

# Structural replication of nanoporous media using procedural noise\*

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In this paper, we aim to develop a method for producing statistically correct simulations of nanoporous media without the use of conventional Molecular Dynamics Simulator (MDS). In short, the proposed model is a binary function that returns either true if the input position is in a void / pore, or false if within a wall. By using procedural noise, we are not restricted to generating media within a limited box, as the noise functions are continuous on all scales. It is therefore possible to validate pores at theoretically arbitrary range. In addition, this method is extremely fast, requiring very little computational power to calculate whether a particle is within a pore or not. After presenting such a model, we choose a method to measure the structural properties of nanoporous media that are created either through regular methods (e.g. LAMMPS) or with our method. The measure we selected is the radial distribution function (RDF)  $g(r)$ , which is regarded as the de-facto standard method for capturing the structural properties of porous media. Using this measure, we define a full likelihood framework for estimating model parameters given any data set, and continue by validating our own framework by analysing procedural noise data sets with known input parameters. Finally, we perform a full likelihood analysis of silica SiO<sub>2</sub> data set simulated in LAMMPS, and show that our model correctly reproduces several of the internal properties of the data set, including  $g(r)$ , porosity and surface area. **TODO: Abstract boer tenkes noe gjennom: faa frem hovedpoenger.**

PACS numbers:

## I. INTRODUCTION

**TODO: Skriv en fin intro! Ogsaa om nanoporous media** Properties of structural patterns that regularly occur in nature are often investigated either through direct observations or through simulations of theoretical models. Model simulations typically require a large computational framework to accurately reproduce the observed effects, while experimental data can be both expensive and hard to obtain, in addition to being riddled with artefacts and instrumental errors.

Procedural generation of physical structures have several advantages over conventional simulations. For example, when producing simulations of nanoporous silica, we are required to calculate and propagate the physical properties of each particle for every time-step throughout the simulation, using a computational framework such as LAMMPS [1]. This is both time-consuming, and the computational cost can sometimes be quite large. In addition, the simulation is constrained to a box, so particles are not allowed to move outside the defined boundaries. On the other hand, using procedural noise to carve out nanoporous media is both extremely fast and computationally cost-efficient, in addition to being continuous on all scales. This means that it is possible to simulate

In this paper, we aim to investigate whether procedural methods are suitable for producing statistically correct 3D physical structures, focusing on nanoporous media. In a sense, we are combining well-known methods from

computer games and real-time graphics-oriented software with experimental observations and simulations. Procedural methods for automated generation of computer game content have been around since the early 1980's, and in those early days algorithms were less advanced, often yielding plain, simple geometrical structures. Nowadays, almost every single computer game produced will contain some level of automated generated content, from textures to level design to landscapes and gameplay.

We do not claim that procedural noise methods completely reproduces all structural properties of nanoporous silica, but show that our approach can be used to efficiently create materials that are structurally similar to simulations. Naturally, this all depends on the statistics used for comparing the two models, which in this case is based on the radial distribution function (RDF)  $g(r)$ .

## II. PROCEDURAL CONTENT GENERATION

By procedural content generation, we generally mean a mathematical algorithm that uses limited input data to create complex, sometimes infinite repeating patterns. A firm example would be fractals, such as the Julia/Mandelbrot [ref mandelbrot] set, where one tests whether the complex quadratic recurrence equation  $z_{n+1} = z_n^2 + C$  for  $z \in \mathbb{C}$  converges for each position in a 2D complex plane. With this seemingly simple equation, the level of complexity generated on the boundary between convergence and divergence is infinite, with self-similar patterns repeating themselves to arbitrary detail.

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Another example, widely used in contemporary game

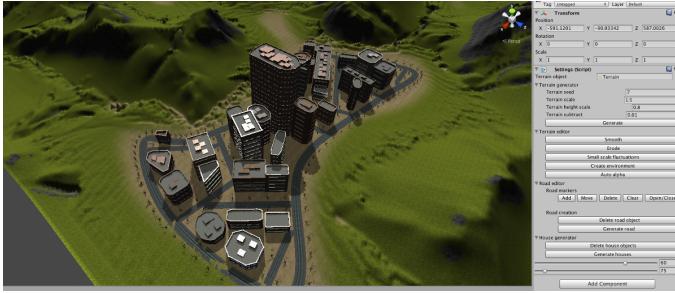


FIG. 1: Example of city building using procedural methods: Landscape, city infrastructure, buildings and all textures are all automatically generated using procedural methods. Created by one of the authors. **TODO: Denne er jo med bare for moro skyld, boer jo fjernes**

content generation, is having prefabs (pre-fabricated 3D models such as doors, walls, tiles and roof segments) automatically being stitched together to create buildings. When designing a city, instead of creating each building manually, you only need specify the position, area and height of a structure. Then, by using an algorithm that combines these prefabs to render the building, it is possible to create cities of arbitrary size with a single command. Naturally, it is also possible to create procedural methods that design the layout and placement of these buildings. See figure 1 for an example of such a city generator tool, developed by one of the authors of this paper.

A much simpler example would be generating a 1 (or 2)-dimensional landscape by choosing random points on a grid and performing a spline interpolation between them to create the illusion of a smooth landscape. In fact, this is the very essence of procedural noise, which we are focusing on in this paper, and the first person to create such a fast algorithm for N-dimensional spline interpolation between pseudo-random points was Ken Perlin.

### A. Perlin/Simplex noise

Procedural algorithmic methods for creating realistic-looking fractal-like patterns have been around for more than 30 years. The most famous of these algorithms is Perlin noise, first developed by Ken Perlin in 1982 for use in the movie “Tron”.

Perlin noise is a type of pseudo-random gradient noise that mimics a Gaussian field, but at low computational cost. An improved version of Perlin noise is called simplex noise, which has several advantages over standard Perlin noise in terms of scalability and speed. Perlin noise was developed in response to the lack of detail 1980’s contemporary graphics, where polygonal surfaces often were bland and left without any detail. In response to this problem, Perlin noise was developed in order to continuously perturb the light bouncing off flat surfaces, effectively yielding bump mapping and producing a much

more realistic image.

An overview of the current state of procedural noise functions can be found in [2]. Perlin noise [3] is a band limited repeatable pseudo-random function from  $\mathbb{R}^n \rightarrow \mathbb{R}$  that is computationally fast, and has properties which make it suitable for creating patterns that mimic nature. Perlin noise is an approximation to Gaussian filtered noise implemented as a pseudo-random spline. The algorithm uses a predefined grid of gradients pointing in a random direction, where for any point within a grid, we interpolate the gradients from the four corners. The algorithm is as follows:

1. For a point, obtain the four closest gradients in the grid.
2. For each of the gradients, calculate the dot product between the gradient and a vector defined by the distance between the the point and the current grid corner.
3. Instead of linear interpolation  $F(t) = t$ , use a fade function to produce smoother interpolated values. Perlin noise typically uses the following fade function:  $F(t) = t^3(t(6 - 15) + 10)$ .
4. Obtain the final value by linearly interpolating between the x-axis and use this result to linearly interpolate the y-axis.

Simplex noise works in a similar manner, but requires fewer computational steps, scales better in higher ( $\geq 3$ ) dimensions and has fewer anisotropic properties.

### B. Properties of Perlin/Simplex noise

Standard Perlin noise is known for having several anisotropic features [2]. Perlin noise also gives rise to a “textile” pattern in the  $x$  and  $y$ -directions, which is evident from the upper left part of figure 2, depicting 2D Perlin noise in a single octave. The upper-right part shows the same node for simplex noise, with less obvious patterns. However, when combining several octaves and adding a random shift to the coordinates, as depicted in the two lower parts, these anisotropic patterns tend to cancel out. In addition, we have calculated the statistical distributions for Perlin and simplex noise with  $\sigma = 0.3$ , and have plotted the results in figure 3. Each procedural noise method has distributions that are close to normal, but with some asymmetrical properties.

### C. Multiple octaves: creating patterns

The different octaves from procedural noise functions can be combined to produce a wide range of nature-like patterns. A generic N-dimensional procedural function

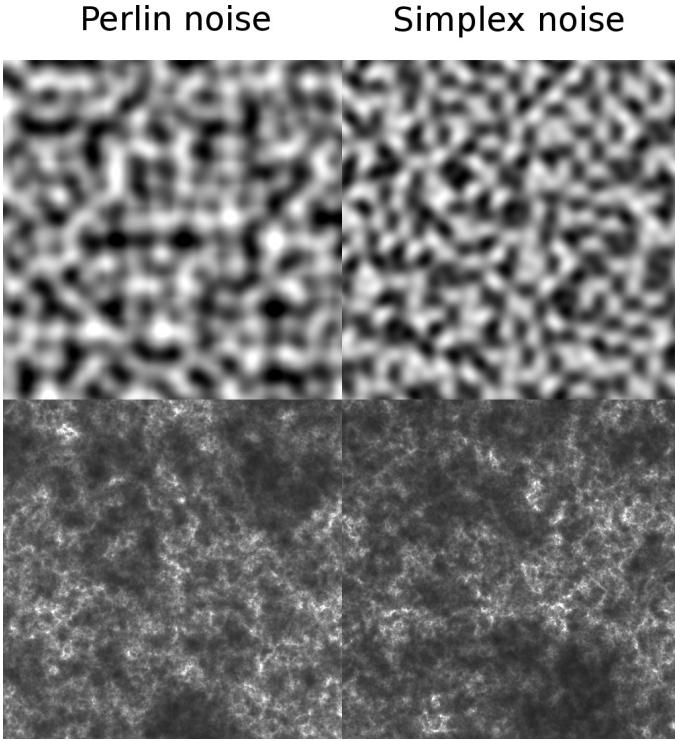


FIG. 2: Perlin noise (left) versus simplex noise (right). Note the straight x-y pattern in the single upper Perlin mode and the less anisotropic simplex mode. Lower part: combining octaves tend to remove these patterns.

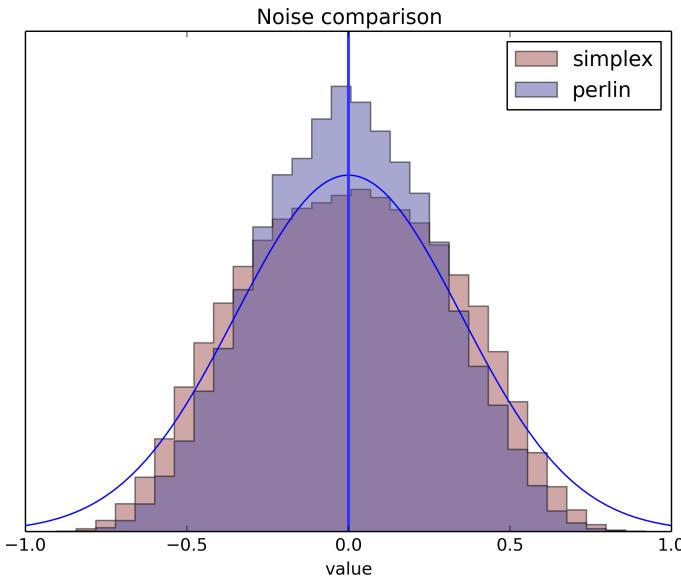


FIG. 3: Normalized distributions of Perlin noise and simplex noise compared with a Gaussian distribution. Note how both noise functions produce near-Gaussian, but slightly different distributions.

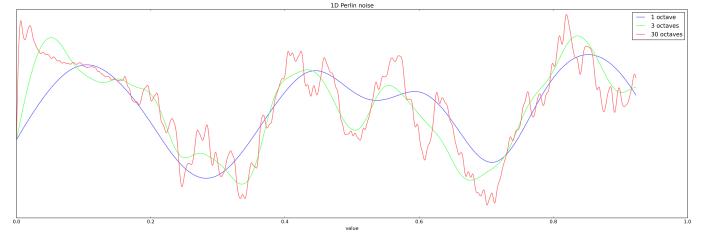


FIG. 4: 1D simplex noise with 1 (blue), 3 (green) and 30 (red) octaves.

$\Phi(\vec{x}) : \mathbb{R}^N \rightarrow \mathbb{R}$  could be expressed as

$$\Phi(\vec{x}) = \Theta \left( \sum_k^\omega \kappa(k) P(f_s(\vec{x}, k)) \right), \quad (1)$$

where  $f_s(\vec{x}, k)$  describes the frequency scale modifier (e.g.  $f_s(\vec{x}, k) = k\vec{x}$ ),  $\omega$  is the amount of octaves (modes),  $\kappa(k)$  is the octave amplitude (e.g.  $\kappa(k) = 1/k$ ) and  $\Theta(x)$  an overall modifier (e.g.  $\Theta(x) = x$  or  $\Theta(x) = \frac{1}{x}$ ). In a sense,  $\kappa(k)$  is similar to Fourier coefficients. In its simplest case, summing directly over the octaves with amplitude  $1/k$  results in

$$\Phi(\vec{x}) = \sum_k^\omega \frac{1}{k} P(2k\vec{x}). \quad (2)$$

In 1 dimension, equation 2 with 1, 3 and 30 octaves is depicted in figure 4, while the 2D procedural noise pattern depicted in the lower part of figure 2. Finally, since simplex noise both scales better with higher dimensions and produces less asymmetric effects, we choose to use this noise method over regular Perlin noise in our method.

### III. MODEL

In this paper, we are interested in developing a model using simplex noise to reproduce nanoporous structures that are as statistically close to actual simulations of porous media. For a given data set and a model, we wish to estimate the parameters that best represent the data. This is performed through a full likelihood analysis, where we in addition validate the model by comparing the radial distribution function  $g(r)$ , porosity and surface area of the system. The simulated system is confined to a cube of size  $159\text{\AA}^3$ , but since the procedural noise function is continuous on all scales, the box could be of arbitrary size.

We construct a generic sum over procedural noise octaves with the expression:

$$M_1(\bar{\theta}) = M_1(\vec{x}, \psi, \Omega, \nu) = \sum_{\omega=0}^{\Omega} \psi^{\omega-1} N((\vec{x} + \sigma \cdot \omega) \nu \cdot 2^{\omega-1}), \quad (3)$$

where  $\Omega$  is the total amount of octaves,  $\psi$  the persistence (scale falloff),  $N$  a generic  $N$ -dimensional noise function,

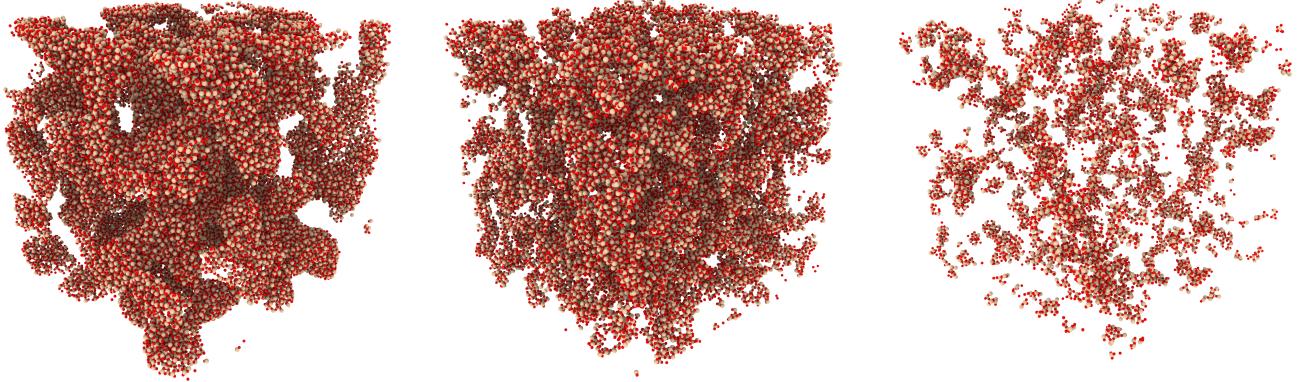


FIG. 5: Examples of 3D simplex noise structures in nanoporous media. Left image: low persistence (large scale dominates), middle image: medium persistence (small scales starts dominating) and right image: high threshold (more atoms are discarded).

$\sigma$  a predefined random vector that removes anisotropic artefacts and  $\nu$  the frequency modifier representing the initial largest scales in the model. For simplicity,  $\bar{\theta}$  here denotes the set of model parameters. For each mode, the frequency is thus multiplied, while the overall amplitude is damped by a given persistence. In the end, we simulate a large set of bulk particles without any walls, and use the noise function to remove particles that are not in a procedural void given by a threshold  $\tau$ . Three examples of this model are depicted in figure 5, where we have used  $\Omega = 6$  octaves and the scale is  $\nu = 0.01$  and cut-off  $\tau = 0$ . The left image depicts low persistence ( $\psi = 0.0$ ), where only the first octave dominates (corresponding to large scales). The middle picture shows the same parameters with a higher persistence ( $\psi = 0.5$ ), where smaller scales become more dominating. In the rightmost picture, the effect of the cut-off threshold  $\tau = -0.3$  is shown.

### A. Model Measure

In order to perform data analysis on the model parameters, we developed a code that uses Monte Carlo Markov chains in order to produce samples for building the likelihood. Before doing so, we need a model measure - a quantitative method that characterizes the internal structure of the porous media. This quantity should be computed for both the original data set and the one produced by our noise model.

Ideally, the model measure should pick up all geometrical properties that are relevant for the physical study of interest. For instance, pore size distribution and porosity are import for studying transport in porous media. Another such measure is the Distance-To-Atom (DTA). The method used for calculating porosity of a media is defined as in [4], and we obtain the surface area of a porous media by using marching cubes triangulation to sum the surface area of the triangles.

In this paper, we choose to use the radial distribution function  $g(r)$  as defined and implemented in LAMMPS [1]. The  $g(r)$  (or pair correlation function) describes how

density varies as a function of distance from a reference particle. Hereafter,  $g_d(r)$  denotes the RDF calculated from simulated or experimental data, while  $g_{M(\bar{\theta})}(r)$  represents the RDF based on the procedural noise model  $M(\bar{\theta})$ , where  $\bar{\theta}$  are the set of model parameters.

**TODO:** skriv litt mer om hvorfor vi velger  $g(r)$

### B. Data analysis and the Likelihood

The posterior probability is defined as the probability of the parameters  $\bar{\theta}$  given the evidence  $d$ , or  $P(\bar{\theta}|d)$ . Bayes' theorem states that

$$P(\bar{\theta}|d) = \frac{P(d|\bar{\theta})P(\bar{\theta})}{P(d)} \propto P(d|\bar{\theta})P(\bar{\theta}), \quad (4)$$

where  $P(d|\bar{\theta})$  is called the Likelihood  $\mathcal{L}$  (the probability of evidence given parameters) and  $P(\bar{\theta})$  is the prior (the beliefs about the quantity before some evidence is taken into account).  $P(d)$  is called the evidence, and is the probability of the observations (here assumed to be 1). Since the prior is a constant, we can therefore assume that the posterior distribution is proportional to the likelihood, or  $P(d|\bar{\theta}) \propto \mathcal{L}$ . In other words, to calculate the posterior and obtaining the best fit model parameters, we need only to estimate the likelihood function, which is connected to the  $\chi^2$  by

$$\mathcal{L} \propto e^{-\chi^2}. \quad (5)$$

In order to test whether two 3D data sets are statistically equivalent up to the model measure  $g(r)$ , we calculate the  $\chi^2$  between the two one-dimensional RDFs. Pearson's  $\chi^2$  is defined as

$$\chi^2 = \sum_r \frac{(g_d(r) - g_{M(\bar{\theta})}(r))^2}{g_{M(\bar{\theta})}(r)^2}, \quad (6)$$

so for low values of  $\chi^2$ , the better the fit between data and model (up to  $g(r)$ ). For a single-parameter model, we

could simply just iterate over the lone parameter to obtain the minimum  $\chi^2$  (where the best-fit parameter value is), however, with increased number of parameters comes increased computational cost. If we divide the parameter space into  $N$  bins, the number of  $\chi^2$  computations scales as  $N^d$ , where  $d$  is the number of model parameters. To be able to build the full  $\chi^2$  (and likelihood) parameter landscape, we there need to use Monte Carlo Markov chain methods (MCMC).

We are now interested in maximising the likelihood  $\mathcal{L}$  as opposed to minimising the  $\chi^2$ , with the goal of mapping out the full  $d$ -dimensional likelihood space for the model parameters. We build the  $d$ -dimensional likelihood by letting random walkers traverse the parameter space guided by the MCMC test: for each step  $M_n(\bar{\theta})$  in parameter space, we calculate the likelihood for this parameter configuration. Then, we create a new set of parameters for the next step  $M_{n+1}(\bar{\theta})$  by choosing new parameters randomly from a  $d$ -dimensional sphere around the previous parameter composition. The model also selects a new random seed. We calculate the likelihood at the new step and perform the MCMC test: accept the new step if  $\frac{\mathcal{L}_n}{\mathcal{L}_{n+1}} \geq 1$ , or reject if the value is lower than a uniform random value  $\in [0, 1]$ .

Finally, we obtain the posterior  $P(\bar{\theta}|d) \propto \mathcal{L}$  by building a  $d$ -dimensional histogram of the likelihood using the stored positions of the parameters. For a sufficiently large amount of steps, the MCMC algorithm ensures that the posterior converges to the likelihood, as long as the surface does not contain unreachable areas such as discontinuous patches or an infinite amount of maxima (as is the case for the function  $f(x) = \sin(\frac{1}{x})$ ). Luckily, as we shall see, the likelihood surface for our models tend to turn out with a single, well-defined maximum.

#### IV. RESULTS

We now turn our attention to applying the MCMC framework on two kinds of data. First, we wish to test and verify the code by performing a full data analysis on mock data with known input parameters. This enables us to investigate the posterior distribution, and determine whether any potential problems could arise with the likelihood landscape, such as random walkers trapped in local minima. We then continue with a full analysis of simulated SiO<sub>2</sub> data, and see whether the resulting best-fit parameter data set is consistent with the SiO<sub>2</sub> data set.

##### A. Model verification: Parameter estimation of mock data

In order to verify our likelihood code, we perform a model verification test on a mock data set with known input values. In this example, we only use standard simplex noise with three free parameters: the persistence  $\psi$ ,

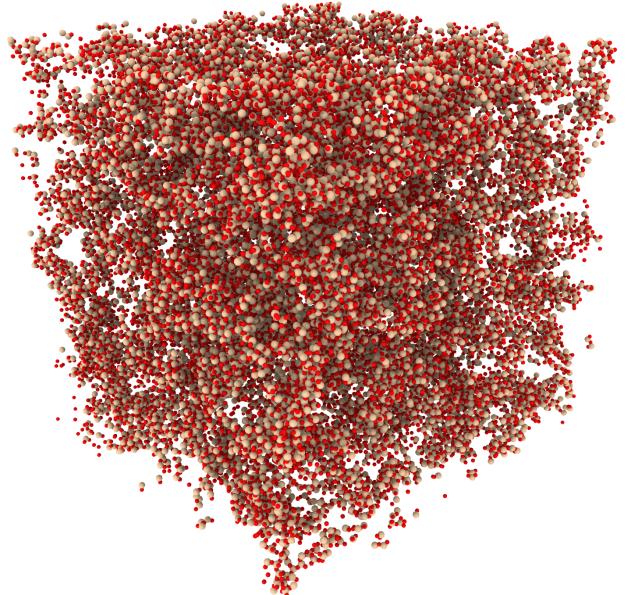


FIG. 6: Simulated mock data used for the initial model testing analysis. Input parameters are  $\nu = 0.03$ ,  $\tau = -0.02$  and  $\psi = 0.6$ .

threshold  $\tau$  and scale  $\nu$ . We simulate a data set of  $159^3$  of  $\sim 255000$  atoms, and perform the cut-off given input parameters  $\Omega = 3$ ,  $\Psi = 0.6$ ,  $\tau = -0.2$ ,  $\nu = 0.03$ . The resulting 3D structure is depicted in figure 6.

We continue by performing a full MCMC analysis of the mock data with using a parallelized code running on a 48 core cluster. In order to produce 300 000 samples, about 48 hours was needed. The results from this analysis can be seen in figure 7, where the upper panel depicts the marginalised 1D posteriors while the lower shows the marginalised 2D posteriors. The centre and left image shows that the input parameters of  $\tau = -0.2$  (threshold),  $\psi = 0.6$  (persistence) and  $\nu = 0.03$  are all reproduced well within  $1\sigma$ .

Note that there seems to be no problems with the posterior distribution in terms of local minima or multiple maxima.

##### B. Parameter estimation of simulated SiO<sub>2</sub> silica

We now perform a parameter fitting analysis on realistic simulated nanoporous media. Using LAMMPS [1], we simulate a  $100^3 \text{\AA}$  box of 100K SiO<sub>2</sub> silica particles at an initial temperature of 4500K, using the Vashishta-potential. After an initial period, we expand the box to  $159^3 \text{\AA}$  and start cooling until quenching is achieved at about 300K. The resulting nanoporous media is depicted on the right side in figure 10, with a porosity of 75%. **TODO: Skrive mer om lagingen?**

With the model described in equation 3, we perform a full likelihood analysis of the data set with the three free parameters  $\tau$ ,  $\nu$  and  $\psi$  using  $g(r)$  as the measure. The

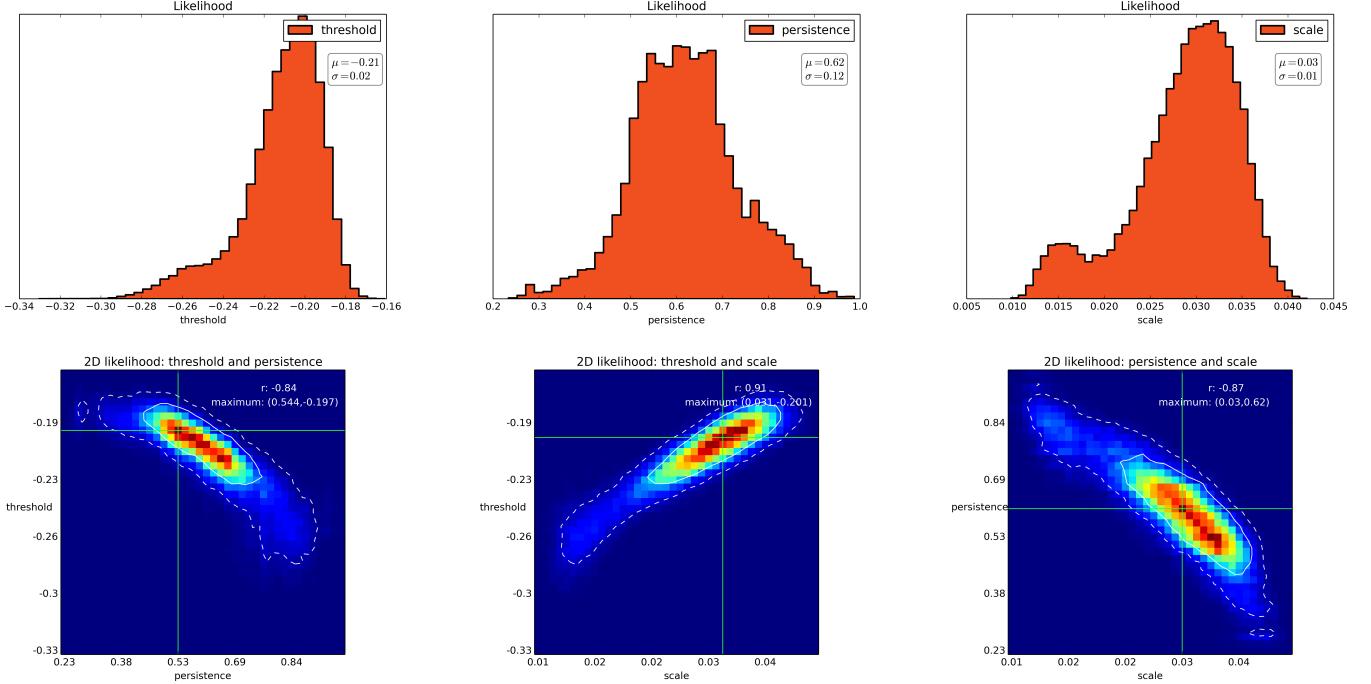


FIG. 7: Results from the model validation simulation. The upper panel displays the marginalised 1D posteriors for each parameter, while the lower panel depicts the marginalised 2D posteriors. Note that all input parameters were reproduced well within  $1\sigma$  (inner contour line).

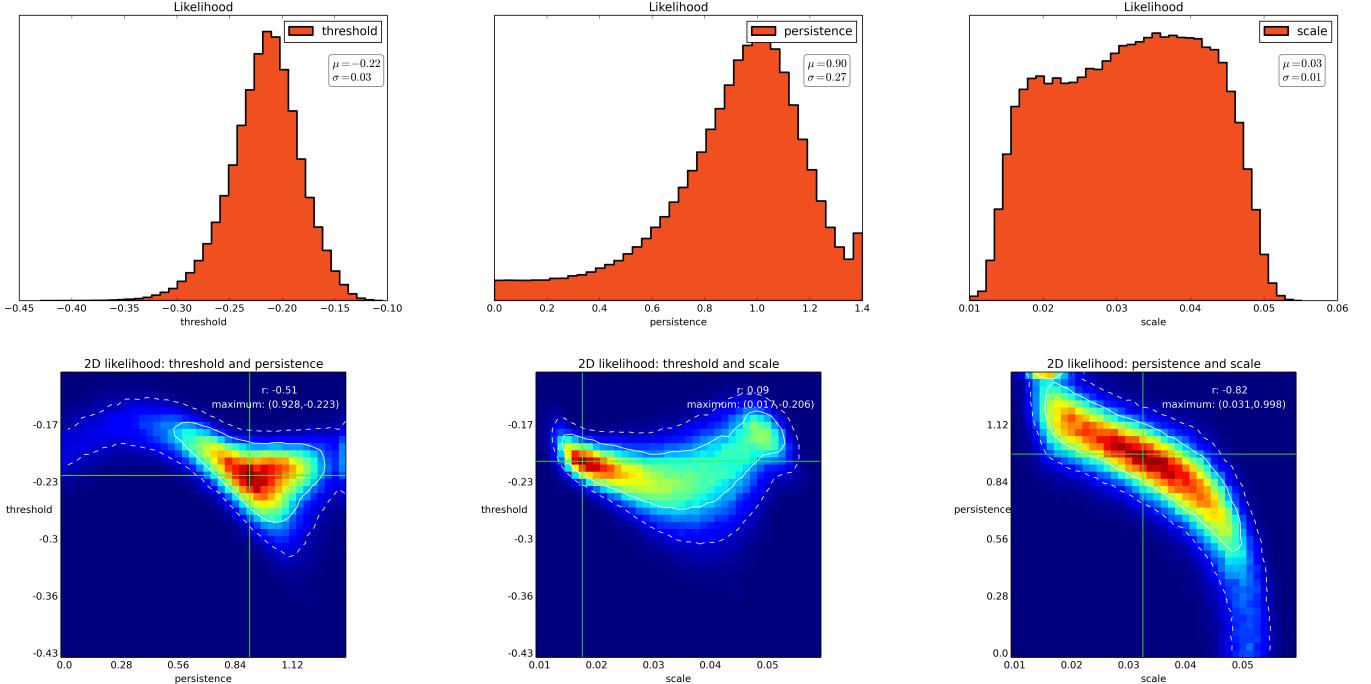


FIG. 8: Results from the analysis of a simulated  $159^3$  Å SiO<sub>2</sub> nanoporous data set. The upper panel displays the marginalised 1D posteriors for each parameter, while the lower panel depicts the marginalised 2D posteriors. Best fit parameters from the maximum 3D likelihood suggest  $\tau = -0.2$ ,  $\psi = 0.8$  and  $\nu = 0.3$ .

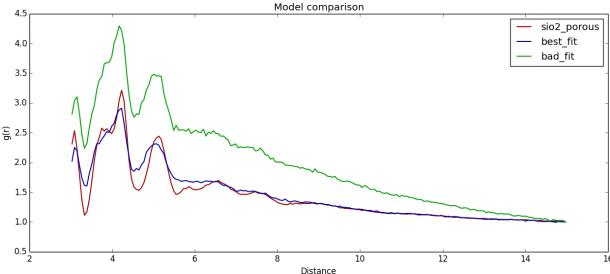


FIG. 9: The RDF  $g(r)$  for three data sets: the simulated SiO<sub>2</sub> input data set (red), the best-fit parameter model (blue) and a random low-fit parameter model (green).

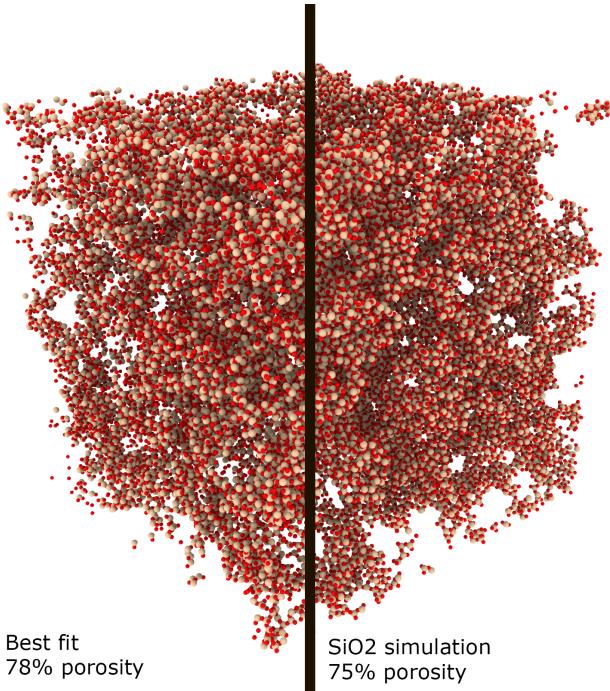


FIG. 10: Right side: A realisation of the best-fit parameters  $\tau = -0.2$ ,  $\psi = 0.8$  and  $\nu = 0.3$ . Left side: Simulated SiO<sub>2</sub> input data set used for parameter estimation.

resulting marginalised posteriors are depicted in figure 8, with best-fit parameters  $\tau = -0.2$ ,  $\psi = 0.8$  and  $\nu = 0.3$  is extracted from the full 3D likelihood. We also display the RFD  $g(r)$  for the input data set, a best-fit parameter data set and a bad-fit data set in figure 9, to illustrated the sensitivity of  $g(r)$  given the model parameters. Note that we are not able to accurately reproduce the structures of the SiO<sub>2</sub>  $g(r)$  with our current model, but hope that we during future work will be able to produce another model that provides a better fit with this measure.

Finally, we depict a comparison of the actual simulated input SiO<sub>2</sub> data set together with a representation of the best-fit parameters in figure 10

The porosity of the input SiO<sub>2</sub> data set is 75%, while the best-fit data set has porosity  $77\% \pm 3\%$ , depending on the random seed. In addition, the surface area of the

original data set was  $\sim 29000\text{\AA}^2$ , while the best-fit data shows similar values with surface are ranging between  $\sim 28000\text{\AA}^2$  and  $\sim 30000\text{\AA}^2$ . **TODO: legg ved 3D plot av likelihood for aa vise at den er kjekk og fin**

### C. Some notes on the results

It is worth to note that since we are chiefly interested in obtaining a set of parameters that reproduces a statistical correct representation of the input data, we are relatively free to choose parameters as desired. In the previous analysis, we selected a best fit threshold value of  $\tau = -0.2$ , but from the width of the likelihood it is clear that nearby parameters would also be suitable. However, the surface area is strongly correlated with this value, so even slight deviations (e.g.  $\Delta\tau = 0.05$ ) yields a relatively large change in surface area.

In addition, we do not claim that this model accurately reproduces the pore structure observed in nanoporous simulations, as is evident from the RDF shown in figure 9.

### D. $g(r)$ variation

We also calculated the variation in the RDF  $g(r)$  given initial conditions on both our model and simulated data. In terms of the data, the variation is attributed as the initial velocities of the particles in the LAMMPS simulation. For the model, it corresponds to the random seed. We found that varying these initial conditions have negligible effect on the calculation of  $g(r)$ .

## V. CONCLUSION

**TODO: konklusjon maa renskrives** In this paper, we have proposed a novel method for generating a simple kind of nanoporous media using procedural methods, namely simplex noise. We have developed tools for creating such porous materials, and also estimating model parameters given data. We have shown that it is possible through a full likelihood analysis to reproduce the input parameters of a simulated model. In addition, we performed an analysis on a simulated  $159^3\text{\AA}$  data set of SiO<sub>2</sub>, and explain that while porosity and surface area corresponds well between the model and data, the RDF  $g(r)$  shows that the current model does not exactly reproduce correct data. However, we do not claim that the current model should do so yet, since we have chosen the simplest kind of summation with regards to procedural noise modes.

### A. Future work

In this paper, we have only considered the simplest kind of procedural noise: a simple sum over modes with threshold cut-off  $\tau$ , scale fall-off persistence  $\psi$  and initial scale  $\nu$ . We have also seen that, even through both porosity and surface area accurately reproduced, there are features in the RDF that are not fully captured with the current model. This is evident from the images of the simulated structure seen in figure 10, where the connecting nearly one-atom thin walls are difficult to reproduce with the current model. However, as procedural noise exert properties closely related to that of fractals, it is possible to extend the number of parameters and define new models with very different properties. Some examples of these models are depicted in figure 11, where the left- and centre images show a new model with two new parameters (offset and gain), while the rightmost panel shows a simulation where the scale  $\nu$  is itself being perturbed by procedural noise, yielding strong circular asymmetric patterns.

Another immediate application would be to estimate model parameters given actual observations of porous media. This would enable us to estimate new parameters such as instrumental noise, deviations from symmetry (yielding asymmetric properties) and pureness of samples. In addition, by analysing just a few samples and producing an accurate statistical model, we are able to produce an arbitrary amount of statistically correct samples, free from instrumental noise and artefacts.

A final key analysis would be to compare properties such as permeability through finite-element simulations of gas/liquid flow through our simulated structures, in addition to exerting shear forces, and comparing with actual simulated data from e.g. LAMMPS. Since the noise function is a continuous boolean function that only checks whether a position is within a wall or void given a threshold, we are not limited to any size of the simulated system, and simulated particles traversing the media has arbitrary range.

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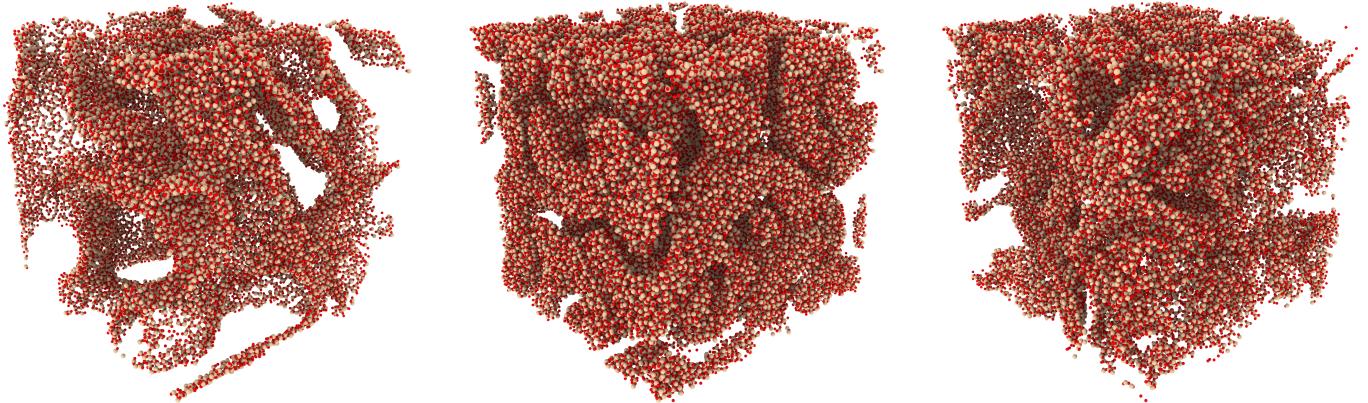


FIG. 11: Example of future models. Left panel: A multi-fractal model with thin surfaces and large pores. Centre panel: a multi fractal with cave-like structures. Right panel: A model with strong asymmetric noise.