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**qmcpy**  
*Release 0.1*

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**Dec 23, 2019**



# CONTENTS

|          |  |           |
|----------|--|-----------|
| <b>1</b> | <b>About Our QMC Software Community</b>    | <b>1</b>  |
| 1.1      | About Our Python QMC Software . . . . .    | 1         |
| 1.1.1    | About QMCPy . . . . .                      | 1         |
| 1.1.2    | About QMCPy Tests . . . . .                | 1         |
| <b>2</b> | <b>License</b>                             | <b>3</b>  |
| <b>3</b> | <b>QMCPy Documentation</b>                 | <b>5</b>  |
| 3.1      | Integration Method . . . . .               | 5         |
| 3.2      | Integrand Class . . . . .                  | 5         |
| 3.2.1    | Asican Call Option Payoff . . . . .        | 5         |
| 3.2.2    | Keister Function . . . . .                 | 6         |
| 3.2.3    | A Linear Function . . . . .                | 6         |
| 3.2.4    | Quick Construct for Function . . . . .     | 7         |
| 3.3      | Measure Class . . . . .                    | 7         |
| 3.4      | Discrete Distribution Class . . . . .      | 8         |
| 3.5      | Data Class . . . . .                       | 10        |
| 3.6      | Stopping Criterion Class . . . . .         | 11        |
| 3.7      | Utilities . . . . .                        | 12        |
| <b>4</b> | <b>Demos</b>                               | <b>15</b> |
| 4.1      | QMCPy Intro . . . . .                      | 15        |
| 4.2      | Integration Examples . . . . .             | 15        |
| 4.3      | Sampling Points Visualization . . . . .    | 15        |
| 4.4      | MC and QMC Comparison . . . . .            | 15        |
| 4.5      | Quasi-Random Sequence Generators . . . . . | 15        |
| <b>5</b> | <b>Indices and tables</b>                  | <b>17</b> |
|          | <b>Python Module Index</b>                 | <b>19</b> |
|          | <b>Index</b>                               | <b>21</b> |



## ABOUT OUR QMC SOFTWARE COMMUNITY

### 1.1 About Our Python QMC Software

#### 1.1.1 About QMCPy

#### 1.1.2 About QMCPy Tests



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## QMCPY DOCUMENTATION

### 3.1 Integration Method

Main driver function for QMCPy.

```
qmcpy.integrate.integrate(integrand, true_measure, discrete_distrib=None, stop-  
ping_criterion=None)
```

Specify and compute integral of  $f(\mathbf{x})$  for  $\mathbf{x} \in \mathcal{X}$ .

#### Parameters

- **integrand** (*Integrand*) – an object from class *Integrand*. If None (default), sum of two variables defined on unit square is used.
- **true\_measure** (*TrueMeasure*) – an object from class *TrueMeasure*. If None (default), standard uniform distribution is used.
- **discrete\_distrib** (*DiscreteDistribution*) – an object from class *DiscreteDistribution*. If None (default), IID standard uniform distribution is used.
- **stopping\_criterion** (*StoppingCriterion*) – an object from class *StoppingCriterion*. If None (default), criterion based on central limit theorem with absolute tolerance equal to 0.01 is used.

#### Returns

tuple containing:

**solution** (*float*): estimated value of the integral

**data** (*AccumData*): input data and information such as number of sampling points and run time used to obtain solution

**Return type** *tuple*

### 3.2 Integrand Class

#### 3.2.1 Asian Call Option Payoff

Definition for class *AsianCall*, a concrete implementation of *Integrand*

```
class qmcpy.integrand.asian_call.AsianCall(bm_measure, volatility=0.5, start_price=30,  
strike_price=25, interest_rate=0,  
mean_type='arithmetic')
```

Specify and generate payoff values of an Asian Call option

```
__init__(bm_measure, volatility=0.5, start_price=30, strike_price=25, interest_rate=0,
         mean_type='arithmetic')
Initialize AsianCall Integrand's
```

**Parameters**

- **bm\_measure** (*TrueMeasure*) – A BrownianMotion Measure object
- **volatility** (*float*) – sigma, the volatility of the asset
- **start\_price** (*float*) –  $S(0)$ , the asset value at  $t=0$
- **strike\_price** (*float*) – strike\_price, the call/put offer
- **interest\_rate** (*float*) –  $r$ , the annual interest rate
- **mean\_type** (*string*) – ‘arithmetic’ or ‘geometric’ mean

**g** (*x*)

Original integrand to be integrated

**Parameters** **x** – nodes,  $x_{u,i} = i^{\text{th}}$  row of an  $n \cdot |u|$  matrix**Returns**  $n \cdot p$  matrix with values  $f(x_{u,i}, c)$  where if  $x'_i = (x_{i,u}, c)_j$ , then  $x'_{ij} = x_{ij}$  for  $j \in u$ , and  $x'_{ij} = c$  otherwise**get\_discounted\_payoffs** (*stock\_path, dimension*)

Calculate the discounted payoff from the stock path

stock\_path (ndarray): option prices at monitoring times dimension (int): number of dimensions

### 3.2.2 Keister Function

Definition for class Keister, a concrete implementation of Integrand

**class** qmcpy.integrand.keister.**Keister** (*dimension*)Specify and generate values  $f(x) = \pi^{d/2} \cos(\|x\|)$  for  $x \in \mathbb{R}^d$ .

The standard example integrates the Keister integrand with respect to an IID Gaussian distribution with variance 1/2.

**Reference:**B. D. Keister, Multidimensional Quadrature Algorithms, *Computers in Physics*, 10, pp. 119-122, 1996.**\_\_init\_\_** (*dimension*)**Parameters** **dimension** (*ndarray*) – dimension(s) of the integrand(s)**g** (*x*)

Original integrand to be integrated

**Parameters** **x** – nodes,  $x_{u,i} = i^{\text{th}}$  row of an  $n \cdot |u|$  matrix**Returns**  $n \cdot p$  matrix with values  $f(x_{u,i}, c)$  where if  $x'_i = (x_{i,u}, c)_j$ , then  $x'_{ij} = x_{ij}$  for  $j \in u$ , and  $x'_{ij} = c$  otherwise

### 3.2.3 A Linear Function

Definition for class Linear, a concrete implementation of Integrand

**class** qmcpy.integrand.linear.**Linear** (*dimension*)Specify and generate values  $f(x) = \sum_{i=1}^d x_i$  for  $x = (x_1, \dots, x_d) \in \mathbb{R}^d$

`__init__` (*dimension*)

**Parameters** *dimension* (*ndarray*) – dimension(s) of the integrand(s)

*g* (*x*)

Original integrand to be integrated

**Parameters** *x* – nodes,  $x_{u,i} = i^{\text{th}}$  row of an  $n \cdot |u|$  matrix

**Returns**  $n \cdot p$  matrix with values  $f(x_{u,i}, c)$  where if  $x'_i = (x_{i,u}, c)_j$ , then  $x'_{ij} = x_{ij}$  for  $j \in u$ , and  $x'_{ij} = c$  otherwise

### 3.2.4 Quick Construct for Function

Definition for class QuickConstruct, a concrete implementation of Integrant

**class** qmcpy.integrant.quick\_construct.**QuickConstruct** (*dimension*, *custom\_fun*)

Specify and generate values of a user-defined function

`__init__` (*dimension*, *custom\_fun*)

Initialize custom Integrant

**Parameters**

- **dimension** (*ndarray*) – dimension(s) of the integrand(s)
- **custom\_fun** (*int*) – a callable univariate or multivariate Python function that returns a real number.

---

**Note:** Input of the function:

*x*: nodes,  $x_{u,i} = i^{\text{th}}$  row of an  $n \cdot |u|$  matrix

---

*g* (*x*)

Original integrand to be integrated

**Parameters** *x* – nodes,  $x_{u,i} = i^{\text{th}}$  row of an  $n \cdot |u|$  matrix

**Returns**  $n \cdot p$  matrix with values  $f(x_{u,i}, c)$  where if  $x'_i = (x_{i,u}, c)_j$ , then  $x'_{ij} = x_{ij}$  for  $j \in u$ , and  $x'_{ij} = c$  otherwise

## 3.3 Measure Class

Definition of Uniform, a concrete implementation of TrueMeasure

**class** qmcpy.true\_measure.uniform.**Uniform** (*dimension*, *lower\_bound=0.0*, *upper\_bound=1.0*)

Uniform Measure

`__init__` (*dimension*, *lower\_bound=0.0*, *upper\_bound=1.0*)

**Parameters**

- **dimension** (*ndarray*) – dimension's' of the integrand's'
- **lower\_bound** (*float*) – a for Uniform(a,b)
- **upper\_bound** (*float*) – b for Uniform(a,b)

Definition of Gaussian, a concrete implementation of TrueMeasure

**class** qmcpy.true\_measure.gaussian.**Gaussian** (*dimension*, *mean=0*, *variance=1*)  
 Gaussian (Normal) Measure

**\_\_init\_\_** (*dimension*, *mean=0*, *variance=1*)

**Parameters**

- **dimension** (*ndarray*) – dimension's' of the integrand's'
- **mean** (*float*) – mu for Normal(mu,sigma^2)
- **variance** (*float*) – sigma^2 for Normal(mu,sigma^2)

Definition of BrownianMotion, a concrete implementation of TrueMeasure

**class** qmcpy.true\_measure.brownian\_motion.**BrownianMotion** (*dimension*,  
*time\_vector=[array([*  
*0.250, 0.500, 0.750,*  
*1.000])])*

Brownian Motion Measure

**\_\_init\_\_** (*dimension*, *time\_vector=[array([ 0.250, 0.500, 0.750, 1.000])])*

**Parameters**

- **dimension** (*ndarray*) – dimension's' of the integrand's'
- **time\_vector** (*list of ndarrays*) – monitoring times for the Integrand's'

Definition of Lebesgue, a concrete implementation of TrueMeasure

**class** qmcpy.true\_measure.lebesgue.**Lebesgue** (*dimension*, *lower\_bound=0.0*, *upper\_bound=1*)

Lebesgue Uniform Measure

**\_\_init\_\_** (*dimension*, *lower\_bound=0.0*, *upper\_bound=1*)

**Parameters** **dimension** (*ndarray*) – dimension's' of the integrand's'

## 3.4 Discrete Distribution Class

Definition for IIDStdUniform, a concrete implementation of DiscreteDistribution

**class** qmcpy.discrete\_distribution.iid\_std\_uniform.**IIDStdUniform** (*rng\_seed=None*)  
 IID Standard Uniform

**\_\_init\_\_** (*rng\_seed=None*)

**Parameters** **rng\_seed** (*int*) – seed the random number generator for reproducibility

**gen\_dd\_samples** (*replications*, *n\_samples*, *dimensions*)

Generate r nxd IID Standard Uniform samples

**Parameters**

- **replications** (*int*) – Number of nxd matrices to generate (sample.size()[0])
- **n\_samples** (*int*) – Number of observations (sample.size()[1])
- **dimensions** (*int*) – Number of dimensions (sample.size()[2])

**Returns** *replications* x *n\_samples* x *dimensions* (numpy array)

Definition for IIDStdGaussian, a concrete implementation of DiscreteDistribution

---

```
class qmcpy.discrete_distribution.iid_std_gaussian.IIDStdGaussian(rng_seed=None)
    Standard Gaussian
```

```
    __init__(rng_seed=None)
```

Parameters **rng\_seed** (*int*) – seed the random number generator for reproducibility

```
gen_dd_samples(replications, n_samples, dimensions)
```

Generate *r* nxd IID Standard Gaussian samples

Parameters

- **replications** (*int*) – Number of nxd matrices to generate (sample.size()[0])
- **n\_samples** (*int*) – Number of observations (sample.size()[1])
- **dimensions** (*int*) – Number of dimensions (sample.size()[2])

Returns *replications* x *n\_samples* x *dimensions* (numpy array)

Definition for Lattice, a concrete implementation of DiscreteDistribution

```
class qmcpy.discrete_distribution.lattice.Lattice(rng_seed=None)
```

Quasi-Random Lattice low discrepancy sequence (Base 2)

```
    __init__(rng_seed=None)
```

Parameters **rng\_seed** (*int*) – seed the random number generator for reproducibility

```
gen_dd_samples(replications, n_samples, dimensions, scramble=True)
```

Generate *r* nxd Lattice samples

Parameters

- **replications** (*int*) – Number of nxd matrices to generate (sample.size()[0])
- **n\_samples** (*int*) – Number of observations (sample.size()[1])
- **dimensions** (*int*) – Number of dimensions (sample.size()[2])
- **scramble** (*bool*) – If true, random numbers are in unit cube, otherwise they are non-negative integers

Returns *replications* x *n\_samples* x *dimensions* (numpy array)

Definition for Sobol, a concrete implementation of DiscreteDistribution

```
class qmcpy.discrete_distribution.sobol.Sobol(rng_seed=None, backend='Pytorch')
```

Quasi-Random Sobol low discrepancy sequence (Base 2)

```
    __init__(rng_seed=None, backend='Pytorch')
```

Parameters **rng\_seed** (*int*) – seed the random number generator for reproducibility

```
gen_dd_samples(replications, n_samples, dimensions, scramble=True)
```

Generate *r* nxd Sobol samples

Parameters

- **replications** (*int*) – Number of nxd matrices to generate (sample.size()[0])
- **n\_samples** (*int*) – Number of observations (sample.size()[1])
- **dimensions** (*int*) – Number of dimensions (sample.size()[2])
- **scramble** (*bool*) – If true, random numbers are in unit cube, otherwise they are non-negative integers

Returns *replications* x *n\_samples* x *dimensions* (numpy array)

`qmcpy.discrete_distribution.sobol.randint` (*low*, *high=None*, *size=None*, *dtype='l'*)

Return random integers from *low* (inclusive) to *high* (exclusive).

Return random integers from the “discrete uniform” distribution of the specified dtype in the “half-open” interval [*low*, *high*). If *high* is None (the default), then results are from [0, *low*).

**low** [int or array-like of ints] Lowest (signed) integers to be drawn from the distribution (unless *high=None*, in which case this parameter is one above the *highest* such integer).

**high** [int or array-like of ints, optional] If provided, one above the largest (signed) integer to be drawn from the distribution (see above for behavior if *high=None*). If array-like, must contain integer values

**size** [int or tuple of ints, optional] Output shape. If the given shape is, e.g., (*m*, *n*, *k*), then *m* \* *n* \* *k* samples are drawn. Default is None, in which case a single value is returned.

**dtype** [dtype, optional] Desired dtype of the result. All dtypes are determined by their name, i.e., ‘int64’, ‘int’, etc, so byteorder is not available and a specific precision may have different C types depending on the platform. The default value is ‘np.int’.

New in version 1.11.0.

**out** [int or ndarray of ints] *size*-shaped array of random integers from the appropriate distribution, or a single such random int if *size* not provided.

**random.random\_integers** [similar to *randint*, only for the closed] interval [*low*, *high*], and 1 is the lowest value if *high* is omitted.

```
>>> np.random.randint(2, size=10)
array([1, 0, 0, 0, 1, 1, 0, 0, 1, 0]) # random
>>> np.random.randint(1, size=10)
array([0, 0, 0, 0, 0, 0, 0, 0, 0, 0])
```

Generate a 2 x 4 array of ints between 0 and 4, inclusive:

```
>>> np.random.randint(5, size=(2, 4))
array([[4, 0, 2, 1], # random
       [3, 2, 2, 0]])
```

Generate a 1 x 3 array with 3 different upper bounds

```
>>> np.random.randint(1, [3, 5, 10])
array([2, 2, 9]) # random
```

Generate a 1 by 3 array with 3 different lower bounds

```
>>> np.random.randint([1, 5, 7], 10)
array([9, 8, 7]) # random
```

Generate a 2 by 4 array using broadcasting with dtype of uint8

```
>>> np.random.randint([1, 3, 5, 7], [[10], [20]], dtype=np.uint8)
array([[ 8,  6,  9,  7], # random
       [ 1, 16,  9, 12]], dtype=uint8)
```

## 3.5 Data Class

Definition of MeanVarData, a concrete implementation of AccumData

**class** qmcpy.accum\_data.mean\_var\_data.**MeanVarData** (*levels, n\_init*)  
 Accumulated data for IIDDistribution calculations, and store the sample mean and variance of integrand values

**\_\_init\_\_** (*levels, n\_init*)  
 Initialize data instance

**Parameters**

- **levels** (*int*) – number of integrands
- **n\_init** (*int*) – initial number of samples

**update\_data** (*integrand, true\_measure*)  
 Update data

**Parameters**

- **integrand** (*Integrand*) – an instance of Integrand
- **true\_measure** (*TrueMeasure*) – an instance of TrueMeasure

**Returns** None

Definition for MeanVarDataRep, a concrete implementation of AccumData

**class** qmcpy.accum\_data.mean\_var\_data\_rep.**MeanVarDataRep** (*levels, n\_init, replications*)  
 Accumulated data Repeated Central Limit Stopping Criterion (CLTRep) calculations.

**\_\_init\_\_** (*levels, n\_init, replications*)  
 Initialize data instance

**Parameters**

- **levels** (*int*) – number of integrands
- **n\_init** (*int*) – initial number of samples
- **replications** (*int*) – number of random nxm matrices to generate

**update\_data** (*integrand, true\_measure*)  
 Update data

**Parameters**

- **integrand** (*Integrand*) – an instance of Integrand
- **true\_measure** (*TrueMeasure*) – an instance of TrueMeasure

**Returns** None

## 3.6 Stopping Criterion Class

Definition for CLT, a concrete implementation of StoppingCriterion

**class** qmcpy.stopping\_criterion.clt.**CLT** (*discrete\_distrib, true\_measure, inflate=1.2, alpha=0.01, abs\_tol=0.01, rel\_tol=0, n\_init=1024, n\_max=10000000000.0*)

Stopping criterion based on the Central Limit Theorem (CLT)

**\_\_init\_\_** (*discrete\_distrib, true\_measure, inflate=1.2, alpha=0.01, abs\_tol=0.01, rel\_tol=0, n\_init=1024, n\_max=10000000000.0*)

**Parameters**

- **discrete\_distrib** –

- **true\_measure** – an instance of DiscreteDistribution
- **inflate** – inflation factor when estimating variance
- **alpha** – significance level for confidence interval
- **abs\_tol** – absolute error tolerance
- **rel\_tol** – relative error tolerance
- **n\_max** – maximum number of samples

**stop\_yet** ()

Determine when to stop

Definition for CLTRep, a concrete implementation of StoppingCriterion

```
class qmcpy.stopping_criterion.clt_rep.CLTRep(discrete_distrib, true_measure, repli-
                                             cations=16, inflate=1.2, alpha=0.01,
                                             abs_tol=0.01, rel_tol=0, n_init=32,
                                             n_max=1073741824)
```

Stopping criterion based on  $\text{var}(\text{stream\_1\_estimate}, \dots, \text{stream\_16\_estimate}) < \text{errorTol}$

```
__init__(discrete_distrib, true_measure, replications=16, inflate=1.2, alpha=0.01, abs_tol=0.01,
          rel_tol=0, n_init=32, n_max=1073741824)
```

#### Parameters

- **discrete\_distrib** –
- **true\_measure** (*DiscreteDistribution*) – an instance of DiscreteDistribution
- **replications** (*int*) – number of random nxm matrices to generate
- **inflate** (*float*) – inflation factor when estimating variance
- **alpha** (*float*) – significance level for confidence interval
- **abs\_tol** (*float*) – absolute error tolerance
- **rel\_tol** (*float*) – relative error tolerance
- **n\_max** (*int*) – maximum number of samples

**stop\_yet** ()

Determine when to stop

## 3.7 Utilities

Meta-data and public utilities for qmcpy

Exceptions and Warnings thrown by qmcpy

**exception** qmcpy.\_util.\_exceptions\_warnings.**DimensionError**

Class for raising error about dimension

**exception** qmcpy.\_util.\_exceptions\_warnings.**DistributionCompatibilityError**

Class for raising error about incompatible distribution

**exception** qmcpy.\_util.\_exceptions\_warnings.**DistributionGenerationError**

Class for raising error about parameter inputs to `gen_dd_samples` (method of a DiscreteDistribution)

**exception** qmcpy.\_util.\_exceptions\_warnings.**DistributionGenerationWarnings**

Class for issuing warnings about parameter inputs to `gen_dd_samples` (method of a DiscreteDistribution)



**exception** qmcpy.\_util.\_exceptions\_warnings.**MaxSamplesWarning**  
Class for issuing warning about using maximum number of data samples

**exception** qmcpy.\_util.\_exceptions\_warnings.**MeasureCompatibilityError**  
Class for raising error of incompatible measures

**exception** qmcpy.\_util.\_exceptions\_warnings.**NotYetImplemented**  
Class for raising error when a component has been implemented yet

**exception** qmcpy.\_util.\_exceptions\_warnings.**ParameterError**  
Class for raising error about input parameters

**exception** qmcpy.\_util.\_exceptions\_warnings.**ParameterWarning**  
Class for issuing warnings about unacceptable parameters

**exception** qmcpy.\_util.\_exceptions\_warnings.**TransformError**  
Class for raising error about transforming function to accommodate distribution



## **4.1 QMCPy Intro**

## **4.2 Integration Examples**

## **4.3 Sampling Points Visualization**

## **4.4 MC and QMC Comparison**

## **4.5 Quasi-Random Sequence Generators**



## INDICES AND TABLES

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



## PYTHON MODULE INDEX

### q

- qmcpy, 12
- qmcpy.\_util.\_exceptions\_warnings, 12
- qmcpy.accum\_data, 10
- qmcpy.accum\_data.mean\_var\_data, 10
- qmcpy.accum\_data.mean\_var\_data\_rep, 11
- qmcpy.discrete\_distribution, 8
- qmcpy.discrete\_distribution.iid\_std\_gaussian, 8
- qmcpy.discrete\_distribution.iid\_std\_uniform, 8
- qmcpy.discrete\_distribution.lattice, 9
- qmcpy.discrete\_distribution.sobol, 9
- qmcpy.integrand, 5
- qmcpy.integrand.asian\_call, 5
- qmcpy.integrand.keister, 6
- qmcpy.integrand.linear, 6
- qmcpy.integrand.quick\_construct, 7
- qmcpy.integrate, 5
- qmcpy.stopping\_criterion, 11
- qmcpy.stopping\_criterion.clt, 11
- qmcpy.stopping\_criterion.clt\_rep, 12
- qmcpy.true\_measure, 7
- qmcpy.true\_measure.brownian\_motion, 8
- qmcpy.true\_measure.gaussian, 7
- qmcpy.true\_measure.lebesgue, 8
- qmcpy.true\_measure.uniform, 7





## Symbols

`__init__()` (*qmcpy.accum\_data.mean\_var\_data.MeanVarData* method), 11  
`__init__()` (*qmcpy.accum\_data.mean\_var\_data\_rep.MeanVarDataRep* method), 11  
`__init__()` (*qmcpy.discrete\_distribution.iid\_std\_gaussian.IIDStdGaussian* method), 9  
`__init__()` (*qmcpy.discrete\_distribution.iid\_std\_uniform.IIDStdUniform* method), 8  
`__init__()` (*qmcpy.discrete\_distribution.lattice.Lattice* method), 9  
`__init__()` (*qmcpy.discrete\_distribution.sobol.Sobol* method), 9  
`__init__()` (*qmcpy.integrand.asian\_call.AsianCall* method), 5  
`__init__()` (*qmcpy.integrand.keister.Keister* method), 6  
`__init__()` (*qmcpy.integrand.linear.Linear* method), 6  
`__init__()` (*qmcpy.integrand.quick\_construct.QuickConstruct* method), 7  
`__init__()` (*qmcpy.stopping\_criterion.clt.CLT* method), 11  
`__init__()` (*qmcpy.stopping\_criterion.clt\_rep.CLTRep* method), 12  
`__init__()` (*qmcpy.true\_measure.brownian\_motion.BrownianMotion* method), 8  
`__init__()` (*qmcpy.true\_measure.gaussian.Gaussian* method), 8  
`__init__()` (*qmcpy.true\_measure.lebesgue.Lebesgue* method), 8  
`__init__()` (*qmcpy.true\_measure.uniform.Uniform* method), 7

## A

AsianCall (class in *qmcpy.integrand.asian\_call*), 5

## B

BrownianMotion (class in *qmcpy.true\_measure.brownian\_motion*), 8

## C

CLT (class in *qmcpy.stopping\_criterion.clt*), 11  
 CLTRep (class in *qmcpy.stopping\_criterion.clt\_rep*), 12

## D

DimensionError, 12  
 DistributionCompatibilityError, 12  
 DistributionGenerationError, 12  
 DistributionGenerationWarnings, 12

## G

`g()` (*qmcpy.integrand.asian\_call.AsianCall* method), 6  
`g()` (*qmcpy.integrand.keister.Keister* method), 6  
`g()` (*qmcpy.integrand.linear.Linear* method), 7  
`g()` (*qmcpy.integrand.quick\_construct.QuickConstruct* method), 7  
 Gaussian (class in *qmcpy.true\_measure.gaussian*), 7  
`gen_dd_samples()` (*qmcpy.discrete\_distribution.iid\_std\_gaussian.IIDStdGaussian* method), 9  
`gen_dd_samples()` (*qmcpy.discrete\_distribution.iid\_std\_uniform.IIDStdUniform* method), 8  
`gen_dd_samples()` (*qmcpy.discrete\_distribution.lattice.Lattice* method), 9  
`gen_dd_samples()` (*qmcpy.discrete\_distribution.sobol.Sobol* method), 9  
`get_discounted_payoffs()` (*qmcpy.integrand.asian\_call.AsianCall* method), 6

## I

IIDStdGaussian (class in *qmcpy.discrete\_distribution.iid\_std\_gaussian*), 8  
 IIDStdUniform (class in *qmcpy.discrete\_distribution.iid\_std\_uniform*), 8  
 integrate() (in module *qmcpy.integrate*), 5

## K

Keister (class in qmcpy.integrand.keister), 6

## L

Lattice (class in qmcpy.discrete\_distribution.lattice), 9

Lebesgue (class in qmcpy.true\_measure.lebesgue), 8

Linear (class in qmcpy.integrand.linear), 6

## M

MaxSamplesWarning, 12

MeanVarData (class in qmcpy.accum\_data.mean\_var\_data), 10

MeanVarDataRep (class in qmcpy.accum\_data.mean\_var\_data\_rep), 11

MeasureCompatibilityError, 13

## N

NotYetImplemented, 13

## P

ParameterError, 13

ParameterWarning, 13

## Q

qmcpy (module), 12

qmcpy.\_util.\_exceptions\_warnings (module), 12

qmcpy.accum\_data (module), 10

qmcpy.accum\_data.mean\_var\_data (module), 10

qmcpy.accum\_data.mean\_var\_data\_rep (module), 11

qmcpy.discrete\_distribution (module), 8

qmcpy.discrete\_distribution.iid\_std\_gaussian (module), 8

qmcpy.discrete\_distribution.iid\_std\_uniform (module), 8

qmcpy.discrete\_distribution.lattice (module), 9

qmcpy.discrete\_distribution.sobol (module), 9

qmcpy.integrand (module), 5

qmcpy.integrand.asian\_call (module), 5

qmcpy.integrand.keister (module), 6

qmcpy.integrand.linear (module), 6

qmcpy.integrand.quick\_construct (module), 7

qmcpy.integrate (module), 5

qmcpy.stopping\_criterion (module), 11

qmcpy.stopping\_criterion.clt (module), 11

qmcpy.stopping\_criterion.clt\_rep (module), 12

qmcpy.true\_measure (module), 7

qmcpy.true\_measure.brownian\_motion (module), 8

qmcpy.true\_measure.gaussian (module), 7

qmcpy.true\_measure.lebesgue (module), 8

qmcpy.true\_measure.uniform (module), 7

QuickConstruct (class in qmcpy.integrand.quick\_construct), 7

## R

randint () (in module qmcpy.discrete\_distribution.sobol), 9

## S

Sobol (class in qmcpy.discrete\_distribution.sobol), 9

stop\_yet () (qmcpy.stopping\_criterion.clt.CLT method), 12

stop\_yet () (qmcpy.stopping\_criterion.clt\_rep.CLTRep method), 12

## T

TransformError, 13

## U

Uniform (class in qmcpy.true\_measure.uniform), 7

update\_data () (qmcpy.accum\_data.mean\_var\_data.MeanVarData method), 11

update\_data () (qmcpy.accum\_data.mean\_var\_data\_rep.MeanVarDataRep method), 11