

Simulation Programming using PythonSim

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Discrete-event simulation

- The foundations of DES modeling & programming:
 - **System State:** Variables and data structures that hold all needed information about the system.
 - **Events:** Countable points in time that change the state in well-defined ways & schedule future events.
 - **Clock:** Current time in the simulation
 - **Event Calendar:** List of future events yet to be executed in chronological order.
- We want to learn programming approaches and structures that facilitate developing large-scale simulation models.

Object orientation

- Discrete-event simulations often contain **multiple instances of similar objects**:
 - **Entities**: things that come and go, like customers, messages, jobs, events
 - **Queues**: ordered lists of entities
 - **Resources**: scarce quantities that entities need, like servers, computers, machines
 - **Statistics**: information to be recorded on all of the above
- These are more naturally treated as “objects” for which we can have many instances.

PythonSim

- A module containing Python classes (objects) that support simulation.
 - You can easily customize and add to these
- A module containing a few useful functions.
- Implementations of the random-number and random-variate generation functions from `simlib` by Law & Kelton.
- Other packages, e.g., SimPy

Python classes

- With classes we define the template for an object.
- A **class** contains...
 - **attributes** → data values
 - **methods** → instructions about how to do things (functions)
- The key benefit of objects is that we can create multiple instances, each uniquely identified and with its own attributes and methods.

CTStat class

```
class CTStat():  
    def __init__(self): ← Automatically called when a New CTStat is created  
        self.Area = 0.0  
        self.Tlast = 0.0  
        self.TClear = 0.0  
        self.Xlast = 0.0 } ← Attributes: each CTStat will have its own copy  
  
    def Record(self,X): ← Called from within your simulation to update the statistic  
        self.Area = self.Area + self.Xlast * (Clock - self.Tlast)  
        self.Tlast = Clock  
        self.Xlast = X  
  
    def Mean(self): ← Called from within your simulation to report the sample mean  
        mean = 0.0  
        if (Clock - self.TClear) > 0.0:  
            mean = (self.Area + self.Xlast*(Clock - self.Tlast))/(Clock - self.TClear)  
        return mean  
  
    def Clear(self): ← Called from within your simulation to reset the CTStat  
        self.Area = 0.0  
        self.Tlast = Clock  
        self.TClear = Clock
```

Anatomy of a class

- Declarations
 - Defines the name of the class (e.g., CTStat)
 - Defines `__init__(self)`: a method called when a new instance is created
 - Can define the attributes and their initial values
 - Each instance of the object will have its own unique copy
 - Think of `self` as a pointer to the specific instance; this is how we can have multiple unique instances

```
class CTStat():  
    def __init__(self):  
        self.Area = 0.0  
        self.Tlast = 0.0  
        self.TClear = 0.0  
        self.Xlast = 0.0
```

Anatomy of a class

- Methods (functions) take arguments and return results just like regular functions
- `self` must be the first argument and used to reference attributes via `self.attributename`

```
def Record(self,X):
    self.Area = self.Area + self.Xlast * (Clock - self.Tlast)
    self.Tlast = Clock
    self.Xlast = X

def Mean(self):
    mean = 0.0
    if (Clock - self.TClear) > 0.0:
        mean = (self.Area + self.Xlast*(Clock - self.Tlast))/(Clock - self.TClear)
    return mean

def Clear(self):
    self.Area = 0.0
    self.Tlast = Clock
    self.TClear = Clock
```


Using PythonSim

- `SimFunctions.py`
 - **Functions**
`SimFunctionsInit, Schedule, SchedulePlus, ClearStats`
- `SimClasses.py`
 - `CTStat, DTStat`
 - `Entity`
 - `EventCalendar, EventNotice`
 - `FIFOQueue`
 - `Resource`
- `SimRNG.py`
 - Random-number generator and a few common distributions.

Python Lists

- A **List** is a Python generalization of an array:
 - It is **ordered** and can store anything, including class objects.
 - It is dynamic, increasing and decreasing in size as we add and remove.
- We use lists for **event calendar** management and **queue** management.

List syntax

`Queue = []` ← declare the list

`Queue[0]` ← element in the first position

`Queue[-1]` ← element in the last position

`Queue[3]` ← element in 3 position (fourth)

`Queue.remove(value)` ← remove element with this value

`Queue.insert(7, whatever)` ← insert element in the 7 position (eighth)

`Queue.append(whatever)` ← insert element in the last position

Model of an M/G/1 queue

- Single-server queue with exponential time between arrivals, and Erlang service time.
- Key objects:
 - A Resource called `Server`
 - A `FIFOQueue` for customers called `Queue`
 - A discrete-time statistic (`DTStat`) to collect total time in the system called `Wait`
 - An `EventCalendar` called `Calendar`
- We make 10 replications of 55,000 time units, deleting the first 5000.

The basic logic

- Customer arrival
 - Schedule the next arrival
 - Put customer in the queue
 - If the server is idle, make busy and schedule an end of service.
- End of service
 - Remove the customer from the queue & record their time in system
 - If more customers in queue, start next service;
Else make the server idle

Using SimRNG

- `SimRNG.InitializeRNSeed()`
 - Call **once** at the beginning of the simulation to initialize the pseudorandom-number generator
- `SimRNG.lcgrand(Stream)`
 - Pseudorandom-number generator
 - Streams 1-100
- `SimRNG.[Expon, Erlang, Random_integer, Normal, Lognormal, Triangular]`
 - Arguments are distribution parameters first, with last argument being the stream number 1-100
 - Ex: `SimRNG.Expon(15.2, 7)`

M/G/1 Queue in PythonSim

```
import SimFunctions  
import SimRNG  
import SimClasses  
import pandas  
Import numpy as np
```

All simulations need
these 3 modules

```
ZSimRNG = SimRNG.InitializeRNSeed()
```

Initialize random-number
generator outside loop

```
Queue = SimClasses.FIFOQueue()
```

```
Wait = SimClasses.DTStat()
```

```
Server = SimClasses.Resource()
```

```
Calendar = SimClasses.EventCalendar()
```

Create instances of the
needed class objects

```
TheCTStats = []
```

```
TheDTStats = []
```

```
TheQueues = []
```

```
TheResources = []
```

Objects in these lists will be
reinitialized between replications

```
TheDTStats.append(Wait)
```

```
TheQueues.append(Queue)
```

```
TheResources.append(Server)
```

Add the objects to the
appropriate lists

```
Server.SetUnits (1) }  
MeanTBA = 1.0  
MeanST = 0.8  
Phases = 3  
RunLength = 55000.0  
WarmUp = 5000.0
```

The SetUnits method sets
the number of units of the
Resource available.

```
AllWaitMean = []  
AllQueueMean = []  
AllQueueNum = []  
AllServerMean = [] }
```

These are just lists to
save the output results;
not required

SimClasses.Clock initiated at 0 and globally updated

```
def Arrival():
    SimFunctions.Schedule(Calendar, "Arrival", SimRNG.Expon(MeanTBA, 1))
    Customer = SimClasses.Entity()
    Queue.Add(Customer)

    if Server.Busy == 0:
        Server.Seize(1)
        SimFunctions.Schedule(Calendar, "EndOfService",
                               SimRNG.Erlang(Phases, MeanST, 2))

def EndOfService():
    DepartingCustomer = Queue.Remove()
    Wait.Record(SimClasses.Clock - DepartingCustomer.CreateTime)

    if Queue.NumQueue() > 0:
        SimFunctions.Schedule(Calendar, "EndOfService",
                               SimRNG.Erlang(Phases, MeanST, 2))
    else:
        Server.Free(1)
```

- **SimFunctionsInit** clears out the event calendar, statistics, queues and resources between replications
- We always need to schedule one or more initial events
- We then find the first event and get the simulation started

```
for reps in range(0,10,1):
    SimFunctions.SimFunctionsInit(Calendar,TheQueues,TheCTStats,
    TheDTStats,TheResources)
    SimFunctions.Schedule(Calendar,"Arrival",SimRNG.Expon(MeanTBA, 1))
    SimFunctions.Schedule(Calendar,"EndSimulation",RunLength)
    SimFunctions.Schedule(Calendar,"ClearIt",WarmUp)

    NextEvent = Calendar.Remove()
    SimClasses.Clock = NextEvent.EventTime
    if NextEvent.EventType == "Arrival":
        Arrival()
    elif NextEvent.EventType == "EndOfService":
        EndOfService()
    elif NextEvent.EventType == "ClearIt":
        SimFunctions.ClearStats(TheCTStats,TheDTStats)
```

```

while NextEvent.EventType != "EndSimulation":
    NextEvent = Calendar.Remove()
    SimClasses.Clock = NextEvent.EventTime
    if NextEvent.EventType == "Arrival":
        Arrival()
    elif NextEvent.EventType == "EndOfService":
        EndOfService()
    elif NextEvent.EventType == "ClearIt":
        SimFunctions.ClearStats(TheCTStats, TheDTStats)

```

The basic
simulation loop
ending at a
particular event
type

```

print (reps+1, Wait.Mean(), Queue.Mean(),
       Queue.NumQueue(), Server.Mean())

```

Here we use the
built-in statistics
collection of
FIFOQueue and
Resource, plus
the DTStat

PythonSim program structure

```
import SimFunctions
import SimRNG
import SimClasses
```

```
ZSimRNG = SimRNG.InitializeRNSeed()
Calendar = SimClasses.EventCalendar()
```

} Initialize random-number generator and
create the event calendar

```
TheCTStats = []
TheDTStats = []
TheQueues = []
TheResources = []
```

} Create and fill the class objects to be
cleared between replications

```
def SomeEvent():
```

} Build your event functions

```
for reps in range(0,10,1):
    SimFunctions.SimFunctionsInit(Calendar,TheQueues,TheCTStats,
        TheDTStats,TheResources)
```

} Reset the class objects for
each new replication

```
SimFunctions.Schedule(Calendar, "SomeEvent", SomeTime)
```

} Schedule some events

```
while SomeConditionIsTrue:
    NextEvent = Calendar.Remove()
    Clock = NextEvent.EventTime
    If NextEvent.EventType == "SomeEvent"
        SomeEvent()
```

} The basic simulation loop

```
# Collect any within statistics from rep
```

```
# Report any overall statistics from simulation
```

Using PythonSim

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 - `Entity`
 - `EventCalendar, EventNotice`
 - `FIFOQueue`
 - `Resource`
- `SimRNG.py`
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SimFunctionsInit

- Usage:

```
SimFunctions.SimFunctionsInit(Calendar, TheQueues, TheCTStats, TheDTStats, TheResources)
```

- Typically placed **inside** the replication loop
- Resets `Calendar`, and all of `TheXXX [...]` lists.
- The order of arguments matters

Schedule & SchedulePlus

```
SimFunctions.Schedule(calendar, EventType, EventTime)
```

```
SimFunctions.SchedulePlus(Calendar, EventType, EventTime,  
TheObject)
```

- Usage:

```
SimFunctions.Schedule(Calendar, "Arrival", RNG.Expon(2,1))
```

```
NewCustomer = SimClasses.Entity()
```

```
SimFunctions.SchedulePlus(Calendar, "Arrival", RNG.Expon(2,1),  
NewCustomer)
```

- Notice that EventTime is how far into the future the event is to occur, not the absolute time.
- The “Plus” version allows another object (usually an Entity) to be attached to the EventNotice.
- EventType should be a string variable.

Entity class

- Usage

```
NewCustomer = SimClasses.Entity()
```

```
Delay = SimClasses.Clock - NewCustomer.CreateTime
```

- You can add as many additional attributes as you need to the Entity Class.

```
class Entity():  
    CreateTime = 0.0  
    def __init__(self):  
        self.CreateTime = Clock  
#    add other attributes here...
```


EventNotice class

- Usage

```
NextEvent = Calendar.Remove()
```

```
SimClassesClock = NextEvent.EventTime
```

```
If NextEvent.EventType == "SomeEvent"
```

```
    Call SomeEvent(NextEvent.WhichObject)
```

If using SchedulePlus



- The EventNotices are usually created by Schedule or SchedulePlus; you use them when advancing to the next event.

```
class EventNotice():  
    def __init__(self):  
        self.EventTime = 0.0  
        self.EventType = ""  
        self.WhichObject = ()
```

CTStat class

- Collects continuous-time statistics
- Methods: Record, Mean and Clear
- Usage

```
InvLevelStat = SimClasses.CTStat()
```

```
InvLevelStat.Record(InvLevel)
```

```
InvLevelStats.Mean()
```

← (Time-average up to time Clock)

```
InvLevelStats.Clear()
```

DTStat class

- Collects discrete-time statistics
- Methods: Record, Mean, StdDev, N and Clear
- Usage

```
TimeInSystemStat = SimClasses.DTStat()
```

```
TimeInSystemStat.Record(SimClasses.Clock -  
Customer.CreateTime)
```

```
TimeInSystemStat.Mean()  
TimeInSystemStat.StdDev()  
TimeInSystemStat.N()
```

```
TimeInSystemStat.Clear()
```

Resource class

- Models resources and also keeps a CTStat on average number in use
- **Attributes:** Busy [current number in use]
- **Methods:** SetUnits, Seize, Free, Mean
- **Usage**

```
Worker = SimClasses.Resource()
```

```
Worker.SetUnits(5)           # resource has capacity 5  
Worker.Seize(1)               # make 1 unit of resource busy  
Worker.Free(1)                # make 1 unit of resource idle
```

```
If Worker.Busy == 5 Then ...
```

```
Worker.Mean()                 # average number in use
```

FIFOQueue class

- Models first-in-first-out queue, and also keeps a CTStat on number in queue
- Methods: NumQueue, Add, Remove, Mean
- Usage

```
MyLine = SimClasses.FIFOQueue()
```

```
Shopper = SimClasses.Entity()  
MyLine.Add(Shopper)
```

```
DepartingShopper = MyLine.Remove()
```

```
If MyLine.NumQueue() = 0 Then ...
```

```
MyLine.Mean()      # average number in queue
```

Some notes...

- The CTStat's created by `FIFOQueue` and `Resource` are automatically added to `TheCTStats` collection, so they are reinitialized by `SimFunctionsInit`.
- The most common change you will make is to add attributes to the `Entity` class.
- When referencing a method there is a `()` even if no arguments, while an attribute has none:
`MyLine.NumQueue ()` ← because it is computed
`Server.Busy`