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This paper introduces the practicalities and benefits of using SimPy, a discrete event simulation (DES) module written in Python, for modeling and simulating complex systems. Through a step-by-step exploration of the classical Dining Philosophers Problem, we demonstrate how SimPy enables the efficient construction of discrete event models, emphasizing system states, transitions, and event handling. We extend the scenario to introduce resources, such as chopsticks, to model contention and deadlock conditions, and showcase SimPy's capabilities in managing these scenarios. Furthermore, we explore the integration of SimPy with other Python libraries for statistical analysis, showcasing how simulation results inform system design and optimization. The versatility of SimPy is further highlighted through additional modeling scenarios, including resource constraints and customer service interactions, providing insights into the process of building, debugging, simulating, and optimizing models for a wide range of applications. This paper aims to make DES accessible to practitioners and researchers alike, emphasizing the ease with which complex simulations can be constructed, analyzed, and visualized using SimPy and the broader Python ecosystem.

1 INTRODUCTION

Computer modeling and simulation (M&S) is the priceless art of bringing to "life" systems and behaviors that would otherwise be prohibitively expensive, unethical, or impossible to build, such as a Mars rover, a centaur or a cruel autocratic regime based on slave ownership.

An M&S project consists of several standard steps [1]:

- (1) First, an M&S specialist builds a *model*. The most common model types are:
 - Mathematical models that represent the relationships between the system variables as one or more linear or differential equations (Ohm's law is an example of a linear model), and
 - Discrete event models that represent the system as a collection of finite states and transitions between them caused by internal or external events. The simulation time "jumps" from one event to the next, and there is a timeless void between events.
- (2) Then, the model is *simulated* to obtain execution traces. The traces describe the evolution of some or all system variables over time.
- (3) The traces are often *visualized* because a picture is worth 1,000 words.
- (4) Optimization is the next step if the project aims to discover the optimal values of the system parameters. The system model is repeatedly simulated during optimization with different parameters to minimize or maximize a predefined goal function. The optimization routine may use constrained or unconstrained functional optimization, curve fitting, simulated annealing, or brutal force.

Once implemented, debugged, simulated, and optimized, a model can be used to evaluate, build, and even replace the original system.

There is a plethora of general-purpose M&S software, both commercial and open source, such as OpenModelica [2], Ptolemy [4], Simulink [7], and even Simula [3]—a complete computer programming

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language designed to support simulation. This narrowly focused article shows how to do simple discrete event simulation with SimPy [6]—an M&S module written in pure Python.

2 INSTALLING SIMPY

The easiest (and the only recommended) way to install SimPy is via pip:

```
pip install simpy
#> ...
#> Successfully installed simpy-4.1.1
```

At the time of writing, simpy-4.1.1 is the most recent version of SimPy and will be used for all examples. To check if SimPy was successfully installed, open a Python shell and import simpy.

Assuming you see no error messages, the next goal is finding a suitable model and simulation system. Why not revisit the good old Dining Philosophers?

3 DINING PHILOSOPHERS

In brief, five outstanding Philosophers sit around a table with an enormous dish of freshly made spaghetti at the center. Most of the time, they think, but now and then, a Philosopher becomes hungry. At that point, he collects two forks—left and right—and starts eating the pasta. Having refueled himself, he puts down the forks and returns to thinking.

Like all fine philosophers, the five dining philosophers barely make ends meet and can afford only five forks, which prevents more than two of them from eating simultaneously. In addition to being poor, the philosophers are stubborn and uncooperative: once they pick up one of the forks, they only put it down once they have a chance to eat. Think what happens if all five guys pick up their left forks at about the same time. (A hint: they starve.)

Edsger Dijkstra introduced the dining philosophers problem in 1965, and it has been a gold standard test framework for concurrent algorithm designers [5]. The problem is simple and well-understood, which makes it an excellent candidate for an introductory simulation project. The proposed solution models each philosopher and the interactions between the philosophers and the chopsticks.

From the discrete event simulation point of view, a philosopher is a finite state machine with four states: Thinking (the initial state), Hungry, Hungry-With-One-Chopstick, and Eating. The diagram has no final state, as the philosophers are never supposed to break the cycle.

The transitions between the states are caused by external or internal events. A thinking philosopher becomes hungry *after some time*—on timeout. The time is based on some internal philosopher's considerations that are unknown to us. It can be modeled as an exponentially distributed random variable¹ with the mean value T0. The transition from the **Eating** state to the **Thinking** state is triggered internally, too. It can be modeled as another exponentially distributed random variable with the mean value T1.

The other two transitions in the state transition diagram result from external events: the availability of the chopsticks. A philosopher becomes Hungry-With-One-Chopstick when he manages to collect the first chopstick, and he becomes Eating when the second chopstick becomes available.

 $^{^{1}}$ It is a common and dangerous mistake to treat times as normally distributed random variables—in the first place, due to the unbounded nature of a normal distribution.



Fig. 1. The five dining philosophers

Last, it is assumeed a philosopher spends some small but finite time DT in the Hungry-With-One-Chopstick state even if the other chopstick is readily available. If he picks up both chopsticks at once, the system never ends up in a deadlock, which is practically desirable—but not very exciting from the S&M point of view.

4 SIMULATING THE "CLASSICAL" DINING PHILOSOPHERS

Enter SimPy.

At the core of any SimPy model, there is an environment (simpy.Environment). The environment, among other things, provides functions for the continuous or step-by-step simulation of the models, dispatches events, and track of the current simulation time. A SimPy program starts by importing the necessary modules and creating a new simulation environment:

```
import simpy
import random
env = simpy.Environment()
```

The environment will be passed to all other entities involved in the model—for example, to the chopsticks.



Fig. 2. State transition diagram of a dining philosopher

Using the S&M terminology, a chopstick is a *renewable resource*. It is managed by the environment and must be created before the first use. During the simulation, a resource can be requested, allocated, and released. SimPy provides three types of resources: "vanilla" resources (simpy.Resource, simpy.PriorityResource, simpy.PreemptiveResource), containers (simpy.Container), and stores (simpy.Store, simpy.FilterStore, simpy.PriorityStore). The first model of a chopstick is the basic simpy.Resource.

Each resource has a capacity that defines how many resource users can share it. If the number of requests exceeds the capacity, SimPy blocks the outstanding requests until some users release the resource. For sanitary and convenience reasons, a chopstick should not be shared; its capacity is set to 1 (making it a *mutually exclusive* resource). Five chopsticks are created:

```
N = 5
chopsticks = [simpy.Resource(env, capacity=1) for i in range(N)]
```

The next step is to define the philosophers. Unlike the chopsticks, the philosophers are active. In SimPy, active entities are known as processes. (Not to be confused with the operating system processes!) A process is a Python generator that yields discrete events. (If your knowledge of the yield keyword is rusty, refresh it before reading further.) The simulation environment has a method env.process() that registers the processes. The following code declares the process function run_the_party() as a Python class method and creates and registers an event generator after initializing the class and instance variables. The purpose of highlighting is explained later.

```
class Philosopher():
```

```
T0 = 10 # Mean thinking time
T1 = 10 # Mean eating time
DT = 1 # Time to pick the other chopstick
def __init__(self, env, chopsticks, my_id, DIAG = False):
```

```
self.env = env
    self.chopsticks = chopsticks
    self.id = my_id
    # START_HIGHLIGHT
    self.waiting = 0
    # END_HIGHLIGHT
    self.DIAG = DIAG
    # Register the process with the environment
    env.process(self.run_the_party())
def get_hungry(self): # Request the resources
    yield # Do nothing so far
def run_the_party(self): # Do everything...
    yield # ...but do nothing so far
def diag(self, message): # Diagnostic routine
    if self.DIAG:
        print("P{} {} @{}".format(self.id, message, self.env.now))
```

The class constructor takes several parameters: the simulation environment, the chopstick resources, and the philosopher's id (for diagnostics). Also note that the current simulation time is available as an attribute of the environment, env.now.

The philosophers are dysfunctional and do not yield any events, but they can already be instantiated and assigned two chopsticks to each:

The event generator run_the_party() yields events of three types: timeout, request, and release. A call to env.timeout(tau) blocks the generator for tau time units. Delays are used to model the thinking and eating activities. A call to resource.request() blocks the generator until the resource becomes available, marks the resource as allocated to the caller, and returns the request ID. Finally, a call to resource.release(rq) deallocates the resource associated with the request id rq. It does not block the generator.

The following code is a translation of Figure 2 to the language of SimPy. It consists of two methods that implement the main process and a subprocess.

```
class Philosopher():
    ...
    def get_hungry(self):
        # START_HIGHLIGHT
        start_waiting = self.env.now
        # END_HIGHLIGHT
```

```
self.diag("requested chopstick")
    rq1 = self.chopsticks[0].request()
    yield rq1
    self.diag("obtained chopstick")
    yield self.env.timeout(self.DT)
    self.diag("requested another chopstick")
    rq2 = self.chopsticks[1].request()
    yield rq2
    self.diag("obtained another chopstick")
    # START_HIGHLIGHT
    self.waiting += self.env.now - start_waiting
    # END_HIGHLIGHT
   return rq1, rq2
def run_the_party(self):
    while True:
        # Thinking
        thinking_delay = random.expovariate(1 / self.T0)
        yield self.env.timeout(thinking_delay)
        # Getting hungry
        get_hungry_p = self.env.process(self.get_hungry())
        rq1, rq2 = yield get_hungry_p
        # Eating
        eating_delay = random.expovariate(1 / self.T1)
        yield self.env.timeout(eating_delay)
        # Done eating, put down the chopsticks
        self.chopsticks[0].release(rq1)
        self.chopsticks[1].release(rq2)
        self.diag("released the chopsticks")
```

The method get_hungry() is a subprocess—a process within a process. It hides the technicalities of getting hungry (get one chopstick, get another chopstick, etc.), letting me concentrate on the party's conceptual flow. The main process is suspended until the subprocess yields all events. Note that the subprocess method returns the chopstick request handlers used later to release the resources.

The model is ready to run. It can be simulated step by step (or event by event) by calling env.step(), or for the first t time units by calling env.run(until=t), or until the simulation naturally stops by calling env.run() without any parameters. Here is a sample output of the script:

```
env.run()
#> P1 requested chopstick @0.10843721582414197
#> P1 obtained chopstick @0.10843721582414197
#> P1 obtained another chopstick @1.108437215824142
#> P1 obtained another chopstick @1.108437215824142
#> P0 requested chopstick @6.642119333001387
#> P0 obtained chopstick @6.642119333001387
#> P0 requested another chopstick @7.642119333001387
#> P2 requested chopstick @7.898070765597094
#> ...
#> P2 obtained chopstick @45632.71748485687
#> P1 requested another chopstick @45632.94176319329
#> P3 requested another chopstick @45633.53086921637
#> P2 requested another chopstick @45633.71748485687
```

The simulation suddenly stops at this point: the system is in a deadlock state where each philosopher holds one chopstick and waits for the other. There is no standard way to detect deadlocks in SimPy. An indirect solution is to look at the counts of requests or actual requests granted for each resource (stored in the attributes resource.count and resource.users, respectively). If at least two counts are greater than zero and the simulation stops, the system has likely been deadlocked:

```
[f.count for f in chopsticks]
#> [1, 1, 1, 1, 1]
```

Incidentally, requests not yet granted can be found in the attribute resource.queue.

One of the well-known solutions to a deadlock is to allocate resources in some globally defined order (say, in the order of their numerical IDs or memory references). The philosophers will never starve if a Python ID-based sorting is added to the second line of the class initializer:

```
self.chopsticks = sorted(chopsticks, key=id)
```

5 GATHERING AND VISUALIZING STATISTICS

The goal of an M&S project is usually to verify the correctness of the modeled system and get a sense of its performance. The most common performance characteristics include waiting time, turnaround time, response time, and resource utilization. As an exercise, let's estimate waiting time—the time a process waits for the requested resources (ready to run but not running).

Unlike other M&S software, SimPy does not provide tools for gathering and visualizing simulation statistics—and, honestly, it does not have to. As a part of the Python ecosystem, SimPy can be easily

integrated with statistics, NumPy, Pandas, SciPy, matplotlib, and other plotting, statistical, and general number-crunching packages.

The mean waiting time of the philosophers is measured by instrumenting the Philosopher class with a time-counting variable waiting. The relevant instrumentation code is highlighted in the listings above.

To compare the waiting times or any other performance metrics for different systems (say, the dining parties with various numbers of philosophers), a function is needed that prepares a model, makes a simulation run, and returns the appropriate performance values:

```
def simulate(n, t):
    """
    Simulate the system of n philosophers for up to t time units.
    Return the average waiting time.
    """
    env = simpy.Environment()
    chopsticks = [simpy.Resource(env, capacity=1) for i in range(n)]
    philosophers = [
        Philosopher(env, chopsticks[i], chopsticks[(i + 1) % n], i)
        for i in range(n)]
    env.run(until=t)
    return sum(ph.waiting for ph in philosophers) / n
```

This all-in-one function will be called for different values of n, and the results will be plotted with matplotlib—the ubiquitous Python plotting engine.

```
# Set up the plotting system
import matplotlib.pyplot as plt
import matplotlib
matplotlib.style.use("ggplot")
# Simulate
N = 20
X = range(2, N)
Y = [simulate(n, 50000) for n in X]
# Plot
plt.plot(X, Y, "-o")
plt.ylabel("Waiting time")
plt.xlabel("Number of philosophers")
plt.show()
```

Figure 3 shows the simulation results. As expected, the waiting time for two philosophers is shorter than for three. A less obvious result is that the waiting time for three or more philosophers is almost constant with respect to the party size.

Any interpretation of these facts is beyond the scope of this story.



Fig. 3. Waiting time vs. the number of philosophers

6 ADDING A CONTAINER

No matter how you feel about the stubborn philosophers, the bottomless bowl of rice at the center of the table is unrealistic. Real-life rice ends soon because it is a *consumable resource*. The model can be made less fictitious by treating the rice bowl as a container with finite capacity. The amount of rice in the bowl will decrease by a fixed amount every time a philosopher eats from it. (For convenience, let's assume that the rice is atomically transferred to the philosopher's plate when he collects both chopsticks.) Let's call the new breed of philosophers "pseudo-philosophers" because genuine philosophers surely do not eat rice or anything material but merely pretend to be eating.

A simpy.Container can yield two events of interest: put(amount) and get(amount). Both can block the generator if the container is nearly full or nearly empty, respectively. A container's capacity and current level are stored in the namesake attributes, container.capacity and container.level.

Since a Philosopher class already exists, the cheapest way to implement a pseudo-philosopher is to add an optional bowl parameter to the constructor and a request for a portion of rice to the get_hunry() method if the bowl has been provided (the highlighted lines are responsible for the interaction with the container):

```
class Philosopher():
   TO = 10 # Mean thinking time
   T1 = 10 # Mean eating time
   DT = 1 # Time to pick the other chopstick
   # START HIGHLIGHT
   PORTION = 20 # Single meal size
   # END_HIGHLIGHT
   # START_HIGHLIGHT
   def __init__(self, env, chopsticks, my_id, bowl = None, DIAG = False):
   # END_HIGHLIGHT
       self.env = env
       self.chopsticks = sorted(chopsticks, key=id)
       self.id = my_id
       self.waiting = 0
       # START_HIGHLIGHT
       self.bowl = bowl
       # END_HIGHLIGHT
       self.DIAG = DIAG
       # Register the process with the environment
       env.process(self.run_the_party())
   def get_hungry(self):
       start_waiting = self.env.now
       self.diag("requested chopstick")
       rq1 = self.chopsticks[0].request()
       yield rq1
       self.diag("obtained chopstick")
       yield self.env.timeout(self.DT)
       self.diag("requested another chopstick")
       rq2 = self.chopsticks[1].request()
       yield rq2
       self.diag("obtained another chopstick")
       # START HIGHLIGHT
       if self.bowl is not None:
            yield self.bowl.get(self.PORTION)
            self.diag("reserved food")
       # END_HIGHLIGHT
```

```
self.waiting += self.env.now - start_waiting
return rq1, rq2
def run_the_party(self):
...
```

Incidentally, the new class design allows me to feed different philosophers from different bowls and even mix "true philosophers" and "pseudo-philosophers."

If the philosophers continue eating their rice, the bowl eventually becomes empty, and the party ends. Another process, a chef, is solely responsible for replenishing the bowl every T2 time units:

```
class Chef():
 T2 = 150
 def __init__(self, env, bowl):
    self.env = env
    self.bowl = bowl
    env.process(self.replenish())
 def replenish(self):
    while True:
       yield self.env.timeout(self.T2)
       if self.bowl.level < self.bowl.capacity:
            yield self.bowl.put(self.bowl.capacity - self.bowl.level)
```

The updated function simulate() has additional code for instantiating the bowl and the chef and passes the bowl parameter to the philosophers:

```
def simulate(n, t):
    ....
   Simulate the system of n philosophers for up to t time units.
   Return the average waiting time.
   .....
   env = simpy.Environment()
   # START_HIGHLIGHT
   rice_bowl = simpy.Container(env, init=1000, capacity=1000)
   chef = Chef(env, rice_bowl)
   # END_HIGHLIGHT
   chopsticks = [simpy.Resource(env, capacity=1) for i in range(n)]
   philosophers = [
       Philosopher(env, (chopsticks[i], chopsticks[(i + 1) % n]), i,
        # START_HIGHLIGHT
                    rice_bowl)
        # END_HIGHLIGHT
```



Fig. 4. Waiting time vs. the number of pseudo-philosophers

```
for i in range(n)]
env.run(until=t)
return sum(ph.waiting for ph in philosophers) / n
```

Figure 4 shows the waiting time for the new realistic model. As expected, there is almost no difference between the two models when the number of dining philosophers is small (less than ten in this case): the chef is cooking fast enough to supply the food. When the number of partygoers increases, the turnaround time of the chef becomes an issue and negatively affects the waiting time of the patrons.

7 LEARNING TO GIVE UP

A hungry philosopher may not be that hungry, after all. If the central bowl has no rice and the chef is nowhere to be found, the philosopher may call it a day: put down the chopsticks and return to thinking. Presumably, he will have a chance to eat a supersized meal next time. Resource requests are generally blocking. They can block the caller forever if the resource never becomes available (this is the reason for deadlocks). SimPy provides a mechanism for restricting the wait time by failing events and waiting for multiple events.

Introducing the new—impatient—kind of philosophers requires changing the methods get_hungry() and run_the_party(). First, a constant MAX_WAIT is added that limits the waiting time to at most half of the time required to replenish the rice bowl. Second, when a philosopher collects both chopsticks, the model fires two events: the container request (as before) and a timeout. The generator process is unblocked when *any* of these events trigger, which is accomplished by combining the events with the logical "or" operator | (a vertical bar). The operator is a shortcut to the function simpy.events.AnyOf(env,events). If the modeling logic requires triggering *all* events before unblocking the process, use the logical "and" operator & or the function simpy.events.AllOf(env,events) instead².

```
class Philosopher():
    . . .
        # START_HIGHLIGHT
   MAX_WAIT = Chef.T2 / 2
        # END_HIGHLIGHT
    . . .
    def get_hungry(self, meal_size):
        start_waiting = self.env.now
        self.diag("requested chopstick")
        rq1 = self.chopsticks[0].request()
        yield rq1
        self.diag("obtained chopstick")
        yield self.env.timeout(self.DT)
        self.diag("requested another chopstick")
        rq2 = self.chopsticks[1].request()
        yield rq2
        self.diag("obtained another chopstick")
        if self.bowl is not None:
            request = self.bowl.get(meal_size)
        # START_HIGHLIGHT
            yield request | self.env.timeout(self.MAX_WAIT)
            if request.processed:
                self.diag("reserved food")
            else: # Timeout
                self.diag("gave up")
```

 2 If you are familiar with UML, note that | corresponds to the UML merge and & corresponds to the UML join.

```
self.waiting += self.env.now - start_waiting
    yield simpy.Event(self.env).fail(ValueError(rq1, rq2))
# END_HIGHLIGHT
# Either no bowl or no timeout!
self.waiting += self.env.now - start_waiting
return rq1, rq2
```

After yielding the compound event, the program if SimPy processed the container request by looking at the attribute request.processed. If it did, the food was reserved, and the philosopher could start eating. Otherwise, the wait has been interrupted by the timeout, and get_hungry() must inform the parent process of the failure. SimPy allows a process to fail (and raise an exception) by yielding a namesake event, as on the last highlighted line of the previous listing. Incidentally, the raised ValueError exception takes the chopstick request handles as the parameters: when get_hungry() fails, there is no other way to return the handles.

The run_the_party() method is instrumented with simple meal size accounting. Whenever a philosopher chooses not to wait for the chef, his next rice allowance is increased by one standard portion size. (Intuitively, his overall wait time increases because some attempts are futile). Failed attempts are detected; the failures are mitigated by catching the exception raised by get_hungry() and extracting the chopstick request handles from the exception.

```
def run_the_party(self):
    # START_HIGHLIGHT
   meal_size = self.PORTION
   # END_HIGHLIGHT
   while True:
        yield self.env.timeout(random.expovariate(1 / self.T0))
        get_hungry_p = self.env.process(self.get_hungry(meal_size))
   # START_HIGHLIGHT
        try:
            rq1, rq2 = yield get_hungry_p
            yield self.env.timeout(random.expovariate(1 / self.T1))
            meal_size = self.PORTION
        except ValueError as values: # Timeout
            rq1, rq2 = values.args
            meal size += self.PORTION
    # END_HIGHLIGHT
        self.chopsticks[0].release(rq1)
        self.chopsticks[1].release(rq2)
        self.diag("released chopsticks")
```



Fig. 5. Waiting time vs. the number of impatient philosophers

The new timeout feature can be disabled by setting MAX_WAIT to a substantially large number—say, larger than T2.

Figure 5 shows the waiting time for the impatient philosophers. The difference between this model and the previous one is visible only when the number of partygoers is large enough.

8 LEARNING TO COMMUNICATE

Another classical example—a customer service counter—explains how to model processes that interact directly rather than by sharing resources. In the new scenario, customers arrive with exponentially distributed delays and queueing into a line. (In the example below, the first ten customers are conveniently "generated" by a customer_generator_p() process.) The operator at the customer service counter takes the next customer from the line and services them in exactly SERVICE_DELAY time units. A customer is served successfully with a probability of 0.9. If there are no customers in the line, the operator becomes idle ("falls asleep," if you like) but is reactivated ("woken up") by the next arriving customer.

SimPy provides two direct interaction mechanisms: process interruption and event-based synchronization. To interact, SimPy processes must have references to either each simpy.events.Process, as returned by calls to env.process(), or to the events involved in the interaction (simpy.events.Event).

The following code illustrates both communication mechanisms. It begins with the imports and definitions of global variables. The Python standard double-ended queue collections.deque models the service line.

SimPy uses Python exceptions to manage process interruptions. A new exception class, CustomerFailedException, is created to distinguish SimPy process-related exceptions from proper Python exceptions.

```
import random
from collections import deque
import simpy
# Shared global variables and "constants"
SERVICE_DELAY = 10
service_line = deque()
counter_idle = False # The state of the operator at the service counter
env = simpy.Environment()
class CustomerFailedException(Exception):
    pass
```

The model consists of three types of processes. The customer_generator() function imitates the rest of the world. In a complete model, customers would arrive from other model components rather than being "born" on the spot.

```
def customer_generator():
    for _ in range(10):
        env.process(customer())
        yield env.timeout(random.expovariate(1 / SERVICE_DELAY))
```

customer_generator_p = env.process(customer_generator())

Customers in the model are simple stateless creatures. Once born, they obtain a service ticket represented as a simpy.events.Event and enter it into the service_line. If the service counter operator is asleep (counter_idle==True), the customer interrupts the counter process by calling counter_p.interrupt(). This method raises a simpy.Interrupt exception in the target process and "awakens" it. The matching lines are highlighted in the code below.

Now that the operator is not asleep anymore, the customer yields the ticket. The event gets *triggered*. The customer is blocked until some other process processes the event. Naturally, the event becomes *processed*, and if it is processed successfully, the execution of the customer resumes³. Otherwise, a CustomerFailedException is raised, which terminates the simulator if it is not correctly handled.

³If you are familiar with the C pthreads, you may recognize a striking similarity between SimPy events and pthread_cond_t. Triggering and processing an event are loose equivalents of pthread_cond_wait() and pthread_cond_signal().

```
def customer():
    print("Customer arrived @{0:.1f}".format(env.now))
    ticket = env.event()
    service_line.append(ticket)
    if counter_idle:
        # START_HIGHLIGHT
        counter_p.interrupt()
        # END_HIGHLIGHT
    try:
        yield ticket
        print("Customer left @{0:.1f}".format(env.now))
except CustomerFailedException:
        print("Customer failed (and left) @{0:.1f}".format(env.now))
```

The service counter is a potentially infinite process. If there is at least one waiting customer, the first ticket is removed from the service line, and the corresponding customer is taken care of. Then the counter process "flips a coin" and either fails the ticket event (ticket.fail("CustomerFailedException")) or succeeds it (ticket.succeed()). In the former case, a CustomerFailedException is raised on the client side, as explained above.

If the service line is empty, the counter operator becomes idle and yields an event. This event is triggered but never processed, putting the operator in eternal sleep. However, as explained above, sleep can also be interrupted by an arriving customer process.

```
def counter():
   global counter_idle
    while True:
        if service_line:
            ticket = service_line.popleft()
            yield env.timeout(SERVICE_DELAY)
            if random.randint(0,9) == 9:
                ticket.fail(CustomerFailedException())
            else:
                ticket.succeed()
        else:
            counter_idle = True
            print("The operator fell asleep @{0:.1f}".format(env.now))
            try:
                yield env.event()
        # START_HIGHLIGHT
            except simpy.Interrupt:
```

The simulation's sample output follows:

```
env.run()
#> The operator fell asleep @0.0
#> Customer arrived @0.0
#> The operator woke up @0.0
#> Customer arrived @0.4
#> Customer left @10.0
#> The operator fell asleep @20.0
#> Customer left @20.0
#> Customer arrived @24.6
#> The operator woke up @24.6
#> The operator fell asleep @34.6
#> Customer left @34.6
#> Customer arrived @59.3
#> The operator woke up @59.3
#> Customer arrived @64.2
#> Customer arrived @65.9
#> Customer left @69.3
#> Customer arrived @75.8
#> Customer left @79.3
#> Customer arrived @83.1
#> Customer arrived @86.7
#> Customer left @89.3
#> Customer arrived @90.9
#> Customer left @99.3
#> Customer left @109.3
#> Customer left @119.3
#> The operator fell asleep @129.3
#> Customer left @129.3
```

You can further instrument the model with statistics-gathering tools.

9 CONCLUSION

This article demonstrates the possibility of using Python for not-so-trivial M&S projects. The "M" (modeling) part of the story is somewhat sketchy. Hovewer, computer modeling, even discrete event modeling alone, is

too vast to be covered in a dozen pages without distracting the reader's attention from the holistic M&S experience.

On the SimPy side, the most notable features that should be sufficient for many simple M&S projects were reviewed. Here is a summary of what was left uncovered:

- env.schedule(event, priority=1, delay=0)—A mechanism for scheduling an event in the future rather than triggering it immediately.
- event.callbacks—A list of callback functions that will be called when the event is processed. (The default callback always resumes the blocked process that triggered the event.)
- PriorityResource, PreemptiveResource, PriorityStore, FilterStore—A collection of specialized resources.
- RealtimeEnvironment—An environment for real-time simulation that requires synchronization between the simulation clock and the "wall clock."

You are referred to the SimPy documentation [6] for additional information.

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