The 8th Eurographics Workshop on Material Appearance Modeling: Issues and Acquisition

A Genetic Algorithm Based Heterogeneous Subsurface Scattering Representation

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In this paper, we present a novel heterogeneous subsurface scattering representation, which is based on a combination of Singular Value Decomposition and genetic optimization techniques.

Introduction

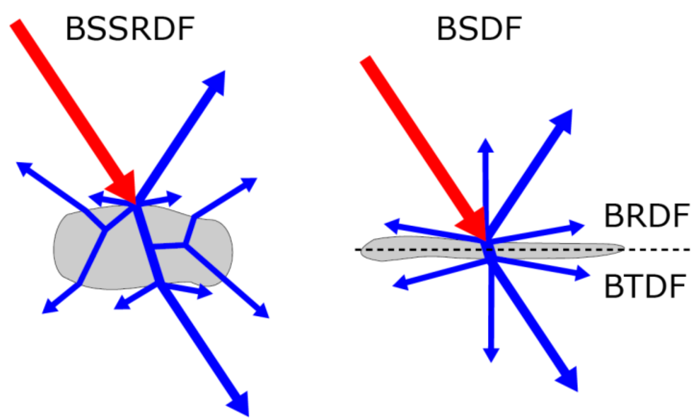
Jensen et al. [JMLH01]
Standard Dipole Model

d'Eon and Irving [dI11]
Quantized Diffusion Model

Frisvad et al. [FHK14]
Directional Dipole Model

Unbiased Path Tracing Reference (Marble Material)

Jimenez et al. [JZJ*15]
Separable Subsurface Scattering Model



Nicodemus et al. [NRH*77] and Frisvad et al. [FJM*20]

The most of the homogeneous subsurface scattering models used in the computer graphics community are derived based on this approximation [JMLH01,JB02,FHK14,JZJ*15].

Introduction

Peers et al. [PvBM*06]
A factored heteregeneous model

Song et al. [STPP09]
SubEdit: A heteregeneous model

Kurt et al. [KÖP13]
A Tucker-based heteregeneous model

Yatagawa et al. [YTYM20]
A compression based heteregeneous model

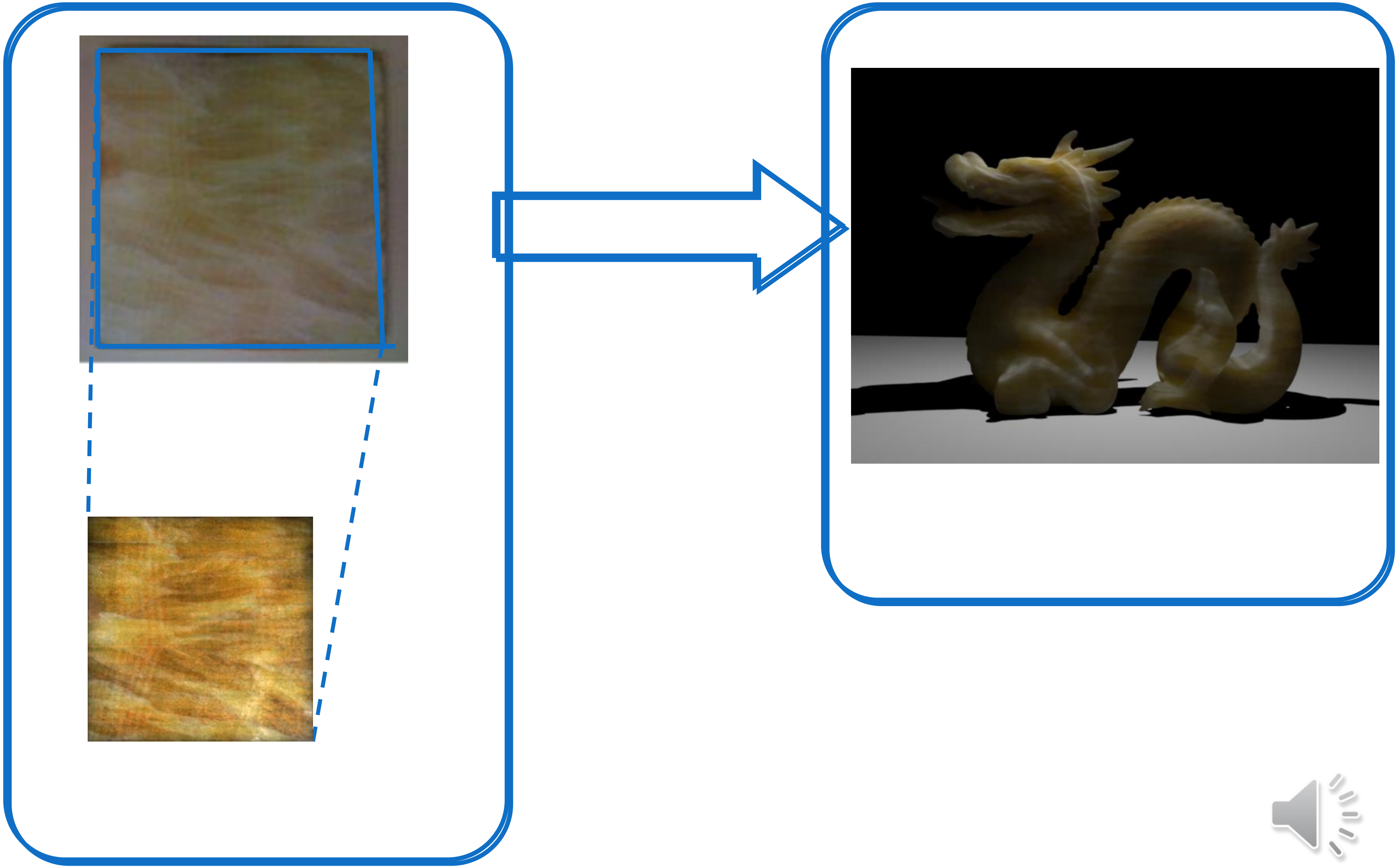
Therefore, a number of data-driven subsurface scattering representations [PvBM*06,

But, it's still an investigation issue to represent measured heterogeneous subsurface scattering data compactly and physically accurately.

Goal

Therefore, we focus in this work on the compact and accurate representation of this spatial component of heterogeneous subsurface scattering.

Goal



Goal

Impractical

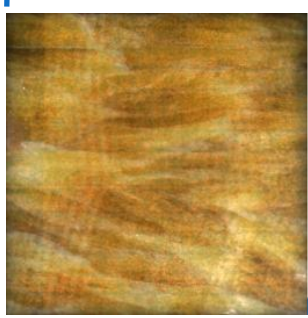
Resolution:

$260^2 \times 260^2$

~40GB

We will use a combination of Genetic Algorithm (GA) [Mit96] and Singular Value Decomposition (SVD) [PSR13] techniques for this.

Goal



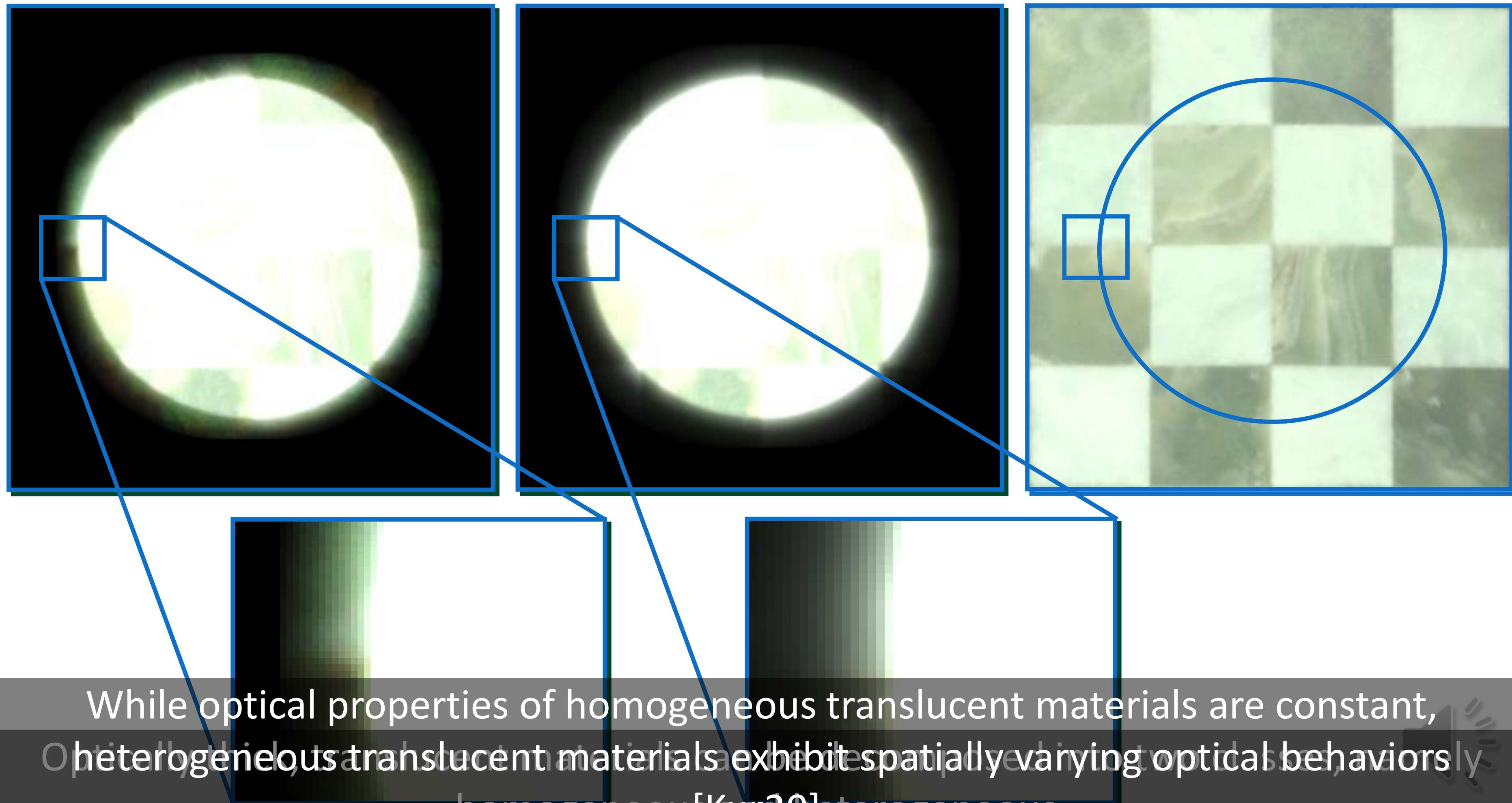
Impractical

Compact and Accurate Representation

(Factorization and Genetic Optimization)

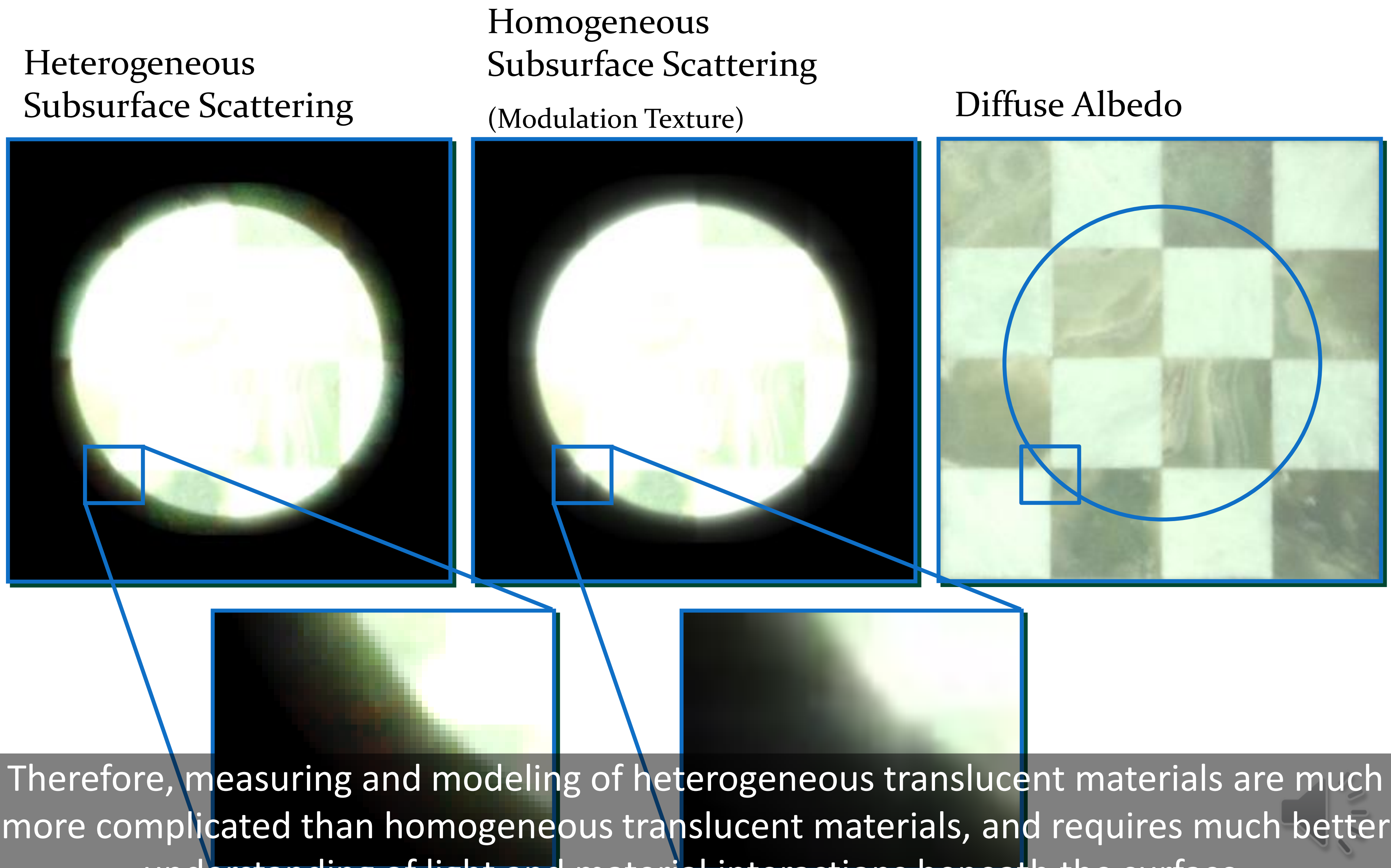
In order to create a good representation, we need to study the structure of the heterogeneous subsurface scattering.

Heterogeneities: Effect



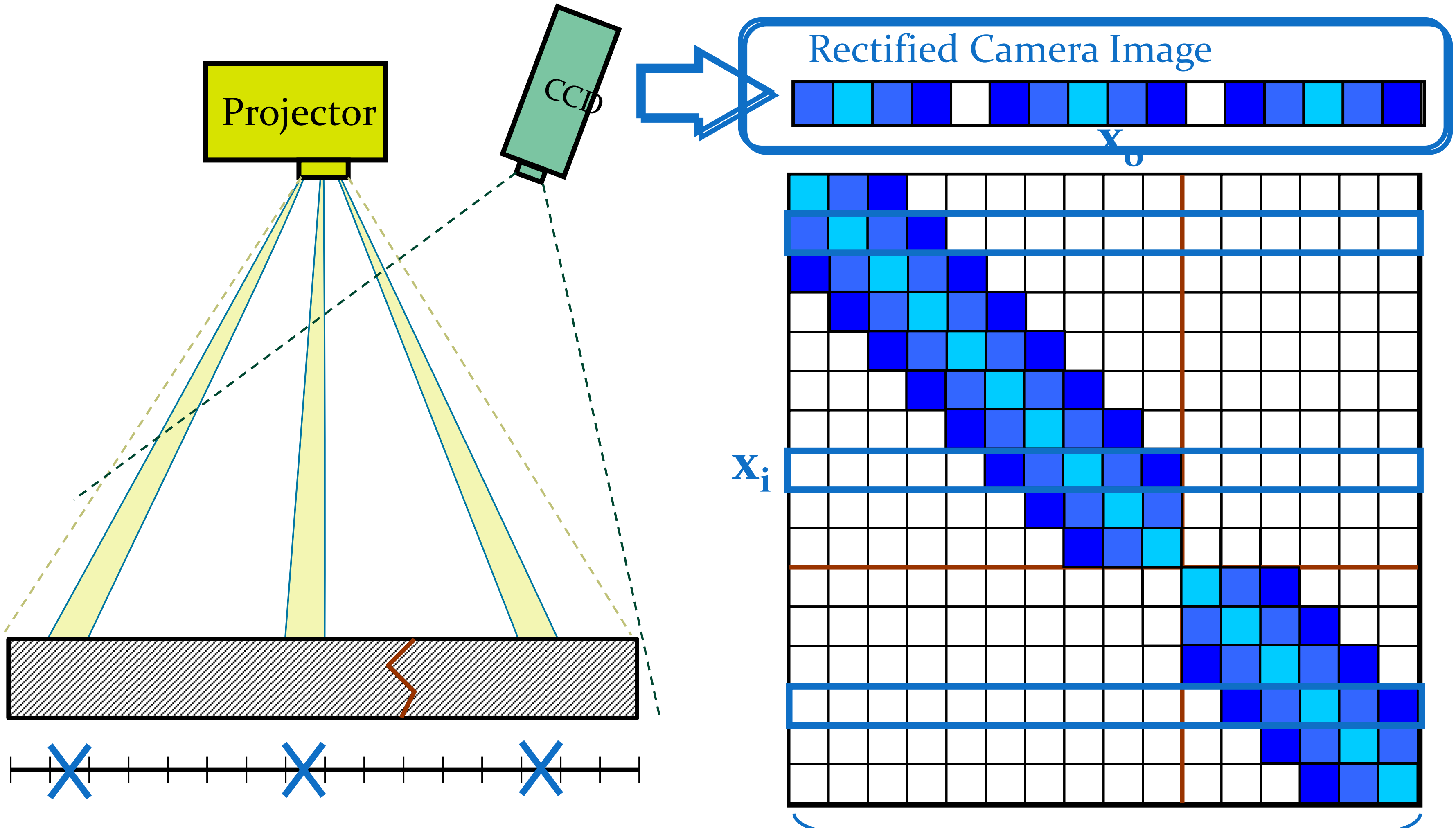
While optical properties of homogeneous translucent materials are constant, heterogeneous translucent materials exhibit spatially varying optical behaviors [Kur20].

Heterogeneities: Effect



Therefore, measuring and modeling of heterogeneous translucent materials are much more complicated than homogeneous translucent materials, and requires much better understanding of light and material interactions beneath the surface.

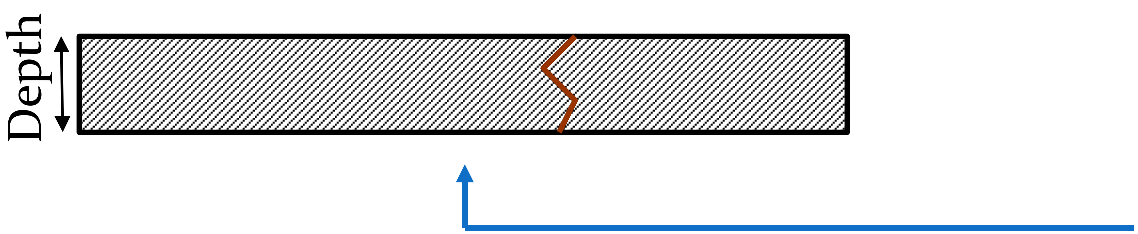
Acquisition: Multiple Beams (1)



In this work, we used Peers et al.'s [2006] Song et al.'s [2009] heteregeneous

After these operations, we get 2D subsurface scattering matrix and this matrix can be used in the rendering algorithms.

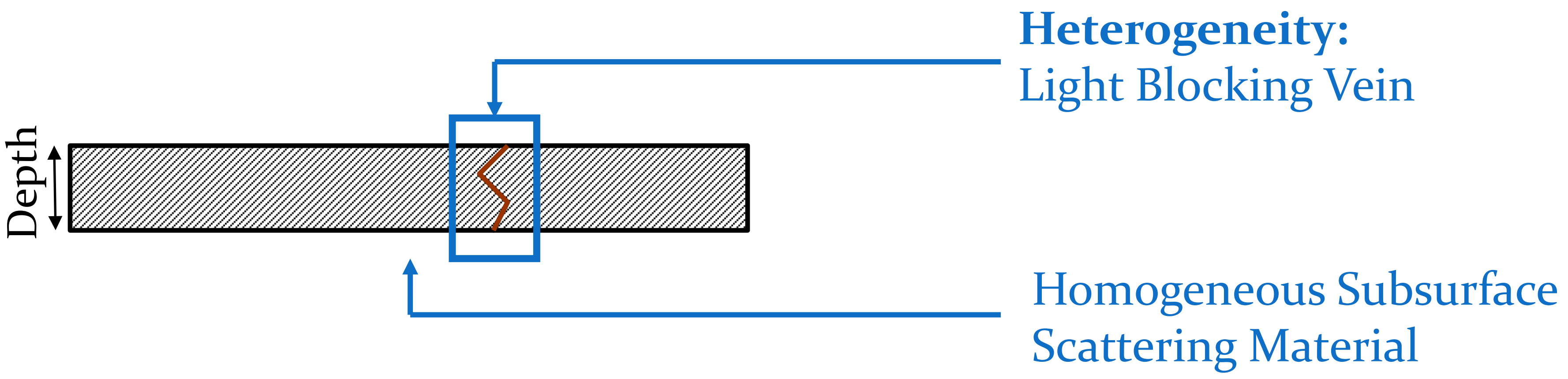
Illustrative Example (1D)



Homogeneous Subsurface Scattering Material

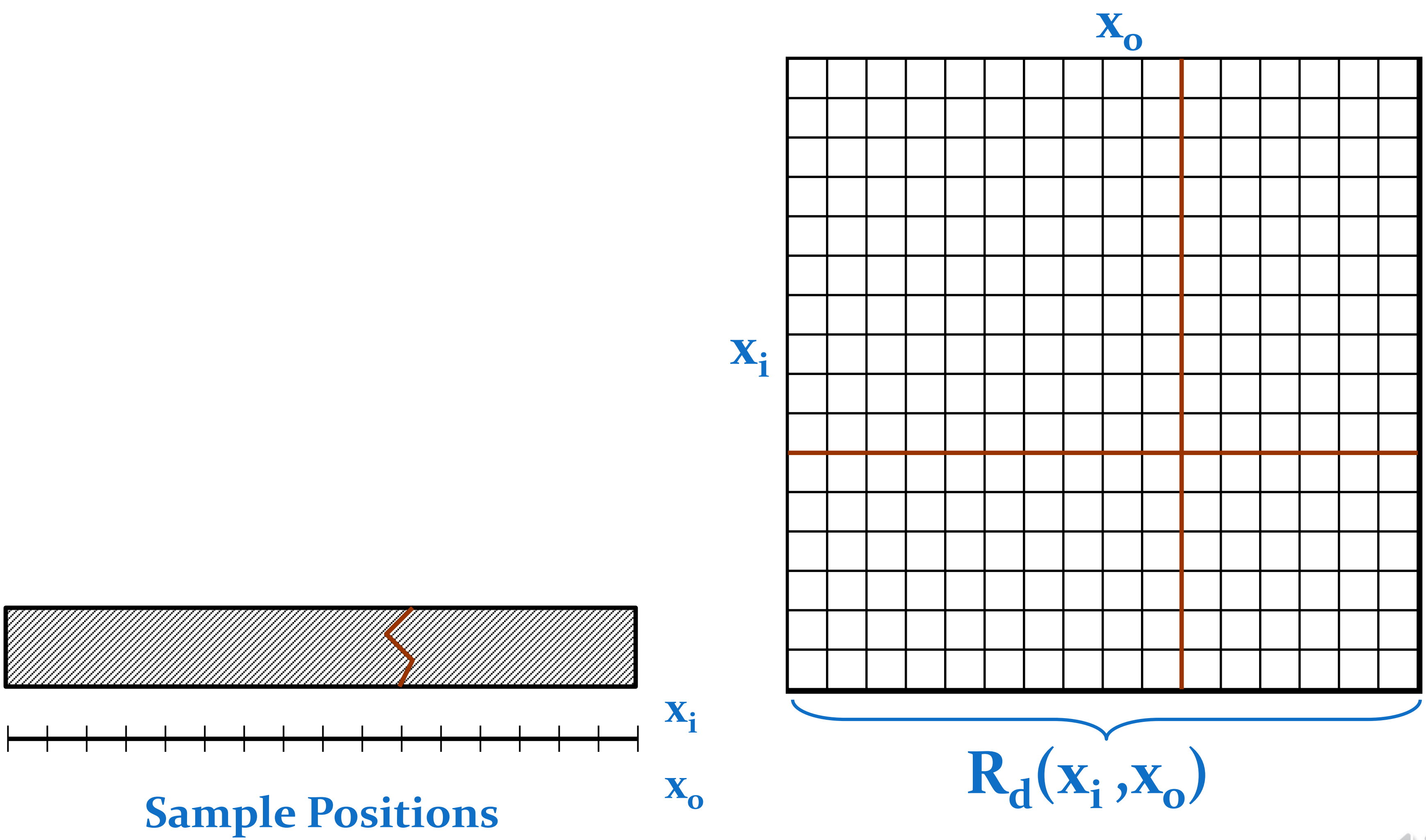
To show how we prepare our subsurface scattering matrix, let's consider the following 1D illustrative example: a planar sample, consisting of a single material exhibiting homogeneous subsurface scattering.

Illustrative Example (1D)



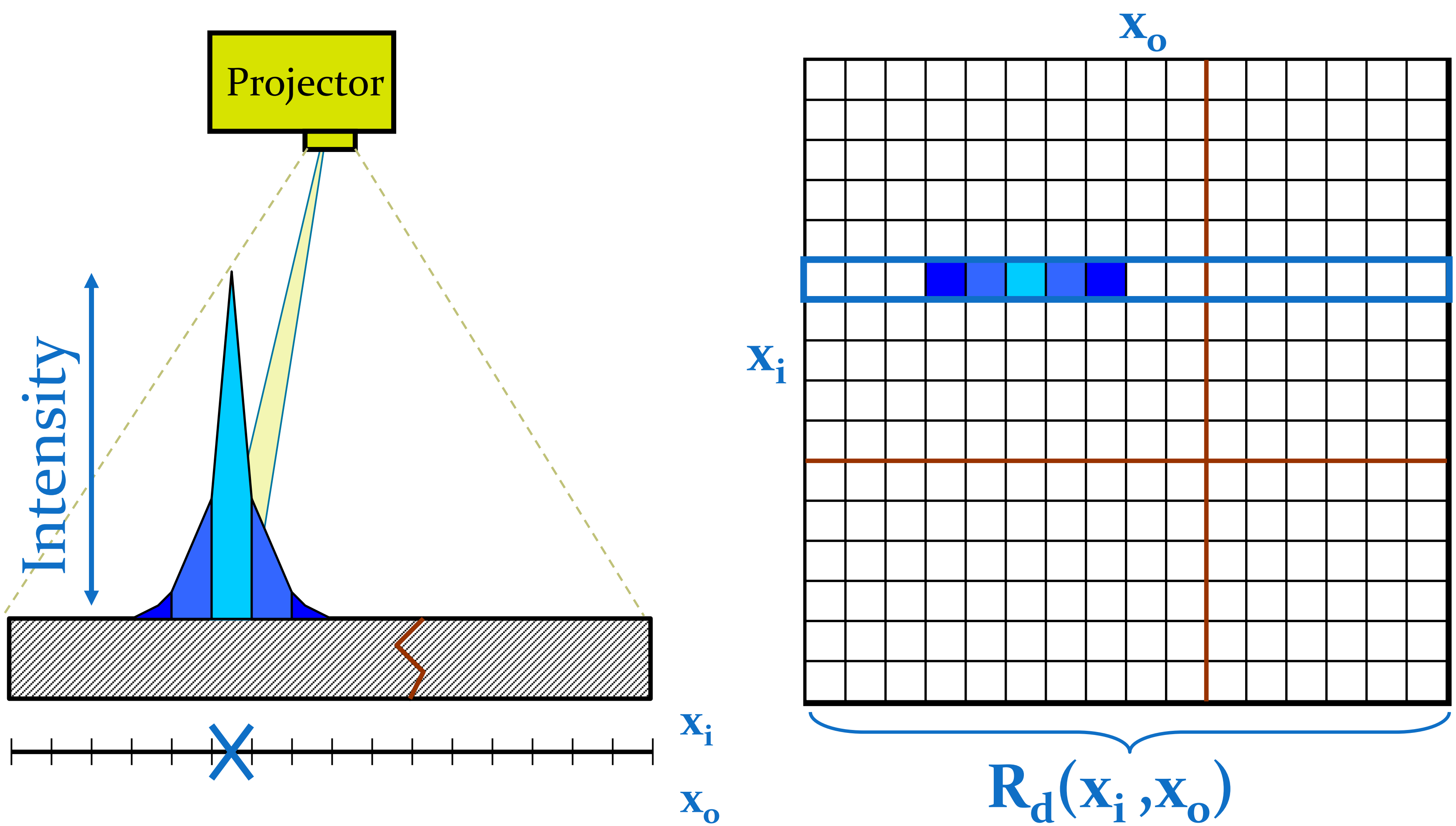
This sample contains a single heterogeneity: a light blocking vein, that blocks a light going from the left side of the sample to the right side, and vice versa.

Subsurface Scattering Matrix



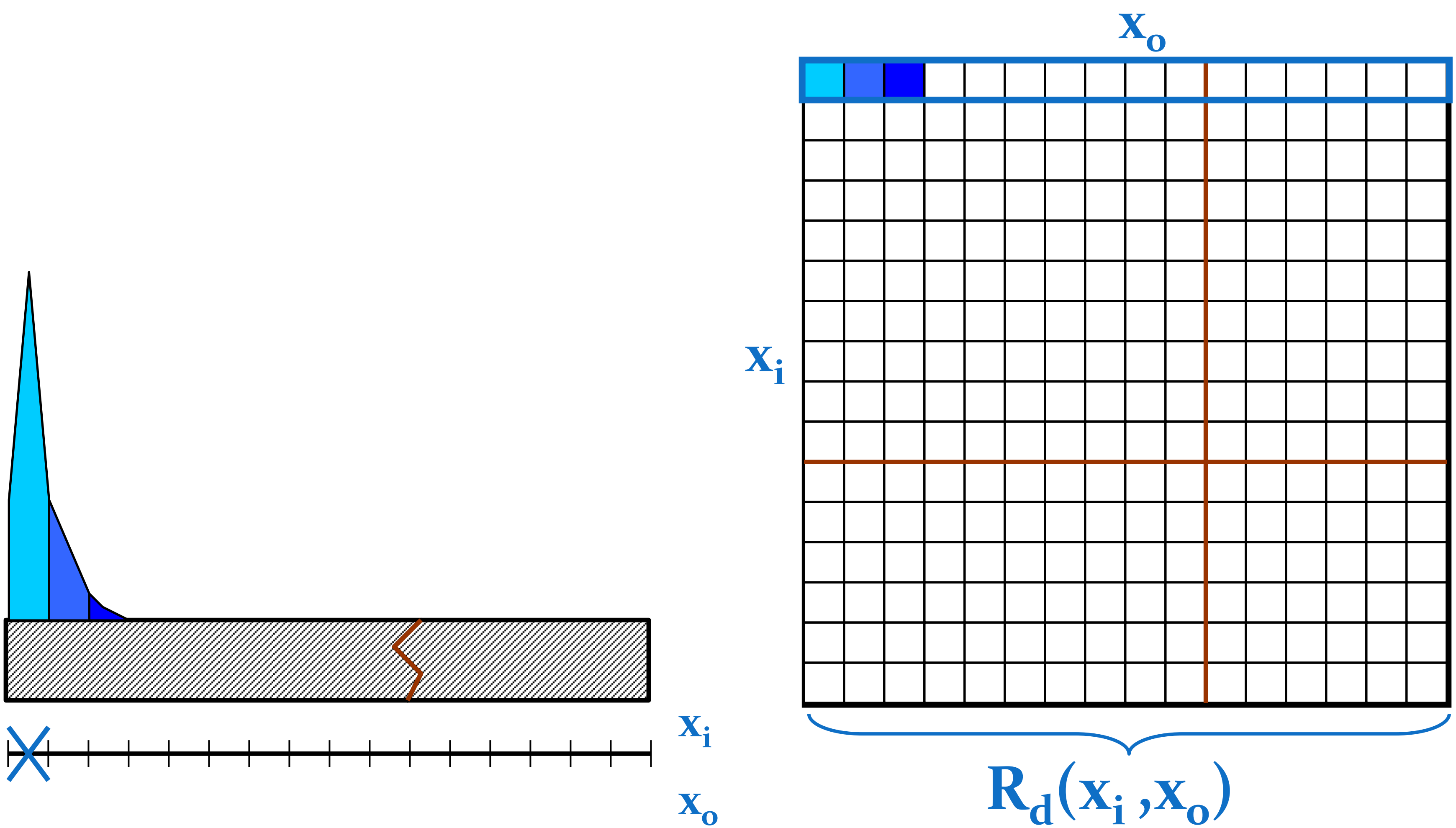
For simplicity we assume that x_i and x_o are parameterized identically over the sample surface and that both have the same resolution.

Subsurface Scattering Matrix



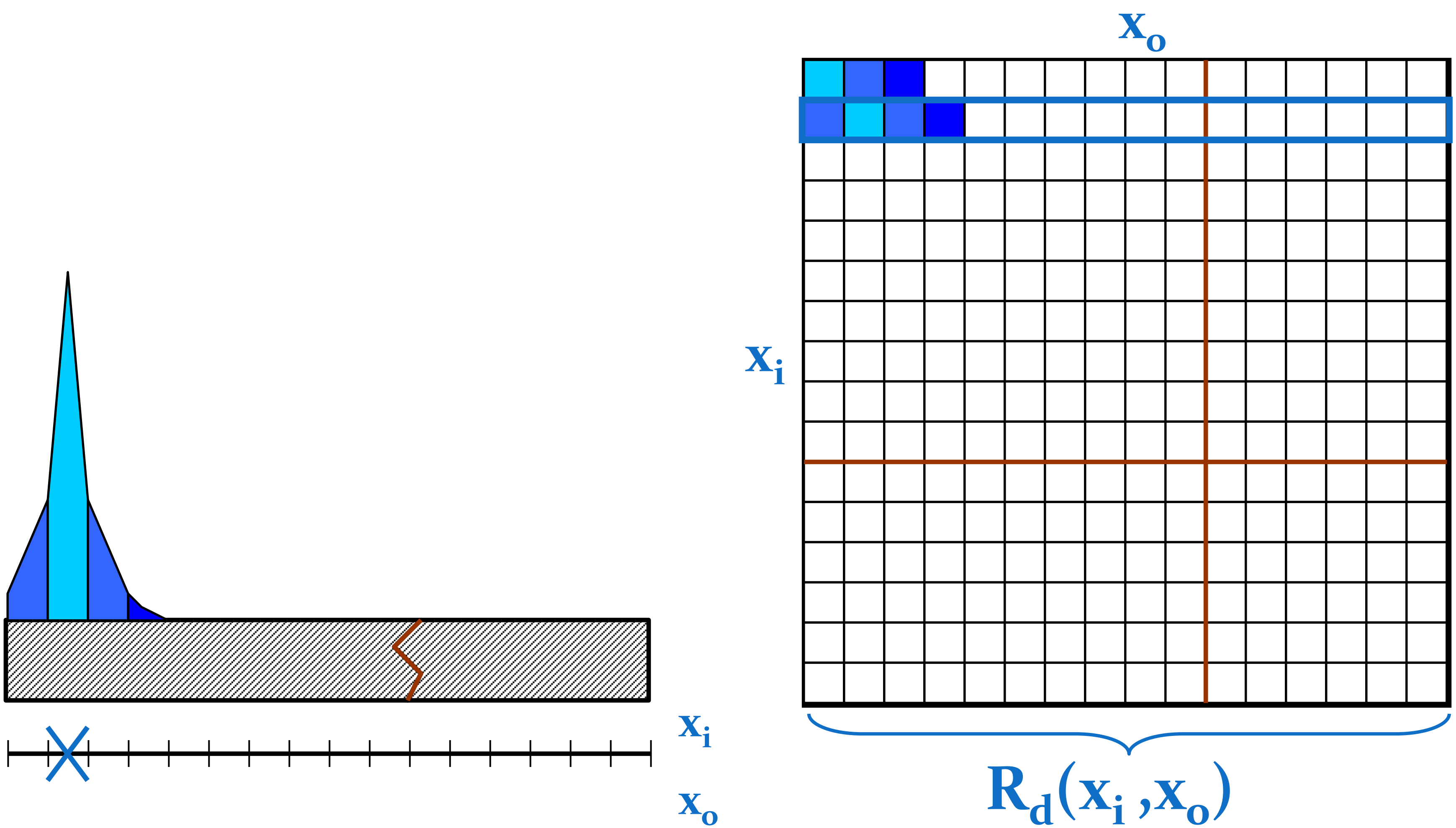
In our case, a projector was used to illuminate surface points, and the observed camera image is copied into the corresponding row of R_d.

Subsurface Scattering Matrix

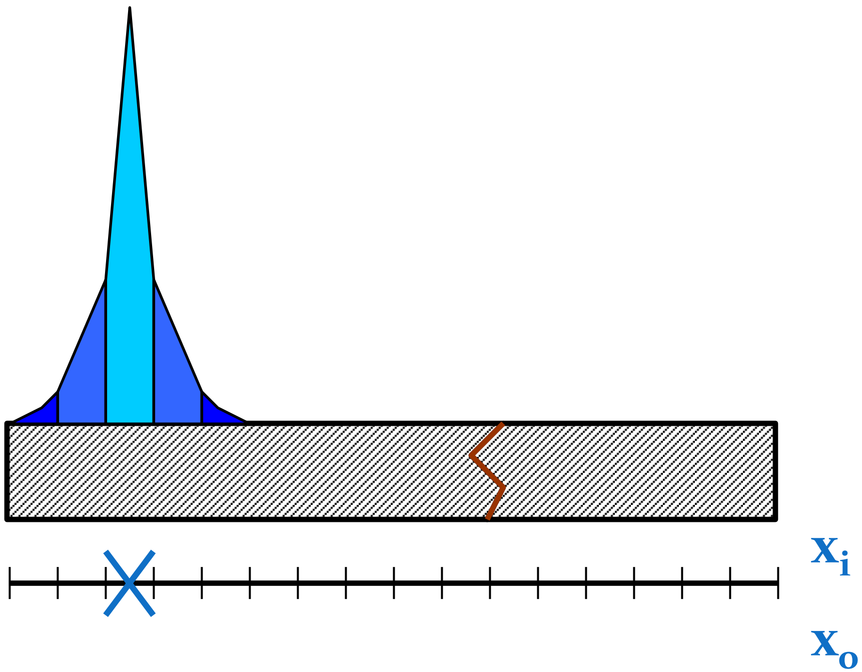


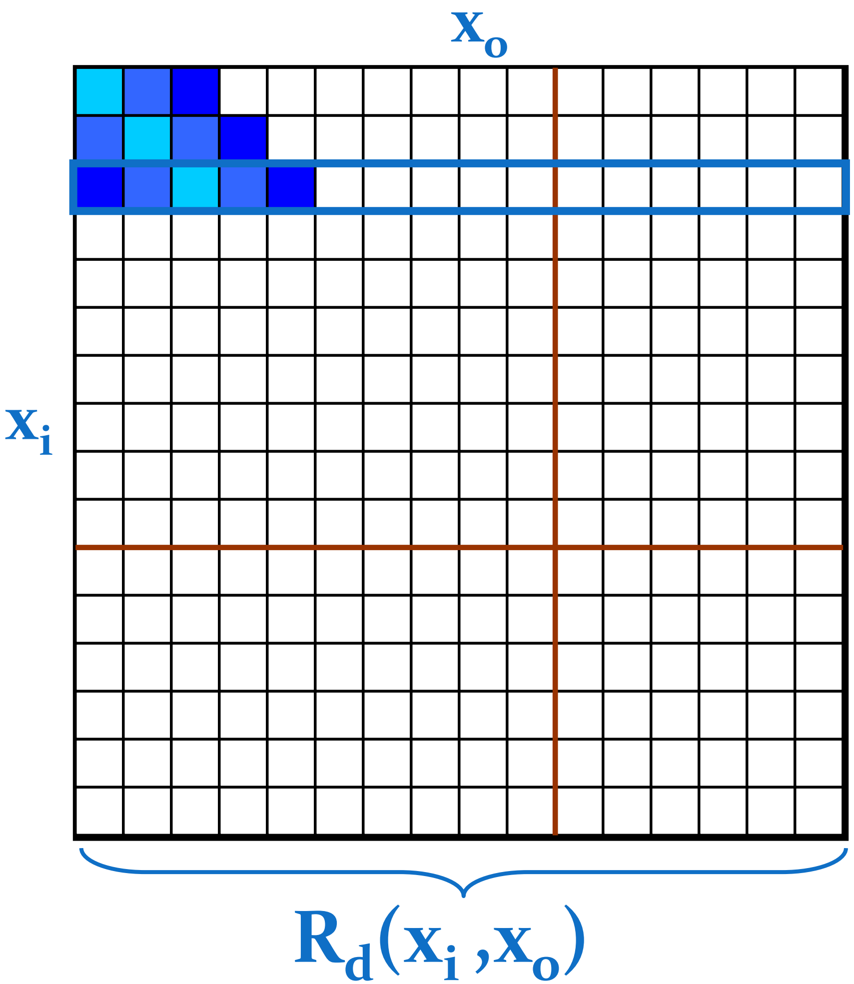
We can repeat this for every incident position and row.

Subsurface Scattering Matrix

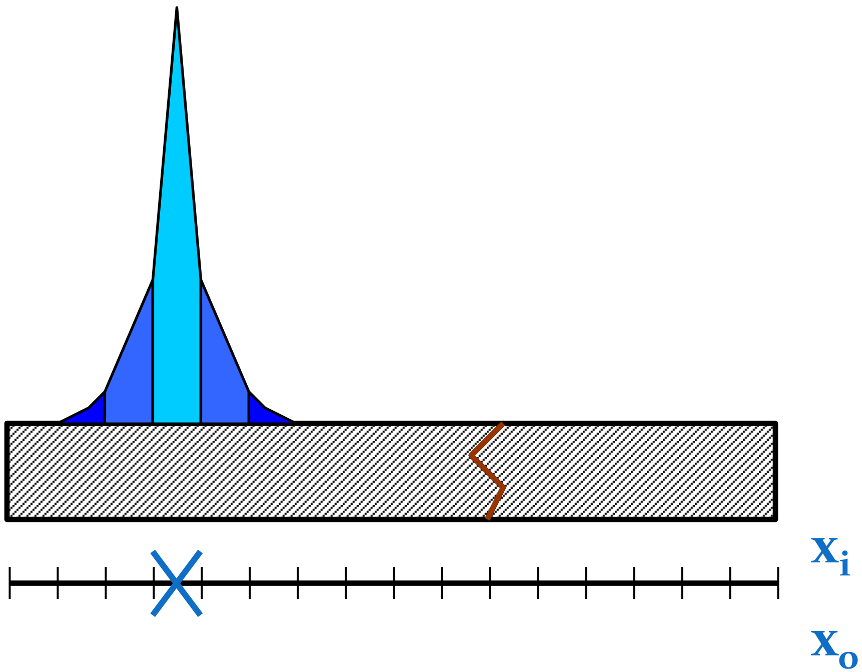


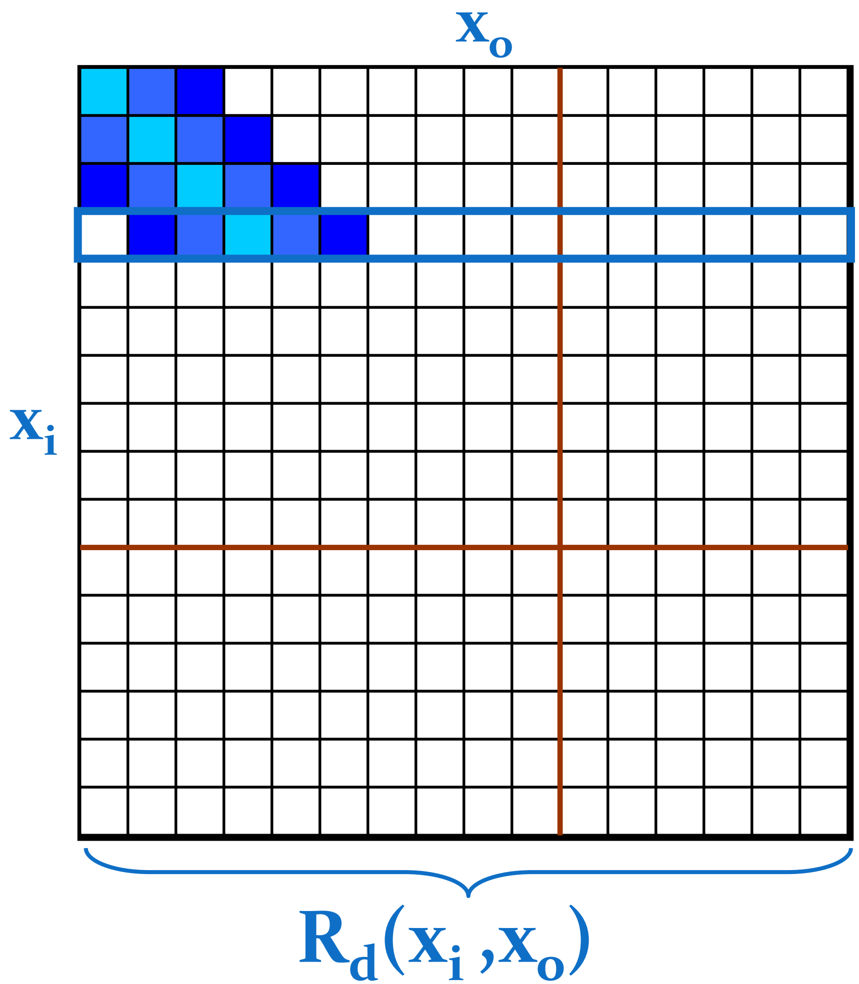
Subsurface Scattering Matrix



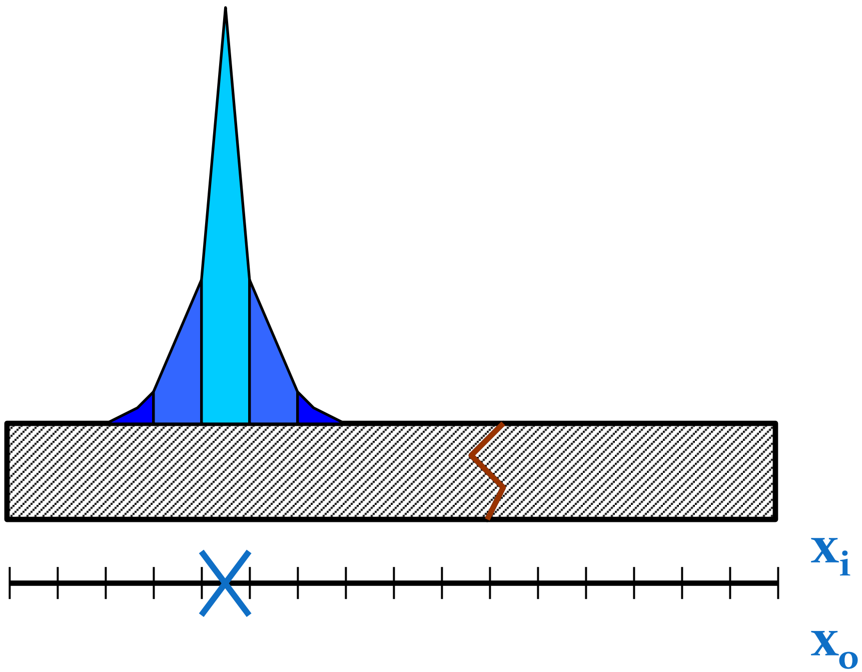


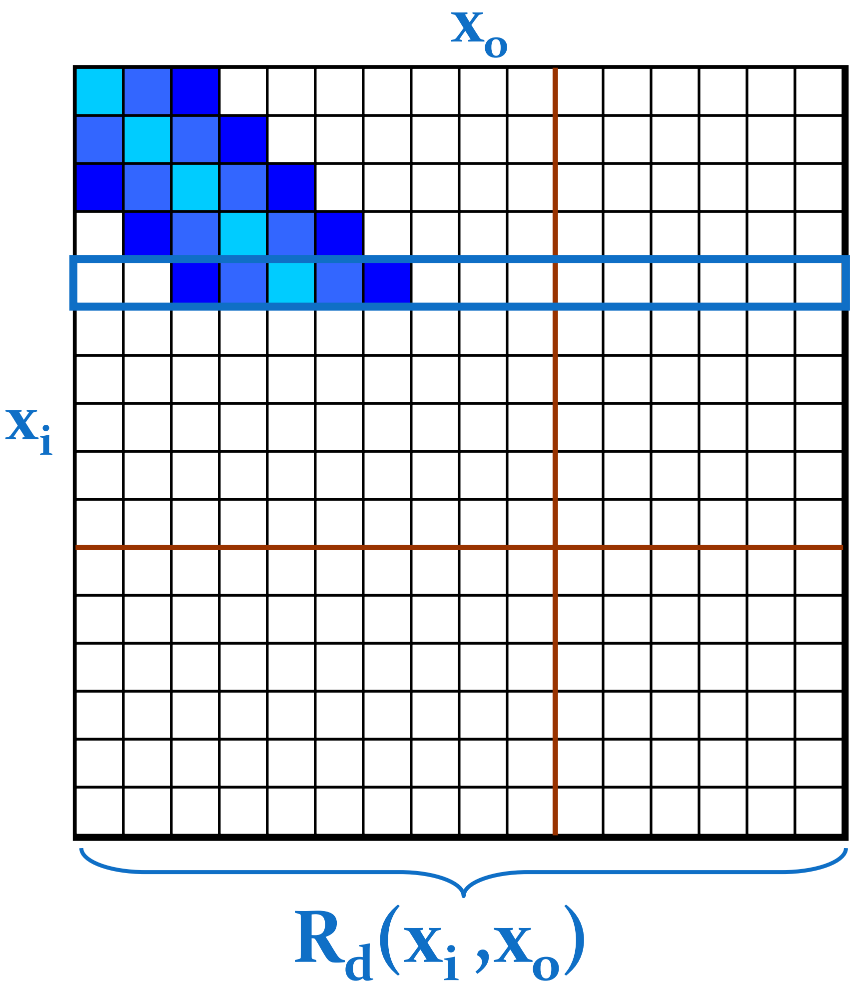
Subsurface Scattering Matrix



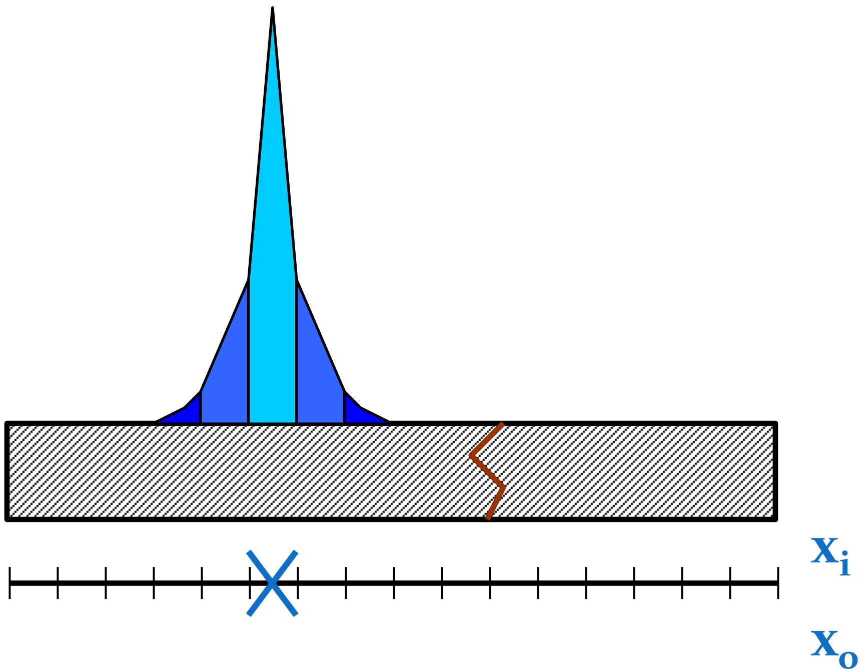


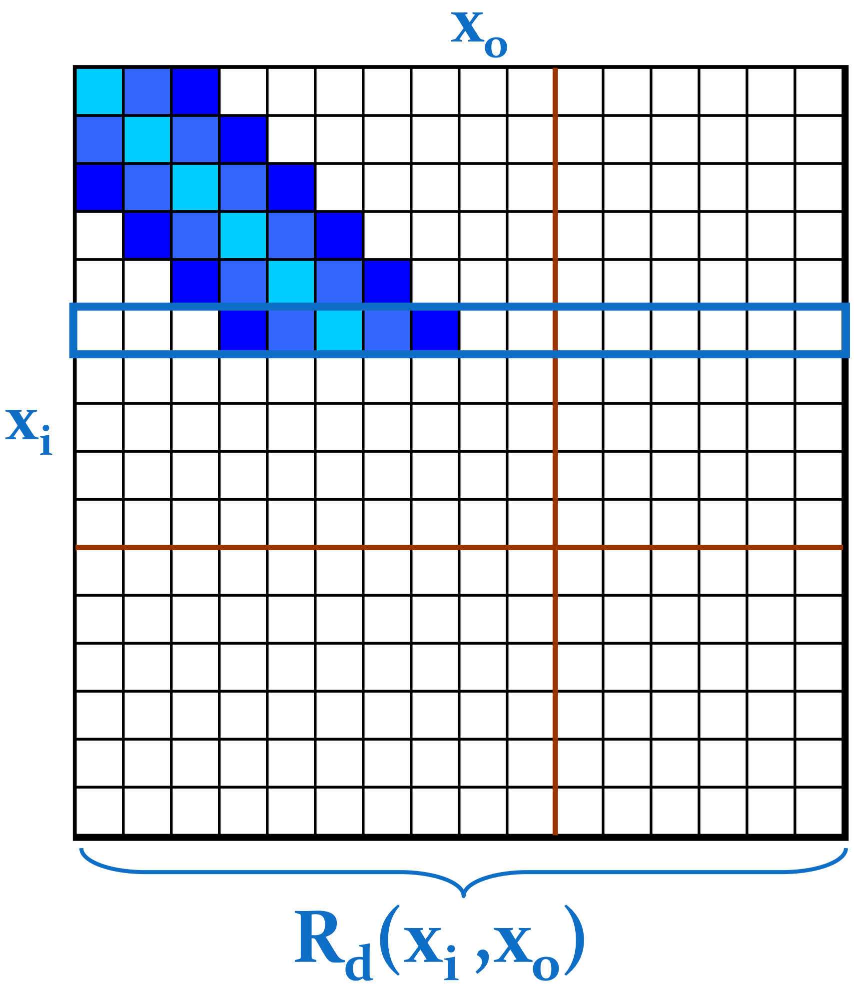
Subsurface Scattering Matrix



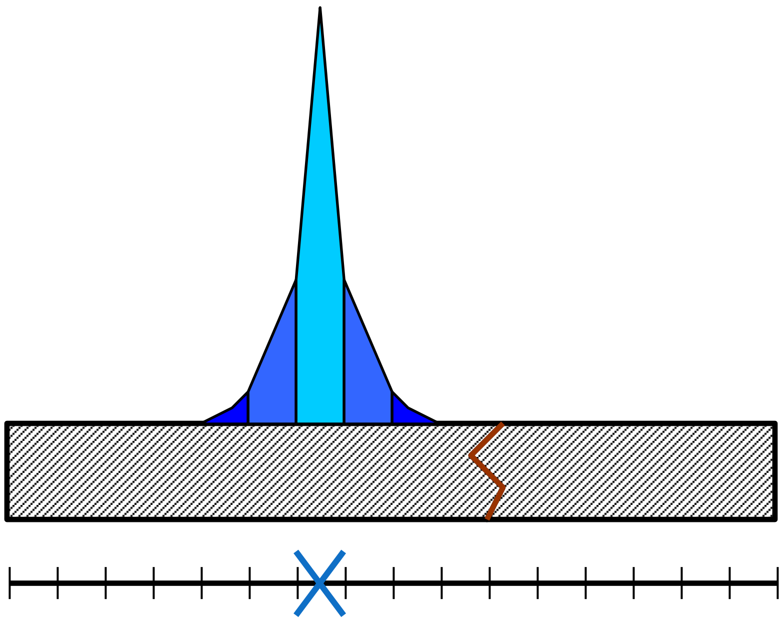


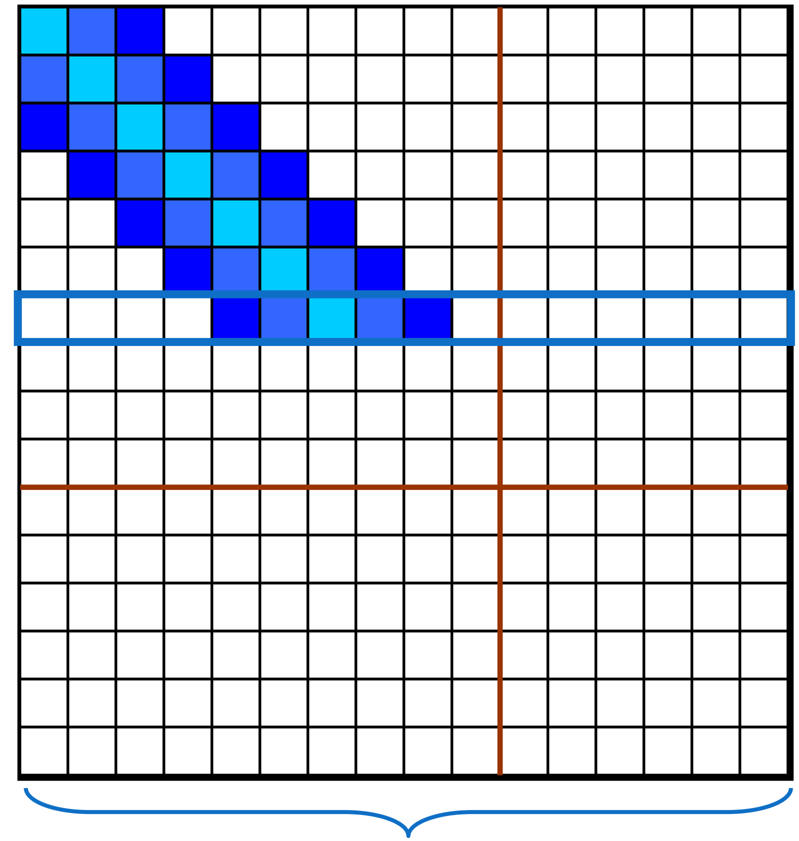
Subsurface Scattering Matrix



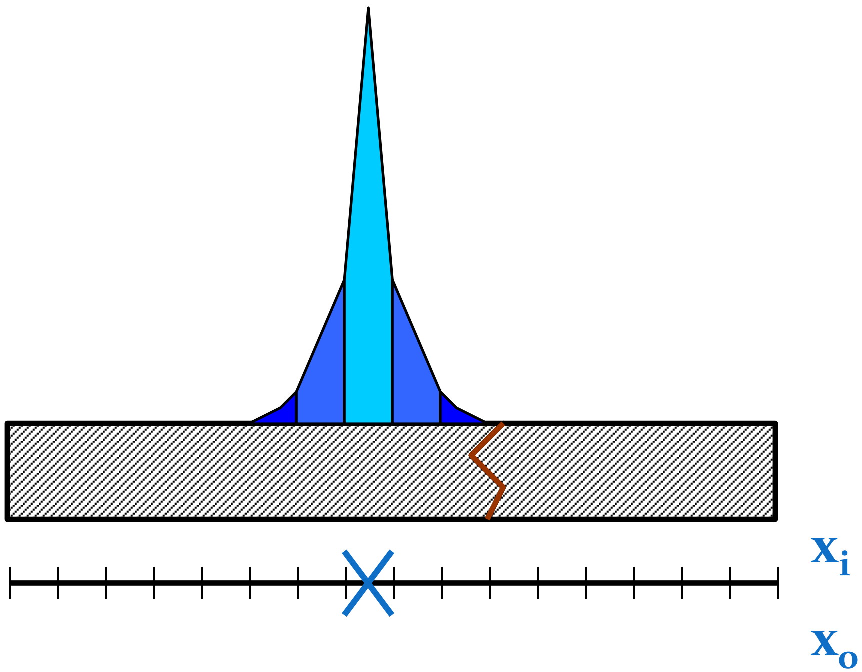


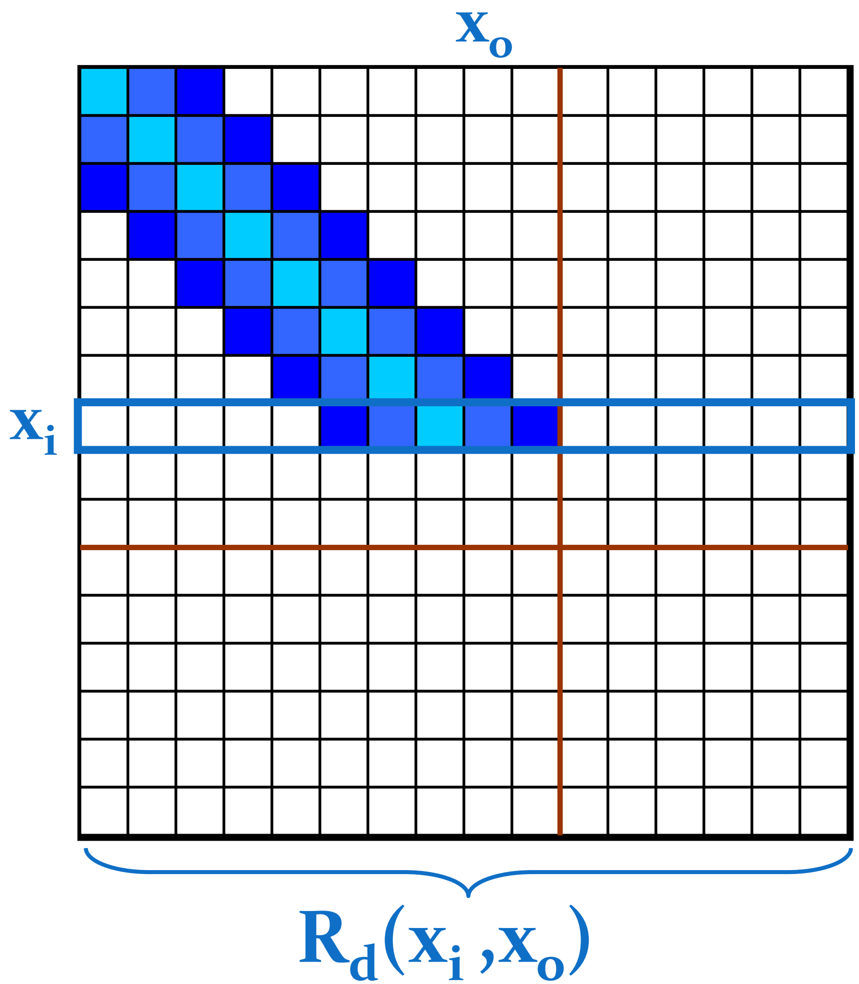
Subsurface Scattering Matrix



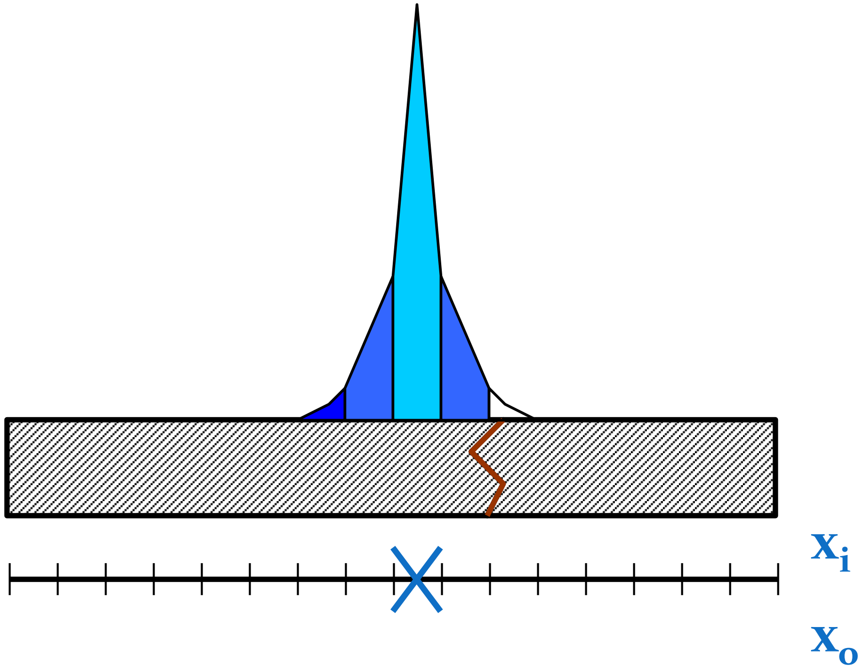


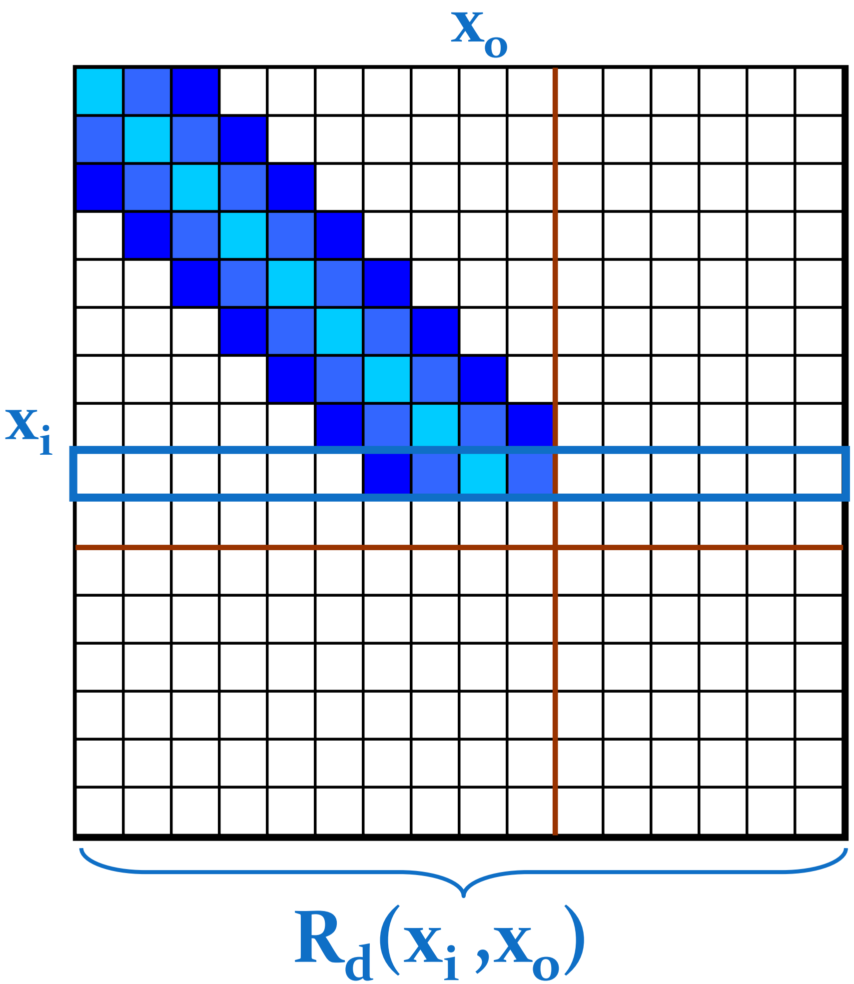
Subsurface Scattering Matrix



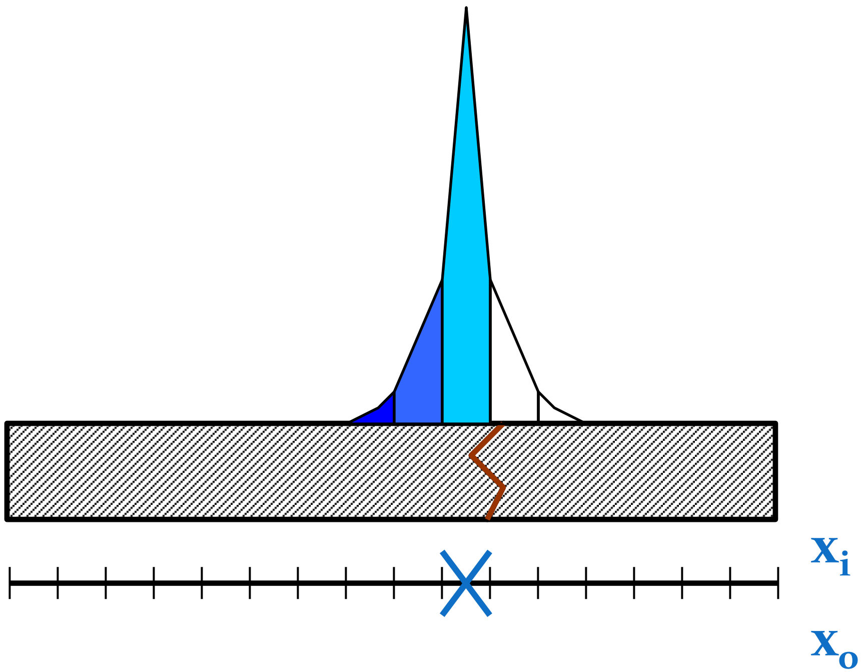


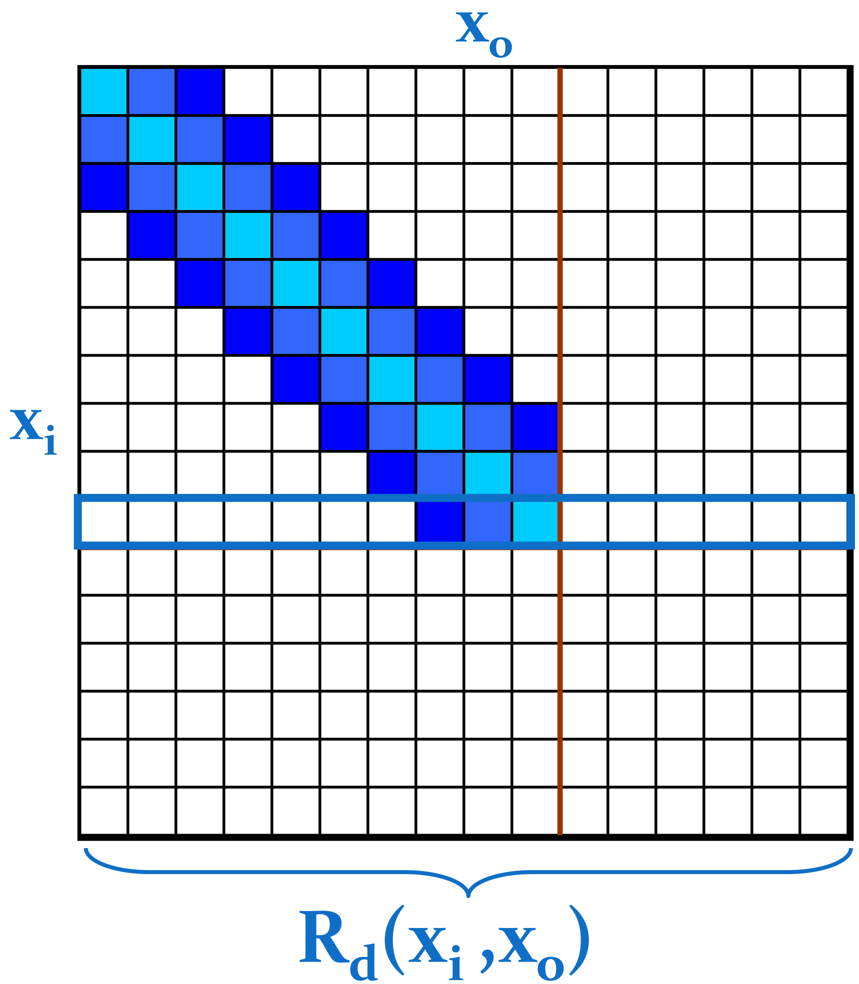
Subsurface Scattering Matrix





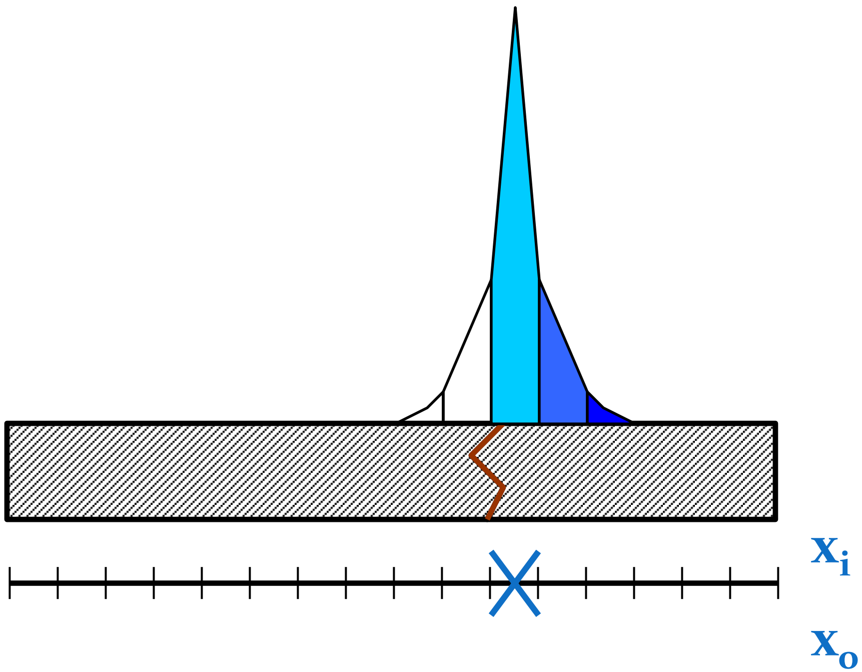
Subsurface Scattering Matrix

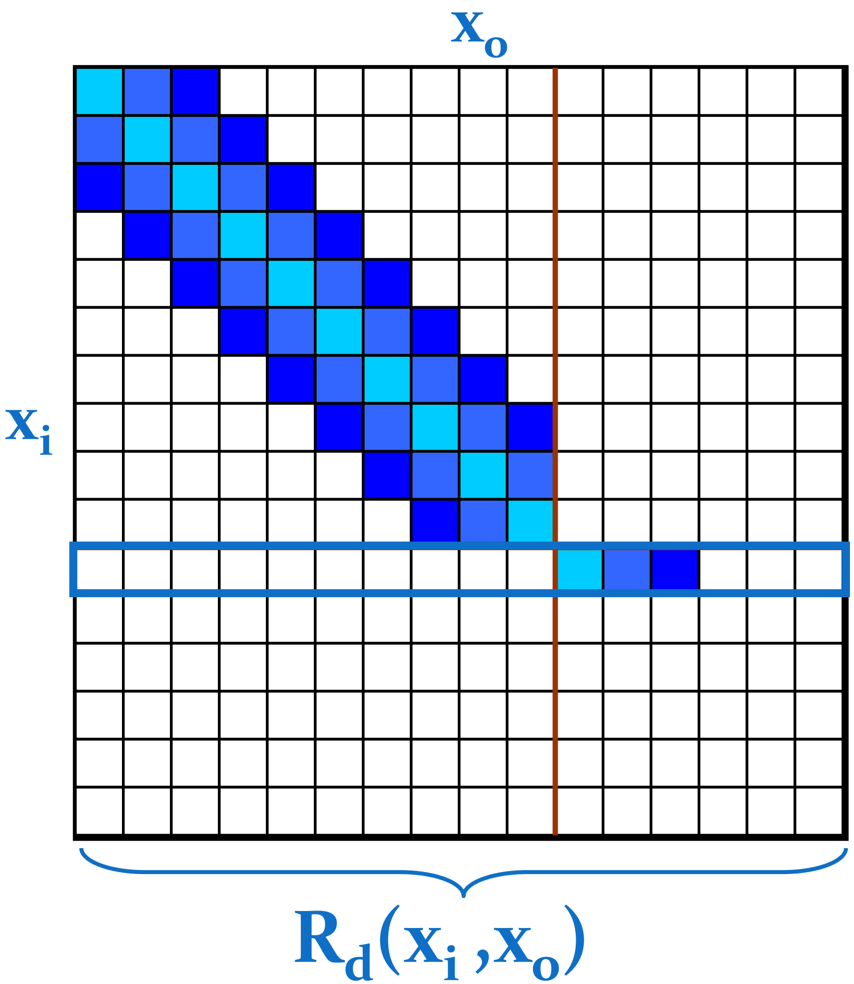




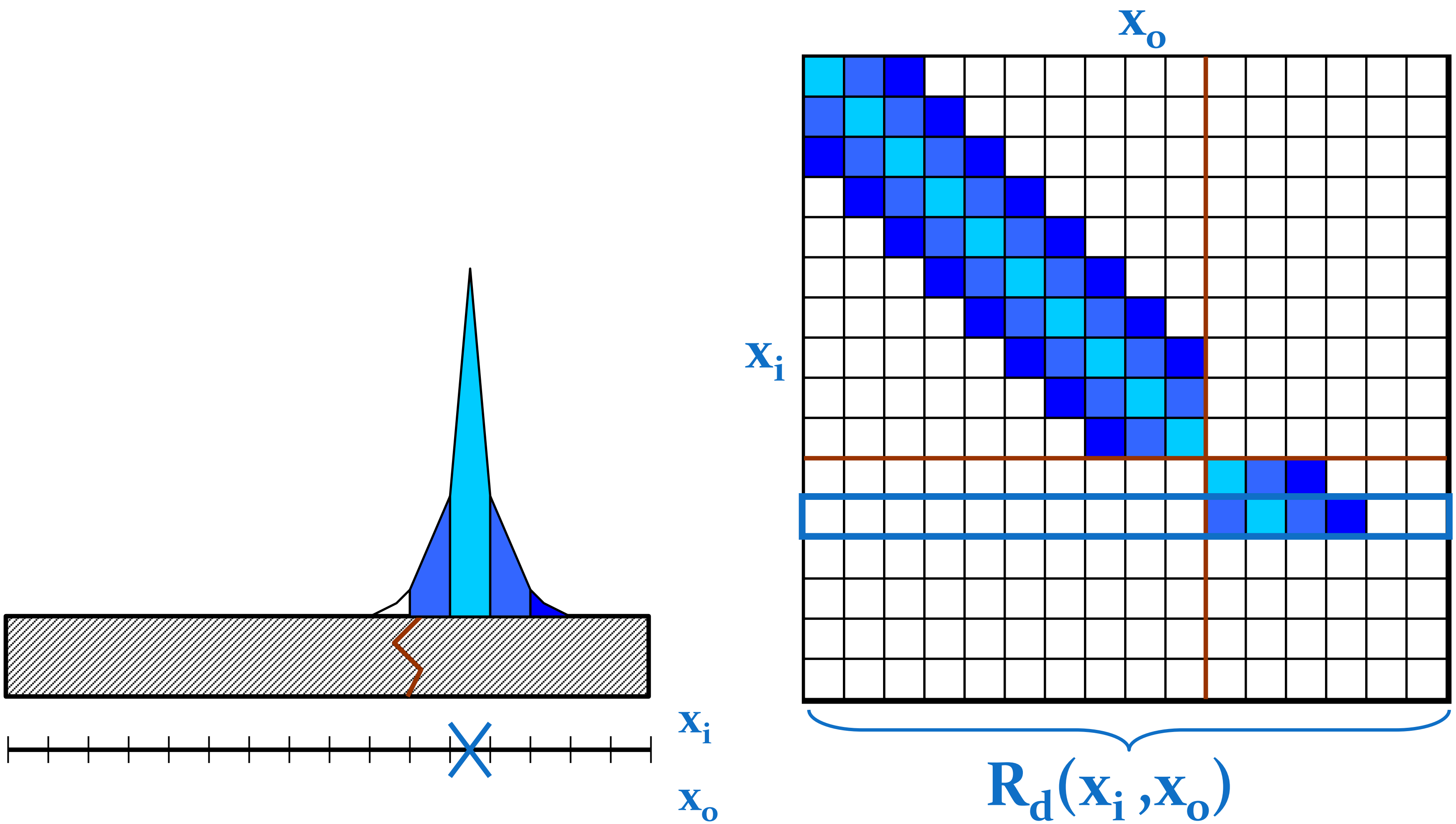
Note that when a point close to the light blocking vein is illuminated, that a part of the homogeneous response is cut off.

Subsurface Scattering Matrix

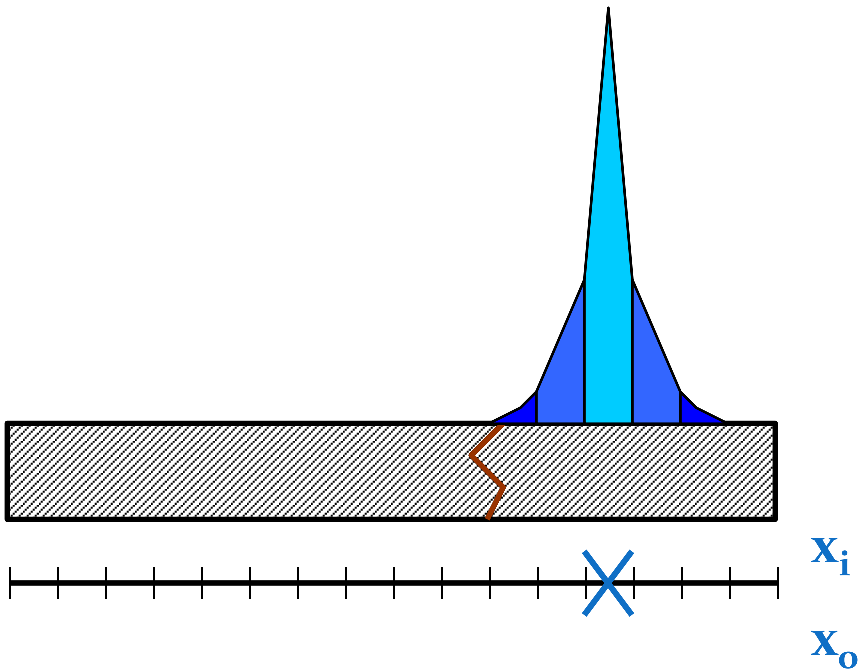


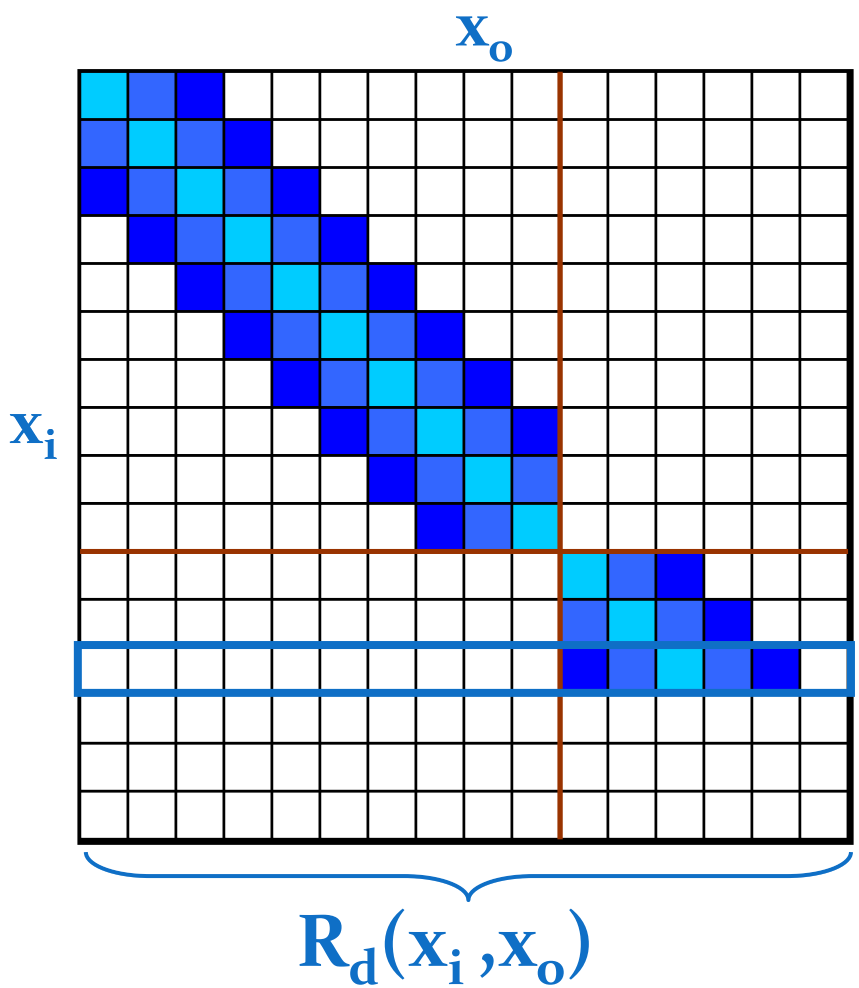


Subsurface Scattering Matrix

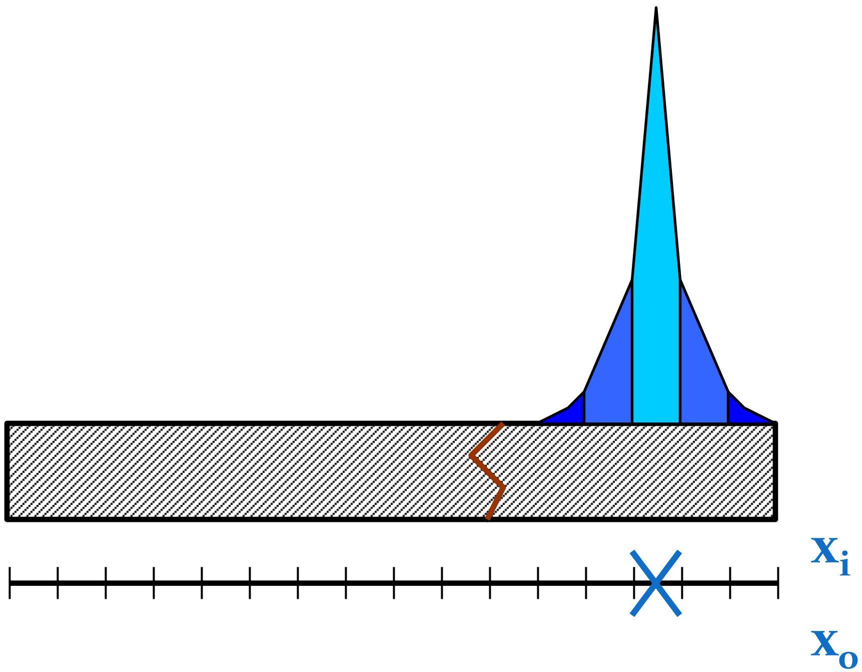


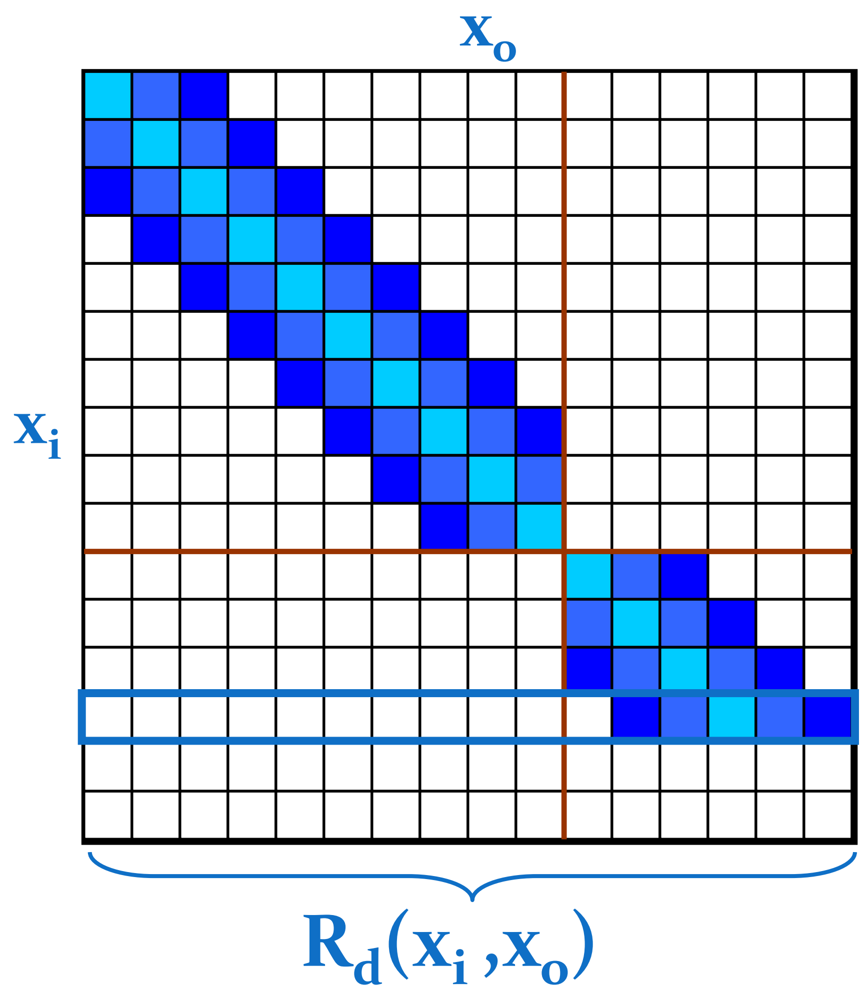
Subsurface Scattering Matrix



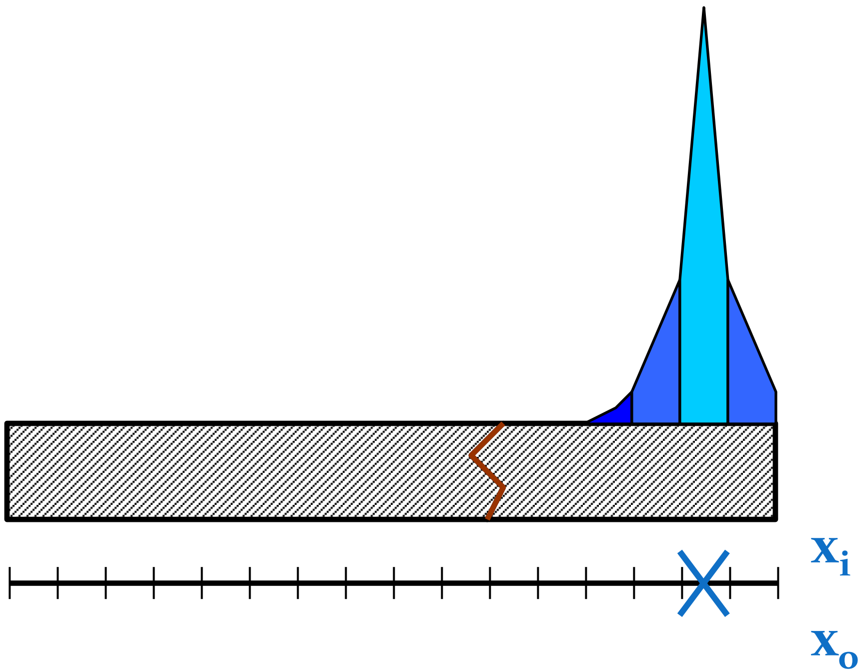


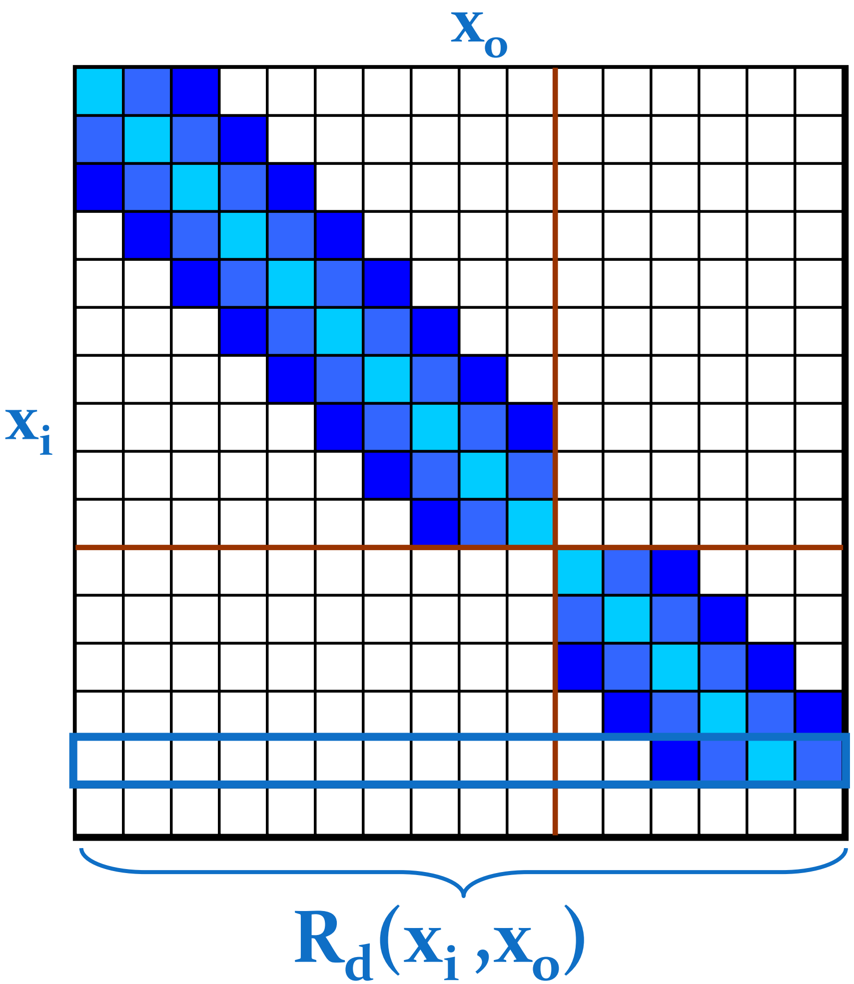
Subsurface Scattering Matrix



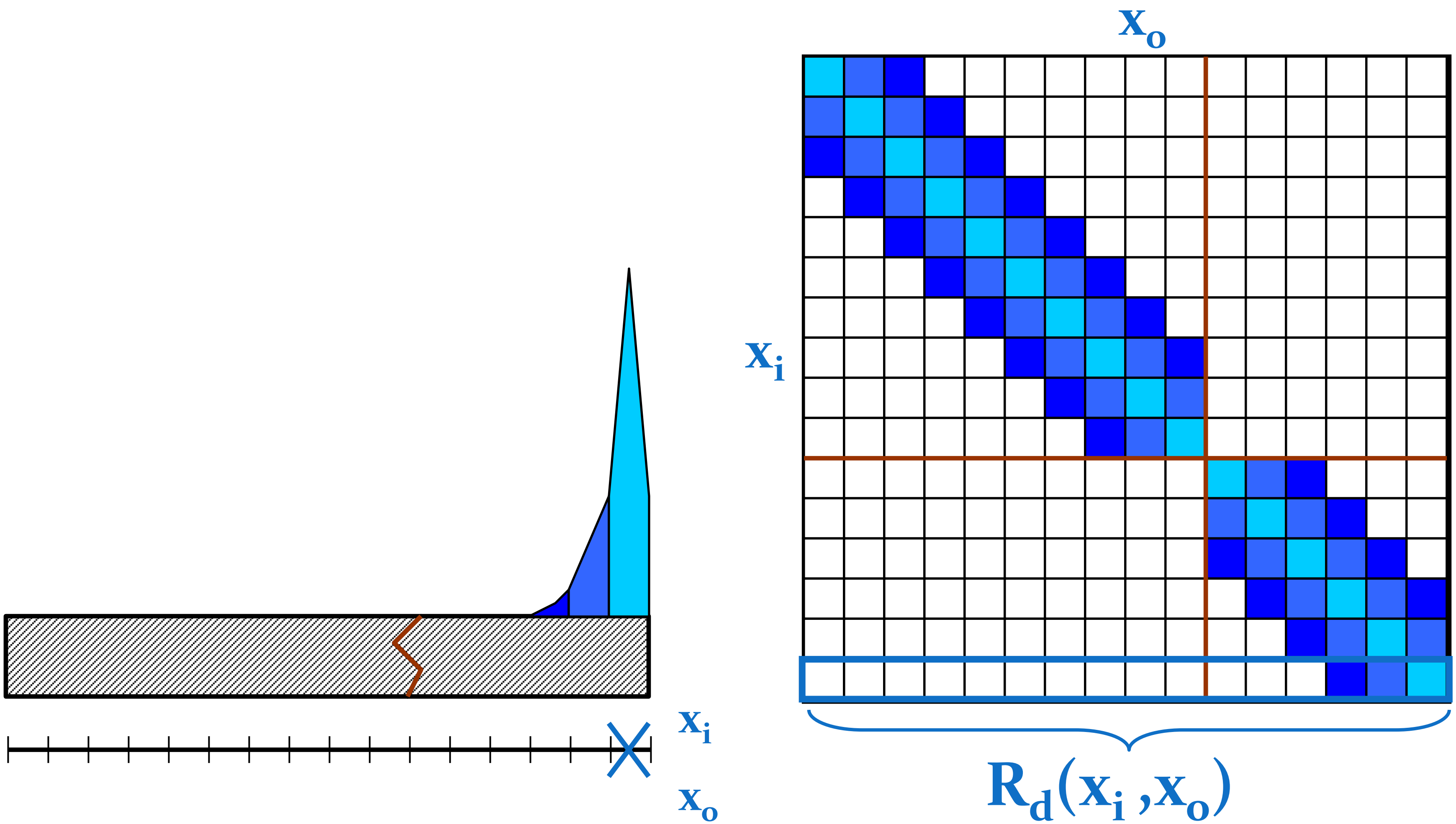


Subsurface Scattering Matrix



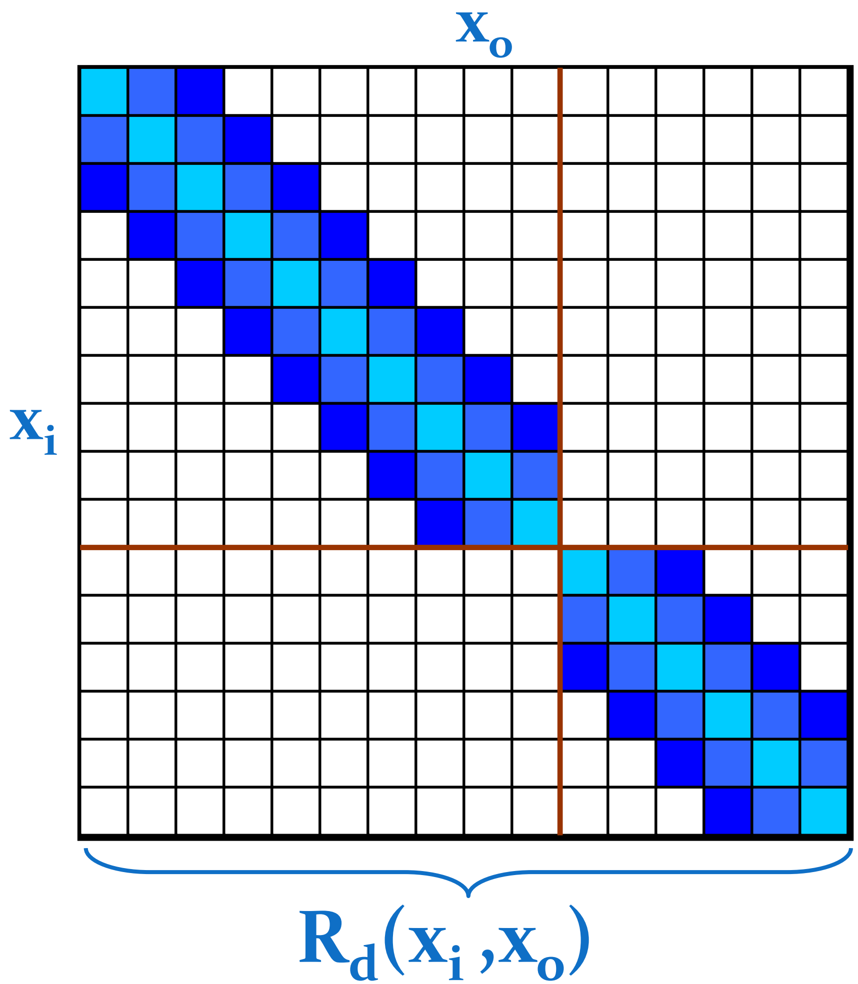


Subsurface Scattering Matrix



Scanning all points, yields a matrix that looks something like this.

Subsurface Scattering Matrix



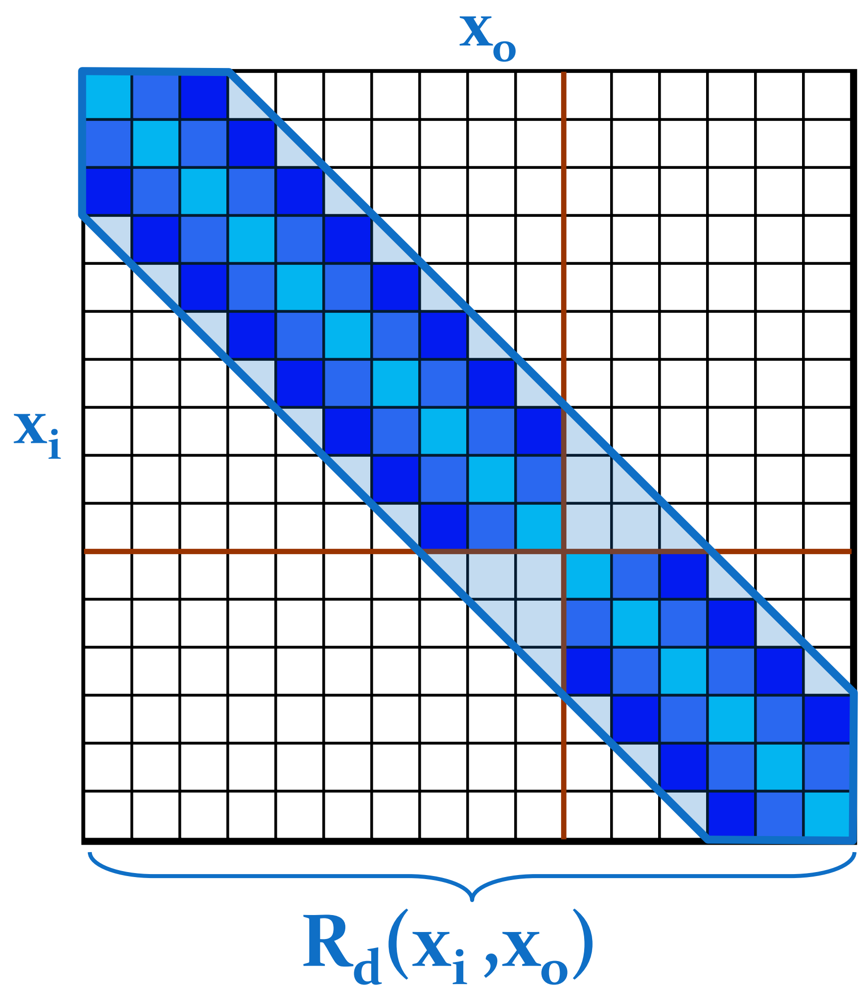
A few important observations can be made regarding the structure of this matrix.

Structure of Homogeneity

Homogeneous Scattering

⇩

Diagonal Band



First of all, it is a band diagonal matrix. Diagonal band is the result of the homogeneous subsurface scattering. This band is interrupted by...

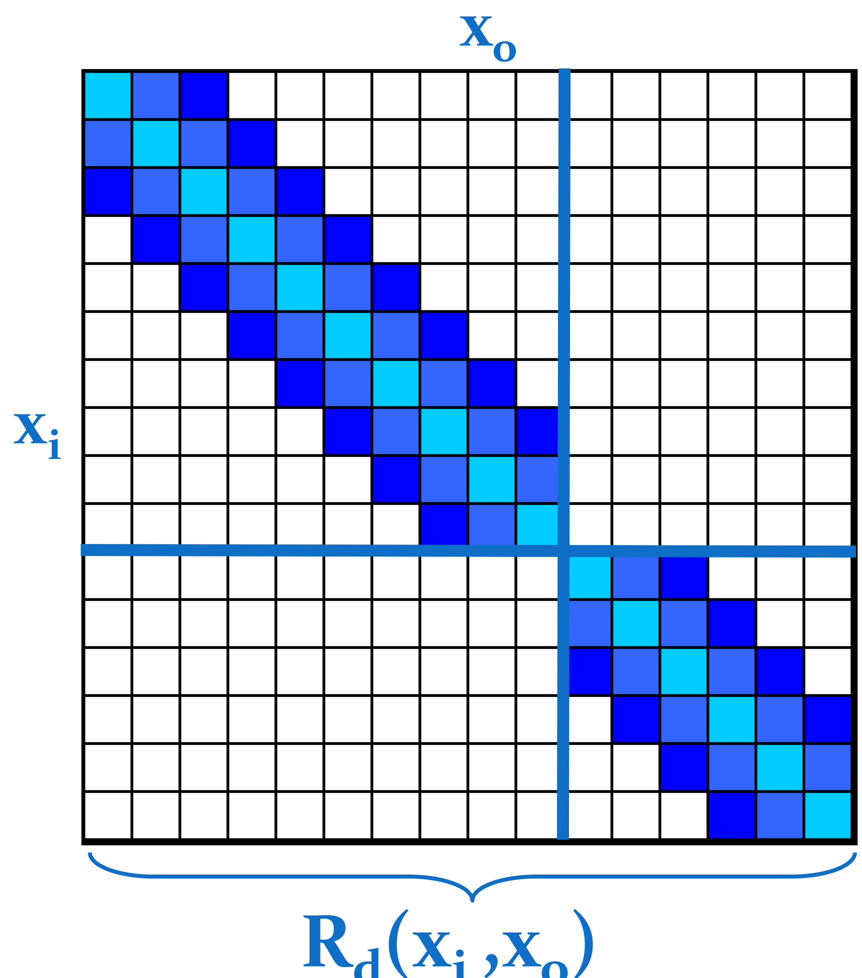
Structure of Heterogeneities

Heterogeneities

⇩

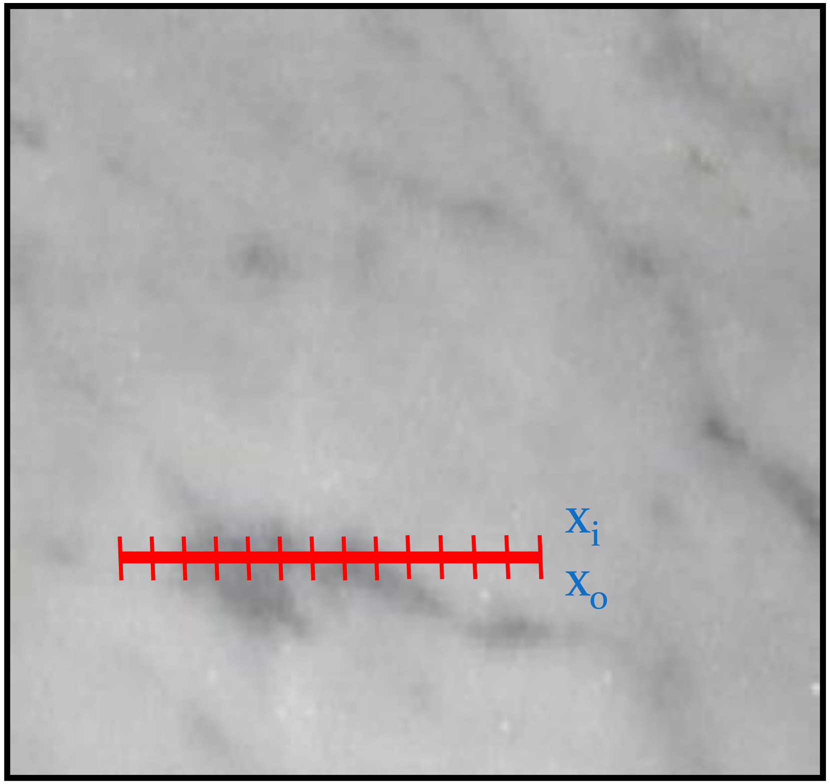
Horizontal & Vertical Discontinuities

(in Matrix R_d)

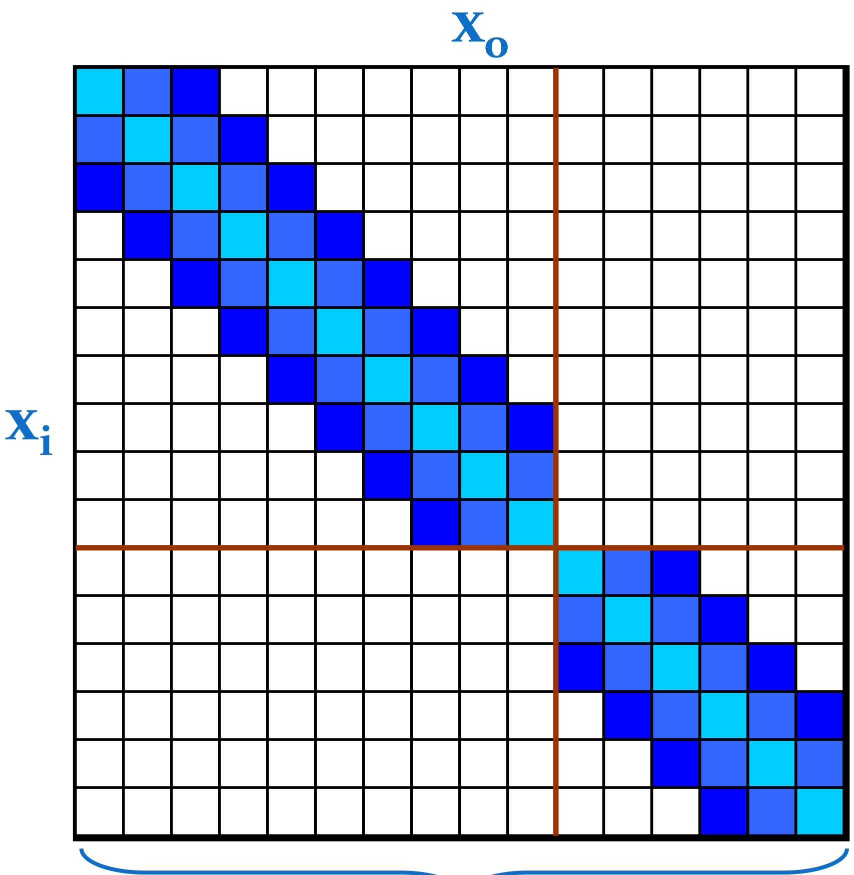


...horizontal and vertical discontinuities. These discontinuities in the matrix R_d are caused by the heterogeneity. Now, this all well for this synthetic example, but how well does this observed structure corresponds to a real subsurface scattering material.

Validation of Structure



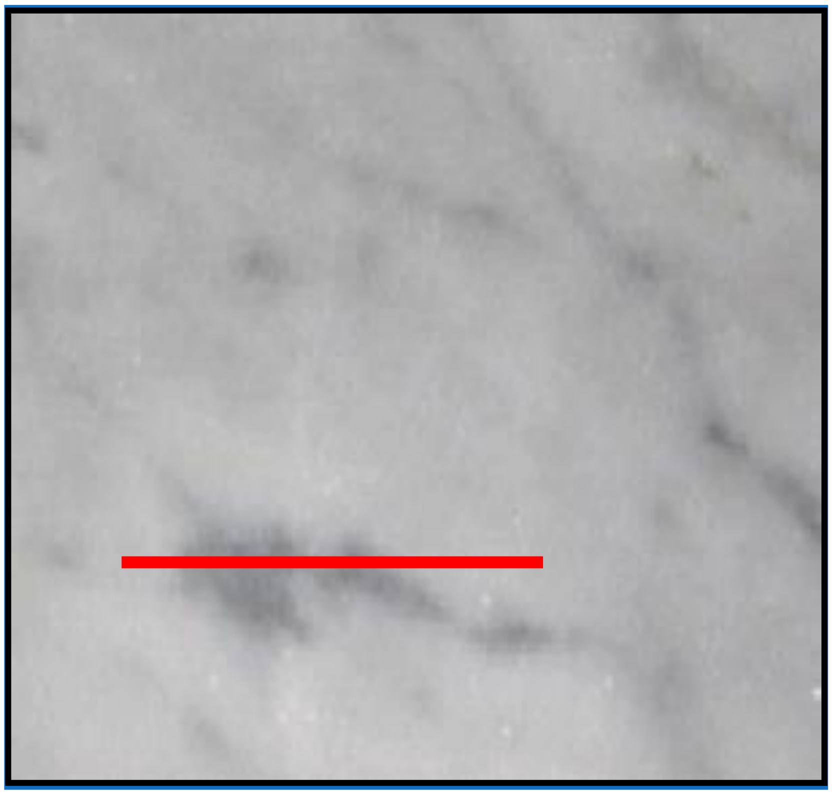
Marble Sample



$R_d(x_i, x_o)$

For this purpose we consider this slab of Marble. On this slab of marble, we are going to illuminate each point on this line <animate>, and are going to observe the response, also on this line.

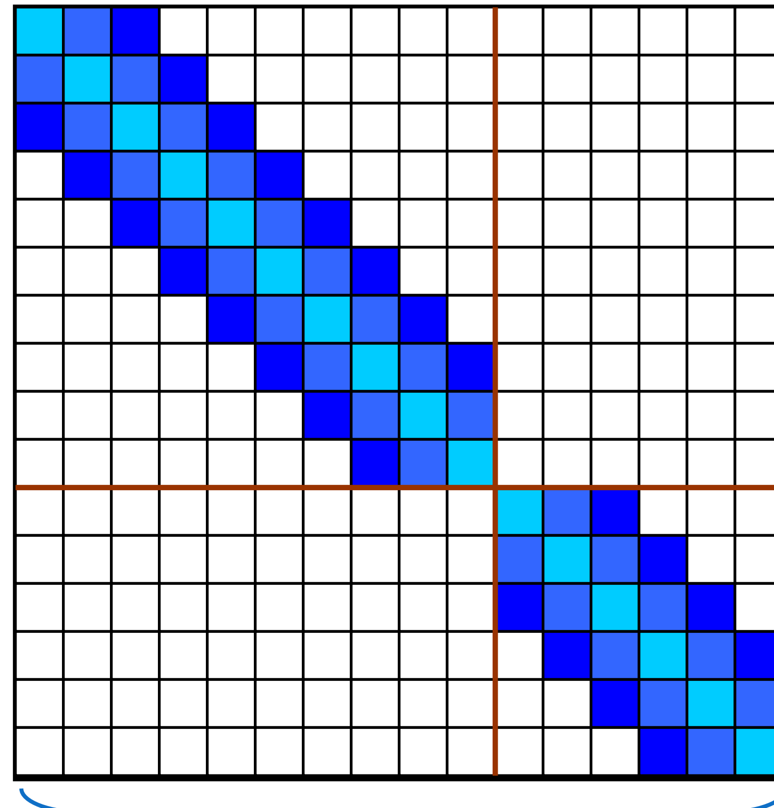
Validation of Structure



Marble: $R_d(x_i, x_o)$

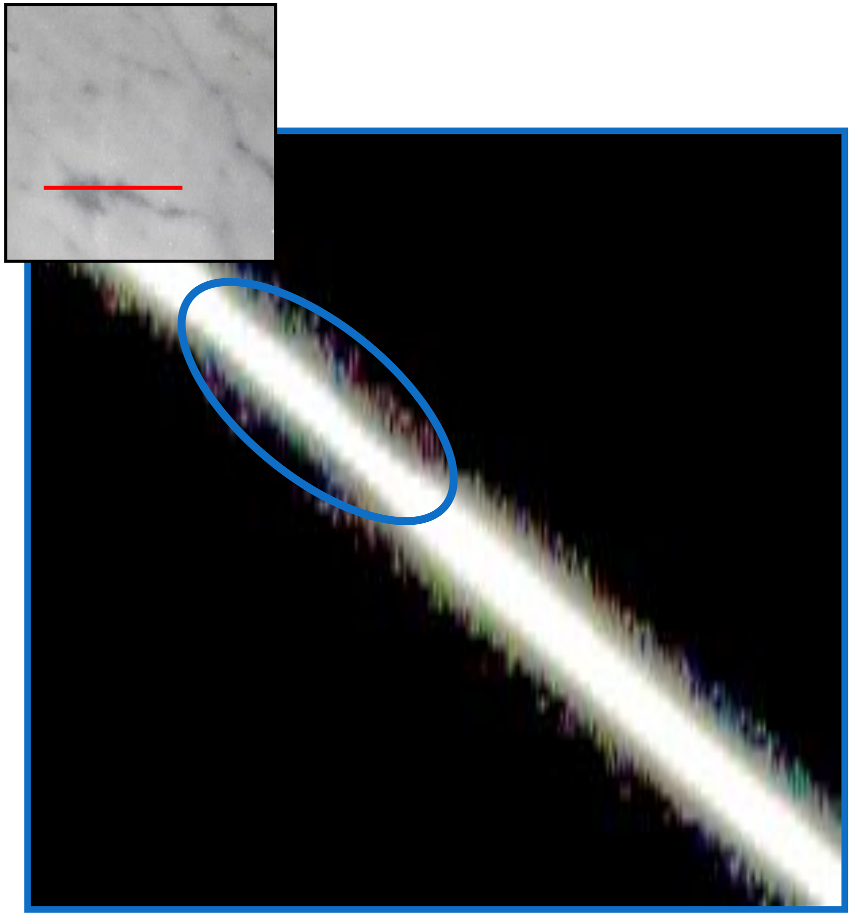
x_o

x_i

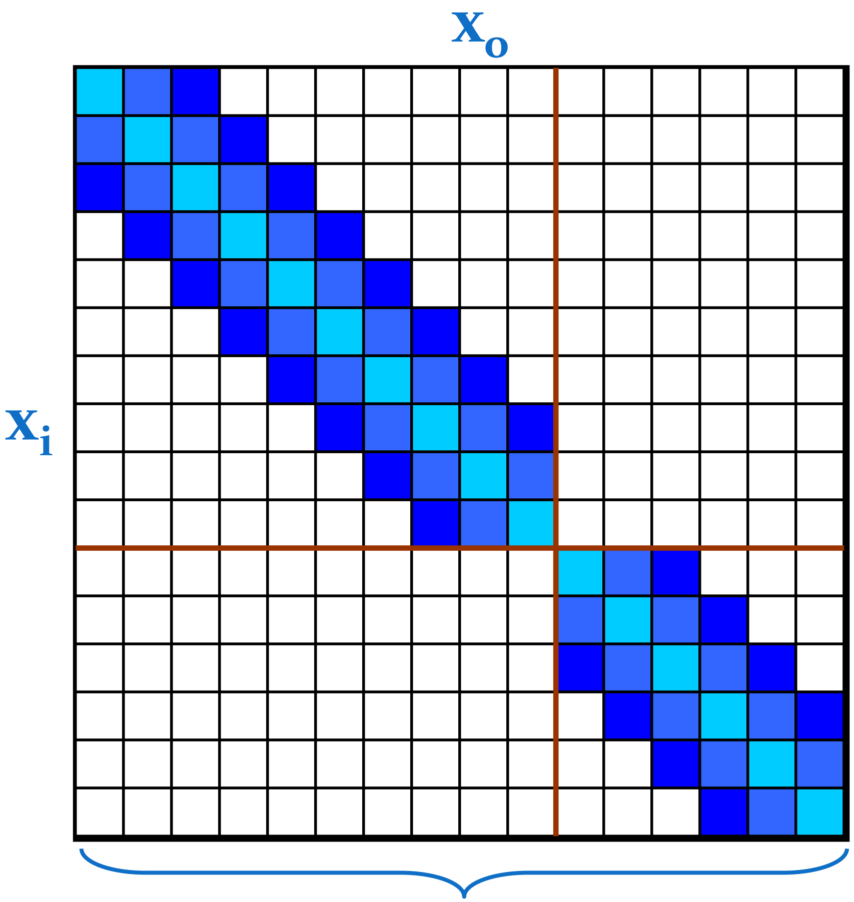


$R_d(x_i, x_o)$

Validation of Structure



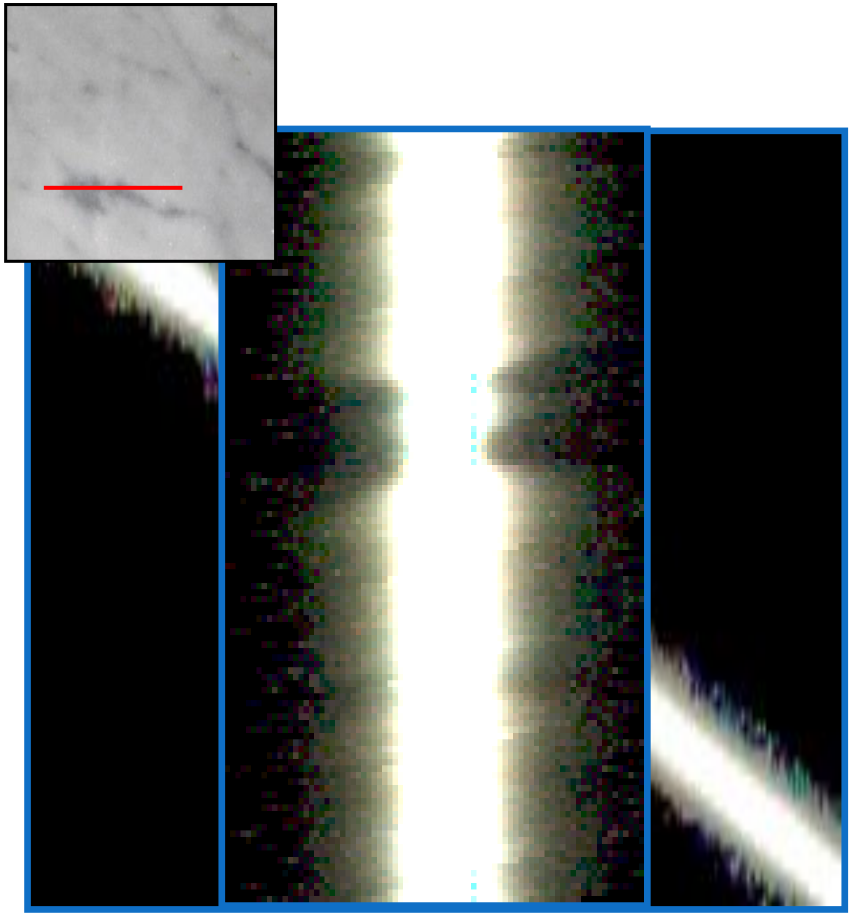
Marble: $R_d(x_i, x_o)$



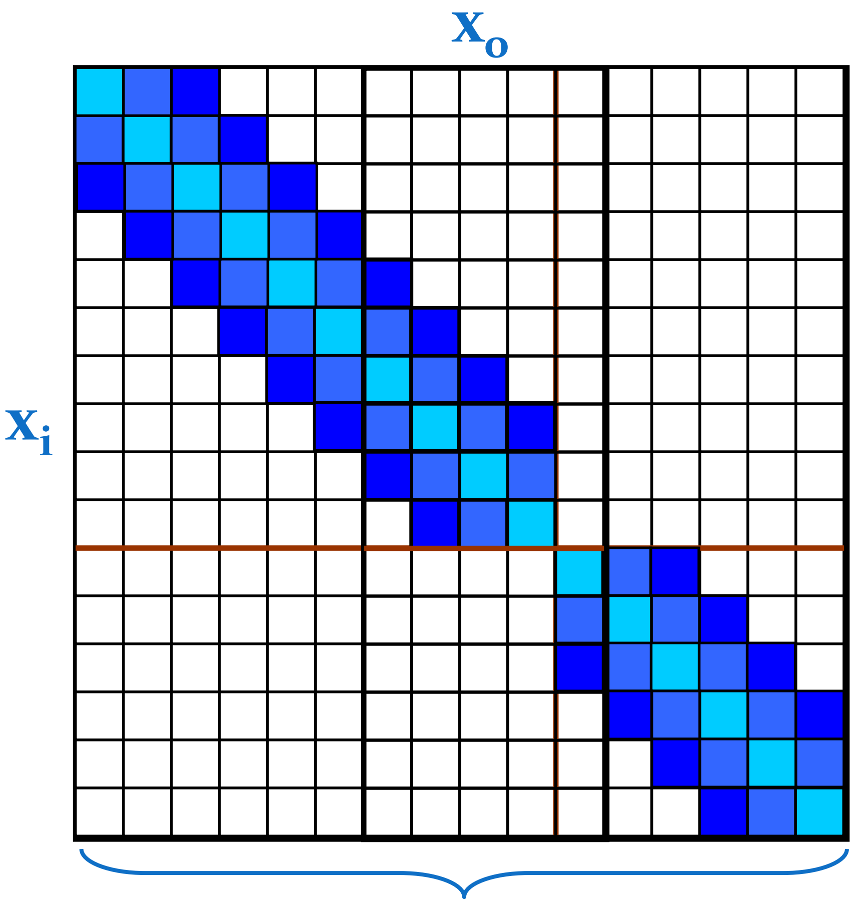
$R_d(x_i, x_o)$

I don't know if you can see it, but the discontinuities are in the left top. The reason why these discontinuities are not as underlined as in the synthetic case, is because the veins in the marble do not block the light transport completely.

Validation of Structure



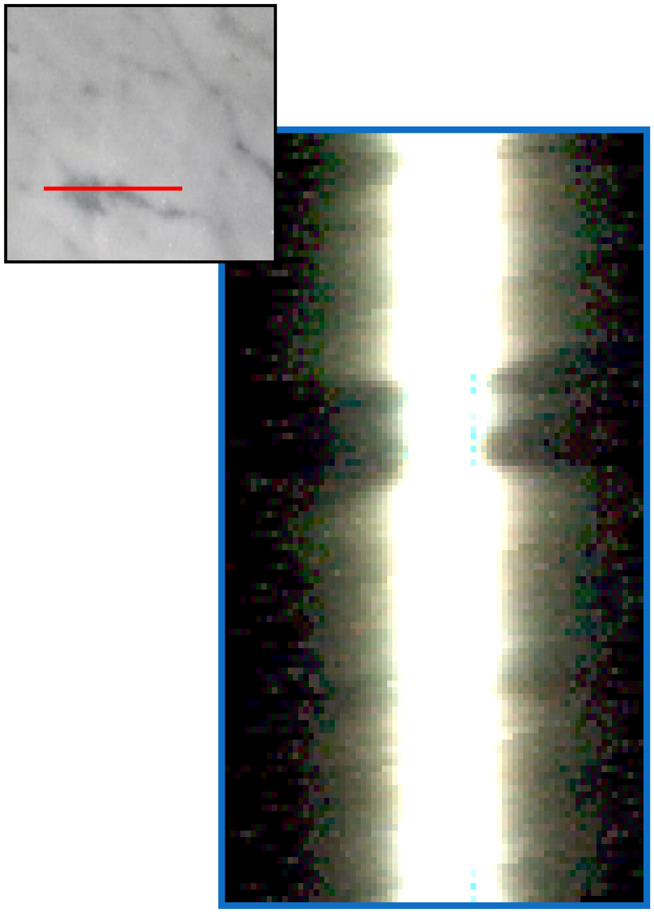
Marble: $R_d(x_i, x_o)$



$R_d(x_i, x_o)$

In order to better bring out these discontinuities, we are going to reparameterize the matrix R_d by shearing it, resulting in a matrix R_d-prime.

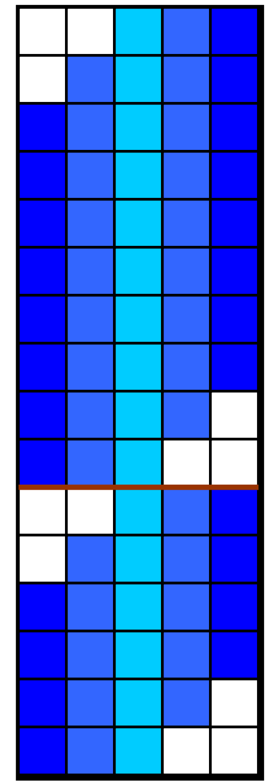
Validation of Structure



Marble: $R'_d(x_i, d)$

$d = x_o - x_i$

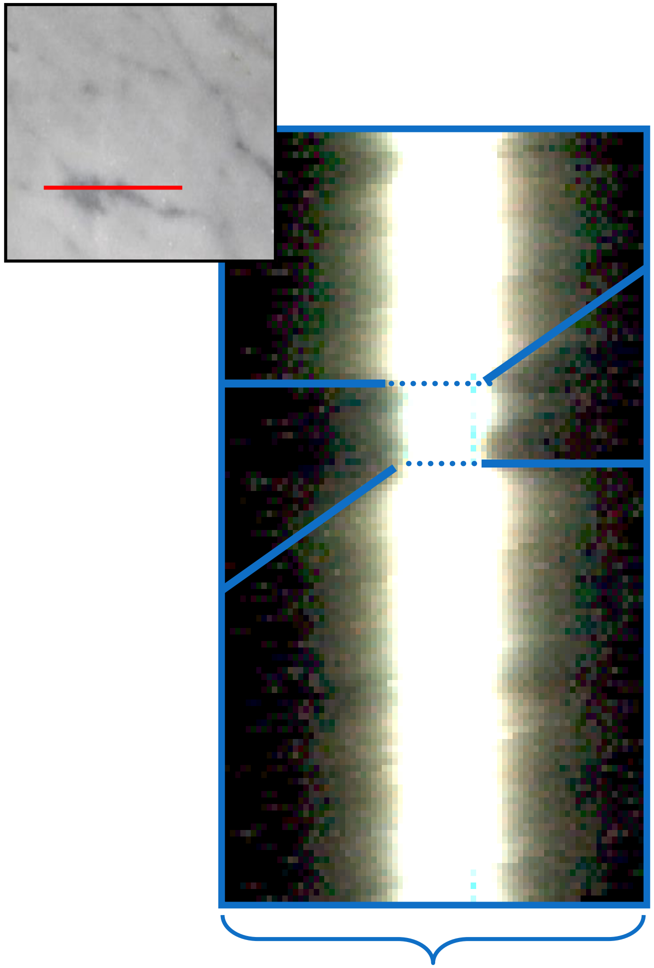
x_i



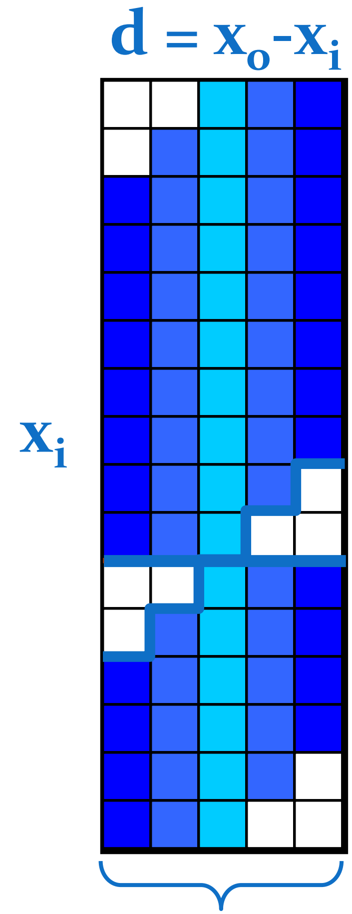
$R'_d(x_i, d)$

As you can see now, the discontinuities are much better visible.

Validation of Structure



Marble: $R'_d(x_i, d)$

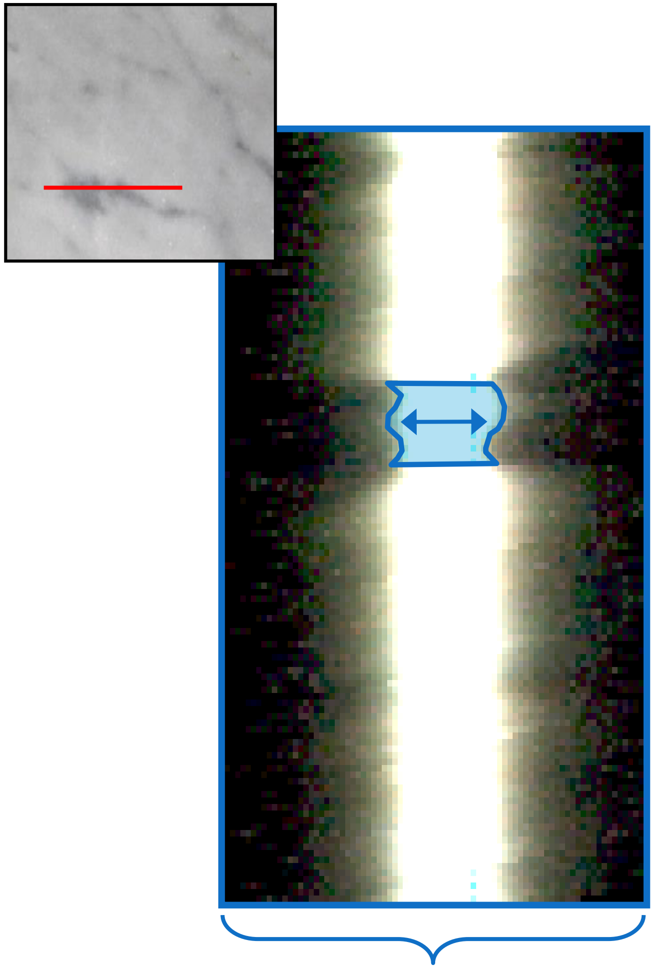


$R'_d(x_i, d)$

Another thing to notice is that the horizontal and vertical discontinuities have now

This example, emprically validates our conclusions regarding the structure in the subsurface scattering matrix.

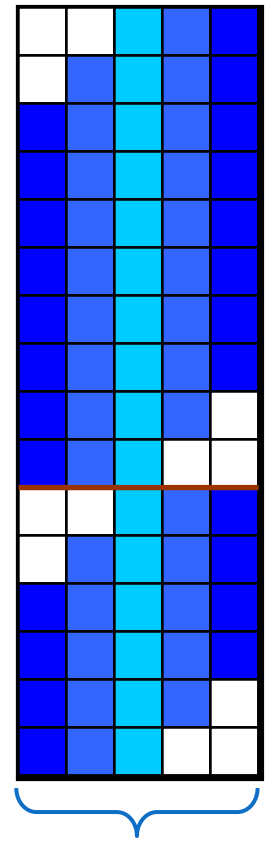
Validation of Structure



Marble: $R'_d(x_i, d)$

$d = x_o - x_i$

x_i



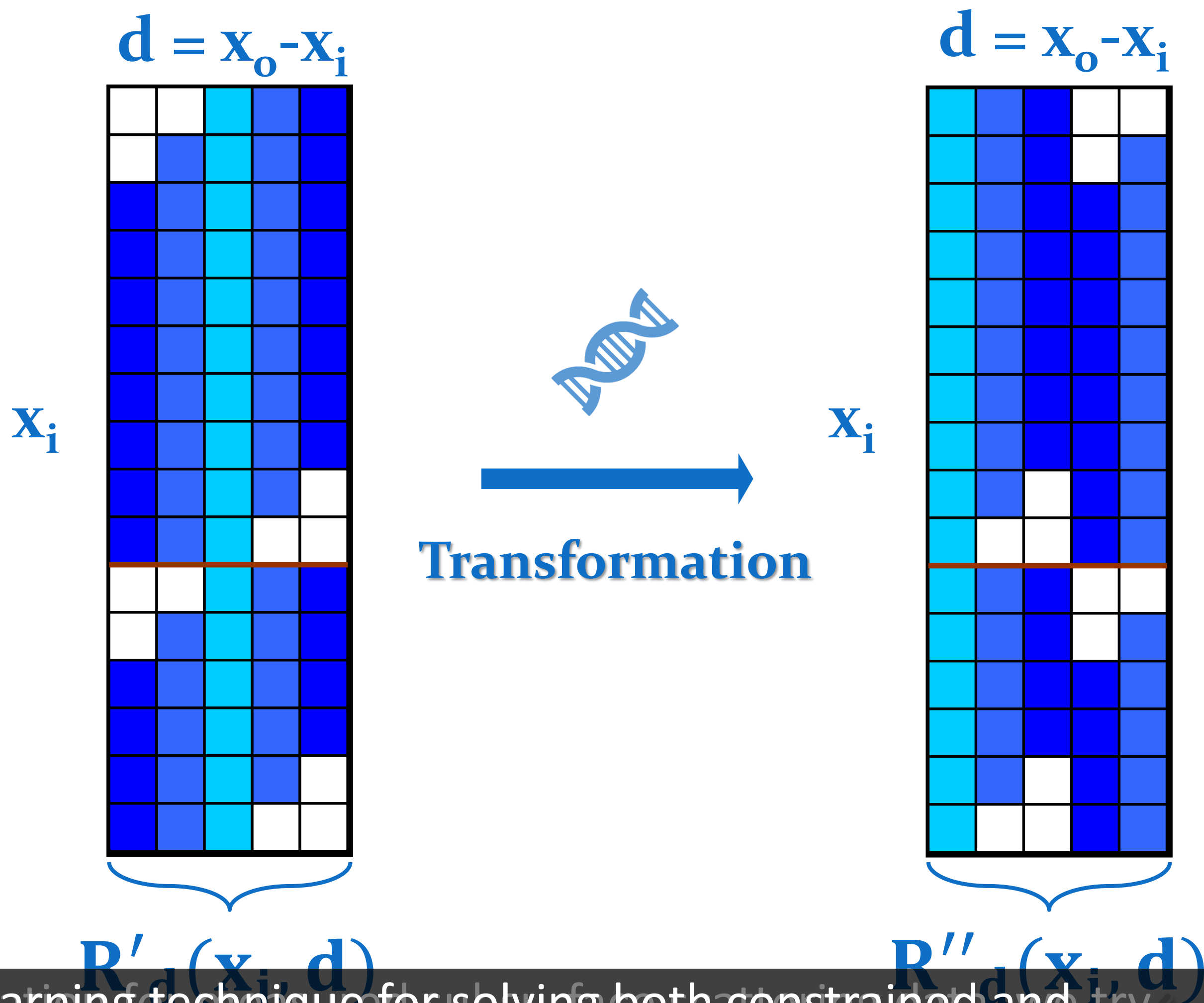
$R'_d(x_i, d)$

Note that the width of this part in the matrix, is dependent on the amount of light blocked by the heterogeneity. Thus in case the veins would block all light, then we get a similar situation as in the synthetic example, and this region would be very thin.

Key Idea for Subsurface Scattering Modeling

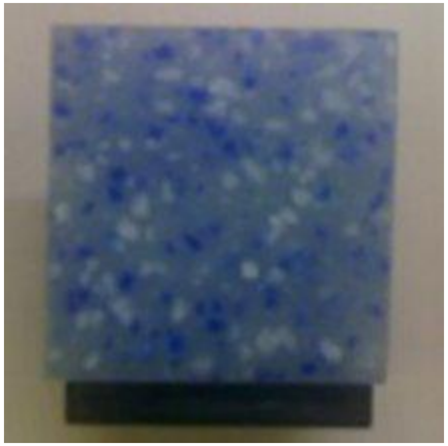
Alignment

$R_d(x_i, x_o) \rightarrow R'_d(x_i, d)$



The GA is a machine learning technique for solving both constrained and unconstrained optimization problems by imitating biological evolution processes. We apply GA to find new transformations for real-world subsurface scattering.

Our Genetic Algorithm (1)



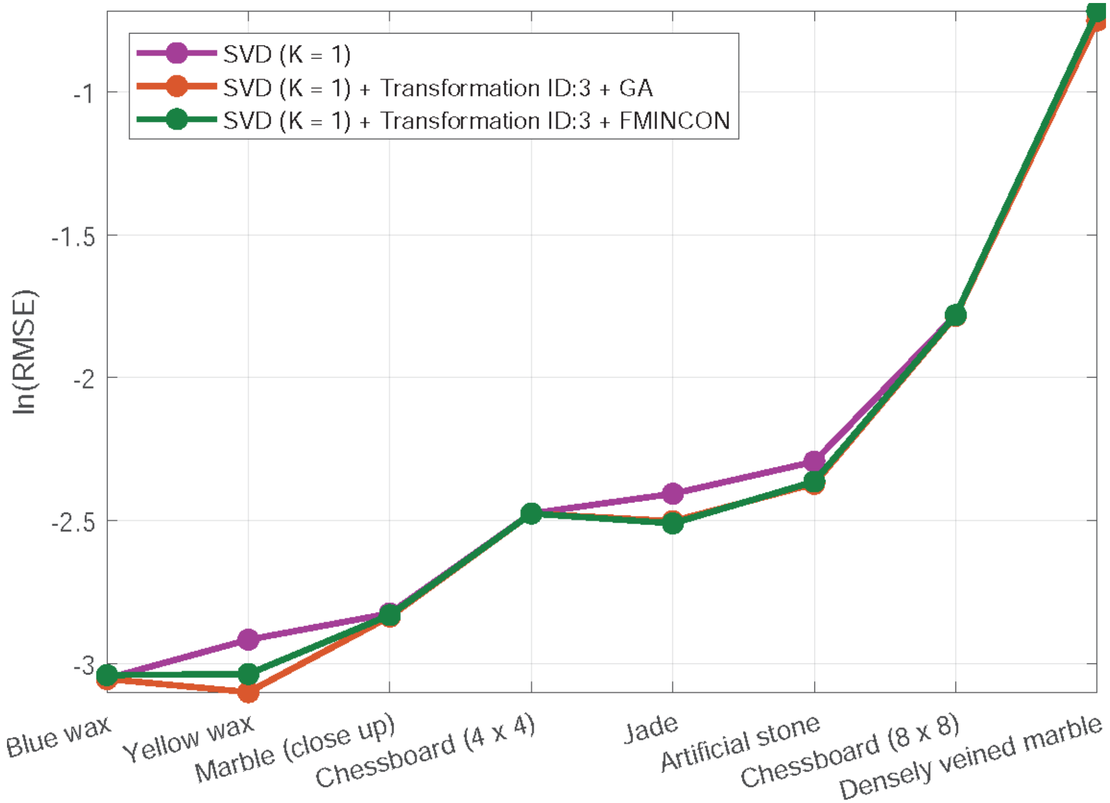
Artificial stone material

Transformation ID	Transformation expression	Chromosome	Population size	Fittest value (RMSE)
1	$R''_d(x_i,d) = \ln\left(1 + \frac{R'_d(x_i,d)}{\alpha_s}\right)$	$\alpha_s(R,G,B)$	30	0.09694
2	$R''_d(x_i,d) = \ln\left(\alpha_d + \frac{R'_d(x_i,d)}{\alpha_s}\right)$	$\alpha_d(intensity), \alpha_s(intensity)$	20	0.09699
3	$R''_d(x_i,d) = \begin{cases} R'_d(x_i,d)/max(R'_d(x_i,d)) & if\, range = 0 \\ \ln\left(1 + \frac{R'_d(x_i,d)}{\alpha_s max(R'_d(x_i,d))}\right) & otherwise \end{cases}$	$\alpha_s(R,G,B),\, d \pm range(R,G,B)$	60	0.09340

Table 1: Properties of the genetic optimization for heterogeneous artificial stone. The table also summarizes some statistics of transformations applied by our genetic algorithm with K = 1. When we don't apply any transformations, the rank-1 approximation of artificial stone gives a RMSE of 0.10091

Over successive generations, the population evolves toward an optimal solution based on a fitness function.

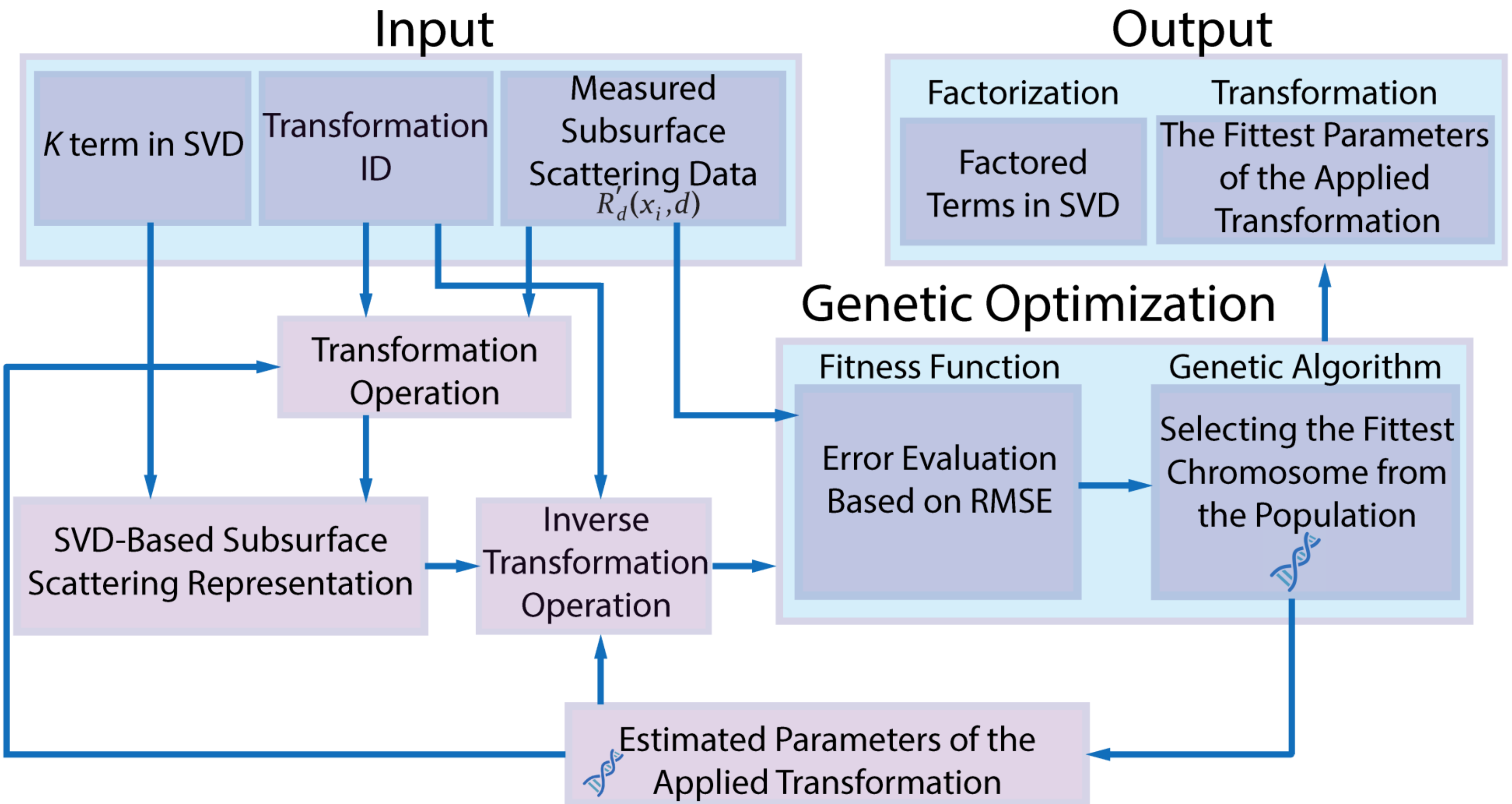
Our Genetic Algorithm (2)



A comparison of the SVD based subsurface scattering model with and without applying various optimization techniques (see Table 1). The model parameter K was selected as 1. The error values were sorted in the logarithmic RMSEs of the SVD technique (purple) for visualization purposes.

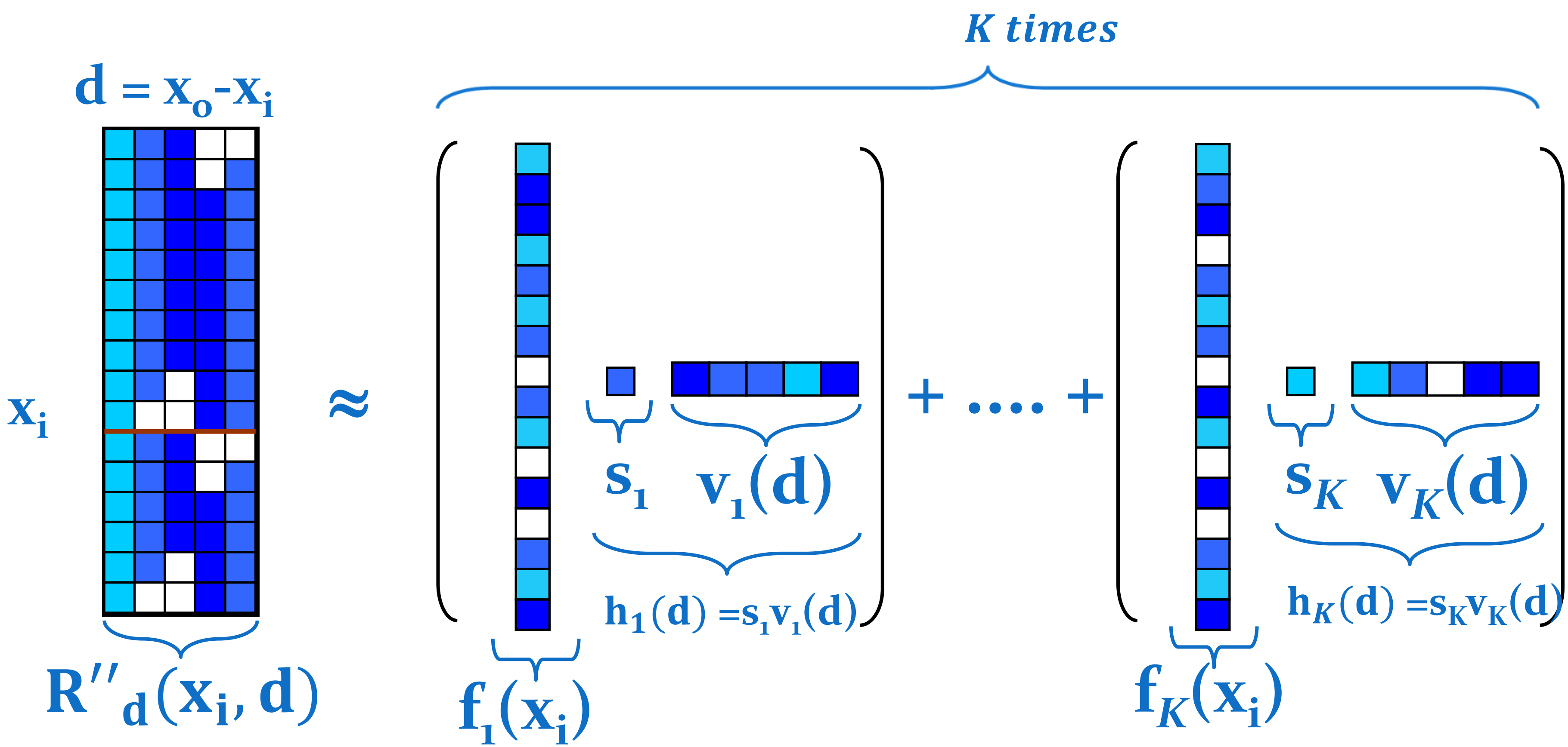
On average, transformation ID:3 with GA decreases the RMSE much more than transformation ID:3 with FMINCON. Therefore, we select and use transformation ID:3 with our GA framework.

Our Genetic Optimization Framework



In this figure, you can see our genetic optimization framework. We investigate various transformation and chromosome combinations (see Table 1) thorough our genetic optimization framework

Our Subsurface Scattering Model



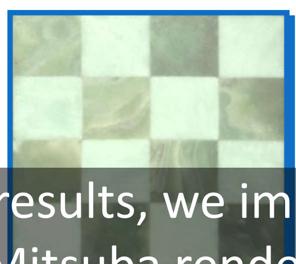
$$R''_d(x_i, d) \approx \sum_{j=1}^{K} f_j(x_i) h_j(d)$$

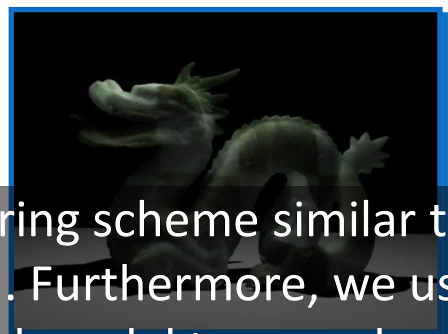
Our final subsurface scattering model will be the sum of the estimation of model errors and the first factorization of R_d prime prime.

Visualization

- *The full Monte Carlo path tracing implementation of MITSUBA [Jak13]:*
  1) *Blue noise sampling of translucent object.*
  2) *The weighting of all samples, within the range of the subsurface scattering response and adding together.*
  3) *The weighting function = the subsurface scattering representation.*
- *A standard texture mapping to apply a material model to a mesh.*

Chessboard (4 × 4)



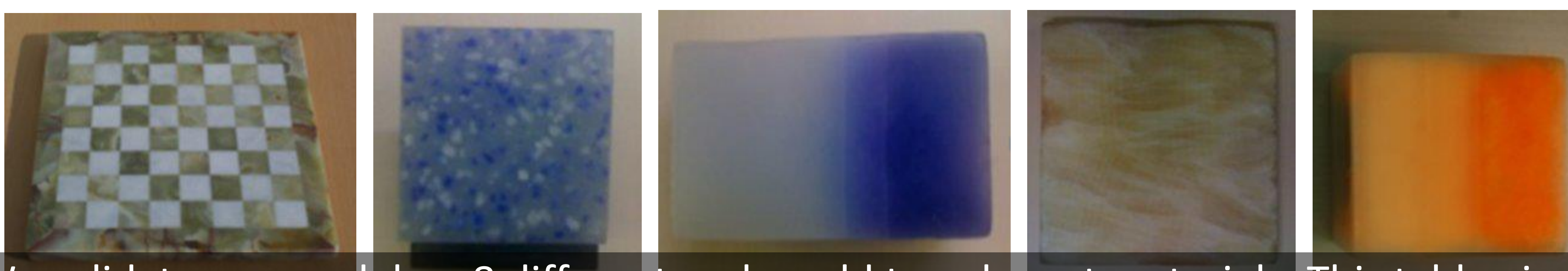


To visualize our results, we implemented a rendering scheme similar to Peers et al. [PvBM06] in the Mitsuba rendering system [Jak13]. Furthermore, we used a standard texture mapping to apply a material model to a mesh.

Results – Validation

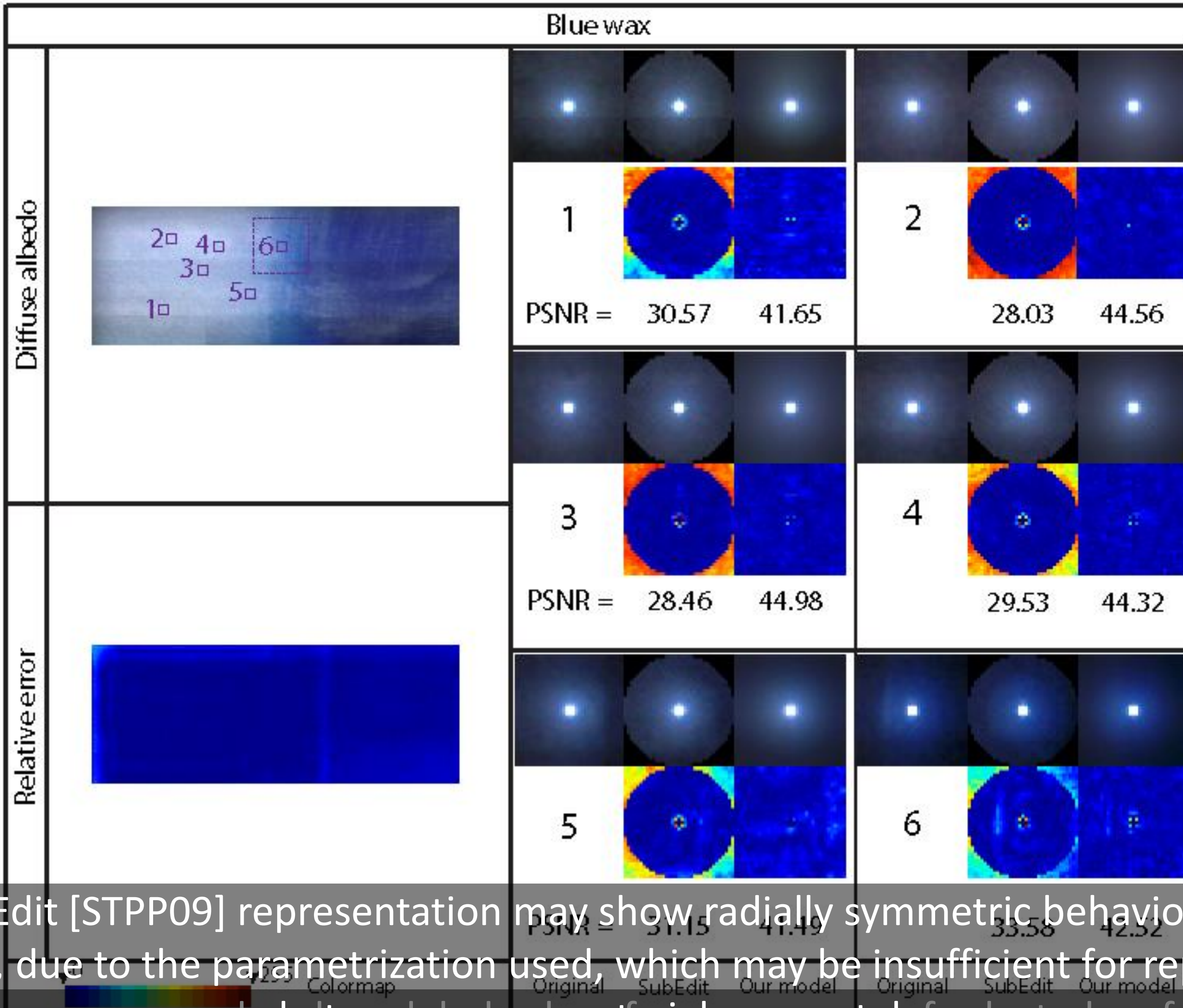
Sample material	Resolution (pixel)	Kernel size (pixel)	Original size	K	Factored size	CR	RMSE
Chessboard (4 × 4)	277 × 277	39 × 39	2.61 GB	5	8.96 MB	1/298	0.0229
Chessboard (8 × 8)	222 × 222	39 × 39	1.68 GB	5	5.82 MB	1/296	0.0421
Marble (close up)	128 × 128	39 × 39	570 MB	5	2.05 MB	1/278	0.0268
Densely veined marble	213 × 211	39 × 39	1.53 GB	5	5.32 MB	1/295	0.0568
Artificial stone	108 × 108	35 × 35	327 MB	5	1.48 MB	1/222	0.0340
Blue wax	88 × 232	35 × 35	572 MB	5	2.48 MB	1/231	0.0192
Jade	260 × 260	35 × 35	1.85 GB	5	7.88 MB	1/240	0.0398
Yellow wax	110 × 110	39 × 39	421 MB	5	1.56 MB	1/270	0.0225

Table 2: Properties of the factored heterogeneous subsurface scattering materials. The table also summarizes some statistics of our GA based subsurface scattering model with typically selected values for K.



We validate our model on 8 different real-world translucent materials. This table gives an overview of the modeled heterogeneous translucent materials and lists a number of statistics for our model, based on typical values for K.

Results - Comparisons (1)

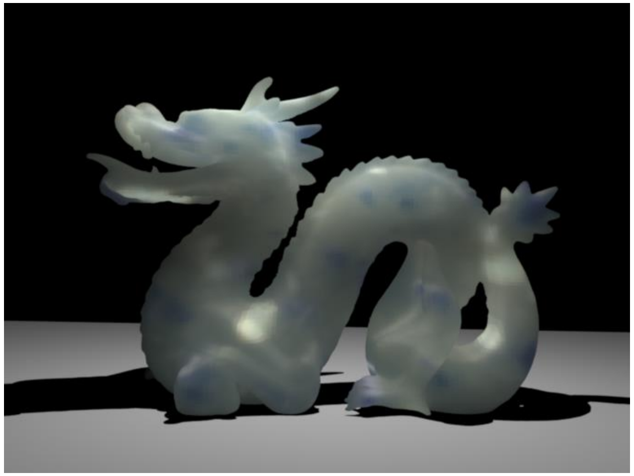


The SubEdit [STPP09] representation may show radially symmetric behavior at some materials, due to the parametrization used, which may be insufficient for representing heterogeneous materials accurately

We compare measured a … f selected surface points.

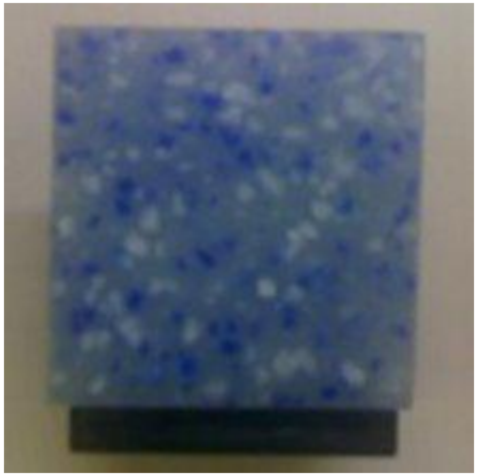
Results - Comparisons (2)

(Storage: 327 MB)

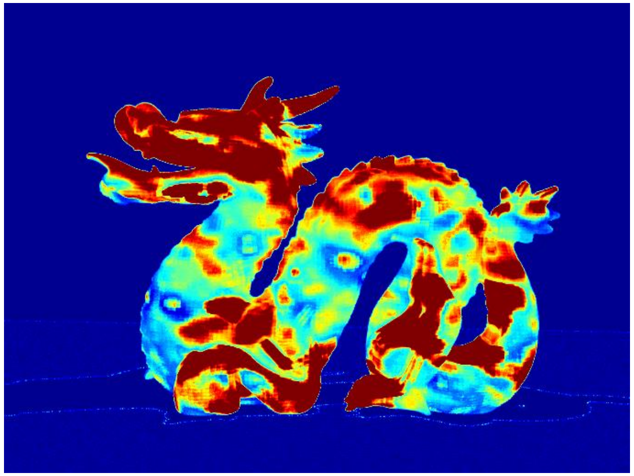


(Storage: 3.29 MB)

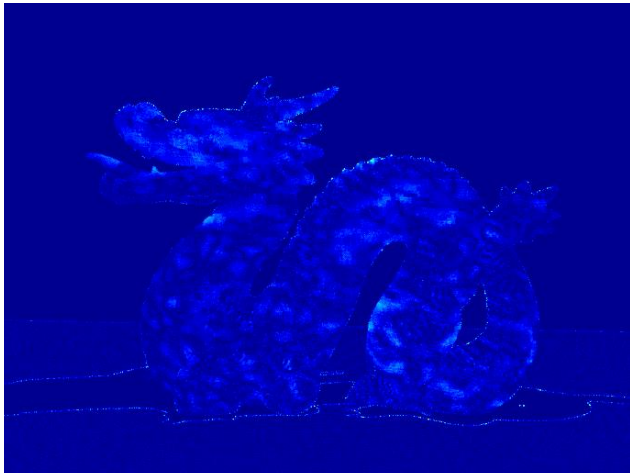
(Storage: 2.94 MB)



Reference image
Artificial Stone



SubEdit Model



Our Model (K=10)

The comparisons outlined show that our model represents heterogeneous translucent materials more accurately for comparable data storage requirements.

Conclusions

- A GA based heterogeneous subsurface scattering model.
- *Apply to any geometry.*
- *Integrate into a standard physically-based rendering system easily.*
- We plan to investigate real-time rendering algorithms to implement our representation in screen-space.

In the future, we plan to investigate real-time rendering algorithms to implement our representation in screen-space.

In this work, we present a GA based heterogeneous subsurface scattering model.

Thank You...

I hope you enjoyed this presentation, and I thank you for your attention.