

Before we start or in a break...

Check that you have the image processing toolbox installed in Matlab

In the Matlab command window write: help medfilt3

**If you get a message similar to: 'medfilt3' requires Image Processing Toolbox,
It means that you haven't got the required toolbox installed.
Click the blue text link, sign in and install it.**

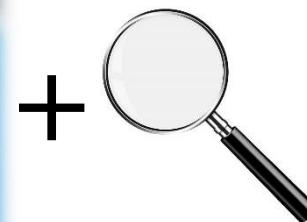
Peter Stanley Jørgensen, psjq@dtu.dk
DTU Energy

Quantitative structure characterization from 3D images

Overview

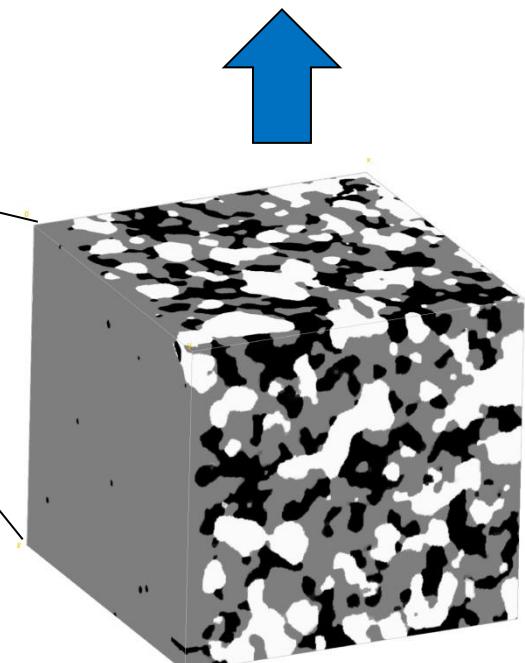


Seeing is believing...



...measuring is knowing... ...or is it?

$$x = ? \pm e$$



Great imaging facilities at DTU and nearby

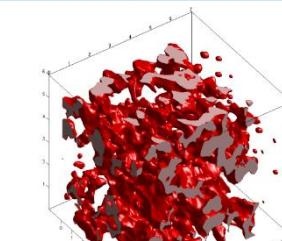
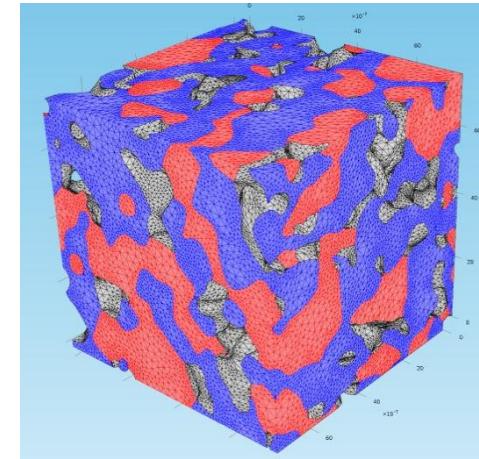


Quantitative applications of 3D image data?

- A source of 3D mesh data for modelling of physics, simulation, visualization etc.
 - Continuum parameters
 - What are the physical properties of the structure?



- A quantitative measurement tool
 - What aspects of the structure gives rise to the physical properties?



Parameter extraction

- Structure size distributions
- Connectivity
- Interfaces
- Etc.

Two main parts to this lecture

- Segmentation
 - Interpreting the image data
- Analysis
 - Performing measurements on the segmented data.
- Exercise
 - Implement a simple pipeline for measuring interface areas in 3D images.

Learning objectives and exam

Course learning objectives for this module

- Identify materials structure property relationship from experimental data

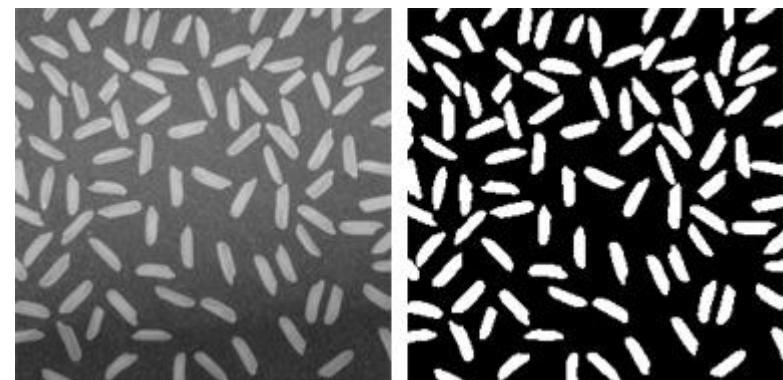
Exam questions

- On the concepts in this presentation
- On the exercise
 - A solution will be uploaded after the module
- You will not be asked to do programming at the exam

Segmentation

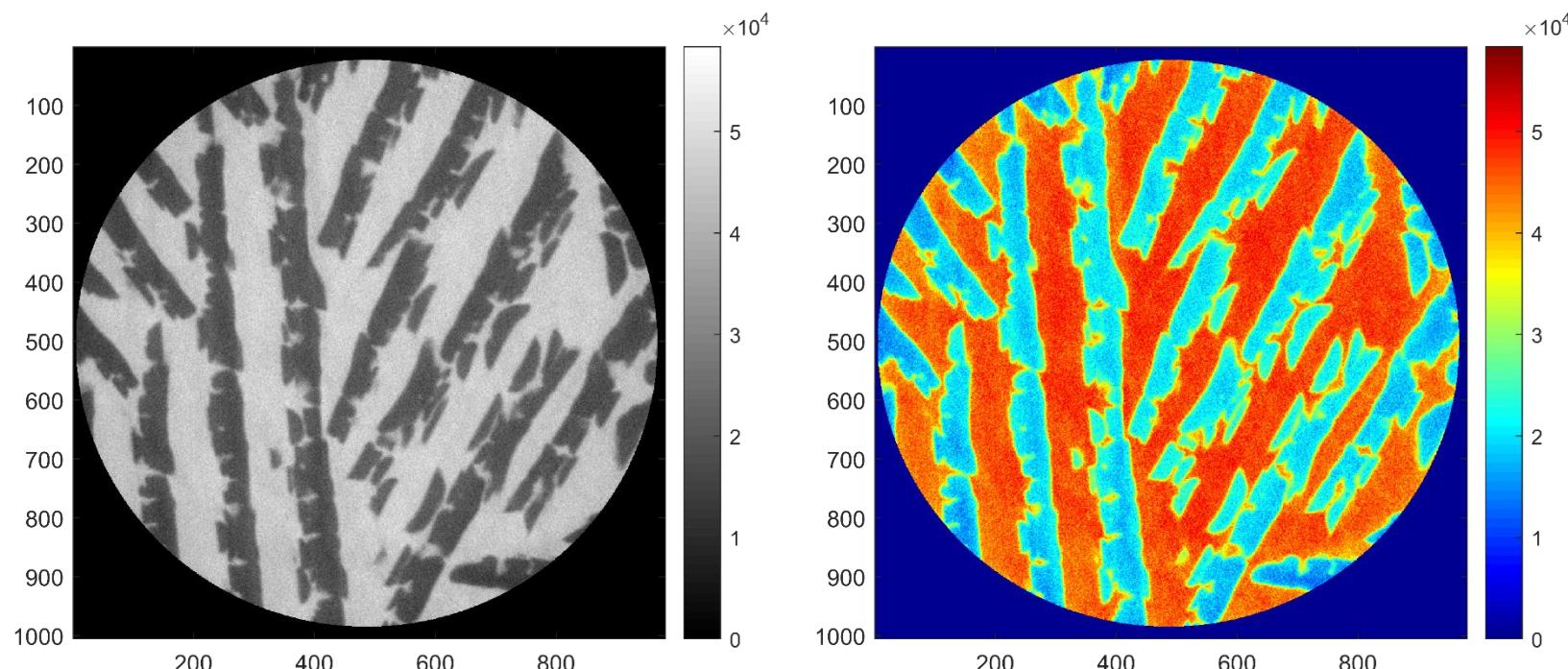
Why is segmentation useful?

- We are giving the computer information about how to interpret the images.
 - Can apply the same computer algorithms on any segmentation to
 - Visualize
 - Measure
- Here we will just introduce the most basic and widely applicable method.



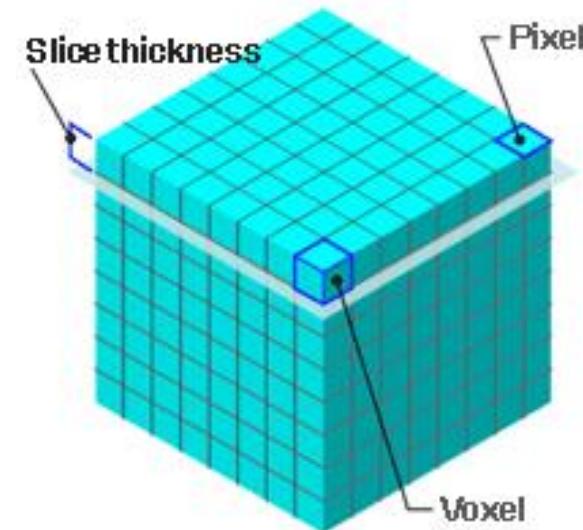
A digital image

- It is just numbers
 - For x-ray tomography it is related to how absorbing the material “in” each voxel is.
- We decide how those numbers are mapped to colours on the screen.

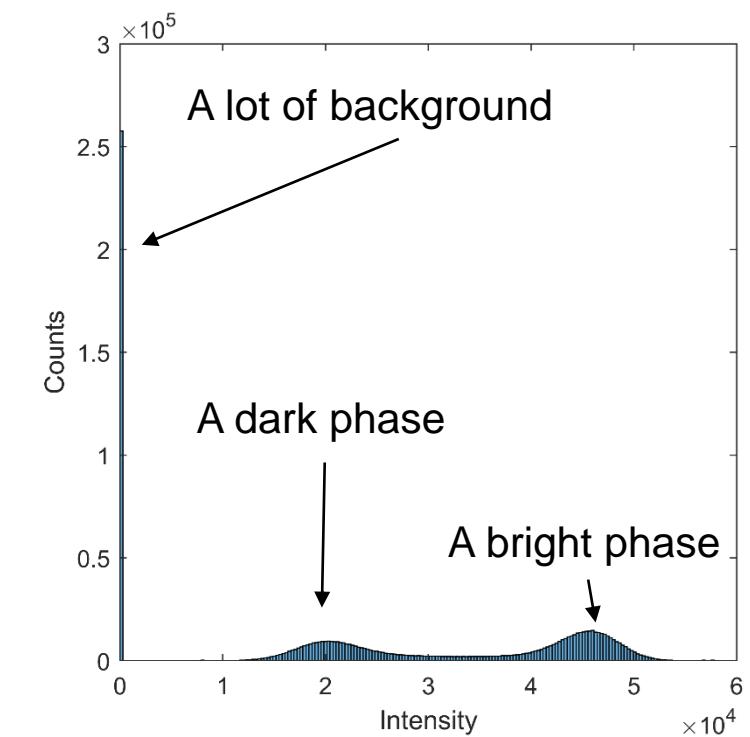
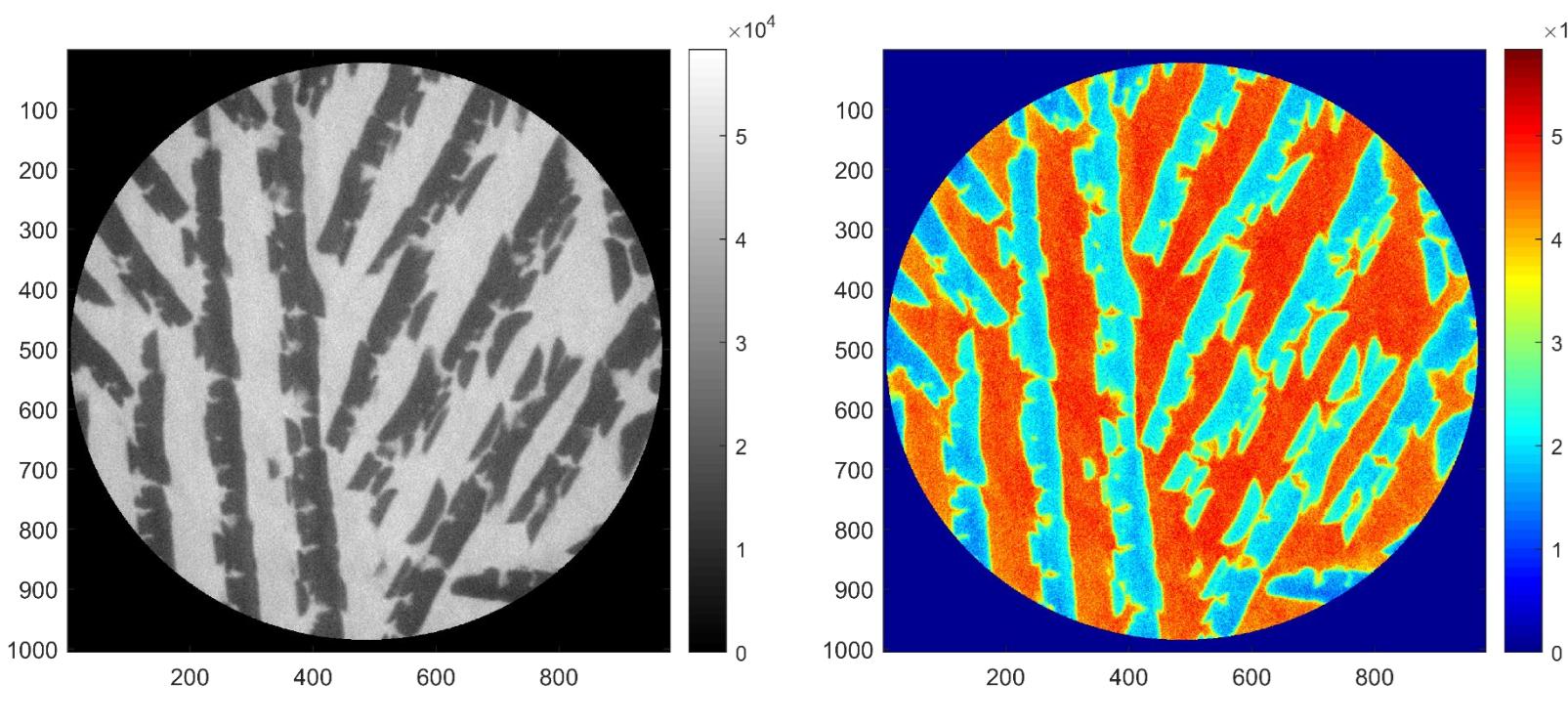


Pixels vs Voxels

- Images consist of pixels (picture elements)
 - Two dimensions
- 3D images consist of voxels (volume elements)
 - Three dimensions
 - A voxel size of [X Y Z]
 - The voxels (cubes) are X by Y by Z
- Knowing the voxel size allows us to perform measurements in physical units on image data.



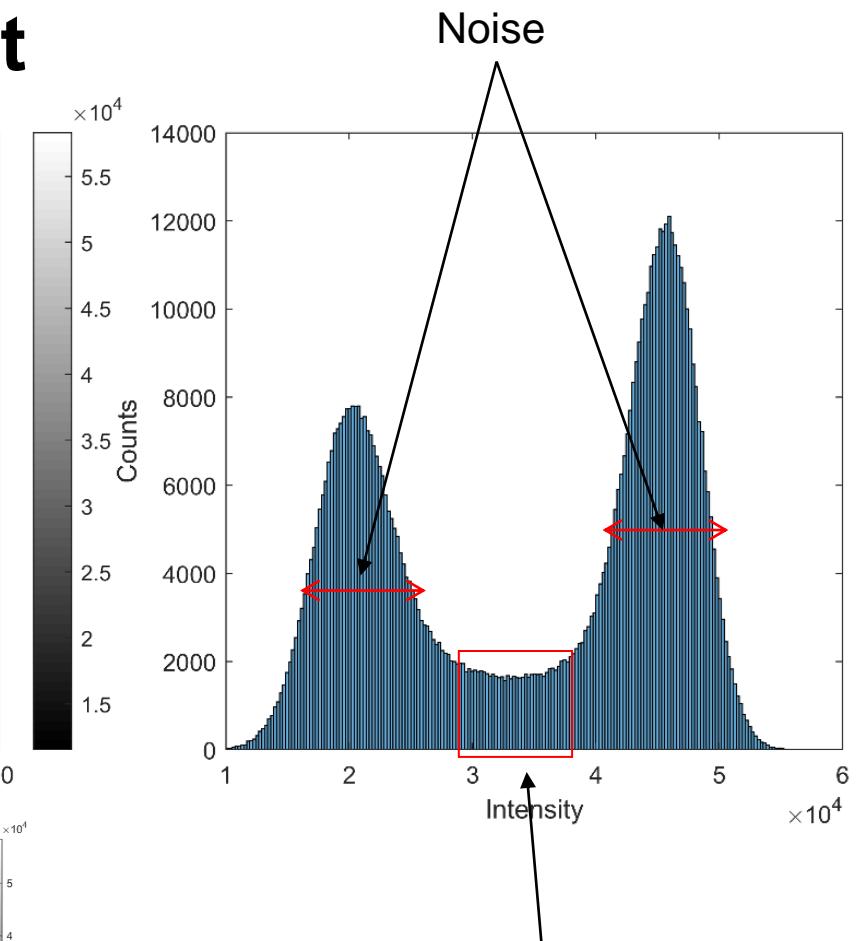
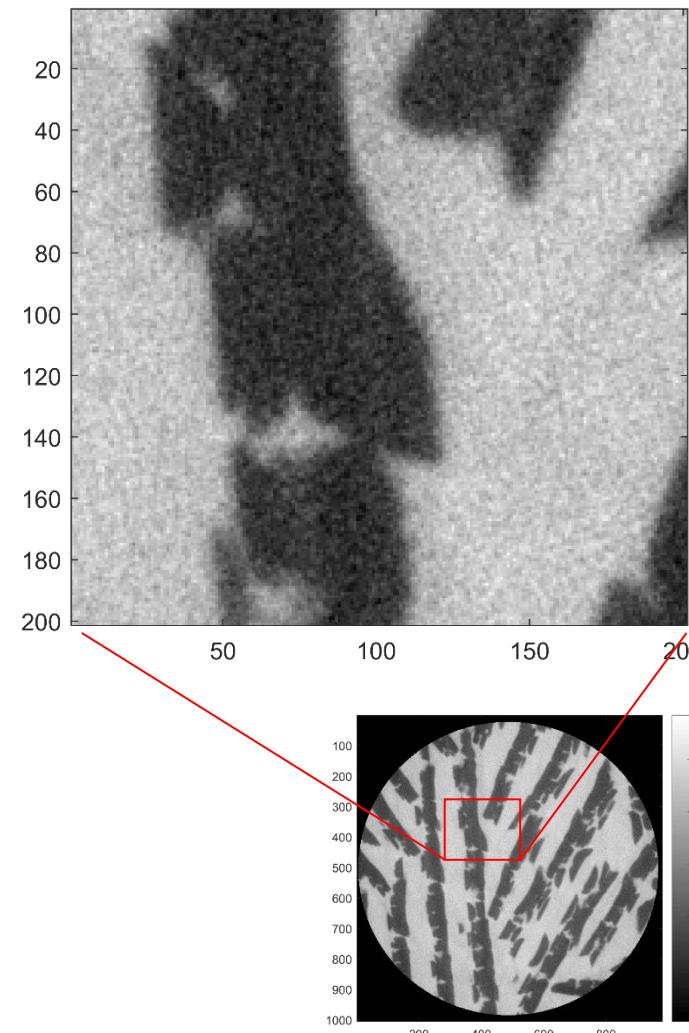
Images and histograms



Only considering the central part

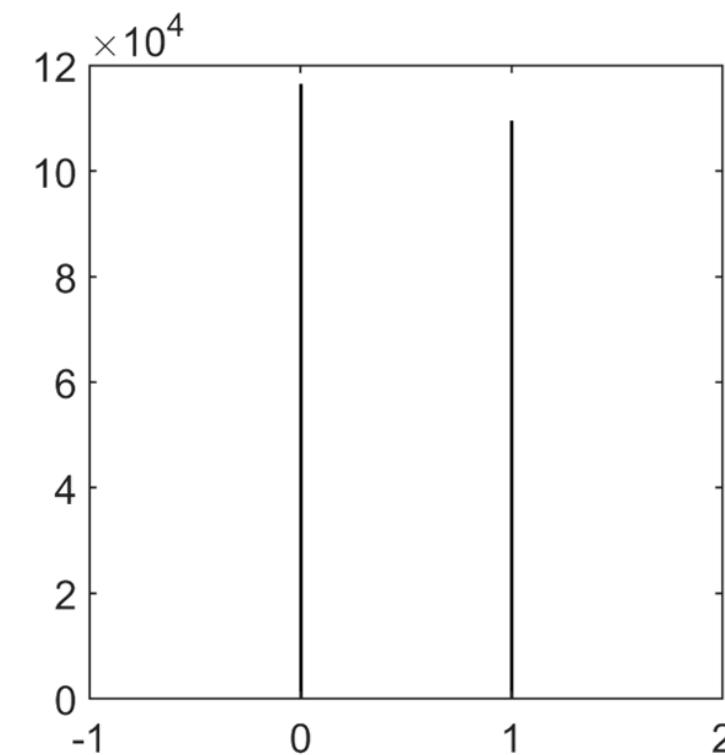
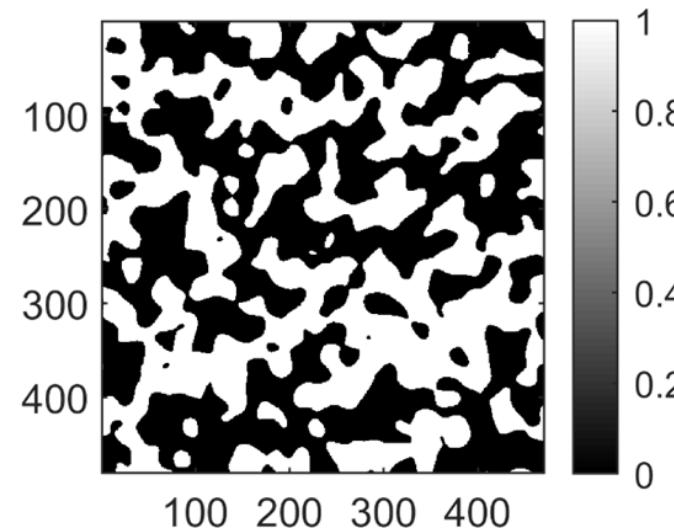
Try to explain how the shape of the histogram relates to the image.

Take a minute to discuss...

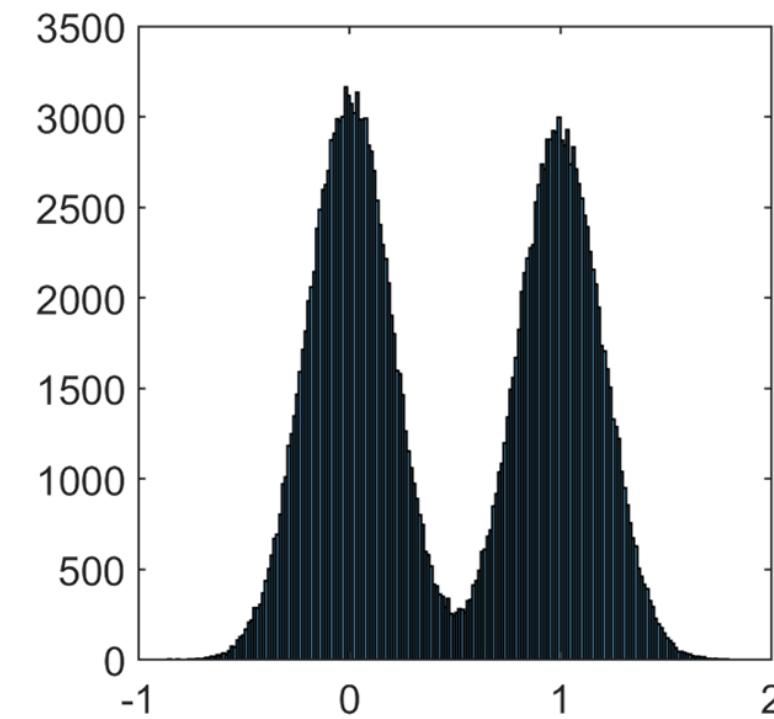
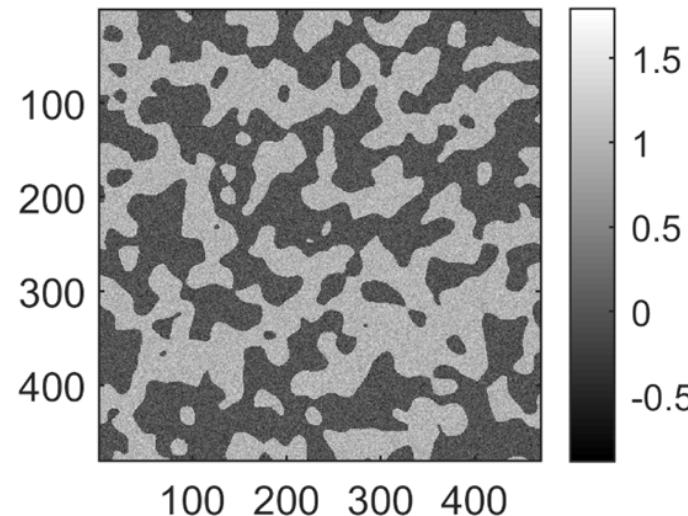


Why are there so many pixels with intensities in this range?

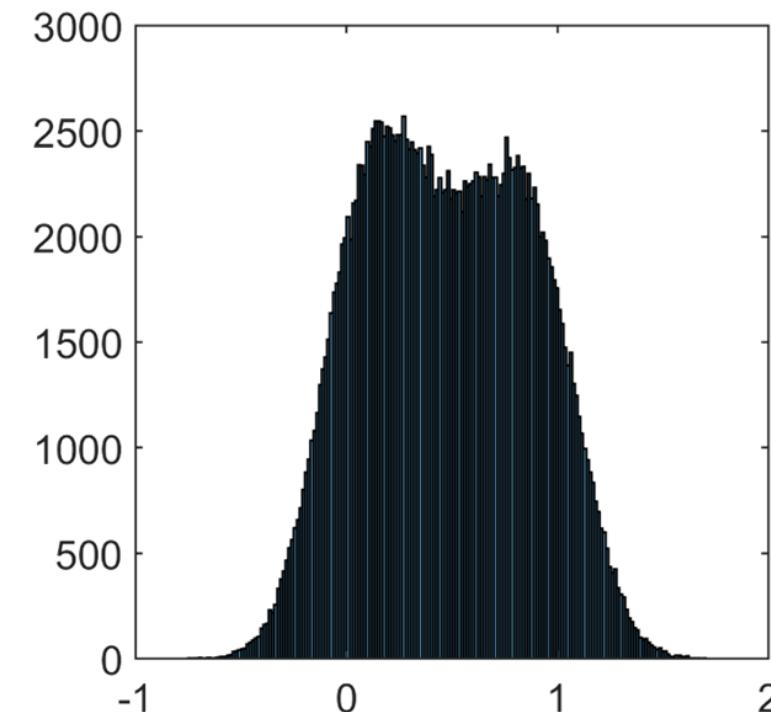
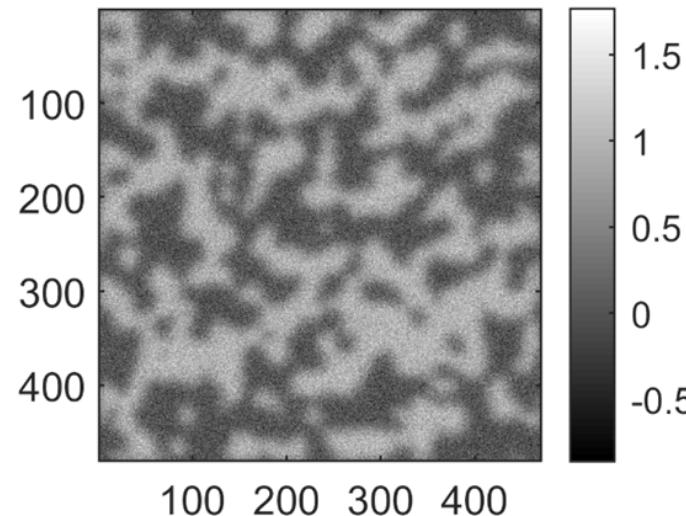
Deconstructing the image and histogram



Structure and Noise

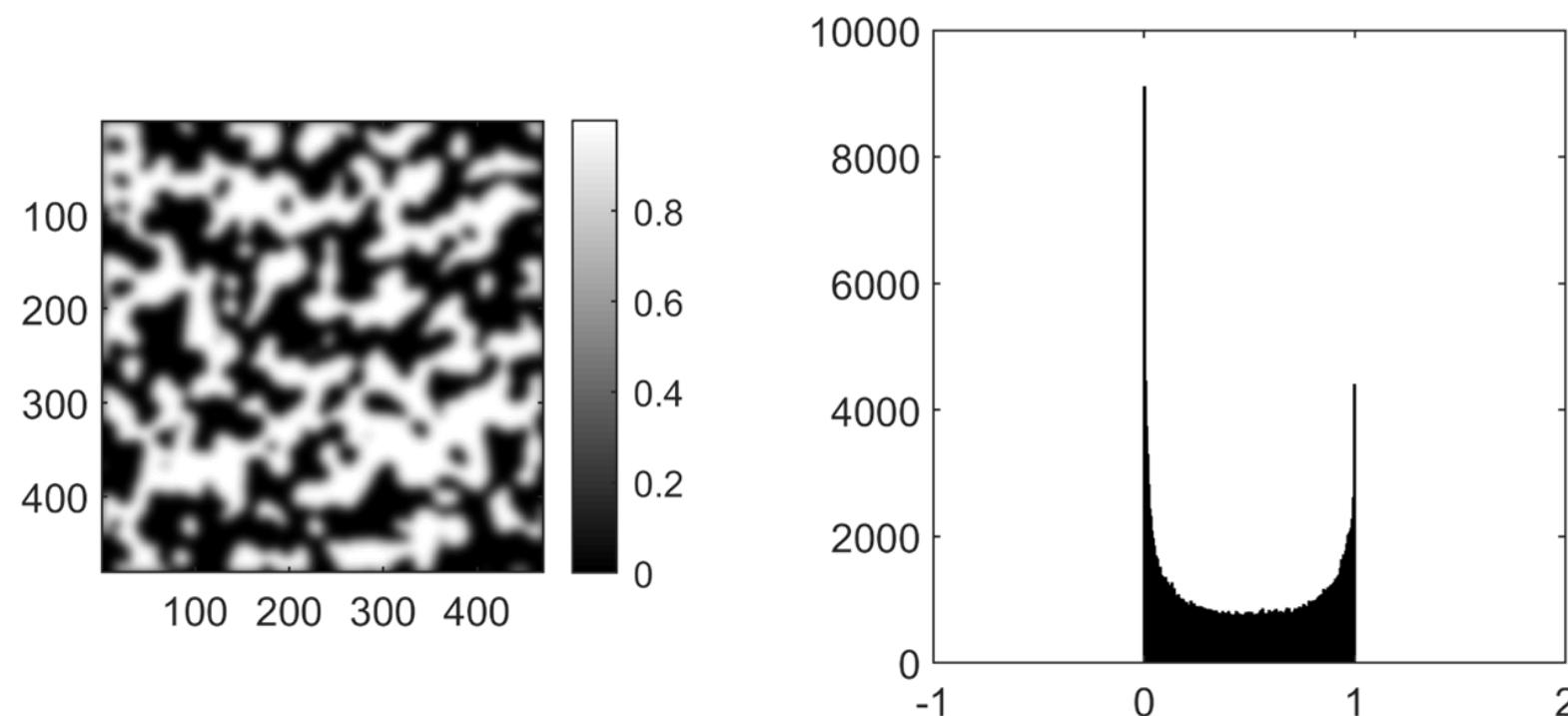


Poor resolution structure + noise



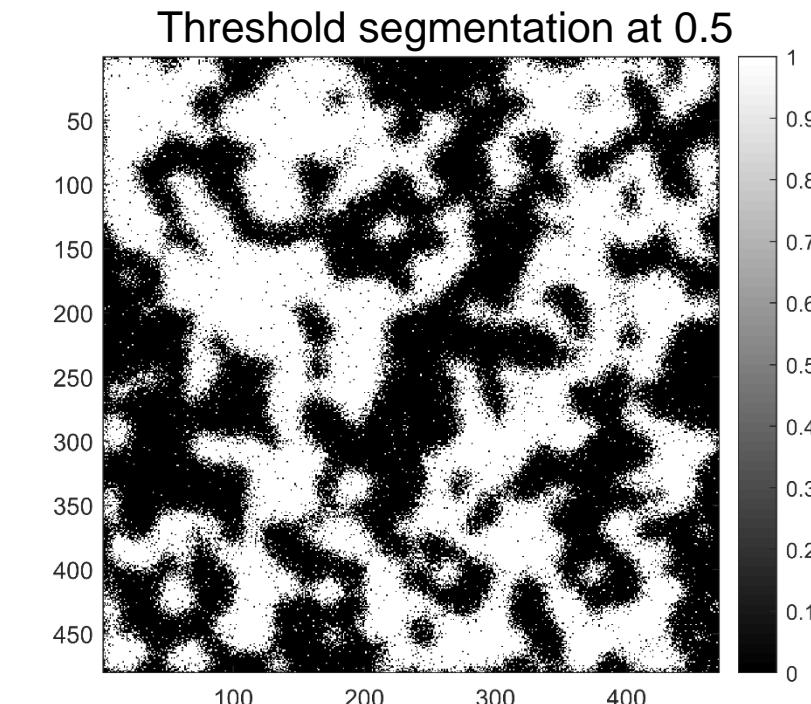
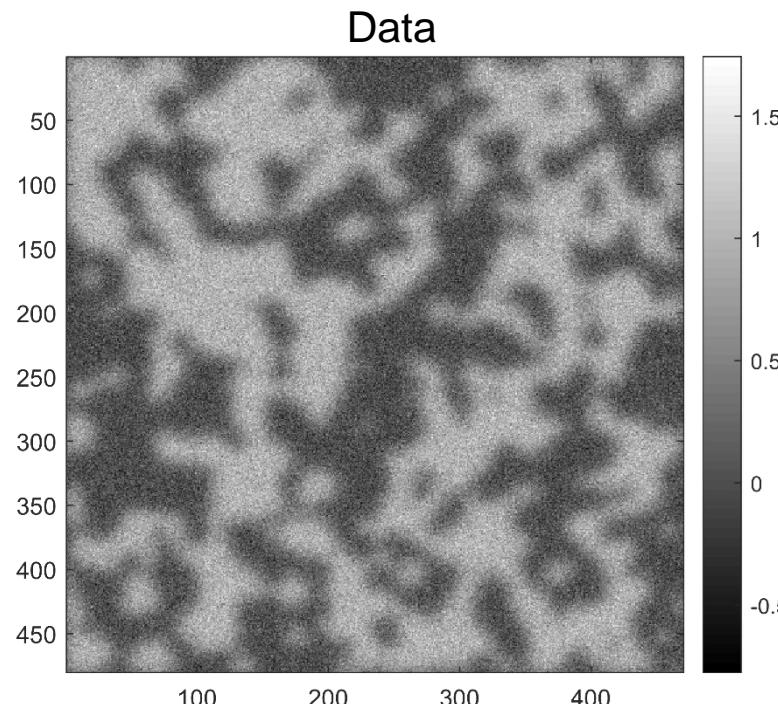
The noise level is exactly the same as before!
Peak positions change!

Poor resolution structure (no noise)



The voxels on the interface can contribute significantly to the histogram shape.

Threshold segmentation



All voxels above a certain threshold intensity level is assigned to the segmented structure.

Why does it look so bad?

- The noise results in a poor correlation between the intensity and the underlying structure

One line of code in Matlab

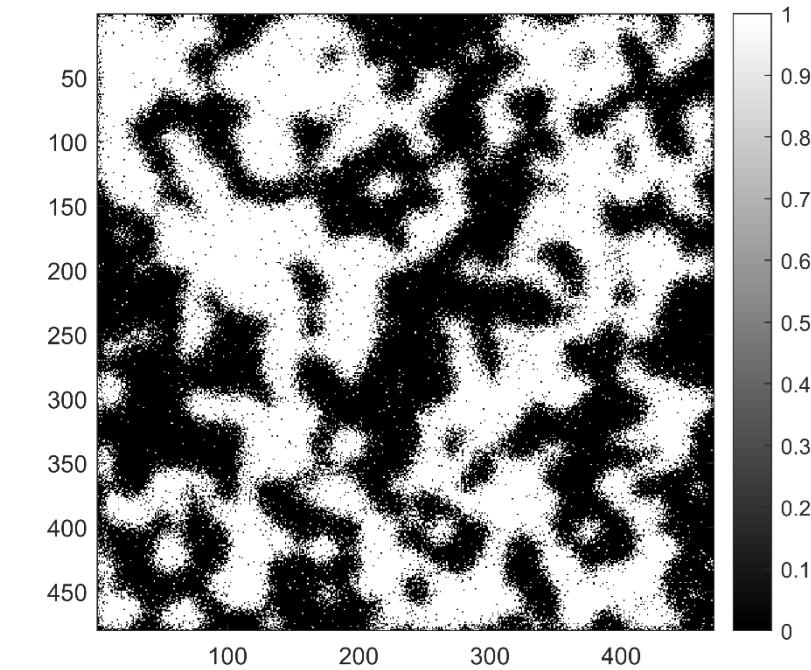
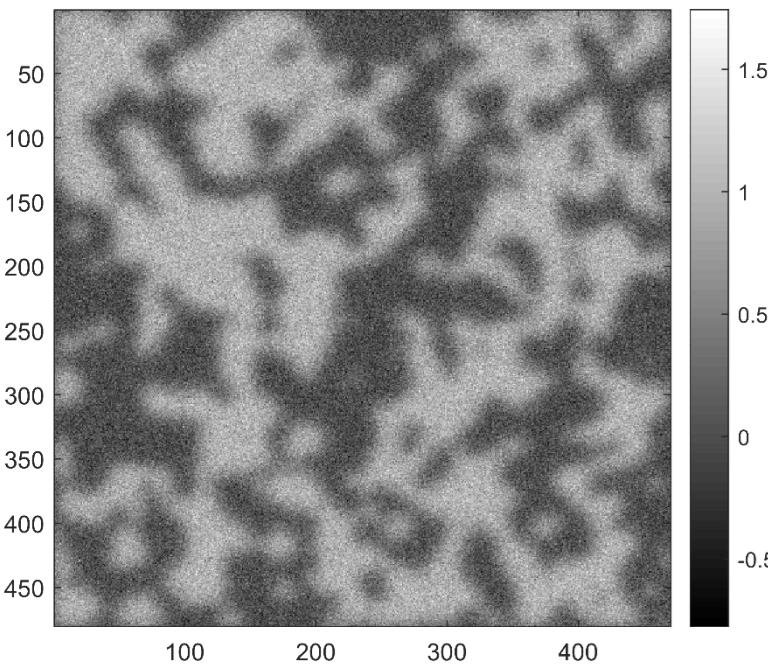
```
% pure threshold  
im_threshold = im_tosegment > 0.5;
```

Break

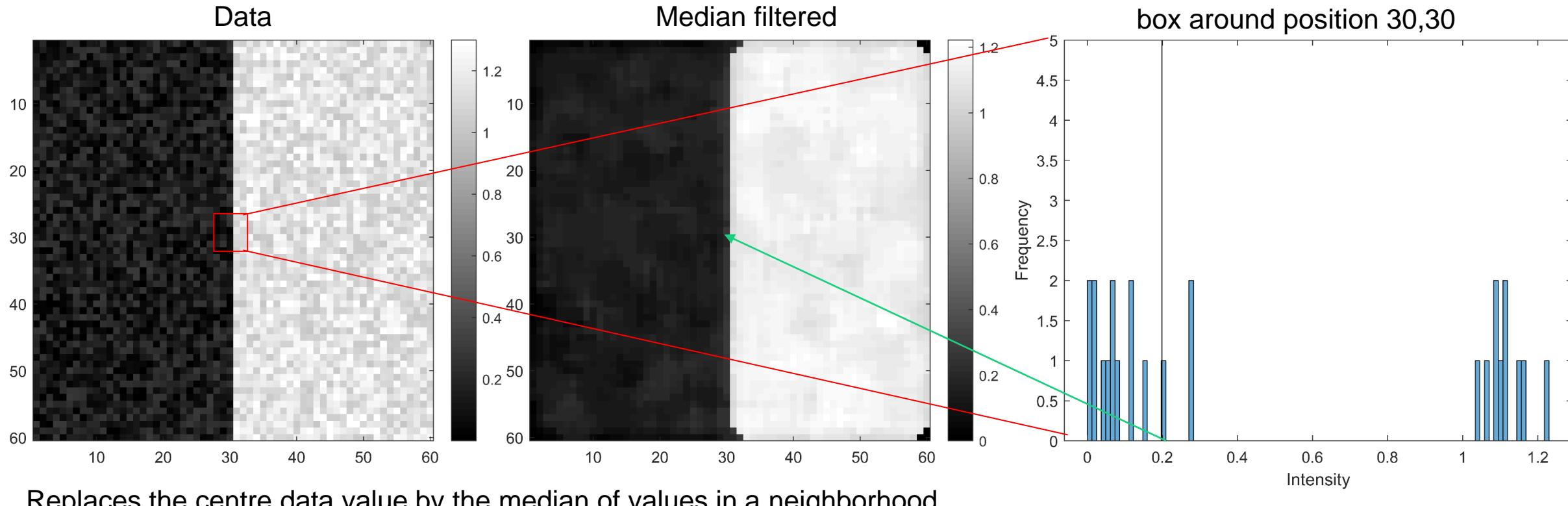
Preprocessing

Filtering

- We assume that neighbouring voxels are likely to be of the same phase.
- Instead of looking at the intensity of one voxel we consider all the intensity values in a neighbourhood around the voxel.

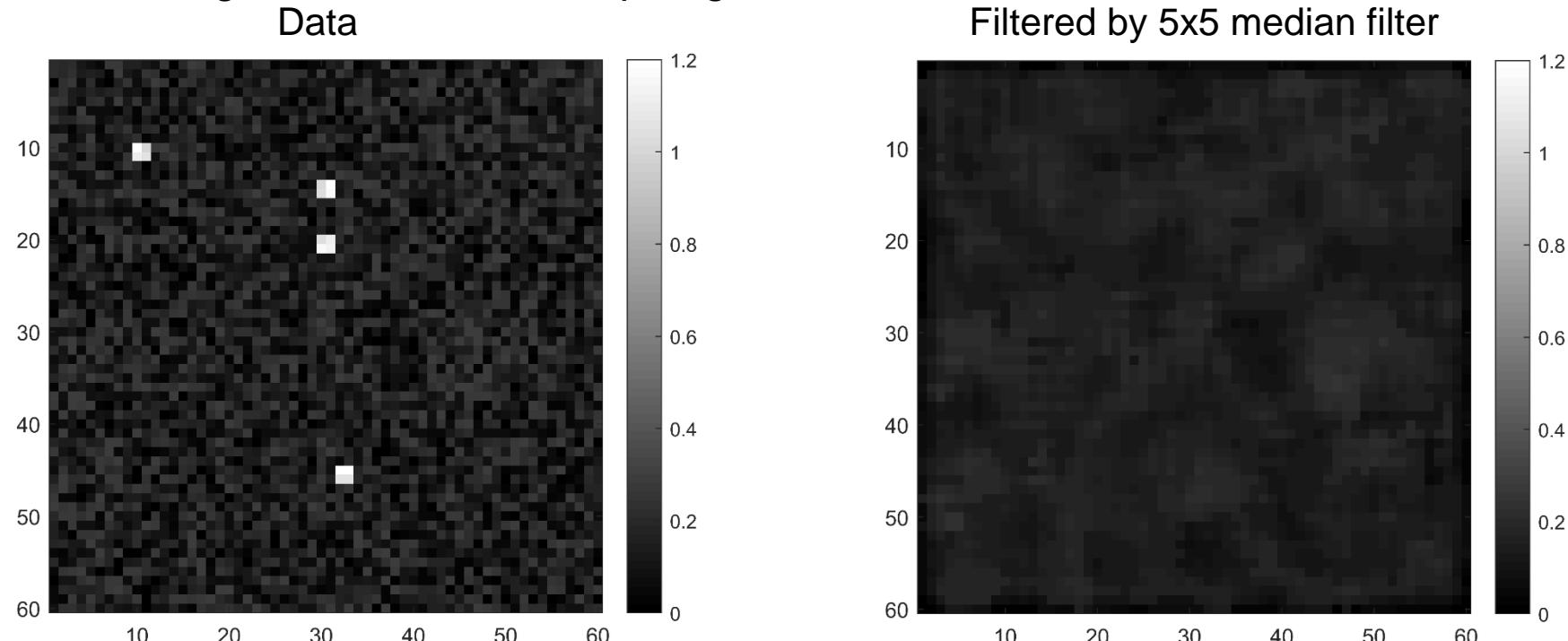


Filtering example: 2D – Median filter



The drawbacks of filtering

- There are many different types of filters. They all have drawbacks!
- It is always a trade-off between removing unwanted artefacts (e.g. noise) and introducing new ones.
 - Filtering tends to remove small features
 - Filtering tends to round sharp edges

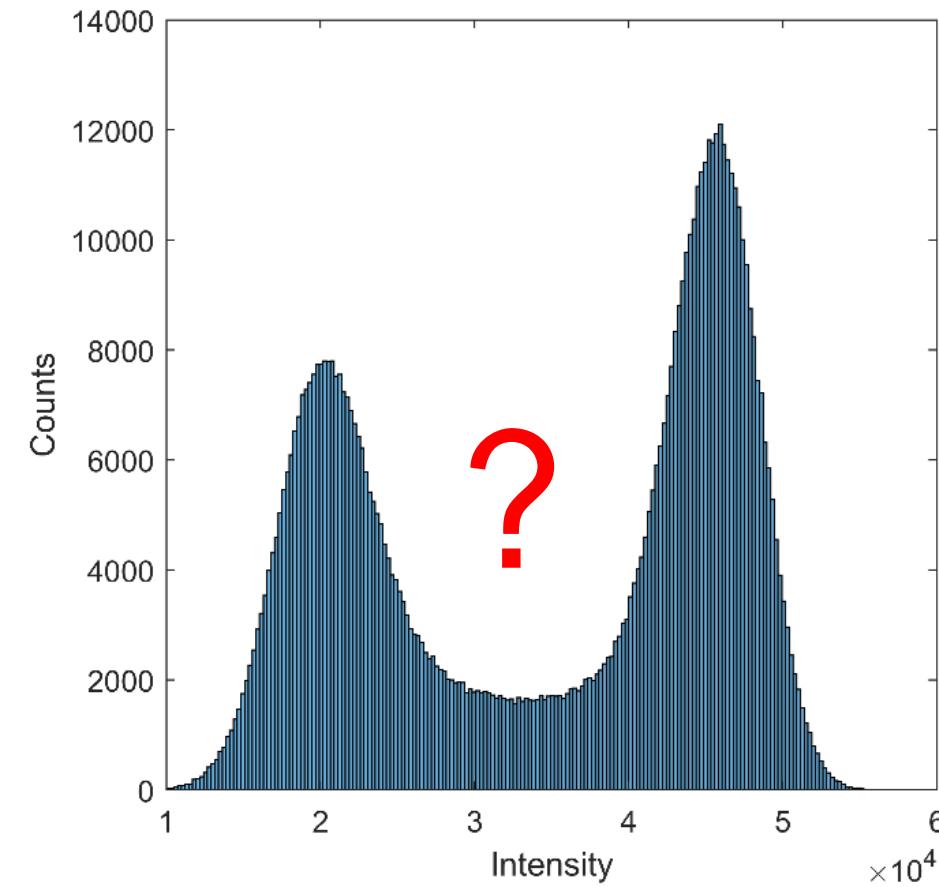


Filtering tips

- Apply the least intrusive filter that allows you to segment your data.
 - Don't filter if it isn't necessary.
- Understand the properties of the filter you are using.
 - E.g. removable of important structural features.
- A small filter is often useful and sufficient!

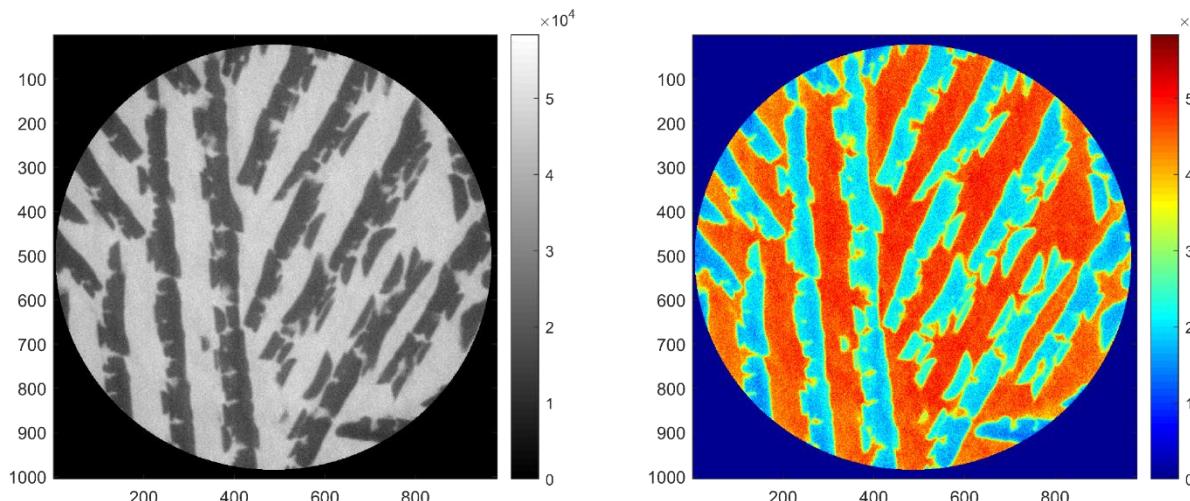
Segmentation

How to find the right threshold?



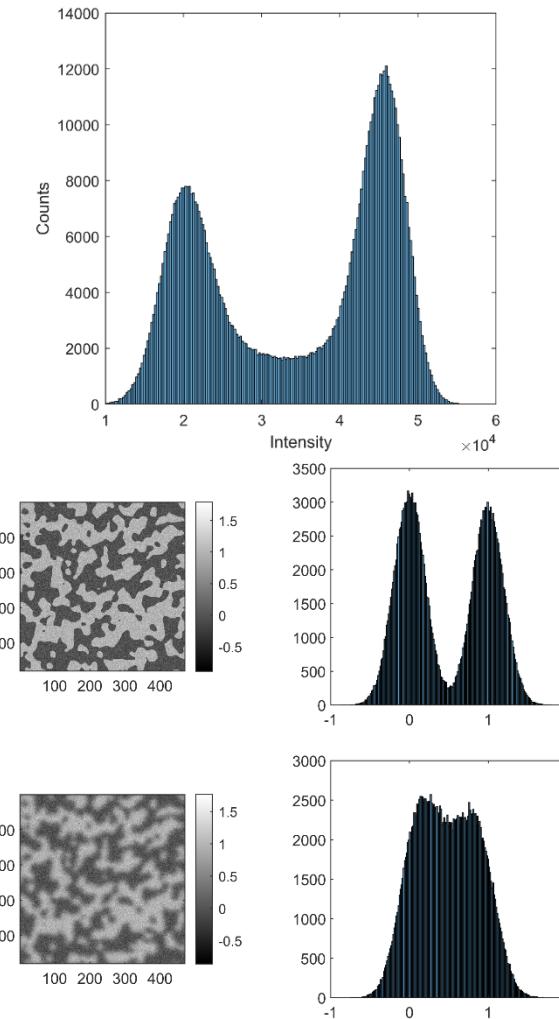
Thresholding by tuning until the segmentation visually looks correct?

- Your decision is likely to depend on:
 - The color map chosen to map the data to color on the screen.
 - The screen you are looking at, the brightness of the room etc.
- Your eyes can deceive you.
- It is not reproducible by others or even yourself!



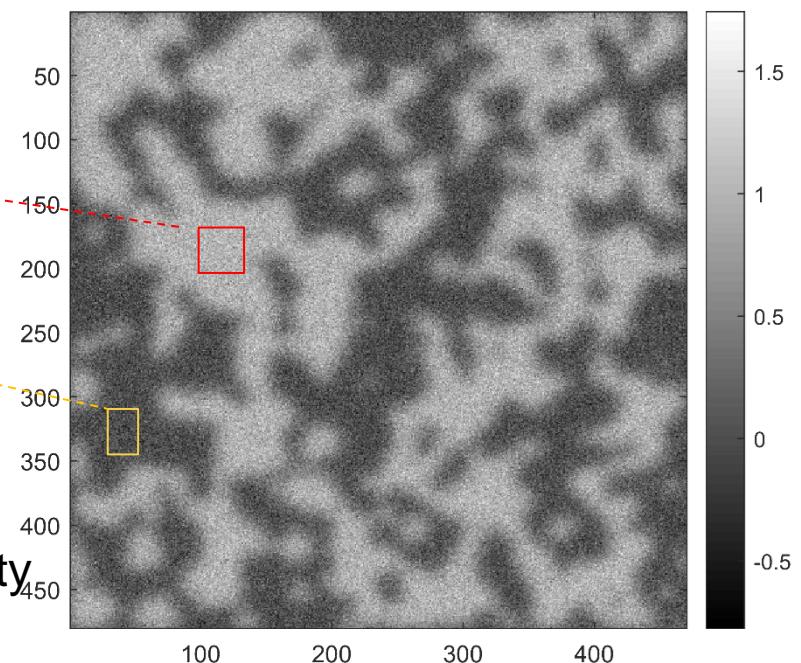
Thresholding halfway between two peaks?

- The peak positions are not necessarily the mean phase intensity.
 - E.g. The presence of blurry interfaces can significantly shift the peaks.
- With decent image quality and similar phase fractions the error is quite small.
 - OK to do this in the exercise!



Thresholding – good practice

- Define regions for each phase far from an interface.
- Set the threshold halfway between the mean intensity in the regions.
- Got bright phase samples here, mean = 1.0011
 - True value is 1.
- Got dark phase samples here, mean = 0.0062
 - True value is 0
- Set threshold at $(1.0011 + 0.0062)/2 = 0.5037$
- Good practice to pick several locations to check for intensity drift.

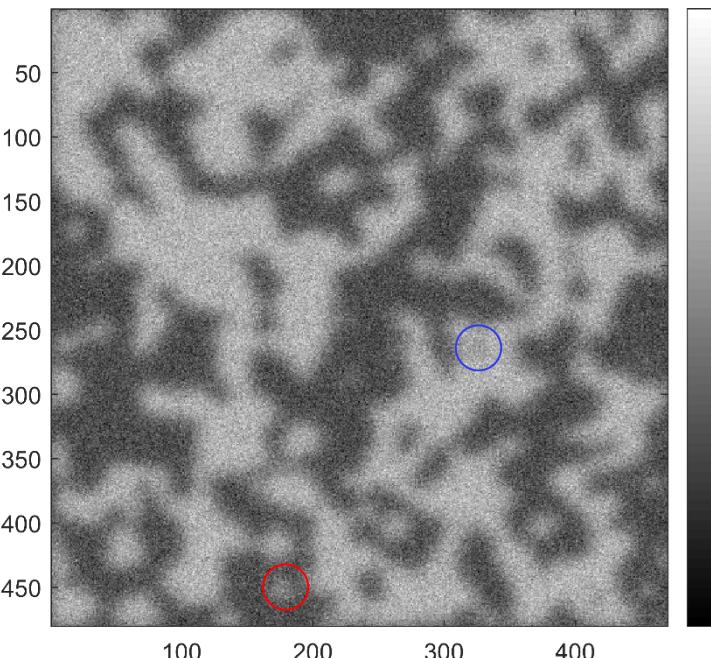


Assessing the quality of the segmentation

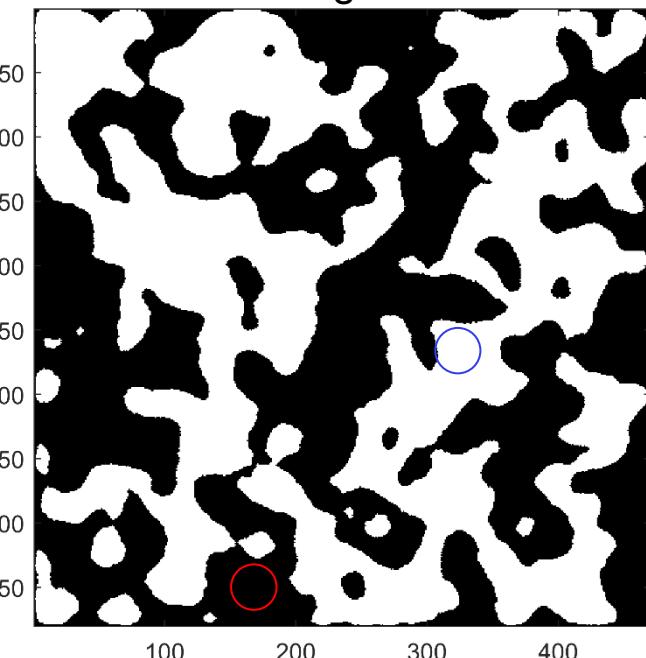
- Compare the raw data to the segmentation.
- The errors are in the details and not easily apparent without zooming in.

We can only do this since this is artificial data!

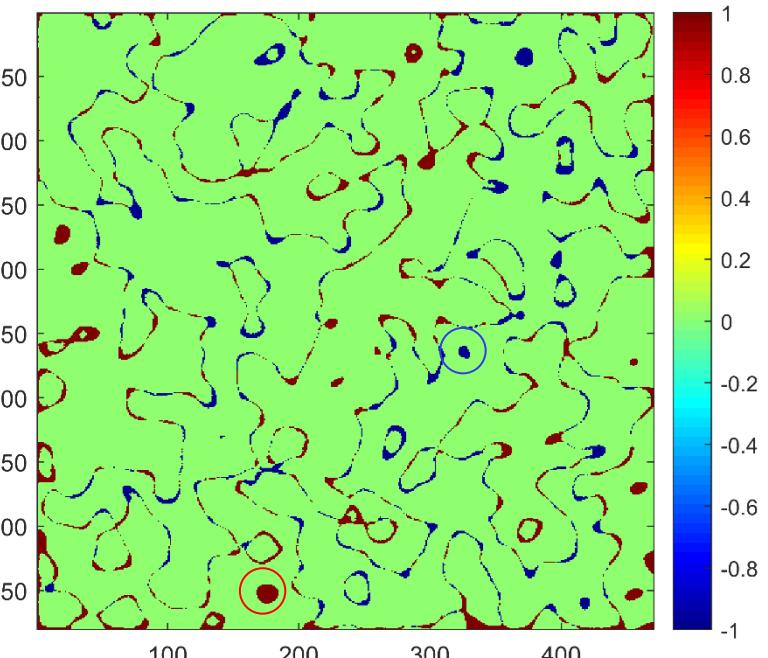
The raw data



The segmentation



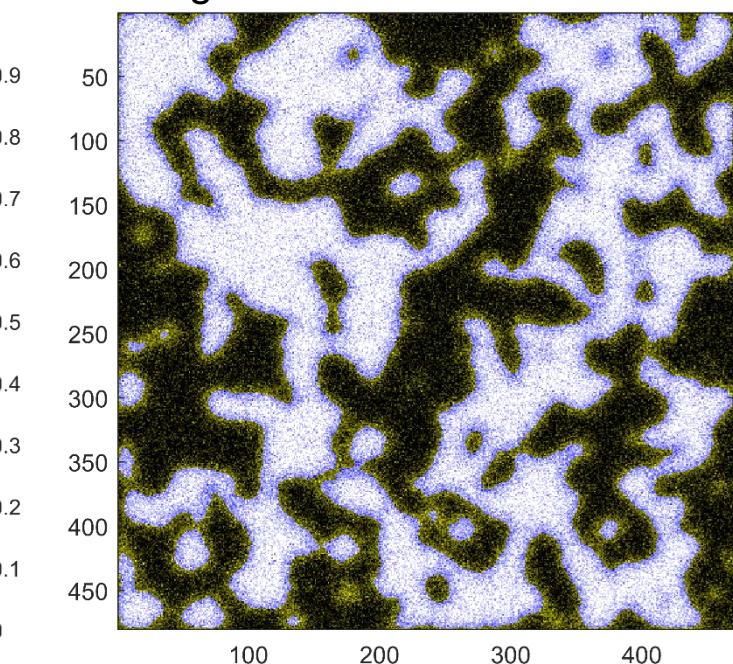
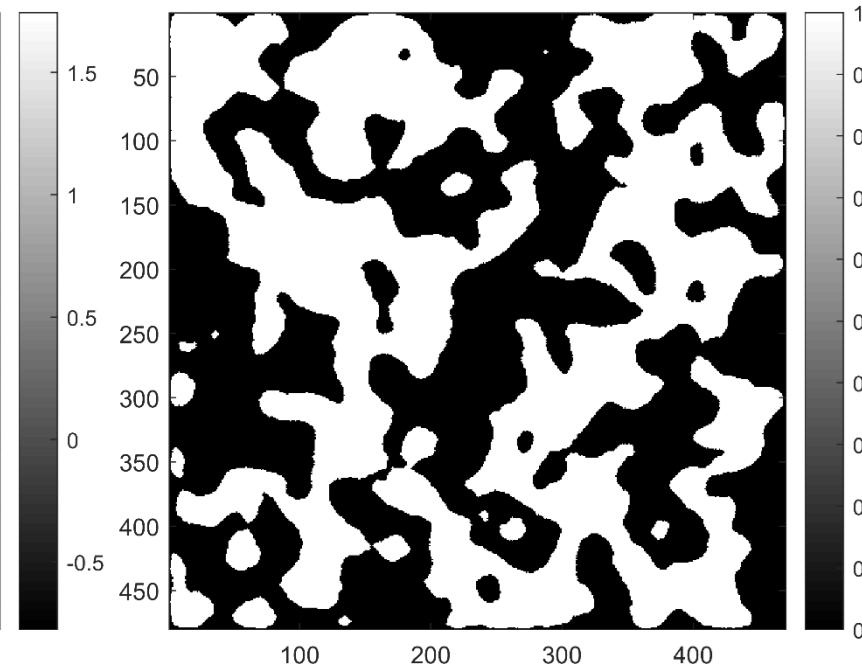
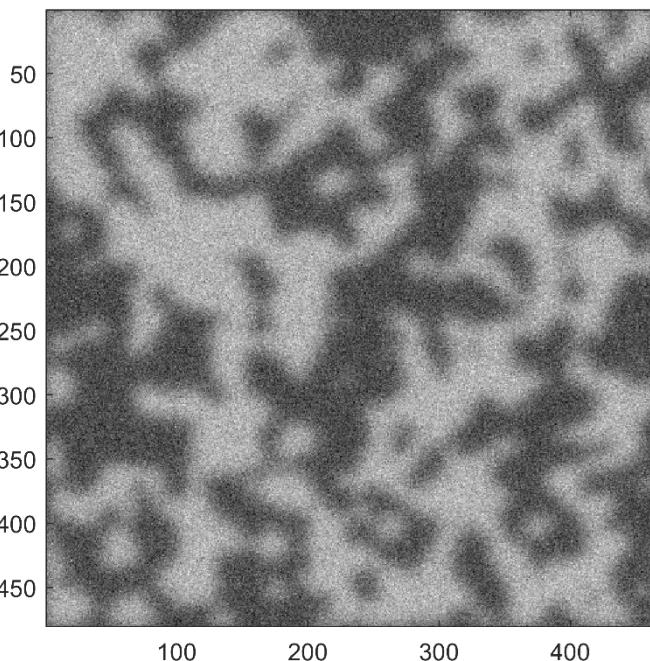
The errors



Blue areas include too much
Red areas remove too much

Assessing the quality of the segmentation on real data

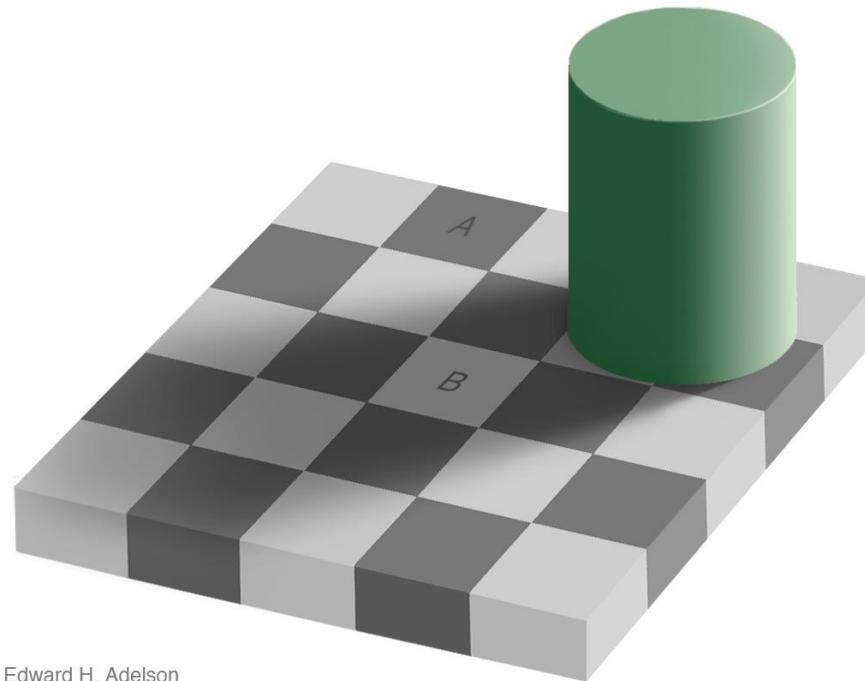
- Flip between the segmentation and the raw data.
- Superimpose the segmentation onto the raw data.
 - Contours
 - Color-coding



The segmentation replacing the blue channel in a greyscale RGB image.

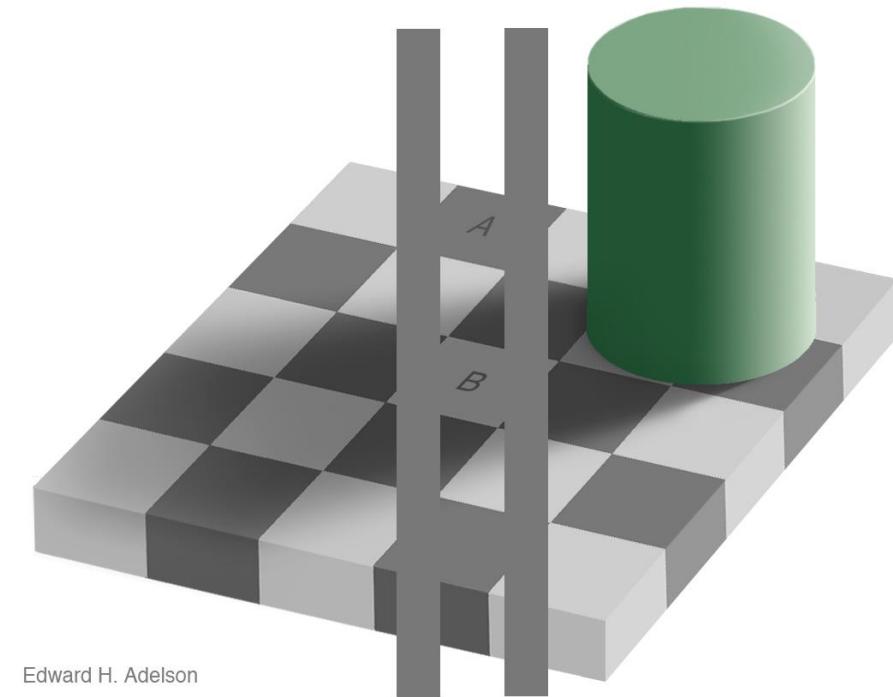
When segmentation becomes more challenging...

Is A or B brightest?



Edward H. Adelson

Different phases
have the same
intensity!



Edward H. Adelson

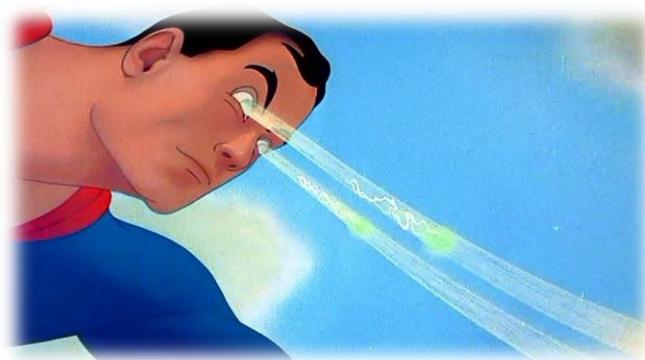
When segmentation becomes more challenging...

- Due to:
 - Artefacts from the scanning.
 - Small structures with low contrast and high noise levels
 - Poor correlation between structure and intensity.
- There is a large amount of different segmentation methods
 - The best one to use depends on the data.
 - The field is moving towards deep learning for image segmentation
- Some image analysis courses at DTU
 - 02502 - Image analysis
 - 02506 - Advanced Image Analysis

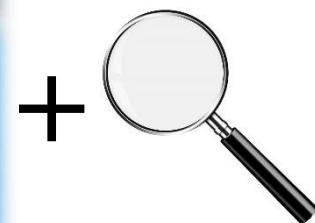
BREAK!

Analysis - Measurements

Overview

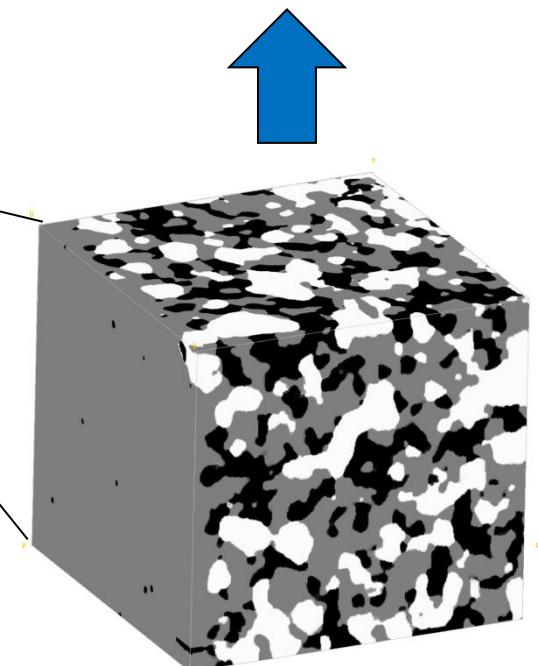


Seeing is believing...

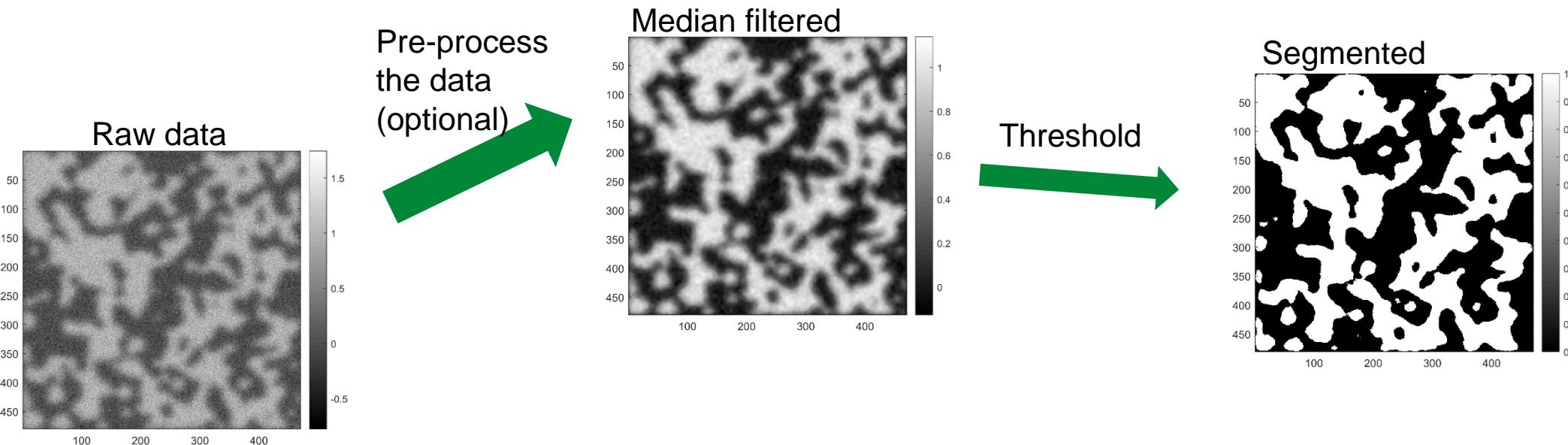


...measuring is knowing... ...or is it?

$$x = ? \pm e$$



Quantitative calculations are performed using the segmentation!



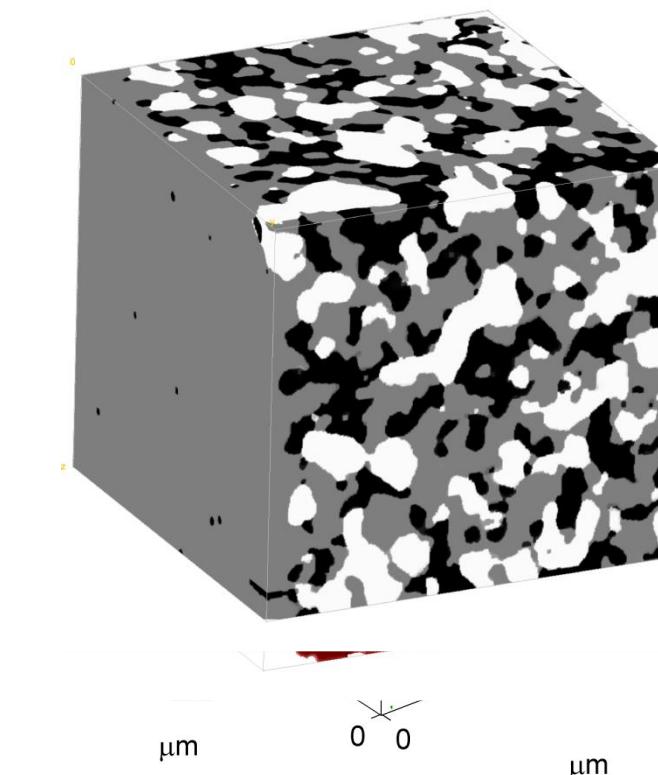
Garbage in => Garbage out!

- You are measuring your segmentation, not your sample!
- Your results will only ever be as accurate as your segmentation!

Some measurement examples

Some types of measurements

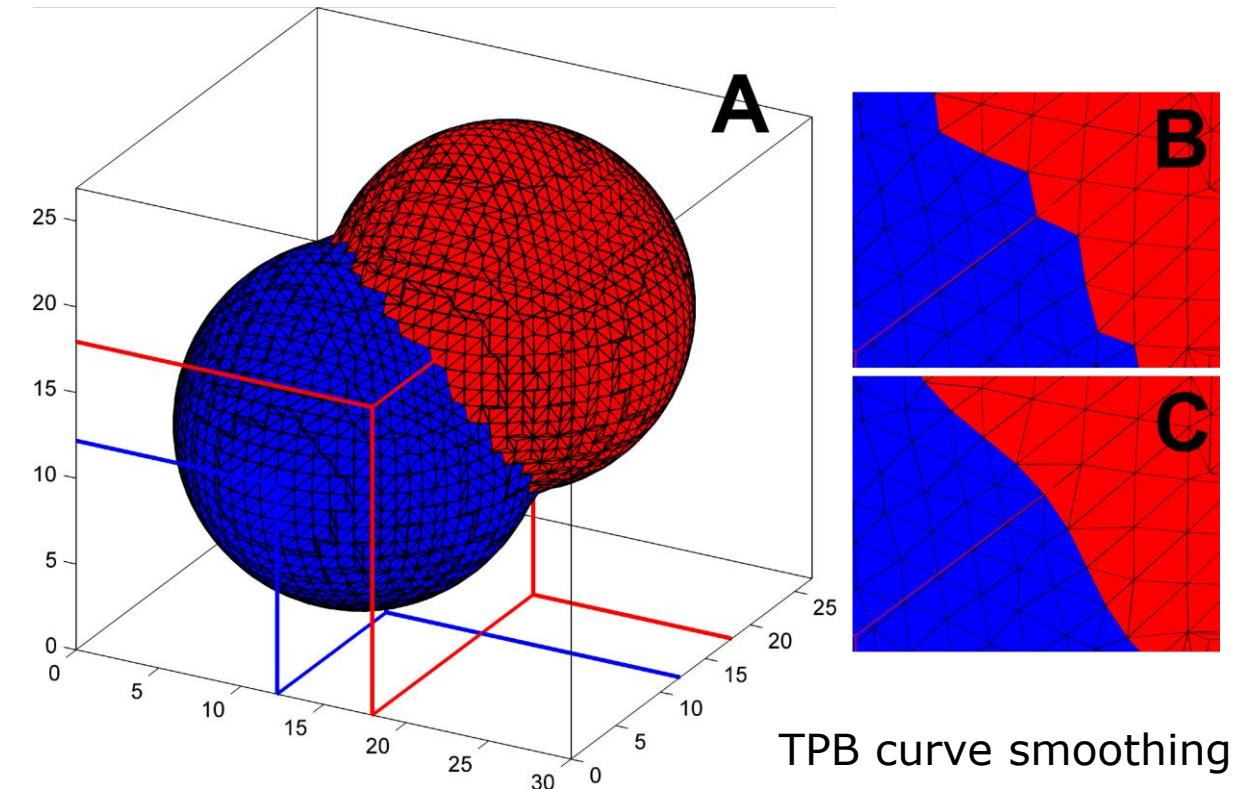
- How could we describe the pore structure?
- Local measurements:
 - Porosity (how much) [m^3/m^3]
 - Interface area [m^2/m^3]
 - Triple phase boundary length [m/m^3]
- Neighborhood measurements
 - Particle size distributions



Example: interface areas

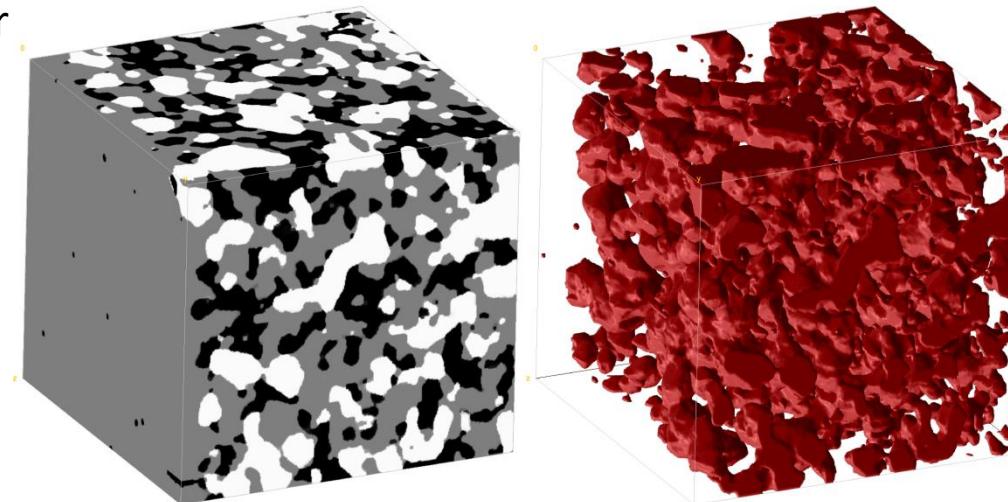
Sum over polygon areas for surface area calculations.

You will do this in the exercise.



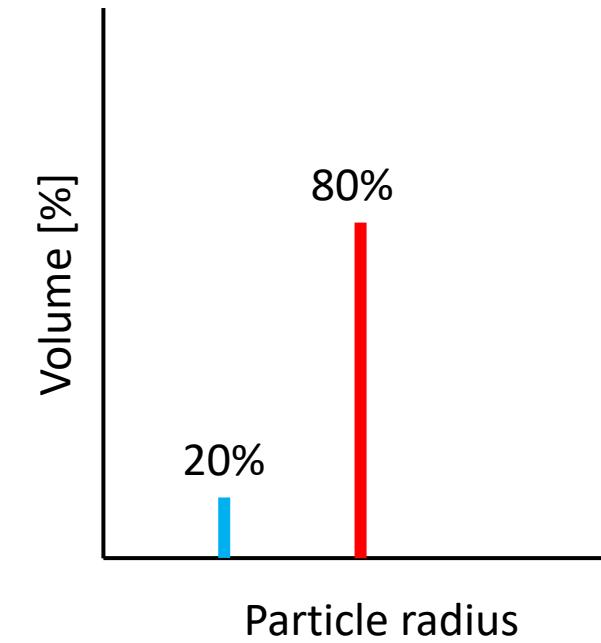
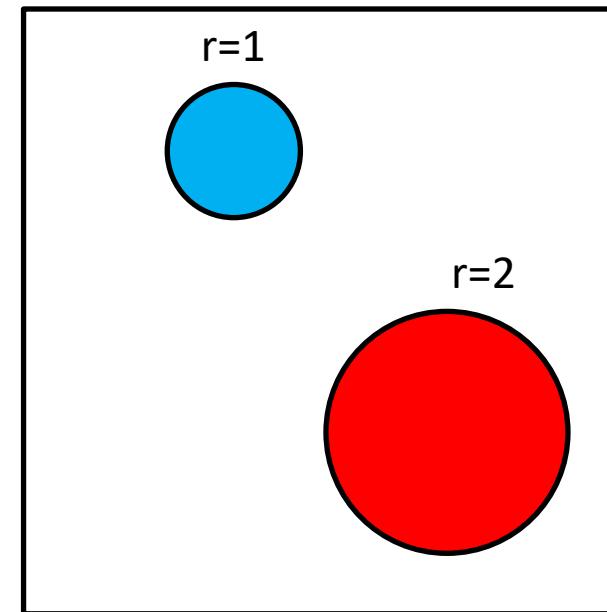
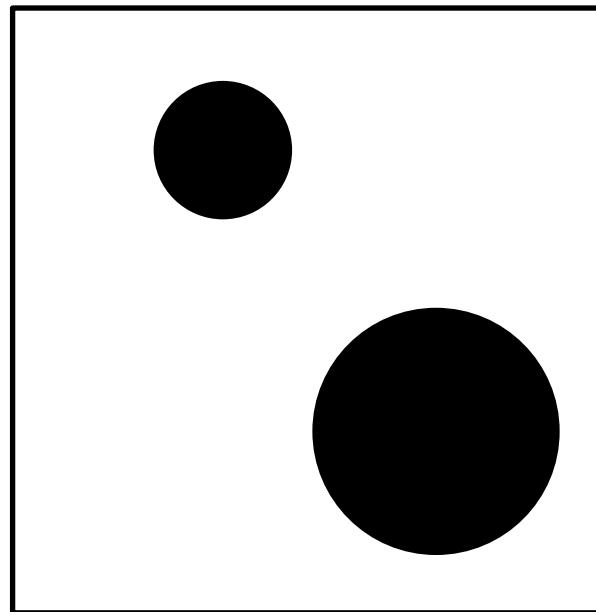
An example: Particle size distributions

- No single right way to do a PSD for arbitrarily shaped particles or networks
 - Line intercepts
 - Volume of connected components
 - For phase networks the continuous PSD method has been found to work well.



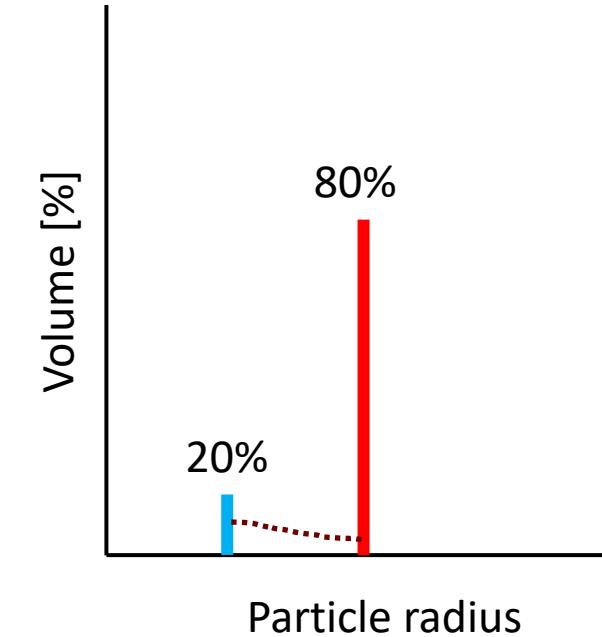
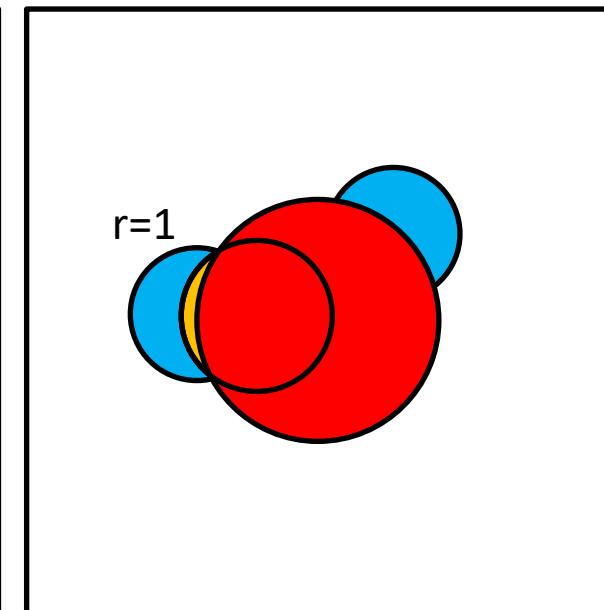
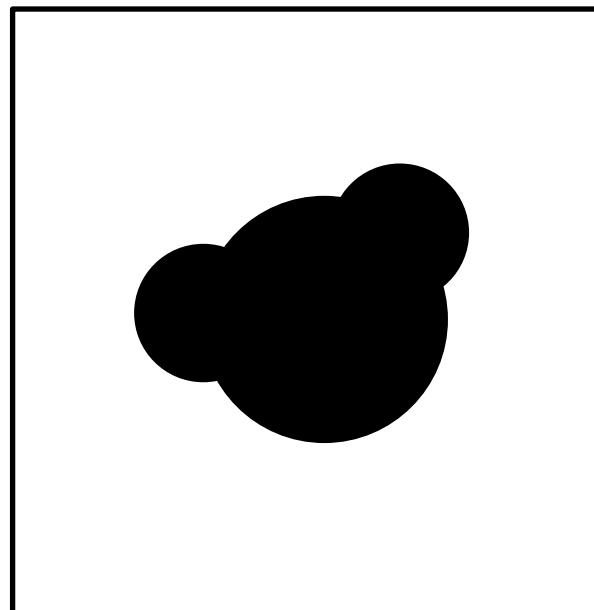
The continuous PSD

- Measures the volume that can be covered by circles (2D)/spheres (3D) of a certain size.



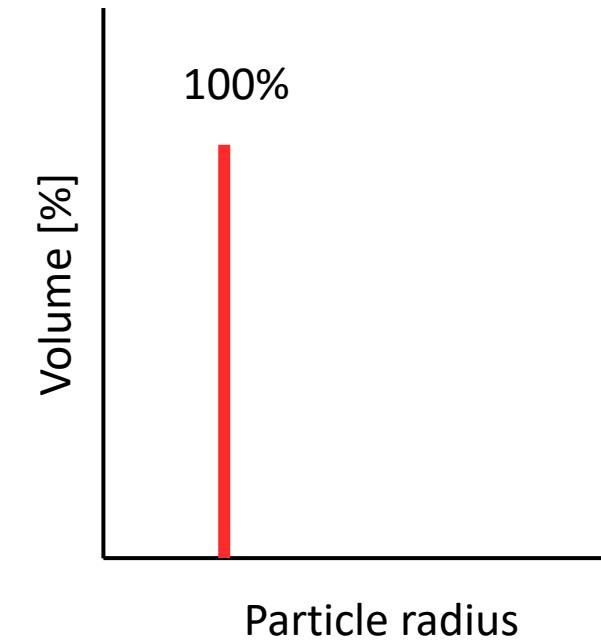
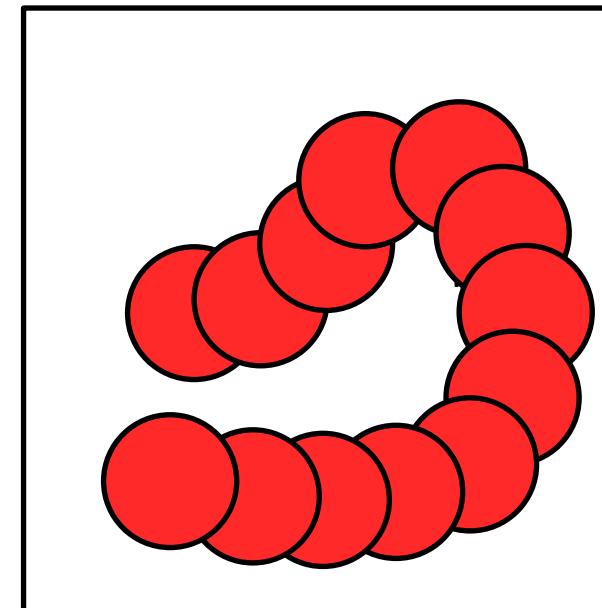
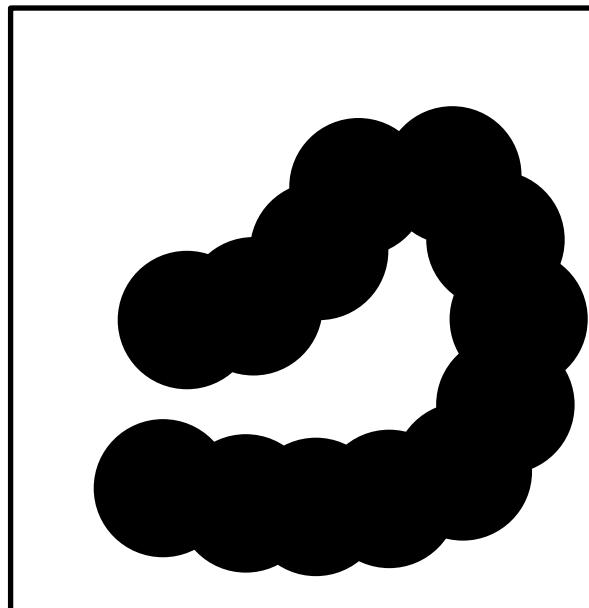
The continuous PSD

- In case of overlap the largest sphere counts.
- Slightly more complicated than my PowerPoint skills can express.



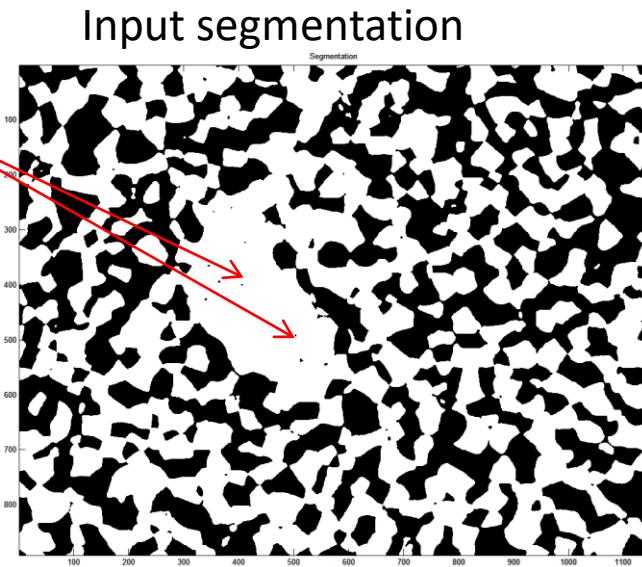
The continuous PSD

Tube like structures of the same diameter are characterized by the radius of the fitted circles/spheres

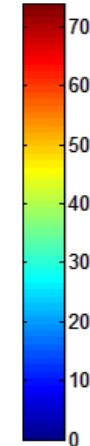
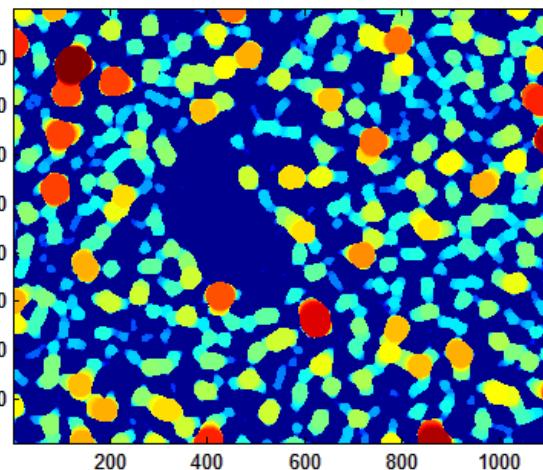


The continuous PSD

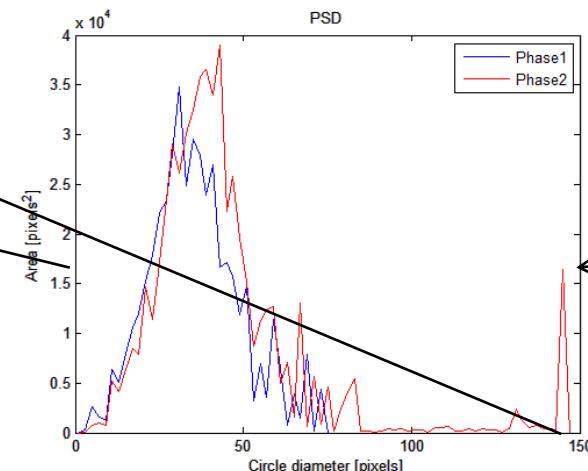
- Very sensitive to single pixel segmentation errors!



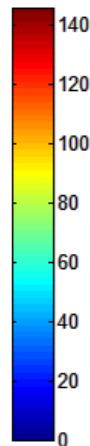
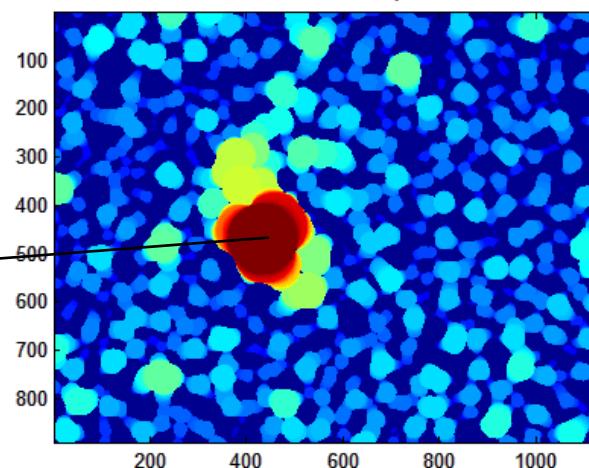
Black phase size map



Continuous PSD



White phase size map
Phase2 size map

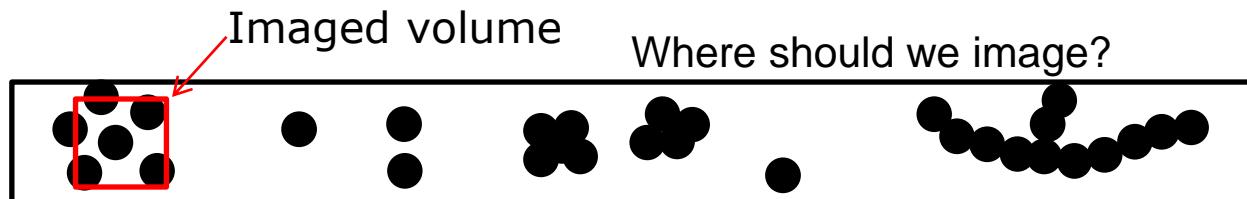


$$A = \pi \left(\frac{d}{2}\right)^2$$

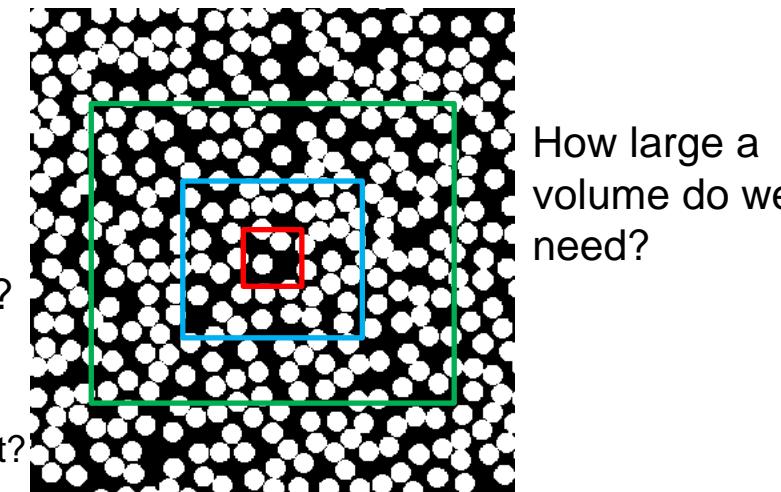
$$16513 = \pi \left(\frac{145}{2}\right)^2$$



Representative volume for bulk properties



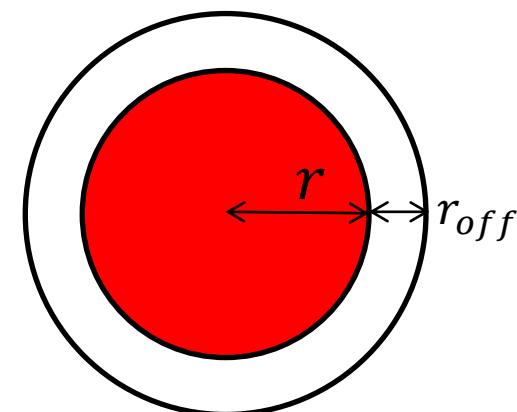
- At what volume size can we consider the sample to be homogeneous?
 - Can we assume that we would get the same result at a different "point" in the sample?
 - What volume size do we need before a given descriptor is not size dependent? (bulk property)





Segmentation sensitivity

- Different measurements are sensitive to different segmentation artefacts/errors.
 - Surface area of rough surfaces – Filtering.
 - Continuous PSD – Single voxel errors.
- An example: interface offsets
 - Suppose we make a systematic segmentation error that pushes the true interface outwards by r_{off}
 - Particle radius
 - Sphere radius: $r + r_{off}$
 - Surface area
 - Sphere surface area: $4\pi(r + r_{off})^2$
 - Volume fraction
 - Sphere volume: $\frac{4}{3}\pi(r + r_{off})^3$
- If we set $r_{off} = r/10$ we get the following relative errors from the offset.
 - Sphere radius: +10%
 - Surface area: +21%
 - Volume: 33%
 - **Phase fractions are notoriously difficult to estimate accurately!**





Scale dependence of measurements

- The interface area can change dramatically depending on structure scale.
- Absolute measurements will often not be accurate!
- Relative measurements are still useful.



$$\begin{array}{l} 11.5 \times 200 = \\ 2300 \text{ km} \end{array} \quad \begin{array}{l} 28 \times 100 = 2800 \\ \text{km} \end{array} \quad \begin{array}{l} 70 \times 50 = 3500 \\ \text{km} \end{array}$$

Figure 1. As the length of the measuring stick is scaled smaller and smaller, the total length of the coastline measured increases.

Source: https://en.wikipedia.org/wiki/Fractal_dimension

BREAK!

Check that you have the image processing toolbox installed in Matlab

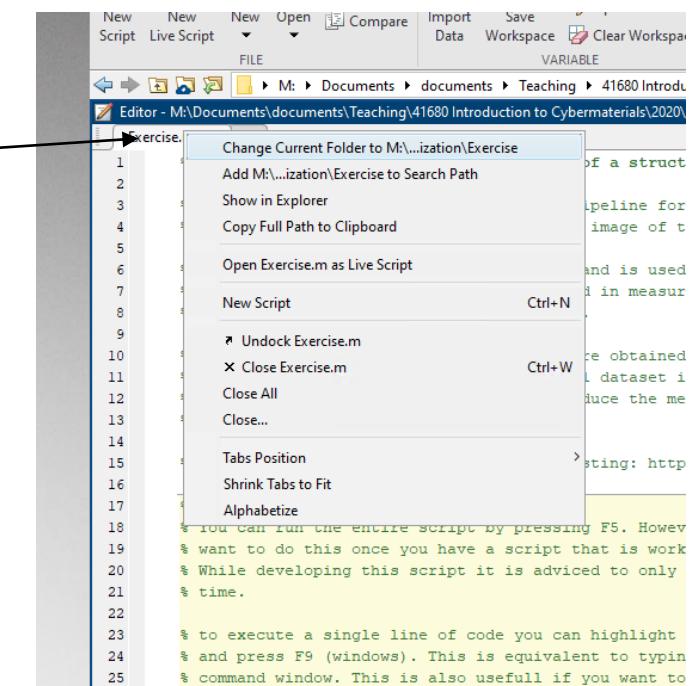
In the Matlab command window write: help medfilt3

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Click the blue text link, sign in and install it.**

Exercise introduction

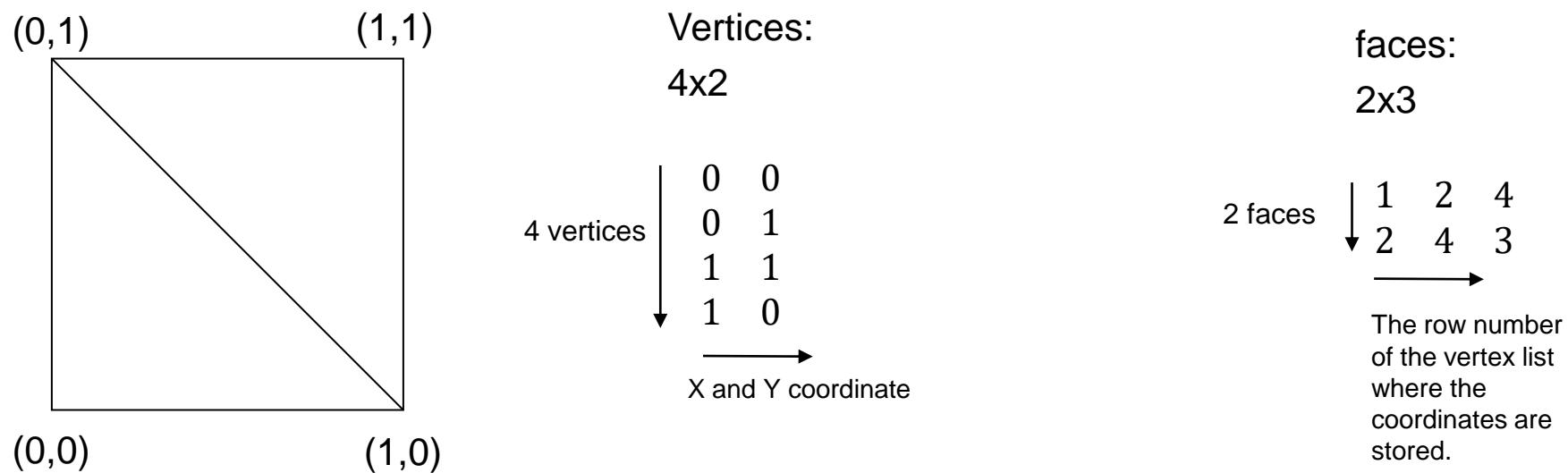
The exercise

- Make a basic pipeline for measuring the volume fraction and interface area of a structure in a 3D image.
- Instructions in the pdf file (Exercise - Quantitative 3D imaging.pdf)
- Additional setup notes
 - Unzip the zip file, then open the unzipped Exercise_start.m script
 - Right click Exercise.m and click Change Current Folder...
 - If you get a message similar to: 'medfilt3' requires Image Processing Toolbox.
 - This means that you haven't installed a required toolbox. Just click the link, sign in and install it.



The indexed face set data structure

- A polygon surface made of 2 triangles (faces) and 4 vertices.



This is an efficient way of storing the data, as vertices used by multiple polygons are only stored once.

- AI can be a great help in understanding code syntax and errors: [Copilot \(microsoft.com\)](#)
- As always, there is no guarantee that the AI answer is correct

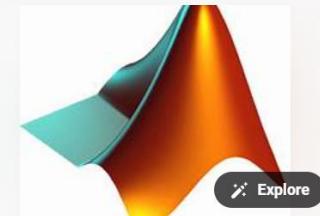
You

what does this line of matlab code do: figure, imagesc(vol(:,:,250)), colormap gray, axis image, title('raw image')

Copilot

Certainly! Let's break down the MATLAB code step by step:

1. `figure` : This command creates a new figure window for displaying plots or images. It ensures that subsequent plotting commands will be applied to this new figure.
2. `imagesc(vol(:,:,250))` :
 - `vol` is a 3D array (volume data).
 - `vol(:,:,250)` extracts a 2D slice from the 3D volume at the 250th depth (or z-slice).
 - `imagesc` displays the data in the specified 2D slice as an image.
 - The color scale is automatically adjusted to use the full range of colors in the colormap.
 - Each element of `vol(:,:,250)` specifies the color for one pixel of the image.
3. `colormap gray` : This sets the colormap to grayscale. In the resulting image, darker values correspond to lower intensity, and lighter values correspond to higher intensity.
4. `axis image` : This command ensures that the aspect ratio of the displayed image is preserved. It prevents distortion due to unequal scaling along the x and y axes.
5. `title('raw image')` : Adds a title to the figure, labeling it as the "raw image."



In summary, this line of MATLAB code creates a new figure, displays a 2D slice from a 3D volume (`vol`) as a grayscale image, and labels it as the "raw image." The specific slice shown corresponds to the 250th depth in the volume data.

For more details, you can refer to the MATLAB documentation on [imagesc](#).

Learn more 1 [mathworks.com](#) 2 [marketsplash.com](#) 3 [stackoverflow.com](#) +3 more

11:15

I will go through a few examples of previous exam questions

Q3 Median filter

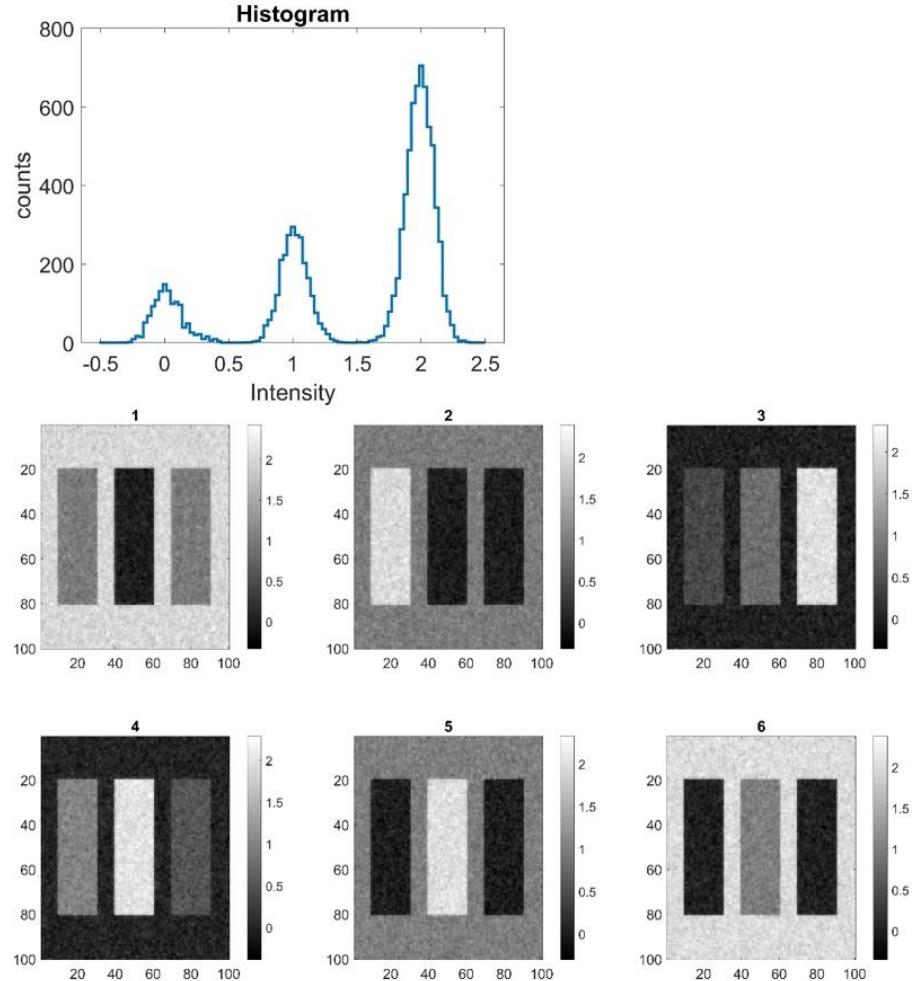
Consider the shown digital image. What is the outcome of applying a 3x3 median filter centered at row 2, column 3.

26	25	18	45	52	38
17	42	20	21	24	21
25	60	51	51	28	06
17	38	74	66	57	11
24	18	14	15	29	04

1. 42
2. 21
3. 45
4. 37
5. 20
6. 38

Answer: (1) 42. In a 3x3 box around row 2, column 3 we have the following sorted values (18,20,21,25,42,45,51,51,60). The median of these values is 42.

The histogram below is the histogram of one of the six images shown. Which image does the histogram correspond to?



Answer: 1 (Image 1), The largest peak in the histogram is around the value 2, this must thus be the background intensity of the image since the background covers the largest area of the image. Of the two remaining images only number 2 shows an image where the phase with a value close to 1 is the most abundant.

Q5 Volume fraction Consider a 3D image of a material consisting of a solid phase and some pores. We have segmented the image into solid phase and pores. We have used a program to measure that the volume of the pores is 0.157 mm^3 . The image has dimensions $300 \times 300 \times 300$ voxels and a voxel size of $20 \mu\text{m} \times 20 \mu\text{m} \times 20 \mu\text{m}$.

What is the volume fraction of the pore phase?

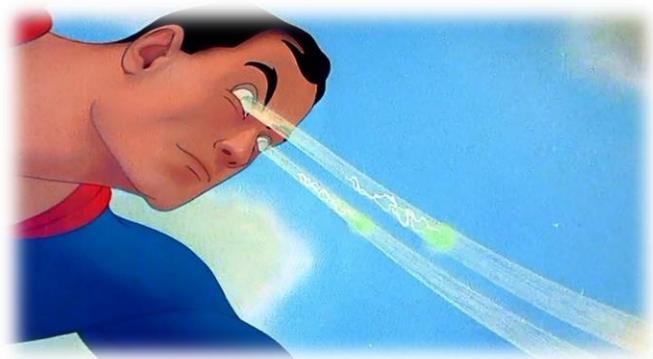
1. 0.58
2. 0.00058
3. 0.73
4. 0.00073
5. 0.19
6. 0.00019

Answer: 4 (0.00073), $0.157 \text{ [mm}^3\text{]} / (\underline{300 \times 300 \times 300} \times 0.02 \times 0.02 \times 0.02 \text{ [mm}^3\text{]}) = 0.00073$

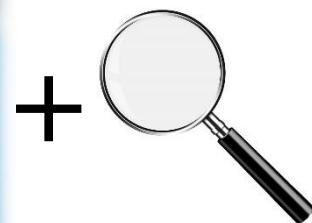
11:45

I will recap and go through
solutions to the exercises

Today

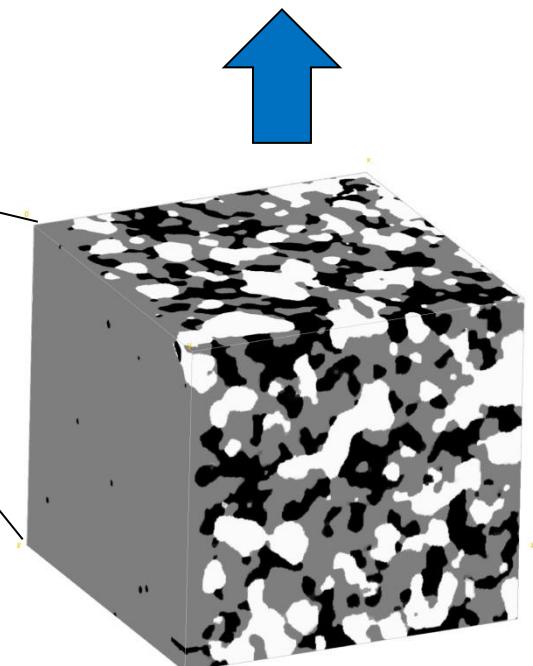


Seeing is believing...



...measuring is knowing... ...or is it?

$$x = ? \pm e$$



Exercise solution

- A solution to the exercise is available on Learn after the module