A Proposal for Community (Quasi-) Monte Carlo Software

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Follow-Up to Discussions, June 28, 2018

Questions that I Ask or Hear Asked

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My initial attempts in this direction over the past 5 years have produced GAIL[1]

[1] Choi, S.-C. T. *et al.* *GAIL: Guaranteed Automatic Integration Library (Versions 1.0–2.2).* MATLAB software. 2013–2017. `http://gailgithub.github.io/GAIL_Dev/`.

Can We Have qMC Community Software that Grows Up to Be Like ...

Chebfun Computing with Chebyhsev polynomials, `chebfun.org`

Clawpack Solution of conservation laws, `clawpack.org`

deal.II Finite-elements, `http://dealii.org`
Mission: To provide well-documented tools to build finite element codes for a broad variety of PDEs, from laptops to supercomputers.
Vision: To create an open, inclusive, participatory community providing users and developers with a state-of-the-art, comprehensive software library that constitutes the go-to solution for all finite element problems.

FEniCS Finite-elements, `fenicsproject.org`

Gromacs Molecular dynamics, `gromacs.org`

Stan Markov Chain Monte Carlo, `mc-stan.org`

Trilinos Multiphysics computations, `trilinos.org`

- Developed and supported by multiple research groups
- Used beyond the research groups that develop it
- A recognized standard in its field

What Is Available Now

John Burkhardt Variety of qMC Software in C++, Fortran, MATLAB, and Python, `people.sc.fsu.edu/~jburkardt/`

Mike Giles Multi-Level Monte Carlo Software in C++, MATLAB, Python, and R, `people.maths.ox.ac.uk/gilesm/mlmc/`

Fred Hickernell Guaranteed Automatic Integration Library (GAIL) in MATLAB, `gailgithub.github.io/GAIL_Dev/`

Stephen Joe & Frances Kuo Sobol' generators in C++, Generating vectors for lattices, `web.maths.unsw.edu.au/~fkuo/`

Pierre L'Ecuyer Random number generators, Stochastic Simulation, Lattice Builder in C/C++ and Java, `simul.iro.umontreal.ca`

Dirk Nuyens Magic Point Shop, QMC4PDE, etc. in MATLAB, Python, and C++, `people.cs.kuleuven.be/~dirk.nuyens/`

Art Owen Various code, `statweb.stanford.edu/~owen/code/`

Christoph Schwab Partial differential equations with random coefficients

MATLAB Sobol' and Halton sequences

Python Sobol' and Halton sequences

R `randtoolbox` Sobol', lattice, and Halton sequences

Decisions to Make If We Want to Succeed

Key Elements

- Sequences—IID, Sobol', lattice, Halton, sparse grid, . . . , including randomization; fixed and extensible sample size and dimension; constructions using optimization

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- Packages that display output in tables or plots

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- How will parallel computing be supported?

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- Marketing on websites and at conferences

Bigger than One Research Group

- We have experience over the past 5 years developing GAIL[2]
- Our group has learned some of the discipline required to develop good software
- Our group does not have the capacity to tackle this whole project, and neither does your group
- A good software library should attract developers
- Let's leave a legacy to our community that goes beyond theorems and algorithms

[2]Choi, S.-C. T. *et al.* *GAIL: Guaranteed Automatic Integration Library (Versions 1.0–2.2).* MATLAB software. 2013–2017. `http://gailgithub.github.io/GAIL_Dev/`.

We Must Weigh . . .

Costs	Benefits
Less time to prove theorems	More impact for our theorems
Learning a new language	Wider access and better performance for our code
Compromise with other research groups	More capable code than can be produced by one research group
Time spent writing documentation and tests	Fewer bugs for those who use the code
	Attract more qMC developers
	Attract more qMC users
	Happier funding agencies

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- We welcome you to join us. Email me to join our Google group

Elements of the Community Software—Discrete Distributions

```
classdef (Abstract) discreteDistribution

%Specifies and generates the components of $a_n \sum_{i=1}^{n} w_i \delta_{\mathbf{x}_i}(\cdot)$

properties (Abstract)
   distribData %information required to generate the distribution
   state %state of the generator
   nStreams
end
properties
   domain = [0 0; 1 1]; %domain of the discrete distribution, $\mathcal{X}$
   domainType = 'box' %domain of the discrete distribution, $\mathcal{X}$
   dimension = 2 %dimension of the domain, $d$
   trueDistribution = 'uniform' %name of the distribution that the discrete ...
       distribution attempts to emulate
end
```

Elements of the Community Software—Discrete Distributions

```
classdef (Abstract) discreteDistribution
methods (Abstract)
   genDistrib(obj, nStart, nEnd, n, coordIndex)
   % nStart = starting value of i
   % nEnd = ending value of i
   % n = value of n used to determine a_n
   % coordIndex = which coordinates in sequence are needed
end
end
```

Elements of the Community Software—Discrete IID Uniform

```
classdef IIDDistribution < discreteDistribution
%Specifies and generates the components of 1/n sum_{i=1}^n delta_{x_i}(.)
%where the x_i are IID uniform on [0,1]^d or IID standard Gaussian
properties
   distribData %stream data
   state = [] %not used
   nStreams = 1
end

methods
   function obj = initStreams(obj,nStreams)
      obj.nStreams = nStreams;
      obj.distribData.stream = ...
         RandStream.create('mrg32k3a','NumStreams',nStreams,'CellOutput',true);
   end
```

$$\frac{1}{n}\sum_{i=1}^{n}\delta_{\mathbf{x}_i}(\cdot)$$

Elements of the Community Software—Discrete IID Uniform

```
classdef IIDDistribution < discreteDistribution
   function [x, w, a] = genDistrib(obj, nStart, nEnd, n, coordIndex, ...
       streamIndex)
      if nargin < 6
         streamIndex = 1;
      end
      nPts = nEnd - nStart + 1; %how many points to be generated
      if strcmp(obj.trueDistribution, 'uniform') %generate uniform points
         x = ...
             rand(obj.distribData.stream{streamIndex},nPts,numel(coordIndex)); ...
             %nodes
      else %standard normal points
         x = ...
             randn(obj.distribData.stream{streamIndex},nPts,numel(coordIndex)); ..
             %nodes
      end
      w = 1;
      a = 1/n;
   end
end
```

Elements of the Community Software—Functions

```
classdef (Abstract) fun
% Specify and generate values f(x) for x ∈ 𝒳
properties
   domain = [0 0; 1 1] %domain of the function, 𝒳
   domainType = 'box' %e.g., 'box', 'ball'
   dimension = 2 %dimension of the domain, d
   distribType = 'uniform' %e.g., 'uniform', 'Gaussian'
   nominalValue = 0 %a nominal number, c, such that (c,...,c) ∈ 𝒳
end

methods (Abstract)
    y = f(obj, xu, coordIndex)
   % xu = nodes, x_{u,i} = i^th row of an n × |u| matrix
   % coordIndex = set of those coordinates in sequence needed, u
   % y = n × 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 ∈ u, and x'_{ij} = c otherwise
end

end
```

Elements of the Community Software—Keister's Function

```
classdef KeisterFun < fun
% Specify and generate values f(x) for x ∈ 𝒳
methods
   function y = f(obj, x, coordIndex)
      %if the nominalValue = 0, this is efficient
      normx2 = sum(x.*x,2);
      if (numel(coordIndex) ≠ obj.dimension) && (obj.nominalValue ≠ 0)
         normx2 = normx2 + (obj.nominalValue.^2) * (obj.dimension - ...
             numel(coordIndex));
      end
      y = exp(-normx2) .* cos(sqrt(normx2));
   end
end
end
```

Elements of the Community Software—StoppingCriteria

```
classdef (Abstract) stoppingCriterion
% Decide when to stop a
properties
   absTol = 1e-2 %absolute tolerance, d
   relTol = 0 %absolute tolerance, d
   nInit = 1024 %initial sample size
   nMax = 1e8 %maximum number of samples allowed
end
properties (Abstract)
   discDistAllowed %which discrete distributions are supported
   decompTypeAllowed %which decomposition types are supported
end
methods (Abstract)
    stopYet(obj, distribObj)
   % distribObj = data or summary of data computed already
end
end
```

Elements of the Community Software—CLTStopping

```
classdef CLTStopping < stoppingCriterion
% Stopping criterion based on the Central Limit Theorem
properties
   discDistAllowed = "IIDDistribution" %which discrete distributions are ...
       supported
   decompTypeAllowed = ["single"; "multi"] %which decomposition types are ...
       supported
   inflate = 1.2 %inflation factor
   alpha = 0.01;
end

properties (Dependent)
   quantile
end
```

Elements of the Community Software—CLTStopping

```
classdef CLTStopping < stoppingCriterion
methods
    function [obj, dataObj, distribObj] = ...
            stopYet(obj, dataObj, funObj, distribObj)
        if ¬numel(dataObj)
            dataObj = meanVarData;
        end
        switch dataObj.stage
```

Elements of the Community Software—CLTStopping

```
classdef CLTStopping < stoppingCriterion
      switch dataObj.stage
         case 'begin' %initialize
            dataObj.timeStart = tic;
            if ¬any(strcmp(obj.discDistAllowed,class(distribObj)))
               error('Stoppoing criterion not compatible with sampling ...
                   distribution')
            end
            nf = numel(funObj); %number of functions whose integrals add up ...
                to the solution
            distribObj = initStreams(distribObj,nf); %need an IID stream ...
                for each function
            dataObj.prevN = zeros(1,nf); %initialize data object
            dataObj.nextN = repmat(obj.nInit,1,nf);
            dataObj.muhat = Inf(1,nf);
            dataObj.sighat = Inf(1,nf);
            dataObj.nSigma = obj.nInit; %use initial samples to estimate ...
                standard deviation
            dataObj.costF = zeros(1,nf);
            dataObj.stage = 'sigma'; %compute standard deviation next
```

Elements of the Community Software—CLTStopping

```
classdef CLTStopping < stoppingCriterion
        case 'sigma'
            dataObj.prevN = dataObj.nextN; %update place in the sequence
            tempA = sqrt(dataObj.costF); %use cost of function values to ...
                decide how to allocate
            tempB = sum(tempA .* dataObj.sighat); %samples for computation ...
                of the mean
            nM = ceil((tempB*(obj.quantile*obj.inflate ...
               /max(obj.absTol,dataObj.solution*obj.relTol))^2) ...
               * (dataObj.sighat./sqrt(dataObj.costF)));
            dataObj.nMu = min(max(dataObj.nextN,nM),obj.nMax - dataObj.prevN);
            dataObj.nextN = dataObj.nMu + dataObj.prevN;
            dataObj.stage = 'mu'; %compute sample mean next
```

Elements of the Community Software—CLTStopping

```
classdef CLTStopping < stoppingCriterion
         case 'mu'
            dataObj.solution = sum(dataObj.muhat);
            dataObj.nSamplesUsed = dataObj.nextN;
            errBar = (obj.quantile * obj.inflate) * ...
               sqrt(sum(dataObj.sighat.^2/dataObj.nMu));
            dataObj.errorBound = dataObj.solution + errBar*[-1 1];
            dataObj.stage = 'done'; %finished with computation
      end
      dataObj.timeUsed = toc(dataObj.timeStart);
   end

   function value = get.quantile(obj)
      value = -norminv(obj.alpha/2);
   end

  end
end
```

Elements of the Community Software—Integration

```
function [solution, dataObj] = integrate(funObj, distribObj, stopCritObj)
%Specify and generate values f(x) for x ∈ 𝒳
% funObj = an object from class fun
% distribObj = an object from class discrete_distribution
% stopcritObj = an object from class stopping_criterion

%Initialize the accumData object and other crucial objects
[stopCritObj, dataObj, distribObj] = stopYet(stopCritObj, [], funObj, ...
    distribObj);
while ¬strcmp(dataObj.stage, 'done') %the dataObj.stage property tells us ...
    where we are in the process
   dataObj = updateData(dataObj, distribObj, funObj); %compute additional data
   [stopCritObj, dataObj] = stopYet(stopCritObj, dataObj, funObj); %update ...
       the status of the computation
end
solution = dataObj.solution; %assign outputs
dataObj.timeUsed = toc(dataObj.timeStart);
```

Elements of the Community Software—Integration Example

```
%% How to integrate a function using our community QMC framework
% An example with Keister's function integrated with respect to the uniform
% distribution over the unit cube
stopObj = CLTStopping %stopping criterion for IID sampling using the ...
    Central Limit Theorem
distribObj = IIDDistribution; %IID sampling with uniform distribution
[sol, out] = integrate(KeisterFun, distribObj, stopObj)
```

```
>> IntegrationExample
sol = 0.4310
out =
timeUsed: 0.0014
nSamplesUsed: 7540
errorBound: [0.4210 0.4410]
```

Elements of the Community Software—Integration Example

```
stopObj.absTol = 1e-3 %decrease tolerance
[sol, out] = integrate(KeisterFun, distribObj, stopObj)
```

```
sol = 0.4253
out =
timeUsed: 0.0333
nSamplesUsed: 652546
errorBound: [0.4243 0.4263]
```

Elements of the Community Software—Integration Example

```
stopObj.absTol = 0; %impossible tolerance
stopObj.nMax = 1e6; %calculation limited by sample budget
[sol, out] = integrate(KeisterFun, distribObj, stopObj)
```

```
sol = 0.4252
out =
timeUsed: 0.0392
nSamplesUsed: 1000000
errorBound: [0.4244 0.4260]
```

Elements of the Community Software—Asian Call, Low D

```
%A multilevel example of Asian option pricing
distribObj.trueDistribution = 'normal'; %Change to normal distribution
stopObj.absTol = 0.01; %increase tolerance
stopObj.nMax = 1e8; %pushing the sample budget back up
OptionObj = AsianCallFun(4) %4 time steps
[sol, out] = integrate(OptionObj, distribObj, stopObj)
```

```
OptionObj =
dimension: 4
sol = 6.1740
out =
timeUsed: 1.0517
nSamplesUsed: 5680546
errorBound: [6.1640 6.1840]
```

Elements of the Community Software—Asian Call, High D

```
OptionObj = AsianCallFun(64) %single level, 64 time steps
[sol, out] = integrate(OptionObj, distribObj, stopObj)
```

```
OptionObj =
AsianCallFun with properties:
dimension: 64
sol =6.2036
out =
meanVarData with properties:
timeUsed: 25.1910
nSamplesUsed: 5610402
errorBound: [6.1936 6.2136]
```

Elements of the Community Software—Asian Call, Multi-Level

```
OptionObj = AsianCallFun([4 4 4]) %multilevel, 64 time steps, faster
[sol, out] = integrate(OptionObj, distribObj, stopObj)
```

```
OptionObj =
1×3 AsianCallFun array with properties:
sol = 6.2052
out =
timeUsed: 2.2171
nSamplesUsed: [8080862 446720 85907]
errorBound: [6.1968 6.2135]
```

Thank you

Slides available on SpeakerDeck at

speakerdeck.com/fjhickernell/qmc-software-presentation-to-gail

Choi, S.-C. T. *et al.* *GAIL: Guaranteed Automatic Integration Library (Versions 1.0–2.2).* MATLAB software. 2013–2017. http://gailgithub.github.io/GAIL_Dev/.