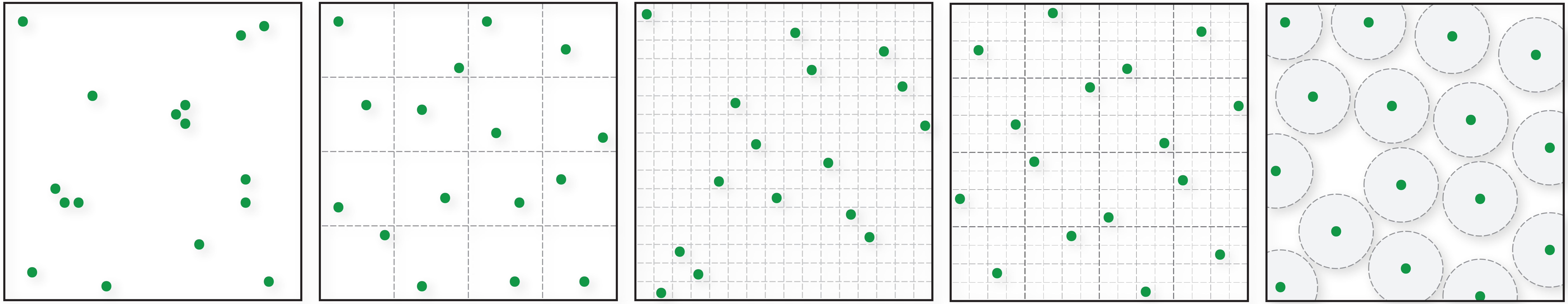
POPULAR SAMPLING PATTERNS

Fourier Analysis of Numerical Integration in Monte Carlo Rendering



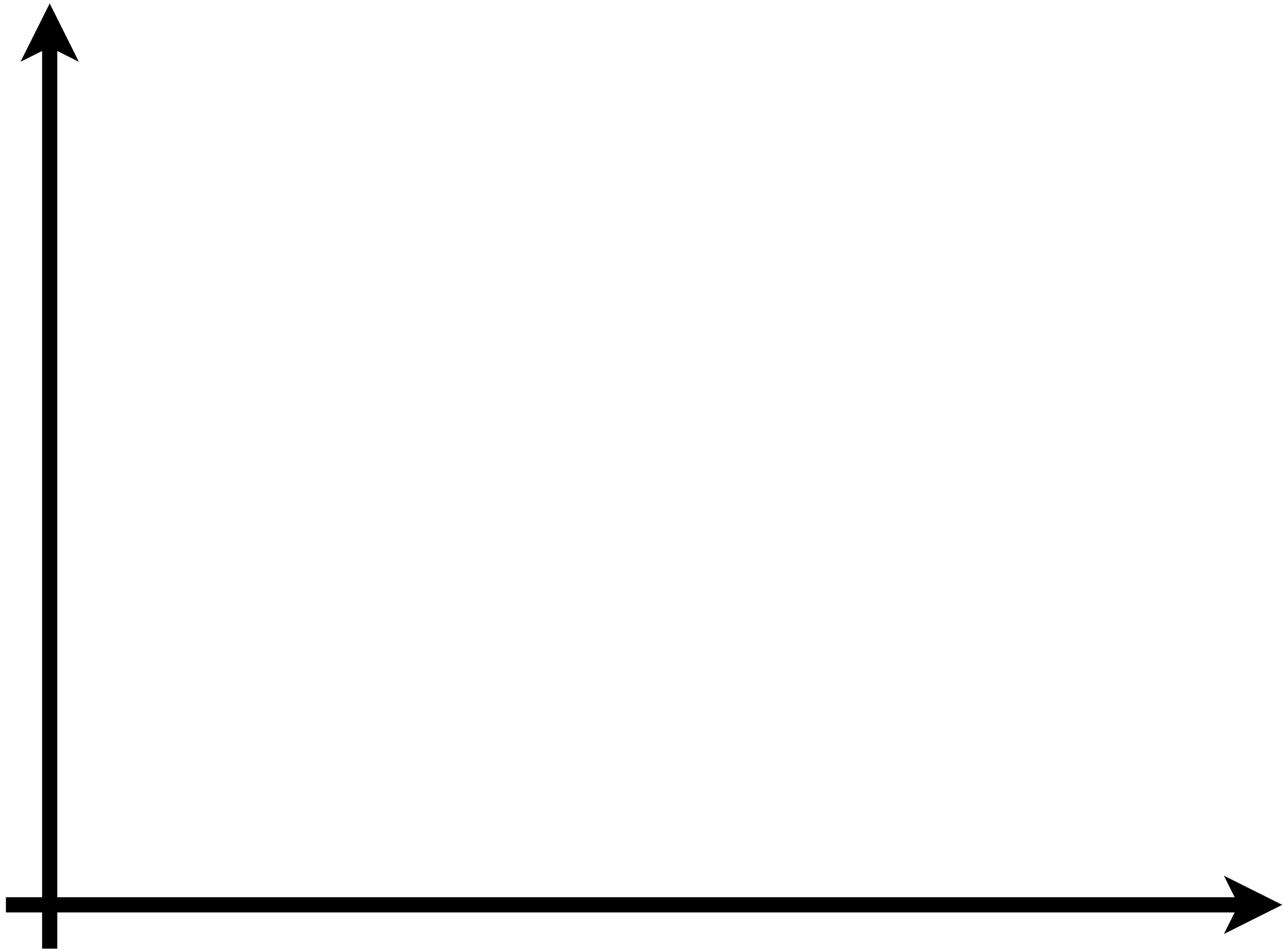
Wojciech Jarosz
wjarosz@dartmouth.edu

DARTMOUTH
VISUAL COMPUTING LAB

Render the Possibilities
SIGGRAPH2016

Recall: Monte Carlo Integration

$$I = \int_D f(x)\,\mathrm{d}x$$



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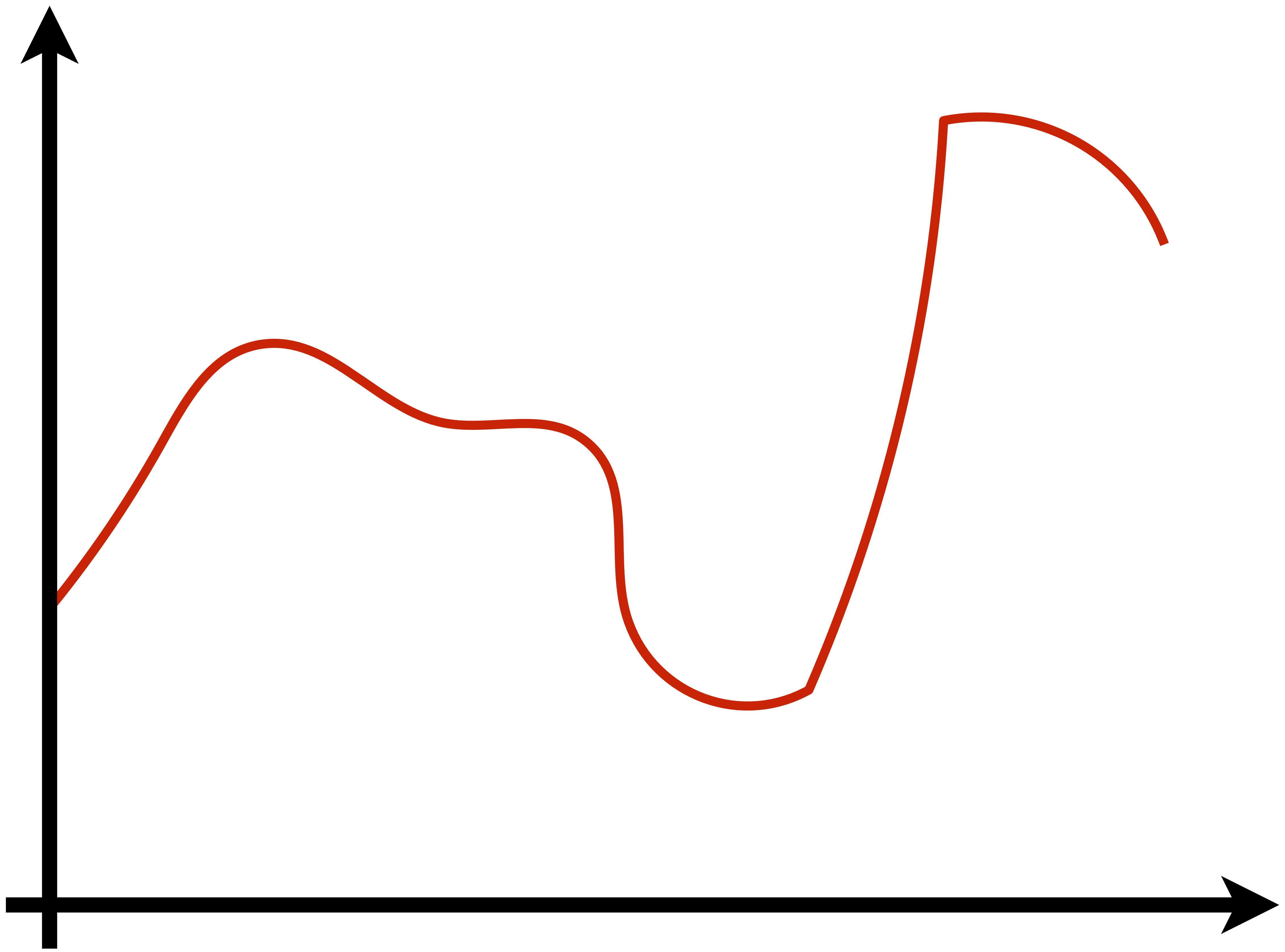

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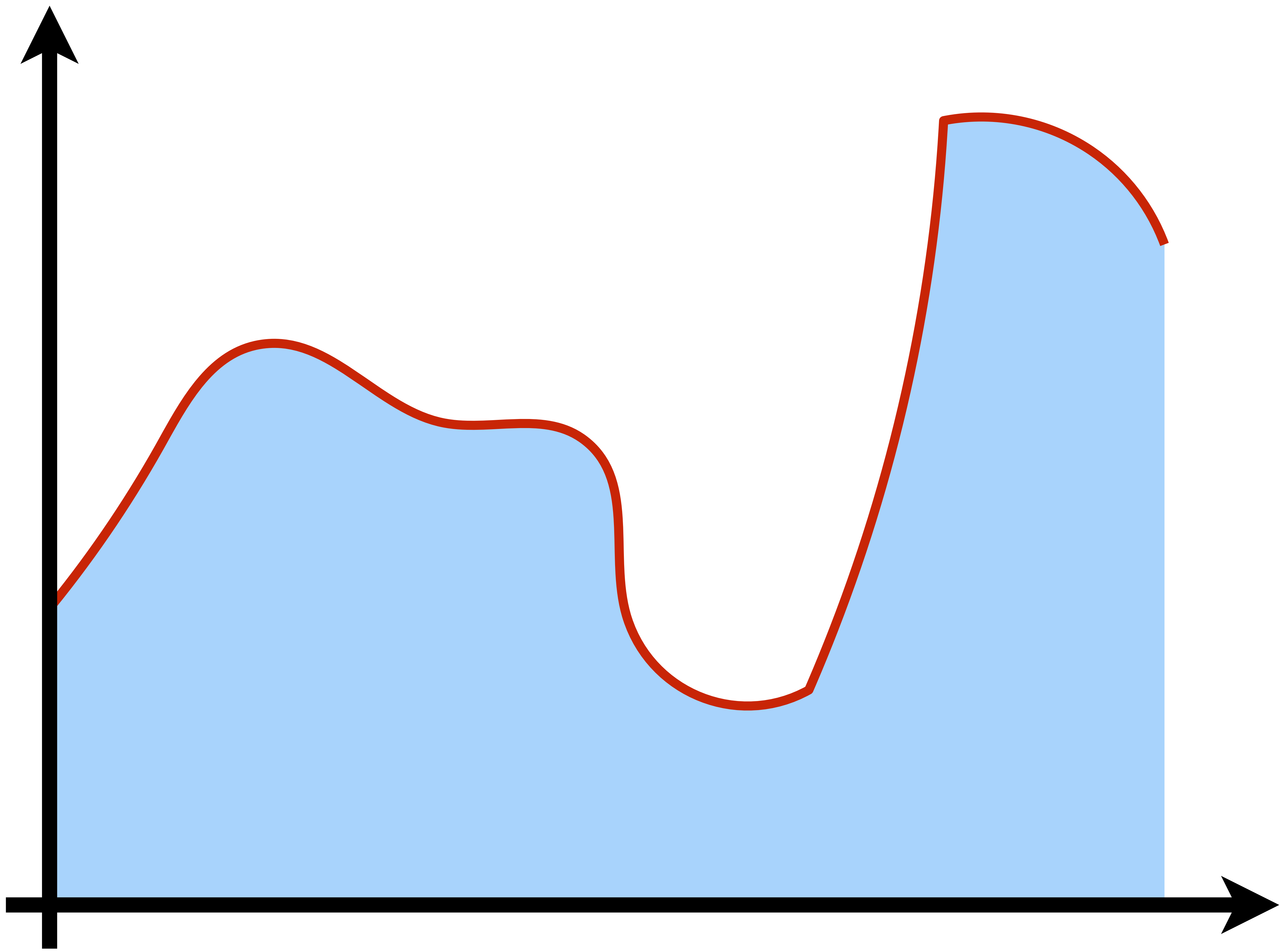
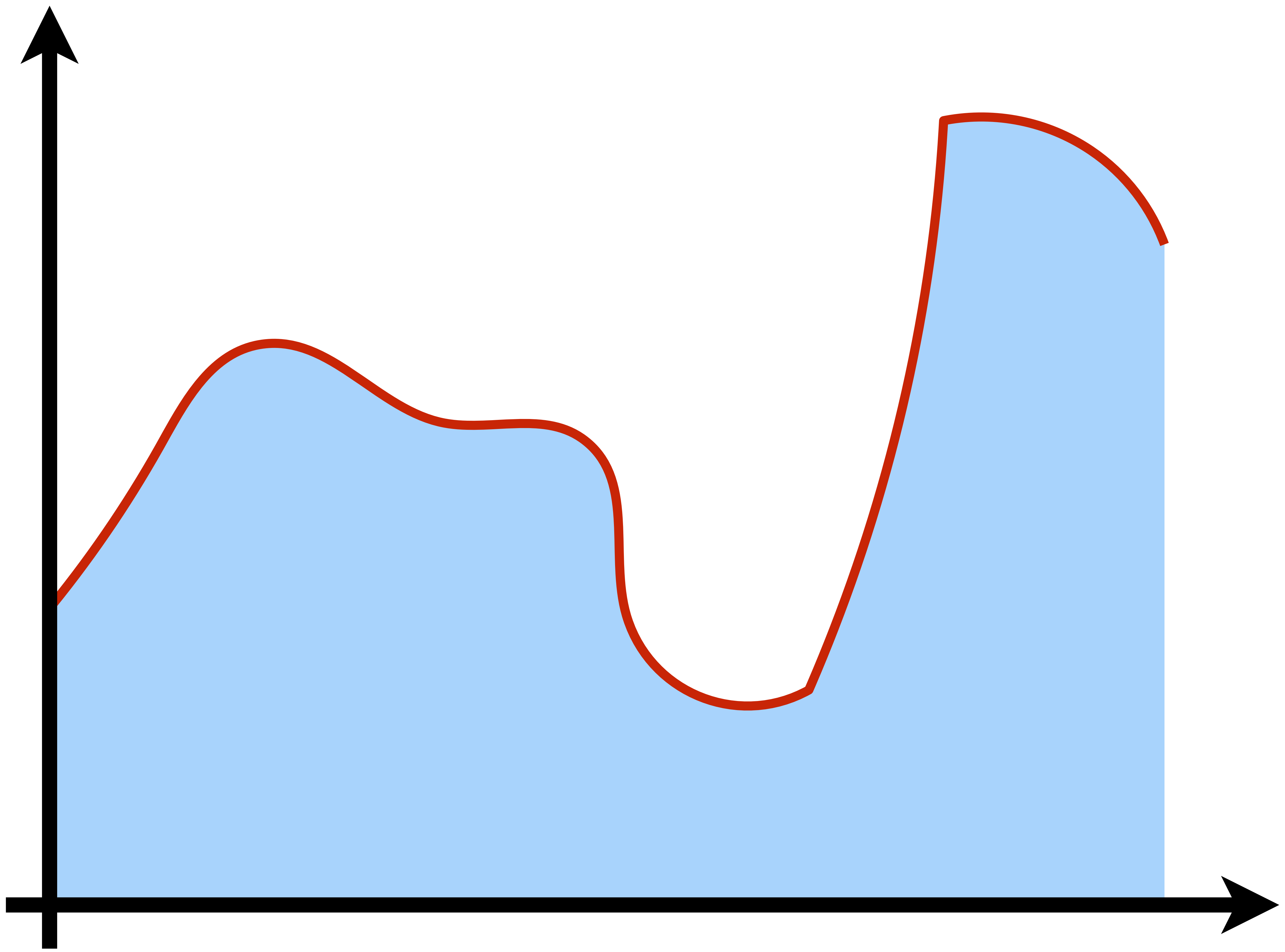


Recall: Monte Carlo Integration

$$I = \int_D f(x)\,\mathrm{d}x$$
$$\approx \int_D f(x)\,\mathbf{S}(x)\,\mathrm{d}x$$



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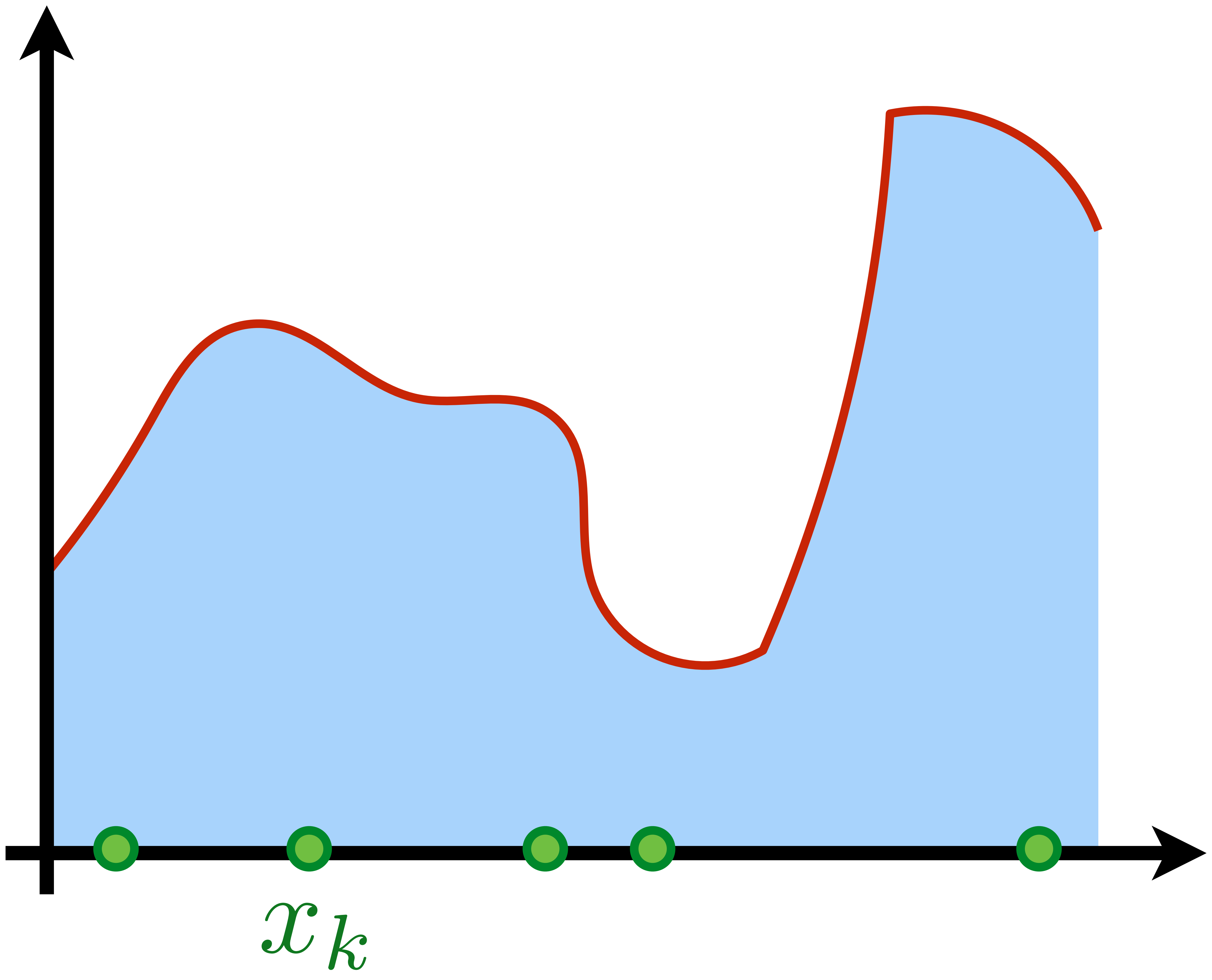

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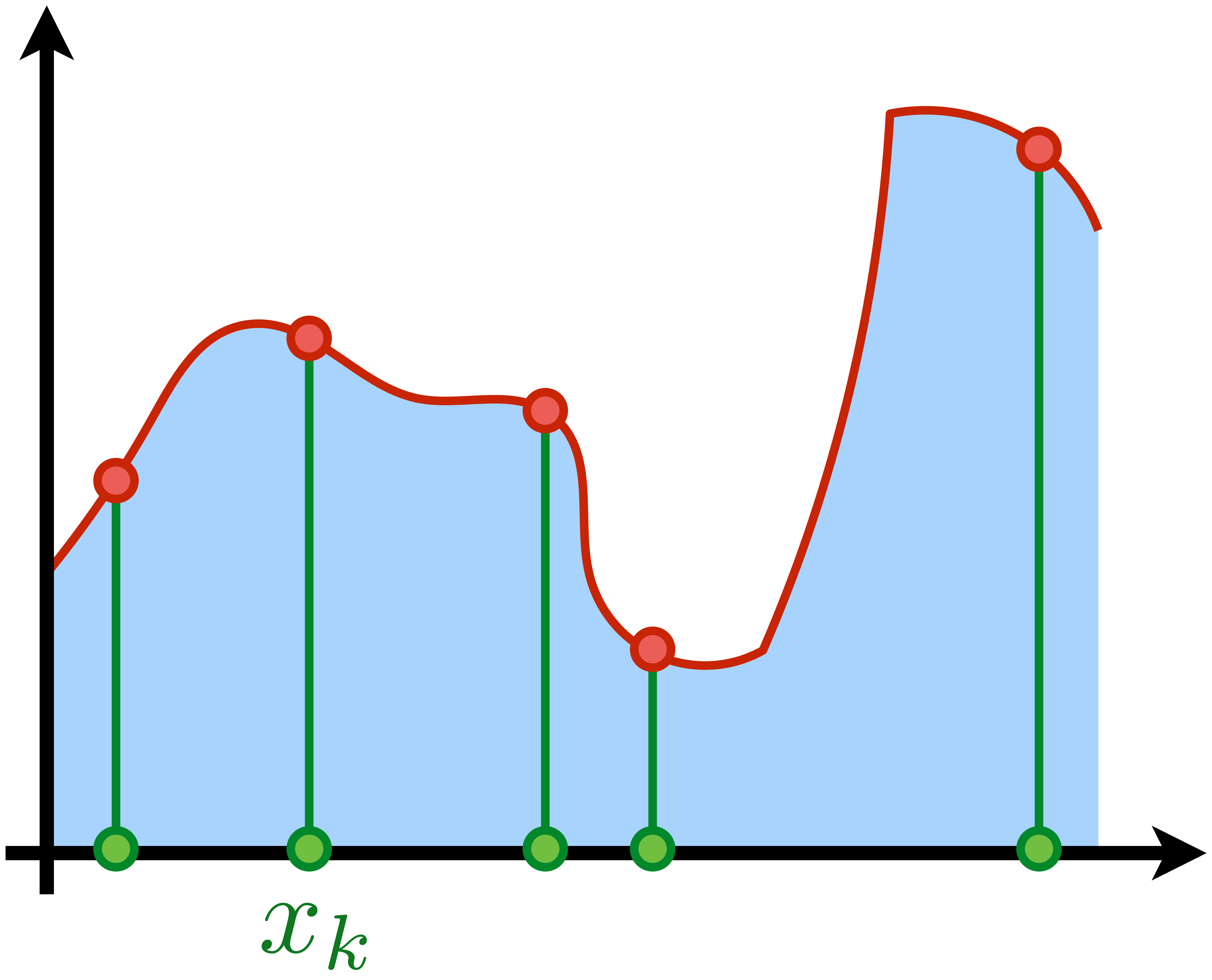

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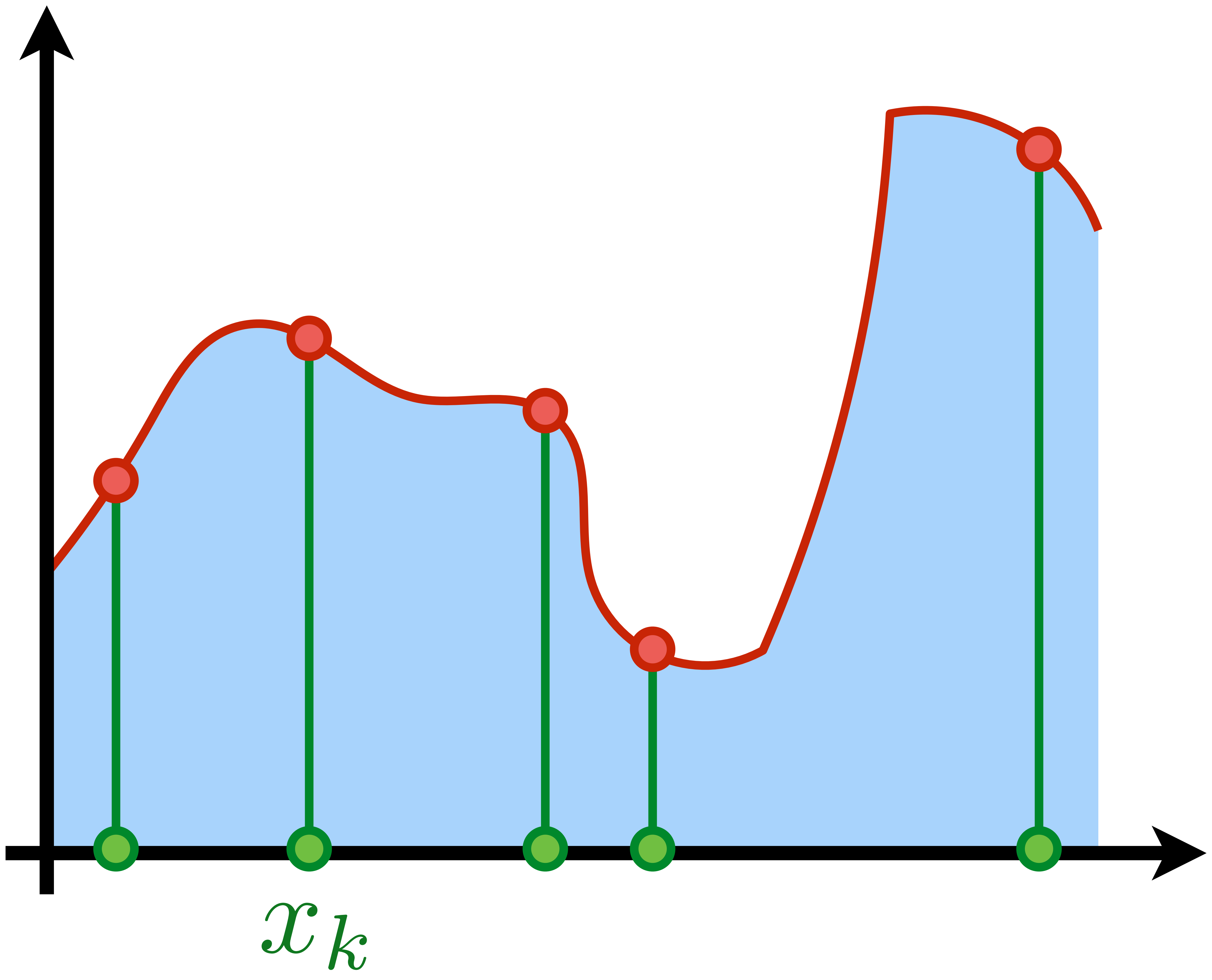
How to generate the locations x_k?



Independent Random Sampling

```
for (int k = 0; k < num; k++)
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    samples(k).x = randf();
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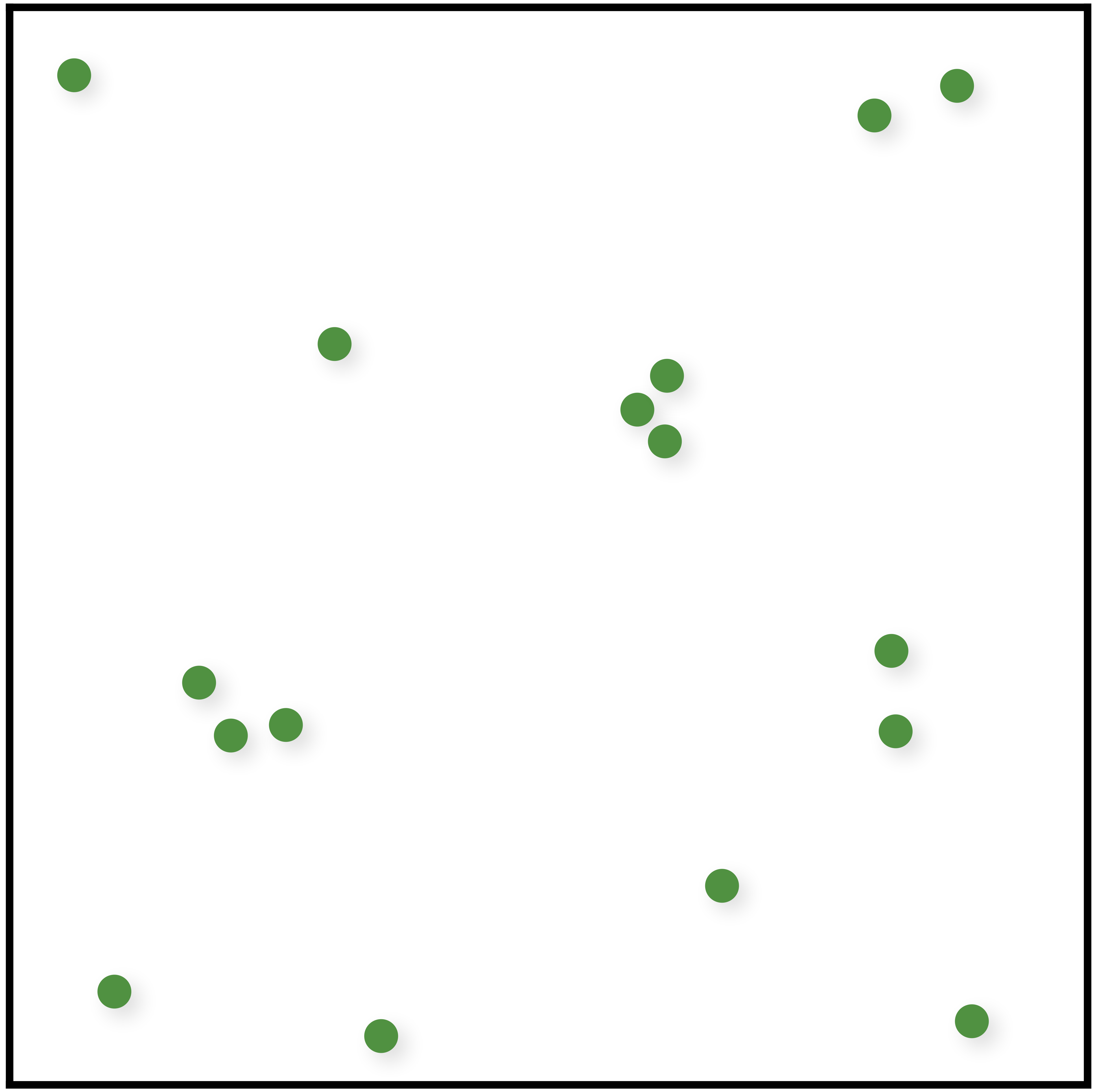

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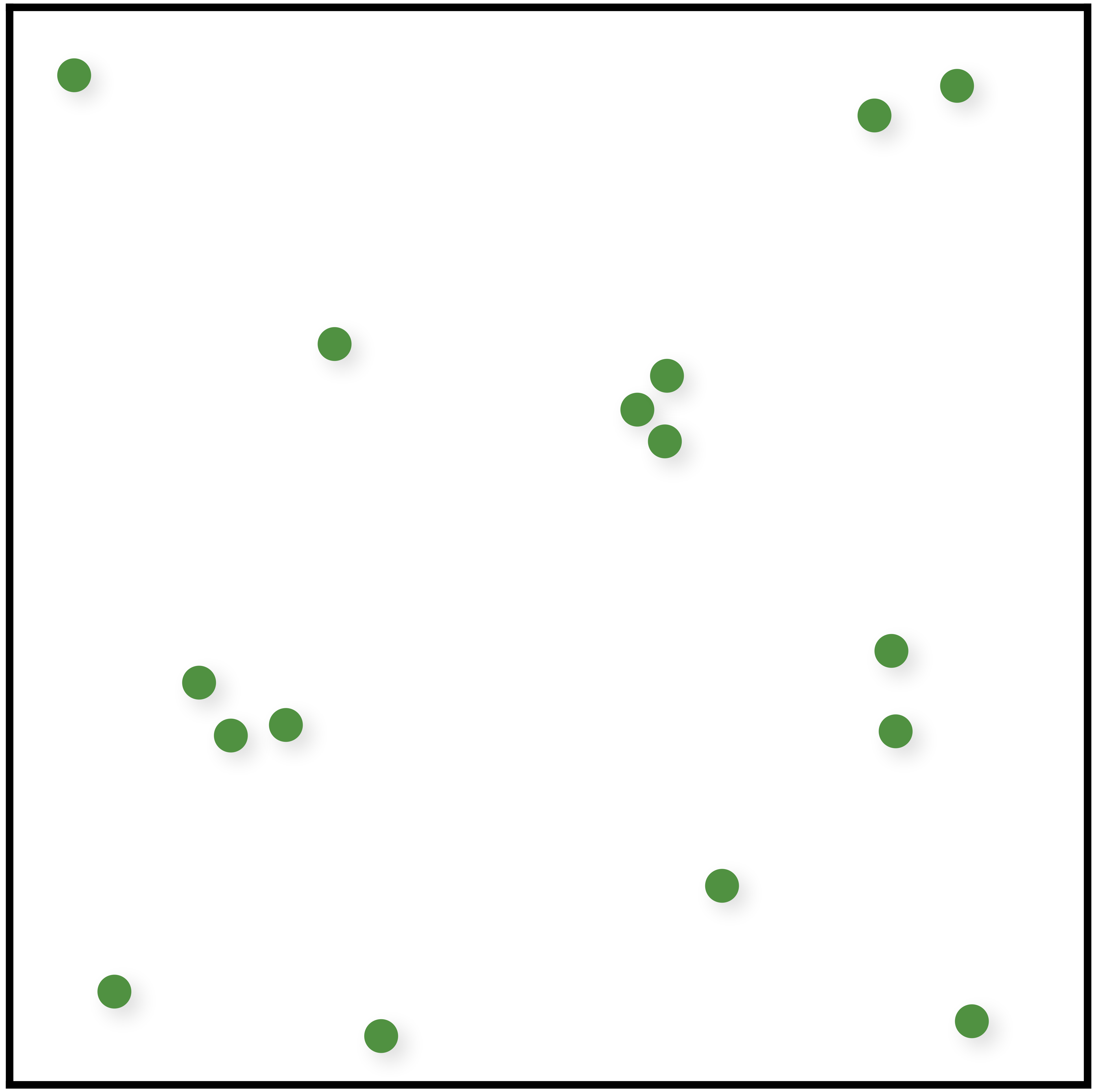
✔ Trivially extends to higher dimensions



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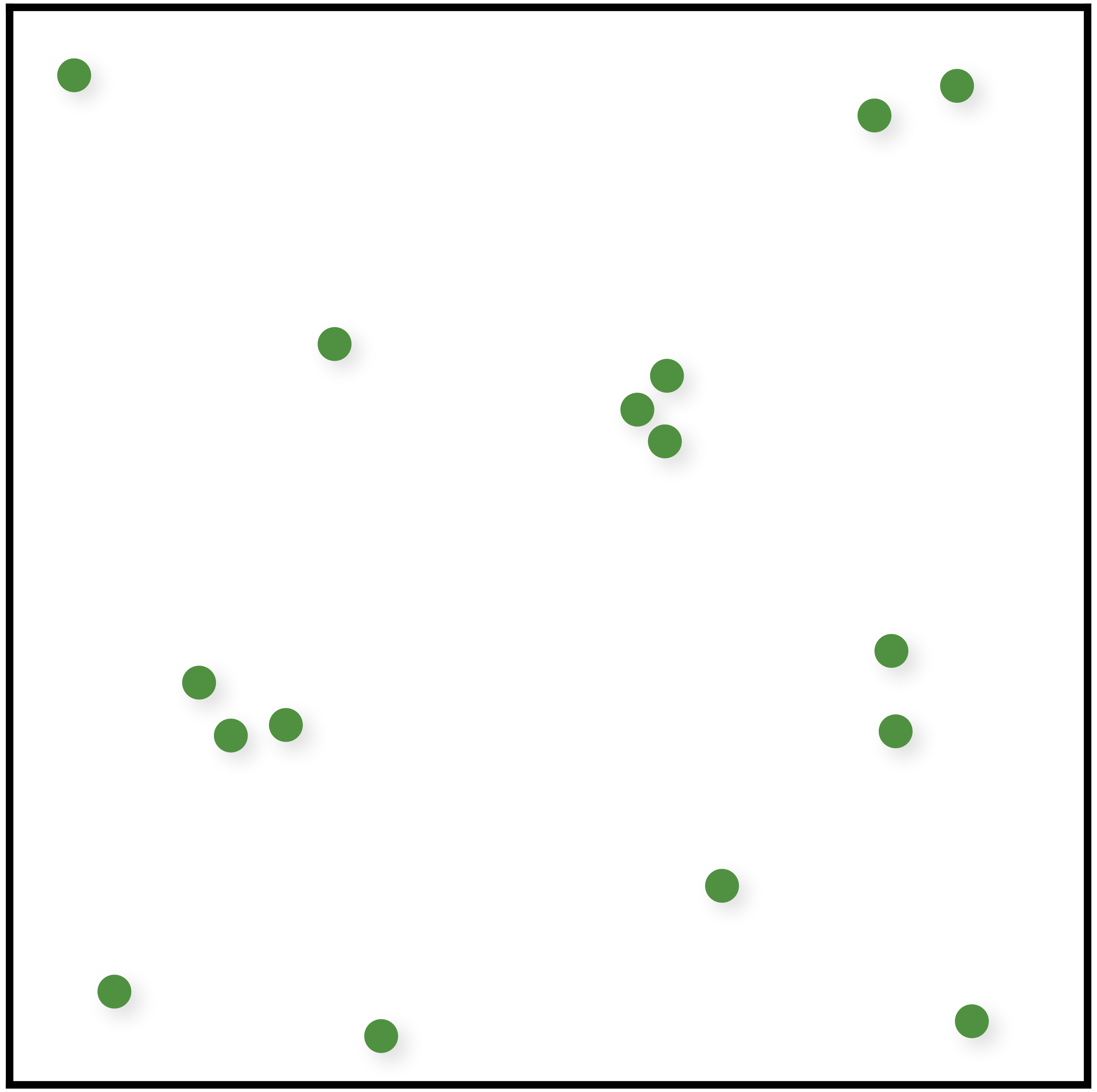
✔ Trivially extends to higher dimensions

✔ Trivially progressive and memory-less



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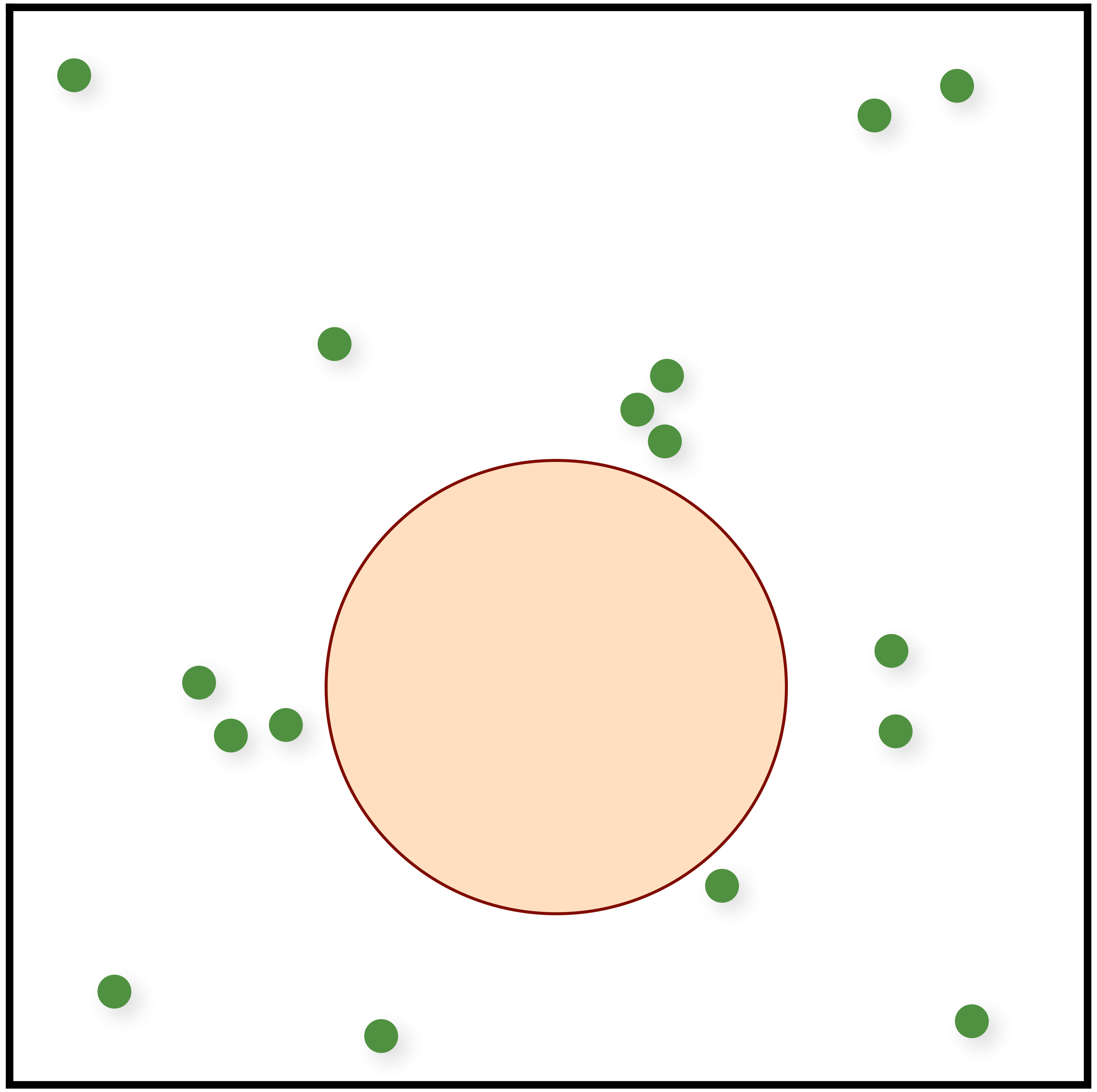

- ✔ Trivially extends to higher dimensions
- ✔ Trivially progressive and memory-less
- ✘ Big gaps

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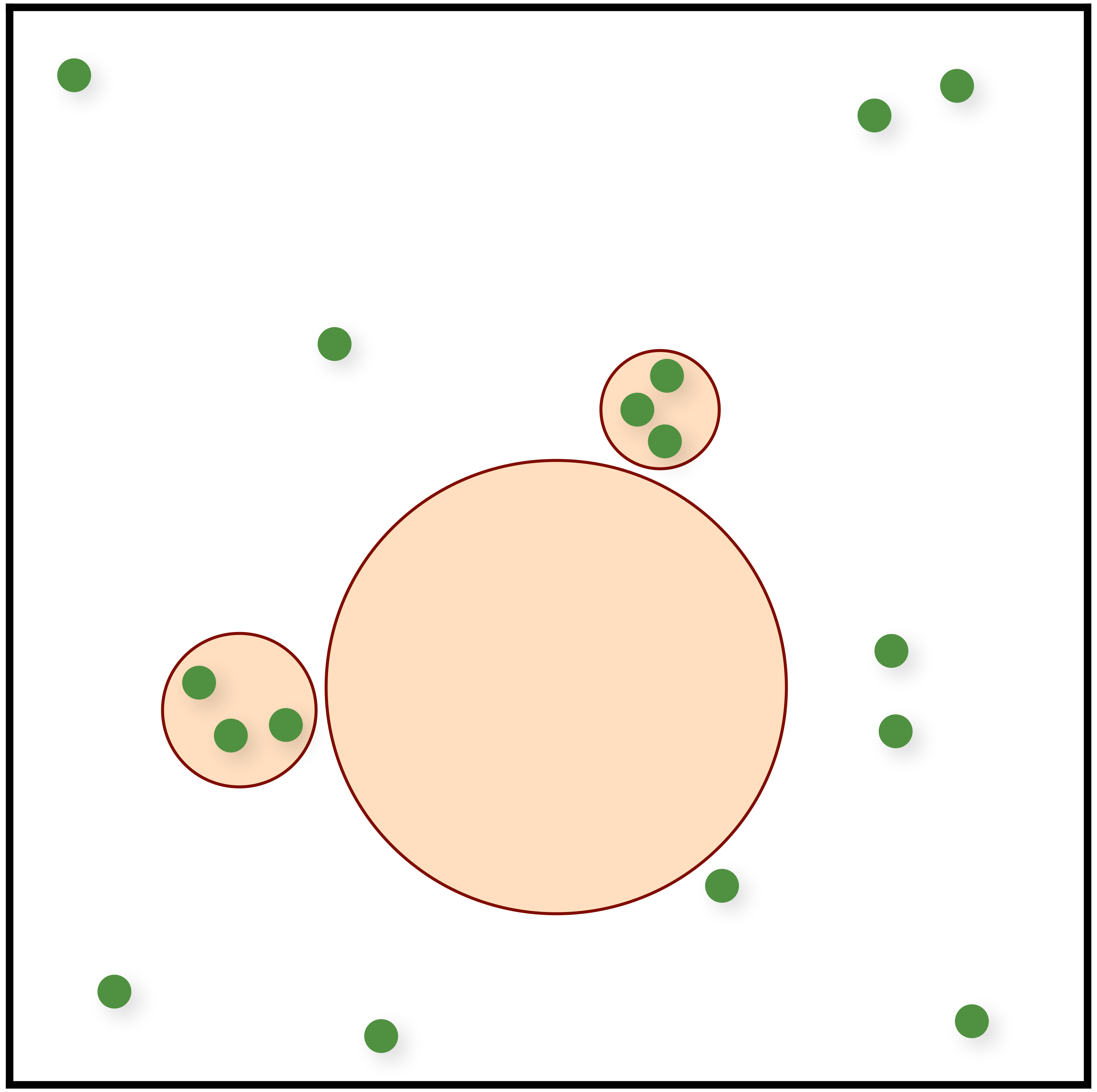

- ✔ Trivially extends to higher dimensions
- ✔ Trivially progressive and memory-less
- ✘ Big gaps
- ✘ Clumping

Recall: Fourier theory

Fourier transform: $$\hat{f}(\omega) = \int_D f(x)\, \mathrm{e}^{-2\pi \imath \omega x}\, \mathrm{d}x$$

Recall: Fourier theory

Fourier transform: $$\hat{f}(\vec{\omega}) = \int_D f(\vec{x})\, \mathrm{e}^{-2\pi\imath(\vec{\omega}\cdot\vec{x})}\, \mathrm{d}\vec{x}$$

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Sampling function: $$\hat{\mathbf{S}}(\vec{\omega}) = \int_D \mathbf{S}(\vec{x})\, \mathrm{e}^{-2\,\pi\,\imath\,(\vec{\omega}\cdot\vec{x})}\; \mathrm{d}\vec{x}$$

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Sampling function: $$\hat{\mathbf{S}}(\vec{\omega}) = \int_D \frac{1}{N} \sum_{k=1}^{N} \delta(|\vec{x} - \vec{x}_k|)\, \mathrm{e}^{-2\,\pi\,\imath\,(\vec{\omega}\cdot\vec{x})}\, \mathrm{d}\vec{x}$$

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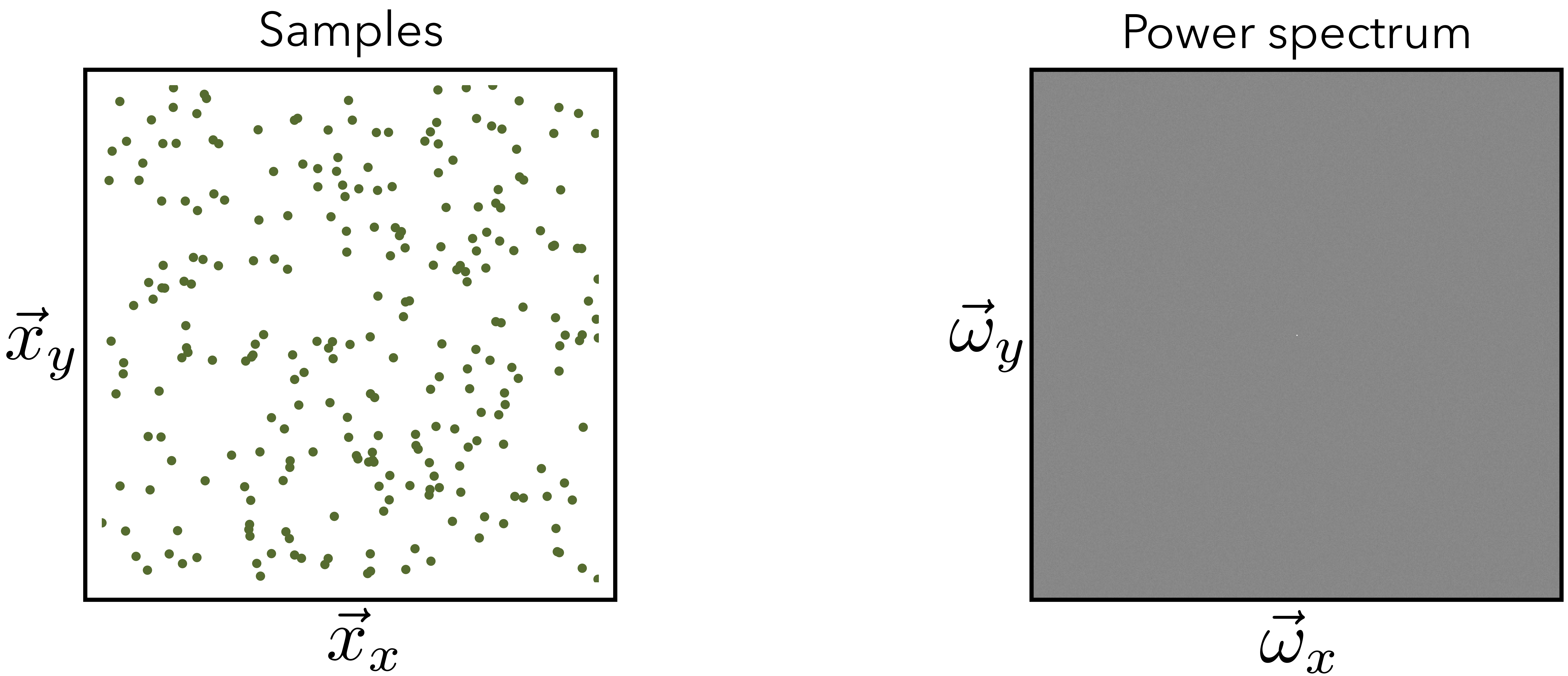
$$= \frac{1}{N}\sum_{k=1}^{N}\mathrm{e}^{-2\,\pi\,\imath\,(\vec{\omega}\cdot\vec{x}_k)}$$

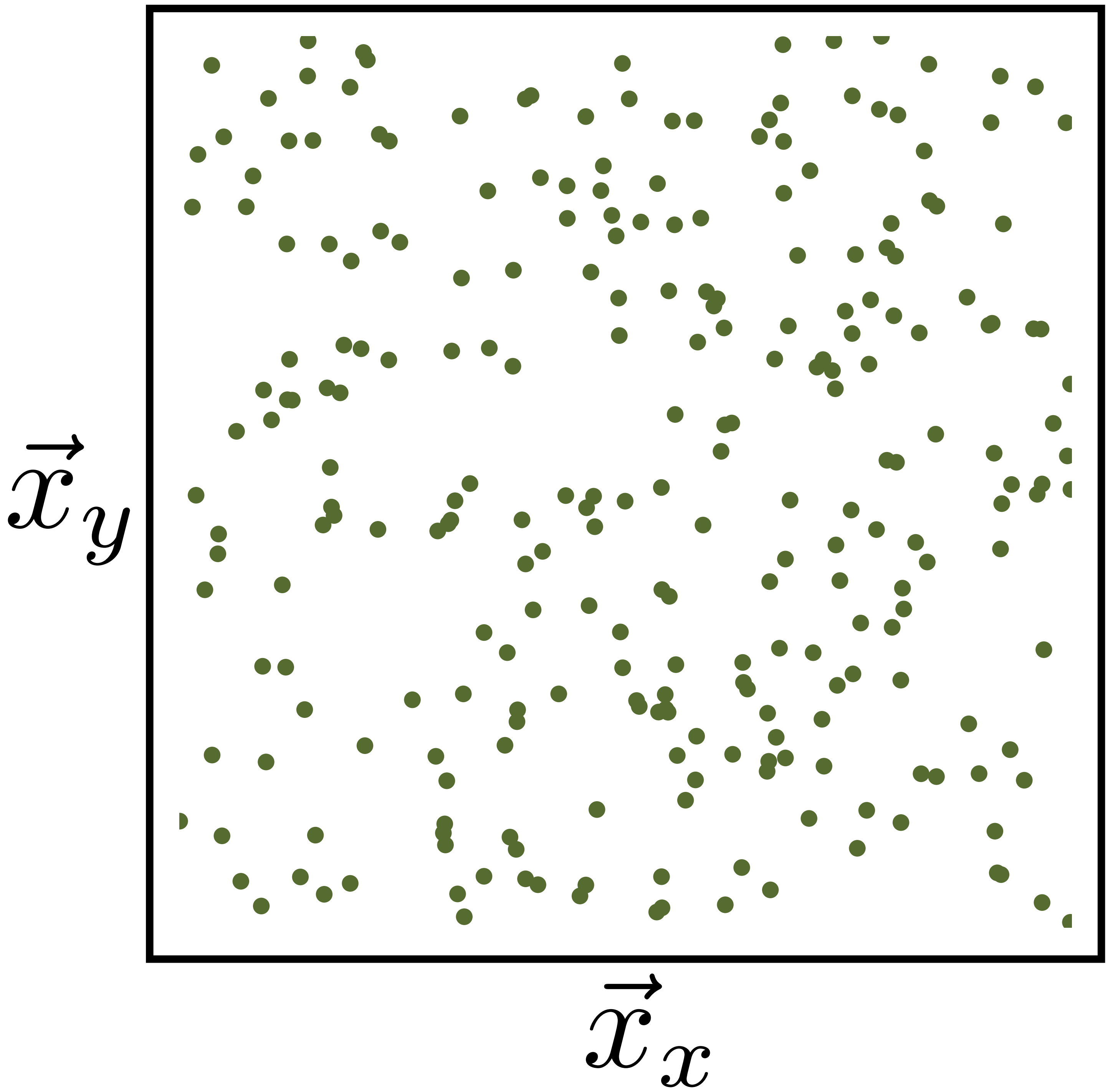
Independent Random Sampling



$$\frac{1}{N}\sum_{k=1}^{N}\delta(|\vec{x}-\vec{x}_k|) \qquad \left|\frac{1}{N}\sum_{k=1}^{N}\mathrm{e}^{-2\,\pi\,\imath\,(\vec{\omega}\cdot\vec{x}_k)}\right|^2$$

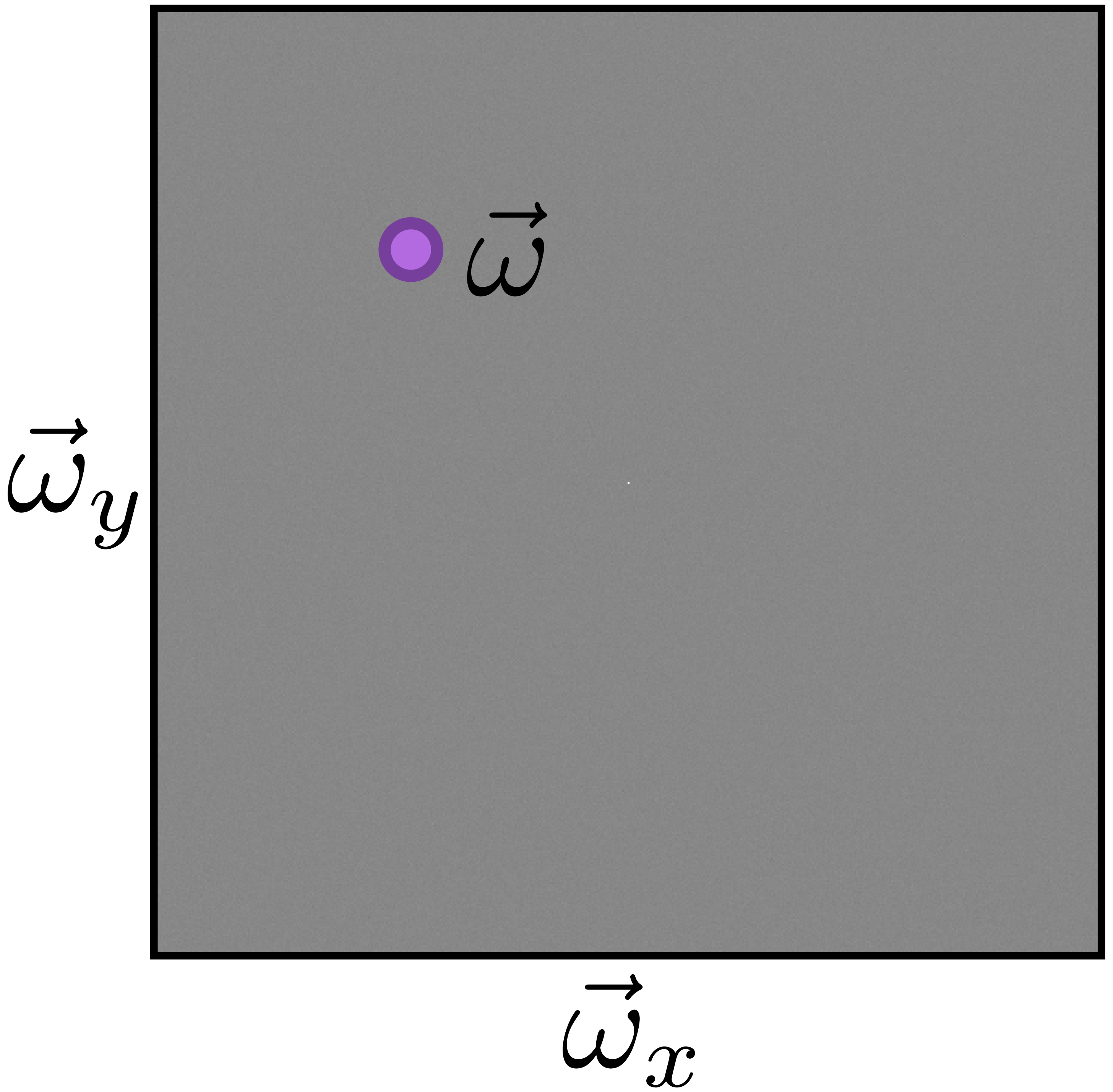
Independent Random Sampling

Samples



$$\frac{1}{N}\sum_{k=1}^{N}\delta(|\vec{x}-\vec{x}_k|)$$

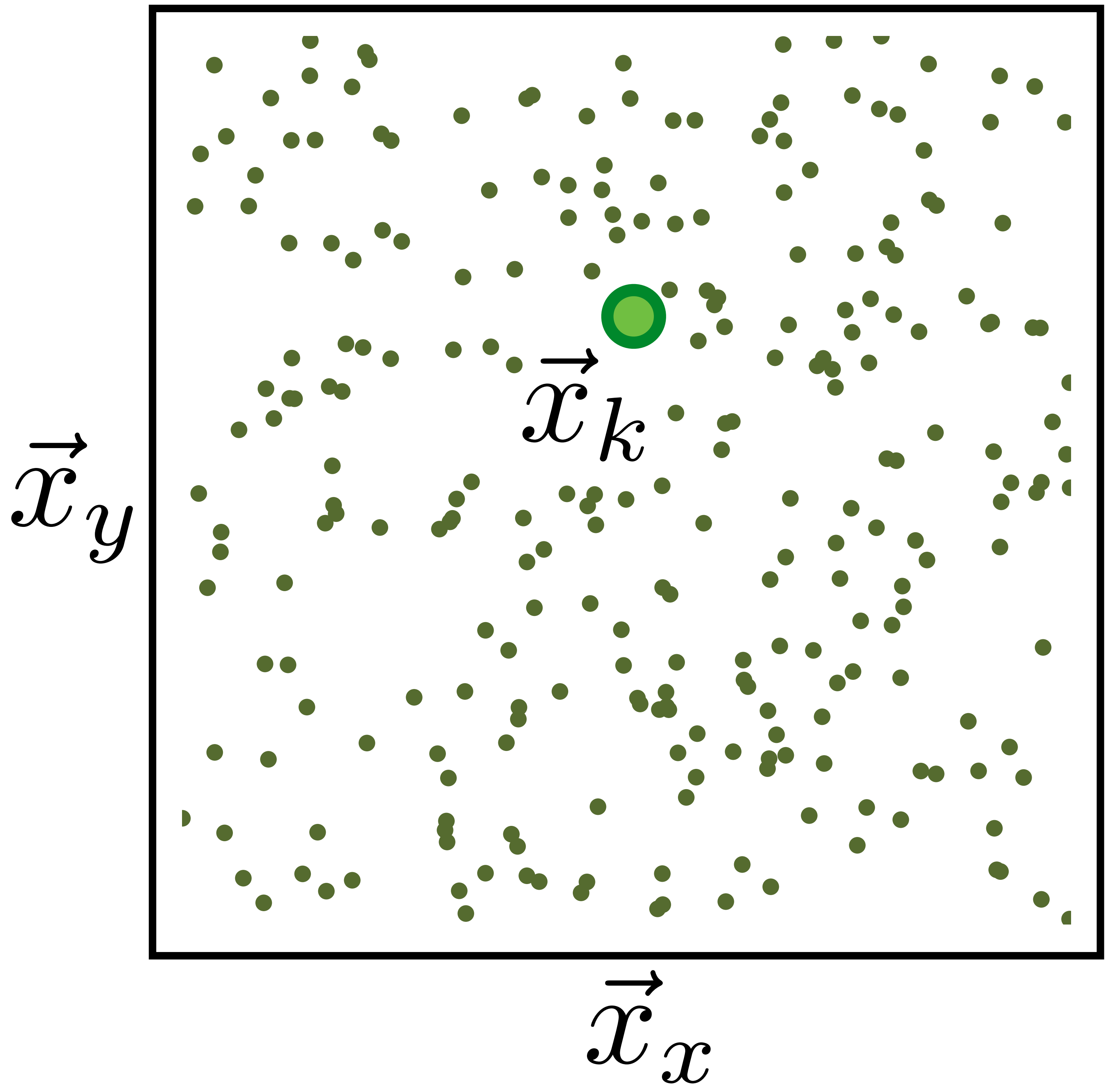
Power spectrum



$$\left|\frac{1}{N}\sum_{k=1}^{N}\mathrm{e}^{-2\pi\imath(\boxed{\vec{\omega}}\cdot\vec{x}_k)}\right|^2$$

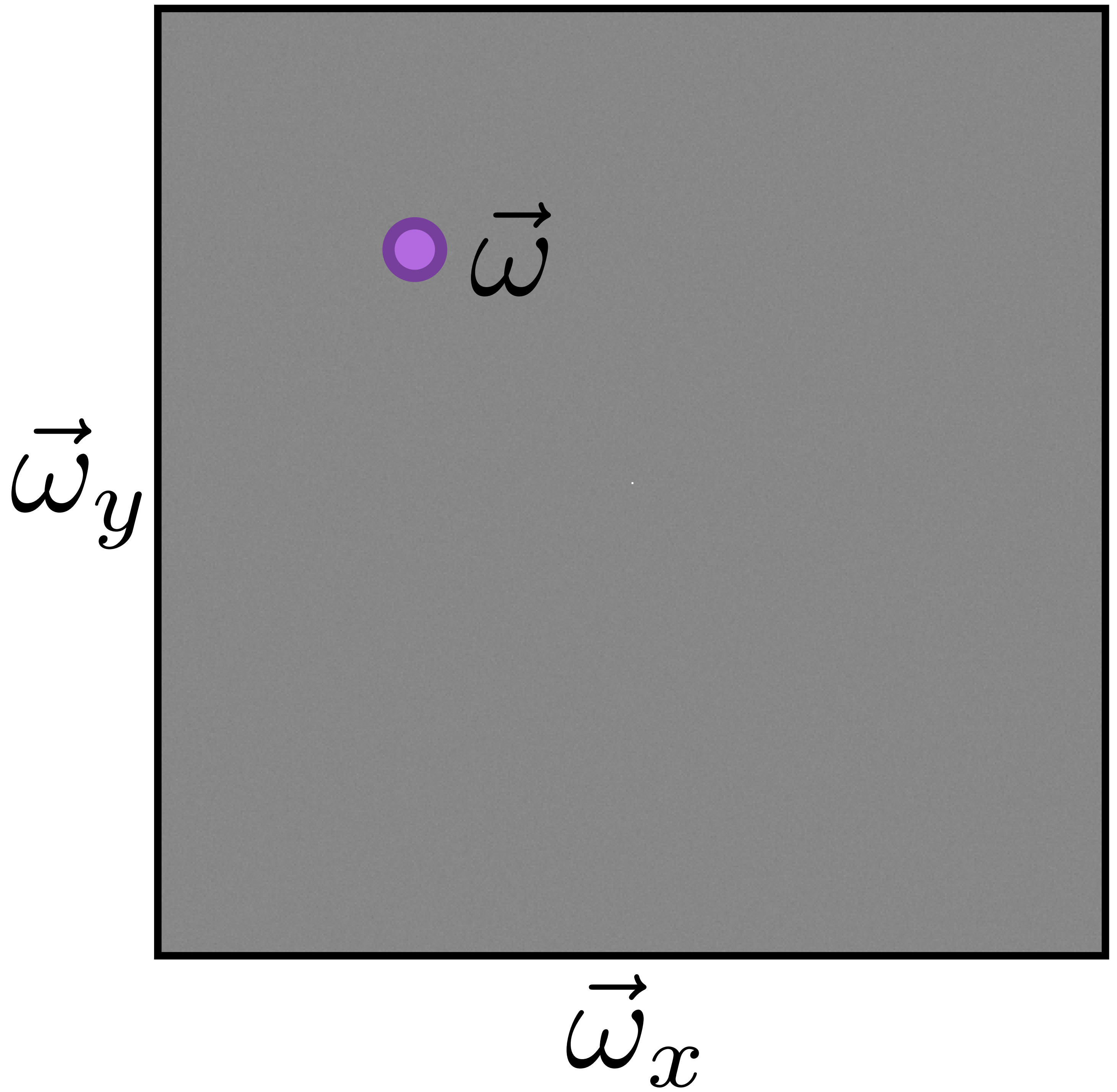
Independent Random Sampling

Samples



$$\frac{1}{N}\sum_{k=1}^{N}\delta(|\vec{x}-\boxed{\vec{x}_k}|)$$

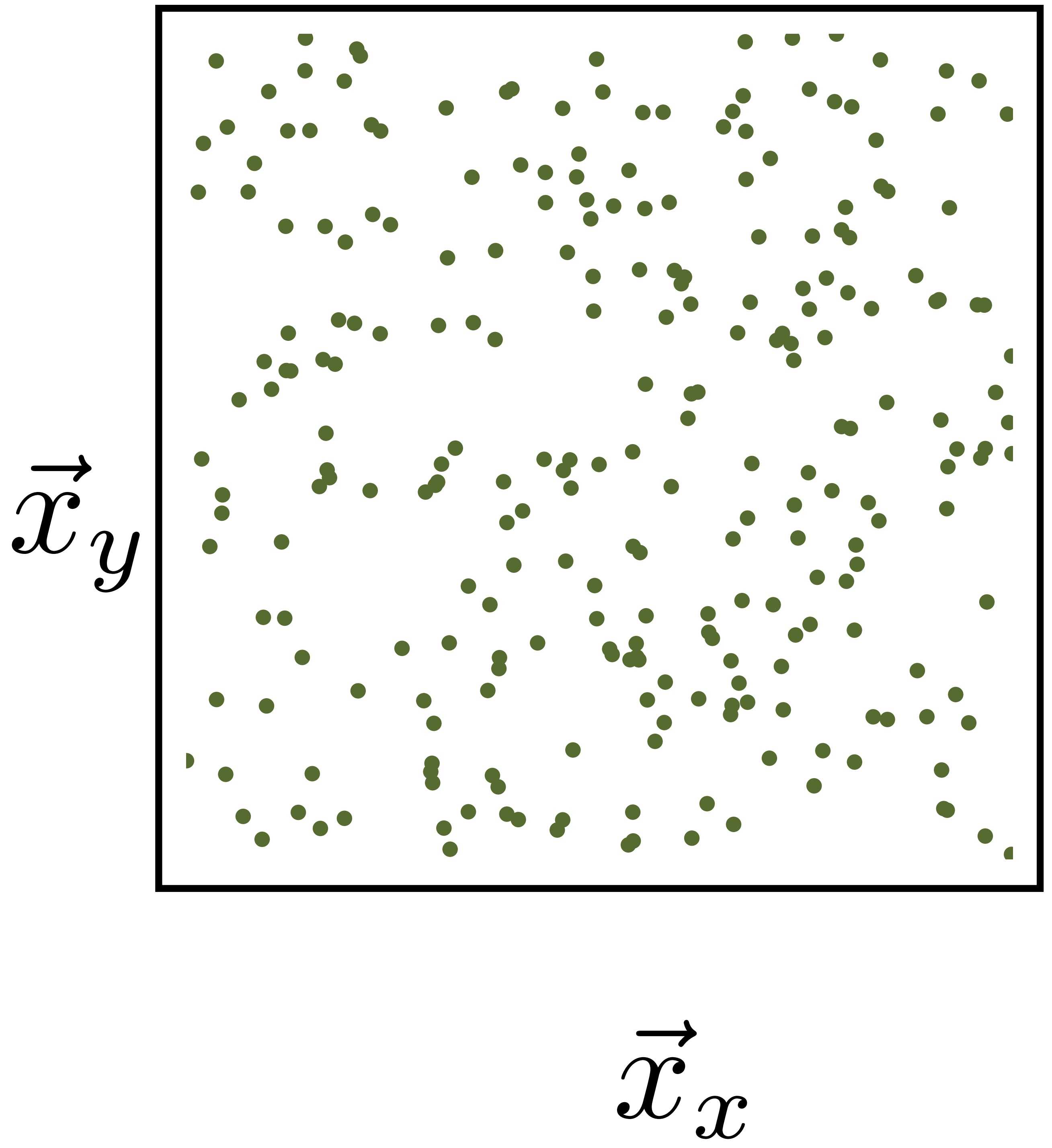
Power spectrum



$$\left|\frac{1}{N}\sum_{k=1}^{N}\mathrm{e}^{-2\pi\imath(\boxed{\vec{\omega}}\cdot\boxed{\vec{x}_k})}\right|^2$$

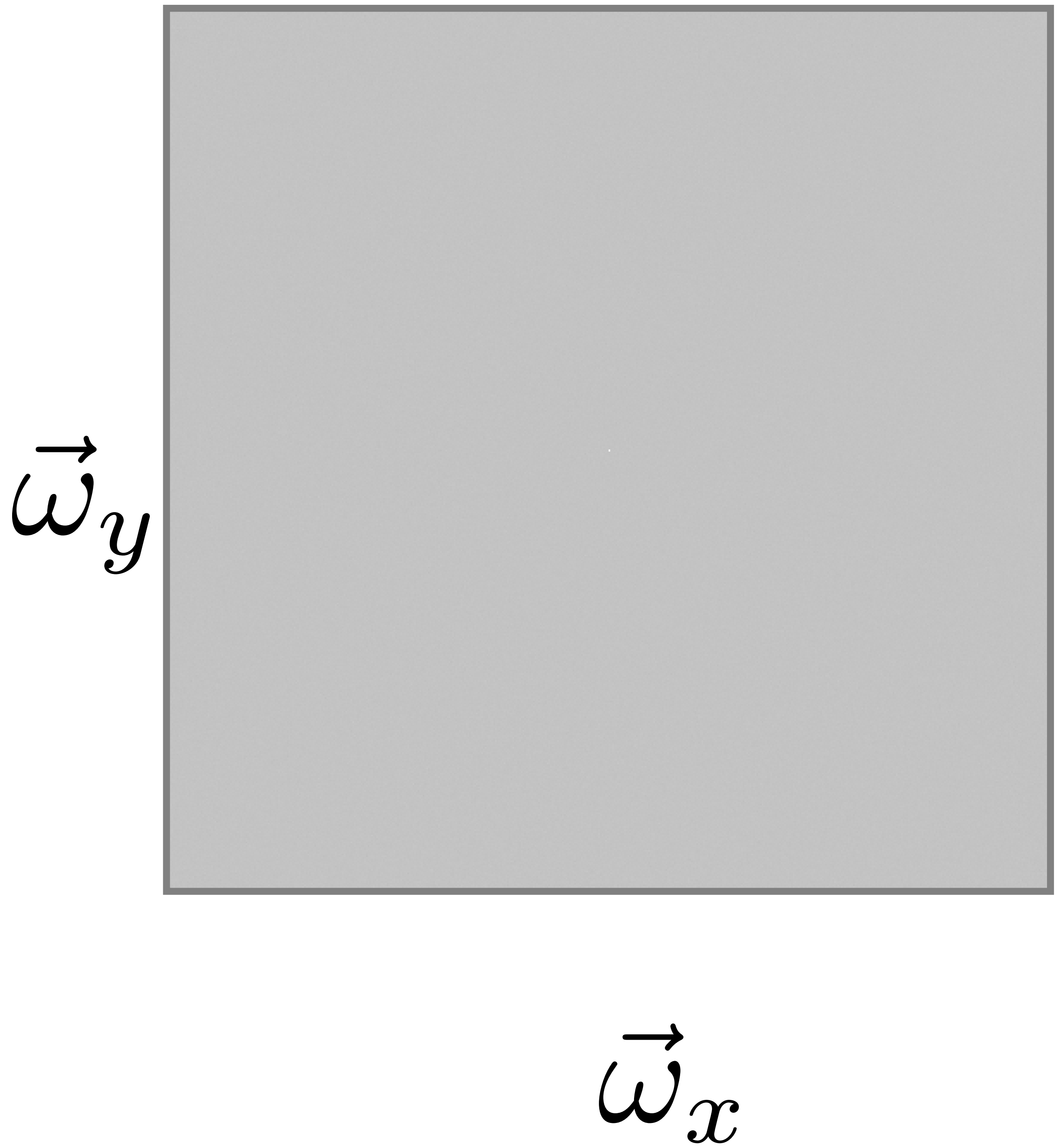
Independent Random Sampling

Many sample set realizations



$$\frac{1}{N}\sum_{k=1}^{N}\delta(|\vec{x}-\vec{x}_k|)$$

Expected power spectrum



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Independent Random Sampling

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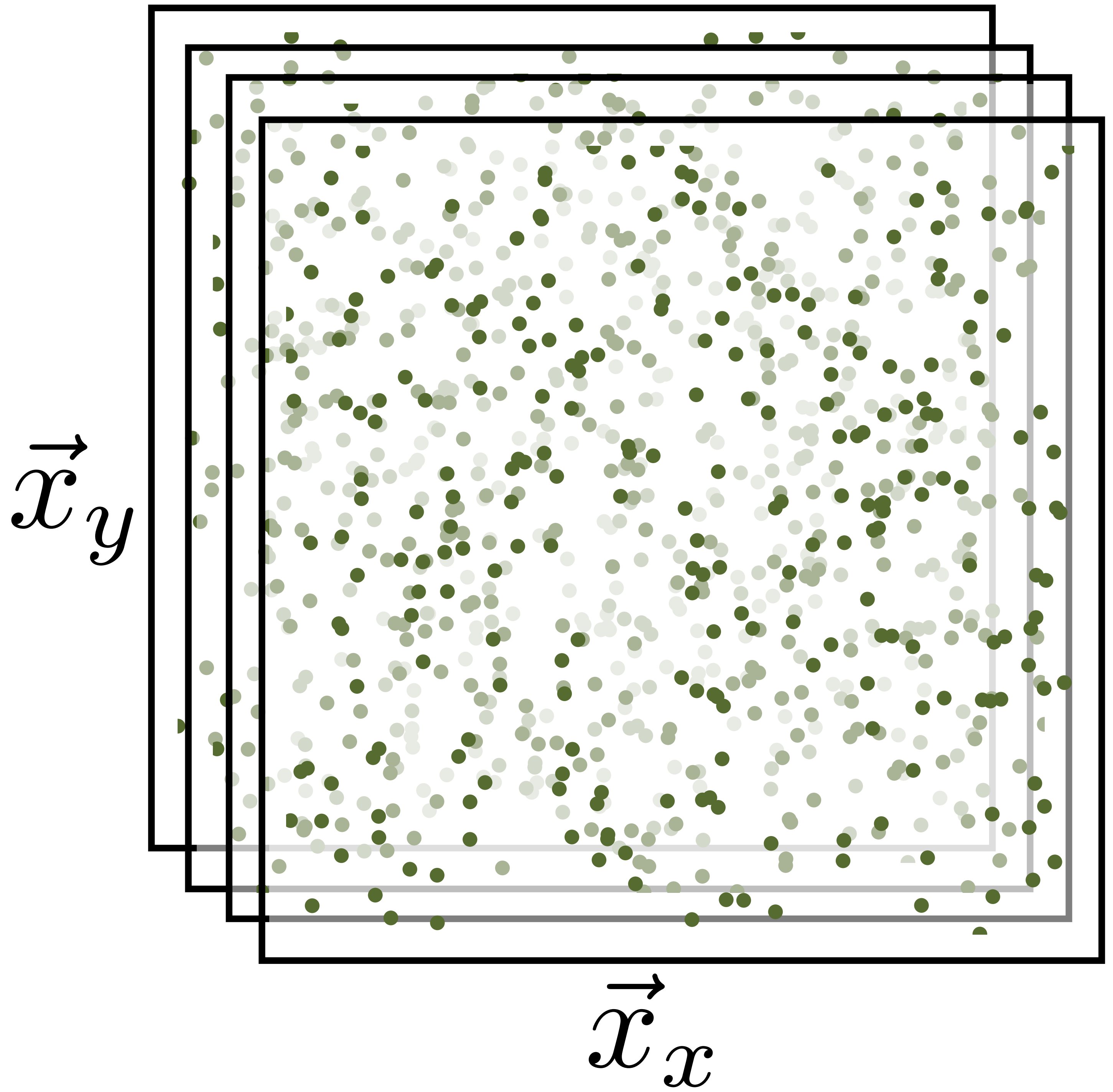

$$\frac{1}{N}\sum_{k=1}^{N}\delta(|\vec{x}-\vec{x}_k|)$$

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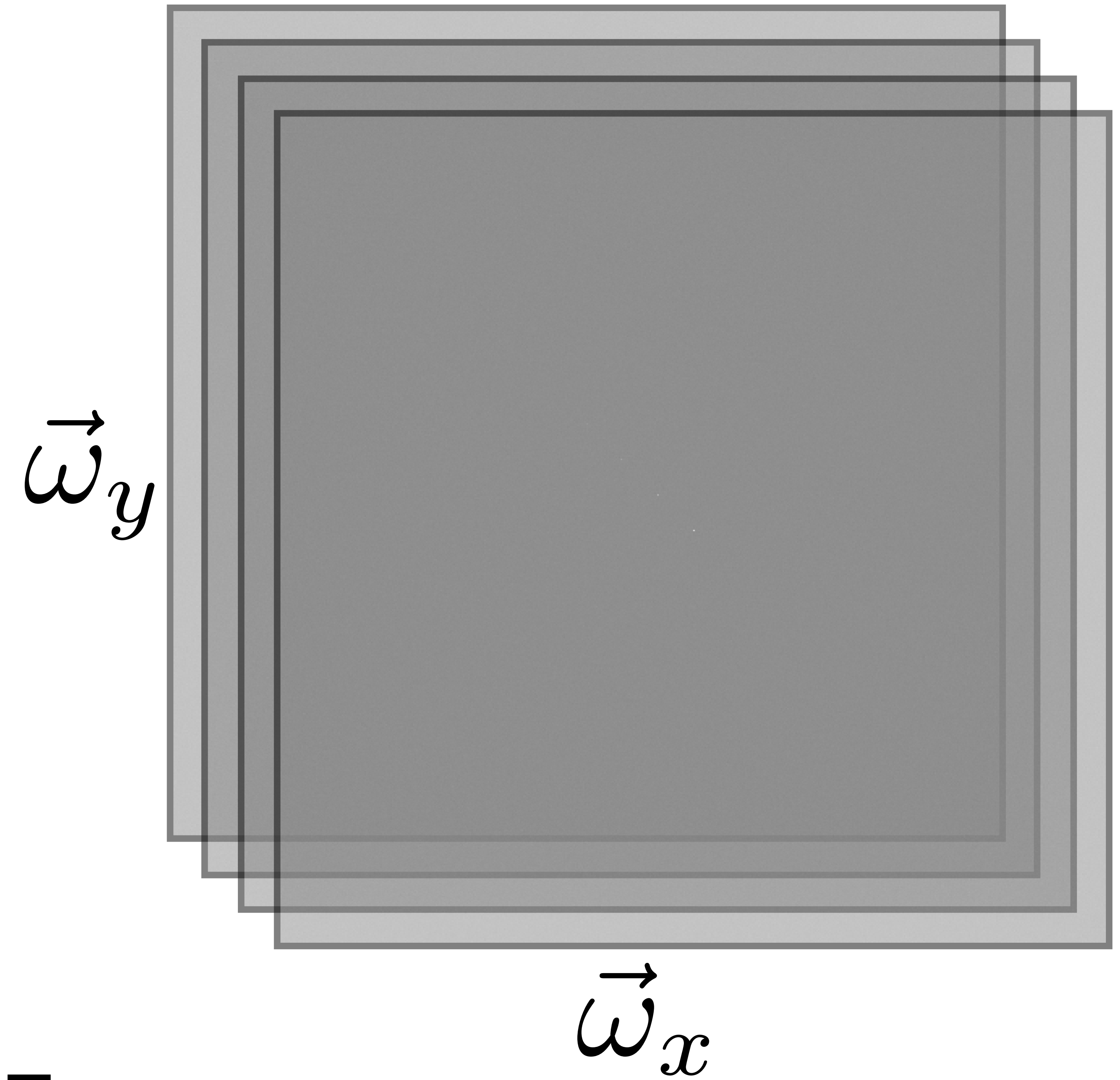
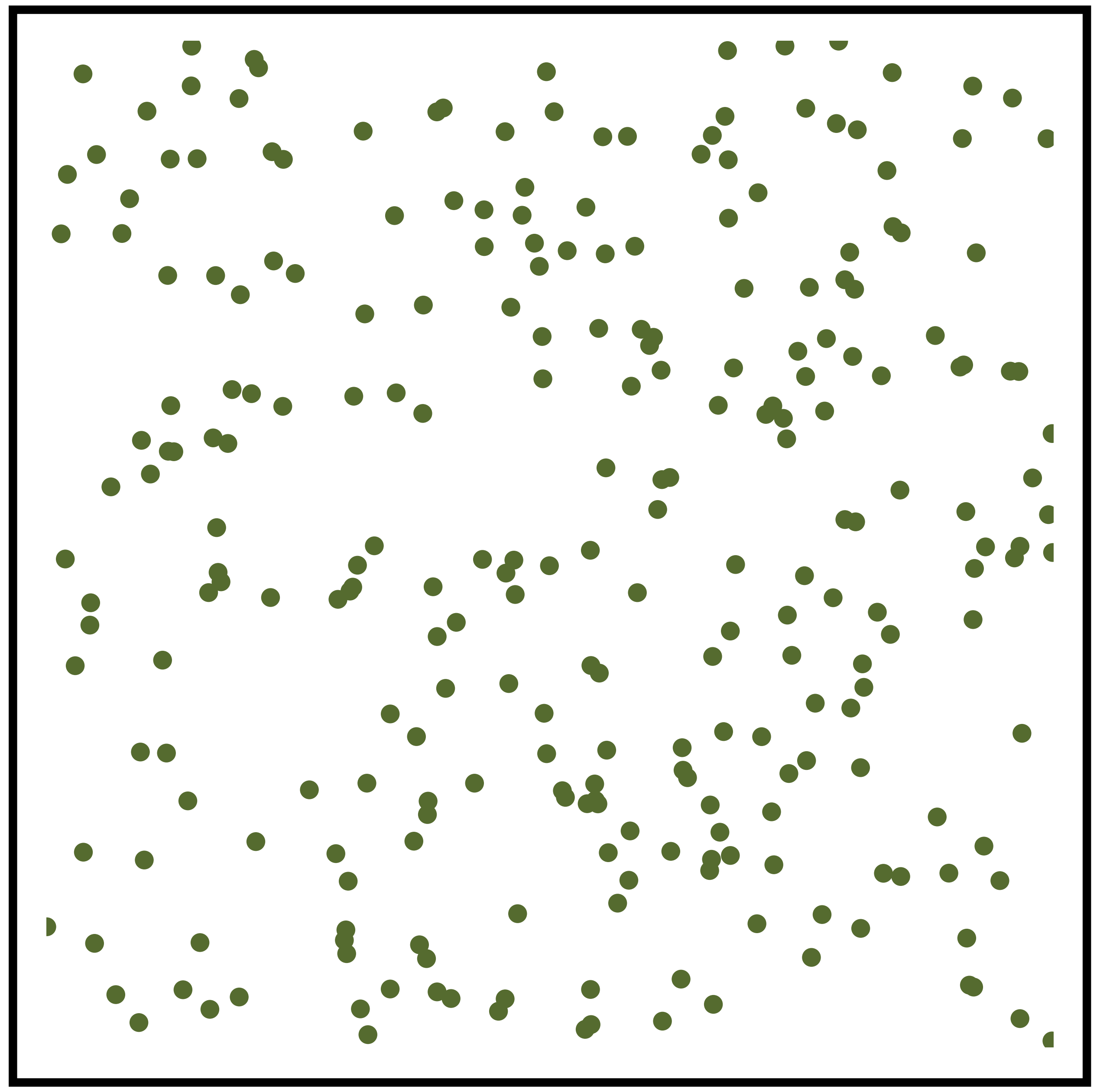


$$\mathrm{E}\left[\left|\frac{1}{N}\sum_{k=1}^{N}\mathrm{e}^{-2\pi\imath(\vec{\omega}\cdot\vec{x}_k)}\right|^2\right]$$

Independent Random Sampling

Samples



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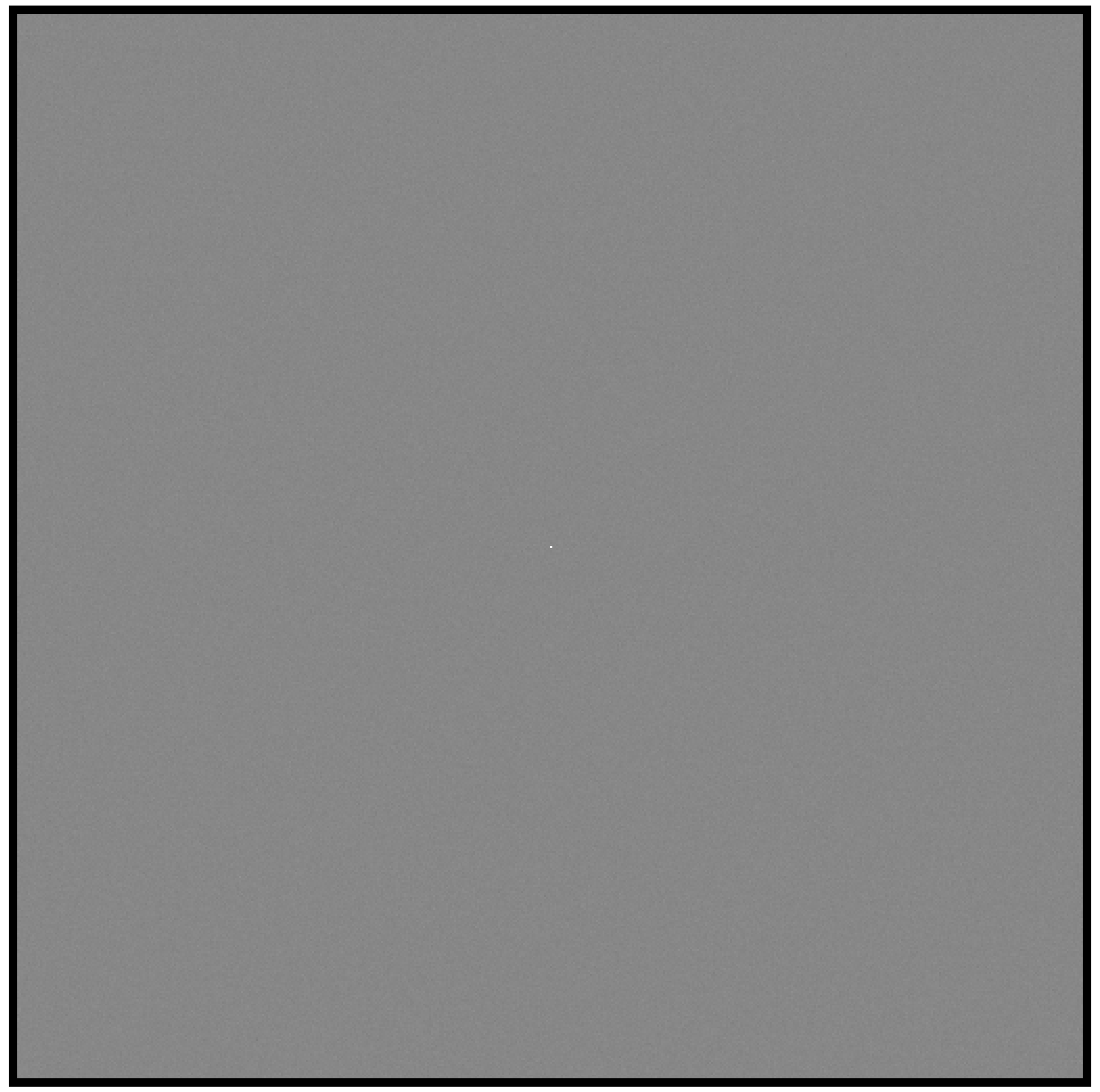


$$\frac{1}{N}\sum_{k=1}^{N}\delta(|\vec{x}-\vec{x}_k|) \quad \mathrm{E}\left[\left|\frac{1}{N}\sum_{k=1}^{N}\mathrm{e}^{-2\,\pi\,\imath\,(\vec{\omega}\cdot\vec{x}_k)}\right|^2\right]$$

Independent Random Sampling

Samples

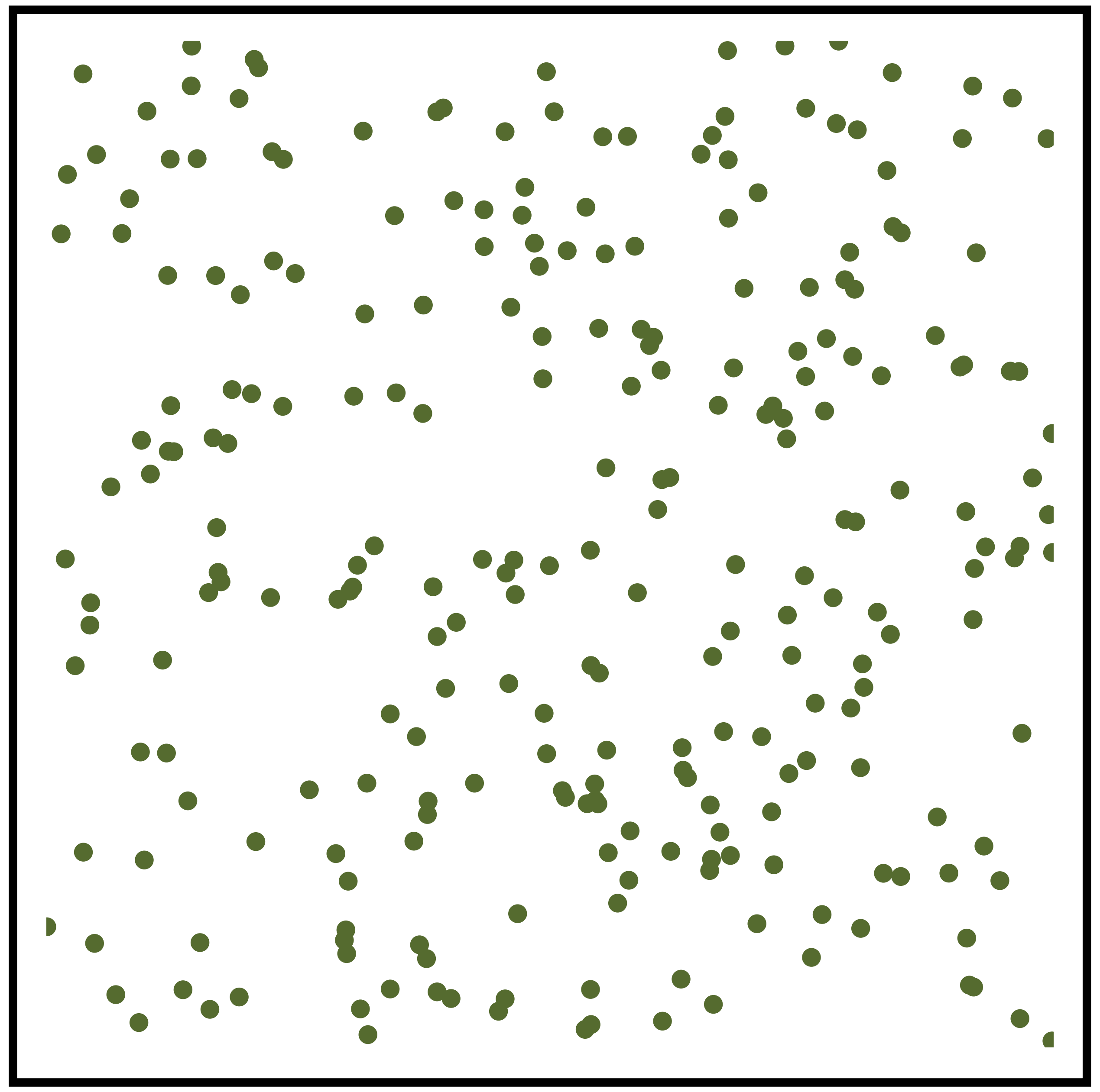
Expected power spectrum

Radial mean

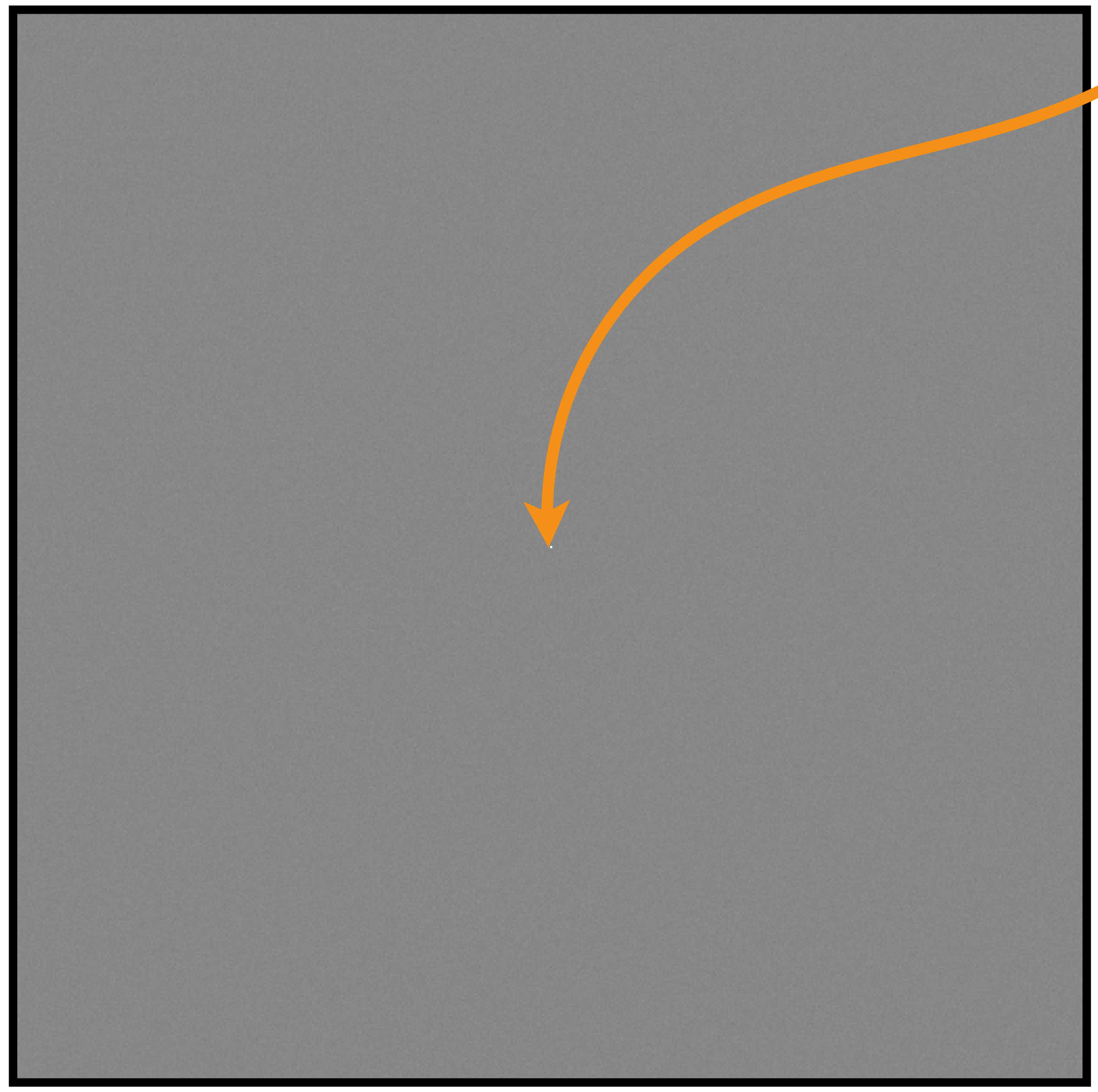
$$\frac{1}{N}\sum_{k=1}^{N}\delta(|\vec{x}-\vec{x}_k|) \quad \mathrm{E}\left[\left|\frac{1}{N}\sum_{k=1}^{N}\mathrm{e}^{-2\,\pi\,\imath\,(\vec{\omega}\cdot\vec{x}_k)}\right|^2\right]$$

Independent Random Sampling

Samples

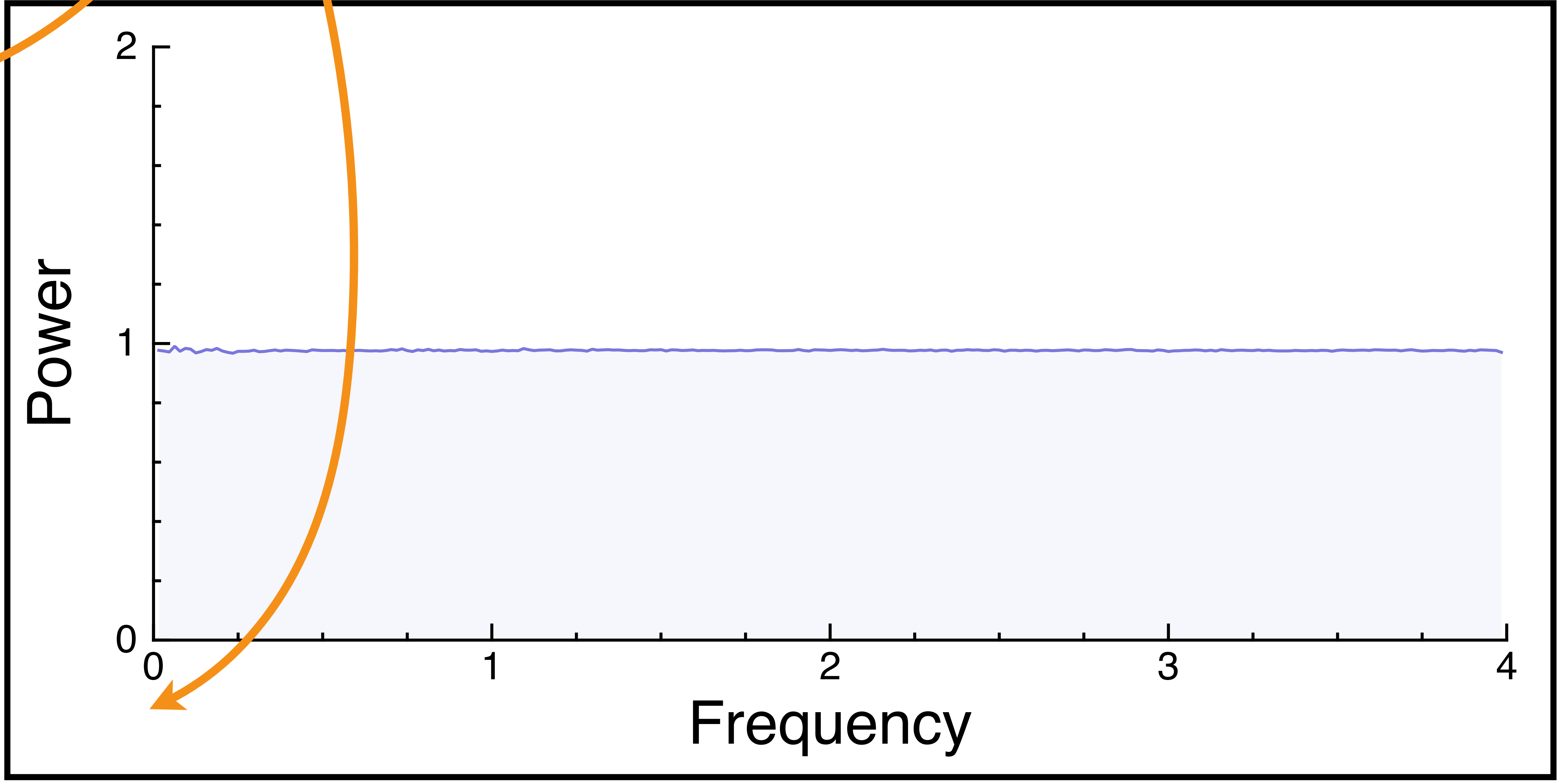


Expected power spectrum



DC Peak

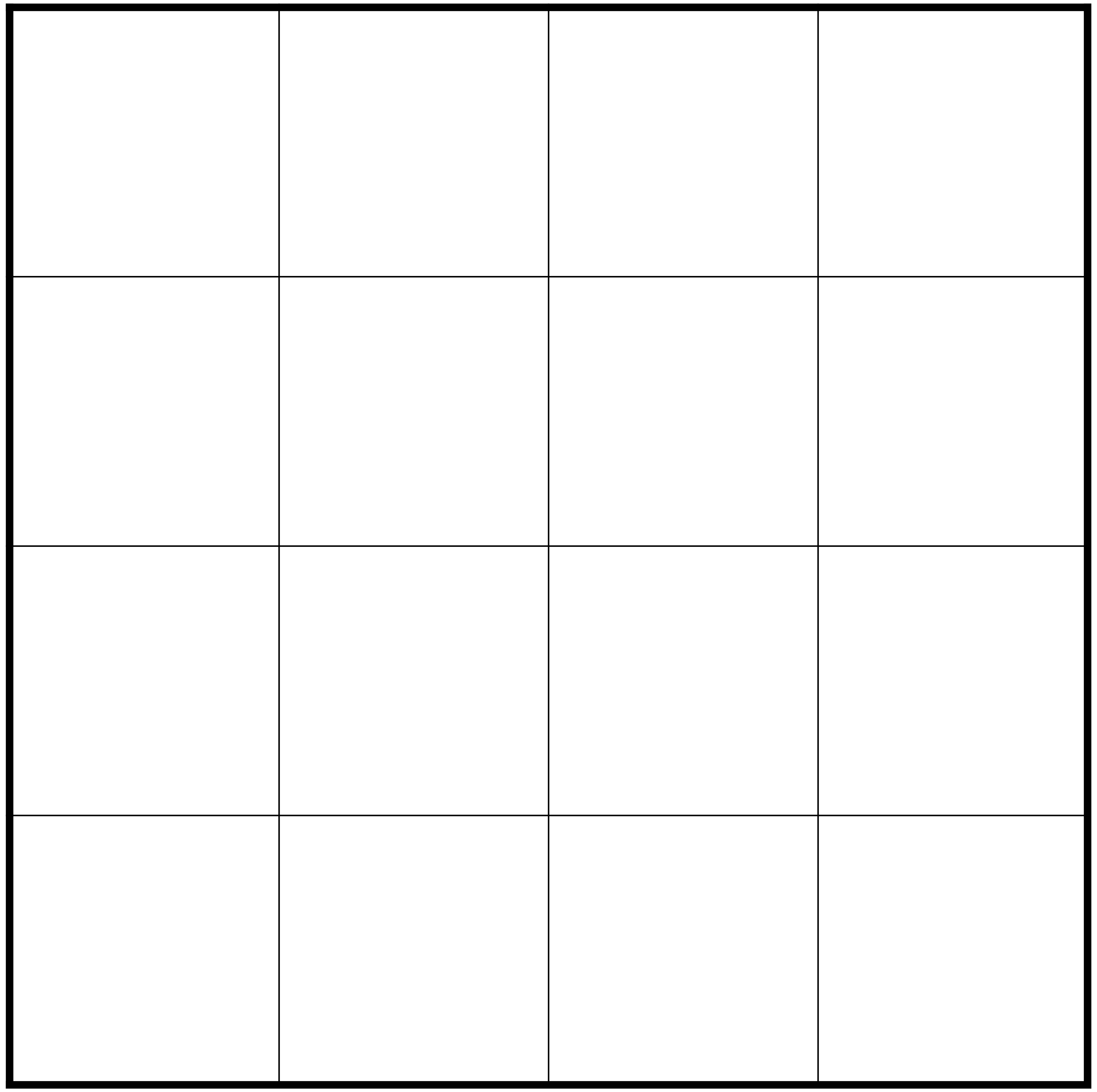
Radial mean



$$\frac{1}{N}\sum_{k=1}^{N}\delta(|\vec{x}-\vec{x}_k|) \quad \mathrm{E}\left[\left|\frac{1}{N}\sum_{k=1}^{N}\mathrm{e}^{-2\,\pi\,\imath\,(\vec{\omega}\cdot\vec{x}_k)}\right|^2\right]$$

Regular Sampling

```
for (uint i = 0; i < numX; i++)
    for (uint j = 0; j < numY; j++)
    {
        samples(i,j).x = (i + 0.5)/numX;
        samples(i,j).y = (j + 0.5)/numY;
    }
```



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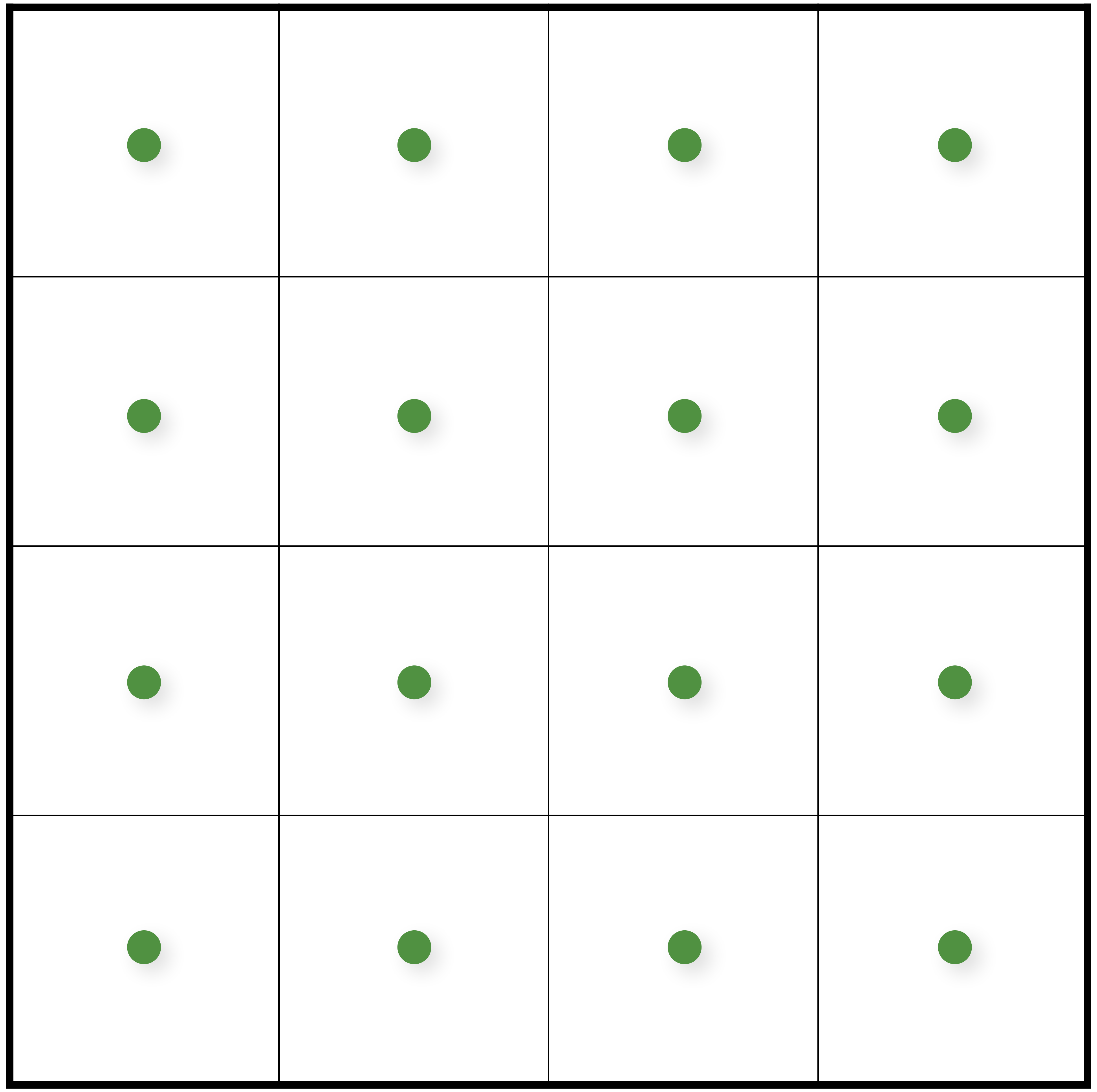

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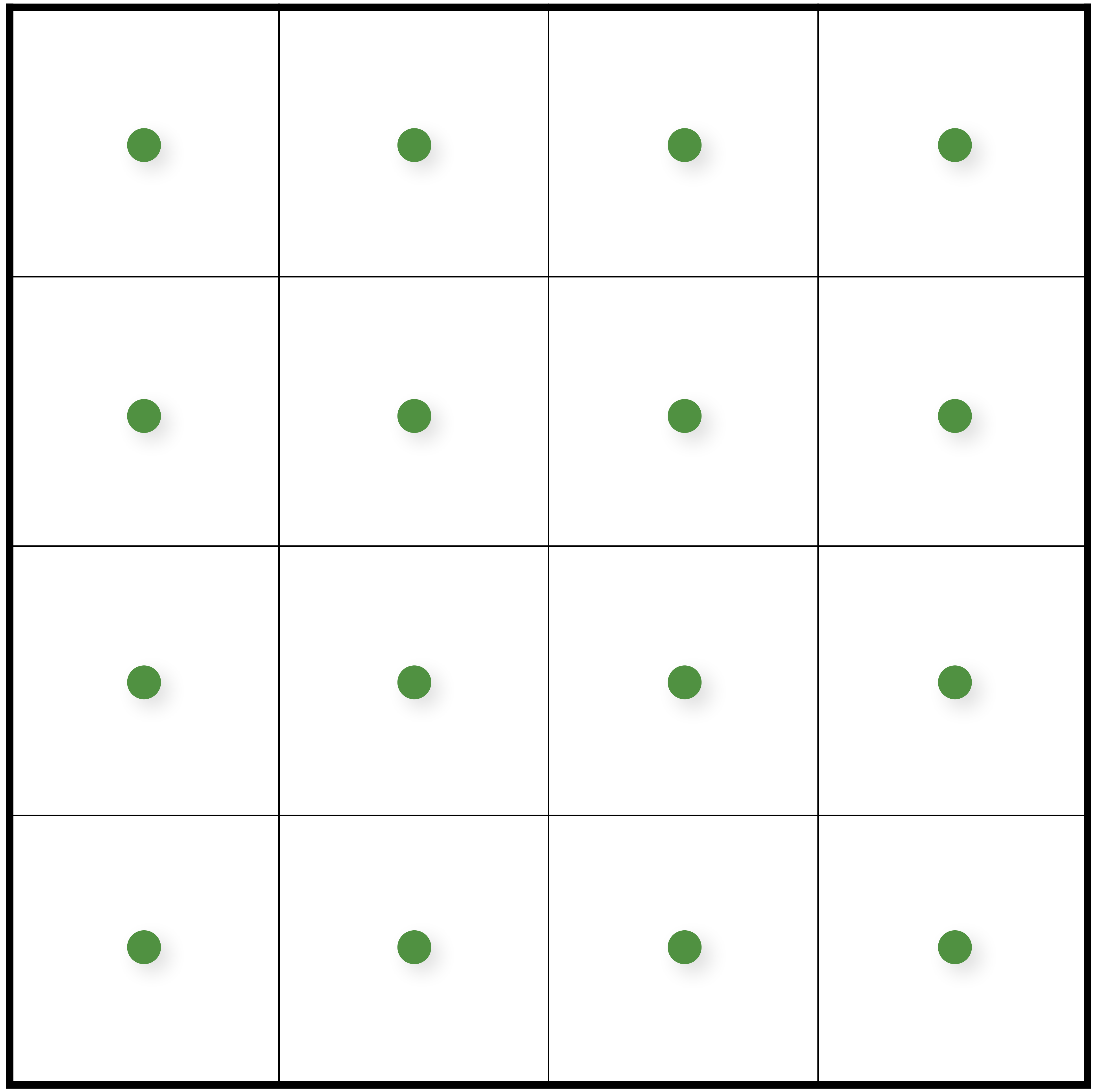

✔ Extends to higher dimensions, but…

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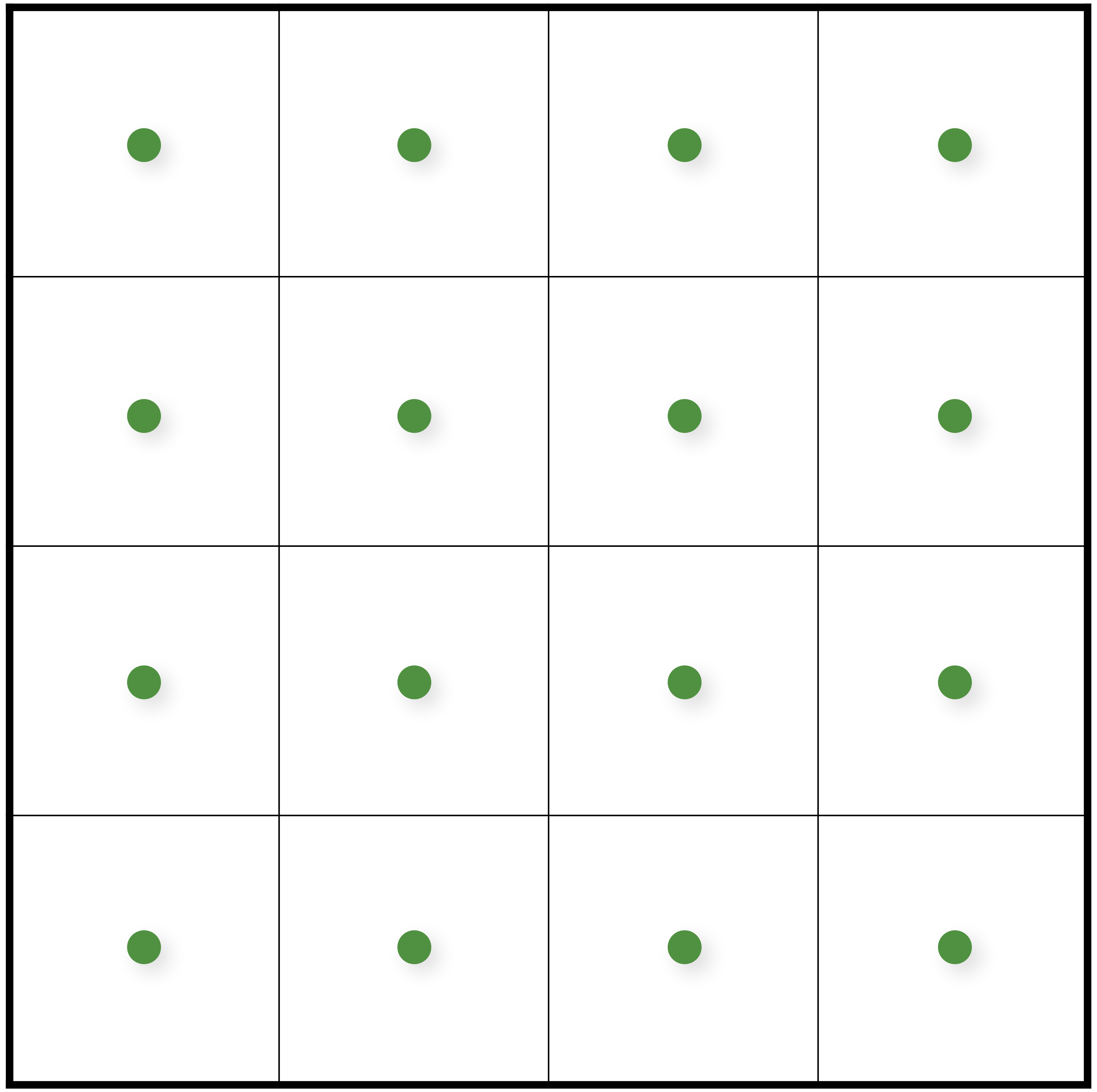

✔ Extends to higher dimensions, but...

✘ Curse of dimensionality

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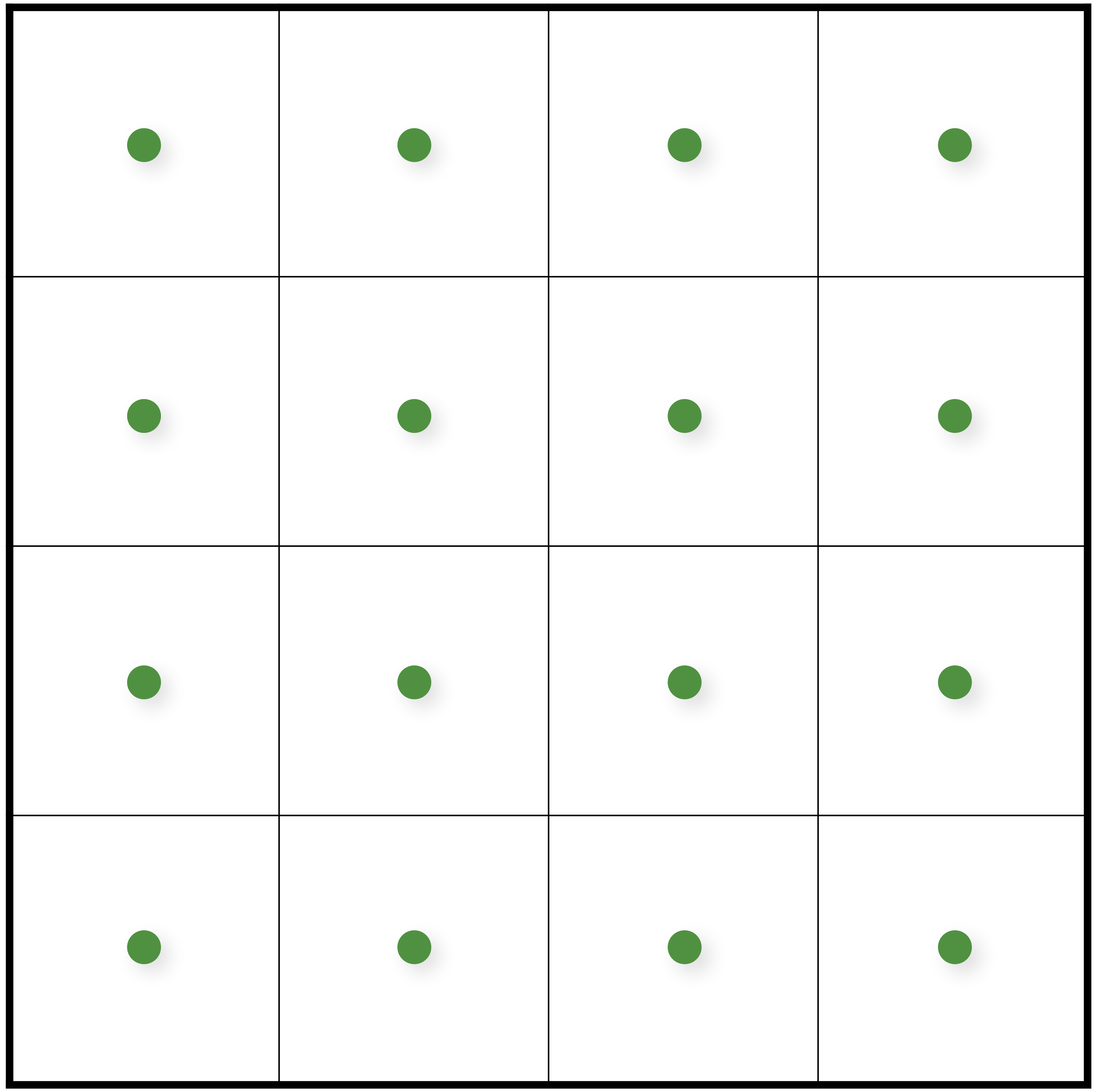

- ✔ Extends to higher dimensions, but…
- ✘ Curse of dimensionality
- ✘ Aliasing

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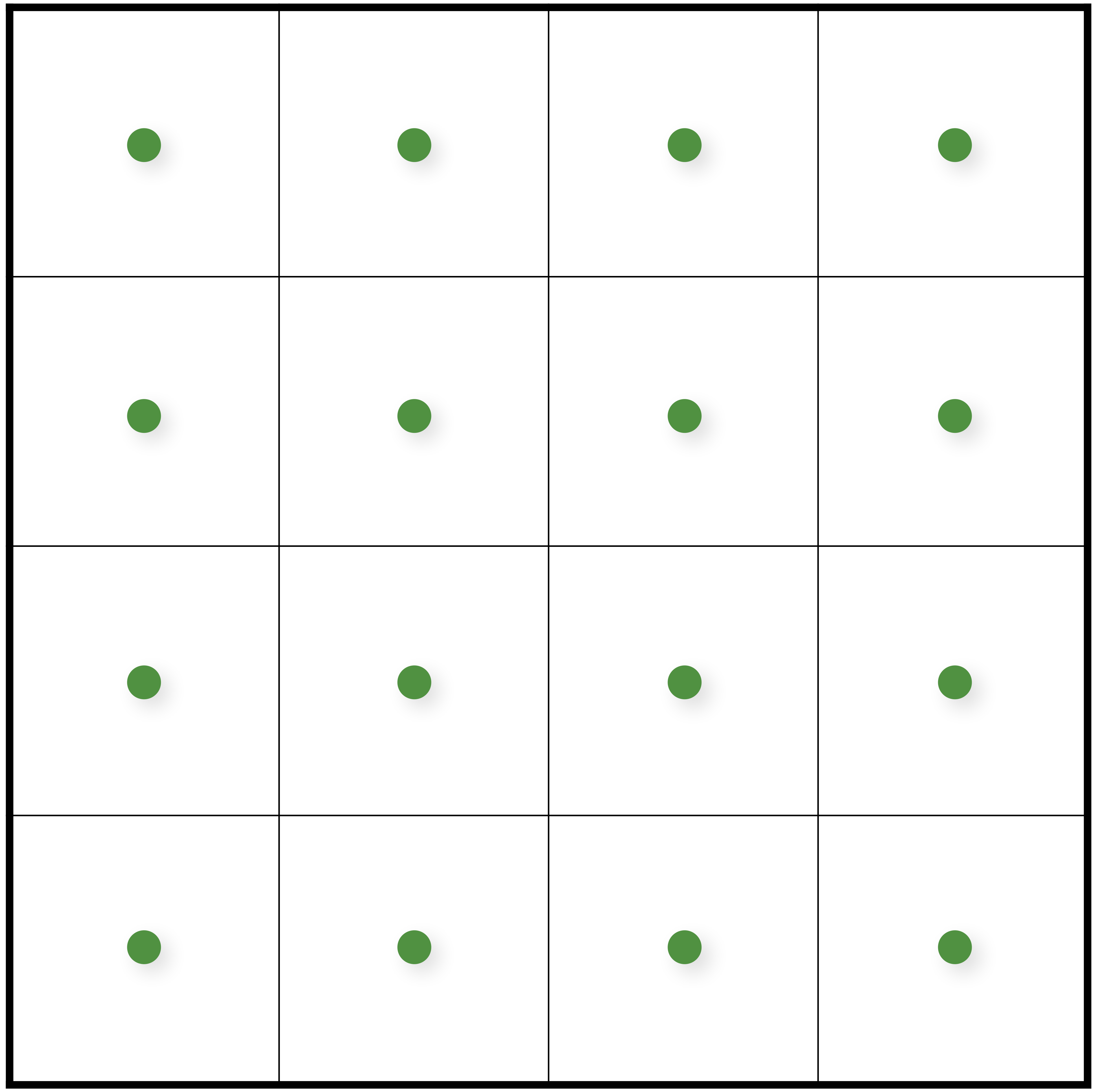

Jittered/Stratified Sampling

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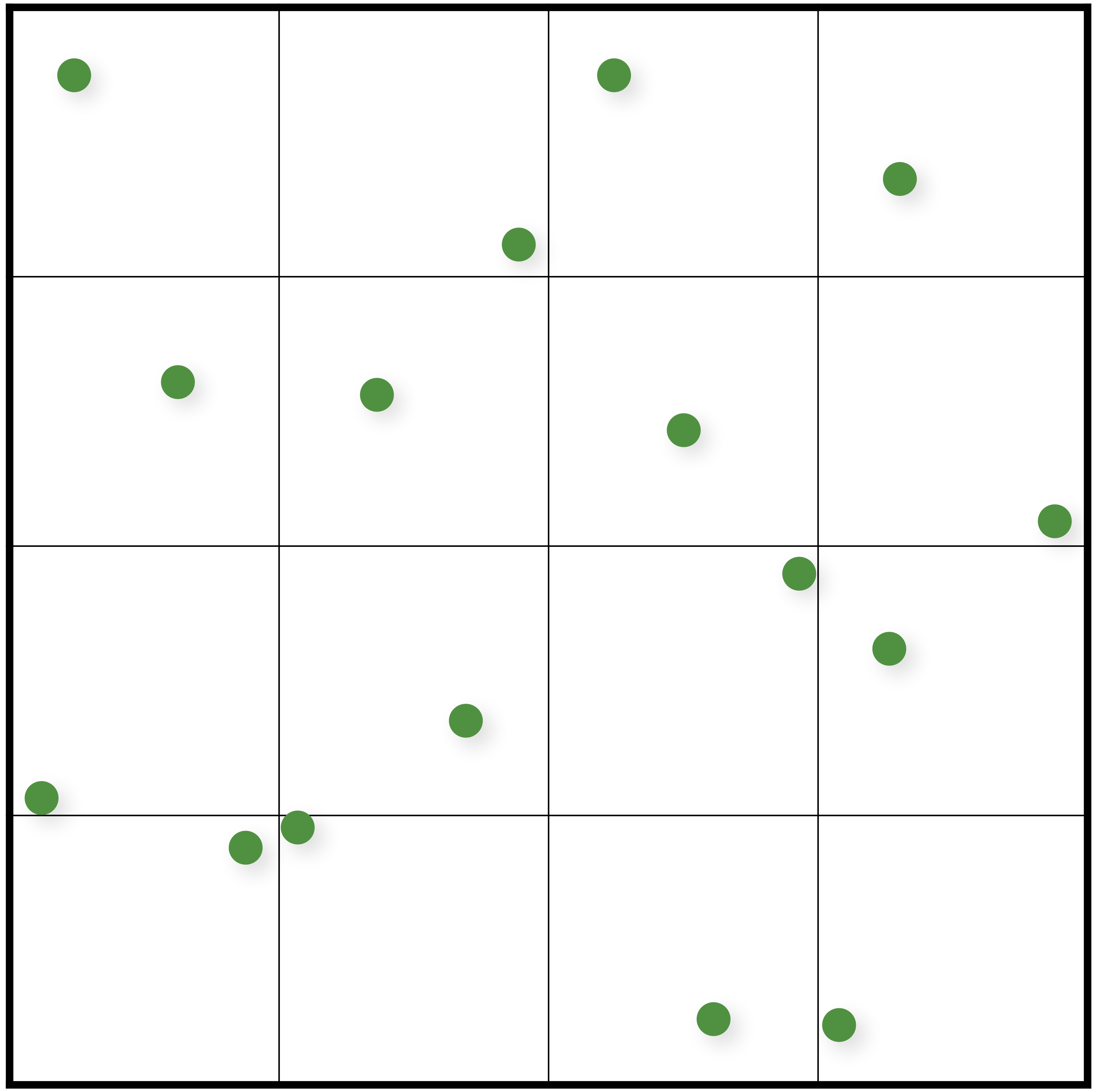

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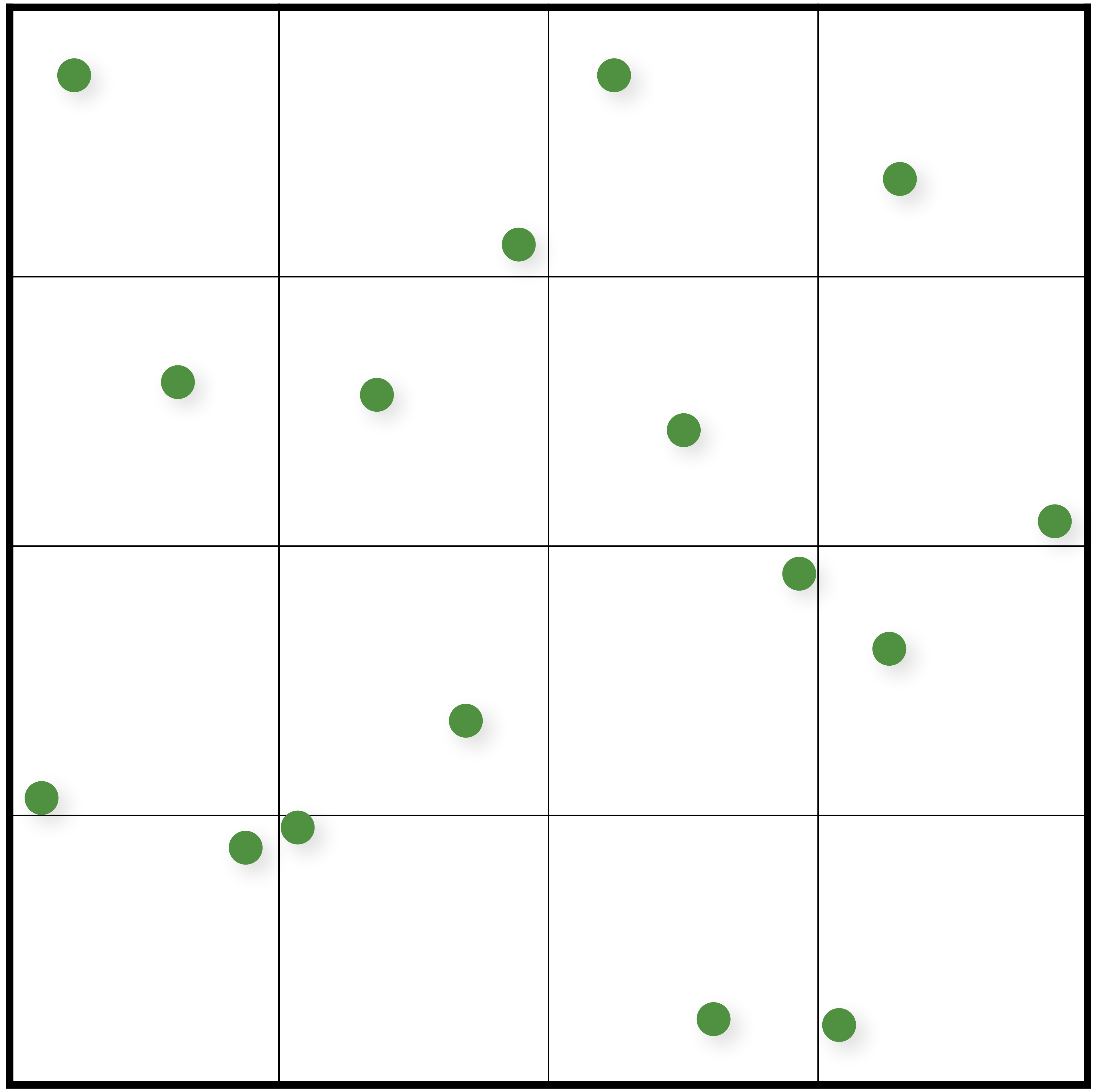

✔ Provably cannot increase variance

Jittered/Stratified Sampling

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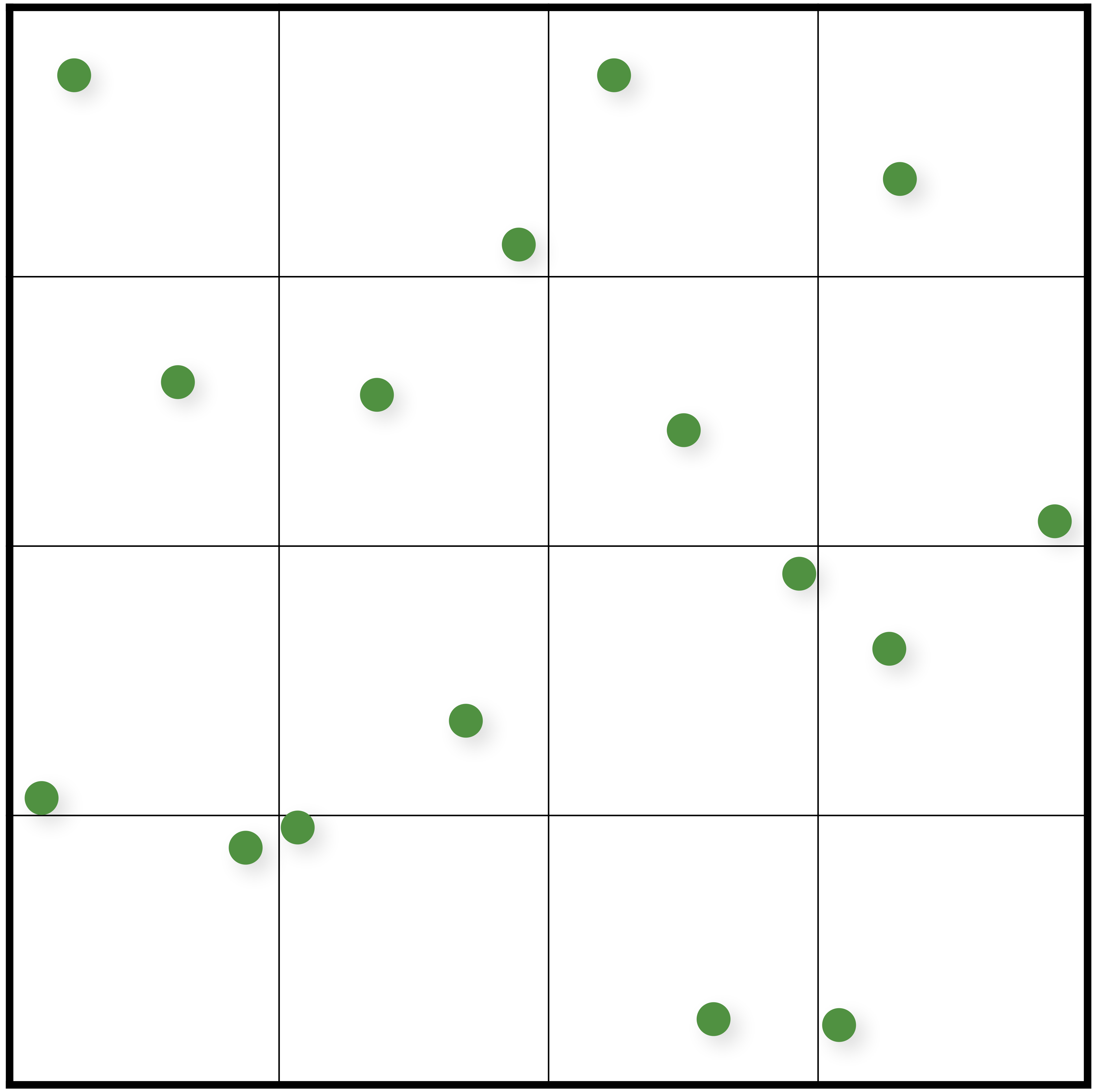

- ✔ Provably cannot increase variance
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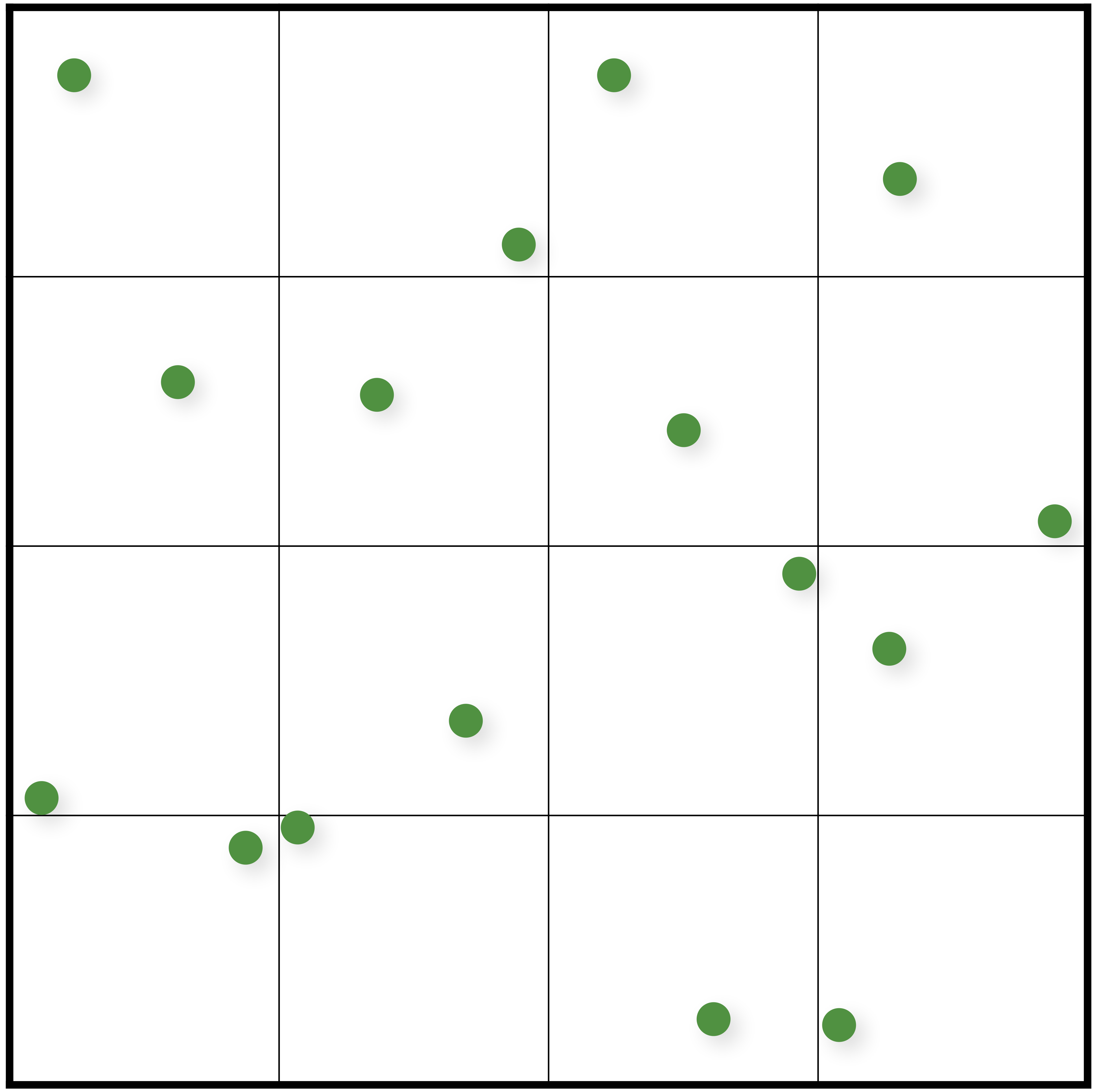

- ✔ Provably cannot increase variance
- ✔ Extends to higher dimensions, but…
- ✘ Curse of dimensionality

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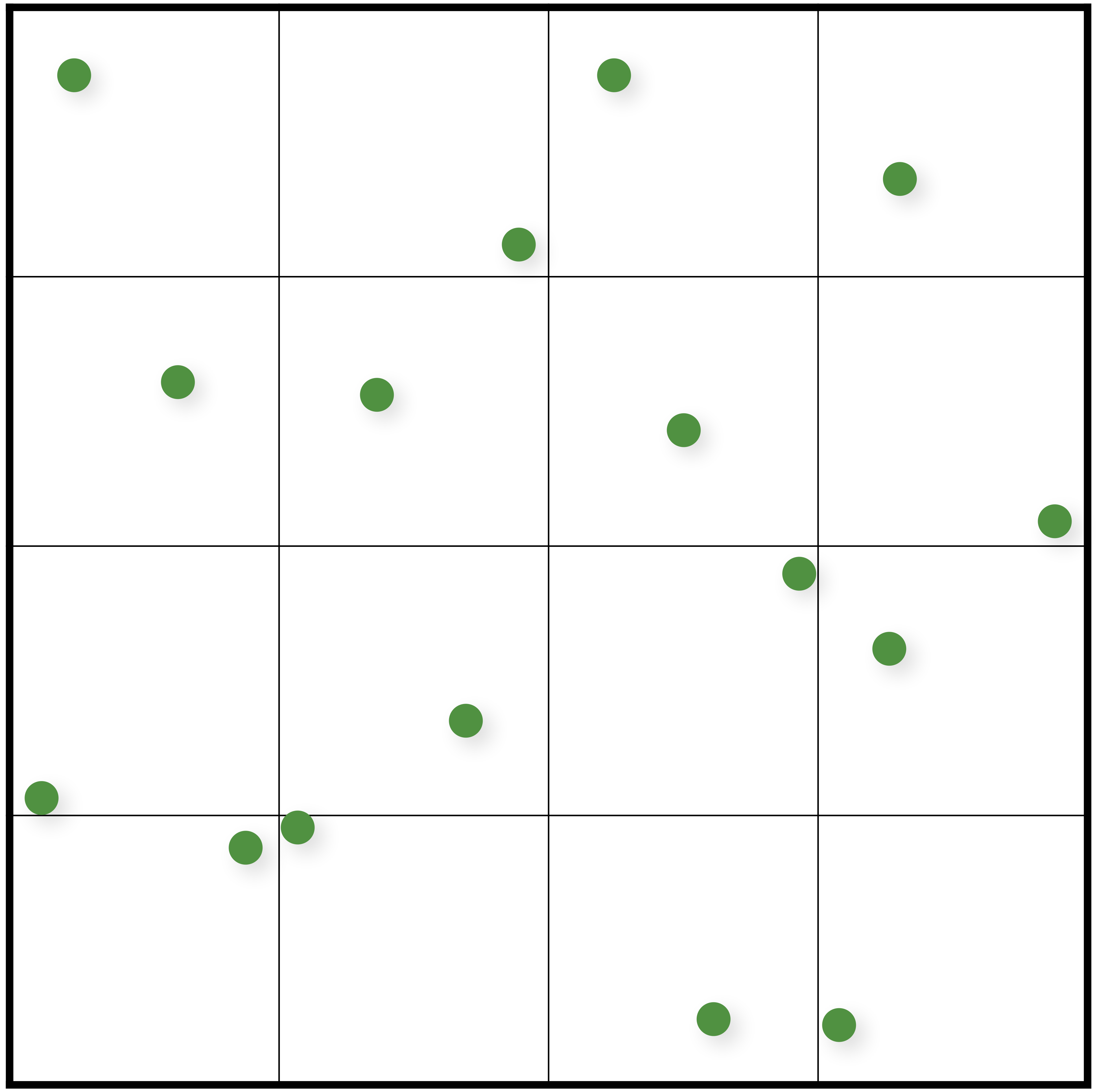


✔ Provably cannot increase variance

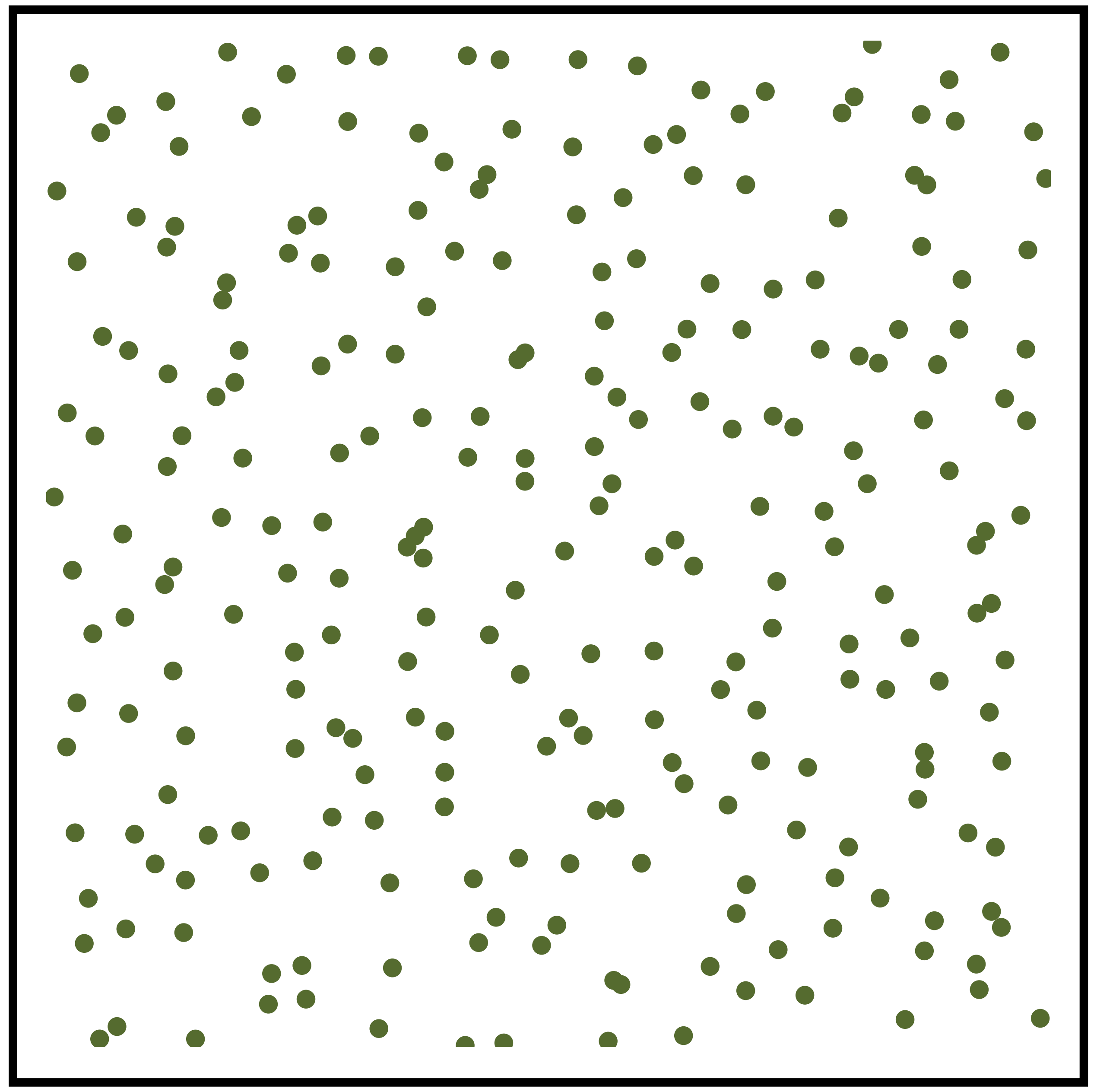
✔ Extends to higher dimensions, but…

✘ Curse of dimensionality

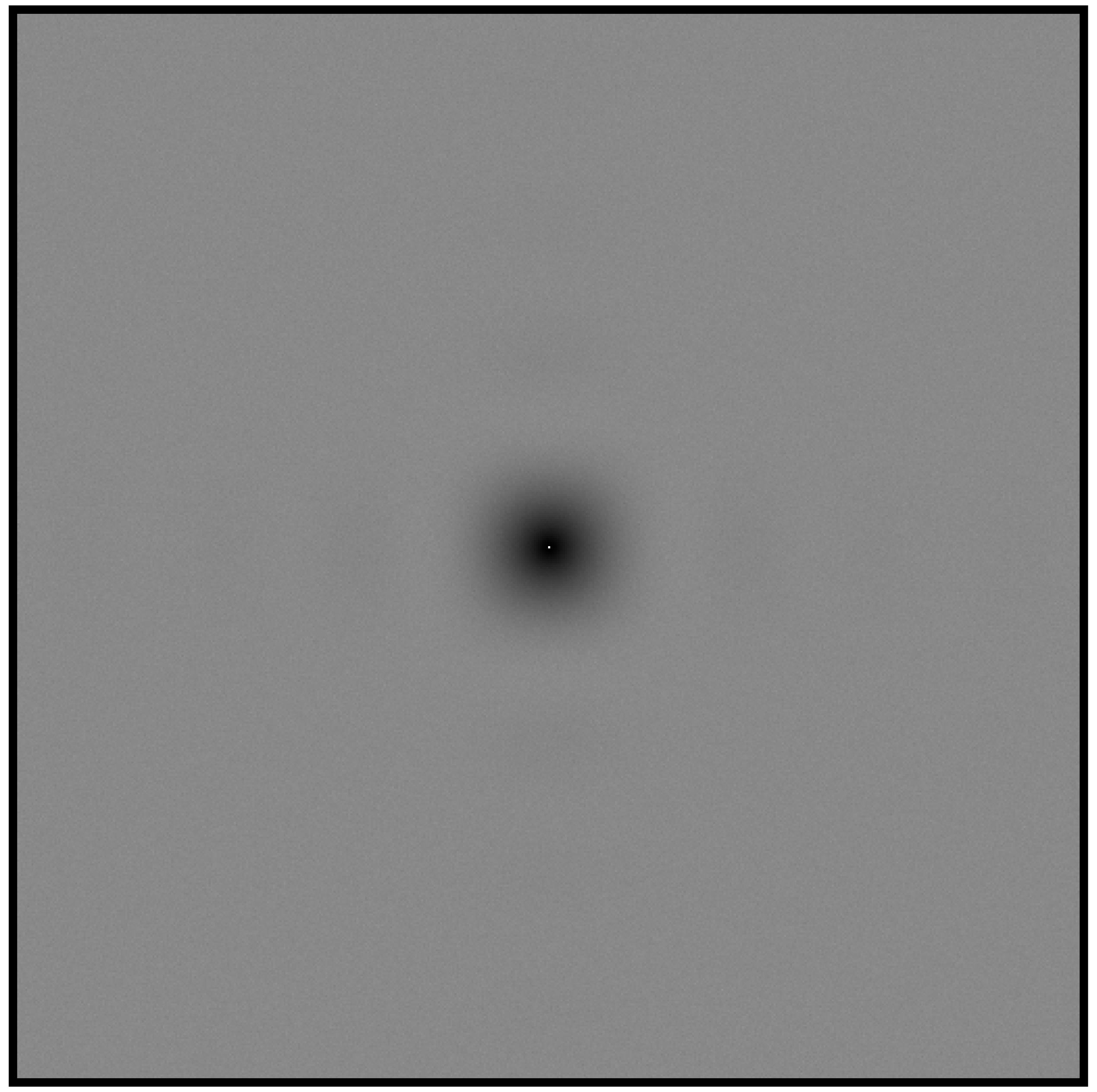
✘ Not progressive

Jittered Sampling

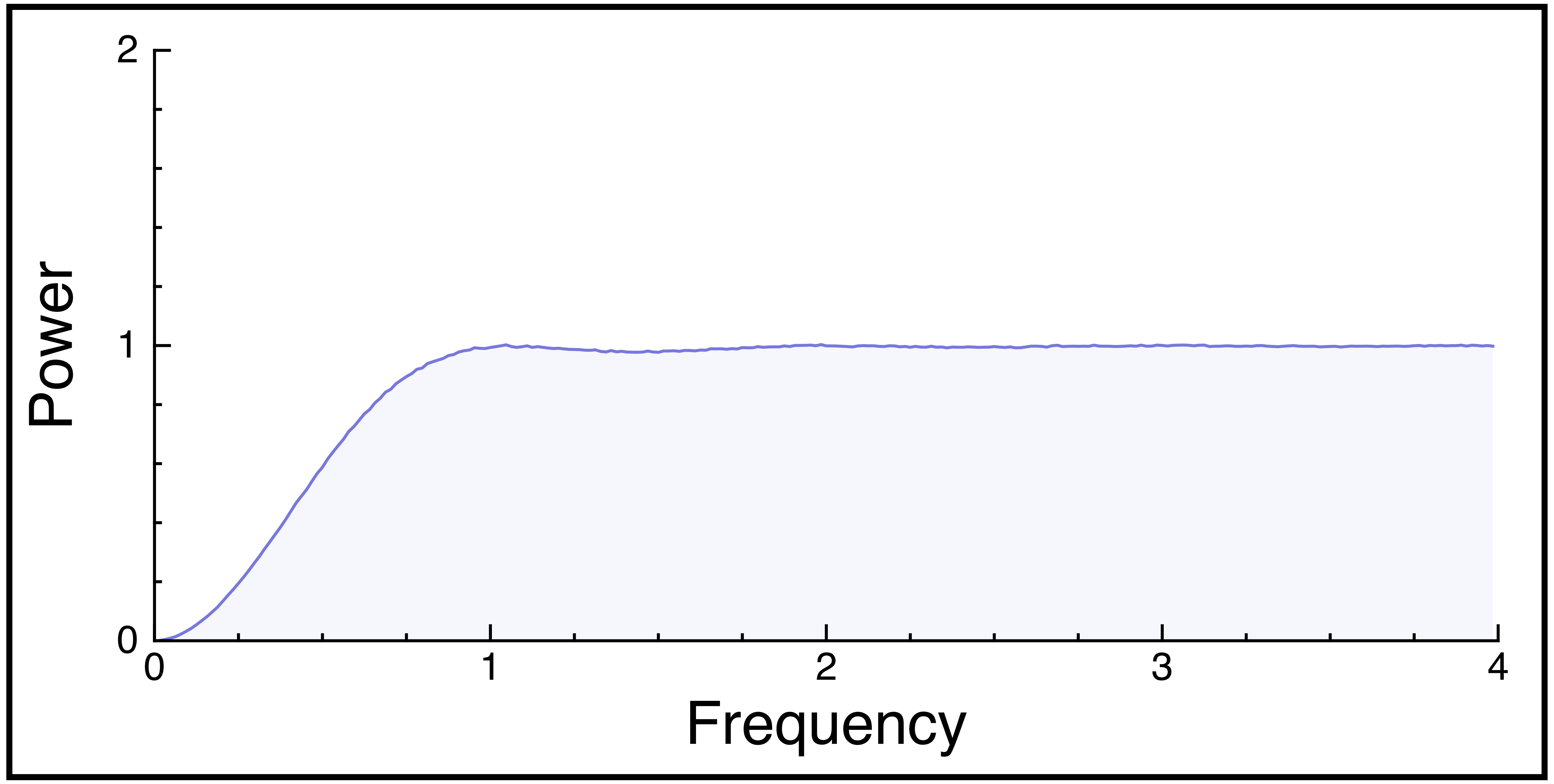
Samples



Expected power spectrum

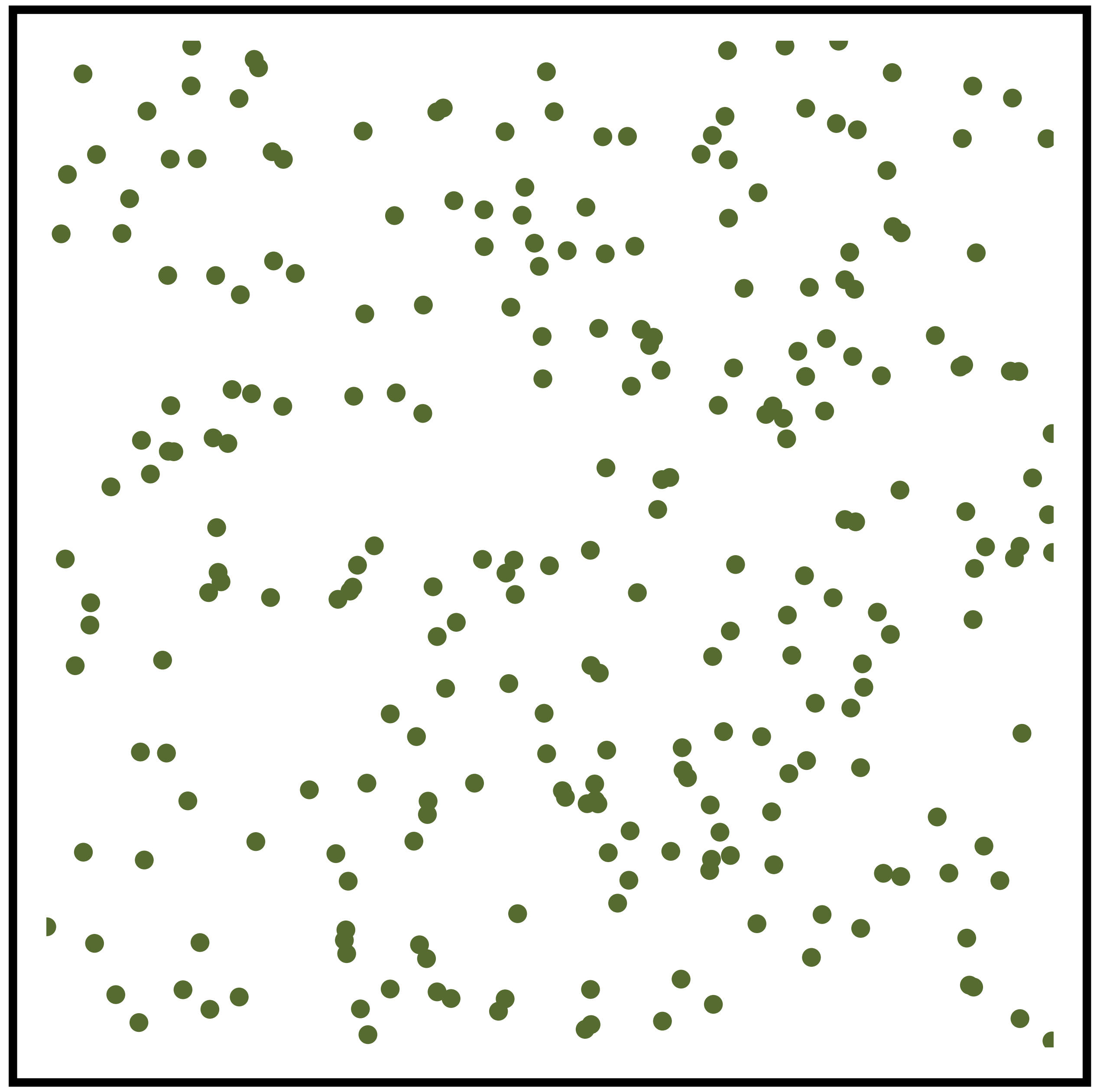


Radial mean



Independent Random Sampling

Samples



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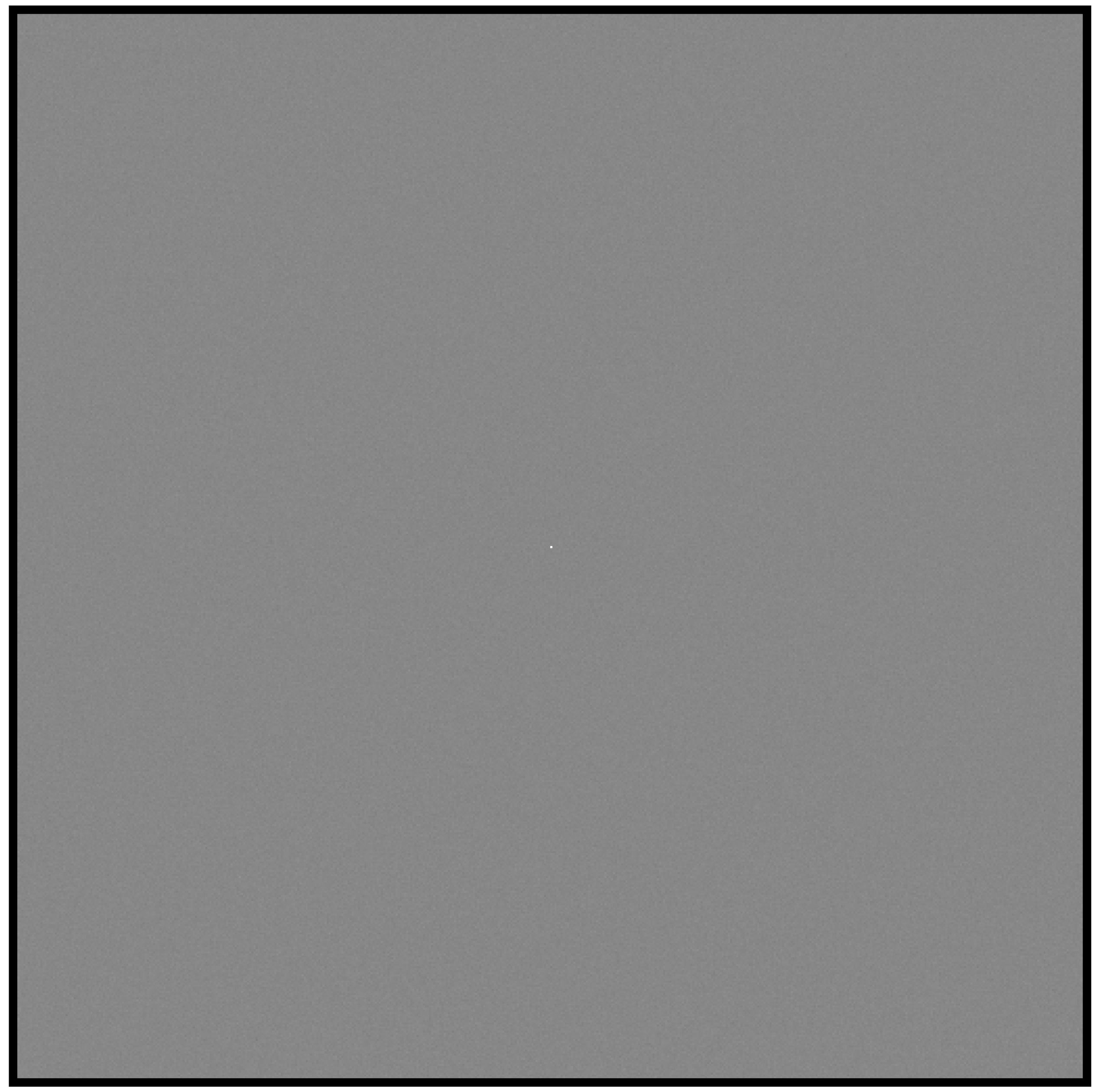
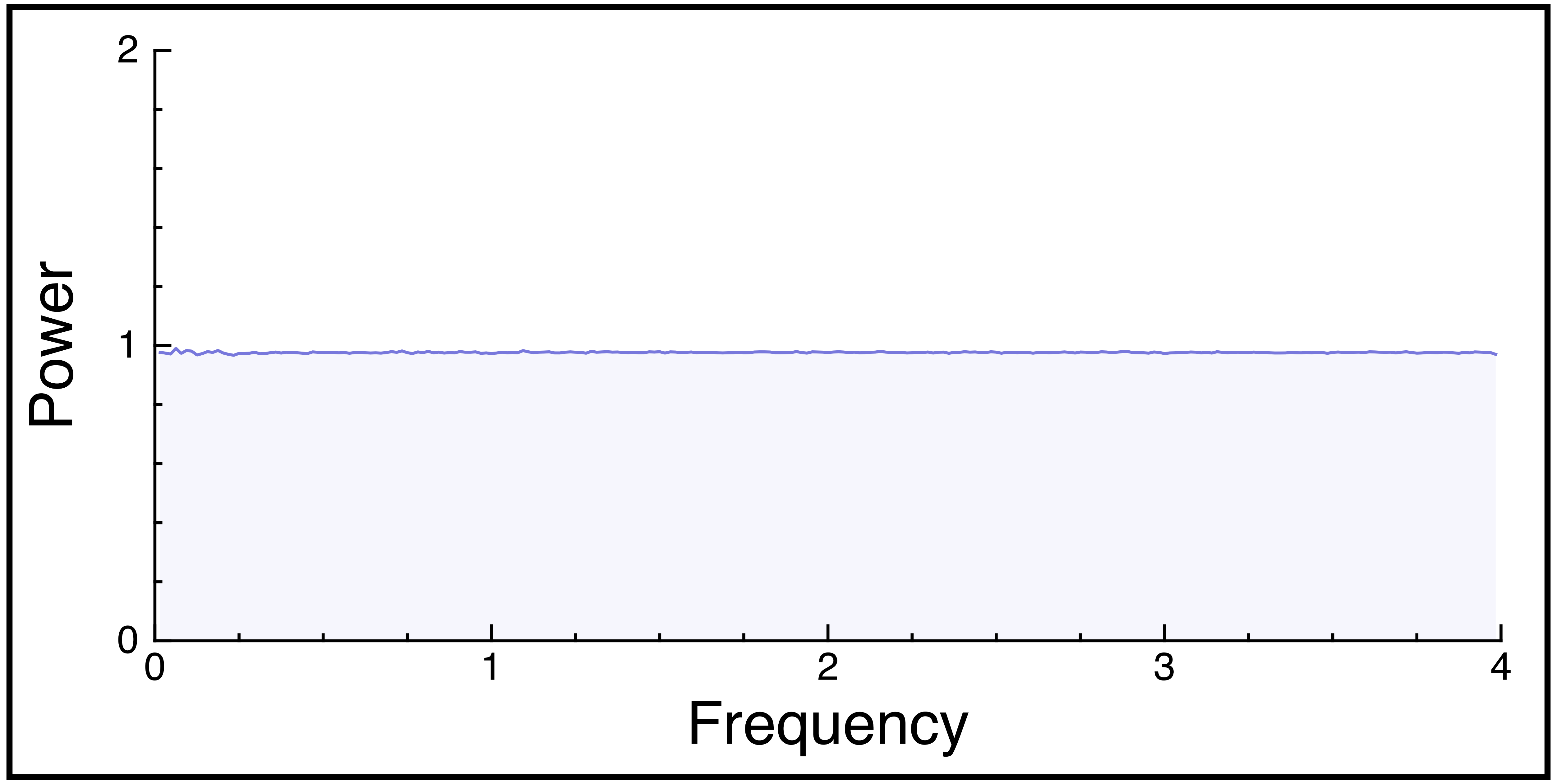
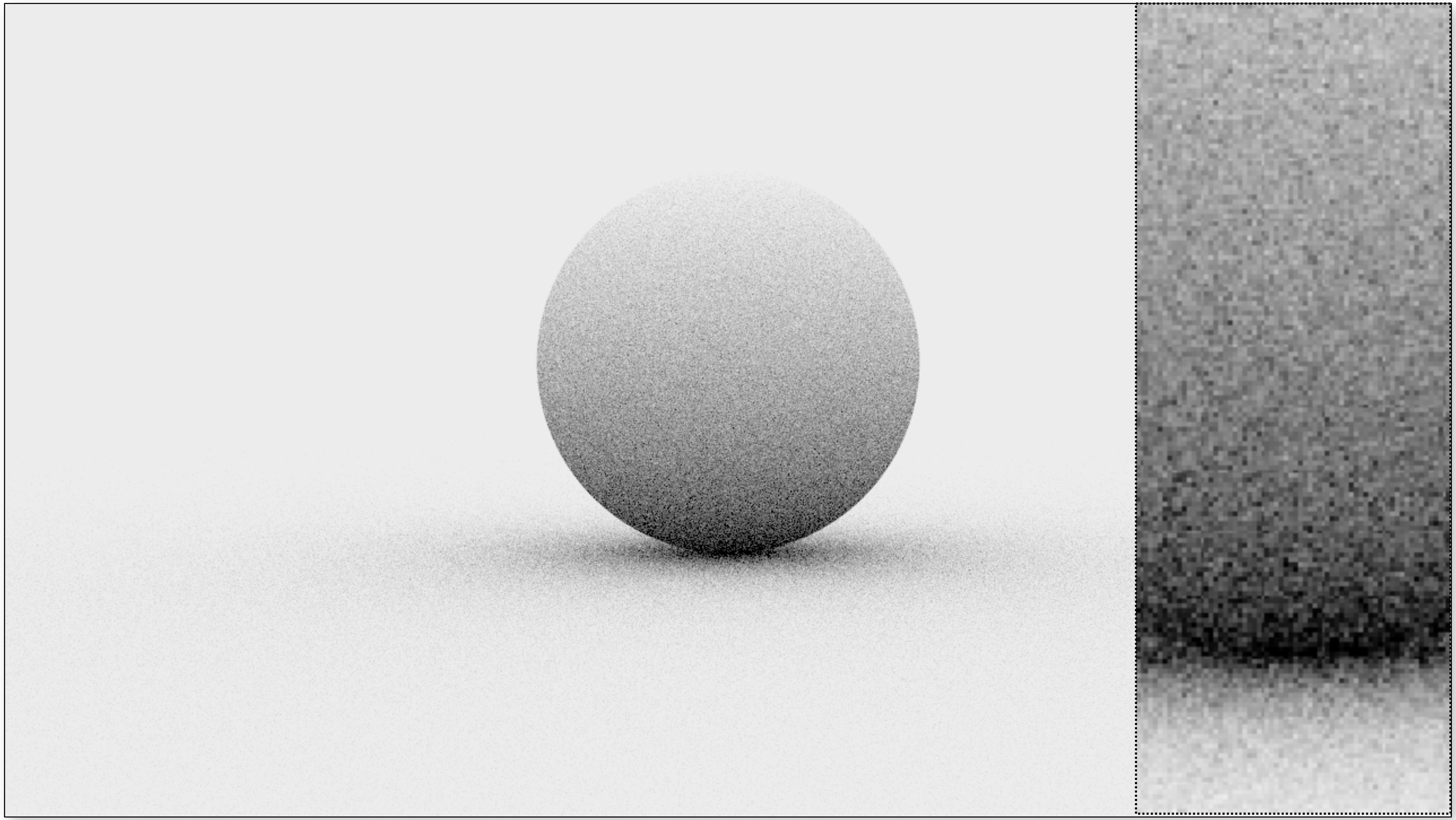


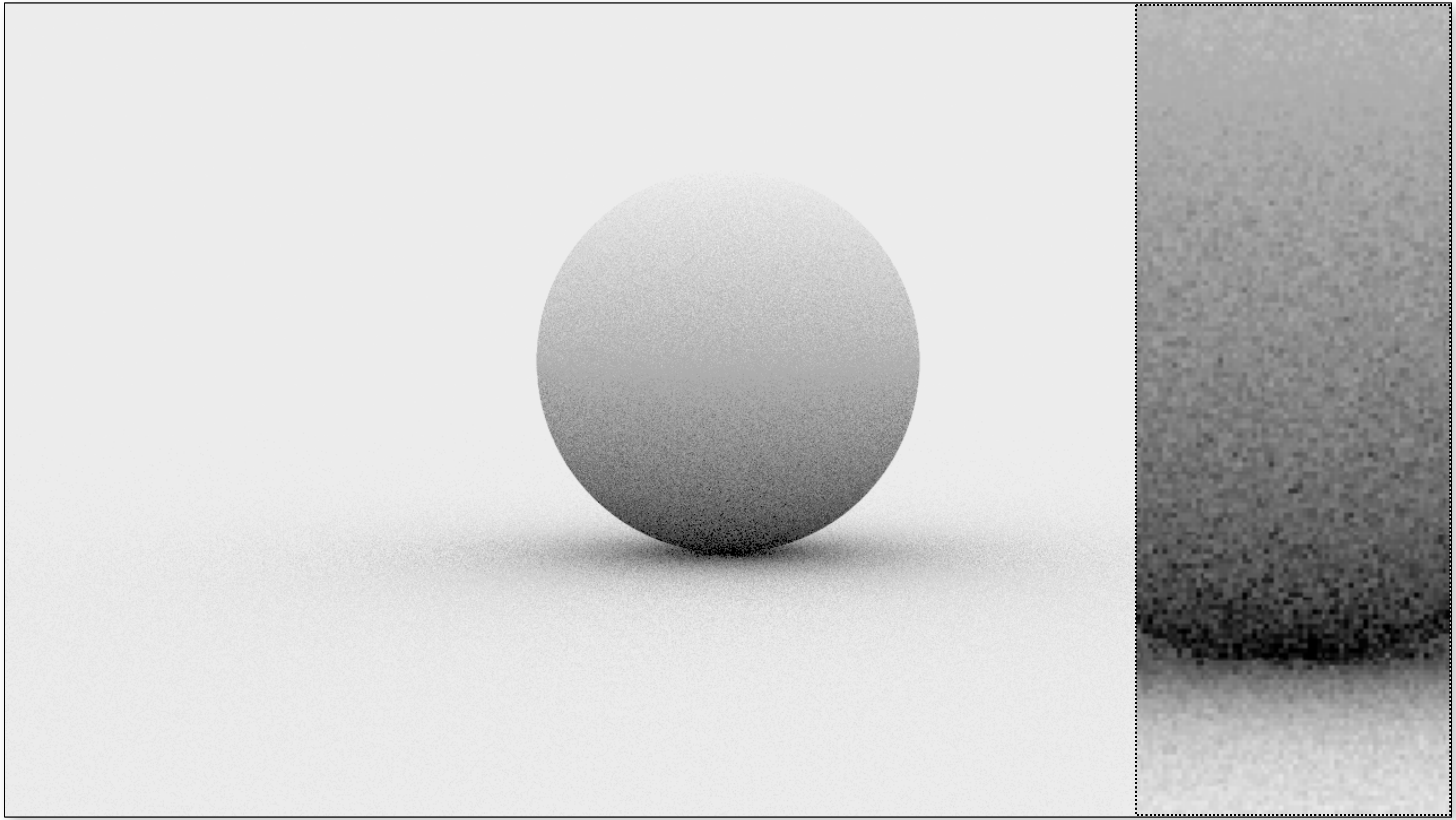
Radial mean



Monte Carlo (16 random samples)



Monte Carlo (16 jittered samples)



Stratifying in Higher Dimensions

Stratification requires O(N^d) samples

- e.g. pixel (2D) + lens (2D) + time (1D) = 5D

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  - splitting 3 times in 5D = 3^5 = 243 samples!

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  - splitting 2 times in 5D = 2^5 = 32 samples
  - splitting 3 times in 5D = 3^5 = 243 samples!

Inconvenient for large d

- cannot select sample count with fine granularity

Uncorrelated Jitter [Cook et al. 84]

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Compute stratified samples in sub-dimensions

Uncorrelated Jitter [Cook et al. 84]

Compute stratified samples in sub-dimensions

- 2D jittered (x,y) for pixel

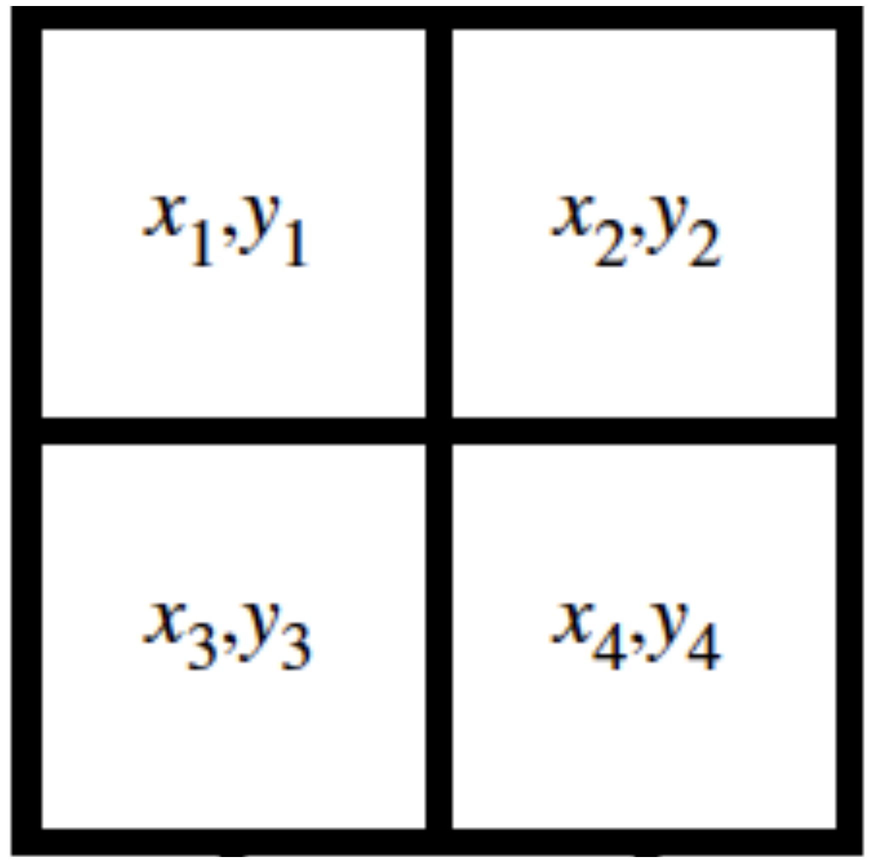
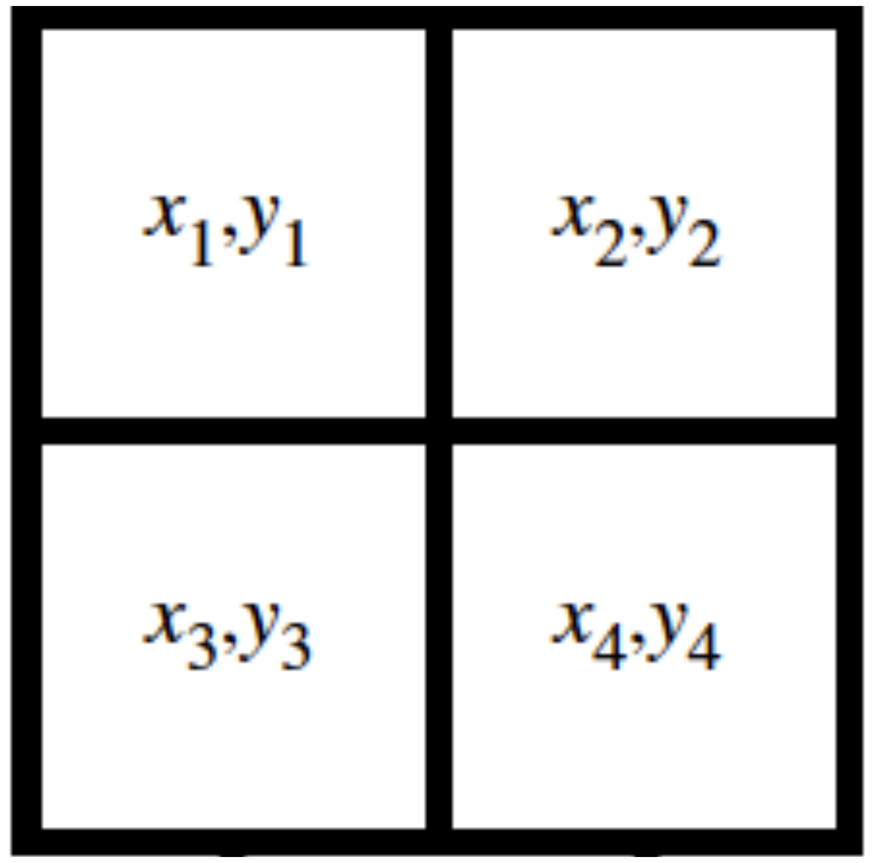


Image source: PBRTe2 [Pharr & Humphreys 2010]

Uncorrelated Jitter [Cook et al. 84]

Compute stratified samples in sub-dimensions

- 2D jittered (x,y) for pixel
- 2D jittered (u,v) for lens



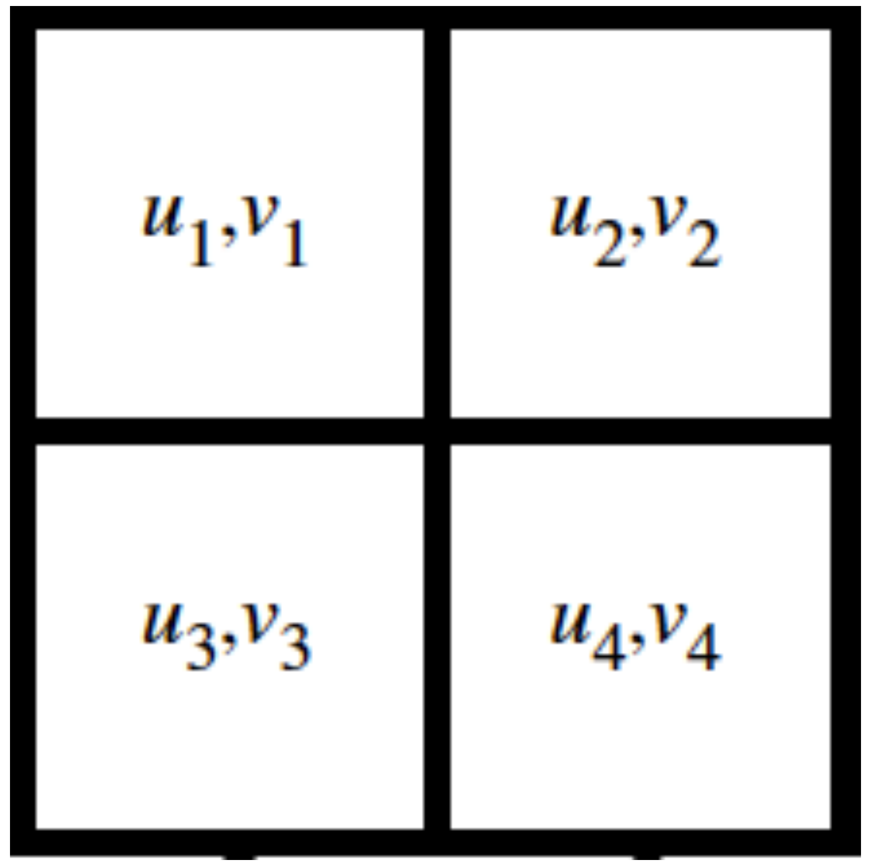


Image source: PBRTe2 [Pharr & Humphreys 2010]

Uncorrelated Jitter [Cook et al. 84]

Compute stratified samples in sub-dimensions

- 2D jittered (x,y) for pixel
- 2D jittered (u,v) for lens
- 1D jittered (t) for time

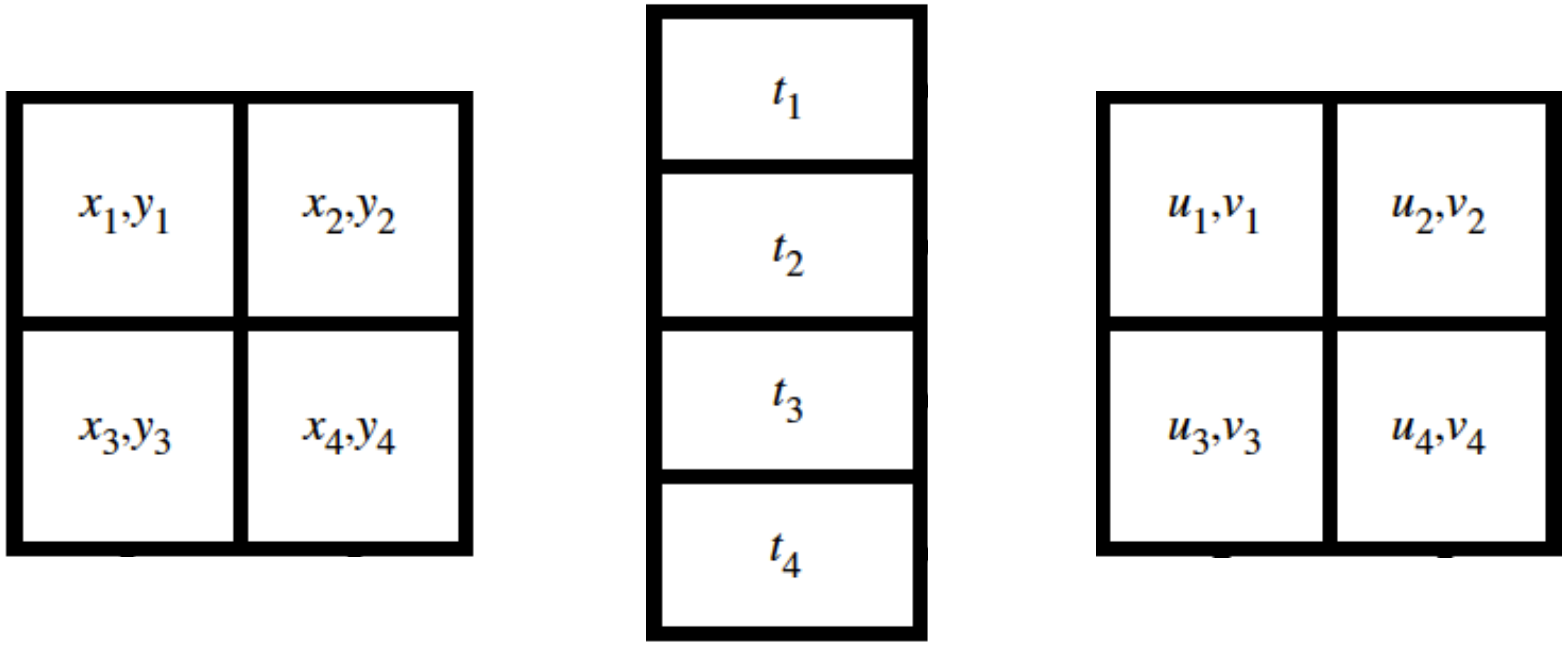


Image source: PBRTe2 [Pharr & Humphreys 2010]

Uncorrelated Jitter [Cook et al. 84]

Compute stratified samples in sub-dimensions

- 2D jittered (x,y) for pixel
- 2D jittered (u,v) for lens
- 1D jittered (t) for time
- combine dimensions in random order

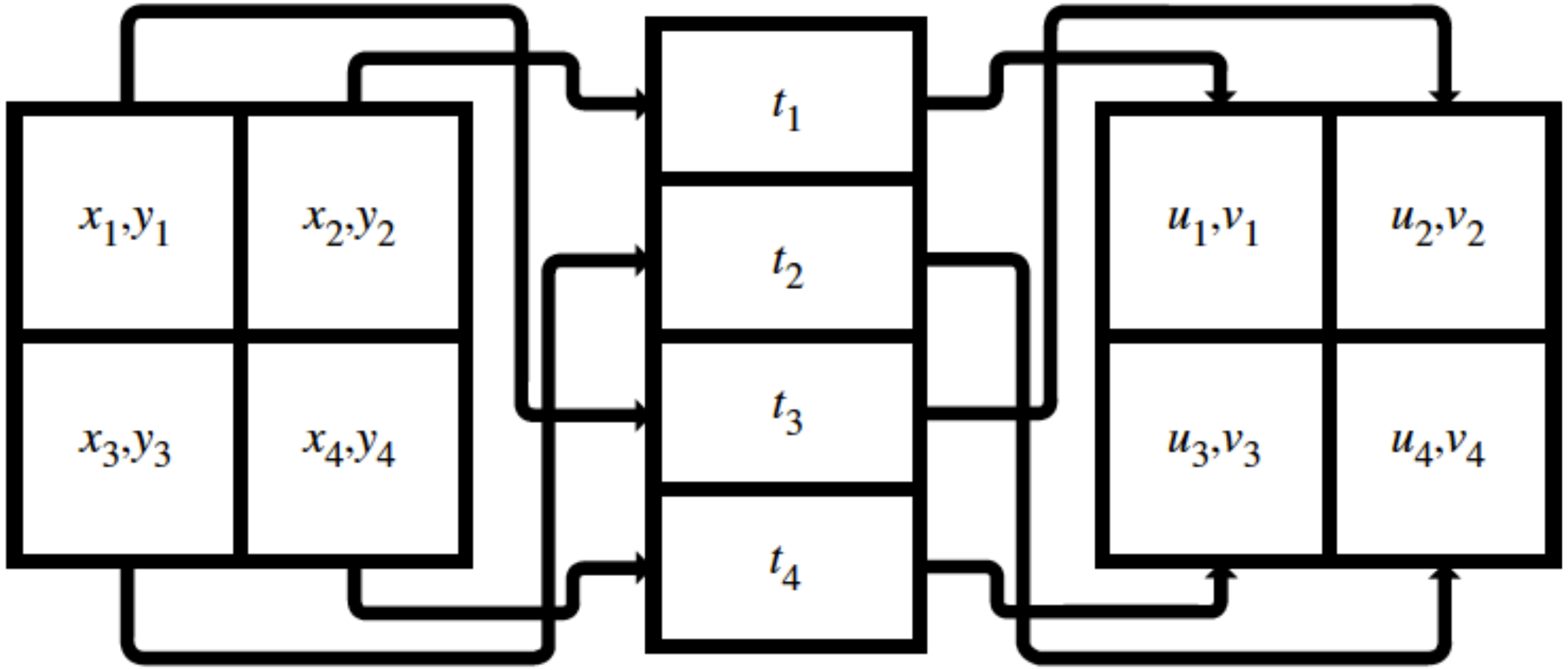


Image source: PBRTe2 [Pharr & Humphreys 2010]

Depth of Field (4D)

Reference

Random Sampling

Uncorrelated Jitter

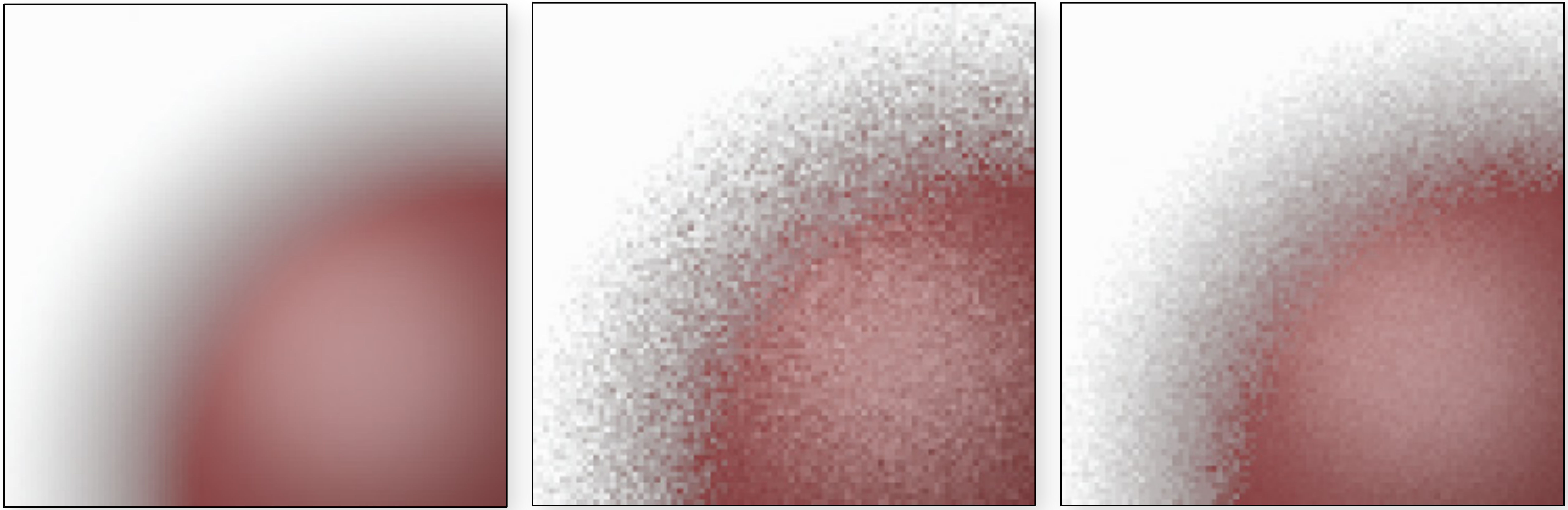


Image source: PBRTe2 [Pharr & Humphreys 2010]

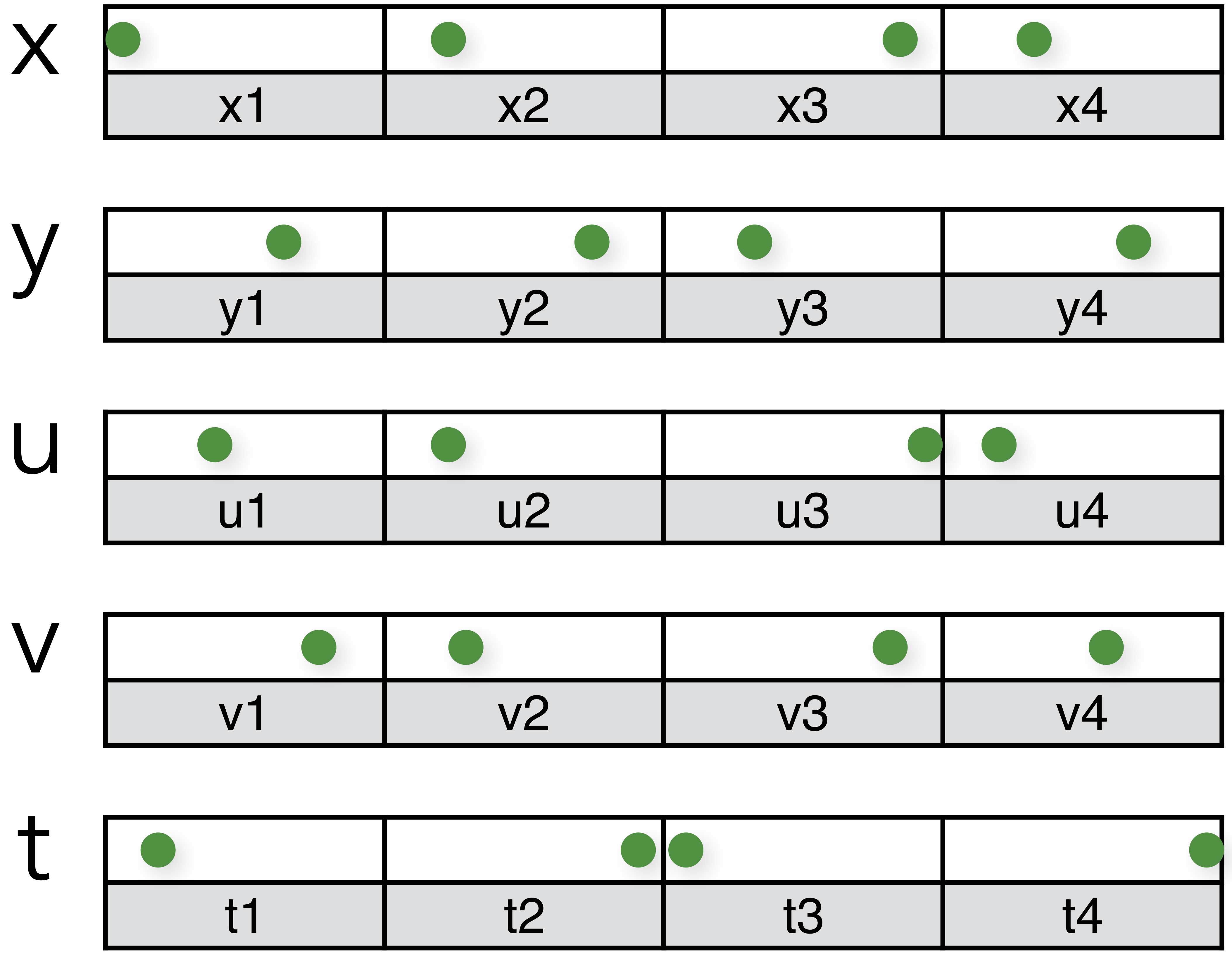
Uncorrelated Jitter → Latin Hypercube

Stratify samples in each dimension separately

Uncorrelated Jitter → Latin Hypercube

Stratify samples in each dimension separately

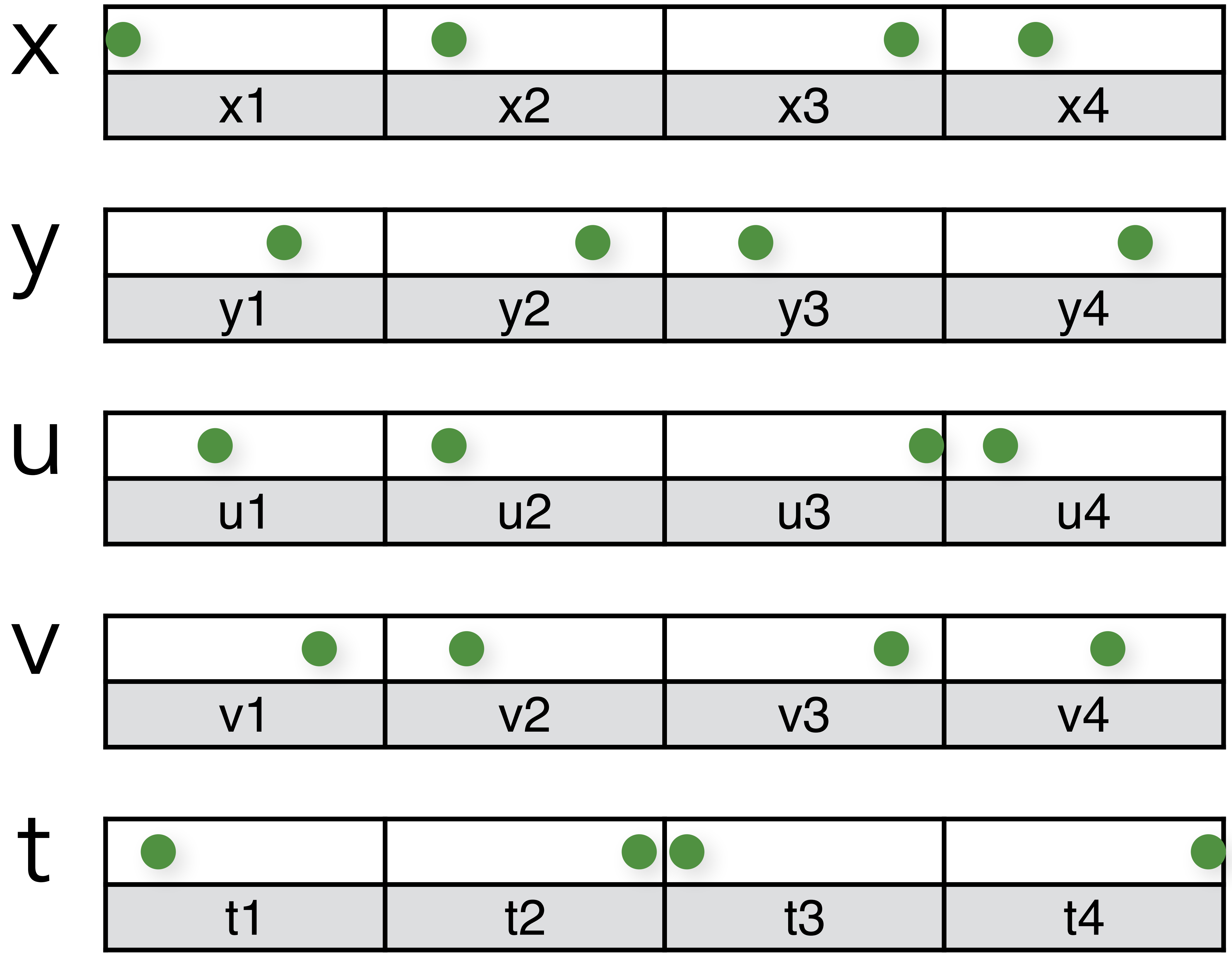
- for 5D: 5 separate 1D jittered point sets



Uncorrelated Jitter → Latin Hypercube

Stratify samples in each dimension separately

- for 5D: 5 separate 1D jittered point sets
- combine dimensions in random order



Uncorrelated Jitter → Latin Hypercube

Stratify samples in each dimension separately

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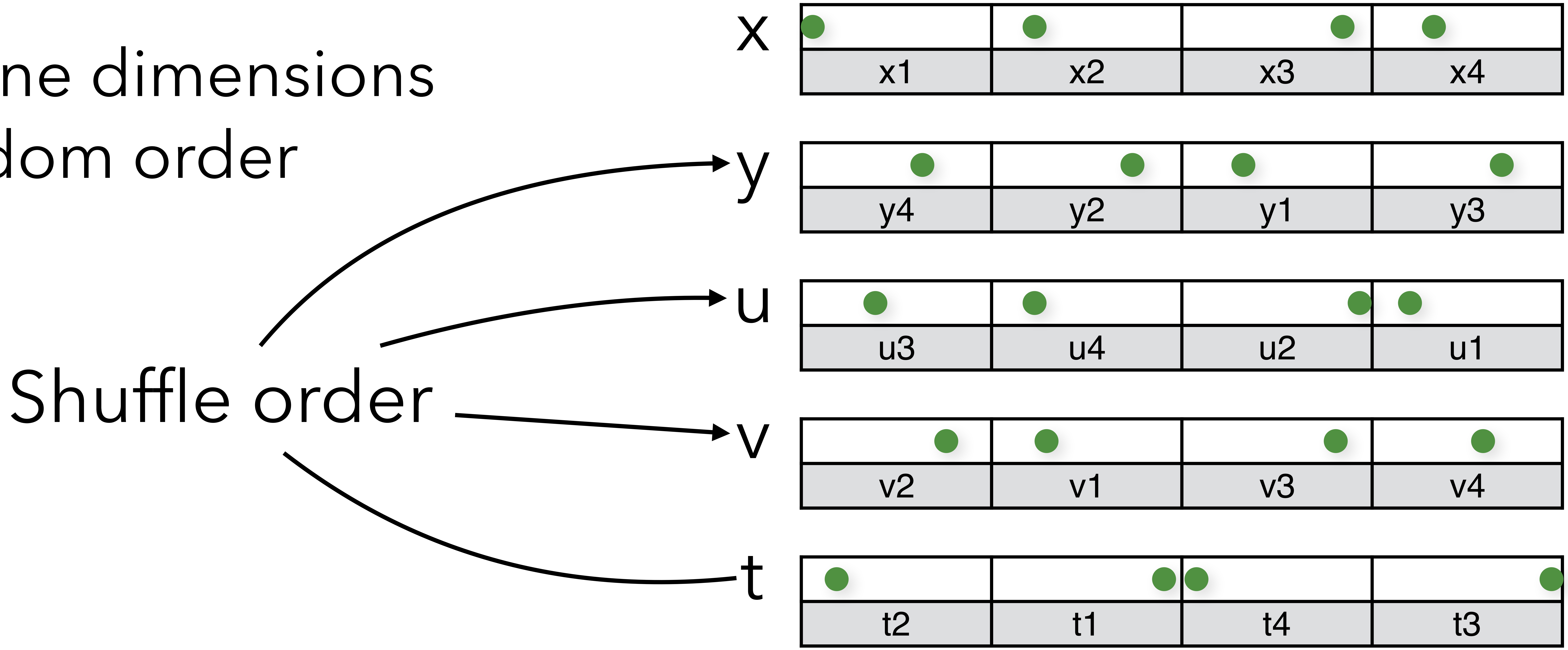
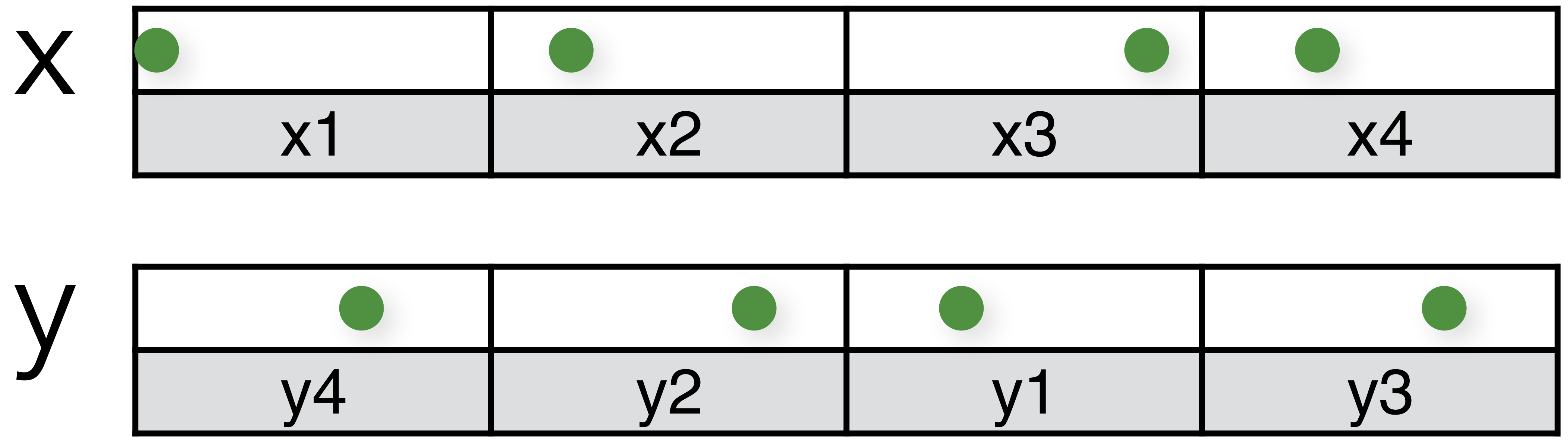


N-Rooks = 2D Latin Hypercube [Shirley 91]

Stratify samples in each dimension separately

- for **2D**: **2** separate 1D jittered point sets
- combine dimensions in random order



Latin Hypercube (N-Rooks) Sampling

[Shirley 91]

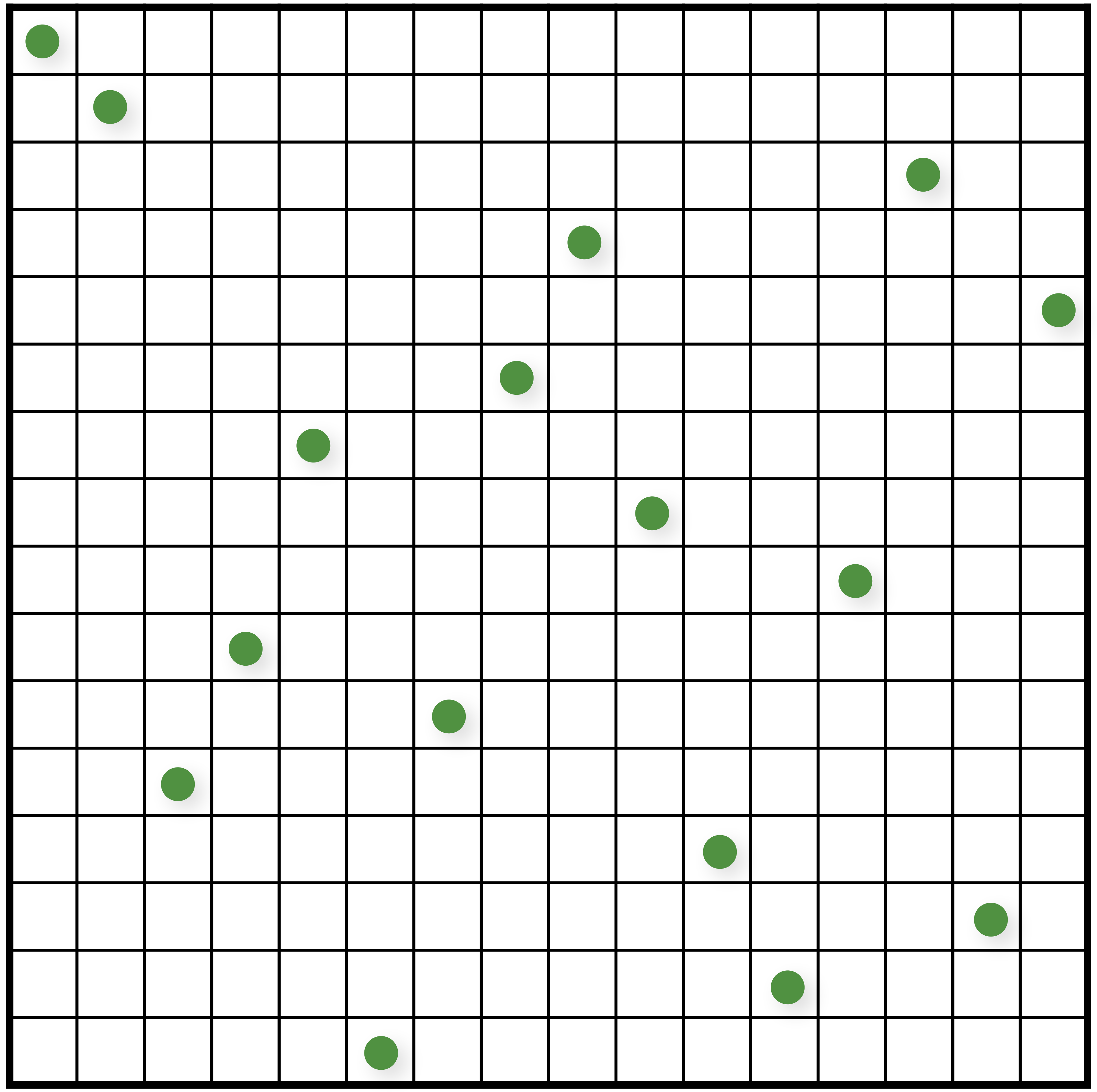
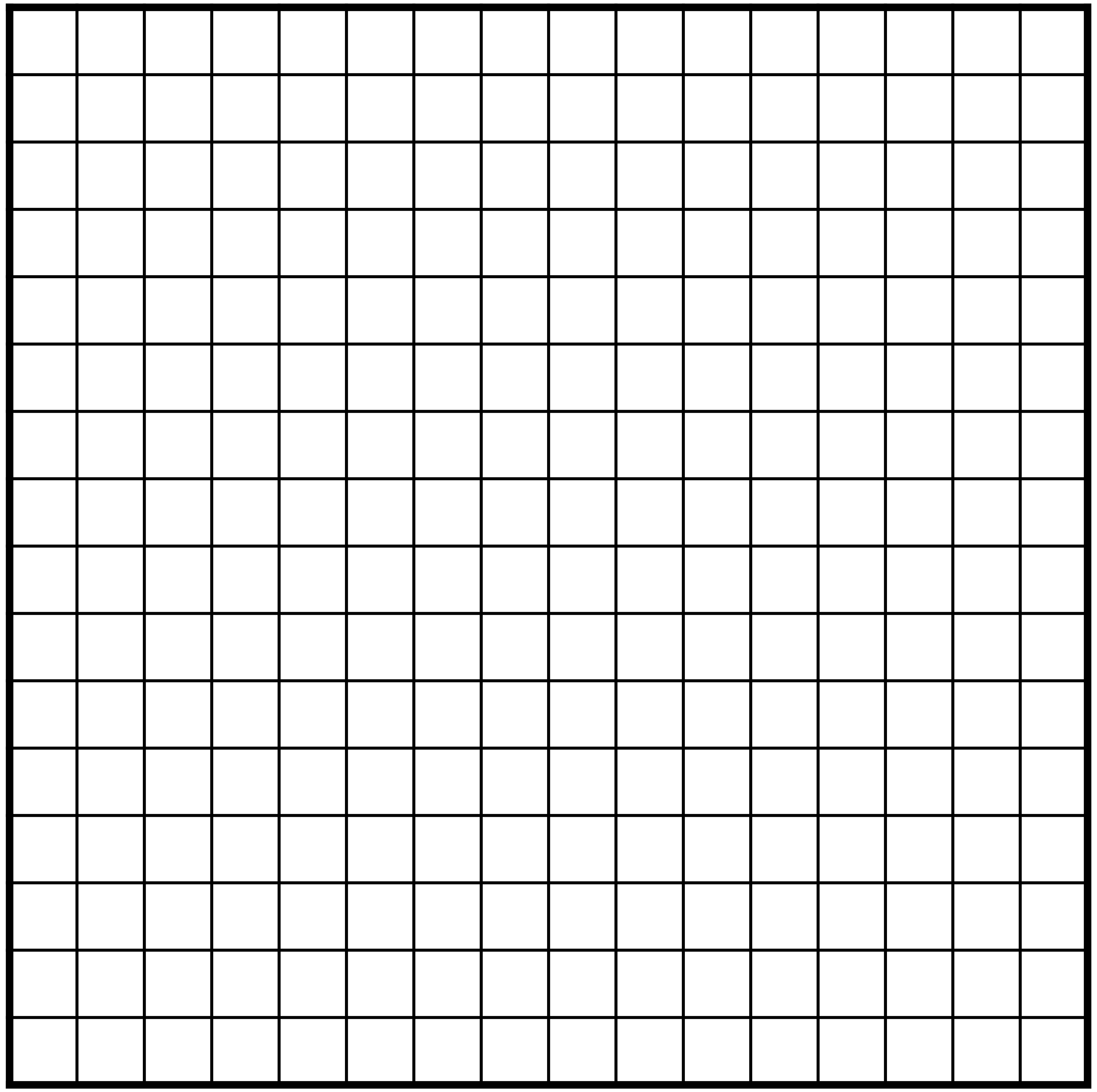


Image source: Michael Maggs, CC BY-SA 2.5

Latin Hypercube (N-Rooks) Sampling

```
// initialize the diagonal
for (uint d = 0; d < numDimensions; d++)
    for (uint i = 0; i < numS; i++)
        samples(d,i) = (i + randf())/numS;

// shuffle each dimension independently
for (uint d = 0; d < numDimensions; d++)
    shuffle(samples(d,:));
```



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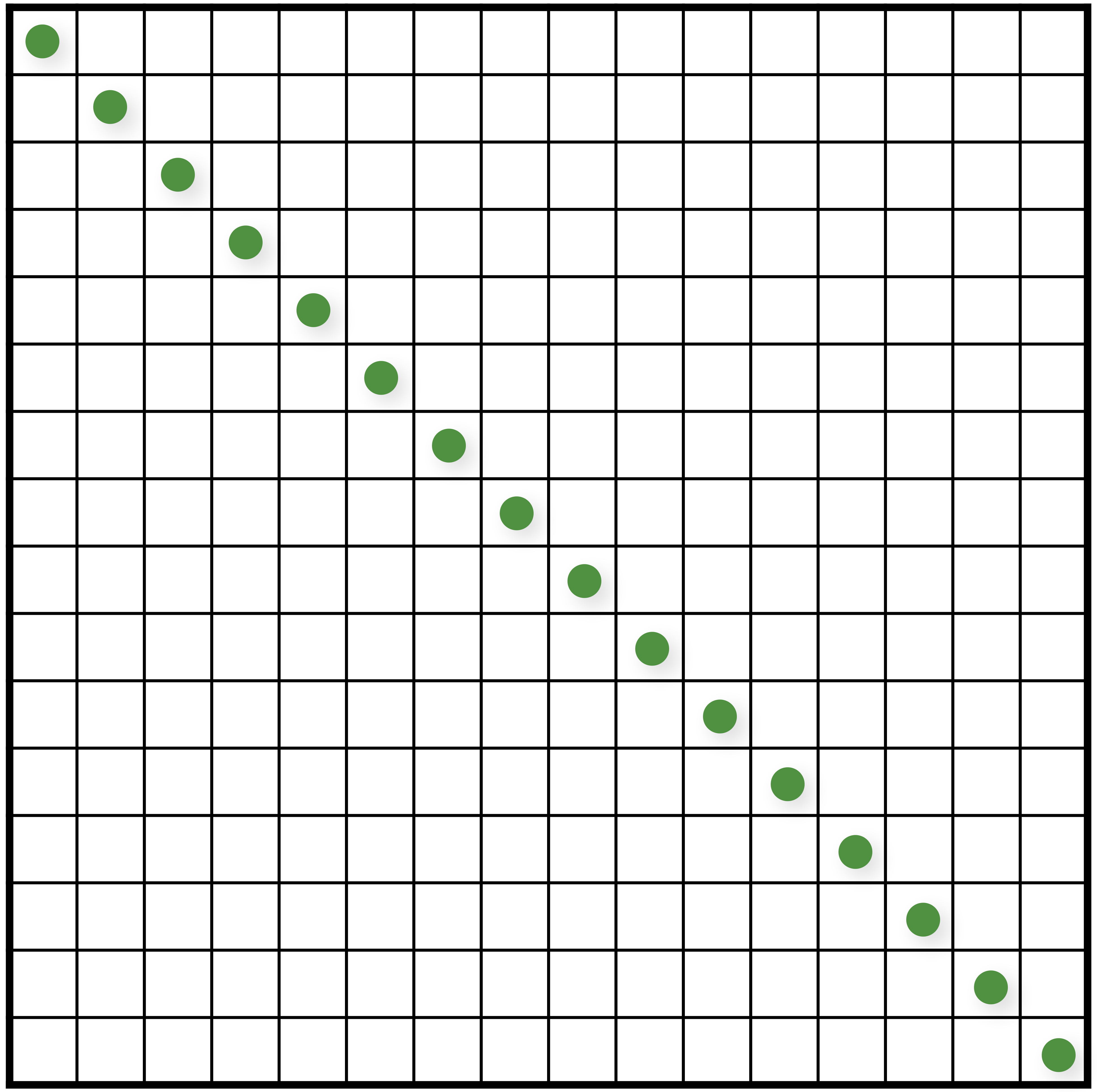

Initialize

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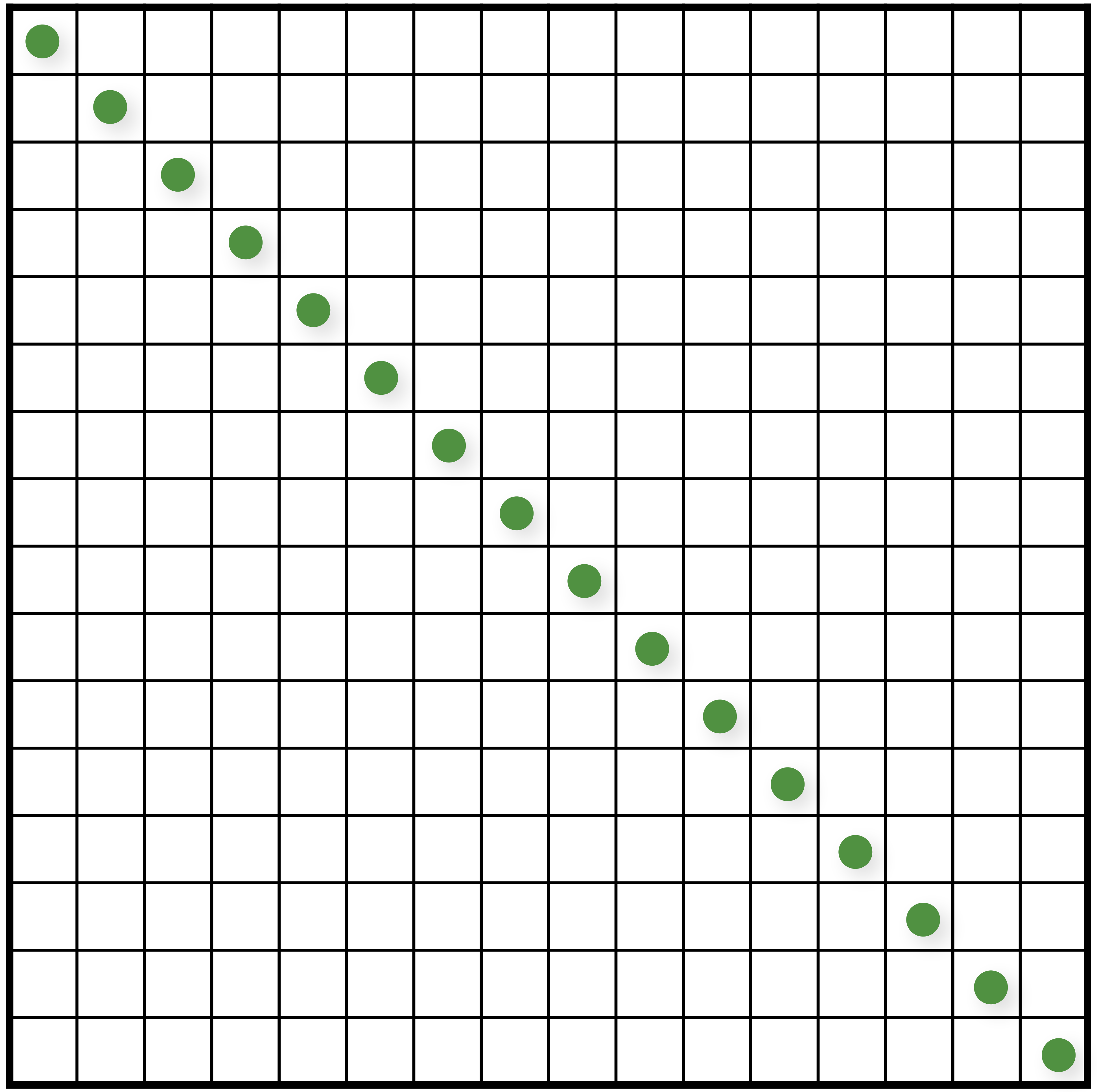

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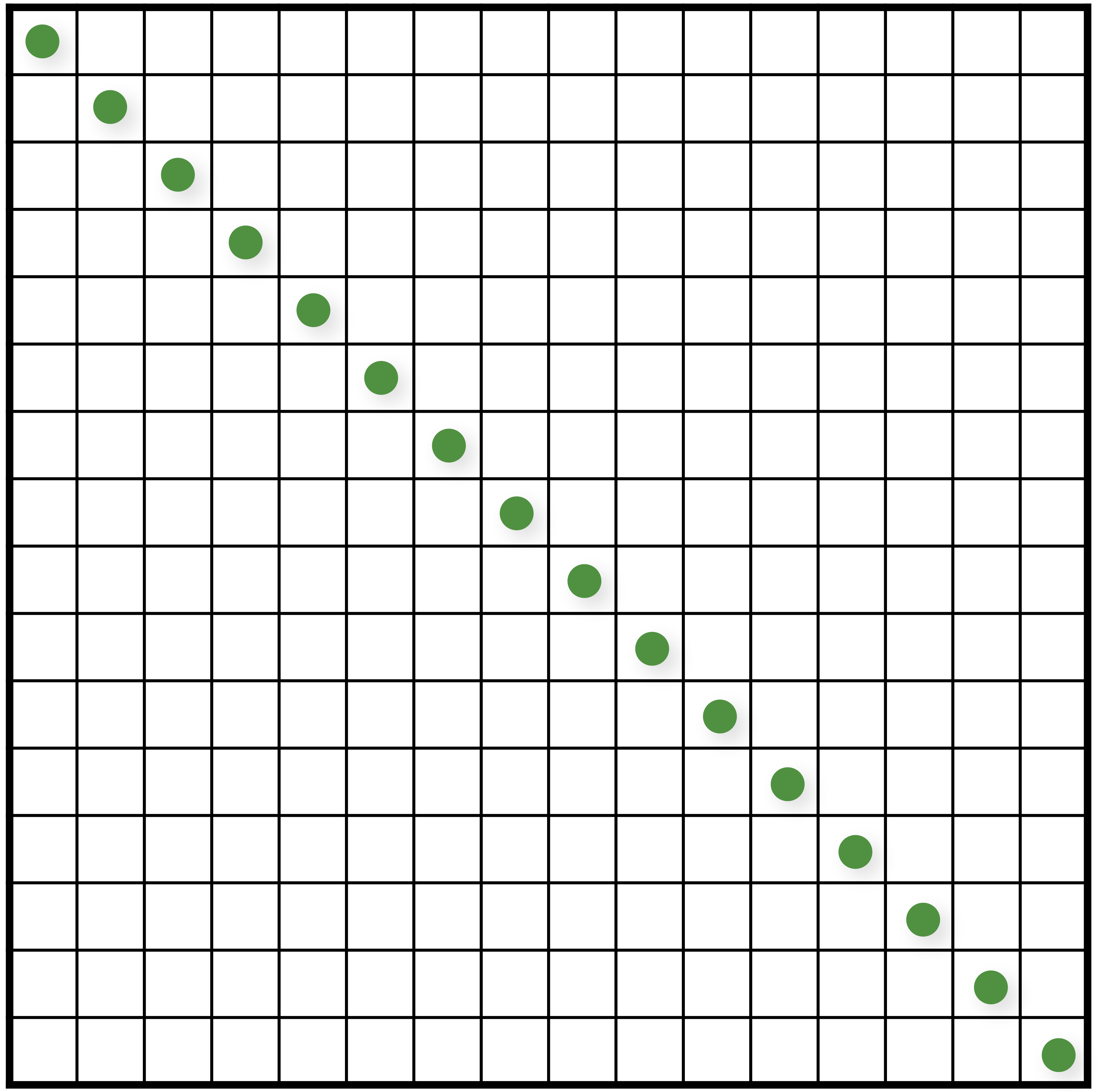

Shuffle rows

Latin Hypercube (N-Rooks) Sampling

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// initialize the diagonal
for (uint d = 0; d < numDimensions; d++)
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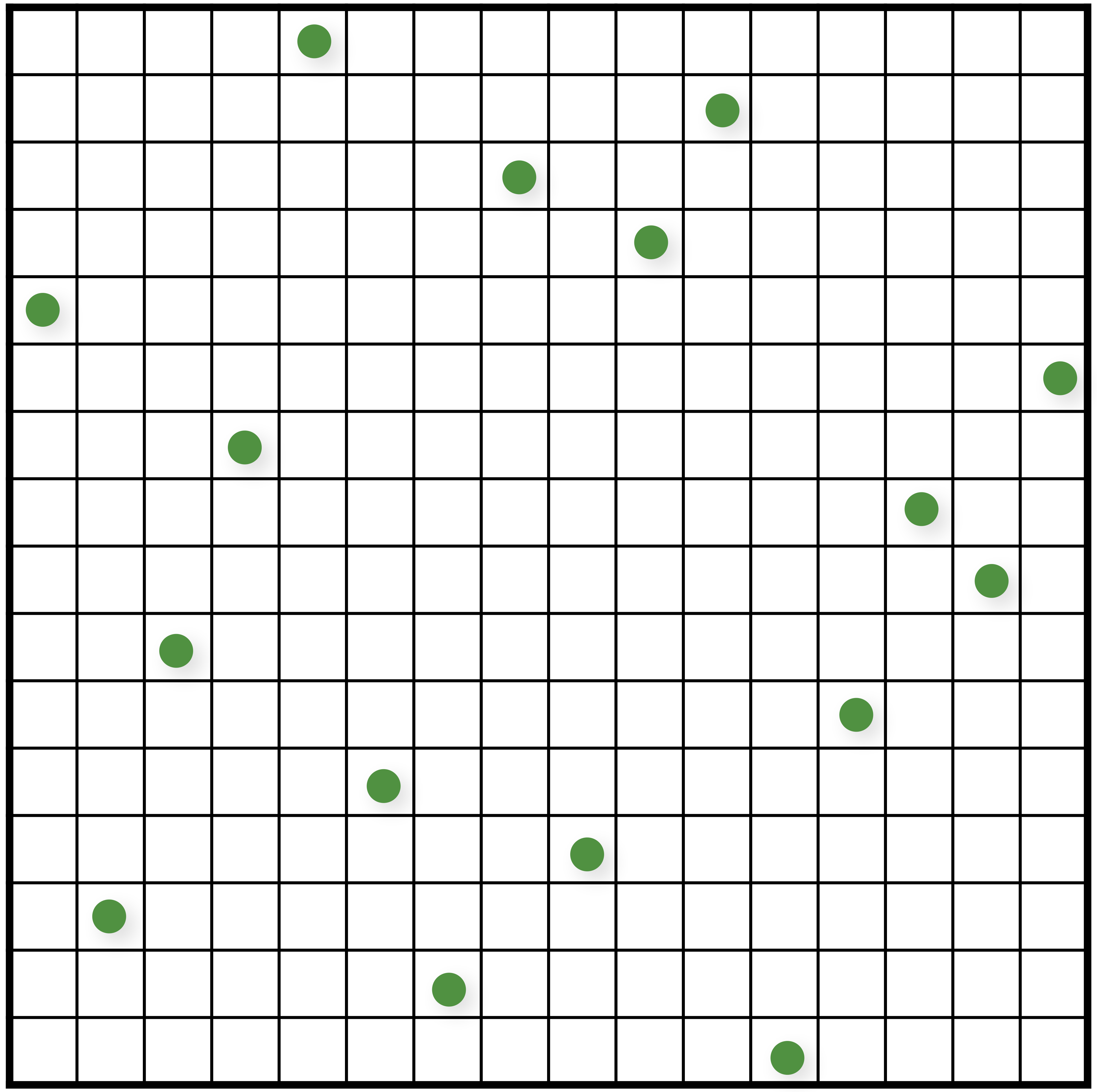

Shuffle rows

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// initialize the diagonal
for (uint d = 0; d < numDimensions; d++)
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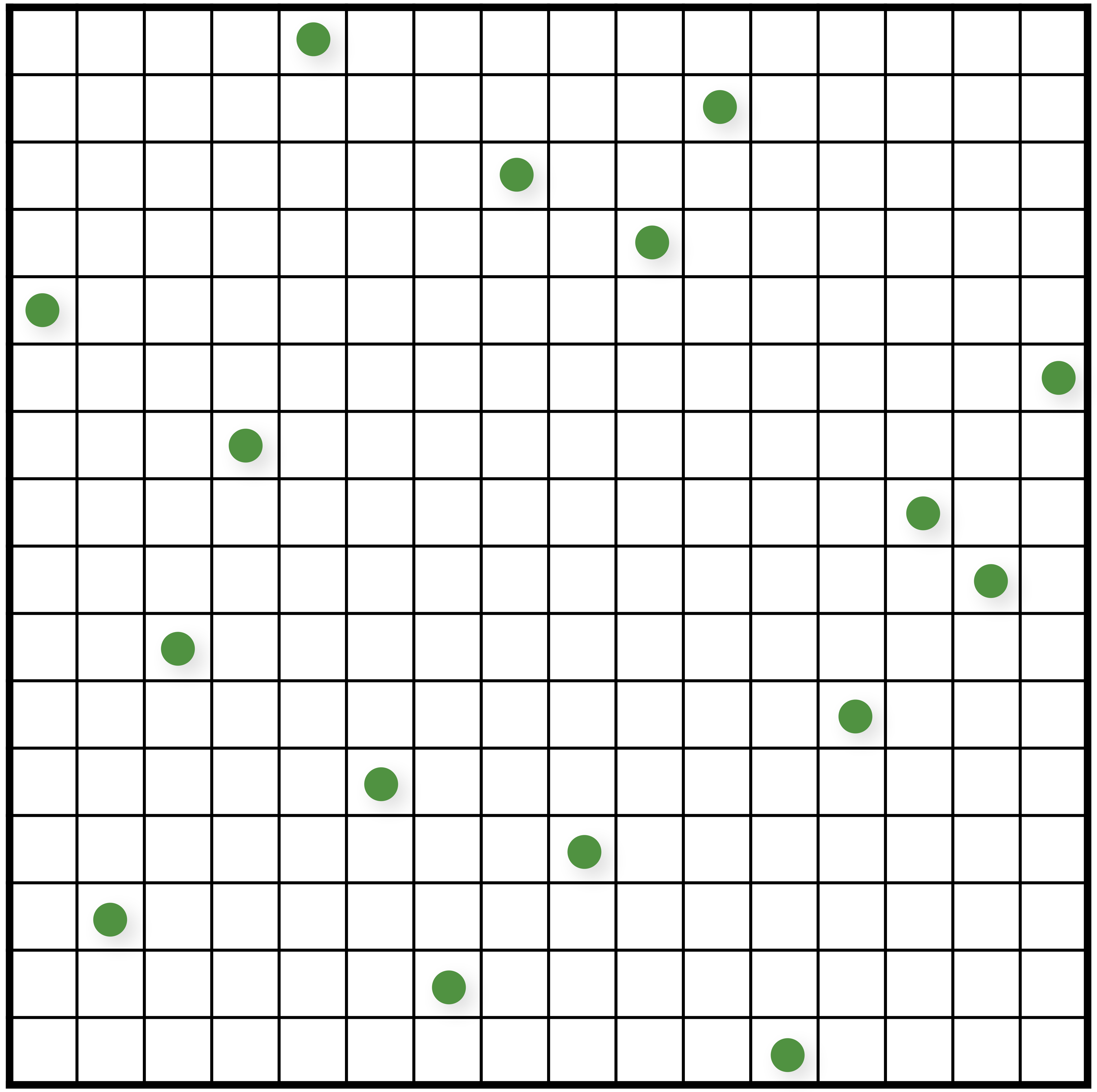

Shuffle rows

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```
// initialize the diagonal
for (uint d = 0; d < numDimensions; d++)
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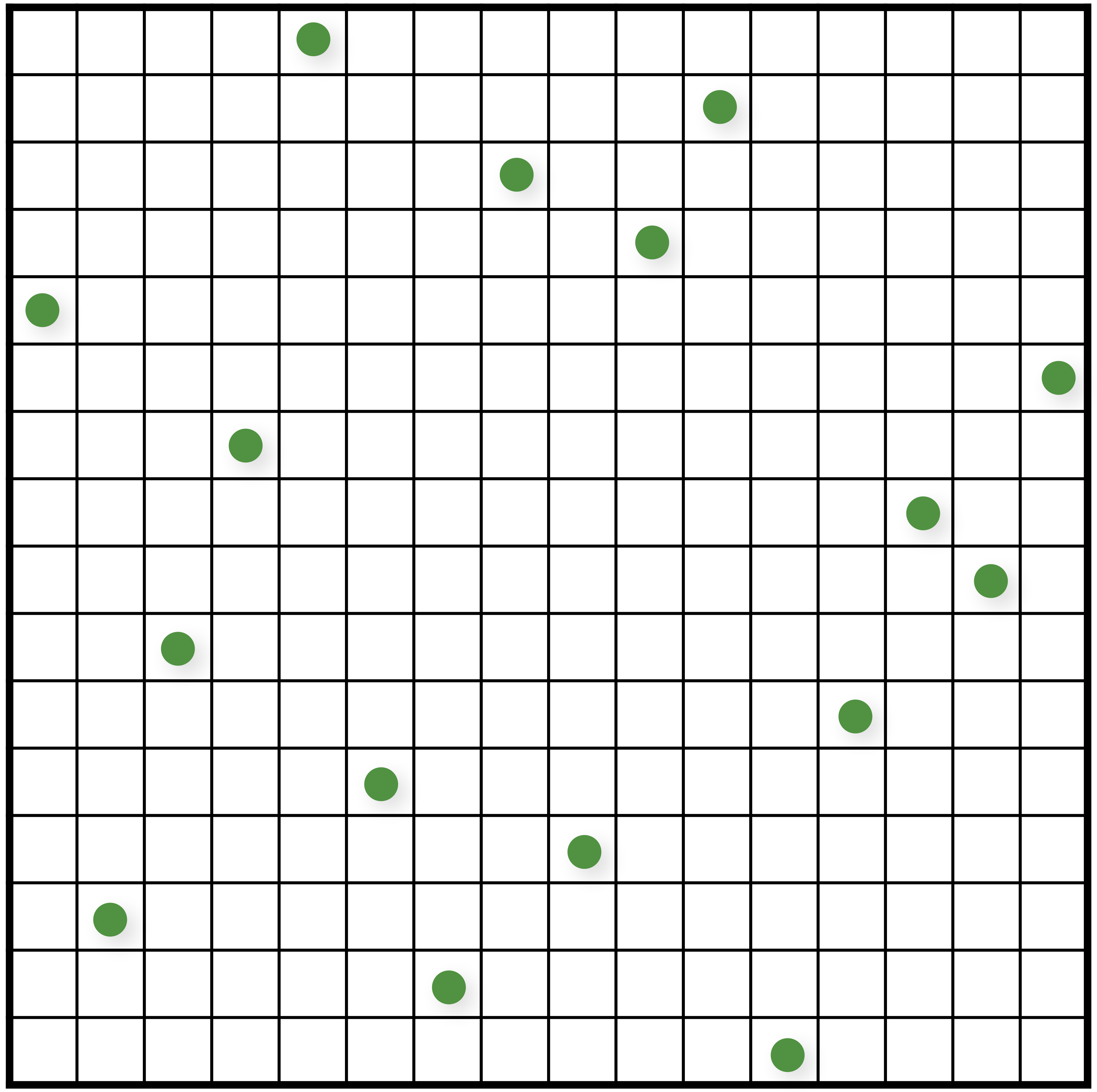

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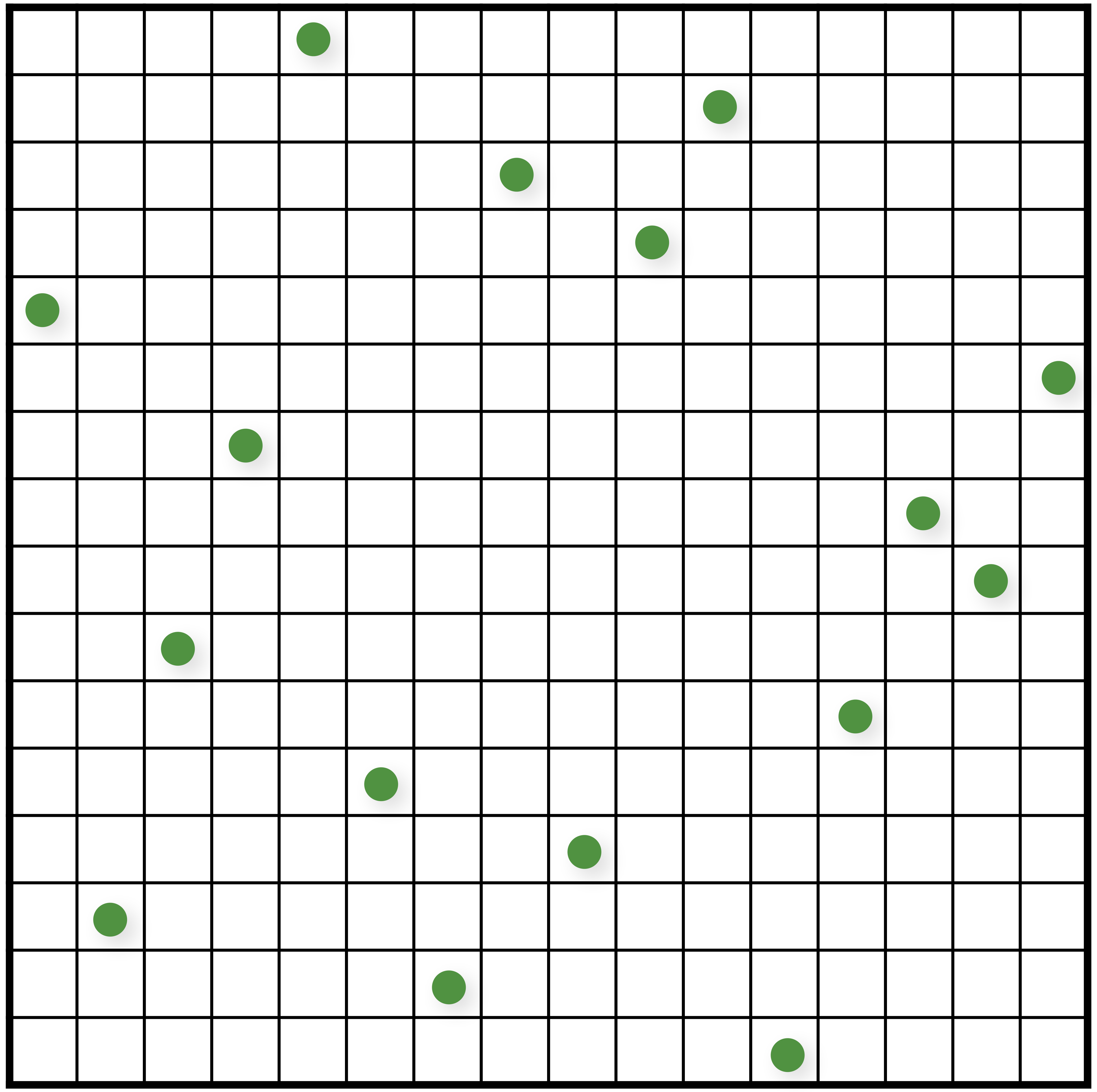
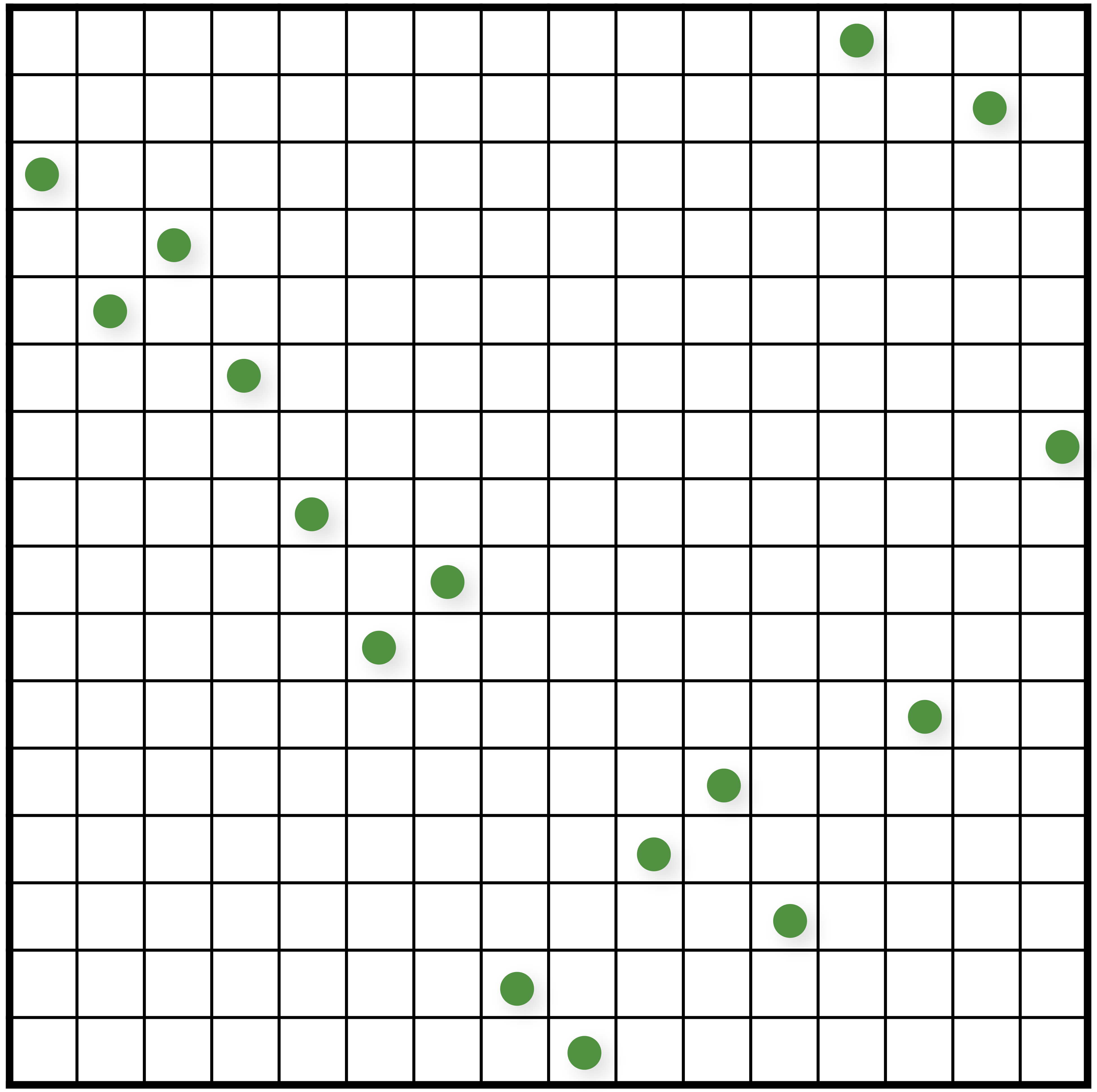


Shuffle columns

Latin Hypercube (N-Rooks) Sampling

```
// initialize the diagonal
for (uint d = 0; d < numDimensions; d++)
    for (uint i = 0; i < numS; i++)
        samples(d,i) = (i + randf())/numS;

// shuffle each dimension independently
for (uint d = 0; d < numDimensions; d++)
    shuffle(samples(d,:));
```



Shuffle columns

Latin Hypercube (N-Rooks) Sampling

```
// initialize the diagonal
for (uint d = 0; d < numDimensions; d++)
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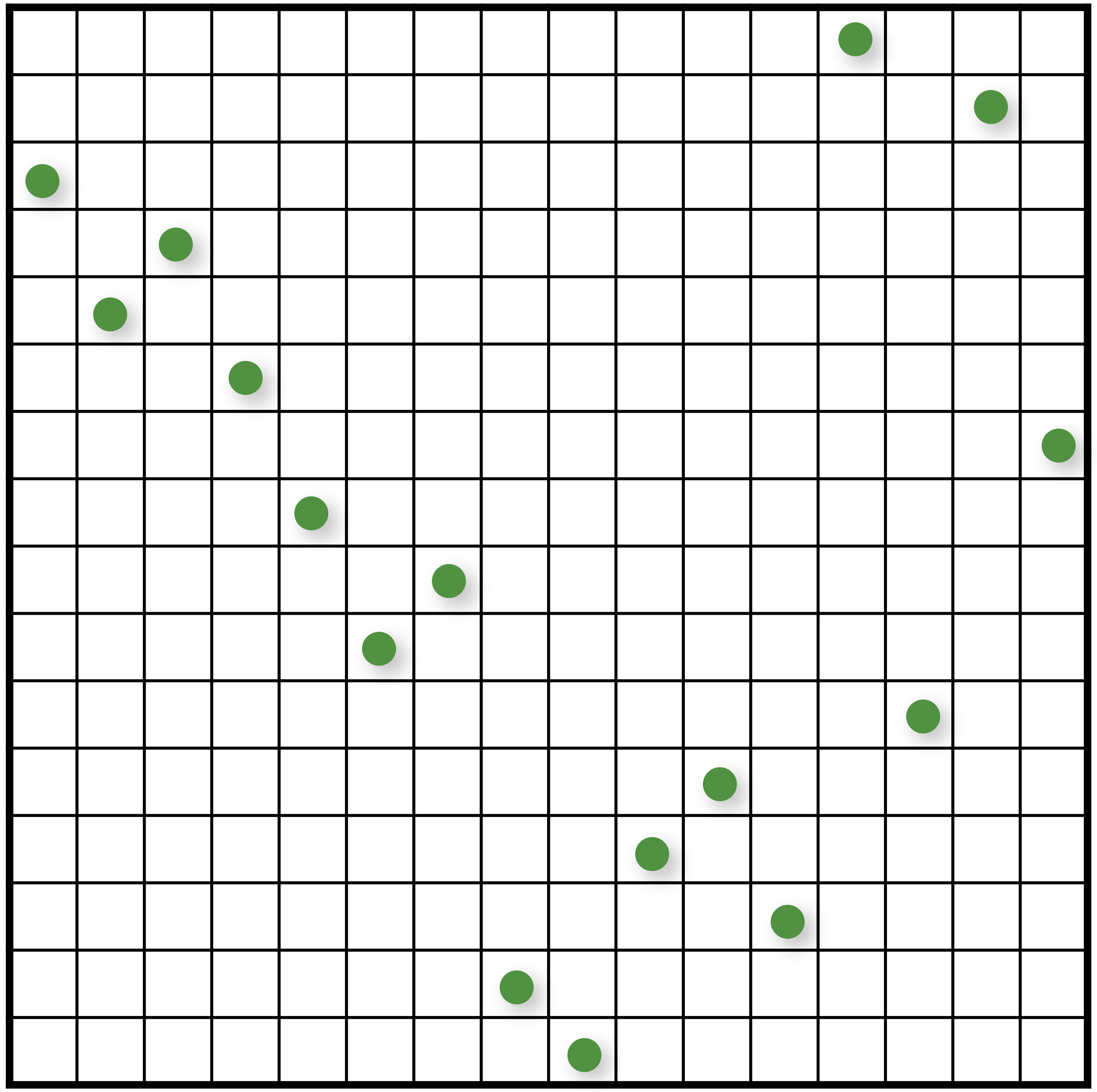
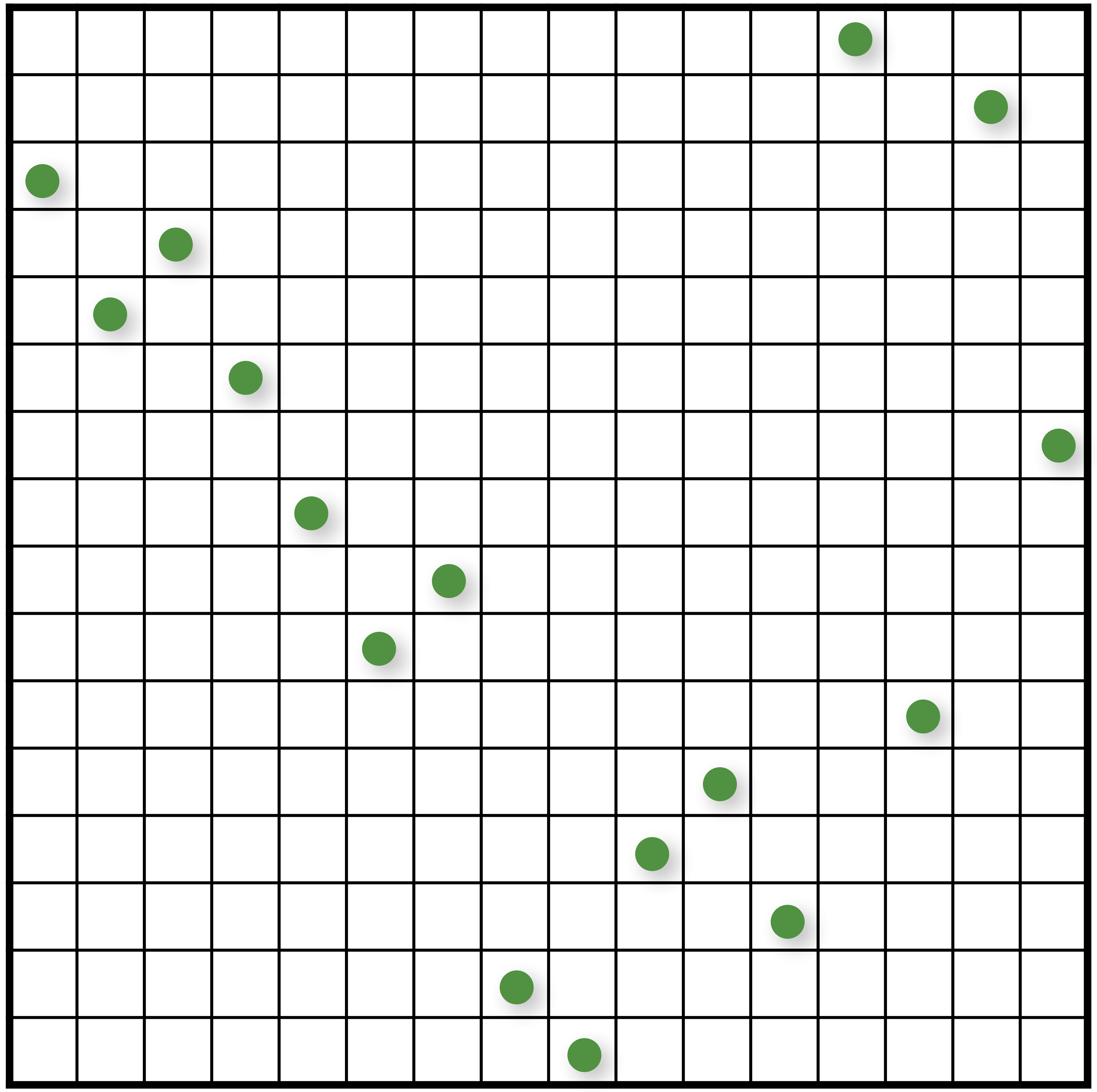
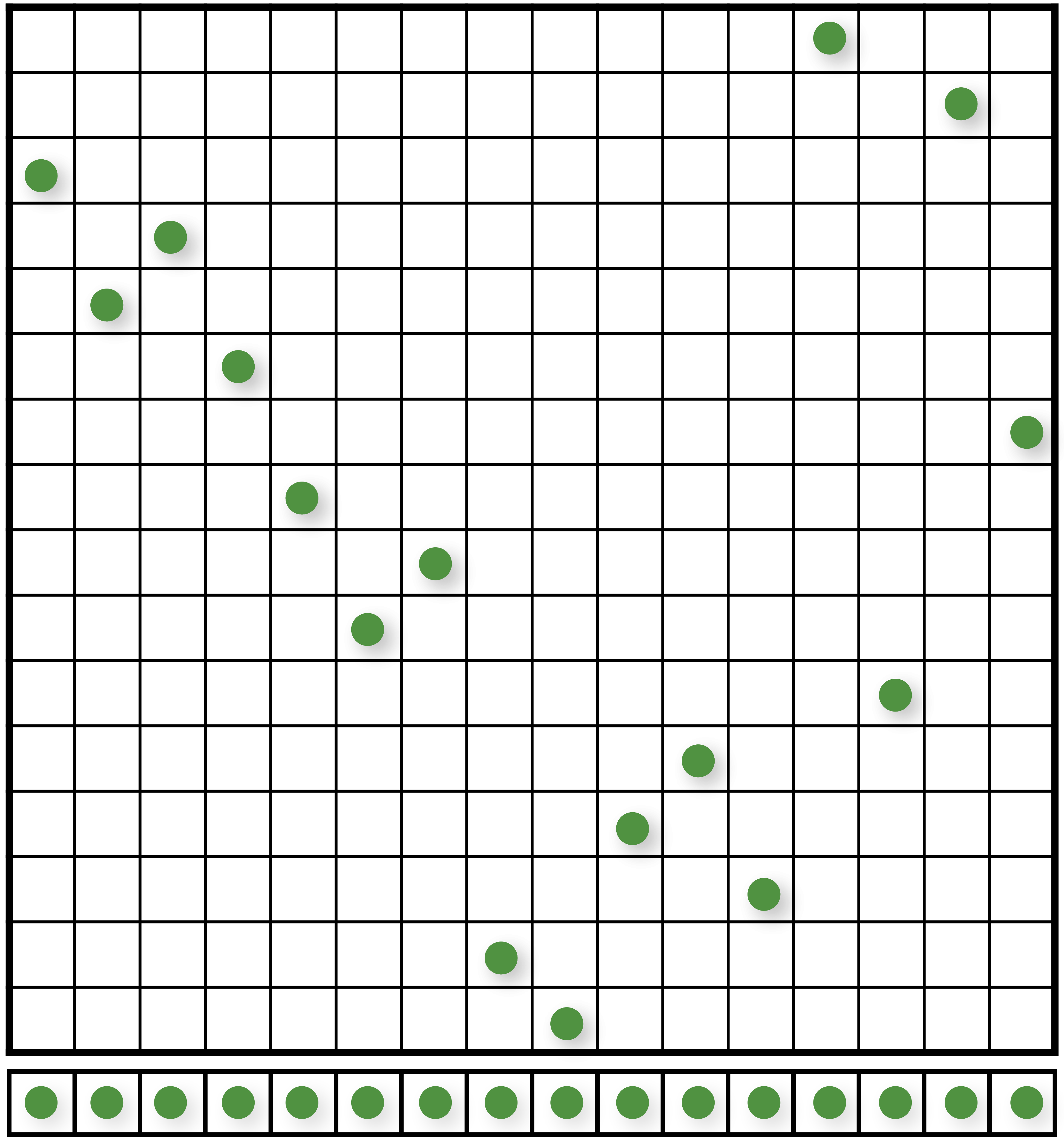


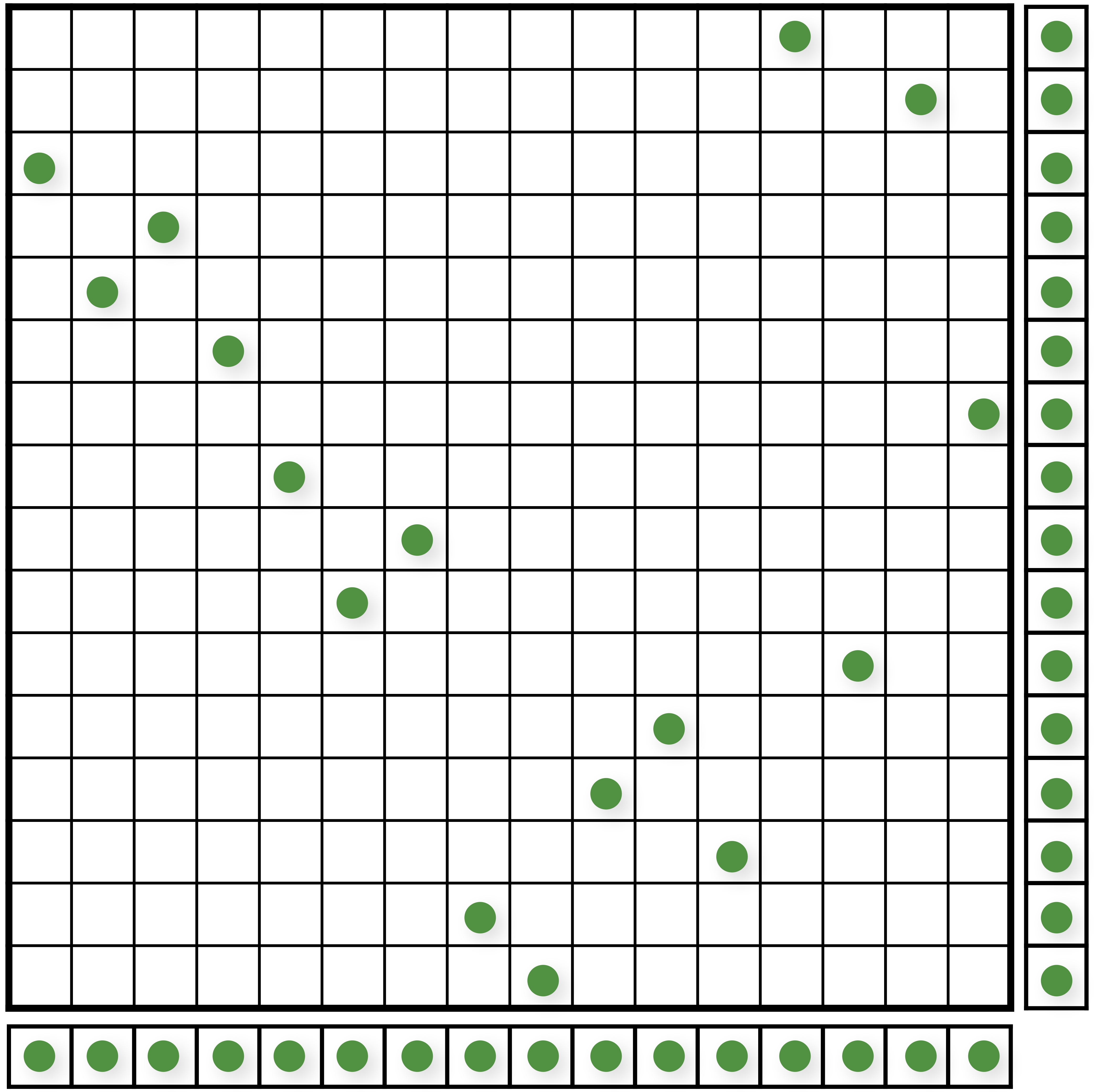
Latin Hypercube (N-Rooks) Sampling



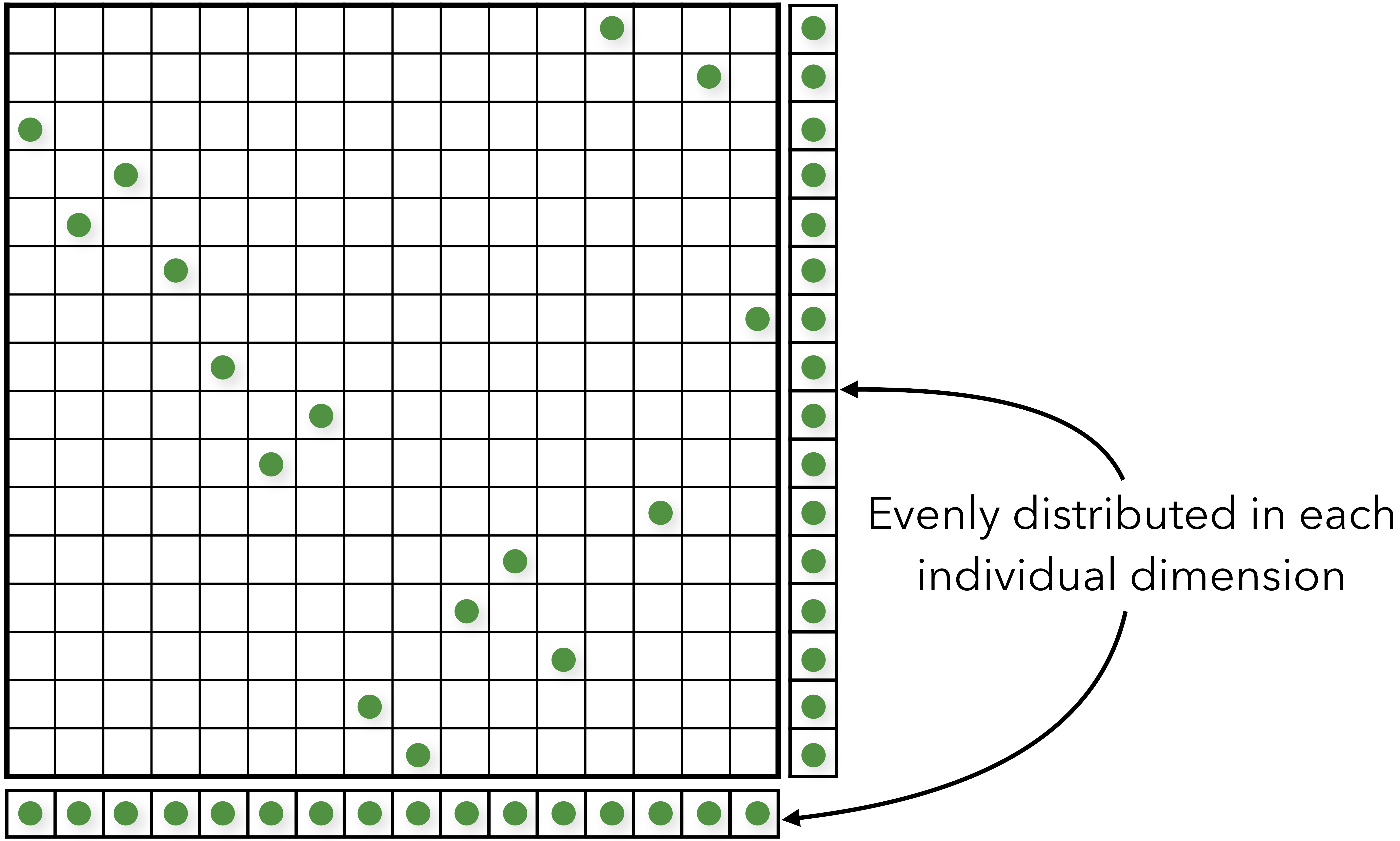
Latin Hypercube (N-Rooks) Sampling



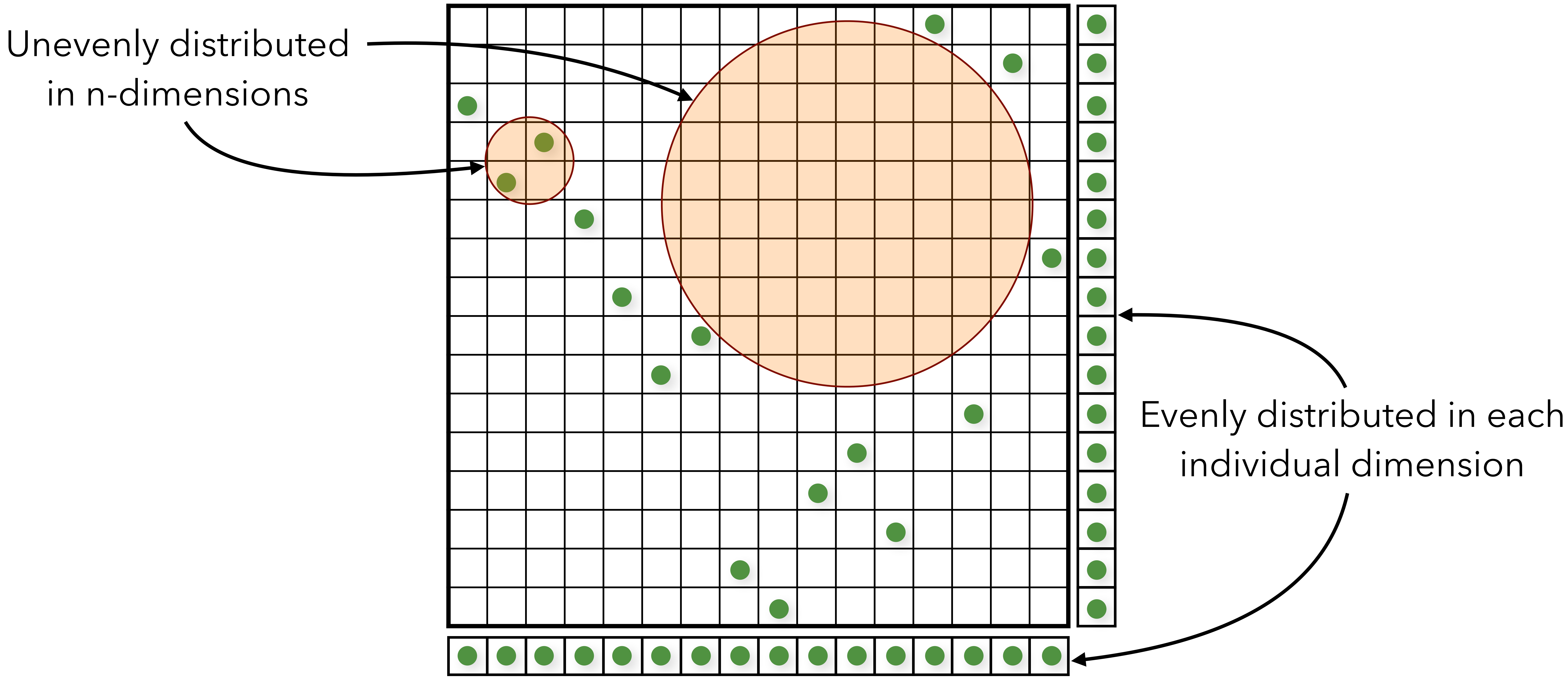
Latin Hypercube (N-Rooks) Sampling



Latin Hypercube (N-Rooks) Sampling

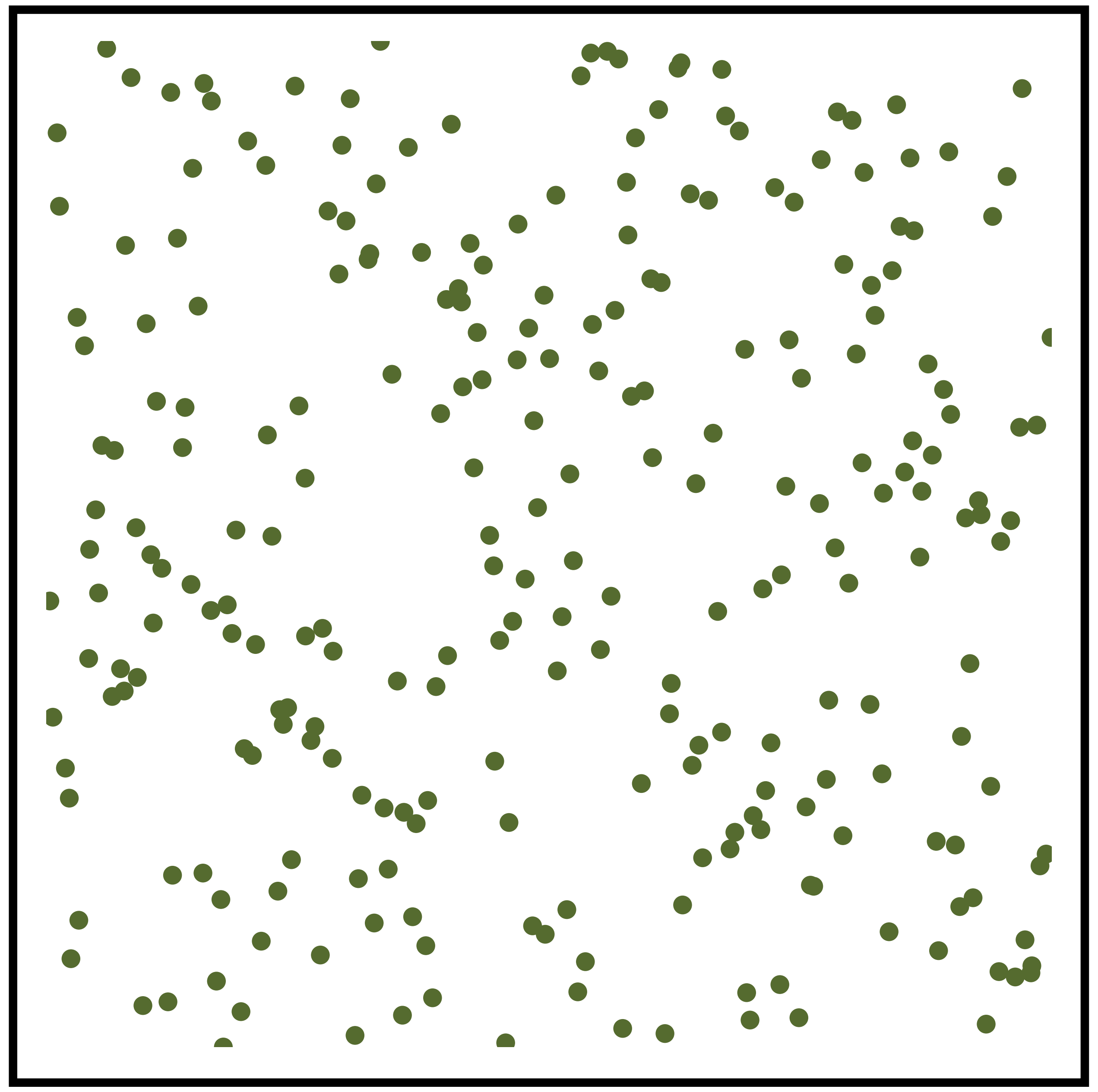


Latin Hypercube (N-Rooks) Sampling

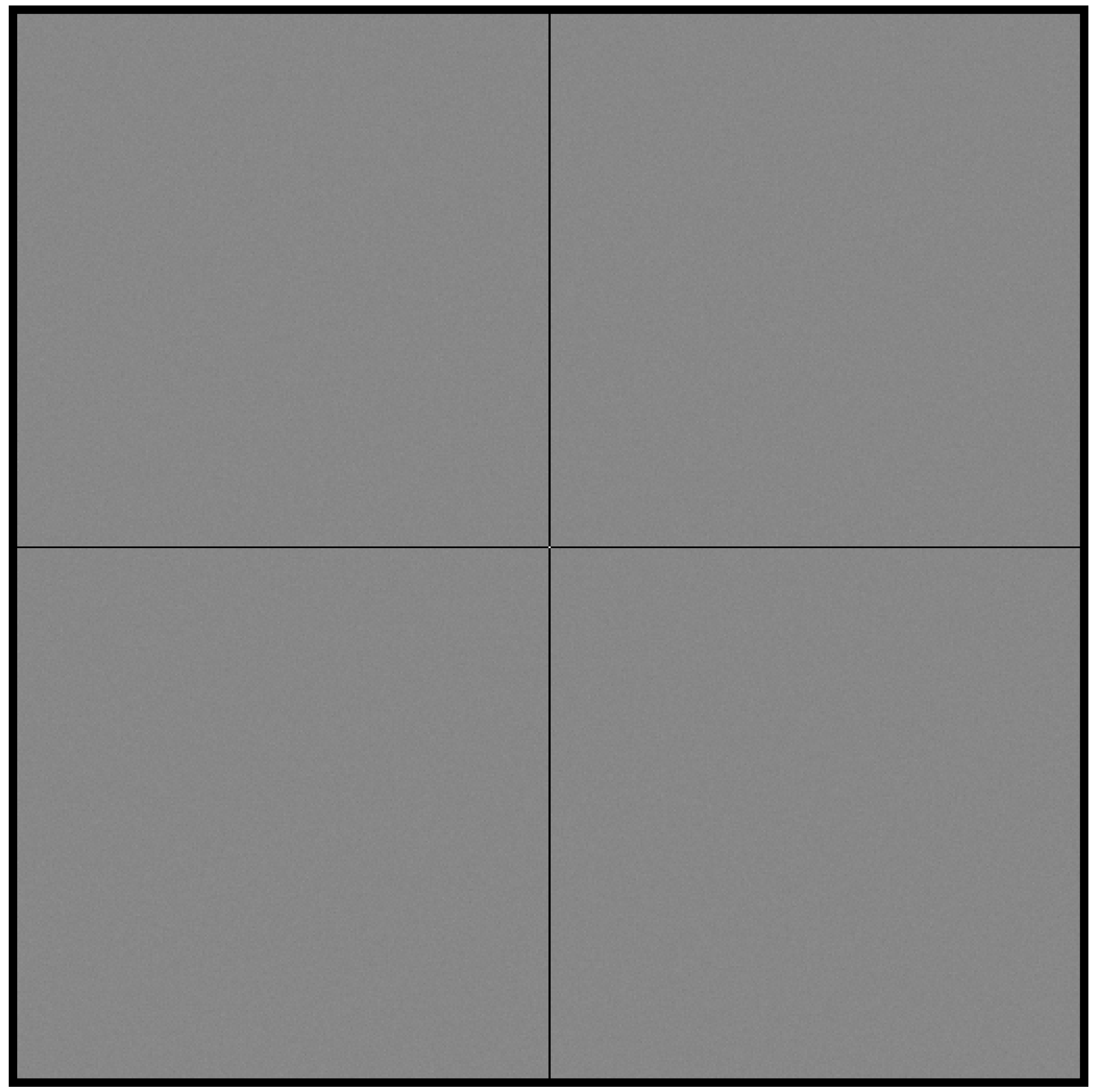


N-Rooks Sampling

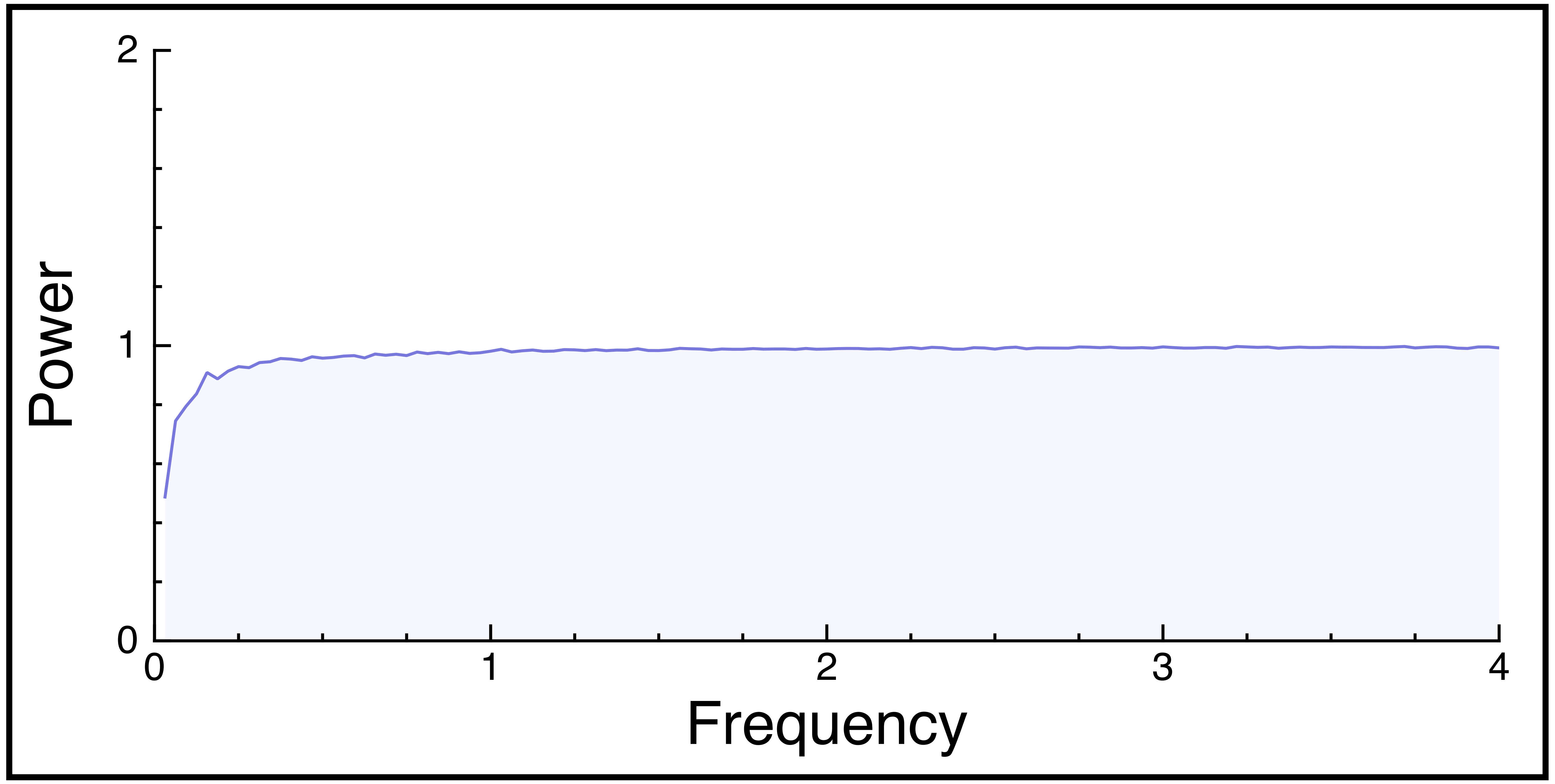
Samples



Expected power spectrum



Radial mean

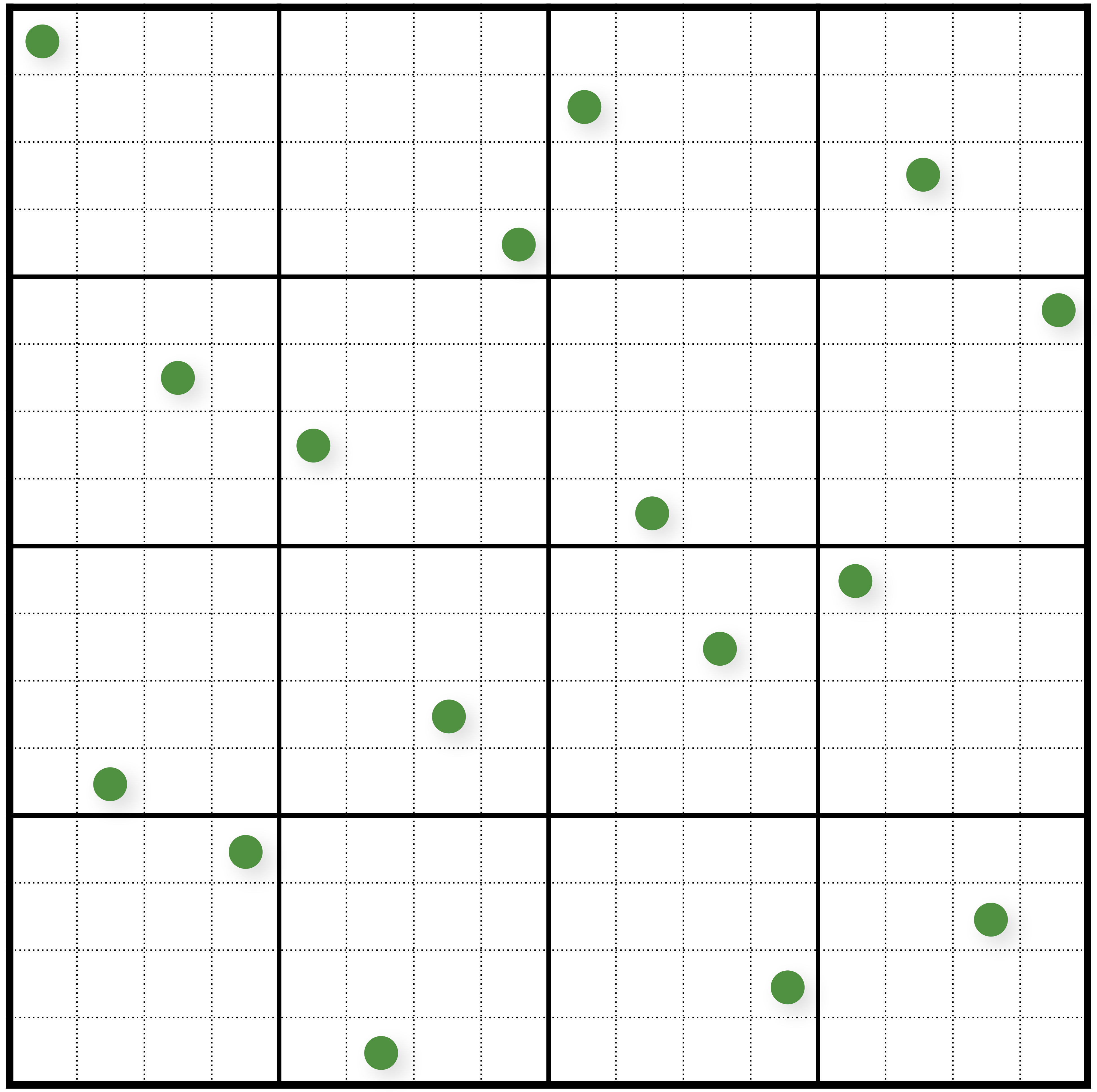


Multi-Jittered Sampling

Kenneth Chiu, Peter Shirley, and Changyaw Wang. "Multi-jittered sampling." In *Graphics Gems IV*, pp. 370–374. Academic Press, May 1994.

– combine N-Rooks and Jittered stratification constraints

Multi-Jittered Sampling



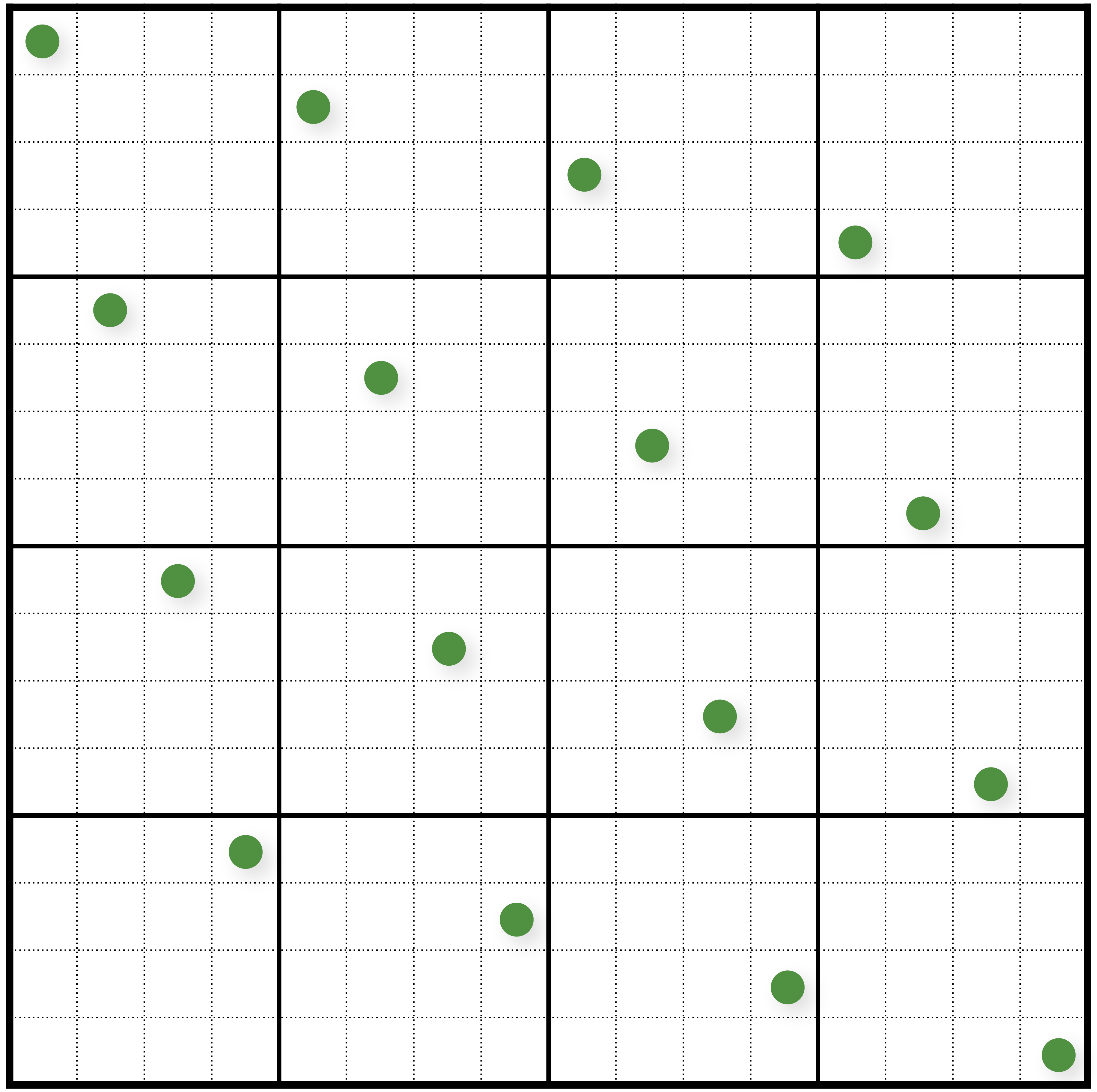
Multi-Jittered Sampling

```
// initialize
float cellSize = 1.0 / (resX*resY);
for (uint i = 0; i < resX; i++)
    for (uint j = 0; j < resY; j++)
    {
        samples(i,j).x = i/resX + (j+randf()) / (resX*resY);
        samples(i,j).y = j/resY + (i+randf()) / (resX*resY);
    }

// shuffle x coordinates within each column of cells
for (uint i = 0; i < resX; i++)
    for (uint j = resY-1; j >= 1; j--)
        swap(samples(i, j).x, samples(i, randi(0, j)).x);

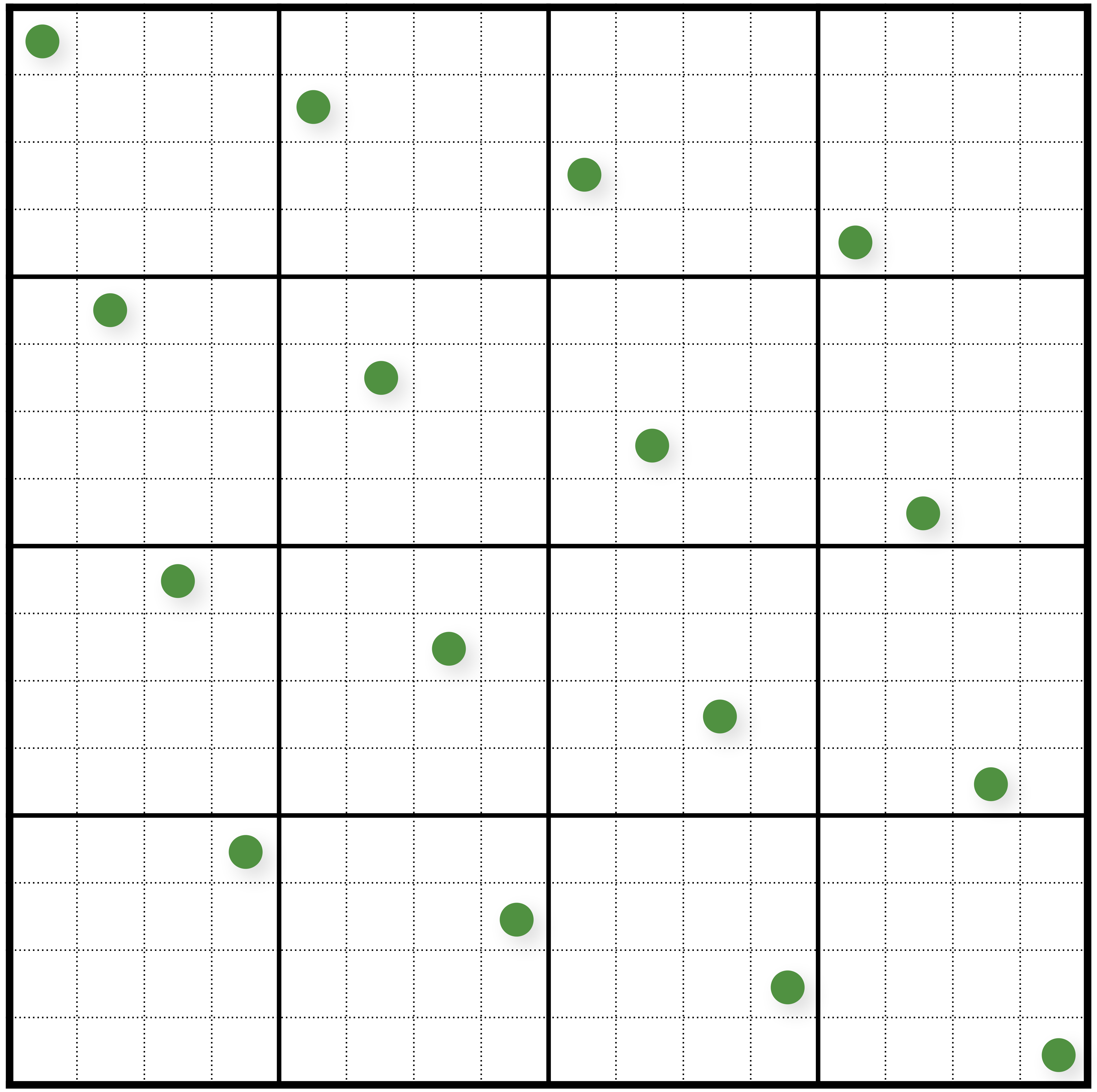
// shuffle y coordinates within each row of cells
for (unsigned j = 0; j < resY; j++)
    for (unsigned i = resX-1; i >= 1; i--)
        swap(samples(i, j).y, samples(randi(0, i), j).y);
```

Multi-Jittered Sampling



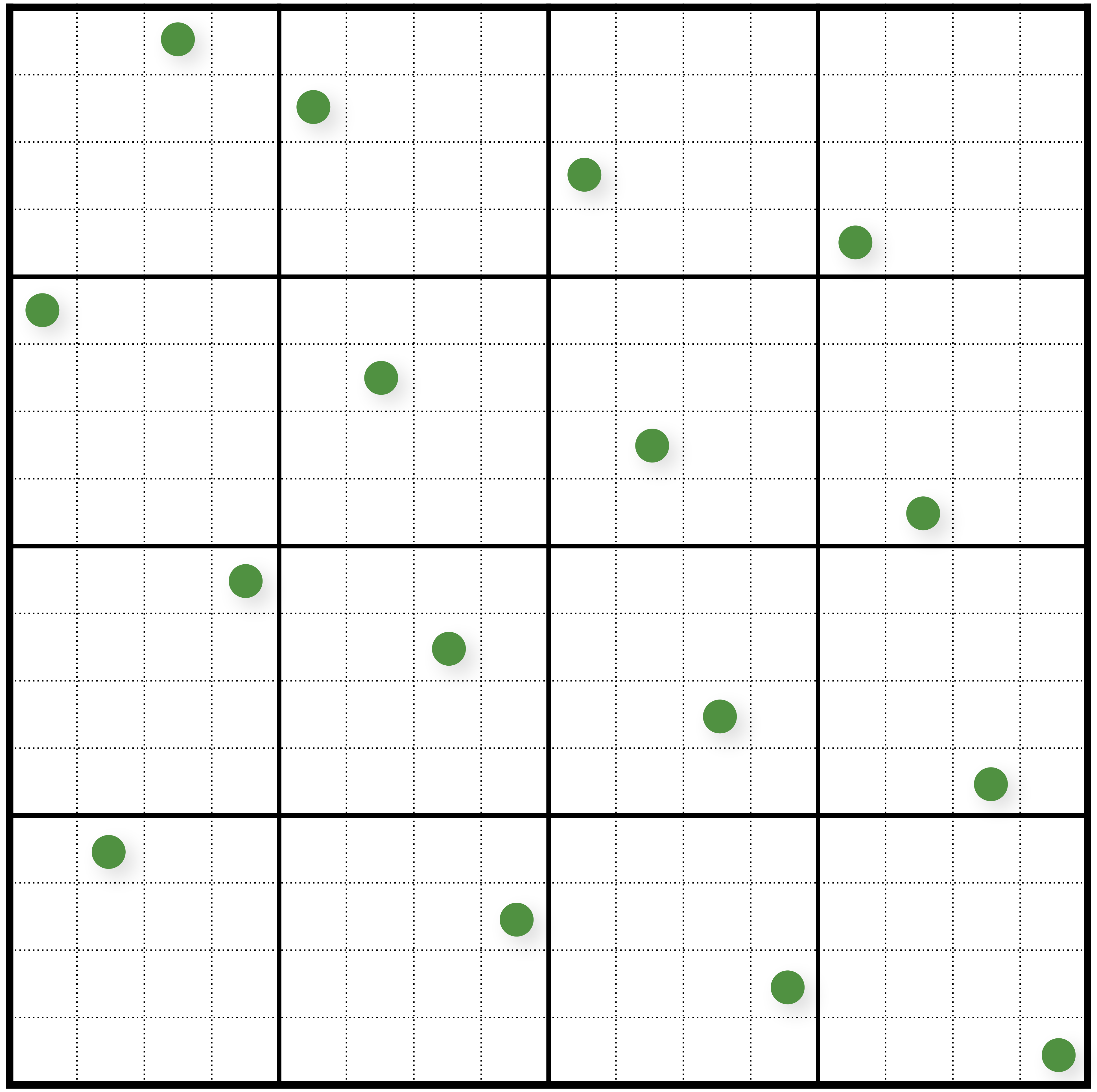
Initialize

Multi-Jittered Sampling



Shuffle x-coords

Multi-Jittered Sampling



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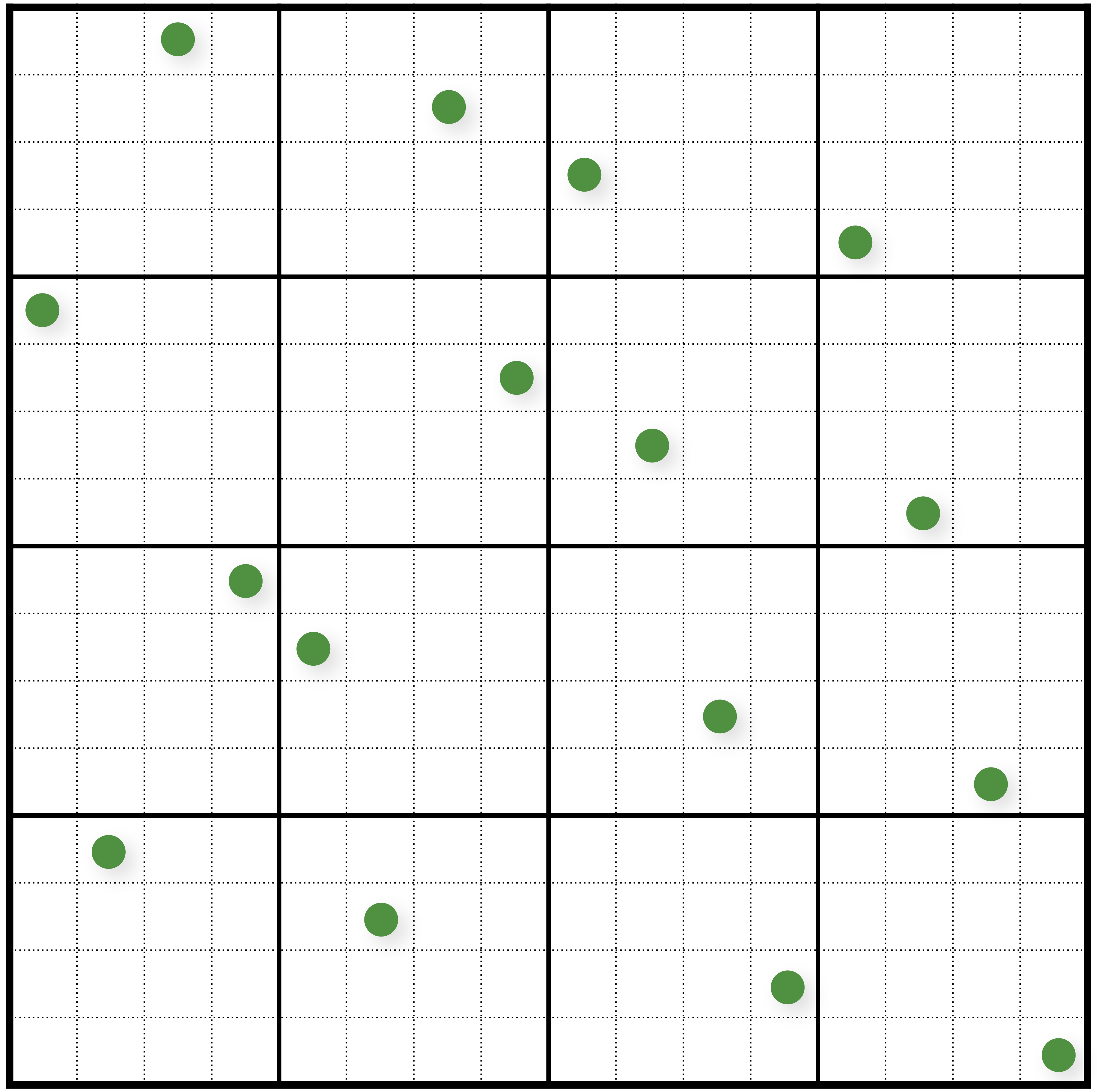
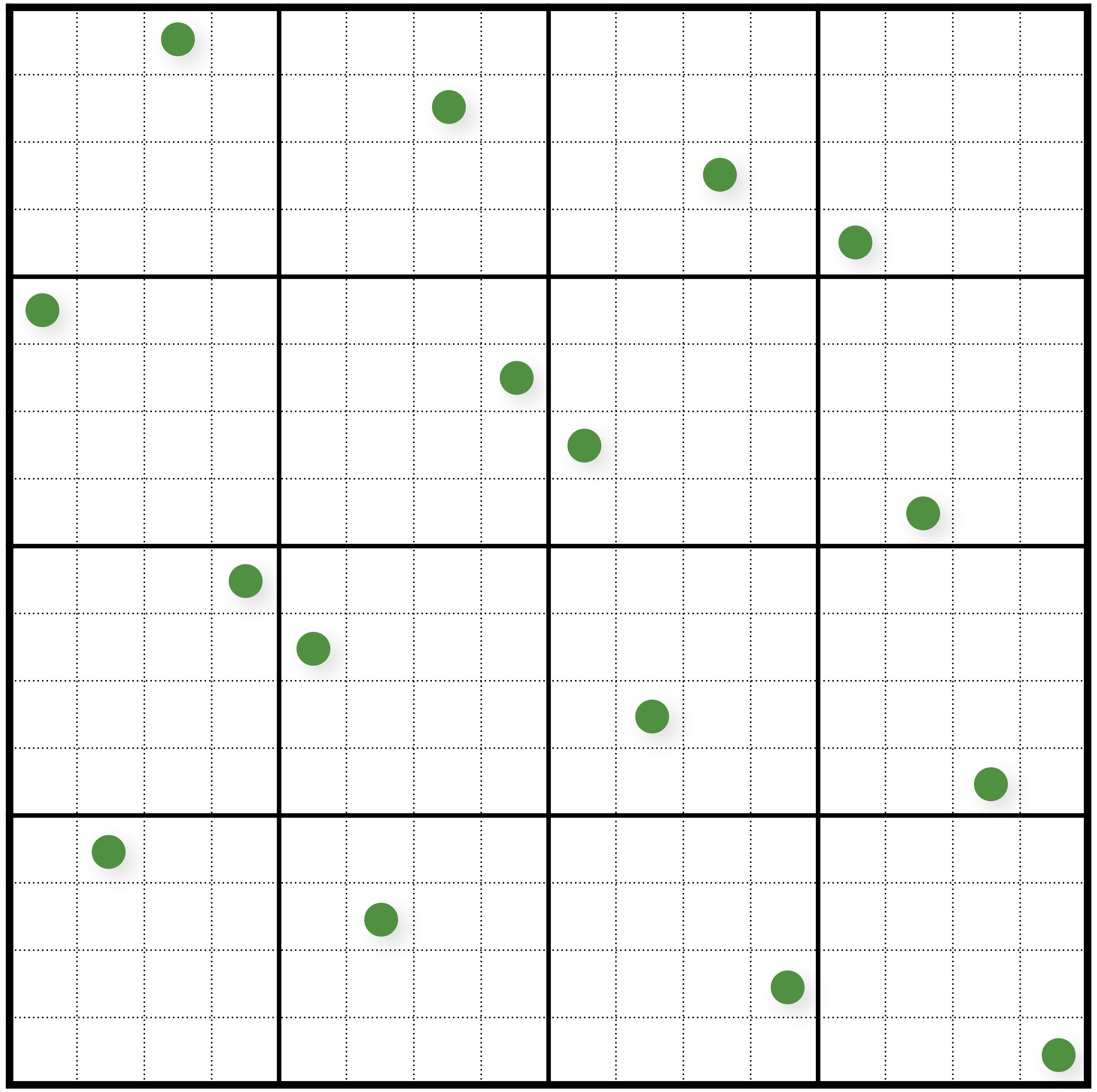
Multi-Jittered Sampling



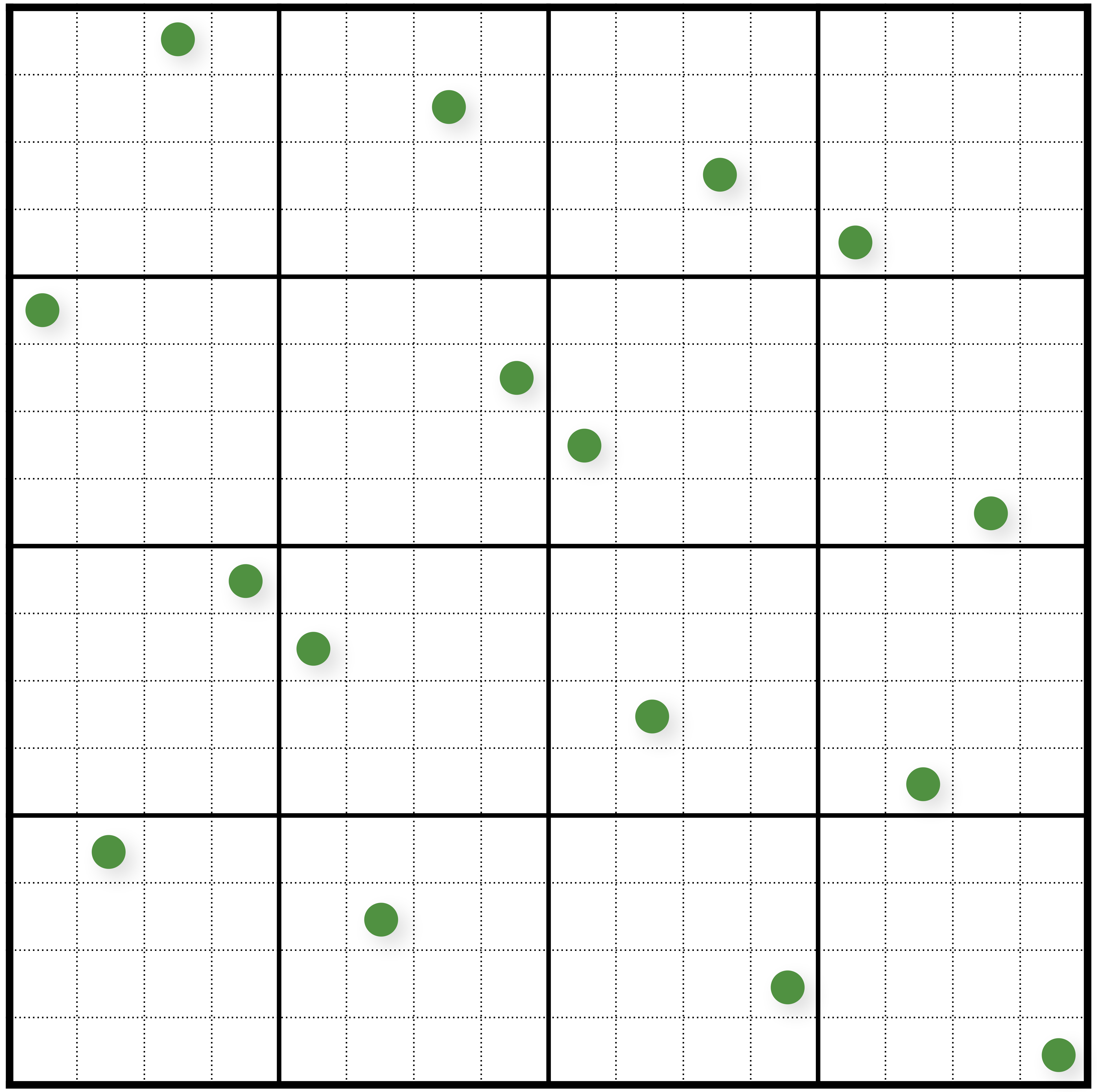
Shuffle x-coords

Multi-Jittered Sampling



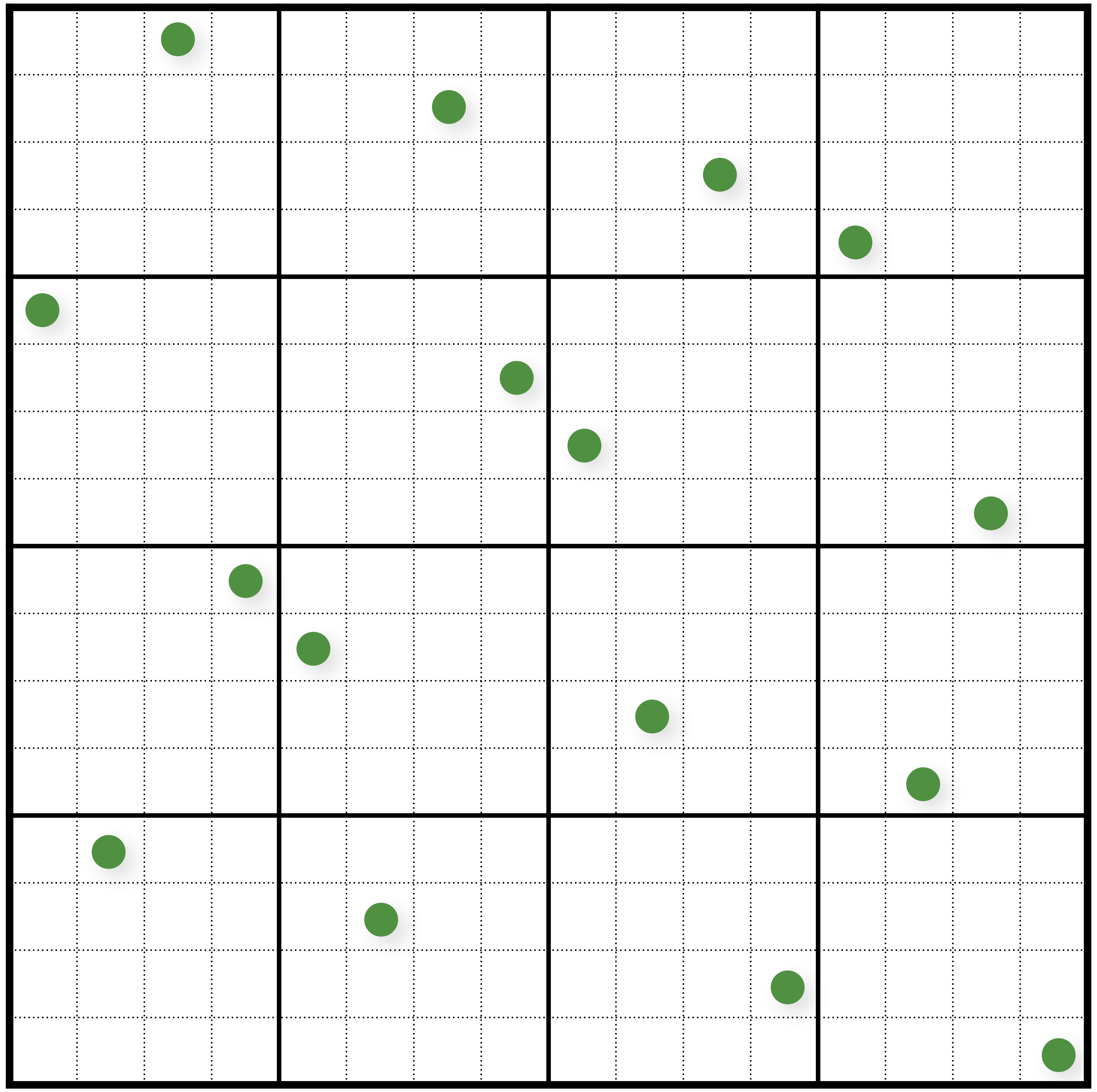
Shuffle x-coords

Multi-Jittered Sampling



Shuffle x-coords

Multi-Jittered Sampling



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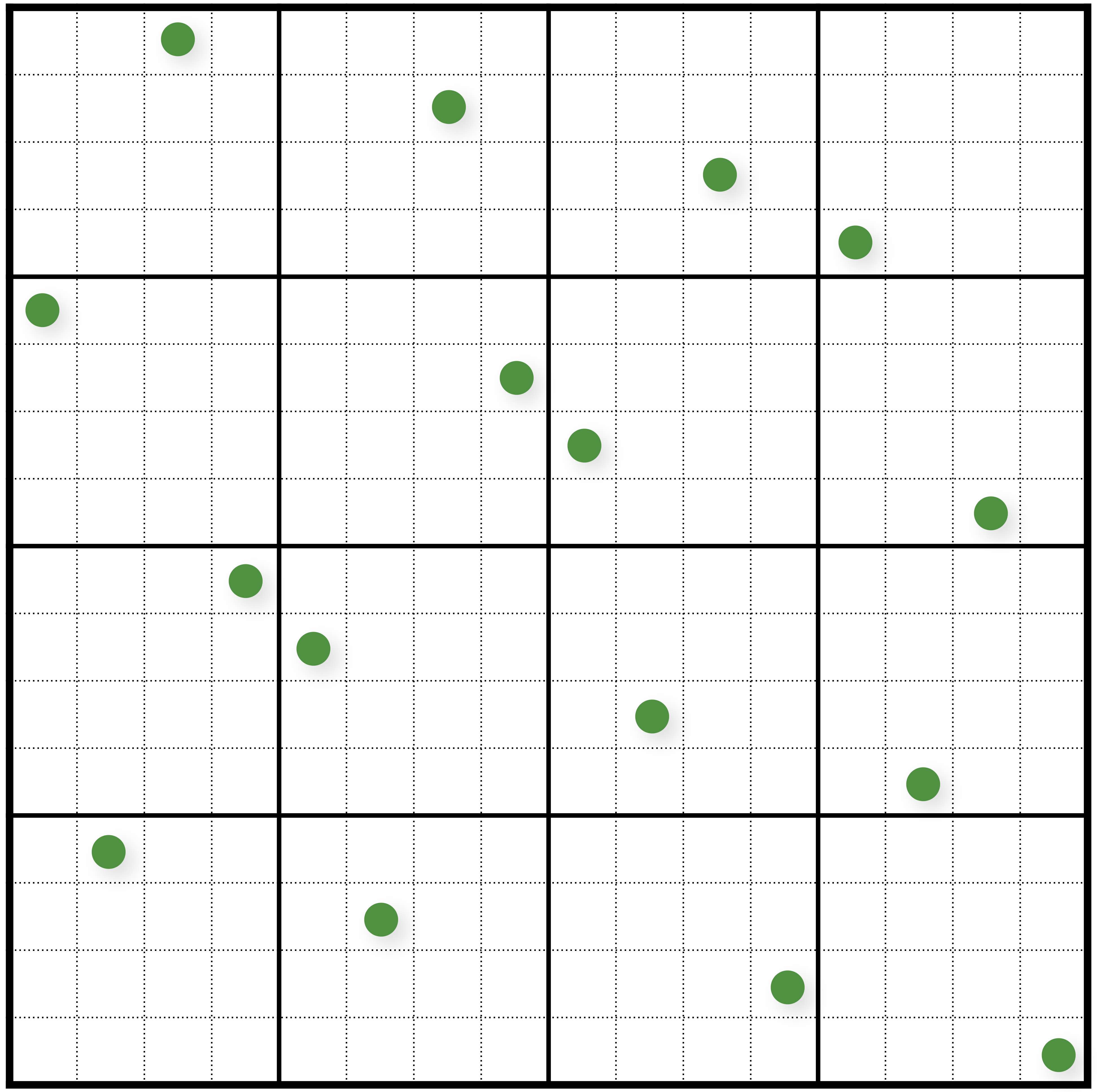
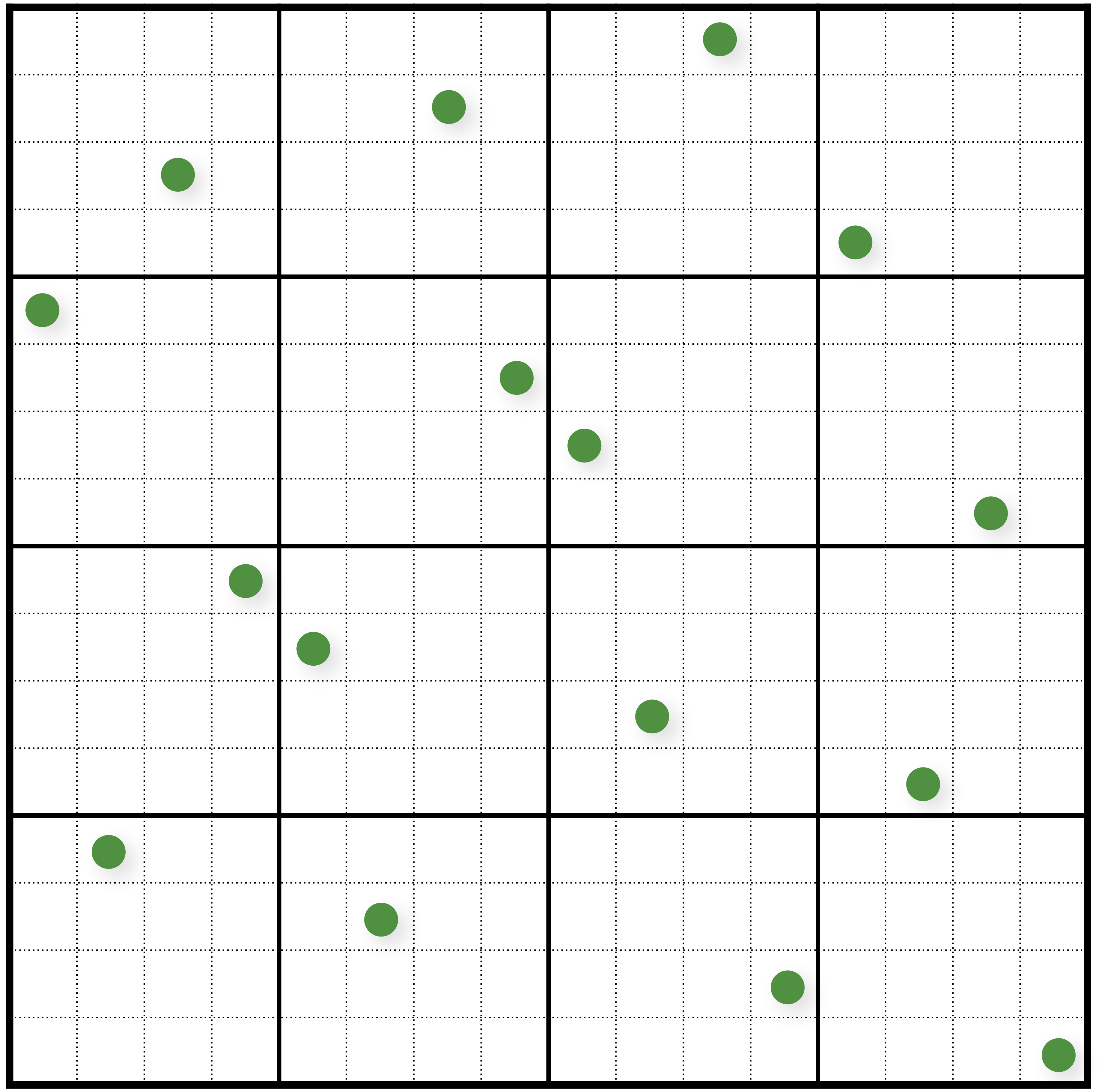


Shuffle y-coords

Multi-Jittered Sampling



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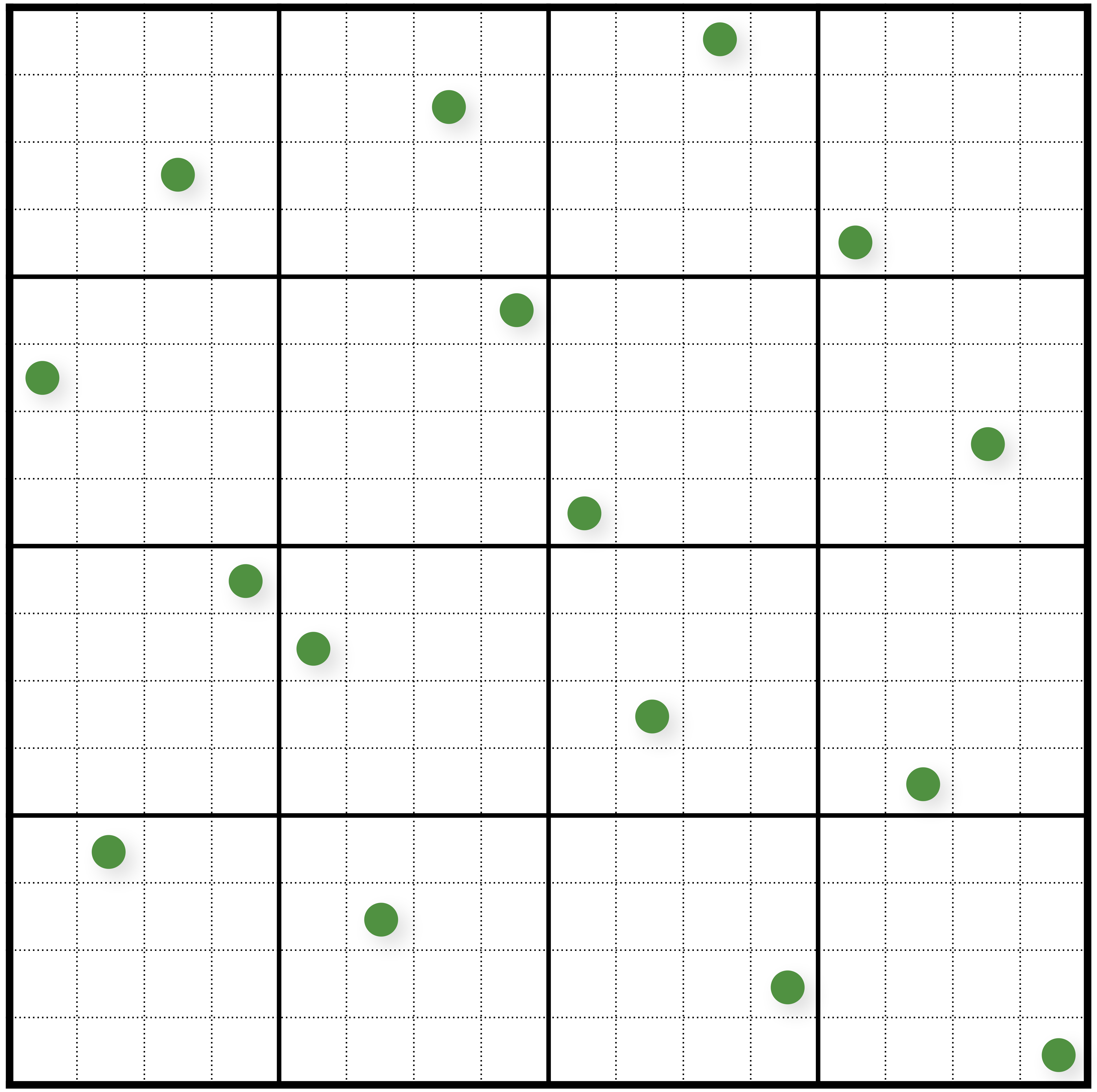
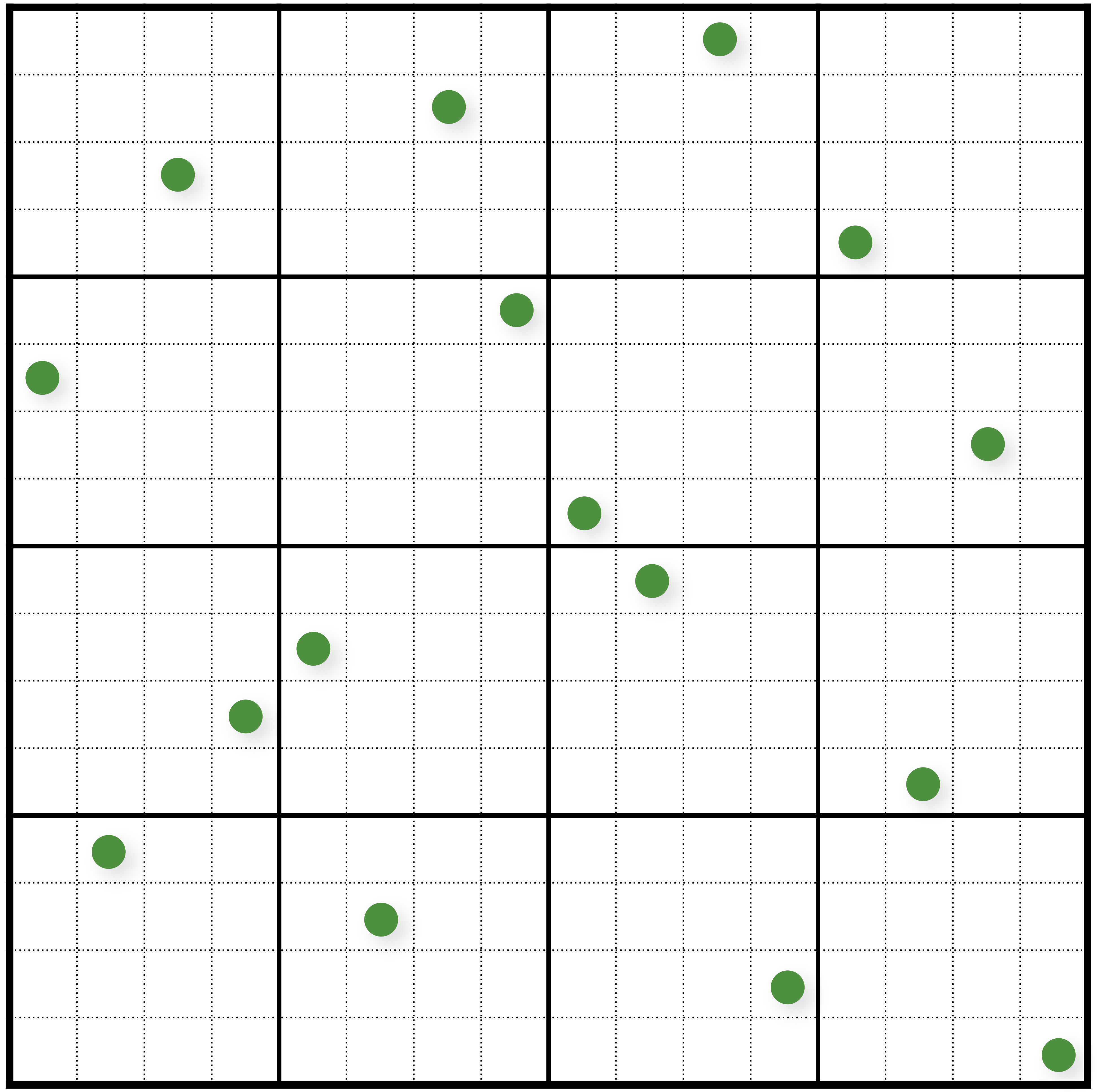
Multi-Jittered Sampling



Shuffle y-coords

Multi-Jittered Sampling



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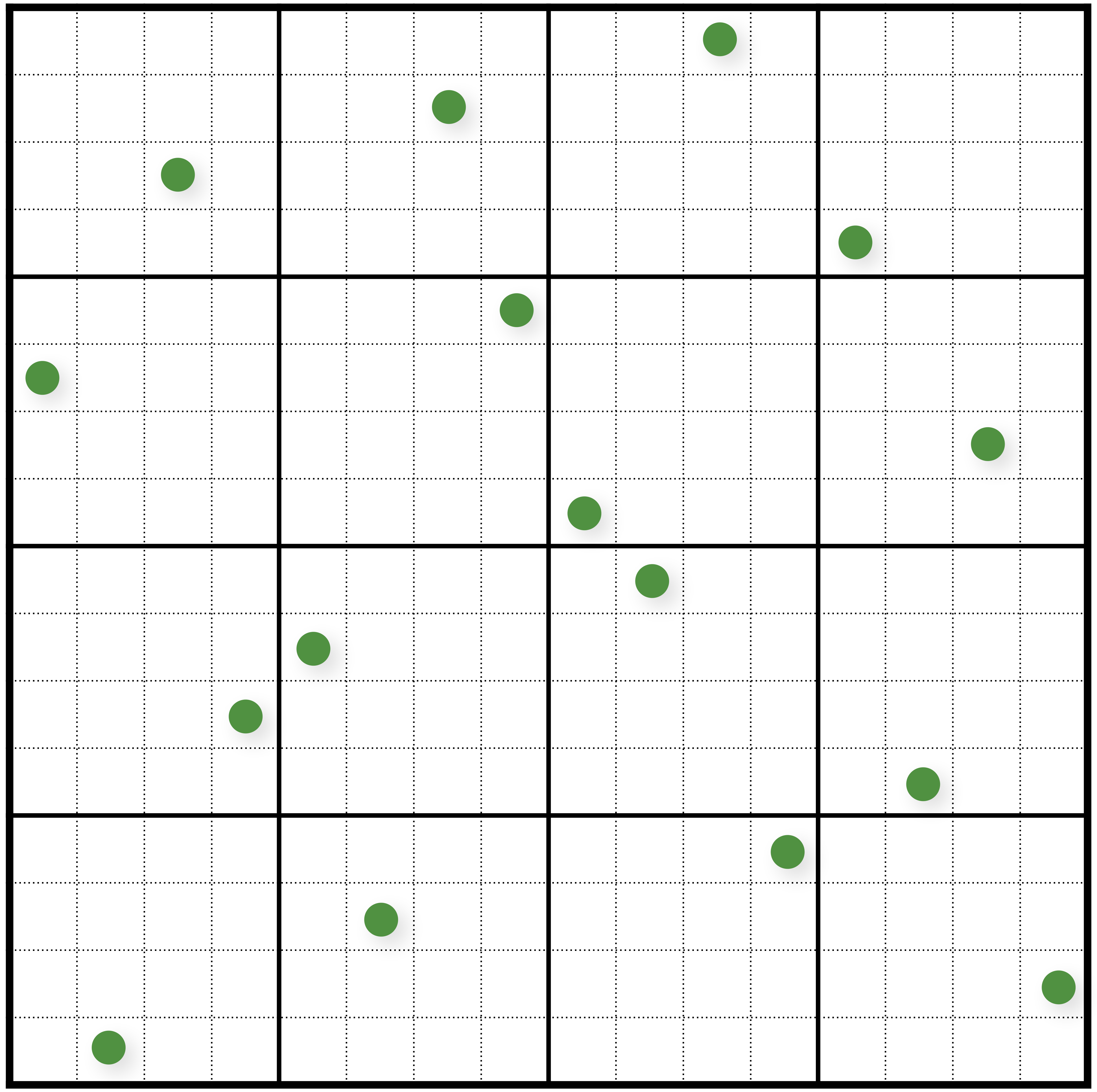
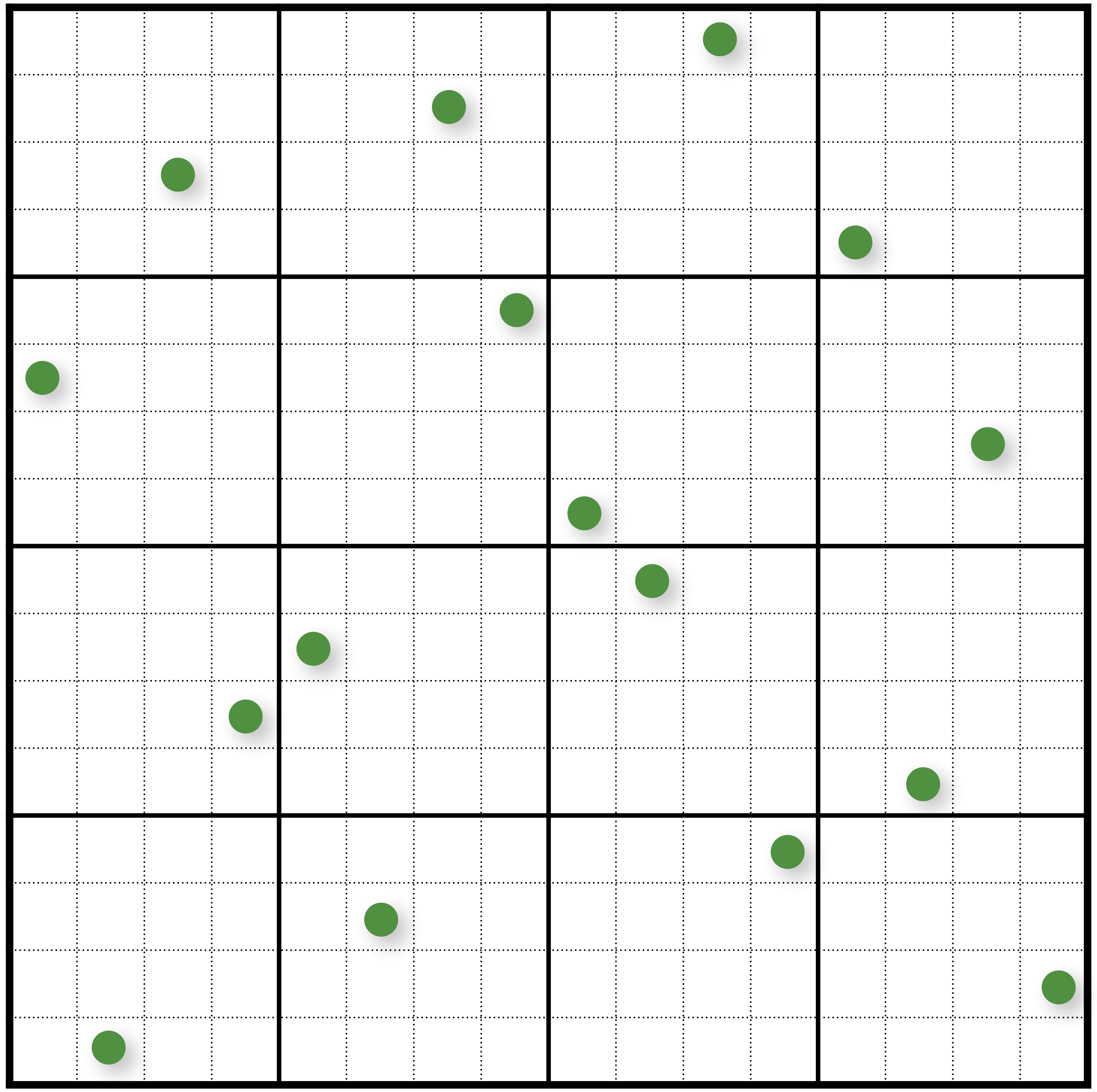
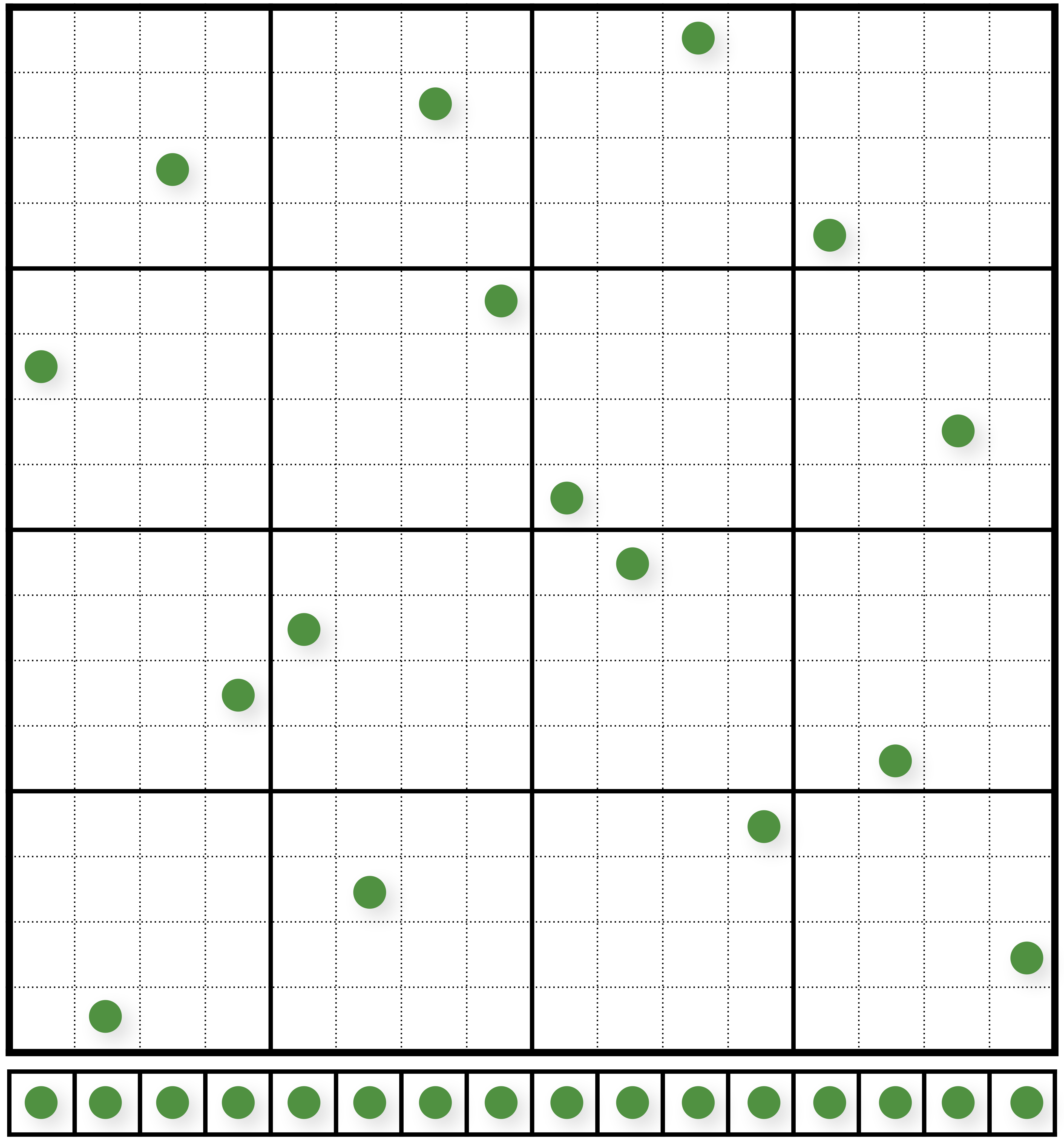


Shuffle y-coords

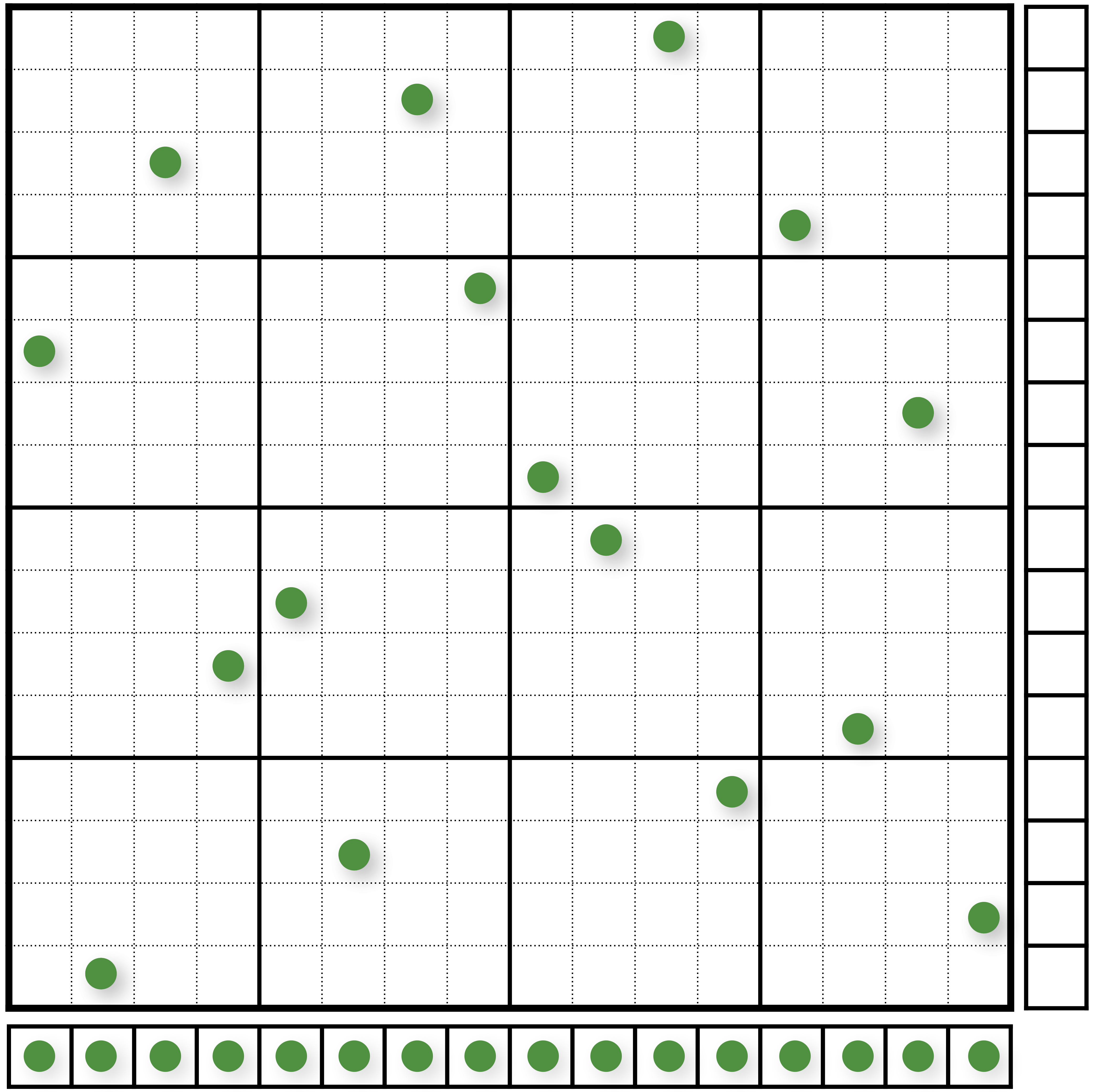
Multi-Jittered Sampling (Projections)



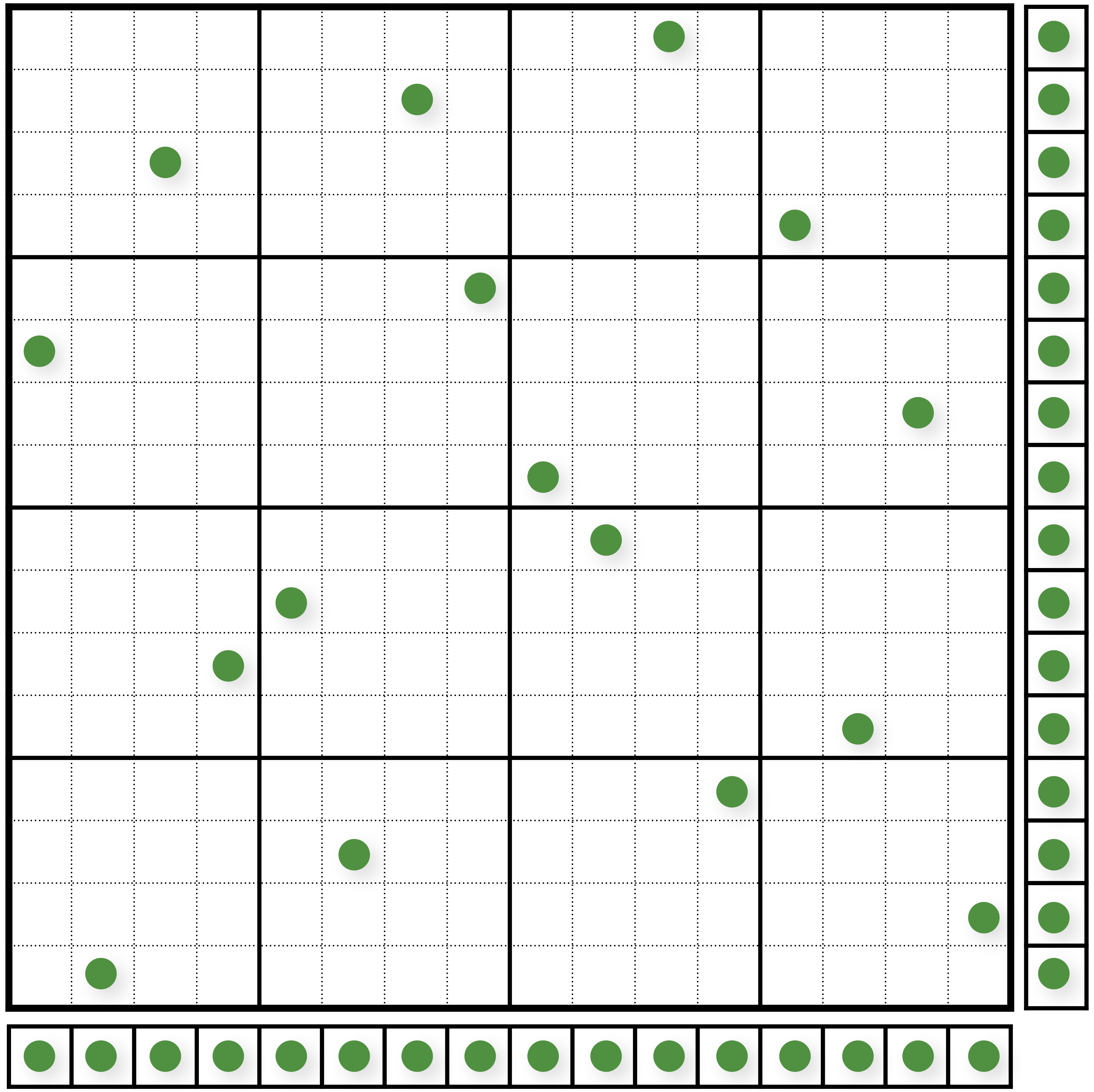
Multi-Jittered Sampling (Projections)



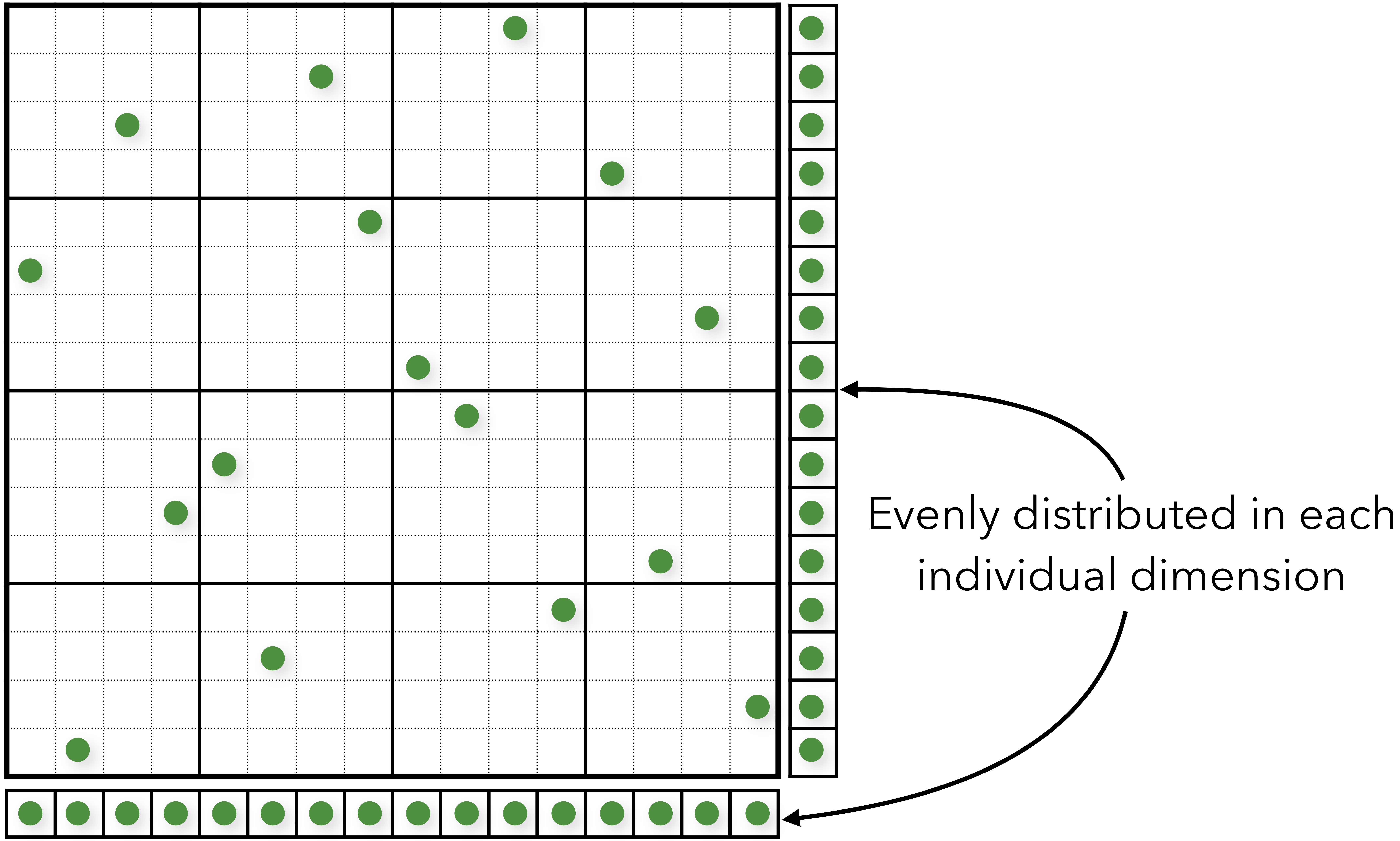
Multi-Jittered Sampling (Projections)



Multi-Jittered Sampling (Projections)

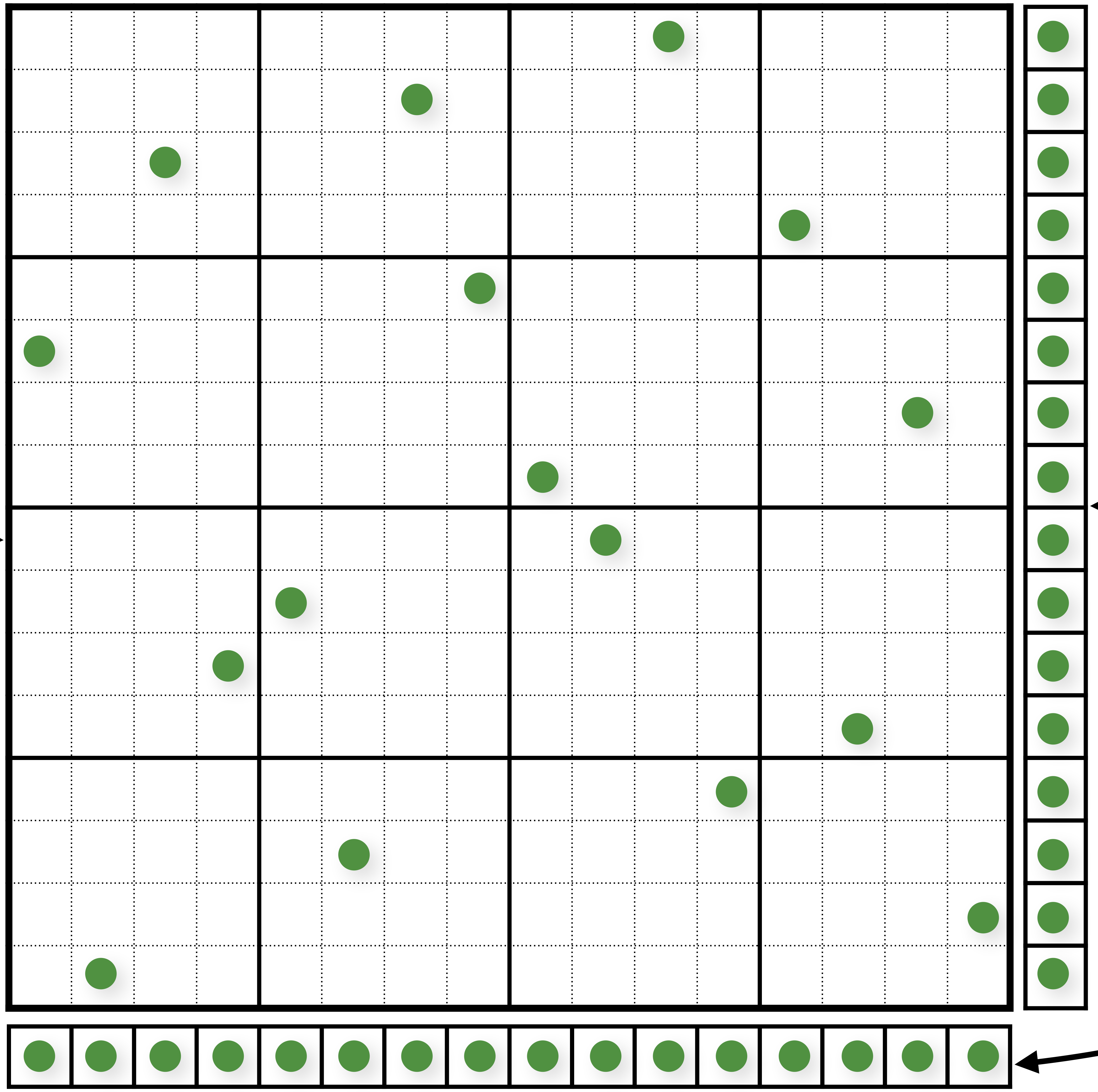


Multi-Jittered Sampling (Projections)



Multi-Jittered Sampling (Projections)

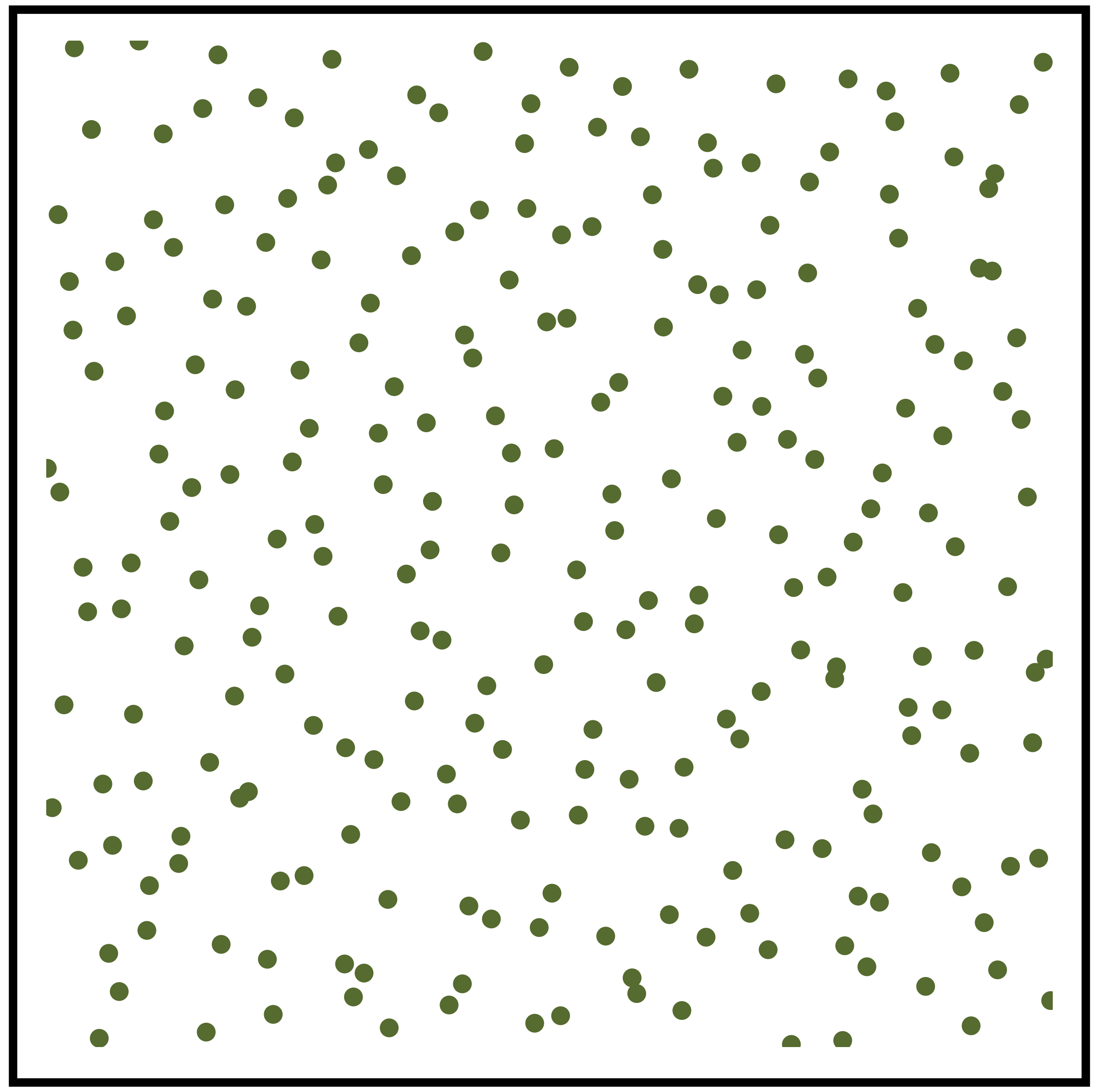
Evenly distributed in 2D!



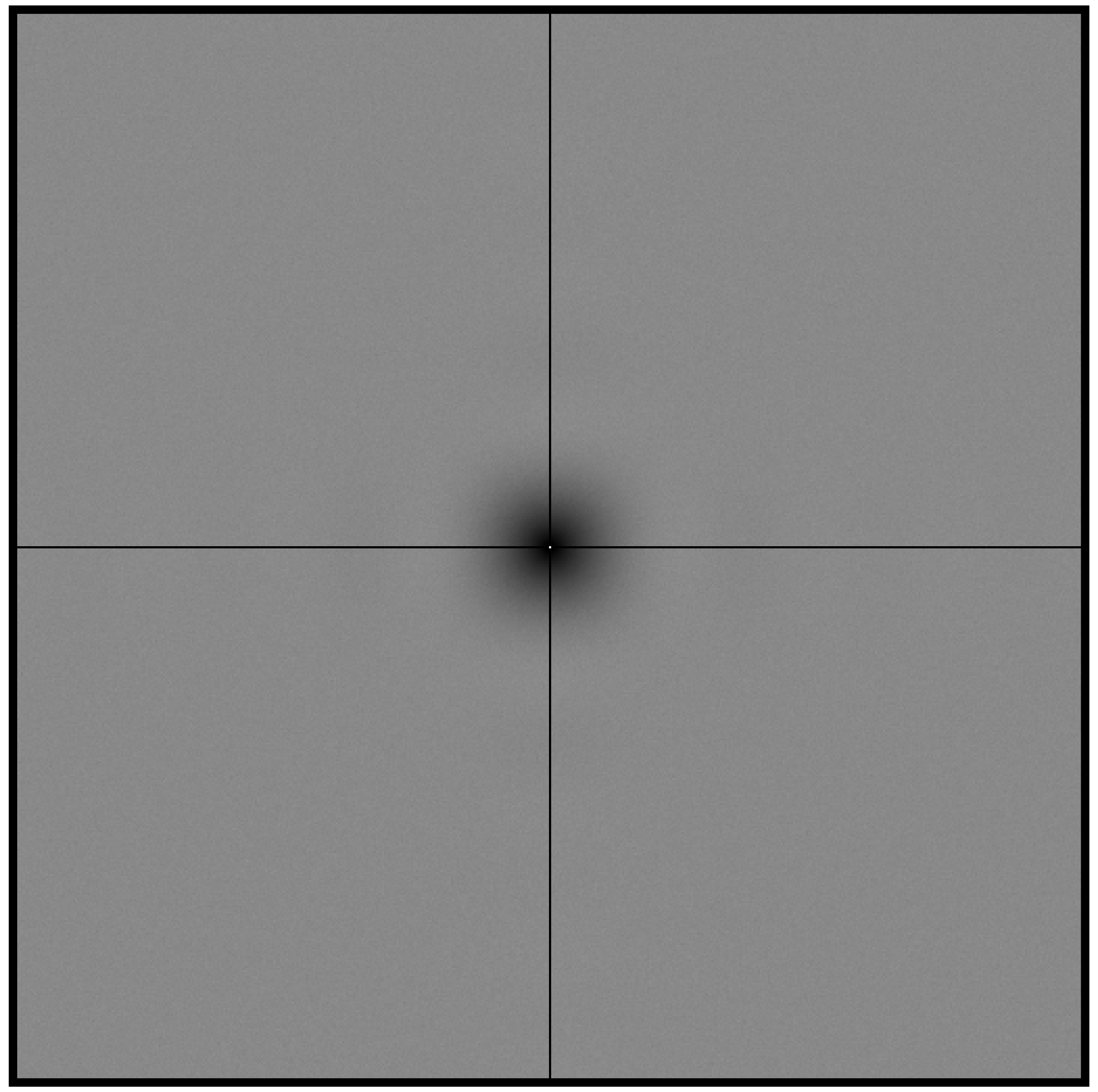
Evenly distributed in each individual dimension

Multi-Jittered Sampling

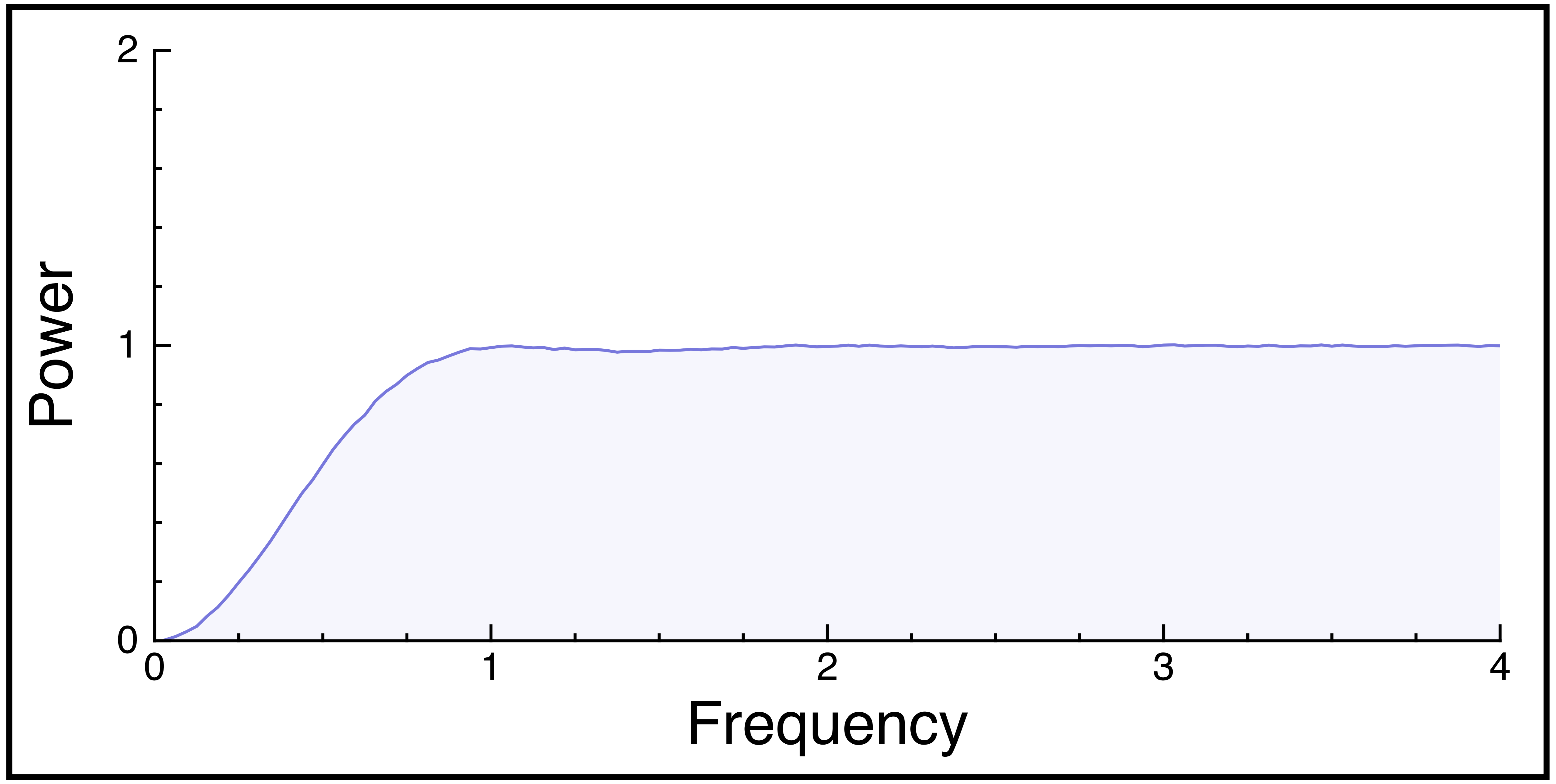
Samples



Expected power spectrum



Radial mean

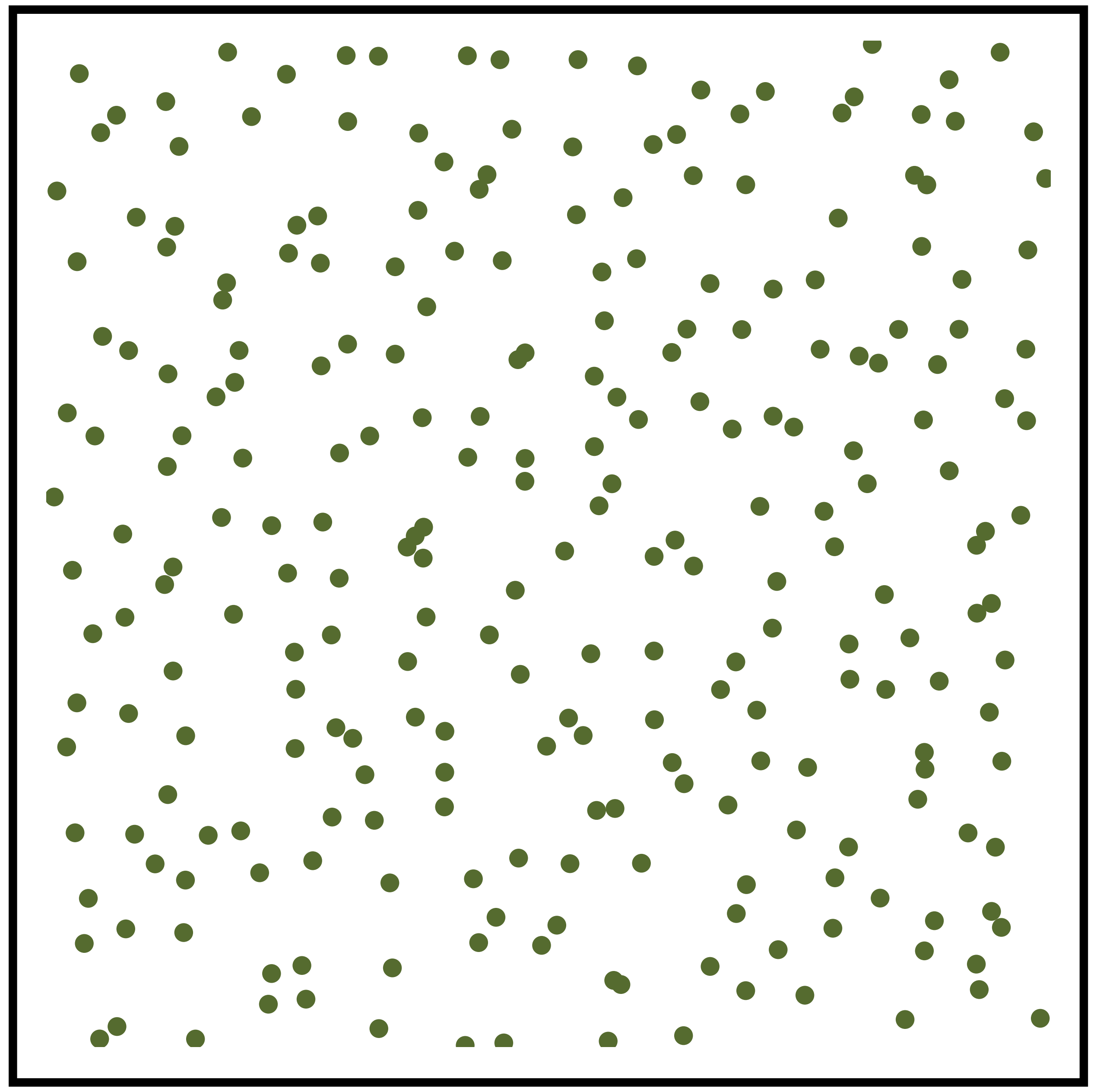


N-Rooks Sampling

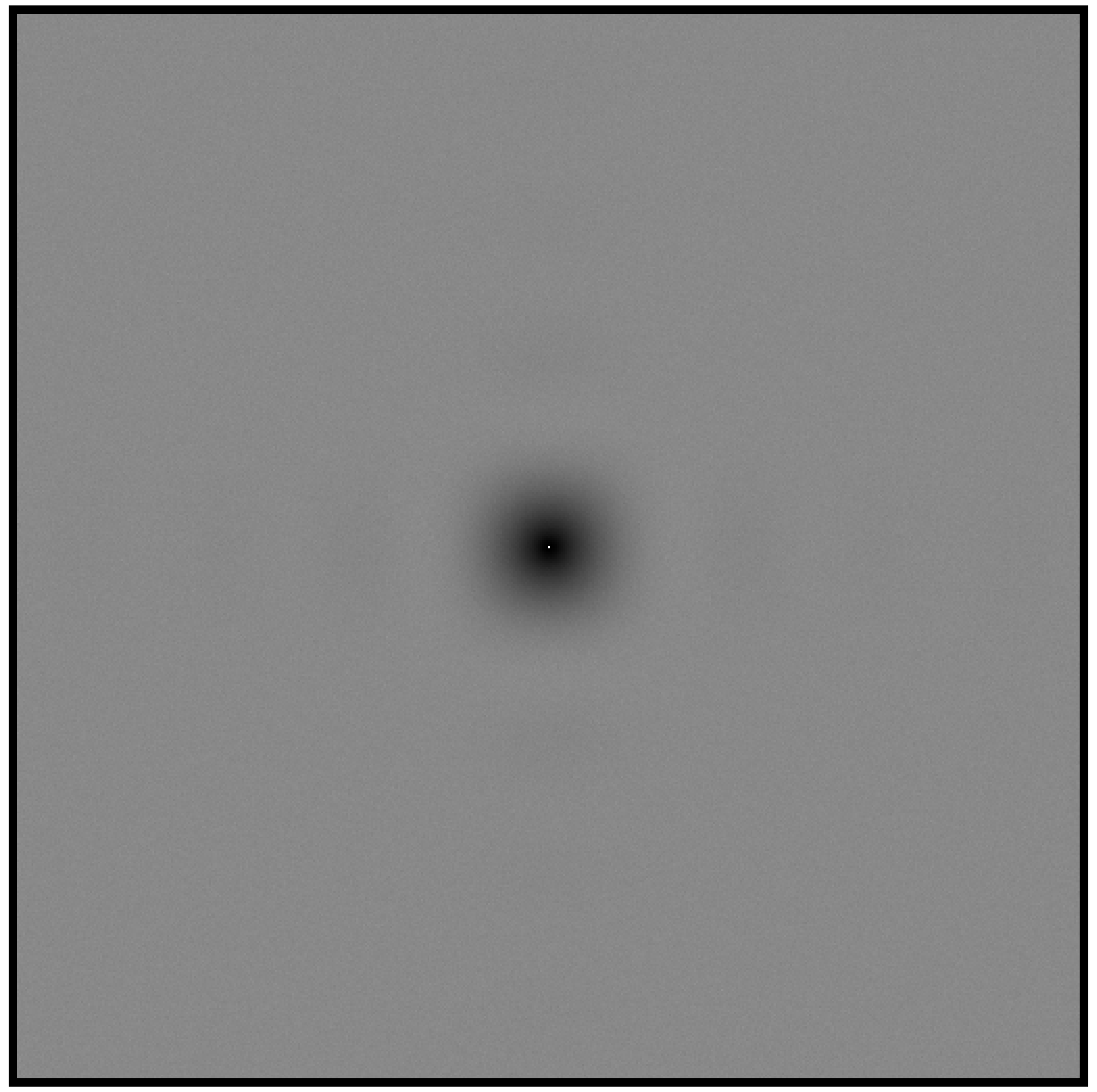
Samples | Expected power spectrum | Radial mean

Jittered Sampling

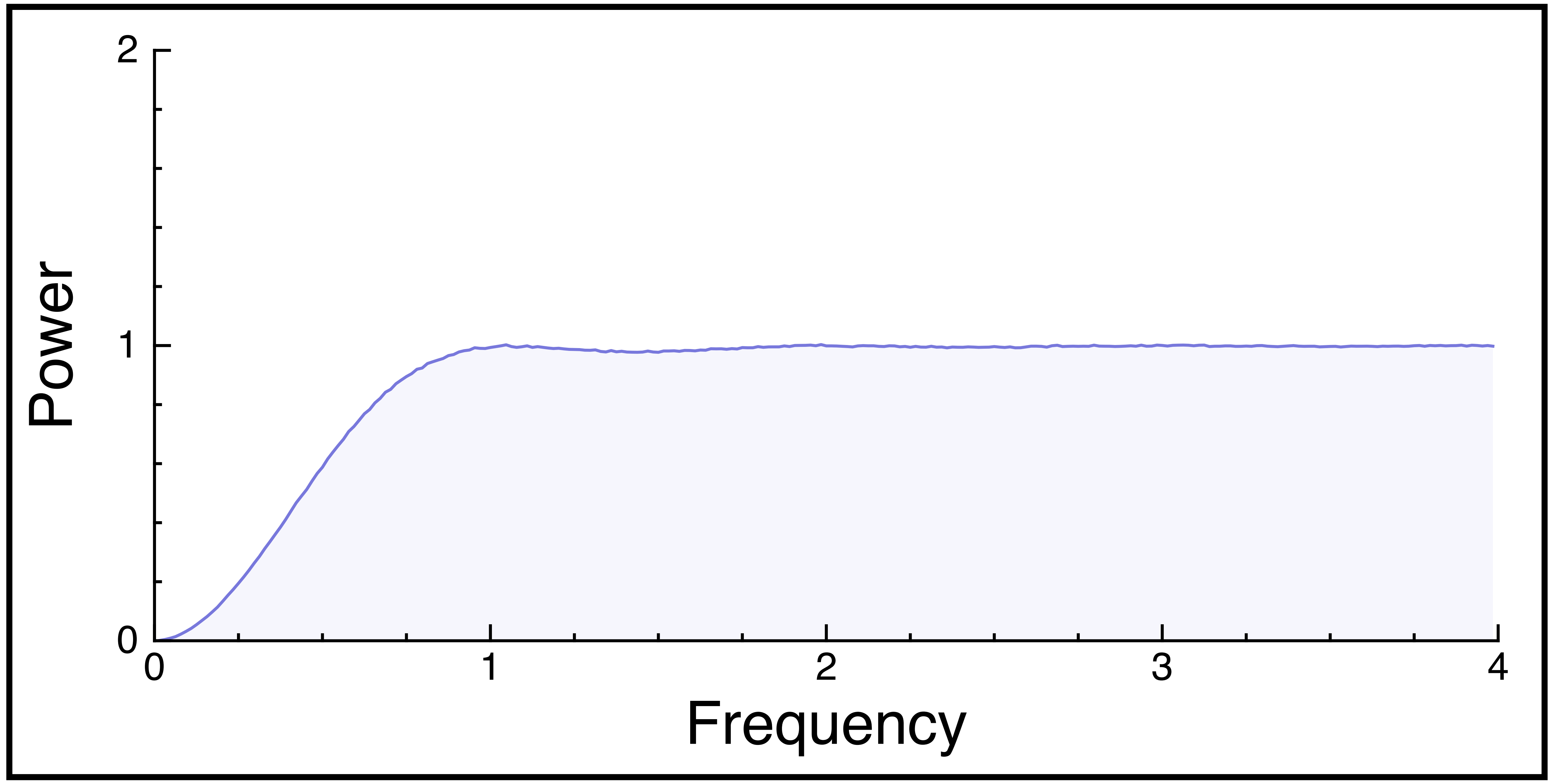
Samples



Expected power spectrum



Radial mean



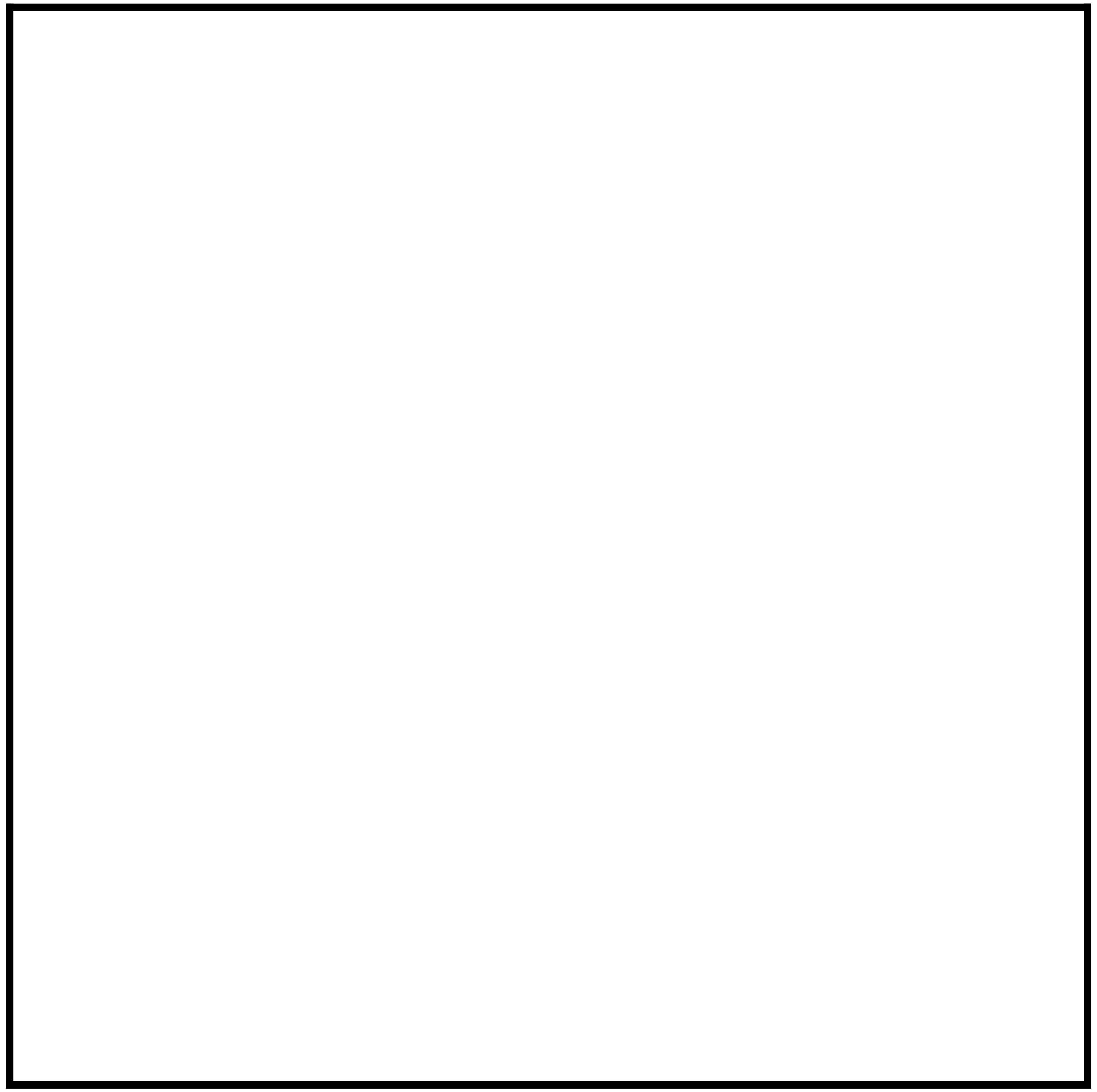
Poisson-Disk/Blue-Noise Sampling

Enforce a minimum distance between points

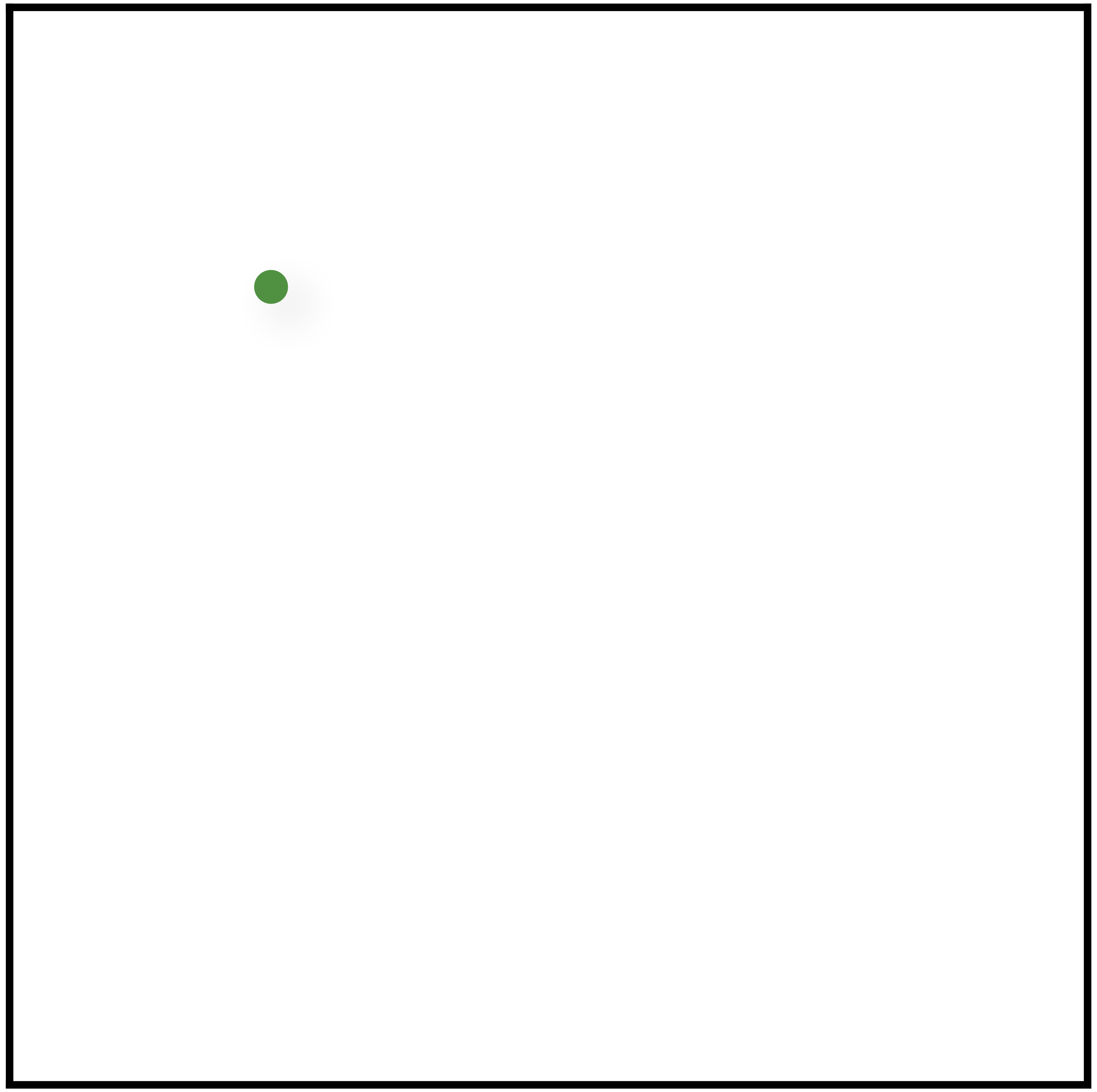
Poisson-Disk Sampling:

- Mark A. Z. Dippé and Erling Henry Wold. "Antialiasing through stochastic sampling." *ACM SIGGRAPH*, 1985.
- Robert L. Cook. "Stochastic sampling in computer graphics." *ACM Transactions on Graphics*, 1986.
- Ares Lagae and Philip Dutré. "A comparison of methods for generating Poisson disk distributions." *Computer Graphics Forum*, 2008.

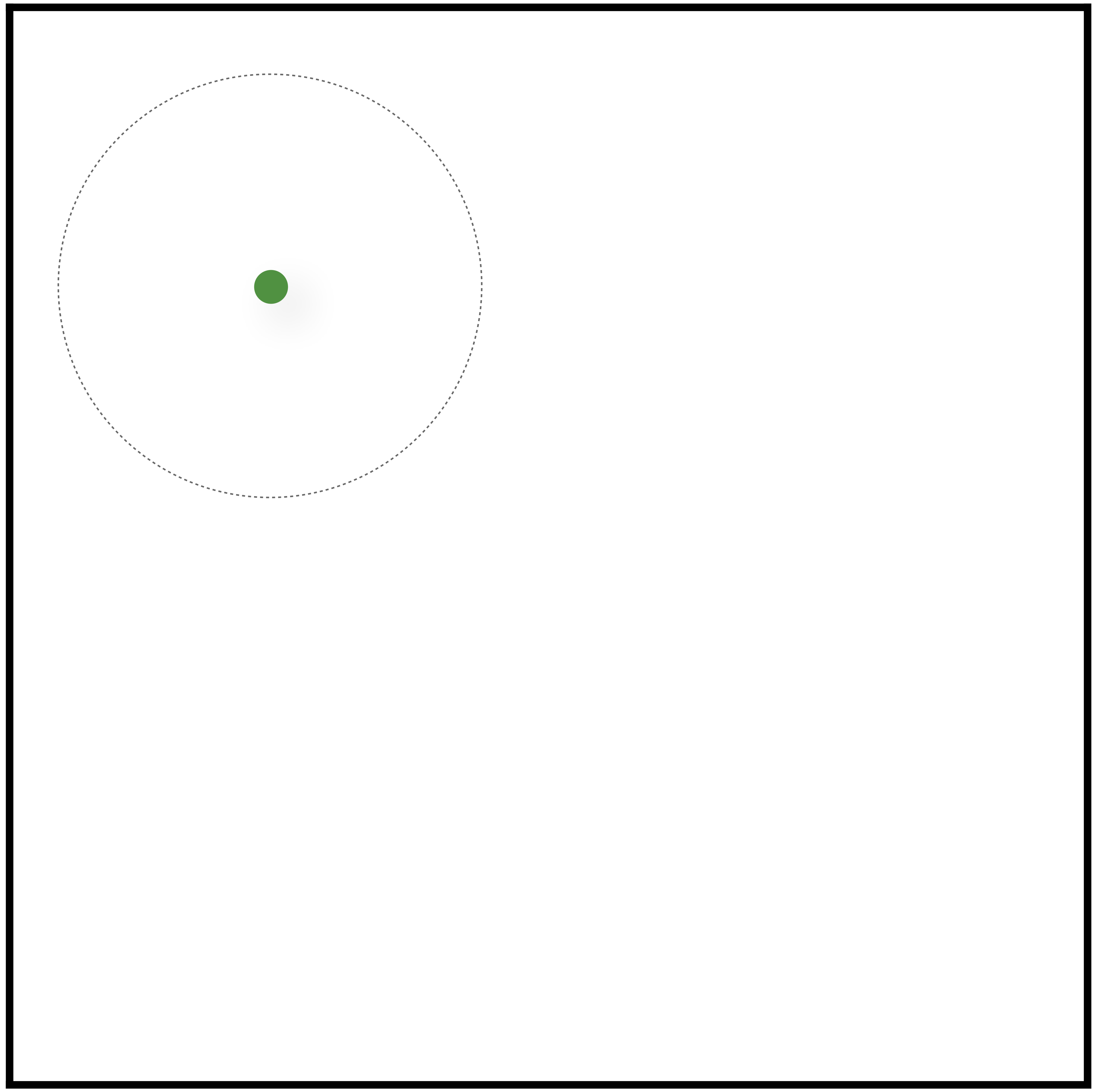
Random Dart Throwing



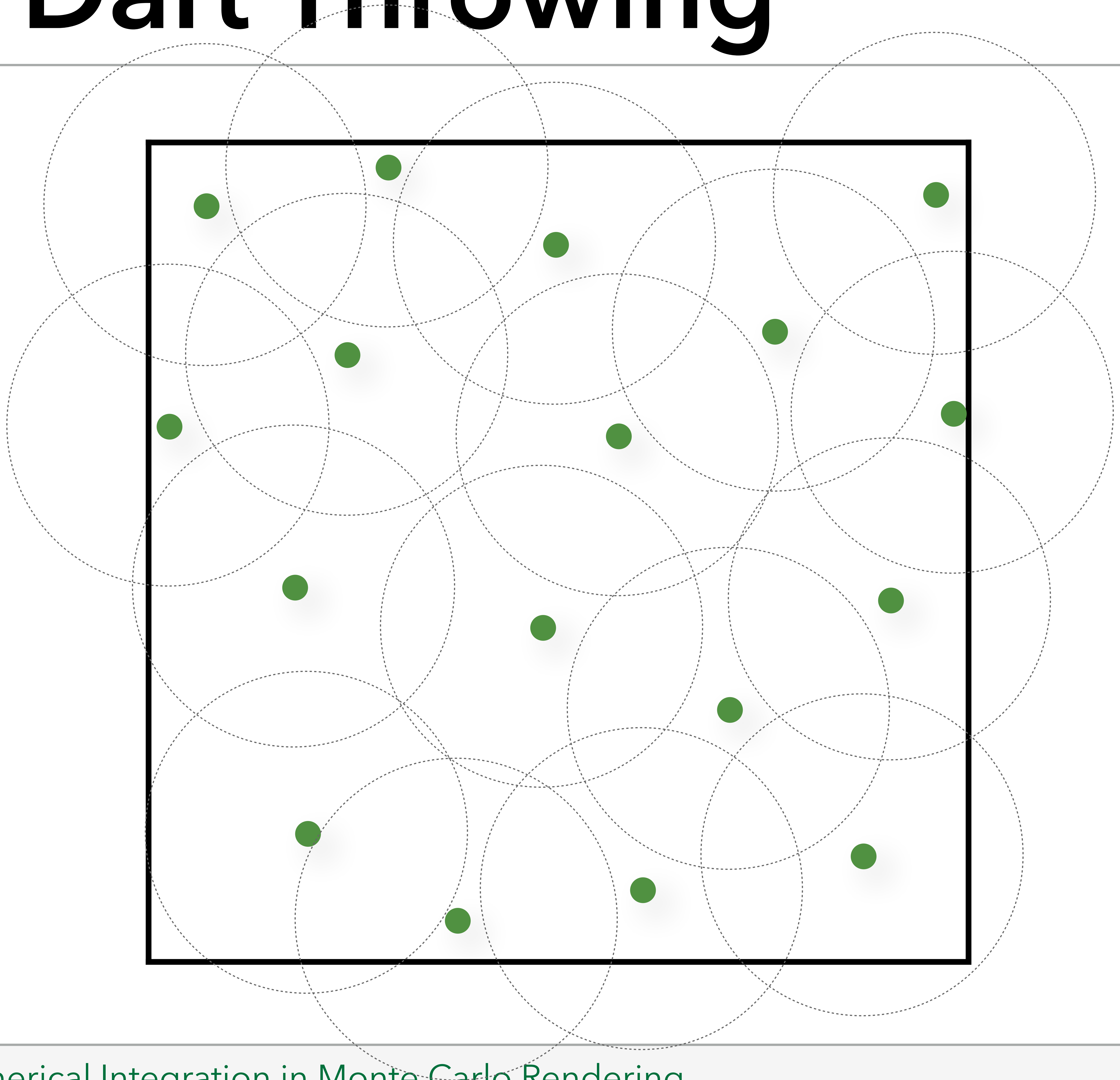
Random Dart Throwing



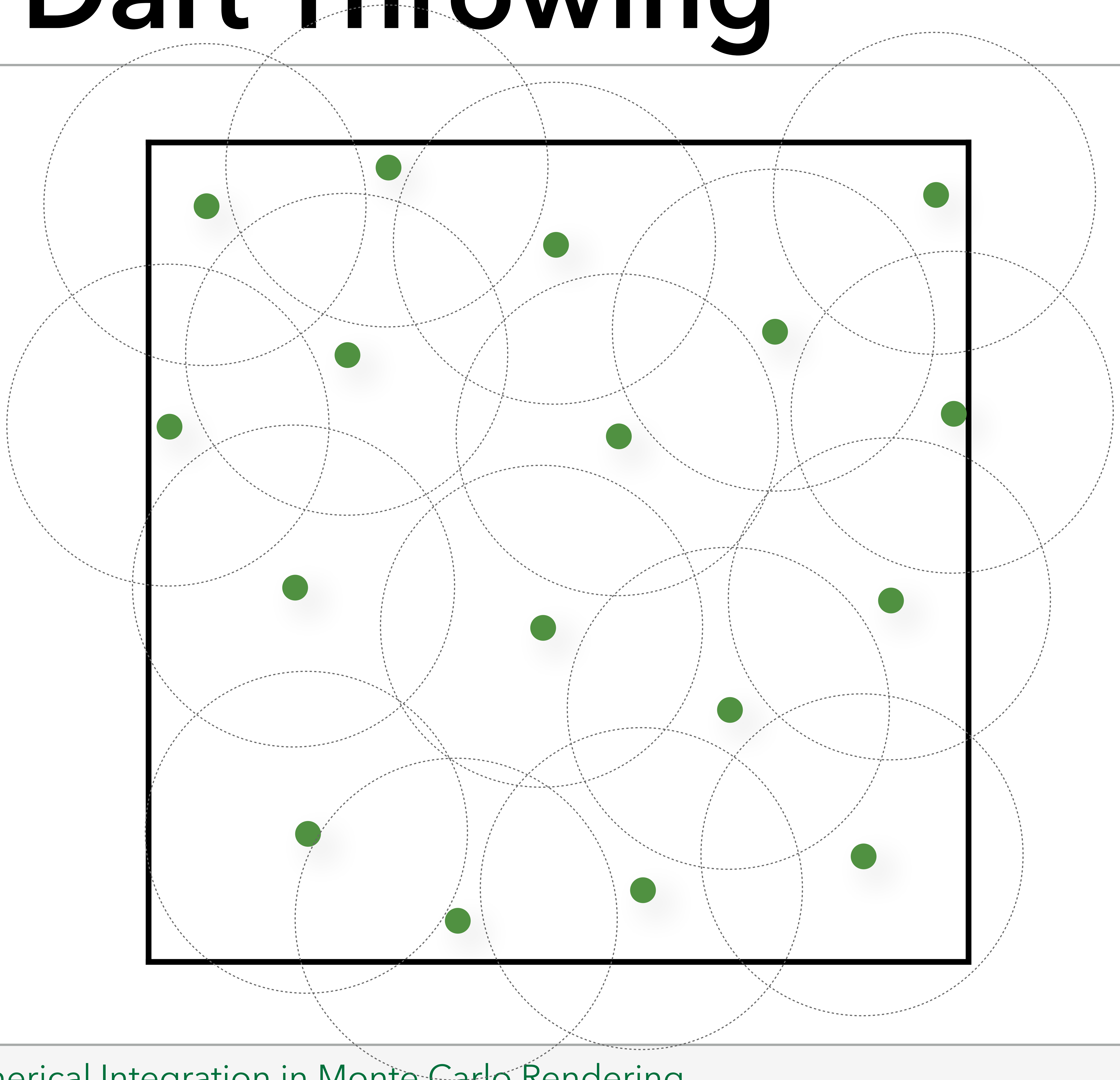
Random Dart Throwing



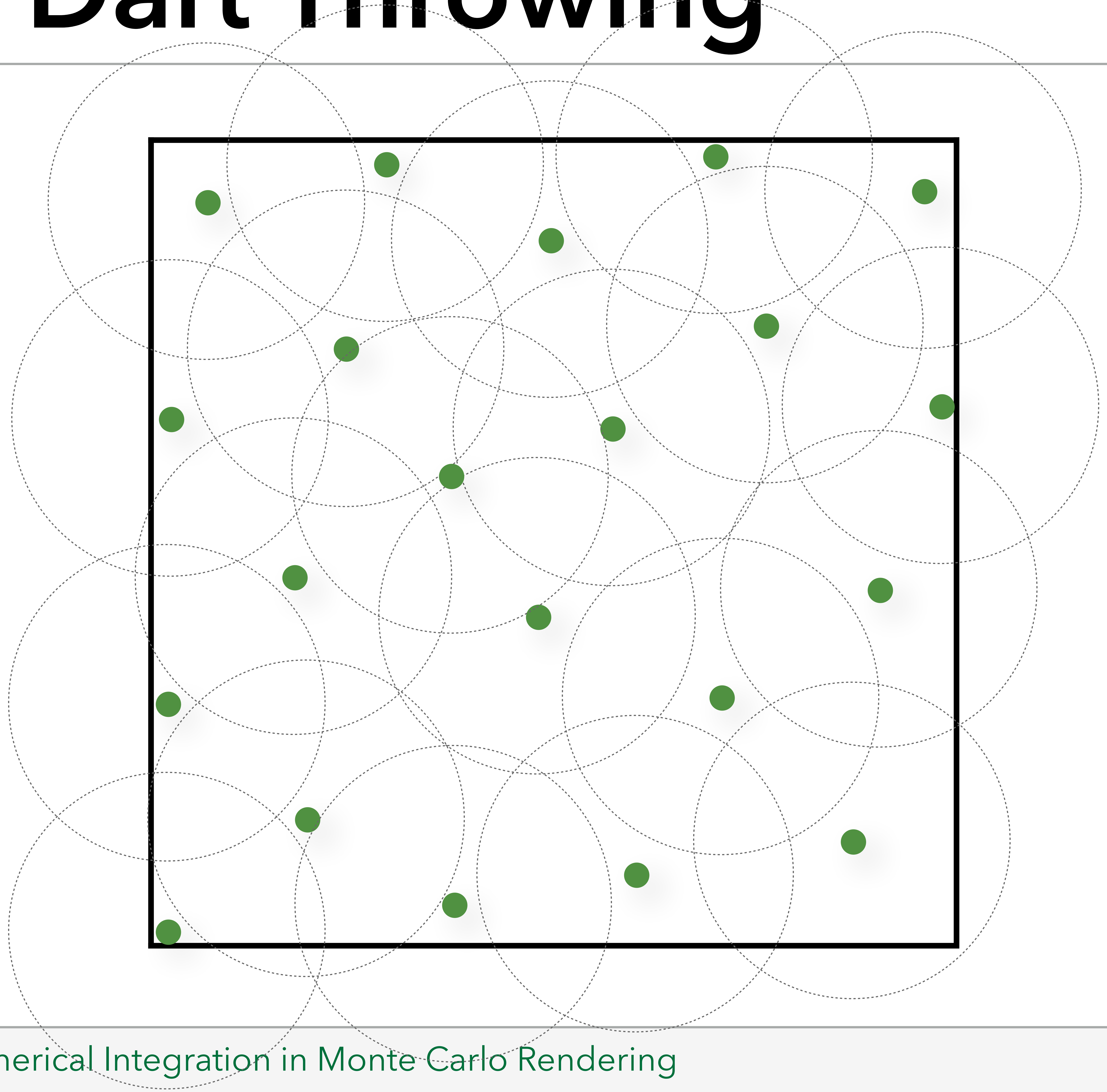
Random Dart Throwing



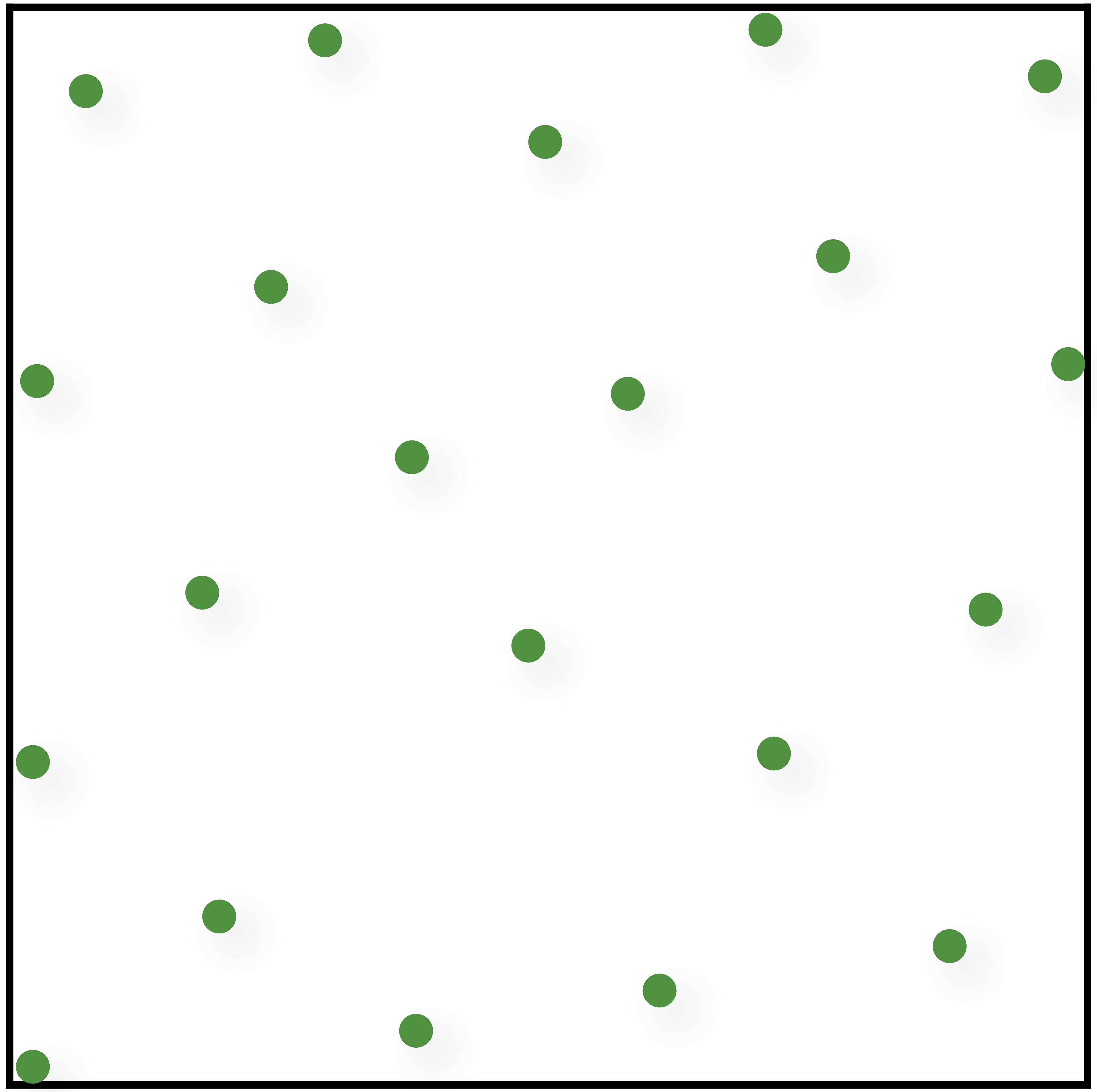
Random Dart Throwing



Random Dart Throwing

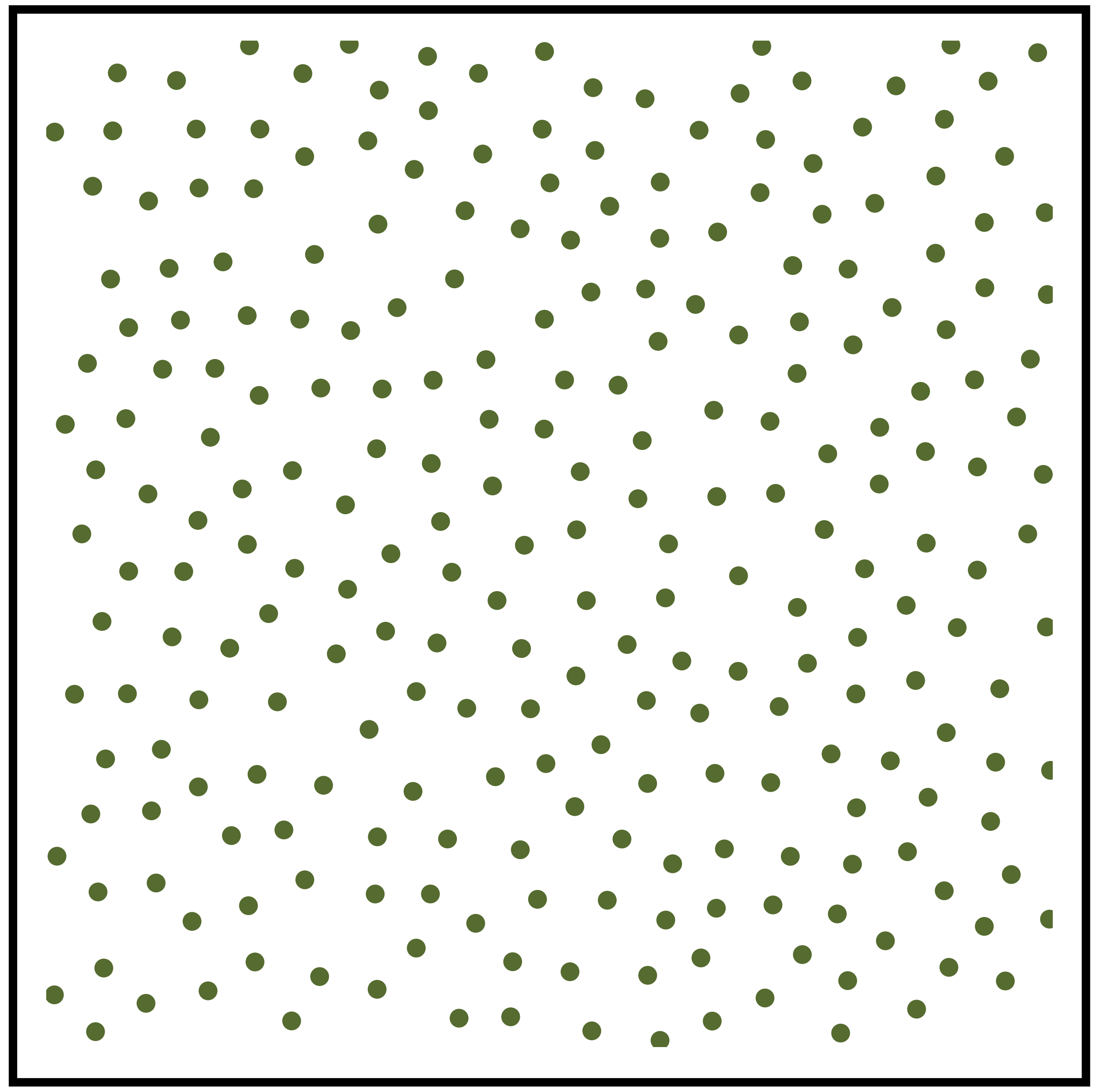


Random Dart Throwing

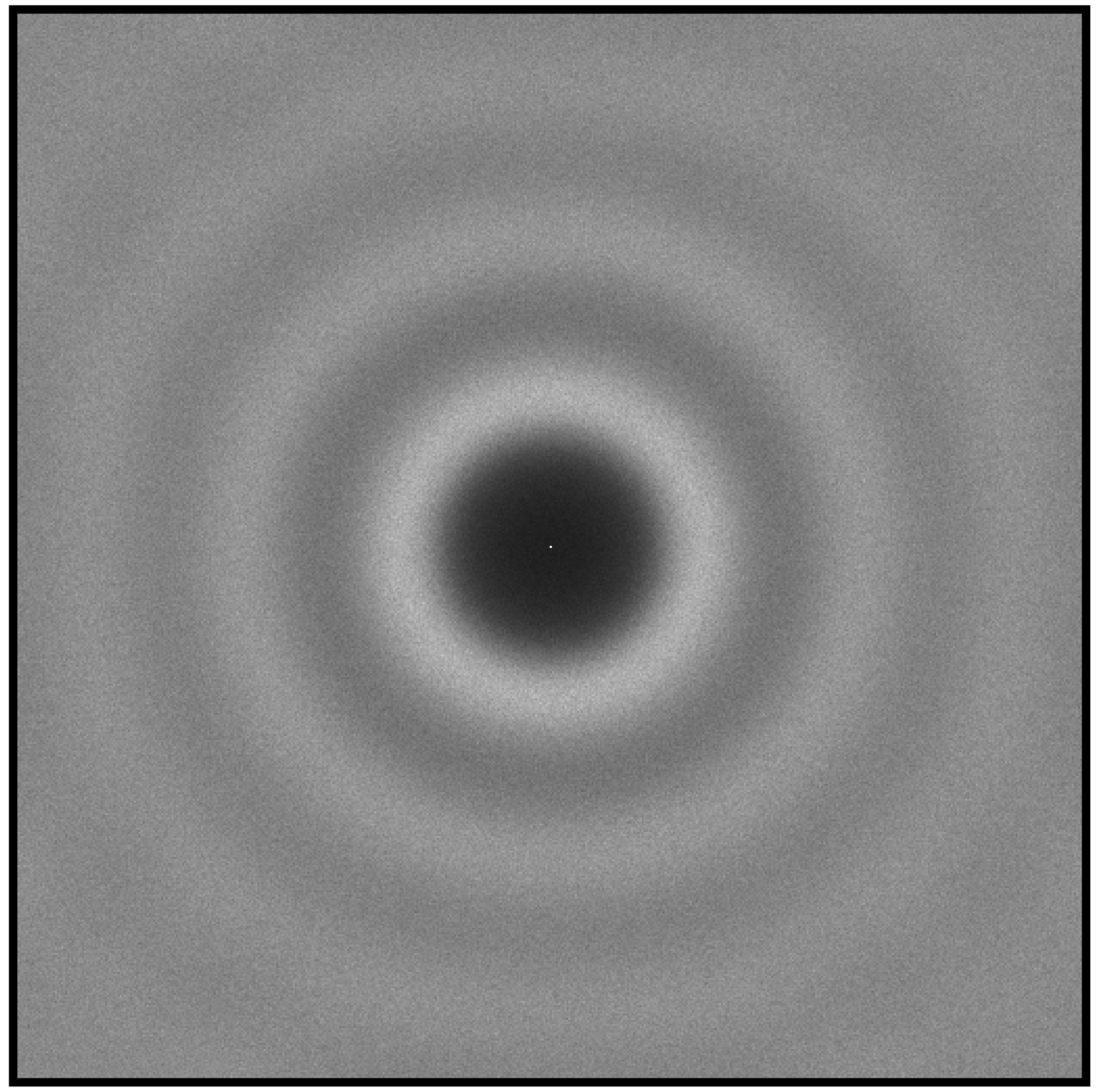


Poisson Disk Sampling

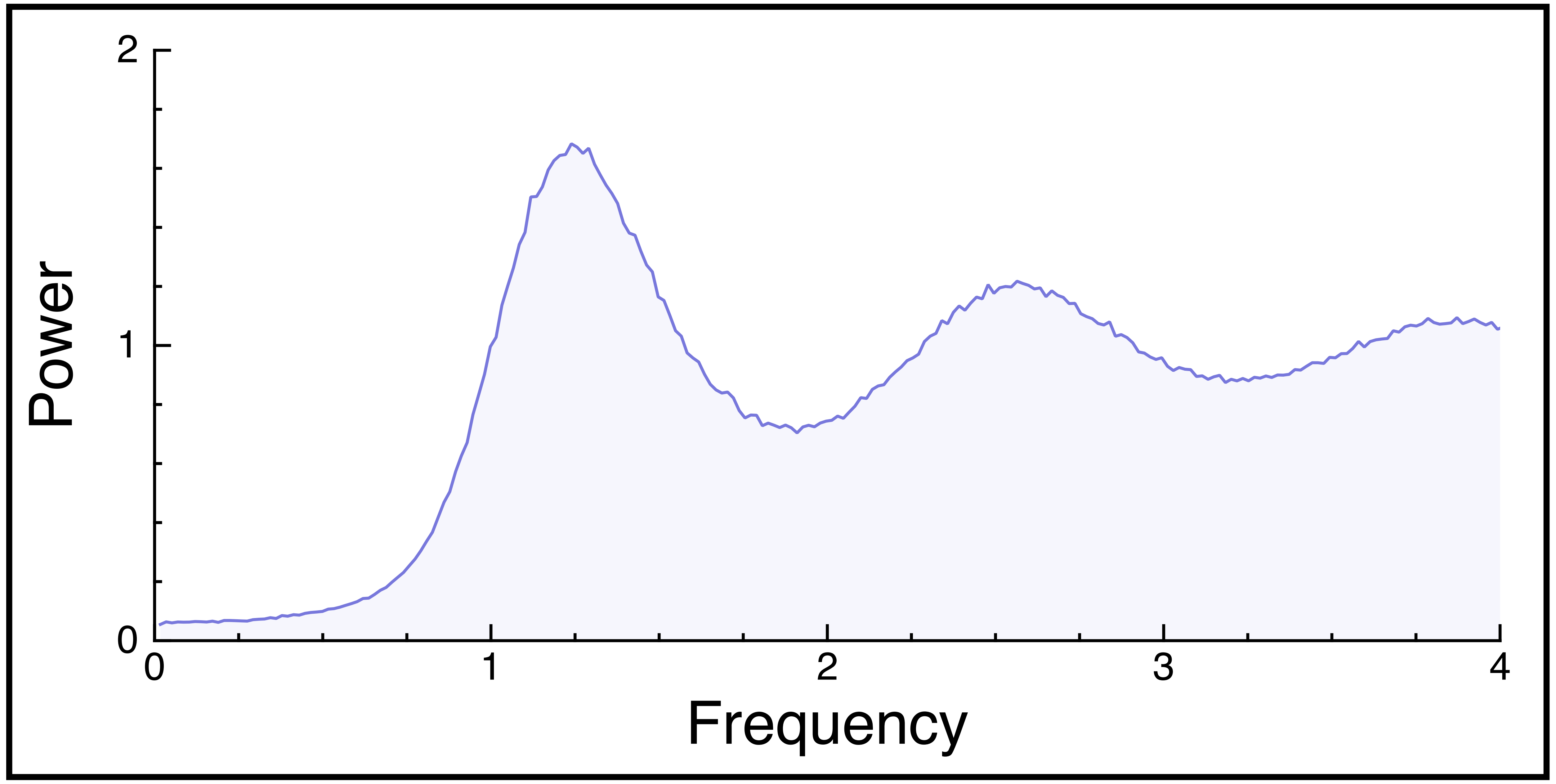
Samples



Expected power spectrum



Radial mean



Blue-Noise Sampling (Relaxation-based)

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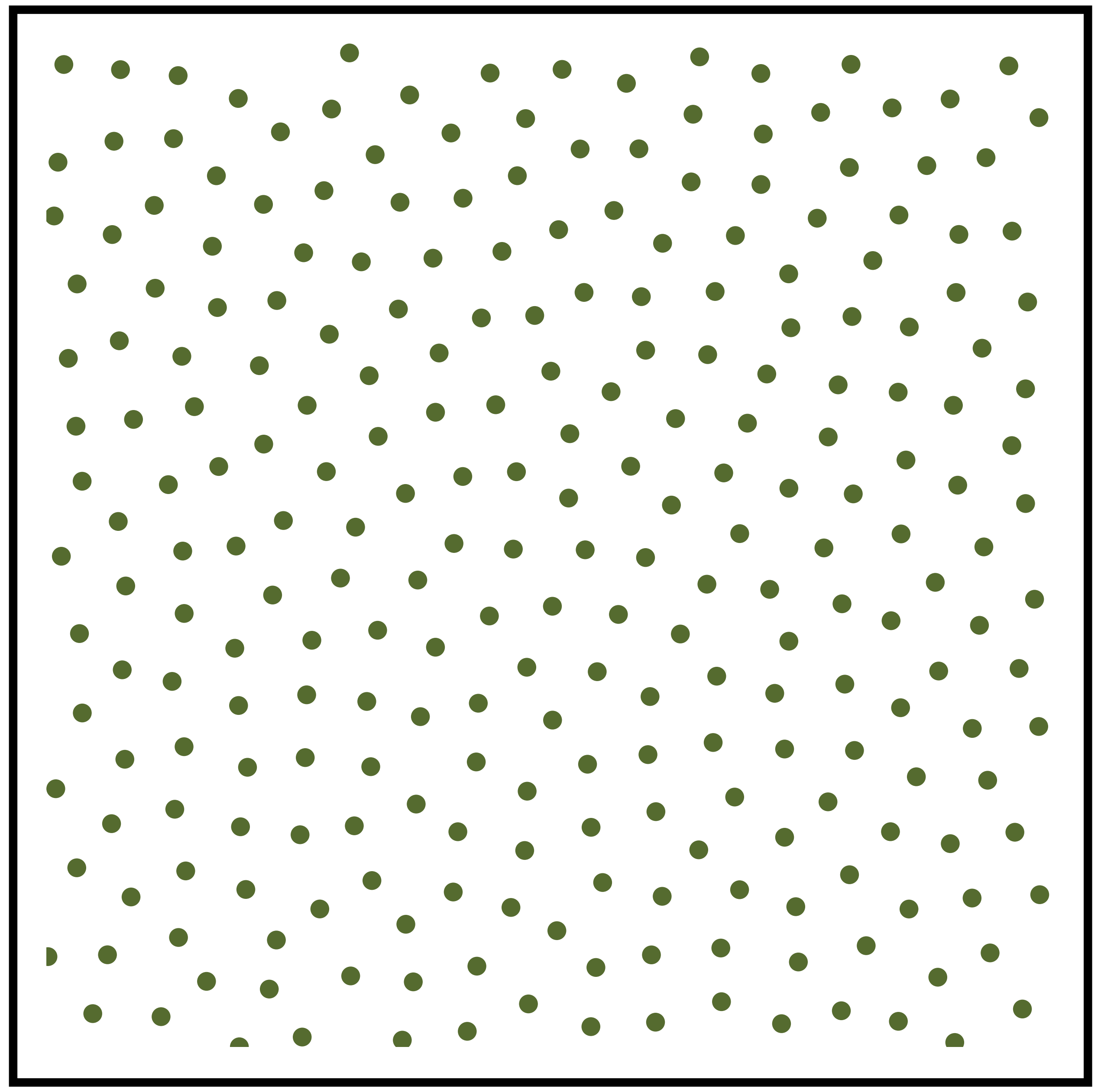
1. Initialize sample positions (e.g. random)

Blue-Noise Sampling (Relaxation-based)

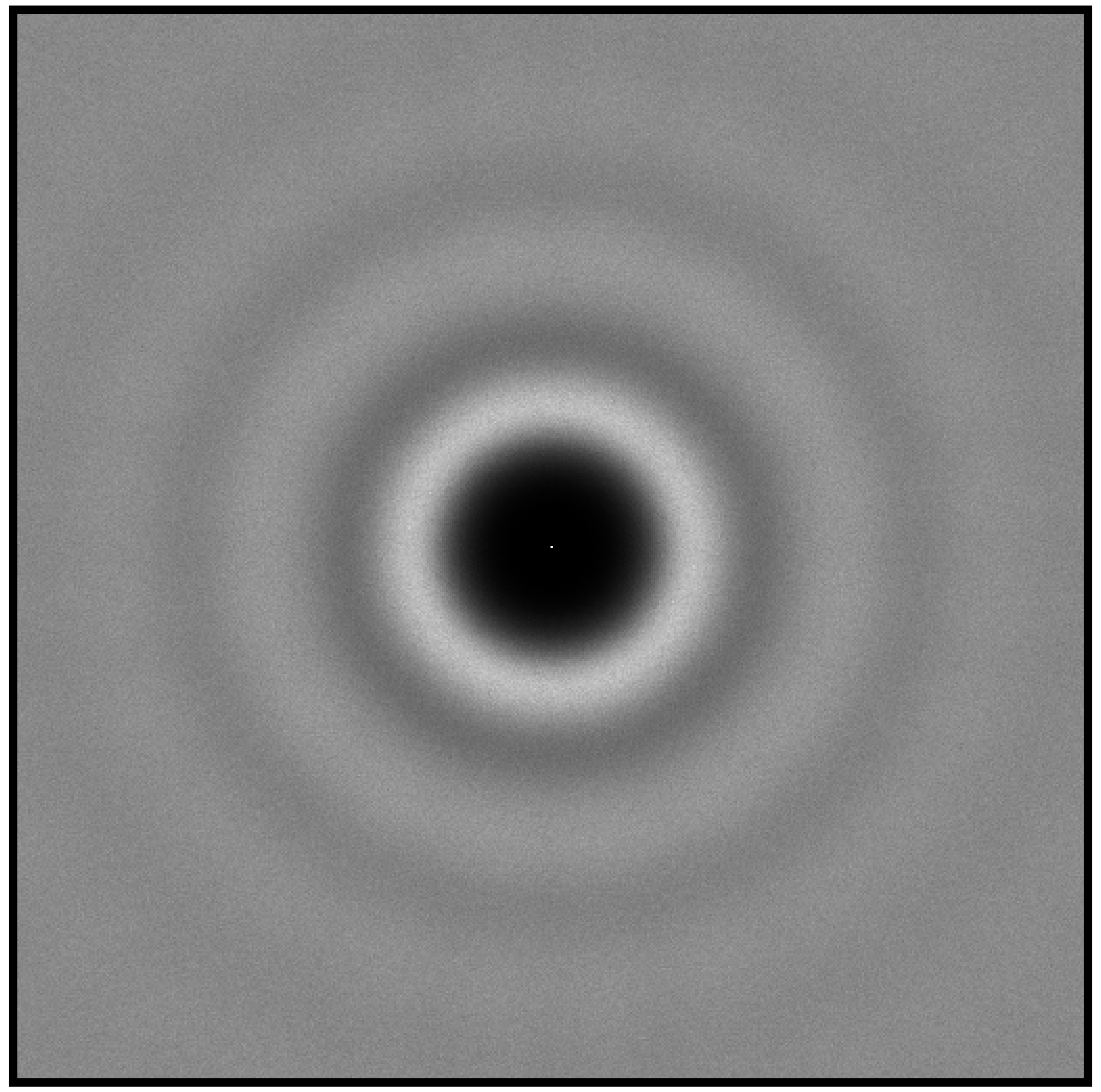
1. Initialize sample positions (e.g. random)
2. Use an iterative relaxation to move samples away from each other.

CCVT Sampling [Balzer et al. 2009]

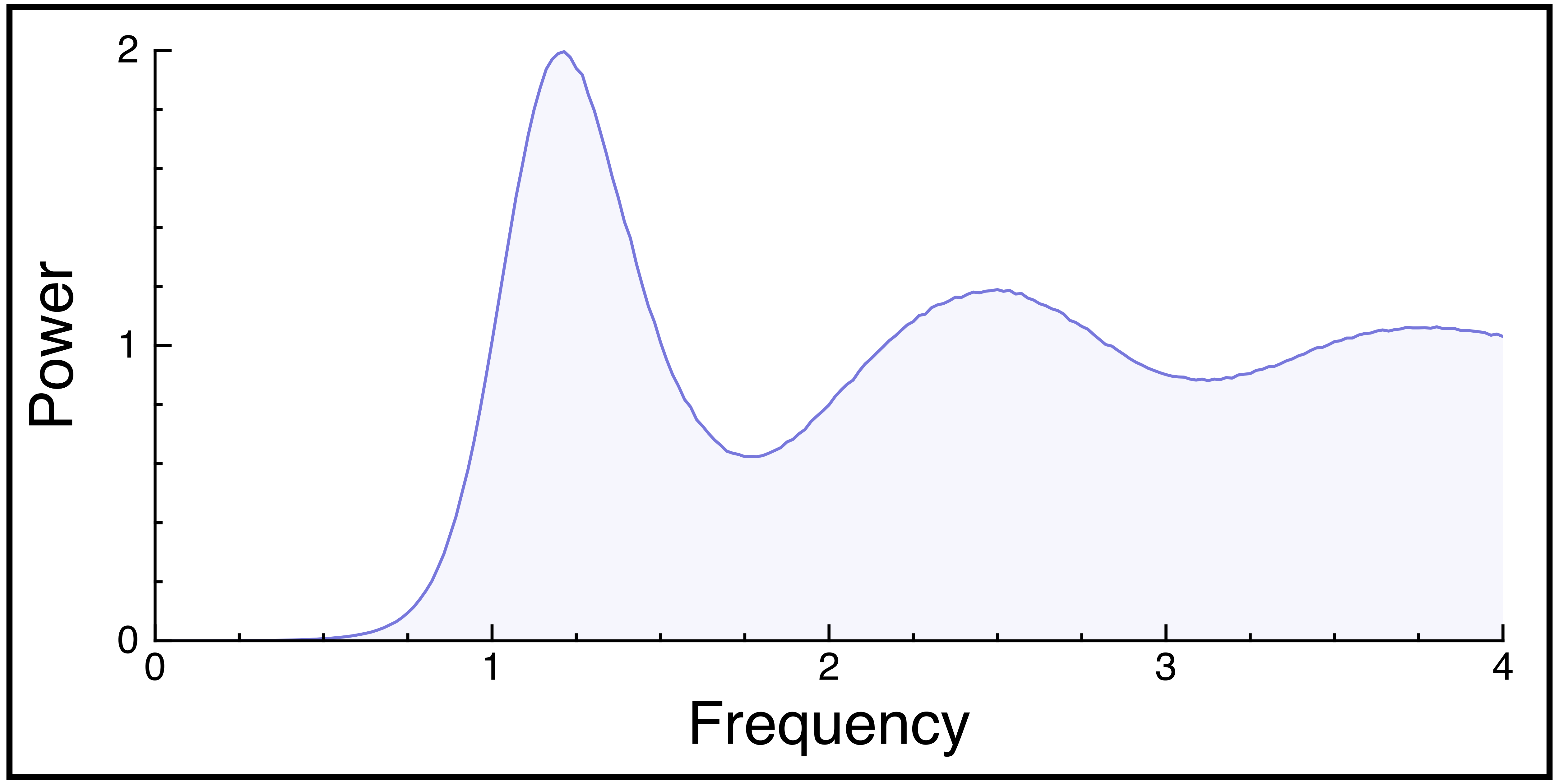
Samples



Expected power spectrum

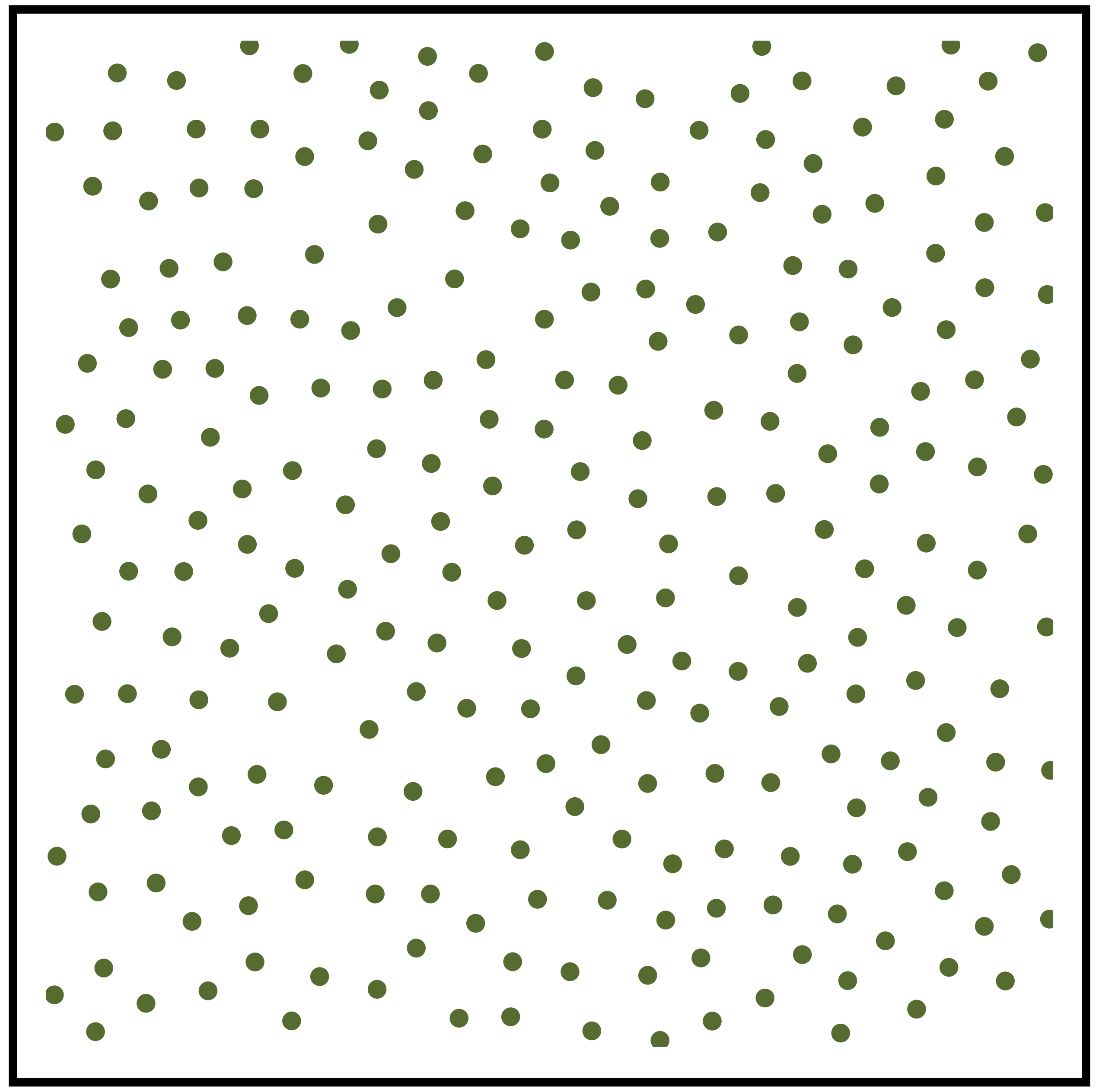


Radial mean



Poisson Disk Sampling

Samples



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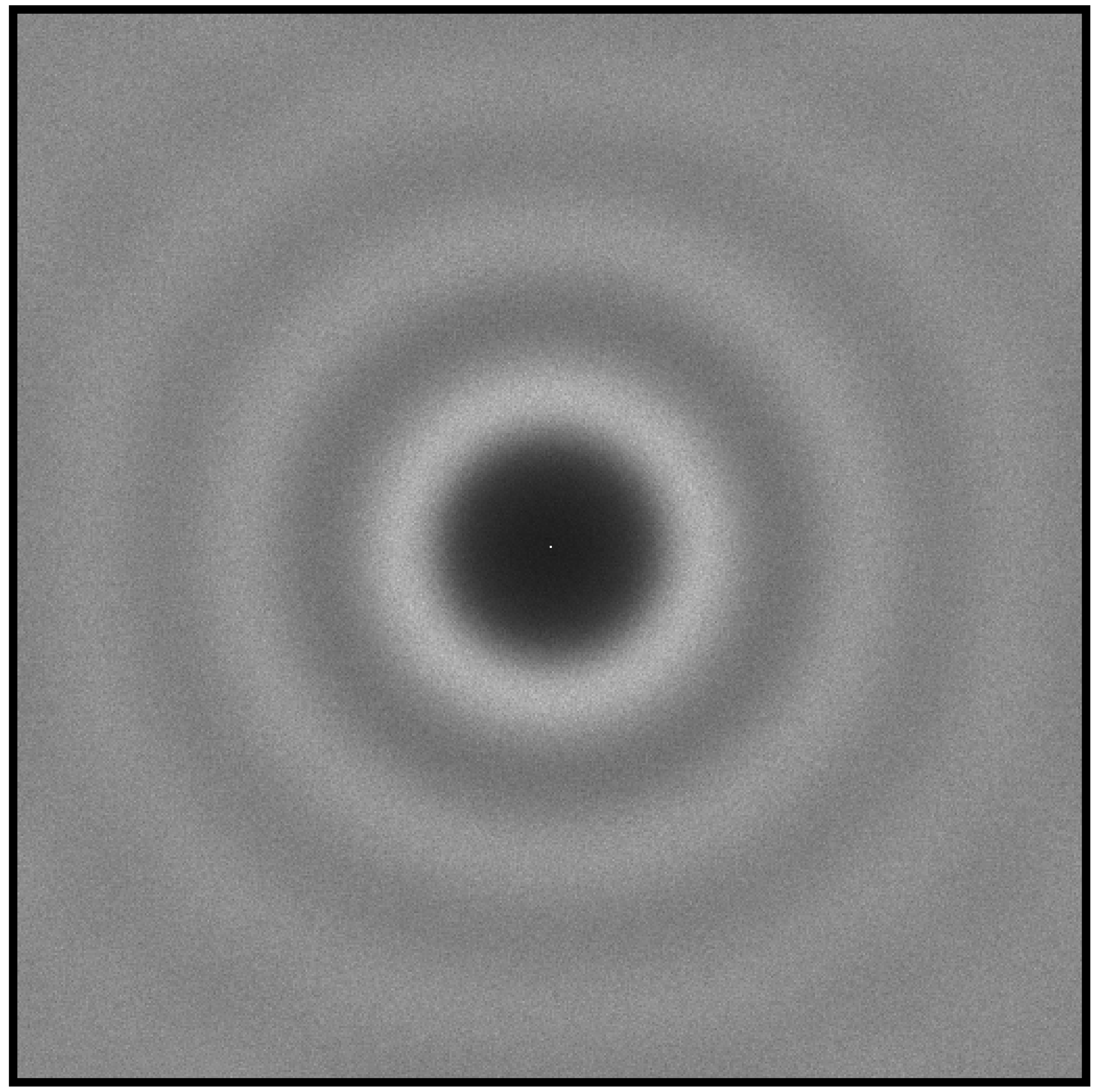
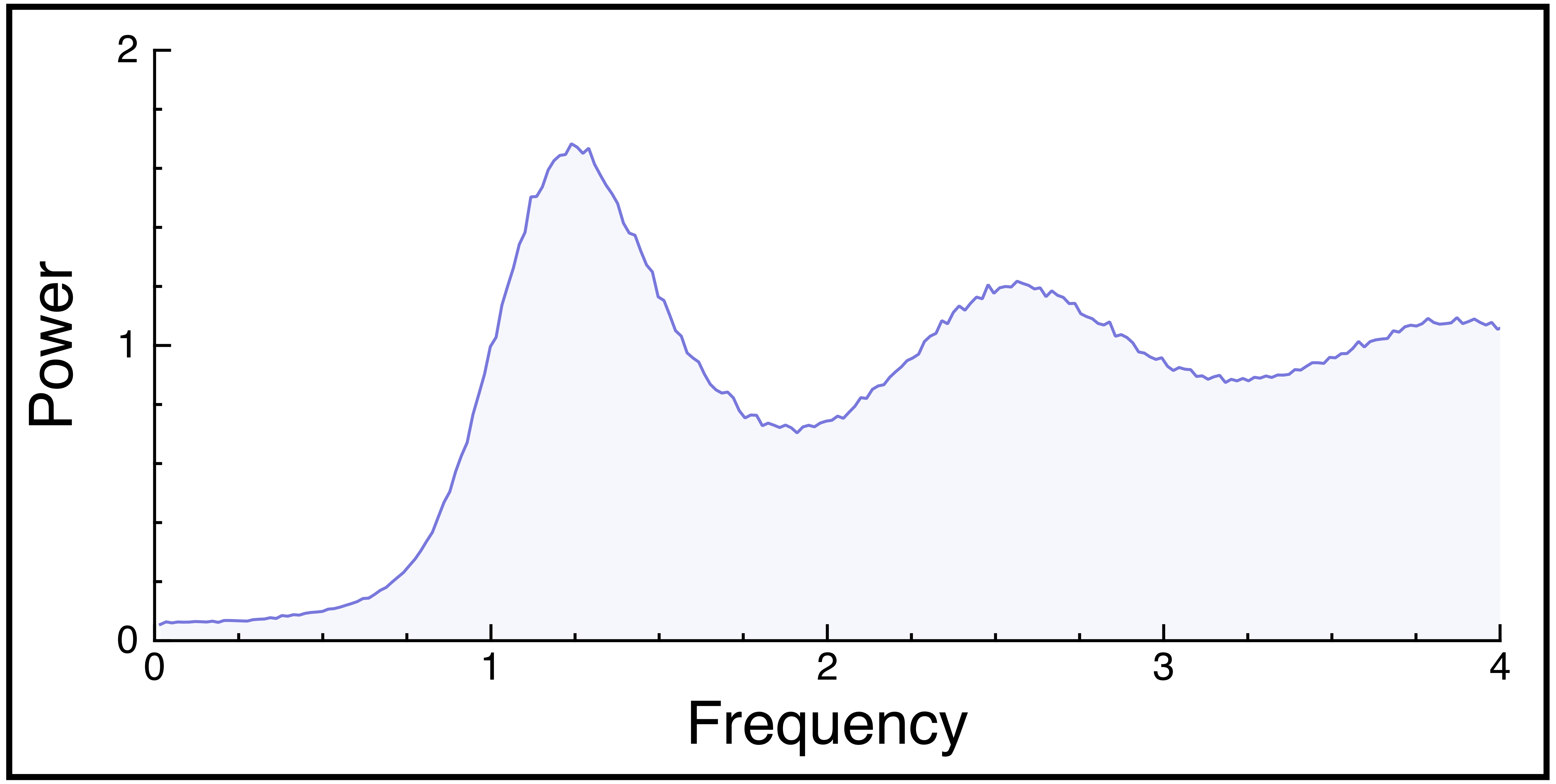


Radial mean



Low-Discrepancy Sampling

Deterministic sets of points specially crafted to be evenly distributed (have low discrepancy).

Entire field of study called Quasi-Monte Carlo (QMC)

The Van der Corput Sequence

Radical Inverse Φ_b in base 2

Subsequent points “fall into biggest holes”

k	Base 2	Φ_b

The Van der Corput Sequence

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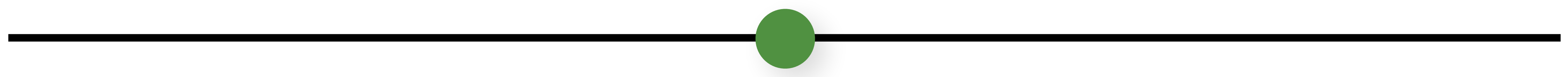

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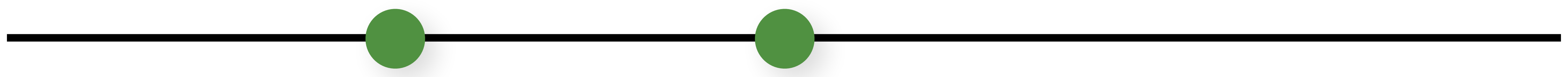

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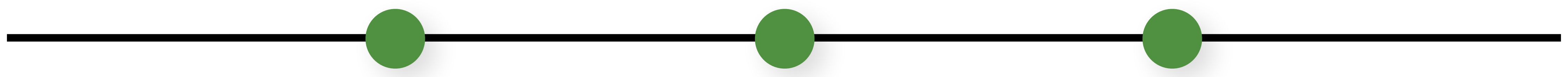

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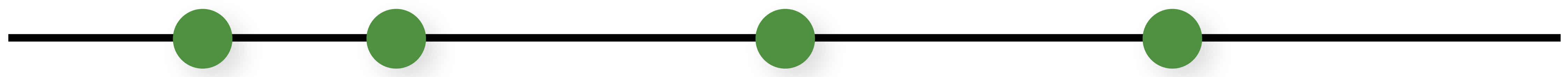

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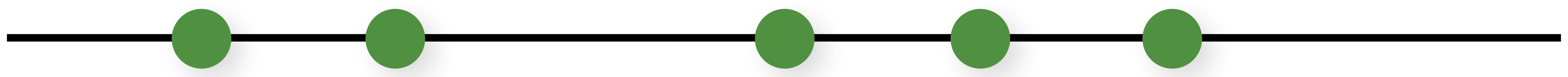

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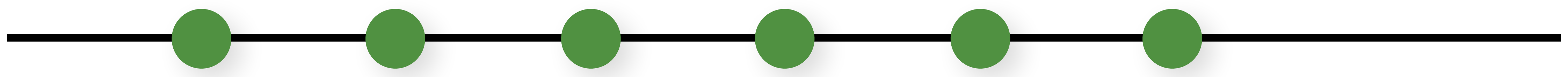

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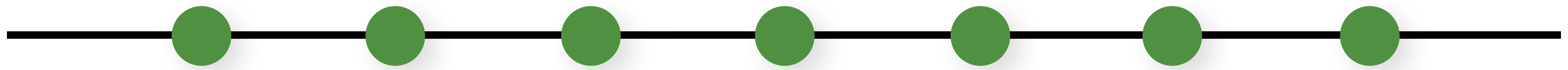
5	101	.101 = 5/8
6	110	.011 = 3/8
7	111	.111 = 7/8



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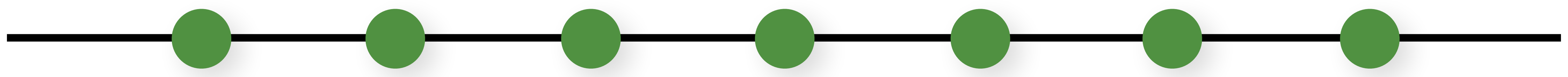
...		



Halton and Hammersley Points

Halton: Radical inverse with different base for each dimension:

$$\vec{x}_k = (\Phi_2(k), \Phi_3(k), \Phi_5(k), \ldots, \Phi_{p_n}(k))$$

Halton and Hammersley Points

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- The bases should all be relatively prime.

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Hammersley: Same as Halton, but first dimension is k/N:

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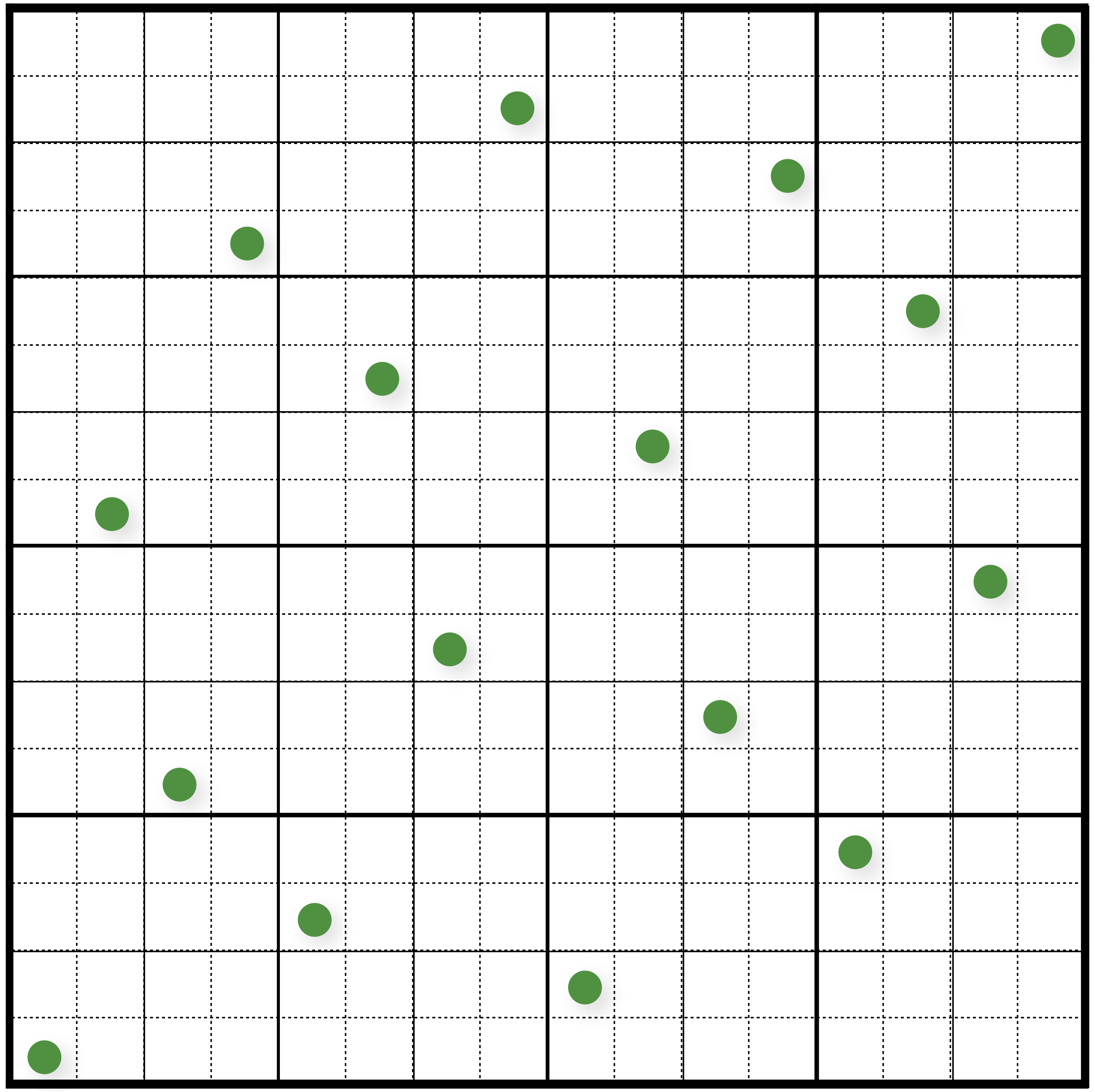
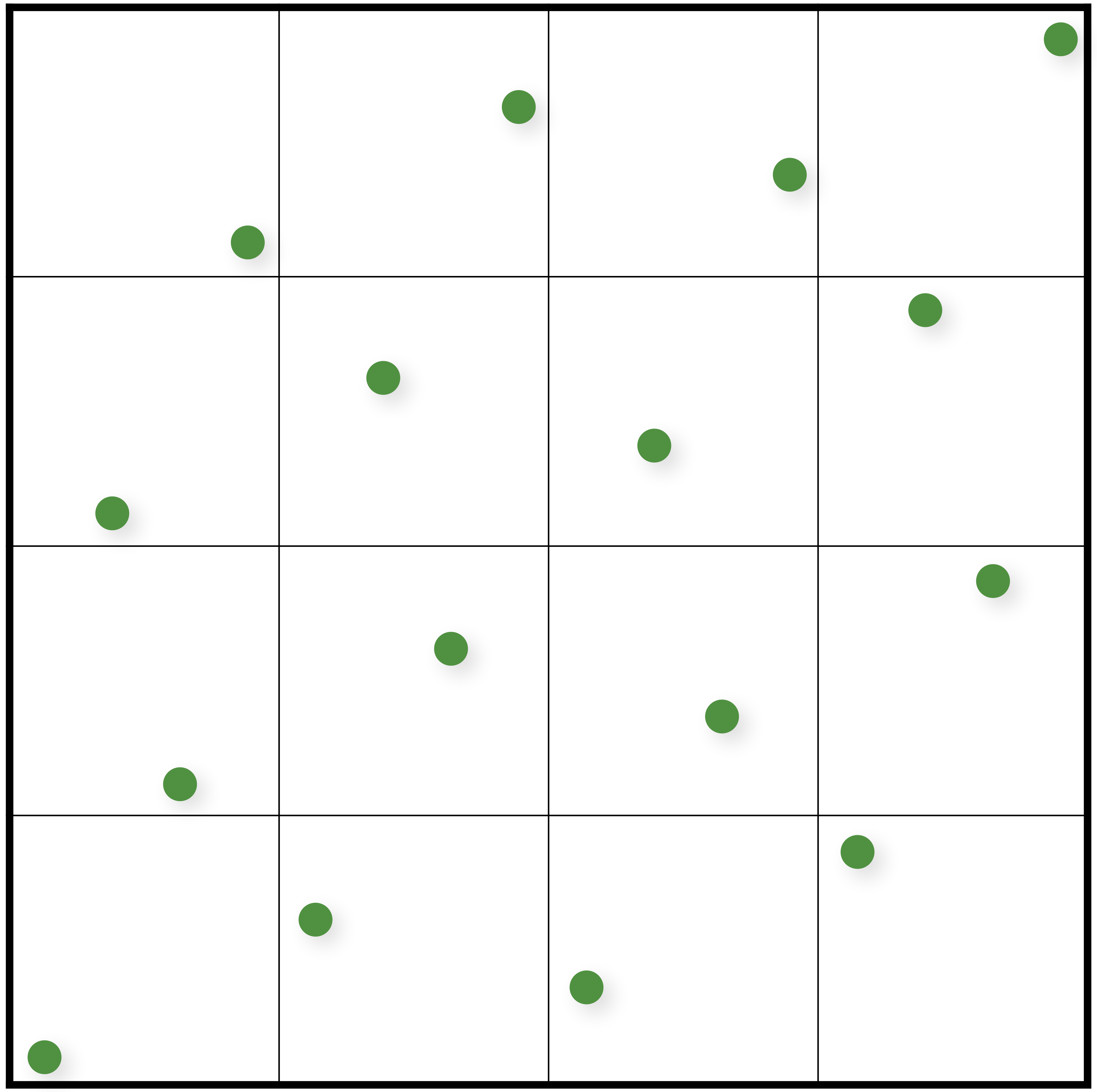
- Not incremental, need to know sample count, N, in advance

The Hammersley Sequence



1 sample in each “elementary interval”

The Hammersley Sequence



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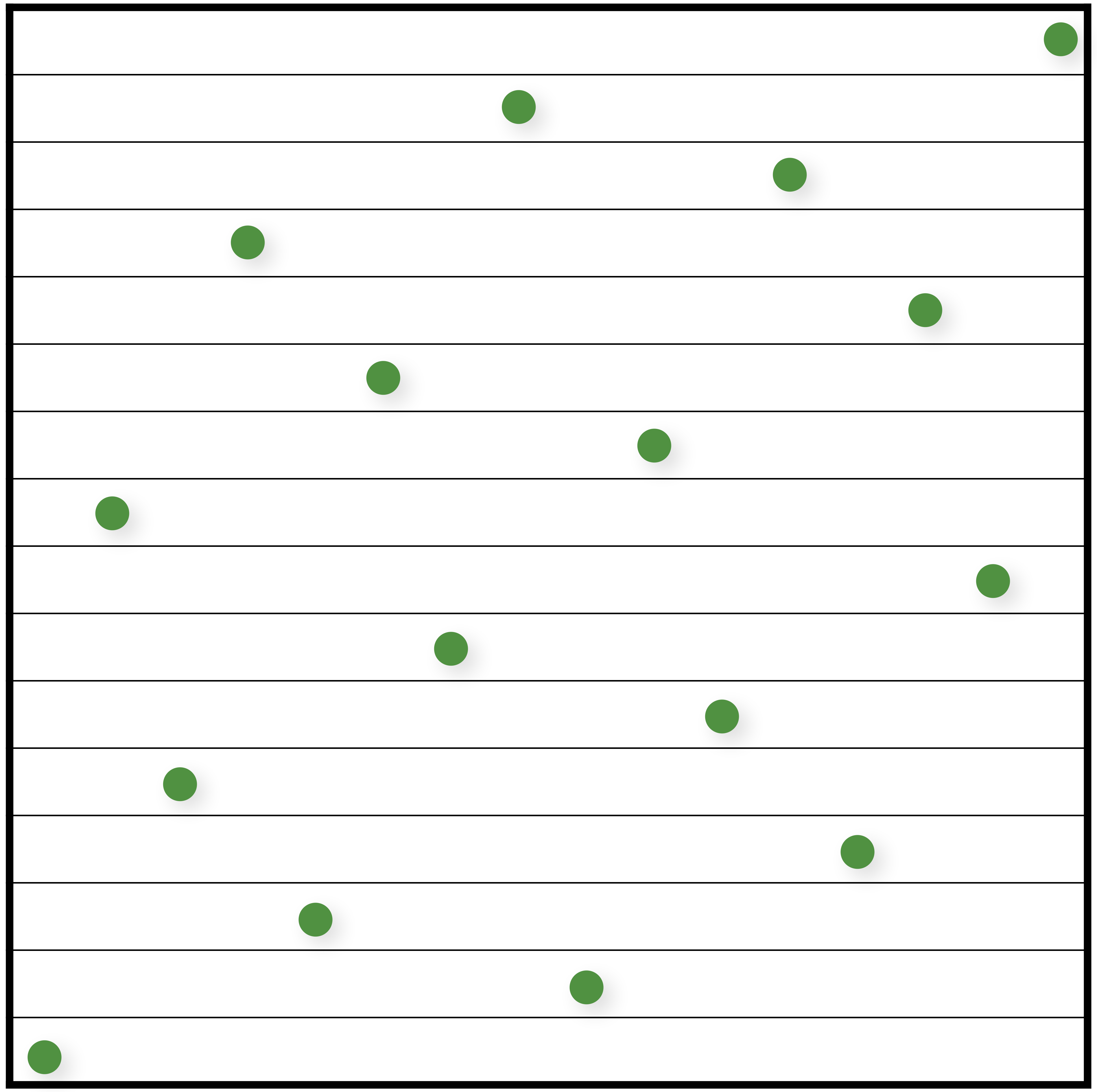

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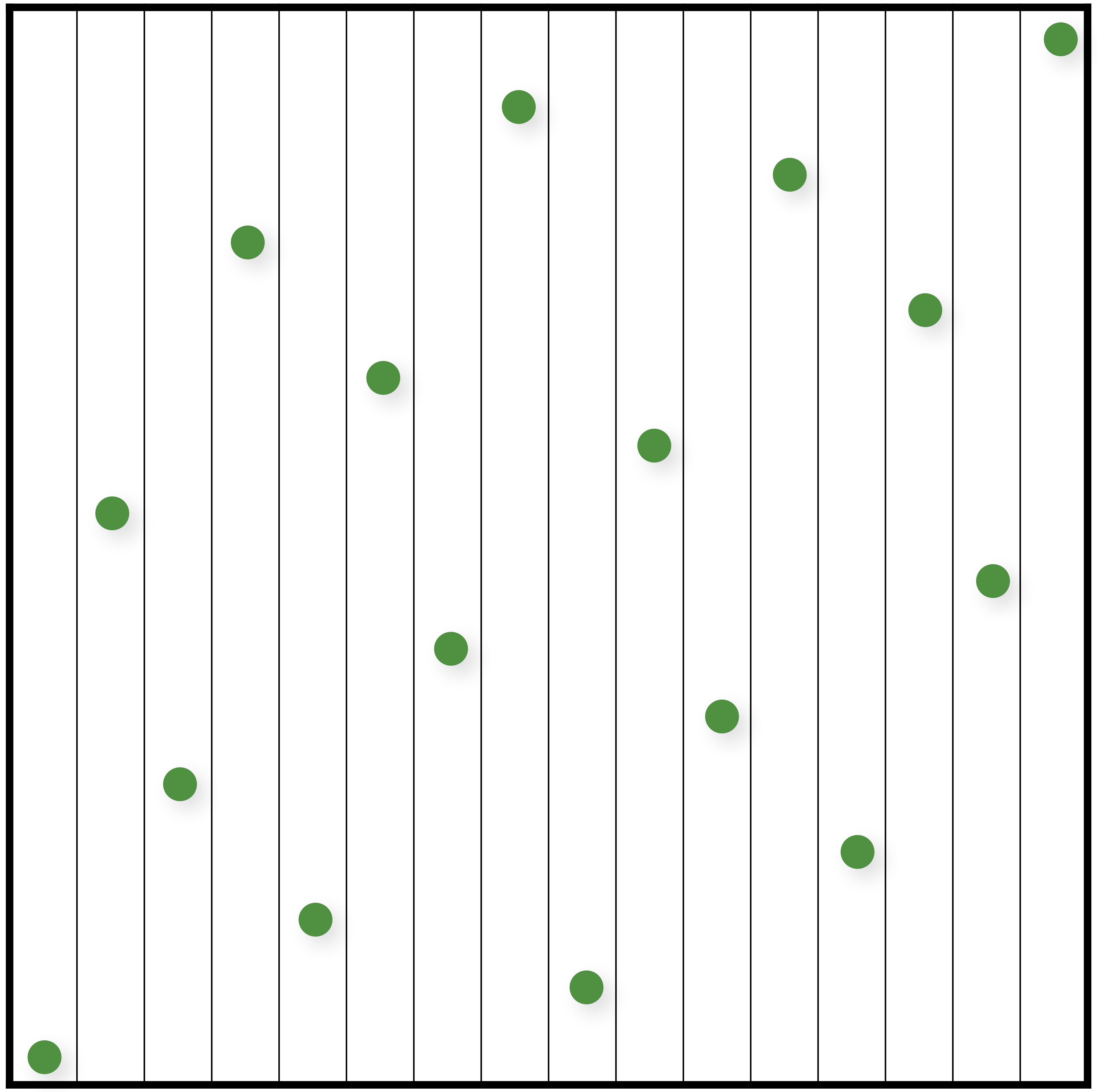

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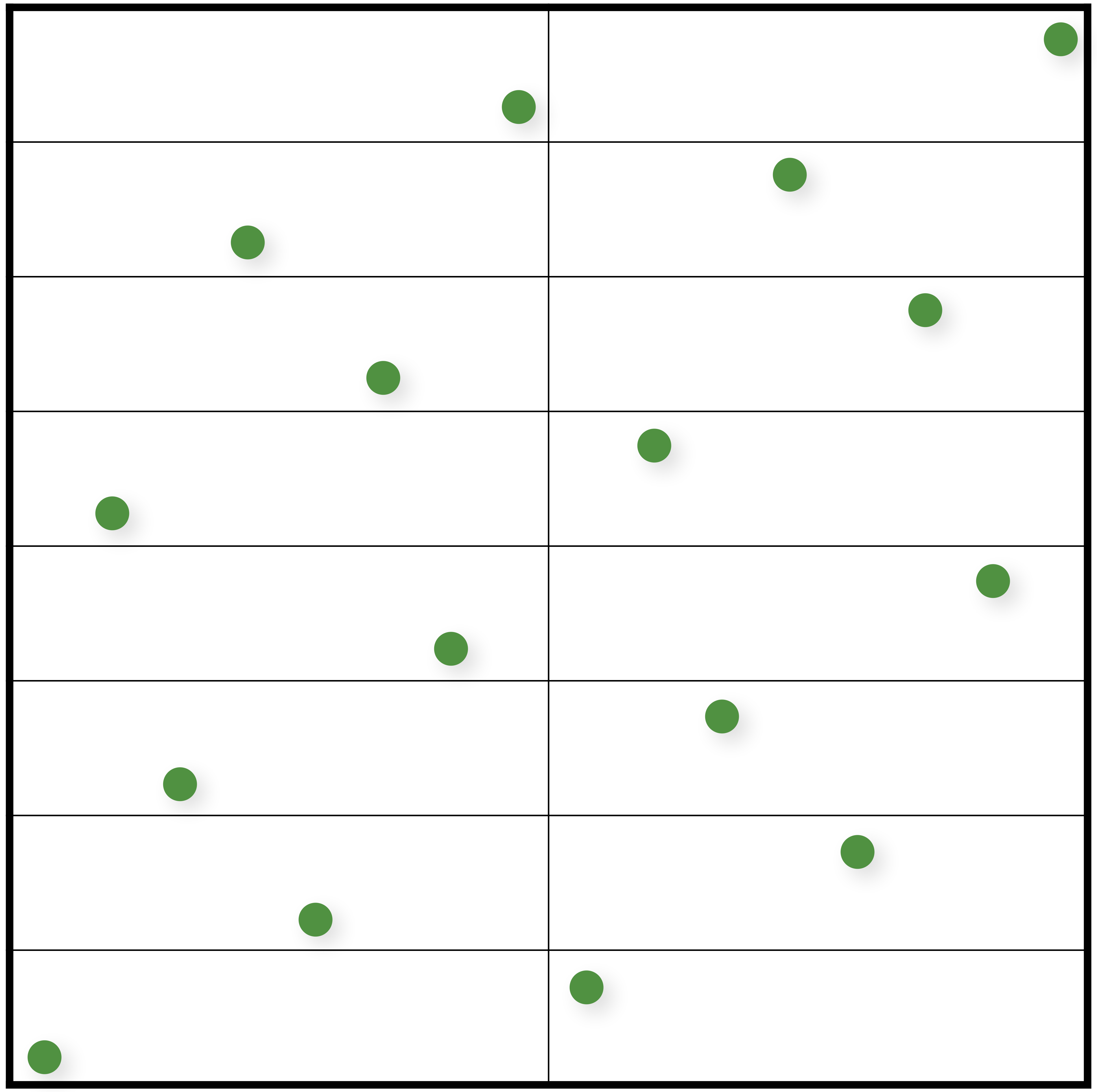

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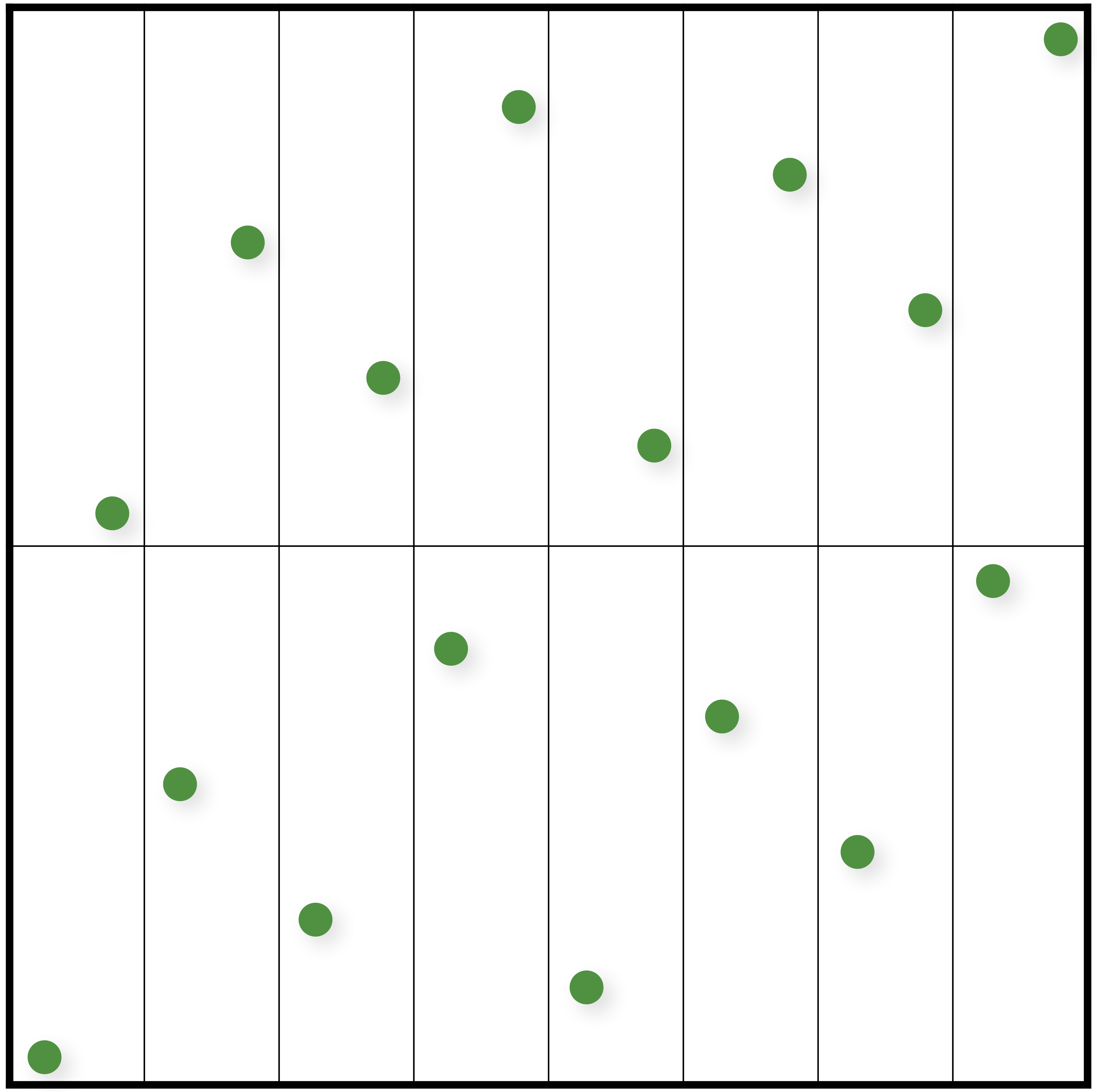

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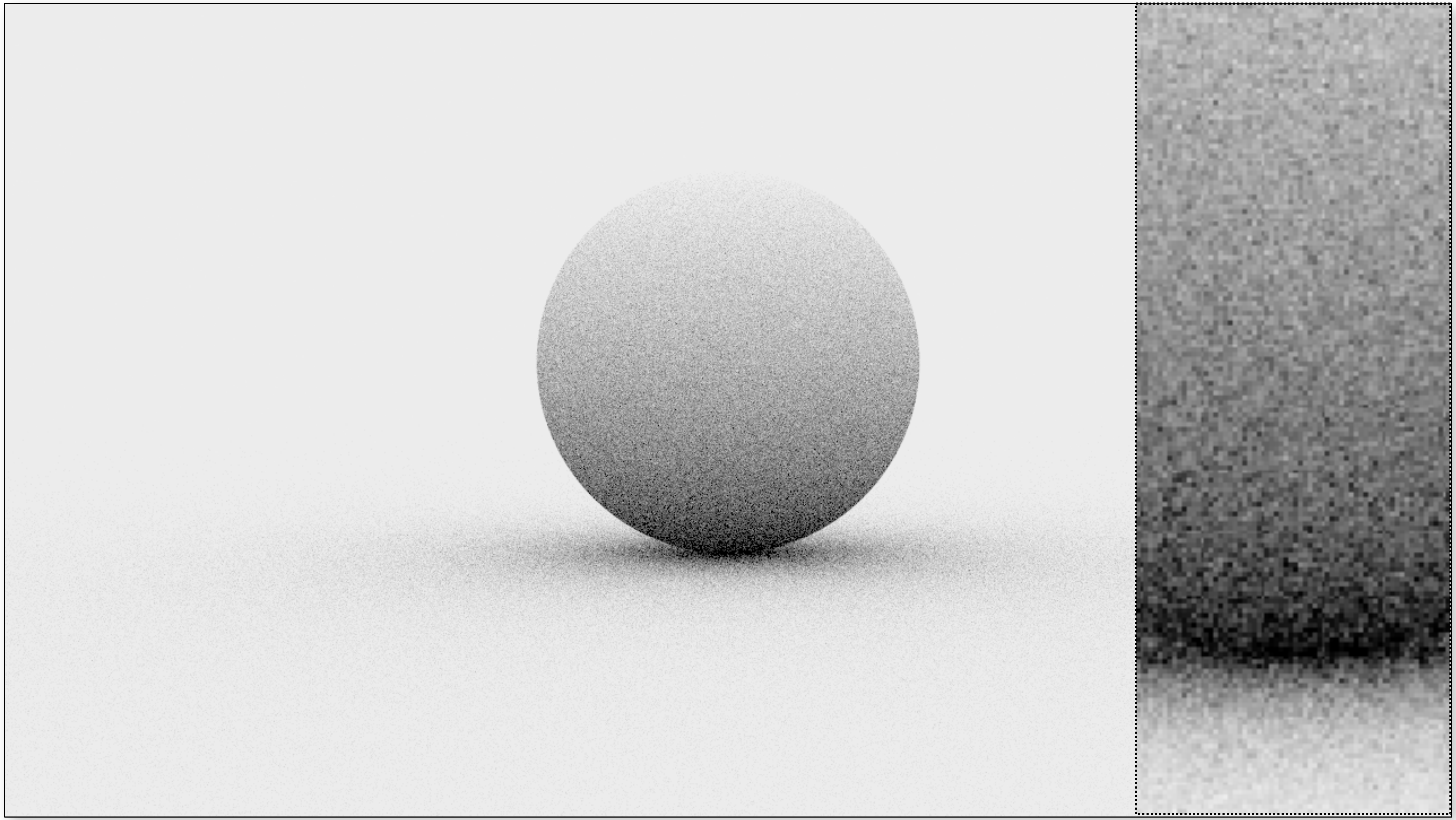
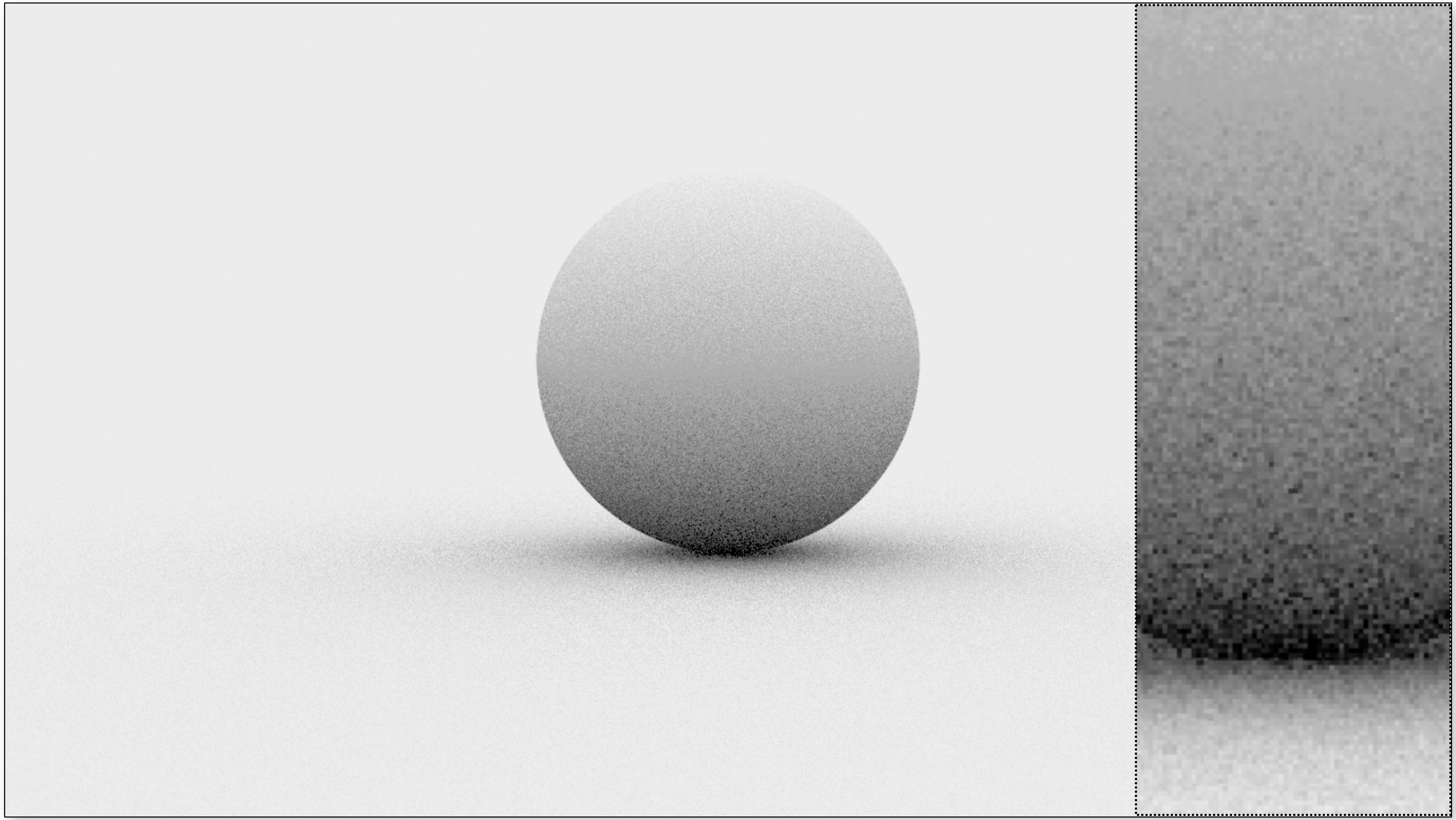
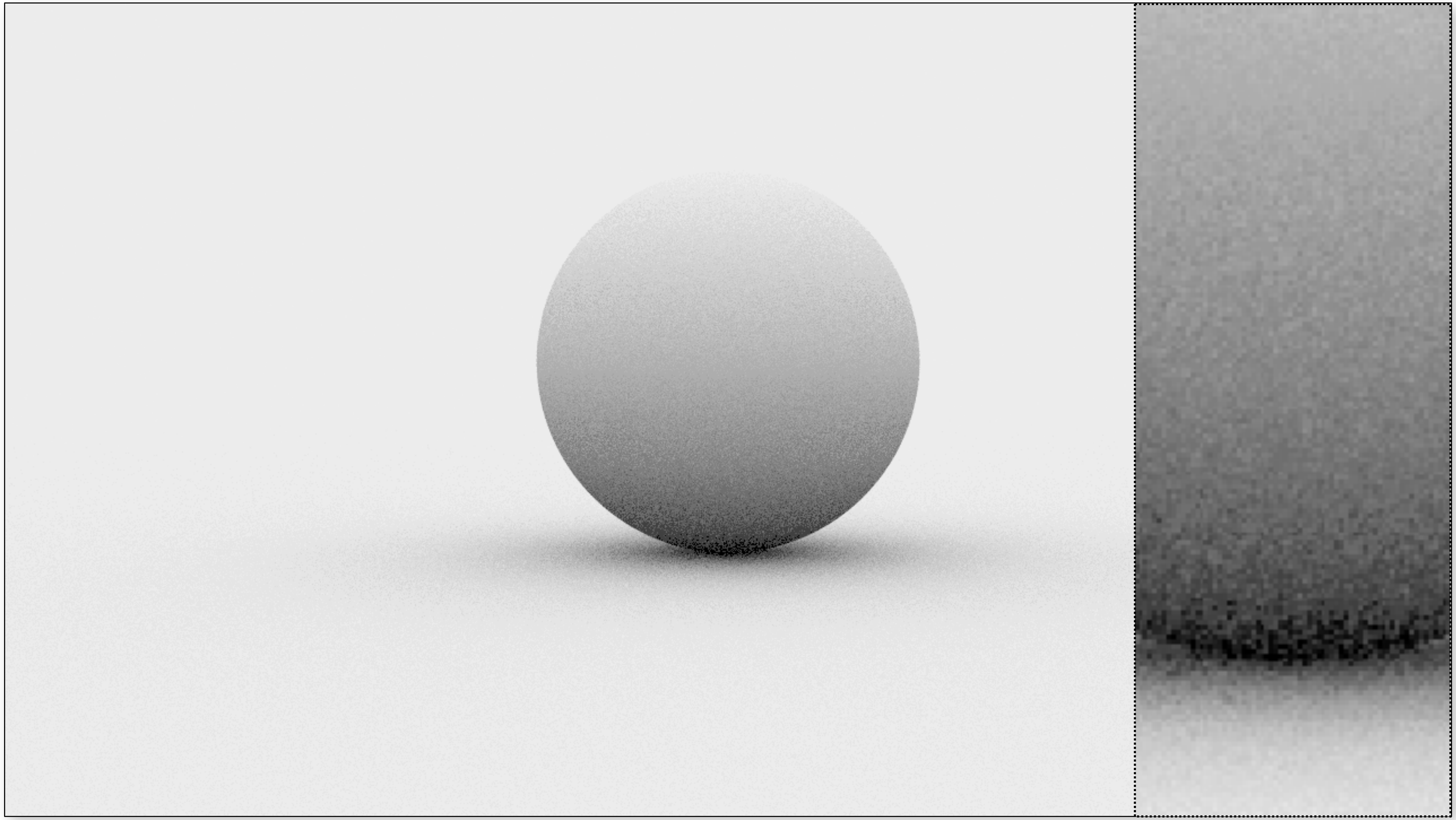
Monte Carlo (16 random samples)



Monte Carlo (16 jittered samples)



Scrambled Low-Discrepancy Sampling



More info on QMC in Rendering

S. Premoze, A. Keller, and M. Raab.
Advanced (Quasi-) Monte Carlo Methods for Image Synthesis.
In SIGGRAPH 2012 courses.

How can we predict error from these?