

---

# **stochastic Documentation**

***Release 0.7.0***

**Christopher Flynn**

**Jan 20, 2023**



# CONTENTS

<b>1</b>	<b>Installation</b>	<b>3</b>
<b>2</b>	<b>Dependencies</b>	<b>5</b>
<b>3</b>	<b>Compatibility</b>	<b>7</b>
<b>4</b>	<b>Performance</b>	<b>9</b>
<b>5</b>	<b>Documentation</b>	<b>11</b>
5.1	General Usage . . . . .	11
5.2	Random Number Generation . . . . .	13
5.3	Continuous-time Processes . . . . .	16
5.4	Diffusion Models . . . . .	31
5.5	Discrete-time Processes . . . . .	36
5.6	Noise Processes . . . . .	41
5.7	Bibliographical Sources . . . . .	49
5.8	Release Notes . . . . .	49
<b>6</b>	<b>Indices</b>	<b>53</b>
	<b>Python Module Index</b>	<b>55</b>
	<b>Index</b>	<b>57</b>



Stochastic is a python package for generating realizations of stochastic processes.



## INSTALLATION

Stochastic is available on [pypi](#) and can be installed using pip:

```
pip install stochastic
```





## DEPENDENCIES

Stochastic depends on `numpy` for most calculations and `scipy` for certain random variable generation.



## COMPATIBILITY

Stochastic is tested on Python versions 3.6, 3.7, and 3.8.



## PERFORMANCE

This package uses `numpy` and `scipy` wherever possible for faster computation. For improved performance under Monte Carlo simulation, some classes will store results of intermediate computations for faster generation on subsequent simulations.



## DOCUMENTATION

## 5.1 General Usage

### 5.1.1 Processes

This package offers a number of common discrete-time, continuous-time, and noise process objects for generating realizations of stochastic processes as `numpy` arrays.

The diffusion processes are approximated using the Euler–Maruyama method.

Here are the currently supported processes and how to access their classes:

- `stochastic.processes`
  - continuous
    - \* `BesselProcess`
    - \* `BrownianBridge`
    - \* `BrownianExcursion`
    - \* `BrownianMeander`
    - \* `BrownianMotion`
    - \* `CauchyProcess`
    - \* `FractionalBrownianMotion`
    - \* `GammaProcess`
    - \* `GeometricBrownianMotion`
    - \* `InverseGaussianProcess`
    - \* `MixedPoissonProcess`
    - \* `MultifractionalBrownianMotion`
    - \* `PoissonProcess`
    - \* `SquaredBesselProcess`
    - \* `VarianceGammaProcess`
    - \* `WienerProcess`
  - diffusion
    - \* `DiffusionProcess` (generalized)

- \* ConstantElasticityVarianceProcess
- \* CoxIngersollRossProcess
- \* ExtendedVasicekProcess
- \* OrnsteinUhlenbeckProcess
- \* VasicekProcess
- discrete
  - \* BernoulliProcess
  - \* ChineseRestaurantProcess
  - \* DirichletProcess
  - \* MarkovChain
  - \* MoranProcess
  - \* RandomWalk
- noise
  - \* BlueNoise
  - \* BrownianNoise
  - \* ColoredNoise
  - \* PinkNoise
  - \* RedNoise
  - \* VioletNoise
  - \* WhiteNoise
  - \* FractionalGaussianNoise
  - \* GaussianNoise

## 5.1.2 Usage patterns

### The sample() method

To use `stochastic`, import the process you want and instantiate with the required parameters. Every process class has a `sample` method for generating realizations. The `sample` methods accept a parameter `n` for the quantity of steps in the realization, but others (Poisson, for instance) may take additional parameters. Parameters can be accessed as attributes of the instance.

```
from stochastic.processes.discrete import BernoulliProcess

bp = BernoulliProcess(p=0.6)
s = bp.sample(16)
success_probability = bp.p
```

Continuous processes provide a default parameter, `t`, which indicates the maximum time of the process realizations. The default value is 1. The `sample` method will generate `n` equally spaced increments on the interval  $[0, t]$ .



## The sample\_at() method

Some continuous processes also provide a `sample_at()` method, in which a sequence of time values can be passed at which the object will generate a realization. This method ignores the parameter, `t`, specified on instantiation.

```
from stochastic.processes.continuous import BrownianMotion

bm = BrownianMotion(drift=1, scale=1, t=1)
times = [0, 3, 10, 11, 11.2, 20]
s = sample_at(times)
```

## The times() method

Continuous-time processes also provide a method `times()` which generates the time values (using `numpy.linspace()`) corresponding to a realization of `n` steps. This is particularly useful for plotting your samples.

```
import matplotlib.pyplot as plt
from stochastic.processes.continuous import FractionalBrownianMotion

fbm = FractionalBrownianMotion(hurst=0.7, t=1)
s = fbm.sample(32)
times = fbm.times(32)

plt.plot(times, s)
plt.show()
```

## The algorithm option

Some processes provide an optional parameter `algorithm`, in which one can specify which algorithm to use to generate the realization using the `sample()` or `sample_at()` methods. See class-specific documentation for implementations.

```
from stochastic.processes.noise import FractionalGaussianNoise

fgn = FractionalGaussianNoise(hurst=0.6, t=1)
s = fgn.sample(32, algorithm='hosking')
```

# 5.2 Random Number Generation

## 5.2.1 Numpy's random number generation

Stochastic relies on `numpy` for random number generation. Since `numpy 1.17`, the newer `Generator` objects provide improved performance:

---

**Note:** From `numpy` docs: The `Generator`'s normal, exponential and gamma functions use 256-step Ziggurat methods which are 2-10 times faster than `NumPy`'s Box-Muller or inverse CDF implementations.

---

By default, the stochastic package uses numpy's faster `Generator` random number generation. With a function call, we can change the default back to the `legacy random number generation`, which uses `RandomState` objects.

If no `rng` arg is passed when instantiating process instances, each instance will reference the `stochastic.random` module's `generator` attribute for random number generation.

## 5.2.2 Examples

Changing the default random number generation on instances without specified `rng`:

```
from stochastic.processes import GaussianNoise
from stochastic import random

gn = GaussianNoise()
print(gn.rng)
# Generator(PCG64)

# use the legacy random number generator
random.use_randomstate()

print(gn.rng)
# <module 'numpy.random' from '/path/to/site-packages/numpy/random/__init__.py'>

# use the newer Generator
random.use_generator()

print(gn.rng)
# Generator(PCG64)
```

Setting the seed value:

```
from stochastic.processes import GaussianNoise
from stochastic import random

gn = GaussianNoise()
print(gn.rng)
# Generator(PCG64)

random.seed(42)
print(gn.rng.bit_generator.state)
# {'bit_generator': 'PCG64', 'state': {'state': 274674114334540486603088602300644985544, 'inc': 332724090758049132448979897138935081983}, 'has_uint32': 0, 'uinteger': 0}
print(gn.sample(4))
# [ 0.15235854 -0.51999205  0.3752256  0.47028236]

random.seed(42)
print(gn.rng.bit_generator.state)
# {'bit_generator': 'PCG64', 'state': {'state': 274674114334540486603088602300644985544, 'inc': 332724090758049132448979897138935081983}, 'has_uint32': 0, 'uinteger': 0}
print(gn.sample(4))
# [ 0.15235854 -0.51999205  0.3752256  0.47028236]
```

Passing custom generators to process instances at instantiation:

```
from numpy.random import Generator
from numpy.random import PCG64
from stochastic.processes import GaussianNoise
from stochastic import random

generator = Generator(PCG64(seed=42))

gn = GaussianNoise(rng=generator)
# generator specific to this gaussian noise instance
print(gn.rng.bit_generator.state)
# {'bit_generator': 'PCG64', 'state': {'state': 274674114334540486603088602300644985544, 'inc':
↳ 332724090758049132448979897138935081983}, 'has_uint32': 0, 'uinteger': 0}

# stochastic's global generator, different from the one attached to `gn`
print(random.generator.bit_generator.state)
# {'bit_generator': 'PCG64', 'state': {'state': 228239801863081385502825691348763076514, 'inc':
↳ 61631449755775032062670113901777656135}, 'has_uint32': 0, 'uinteger': 0}
```

## 5.2.3 Documentation

**stochastic.random.generator = Generator(PCG64) at 0x7F185FB37A00**

The default random number generator for the stochastic package

**stochastic.random.seed(value)**

Sets the seed for numpy legacy or default\_rng generators.

If using the legacy generator, this will call `numpy.random.seed(value)`. Otherwise a new random number generator is created using `numpy.random.default_rng(value)`.

**stochastic.random.use\_generator(rng=None)**

Use the new numpy Generator as default for stochastic.

Sets the default random number generator for stochastic processes to the newer `np.random.default_rng()`.

---

**Note:** This is the default generator and there is no need to call this function unless returning to the default after switching away from it.

---

### Parameters

**rng** (*numpy.random.Generator*) – a Generator instance to use as the default random number generator for stochastic.

**stochastic.random.use\_randomstate(rng=None)**

Use the legacy numpy RandomState generator as default for stochastic.

Sets the default random number generator for stochastic processes to the legacy `np.random`.

### Parameters

**rng** (*numpy.random.RandomState*) – a RandomState instance to use as the default random number generator for stochastic.

## 5.3 Continuous-time Processes

The `stochastic.processes.continuous` module provides classes for generating discretely sampled continuous-time stochastic processes.

- `stochastic.processes.continuous.BesselProcess`
- `stochastic.processes.continuous.BrownianBridge`
- `stochastic.processes.continuous.BrownianExcursion`
- `stochastic.processes.continuous.BrownianMeander`
- `stochastic.processes.continuous.BrownianMotion`
- `stochastic.processes.continuous.CauchyProcess`
- `stochastic.processes.continuous.FractionalBrownianMotion`
- `stochastic.processes.continuous.GammaProcess`
- `stochastic.processes.continuous.GeometricBrownianMotion`
- `stochastic.processes.continuous.InverseGaussianProcess`
- `stochastic.processes.continuous.MixedPoissonProcess`
- `stochastic.processes.continuous.MultifractionalBrownianMotion`
- `stochastic.processes.continuous.PoissonProcess`
- `stochastic.processes.continuous.SquaredBesselProcess`
- `stochastic.processes.continuous.VarianceGammaProcess`
- `stochastic.processes.continuous.WienerProcess`

**class** `stochastic.processes.continuous.BesselProcess(dim=1, t=1, rng=None)`

Bessel process.



The Bessel process is the Euclidean norm of an  $n$ -dimensional Wiener process, e.g.  $\|\mathbf{W}_t\|$

Generate Bessel process realizations using `dim` independent Brownian motion processes on the interval  $[0, t]$

### Parameters

- **dim** (*int*) – the number of underlying independent Brownian motions to use
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*)

Generate a realization.

**Parameters**

**n** (*int*) – the number of increments to generate

**sample\_at**(*times*)

Generate a realization using specified times.

**Parameters**

**times** – a vector of increasing time values at which to generate the realization

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

**n** (*int*) – the number of increments

**class** stochastic.processes.continuous.**BrownianBridge**(*b=0, t=1, rng=None*)

Brownian bridge.



A Brownian bridge is a Brownian motion with a conditional value on the right endpoint of the process.

**Parameters**

- **b** (*float*) – the right endpoint value of the Brownian bridge at time *t*
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**property b**

Right endpoint value.

**sample**(*n*)

Generate a realization.

**Parameters**

**n** (*int*) – the number of increments to generate

**sample\_at**(*times, b=None*)

Generate a realization using specified times.

**Parameters**

- **times** – a vector of increasing time values at which to generate the realization
- **b** (*float*) – the right endpoint value for *times* [-1]

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

**n** (*int*) – the number of increments

**class** stochastic.processes.continuous.**BrownianExcursion**(*t=1, rng=None*)

Brownian excursion.



A Brownian excursion is a Brownian bridge from  $(0, 0)$  to  $(t, 0)$  which is conditioned to be nonnegative on the interval  $[0, t]$ .

Generated using method by

- Biane, Philippe. “Relations entre pont et excursion du mouvement Brownien reel.” Ann. Inst. Henri Poincare 22, no. 1 (1986): 1-7.
- Vervaat, Wim. “A relation between Brownian bridge and Brownian excursion.” The Annals of Probability (1979): 143-149.

**Parameters**

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*)

Generate a realization.

**Parameters**

**n** (*int*) – the number of increments to generate.

**sample\_at**(*times*)

Generate a realization using specified times.

**Parameters**

**times** – a vector of increasing time values at which to generate the realization

**property t**

End time of the process.

**times**(*n*)

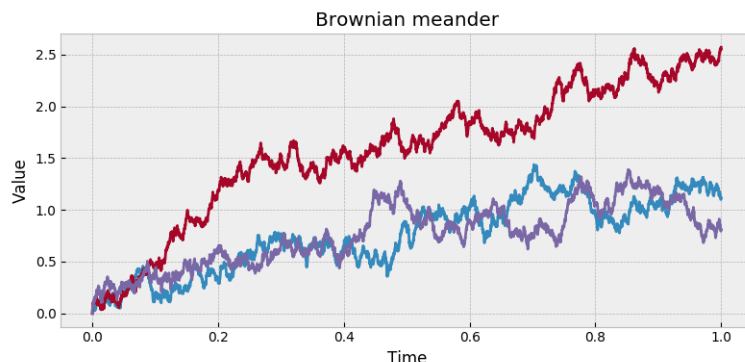
Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

**n** (*int*) – the number of increments

**class** stochastic.processes.continuous.**BrownianMeander**(*t=1, rng=None*)

Brownian meander process.



A Brownian motion conditioned such that the process is nonnegative.

Generated using method by

- Williams, David. “Decomposing the Brownian path.” Bulletin of the American Mathematical Society 76, no. 4 (1970): 871-873.
- Imhof, J-P. “Density factorizations for Brownian motion, meander and the three-dimensional Bessel process, and applications.” Journal of Applied Probability 21, no. 3 (1984): 500-510.

**Parameters**

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n, b=None*)

Generate a realization.

**Parameters**

- **n** (*int*) – the number of increments to generate
- **b** (*float*) – the nonnegative right hand endpoint of the meander. If not provided, one is randomly selected from a  $\sqrt{2E}$  random variable where  $E$  is exponential.

**sample\_at**(*times, b=None*)

Generate a realization using specified times.

**Parameters**

- **times** – a vector of increasing time values at which to generate the realization
- **b** (*float*) – the right endpoint value for **times** [-1]. If not provided, one is randomly selected from a  $\sqrt{2tE}$  random variable where  $E$  is exponential and  $t$  is **times** [-1].

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

**n** (*int*) – the number of increments

**class** stochastic.processes.continuous.**BrownianMotion**(*drift=0, scale=1, t=1, rng=None*)

Brownian motion.



A standard Brownian motion (discretely sampled) has independent and identically distributed Gaussian increments with variance equal to increment length. Non-standard Brownian motion includes a linear drift parameter and scale factor.

**Parameters**

- **drift** (*float*) – rate of change of the expected value
- **scale** (*float*) – scale factor of the Gaussian process
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**property drift**

Drift parameter.

**sample**(*n*)

Generate a realization.

**Parameters**

**n** (*int*) – the number of increments to generate

**sample\_at**(*times*)

Generate a realization using specified times.

**Parameters**

**times** – a vector of increasing time values at which to generate the realization

**property scale**

Scale parameter.

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .



### Parameters

**n** (*int*) – the number of increments

**class** stochastic.processes.continuous.CauchyProcess(*t=1, rng=None*)

Symmetric Cauchy process.



The symmetric Cauchy process is a Brownian motion with a Levy subordinator using location parameter 0 and scale parameter  $t^2/2$ .

### Parameters

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*)

Generate a realization.

### Parameters

**n** (*int*) – the number of increments to generate.

**sample\_at**(*times*)

Generate a realization using specified times.

### Parameters

**times** – a vector of increasing time values at which to generate the realization

**property t**

End time of the process.

**times**(*n*)

Generate times associated with n increments on  $[0, t]$ .

### Parameters

**n** (*int*) – the number of increments

**class** stochastic.processes.continuous.FractionalBrownianMotion(*hurst=0.5, t=1, rng=None*)

Fractional Brownian motion process.



A fractional Brownian motion (discretely sampled) has correlated Gaussian increments defined by Hurst parameter  $H$ . When  $H = 1/2$ , the process is a standard Brownian motion. When  $H > 1/2$ , the increments are positively correlated. When  $H < 1/2$ , the increments are negatively correlated.

Hosking's method:

- Hosking, Jonathan RM. "Modeling persistence in hydrological time series using fractional differencing." Water resources research 20, no. 12 (1984): 1898-1908.

Davies Harte method:

- Davies, Robert B., and D. S. Harte. "Tests for Hurst effect." Biometrika 74, no. 1 (1987): 95-101.

#### Parameters

- **hurst** (*float*) – the Hurst parameter on the interval (0, 1)
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

#### property hurst

Hurst parameter.

#### sample(*n*)

Generate a realization.

#### Parameters

- **n** (*int*) – the number of increments to generate

#### property t

End time of the process.

#### times(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

#### Parameters

- **n** (*int*) – the number of increments

**class** stochastic.processes.continuous.**GammaProcess**(*mean=None, variance=None, rate=None, scale=None, t=1, rng=None*)

Gamma process.



A Gamma process (discretely sampled) is the summation of stationary independent increments which are distributed as gamma random variables. This class supports instantiation using the mean/variance parametrization or the rate/scale parametrization.

#### Parameters

- **mean** (*float*) – mean increase per unit time; supply with *variance*
- **variance** (*float*) – variance of increase per unit time; supply with *mean*
- **rate** (*float*) – the rate of jump arrivals; supply with *scale*
- **scale** (*float*) – the size of the jumps; supply with *rate*
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

#### property mean

Mean increase per unit time.

#### property rate

Rate of jump arrivals.

#### sample(*n*)

Generate a realization.

##### Parameters

- **n** (*int*) – the number of increments to generate

#### sample\_at(*times*)

Generate a realization at specified times.

##### Parameters

- **times** – a vector of increasing time values at which to generate the realization

#### property scale

Scale parameter for jump sizes.

#### property t

End time of the process.

#### times(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

##### Parameters

- **n** (*int*) – the number of increments

### property variance

Variance of increase per unit time.

**class** `stochastic.processes.continuous.GeometricBrownianMotion`(*drift=0, volatility=1, t=1, rng=None*)

Geometric Brownian motion process.



A geometric Brownian motion  $S_t$  is the analytic solution to the stochastic differential equation with Wiener process  $W_t$ :

$$dS_t = \mu S_t dt + \sigma S_t dW_t$$

and can be represented with initial value  $S_0$  in the form:

$$S_t = S_0 \exp \left( \left( \mu - \frac{\sigma^2}{2} \right) t + \sigma W_t \right)$$

### Parameters

- **drift** (*float*) – the parameter  $\mu$
- **volatility** (*float*) – the parameter  $\sigma$
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

### property drift

Geometric Brownian motion drift parameter.

**sample**(*n, initial=1*)

Generate a realization.

### Parameters

- **n** (*int*) – the number of increments to generate.
- **initial** (*float*) – the initial value of the process  $S_0$ .

**sample\_at**(*times, initial=1*)

Generate a realization using specified times.

### Parameters

- **times** – a vector of increasing time values at which to generate the realization
- **initial** (*float*) – the initial value of the process  $S_0$ .

**property t**

End time of the process.

**times(n)**

Generate times associated with n increments on [0, t].

**Parameters**

**n** (*int*) – the number of increments

**property volatility**

Geometric Brownian motion volatility parameter.

**class** stochastic.processes.continuous.**InverseGaussianProcess**(*mean=None, scale=1, t=1, rng=None*)

Inverse Gaussian process.



An inverse Gaussian process has independent increments which follow an inverse Gaussian distribution with parameters defined by a monotonically increasing function,  $\Gamma(t)$ . E.g. for increment  $[s, t]$ :

$$\mathcal{IG}(\Gamma(t) - \Gamma(s), \eta(\Gamma(t) - \Gamma(s))^2)$$

Uses a method for generating inverse Gaussian variates from:

- Michael, John R., William R. Schucany, and Roy W. Haas. “Generating random variates using transformations with multiple roots.” The American Statistician 30, no. 2 (1976): 88-90.

**Parameters**

- **mean** (*callable*) – a callable with one argument  $\Gamma(t)$  such that  $\Gamma(t') > \Gamma(t) \forall t' > t$ . Default is the identity function.
- **scale** (*float*) – scale factor of the shape parameter of the inverse gaussian, or  $\eta$  from the above equation.
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**property mean**

Mean function.

**sample(n)**

Generate a realization.

**Parameters**

**n** (*int*) – the number of increments to generate

**sample\_at**(*times*)

Generate a realization using specified times.

**Parameters**

**times** – a vector of increasing time values at which to generate the realization

**property scale**

Scale parameter.

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

**n** (*int*) – the number of increments

**class** stochastic.processes.continuous.**MixedPoissonProcess**(*rate\_func*, *rate\_args*=None, *rate\_kwargs*=None, *rng*=None)

Mixed poisson process.



A mixed poisson process is a Poisson process for which the rate is a scalar random variate. The sample method will generate a random variate for the rate before generating a Poisson process realization with the rate. A Poisson process with rate  $\lambda$  is a count of occurrences of i.i.d. exponential random variables with mean  $1/\lambda$ . Use the `rate` attribute to get the most recently generated random rate.

**Parameters**

- **rate\_func** (*callable*) – a callable to generate variates of the random rate
- **rate\_args** (*tuple*) – positional args for `rate_func`
- **rate\_kwargs** (*dict*) – keyword args for `rate_func`
- **rng** (*numpy.random.Generator*) – a custom random number generator

**property rate**

The most recently generated rate.

Attempting to get the rate prior to generating a sample will raise an `AttributeError`.

**property rate\_args**

Positional arguments for the rate function.

**property rate\_func**

Current rate's distribution.

**property rate\_kwargs**

Keyword arguments for the rate function.

**sample**(*n=None, length=None*)

Generate a realization.

Exactly one of *n* and *length* must be provided. Generates a random variate for the rate, then generates a Poisson process realization using this rate.

**Parameters**

- **n** (*int*) – the number of arrivals to simulate
- **length** (*int*) – the length of time to simulate; will generate arrivals until length is met or exceeded.

**class** stochastic.processes.continuous.MultifractionalBrownianMotion(*hurst=None, t=1, rng=None*)

Multifractional Brownian motion process.



A multifractional Brownian motion generalizes a fractional Brownian motion with a Hurst parameter which is a function of time,  $h(t)$ . If the Hurst is constant, the process is a fractional Brownian motion. If Hurst is constant equal to 0.5, the process is a Brownian motion.

Approximate method originally proposed for fBm in

- Rambaldi, Sandro, and Ombretta Pinazza. “An accurate fractional Brownian motion generator.” *Physica A: Statistical Mechanics and its Applications* 208, no. 1 (1994): 21-30.

Adapted to approximate mBm in

- Muniandy, S. V., and S. C. Lim. “Modeling of locally self-similar processes using multifractional Brownian motion of Riemann-Liouville type.” *Physical Review E* 63, no. 4 (2001): 046104.

**Parameters**

- **hurst** (*float*) – a callable with one argument  $h(t)$  such that  $h(t') \in (0, 1) \forall t' \in [0, t]$ . Default is  $h(t) = 0.5$ .
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**property hurst**

Hurst function.

**sample**(*n*)

Generate a realization.

**Parameters**

**n** (*int*) – the number of increments to generate

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on [0, *t*].

**Parameters**

**n** (*int*) – the number of increments

**class** stochastic.processes.continuous.**PoissonProcess**(*rate=1, rng=None*)

Poisson process.



A Poisson process with rate  $\lambda$  is a count of occurrences of i.i.d. exponential random variables with mean  $1/\lambda$ . This class generates samples of times for which cumulative exponential random variables occur.

**Parameters**

- **rate** (*float*) – the parameter  $\lambda$  which defines the rate of occurrences of the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**property rate**

Rate parameter.

**sample**(*n=None, length=None*)

Generate a realization.

Exactly one of *n* and *length* must be provided.

**Parameters**

- **n** (*int*) – the number of arrivals to simulate
- **length** (*int*) – the length of time to simulate; will generate arrivals until length is met or exceeded.

**class** stochastic.processes.continuous.**SquaredBesselProcess**(*dim=1, t=1, rng=None*)

Squared Bessel process.





The square of a Bessel process:  $\|\mathbf{W}_t\|^2$ .

The Bessel process is the Euclidean norm of an  $n$ -dimensional Wiener process, e.g.  $\|\mathbf{W}_t\|$

#### Parameters

- **dim** (*int*) – the number of underlying independent Brownian motions to use
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process

#### property dim

Dimensions, or independent Brownian motions.

#### sample(*n*)

Generate a realization.

#### Parameters

- **n** (*int*) – the number of increments to generate

#### sample\_at(*times*)

Generate a realization using specified times.

#### Parameters

- **times** – a vector of increasing time values at which to generate the realization

#### property t

End time of the process.

**class** stochastic.processes.continuous.VarianceGammaProcess(*drift=0, variance=1, scale=1, t=1, rng=None*)

Variance Gamma process.



A variance gamma process has independent increments which follow the variance-gamma distribution. It can be represented as a Brownian motion with drift subordinated by a Gamma process:

$$\theta\Gamma(t; 1, \nu) + \sigma W(\Gamma(t; 1, \nu))$$

#### Parameters

- **drift** (*float*) – the drift parameter of the Brownian motion, or  $\theta$  above
- **variance** (*float*) – the variance parameter of the Gamma subordinator, or  $\nu$  above
- **scale** (*float*) – the scale parameter of the Brownian motion, or  $\sigma$  above
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

#### property drift

Drift parameter.

#### sample(*n*)

Generate a realization.

##### Parameters

- **n** (*int*) – the number of increments to generate

#### sample\_at(*times*)

Generate a realization using specified times.

##### Parameters

- **times** – a vector of increasing time values at which to generate the realization

#### property scale

Scale parameter.

#### property t

End time of the process.

#### property variance

Variance parameter.

**class** stochastic.processes.continuous.**WienerProcess**(*t=1, rng=None*)

Wiener process, or standard Brownian motion.



#### Parameters

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process

- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*)

Generate a realization.

**Parameters**

**n** (*int*) – the number of increments to generate

**sample\_at**(*times*)

Generate a realization using specified times.

**Parameters**

**times** – a vector of increasing time values at which to generate the realization

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on [0, *t*].

**Parameters**

**n** (*int*) – the number of increments

## 5.4 Diffusion Models

The `stochastic.processes.diffusion` module provides classes for generating discretely sampled continuous-time diffusion processes using the Euler–Maruyama method.

- `stochastic.processes.diffusion.DiffusionProcess`
- `stochastic.processes.diffusion.ConstantElasticityVarianceProcess`
- `stochastic.processes.diffusion.CoxIngersollRossProcess`
- `stochastic.processes.diffusion.OrnsteinUhlenbeckProcess`
- `stochastic.processes.diffusion.VasicekProcess`

**class** `stochastic.processes.diffusion.DiffusionProcess`(*speed=1, mean=0, vol=1, volexp=0, t=1, rng=None*)

Generalized diffusion process.

A base process for more specific diffusion processes.

The process  $X_t$  that satisfies the following stochastic differential equation with Wiener process  $W_t$ :

$$dX_t = \theta_t(\mu_t - X_t)dt + \sigma_t X_t^{\gamma_t} dW_t$$

Realizations are generated using the Euler-Maruyama method.

---

**Note:** Since the family of diffusion processes have parameters which generalize to functions of *t*, parameter attributes will be returned as callables, even if they are initialized as constants. e.g. a `speed` parameter of 1 accessed from an instance attribute will return a function which accepts a single argument and always returns 1.

---

**Parameters**

- **speed** (*func*) – the speed of reversion, or  $\theta_t$  above

- **mean** (*func*) – the mean of the process, or  $\mu_t$  above
- **vol** (*func*) – volatility coefficient of the process, or  $\sigma_t$  above
- **volexp** (*func*) – volatility exponent of the process, or  $\gamma_t$  above
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*, *initial*=1.0)

Generate a realization.

#### Parameters

- **n** (*int*) – the number of increments to generate
- **initial** (*float*) – the initial value of the process

**property t**

End time of the process.

**times**(*n*)

Generate times associated with n increments on  $[0, t]$ .

#### Parameters

- **n** (*int*) – the number of increments

**class** stochastic.processes.diffusion.ConstantElasticityVarianceProcess(*drift*=1, *vol*=1, *volexp*=1, *t*=1, *rng*=None)

Constant elasticity of variance process.



The process  $X_t$  that satisfies the following stochastic differential equation with Wiener process  $W_t$ :

$$dX_t = \mu X_t dt + \sigma X_t^\gamma dW_t$$

Realizations are generated using the Euler-Maruyama method.

---

**Note:** Since the family of diffusion processes have parameters which generalize to functions of  $t$ , parameter attributes will be returned as callables, even if they are initialized as constants. e.g. a speed parameter of 1 accessed from an instance attribute will return a function which accepts a single argument and always returns 1.

---

#### Parameters

- **drift** (*float*) – the drift coefficient, or  $\mu$  above
- **vol** (*float*) – the volatility coefficient, or  $\sigma$  above
- **volexp** (*float*) – the volatility-price exponent, or  $\gamma$  above
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*, *initial=1.0*)

Generate a realization.

#### Parameters

- **n** (*int*) – the number of increments to generate
- **initial** (*float*) – the initial value of the process

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

#### Parameters

- **n** (*int*) – the number of increments

**class** `stochastic.processes.diffusion.CoxIngersollRossProcess`(*speed=1*, *mean=0*, *vol=1*, *t=1*,  
*rng=None*)

Cox-Ingersoll-Ross process.



A model for instantaneous interest rate.

The process  $X_t$  that satisfies the following stochastic differential equation with Wiener process  $W_t$ :

$$dX_t = \theta(\mu - X_t)dt + \sigma\sqrt{X_t}dW_t$$

Realizations are generated using the Euler-Maruyama method.

---

**Note:** Since the family of diffusion processes have parameters which generalize to functions of **t**, parameter attributes will be returned as callables, even if they are initialized as constants. e.g. a **speed** parameter of 1 accessed from an instance attribute will return a function which accepts a single argument and always returns 1.

---

#### Parameters

- **speed** (*float*) – the speed of reversion, or  $\theta$  above
- **mean** (*float*) – the mean of the process, or  $\mu$  above
- **vol** (*float*) – volatility coefficient of the process, or  $\sigma$  above
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*, *initial=1.0*)

Generate a realization.

**Parameters**

- **n** (*int*) – the number of increments to generate
- **initial** (*float*) – the initial value of the process

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

- **n** (*int*) – the number of increments

**class** stochastic.processes.diffusion.**OrnsteinUhlenbeckProcess**(*speed=1*, *vol=1*, *t=1*, *rng=None*)

Ornstein-Uhlenbeck process.



The process  $X_t$  that satisfies the following stochastic differential equation with Wiener process  $W_t$ :

$$dX_t = -\theta X_t dt + \sigma dW_t$$

Realizations are generated using the Euler-Maruyama method.

---

**Note:** Since the family of diffusion processes have parameters which generalize to functions of **t**, parameter attributes will be returned as callables, even if they are initialized as constants. e.g. a **speed** parameter of 1 accessed from an instance attribute will return a function which accepts a single argument and always returns 1.

---

**Parameters**

- **speed** (*float*) – the speed of reversion, or  $\theta$  above
- **vol** (*float*) – volatility coefficient of the process, or  $\sigma$  above

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*, *initial*=1.0)

Generate a realization.

#### Parameters

- **n** (*int*) – the number of increments to generate
- **initial** (*float*) – the initial value of the process

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

#### Parameters

- **n** (*int*) – the number of increments

**class stochastic.processes.diffusion.VasicekProcess**(*speed*=1, *mean*=1, *vol*=1, *t*=1, *rng*=None)

Vasicek process.

A model for instantaneous interest rate.



The Vasicek process  $X_t$  that satisfies the following stochastic differential equation with Wiener process  $W_t$ :

$$dX_t = \theta(\mu - X_t)dt + \sigma dW_t$$

Realizations are generated using the Euler-Maruyama method.

---

**Note:** Since the family of diffusion processes have parameters which generalize to functions of **t**, parameter attributes will be returned as callables, even if they are initialized as constants. e.g. a **speed** parameter of 1 accessed from an instance attribute will return a function which accepts a single argument and always returns 1.

---

#### Parameters

- **speed** (*float*) – the speed of reversion, or  $\theta$  above
- **mean** (*float*) – the mean of the process, or  $\mu$  above
- **vol** (*float*) – volatility coefficient of the process, or  $\sigma$  above
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process

- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*, *initial=1.0*)

Generate a realization.

**Parameters**

- **n** (*int*) – the number of increments to generate
- **initial** (*float*) – the initial value of the process

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

- **n** (*int*) – the number of increments

## 5.5 Discrete-time Processes

The `stochastic.processes.discrete` module provides classes for generating discrete-time stochastic processes.

- `stochastic.processes.discrete.BernoulliProcess`
- `stochastic.processes.discrete.ChineseRestaurantProcess`
- `stochastic.processes.discrete.DirichletProcess`
- `stochastic.processes.discrete.MarkovChain`
- `stochastic.processes.discrete.MoranProcess`
- `stochastic.processes.discrete.RandomWalk`

**class** `stochastic.processes.discrete.BernoulliProcess`(*p=0.5*, *rng=None*)

Bernoulli process.



A Bernoulli process consists of a sequence of Bernoulli random variables. A Bernoulli random variable is

- 1 with probability  $p$
- 0 with probability  $1 - p$

**Parameters**



- **p** – in  $[0, 1]$ , the probability of success of each Bernoulli random variable
- **rng** (*numpy.random.Generator*) – a custom random number generator

#### property **p**

Probability of success.

#### **sample**(*n*)

Generate a Bernoulli process realization.

#### Parameters

**n** (*int*) – the number of steps to simulate.

**class** `stochastic.processes.discrete.ChineseRestaurantProcess` (*discount=0, strength=1, rng=None*)

Chinese restaurant process.



A Chinese restaurant process consists of a sequence of arrivals of customers to a Chinese restaurant. Customers may be seated either at an occupied table or a new table, there being infinitely many customers and tables.

The first customer sits at the first table. The  $n$ -th customer sits at a new table with probability  $1/n$ , and at each already occupied table with probability  $t_k/n$ , where  $t_k$  is the number of customers already seated at table  $k$ . This is the canonical process with *discount* = 0 and *strength* = 1.

The generalized process gives the  $n$ -th customer a probability of  $(\text{strength} + T * \text{discount}) / (n - 1 + \text{strength})$  to sit at a new table and a probability of  $(t_k - \text{discount}) / (n - 1 + \text{strength})$  of sitting at table  $k$ .  $T$  is the number of occupied tables.

Samples provide a sequence of tables selected by a sequence of customers.

#### Parameters

- **discount** (*float*) – the discount value of existing tables. Must be strictly less than 1.
- **strength** (*float*) – the strength of a new table. If discount is negative, strength must be a multiple of discount. If discount is nonnegative, strength must be strictly greater than the negative discount.
- **rng** (*numpy.random.Generator*) – a custom random number generator

#### property **discount**

Discount parameter.

#### **partition\_to\_sequence**(*partition*)

Create a sequence from a partition.

#### Parameters

**partition** – a Chinese restaurant partition.

**sample(*n*)**

Generate a Chinese restaurant process with *n* customers.

**Parameters**

**n** – the number of customers to simulate.

**sample\_partition(*n*)**

Generate a Chinese restaurant process partition.

**Parameters**

**n** – the number of customers to simulate.

**sequence\_to\_partition(*sequence*)**

Create a partition from a sequence.

**Parameters**

**sequence** – a Chinese restaurant sample.

**property strength**

Strength parameter.

**class stochastic.processes.discrete.DirichletProcess(*base=None, alpha=1, rng=None*)**

Dirichlet process.



A Dirichlet process is a stochastic process in which the resulting samples can be interpreted as discrete probability distributions.

For each step  $k \geq 1$ , draw from the base distribution with probability

$$\frac{\alpha}{\alpha + k - 1}$$

Otherwise draw randomly from the previous steps.

**Parameters**

- **base** (*callable*) – a zero argument callable used as the base distribution sampler. The default base distribution is `Uniform(0, 1)`.
- **alpha** (*float*) – a non-negative value used to determine probability of drawing a new value from the base distribution
- **rng** (*numpy.random.Generator*) – a custom random number generator

**property alpha**

Parameter for determining the probability of sampling new values.

**property base**

The base distribution callable for sampling new step values.

**sample(*n*)**

Generate a realization of the Dirichlet process.

**Parameters**

**n** (*int*) – the number of steps of the Dirichlet process to generate.

**class** stochastic.processes.discrete.**MarkovChain**(*transition=None, initial=None, rng=None*)

Finite state Markov chain.



A Markov Chain which changes between states according to the transition matrix.

**Parameters**

- **transition** (*2darray*) – a square matrix representing the transition probabilities between states.
- **initial** (*1darray*) – a vector representing the initial state probabilities. If not provided, each state has equal initial probability.
- **rng** (*numpy.random.Generator*) – a custom random number generator

**property initial**

Vector of initial state probabilities.

**sample(*n*)**

Generate a realization of the Markov chain.

**Parameters**

**n** (*int*) – the number of steps of the Markov chain to generate.

**property transition**

Transition probability matrix.

**class** stochastic.processes.discrete.**MoranProcess**(*maximum, rng=None*)

Moran process.



A neutral drift Moran process, typically used to model populations. At each step this process will increase by one, decrease by one, or remain at the same value between values of zero and the number of states,  $n$ . The process ends when its value reaches zero or the maximum valued state.

#### Parameters

- **maximum** (*int*) – the maximum possible value for the process.
- **rng** (*numpy.random.Generator*) – a custom random number generator

#### property maximum

Maximum value.

#### sample(*n*, *start*)

Generate a realization of the Moran process.

Generate a Moran process until absorption occurs (state 0 or *maximum*) or length of process reaches length *n*.

#### Parameters

- **n** (*int*) – the maximum number of steps to generate assuming absorption does not occur.
- **start** (*int*) – the initial state of the process.

**class** stochastic.processes.discrete.**RandomWalk**(*steps=None*, *weights=None*, *rng=None*)

Random walk.



A random walk is a sequence of random steps taken from a set of step sizes with a probability distribution. By default this object defines the steps to be  $[-1, 1]$  with probability  $1/2$  for each possibility.

#### Parameters

- **steps** – a vector of possible deltas to apply at each step.

- **weights** – a corresponding vector of weights associated with each step value. If not provided each step has equal weight/probability.

**property p**

Step probabilities, normalized from *weights*.

**sample(*n*)**

Generate a sample random walk.

**Parameters**

**n** (*int*) – the number of steps to generate

**sample\_increments(*n*)**

Generate a sample of random walk increments.

**Parameters**

**n** (*int*) – the number of increments to generate.

**property steps**

Possible steps.

**property weights**

Step weights provided.

## 5.6 Noise Processes

The `stochastic.processes.noise` module provides classes for generating noise processes.

Gaussian increments

- `stochastic.processes.noise.GaussianNoise`
- `stochastic.processes.noise.FractionalGaussianNoise`

Colored noise

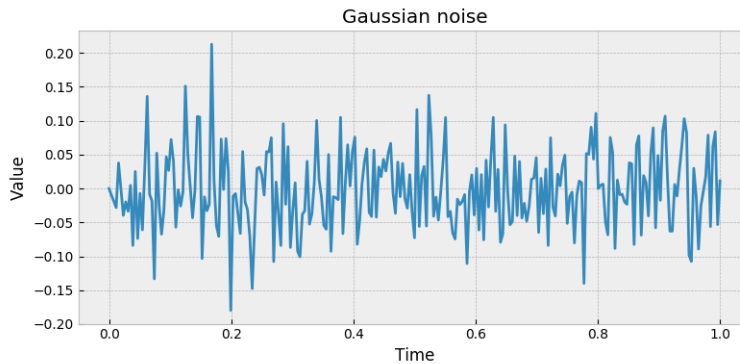
- `stochastic.processes.noise.BlueNoise`
- `stochastic.processes.noise.BrownianNoise`
- `stochastic.processes.noise.ColoredNoise`
- `stochastic.processes.noise.RedNoise`
- `stochastic.processes.noise.PinkNoise`
- `stochastic.processes.noise.VioletNoise`
- `stochastic.processes.noise.WhiteNoise`

## 5.6.1 Gaussian increments

Noise processes which are increments of their continuous counterparts.

**class** stochastic.processes.noise.**GaussianNoise**(*t=1, rng=None*)

Gaussian noise process.



Generate a sequence of Gaussian random variables.

### Parameters

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*)

Generate a realization of Gaussian noise.

Generate a Gaussian noise realization with *n* increments.

### Parameters

**n** (*int*) – the number of increments to generate.

**sample\_at**(*times*)

Generate Gaussian noise increments at specified times from zero.

### Parameters

**times** – a vector of increasing time values for which to generate noise increments.

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

### Parameters

**n** (*int*) – the number of increments

**class** stochastic.processes.noise.**FractionalGaussianNoise**(*hurst=0.5, t=1, rng=None*)

Fractional Gaussian noise process.



Generate sequences of fractional Gaussian noise.

Hosking's method:

- Hosking, Jonathan RM. "Modeling persistence in hydrological time series using fractional differencing." Water resources research 20, no. 12 (1984): 1898-1908.

Davies Harte method:

- Davies, Robert B., and D. S. Harte. "Tests for Hurst effect." Biometrika 74, no. 1 (1987): 95-101.

#### Parameters

- **hurst** (*float*) – The Hurst parameter value in  $(0, 1)$ .
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

#### property hurst

Hurst parameter.

**sample**(*n*, *algorithm*='daviesharte')

Generate a realization of fractional Gaussian noise.

#### Parameters

- **n** (*int*) – number of increments to generate
- **algorithm** (*str*) – either 'daviesharte' or 'hosking' algorithms

#### property t

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

#### Parameters

- **n** (*int*) – the number of increments

## 5.6.2 Colored noise

Signals with spectral densities proportional to the power law.

**class** stochastic.processes.noise.**BlueNoise**(*t=1, rng=None*)

Blue noise.



Colored noise, or power law noise with spectral density exponent  $\beta = -1$ .

### Parameters

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*)

Generate a realization of colored noise.

Generate a colored noise realization with *n* increments.

### Parameters

**n** (*int*) – the number of increments to generate.

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

### Parameters

**n** (*int*) – the number of increments

**class** stochastic.processes.noise.**BrownianNoise**(*t=1, rng=None*)

Brownian (red) noise.





Colored noise, or power law noise with spectral density exponent  $\beta = 2$ .

**Parameters**

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample(n)**

Generate a realization of colored noise.

Generate a colored noise realization with n increments.

**Parameters**

**n** (*int*) – the number of increments to generate.

**property t**

End time of the process.

**times(n)**

Generate times associated with n increments on  $[0, t]$ .

**Parameters**

**n** (*int*) – the number of increments

**class** stochastic.processes.noise.ColoredNoise(beta=0, t=1, rng=None)

Colored noise processes.



Also referred to as power law noise, colored noise refers to noise processes with power law spectral density. That is, their spectral density per unit bandwidth is proportional to  $(1/f)^\beta$ , where  $f$  is frequency with exponent  $\beta$ .

Uses the algorithm from:

- Timmer, J., and M. Koenig. “On generating power law noise.” *Astronomy and Astrophysics* 300 (1995): 707.

Generates a normalized power-law spectral noise.

**Parameters**

- **beta** (*float*) – the power law exponent for the spectral density, with 0 being white noise, 1 being pink noise, 2 being red noise (Brownian noise), -1 being blue noise, -2 being violet noise. Default is 0 (white noise).
- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**property beta**

Power law exponent.

**sample(*n*)**

Generate a realization of colored noise.

Generate a colored noise realization with *n* increments.

**Parameters**

**n** (*int*) – the number of increments to generate.

**property t**

End time of the process.

**times(*n*)**

Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

**n** (*int*) – the number of increments

**class** stochastic.processes.noise.RedNoise(*t=1, rng=None*)

Red (Brownian) noise.



Colored noise, or power law noise with spectral density exponent  $\beta = 2$ .

**Parameters**

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample(*n*)**

Generate a realization of colored noise.

Generate a colored noise realization with *n* increments.

**Parameters**

**n** (*int*) – the number of increments to generate.

**property t**

End time of the process.

**times(*n*)**

Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

**n** (*int*) – the number of increments

```
class stochastic.processes.noise.PinkNoise(t=1, rng=None)
```

Pink (flicker) noise.



Colored noise, or power law noise with spectral density exponent  $\beta = 1$ .

#### Parameters

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

```
sample(n)
```

Generate a realization of colored noise.

Generate a colored noise realization with *n* increments.

#### Parameters

- **n** (*int*) – the number of increments to generate.

```
property t
```

End time of the process.

```
times(n)
```

Generate times associated with *n* increments on  $[0, t]$ .

#### Parameters

- **n** (*int*) – the number of increments

```
class stochastic.processes.noise.VioletNoise(t=1, rng=None)
```

Violet noise.



Colored noise, or power law noise with spectral density exponent  $\beta = -2$ .

#### Parameters

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*)

Generate a realization of colored noise.

Generate a colored noise realization with *n* increments.

**Parameters**

**n** (*int*) – the number of increments to generate.

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

**n** (*int*) – the number of increments

**class** stochastic.processes.noise.**WhiteNoise**(*t=1, rng=None*)

White noise.



Colored noise, or power law noise with spectral density exponent  $\beta = 0$ .

**Parameters**

- **t** (*float*) – the right hand endpoint of the time interval  $[0, t]$  for the process
- **rng** (*numpy.random.Generator*) – a custom random number generator

**sample**(*n*)

Generate a realization of colored noise.

Generate a colored noise realization with *n* increments.

**Parameters**

**n** (*int*) – the number of increments to generate.

**property t**

End time of the process.

**times**(*n*)

Generate times associated with *n* increments on  $[0, t]$ .

**Parameters**

**n** (*int*) – the number of increments

## 5.7 Bibliographical Sources

- Asmussen, Søren. Stochastic simulation with a view towards stochastic processes. University of Aarhus. Centre for Mathematical Physics and Stochastics (MaPhySto)[MPS], 1998.
- Biane, Philippe. “Relations entre pont et excursion du mouvement Brownien réel.” *Ann. Inst. Henri Poincaré* 22, no. 1 (1986): 1-7.
- Davies, Robert B., and D. S. Harte. “Tests for Hurst effect.” *Biometrika* 74, no. 1 (1987): 95-101.
- Devroye, Luc. “On exact simulation algorithms for some distributions related to Brownian motion and Brownian meanders.” In *Recent developments in applied probability and statistics*, pp. 1-35. Physica-Verlag HD, 2010.
- Hosking, Jonathan RM. “Modeling persistence in hydrological time series using fractional differencing.” *Water resources research* 20, no. 12 (1984): 1898-1908.
- Imhof, J-P. “Density factorizations for Brownian motion, meander and the three-dimensional Bessel process, and applications.” *Journal of Applied Probability* 21, no. 3 (1984): 500-510.
- Michael, John R., William R. Schucany, and Roy W. Haas. “Generating random variates using transformations with multiple roots.” *The American Statistician* 30, no. 2 (1976): 88-90.
- Muniandy, S. V., and S. C. Lim. “Modeling of locally self-similar processes using multifractional Brownian motion of Riemann-Liouville type.” *Physical Review E* 63, no. 4 (2001): 046104.
- Rambaldi, Sandro, and Ombretta Pinazza. “An accurate fractional Brownian motion generator.” *Physica A: Statistical Mechanics and its Applications* 208, no. 1 (1994): 21-30.
- Timmer, J., and M. Koenig. “On generating power law noise.” *Astronomy and Astrophysics* 300 (1995): 707.
- Vervaat, Wim. “A relation between Brownian bridge and Brownian excursion.” *The Annals of Probability* (1979): 143-149.
- Williams, David. “Decomposing the Brownian path.” *Bulletin of the American Mathematical Society* 76, no. 4 (1970): 871-873.
- Wood, Andrew TA, and Grace Chan. “Simulation of stationary Gaussian processes in  $[0, 1]^d$ .” *Journal of computational and graphical statistics* 3, no. 4 (1994): 409-432.

## 5.8 Release Notes

### 5.8.1 Contributing

Stochastic is an open source python package.

If you have additional processes, generalizations, or algorithms that you think would be suitable for this package, please let me know on this project’s [GitHub page](#).

## 5.8.2 License

### MIT License

Copyright (c) 2018-2020 Christopher Flynn

Permission **is** hereby granted, free of charge, to **any** person obtaining a copy of this software **and** associated documentation files (the "**Software**"), to deal **in** the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, **and/or** sell copies of the Software, **and** to permit persons to whom the Software **is** furnished to do so, subject to the following conditions:

The above copyright notice **and** this permission notice shall be included **in all** copies **or** substantial portions of the Software.

THE SOFTWARE IS PROVIDED "**AS IS**", WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.

## 5.8.3 Release Changelog

### 0.7.0 (2022-07-11)

- Don't install meta assets to site-packages folder
- Pass GBM rng to underlying BrownianMotion
- Update dependencies, and support Python 3.8+

### 0.6.0 (2020-11-02)

- Removes zero args for dropping first sample vector value (breaking)
- Changes to diffusion process classes to align with common definitions (breaking)
- Refactor into processes and utils subpackages (breaking)
- Move base class checks into utils.validation and create abstract base classes for processes
- Provide RNG control and seeding functionality per instance and globally
- Add Dirichlet process
- Add generalized Diffusion process

### 0.5.0 (2020-09-22)

- Fixed a bug with missing drift when sampling Brownian motion at specific times (thanks to [MichaelHogervorst](#))
- Fixed implementation of fractional Brownian motion (thanks to [Antony Lee](#))
- Fixed a bug with Bernoulli process success probability

### 0.4.0 (2018-08-19)

- Added a `MixedPoissonProcess` (thanks to [Gabinou](#))

### 0.3.0 (2018-07-22)

- Introduced breaking changes that move the `t` argument of all processes to the end of the `__init__` signature
- Added support for inverse Gaussian process

### 0.2.0 (2018-07-11)

- Added support for colored noise processes (generalized power law, violet, blue, white, pink, red/Brownian)
- Added support for multifractional brownian motion
- Added more citations and bibliographical source page to docs

### 0.1.0 (2018-01-04)

- First release.
- Support for multiple continuous-time, discrete-time, diffusion, and noise processes.





## INDICES

- `genindex`
- `modindex`
- `search`



## PYTHON MODULE INDEX

### S

`stochastic.random`, [15](#)



## INDEX

### A

`alpha` (*stochastic.processes.discrete.DirichletProcess* property), 38

### B

`b` (*stochastic.processes.continuous.BrownianBridge* property), 17

`base` (*stochastic.processes.discrete.DirichletProcess* property), 38

`BernoulliProcess` (class in *stochastic.processes.discrete*), 36

`BesselProcess` (class in *stochastic.processes.continuous*), 16

`beta` (*stochastic.processes.noise.ColoredNoise* property), 45

`BlueNoise` (class in *stochastic.processes.noise*), 44

`BrownianBridge` (class in *stochastic.processes.continuous*), 17

`BrownianExcursion` (class in *stochastic.processes.continuous*), 18

`BrownianMeander` (class in *stochastic.processes.continuous*), 19

`BrownianMotion` (class in *stochastic.processes.continuous*), 20

`BrownianNoise` (class in *stochastic.processes.noise*), 44

### C

`CauchyProcess` (class in *stochastic.processes.continuous*), 21

`ChineseRestaurantProcess` (class in *stochastic.processes.discrete*), 37

`ColoredNoise` (class in *stochastic.processes.noise*), 45

`ConstantElasticityVarianceProcess` (class in *stochastic.processes.diffusion*), 32

`CoxIngersollRossProcess` (class in *stochastic.processes.diffusion*), 33

### D

`DiffusionProcess` (class in *stochastic.processes.diffusion*), 31

`dim` (*stochastic.processes.continuous.SquaredBesselProcess* property), 29

`DirichletProcess` (class in *stochastic.processes.discrete*), 38

`discount` (*stochastic.processes.discrete.ChineseRestaurantProcess* property), 37

`drift` (*stochastic.processes.continuous.BrownianMotion* property), 20

`drift` (*stochastic.processes.continuous.GeometricBrownianMotion* property), 24

`drift` (*stochastic.processes.continuous.VarianceGammaProcess* property), 30

### F

`FractionalBrownianMotion` (class in *stochastic.processes.continuous*), 21

`FractionalGaussianNoise` (class in *stochastic.processes.noise*), 42

### G

`GammaProcess` (class in *stochastic.processes.continuous*), 22

`GaussianNoise` (class in *stochastic.processes.noise*), 42

`generator` (in module *stochastic.random*), 15

`GeometricBrownianMotion` (class in *stochastic.processes.continuous*), 24

### H

`hurst` (*stochastic.processes.continuous.FractionalBrownianMotion* property), 22

`hurst` (*stochastic.processes.continuous.MultifractionalBrownianMotion* property), 27

`hurst` (*stochastic.processes.noise.FractionalGaussianNoise* property), 43

### I

`initial` (*stochastic.processes.discrete.MarkovChain* property), 39

`InverseGaussianProcess` (class in *stochastic.processes.continuous*), 25

### M

`MarkovChain` (class in *stochastic.processes.discrete*), 39

**maximum** (*stochastic.processes.discrete.MoranProcess* property), 40  
**mean** (*stochastic.processes.continuous.GammaProcess* property), 23  
**mean** (*stochastic.processes.continuous.InverseGaussianProcess* property), 25  
**MixedPoissonProcess** (class in *stochastic.processes.continuous*), 26  
**module**  
     *stochastic.random*, 15  
**MoranProcess** (class in *stochastic.processes.discrete*), 39  
**MultifractionalBrownianMotion** (class in *stochastic.processes.continuous*), 27  
**O**  
**OrnsteinUhlenbeckProcess** (class in *stochastic.processes.diffusion*), 34  
**P**  
**p** (*stochastic.processes.discrete.BernoulliProcess* property), 37  
**p** (*stochastic.processes.discrete.RandomWalk* property), 41  
**partition\_to\_sequence()** (*stochastic.processes.discrete.ChineseRestaurantProcess* method), 37  
**PinkNoise** (class in *stochastic.processes.noise*), 46  
**PoissonProcess** (class in *stochastic.processes.continuous*), 28  
**R**  
**RandomWalk** (class in *stochastic.processes.discrete*), 40  
**rate** (*stochastic.processes.continuous.GammaProcess* property), 23  
**rate** (*stochastic.processes.continuous.MixedPoissonProcess* property), 26  
**rate** (*stochastic.processes.continuous.PoissonProcess* property), 28  
**rate\_args** (*stochastic.processes.continuous.MixedPoissonProcess* property), 26  
**rate\_func** (*stochastic.processes.continuous.MixedPoissonProcess* property), 26  
**rate\_kwargs** (*stochastic.processes.continuous.MixedPoissonProcess* property), 26  
**RedNoise** (class in *stochastic.processes.noise*), 46  
**S**  
**sample()** (*stochastic.processes.continuous.BesselProcess* method), 16  
**sample()** (*stochastic.processes.continuous.BrownianBridge* method), 17  
**sample()** (*stochastic.processes.continuous.BrownianExcursion* method), 18  
**sample()** (*stochastic.processes.continuous.BrownianMeander* method), 19  
**sample()** (*stochastic.processes.continuous.BrownianMotion* method), 20  
**sample()** (*stochastic.processes.continuous.CauchyProcess* method), 21  
**sample()** (*stochastic.processes.continuous.FractionalBrownianMotion* method), 22  
**sample()** (*stochastic.processes.continuous.GammaProcess* method), 23  
**sample()** (*stochastic.processes.continuous.GeometricBrownianMotion* method), 24  
**sample()** (*stochastic.processes.continuous.InverseGaussianProcess* method), 25  
**sample()** (*stochastic.processes.continuous.MixedPoissonProcess* method), 27  
**sample()** (*stochastic.processes.continuous.MultifractionalBrownianMotion* method), 27  
**sample()** (*stochastic.processes.continuous.PoissonProcess* method), 28  
**sample()** (*stochastic.processes.continuous.SquaredBesselProcess* method), 29  
**sample()** (*stochastic.processes.continuous.VarianceGammaProcess* method), 30  
**sample()** (*stochastic.processes.continuous.WienerProcess* method), 31  
**sample()** (*stochastic.processes.diffusion.ConstantElasticityVarianceProcess* method), 33  
**sample()** (*stochastic.processes.diffusion.CoxIngersollRossProcess* method), 34  
**sample()** (*stochastic.processes.diffusion.DiffusionProcess* method), 32  
**sample()** (*stochastic.processes.diffusion.OrnsteinUhlenbeckProcess* method), 35  
**sample()** (*stochastic.processes.diffusion.VasicekProcess* method), 36  
**sample()** (*stochastic.processes.discrete.BernoulliProcess* method), 37  
**sample()** (*stochastic.processes.discrete.ChineseRestaurantProcess* method), 37  
**sample()** (*stochastic.processes.discrete.DirichletProcess* method), 39  
**sample()** (*stochastic.processes.discrete.MarkovChain* method), 39  
**sample()** (*stochastic.processes.discrete.MoranProcess* method), 40  
**sample()** (*stochastic.processes.discrete.RandomWalk* method), 41  
**sample()** (*stochastic.processes.noise.BlueNoise* method), 44  
**sample()** (*stochastic.processes.noise.BrownianNoise* method), 45

`sample()` (*stochastic.processes.noise.ColoredNoise* method), 46  
`sample()` (*stochastic.processes.noise.FractionalGaussianNoise* method), 43  
`sample()` (*stochastic.processes.noise.GaussianNoise* method), 42  
`sample()` (*stochastic.processes.noise.PinkNoise* method), 47  
`sample()` (*stochastic.processes.noise.RedNoise* method), 46  
`sample()` (*stochastic.processes.noise.VioletNoise* method), 48  
`sample()` (*stochastic.processes.noise.WhiteNoise* method), 48  
`sample_at()` (*stochastic.processes.continuous.BesselProcess* method), 17  
`sample_at()` (*stochastic.processes.continuous.BrownianBridge* method), 17  
`sample_at()` (*stochastic.processes.continuous.BrownianExcursion* method), 18  
`sample_at()` (*stochastic.processes.continuous.BrownianMeander* method), 19  
`sample_at()` (*stochastic.processes.continuous.BrownianMotion* method), 20  
`sample_at()` (*stochastic.processes.continuous.CauchyProcess* method), 21  
`sample_at()` (*stochastic.processes.continuous.GammaProcess* method), 23  
`sample_at()` (*stochastic.processes.continuous.GeometricBrownianMotion* method), 24  
`sample_at()` (*stochastic.processes.continuous.InverseGaussianProcess* method), 25  
`sample_at()` (*stochastic.processes.continuous.SquaredBesselProcess* method), 29  
`sample_at()` (*stochastic.processes.continuous.VarianceGammaProcess* method), 30  
`sample_at()` (*stochastic.processes.continuous.WienerProcess* method), 31  
`sample_at()` (*stochastic.processes.noise.GaussianNoise* method), 42  
`sample_increments()` (*stochastic.processes.discrete.RandomWalk* method), 41  
`sample_partition()` (*stochastic.processes.discrete.ChineseRestaurantProcess* method), 38  
`scale` (*stochastic.processes.continuous.BrownianMotion* property), 20  
`scale` (*stochastic.processes.continuous.GammaProcess* property), 23  
`scale` (*stochastic.processes.continuous.InverseGaussianProcess* property), 26  
`scale` (*stochastic.processes.continuous.VarianceGammaProcess* property), 30  
`seed()` (in module *stochastic.random*), 15  
`sequence_to_partition()` (*stochastic.processes.discrete.ChineseRestaurantProcess* method), 38  
`SquaredBesselProcess` (class in *stochastic.processes.continuous*), 28  
`steps` (*stochastic.processes.discrete.RandomWalk* property), 41  
`stochastic.random` module, 15  
`strength` (*stochastic.processes.discrete.ChineseRestaurantProcess* property), 38

## T

`t` (*stochastic.processes.continuous.BesselProcess* property), 17  
`t` (*stochastic.processes.continuous.BrownianBridge* property), 18  
`t` (*stochastic.processes.continuous.BrownianExcursion* property), 18  
`t` (*stochastic.processes.continuous.BrownianMeander* property), 19  
`t` (*stochastic.processes.continuous.BrownianMotion* property), 20  
`t` (*stochastic.processes.continuous.CauchyProcess* property), 21  
`t` (*stochastic.processes.continuous.FractionalBrownianMotion* property), 22  
`t` (*stochastic.processes.continuous.GammaProcess* property), 23  
`t` (*stochastic.processes.continuous.GeometricBrownianMotion* property), 24  
`t` (*stochastic.processes.continuous.InverseGaussianProcess* property), 26  
`t` (*stochastic.processes.continuous.MultifractionalBrownianMotion* property), 28  
`t` (*stochastic.processes.continuous.SquaredBesselProcess* property), 29  
`t` (*stochastic.processes.continuous.VarianceGammaProcess* property), 30  
`t` (*stochastic.processes.continuous.WienerProcess* property), 31

- `t` (*stochastic.processes.diffusion.ConstantElasticityVarianceProcess* property), 33
  - `t` (*stochastic.processes.diffusion.CoxIngersollRossProcess* property), 34
  - `t` (*stochastic.processes.diffusion.DiffusionProcess* property), 32
  - `t` (*stochastic.processes.diffusion.OrnsteinUhlenbeckProcess* property), 35
  - `t` (*stochastic.processes.diffusion.VasicekProcess* property), 36
  - `t` (*stochastic.processes.noise.BlueNoise* property), 44
  - `t` (*stochastic.processes.noise.BrownianNoise* property), 45
  - `t` (*stochastic.processes.noise.ColoredNoise* property), 46
  - `t` (*stochastic.processes.noise.FractionalGaussianNoise* property), 43
  - `t` (*stochastic.processes.noise.GaussianNoise* property), 42
  - `t` (*stochastic.processes.noise.PinkNoise* property), 47
  - `t` (*stochastic.processes.noise.RedNoise* property), 46
  - `t` (*stochastic.processes.noise.VioletNoise* property), 48
  - `t` (*stochastic.processes.noise.WhiteNoise* property), 48
  - `times()` (*stochastic.processes.continuous.BesselProcess* method), 17
  - `times()` (*stochastic.processes.continuous.BrownianBridge* method), 18
  - `times()` (*stochastic.processes.continuous.BrownianExcursion* method), 18
  - `times()` (*stochastic.processes.continuous.BrownianMeander* method), 19
  - `times()` (*stochastic.processes.continuous.BrownianMotion* method), 20
  - `times()` (*stochastic.processes.continuous.CauchyProcess* method), 21
  - `times()` (*stochastic.processes.continuous.FractionalBrownianMotion* method), 22
  - `times()` (*stochastic.processes.continuous.GammaProcess* method), 23
  - `times()` (*stochastic.processes.continuous.GeometricBrownianMotion* method), 25
  - `times()` (*stochastic.processes.continuous.InverseGaussianProcess* method), 26
  - `times()` (*stochastic.processes.continuous.MultifractionalBrownianMotion* method), 28
  - `times()` (*stochastic.processes.continuous.WienerProcess* method), 31
  - `times()` (*stochastic.processes.diffusion.ConstantElasticityVarianceProcess* method), 33
  - `times()` (*stochastic.processes.diffusion.CoxIngersollRossProcess* method), 34
  - `times()` (*stochastic.processes.diffusion.DiffusionProcess* method), 32
  - `times()` (*stochastic.processes.diffusion.OrnsteinUhlenbeckProcess* method), 35
  - `times()` (*stochastic.processes.diffusion.VasicekProcess* method), 36
  - `times()` (*stochastic.processes.noise.BlueNoise* method), 44
  - `times()` (*stochastic.processes.noise.BrownianNoise* method), 45
  - `times()` (*stochastic.processes.noise.ColoredNoise* method), 46
  - `times()` (*stochastic.processes.noise.FractionalGaussianNoise* method), 43
  - `times()` (*stochastic.processes.noise.GaussianNoise* method), 42
  - `times()` (*stochastic.processes.noise.PinkNoise* method), 47
  - `times()` (*stochastic.processes.noise.RedNoise* method), 46
  - `times()` (*stochastic.processes.noise.VioletNoise* method), 48
  - `times()` (*stochastic.processes.noise.WhiteNoise* method), 48
  - `transition` (*stochastic.processes.discrete.MarkovChain* property), 39
- U**
- `use_generator()` (in module *stochastic.random*), 15
  - `use_randomstate()` (in module *stochastic.random*), 15
- V**
- `variance` (*stochastic.processes.continuous.GammaProcess* property), 23
  - `variance` (*stochastic.processes.continuous.VarianceGammaProcess* property), 30
  - `VarianceGammaProcess` (class in *stochastic.processes.continuous*), 29
  - `VasicekProcess` (class in *stochastic.processes.diffusion*), 35
  - `VioletNoise` (class in *stochastic.processes.noise*), 47
  - `volatility` (*stochastic.processes.continuous.GeometricBrownianMotion* property), 25
- W**
- `weights` (*stochastic.processes.discrete.RandomWalk* property), 41
  - `WhiteNoise` (class in *stochastic.processes.noise*), 48
  - `WienerProcess` (class in *stochastic.processes.continuous*), 30



Some radii options for box corners used; they were ignored as pict2e was not found