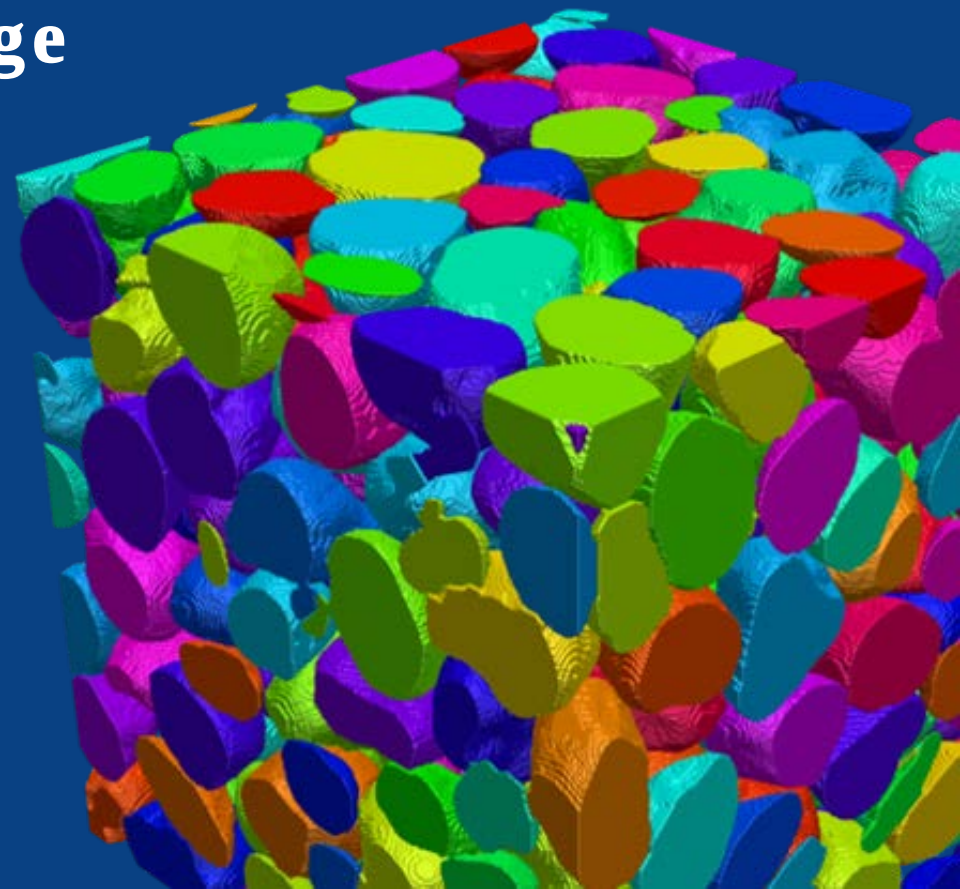
THE UNIVERSITY OF MELBOURNE

X-ray computed tomography (CT) image processing of granular materials

Compute particle shape in assemblies automatically



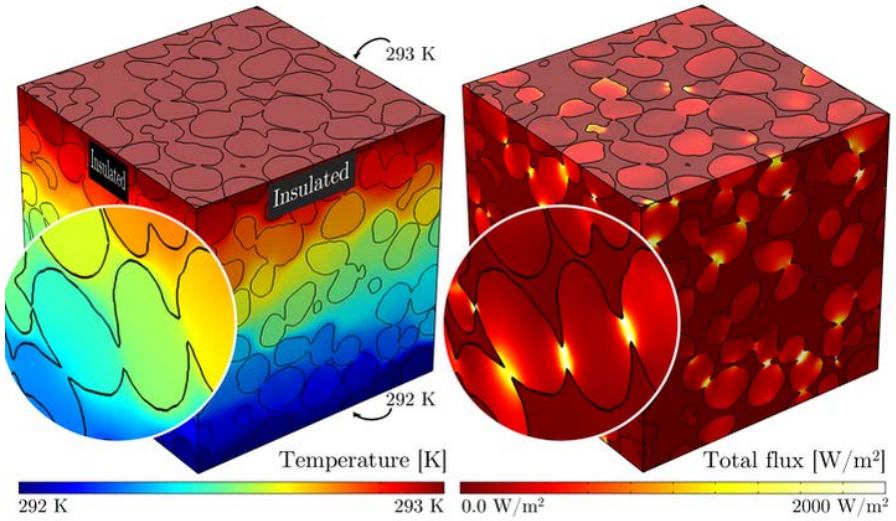
29th of November, 2021, Newcastle, Grain Days 2021

Wenbin Fei, Guillermo Narsilio, & others…

…Joost van der Linden, Antoinette Tordesillas,
J Carlos Santamarina, …

Heat and fluid flow in our research group…

Fundamental research



Applied research

Numerical modelling: FEM, Artificial Intelligence, Complex Network Theory, LBM-DEM …
Testing: MicroCT, Australian synchrotron, full scale testing, …

Energy: Need for change

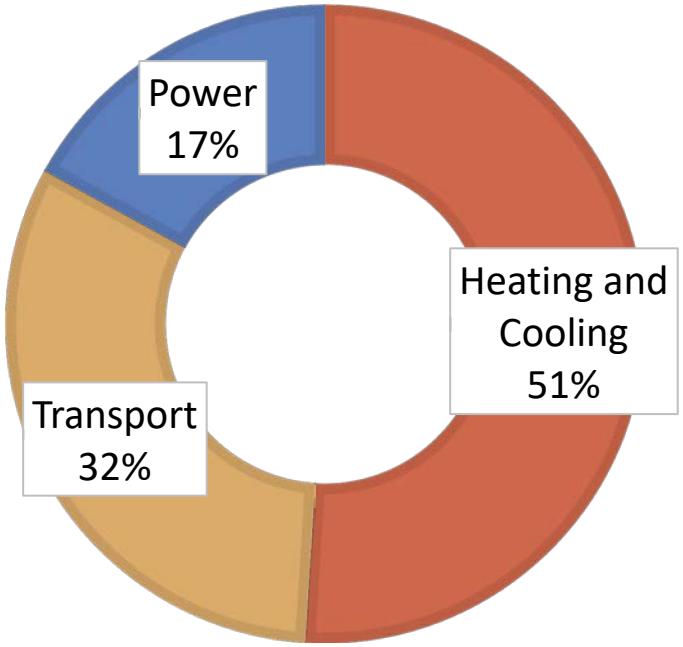
Key challenges for the 21st Century:

- Managing energy resources
- Moving towards cleaner sources of energy

Space heating and cooling accounts for **>50% of total energy** consumption (REN21, 2019)

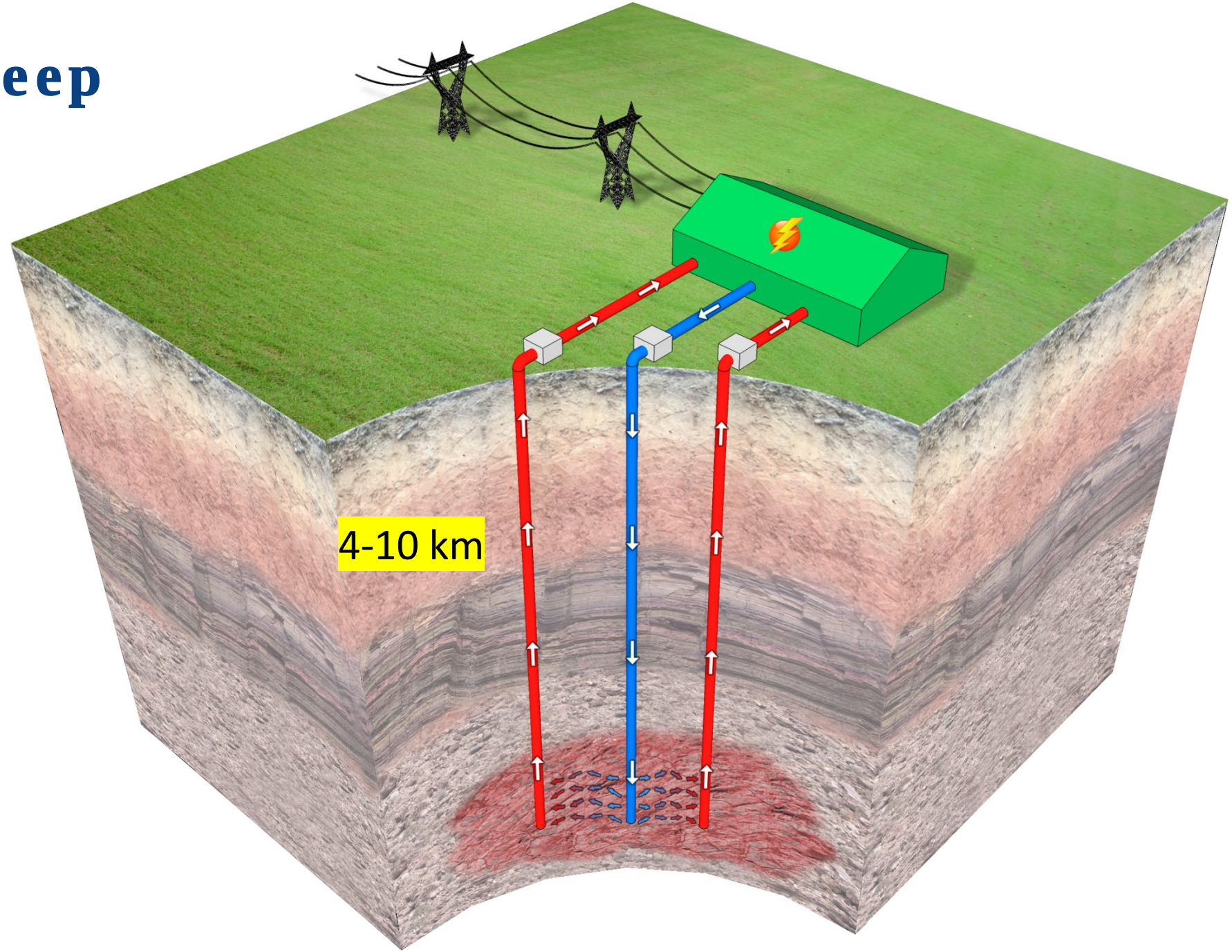
Alternative renewable low carbon energy sources:

- "Deep" geothermal systems
- "Shallow" ground source heat pump (GSHP)

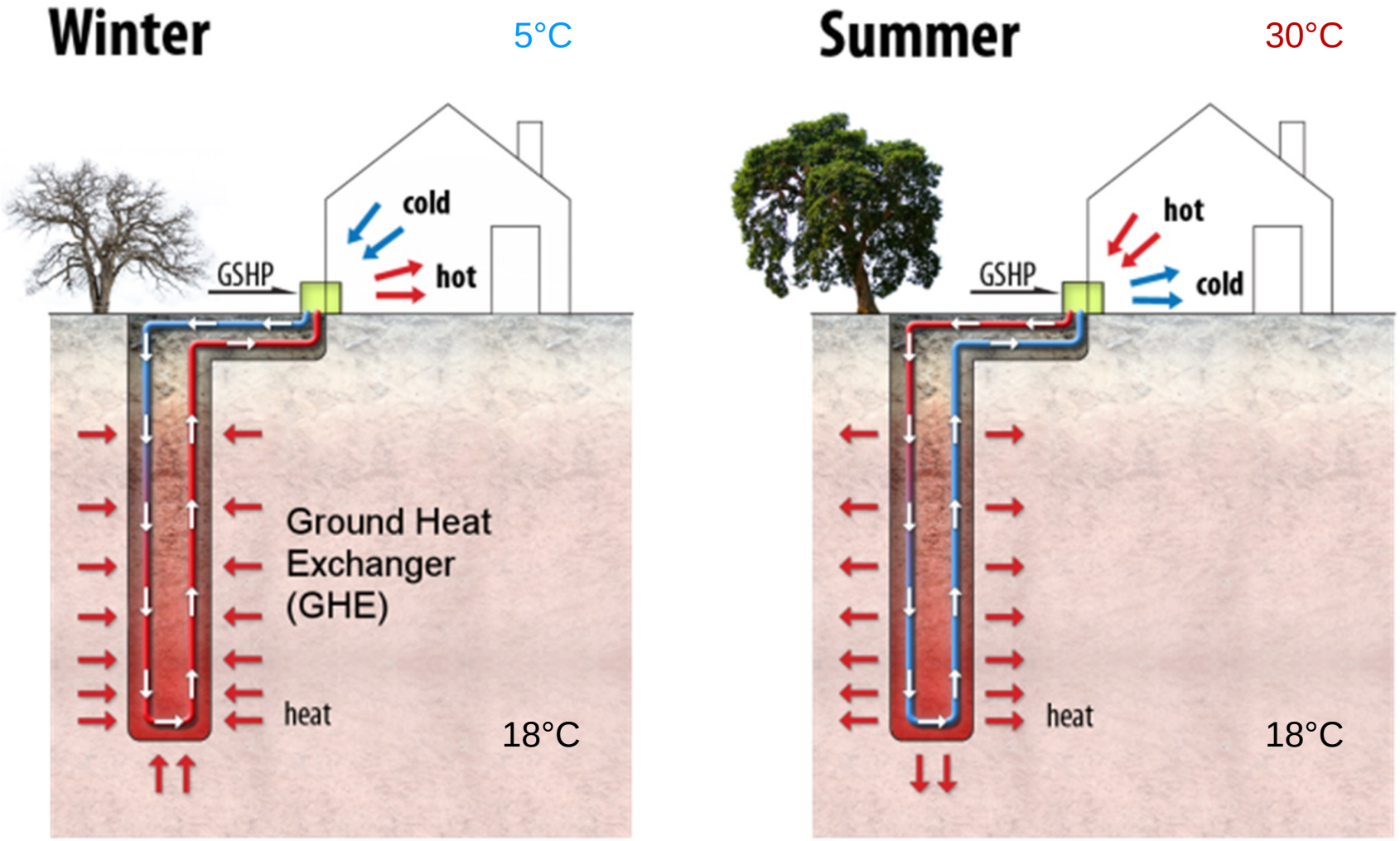


Total final energy consumption (REN21,2019)

Deep



GSHP and energy geo-structures



1.5-2.5 m (horizontal)

50-150 m (vertical)

(Johnston, Narsilio and Colls, 2011 - Not to scale)

Shallow & deep geothermal: Commonality?

Fluid flow and heat transfer in porous, **granular** materials:

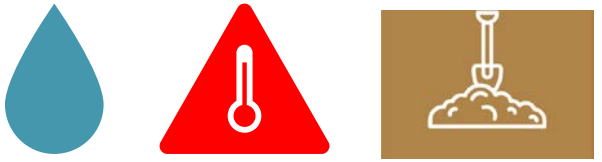
- uncemented: soils
- cemented: rocks!

Other applications:

- Oil & gas industry
- Carbon sequestration
- Earthen dam design
- …

(Geo)-mechanics also play a role in many engineering applications

Why?



Microstructure of geomaterials **controls** conduction **properties**.

Poorly understood in the past **due to** the **difficult access** to microstructure.

New techniques prompted a need for **data-driven concepts.**

- computered tomography [Sydney U.- Benjy et al.; ANU/UNSW ; Australian Synchrotron]
- complex network theory [Melbourne U. – Antoinette T.]
- numerical simulation [Many!]
- machine learning techniques [Melbourne U. – Guillermo et al., UTS, others…]

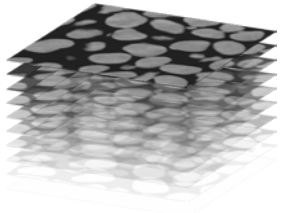
Microstructure features in this lecture:

- *Microscale* **particle shape descriptors** circularity, sphericity, roundness, convexity, compactness and solidity
- *Mesoscale* connectivity

Pore/particle scale modeling platform

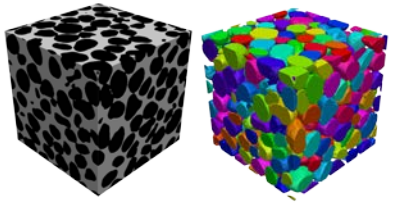
Data

Real materials images



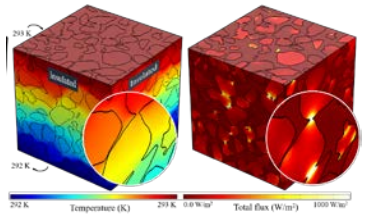
1

Particle/Pore geometry and morphology



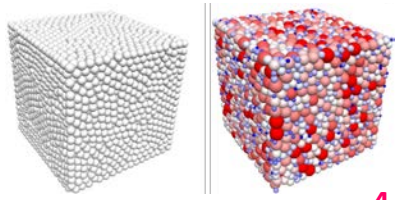
2

Finite element modelling



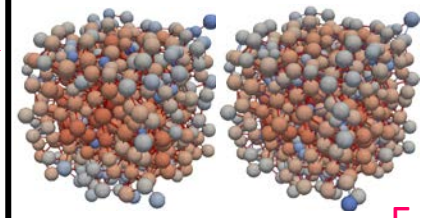
3

Discrete element modelling



4

Complex networks



5

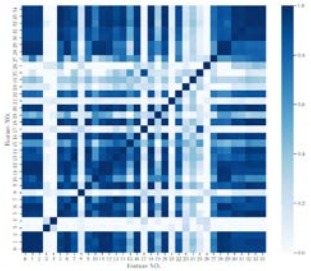
Feature set

Input variables
Feature 1
Feature 2
…
Output variables
ETC

6

Machine learning

Feature importance



8

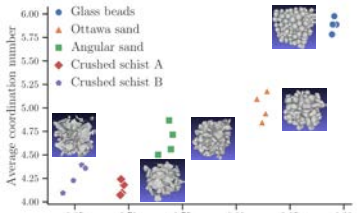
Model selection

$y = a \cdot x + b$
$y = a \cdot x^2 + b \cdot x + c$
$y = a \cdot x^3 + b \cdot x^2 + c \cdot x + d$
$y = a \cdot e^x$
$y = a \cdot ln(x) + b$
$y = a \cdot x^b$
Random forest regression
Artificial neural network

7

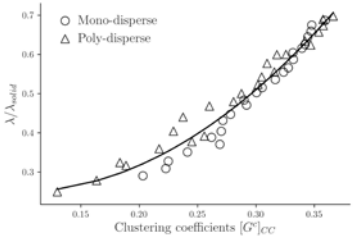
Output

Unveiling patterns



10

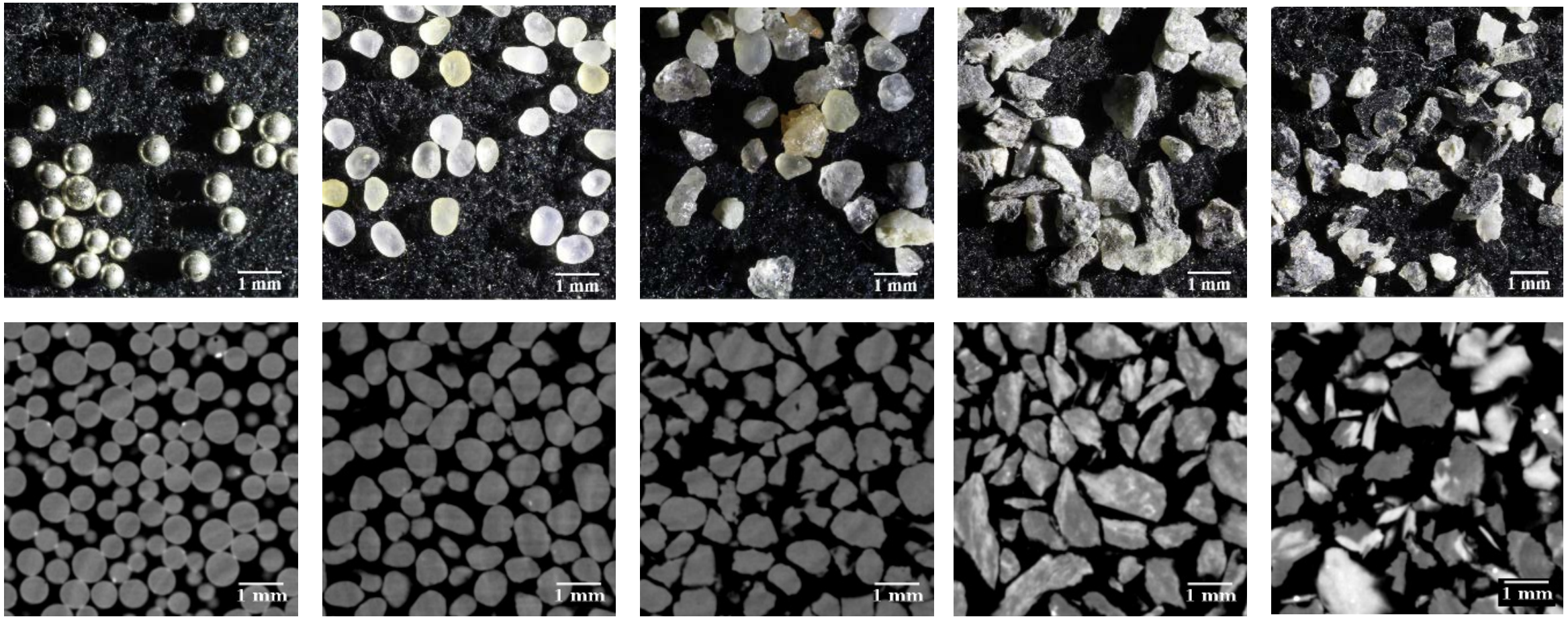
Predictions



9

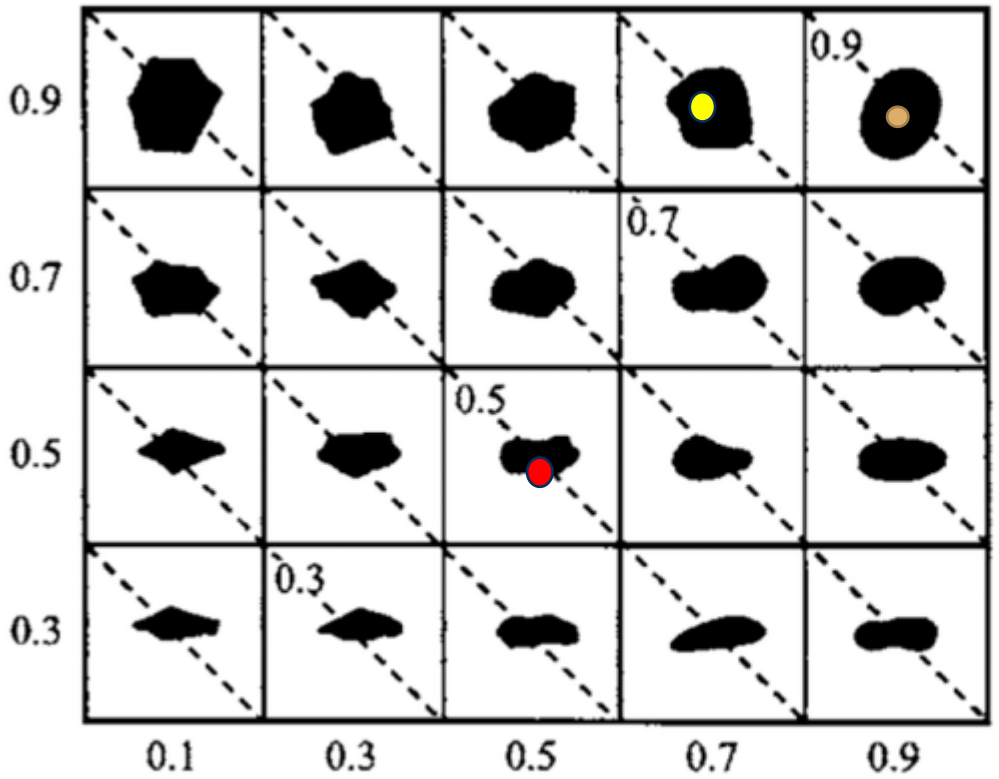
Particle shape (box 2)

W Fei, et al. (2021) X-ray computed tomography images and network data of sands under compression. Data in brief 2021, 6, 107122.

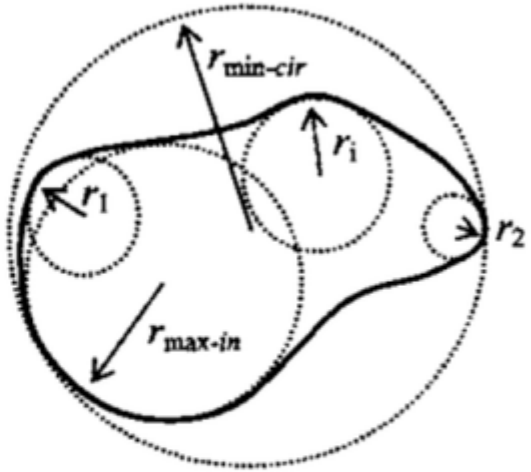


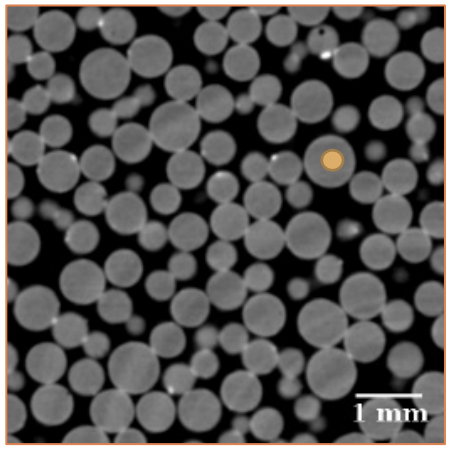
Particle shape: Krumbein and Sloss charts (1963)

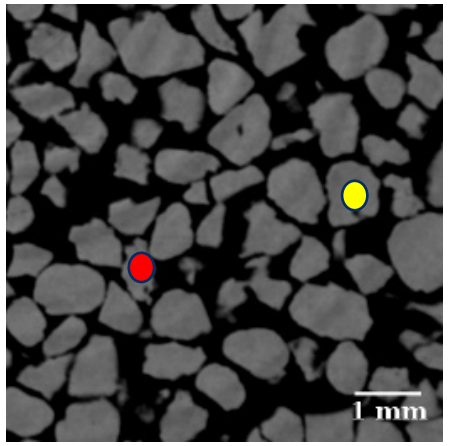
$$Sphericity = \frac{36\pi V^2}{SA^3}$$



$$Roundness = \frac{\sum r_i / N}{r_{max-in}}$$



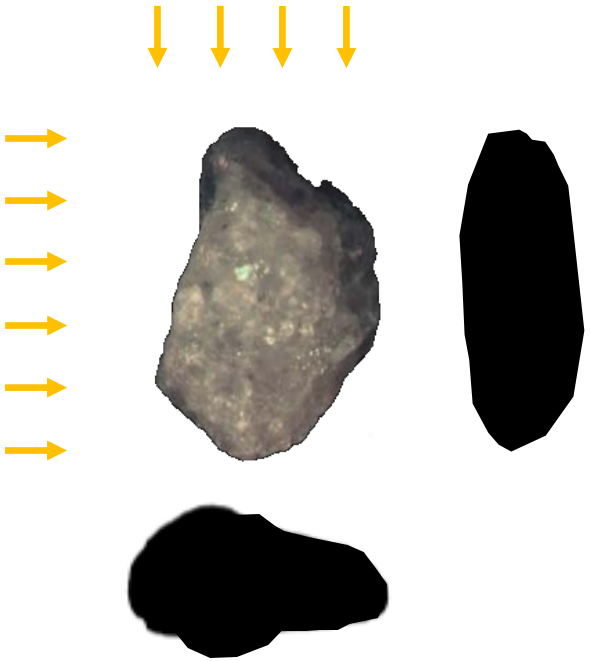




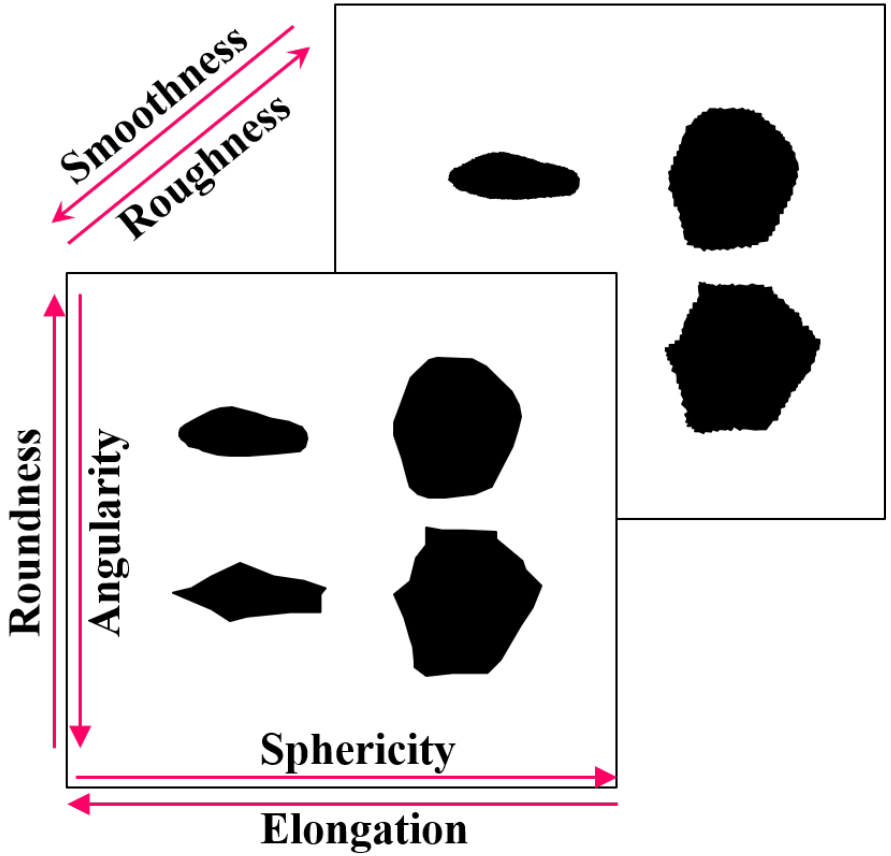
Fei W, Narsilio GA, Disfani MM. Impact of three-dimensional sphericity and roundness on heat transfer in granular materials. Powder Technology 2019, 355:770-781.

2D vs 3D

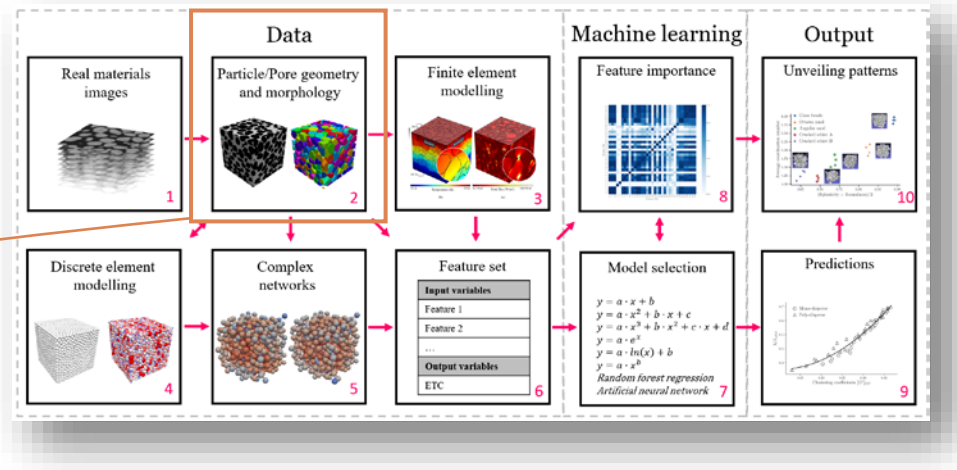
Limitation of 2D descriptors



Particle shape scales

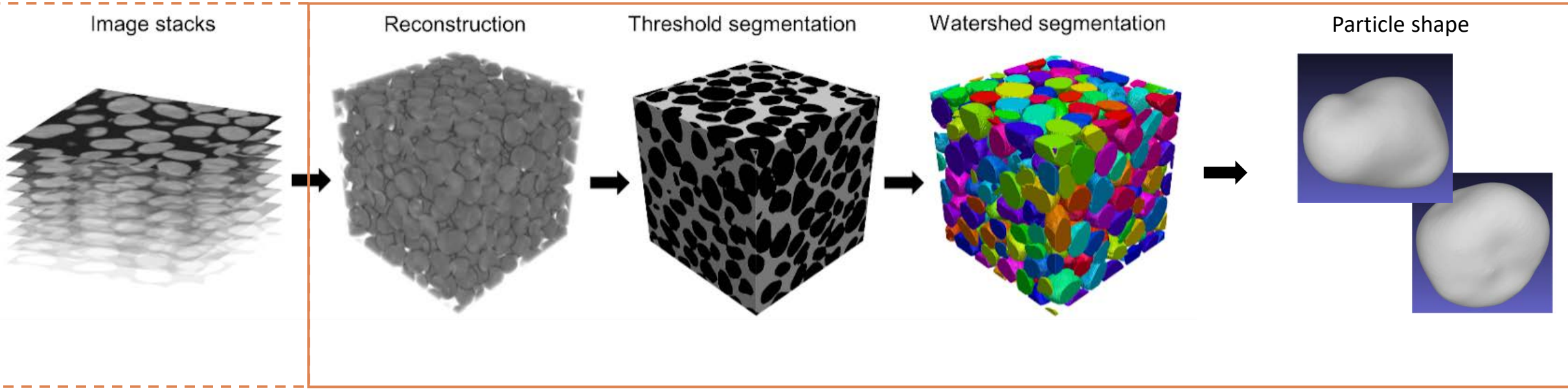


Focus of today's doctoral school lecture/hands-on

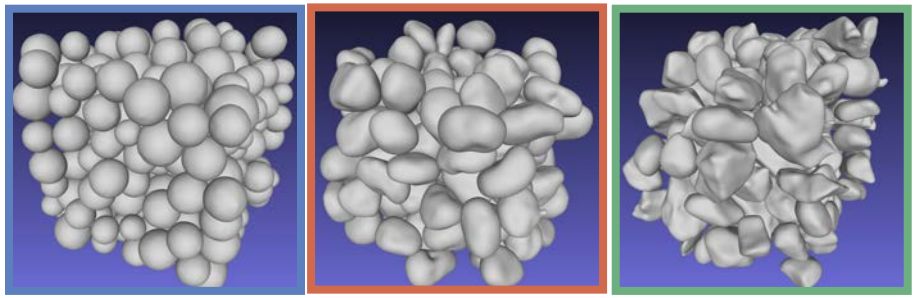


Block 1

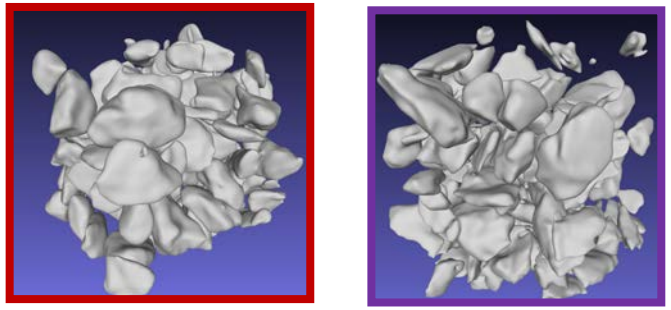
Block 2



Particle shape

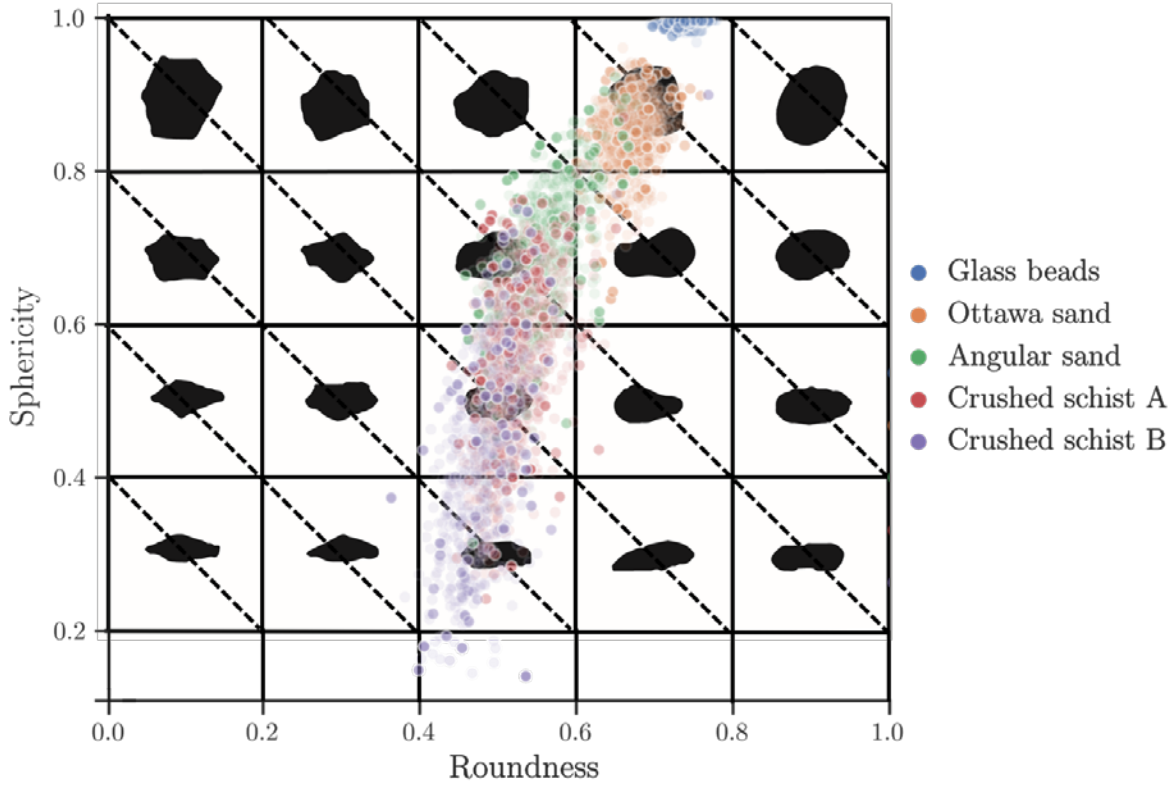


Glass beads Ottawa sand Angular sand



Crushed schist A Crushed schist B

1 click



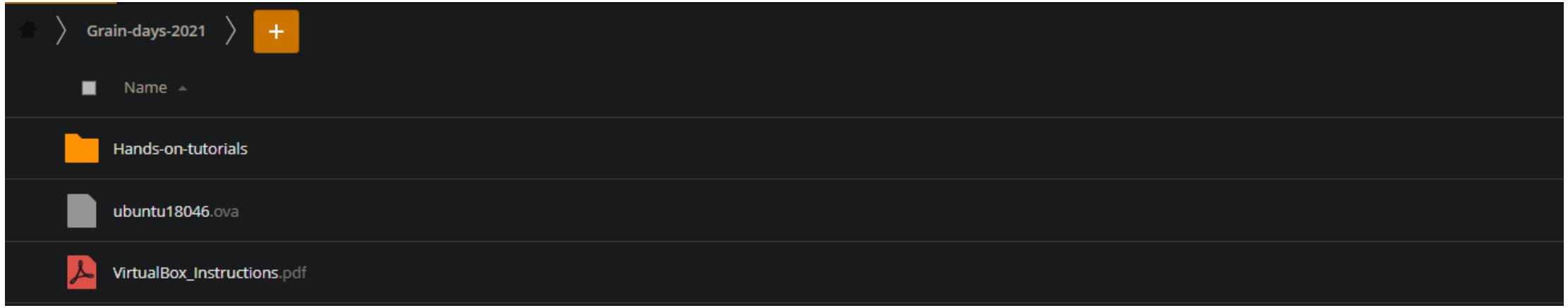
Fei W, Narsilio GA, Disfani MM. Impact of three-dimensional sphericity and roundness on heat transfer in granular materials. Powder Technology 2019, 355:770-781.

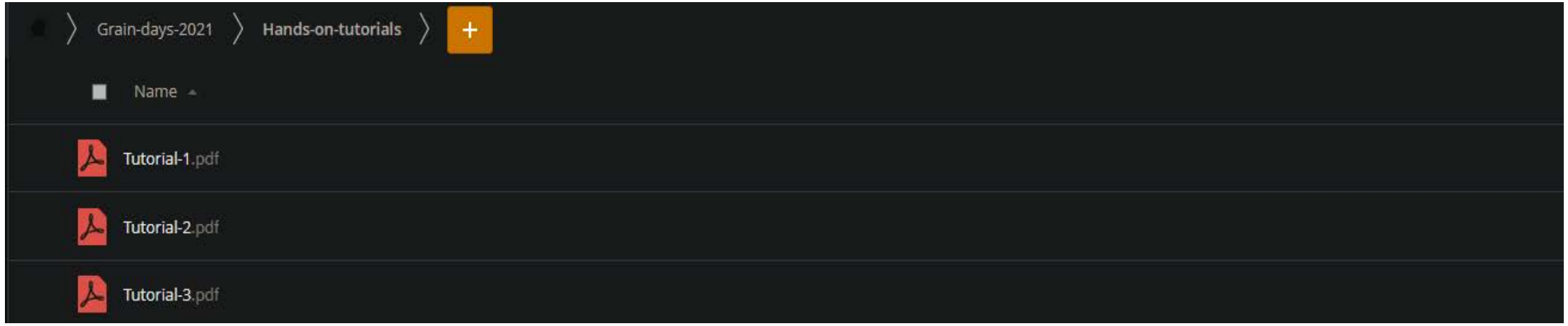
Fei W, Narsilio GA, van der Linden JH, Tordesillas A, Disfani MM, Santamarina JC. Impact of particle shape on networks in sands. Computers and Geotechnics 2021, 137, 104258.

What to have ready…

1. Download instructions & tutorials
   Link: https://cloudstor.aarnet.edu.au/plus/s/YRnAMis6vR2ZKmo
   Password: GrainDays_123456
2. Install a virtual machine
   Follow: "VirtualBox_Instructions.pdf"

We will use…
- Fiji (ImageJ) and plugins
- Python (libraries)
- MeshLab





Today…

Overall: Relearning images → CT Image processing pipeline → Microstructural analysis

Hands-on tutorial #1

ImageJ basics, macro script for batch processing CT images

Hands-on tutorial #2

Enhance image: contrast, reduce noise, segment solid and void phases

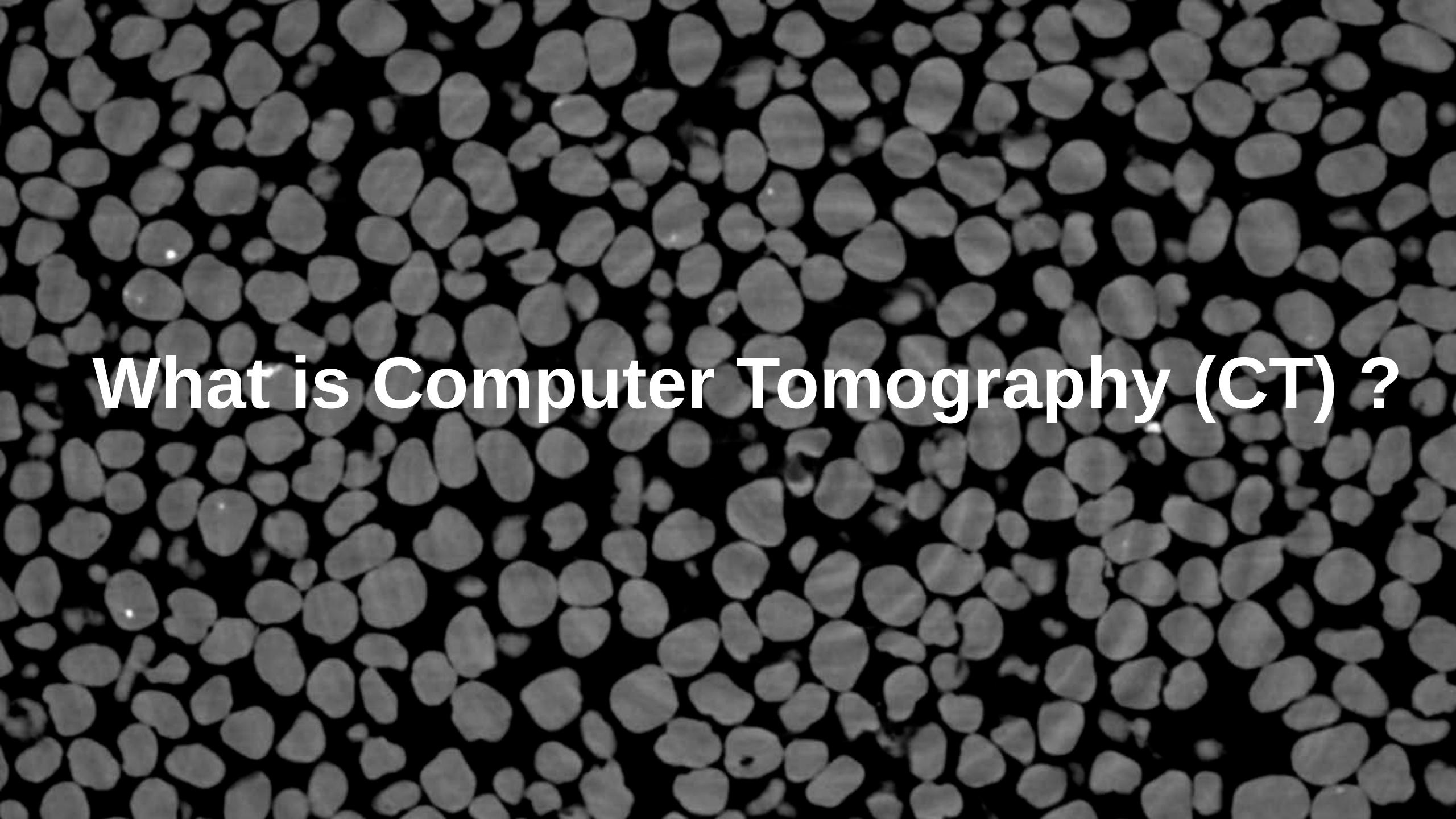
Hands-on tutorial #3

Watershed segmentation, particle extraction &analysis: calculate particle size and shape

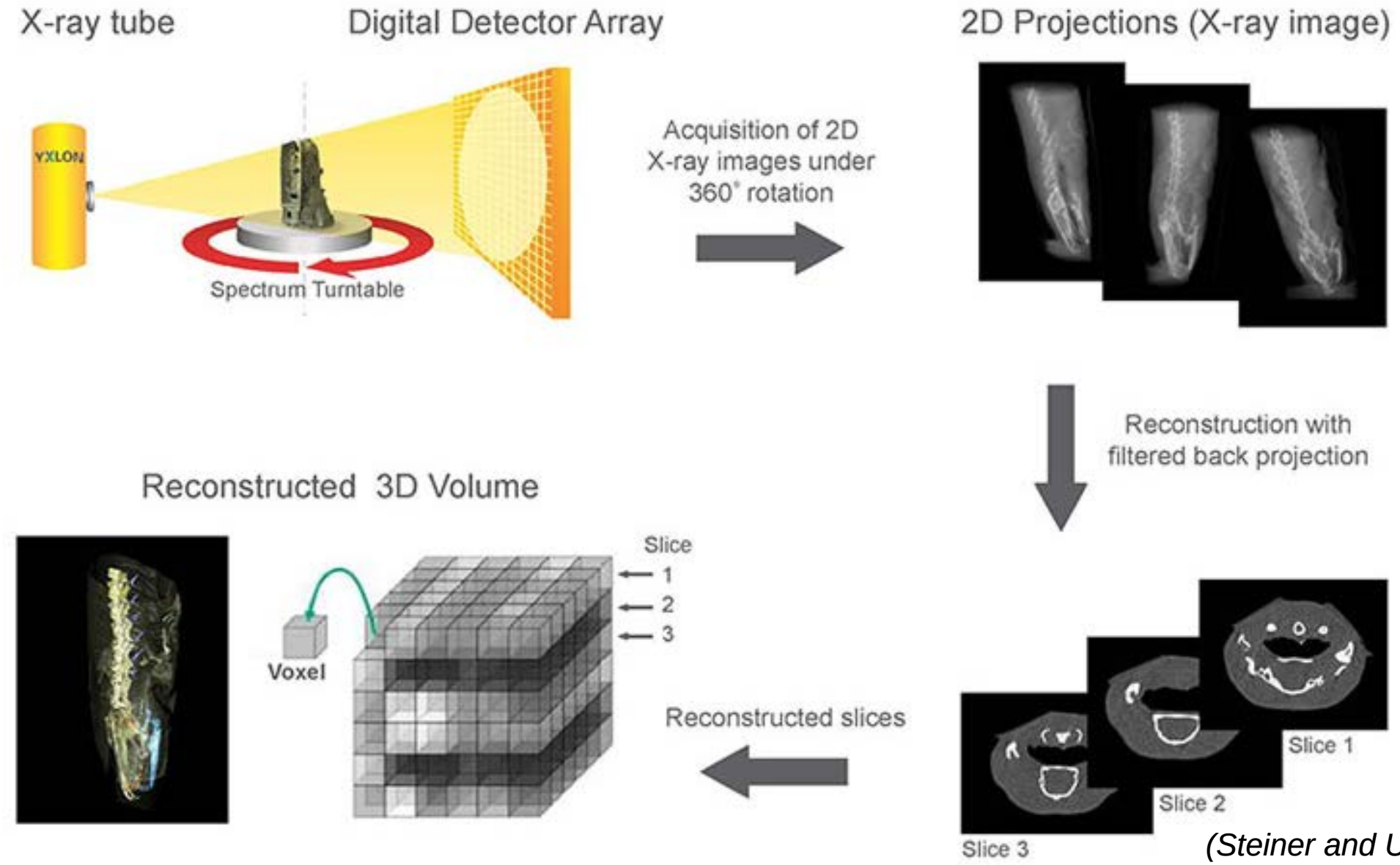
Software, sample data: *https://cloudstor.aarnet.edu.au/plus/s/YRnAMis6vR2ZKmo* pwd: GrainDays_123456

Objectives

1. Relearning images
2. CT Image processing pipeline
3. Microstructural analysis


What is Computer Tomography (CT) ?

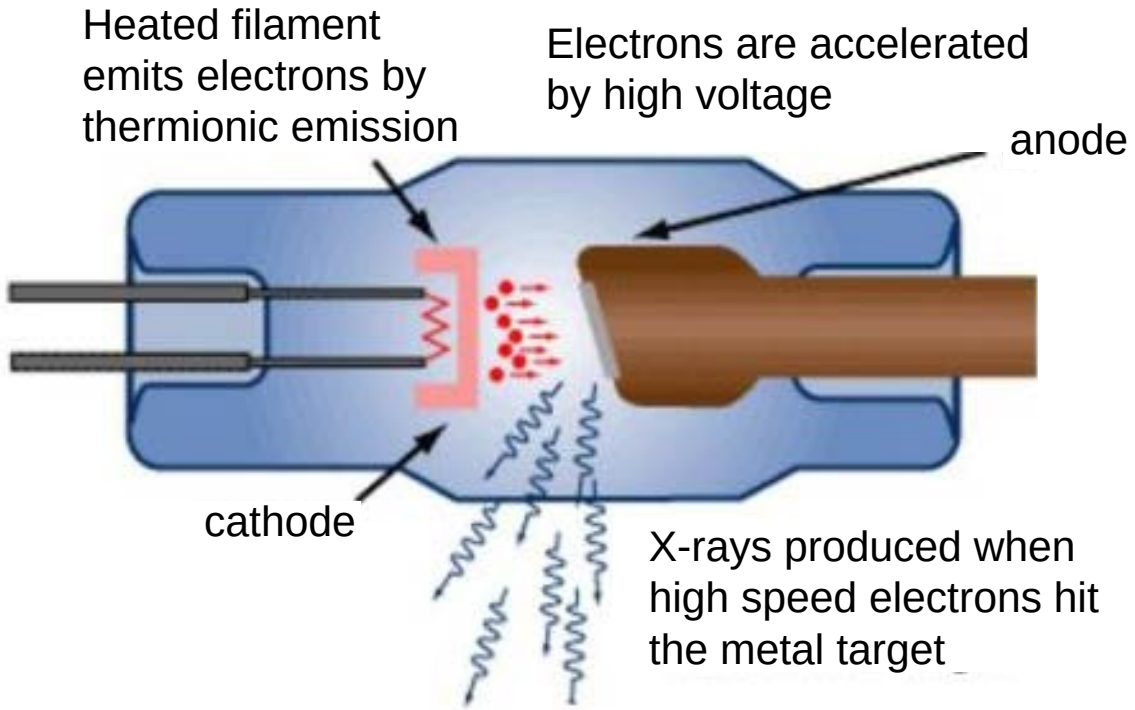
Computer Tomography



(Steiner and Urbanski, 2018)

X-ray tube-based CT

(Waygate Technologies, 2021)



(Herres, 2015)

Synchrotron radiation-based CT

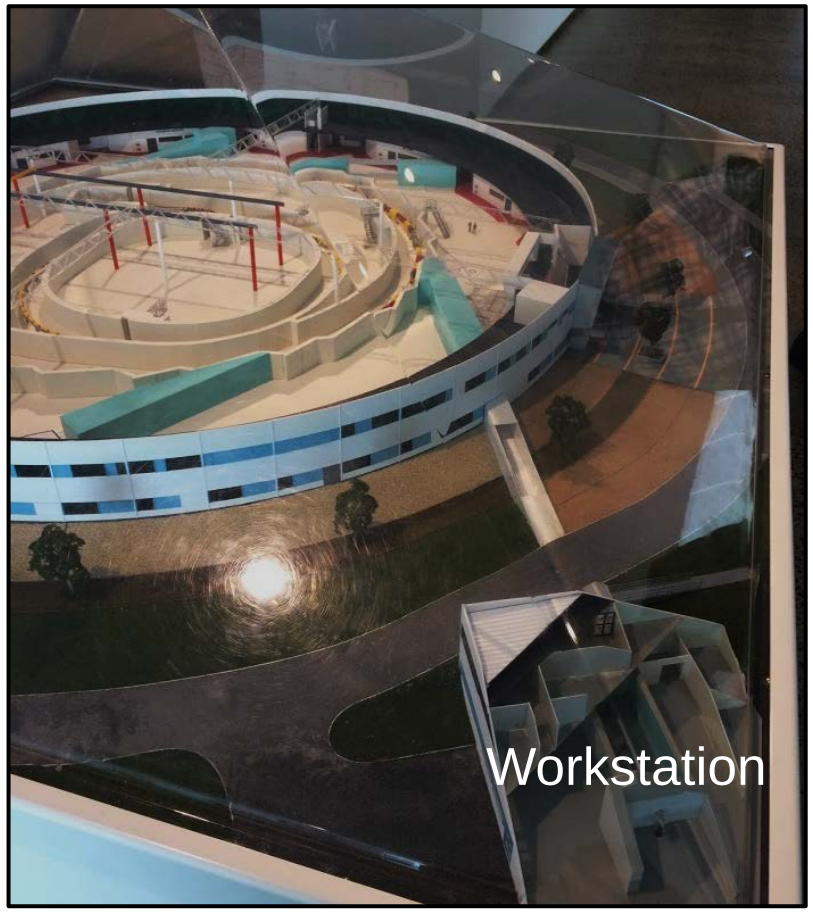
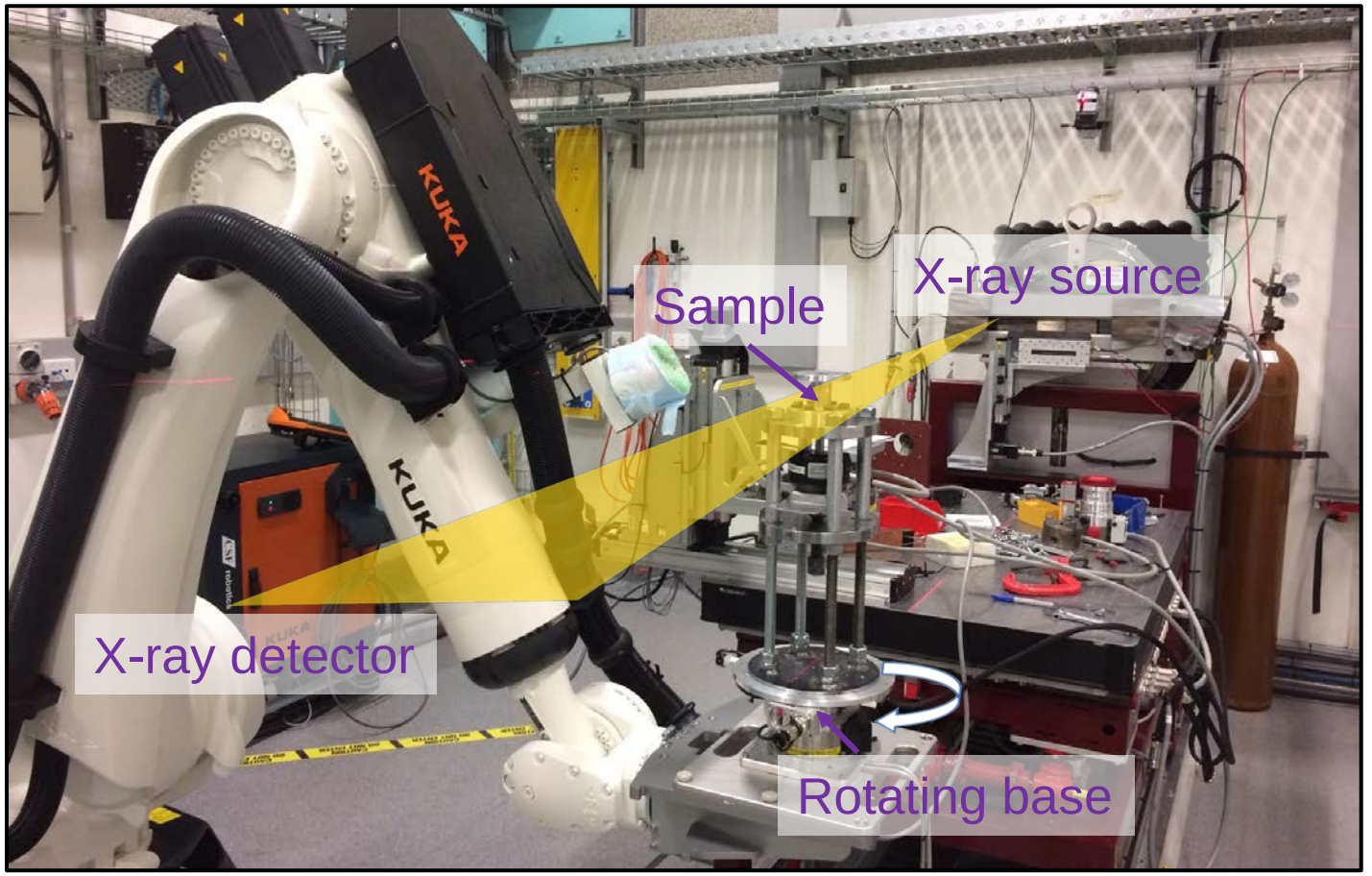
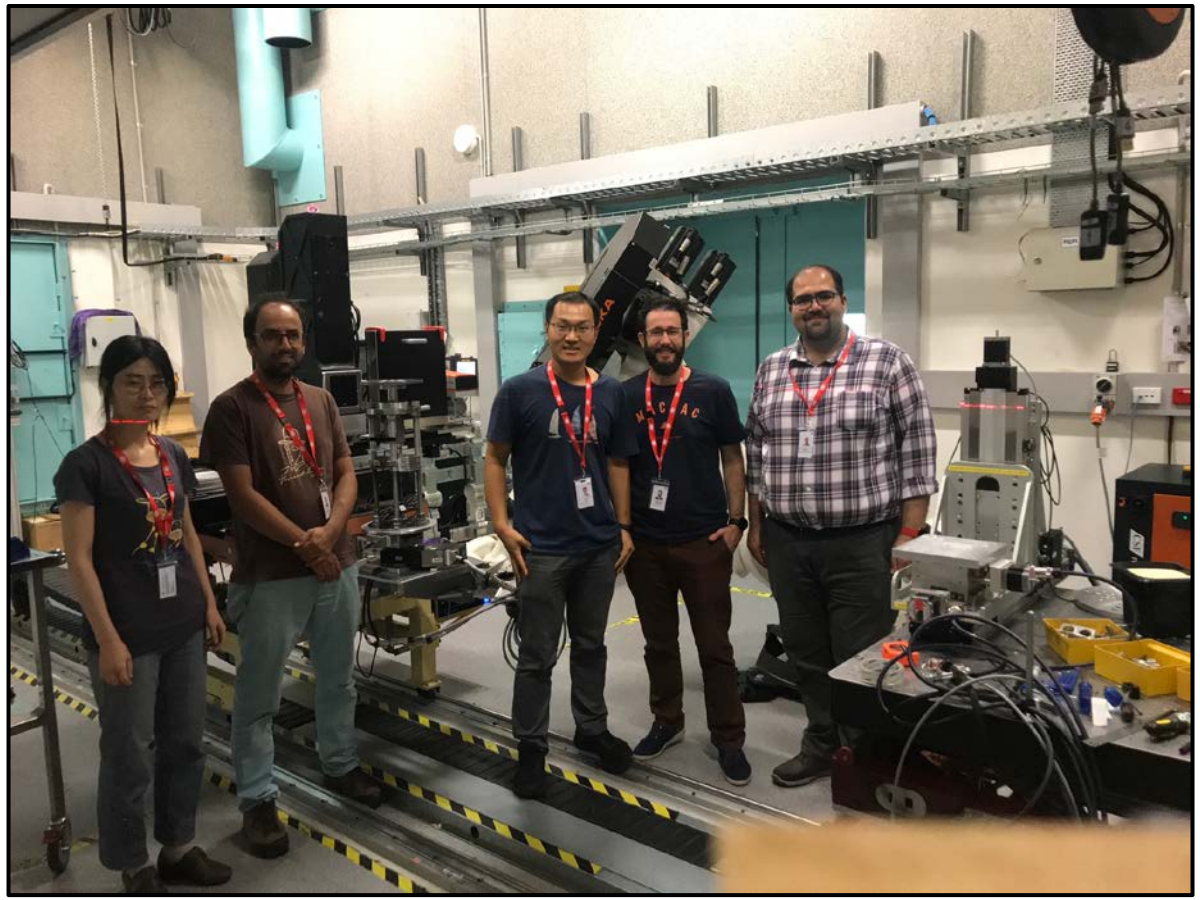


Illustration of Australian synchrotron



Beamline and loading apparatus

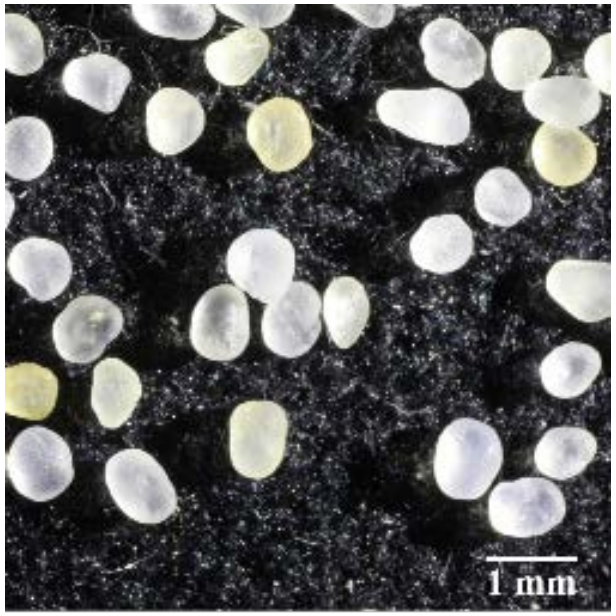
Synchrotron radiation-based CT

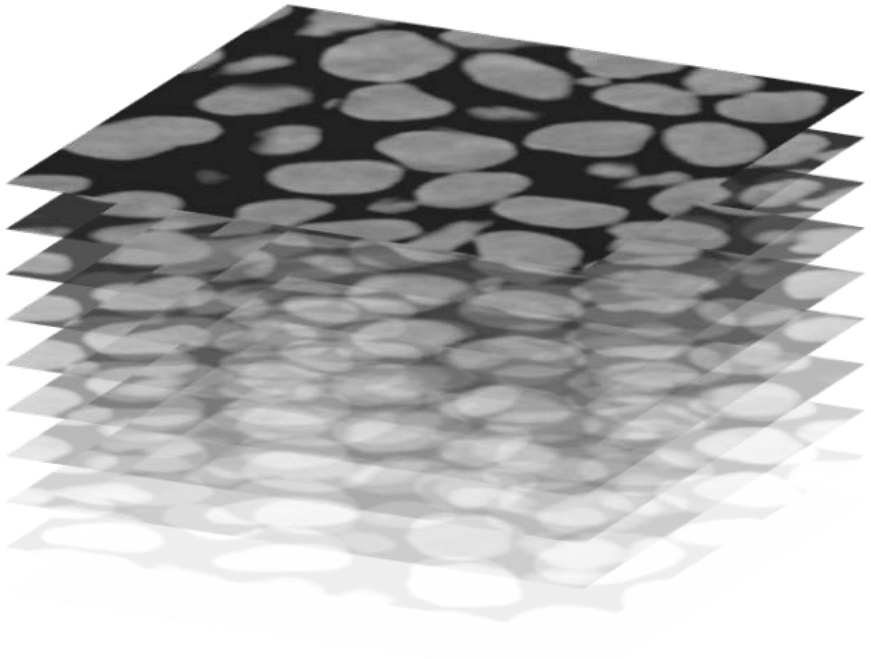


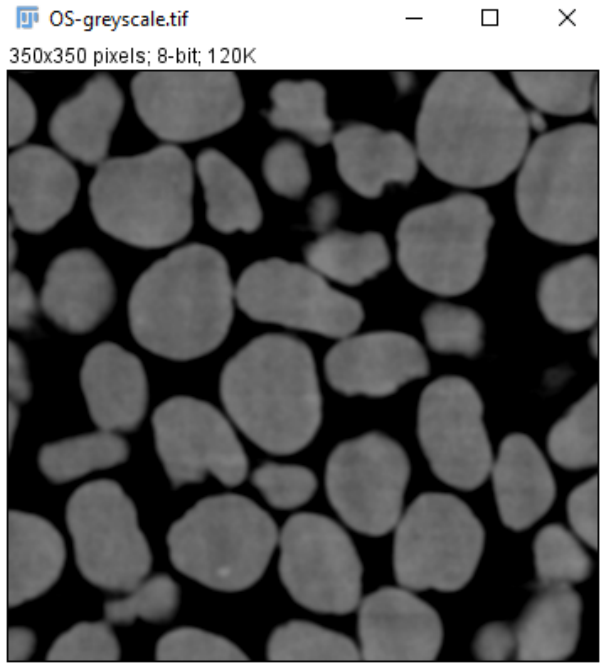
IBML hatch at Australian synchrotron: 8 hrs shifts

Preparing samples

Synchrotron radiation-based CT







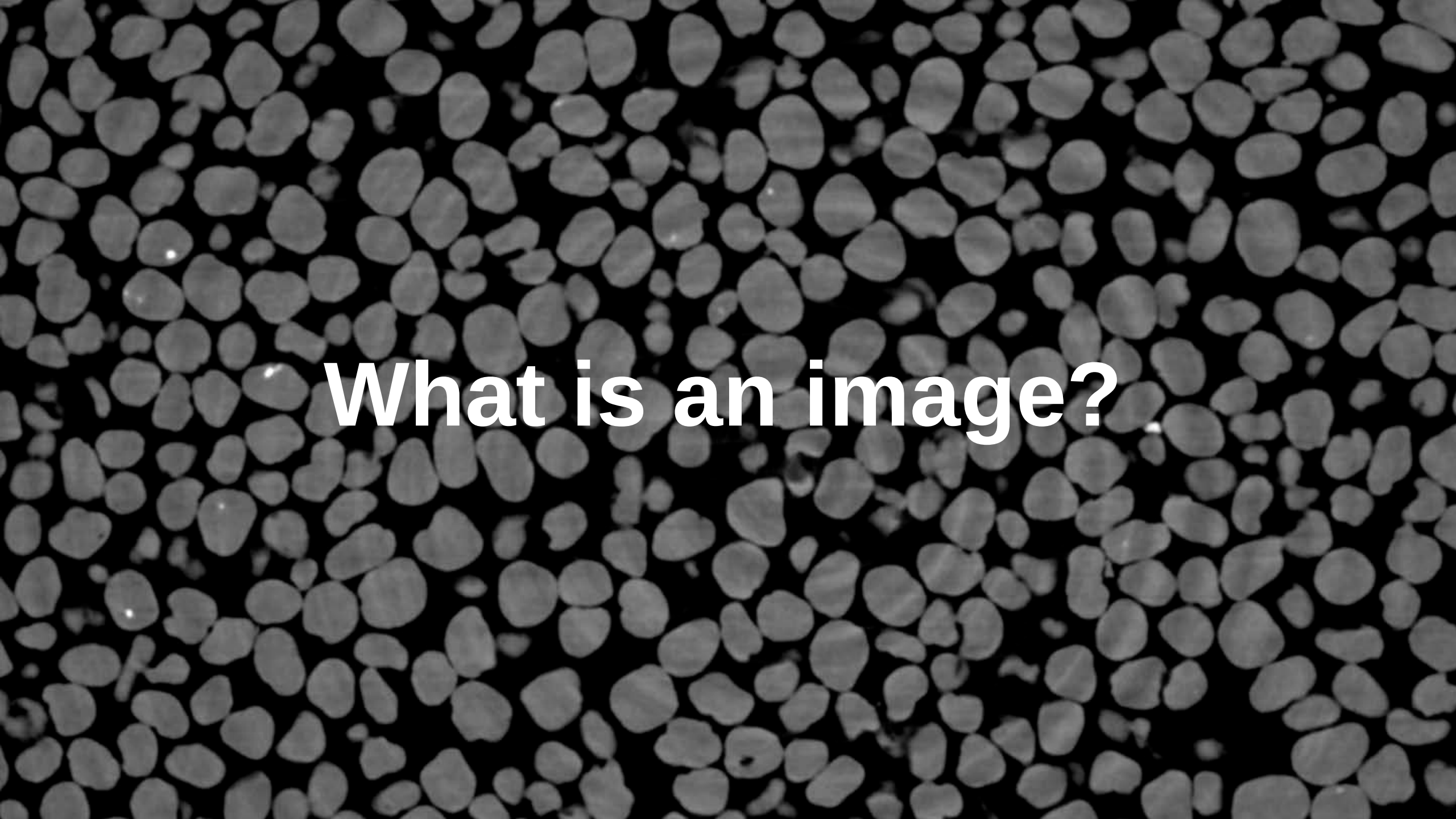

What is an image?

Image as array

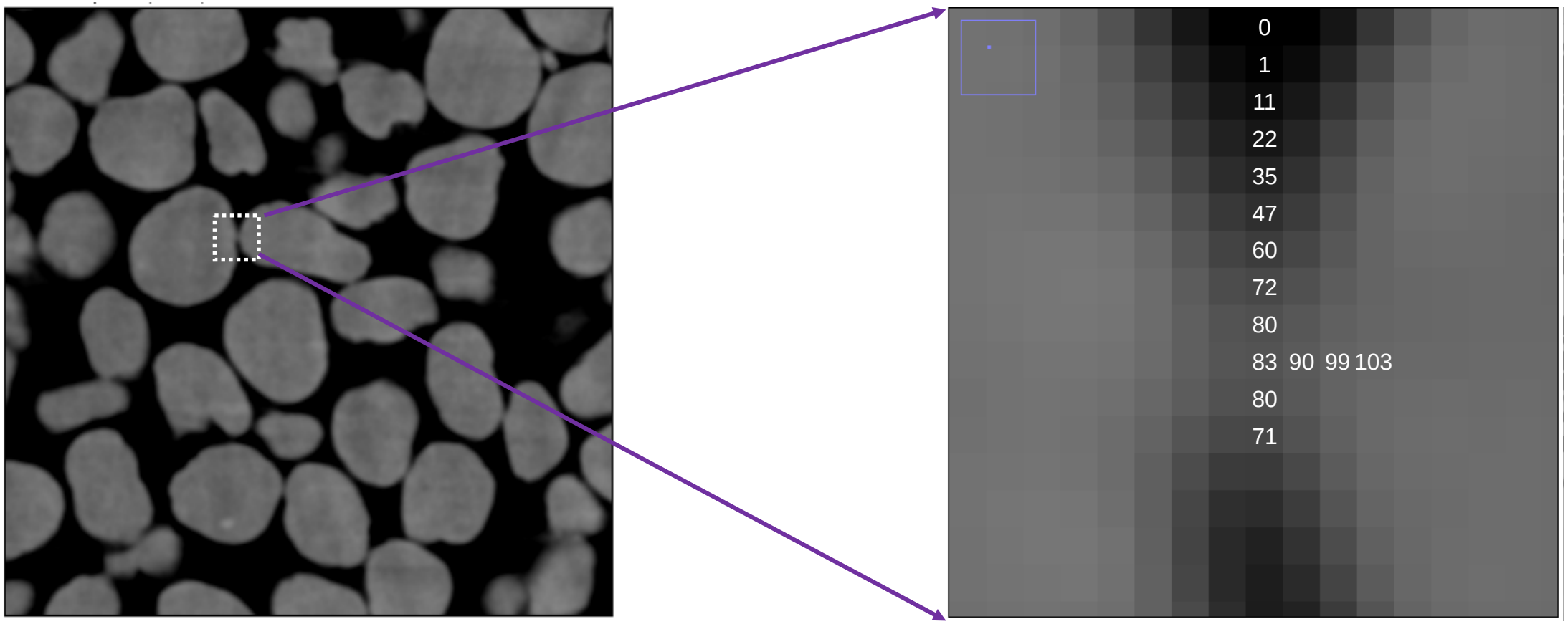


Image source: X-ray computed tomography images and network data of sands under compression - ScienceDirect

Pixel types

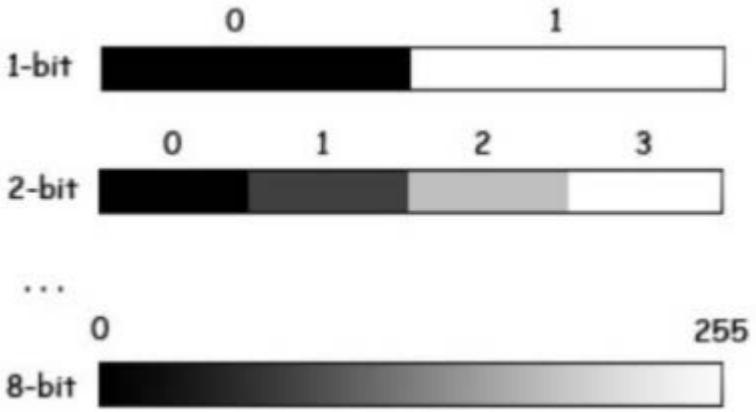
24-bit colour:
2^{24} = 16,777,216 colours

8-bit colour:
2^{8} = 256 colours

6-bit colour:
2^{6} = 64 colours

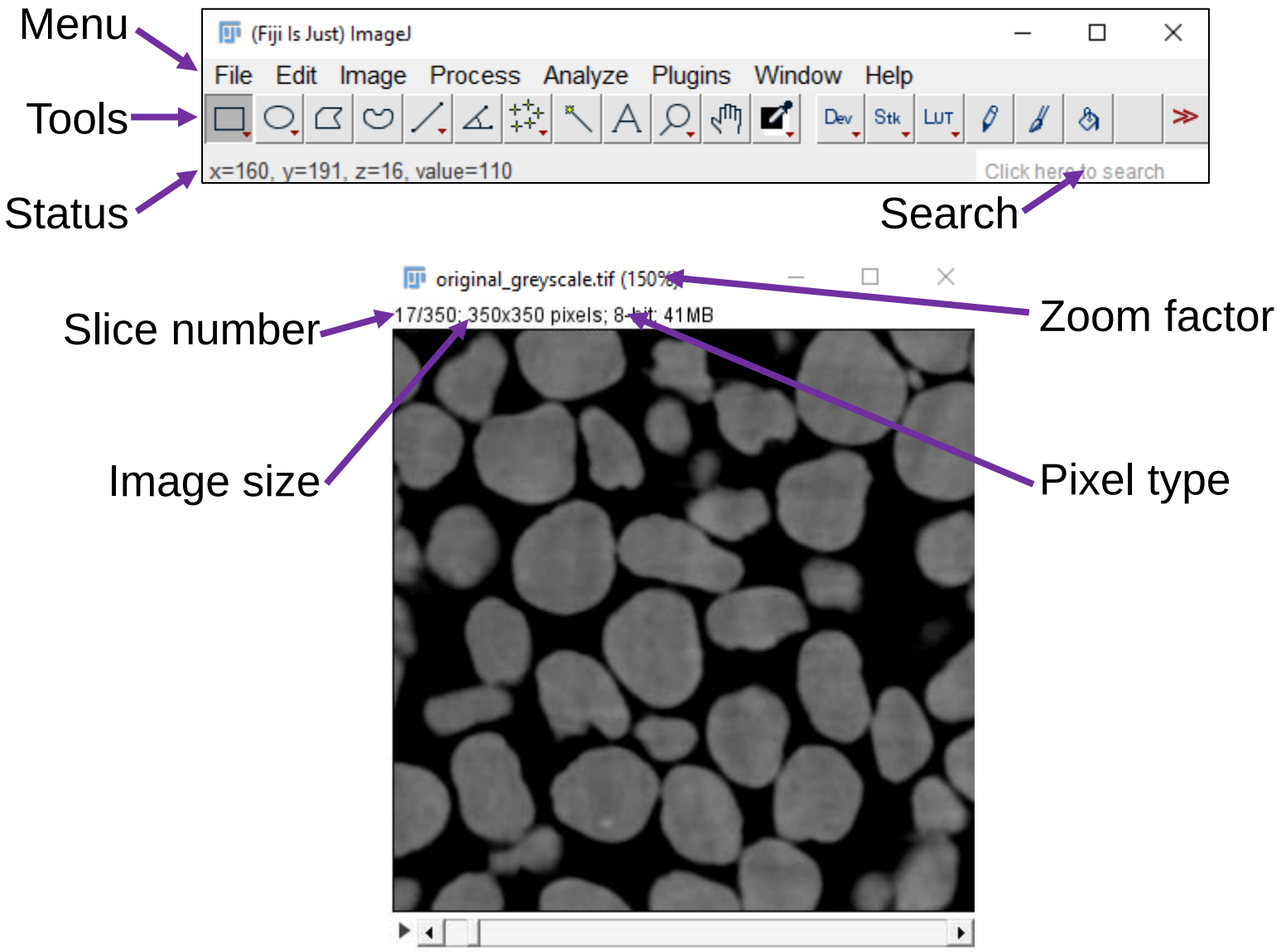
Binary

1-bit colour:
2^{1} = 2 colours

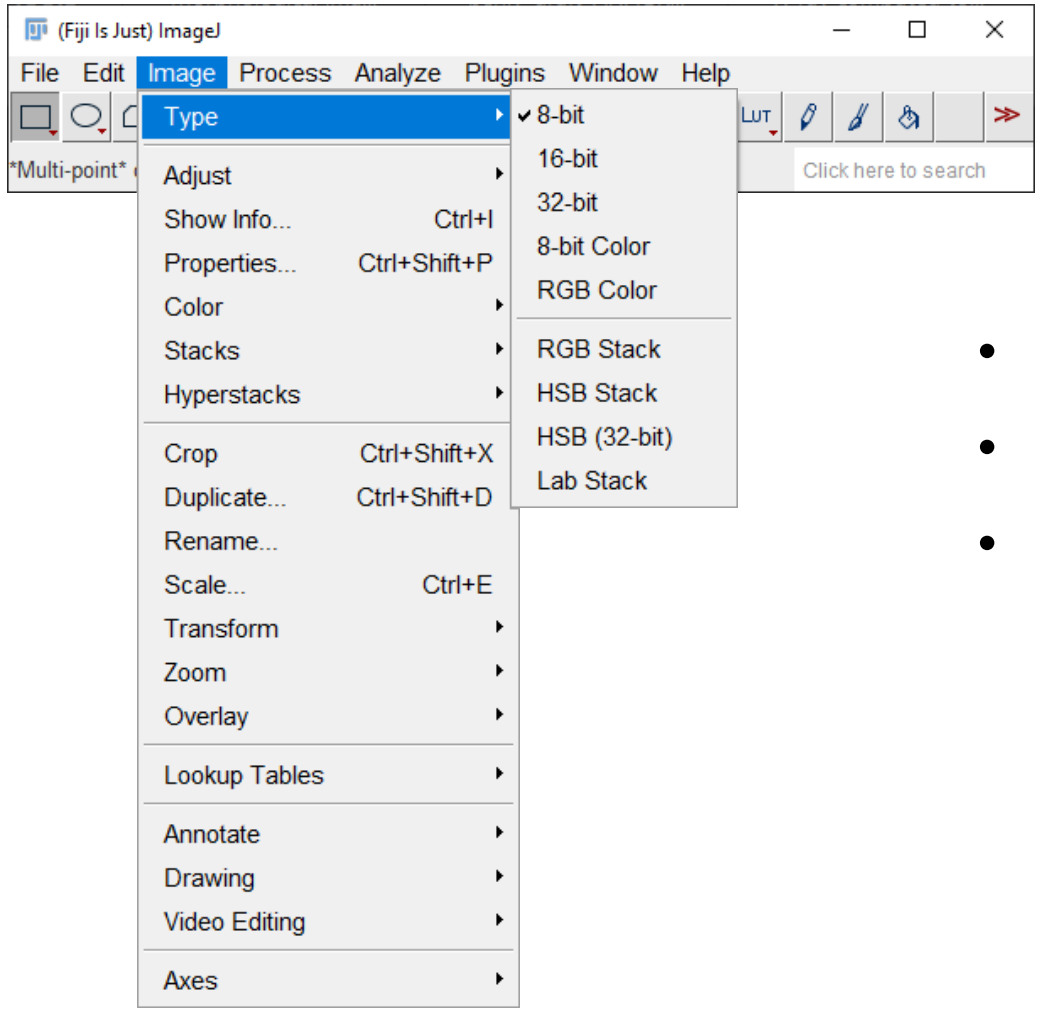


(etc.usf.edu)

Fiji is ImageJ

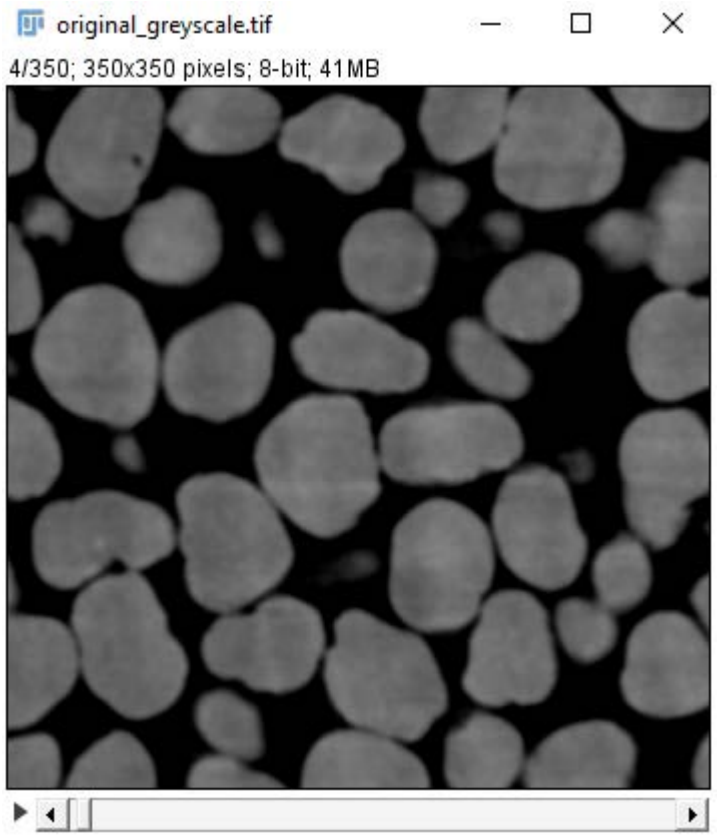


Pixel types

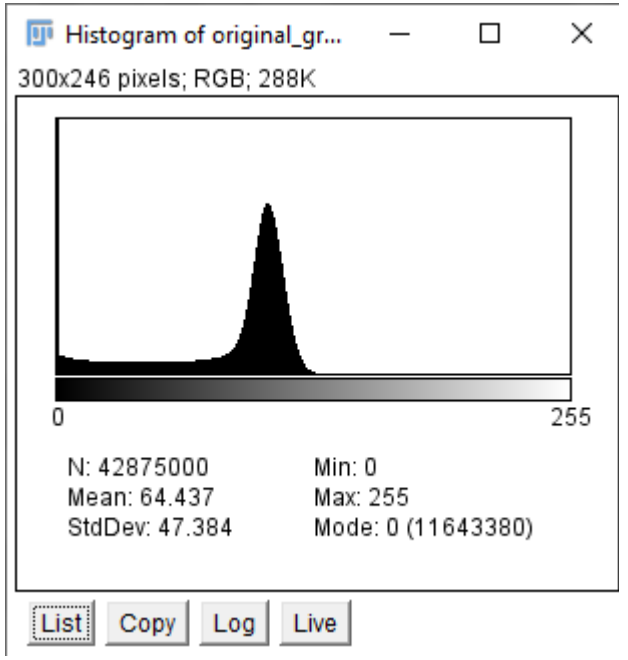


- 8-bit = 256 levels (integers only)
- 16-bit = 65, 536 levels (integers only)
- 32-bit = 4, 294, 967, 296 levels (float)

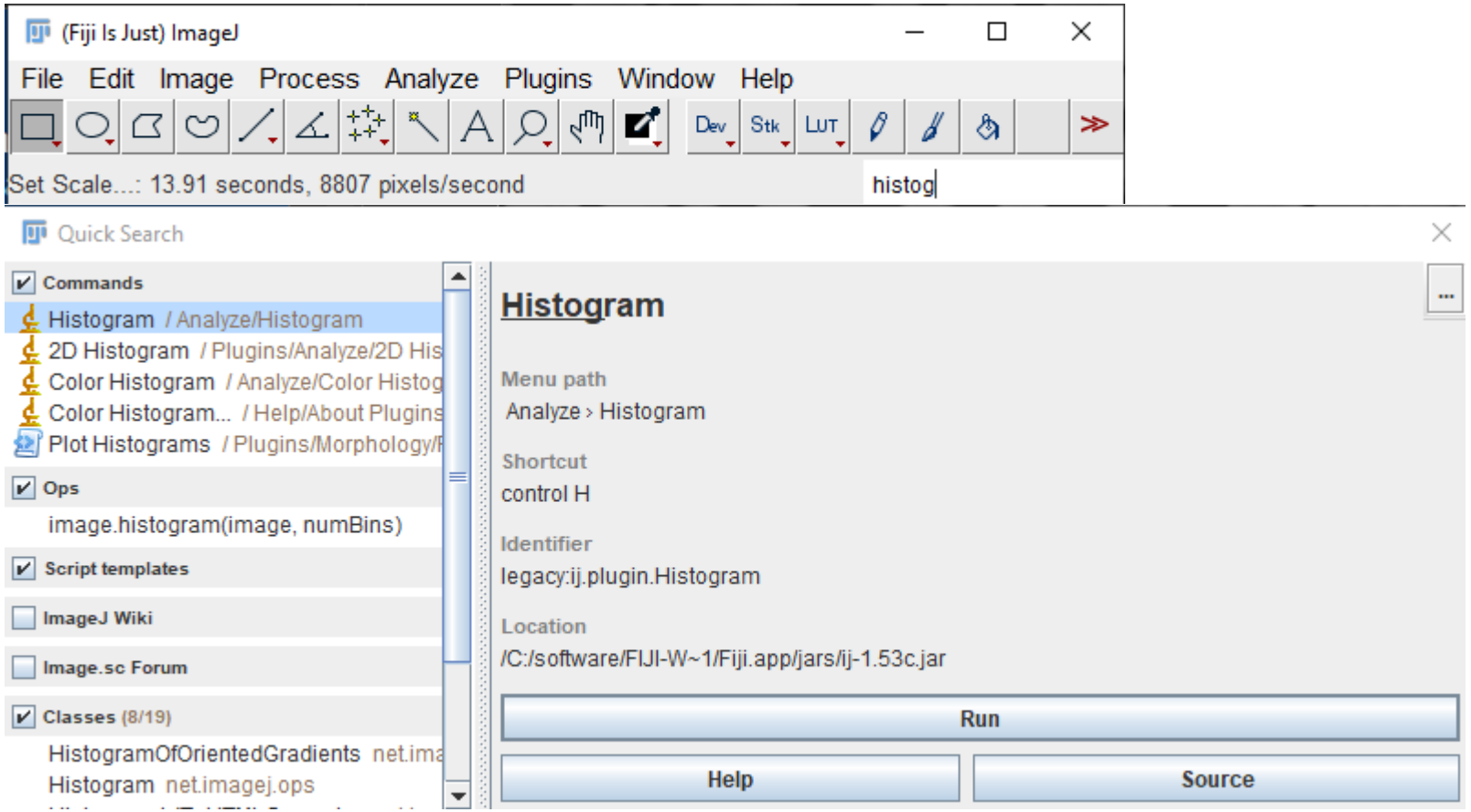
Histogram



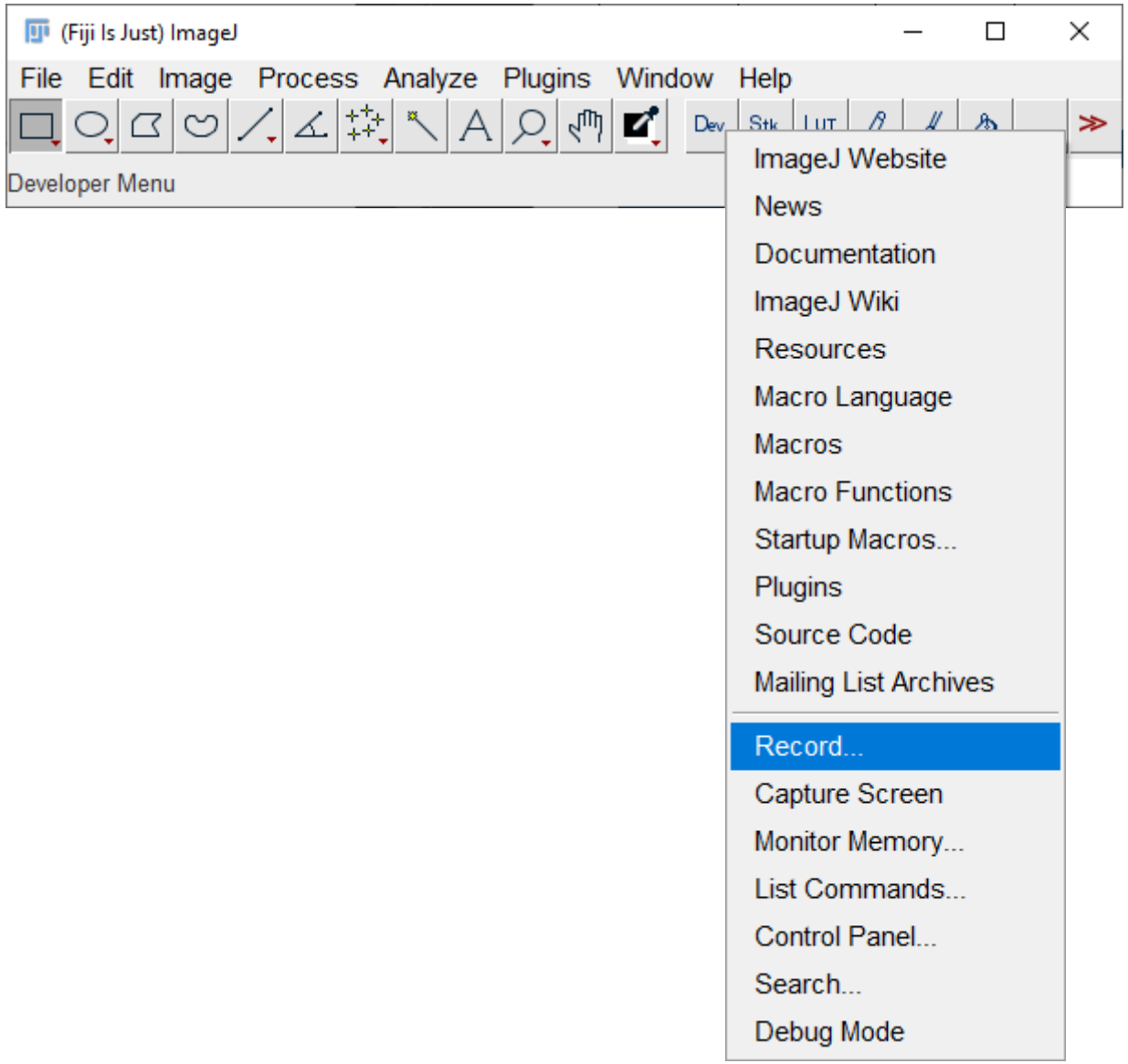
Analyze > Histogram

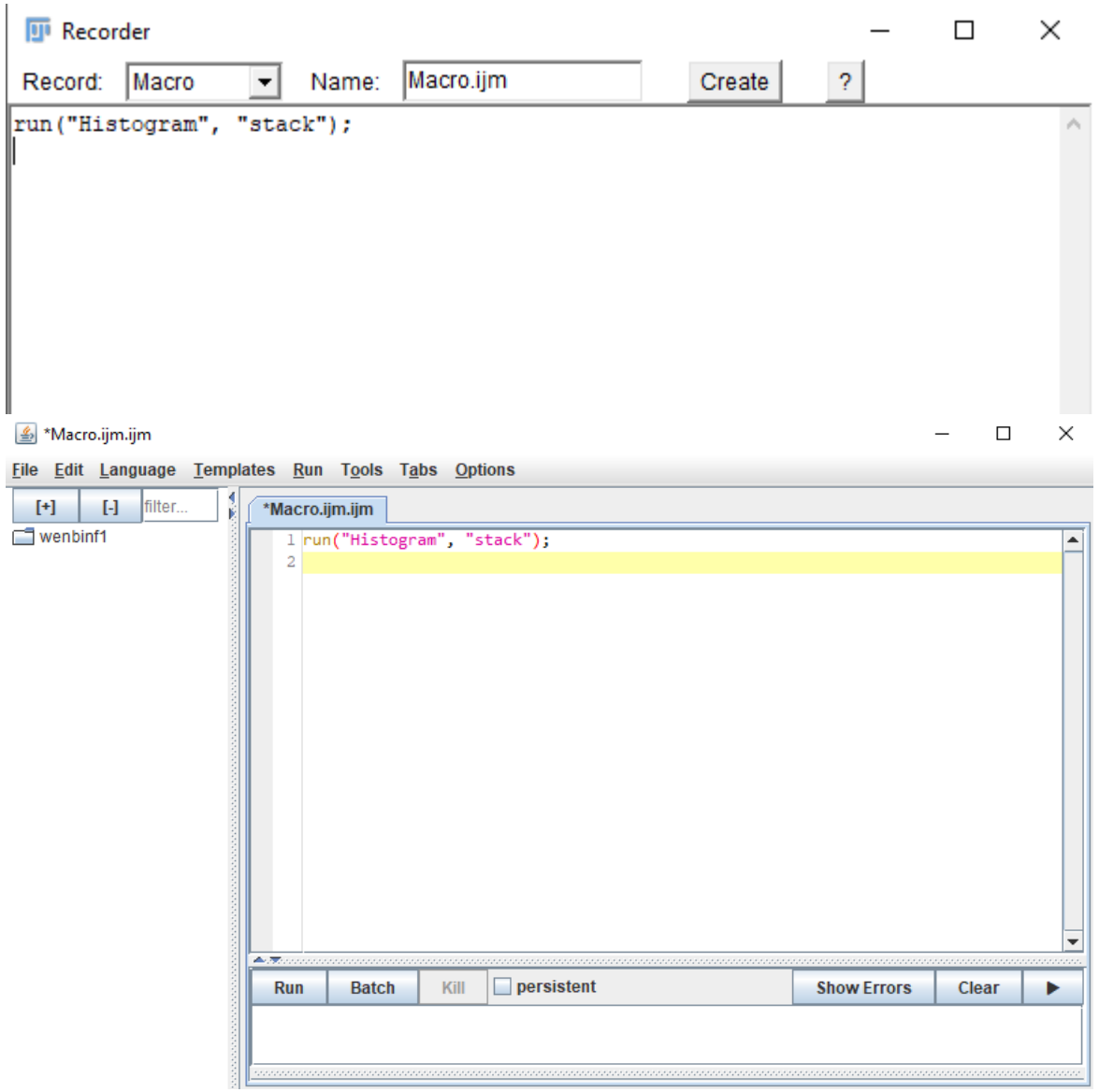


Histogram

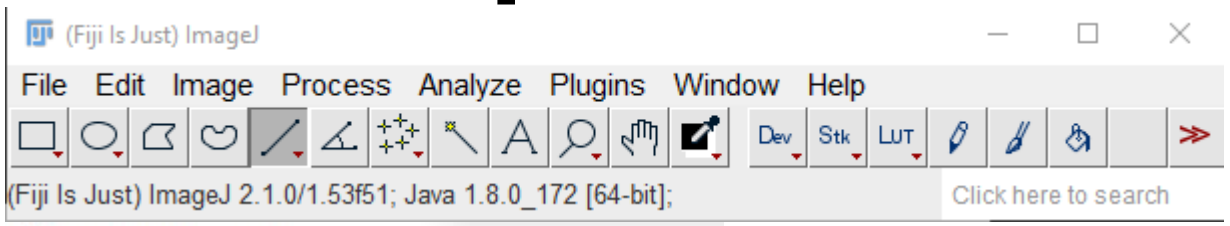

(Fiji Is Just) ImageJ
File Edit Image Process Analyze Plugins Window Help
Dev Stk LUT
Set Scale...: 13.91 seconds, 8807 pixels/second
histog
Quick Search
Commands
Histogram / Analyze/Histogram
2D Histogram / Plugins/Analyze/2D His
Color Histogram / Analyze/Color Histog
Color Histogram... / Help/About Plugins
Plot Histograms / Plugins/Morphology/
Ops
image.histogram(image, numBins)
Script templates
ImageJ Wiki
Image.sc Forum
Classes (8/19)
HistogramOfOrientedGradients net.ima
Histogram net.imagej.ops
Histogram
Menu path
Analyze › Histogram
Shortcut
control H
Identifier
legacy:ij.plugin.Histogram
Location
/C:/software/FIJI-W~1/Fiji.app/jars/ij-1.53c.jar
Run
Help
Source

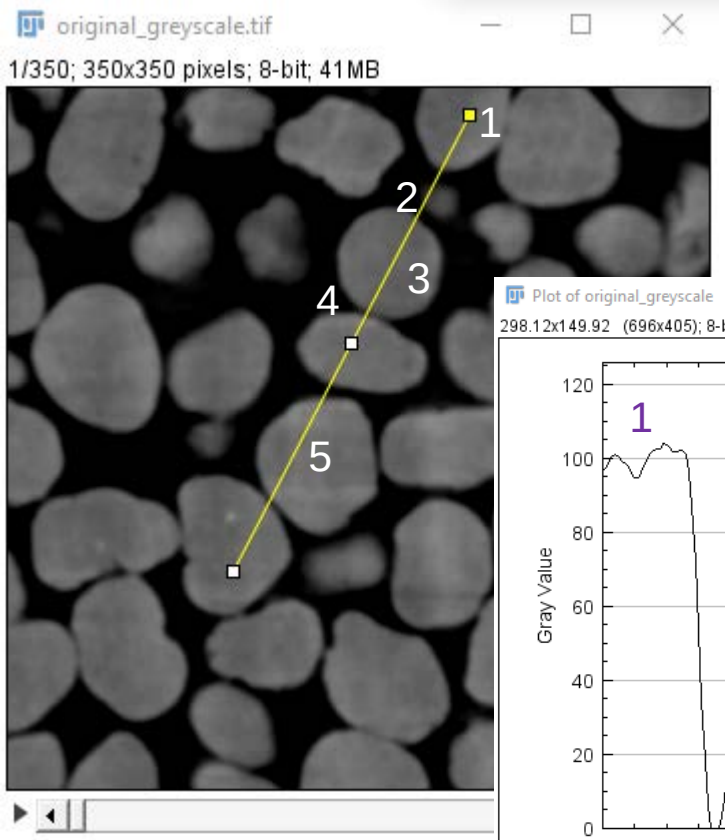
ImageJ scripts – IJ1 Macro





Profile plots





Analyze > Plot profile

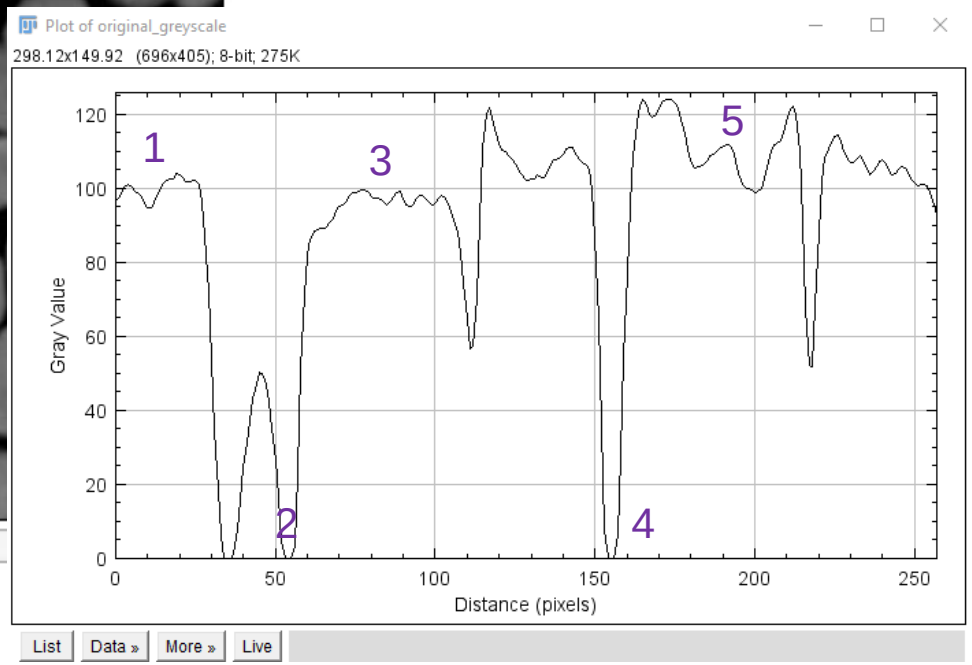
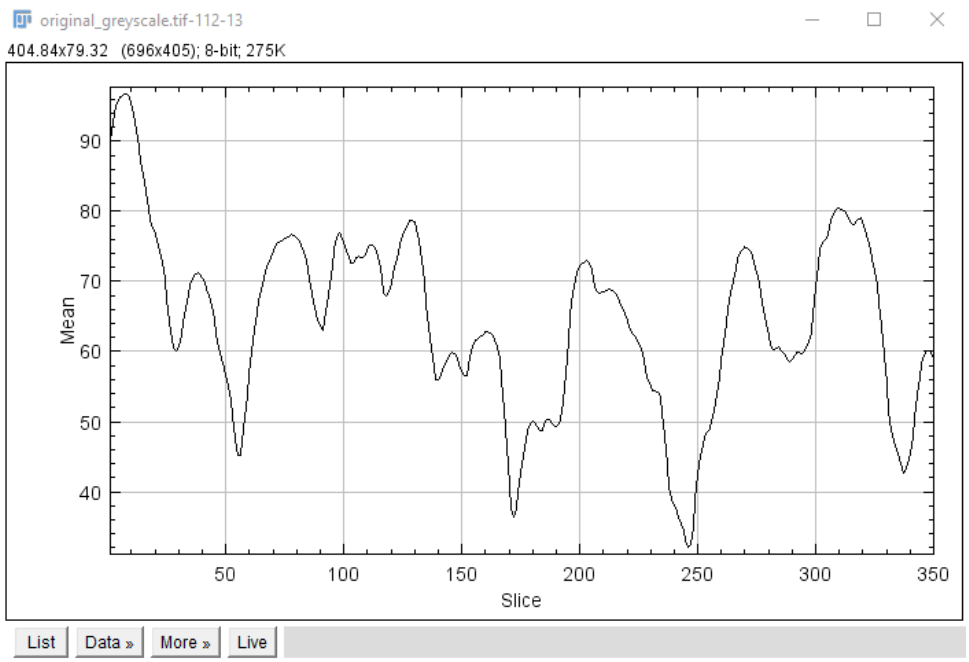
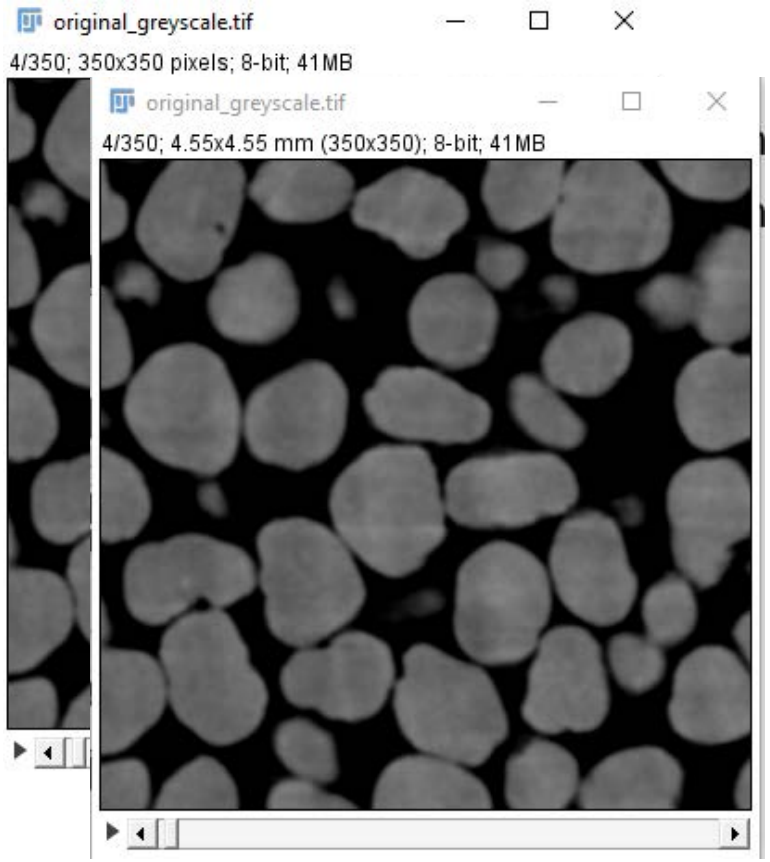
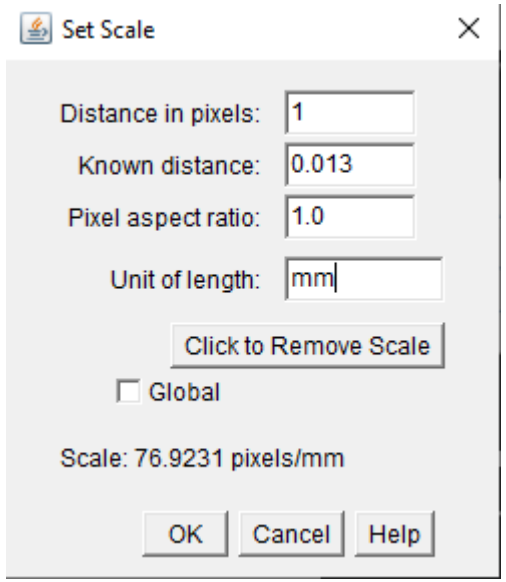


Image > Stacks > Plot Z-Axis Profile

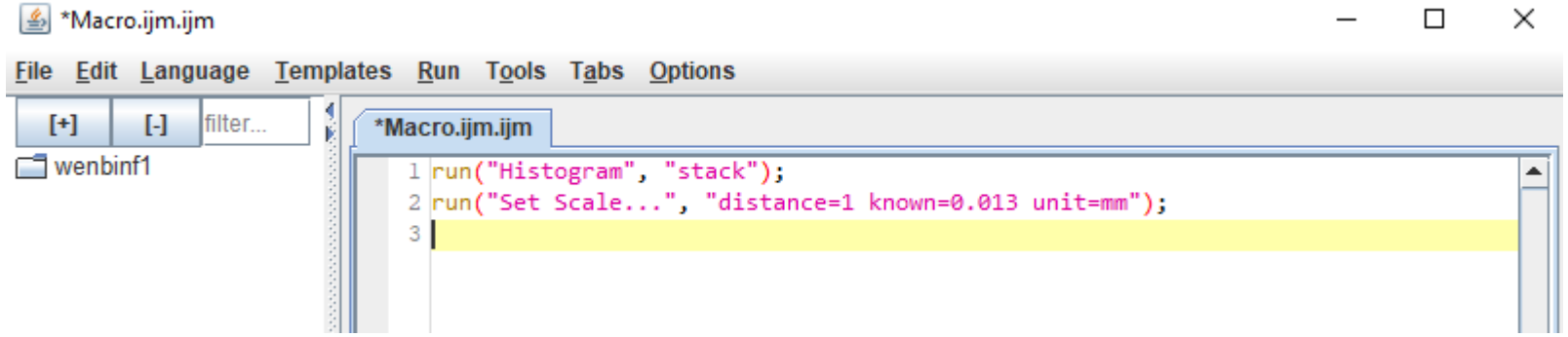


Set scale



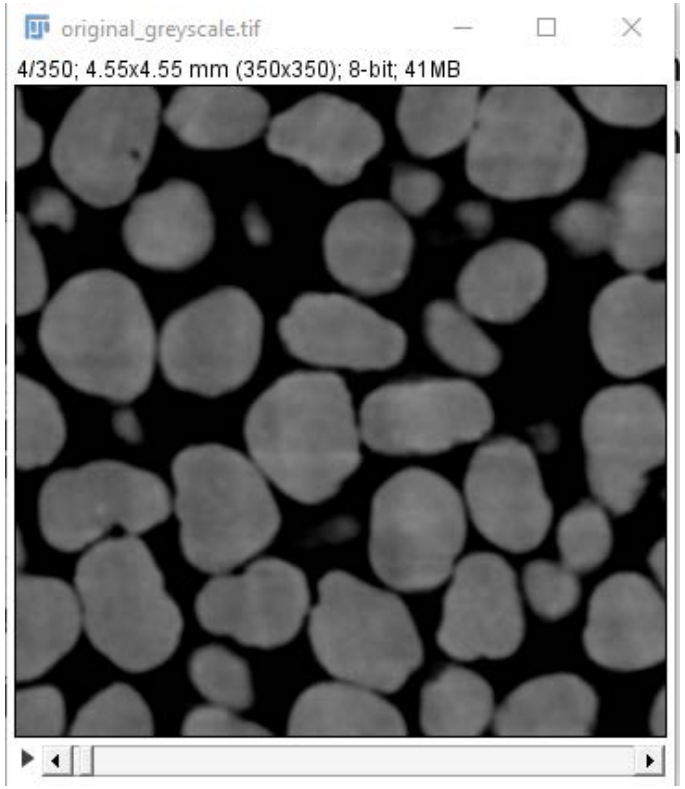


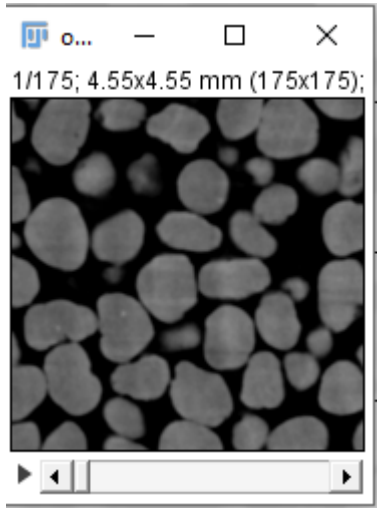
Analyze > Set scale…

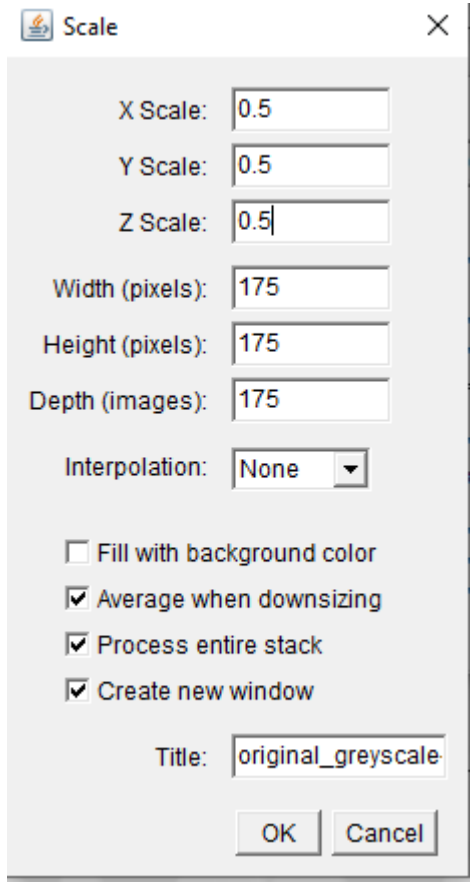


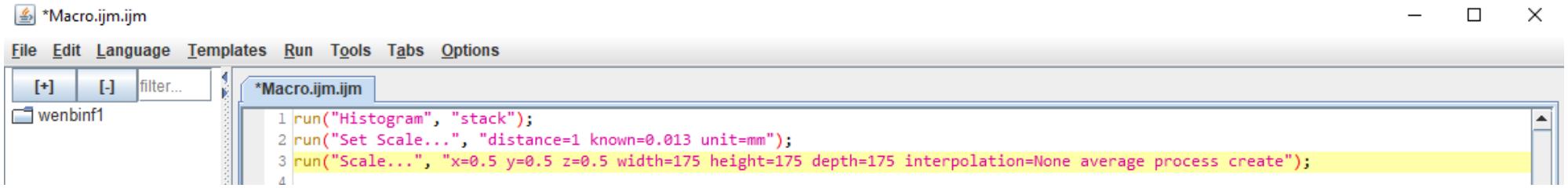
Scale images

Image > Scale…



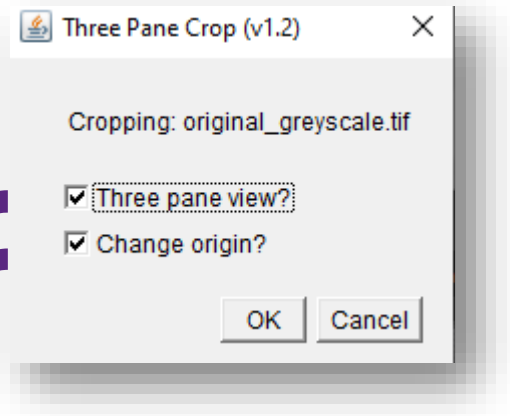






Crop 1 - Three pane

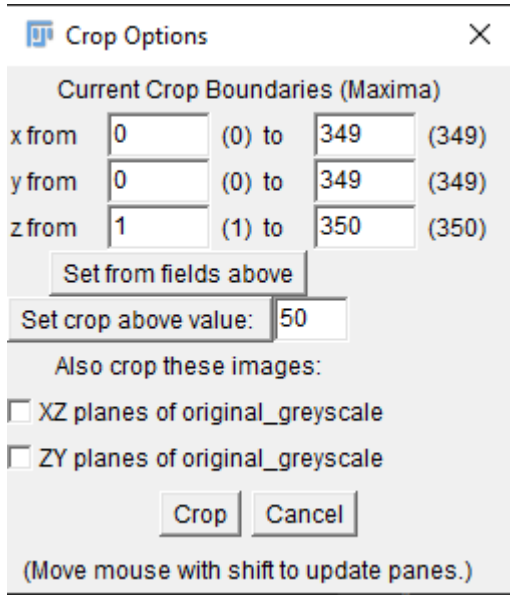
Plugins > Stacks > Crop (3D)…

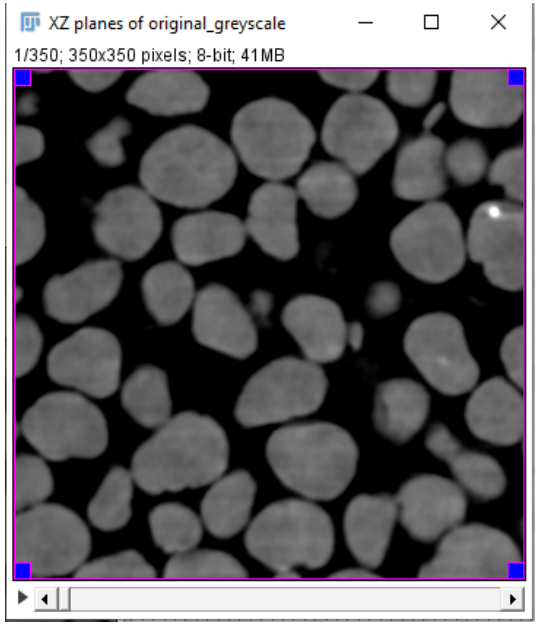


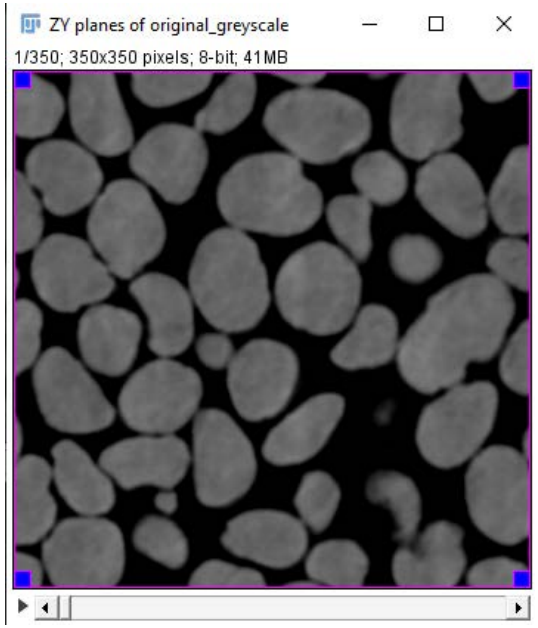
Unselect: just xy pane to save memory

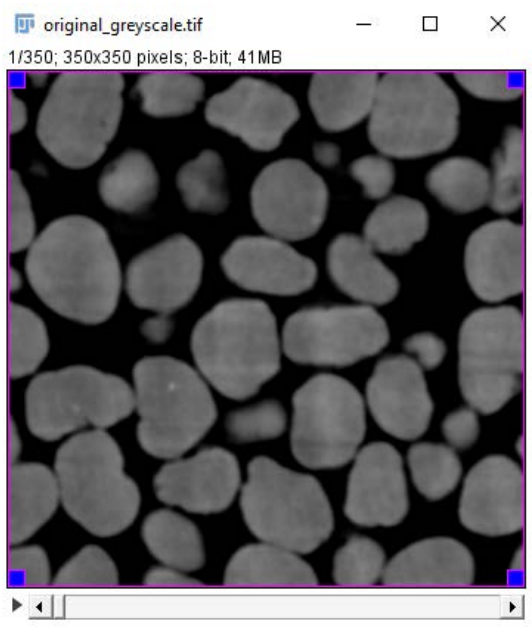
Unselect: keep the origin values as 0,0,0

Image > Show info…

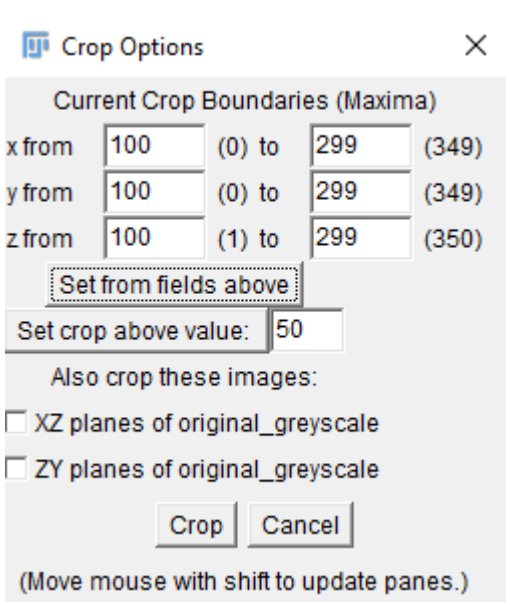


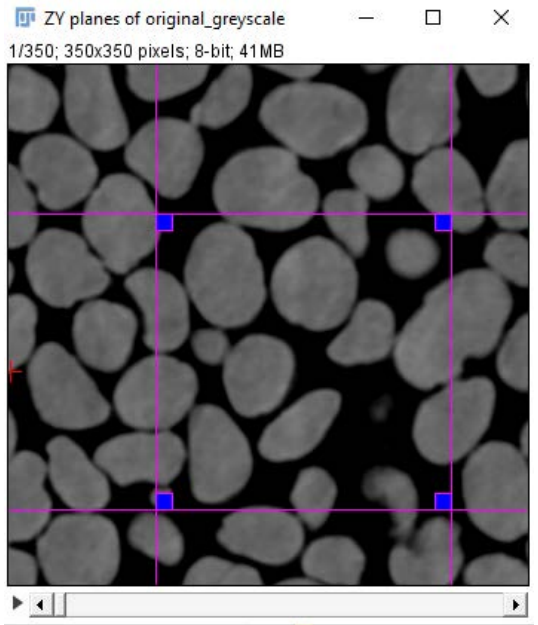


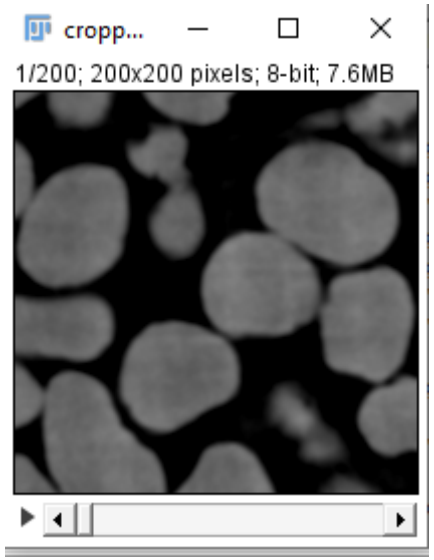


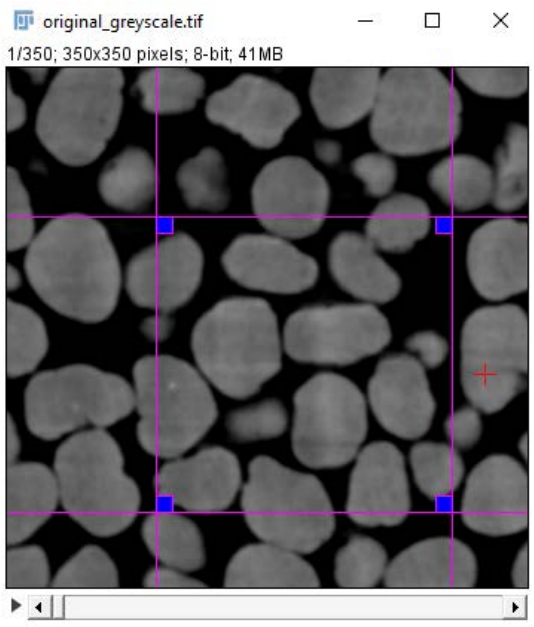


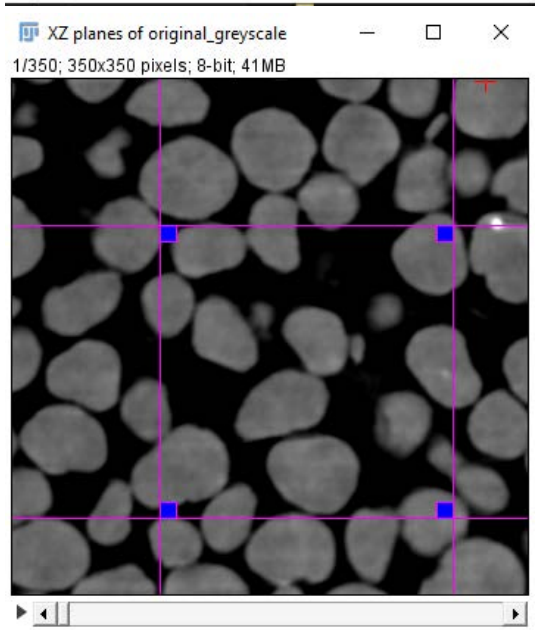
Crop 1 - Three pane

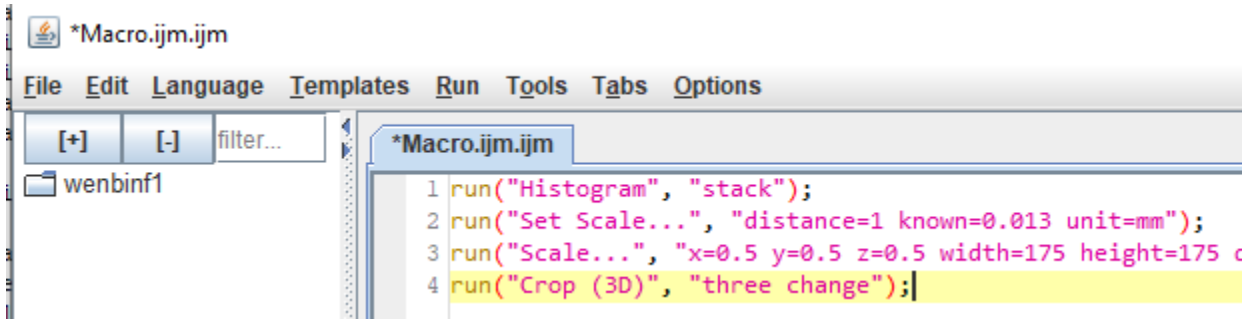






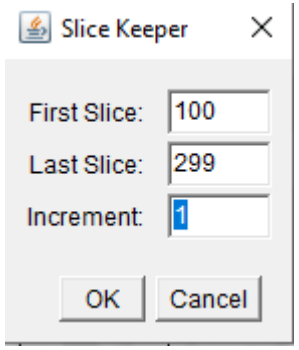


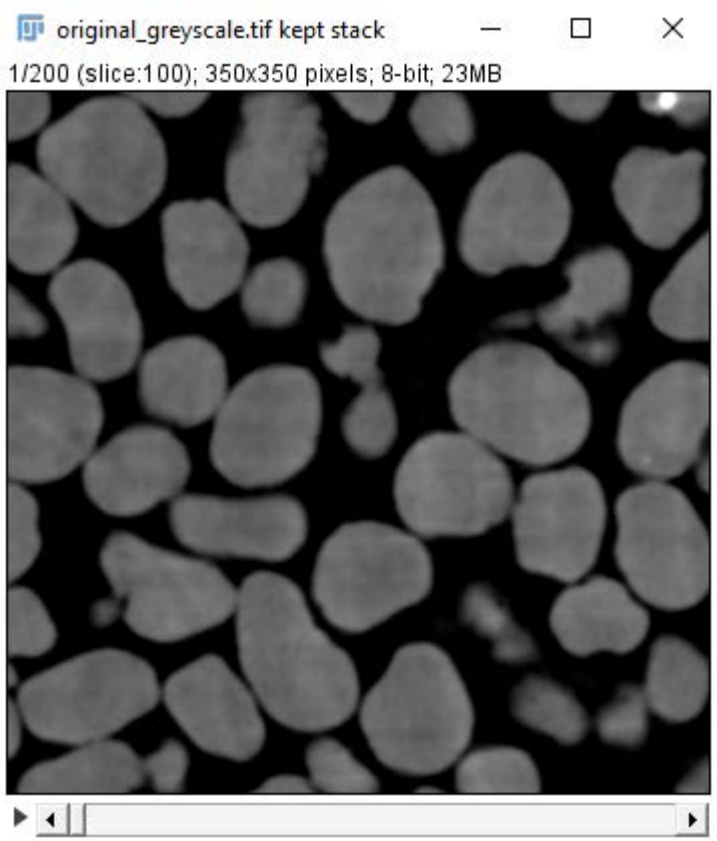




Crop 2 - Macro script

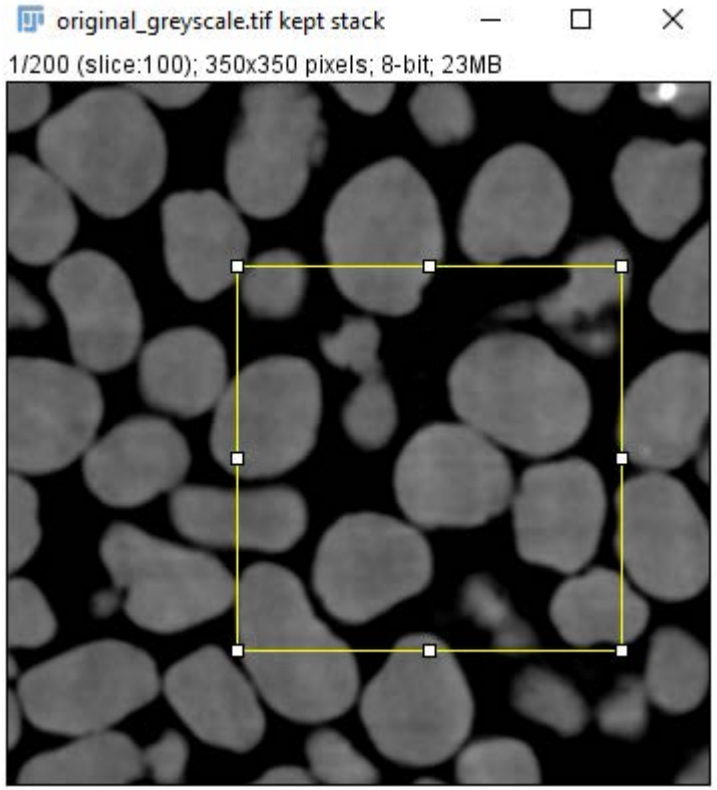
Image > Stacks > Tools > Slice Keeper






```
// Crop
// run("Crop (3D)", "three change");
setSlice(100-299);
```

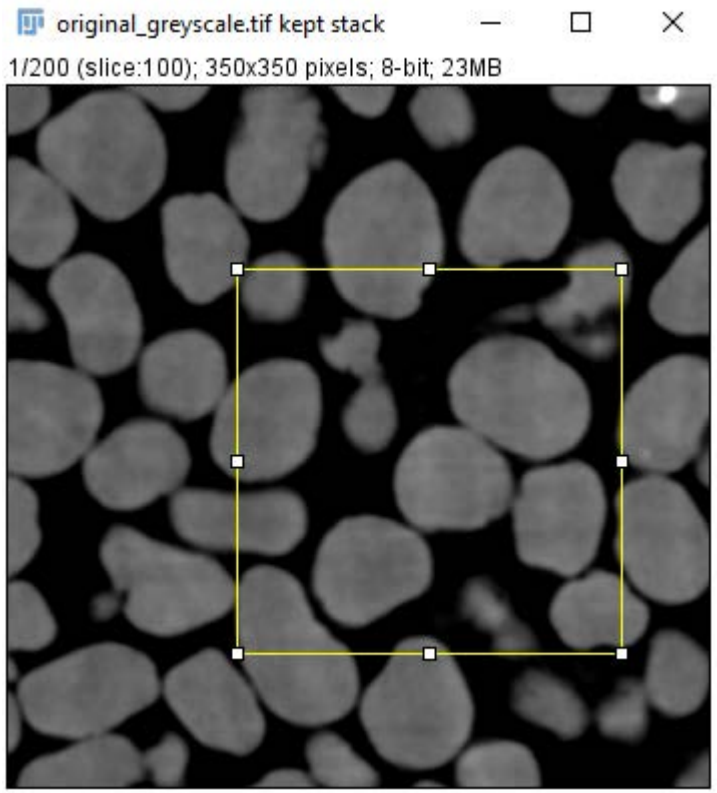
Image > Crop



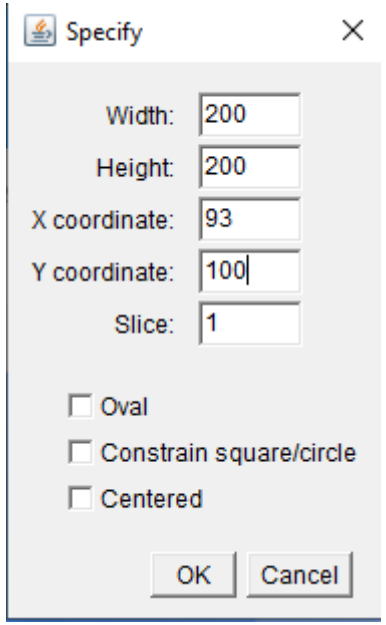

```
run("Slice Keeper", "first=100 last=299 increment=1");
makeRectangle(114, 91, 192, 192);
run("Crop");
```

Crop 2 - Macro script

Image > Crop



Edit > Selection > Specify…

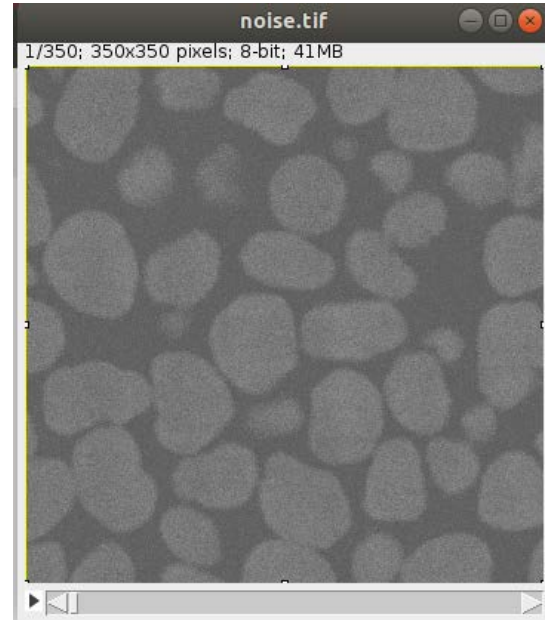



```
7 run("Slice Keeper", "first=100 last=299 increment=1");
8 makeRectangle(114, 91, 192, 192);
9 run("Crop");
```

Hands-on Tutorial #1

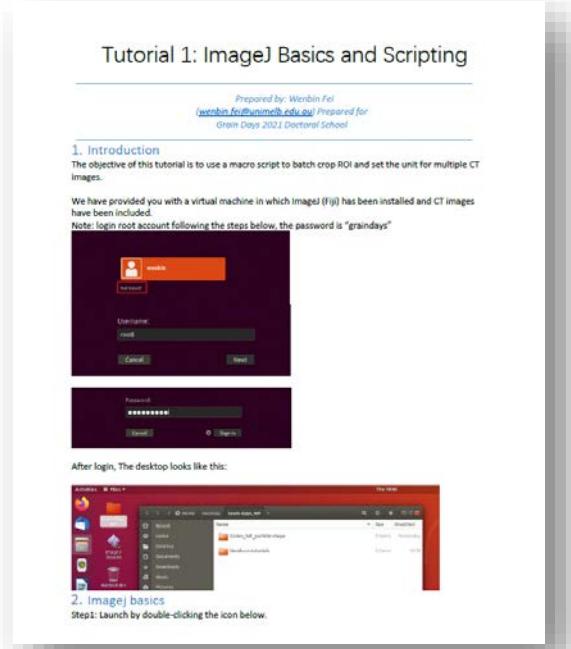
Hands-on Tutorial #1

15 minutes



Objectives:

- ImageJ(Fiji) basics
- IJ1 Macro script for batch processing CT images


Tutorial 1: ImageJ Basics and Scripting

Prepared by: Wenbin Fei
(wenbin.fei@unimelb.edu.au) Prepared for
Grain Days 2021 Doctoral School

1. Introduction

The objective of this tutorial is to use a macro script to batch crop ROI and set the unit for multiple CT images.

We have provided you with a virtual machine in which ImageJ (Fiji) has been installed and CT images have been included.
Note: login root account following the steps below, the password is "graindays"

After login, The desktop looks like this:

2. Imagej basics

Step1: Launch by double-clicking the icon below.

Download tutorial using the following link:

Link: *https://cloudstor.aarnet.edu.au/plus/s/YRnAMis6vR2ZKmo*
Password: **GrainDays_123456**

Hands-on Tutorial #1

Data in Brief 36 (2021) 107122

Contents lists available at ScienceDirect

Data in Brief

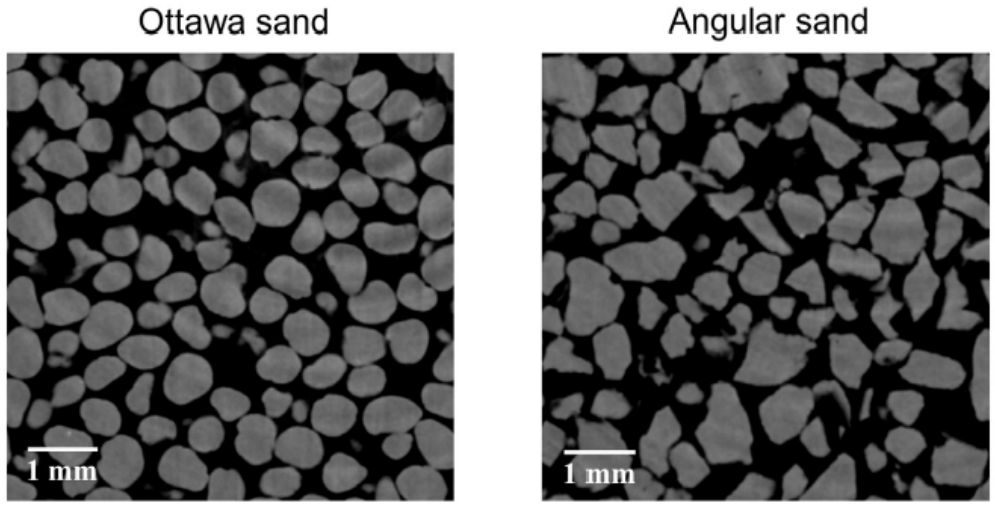
journal homepage: www.elsevier.com/locate/dib

Data Article

X-ray computed tomography images and network data of sands under compression

Wenbin Fei[a], Guillermo Narsilio[a,*], Joost van der Linden[a], Mahdi Disfani[a], Xiuxiu Miao[b], Baohua Yang[c], Tabassom Afshar[d]

[a] Department of Infrastructure Engineering, The University of Melbourne, Parkville, Australia
[b] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou, Jiangsu Province 221116, China
[c] Information Science and Engineering School, Hunan Women's University, Changsha, Hunan Province 10004, China
[d] FSG Geotechnics and Foundations, Abbotsford, Australia



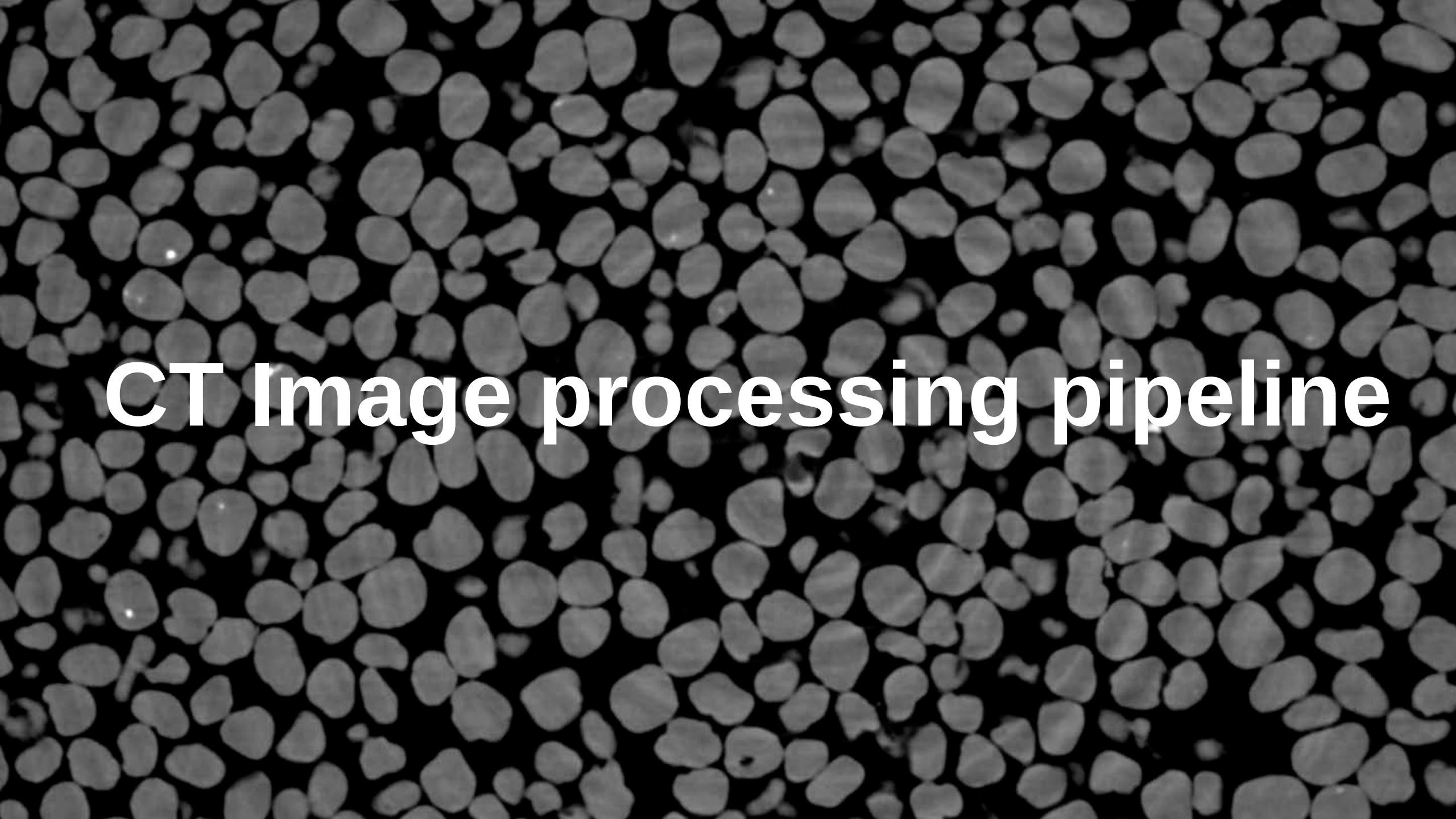
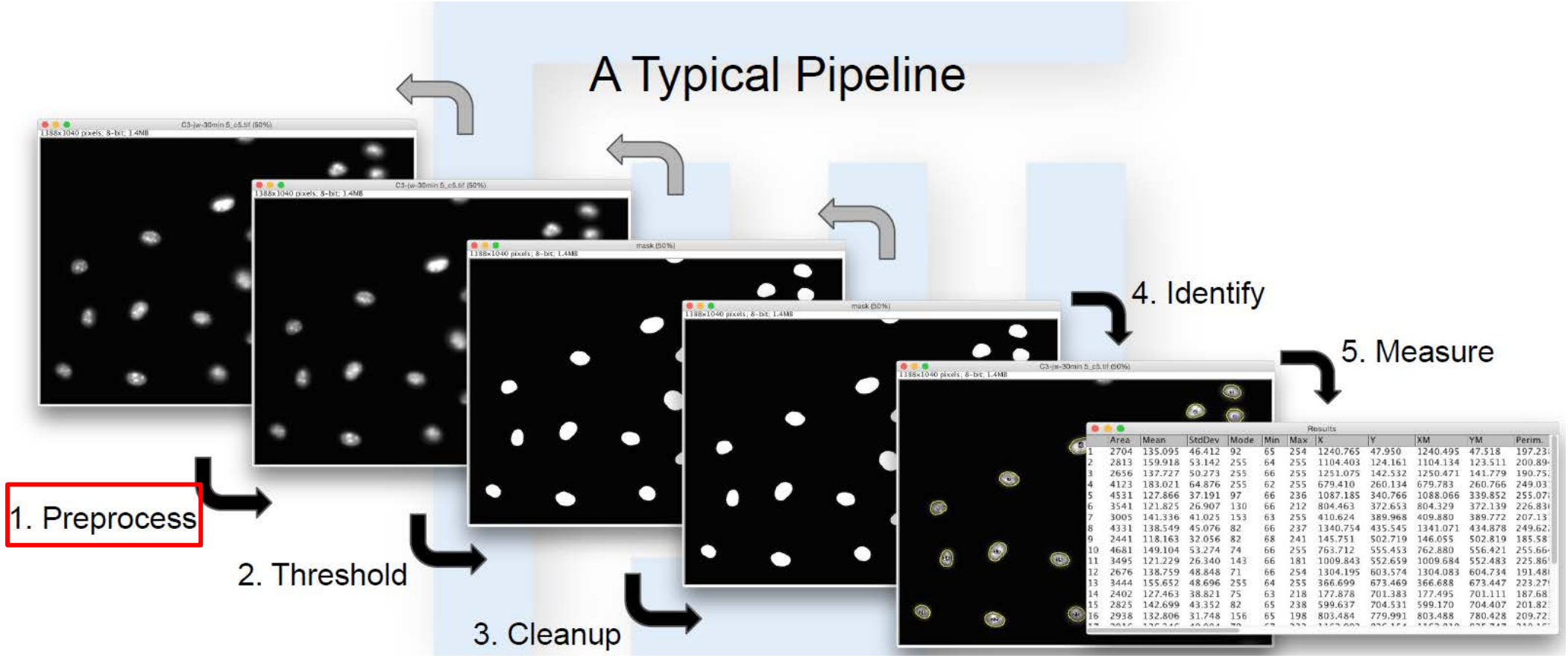
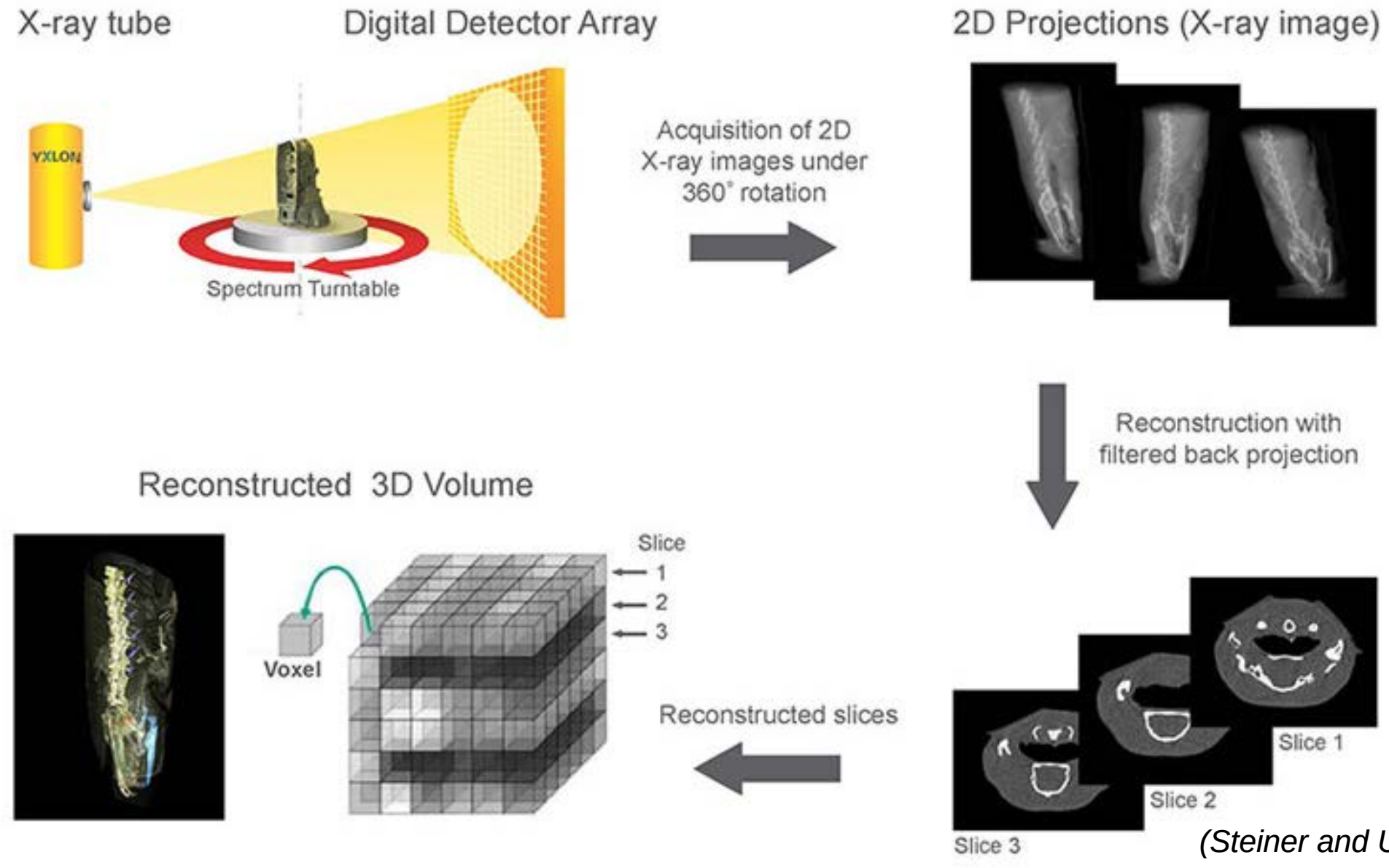

CT Image processing pipeline

Image processing pipeline



(LOCI, 2021)

Noise



(Steiner and Urbanski, 2018)

Noise

- **Dose**

High dose -> less noise

2 x mAs = 40% increase SNR

- **Sample size**

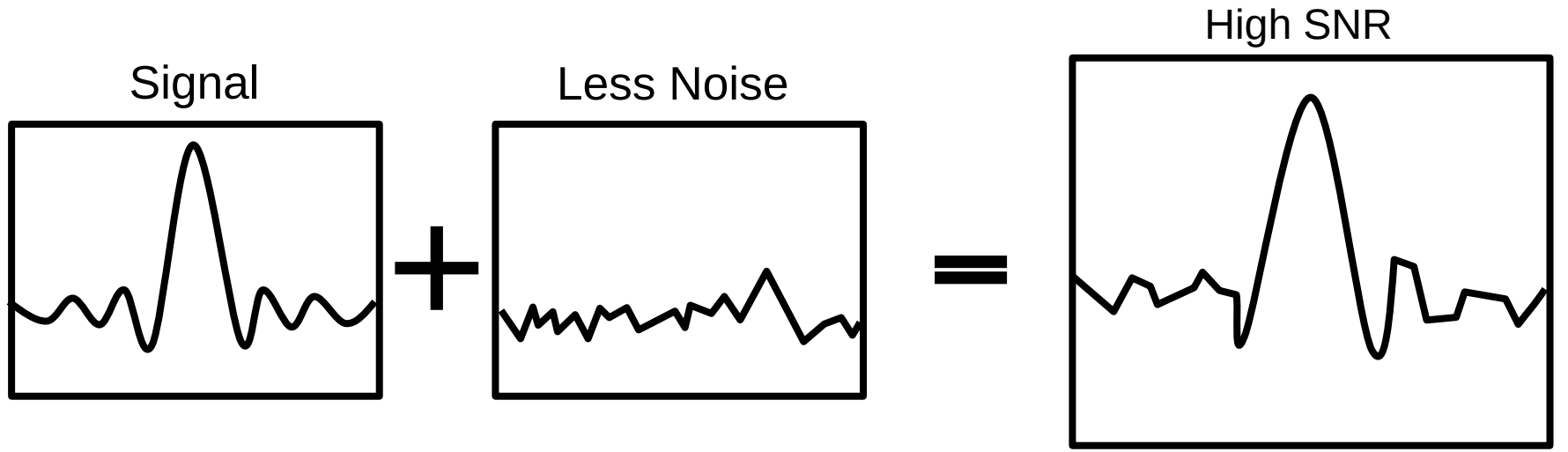
Large sample absorb more radiation, fewer photons will reach the detector

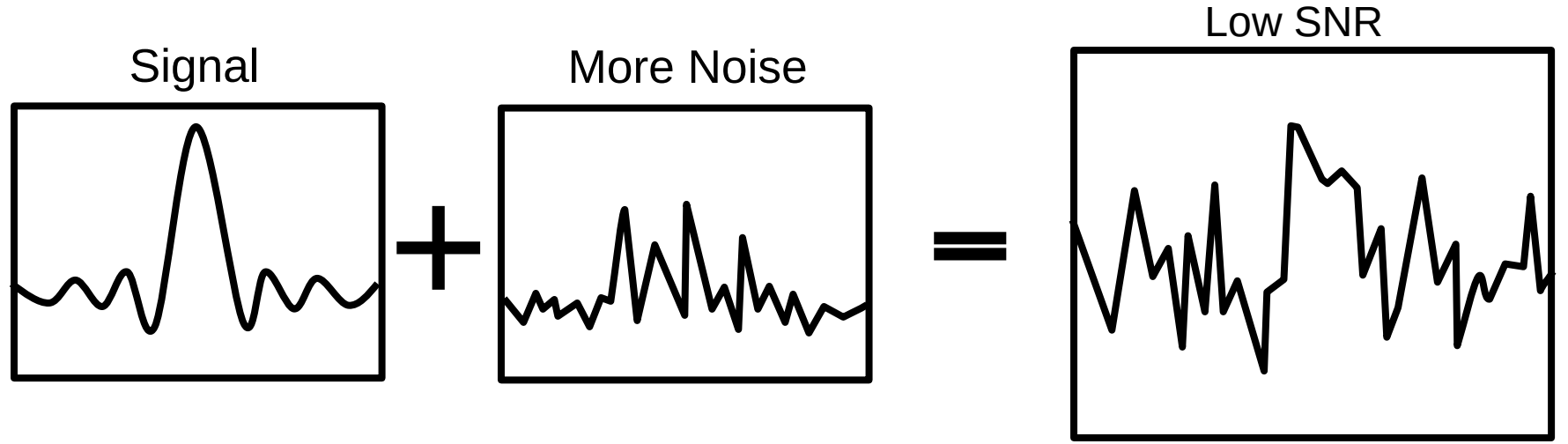
- **Reconstruction algorithms**

(Boas and Fleischmann, 2012)

Signal Noise Ratio (SNR)

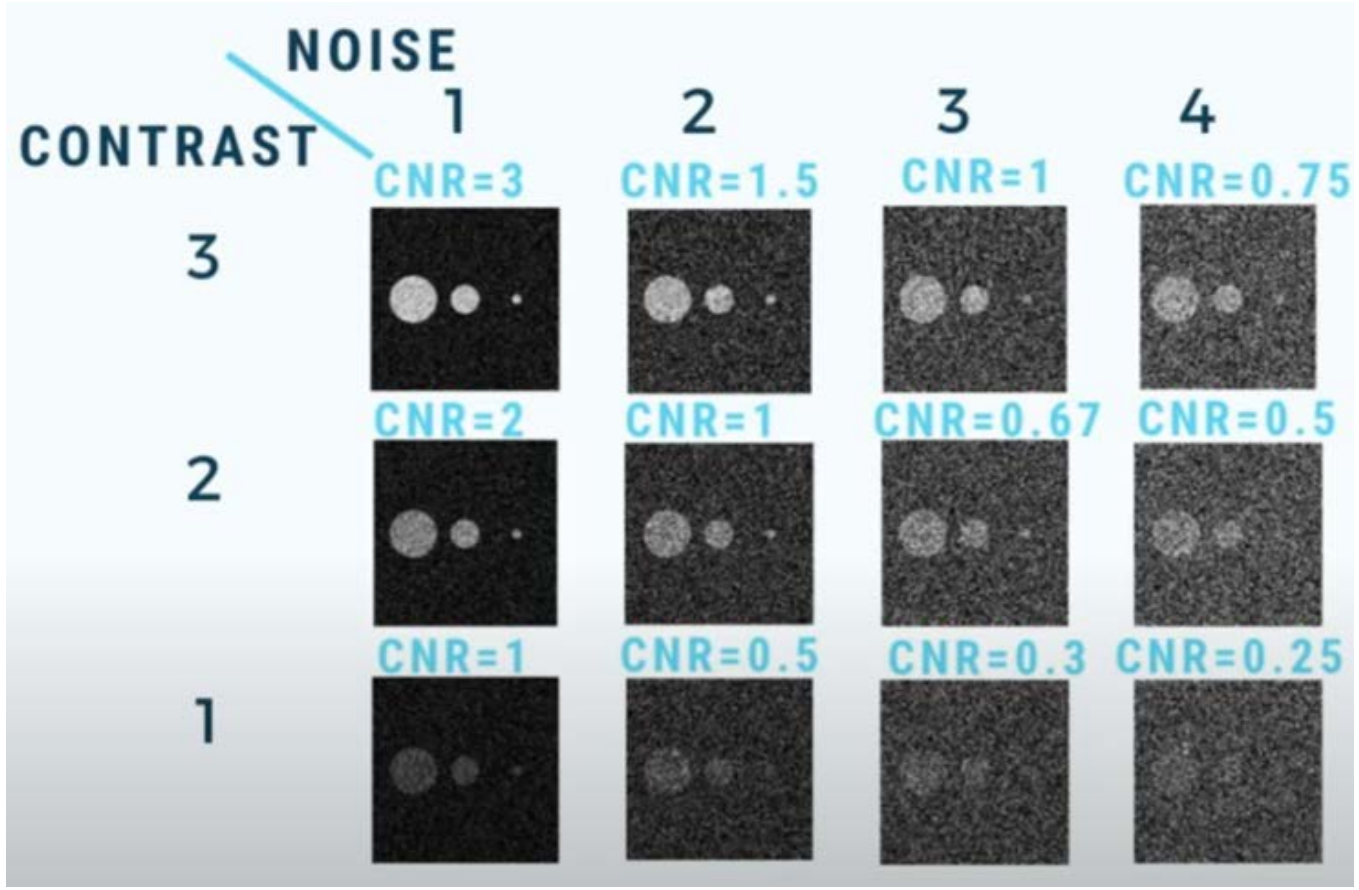
$$SNR = \frac{Signal}{Noise}$$





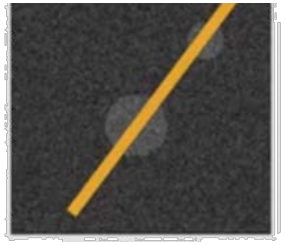
Contrast Noise Ratio (CNR)

$$CNR = \frac{Contrast}{Noise}$$



(Nett, 2021)

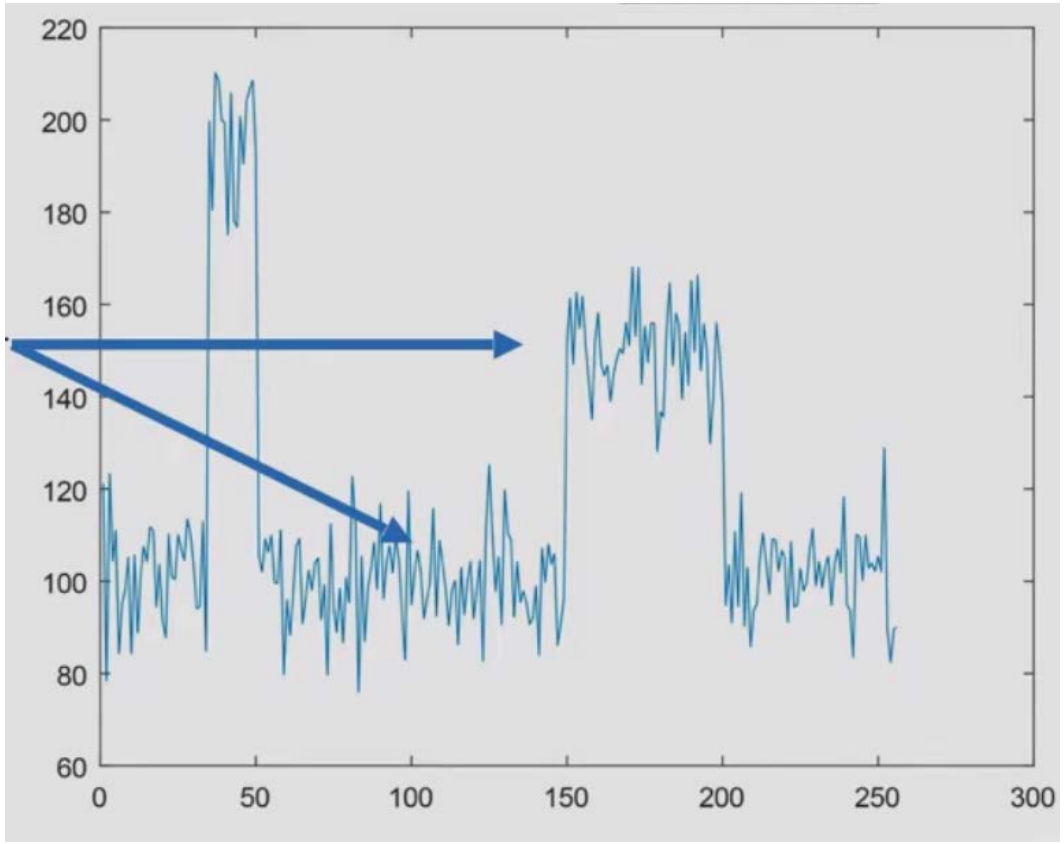
SNR and CNR



$$SNR = \frac{Signal}{Noise}$$

$$SNR = \frac{Avg\ Pixel\ Values}{Std\ Background}$$

$$SNR = \frac{150}{10} = 15$$



$$CNR = \frac{Contrast}{Noise}$$

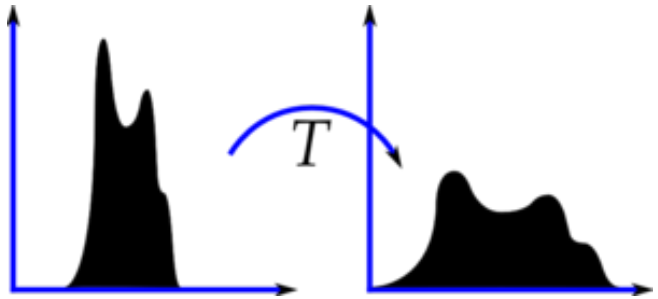
$$SNR = \frac{Avg\ ROI\ - Avg\ Background}{Std\ Background}$$

$$SNR = \frac{150 - 100}{10} = 5$$

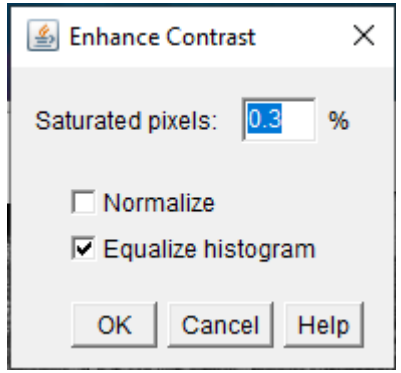
(Nett, 2021)

Enhance contrast

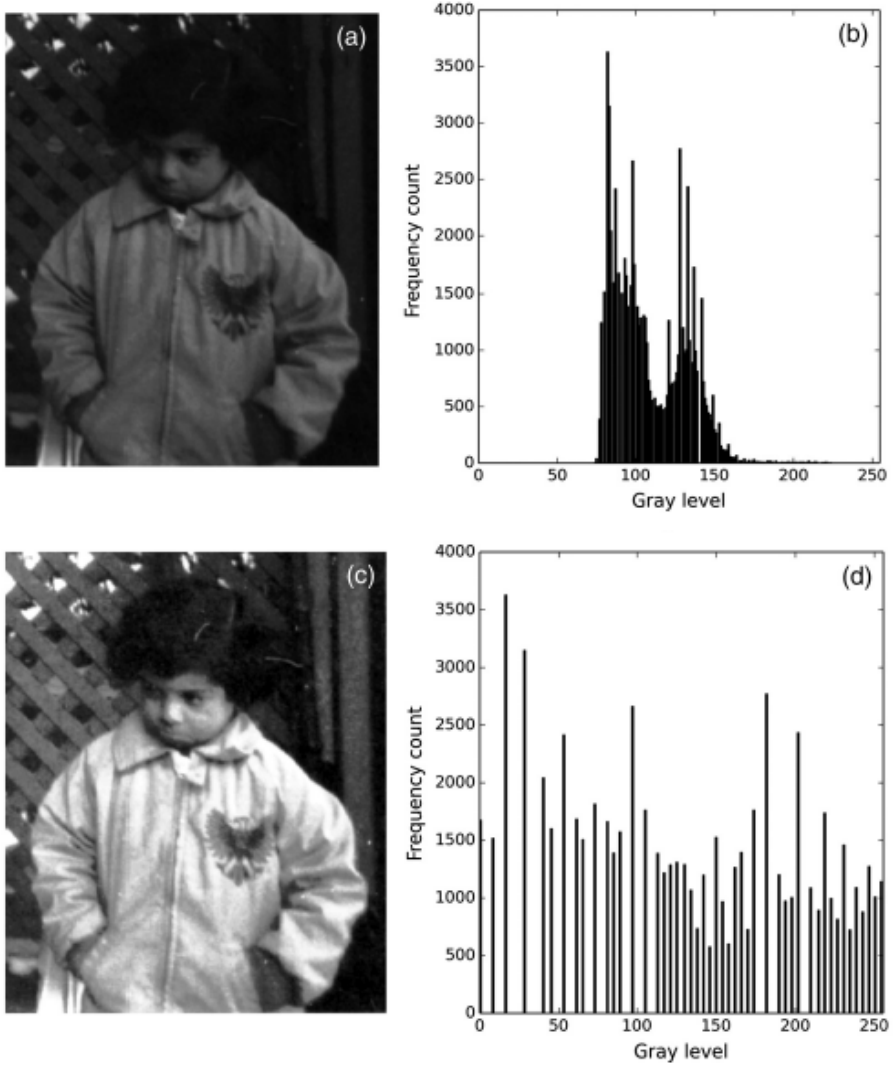
Global Histogram Equalization



Process > Enhance Contrast…



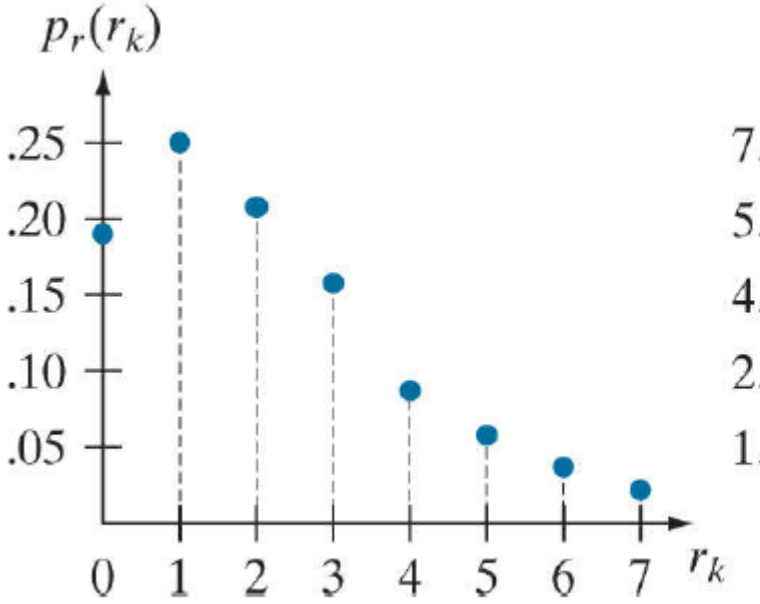

```
*Macro.ijm.ijm
1 run("Enhance Contrast...", "saturated=20 equalize");
```



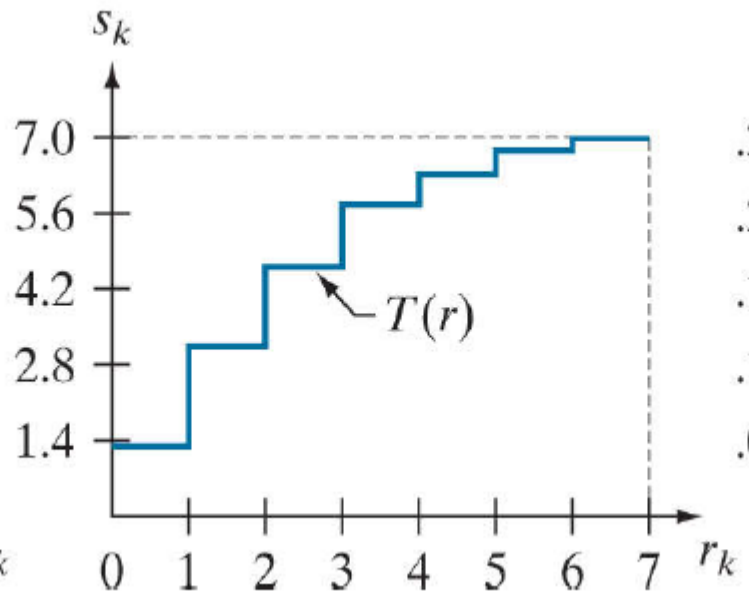
(Toet and Wu, 2014)

Histogram Equalization

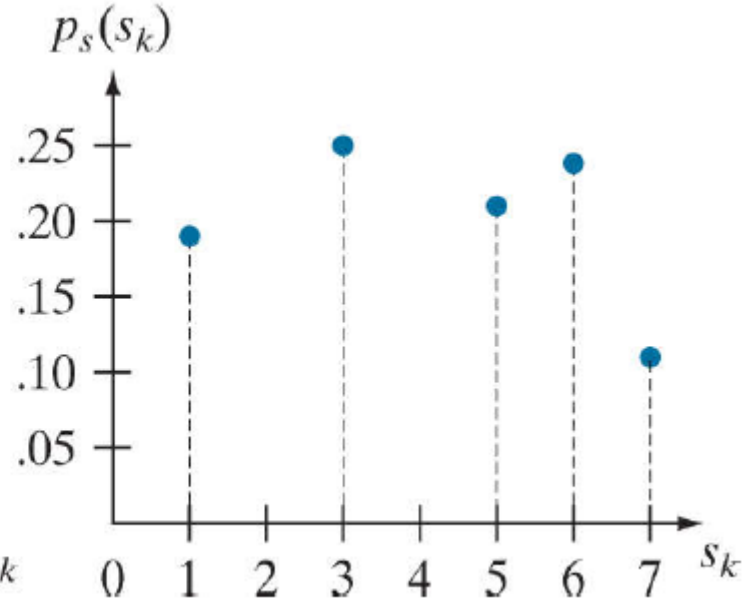
Original histogram



Transformation function



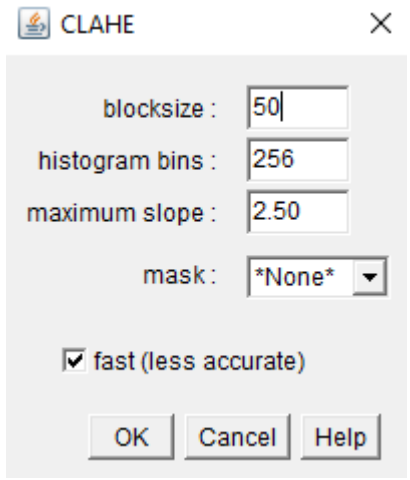
Equalized histogram



(Gonzalez and Woods, 2018)

CLAHE-Contrast Limited Adaptive Histogram Equalization

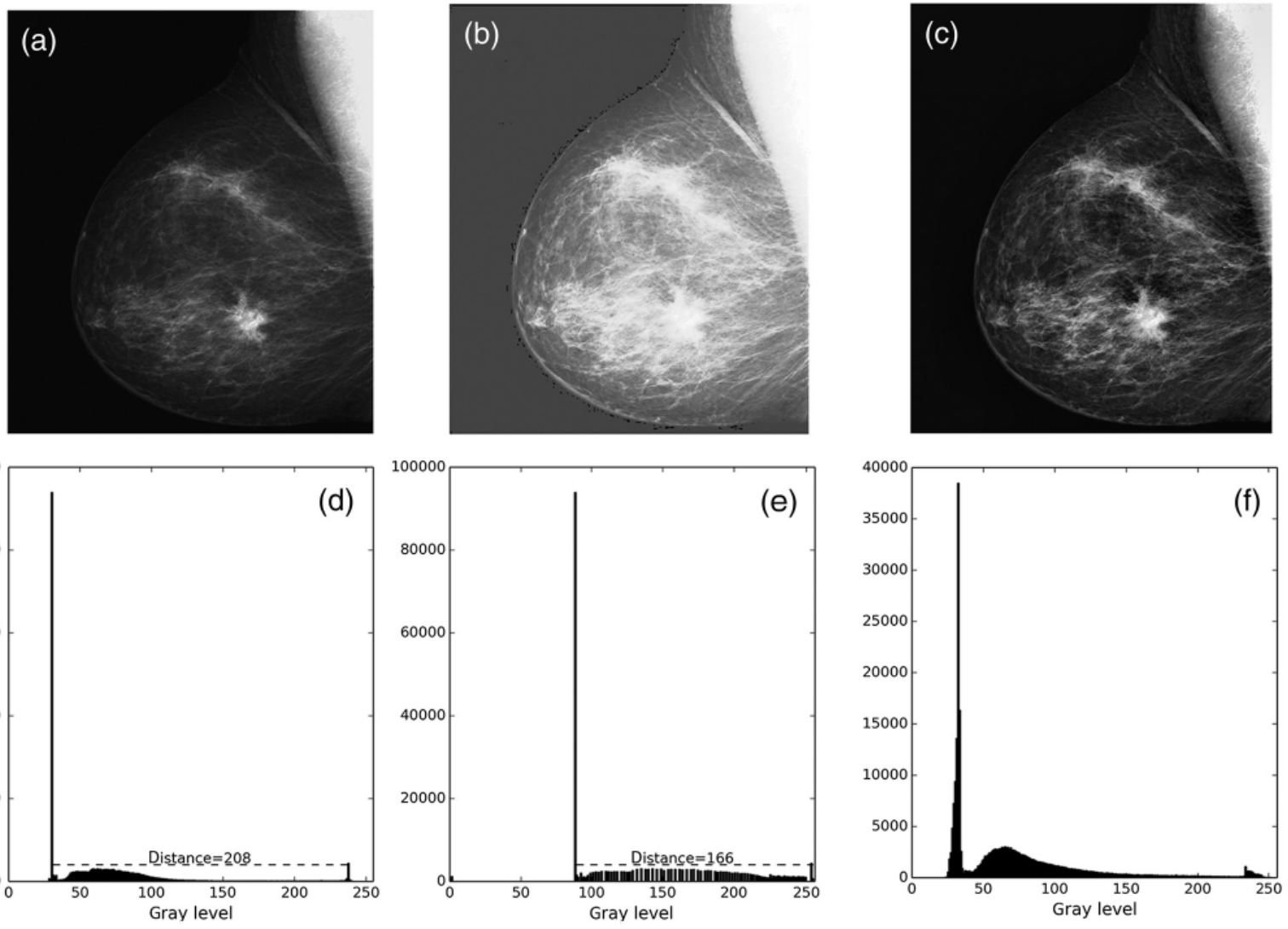
Process > Enhance Local Contrast (CLAHE)




```
run("Enhance Local Contrast (CLAHE)", "blocksize=50
histogram=256 maximum=2.5 mask=*None* fast_(less_accurate)");
```

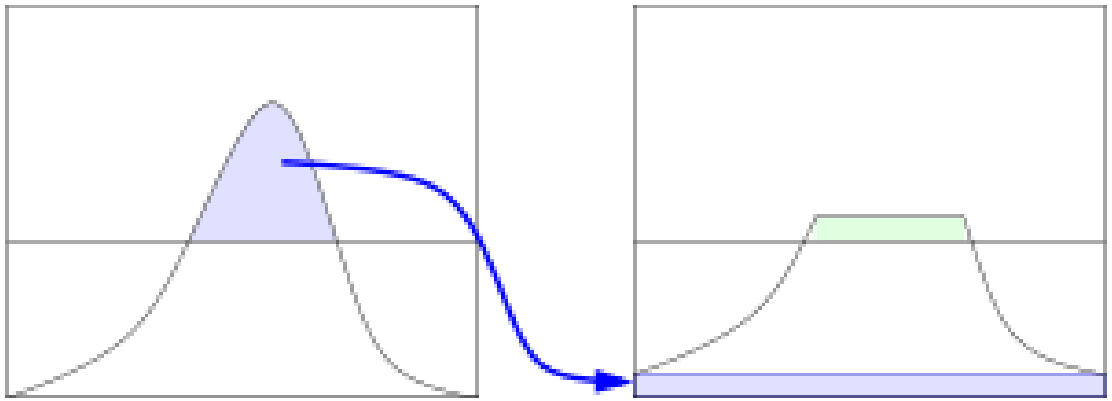
Histogram Equalization

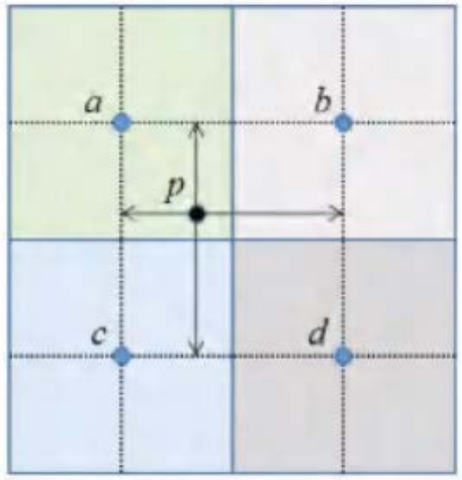
CLAHE



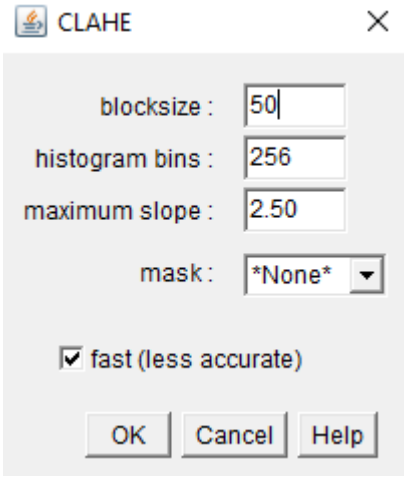
(Toet and Wu, 2014)

CLAHE-Contrast Limited Adaptive Histogram Equalization





Process > Enhance Local Contrast (CLAHE)




```
run("Enhance Local Contrast (CLAHE)", "blocksize=50
histogram=256 maximum=2.5 mask=*None* fast_(less_accurate)");
```

(Toet and Wu, 2014)

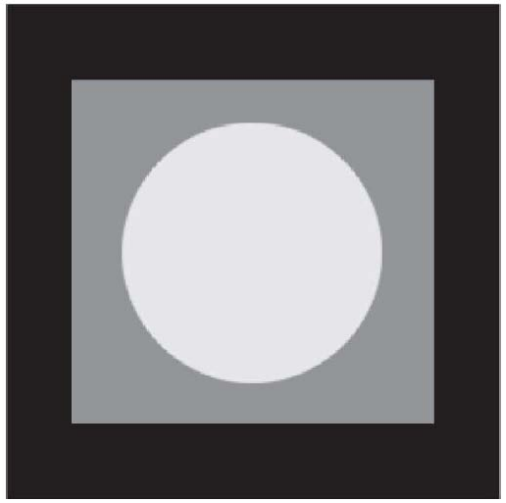
CLAHE-Contrast Limited Adaptive Histogram Equalization

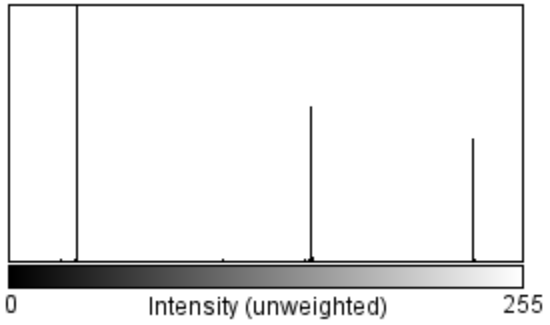
CLAHE-stack.ijm

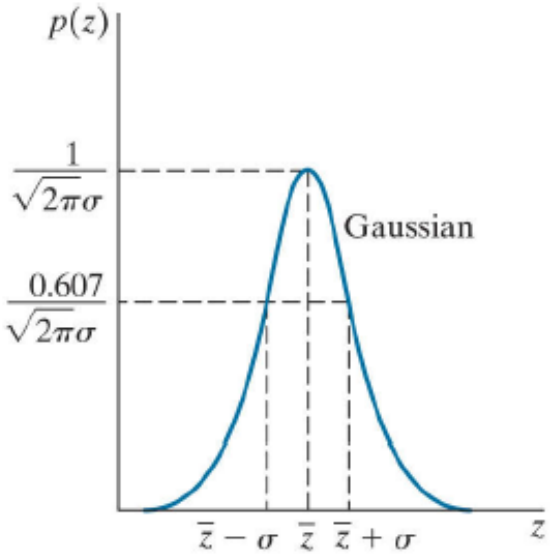
```
blocksize = 50;
histogram_bins = 256;
maximum_slope = 2.5;
mask = "*None*";
fast = true;
process_as_composite = true;

getDimensions( width, height, channels, slices, frames );
isComposite = channels > 1;
parameters =
  "blocksize=" + blocksize +
  " histogram=" + histogram_bins +
  " maximum=" + maximum_slope +
  " mask=" + mask;
if ( fast )
  parameters += " fast_(less_accurate)";
if ( isComposite && process_as_composite ) {
  parameters += " process_as_composite";
  channels = 1;
}

for ( f=1; f<=frames; f++ ) {
  Stack.setFrame( f );
  for ( s=1; s<=slices; s++ ) {
    Stack.setSlice( s );
    for ( c=1; c<=channels; c++ ) {
      Stack.setChannel( c );
      run( "Enhance Local Contrast (CLAHE)", parameters );
    }
  }
}

```

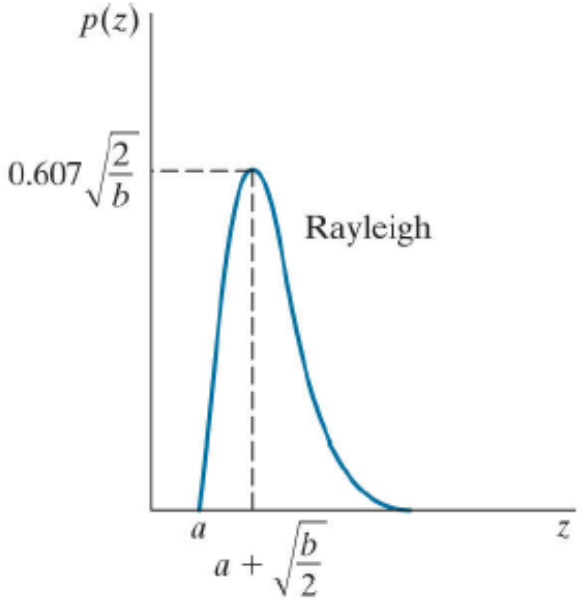
Noise

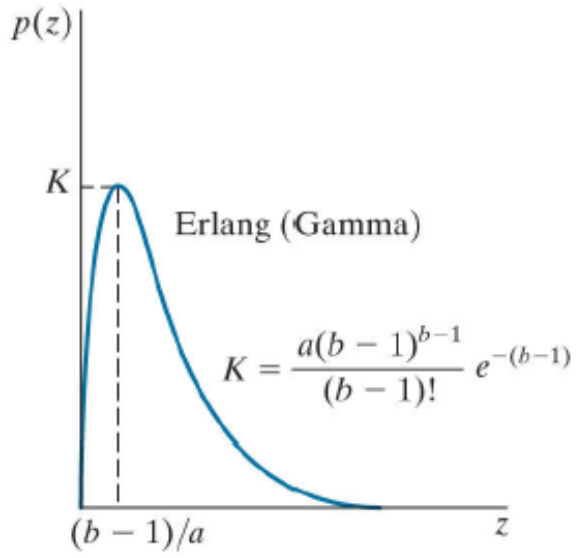
Original

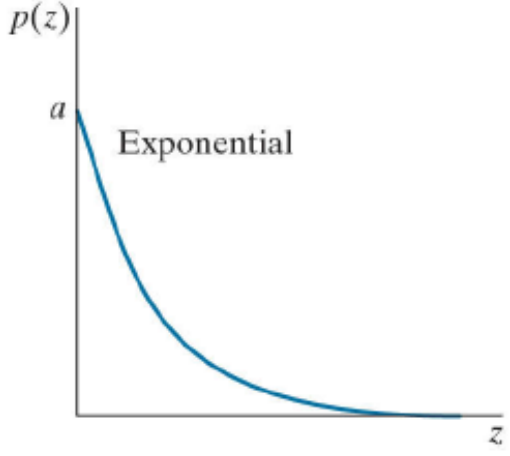


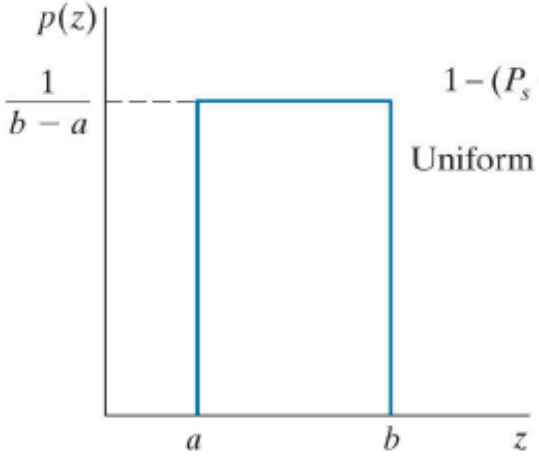


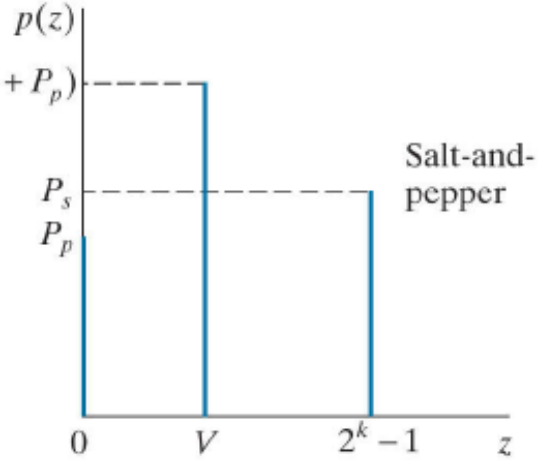






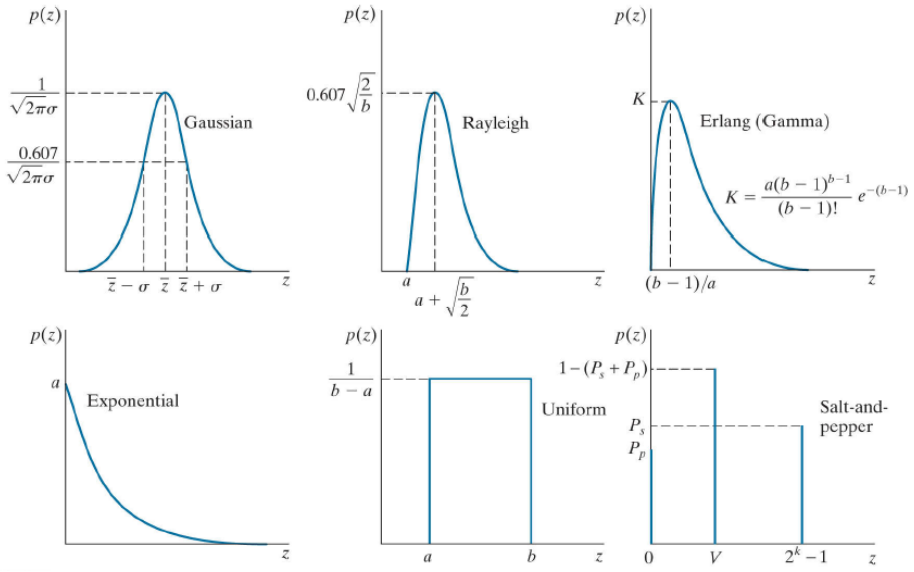




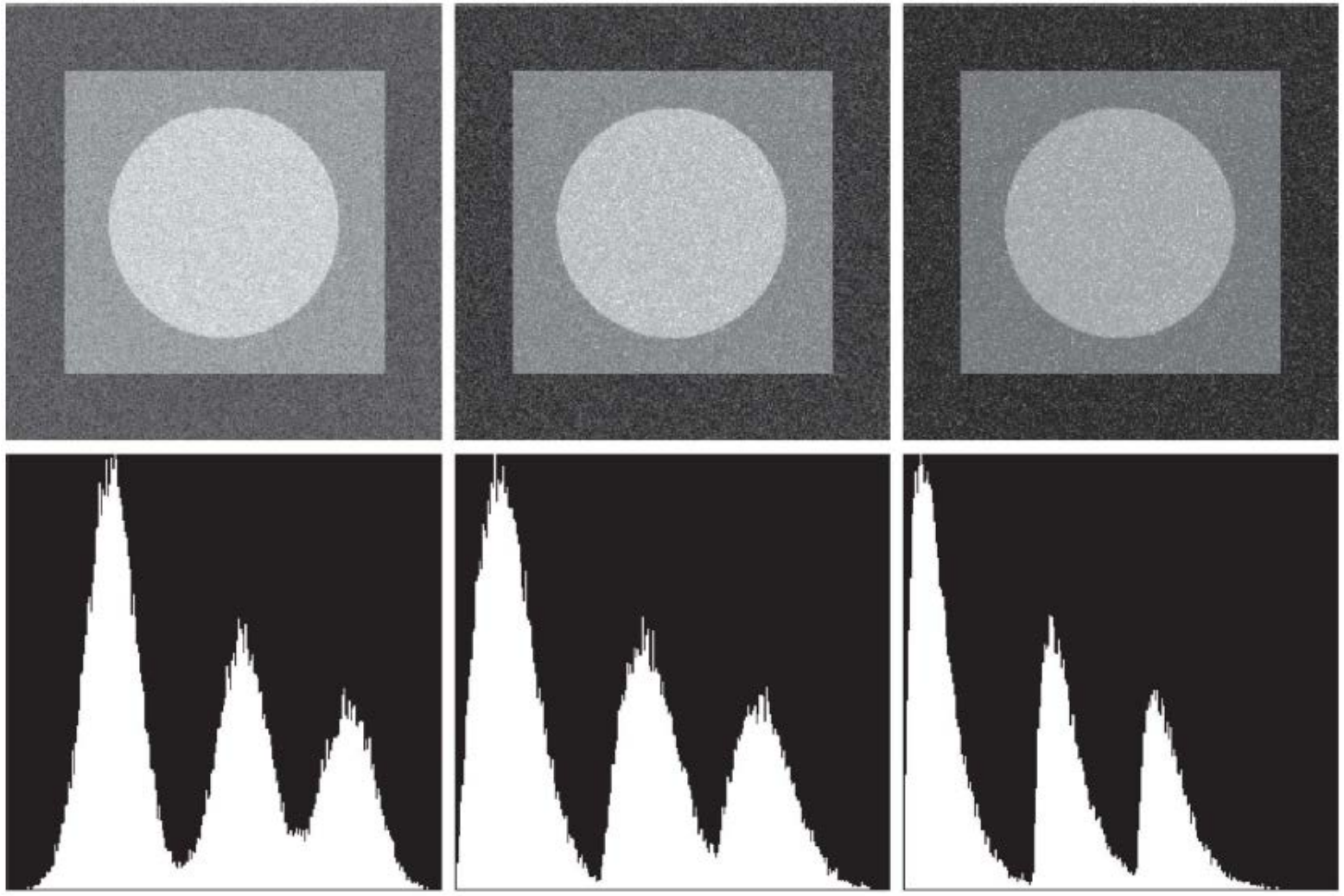


(Gonzalez and Woods, 2018)

Noise

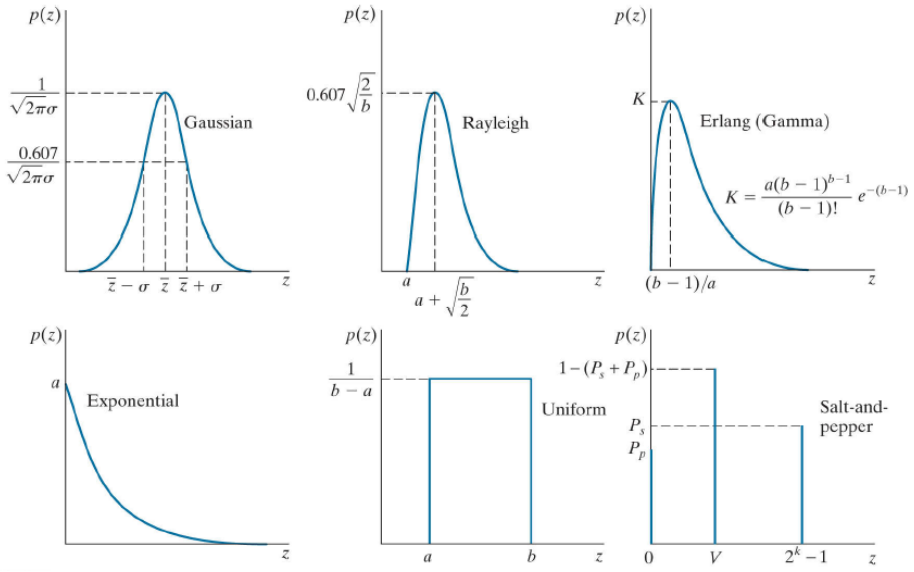


Gaussian Rayleigh Erlanga

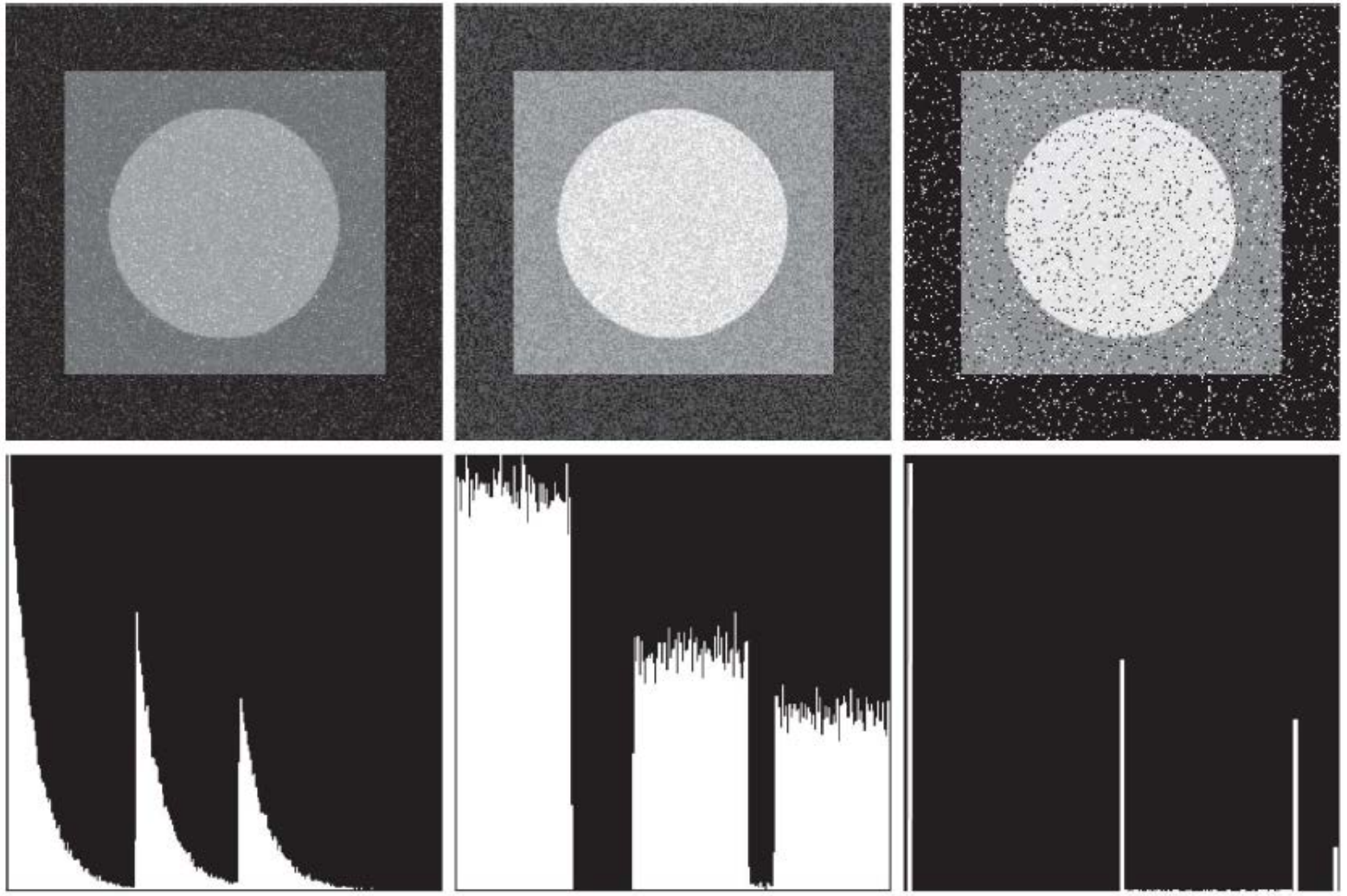


(Gonzalez and Woods, 2018)

Noise



Exponential | Uniform | Salt and pepper



(Gonzalez and Woods, 2018)

Signal Noise Ratio (SNR)

$$SNR = \frac{Signal}{Noise}$$

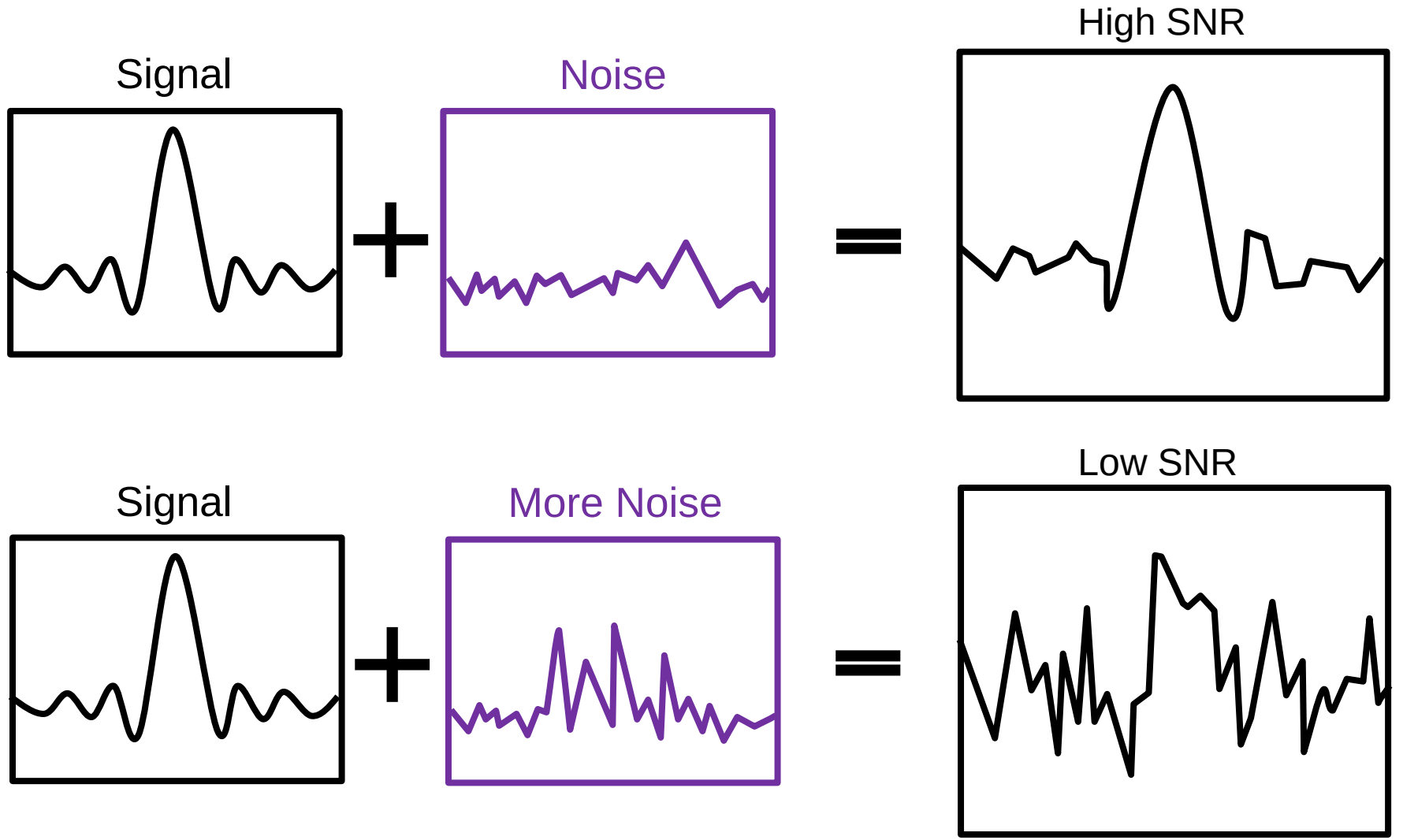
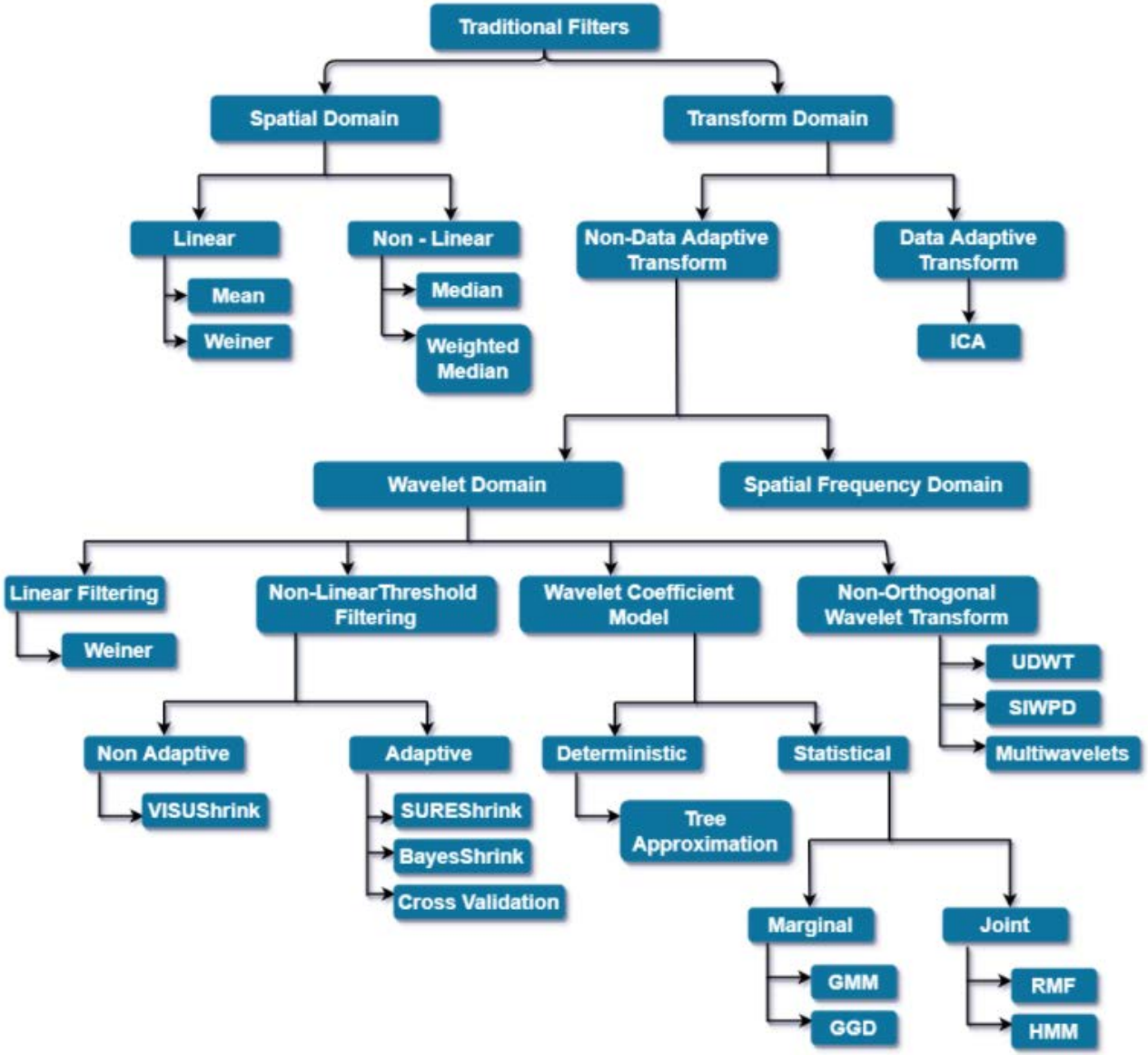


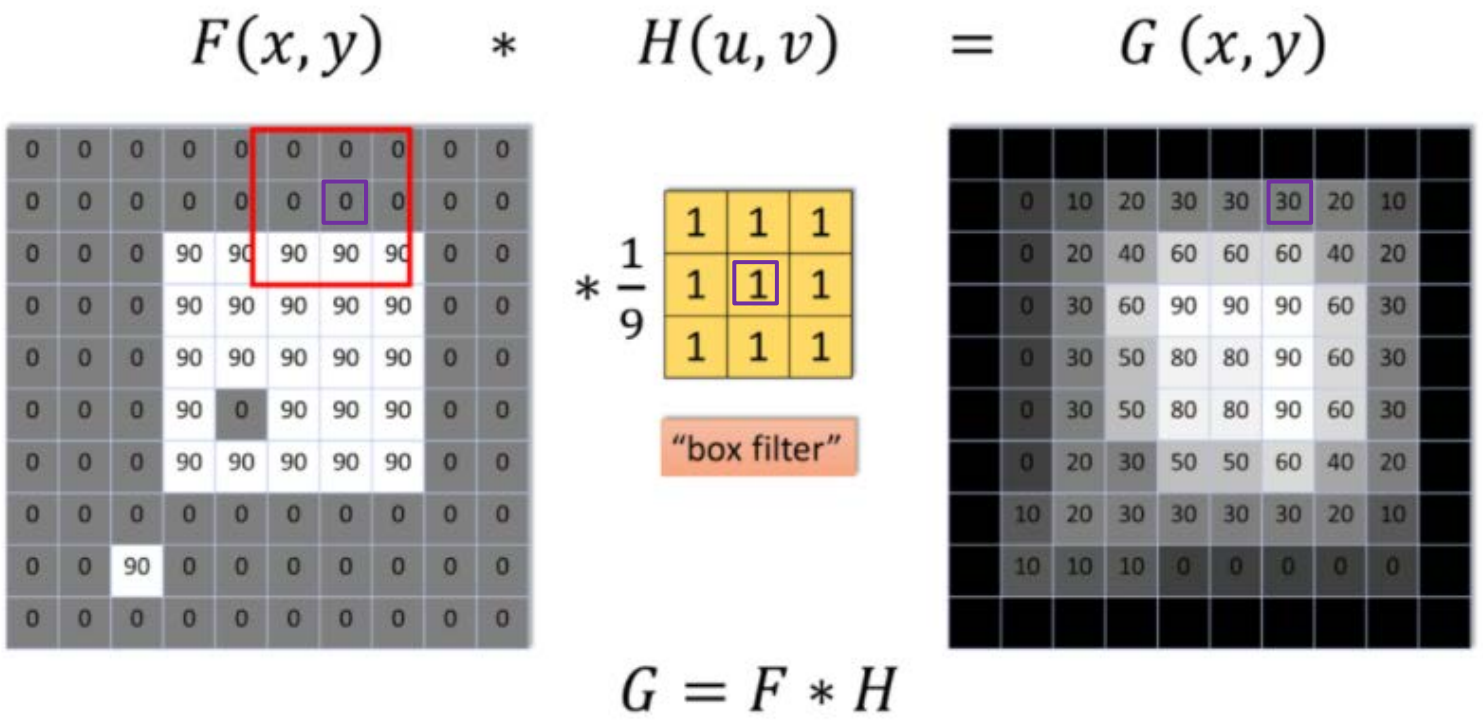
Image denoising filters

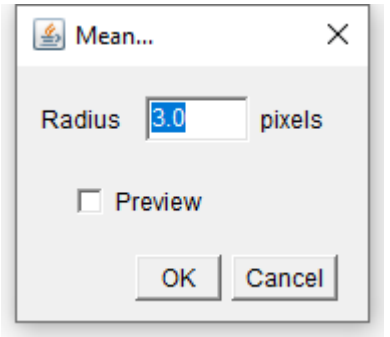


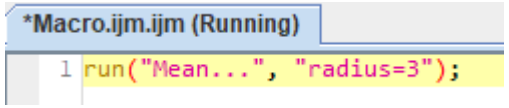
(Mantri, 2020)

Mean filter

Process > Filters > Mean…

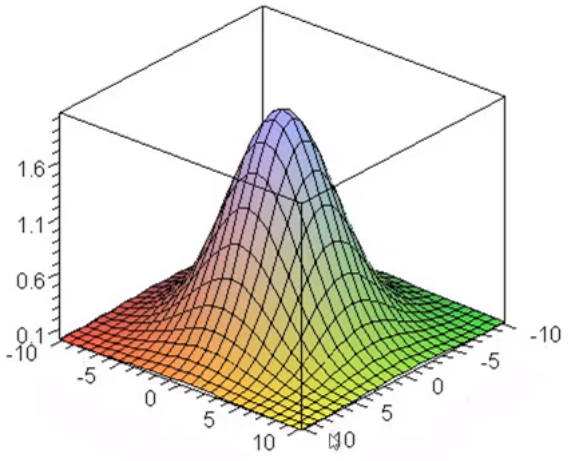


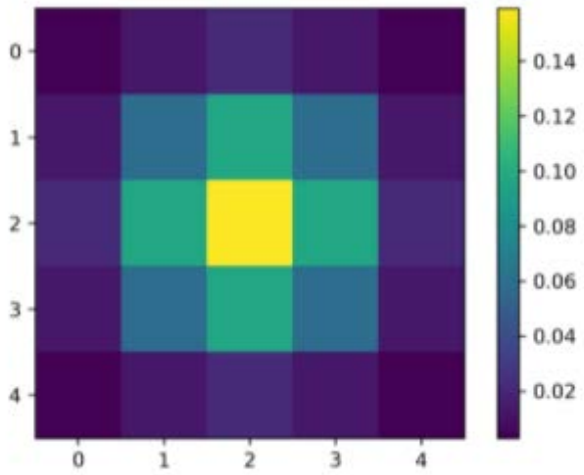




Gaussian filter/blur

$$G(x,y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

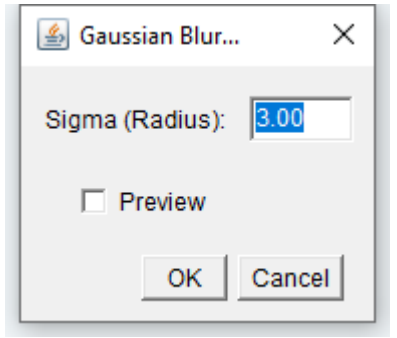


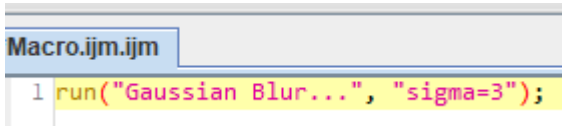


$$\frac{1}{16} * \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

$$H(u,v)$$

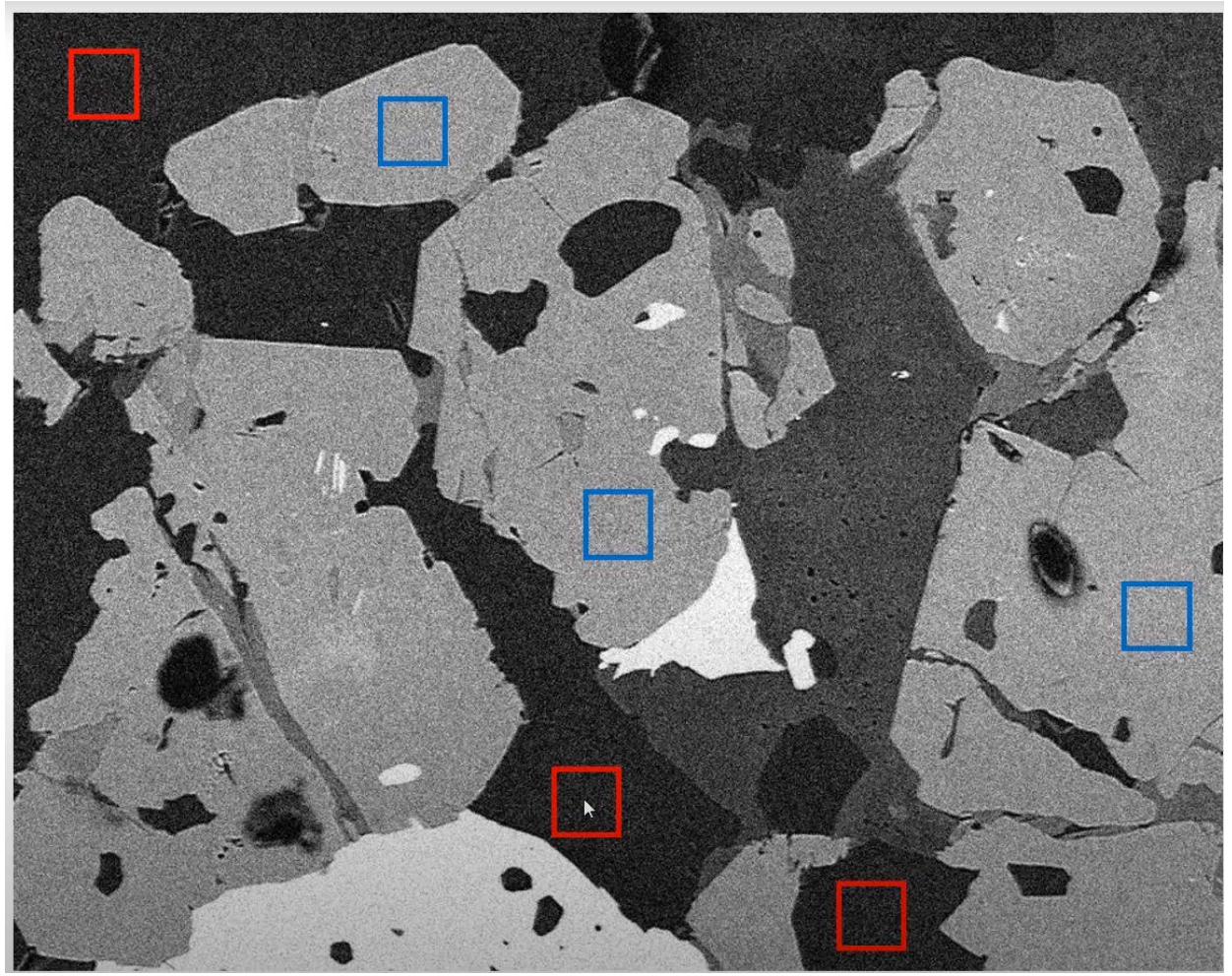
Process > Filters > Gaussian Blur…





Non-local means denoising

$$NL[v](i) = \sum_{j \in I} w(i,j)v(j)$$

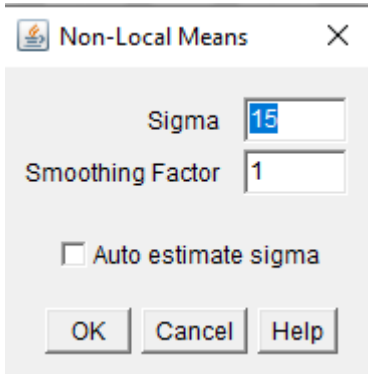


(Sreeni, 2019)

Non-local means denoising

1. Download plugin: Non Local Means Denoise (imagej.net)
2. Copy the .jar to floder …/Fiji.app/plugins
3. Restart Fiji
4. *Plugins > Non-local Means Denoising*

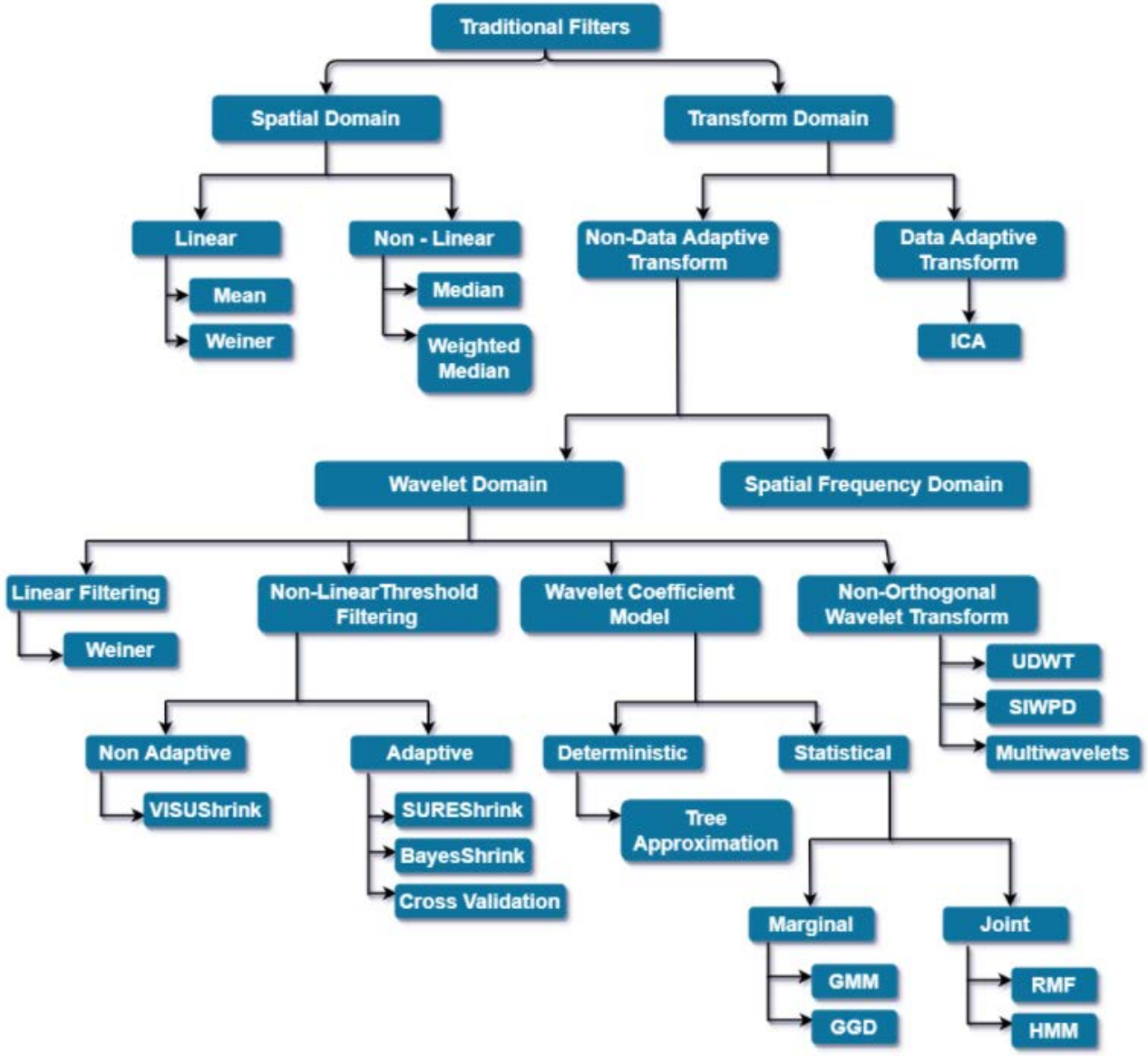
Figure 1: Example of NLmeans results. From left to right: original image, noisy image ($\sigma = 15$), denoised image.




```
run("Non-local Means Denoising", "sigma=15 smoothing_factor=1 auto");
```

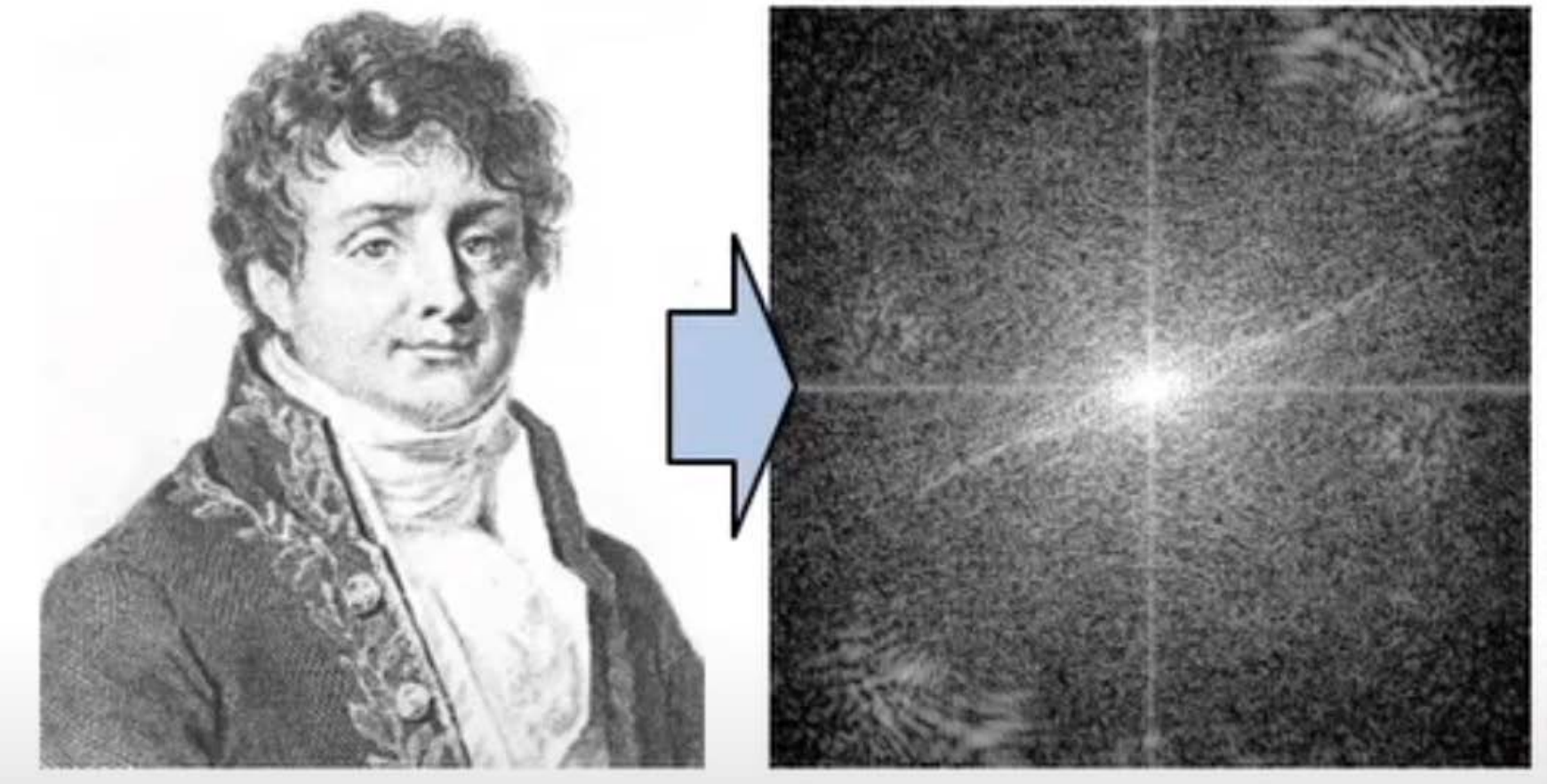
(Buades et al., 2011)

Image denoising filters



(Mantri, 2020)

Fourier space



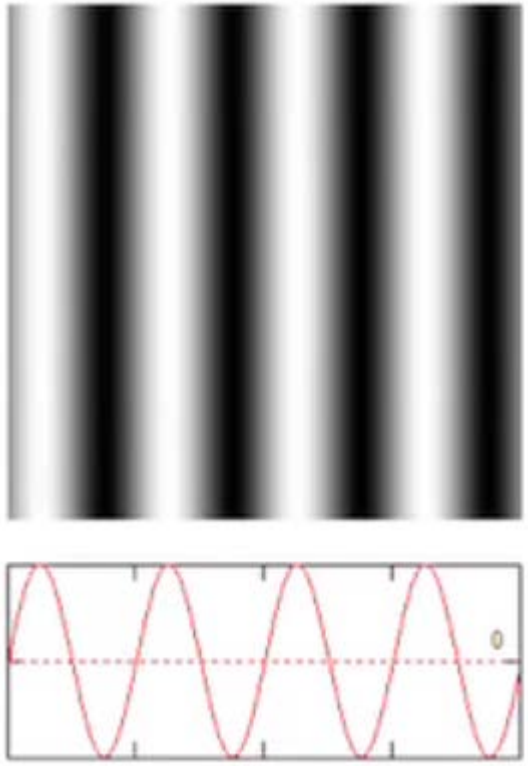
Original Image (real space) Fourier transform (frequency space)

(Huang, 2013)

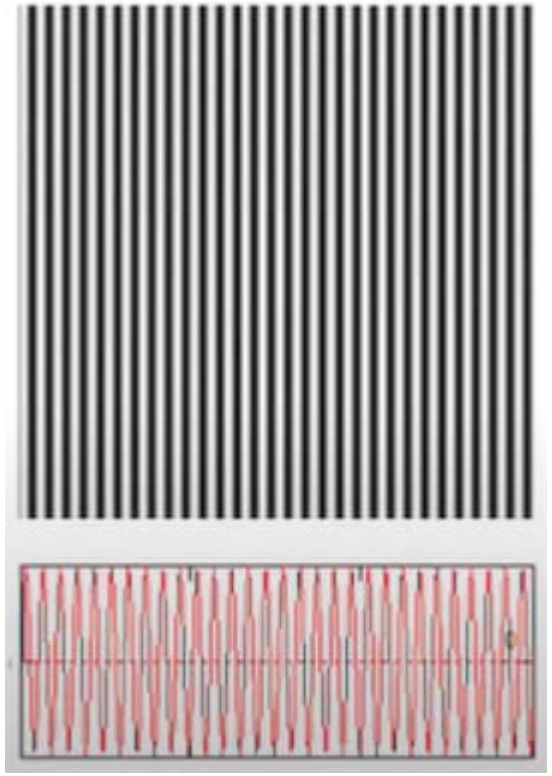
Fourier space

$$I = \sin(kx)$$

$k = 4$



$k = 30$

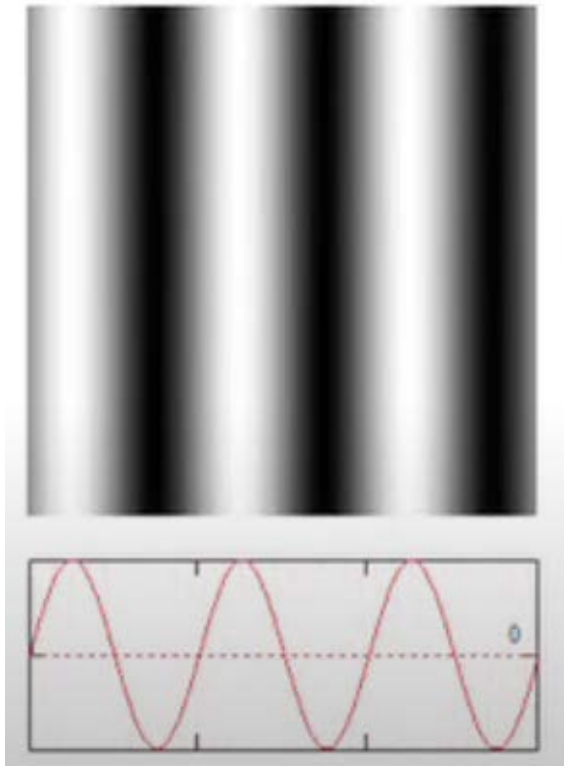


(Huang, 2013)

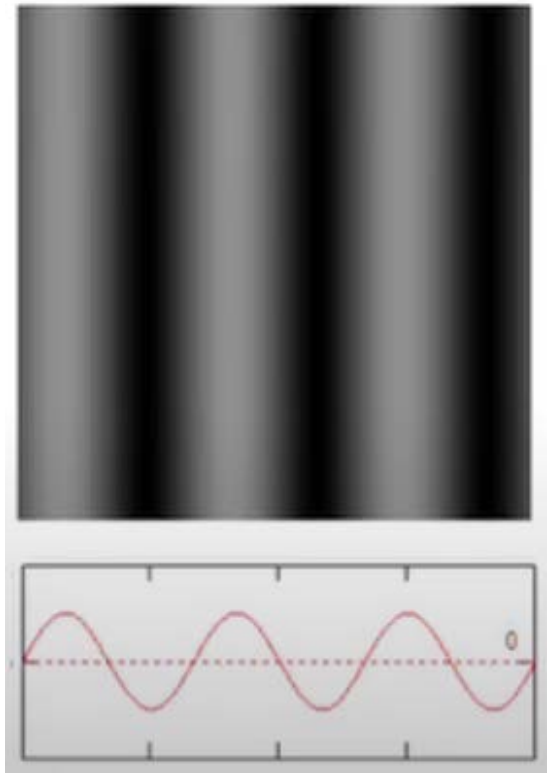
Fourier space

$$I = A\sin(kx)$$

$A = 1$



$A = 0.5$

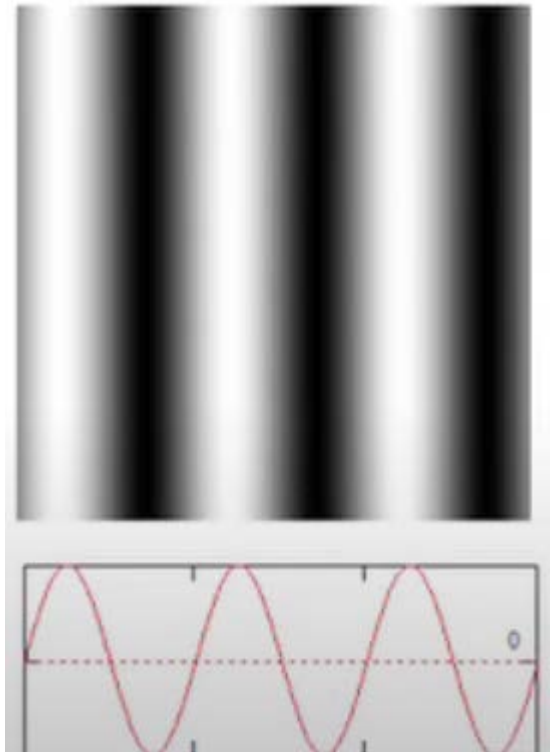


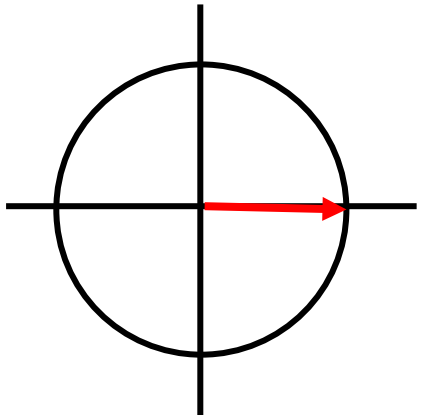
(Huang, 2013)

Fourier space

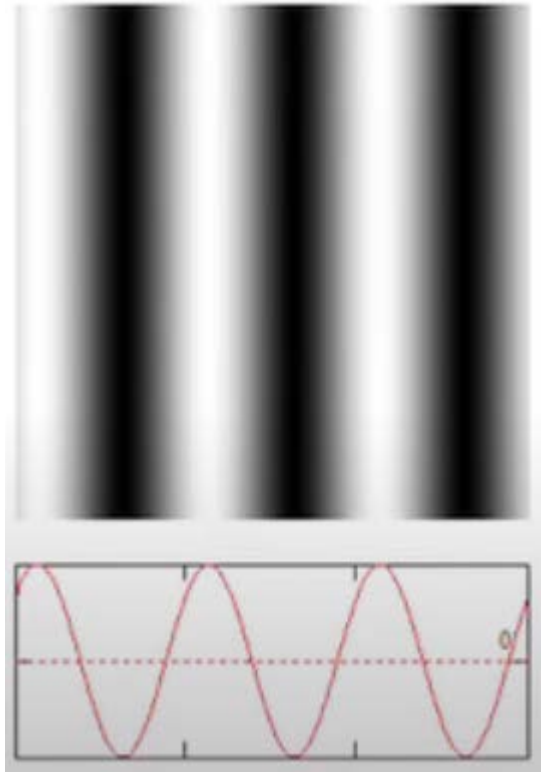
$$I = \mathrm{A}\sin(kx + \varphi_0)$$

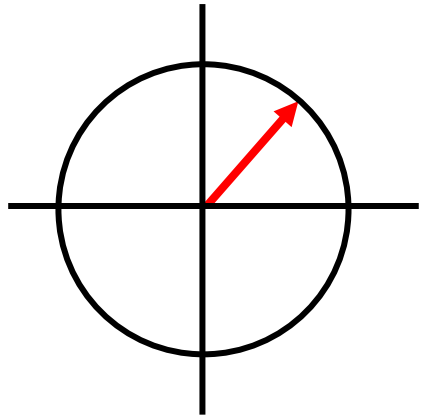
$\varphi_0 = 0$





$\varphi_0 = 45°$

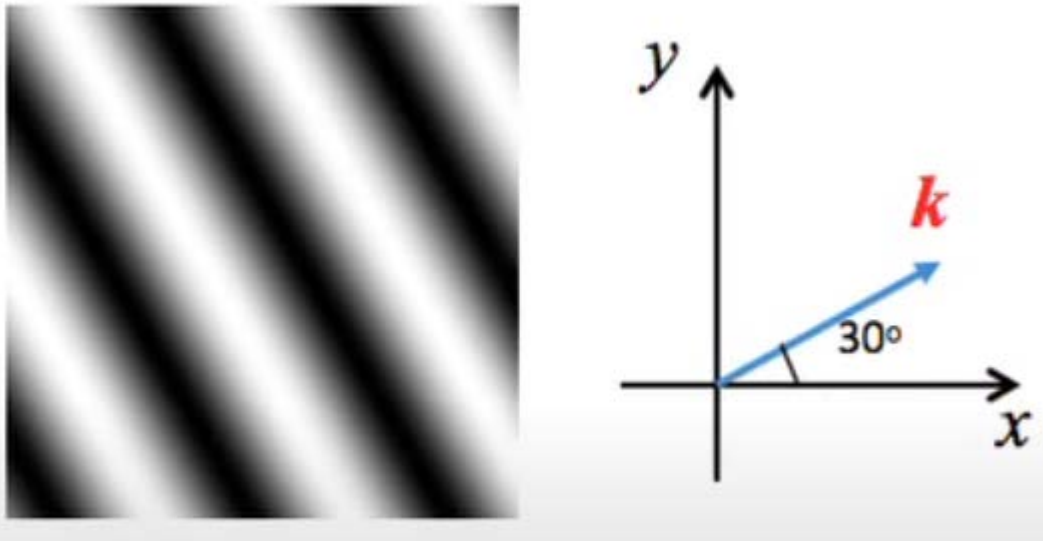


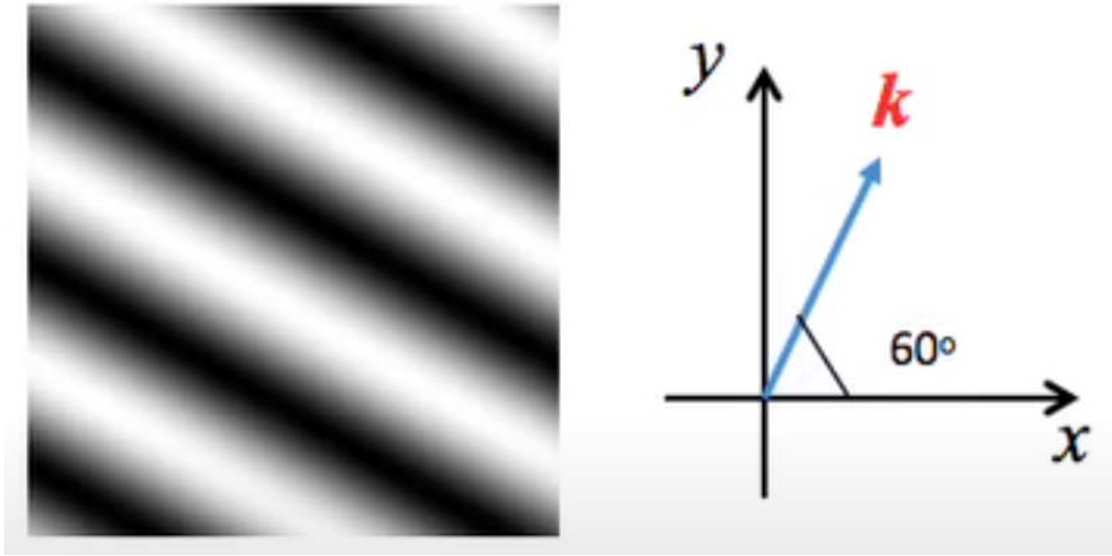


(Huang, 2013)

Fourier space

$$I(x,y) = \mathrm{A}\sin(\boldsymbol{k}\cdot\boldsymbol{r} + \varphi_0)$$



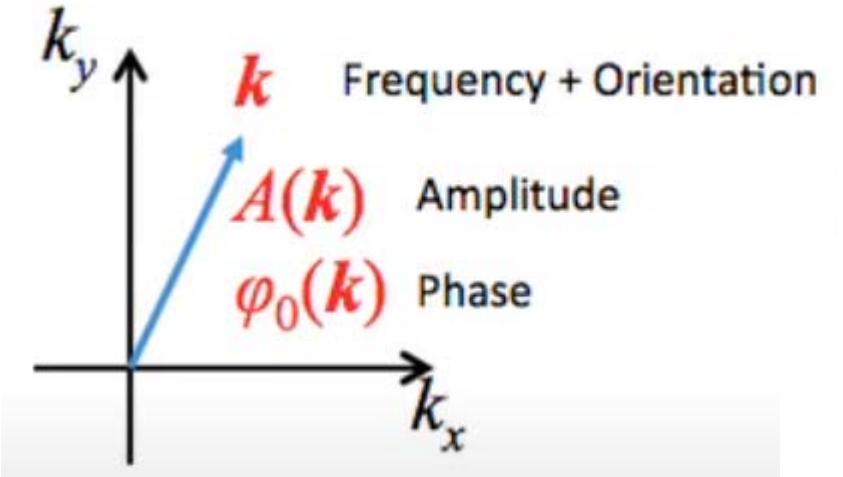


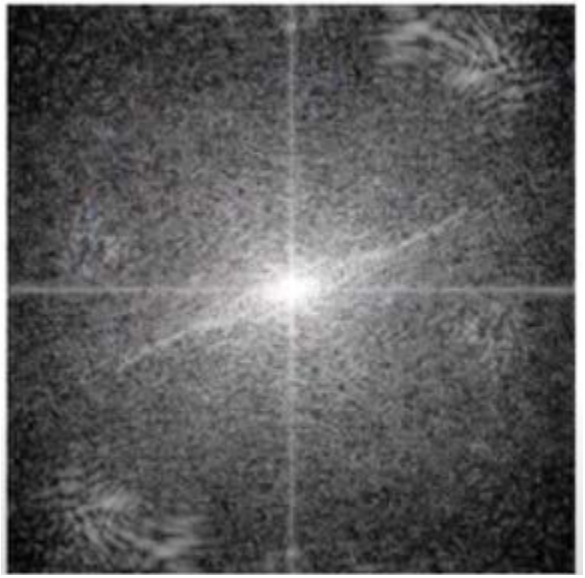
(Huang, 2013)

Fourier space

$$I(\boldsymbol{r}) = \mathrm{A}\sin(\boldsymbol{k} \cdot \boldsymbol{r} + \varphi_0)$$

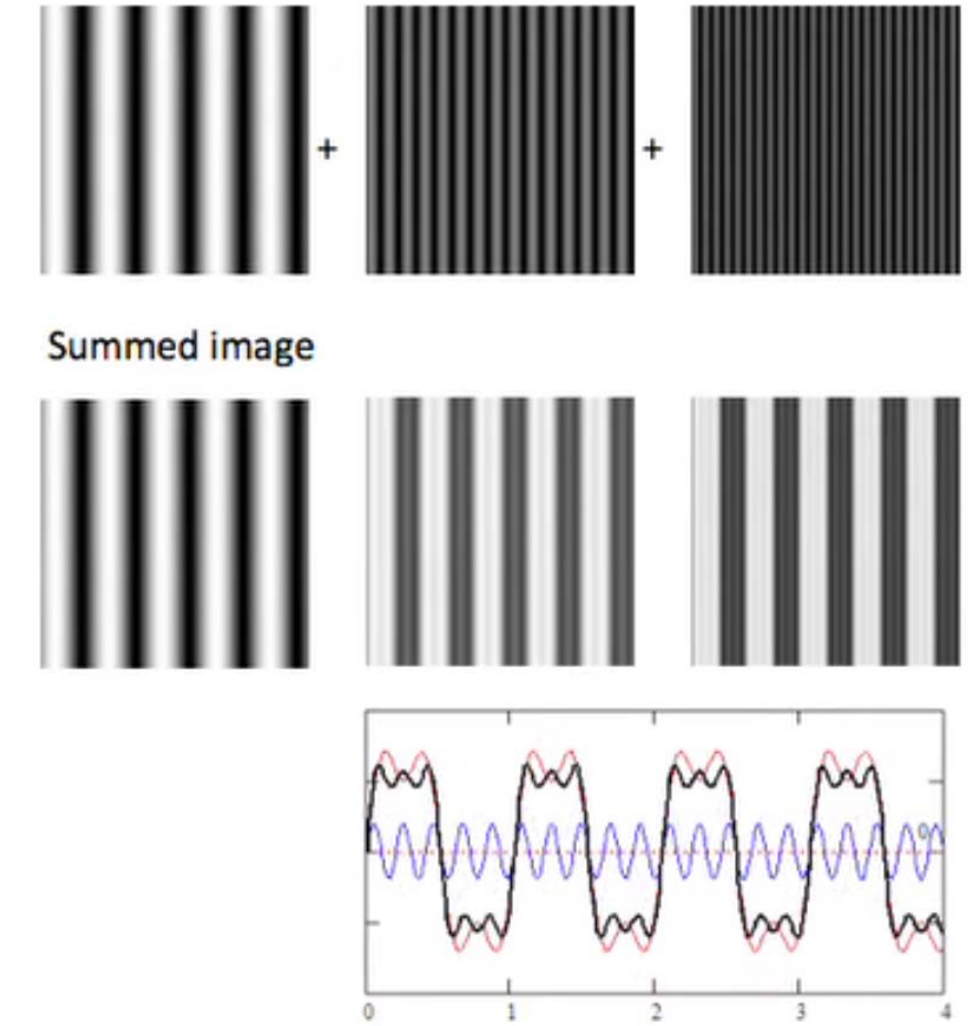
- Frequency
- Orientation
- Amplitude
- Phase

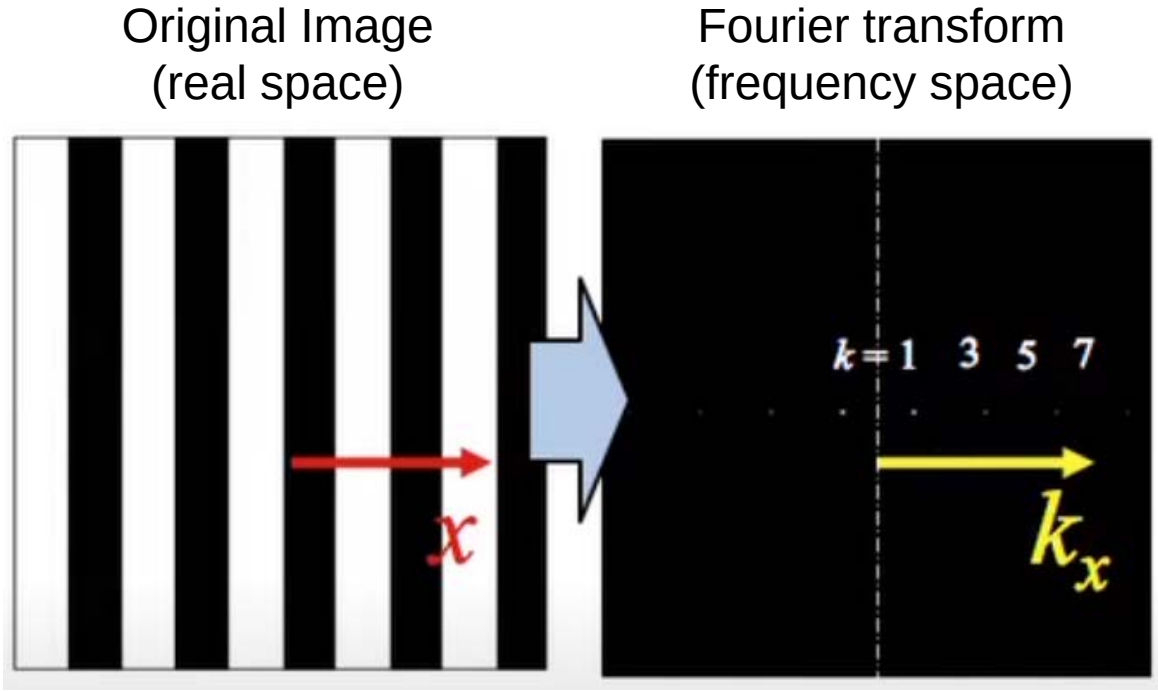




(Huang, 2013)

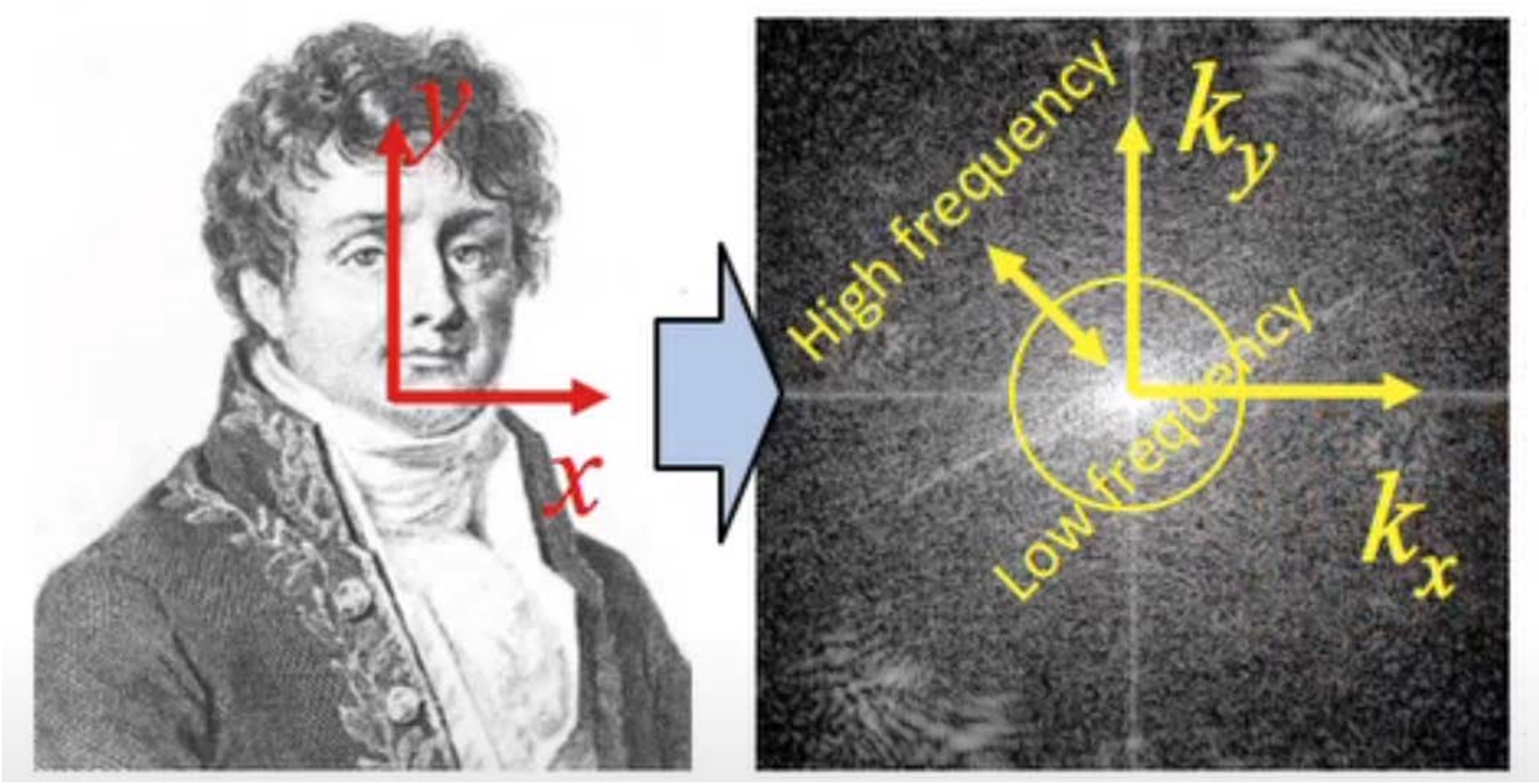
Fourier space





(Huang, 2013)

Fourier space

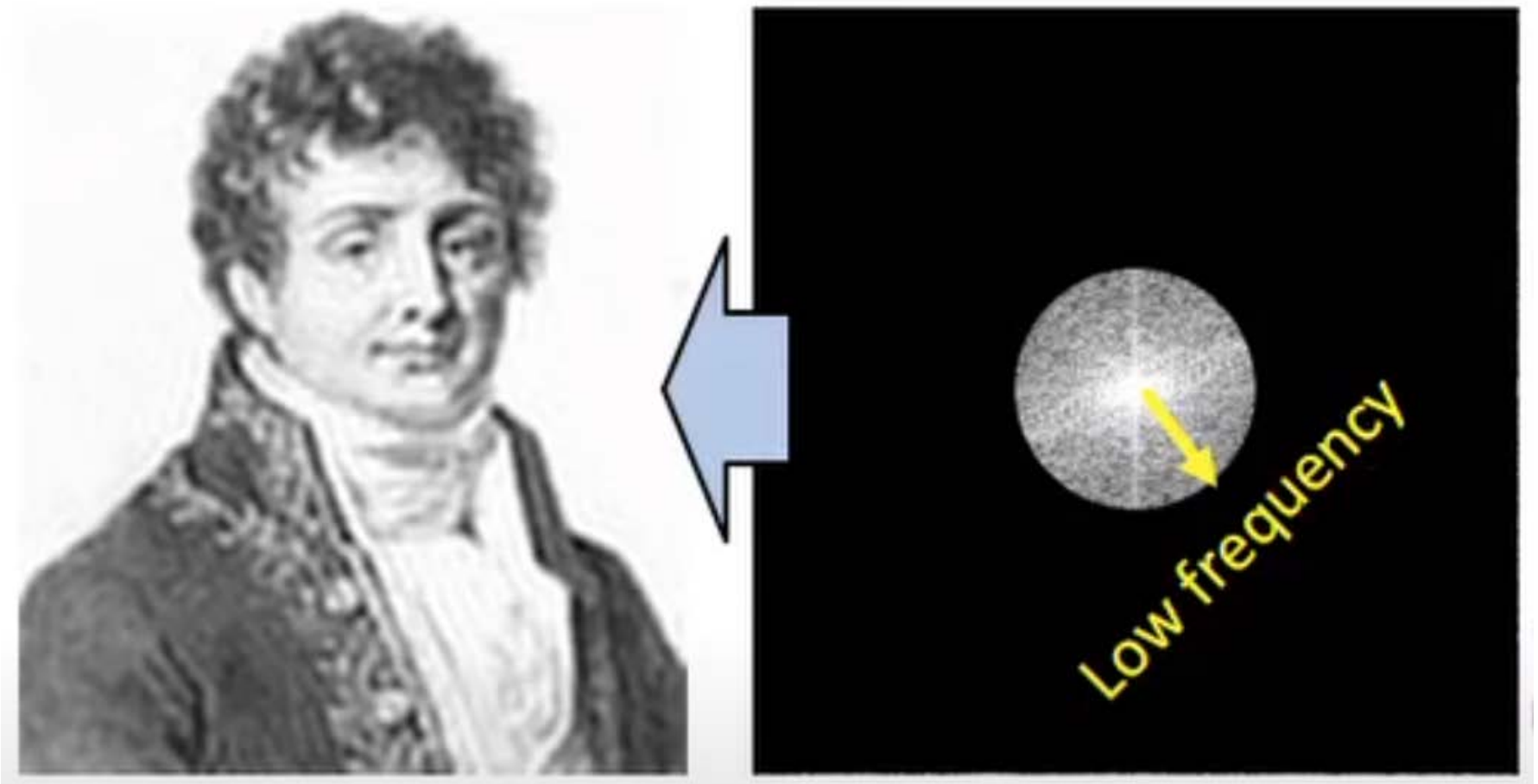


Original Image (real space)

Fourier transform (frequency space)

(Huang, 2013)

Fourier space

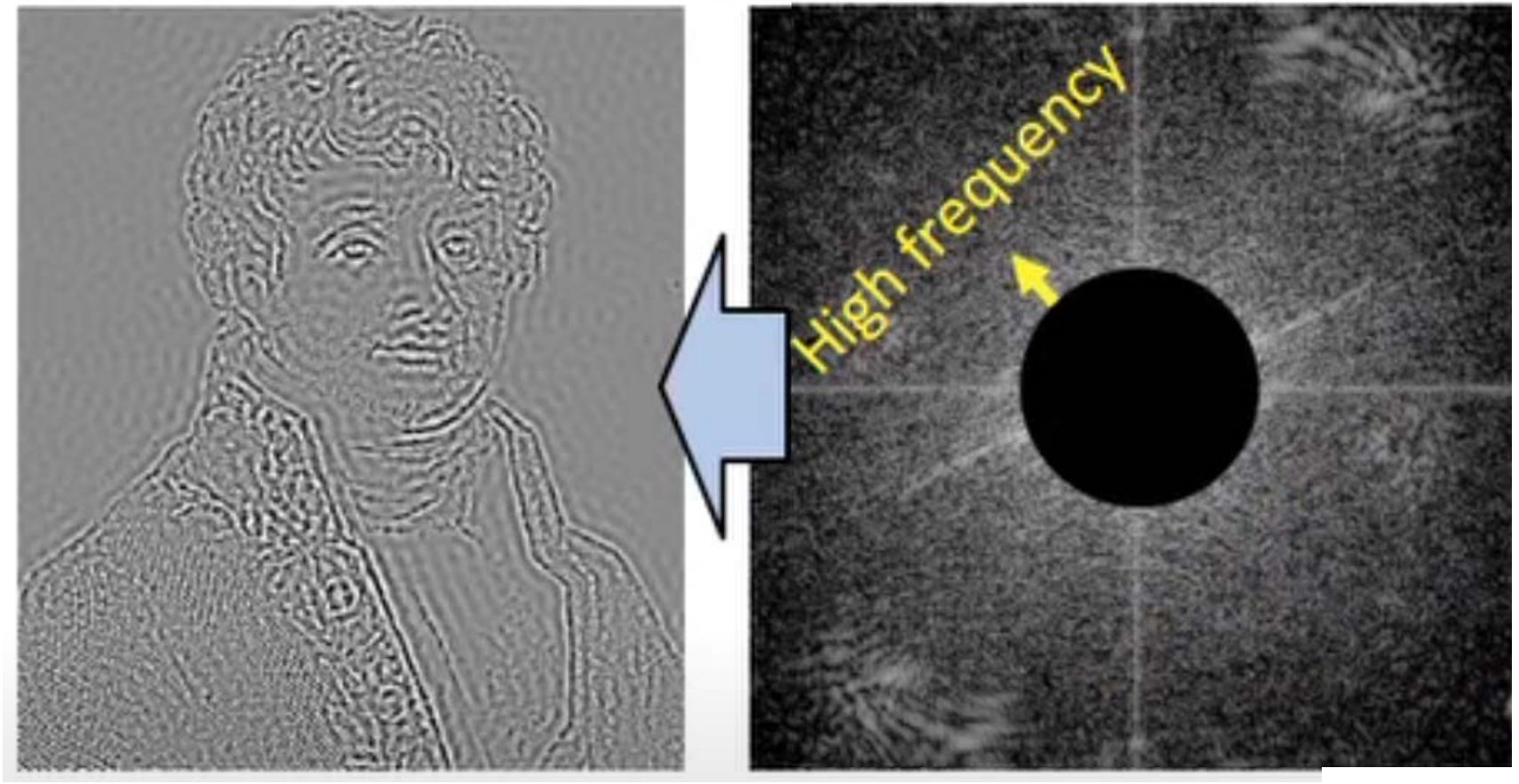


Original Image (real space)

Fourier transform (frequency space)

(Huang, 2013)

Fourier space



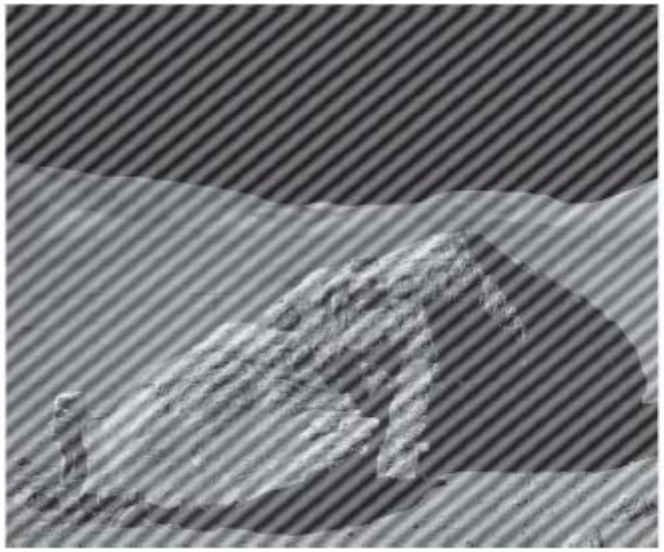
Original Image (real space)

Fourier transform (frequency space)

(Huang, 2013)

Noise

Sinusoidal noise

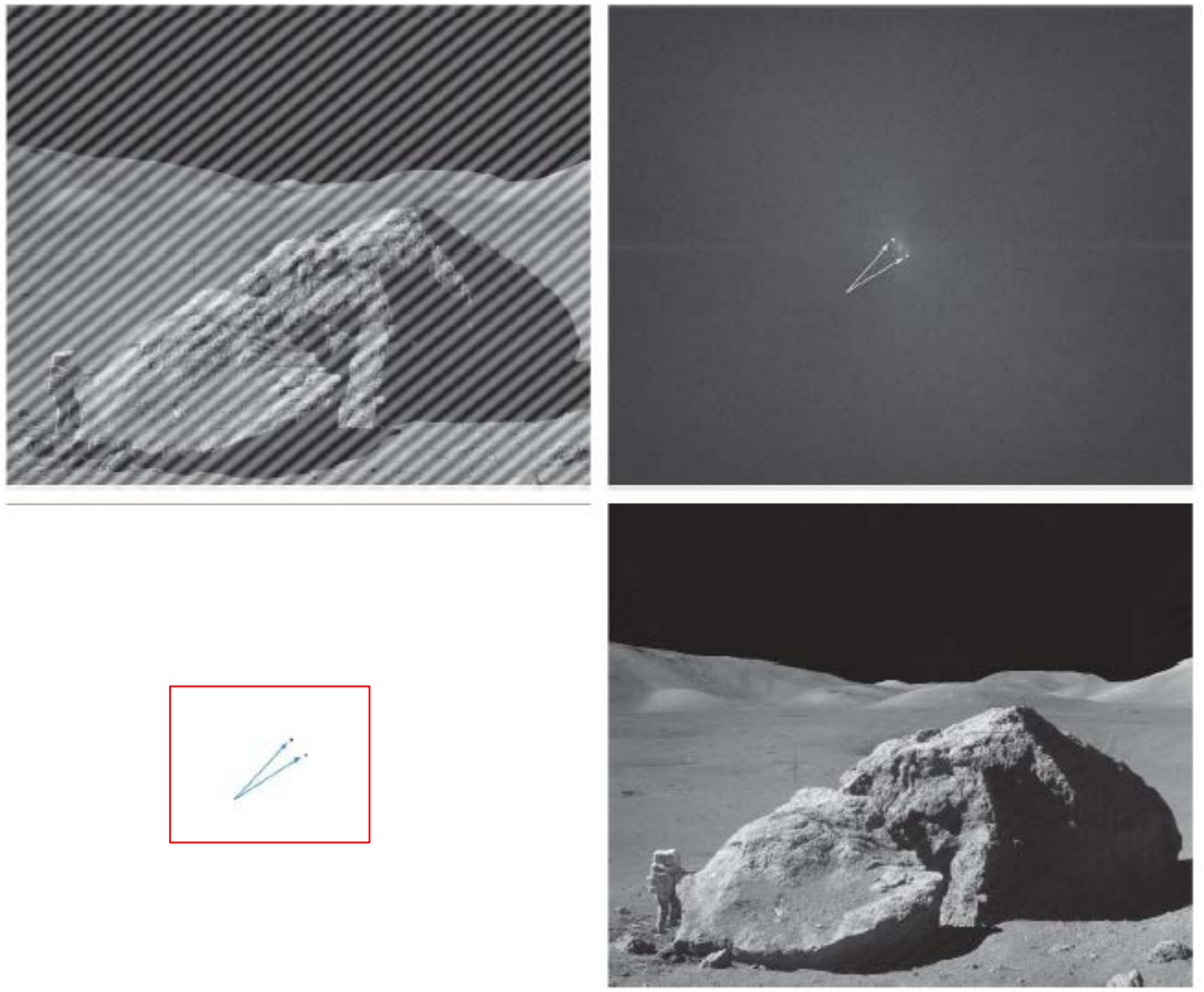


Spectrum

(Gonzalez and Woods, 2018)

Image denoising

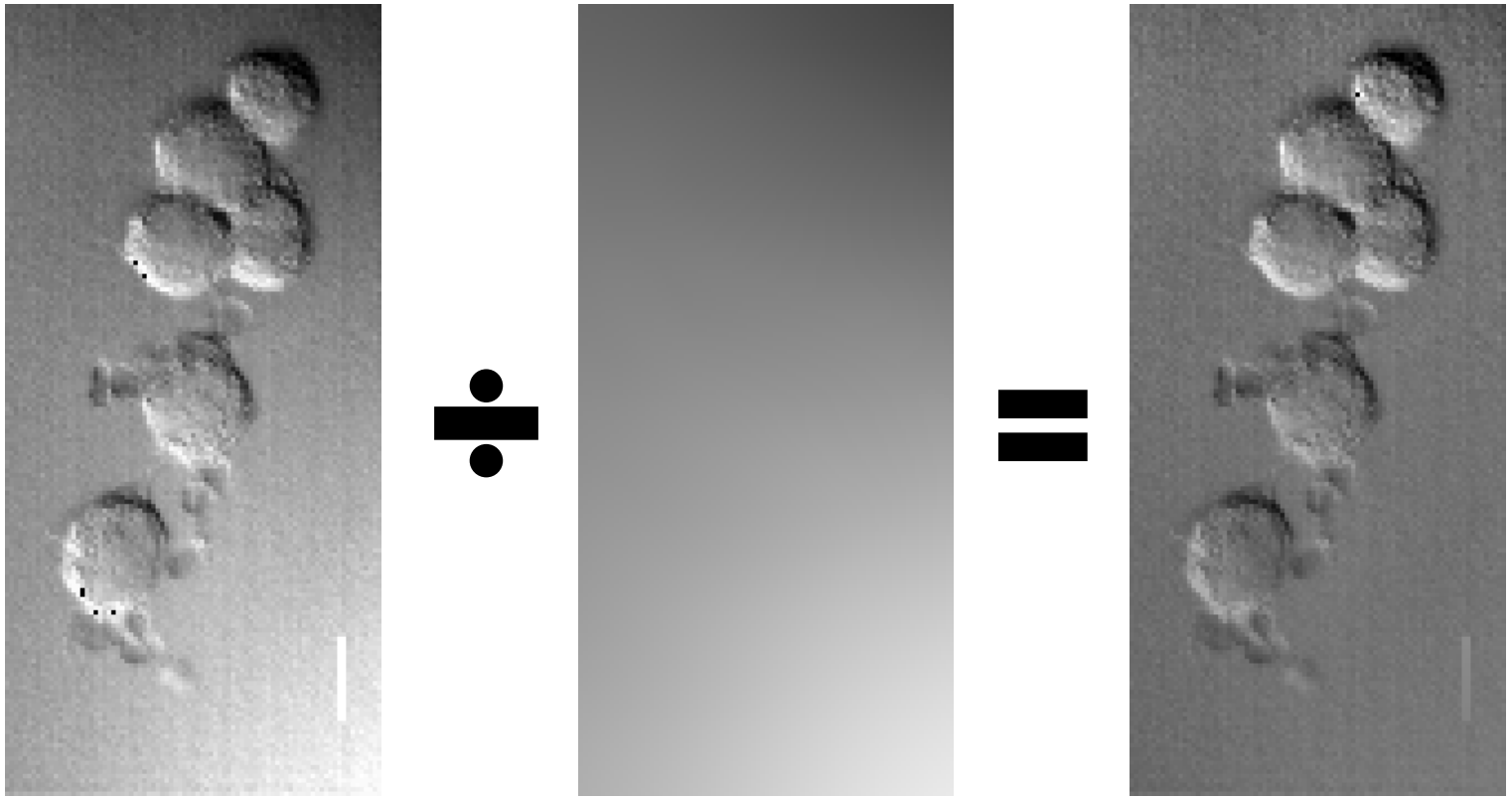
Process > FTT…

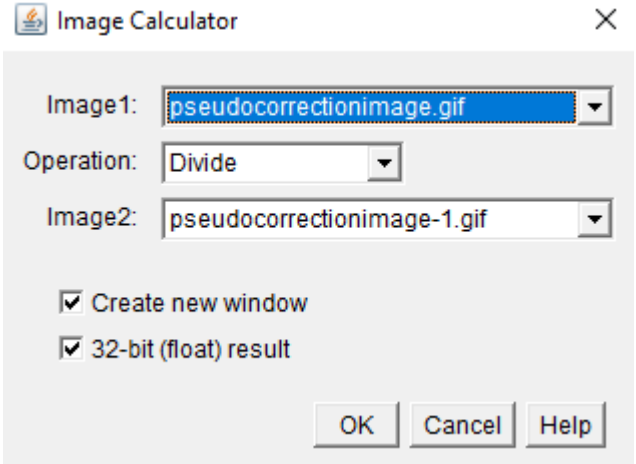


(Gonzalez and Woods, 2018)

Background correction

Process > Image Calculator…






```
run("Duplicate...", " ");
run("Mean...", "radius=50");
imageCalculator("Divide create 32-bit", "pseudocorrectionimage.gif","pseudocorrectionimage-1.gif");
```

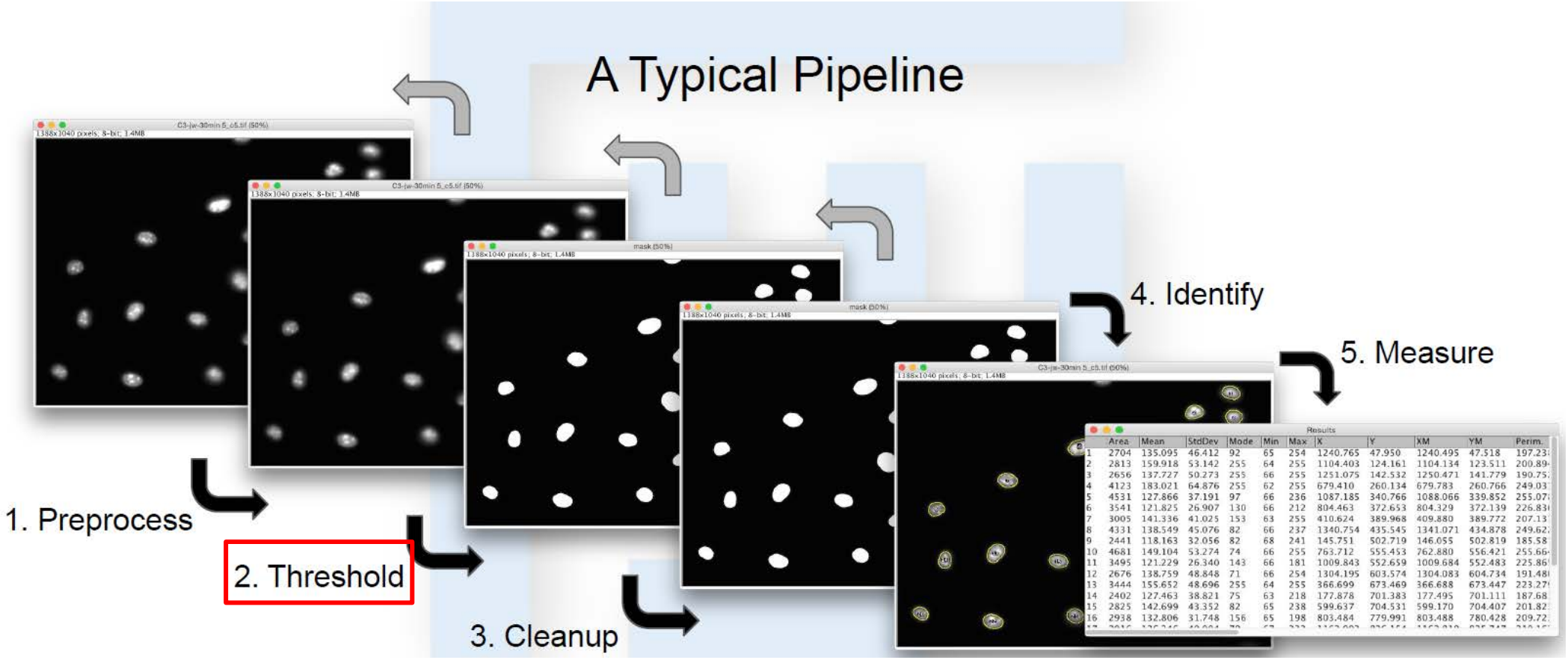
(imagej.net)

Image calculator…

Source image (*img1*):		**Destination image** (*img2*):	

Operator	Result	Operator	Result
Add: $img1 = img1 + img2$		**Min**: $img1 = \min(img1, img2)$	
Subtract: $img1 = img1 - img2$		**Max**: $img1 = \max(img1, img2)$	
Multiply: $img1 = img1 \times img2$		**Average**: $img1 = (img1 + img2)/2$	
Divide: $img1 = img1 \div img2$		**Difference**: $img1 = \lvert img1 - img2 \rvert$	
AND: $img1 = img1 \wedge img2$		**Copy**: $img1 = img2$	
OR: $img1 = img1 \vee img2$		**Transparent--zero**	
XOR: $img1 = img1 \oplus img2$			

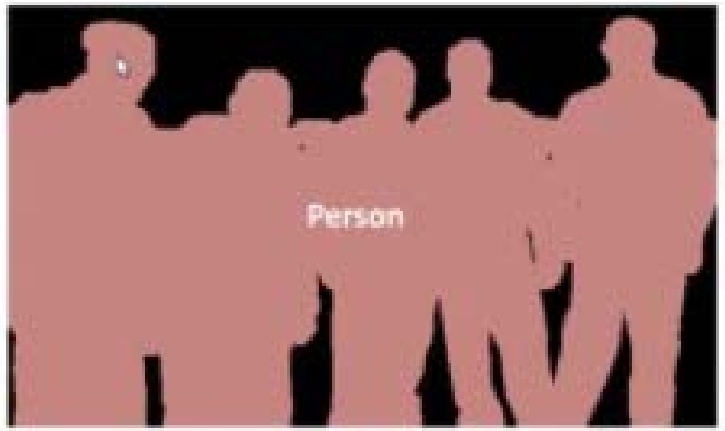
Image processing pipeline



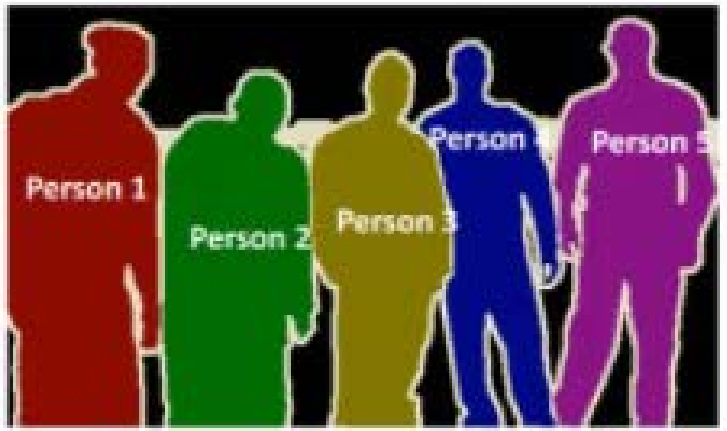
(LOCI, 2021)

Segmentation

Object Detection



Sematic Segmentation



Instance Segmentation

(Sreeni, 2019)

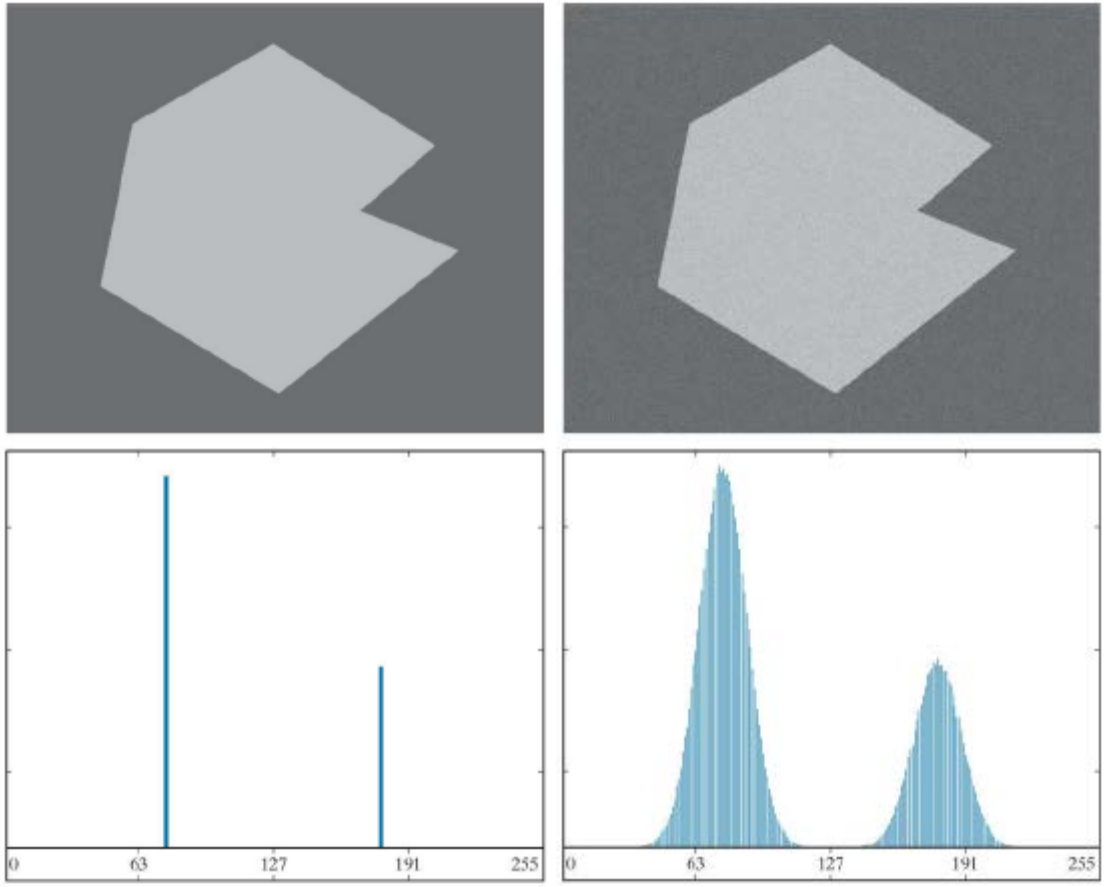
Semantic segmentation

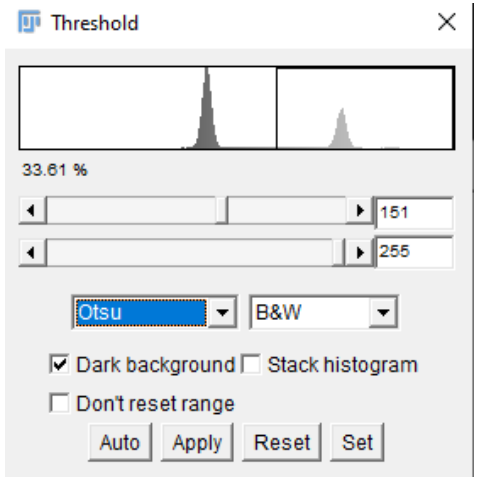
- Global thresholding
- Local thresholding
- Region growing methods
- Probabilistic clustering
- Graph-cuts
- Deformable surface (snakes and level sets)
- Optimum (Bayes) Statistical Classifiers
- Machine learning – Random forest (Trainable Weka Segmentation)
- Deep Convolutional Neural Networks

Explore at *Category:Segmentation - ImageJ*

Thresholding segmentation

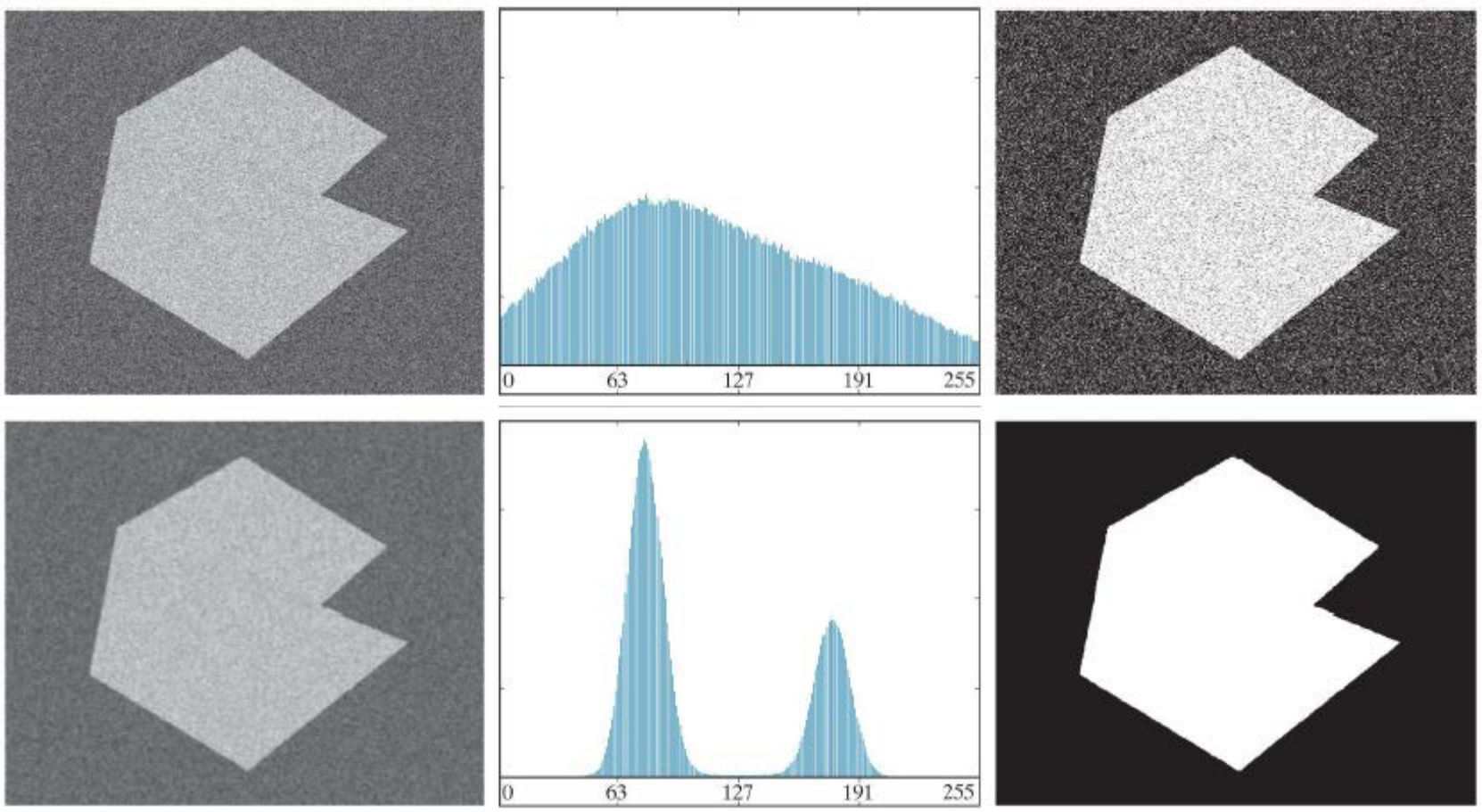
Image > Adjust > Threshold…

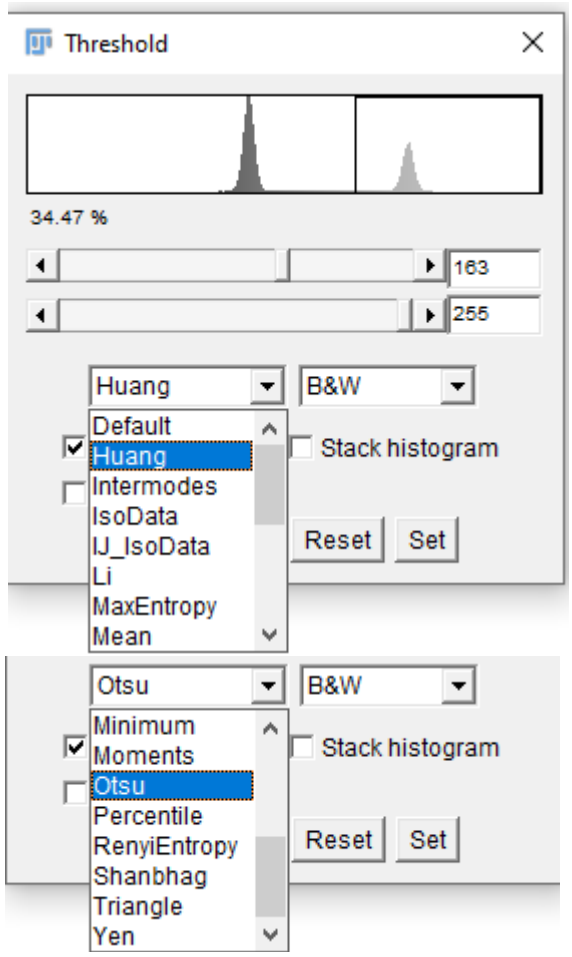




(Gonzalez and Woods, 2018)

Image smoothing + Thresholding

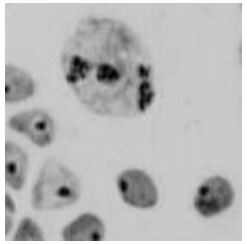


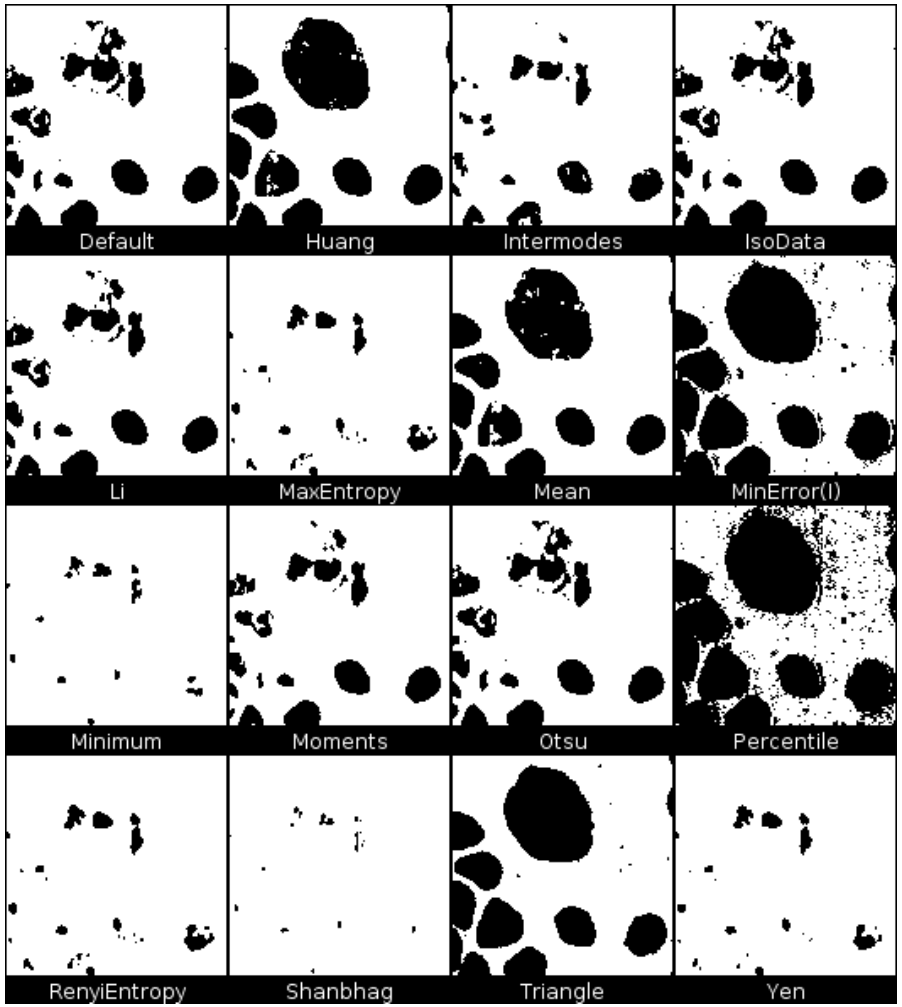


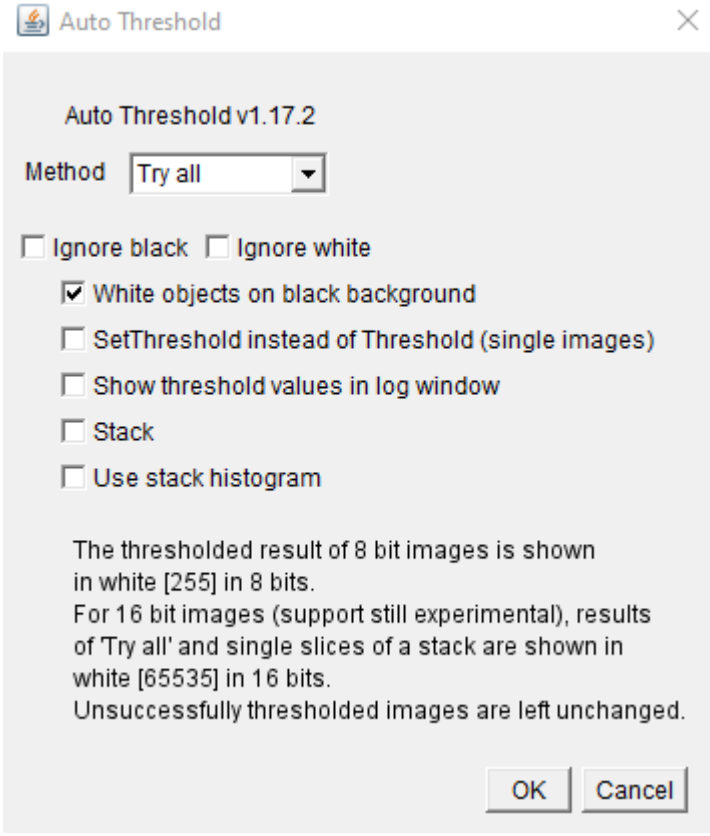
(Gonzalez and Woods, 2018)

Automatic threshold

Image > Adjust > Auto Threshold



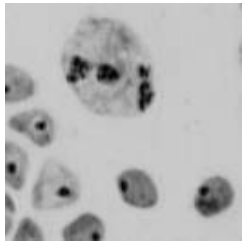


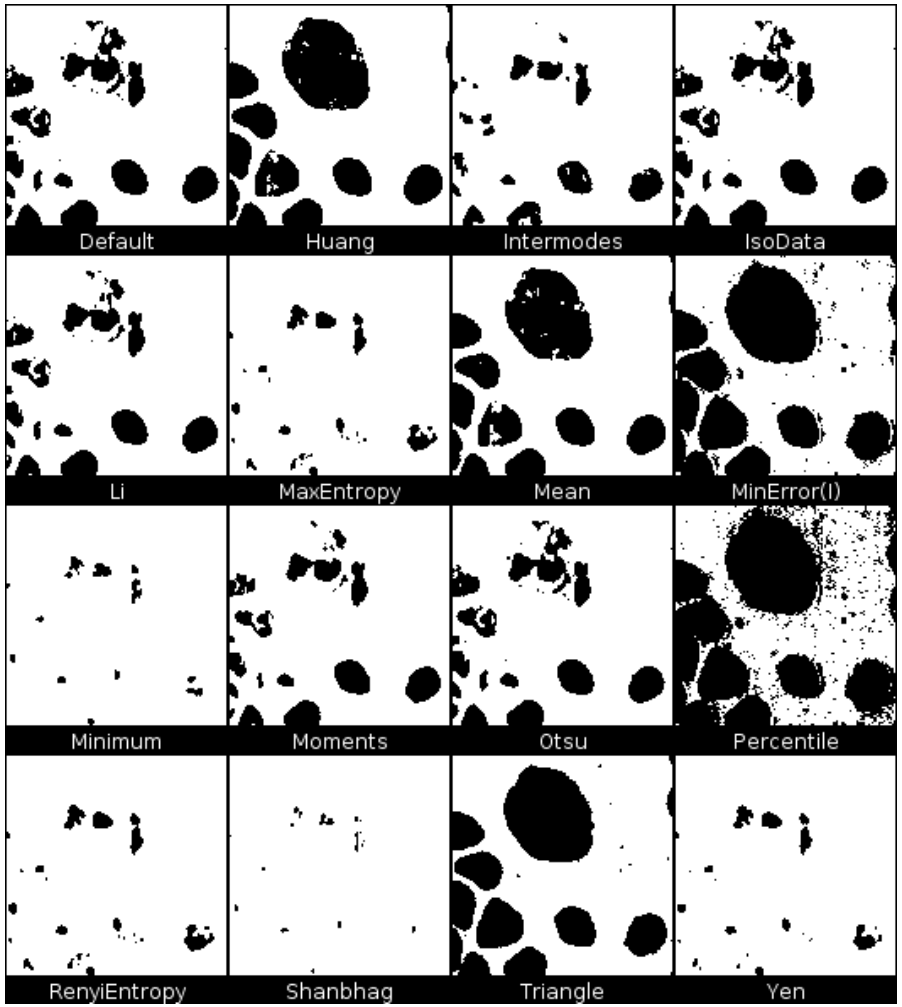


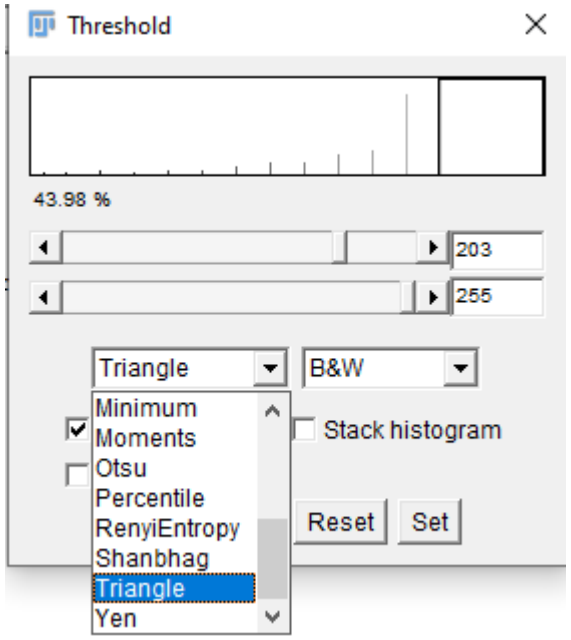

```
run("Auto Threshold", "method=[Try all] white stack");
```

Automatic threshold

Image > Adjust > Threshold…



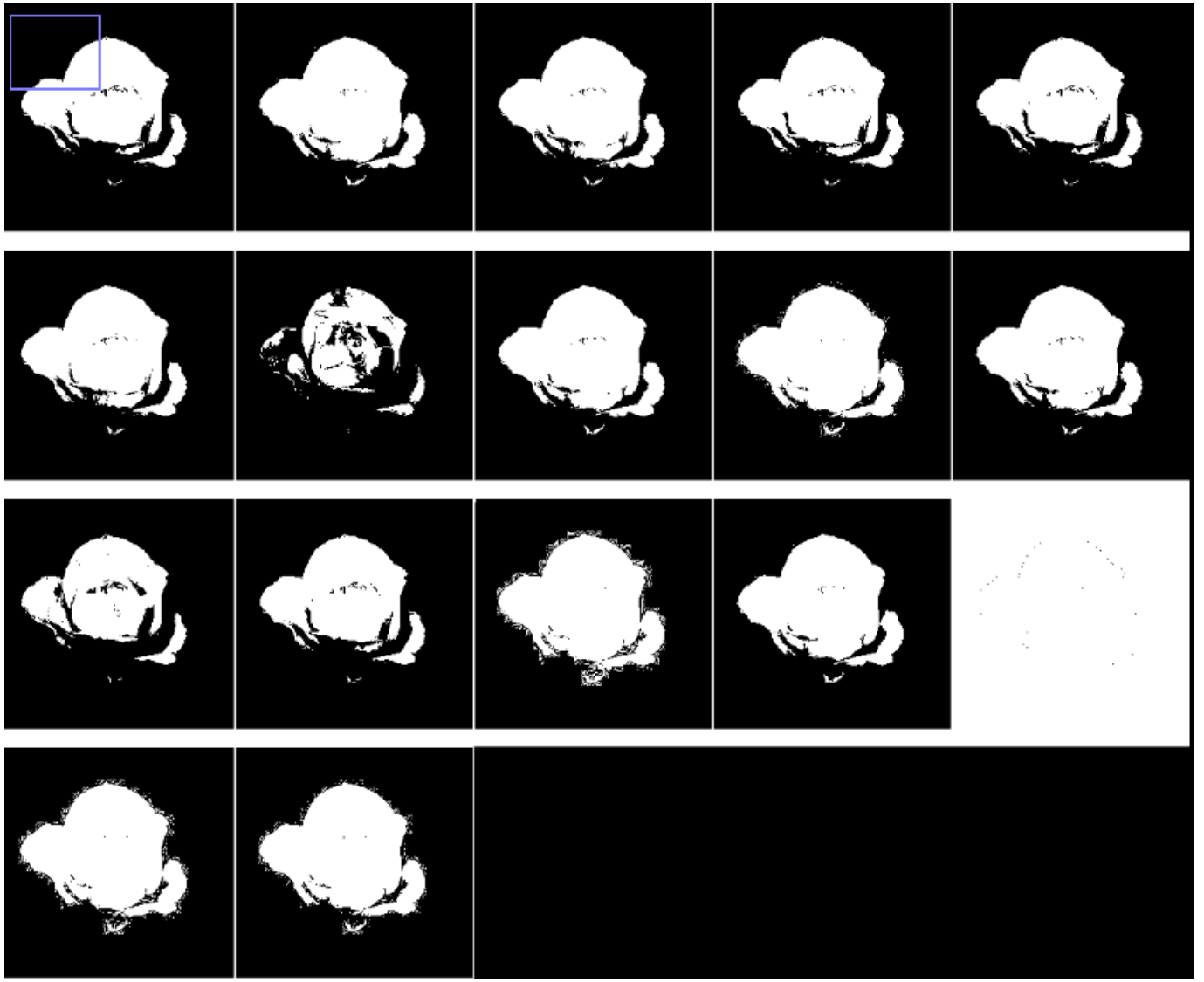




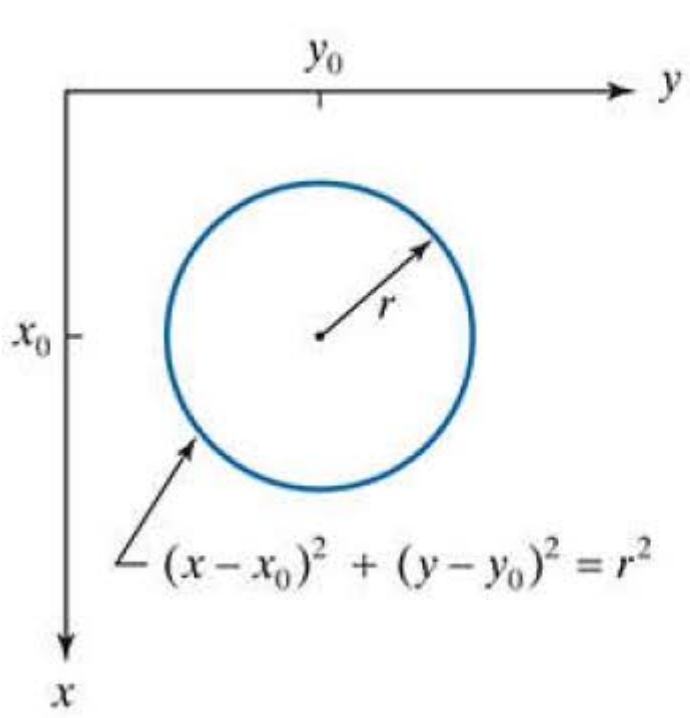
*Macro.ijm.ijm

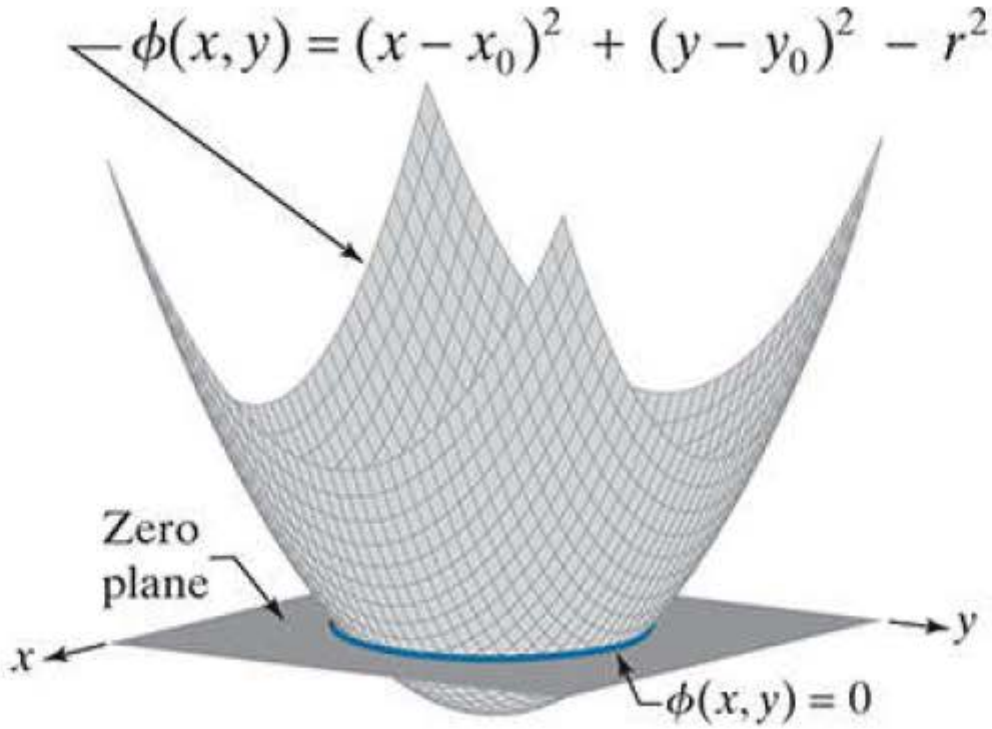
```
1 //run("Threshold...");
2 setAutoThreshold("Triangle dark");
```

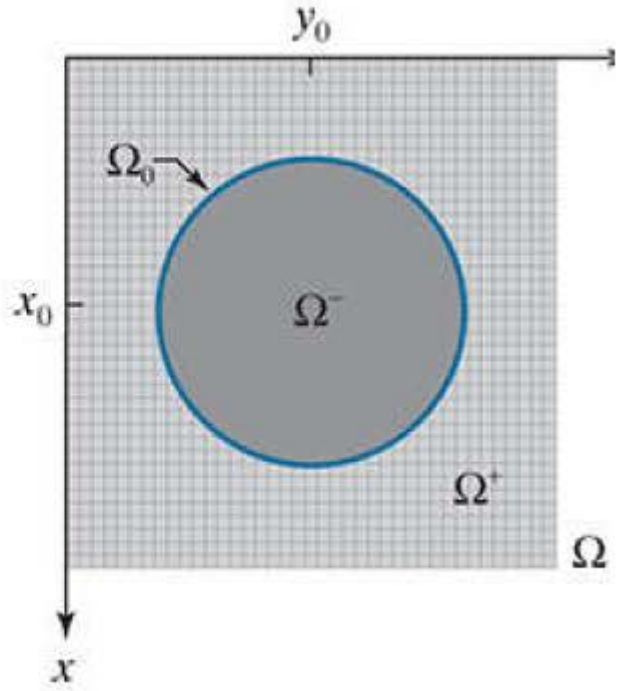
Automatic threshold



Level sets

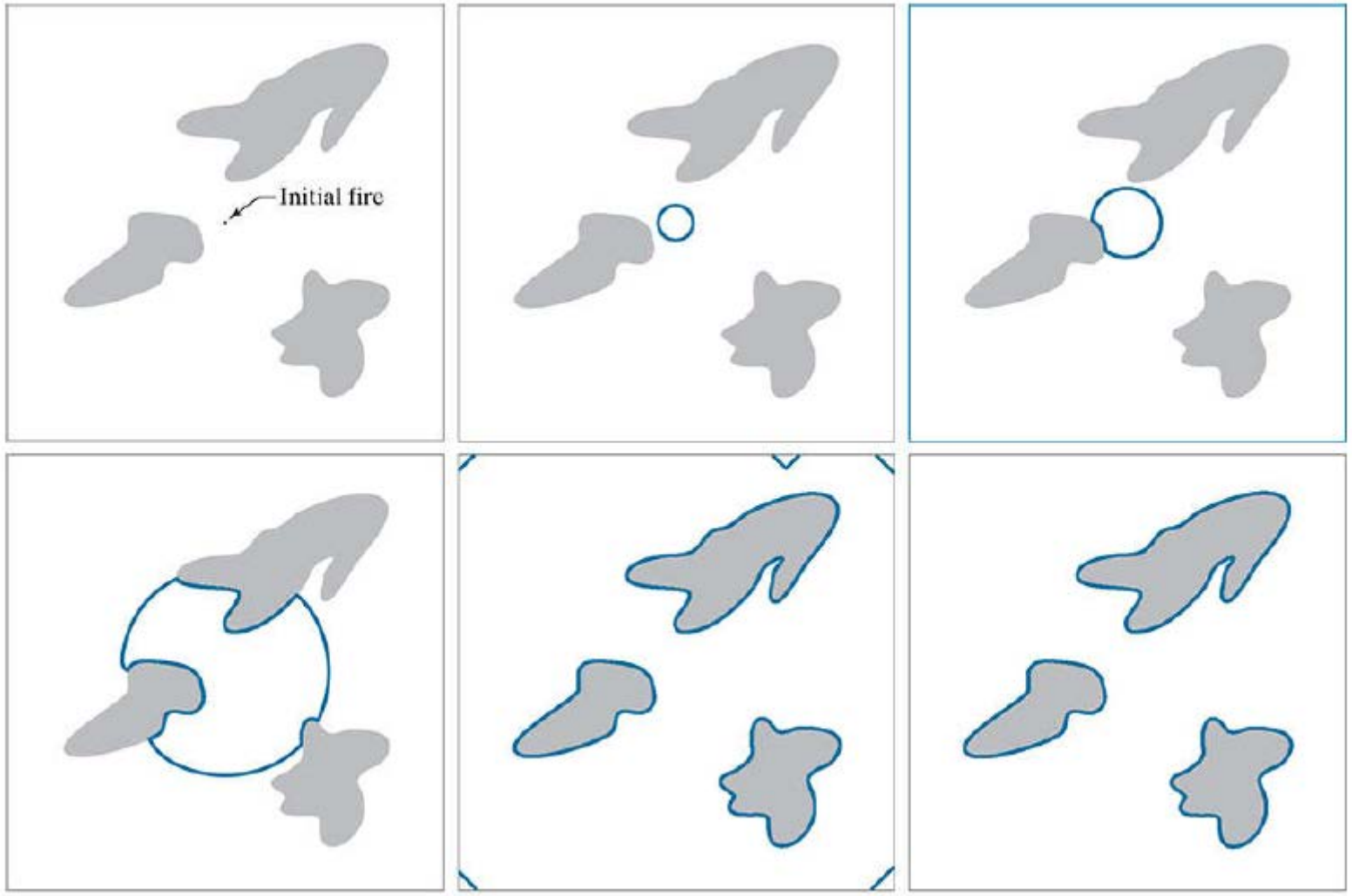






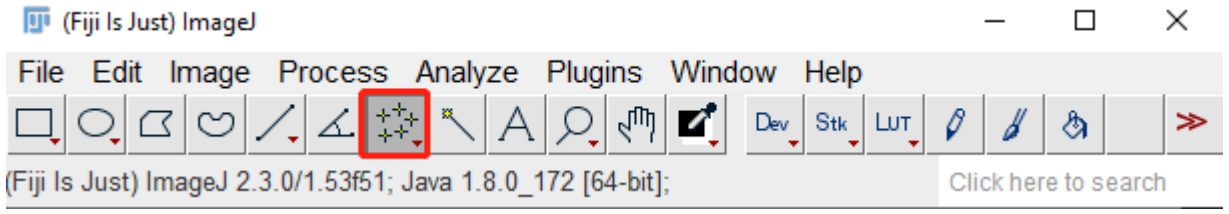
(Gonzalez and Woods, 2018)

Level sets

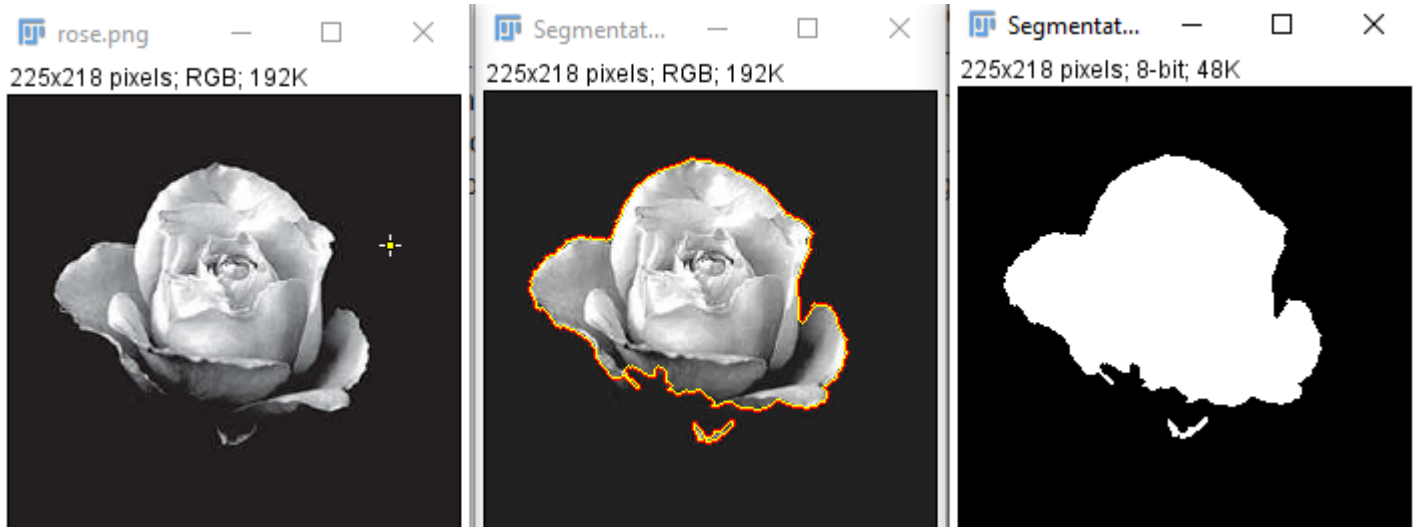


(Gonzalez and Woods, 2018)

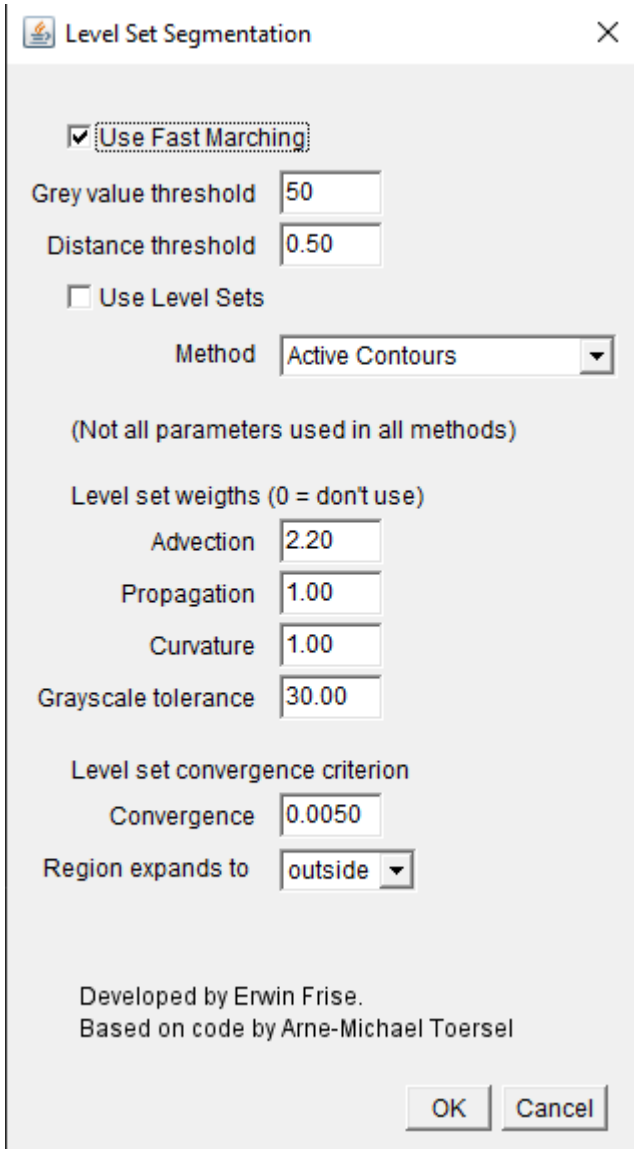
Level sets



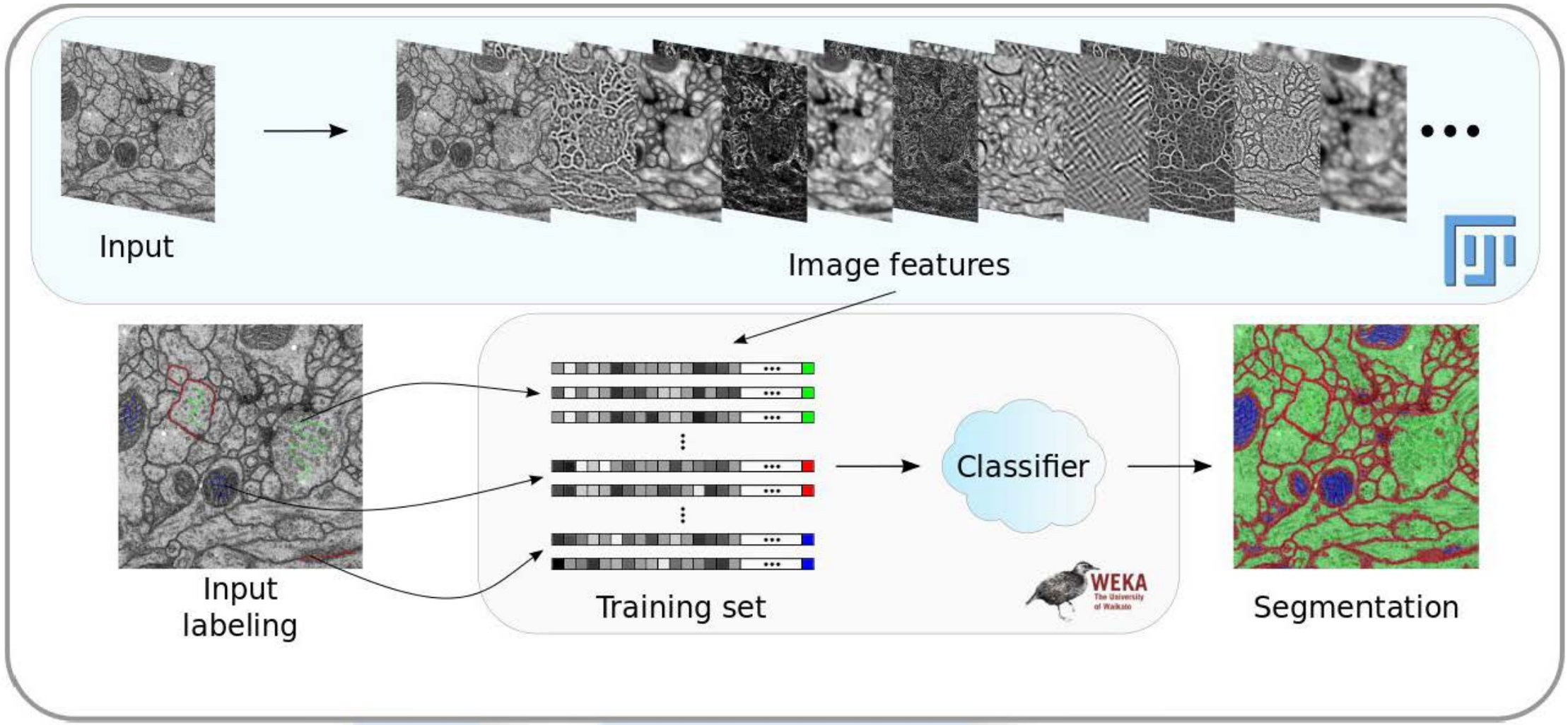
Plugins > Segmentation > Level Sets



(Level Sets – ImageJ)



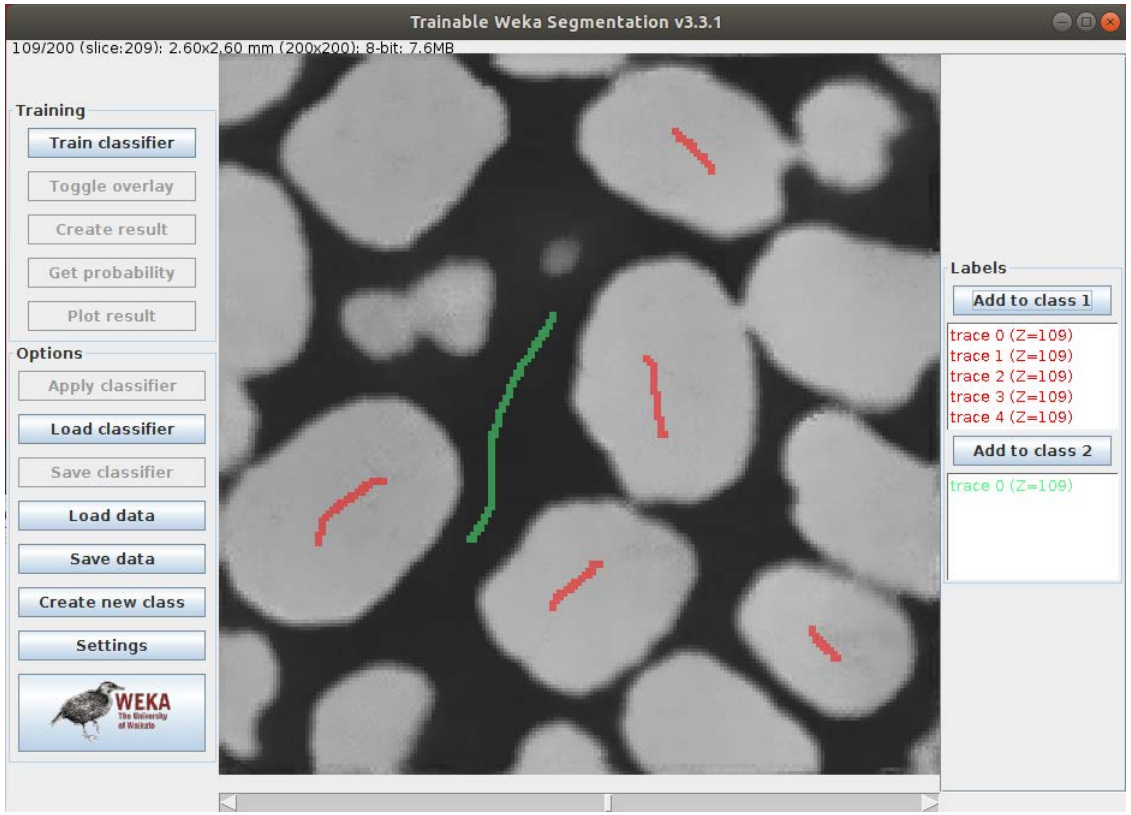
Trainable Weka Segmentation (TWS)

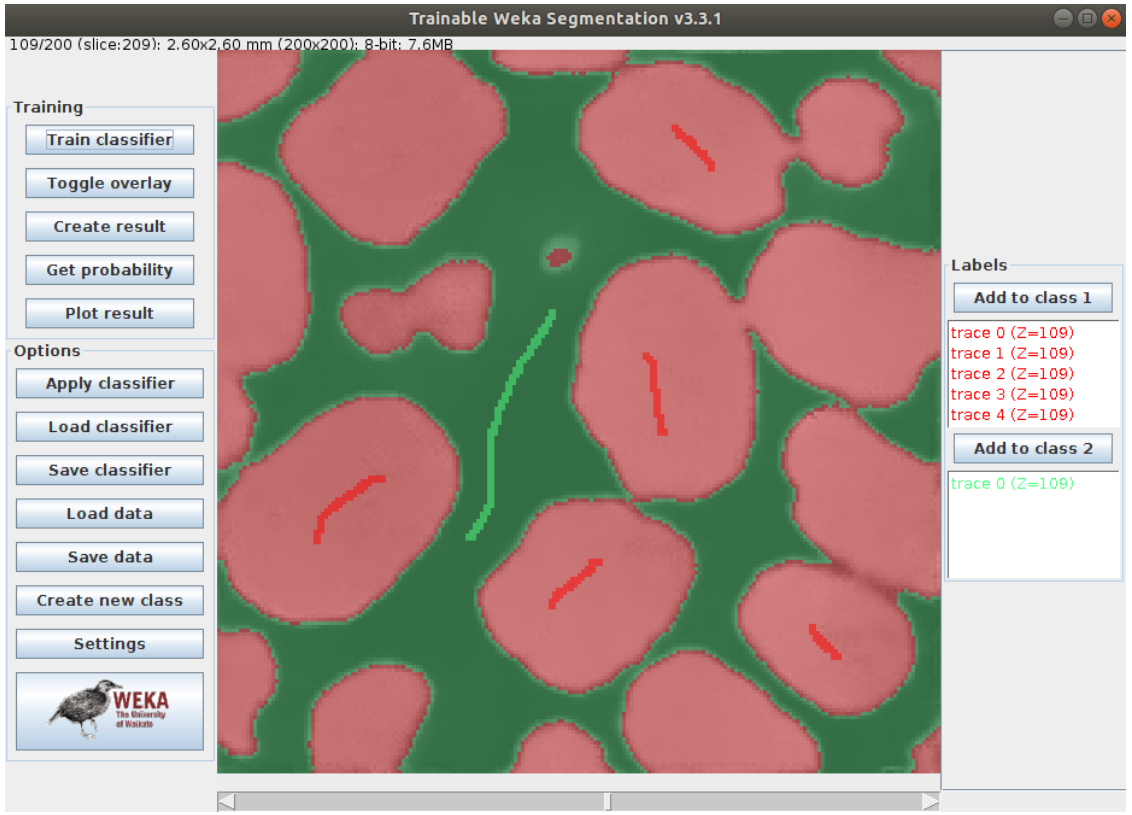


(Arganda-Carreras et al., 2017)

Trainable Weka Segmentation (TWS)

Plugins > Segmentation >Trainable Weka Segmentation (3D)

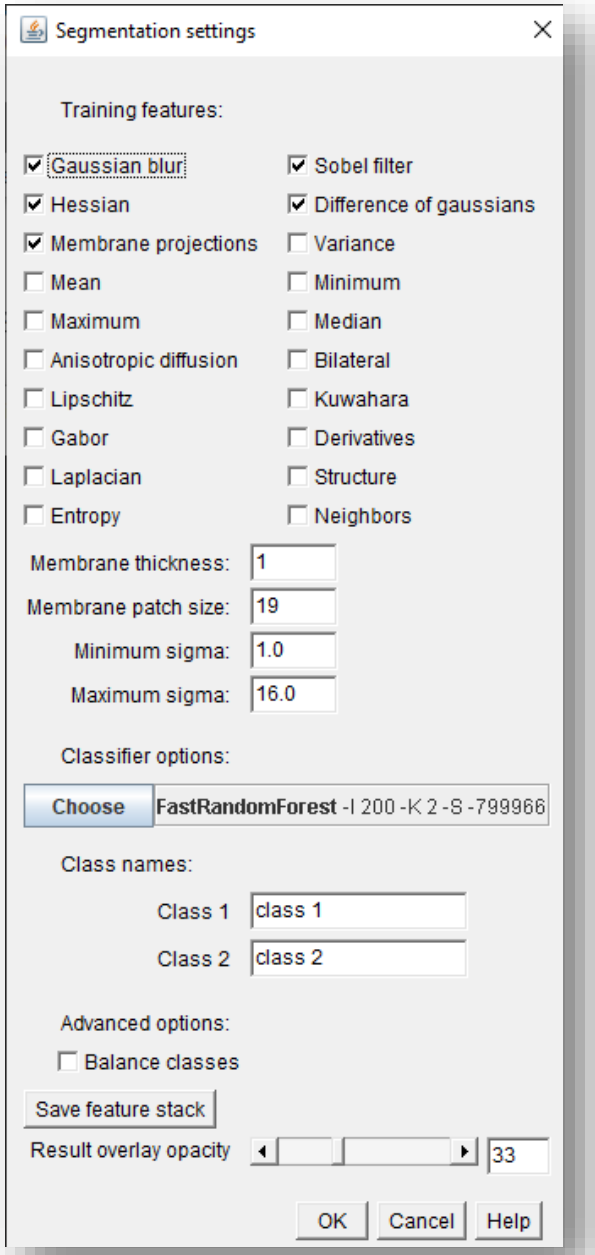




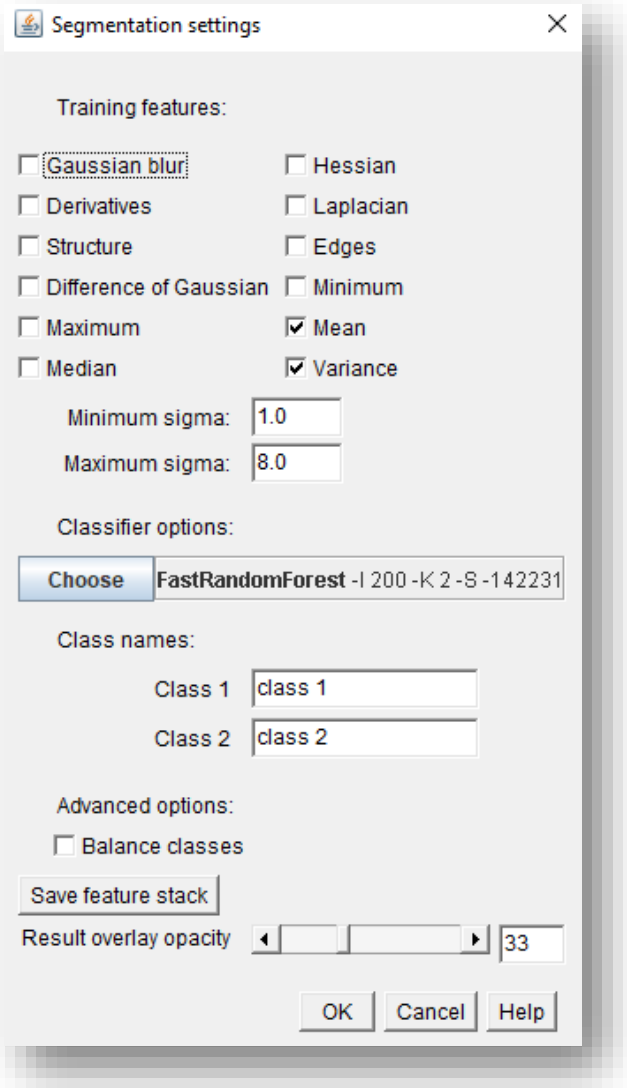
(Arganda-Carreras et al., 2017)

Training features

2D



3D



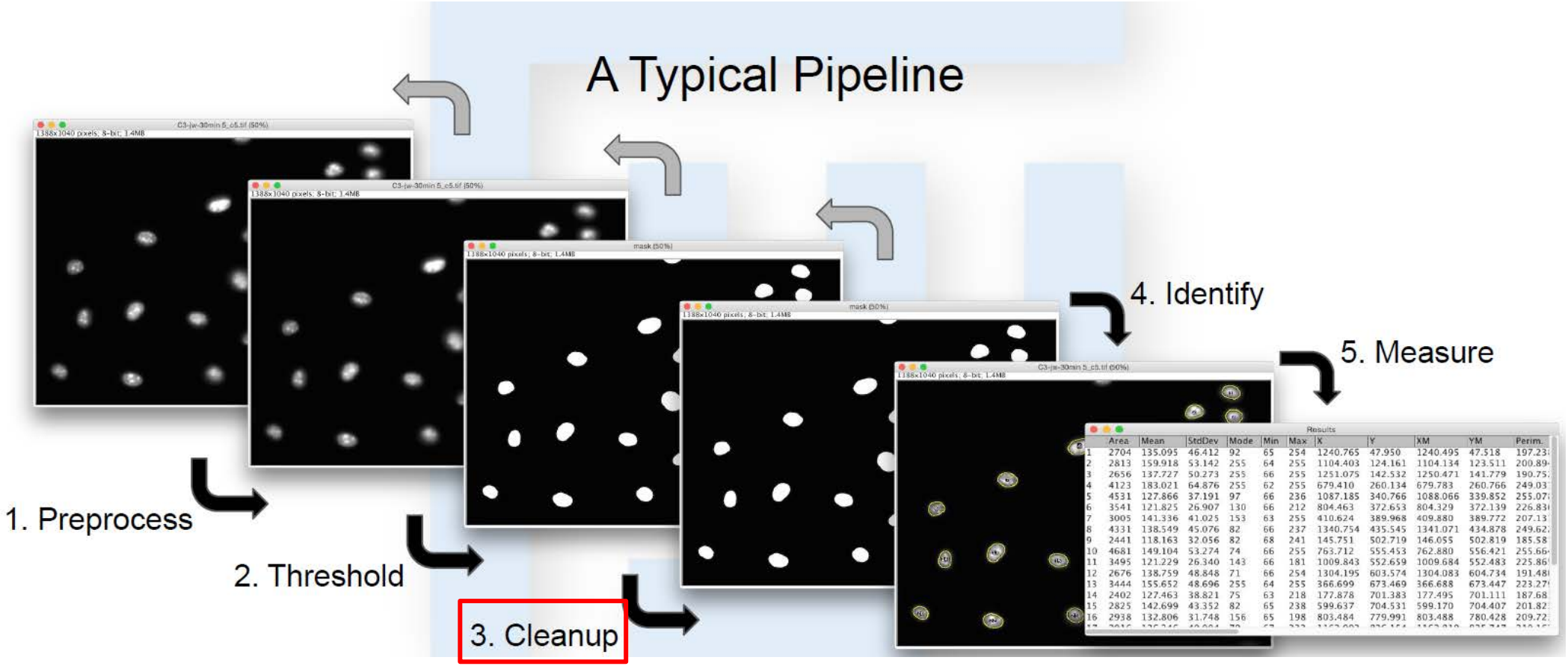
Edge detectors: *Laplacian, Sobel, Difference of gaussian, Hessian, Gabor.*

Texture filters: *minimum, maximum, median, variance, entropy, structure tensor.*

Noise reduction: *Gaussian blur, bilateral filter, Anisotropic diffusion, Kuwahara and Lipschitz; and membrane detectors.*

Trainable Weka Segmentation (imagej.net)

Image processing pipeline



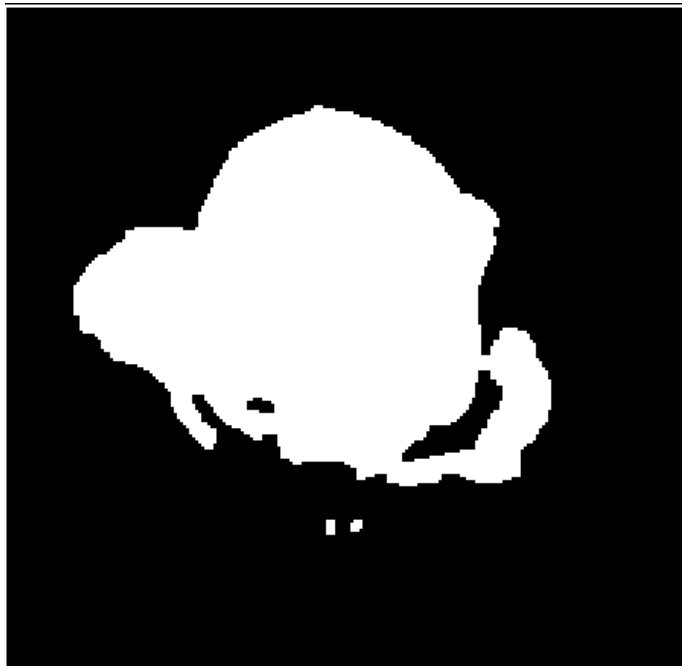
(LOCI, 2021)

Cleanup

Process > Binary >

Huang Auto Thresholding

Close

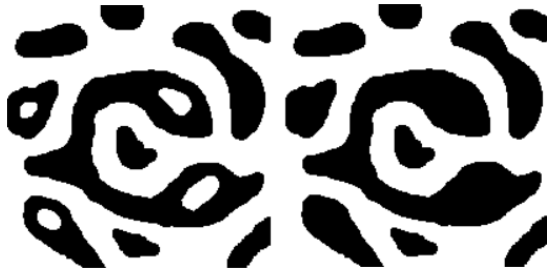


Open

Cleanup

Process > Binary >

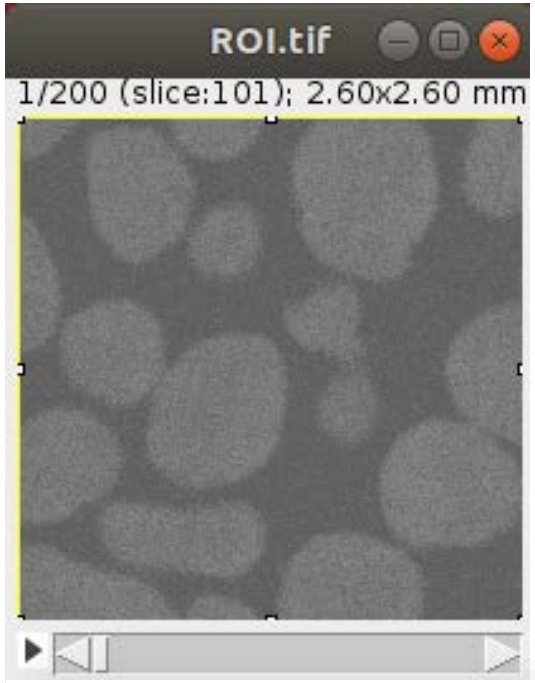
Fill Holes



Hands-on Tutorial #2

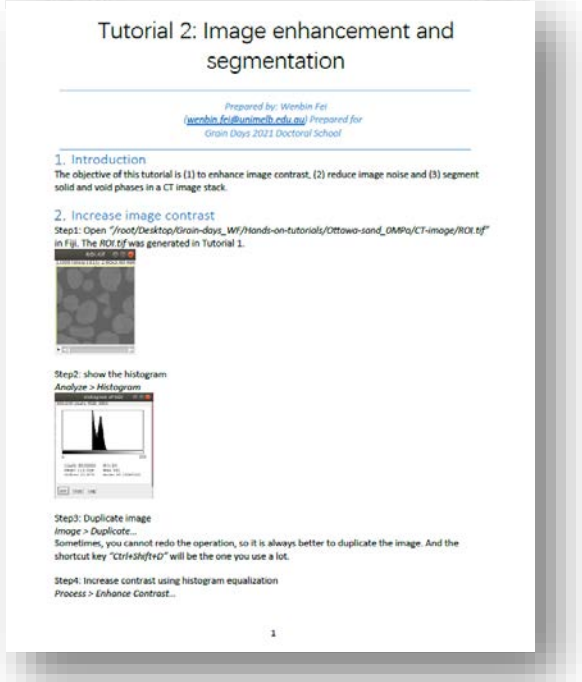
Hands-on Tutorial #2

15 minutes



Objectives:

- Enhance image contrast
- Reduce image noise and
- Segment solid and void phases


Tutorial 2: Image enhancement and segmentation

Prepared by: Wenbin Fei
(wenbin.fei@unimelb.edu.au) Prepared for
Grain Days 2021 Doctoral School

1. Introduction

The objective of this tutorial is (1) to enhance image contrast, (2) reduce image noise and (3) segment solid and void phases in a CT image stack.

2. Increase image contrast

Step1: Open "/root/Desktop/Grain-days_ WF/Hands-on-tutorials/Ottawa-sand_0MPa/CT-image/ROI.tif" in Fiji. The ROI.tif was generated in Tutorial 1.

Step2: show the histogram
Analyze > Histogram

Step3: Duplicate image
Image > Duplicate...
Sometimes, you cannot redo the operation, so it is always better to duplicate the image. And the shortcut key "Ctrl+Shift+D" will be the one you use a lot.

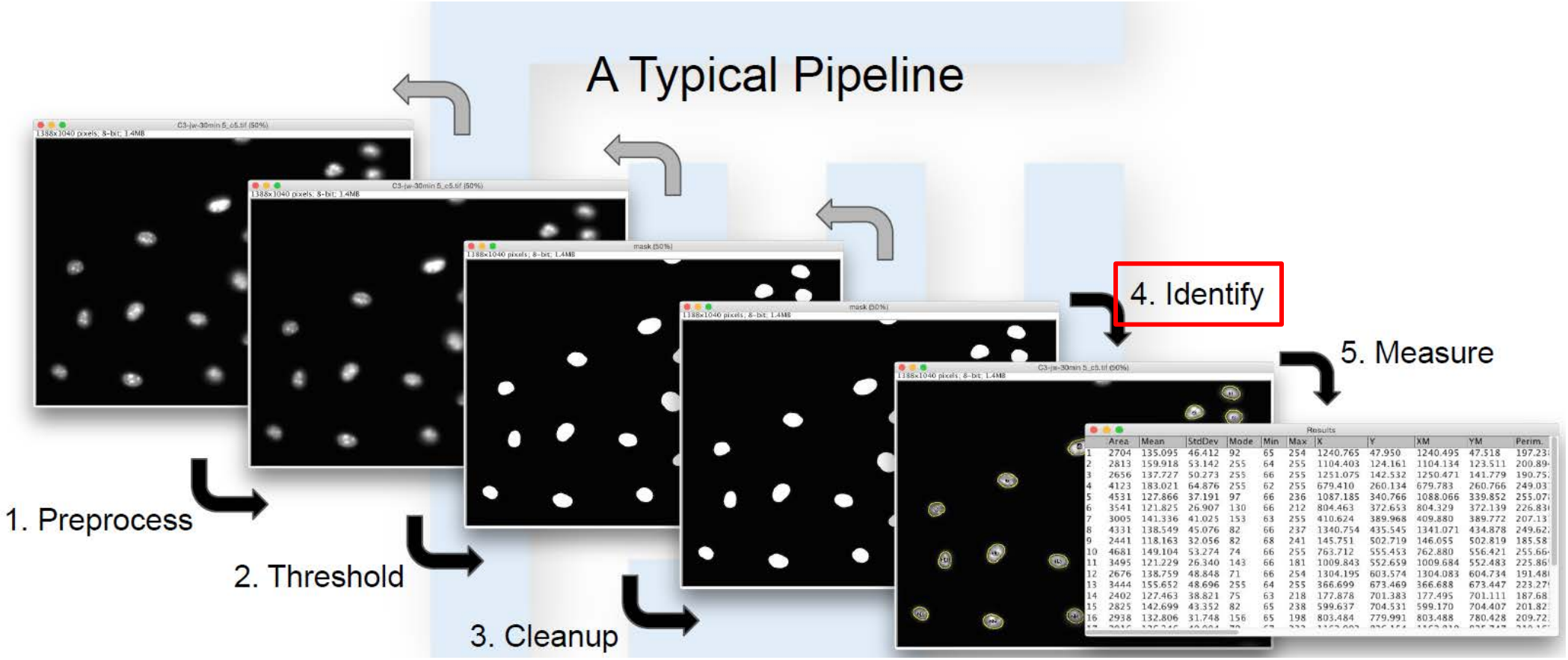
Step4: Increase contrast using histogram equalization
Process > Enhance Contrast...

1

Download tutorial using the following link:

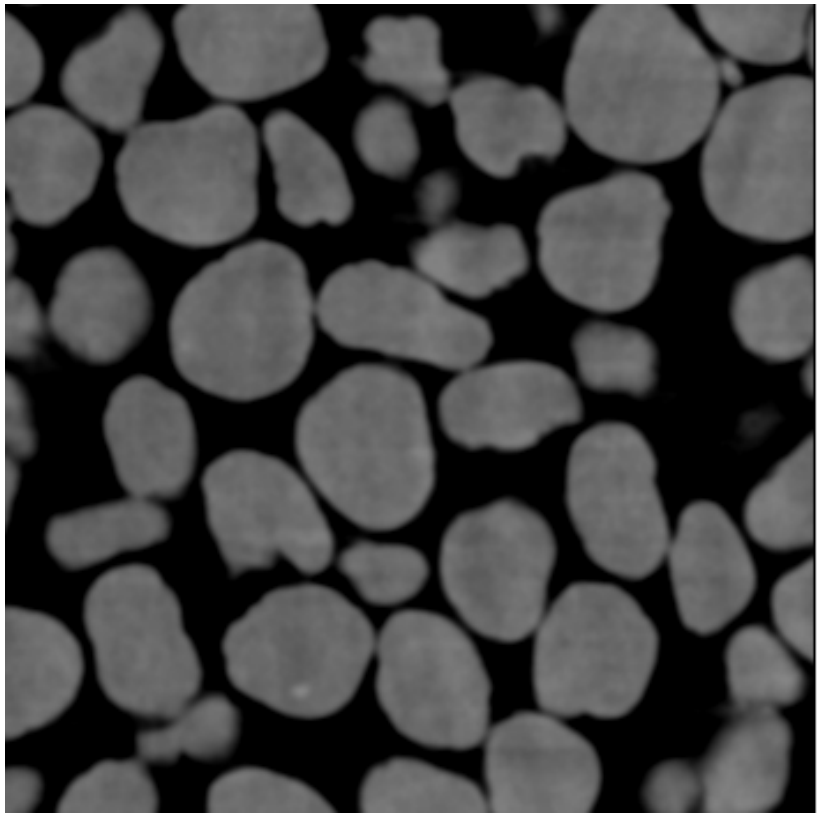
Link: *https://cloudstor.aarnet.edu.au/plus/s/YRnAMis6vR2ZKmo*
Password: **GrainDays_123456**

Image processing pipeline

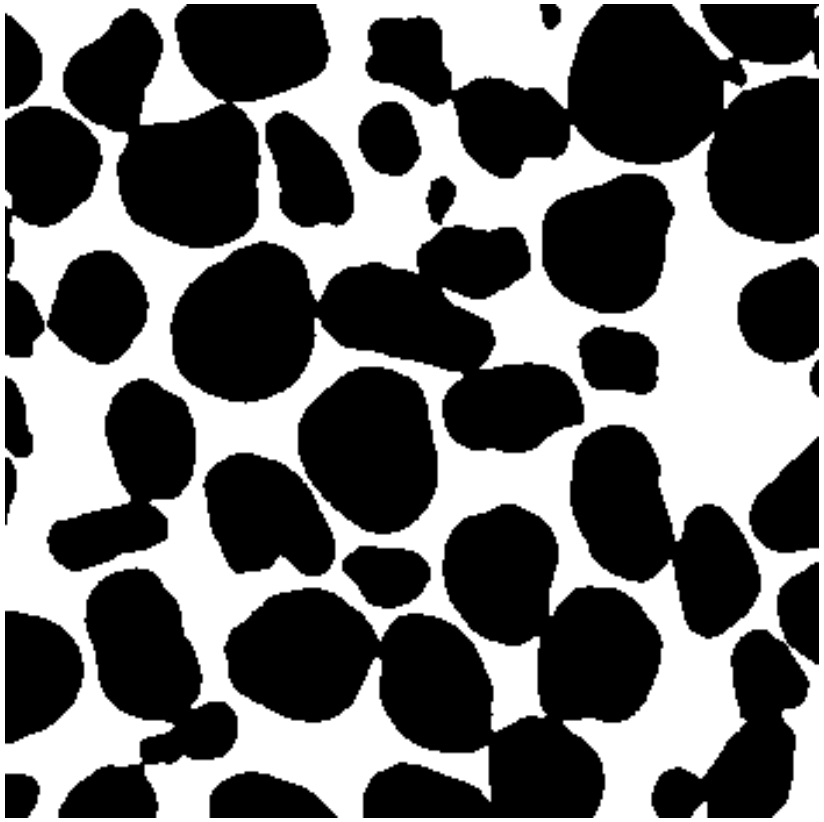


(LOCI, 2021)

Watershed

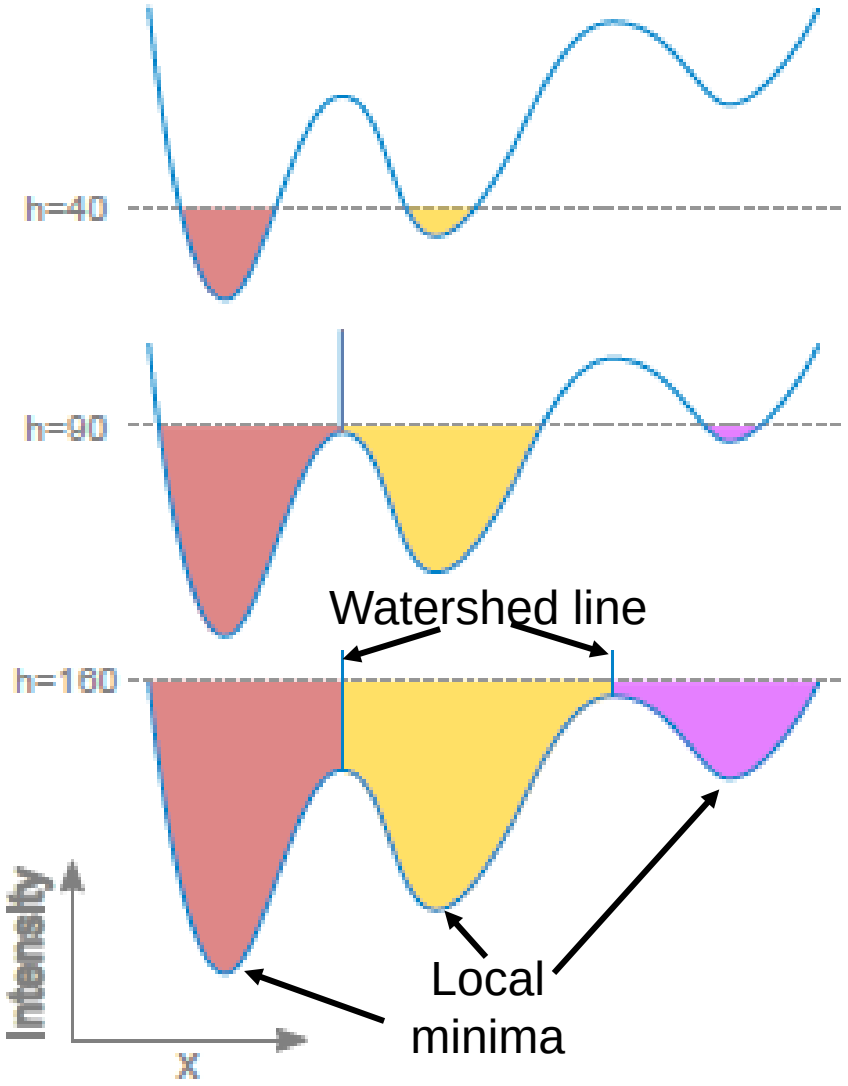


Threshold



Classic watershed

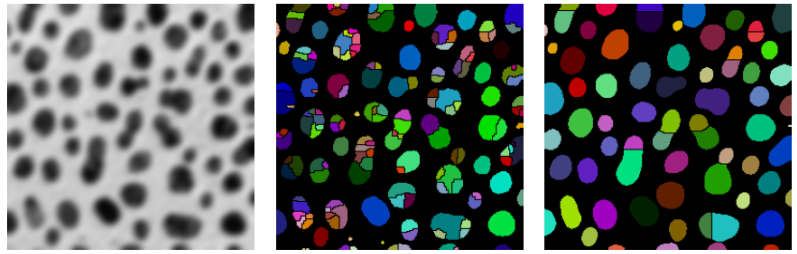
- Consider grey levels as altitudes
- Identify local minima
- Flood basins starting from minima
- Separate the basins by a “dam” → the watershed



(Legland and Arganda-Carreras, 2017)

Watershed

Classic watershed



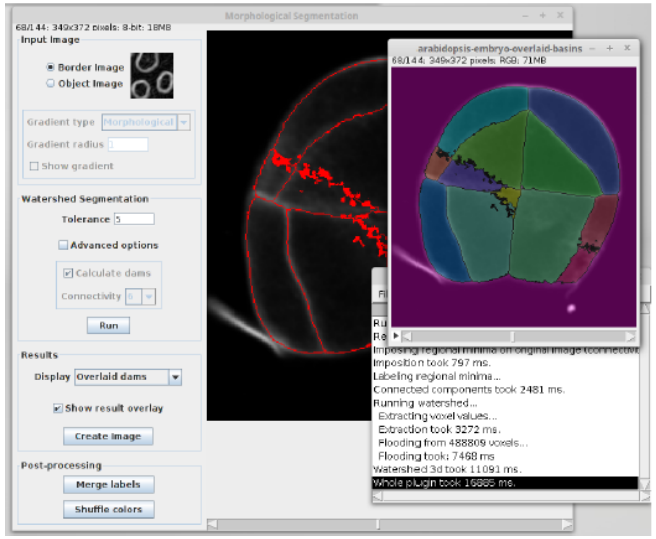
(a) Gaussian-blurred blobs image used as input (radius = 3).

(b) Watershed segmentation on original image ($h_{min} = 0$, $h_{max} = 150$).

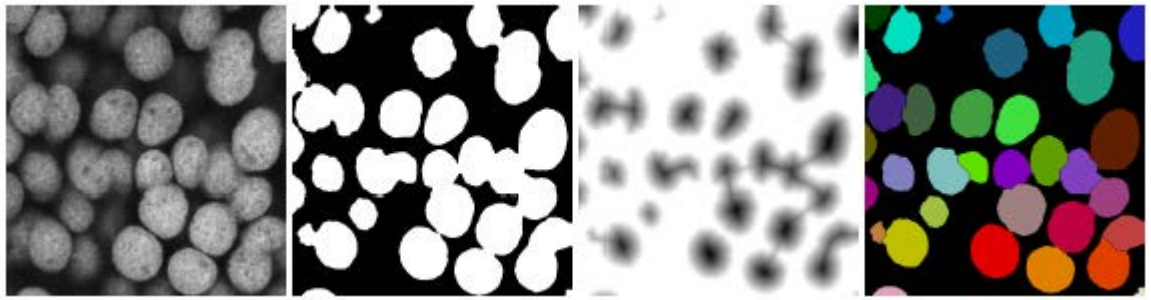
(c) Watershed segmentation on Gaussian-blurred original image (radius = 3, $h_{min} = 0$, $h_{max} = 150$).

Marker-controlled watershed

Morphological segmentation

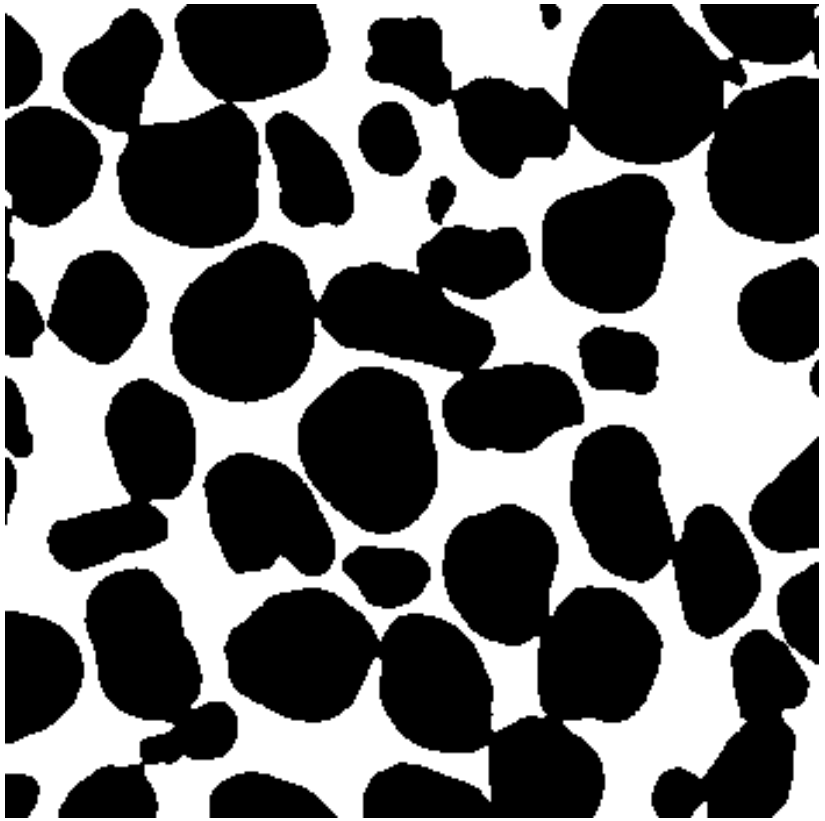


Distance transform watershed

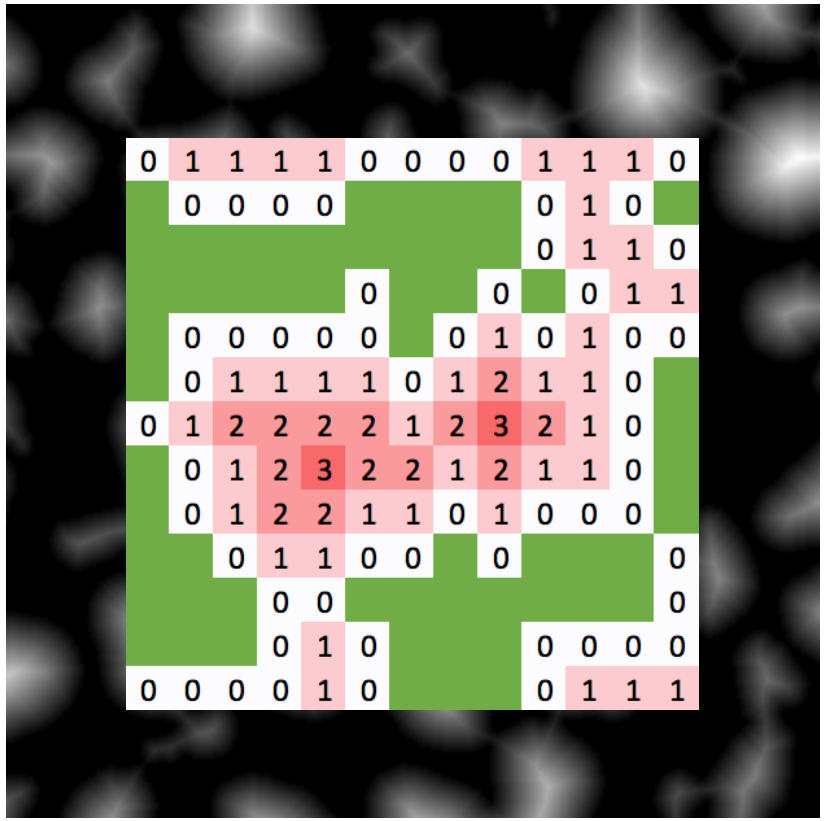


MorphoLibJ (imagej.net)

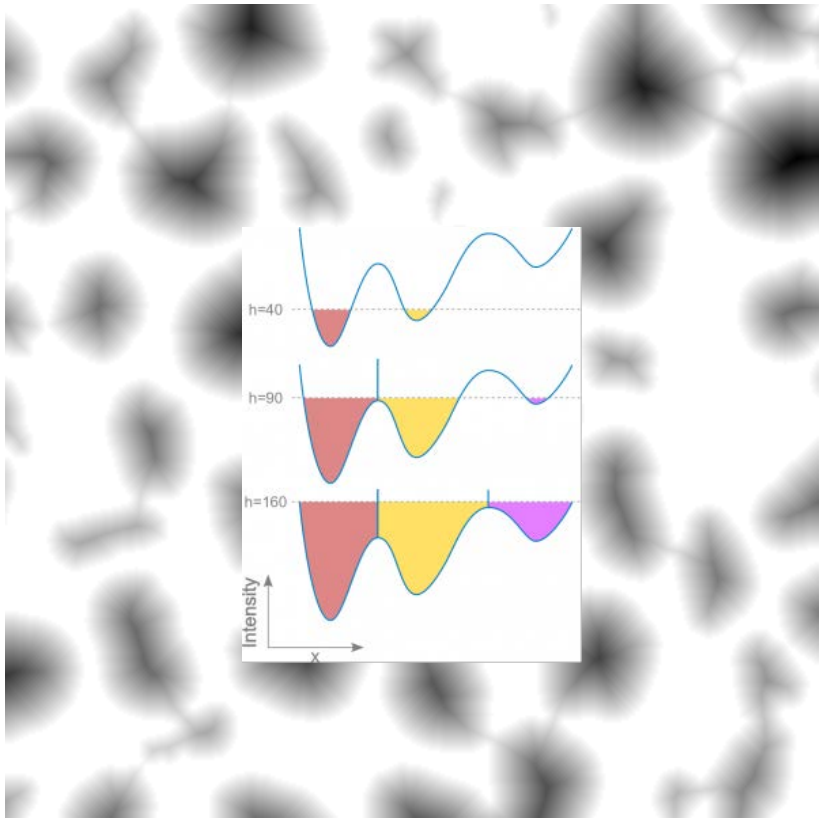
Distance Transform Watershed



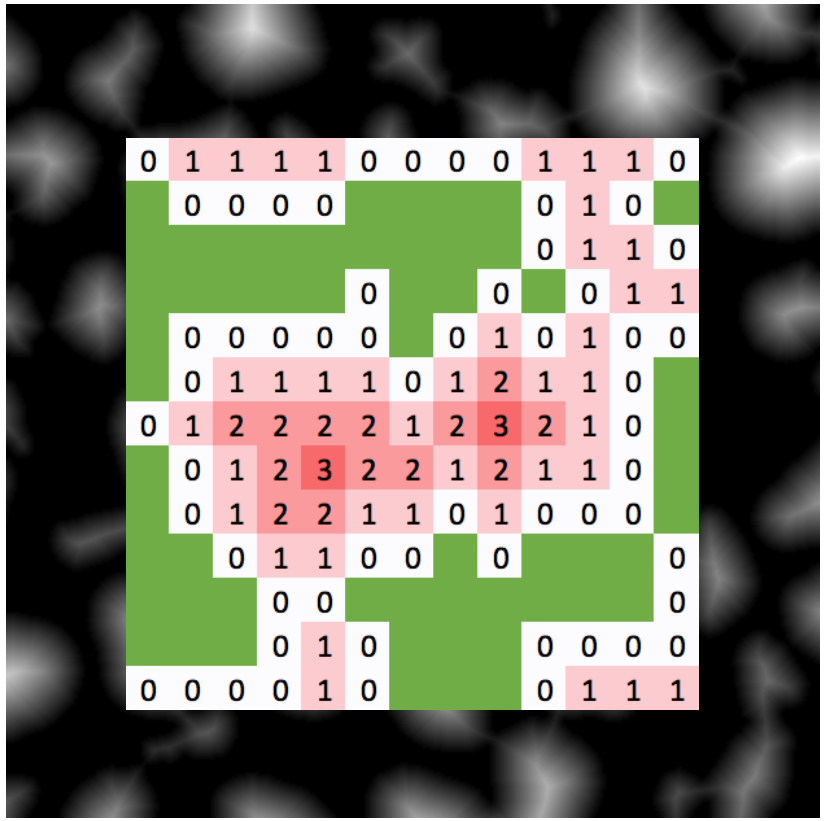
Distance map



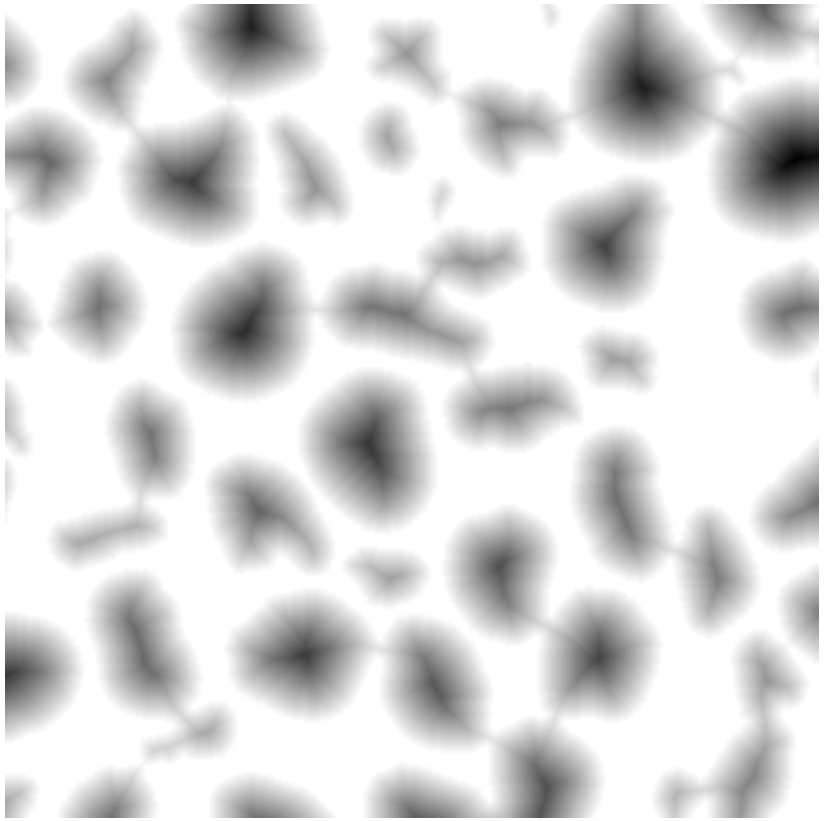
Distance Transform Watershed



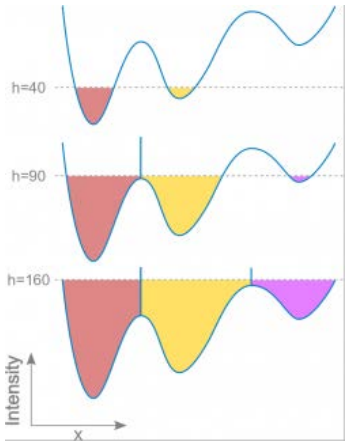
Inverse

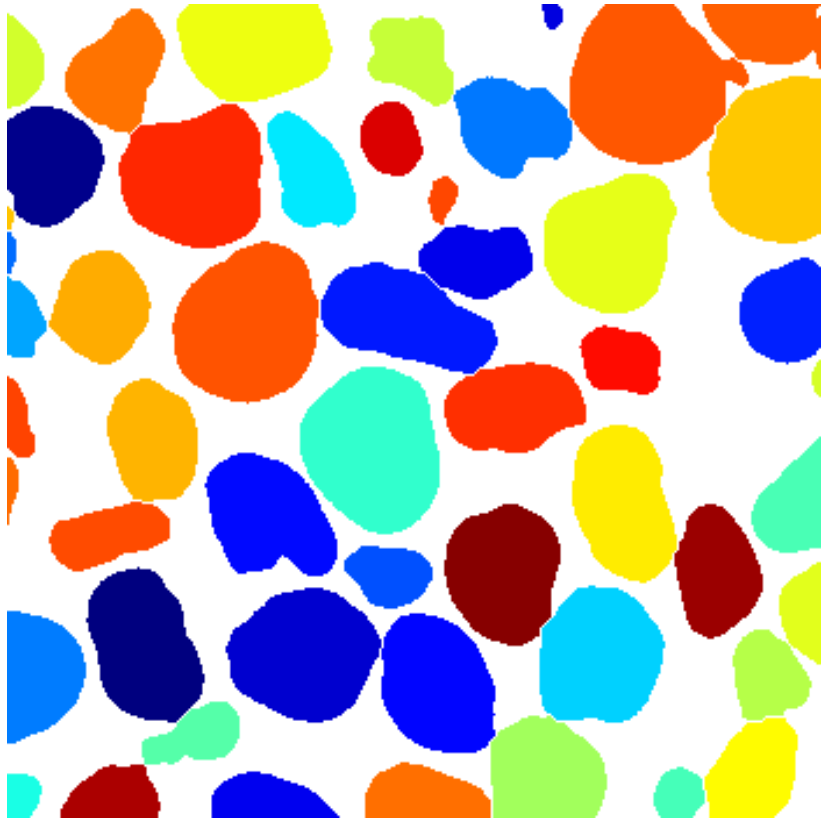


Distance Transform Watershed



Watershed



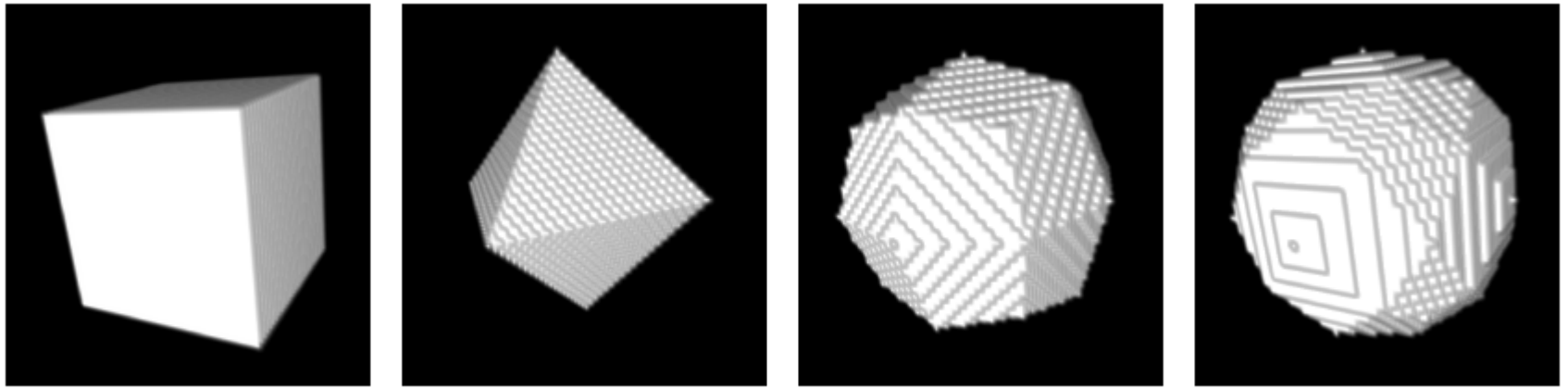


Distance Transform Watershed

Chamfer distances

(a) Chessboard (1,1) (b) City-block (1,2) (c) Borgefors (3,4) (d) Chess knight (5,7,11)

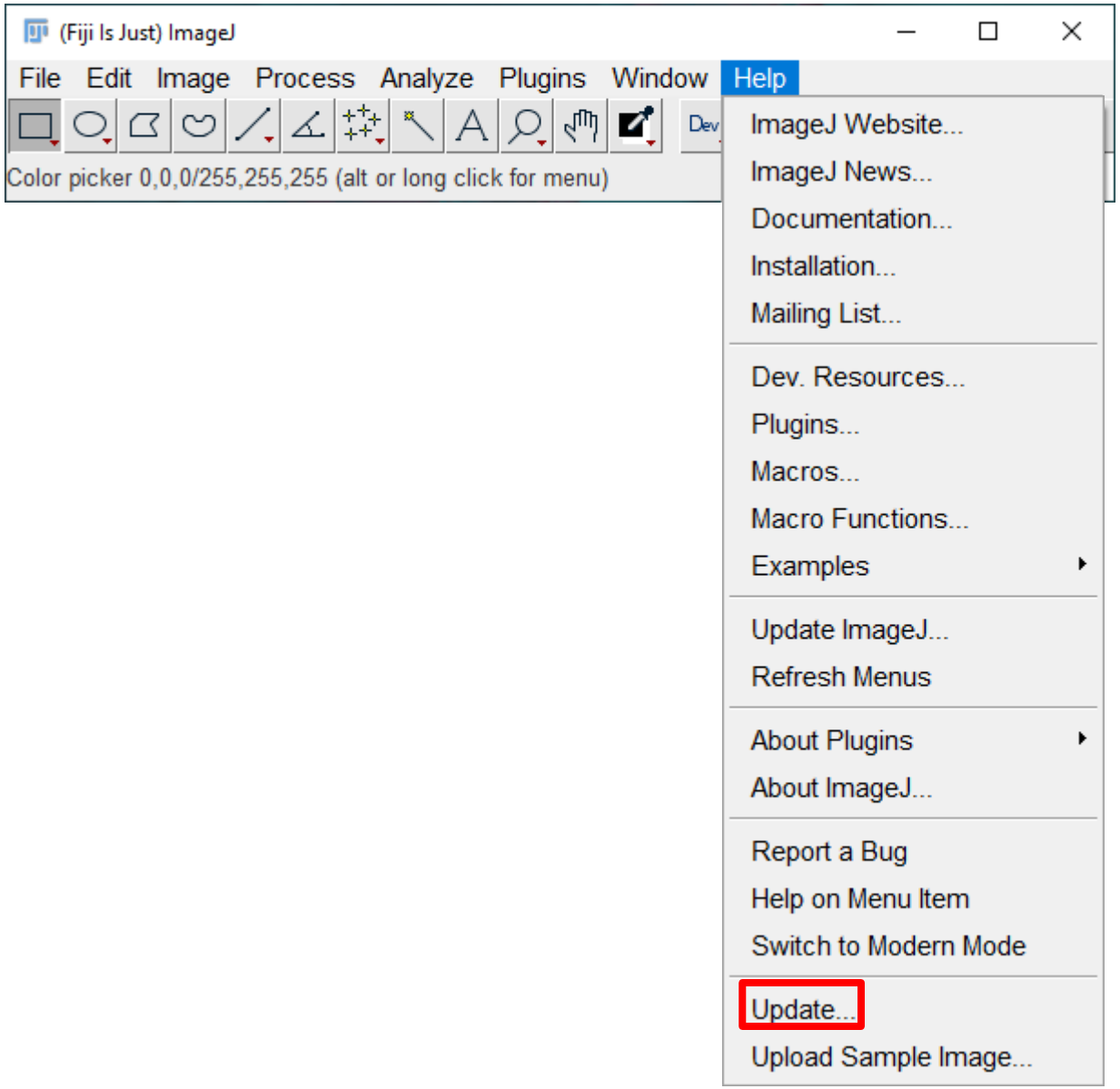
Chamfer distances for 3D images



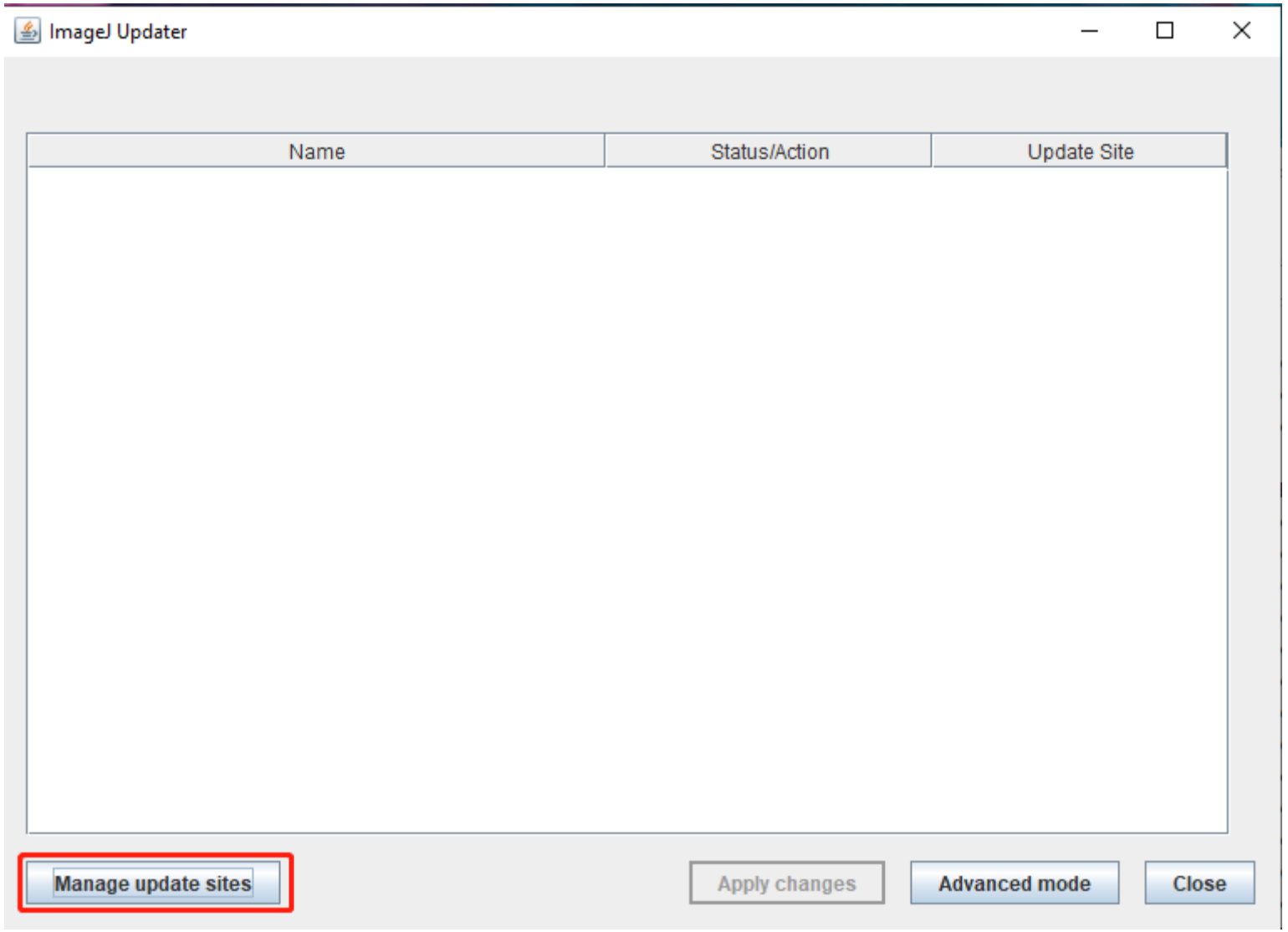
(a) Chessboard (1,1,1) (b) City-block (1,2,3) (c) Borgefors (3,4,5) (d) Svensson (3,4,5,7)

(Legland and Arganda-Carreras, 2017)

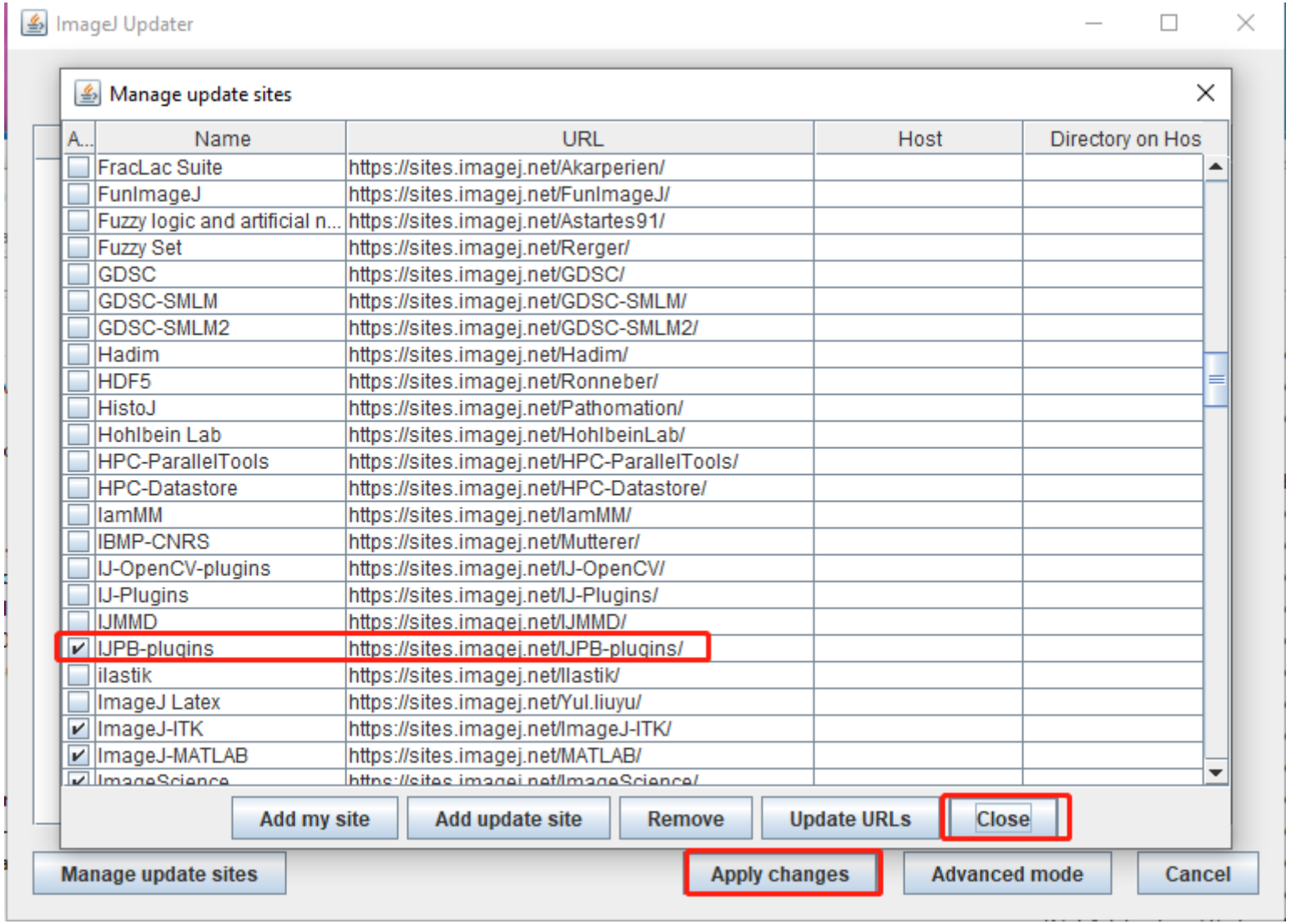
MorphoLibJ


(Fiji Is Just) ImageJ
File Edit Image Process Analyze Plugins Window Help
Color picker 0,0,0/255,255,255 (alt or long click for menu)
ImageJ Website...
ImageJ News...
Documentation...
Installation...
Mailing List...
Dev. Resources...
Plugins...
Macros...
Macro Functions...
Examples
Update ImageJ...
Refresh Menus
About Plugins
About ImageJ...
Report a Bug
Help on Menu Item
Switch to Modern Mode
Update...
Upload Sample Image...

MorphoLibJ


ImageJ Updater
Name
Status/Action
Update Site
Manage update sites
Apply changes
Advanced mode
Close

MorphoLibJ

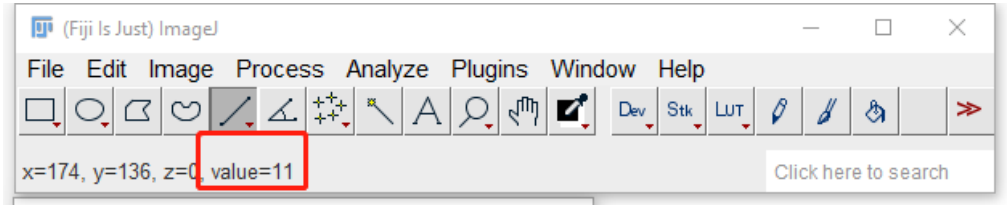


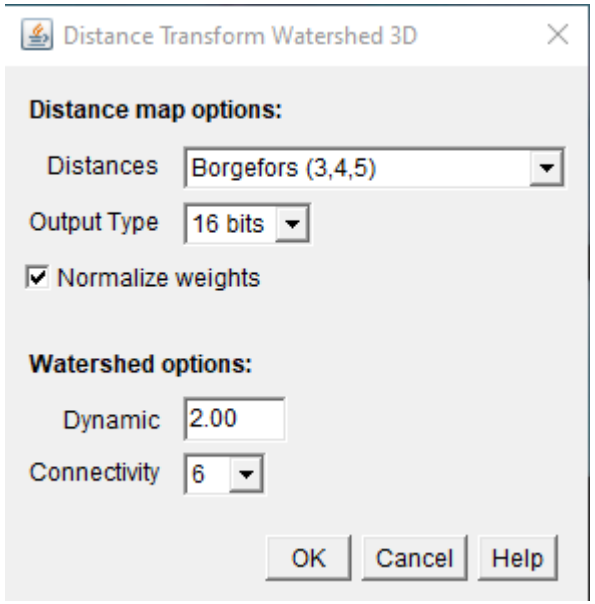
Restart Fiji

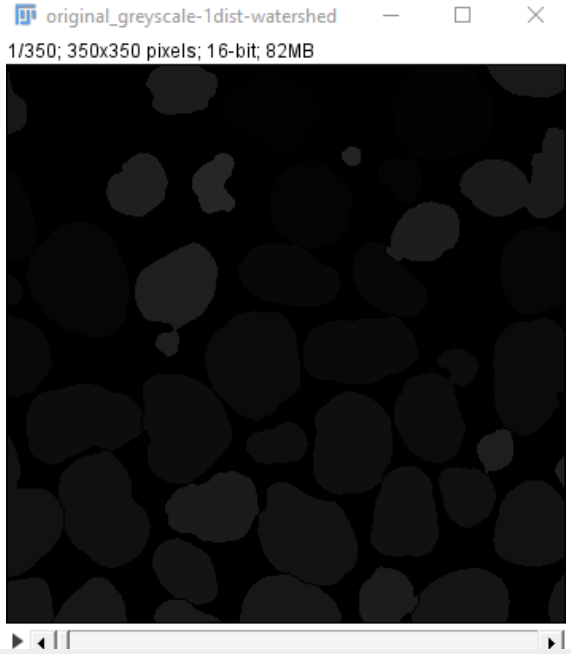
Distance Transform Watershed

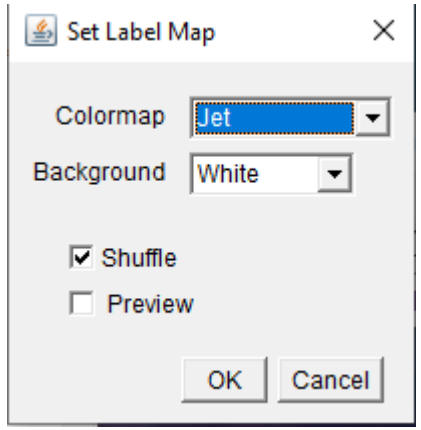
Plugins > MorphoLibJ > Binary Images > Distance Transform Watershed 3D

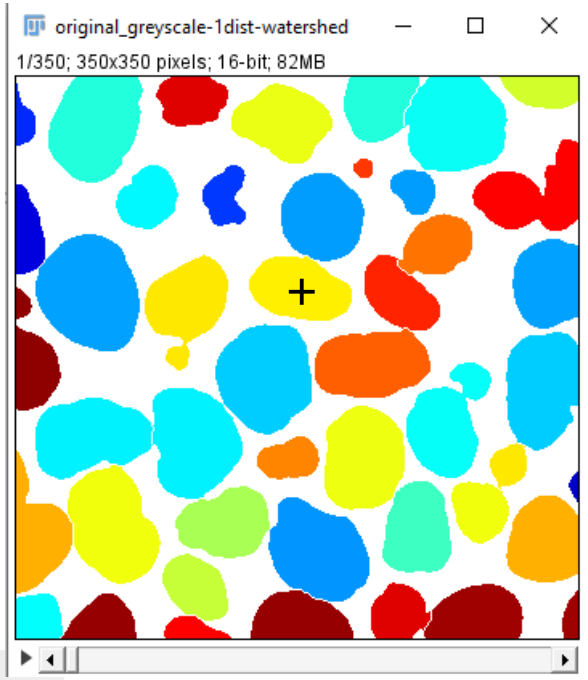
Plugins > MorphoLibJ > Label Images > Set Label Map

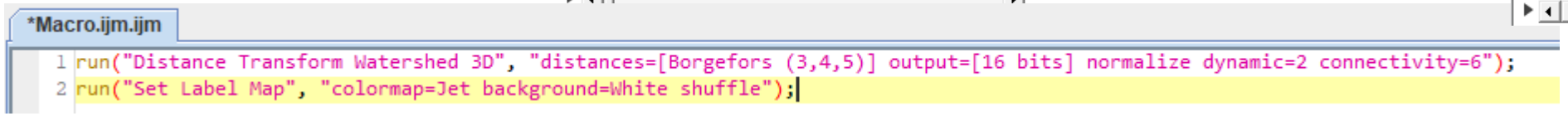






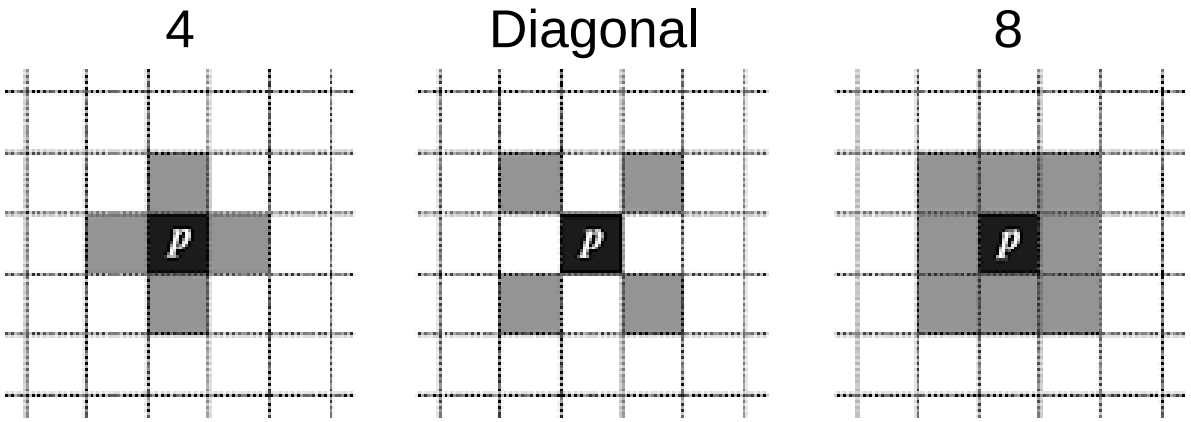






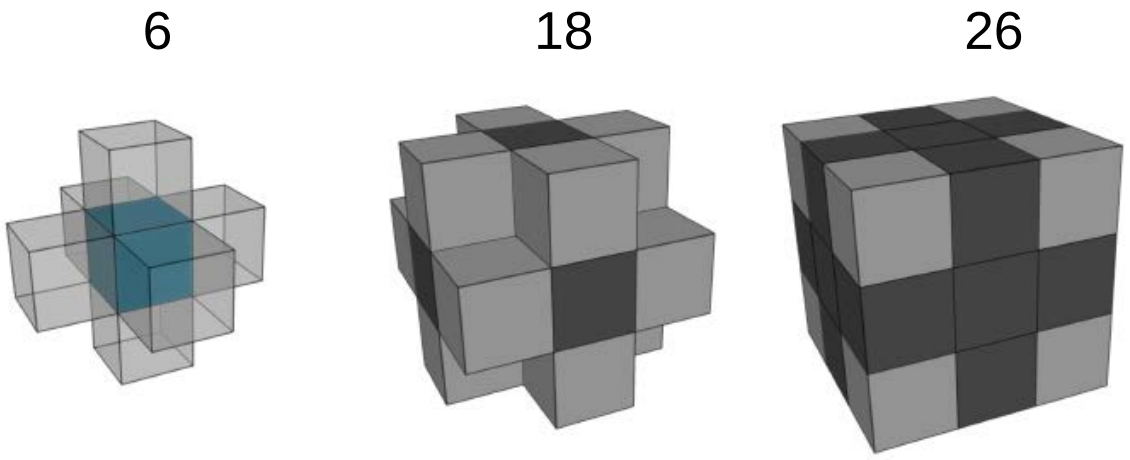
Connectivity/neighbourhood

2D



(Forensic Multimedia Analysis blog)

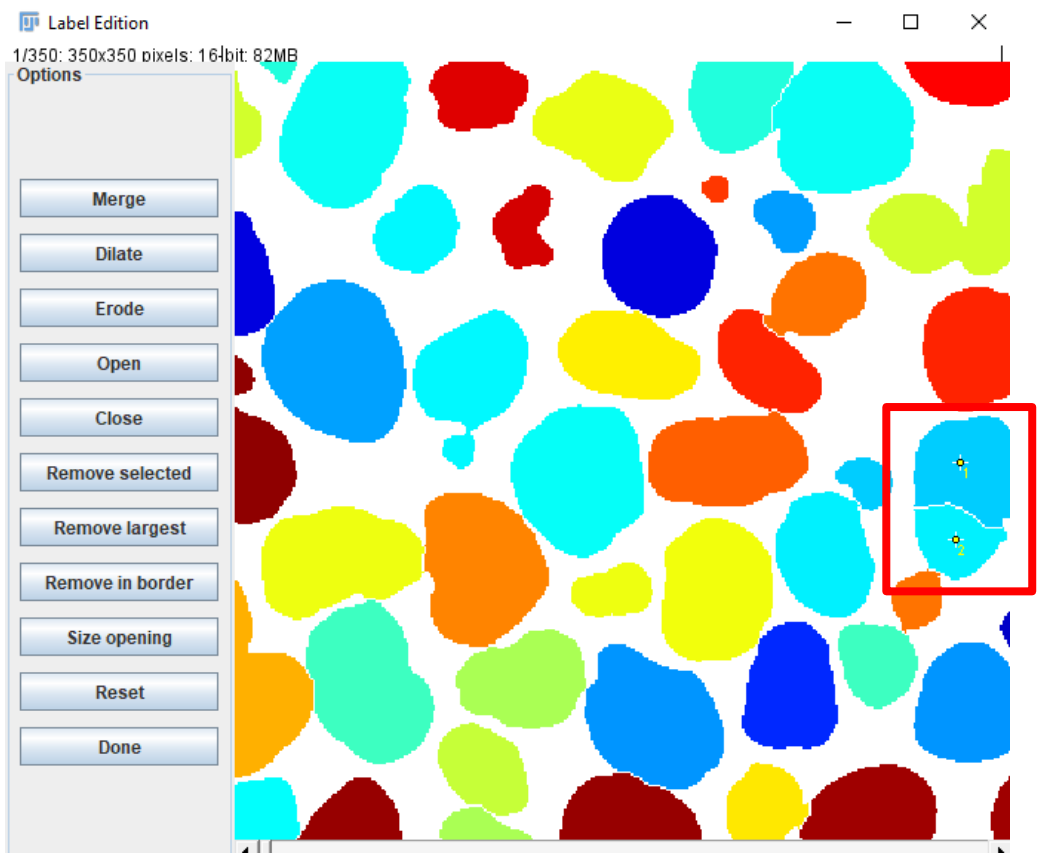
3D

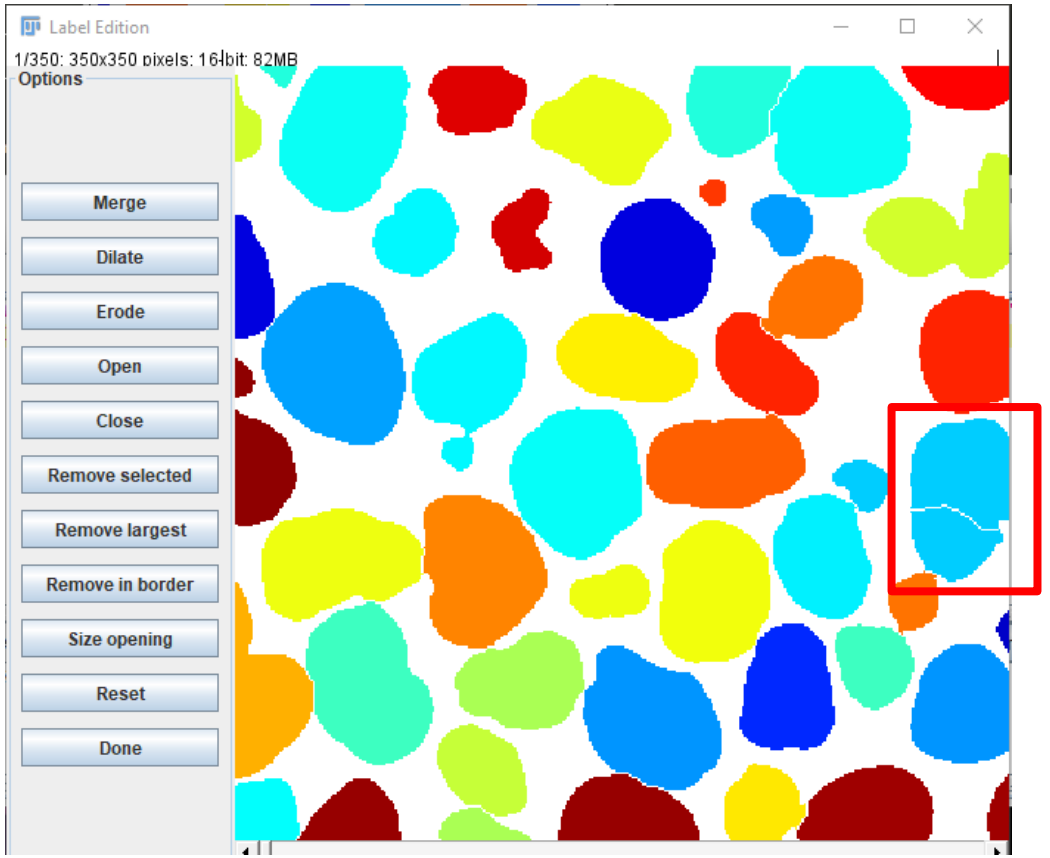


(Plougonven, 2009)

Distance Transform Watershed

Plugins > MorphoLibJ > Label Images > Label Edition





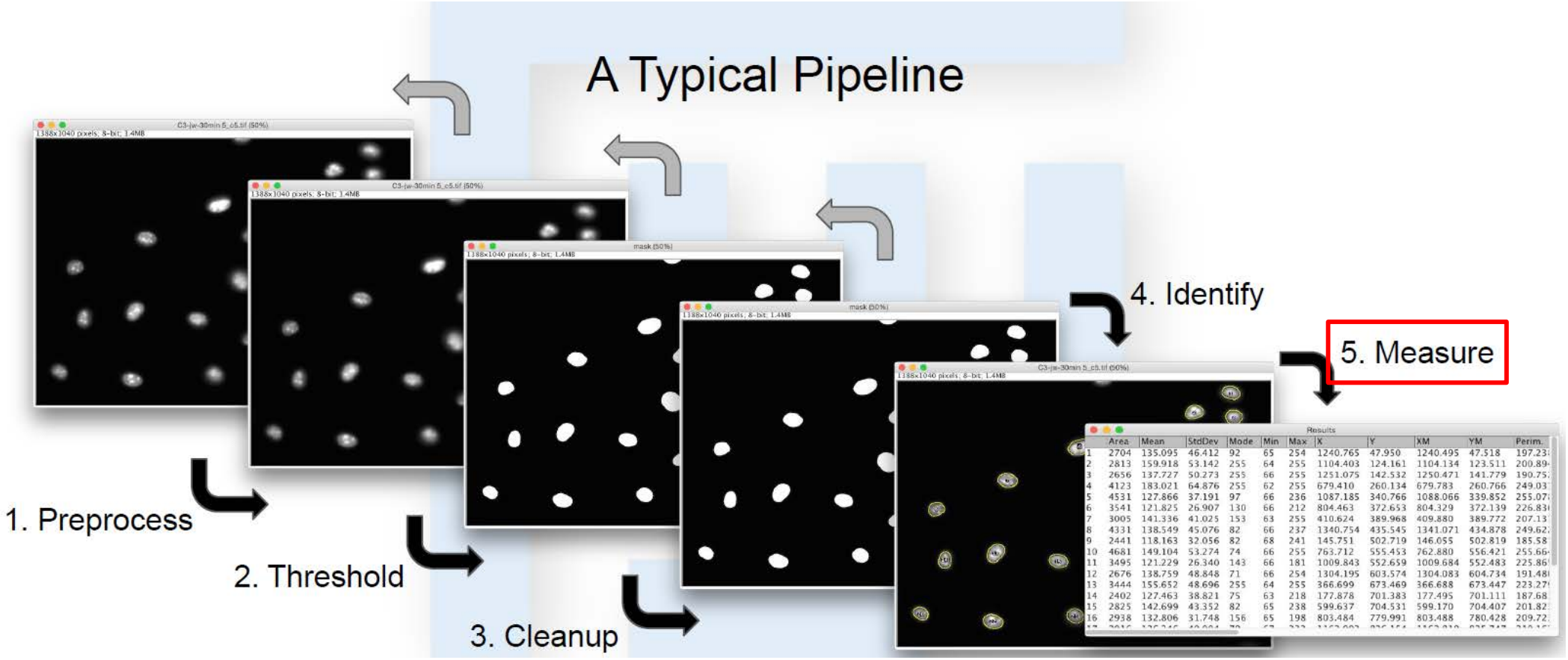
3D Rendering

Process > 3D Viewer

Plugin Name	Short Description	Highlights	Plugin Snapshot
3D Viewer	A tool for hardware-accelerated visualization possibilities for image stacks, using the Java 3D library.	• Stacks can be displayed as texture-based volume renderings, surfaces, or orthoslices • Macro-recordable functions • Adjust the transfer functions, edit volumes, point lists, landmark-based registration, transformations, 3D Content in PDFs	

(Visualization – ImageJ)

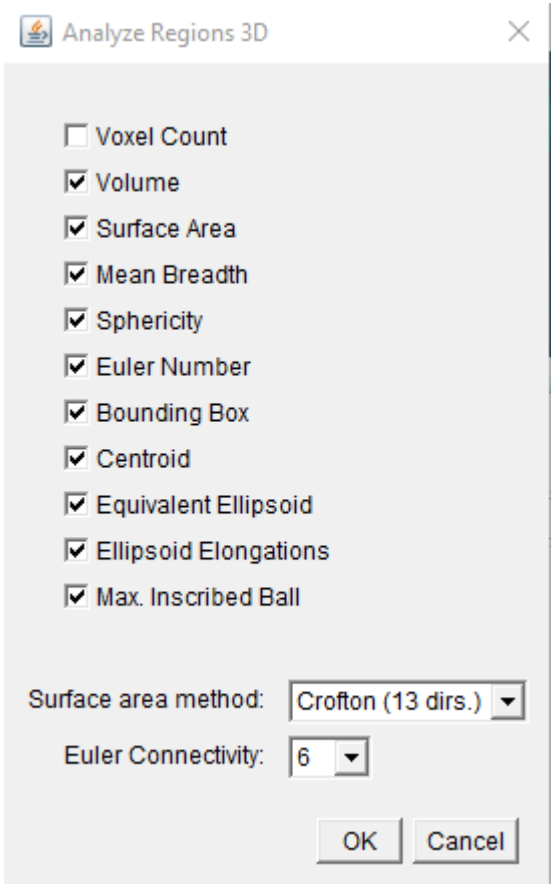
Image processing pipeline



(LOCI, 2021)

Measure

Plugins > MorphoLibJ > Analyze > Analyze Regions 3D



Shape	(φ,θ)	S	$S_{crofton^3}$	$S_{crofton^{13}}$	$S_{VTKmarch}$	S_{ITKiso}
ball	*n.a.*	11309.8	11312.0 (+0.0%)	11306.6 (−0.0%)	12298.2 (+8.7%)	12299.5 (+8.8%)
prolate	(0,0)	3082.9	2938.7 (−4.7%)	3084.6 (+0.1%)	3354.1 (+8.8%)	3354.9 (+8.8%)
-	(45,0)	–	3137.3 (+1.8%)	3086.3 (+0.1%)	3353.9 (+8.8%)	3354.7 (+8.8%)
-	(45,45)	–	3150.6 (+2.2%)	3083.3 (+0.0%)	3351.5 (+8.7%)	3352.2 (+8.7%)
oblate	(0,0)	6856.8	6290.7 (−8.3%)	6807.6 (−0.7%)	7410.2 (+8.1%)	7411.3 (+8.1%)
-	(45,0)	–	6872.0 (+0.2%)	6789.0 (−1.0%)	7369.7 (+7.5%)	7370.7 (+7.5%)
-	(45,45)	–	7154.7 (+4.3%)	6808.5 (−0.7%)	7385.9 (+7.7%)	7386.7 (+7.7%)
torus	(0,0)	11843.5	11417.3 (−3.6%)	11792.9 (−0.4%)	12826.6 (+8.3%)	12828.7 (+8.3%)
-	(45,0)	–	11809.3 (−0.3%)	11766.8 (−0.6%)	12787.4 (+8.0%)	12789.3 (+8.0%)
-	(45,45)	–	12086.0 (+1.9%)	11822.4 (−0.2%)	12849.1 (+8.5%)	12851.1 (+8.5%)

Table 1: Differences between actual surface area and its measures with different methods, on shapes with various orientations. The orientation is given by the direction of the shape rotation axis, defined by the azimut φ (between 0 and 360 degrees) and the colatitude θ (between 0 and 180 degrees).

(MorphoLibJ, imagej.net)

(Lehmann and Legland, 2012)

Measure

Plugins > MorphoLibJ > Analyze > Analyze Regions 3D

watershed_solid-morpho

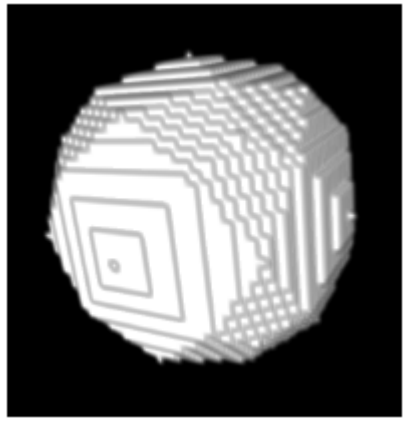
File Edit Font

Label	Volume	SurfaceArea	MeanBreadth	Sphericity	EulerNumber	Box.X.Min	Box.X.Max	Box.Y.Min	Box.Y.Max	Box.Z.Min	Box.Z.Max	Centroid.X	Centroid.Y	Centroid.Z	Elli.Center.X	Elli.Center.Y	Elli.Center.Z
1	14670	3913.824	39.284	0.406	1	204	251	0	41	0	16	227.068	15.554	5.822	227.068	15.554	5.822
2	47184	8189.105	53.617	0.458													
3	34333	6456.097	49.789	0.495													
4	121880	13624.422	80.988	0.664													
5	1469	1194.889	22.304	0.143													
6	21366	5231.492	43.800	0.361													
7	7470	2762.852	35.483	0.299													
8	50448	8901.054	57.658	0.408													
9	7256	3117.750	36.927	0.196													
10	35127	6134.366	46.858	0.605													
11	86573	10977.533	62.631	0.641													
12	364	346.774	12.419	0.359													
13	14117	3602.410	37.873	0.482													
14	24588	6408.712	51.930	0.260													
15	52376	8221.709	54.716	0.558													
16	90011	11144.197	62.280	0.662													
17	63710	9436.704	72.715	0.546													
18	66114	9704.502	60.142	0.541													
19	36158	7175.644	53.328	0.400													

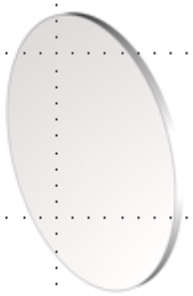
watershed_solid-morpho

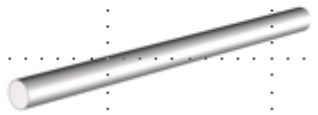
File Edit Font

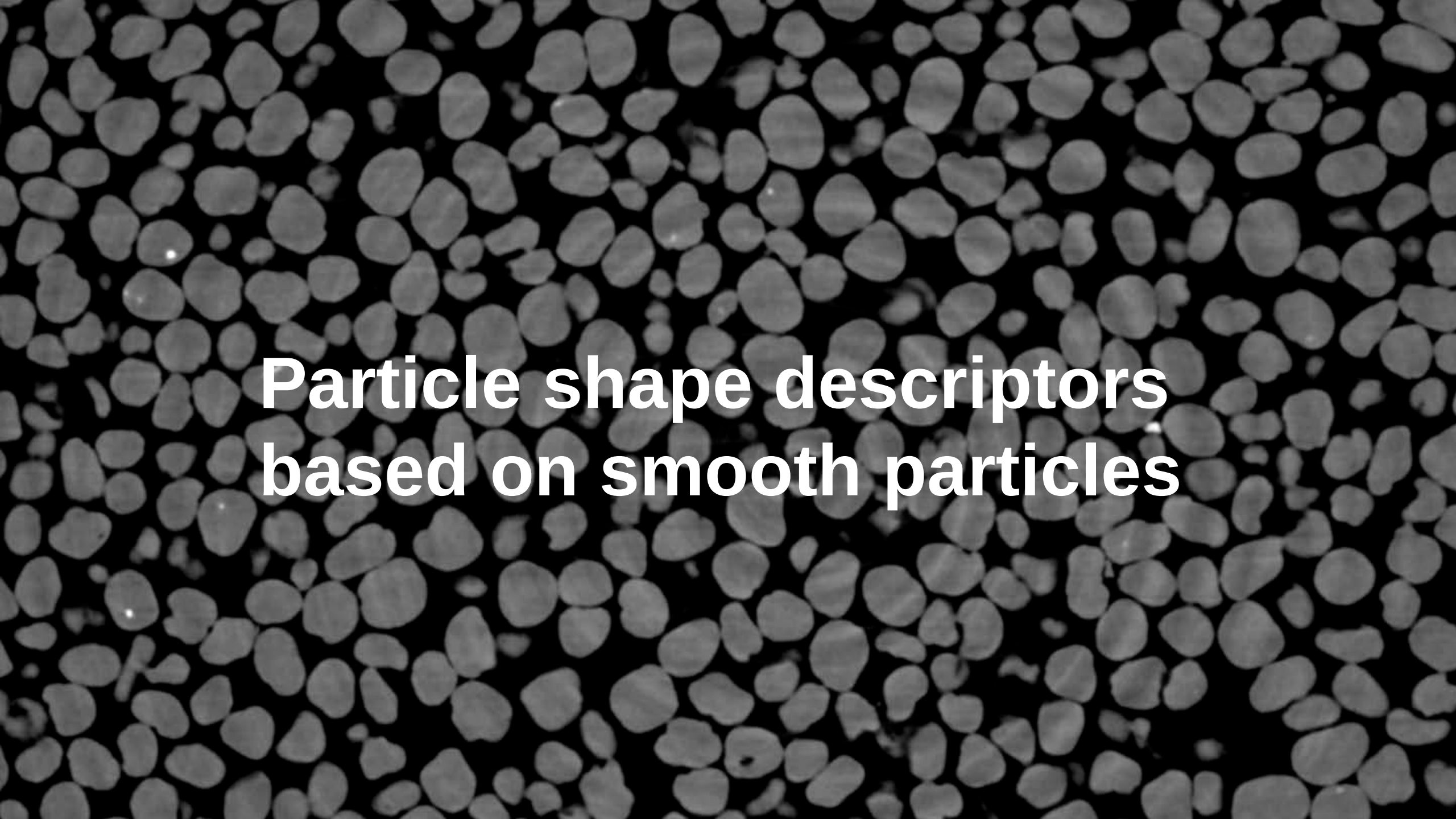
Z	Elli.R1	Elli.R2	Elli.R3	Elli.Azim	Elli.Elev	Elli.Roll	Elli.R1/R2	Elli.R1/R3	Elli.R2/R3	InscrBall.Center.X	InscrBall.Center.Y	InscrBall.Center.Z	InscrBall.Radius
	24.323	20.049	8.310	-37.247	-4.878	178.108	1.213	2.927	2.413	232	0	0	15.333
	36.091	26.252	13.556	-64.047	-0.369	177.167	1.375	2.662	1.936	42	34	0	21.667
	30.842	24.014	12.768	10.154	-5.082	-11.832	1.284	2.415	1.881	168	24	0	18.333
	37.128	36.141	22.828	-116.035	7.050	0.442	1.027	1.626	1.583	273	30	5	30.667
	15.129					-0.345	1.270	6.512	5.128	243	67	0	4.667
	26.475					2.042	1.103	2.839	2.574	187	84	0	17.667
	28.261					49.325	2.525	3.849	1.524	0	107	0	14.333
	36.566					2.168	1.161						
	27.883					-0.481	1.835						
	29.413					-170.832	1.287						
	42.043					-68.643	1.588						
	9.413					7.369	1.813						
	27.232					17.961	1.849						
	36.050					179.818	1.507						
	36.997					156.464	1.610						
	39.454					-2.372	1.236	2.179	1.764	155	187	0	29.000
	38.326					-3.929	1.635	2.049	1.254	263	219	3	21.667
	36.728	28.871	17.203	61.025	7.697	-10.380	1.272	2.135	1.678	109	221	0	24.333
	38.956	21.763	11.907	-12.234	1.361	-174.342	1.790	3.272	1.828	32	229	0	18.333



$$Sphericity = \frac{36\pi V^2}{SA^3}$$



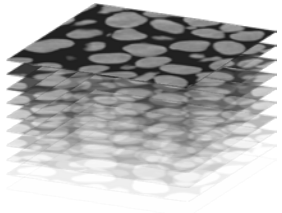



Particle shape descriptors
based on smooth particles

Pore/particle scale modeling platform

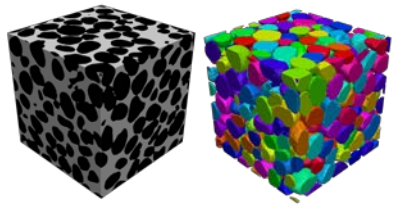
Data

Real materials images



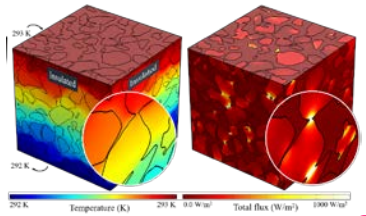
1

Particle/Pore geometry and morphology



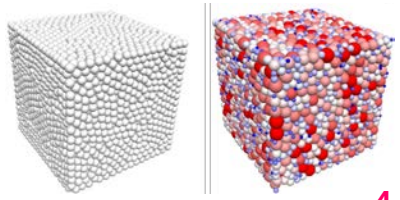
2

Finite element modelling



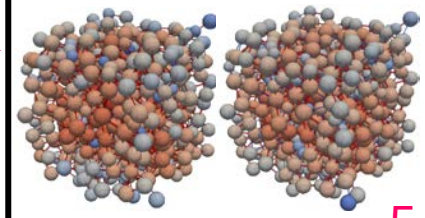
3

Discrete element modelling



4

Complex networks



5

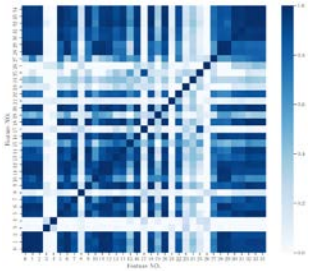
Feature set

Input variables
Feature 1
Feature 2
…
Output variables
ETC

6

Machine learning

Feature importance



8

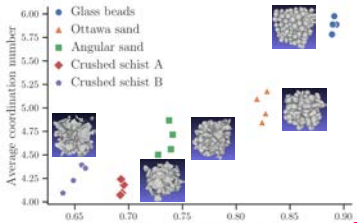
Model selection

$y = a \cdot x + b$
$y = a \cdot x^2 + b \cdot x + c$
$y = a \cdot x^3 + b \cdot x^2 + c \cdot x + d$
$y = a \cdot e^x$
$y = a \cdot ln(x) + b$
$y = a \cdot x^b$
Random forest regression
Artificial neural network

7

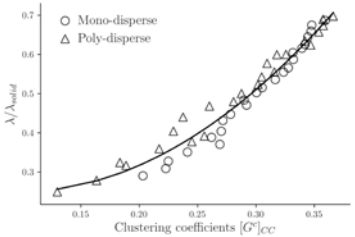
Output

Unveiling patterns



10

Predictions

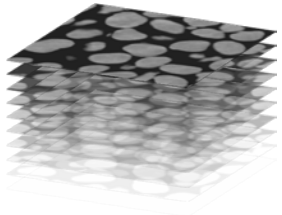


9

Toolbox

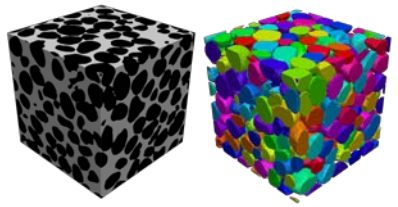
Data

Real materials images



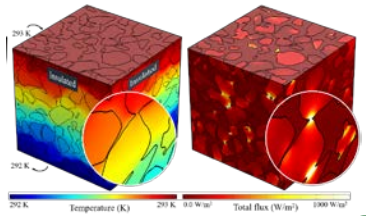
1

Particle/Pore geometry and morphology



2

Finite element modelling



3

Discrete element modelling

4

Complex networks

5

Feature set

Input variables
Feature 1
Feature 2
…
Output variables
ETC

6

Machine learning

Feature importance

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$y = a \cdot e^x$
$y = a \cdot ln(x) + b$
$y = a \cdot x^b$
Random forest regression

7

Output

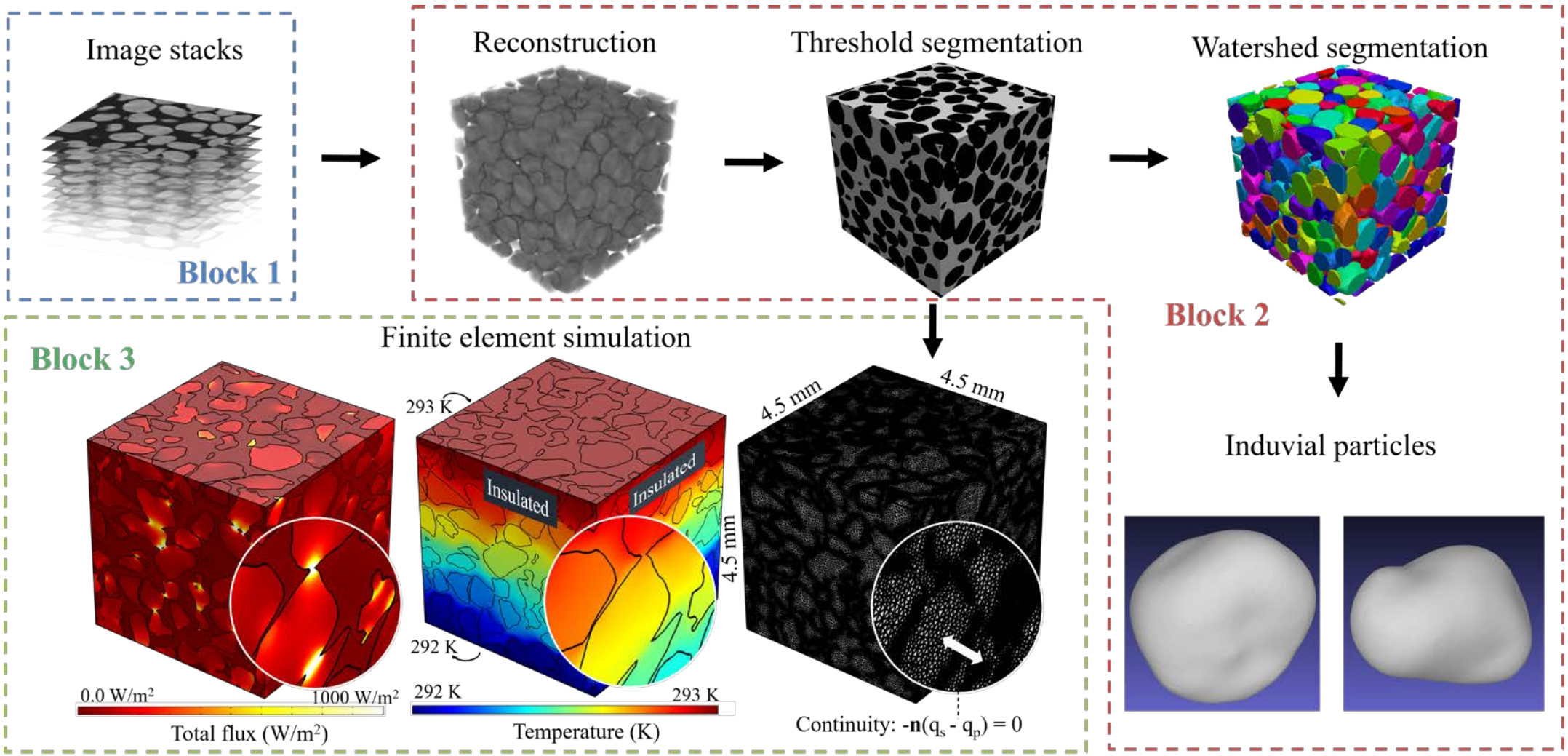
Unveiling patterns

10

Predictions

9

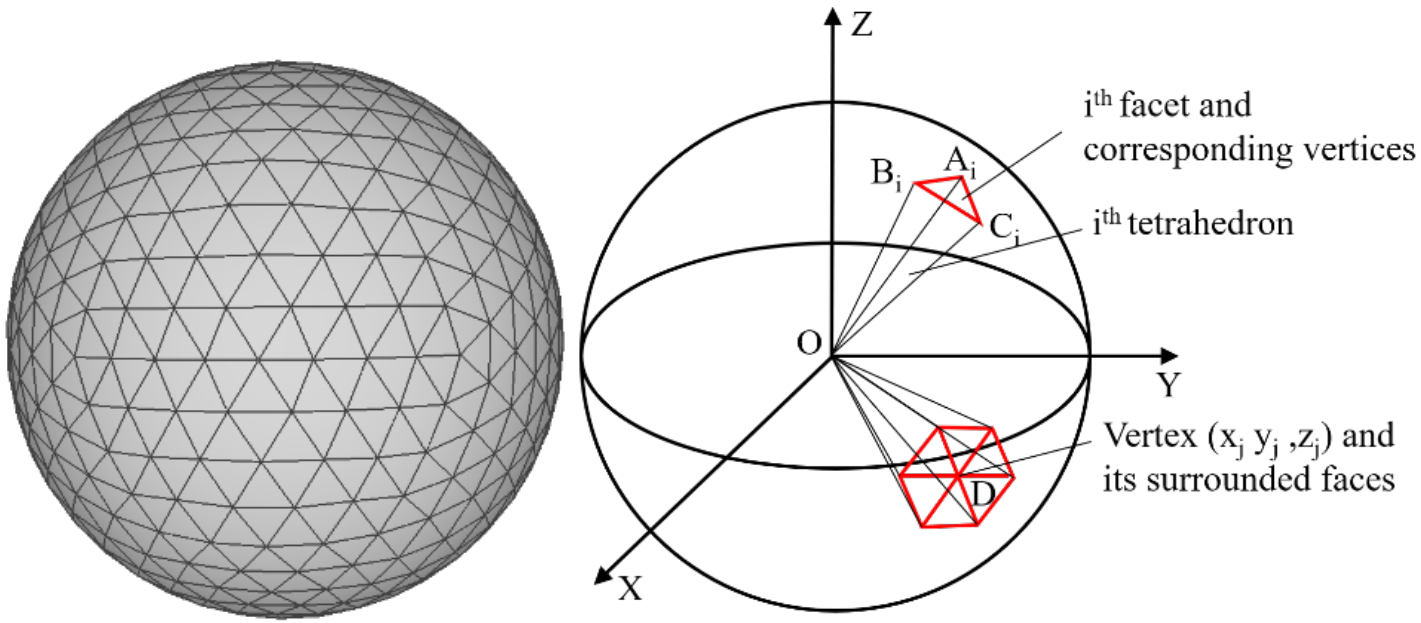
Particle shape *vs* thermal conductivity

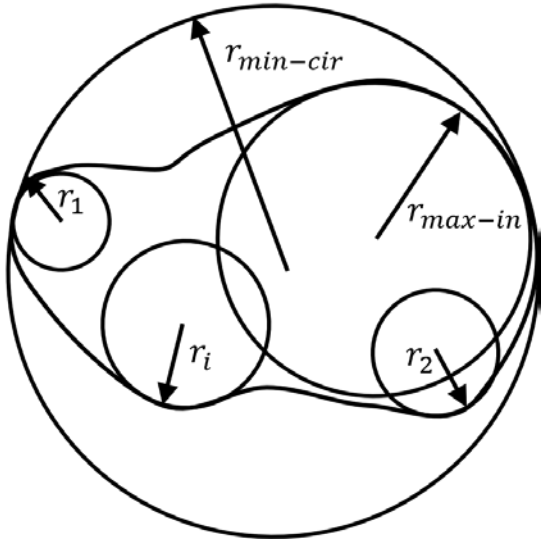


Particle shape

$$Sphericity = \frac{36\pi V^2}{SA^3}$$

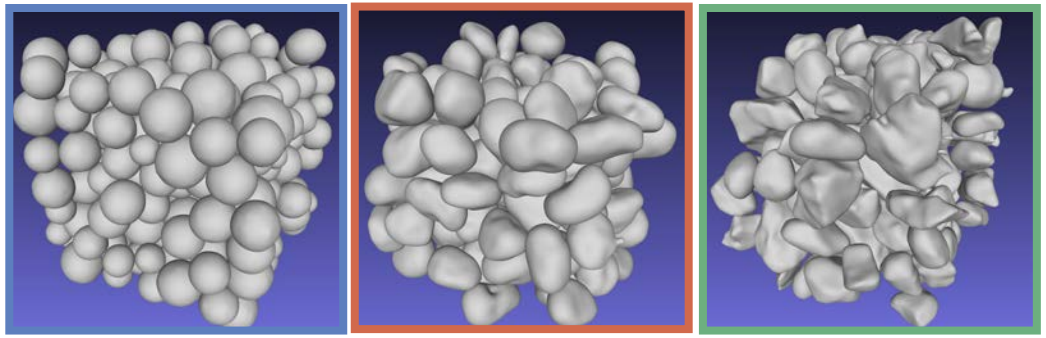
$$Roundness = \frac{\sum r_i / N}{r_{max-in}}$$



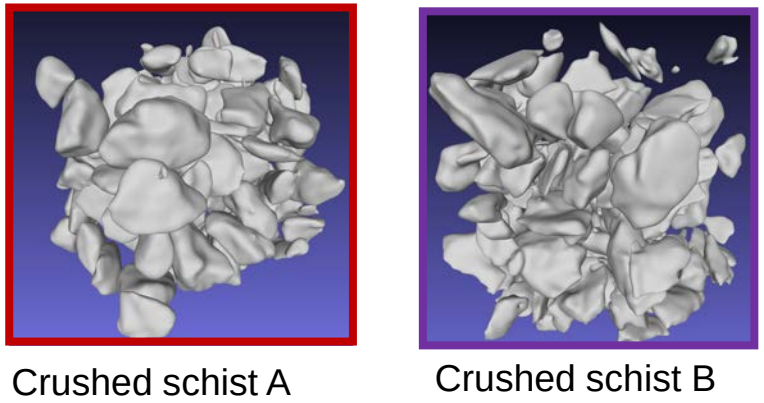


(Zhou et al, 2017)

Particle shape

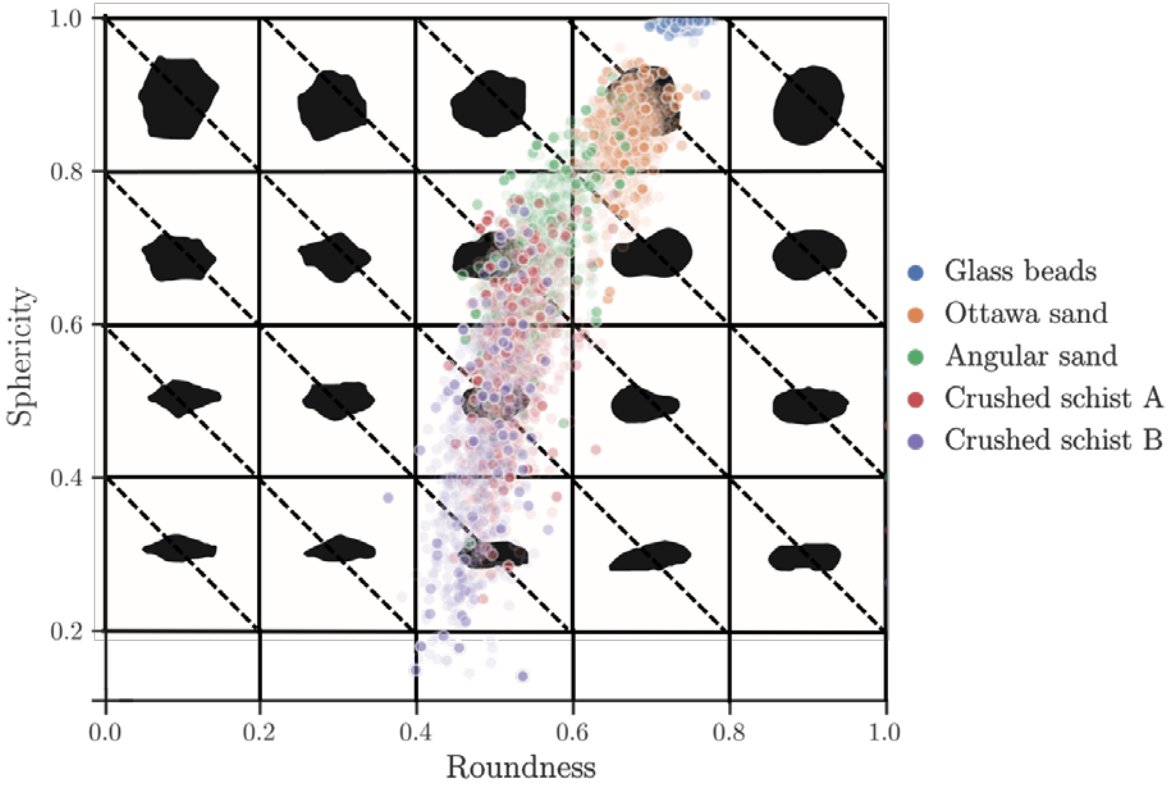


Glass beads Ottawa sand Angular sand



Crushed schist A Crushed schist B

1 click



Fei W, Narsilio GA, Disfani MM. Impact of three-dimensional sphericity and roundness on heat transfer in granular materials. Powder Technology 2019, 355:770-781.

Fei W, Narsilio GA, van der Linden JH, Tordesillas A, Disfani MM, Santamarina JC. Impact of particle shape on networks in sands. Computers and Geotechnics 2021, 137, 104258.

Python libraries

PIL (Pillow)

matplotlib

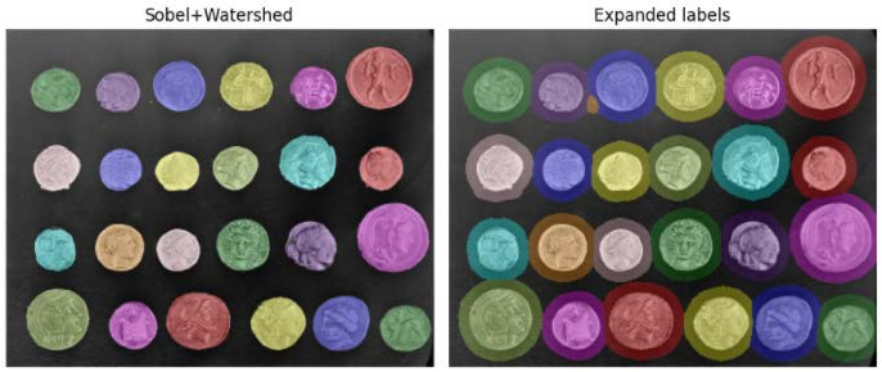
SciPy

Scikit-image

OpenCV

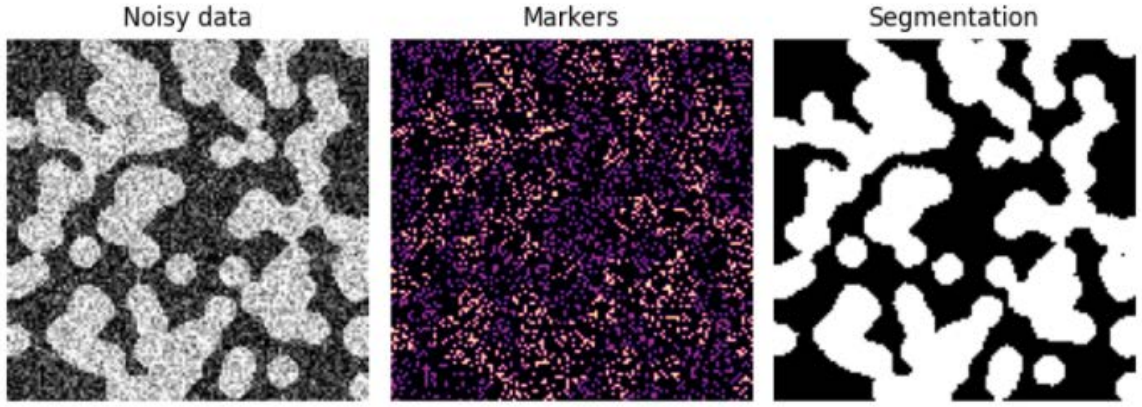
TensorFlow/Keras

Expand segmentation labels without overlap



Unet

Random walker segmentation



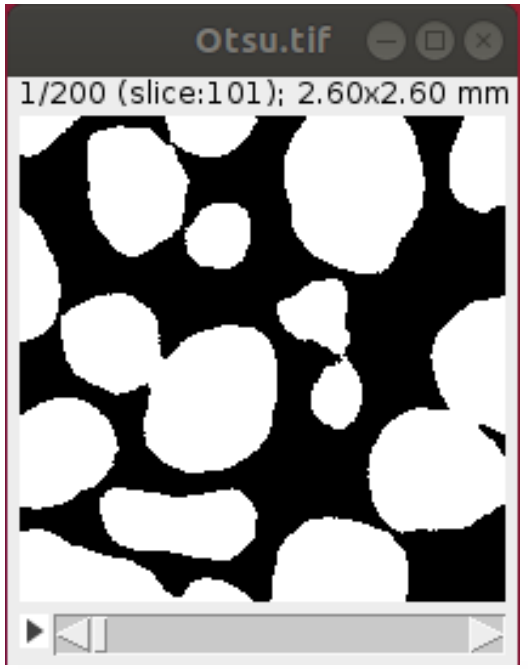
Hands-on Tutorial #3

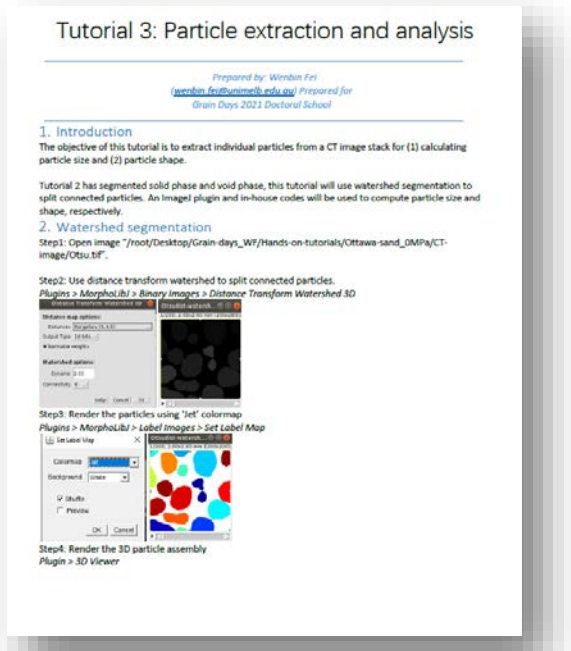
Hands-on Tutorial #3

15 minutes

Objectives:

- Watershed segmentation
- Particle extraction
- Particle analysis: calculate particle size and shape




Tutorial 3: Particle extraction and analysis

1. Introduction

The objective of this tutorial is to extract individual particles from a CT image stack for (1) calculating particle size and (2) particle shape.

Tutorial 2 has segmented solid phase and void phase, this tutorial will use watershed segmentation to split connected particles. An ImageJ plugin and in-house codes will be used to compute particle size and shape, respectively.

2. Watershed segmentation

Step1: Open image "/root/Desktop/Grain-days_WF/Hands-on-tutorials/Ottawa-sand_0MPa/CT-image/Otsu.tif".

Step2: Use distance transform watershed to split connected particles.

Plugins > MorphoLibJ > Binary Images > Distance Transform Watershed 3D

Step3: Render the particles using "Jet" colormap

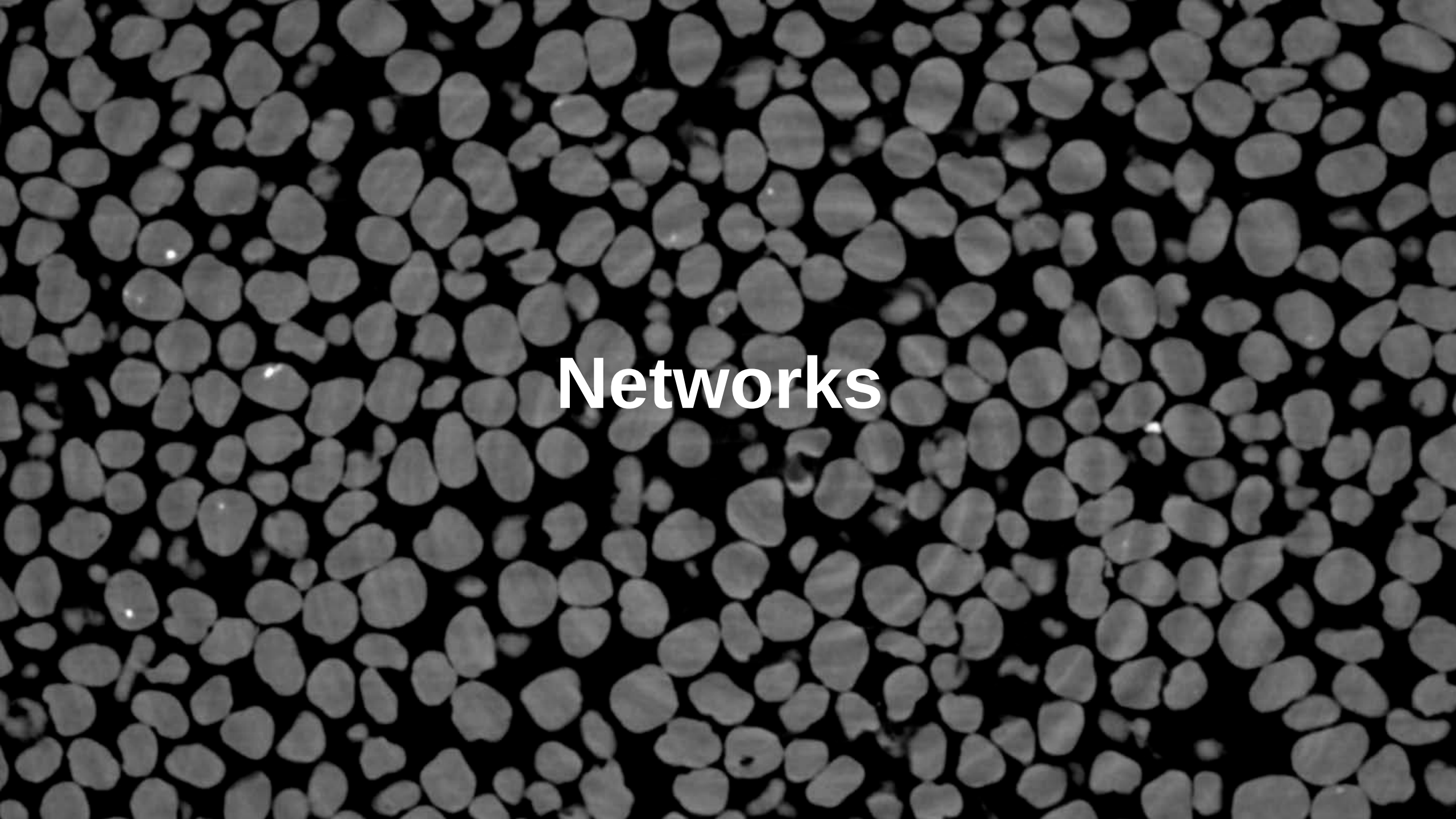
Plugins > MorphoLibJ > Label Images > Set Label Map

Step4: Render the 3D particle assembly

Plugin > 3D Viewer

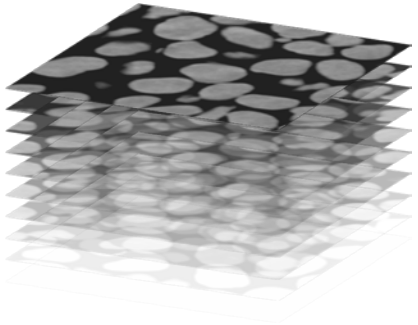
Download tutorial using the following link:

Link: *https://cloudstor.aarnet.edu.au/plus/s/YRnAMis6vR2ZKmo*
Password: **GrainDays_123456**

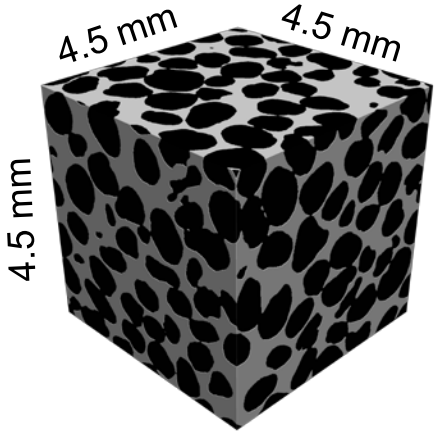

Networks

Network construction

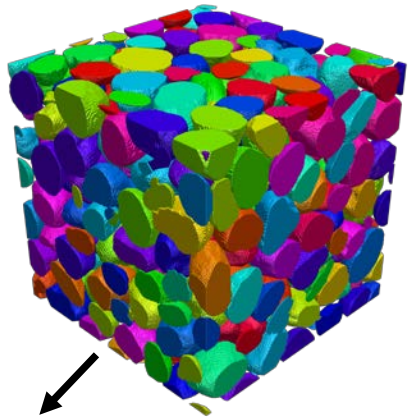
1. Image stacks



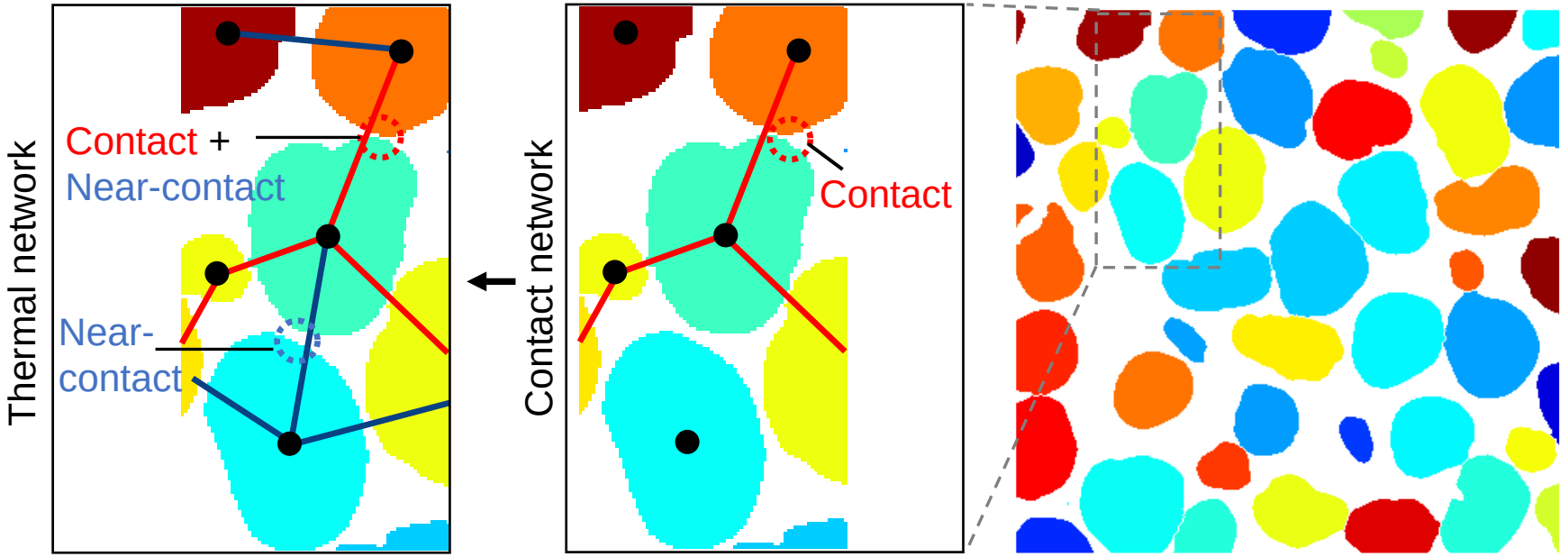
2. Reconstruction



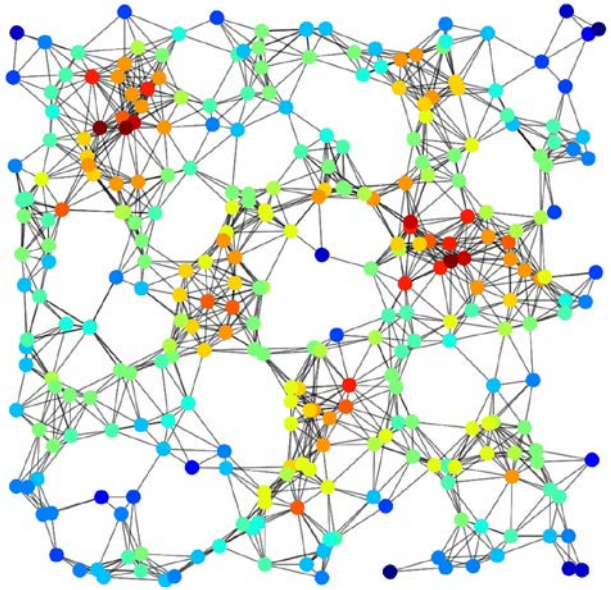
3. Watershed segmentation



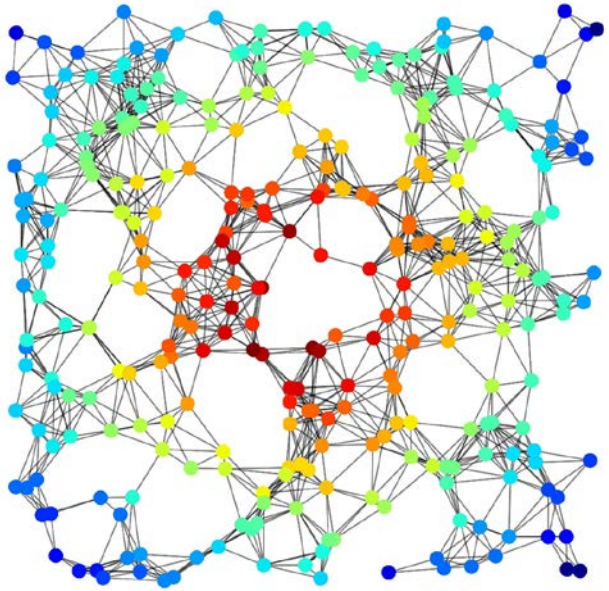
4. Network construction



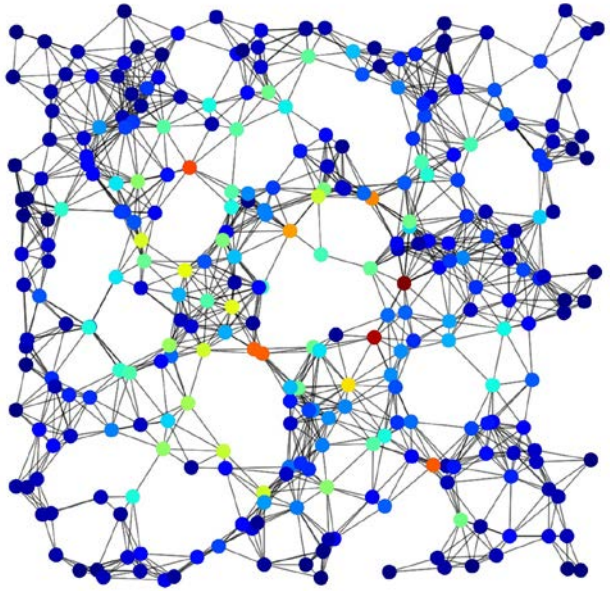
Network features



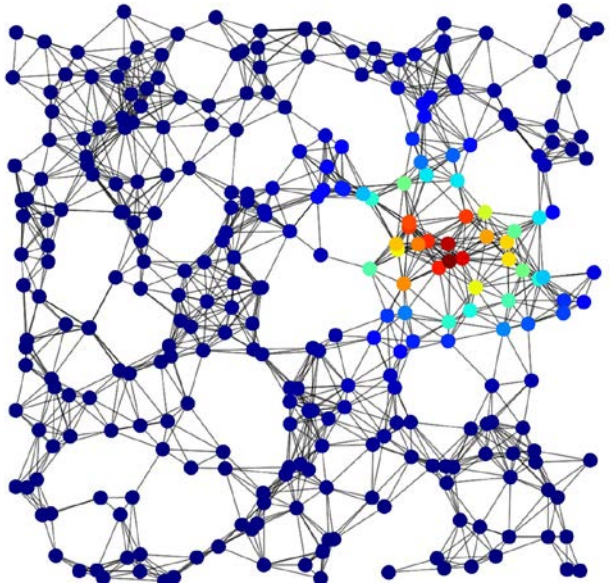
Degree



Closeness centrality



Betweenness centrality



Eigenvector centrality

Network features vs thermal conductivity

Computers and Geotechnics 127 (2020) 103773

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Network analysis of heat transfer in sands

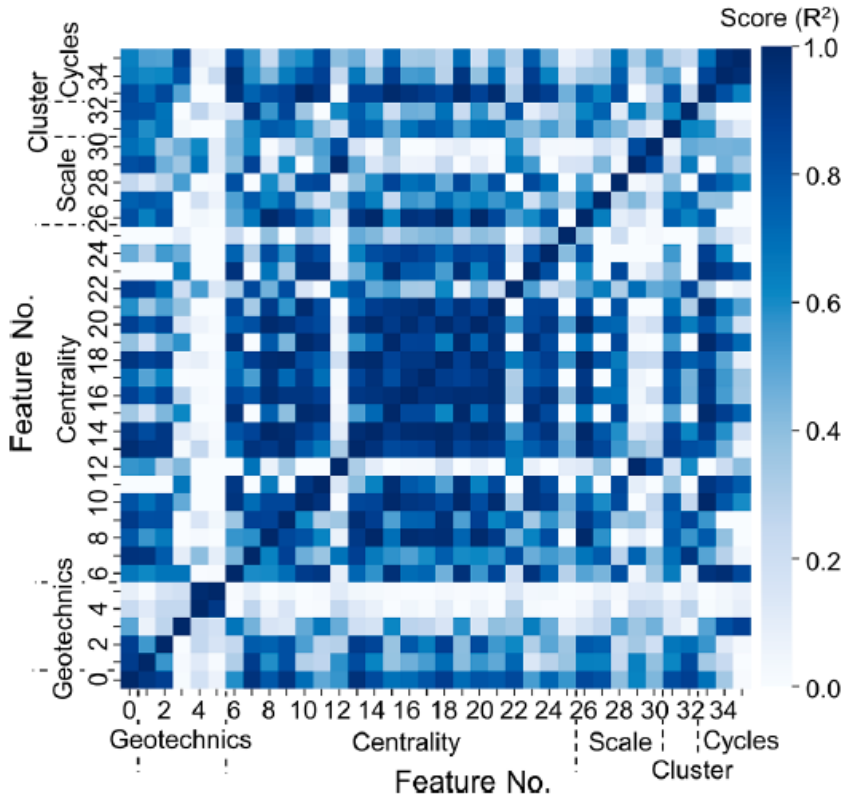
Wenbin Fei, Guillermo A. Narsilio*

Department of Infrastructure Engineering, The University of Melbourne, Parkville, Australia

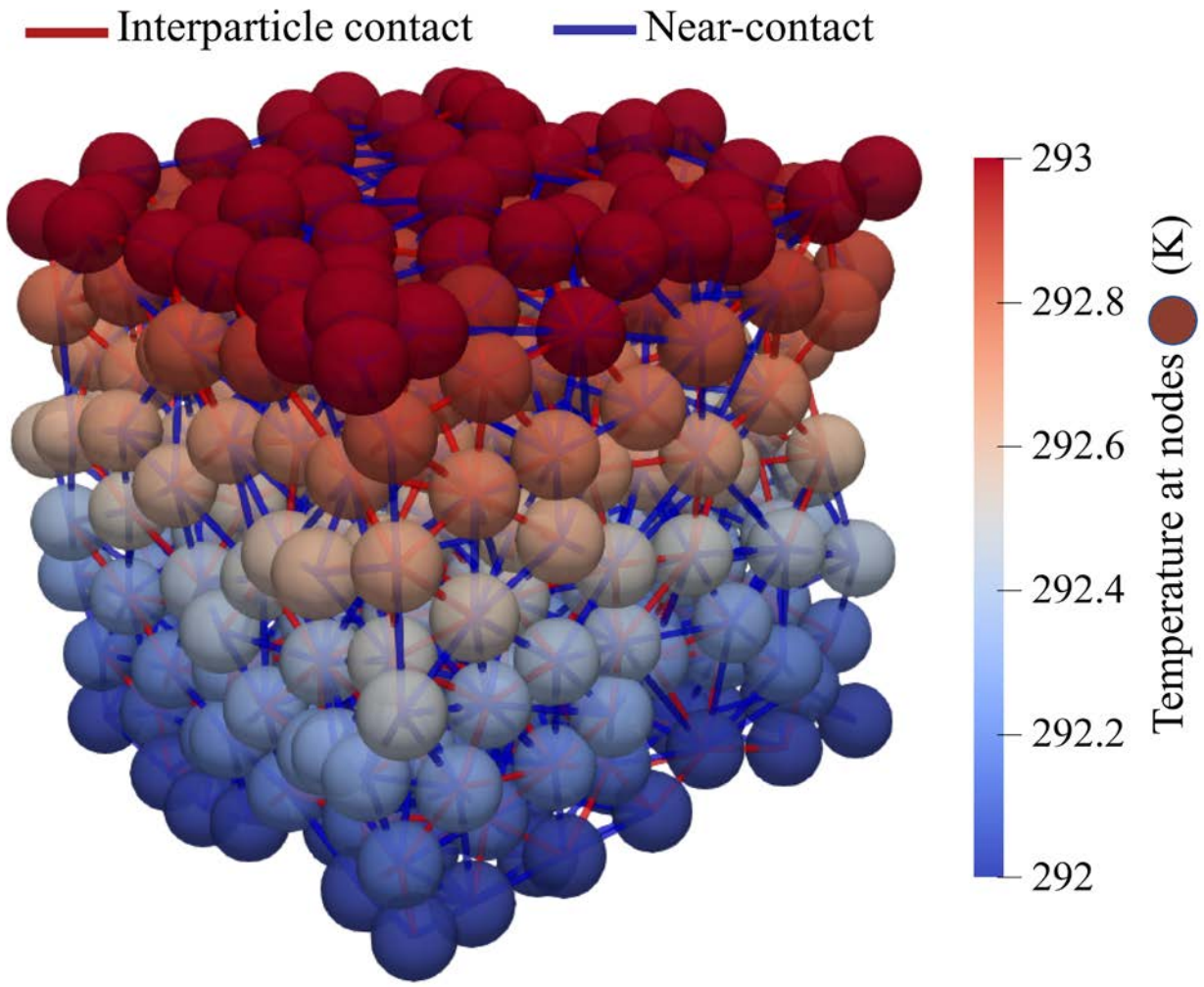
Summary of features used in this work.

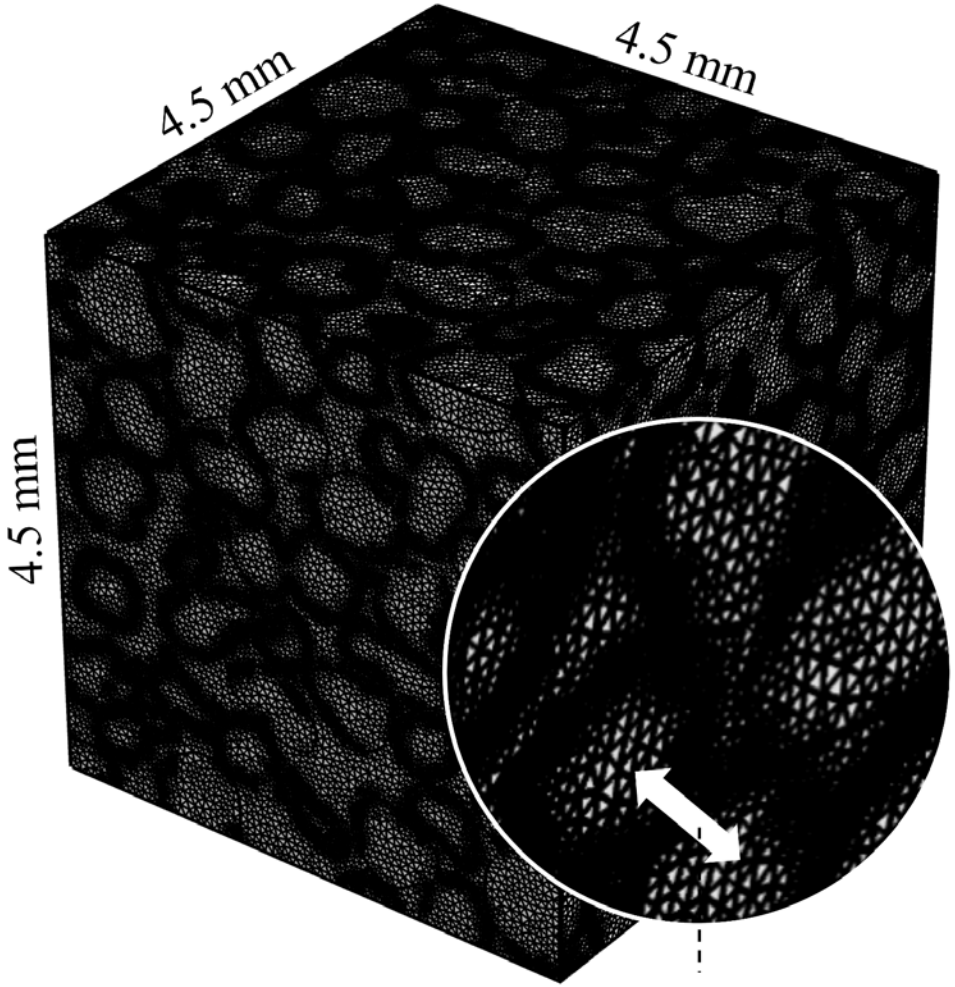
Type	No.	Notation	Attribute
Geotechnics	1	n	Porosity
	2	γ	Contact radius ratio
	3	D_{50}	Average particle diameter
	4	C_u	Coefficient of uniformity
	5	C_c	Coefficient of curvature
Centrality	6	$[G^*]_k$	Degree ('coordination number' in a contact network)
	7	$[G^*]_{kw}$	Weighted degree
	8	$[G^*]_C$	Closeness centrality
	9	$[G^*]_{C_{n1}}$	Closeness centrality normalised by$\|V\| - 1$
	10	$[G^*]_{C_{n2}}$	Closeness centrality normalised by$[\|V\|(\|V\| - 1)]/2$
	11	$[G^*]_{C_w}$	Weighted closeness centrality
	12	$[G^*]_{C_{new1}}$	Weighted closeness centrality normalised by$\|V\| - 1$
	13	$[G^*]_{C_{new2}}$	Weighted closeness centrality normalised by$[\|V\|(\|V\| - 1)]/2$
	14	$[G^*]_{B^{node}}$	Node betweenness centrality
	15	$[G^*]_{B_n^{node}}$	Normalised node betweenness centrality
	16	$[G^*]_{B_w^{node}}$	Weighted node betweenness centrality
	17	$[G^*]_{B_{nw}^{node}}$	Normalised weighted node betweenness centrality
	18	$[G^*]_{B^{edge}}$	Edge betweenness centrality
	19	$[G^*]_{B_n^{edge}}$	Normalised edge betweenness centrality
	20	$[G^*]_{B_w^{edge}}$	Weighted edge betweenness centrality
	21	$[G^*]_{B_{nw}^{edge}}$	Normalised weighted edge betweenness centrality
	22	$[G^*]_{B_w^{edge^{tp}}}$	Weighted top-to-bottom edge betweenness centrality average
	23	$[G^*]_{B_{nw}^{edge^{tp}}}$	Normalised weighted top-to-bottom edge betweenness centrality average
	24	$[G^*]_E$	Eigenvector centrality
	25	$[G^*]_{E_w}$	Weighted eigenvector centrality
Network scale	26	G^*_ρ	Network density
	27	G^*_D	Network diameter
	28	$G^*_{D_n}$	Normalised network diameter
	29	$[G^*]_{P_w}$	Weighted shortest path (average)
	30	$[G^*]_{P_w^{tp}}$	Average weighted shortest path between inlet and outlet nodes
Clustering	31	G^*_{GC}	Global clustering coefficient
	32	$[G^*]_{LC}$	Local clustering coefficient
Cycles	33	G^*_{SC}	Number of 3-cycles
	34	$[G^*]_{3C^{node}}$	Average number of node 3-cycles
	35	$[G^*]_{3C^{edge}}$	Average number of edge 3-cycles

$[G^*]$ is a unified characteristic, and $[G^C]$ refers to *contact* network features, while $[G^T]$ refers to *thermal* networks. The brackets in $[G^*]$ indicate an average value of the parameter. $|V|$ is the total number of nodes in the network.

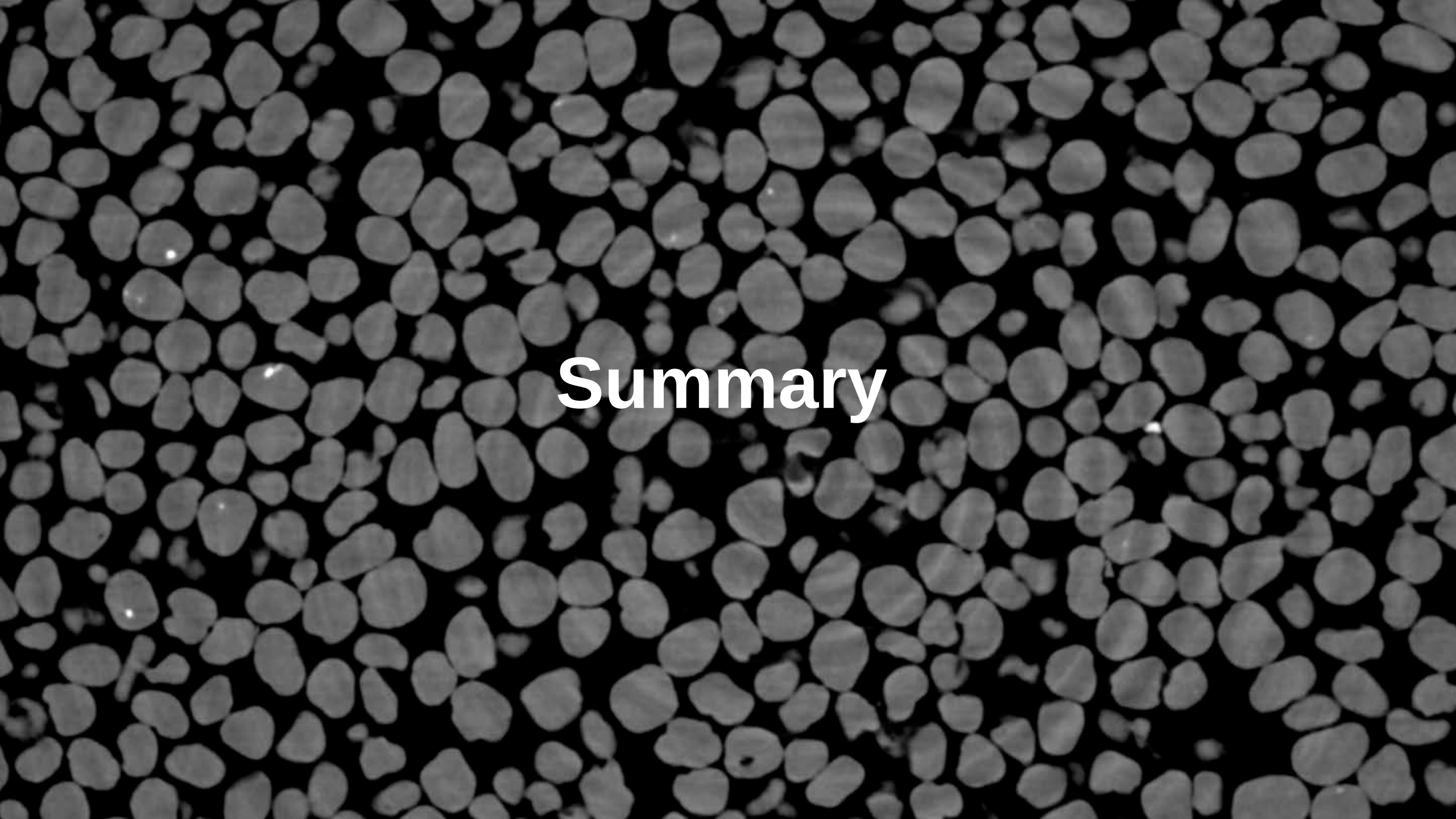


Thermal conductance network model





Continuity: $-\mathbf{n}(q_s - q_p) = 0$


Summary

Summary

Overall: Relearning images → CT Image processing pipeline → Microstructural analysis

Hands-on tutorial #1

ImageJ basics
IJ1 Macro script for batch processing CT images

Hands-on tutorial #2

Enhance image contrast
Reduce image noise and
Segment solid and void phases

Hands-on tutorial #3

Watershed segmentation
Particle extraction
Particle analysis: calculate particle size and shape

Codes, sample data: *https://cloudstor.aarnet.edu.au/plus/s/YRnAMis6vR2ZKmo* pwd: GrainDays_123456

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Thank you

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