# Advanced Features of the SimPy Language

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1 Overview

In this document we present several advanced features of the SimPy language. These will make your SimPy programming more convenient and enjoyable. In small programs, use of some of these features will produce a modest but worthwhile reduction on programming effort and increase in program clarity. In large programs, the savings add up, and can make a very significant improvement.

2 Use of SimPy’s cancel() Function

In many simulation programs, a thread is waiting for one of two events; whichever occurs first will trigger a resumption of execution of the thread. The thread will typically want to ignore the other, later-occurring event. We can use SimPy’s cancel() function to cancel the later event.

2.1 Example: Network Timeout

An example of this is in the program TimeOut.py. The model consists of a network node which transmits but also sets a timeout period, as follows: After sending the message out onto the network, the node waits for an acknowledgement from the recipient. If an acknowledgement does not arrive within a certain specified period of time, it is assumed that the message was lost, and it will be sent again. We wish to determine the percentage of attempted transmissions which result in timeouts.

The timeout period is assumed to be 0.5, and acknowledgement time is assumed to be exponentially distributed with mean 1.0. Here is the code:

```python
#!/usr/bin/env python

from SimPy.Simulation import *
from random import Random,expovariate

# Introductory SimPy example to illustrate the modeling of "competing events" such as timeouts, especially using SimPy's cancel() method. A network node sends a message but also sets a timeout period; if the node times out, it assumes the message it had sent was lost, and it will send again. The time to get an acknowledgement for a message is exponentially distributed with mean 1.0, and the timeout period is 0.5. Immediately after receiving an acknowledgement, the node sends out a new message.

# We find the proportion of messages which timeout. The output should be about 0.61.

# the main classes are:

# Node, simulating the network node, with our instance being Nd
# TimeOut, simulating a timeout timer, with our instance being TO
# Acknowledge, simulating an acknowledgement, with our instance being ACK

# overview of program design:

# Nd acts as the main "driver," with a loop that continually creates TimeOuts and Acknowledge objects, passivating itself until one of those objects' events occurs; if for example the timeout occurs before the acknowledge, the TO object will reactivate Nd and cancel the ACK object's event, and vice versa

# from SimPy.Simulation import *
from random import Random,expovariate
```

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2
The main driver here is a class Node, whose PEM code includes the lines

```python
class Node(Process):
    def __init__(self):
        Process.__init__(self)
        self.NMsgs = 0  # number of messages sent
        self.NTimeOuts = 0  # number of timeouts which have occurred
        # ReactivatedCode will be 1 if timeout occurred, 2 ACK if received
        self.ReactivatedCode = None
    def Run(self):
        while 1:
            self.NMsgs += 1
            # set up the timeout
            G.TO = TimeOut()
            activate(G.TO, G.TO.Run())
            # set up message send/ACK
            G.ACK = Acknowledge()
            activate(G.ACK, G.ACK.Run())
            yield passivate, self
            if self.ReactivatedCode == 1:
                self.NTimeOuts += 1
                self.ReactivatedCode = None

class TimeOut(Process):
    TOPeriod = 0.5
    def __init__(self):
        Process.__init__(self)
    def Run(self):
        yield hold, self, TimeOut.TOPeriod
        G.Nd.ReactivatedCode = 1
        reactivate(G.Nd)
        self.cancel(G.ACK)

class Acknowledge(Process):
    ACKRate = 1/1.0
    def __init__(self):
        Process.__init__(self)
    def Run(self):
        yield hold, self, G.Rnd.expovariate(Acknowledge.ACKRate)
        G.Nd.ReactivatedCode = 2
        reactivate(G.Nd)
        self.cancel(G.TO)

class G:  # globals
    Rnd = Random(12345)
    Nd = Node()

def main():
    initialize()
    activate(G.Nd, G.Nd.Run())
    simulate(until=10000.0)
    print 'the percentage of timeouts was', float(G.Nd.NTimeOuts)/G.Nd.NMsgs
if __name__ == '__main__': main()
```

while 1:
    self.NMsgs += 1
    G.TO = TimeOut()
    activate(G.TO, G.TO.Run())
    G.ACK = Acknowledge()
    activate(G.ACK, G.ACK.Run())
    yield passivate, self
    if self.ReactivatedCode == 1:
        self.NTimeOuts += 1
        self.ReactivatedCode = None
The node creates an object $\text{G.TO}$ of our \texttt{TimeOut} class, which will simulate a timeout period, and creates an object $\text{G.ACK}$ of our \texttt{Acknowledge} class to simulate a transmission and acknowledgement. Then the node passivates itself, allowing $\text{G.TO}$ and $\text{G.ACK}$ to do their work. One of them will finish first, and then will call SimPy’s \texttt{reactivate()} function to “wake up” the suspended node. The node senses whether it was a timeout or acknowledgement which woke it up, via the variable \texttt{ReactivatedCode}, and then updates its timeout count accordingly.

Here’s what \texttt{TimeOut.Run()} does:

```python
yield hold, self, TimeOut.TOPeriod
G.Nd.ReactivatedCode = 1
reactivate(G.Nd)
sel.cancel(G.ACK)
```

It holds a random timeout time, then sets a flag in $\text{Nd}$ to let the latter know that it was the timeout which occurred first, rather than the acknowledgement. Then it reactivates $\text{Nd}$ and cancels $\text{ACK}$. $\text{ACK}$ of course has similar code for handling the case in which the acknowledgement occurs before the timeout.

Note that in our case here, we want the thread to go out of existence when canceled. The \texttt{cancel()} function does not make that occur. It simply removes the pending events associated with the given thread. The thread is still there.

However, here the $\text{TO}$ and $\text{ACK}$ threads will go out of existence anyway, for a somewhat subtle reason\cite{1}. Think of what happens when we finish one iteration of the while loop in \texttt{main()}. A new object of type \texttt{TimeOut} will be created, and then assigned to $\text{G.TO}$. That means that the $\text{G.TO}$ no longer points to the old $\text{TimeOut}$ object, and since nothing else points to it either, the Python interpreter will now garbage collect that old object.

### 2.2 Example: Machine with Breakdown

Here is another example of \texttt{cancel()}:

```python
#!/usr/bin/env python
# JobBreak.py

# One machine, which sometimes breaks down. Up time and repair time are
# exponentially distributed. There is a continuing supply of jobs
# waiting to use the machine, i.e. when one job finishes, another
# immediately begins. When a job is interrupted by a breakdown, it
# resumes "where it left off" upon repair, with whatever time remaining
# that it had before.

from SimPy.Simulation import *
from random import Random, expovariate
import sys

class G:  # globals
    CurrentJob = None
    Rnd = Random(12345)
    M = None  # our one machine

class Machine(Process):
    Thanks to Travis Grathwell for pointing this out.
```
Here we have one machine, with occasional breakdown, but we also keep track of the number of jobs done. See the comments in the code for details.

Here we have set up a class `Job`. When a new job starts service, an instance of this class is set up to model that job. If its service then runs to completion without interruption, fine. But if the machine breaks down in the midst of service, this instance of the `Job` class will be discarded, and a new instance will later be created when this job resumes service after the repair. In other words, each object of the class `Job` models one job
to be done, but it can be either a brand new job or the resumption of an interrupted job.

Let’s take a look at Job.Run():

```python
1 yield hold, self, self.TimeLeft
2 Job.NDone += 1
3 Job.TotWait += now() - self.OrigStart
4 if self.NInts == 0: Job.NNoInts += 1
5 SrvTm = G.Rnd.expovariate(Job.ServiceRate)
6 G.CurrentJob = Job(G.CurrentJob.ID+1, SrvTm, 0, now(), now())
7 activate(G.CurrentJob, G.CurrentJob.Run())
```

This looks innocuous enough. We hold for the time it takes to finish the job, then update our totals, and launch the next job. What is not apparent, though, is that we may actually never reach that second line, Job.NDone += 1

The reason for this is that the machine may break down before the job finishes. In that case, what we have set up is that Machine.Run() will cancel the pending job completion event,

```python
self.cancel(CJ)
```

simulate the repair of the machine,

```python
RepairTime = G.Rnd.expovariate(Machine.RepairRate)
yield hold, self, RepairTime
```

and then create a new instance of Job which will simulate the processing of the remainder of the interrupted job (which may get interrupted too):

```python
NewNInts = CJ.NInts + 1
NewTimeLeft = CJ.TimeLeft - (now()-CJ.LatestStart)
... G.CurrentJob = Job(CJ.ID, NewTimeLeft, NewNInts, CJ.OrigStart, now()) activate(G.CurrentJob, G.CurrentJob.Run())
```

There are other ways of doing this, in particular by using SimPy’s `interrupt()` and `interrupted()` functions, but we defer this to Section 3.

2.3 Example: Cell Phone Network

```bash
# simulates one cell in a cellular phone network; here all calls are
# local, no handoffs; calls last a random time; if a channel is not
# available when a new call arrives, the oldest one is pre-empted
# usage:
python Cell2.py ArrRate DurRate NChnls MaxSimTime
# where:
# ArrRate = rate of arrivals of calls (reciprocal of mean time
```
import sys, random

from SimPy.Simulation import *
from PeriodicSampler import *

class Globals:
    Rnd = random.Random(12345)
    Debug = False

class Cell:
    NChnls = None
    NFreeChannels = None

class CellMonClass:  # to set up PeriodicSampler
    def __init__(self):
        self.ChnlMon = Monitor()
    def RecordNBusyChnls(self):
        return Cell.NChnls - Cell.NFreeChannels

class Call(Process):
    DurRate = None  # reciprocal of mean call duration
    NArrv = 0  # number of calls arrived so far
    NPre_empted = 0  # number of calls pre-empted so far
    NextID = 0  # for debugging
    CurrentCalls = []  # pointers to the currently-active calls
    ChnlMon = Monitor()  # to monitor number of busy channels
    FracMon = Monitor()  # to monitor pre-emption fractions
    
    def __init__(self):
        Process.__init__(self)
        self.ID = Call.NextID
        Call.NextID += 1
        self.MyStartTime = now()
        self.MyFinishTime = None

    def Run(self):  # simulates one call
        Call.NArrv += 1
        CallTime =Globals.Rnd.expovariate(Call.DurRate)
        self.MyFinishTime = now() + CallTime
        if Globals.Debug: self.ShowStatus()
        Call.CurrentCalls.append(self)
        if Cell.NFreeChannels == 0:  # no channels available
            Oldest = Call.CurrentCalls.pop(0)
            self.cancel(Oldest)
            Cell.NFreeChannels += 1  # one channel freed
            FullCallLength = Oldest.MyFinishTime - Oldest.MyStartTime
            AmountPre_empted = Oldest.MyFinishTime - now()
            Call.FracMon.observe(AmountPre_empted/FullCallLength)
            del Oldest
            Cell.NFreeChannels -= 1  # grab the channel
            Cell.ChnlMon.observe(Cell.NChnls-Cell.NFreeChannels)
            yield hold,self,CallTime
            Cell.NFreeChannels += 1  # release the channel
            Cell.ChnlMon.observe(Cell.NChnls-Cell.NFreeChannels)
            if Call.CurrentCalls != []:
                Call.CurrentCalls.remove(self)
            return  # not needed, but enables a breakpoint here

    def ShowStatus(self):  # for debugging and program verification
        print
        print 'time', now()
        print Cell.NFreeChannels, 'free channels'
        print 'ID',self.ID,'finish time is',self.MyFinishTime
        print 'current calls:'
        for CurrCall in Call.CurrentCalls:
class Arrivals(Process):
    ArrRate = None
    NextArrival = None  # for debugging and program verification
    def __init__(self):
        Process.__init__(self)
    def Run(self):
        while 1:
            TimeToNextArrival = Globals.Rnd.expovariate(Arrivals.ArrRate)
            Arrivals.NextArrival = now() + TimeToNextArrival
            yield hold, self, TimeToNextArrival
            C = Call()
            activate(C, C.Run())

def main():
    if 'debug' in sys.argv: Globals.Debug = True
    Arrivals.ArrRate = float(sys.argv[1])
    Call.DurRate = float(sys.argv[2])
    Cell.NChnls = int(sys.argv[3])
    Cell.NFreeChannels = Cell.NChnls
    initialize()
    Arr = Arrivals()
    activate(Arr, Arr.Run())
    CMC = CellMonClass()
    CMC.PrSm = PerSmp(0.1, CMC.ChnlMon, CMC.RecordNBsryChnls)
    activate(CMC.PrSm, CMC.PrSm.Run())
    MaxSimtime = float(sys.argv[4])
    simulate(until=MaxSimtime)
    print 'fraction of pre-empted calls:', Call.NPre_empted/float(Call.NArrv)
    print 'average fraction cut among pre-empted:', Call.FracMon.mean()
    print 'mean number of active channels, Method I:', Call.ChnlMon.timeAverage()
    print 'mean number of active channels, Method II:', CMC.ChnlMon.mean()

if __name__ == '__main__': main()

3 Job Interruption

SimPy allows one thread to interrupt another, which can be very useful.

3.1 Example: Machine Breakdown Again

In Section 2.2 we had a program JobBreak.py, which modeled a machine with breakdown on which we collected job time data. We presented that program as an example of cancel(). However, it is much more easily handled via the function interrupt(). Here is a new version of the program using that function:
import sys

class G:
    CurrentJob = None
    Rnd = Random(12345)
    M = None  # our one machine

class Machine(Process):
    def __init__(self):
        Process.__init__(self)
    def Run(self):
        from SimPy.Simulation import _e
        while 1:
            UpTime = G.Rnd.expovariate(Machine.UpRate)
            yield hold, self, UpTime
            self.interrupt(G.CurrentJob)
            RepairTime = G.Rnd.expovariate(Machine.RepairRate)
            yield hold, self, RepairTime
            reactivate(G.CurrentJob)

class Job(Process):
    ServiceRate = None
    NDone = 0  # jobs done so far
    TotWait = 0.0  # total wait for those jobs
    NNoInts = 0  # jobs done so far that had no interruptions
    NextID = 0
    def __init__(self):
        Process.__init__(self)
        self.ID = Job.NextID
        Job.NextID += 1
        # amount of work left for this job
        self.TimeLeft = G.Rnd.expovariate(Job.ServiceRate)
        self.NInts = 0  # number of interruptions so far
        # time this job originally started
        self.OrigStart = now()
        # time the latest work period began for this job
        self.LatestStart = now()
    def Run(self):
        from SimPy.Simulation import _e
        while True:
            yield hold, self, self.TimeLeft
            # did the job run to completion?
            if not self.interrupted(): break
            self.NInts += 1
            self.TimeLeft -= now() - self.LatestStart
            yield passivate, self  # wait for repair
            self.LatestStart = now()
            Job.NDone += 1
            Job.TotWait += now() - self.OrigStart
            if self.NInts == 0: Job.NNoInts += 1
            # start the next job
            G.CurrentJob = Job()
            activate(G.CurrentJob, G.CurrentJob.Run())

def main():
    Job.ServiceRate = float(sys.argv[1])
    Machine.UpRate = float(sys.argv[2])
    Machine.RepairRate = float(sys.argv[3])
    initialize()
    G.CurrentJob = Job()
    activate(G.CurrentJob, G.CurrentJob.Run())
    G.M = Machine()
    activate(G.M, G.M.Run())
    MaxSimtime = float(sys.argv[4])
    simulate(until=MaxSimtime)
    print 'mean wait:', Job.TotWait/Job.NDone
    print '% of jobs with no interruptions:', \

float(Job.NNoInts)/Job.NDone
if __name__ == '__main__': main()

The first key part of Machine.Run() is

yield hold, self, UpTime
self.interrupt(G.CurrentJob)

A call to interrupt() cancels the pending yield hold operation of its “victim,” i.e. the thread designated in the argument. A new artificial event will be created for the victim, with event time being the current simulated time, now(). The caller does not lose control of the CPU, and continues to execute, but when it hits its next yield statement (or passivate() etc.) and thus loses control of the CPU, the victim will probably be next to run, as its (new, artificial) event time will be the current time.

In our case here, at the time

self.interrupt(G.CurrentJob)

is executed by the Machine thread, the current job is in the midst of being serviced. The call interrupts that service, to reflect the fact that the machine has broken down. At this point, the current job’s event is canceled, with the artificial event being created as above. The current job’s thread won’t run yet, and the Machine thread will continue. But when the latter reaches the line

yield hold, self, RepairTime

the Machine thread loses control of the CPU and the current job’s thread runs. The latter executes

if not self.interrupted(): break
self.NInts += 1
self.TimeLeft -= now() - self.LatestStart
yield passivate, self # wait for repair

The interruption will be sensed by self.interrupted() returning True. The job thread will then do the proper bookkeeping, and then passivate itself, waiting for the machine to come back up. When the latter event occurs, the machine’s thread executes

reactivate(G.CurrentJob)

to get the interrupted job started again.

Note that a job may go through multiple cycles of run, interruption, run, interruption, etc., depending on how many breakdowns the machine has during the lifetime of this job. This is the reason for the while loop in Job.Run():

\[2\] The function interrupt() should not be called unless the thread to be interrupted is in the midst of yield hold.
while True:
    yield hold, self, self.TimeLeft
    # did the job run to completion?
    if not self.interrupted(): break
    self.NInts += 1
    self.TimeLeft -= now() - self.LatestStart
    yield passivate, self  # wait for repair
    self.LatestStart = now()
    Job.NDone += 1
    Job.TotWait += now() - self.OrigStart
...

In the job’s final cycle (which could be its first), the yield hold will not be interrupted. In this case the call to interrupted() will inform the thread that it had not been interrupted. The loop will be exited, the final bookkeeping for this job will be done, and the next job will be started.

By the way, we did not have to have our instance variable TimeLeft in Job. SimPy’s Process class has its own built-in instance variable interruptLeft which records how much time in the yield hold had been remaining at the time of the interruption.

### 3.2 Example: Network Timeout Again

Use of interrupts makes our old network node acknowledgement/timeout program TimeOut.py in Section 2.1 considerably simpler:

```python
#!usr/bin/env python

# TimeOutInt.py

# Same as TimeOut.py but using interrupts. A network node sends a message
# but also sets a timeout period; if the node times out, it assumes the
# message it had sent was lost, and it will send again. The time to get
# an acknowledgement for a message is exponentially distributed with
# mean 1.0, and the timeout period is 0.5. Immediately after receiving
# an acknowledgement, the node sends out a new message.
#
# We find the proportion of messages which timeout. The output should
# be about 0.61.

from SimPy.Simulation import *
from random import Random, expovariate

class Node(Process):
    def __init__(self):
        Process.__init__(self)
        self.NMsgs = 0  # number of messages sent
        self.NTimeOuts = 0  # number of timeouts which have occurred

    def Run(self):
        from SimPy.Simulation import _e
        while 1:
            self.NMsgs += 1
            # set up the timeout
            G.TO = TimeOut()
            activate(G.TO, G.TO.Run())
            # wait for ACK, but could be timeout
            yield hold, self, G.Rnd.expovariate(1.0)
            if self.interrupted():
                self.NTimeOuts += 1
            else:
                self.cancel(G.TO)

class TimeOut(Process):
```

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Use of interrupts allowed us to entirely eliminate our old **ACK** class. Moreover, the code looks more natural now, as a timeout could be thought of as “interrupting” the node.

## 4 Interthread Synchronization

In our introductory SimPy document, in cases in which one thread needed to wait for some other thread to take some action\(^3\) we made use of `passivate()` and `reactivate()`. Those can be used in general, but more advanced constructs would make our lives easier.

For example, suppose many threads are waiting for the same action to occur. The thread which triggered that action would then have to call `reactivate()` on all of them. Among other things, this would mean we would have to have code which kept track of which threads were waiting. We could do that, but it would be nicer if we didn’t have to.

In fact, actions like `yield waitevent` alleviate us of that burden. This makes our code easier to write and maintain, and easier to read.

### 4.1 Example: Yet Another Machine Breakdown Model

Below is an example, again modeling a machine repair situation. It is similar to `MachRep3.py` from our introductory document, but with R machines instead of two, and a policy that the repairperson is called if the number of operating machines falls below K.

\(^3\)I’ve used the word *action* here rather than *event*, as the latter term refers to items in SimPy’s internal event list, generated by `yield hold` operations. But this won’t completely remove the confusion, as the SimPy keyword *waitevent* will be introduced below. But again, that term will refer to what I’m describing as *actions* here. The official SimPy term is a *SimEvent*. 

---

```python
TOPeriod = 0.5

def __init__(self):
    Process.__init__(self)

def Run(self):
    from SimPy.Simulation import _e
    yield hold, self, TimeOut.TOPeriod
    self.interrupt(G.Nd)

class G: # globals
    Rnd = Random(12345)
    Nd = Node()

def main():
    initialize()
    activate(G.Nd, G.Nd.Run())
    simulate(until=10000.0)
    print 'the percentage of timeouts was', float(G.Nd.NTimeOuts)/G.Nd.NMsgs

if __name__ == '__main__': main()
```
# summoned when fewer than K of the machines are up, and reaches the
# site after a negligible amount of time. He keeps repairing machines
# until there are none that need it, then leaves.
# usage: python MachRep4.py R UpRate RepairRate K MaxSimTime

from SimPy.Simulation import *
from random import Random,expovariate

class G: # globals
    Rnd = Random(12345)
    RepairPerson = Resource(1)
    RepairPersonOnSite = False
    RPArrive = SimEvent()

class MachineClass(Process):
    MachineList = [] # list of all objects of this class
    UpRate = None # reciprocal of mean up time
    RepairRate = None # reciprocal of mean repair time
    R = None # number of machines
    K = None # threshold for summoning the repairperson
    TotalUpTime = 0.0 # total up time for all machines
    NextID = 0 # next available ID number for MachineClass objects
    NUp = 0 # number of machines currently up
    # create an event to signal arrival of repairperson
    def __init__(self):
        Process.__init__(self)
        self.StartUpTime = None # time the current up period started
        self.ID = MachineClass.NextID # ID for this MachineClass object
        MachineClass.NextID += 1
        MachineClass.MachineList.append(self)
        MachineClass.NUp += 1 # start in up mode
        def Run(self):
            from SimPy.Simulation import _e
            while 1:
                self.StartUpTime = now()
                yield hold,self,G.Rnd.expovariate(MachineClass.UpRate)
                MachineClass.TotalUpTime += now() - self.StartUpTime
                MachineClass.NUp -= 1
                # if the repairperson is already onsite, just request him;
                # otherwise, check whether fewer than K machines are up
                if not G.RepairPersonOnSite:
                    if MachineClass.NUp < MachineClass.K:
                        G.RPArrive.signal()
                        G.RepairPersonOnSite = True
                    else:
                        yield waitevent,self,G.RPArrive
                        yield request,self,G.RepairPerson
                        yield hold,self,G.Rnd.expovariate(MachineClass.RepairRate)
                        MachineClass.NUp += 1
                        # if no more machines waiting for repair, dismiss repairperson
                        if G.RepairPerson.waitQ == []:
                            G.RepairPersonOnSite = False
                            yield release,self,G.RepairPerson

    def main():
        initialize()
        MachineClass.R = int(sys.argv[1])
        MachineClass.UpRate = float(sys.argv[2])
        MachineClass.RepairRate = float(sys.argv[3])
        MachineClass.K = int(sys.argv[4])
        for I in range(MachineClass.R):
            M = MachineClass()
            activate(M,M.Run())
        MaxSimtime = float(sys.argv[5])
        simulate(until=MaxSimtime)
        print 'proportion of up time was',
            MachineClass.TotalUpTime/(MachineClass.R*MaxSimtime)
Here we make use of a new SimPy class, SimEvent:

```python
RepairPersonOnSite = False
RPArrive = SimEvent()
```

We also set up a variable `RepairPersonOnSite` to keep track of whether the repairperson is currently available; more on this point below.

Here is the core code, executed when a machine goes down:

```python
MachineClass.NUp -= 1
if not G.RepairPersonOnSite:
    if MachineClass.NUp < MachineClass.K:
        G.RPArrive.signal()
        G.RepairPersonOnSite = True
    else:
        yield waitevent, self, G.RPArrive
        yield request, self, G.RepairPerson
```

If the repairperson is on site already, then we go straight to the `yield request` to queue up for repair. If the repairperson is not on site, and the number of working machines has not yet dropped below K, our machine executes `yield waitevent` on our action `G.RPArrive`, which basically passivates this thread. If on the other hand our machine’s failure does make the number of working machines drop below K, we execute the `signal()` function, which reactivates all the machines which had been waiting.

Again, all of that could have been done via explicit `passivate()` and `reactivate()` calls, but it’s much more convenient to let SimPy do that work for us, behind the scenes.

One of the member variables of `SimEvent` is `occurred`, which of course is a boolean variable stating whether the action has occurred yet. Note that as soon as a wait for an event finishes, this variable reverts to False. This is why we needed a separate variable above, `G.RepairPersonOnSite`.

### 4.2 Which Comes First?

In general thread terminology, we say that we **post** a signal when we call `signal()`. One of the issues to resolve when you learn any thread system concerns what happens when a signal is posted before any waits for it are executed. In many thread systems, that posting will be completely ignored, and subsequent waits will thus last forever, or at least until another signal is posted. This obviously can cause bugs and makes programming more difficult.

In SimPy it’s the opposite: If a signal is posted first, before any waits are started, the next wait will return immediately. That was not an issue in this program, but it’s important to keep in mind in general.

### 4.3 Waiting for Whichever Action Comes First

You can also use `yield waitevent` to wait for several actions, producing a “whichever comes first” operation. To do this, instead of using the form

```python
yield waitevent, self, action_name
```
use

yield wait_event, self, tuple_or_list_of_action_names

Then whenever a signal is invoked on any one of the specified actions, all waits queued will be reactivated.

### 4.4 The yield queue-event Operation

This works just like `yield wait_event`, but when the signal is invoked, only the action at the head of the queue will be reactivated.

### 4.5 Example: Carwash

```python
# simulates a carwash; cars queue up at the entrance; each car chooses
# one of two grades of wash, MostlyClean (1.0 unit of time) and Gleaming
# (2.0 units of time); there is only one bay in the carwash, so only one
# is served at a time; at the exit there is a buffer space where cars
# wait to go out onto the street; cross traffic does not stop, so a car
# must wait for a large enough gap in the traffic in order to move out
# onto the street

# usage:

python CarWash.py ArrRate PropMostlyClean BufSize CrossRate ExitTime MaxSimTime

# where:

ArrRate = rate of arrivals of calls to carwash (reciprocal of mean
time between arrivals)
PropMostlyClean = proportion of cars that opt for the MostlyClean wash
BufSize = number of cars that can fit in the exit buffer
CrossRate = rate of arrivals of cars on the street passing the carwash
ExitTime = time needed for one car to get out onto the street
MaxSimtime = amount of time to simulate

# basic strategy of the simulation: model the carwash itself as a
# Resource, and do the same for the buffer and the front spot in the
# buffer; when a car acquires the latter, it watches for a gap big
# enough to enter the street

import sys, random

from SimPy.Simulation import *
from PeriodicSampler import *

class Globals:
    Rnd = random.Random(12345)
    Debug = False

class Street(Process):
    CrossRate = None
    ExitTime = None
    NextArrival = None  # time of next street arrival
    CrossArrive = SimEvent()
    def Run(self):
        while 1:
            TimeToNextArrival = Globals.Rnd.expovariate(Street.CrossRate)
            Street.NextArrival = now() + TimeToNextArrival
            Street.CrossArrive.signal()  # tells car at front of buffer to
            # check new TimeToNextArrival
            yield hold, self, TimeToNextArrival
            if Globals.Debug:
```
print 'time', now()
print 'street arrival'

class Car(Process):
    NextID = 0 # for debugging
    PropMostlyClean = None
    CurrentCars = [] # for debugging and code verification
    TotalWait = 0.0 # total wait times of all cars, from arrival to
    # carwash to exit onto the street
    TotalBufTime = 0.0 # total time in buffer for all cars
    NStuckInBay = 0 # number of cars stuck in bay when wash done, due to
    # full buffer
    AllDone = 0 # number of cars that have gotten onto the street
    def __init__(self):
        Process.__init__(self)
        self.ID = Car.NextID
        Car.NextID += 1
        self.ArrTime = None # time this car arrived at carwash
        self.WashDoneTime = None # time this car will finish its wash
        self.LeaveTime = None # time this car will exit
        self.StartBufTime = None # start of period in buffer
        Car.CurrentCars.append(self)
        self.ArrTime = now()
        if Globals.Debug: ShowStatus('carwash arrival')
        yield request, self, CarWash.Bay
        self.State = 'in bay'
        if Globals.Rnd.uniform(0,1) < Car.PropMostlyClean: WashTime = 1.0
        else: WashTime = 2.0
        self.WashDoneTime = now() + WashTime
        if Globals.Debug: ShowStatus('start wash')
        yield hold, self, WashTime
        self.WashDoneTime = None
        if Globals.Debug: ShowStatus('wash done')
        yield request, self, CarWash.Buf
        self.StartBufTime = now()
        yield release, self, CarWash.Bay
        self.State = 'in buffer'
        if Globals.Debug: ShowStatus('got into buffer')
        yield request, self, CarWash.BufFront
        while True:
            PossibleLeaveTime = now() + Street.ExitTime
            if Street.NextArrival >= PossibleLeaveTime:
                self.State = 'on the way out'
                self.LeaveTime = PossibleLeaveTime
                if Globals.Debug: ShowStatus('leaving')
                yield hold, self, Street.ExitTime
                Car.CurrentCars.remove(self)
                self.LeaveTime = None
                Car.TotalWait += now() - self.ArrTime
                Car.TotalBufTime += now() - self.StartBufTime
                if Globals.Debug: ShowStatus('gone')
                Car.AllDone += 1
                yield release, self, CarWash.BufFront
                yield release, self, CarWash.Buf
                return
            if Street.NextArrival >= PossibleLeaveTime:
                self.State = 'on the way out'
                self.LeaveTime = PossibleLeaveTime
                if Globals.Debug: ShowStatus('leaving')
                yield hold, self, Street.ExitTime
                Car.CurrentCars.remove(self)
                self.LeaveTime = None
                Car.TotalWait += now() - self.ArrTime
                Car.TotalBufTime += now() - self.StartBufTime
                if Globals.Debug: ShowStatus('gone')
                Car.AllDone += 1
                yield release, self, CarWash.BufFront
                yield release, self, CarWash.Buf
                return
            yield waitevent, self, Street.CrossArrive

class CarWash(Process):
    ArrRate = None
    BufSize = None
Buf = None  # will be Resource(BufSize) instance representing buffer
BufFront = Resource(1)  # front buffer slot, by the street
NextArrival = None  # time of next carwash arrival (for debugging/code verification)
Bay = Resource(1)  # the carwash
def __init__(self):
    Process.__init__(self)
def Run(self):  # arrivals
    while 1:
        TimeToNextArrival = Globals.Rnd.expovariate(CarWash.ArrRate)
        CarWash.NextArrival = now() + TimeToNextArrival
        yield hold, self, TimeToNextArrival
        C = Car()
        activate(C, C.Run())

class BufMonClass(Process):  # to enable use of PeriodicSampler
    def __init__(self):
        Process.__init__(self)
        self.BufMon = Monitor()
    def RecordNInBuf(self):
        return CarWash.BufSize - CarWash.Buf.n
    def ShowStatus(msg):  # for debugging and code verification
        print
        print 'time', now()
        print msg
        print 'current cars:'
        for C in Car.CurrentCars:
            print ' ', C.ID, C.State,
            if C.WashDoneTime != None:
                print 'wash will be done at', C.WashDoneTime
            elif C.LeaveTime != None:
                print 'gone at', C.LeaveTime
            else: print
        print 'next carwash arrival at', CarWash.NextArrival
        print 'next street arrival at', Street.NextArrival

def main():
    if 'debug' in sys.argv: Globals.Debug = True
    CarWash.ArrRate = float(sys.argv[1])
    Car.PropMostlyClean = float(sys.argv[2])
    CarWash.BufSize = int(sys.argv[3])
    CarWash.Buf = Resource(CarWash.BufSize)
    Street.CrossRate = float(sys.argv[4])
    Street.ExitTime = float(sys.argv[5])
    initialize()
    CWArr = CarWash()
    activate(CWArr, CWArr.Run())
    StArr = Street()
    activate(StArr, StArr.Run())
    MaxSimtime = float(sys.argv[6])
    BMC = BufMonClass()
    BMC.PrSmp = PerSmp(0.1, BMC.BufMon, BMC.RecordNInBuf)
    activate(BMC.PrSmp, BMC.PrSmp.Run())
simulate(until=MaxSimtime)
    print 'number of cars getting onto the street', Car.AllDone
    print 'mean total wait:', Car.TotalWait / Car.AllDone
    MeanWaitInBuffer = Car.TotalBufTime / Car.AllDone
    print 'mean wait in buffer:', MeanWaitInBuffer
    print 'proportion of cars blocked from exiting bay:', float(Car.NStuckInBay) / Car.AllDone
    print "mean number of cars in buffer, using Little's Rule:", \
      float(Car.NStuckInBay) / Car.AllDone
    print "mean number of cars in buffer, using alternate method:", \
      BMC.BufMon.mean()
if __name__ == '__main__': main()
5 Advanced Use of the Resource Class

The default queuing discipline, i.e. priority policy, for the Resource class is First Come, First Served (FCFS). The alternative is to assign different priorities to threads waiting for the resource, which you do by the named argument qType. For example,

\[ R = \text{Resource}(8, \text{qType}=\text{PriorityQ}) \]

creates a resource \( R \) with eight service units, the queue for which has priorities assigned. The priorities are specified in the \texttt{yield request} statement. For instance,

\[ \text{yield request, self, } R, 88 \]
requests to use the resource \( R \), with priority 88. The priorities are user-defined.

5.1 Example: Network Channel with Two Levels of Service

Below is an example of a model in which we use the non-FCFS version of Resource. Here we have a shared network channel on which both video and data are being transmitted. The two types of traffic act in complementary manners:

- We can tolerate a certain percentage of lost video packets, as small loss just causes a bit of jitter on the screen. But we can’t have any noticeable delay.
- We can tolerate a certain increase in delay for data packets. We won’t care about or even notice a small increase in delay. But we can’t lose packets.

Accordingly,

- We discard video packets that are too “old,” with threshold being controlled by the design parameter \( L \) explained in the comments in the program below.
- We don’t discard data packets.

For a fixed level of data traffic, we can for example use simulation to study the tradeoff arising from our choice of the value of \( L \). Smaller \( L \) means more lost video packets but smaller delay for data, and vice versa.

Here is the program:

```python
# QoS.py: illustration of non-FCFS priorities in Resource class
# Communications channel, shared by video and data. Video packets
# arrive every 2.0 amount of time, and have transmission time 1.0. Data
# packet interarrivals are exponentially distributed with rate DArrRate,
# and their transmission time is uniformly distributed on {1,2,3,4,5}.
# Video packets have priority over data packets but the latter are not
```
# pre-emptable. A video packet is discarded upon arrival if it would be
# sent L or more amount of time late.

# usage: python QoS.py DArrRate L MaxSimTime

from SimPy.Simulation import *
from random import Random, expovariate

class G: # globals
    Rnd = Random(12345)
    Chnl = None  # our one channel
    VA = None  # our one video arrivals process
    DA = None  # our one video arrivals process

    # globals
    class ChannelClass(Resource):
        def __init__(self):
            # note arguments to parent constructor:
            Resource.__init__(self, capacity=1, qType=PriorityQ)
            # if a packet is currently being sent, here is when transmit will end
            self.TimeEndXMit = None
            self.NWaitingVid = 0  # number of video packets in queue

    class VidJob(Process):
        def __init__(self):
            Process.__init__(self)
        def Run(self):
            Lost = False
            # if G.Chnl.TimeEndXMit is None, then no jobs in the system
            # now, so this job will start right away (handled below);
            # otherwise:
            if G.Chnl.TimeEndXMit != None:
                # first check for loss
                TimeThisPktStartXMit = G.Chnl.TimeEndXMit + G.Chnl.NWaitingVid
                if TimeThisPktStartXMit - now() > VidArrivals.L:
                    Lost = True
                    VidArrivals.NLost += 1
                    return
            G.Chnl.NWaitingVid += 1
            yield request, self, G.Chnl, 1  # higher priority
            XMitTime = G.Rnd.randint(1, 6) - 0.000000000001
            G.Chnl.TimeEndXMit = now() + XMitTime
            yield hold, self, XMitTime
            G.Chnl.TimeEndXMit = None
            yield release, self, G.Chnl

    class VidArrivals(Process):
        L = None  # threshold for discarding packet
        NArrived = 0  # number of video packets arrived
        NLost = 0  # number of video packets lost
        def __init__(self):
            Process.__init__(self)
        def Run(self):
            while 1:
                yield hold, self, 2.0
                VidArrivals.NArrived += 1
                V = VidJob()
                activate(V, V.Run())

    class DataJob(Process):
        def __init__(self):
            Process.__init__(self)
            self.ArrivalTime = now()
        def Run(self):
            yield request, self, G.Chnl, 0  # lower priority
            XMitTime = G.Rnd.randint(1, 6) - 0.000000000001
            G.Chnl.TimeEndXMit = now() + XMitTime
            yield hold, self, XMitTime
            G.Chnl.TimeEndXMit = None
We have chosen to make a subclass of `Resource` for channels. In doing so, we do have to be careful when our subclass' constructor calls `Resource`'s constructor:

```
Resource.__init__(self, capacity=1, qType=PriorityQ)
```

The named argument `capacity` is the number of resource units, which is 1 in our case. I normally don’t name it in my `Resource` calls, as it is the first argument and thus doesn’t need to be named, but in this case I’ve used the name for clarity. And of course I’ve put in the `qType` argument.

Here is where I set the priorities:

```
yield request, self, G.Chnl, 1  # video
...
yield request, self, G.Chnl, 0  # data
```

I chose the values 1 and 0 arbitrarily. Any values would have worked, as long as the one for video was higher, to give it a higher priority.
Note that I have taken transmission times to be 0.000000000001 lower than an integer, so as to avoid “ties,” in which a transmission would end exactly when messages might arrive. This is a common issue when yield hold times are integers.

5.2 Example: Call Center

This program simulates the operation of a call-in advice nurse system, such as the one in Kaiser Permanente. The key issue here is that the number of servers (nurses) varies through time, as the policy here is to take nurses off the shift when the number of callers is light, and to add more nurses during periods of heavy usage.
def Run(self):
    self.NrsCurrOnline = self.MOL
    # system starts empty, so start timebomb
    self.StartTimeBomb()
    # this thread is a server, usually sleeping but occasionally being
    # wakened to handle an event:
    while True:
        yield passivate, self  # sleep until an event occurs:
        if self.WakingEvent == 'arrival':
            # if system had been empty, cancel timebomb
            if PtClass.NPtsInSystem == 1:
                self.cancel(self.TB)
                self.TB = None
            else:
                # check for need to expand pool
                # how many in queue, including this new patient?
                NewQL = len(self.Rsrc.waitQ) + 1
                if NewQL >= self.R and self.NrsCurrOnline < self.MOL:
                    # bring a new nurse online
                    yield release, self, self.Rsrc
                    self.NrsCurrOnline += 1
                    continue  # go back to sleep
        if self.WakingEvent == 'departure':
            if PtClass.NPtsInSystem == 0:
                self.StartTimeBomb()
                continue  # go back to sleep
        if self.WakingEvent == 'timebomb exploded':
            if self.NrsCurrOnline > 1:
                # must take 1 nurse offline
                yield request, self, self.Rsrc, 1
                self.NrsCurrOnline -= 1
                self.StartTimeBomb()
                continue  # go back to sleep

class TimeBomb(Process):
    def __init__(self, TO, NrsPl):
        Process.__init__(self)
        self.TO = TO  # timeout period
        self.NrsPl = NrsPl  # nurse pool
        self.TimeStarted = now()  # for debugging
    def Run(self):
        yield hold, self, self.TO
        NursePool.Wakeup(G.NrsPl, 'timebomb exploded')

class PtClass(Process):  # simulates one patient
    SrvRate = None  # service rate
    NPtsInSystem = 0
    Mon = Monitor()
    def __init__(self):
        Process.__init__(self)
        self.ArrivalTime = now()
    def Run(self):
        # changes which trigger expansion or contraction of the nurse pool
        # occur at arrival points and departure points
        PtClass.NPtsInSystem += 1
        NursePool.Wakeup(G.NrsPl, 'arrival')
        # dummy to give nurse pool thread a chance to wake up, possibly
        # change the number of nurses, and reset the timebomb:
        yield hold, self, 0.00000000000001
        if G.Debug: ShowStatus('service starts')
        yield hold, self, G.Rnd.expovariate(PtClass.SrvRate)
        yield release, self, G.NrsPl.Rsrc
        PtClass.NPtsInSystem -= 1
        Wait = now() - self.ArrivalTime
        PtClass.Mon.observe(Wait)
        NursePool.Wakeup(G.NrsPl, 'departure')

class ArrivalClass(Process):  # simulates patients arrivals
Since the number of servers varies through time, we cannot use the SimPy Resource class in a straightforward manner, as that class assumes a fixed number of servers. However, by making use of that class’ priorities capability, we can achieve the effect of a varying number of servers. Here we make use of an idea from a page on the SimPy Web site, http://simpy.sourceforge.net/changingcapacity.htm.

The way this works is that we remove a server from availability by performing a yield request with a very high priority level, a level higher than is used for any real request. In our case here, a real request is done via the line

```python
yield request, self, G.NrsPl.Rsrc, 1
```

with priority 1. By contrast, in order to take one nurse off the shift, we perform

```python
yield request, self, self.Rsrc, 100
self.NrsCurrOnline -= 1
```

The high priority ensures that this bogus “request” will prevail over any real one, with the effect that the nurse is taken offline. Note, though, that existing services are not pre-empted, i.e. a nurse is not removed from the shift in the midst of serving someone.

Note the necessity of the line

```python
if __name__ == '__main__': main()
```
The member variable of SimPy’s `Resource` class, which records the number of available resource units, would not tell us here how many nurses are available, because some of the resource units are held by the bogus “requests” in our scheme here. Thus we need a variable of our own, `NrsCurrOnline`.

As you can see from the call to `passivate()` in `NursePool.Run()`, the thread `NursePool.Run()` is mostly dormant, awakening only when it needs to add or delete a nurse from the pool. It is awakened for this purpose by the patient and “timebomb” classes, `PtClass` and `TimeBomb`, which call this function in `NursePool`:

```python
def Wakeup(NrsPl,Evt):
    reactivate(NrsPl)
    NrsPl.WakingEvent = Evt
```

It wakes up the `NursePool` thread, which will then decide whether it should take action to change the size of the nurse pool, based on the argument `Evt`.

For example, when a new patient call arrives, generated by the `ArrivalClass` thread, the latter creates a `PtClass` thread, which simulates that one patient’s progress through the system. The first thing this thread does is

```python
NursePool.Wakeup(G.NrsPl,'arrival')
```

so as to give the `NursePool` thread a chance to check whether the pool should be expanded.

We also have a `TimeBomb` class, which deals with the fact that if the system is devoid of patients for a long time, the size of the nurse pool will be reduced. After the given timeout period, this thread awakenens the `NursePool` thread with the event ‘timebomb exploded’.

By the way, since `activate()` requires that its first argument be a class instance rather than a class, we are forced to create an instance of `NursePool`, `G.NrsPl`, even though we only have one nurse pool. That leads to the situation we have with the function `NursePool.Wakeup()` being neither a class method nor an instance method.

Note the use of monitors, including in our `PeriodicSampler` class.

I have included a function `ShowStatus()` to help with debugging, and especially with verification of the program. Here is some sample output:

```
timebomb exploded at time 0.5
6 nurse(s) online
0 patient(s) in system
timebomb started at time 0
arrival at time 0.875581049552
5 nurse(s) online
1 patient(s) in system
timebomb started at time 0.5
service starts at time 0.875581049552
5 nurse(s) online
1 patient(s) in system
no timebomb ticking
```
departure at time 1.19578373243
5 nurse(s) online
0 patient(s) in system
no timebomb ticking

timebomb exploded at time 1.69578373243
5 nurse(s) online
0 patient(s) in system
timebomb started at time 1.19578373243

timebomb exploded at time 2.19578373243
4 nurse(s) online
0 patient(s) in system
timebomb started at time 1.69578373243

timebomb exploded at time 2.69578373243
3 nurse(s) online
0 patient(s) in system
timebomb started at time 2.19578373243

timebomb exploded at time 3.19578373243
2 nurse(s) online
0 patient(s) in system
timebomb started at time 2.69578373243

timebomb exploded at time 3.69578373243
1 nurse(s) online
0 patient(s) in system
timebomb started at time 3.19578373243