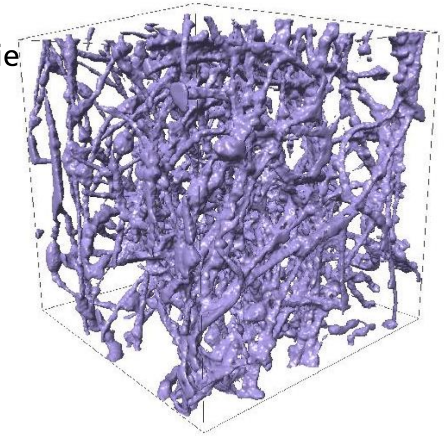
Characterization of the microstructure of filter materials

Fraunhofer Institut Techno- und Wirtschaftsmathematik

Department Models and Algorithms in Image Processing

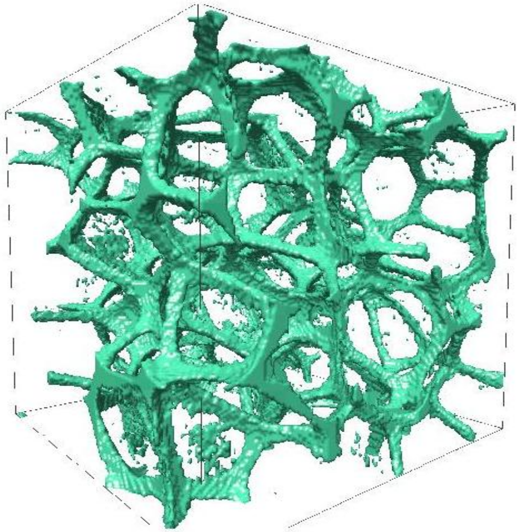
Katja Schladitz

Filter materials

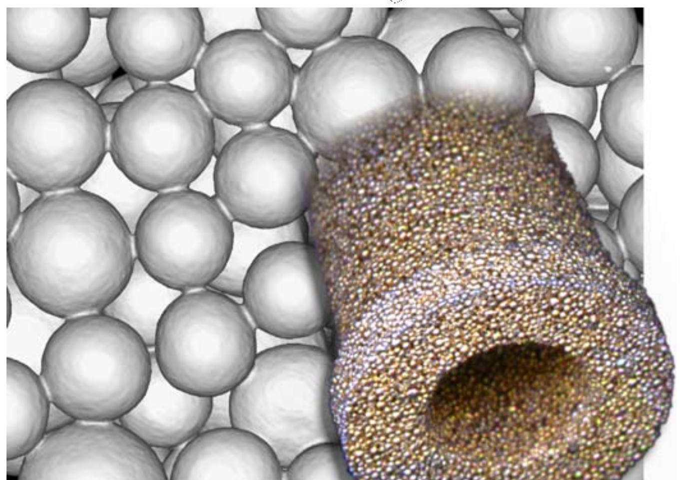


Non-woven, Fraunhofer Institut Zerstörungsfreie Prüfverfahren (IZFP), resolution 10µm

- fiber material (non-woven or felt, homogeneous or in layers)
- open foams (polymer, metal or ceramics)
- sinter material



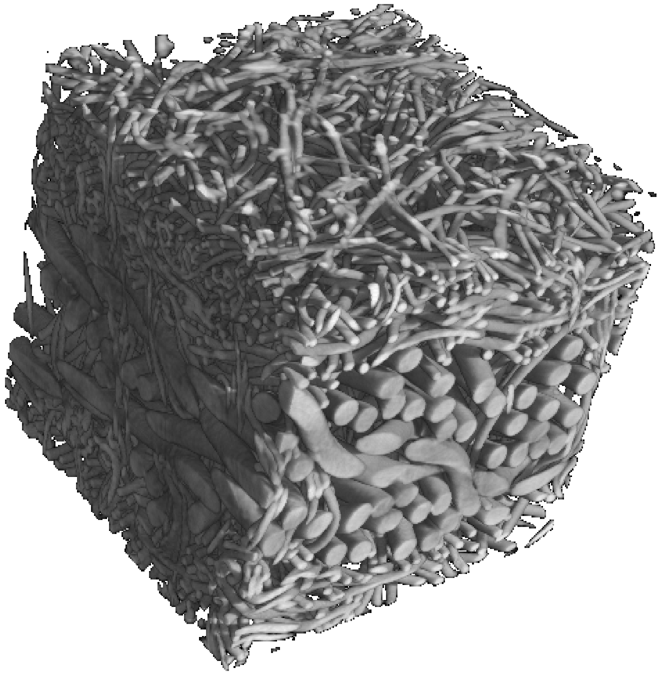
Polyurethan foam, RJL Analytic, resolution 5µm



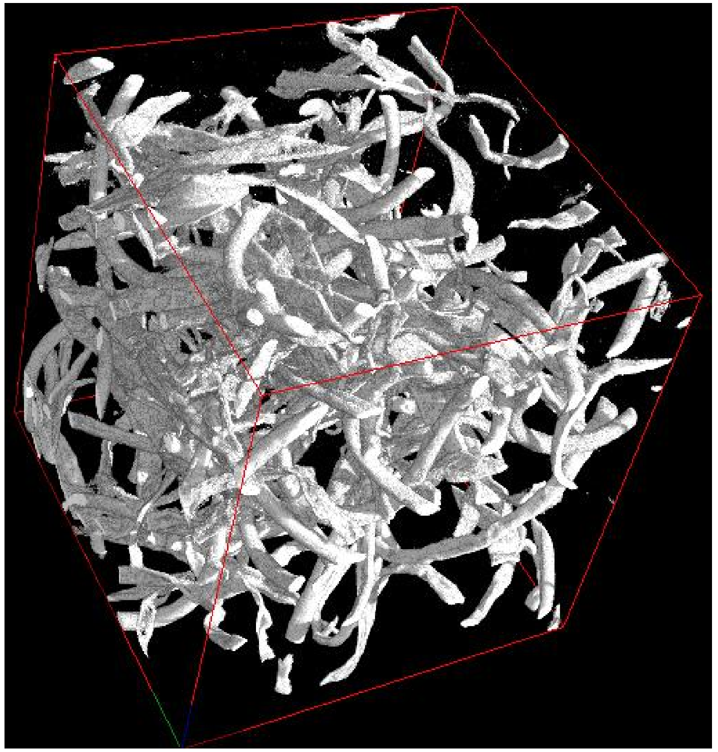
Sintered copper, Bundesanstalt für Materialprüfung, resolution 14µm

Types of microstructures and constituents

layers or spatially homogeneous

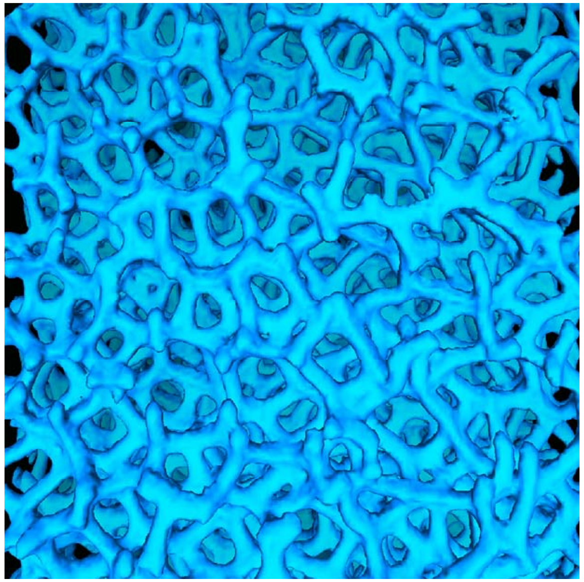


fiber felt, European Synchrotron Radiation Facility (ESRF), resolution 7µm

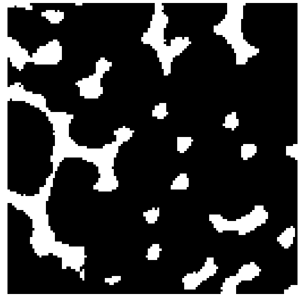


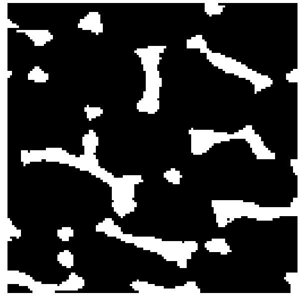
Non-woven, ESRF, resolution 1.4µm

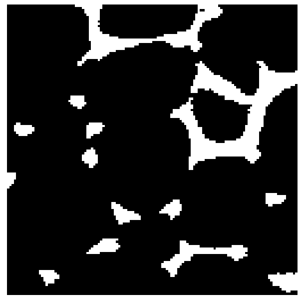
Why 3d images?



Nickelfoam, IZFP, resolution 10µm







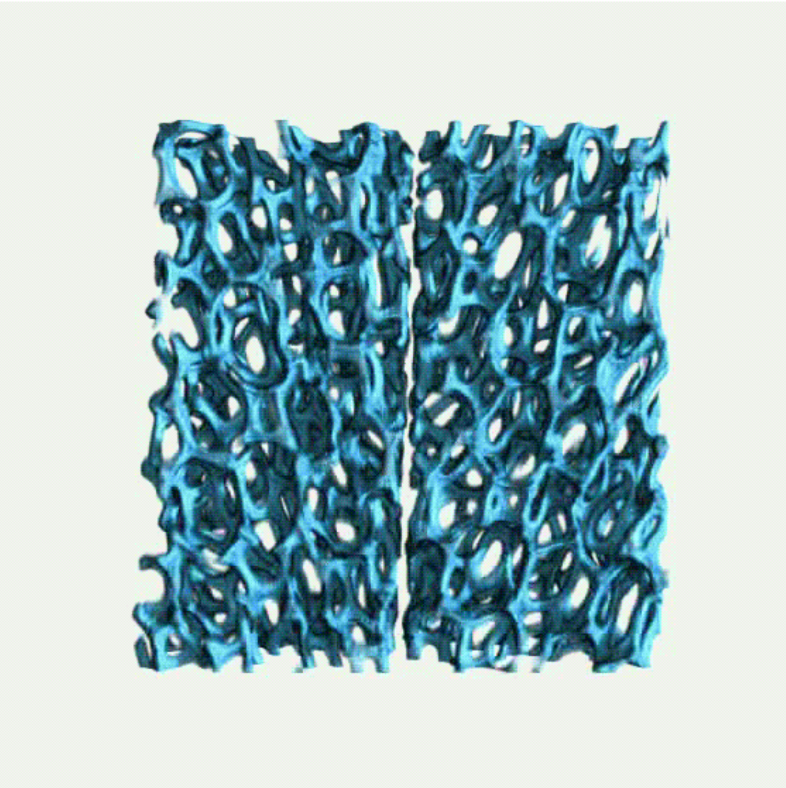
Filter materials are often

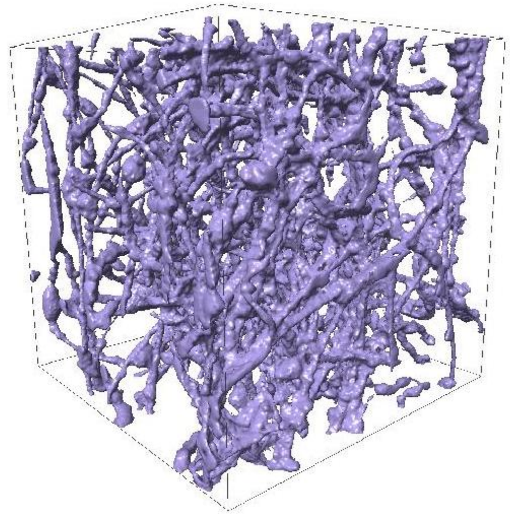
- strongly porous (porosities > 95% are possible)
- weak (e.g. non-woven)

Classical materialographics reaches its limits, as

- preparation of planar sections or cross sections is difficult or even impossible
- 2d images contain only a small fraction of the information

Goals of geometric analysis of microstructures





• geometric characterization for

  o quality control,

  o comparison and

  o choice of materials

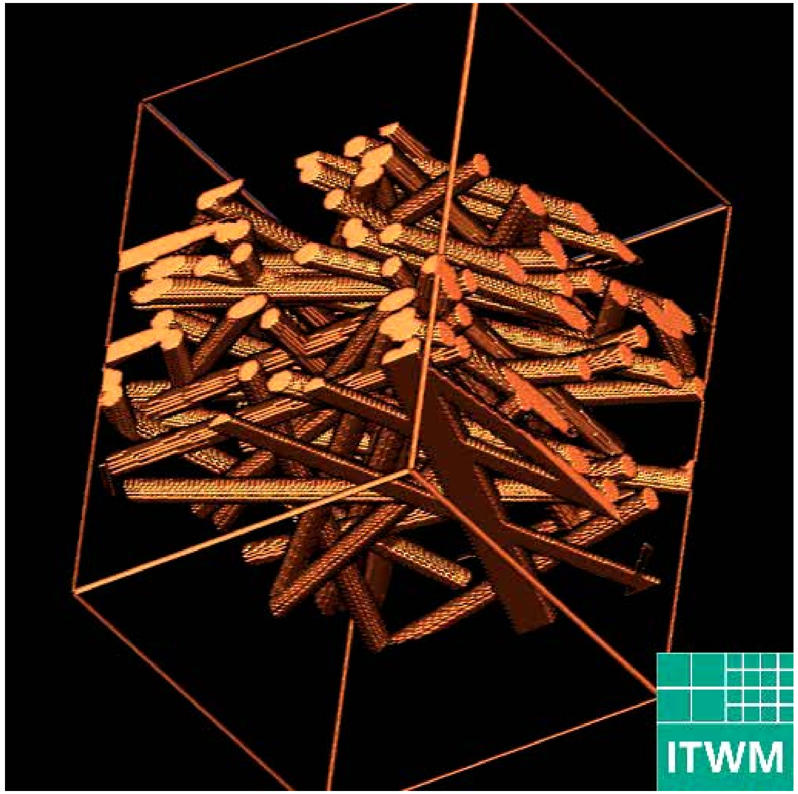
• preparation of image data for direct use in simulations (macroscopic materials properties)

• fitting of modells: parameters are deduced from geometric characteristics of the microstructure (virtual material design)

Goal: virtual material design

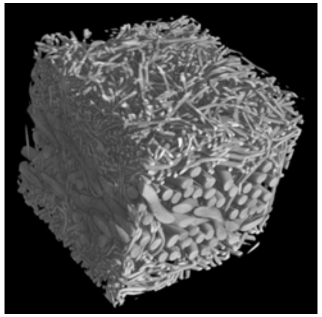
3d analysis opens new opportunities like

- fitting of three dimensional geometric models
- computing macroscopic material properties (permeability, filtration, stability…) using numeric simulations in the modell or the preprocessed 3d image
- determining the optimal material parameters for the desired properties

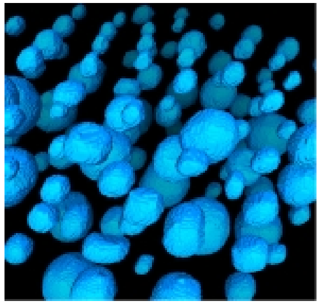


Flow of air through a non-woven, flow simulation
A. Wiegmann, ITWM, visualisation C. Lojewski, ITWM
modeling: GeoDict

Field features (Minkowski functionals)



$L_V = 23.3\text{mm}^{-2}$



$\chi = 133$

Volume V, surface S, integral of mean curvature M, integral of total curvature K (Euler number $\chi = 4\pi K$)

Interpretation:

- fibers - $L_V = \dfrac{M_V}{\pi(1 - V_V)}$ (specific fiber length)
- isolated particles – Euler number = number of particles
- open foam - $\dfrac{S_V}{\pi L_V}$ mean thickness of edges

Theorem (Hadwiger, 1957): Every nonnegative, motion invariant, monotonously increasing, c-additive functional on the convex bodies is a linear combination of the Minkowski functionals. However, Minkowski functionals do not describe all features of a microstructure. (Baddeley, Averback, 1983): example with same Minkowski functionals, completely different tortuosity.

Crofton's intersection formulae

Minkowski functionals from intersections with planes/lines/points,
measurement of the Minkowski functionals by counting

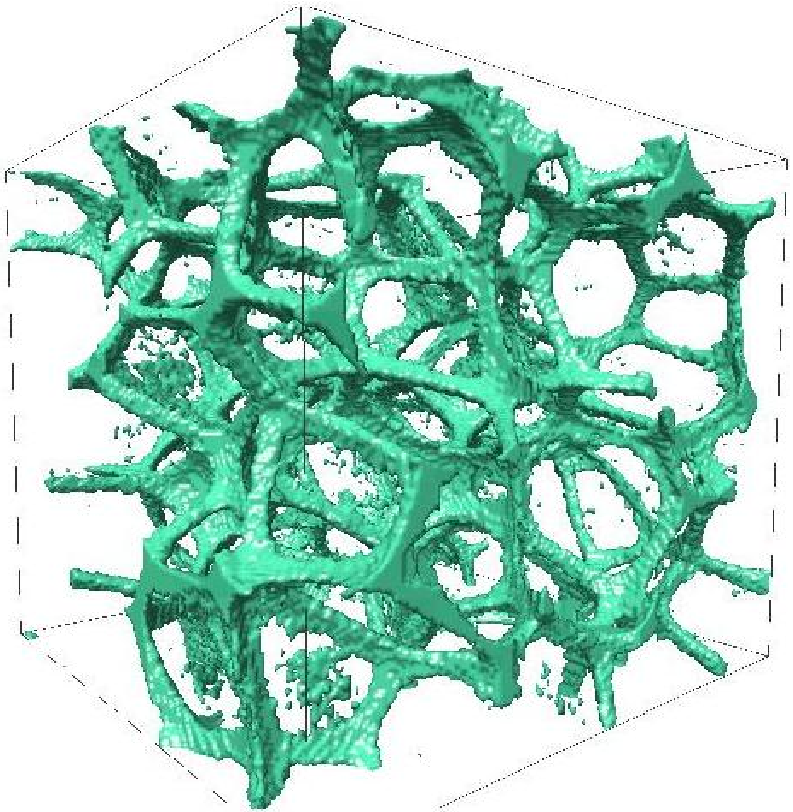
$$
\begin{array}{rlll}
d=3 & d=2 & d=1 & d=0 \\
\hline
V(X) & = \int A(X \cap E_{r,\omega_0})\,dr & = \int L(X \cap e_{y,\omega_0})\,dy & = \int \chi(X \cap \{x\})\,dx \\
S(X) & = \frac{4}{\pi} \int \int L(X \cap E_{r,\omega})\,dr\,\mu(d\omega) & = 4 \int \int \chi(X \cap e_{y,\omega})\,dy\,\mu(d\omega) & \\
M(X) & = 2\pi \int \int \chi(X \cap E_{r,\omega})\,dr\,\mu(d\omega) & & \\
\hline
\end{array}
$$

$E_{r,\omega}$ – plane at distance r from the origin, direction ω

$e_{y,\omega}$ – line with intersection point y in plane with direction ω

μ – invariant measure on $\mathbb{S}^2$

Analysis of open foams



- measurement of field features, compute e.g. mean length of edges per unit volume
- model based computation of quantities relevant for application (e.g. mean size of cells, ppi value)
- segmentation/reconstruction of the cells, measurement of pore sizes
- spectral analysis

Characteristics of the edge system from Minkowski functionals

Example: nickel foam

Estimated densities of the Minkowski functionals:

$$\begin{aligned} V_V &= 14.5\% \\ S_V &= 7.54\text{mm}^{-1} \\ M_V &= 57.6\text{mm}^{-2} \end{aligned}$$

Porosity: $p = 1 - V_V = 85.5\%$

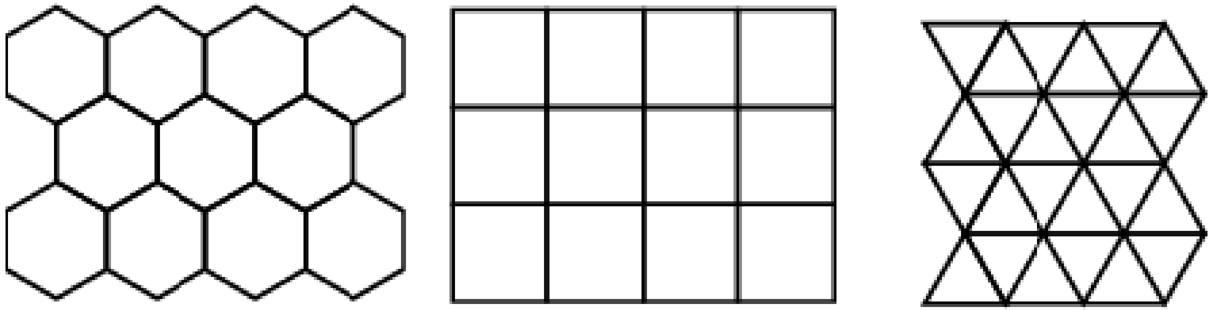
Edge density (total edge length per unit volume): $L_V = \dfrac{M_V}{\pi(1 - V_V)} = 21.45\text{mm}^{-2}$

Mean edge thickness: $\dfrac{S_V}{\pi M_V} = 111.9\mu\text{m}$

Mean section area of the edges: $\dfrac{V_V}{L_V} = 6750\mu\text{m}^2$

Open foams as edge system of a tessellation

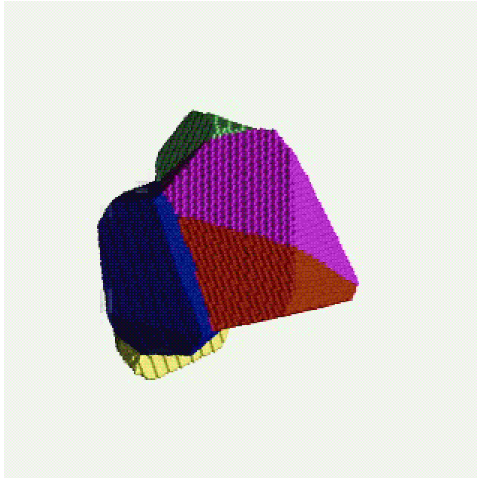
Tessellation – partitioning of space in cells



Models for open foam should

- be macroscopically homogeneous, microscopically heterogeneous
- have predominantly pentagonal faces
- be analytically describable.

Random Voronoi tessellations

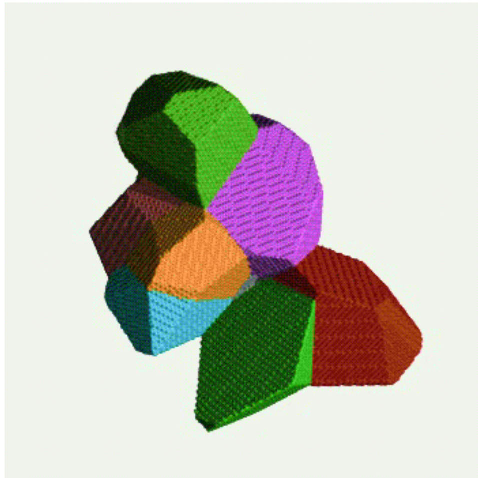


Step 1: Generate cell centres

Step 2: Centers grow uniformly. Growth stops when touching.
Each center is assigned its influence region.

Poisson Voronoi: Centers are i.i.d. uniform.

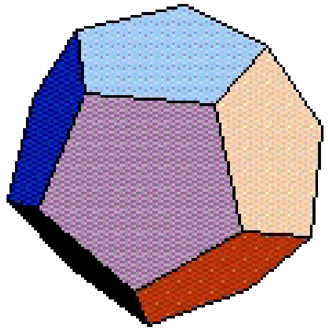
Drawback: cells not sufficiently regular



Hard-core Voronoi: centers have minimal distance R

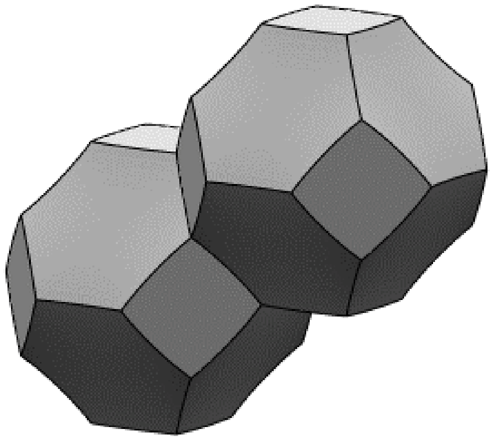
Drawback: no analytic description, too many faces with 4 vertices

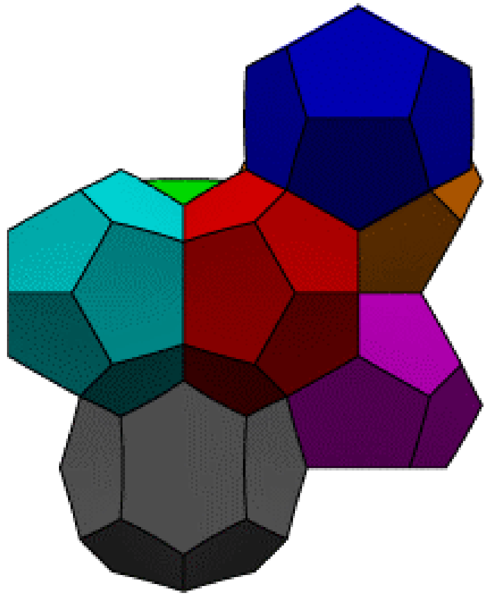
Deterministic tessellations



Desired: tessellation by regular dodecahedra

Problem: pentagonal dodecahedra are not space filling





Alternatives: Kelvin foam – identical cells
(truncated octahedra)

Weaire-Phelan foam

Drawback: microscopic heterogeneity not captured

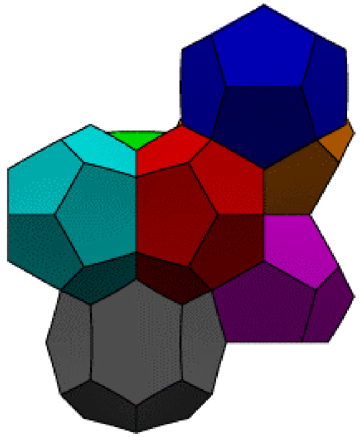
The Weaire-Phelan foam

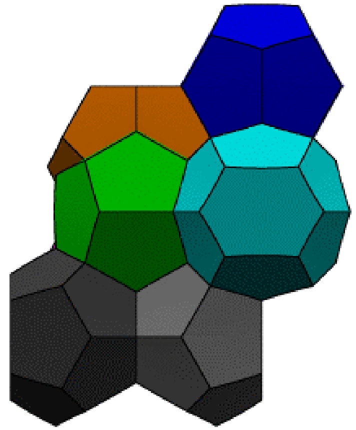
2 types of cells: pentagonal dodecahedra and
polyhedra with 14 faces (2 hexagonal and 12 pentagonal)

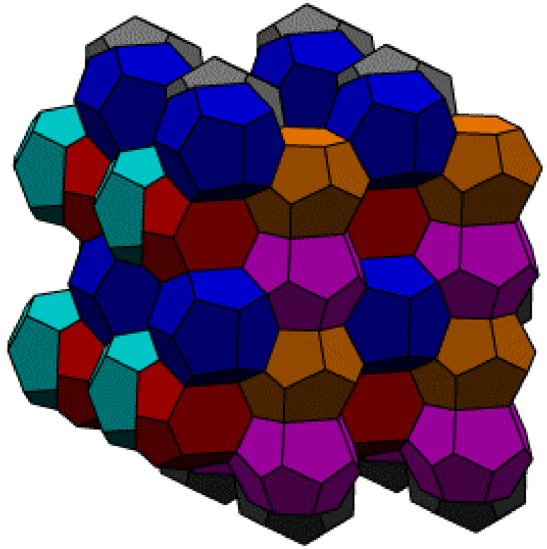
Proportion of the 2 types: 2:6

A version of the Weaire-Phelan foam with slightly bend faces is the currently best known solution for Kelvin‘s problem – minimal surface of equal volume cells.

Images: Ken Brakke, www.susqu.edu/facstaff/b/brakke/





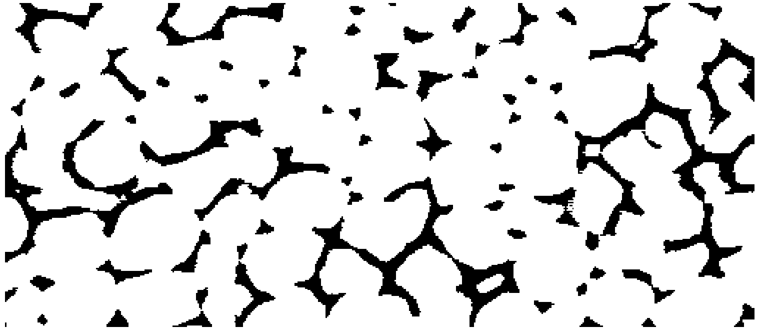


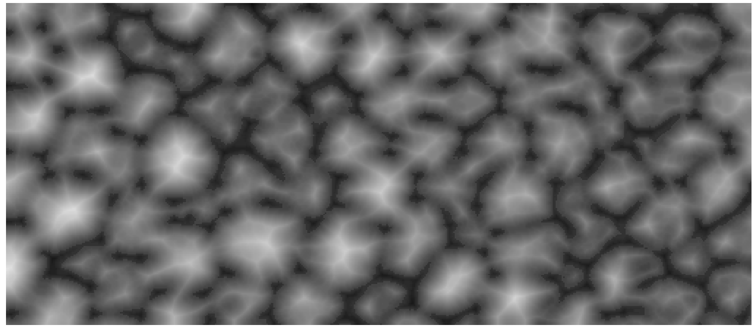
Measurements under model assumptions

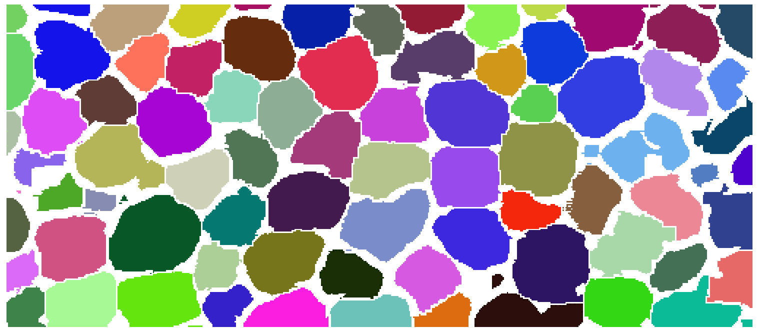
Example: nickel foam, Weaire-Phelan model, in braces Poisson-Voronoi tessellation

mean number of cells per unit volume	8.1mm^{-3} (7.0mm^{-3})
mean cell volume	0.123mm^3 (0.142mm^3)
ppi (pores per inch)	67.5 (70.8)
mean cell diameter	0.741mm (0.761mm)
mean diameter of faces	0.381mm (0.374mm)
mean area of faces	0.099mm^2 (0.102mm^2)

Segmentation/reconstruction of the cells







Step 1: binarization

Step 2: distance transformation – assigns each background pixel its distance to the edge system

Step 3: supression of „wrong“ maxima

Step 4: watershed transform – interpretation of greyvalues as topographic depths, „flooding“ of the catchment basins

Step 5: superposition with original edge system

Step 6: measuring features of cells (e.g. size)

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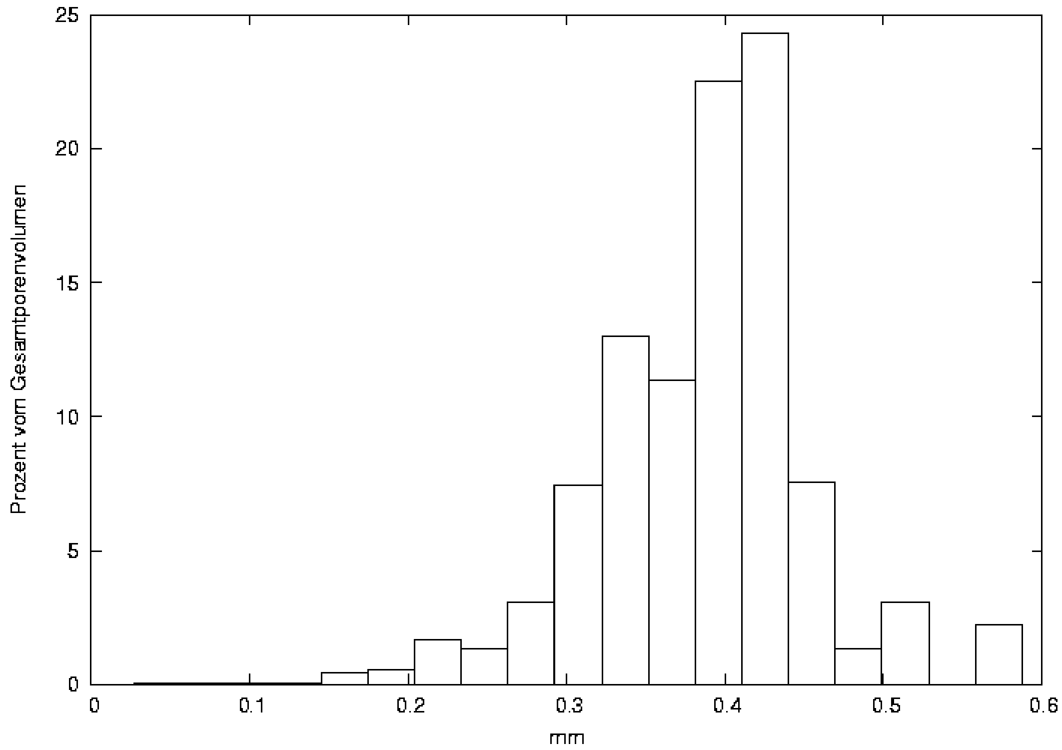
Pore size distribution

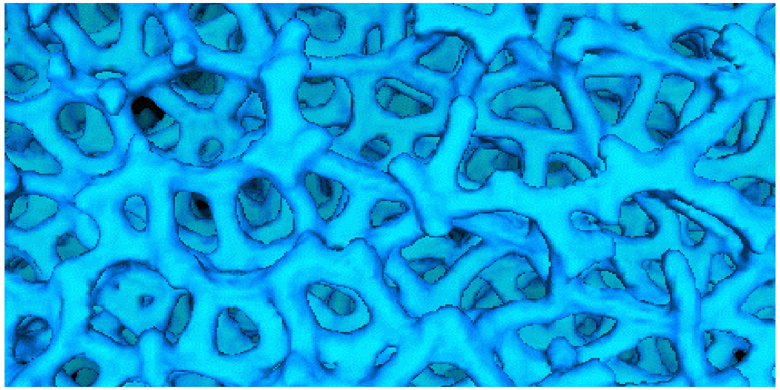


Example: nickel foam

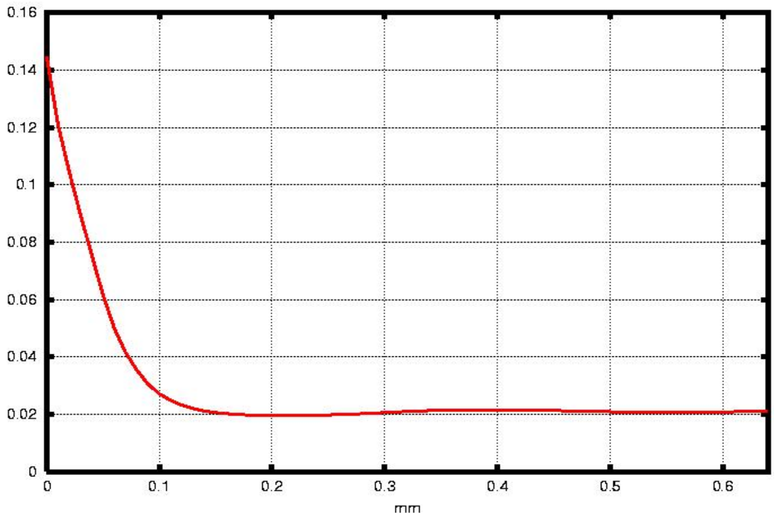
Pore size = diameter of ball of equal volume

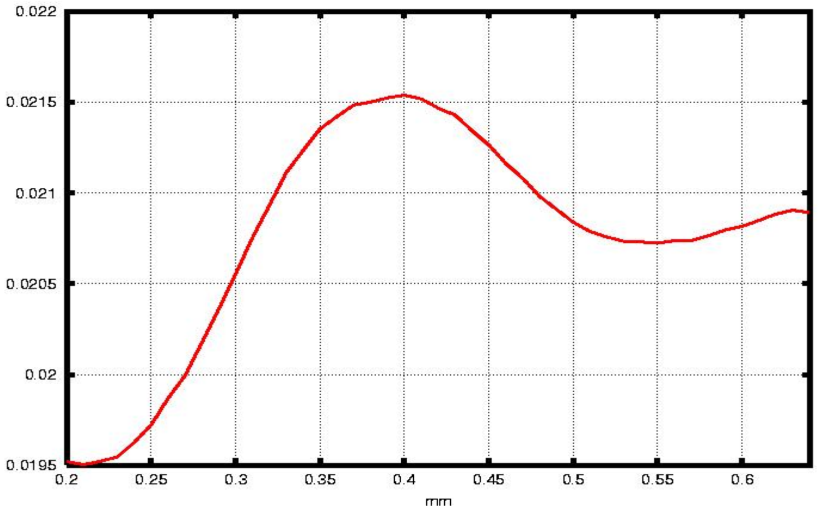
Pores cutting the edge are not considered (size biased sample), therefore the volume weighted distribution is given.

Spectral analysis



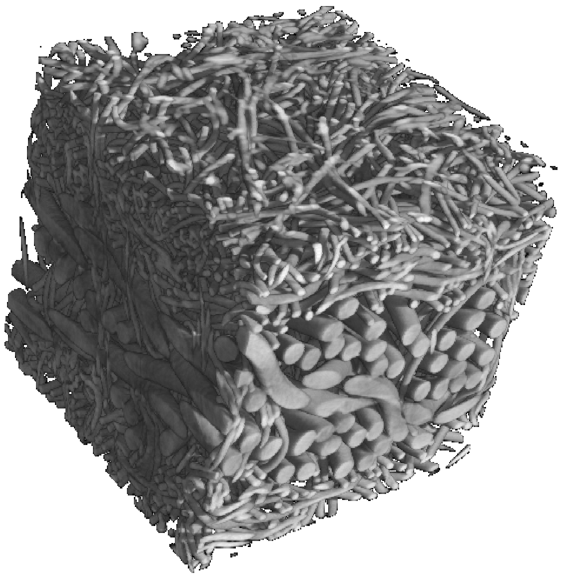
Covariance of the open nickel foam,
local maximum at 0.4mm corresponds to
diameter of faces.

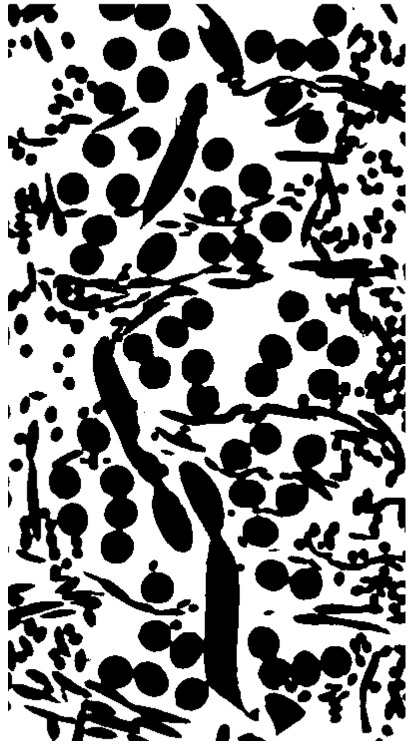




Analysis of fiber material

Essential characteristics of the fiber system: specific fiber length and directional distribution





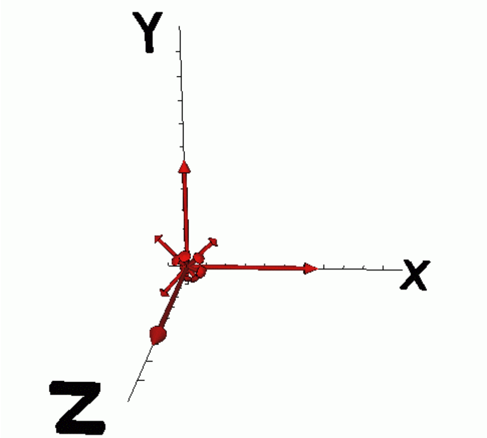
Directional distribution of the fibers

Directional information is contained in generalized projections when computing the integral of mean curvature (Crofton formulae)

$$\frac{M(X)}{2\pi} = \int\!\!\int \chi(X \cap E_{r,\omega})\, dr\, \mu(d\omega) = \int \wp_M^\omega (X \cap E_{r,\omega})\, \mu(d\omega)$$

Directional distribution – distribution of the direction in the typical fiber point, connection to projections

$$\wp_M^\omega(X) = \int_{S^2} |\langle \omega, u \rangle|\, \vartheta(du).$$



Discrete inversion of the cosine transformation:
linear program (Kiderlen 2000, result discrete) or
approximation by finite expansion in spherical harmonics
(Legendre polynomials, result with smooth density)

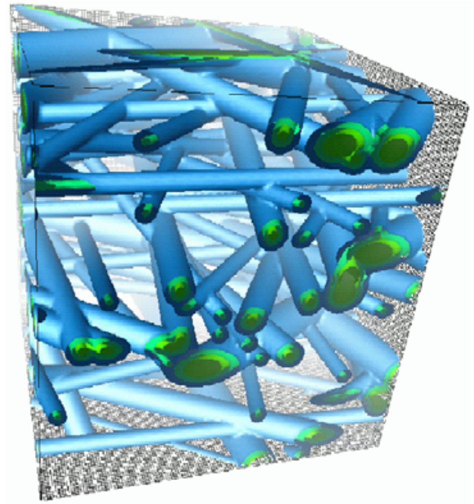
Characterization of the pore space in fiber material

Problem: no clear definition for „pore“

Possibilities for characterization:

1. Spherical contact distribution – distribution of the distance to the nearest fiber
2. Granulometry distribution – sieving of pores with growing mesh size using morphological openings with growing structuring element
3. Percolation – measure fraction of pore space being for balls of growing size
4. Tortuosity – mean length of paths inside the pore space/thickness of the material

Modeling of Microstructures



modeling of
microscopically heterogeneous but
macroscopically homogeneous
material

- measure geometric characteristics

- choose a model (basis: spatially homogeneous models from stochastic geometry)

-determine model parameters (fit the model)

- goal: optimal acoustic absorption

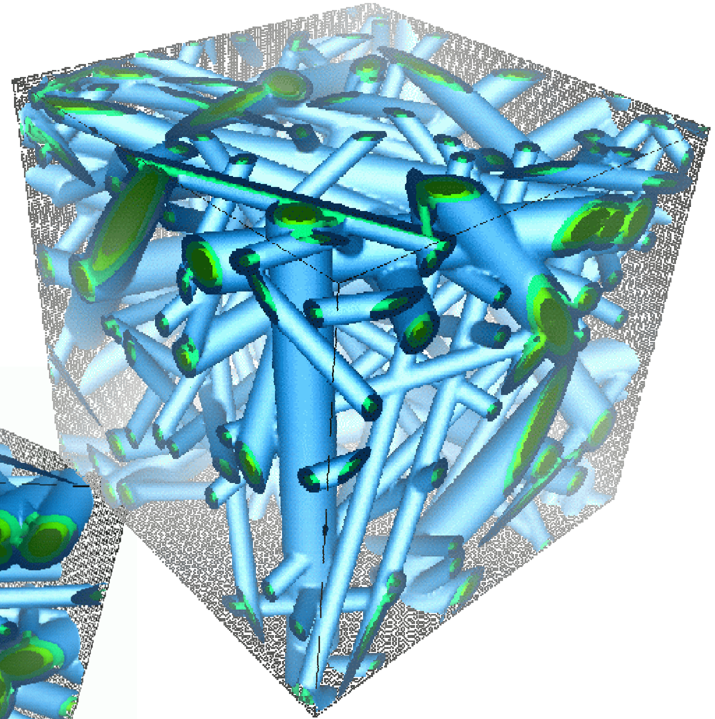
Modeling of a stacked fiber non-woven

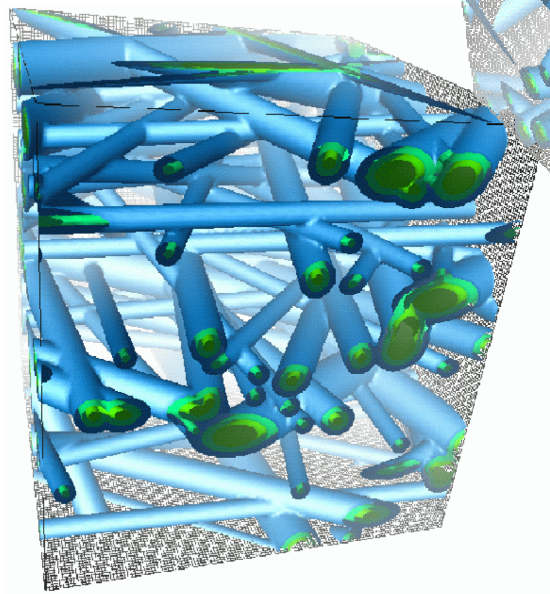
Known: pressed non-woven, long fibers, fiber radia

Image data: confocal laser scanning microscopy, 2D sections

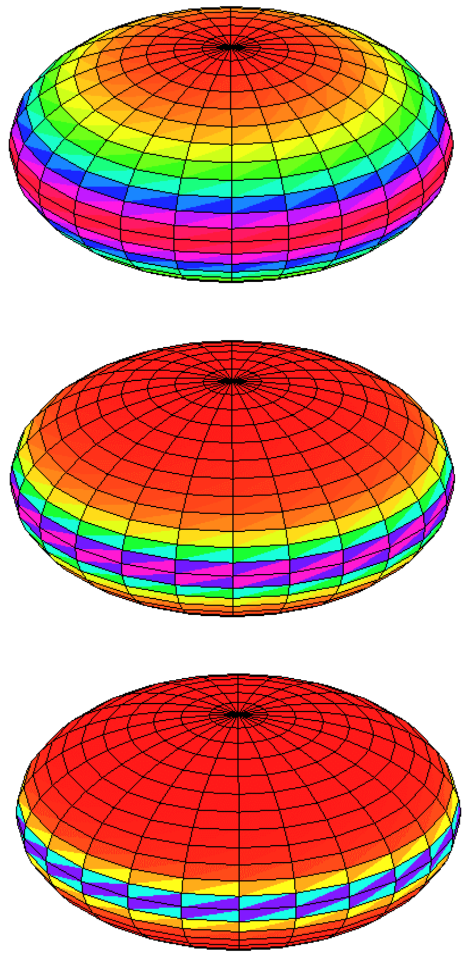
Model: cylinders, centres forming a Poisson line process with a one parametric directional distribution

Parameters to determine: length intensity, anisotropy parameter





Directional distribution



Isotropy: direction given by point uniformly distributed on sphere, that is
longitude uniformly distributed,
latitude weighted by $\sin\theta$

Pressing: directions near the equator preferred

Density: $$\frac{1}{4\pi}\frac{\beta\sin\theta}{\left(1+(\beta^2-1)\cos^2\theta\right)^{\frac{3}{2}}},$$

$$\theta\in[0,\pi),\phi\in[0,2\pi).$$

Estimation of the model parameters

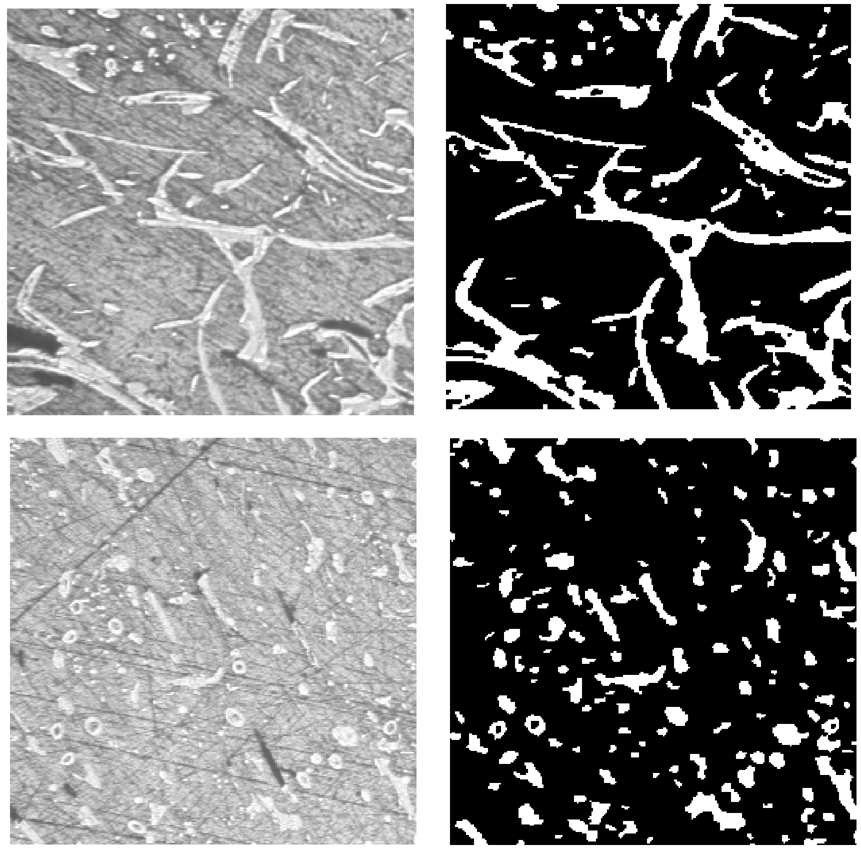
Known: fiber section profiles, porosity

To estimate: anisotropy parameter from intensities of fibers in parallel and orthogonal planar sections

Estimation of the fiber intensity using an edge corrected component count

Result: 2.93 – intermediate degree of pressing

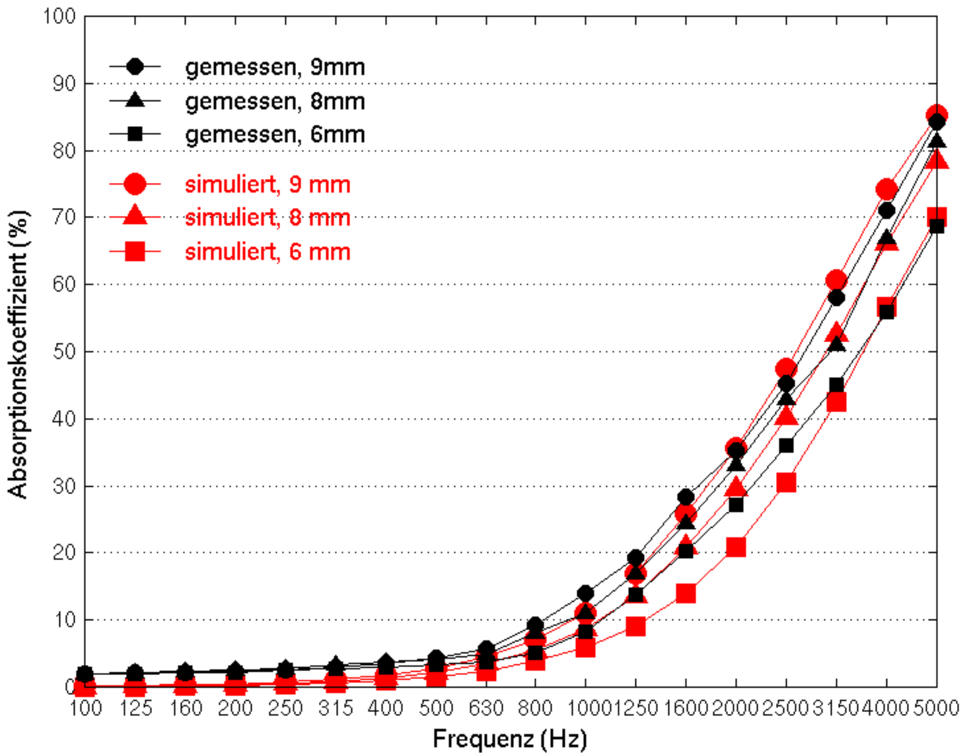
Preparation and light microscopic images, C. Maas,
Institute for Materials Science, Universität des Saarlandes



Segmentation: Canny edge detection, region growing

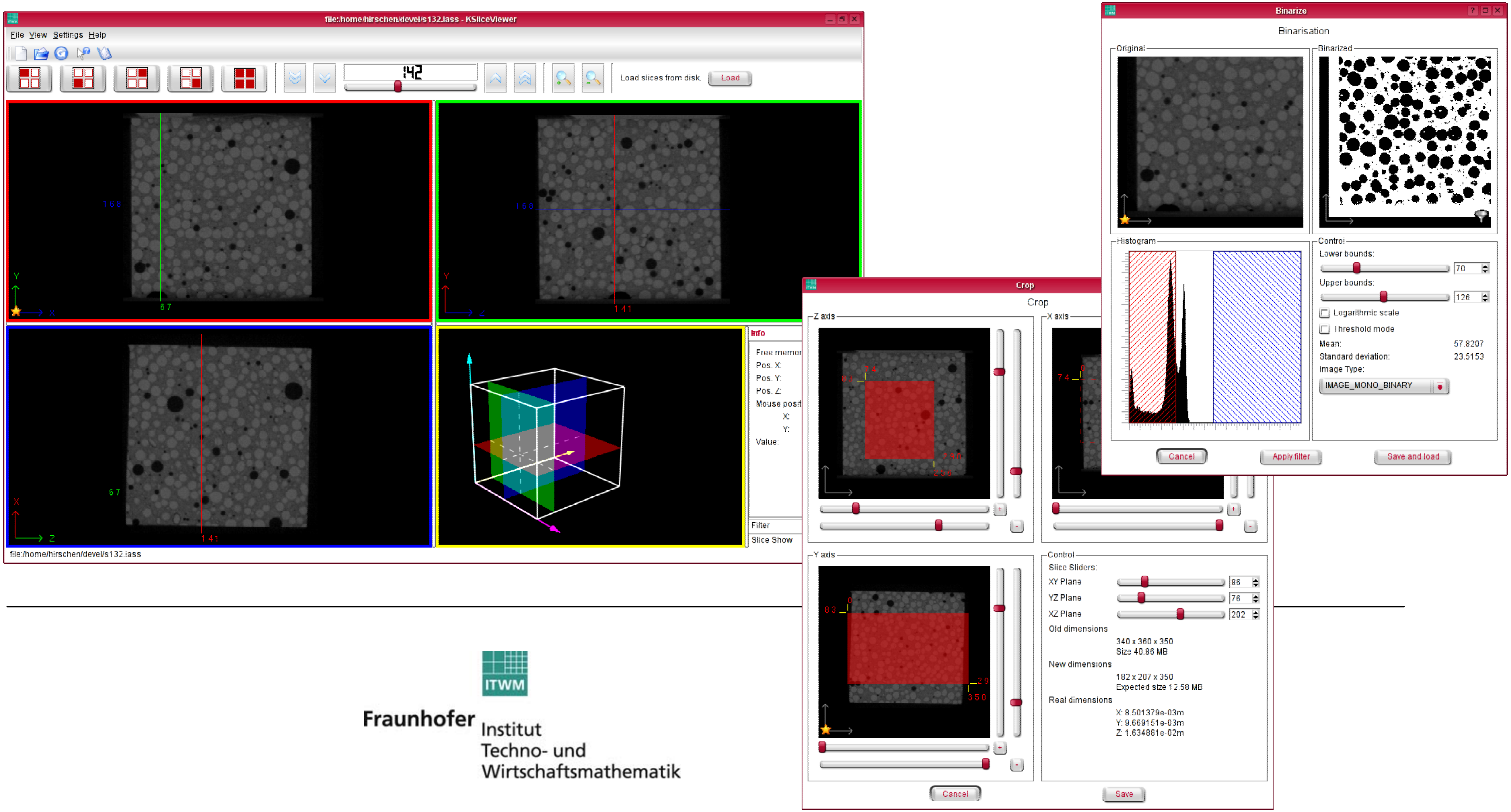
Virtual material design

1. (3d) image of the microstructure
2. Fitting a geometry model
3. Numeric simulation of macroscopic materials properties (permeability, acoustic absorption, stability...)
4. Change of model parameters (e.g. fiber profiles or thickness)
5. Iteration of 3. and 4.
   ➡ optimization



Products: current - a4iL (C library for Linux)

soon (10/2004) – MAVI, MAVI-OpenFoam (with GUI, system independent)



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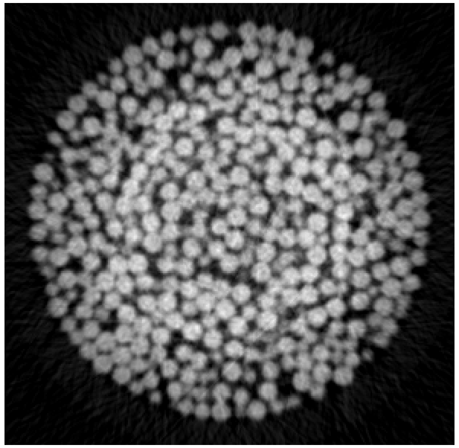
Challenges

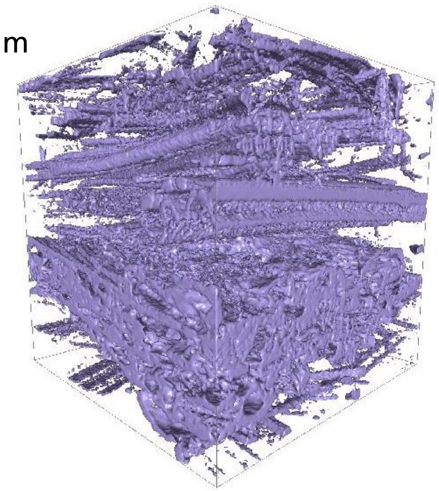
Image aquisition:
- resolution,
- absorption contrast

Technical:
- image/data sizes (2GB, soon 16GB),
- visualization

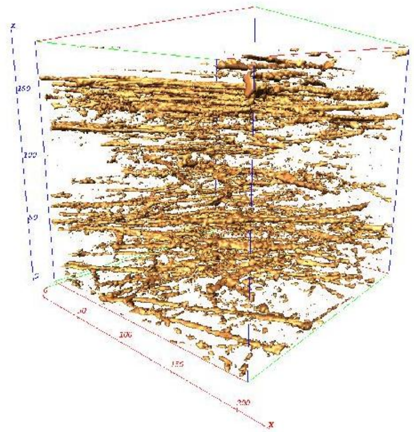
Mathematical/algorithmic:
- difficulties/ambiguities when generalising 2d algorithms
- efficiency (due to image sizes)
- new tasks (e.g. pore size distribution in fiber materials)
- segmentation



Straw, IZFP, 15µm



100 pixels = 3.91e-4 m



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Tanja Sych, Marius Renn, Steffi Peters