS:
  Start time: -Infinity.
  End Time   : 11.0.
  Average number of jobs: 0.0.
```

### 9.1.2 Example: The Total Sojourn of a Job at Visited Queues

## 9.2 The AbstractSimQueueStat Base Class

The examples in the previous sections explained how to obtain statistics on `SimQueues` and `SimJobs`. The next sections in this chapter introduce a few classes that either directly provide a few of the most basic statistics or allow you to define your own statistics more easily.

The `AbstractSimQueueStat` is the (abstract) base class for all subsequent classes. Its functionality is comparable to `AvgJStatListener` introduced in Section 9.1.1, with a few new functions and increased robustness, and delegating the actual maintenance and calculation of the statistic(s) to only a few abstract methods. To illustrate its use, we show in Listings 9.5 and 9.6 the modified listener and main program, respectively, from the example in Section 9.1.1 now using `AbstractSimQueueStat`.

Listing 9.5: Using `AbstractSimQueueStat` for a listener for maintaining and calculating the average number of jobs at a `SimQueue`.

```
private static class AvgJStatListener
extends AbstractSimQueueStat
{
    public AvgJStatListener (SimQueue queue)
    {
        super (queue);
    }

    private double cumJ = 0;
    private double avgJ = 0;

    @Override
    protected void resetStatistics ()
    {
```

```

        cumJ = 0;
        avgJ = 0;
    }

    @Override
    protected void updateStatistics (double time, double dt)
    {
        cumJ += getQueue ().getNumberOfJobs () * dt;
    }

    @Override
    protected void calculateStatistics (double startTime, double endTime)
    {
        if (startTime == endTime)
            return;
        if (! Double.isInfinite (endTime - startTime))
            avgJ = cumJ / (endTime - startTime);
        else
            avgJ = 0;
    }

    public double getAvgJ ()
    {
        calculate ();
        return this.avgJ;
    }
}

```

Listing 9.6: Example program for calculating the average number of jobs at two queues using AbstractSimQueueStat.

```

public static void main (final String[] args)
{
    final SimEventList el = new DefaultSimEventList ();
    el.reset (0);
    // Schedule 5 jobs, 0 through 4 at t = 0, 1, 2, 3, 4
    // and service times 0, 1, 2, 3, 4, respectively.
    //
    // Departure times with FCFS: 0, 2, 4, 7, 11.
    // cumJ = 0 + 1 + 1 + 2 + 2 + 2 + 2 + 1 + 1 + 1 + 1 = 14.
    // avgJ = 14 / 11 = 1.2727.
    //
    // WITH P-LCFS: AMBIGUITY!
    //
    // Departure times with P-LCFS [2 arrives after departure of 1]: 0, 2, 8, 10, 11.
    // cumJ = 0 + 1 + 1 + 2 + 3 + 3 + 3 + 3 + 2 + 2 + 1 = 21.
    // avgJ = 21 / 11 = 1.9090.
    //
    // Departure times with P-LCFS [2 arrives before departure of 1]: 0, 8, 10, 11, 11.
    // cumJ = 0 + 1 + 2 + 3 + 4 + 4 + 4 + 4 + 3 + 3 + 2 = 30.
    // avgJ = 30 / 11 = 2.7272.
    //
    final FCFS fcfs = new FCFS (el);
    final P-LCFS lcfs = new P-LCFS (el, null);
    for (int j = 0; j <= 4; j++)
    {
        fcfs.scheduleJobArrival (j, new DefaultSimJob (el, "JobF_" + j, j));
        lcfs.scheduleJobArrival (j, new DefaultSimJob (el, "JobL_" + j, j));
    }
    final AvgJStatListener avgJStatListener_fcfs = new AvgJStatListener (fcfs);
    final AvgJStatListener avgJStatListener_lcfs = new AvgJStatListener (lcfs);
    el.run ();
    System.out.println ("FCFS:");
    System.out.println ("__Start_time:__" + avgJStatListener_fcfs.getStartTime () + ".");
    System.out.println ("__End_time:__" + avgJStatListener_fcfs.getLastUpdateTime () + ".");
    System.out.println ("__Average_number_of_jobs:__" + avgJStatListener_fcfs.getAvgJ () + ".");
    System.out.println ("P-LCFS:");
    System.out.println ("__Start_time:__" + avgJStatListener_lcfs.getStartTime () + ".");
    System.out.println ("__End_time:__" + avgJStatListener_lcfs.getLastUpdateTime () + ".");
    System.out.println ("__Average_number_of_jobs:__" + avgJStatListener_lcfs.getAvgJ () + ".");
}

```

Compared to the manual approach in Section 9.1.1, we highlight the following

differences:

- In the listener, we only have to implement what to do upon a reset (`resetStatistics`) and upon an update (`updateStatistics`), and how to calculate the (internally stored) result (`calculateStatistics`); the base class takes care of registering at `SimQueue` and internally storing the times of the last reset (or the time at construction) and of the last update.
- In the concrete listener, we provide a method for access to the internally stored result, but that method automatically invokes the base class' `calculate ()` method first. The base class attempts to avoid unnecessary recalculations of the result in its subclass.
- Users of the concrete subclass have access to the methods `getStartTime` and `getLastUpdateTime` at all times. Upon calculation (without a time argument), the time of the last update determines the upper boundary of the measurement interval.
- Users may also invoke `calculate (double endTime)` which allows the extension of the measurement interval beyond the last update time. This, however, prevents subsequent update *before* the `endTime` provided, unless the object (or the queue, or the underlying event list) is reset. Nonetheless, the feature is handy because in many practical cases, one wants to take the time average over a fixed time interval, instead of a time interval of which the upper boundary is determined by the last update. Unfortunately, one cannot chose and `endTime` smaller than the last update time (at the expense of an exception thrown).
- Users can change the `SimQueue` from which the statistics are obtained through `setQueue (Q)`. Setting the queue will immediately reset the statistics object. As expected, the base class `AbstractSimQueueStat` takes care of registering at the new queue (if any) after unregistering at the old queue. The only sensible use for that feature that we can think of is delayed initialization.

## 9.3 The SimpleSimQueueStat Class

The `SimpleSimQueueStat` class implements `AbstractSimQueueStat` described in Section 9.2 for some important statistics on a `SimQueue`:

- The average number of jobs;

- The average number of jobs in the service area;
- The maximum and minimum number of jobs;
- The maximum and minimum number of jobs in the service area.

Attaching a `SimpleSimQueueStat` to a `SimQueue` is a very convenient way of obtaining a first impression of the performance of the queue; we have used it a lot ourselves during testing. Below in Listing 9.7 we illustrate its use for the example in Section 9.1.1; the output (still ambiguous!) is shown in Listing 9.8. Note that the number of updates is also available from `SimpleSimQueueStat`, which is very handy for detailed update-related debugging on `SimQueue` implementations.

Listing 9.7: Example program for obtaining basic statistics using `SimpleSimQueueStat`.

```
public static void main (final String[] args)
{
    final SimEventList el = new DefaultSimEventList ();
    el.reset (0);
    // Schedule 5 jobs, 0 through 4 at t = 0, 1, 2, 3, 4
    // and service times 0, 1, 2, 3, 4, respectively.
    //
    // Departure times with FCFS: 0, 2, 4, 7, 11.
    // cumJ = 0 + 1 + 1 + 2 + 2 + 2 + 2 + 1 + 1 + 1 + 1 = 14.
    // avgJ = 14 / 11 = 1.2727.
    //
    // WITH P_LCFS: AMBIGUITY!
    //
    // Departure times with P_LCFS [2 arrives after departure of 1]: 0, 2, 8, 10, 11.
    // cumJ = 0 + 1 + 1 + 2 + 3 + 3 + 3 + 3 + 2 + 2 + 1 = 21.
    // avgJ = 21 / 11 = 1.9090.
    //
    // Departure times with P_LCFS [2 arrives before departure of 1]: 0, 8, 10, 11, 11.
    // cumJ = 0 + 1 + 2 + 3 + 4 + 4 + 4 + 4 + 3 + 3 + 2 = 30.
    // avgJ = 30 / 11 = 2.7272.
    //
    final FCFS fcfs = new FCFS (el);
    final P_LCFS lcfs = new P_LCFS (el, null);
    for (int j = 0; j <= 4; j++)
    {
        fcfs.scheduleJobArrival (j, new DefaultSimJob (el, "JobF_" + j, j));
        lcfs.scheduleJobArrival (j, new DefaultSimJob (el, "JobL_" + j, j));
    }
    final SimpleSimQueueStat avgJStatListener_fcfs = new SimpleSimQueueStat (fcfs);
    final SimpleSimQueueStat avgJStatListener_lcfs = new SimpleSimQueueStat (lcfs);
    el.run ();
    System.out.println ("FCFS:");
    System.out.println ("__Start_time__: " + avgJStatListener_fcfs.getStartTime () + ".");
    System.out.println ("__End_Time__: " + avgJStatListener_fcfs.getLastUpdateTime () + ".");
    System.out.println ("__Number_of_updates__");
    System.out.println ("  + avgJStatListener_fcfs.getNumberOfUpdates () + ".");
    System.out.println ("__Average_number_of_jobs__");
    System.out.println ("  + avgJStatListener_fcfs.getAvgNrOfJobs () + ".");
    System.out.println ("__Average_number_of_jobs_in_service_area__");
    System.out.println ("  + avgJStatListener_fcfs.getAvgNrOfJobsInServiceArea () + ".");
    System.out.println ("__Maximum_number_of_jobs__");
    System.out.println ("  + avgJStatListener_fcfs.getMaxNrOfJobs () + ".");
    System.out.println ("P_LCFS:");
    System.out.println ("__Start_time__: " + avgJStatListener_lcfs.getStartTime () + ".");
    System.out.println ("__End_Time__: " + avgJStatListener_lcfs.getLastUpdateTime () + ".");
    System.out.println ("__Number_of_updates__");
    System.out.println ("  + avgJStatListener_fcfs.getNumberOfUpdates () + ".");
    System.out.println ("__Average_number_of_jobs__");
    System.out.println ("  + avgJStatListener_lcfs.getAvgNrOfJobs () + ".");
    System.out.println ("__Average_number_of_jobs_in_service_area__");
    System.out.println ("  + avgJStatListener_lcfs.getAvgNrOfJobsInServiceArea () + ".");
    System.out.println ("__Maximum_number_of_jobs__");
    System.out.println ("  + avgJStatListener_lcfs.getMaxNrOfJobs () + ".");
}
```

Listing 9.8: Output from the example program in Listing 9.7.

```

FCFS:
  Start time: 0.0.
  End Time   : 11.0.
  Number of updates           : 6.
  Average number of jobs      : 1.2727272727272727.
  Average number of jobs in service area: 0.9090909090909091.
  Maximum number of jobs      : 2.0.
P_LCFS:
  Start time: 0.0.
  End Time   : 11.0.
  Number of updates           : 6.
  Average number of jobs      : 1.9090909090909092 [OR 2.727272727272727, see comments].
  Average number of jobs in service area: 1.9090909090909092 [OR 2.727272727272727, see comments].
  Maximum number of jobs      : 3.0 [OR 4.0, see comments].

```

Note the remarkable difference in the average number of jobs in the service area between FCFS and P\_LCFS. In the former, jobs waiting are only admitted to the service area if the previously arrived job has departed, whereas in the latter, jobs are admitted immediately to the service area upon arrival (because their service starts immediately), and preempted jobs are *not* transferred back into the waiting area. This illustrates the (surprising) distinction between the number of jobs *in service* (a concept not directly supported by `SimQueue`) and the number of jobs *in the service area* (in which service is allowed, but not guaranteed).

## 9.4 The AutoSimQueueStat Class

### 9.4.1 Introduction

The `SimpleSimQueueStat` class described in Section 9.3 provides a convenient way of obtaining some important statistics related to the number of jobs at a queue or at its service area. Although it is fairly easy to extend `SimpleSimQueueStat`, or even `AbstractSimQueueStat` for that matter, for other time-dependent performance measures, we quickly realize that the resulting code would only differ in *which* statistic we take from the queue upon updates. The `AutoSimQueueStat` class introduced in this section honors this observation, and relies on a so-called `SimQueueProbe` to obtain the momentary value of a specific performance measure at a `SimQueue`. It then automatically maintains the average, maximum and minimum values for all registered probes.

### 9.4.2 The SimQueueProbe Interface

As described in the previous section, the `SimQueueProbe` interface features obtaining the momentary value of a specific performance measure at a queue (the queue is actually a parameter, so probes can be reused). Its interface definition is shown in

Listing 9.9. Note that only double values (or values that can be cast to double) are supported.

Listing 9.9: The SimQueueProbe interface.

```
public interface SimQueueProbe<Q extends SimQueue>
{
    public double get (Q queue);
}
```

### 9.4.3 The AutoSimQueueStatEntry Class

The `AutoSimQueueStatEntry` class connects a `SimQueueProbe` with a name, and adds statistics maintenance for the values the probe provides. Unfortunately, unlike a `SimQueueProbe`, you cannot reuse a `AutoSimQueueStatEntry` among different queues.

### 9.4.4 Example

Below in Listing 9.10 we illustrate the use of `AutoSimQueueStat` for the example in Section 9.1.1; the output (still ambiguous!) is shown in Listing 9.11. Note that two probes are created, one for the number of jobs at a queue, and one for the number of jobs in the service area at a queue. For each queue, FCFS and P\_LCFS, an array of entries is created, holding unique entries for the statistics required. Finally, note that `AutoSimQueueStat` features a method `report ()` (optionally, with an integer indentation parameter) for quickly reporting the calculated statistics for all registered probes.

Listing 9.10: Example program for obtaining statistics using `AutoSimQueueStat`.

```
public static void main (final String[] args)
{
    final SimEventList el = new DefaultSimEventList ();
    el.reset (0);
    // Schedule 5 jobs, 0 through 4 at t = 0, 1, 2, 3, 4
    // and service times 0, 1, 2, 3, 4, respectively.
    //
    // Departure times with FCFS: 0, 2, 4, 7, 11.
    // cumJ = 0 + 1 + 1 + 2 + 2 + 2 + 2 + 1 + 1 + 1 + 1 = 14.
    // avgJ = 14 / 11 = 1.2727.
    //
    // WITH P_LCFS: AMBIGUITY!
    //
    // Departure times with P_LCFS [2 arrives after departure of 1]: 0, 2, 8, 10, 11.
    // cumJ = 0 + 1 + 1 + 2 + 3 + 3 + 3 + 3 + 2 + 2 + 1 = 21.
    // avgJ = 21 / 11 = 1.9090.
    //
    // Departure times with P_LCFS [2 arrives before departure of 1]: 0, 8, 10, 11, 11.
    // cumJ = 0 + 1 + 2 + 3 + 4 + 4 + 4 + 4 + 3 + 3 + 2 = 30.
    // avgJ = 30 / 11 = 2.7272.
    //
    final FCFS fcfs = new FCFS (el);
    final P_LCFS lcfs = new P_LCFS (el, null);
}
```

```

for (int j = 0; j <= 4; j++)
{
    fcfs.scheduleJobArrival (j, new DefaultSimJob (el, "JobF_" + j, j));
    lcfs.scheduleJobArrival (j, new DefaultSimJob (el, "JobL_" + j, j));
}
final SimQueueProbe probeJ =
    (SimQueueProbe) (SimQueue queue) -> queue.getNumberOfJobs ();
final SimQueueProbe probeJX =
    (SimQueueProbe) (SimQueue queue) -> queue.getNumberOfJobsInServiceArea ();
final List<AutoSimQueueStatEntry> entries_fcfs = new ArrayList<> ();
final List<AutoSimQueueStatEntry> entries_lcfs = new ArrayList<> ();
entries_fcfs.add (new AutoSimQueueStatEntry ("J", probeJ));
entries_fcfs.add (new AutoSimQueueStatEntry ("JX", probeJX));
entries_lcfs.add (new AutoSimQueueStatEntry ("J", probeJ));
entries_lcfs.add (new AutoSimQueueStatEntry ("JX", probeJX));
final AutoSimQueueStat stat_fcfs = new AutoSimQueueStat (fcfs, entries_fcfs);
final AutoSimQueueStat stat_lcfs = new AutoSimQueueStat (lcfs, entries_lcfs);
el.run ();
System.out.println ("FCFS:");
stat_fcfs.report (2);
System.out.println ("P.LCFS:");
stat_lcfs.report (2);
}

```

Listing 9.11: Output from the example program in Listing 9.7.

```

FCFS:
Average J: 1.2727272727272727.
Minimum J: 0.0.
Maximum J: 2.0.
Average JX: 0.9090909090909091.
Minimum JX: 0.0.
Maximum JX: 1.0.
P.LCFS:
Average J: 1.9090909090909092 [OR 2.727272727272727, see comments].
Minimum J: 0.0.
Maximum J: 3.0 [OR 4.0, see comments].
Average JX: 1.9090909090909092 [OR 2.727272727272727, see comments].
Minimum JX: 0.0.
Maximum JX: 3.0 [OR 4.0, see comments].

```

## 9.5 The SimpleSimQueueVisitsStat Class

The `SimpleSimQueueVisitsStat` maintains and calculates some important visits-related statistics on the queue it is registered at:

- The number of arrivals, of jobs that started and the number of departures;
- The number of dropped and (successfully) revoked jobs;
- The average waiting time (averaged over jobs that started);
- The average sojourn time (averaged over jobs that departed);
- The maximum and minimum waiting time (averaged over jobs that started);
- The maximum and minimum sojourn time (averaged over jobs that departed).

In Listing 9.12 below we provide an example of its use, again using the scheduling example from *YYY*; its corresponding output is shown in Listing 9.13.

Listing 9.12: Example program for obtaining basic statistics using SimpleSimQueueVisitsStat.

```
public static void main (final String[] args)
{
    final SimEventList el = new DefaultSimEventList ();
    el.reset (0);
    // Schedule 5 jobs, 0 through 4 at t = 0, 1, 2, 3, 4
    // and service times 0, 1, 2, 3, 4, respectively.
    //
    // Departure times with FCFS: 0, 2, 4, 7, 11.
    // cumJ = 0 + 1 + 1 + 2 + 2 + 2 + 2 + 1 + 1 + 1 + 1 = 14.
    // avgJ = 14 / 11 = 1.2727.
    // avgWaitJ = 0 + 0 + 0 + 1 + 3 / 5 = 0.8.
    // avgSojJ = 0 + 1 + 2 + 4 + 7 / 5 = 14 / 5 = 2.8.
    //
    // WITH P_LCFS: AMBIGUITY!
    //
    // Departure times with P_LCFS [2 arrives after departure of 1]: 0, 2, 8, 10, 11.
    // cumJ = 0 + 1 + 1 + 2 + 3 + 3 + 3 + 3 + 2 + 2 + 1 = 21.
    // avgJ = 21 / 11 = 1.9090.
    // avgWaitJ = 0.
    // avgSojJ = 0 + 1 + 9 + 7 + 4 / 5 = 21 / 5 = 4.2.
    //
    // Departure times with P_LCFS [2 arrives before departure of 1]: 0, 8, 10, 11, 11.
    // cumJ = 0 + 1 + 2 + 3 + 4 + 4 + 4 + 4 + 3 + 3 + 2 = 30.
    // avgJ = 30 / 11 = 2.7272.
    // avgWaitJ = 0.
    // avgSojJ = 0 + 10 + 9 + 7 + 4 / 5 = 30 / 5 = 6.0.
    //
    final FCFS fcfs = new FCFS (el);
    final P_LCFS lcfs = new P_LCFS (el, null);
    for (int j = 0; j <= 4; j++)
    {
        fcfs.scheduleJobArrival (j, new DefaultSimJob (el, "JobF_" + j, j));
        lcfs.scheduleJobArrival (j, new DefaultSimJob (el, "JobL_" + j, j));
    }
    final SimpleSimQueueVisitsStat visitsStatListener_fcfs = new SimpleSimQueueVisitsStat (fcfs);
    final SimpleSimQueueVisitsStat visitsStatListener_lcfs = new SimpleSimQueueVisitsStat (lcfs);
    el.run ();
    System.out.println ("FCFS:");
    System.out.println ("__Start_Time_____:_" + ".");
    System.out.println ("__End_Time_____:_" + ".");
    System.out.println ("__Last_Update_Time_____:_" + ".");
    System.out.println ("__Number_of_Arrivals_____:_" + ".");
    System.out.println ("__Number_of_Started_Jobs_____:_" + ".");
    System.out.println ("__Number_of_Departures_____:_" + ".");
    System.out.println ("__Minimum_Waiting_Time_____:_" + ".");
    System.out.println ("__Maximum_Waiting_Time_____:_" + ".");
    System.out.println ("__Average_Waiting_Time_____:_" + ".");
    System.out.println ("__Minimum_Sojourn_Time_____:_" + ".");
    System.out.println ("__Maximum_Sojourn_Time_____:_" + ".");
    System.out.println ("__Average_Sojourn_Time_____:_" + ".");
    System.out.println ("P_LCFS:");
    System.out.println ("__Start_Time_____:_" + ".");
    System.out.println ("__End_Time_____:_" + ".");
    System.out.println ("__Last_Update_Time_____:_" + ".");
    System.out.println ("__Number_of_Arrivals_____:_" + ".");
    System.out.println ("__Number_of_Started_Jobs_____:_" + ".");
    System.out.println ("__Number_of_Departures_____:_" + ".");
}
```



```

    + visitsStatListener_lcfs.getNumberOfDepartures () + ".");
System.out.println ("__Minimum_Waiting_Time__:"
+ visitsStatListener_lcfs.getMinWaitingTime () + ".");
System.out.println ("__Maximum_Waiting_Time__:"
+ visitsStatListener_lcfs.getMaxWaitingTime () + ".");
System.out.println ("__Average_Waiting_Time__:"
+ visitsStatListener_lcfs.getAvgWaitingTime () + ".");
System.out.println ("__Minimum_Sojourn_Time__:"
+ visitsStatListener_lcfs.getMinSojournTime () + ".");
System.out.println ("__Maximum_Sojourn_Time__:"
+ visitsStatListener_lcfs.getMaxSojournTime () + ".");
System.out.println ("__Average_Sojourn_Time__:"
+ visitsStatListener_lcfs.getAvgSojournTime () + ".");
}

```

Listing 9.13: Output from the example program in Listing 9.12.

```

FCFS:
Start Time          : 0.0.
End Time            : 11.0.
Number of Arrivals  : 5.
Number of Started Jobs: 5.
Number of Departures : 5.
Minimum Waiting Time : 0.0.
Maximum Waiting Time : 3.0.
Average Waiting Time : 0.8.
Minimum Sojourn Time : 0.0.
Maximum Sojourn Time : 7.0.
Average Sojourn Time : 2.8.
P.LCFS:
Start Time          : 0.0.
End Time            : 11.0.
Number of Arrivals  : 5.
Number of Started Jobs: 5.
Number of Departures : 5.
Minimum Waiting Time : 0.0.
Maximum Waiting Time : 0.0.
Average Waiting Time : 0.0.
Minimum Sojourn Time : 0.0.
Maximum Sojourn Time : 9.0. [OR 10.0, see comments].
Average Sojourn Time : 4.2. [OR 6.0, see comments].

```

## 9.6 Conclusions



# Chapter 10

## Visualization



# Chapter 11

## Building Custom Queues and Jobs

### 11.1 Introduction

### 11.2 The AbstractSimEntity Class

### 11.3 The AbstractSimQueue Class

### 11.4 The AbstractSimQueueComposite Class

### 11.5 The AbstractSimJob and DefaultSimJob Classes

### 11.6 Building Custom Listeners



# Chapter 12

## Use Cases

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12.2 Busy/Idle Notifications and Statistics

12.3 A Weird Statistic: The Fraction of Stayers

12.4 The M/M/1/FCFS Queue

12.5 Customers with Varying Impatience

12.6 Customers in a Party

12.7 Waiters with Varying Enthusiasm

12.8 A (Dutch) Restaurant and Its Performance







# Chapter 13

## Testing

### 13.1 Introduction

### 13.2 Test Infrastructure

### 13.3 Generating Workloads

#### 13.3.1 Job Factories

#### 13.3.2 Queue Workloads

#### 13.3.3 Queue Events and Schedules

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Standardized Workload Patterns

### 13.4 Queue Predictors

### 13.5 Confronting Queue Workloads, Predictors, and Queues

### 13.6 Building a Predictor

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## Chapter 14

## Conclusions