QMCPy Quasi-Monte Carlo Software

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Rewrite an Integral as an Expectation

Applications in applied statistics, finance, computer graphics, ...

$$\mu = \int_{\mathcal{T}} g(\boldsymbol{t})\lambda(\boldsymbol{t})\,\mathrm{d}\boldsymbol{t} = \int_{[0,1]^d} g(\boldsymbol{\Psi}(\boldsymbol{x}))\lambda(\boldsymbol{\Psi}(\boldsymbol{x}))\lvert\boldsymbol{\Psi}'(\boldsymbol{x})\rvert\,\mathrm{d}\boldsymbol{x} = \int_{[0,1]^d} f(\boldsymbol{x})\,\mathrm{d}\boldsymbol{x} = \mathbb{E}[f(\boldsymbol{X})]$$

$$\boldsymbol{X} \sim \mathcal{U}[0,1]^d$$

Original Integrand $g : \mathcal{T} \to \mathbb{R}$

True Measure $\lambda : \mathcal{T} \to \mathbb{R}^+$ e.g. probability density or 1 for Lebesgue measure

Transformation $\boldsymbol{\Psi} : [0,1]^d \to \mathcal{T}$ with Jacobian $\lvert\boldsymbol{\Psi}'(\boldsymbol{x})\rvert$

Transformed Integrand $f : [0,1]^d \to \mathbb{R}$

QMCPy automatically approximates integrals

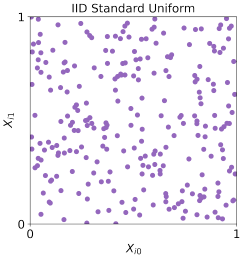
Approximate the Integral by Sampling Well

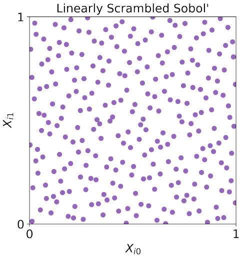
$$\text{sample mean} = \hat{\mu}_n = \frac{1}{n}\sum_{i=1}^{n} f(\boldsymbol{x}_i) \approx \int_{[0,1]^d} f(\boldsymbol{x})\,\mathrm{d}\boldsymbol{x} = \mu = \text{mean}$$

Discrete Distribution: $\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots \boldsymbol{x}_n \sim \mathcal{U}[0,1]^d$

Monte Carlo: $\{\boldsymbol{x}_i\}_{i=1}^n$ IID (Independent Identically Distributed)

Quasi-Monte Carlo: $\{\boldsymbol{x}_i\}_{i=1}^n$ LD (Low-Discrepancy)

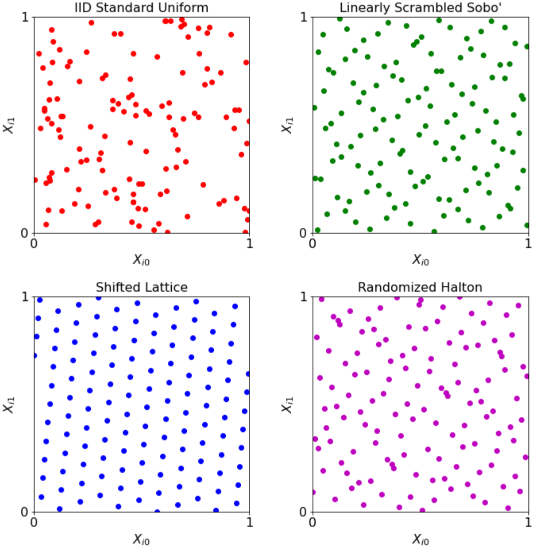




Discrete Distribution Samplers: Generate sampling locations

Sobol' Example

```
>>> import qmcpy as qp
>>> sobol = qp.Sobol(2)
>>> sobol.gen_samples(2**3)
array([[0.387, 0.146],
       [0.552, 0.506],
       [0.169, 0.901],
       [0.771, 0.258],
       [0.303, 0.724],
       [0.639, 0.116],
       [0.023, 0.48 ],
       [0.922, 0.867]])
```

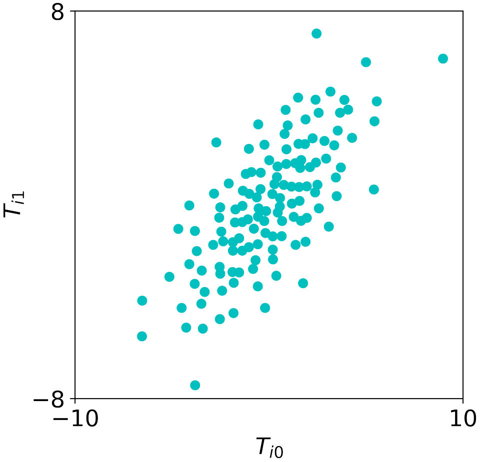


True Measure Transforms: Apply change of variables

Gaussian Example

$$\boldsymbol{\Psi}(\boldsymbol{X}) = \boldsymbol{a} + \mathsf{A}\boldsymbol{\Phi}^{-1}(\boldsymbol{X}) \sim \mathcal{N}(\boldsymbol{a}, \Sigma = \mathsf{A}\mathsf{A}^T)$$

```
>>> gauss = qp.Gaussian(sobol,
...     mean =             [0,0],
...     covariance = [[7,5],
...                   [5,7]])
>>> gauss.gen_samples(2**2)
array([[ 0.352, -1.754],
       [ 0.302,  0.333],
       [-3.633, -1.054],
       [ 2.462,  1.166]])
```



Integrand Examples: Define the original integrand

Keister Example [1]

$$\mu = \int_{\mathbb{R}^d} \cos(\|\boldsymbol{t}\|) \exp(-\|\boldsymbol{t}\|^2) \, \mathrm{d}\boldsymbol{t}$$

$$= \int_{\mathbb{R}^d} \underbrace{\pi^{d/2} \cos(\|\boldsymbol{t}\|)}_{g(\boldsymbol{t})} \underbrace{\mathcal{N}(\boldsymbol{t}|\boldsymbol{0},\mathsf{I}/2)}_{\lambda(\boldsymbol{t})} \, \mathrm{d}\boldsymbol{t}$$

$$= \int_{[0,1]^d} \pi^{d/2} \cos(\|\boldsymbol{\Psi}(\boldsymbol{x})\|) \, \mathrm{d}\boldsymbol{x}$$

$$= \int_{[0,1]^d} \underbrace{g(\boldsymbol{\Psi}(\boldsymbol{x}))}_{f(\boldsymbol{x})} \, \mathrm{d}\boldsymbol{x}$$

```
>>> from numpy import sqrt,pi,cos
>>> def my_keister(t):
...     d = t.shape[1]
...     norm = sqrt((t**2).sum(1))
...     k = pi**(d/2)*cos(norm)
...     return k
>>> sob5 = qp.Sobol(5)
>>> gauss_sob = qp.Gaussian(sob5,
...     mean = 0, covariance = 1/2)
>>> keister = qp.CustomFun(
...     true_measure = gauss_sob,
...     g = my_keister)
>>> x = sob5.gen_samples(2**20)
>>> y = keister.f(x)
>>> mu_hat = y.mean()
>>> mu_hat
1.1353362571289711
```

Stopping Criterion: Determine n so $|\mu - \hat{\mu}_n| < \epsilon$

Samples n required for

$$\text{Monte Carlo: } \mathcal{O}(\epsilon^{-2})$$

$$\text{Quasi-Monte Carlo: } \mathcal{O}(\epsilon^{-1})$$

QMC is significantly more efficient!

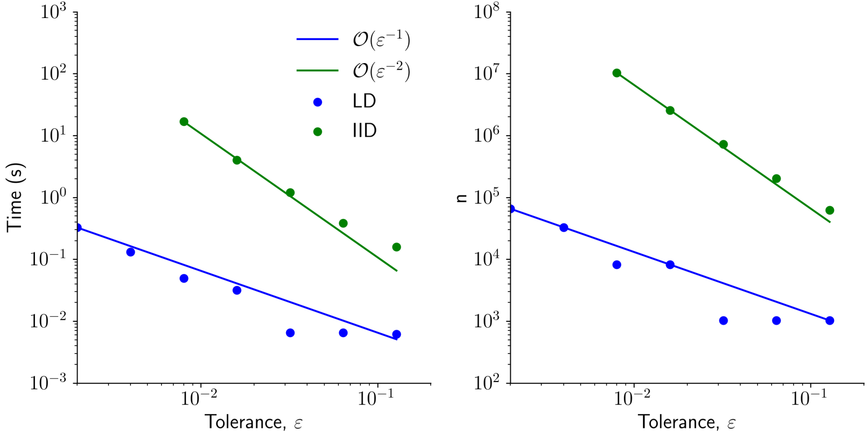
Sobol' Cubature Example [2]

```
>>> sc = qp.CubQMCSobolG(
...         integrand = keister,
...         abs_tol = 1e-4)
>>> sol,data = sc.integrate()
```

```
>>> data
Solution: 1.1353
CustomFun (Integrand)
Sobol (DiscreteDistribution)
    d                   5
    mimics              StdUniform
Gaussian (TrueMeasure)
    mean                0
    covariance          2^(-1)
CubQMCSobolG (StoppingCriterion)
    abs_tol             1.00e-04
    rel_tol             0
LDTransformData (AccumulateData)
    n_total             2^(20)
    solution            1.135
    error_bound         9.89e-05
    time_integrate      1.219
```

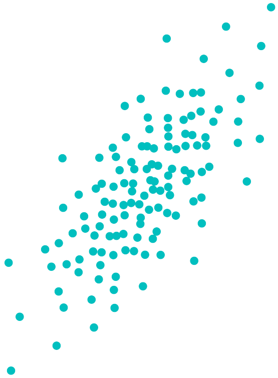
QMC Beats MC

Standard Keister Integrand in 5 Dimensions



QMCPy Resources

- PyPI: pypi.org/project/qmcpy/
- GitHub: github.com/QMCSoftware/QMCSoftware
- Documentation: qmcpy.readthedocs.io
- Blogs: qmcpy.org
- MCQMC2020 Tutorial
  - Slides: qmcpy.org/mcqmc-2020-tutorial/
  - Notebook: tinyurl.com/QMCPyTutorial
  - "Quasi-Monte Carlo Software" Article [3]



References

1. Keister, B. D. Multidimensional Quadrature Algorithms. *Computers in Physics* **10**, 119–122 (1996).
2. Hickernell, F. J. & Jiménez Rugama, L. A. *Reliable Adaptive Cubature Using Digital Sequences.* 2014. arXiv: 1410.8615 [math.NA].
3. Choi, S.-C. T., Hickernell, F. J., Jagadeeswaran, R., McCourt, M. J. & Sorokin, A. G. *Quasi-Monte Carlo Software.* 2021. arXiv: 2102.07833 [cs.MS].