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Bimodal imaging with neutrons

Outline

1 Introduction

2 Some considered modialities

3 Acquisition

4 Image fusion

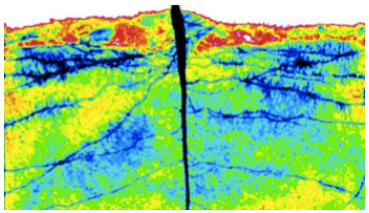
5 Applications

6 Summary and discussion

Introduction

Typical neutron imaging experiment and challenges

Hydrology

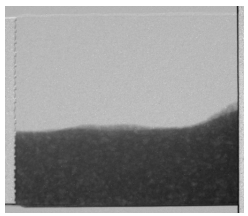


- Segmentation accuracy
- Estimate water content

Cultural heritage

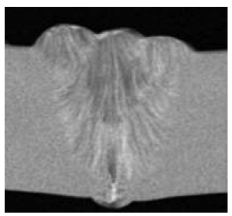
- Segmentation accuracy
- Material classification

Buildung materials



- Estimate water content
- Dimensional changes

Materials science



- Penetration power
- Ambiguous readings

Why multiple modalities?

Reasons to select or reject a specific imaging method

Advantages

- Good transmission
- Good contrast
- Relevant features visible
- Materials can be identified

Disadvantages

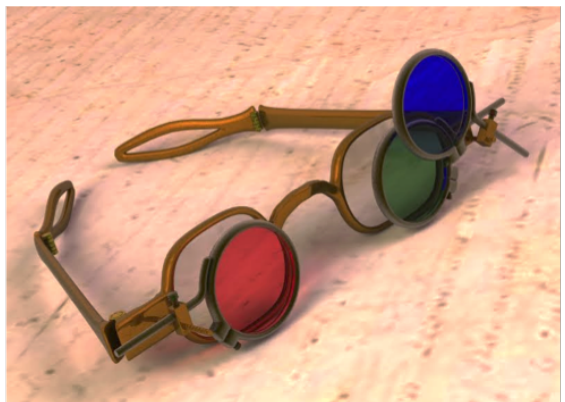
- Low transmission
- Low contrast
- Not all features visible
- Ambiguous response

The aim of multimodal imaging

Purpose of multi-modality

Match the advantages of each method against the disadvantages of the other methods to obtain more information than using each method individually.

1. Extend range of operation.
2. Extend spatial and temporal coverage.
3. Reduce uncertainty.
4. Increase reliability.
5. Robust system performance.

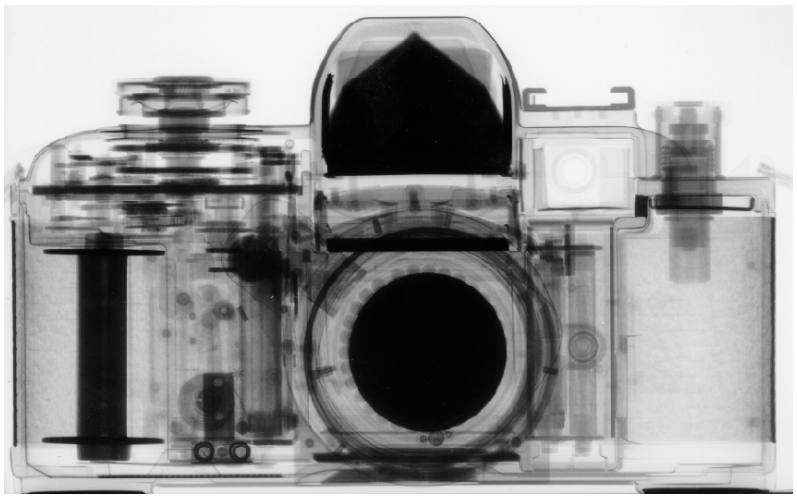


Multispectral glasses (National Treasure, 2004)

Some considered modialities

Neutrons and X-rays

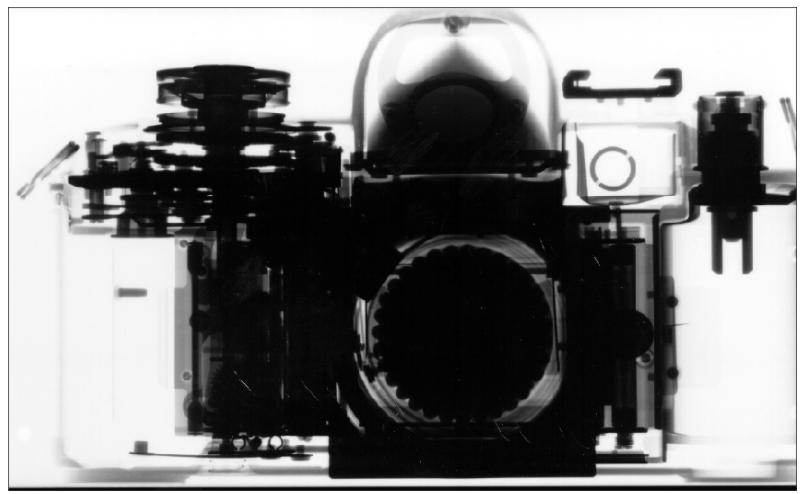
Neutrons



Group → / ↓Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 3.44																	He 0.02
2	Li 3.30	Be 0.79											B 101.6	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
3	Na 0.09	Mg 0.15											Al 0.1	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
4	K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
5	Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.1	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
6	Cs 0.29	Ba 0.07		Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po -	At -	Rn -
7	Fr -	Ra 0.34		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -

Lanthanides	La 0.52	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.0	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75			
Actinides	Ac -	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -			

X-rays

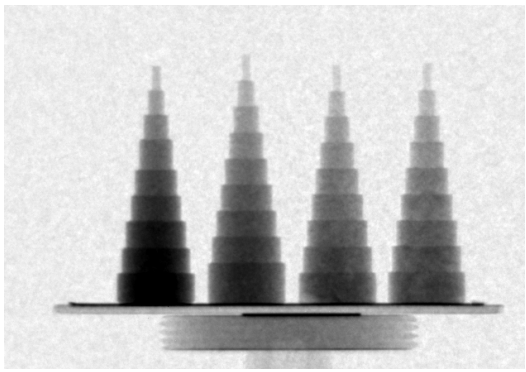


Group → / ↓Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 0.02																	He 0.02
2	Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
3	Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
4	K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
5	Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
6	Cs 1.47	Ba 2.73		Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At -	Rn 9.77
7	Fr -	Ra 11.80		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -

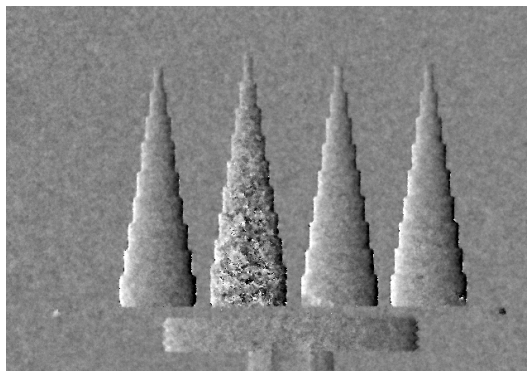
Lanthanides	La 5.04	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.17	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07			
Actinides	Ac 24.47	Th 28.95	Pa 39.65	U 49.08	Np -	Pu -	Am -	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -			

Grating interferometry

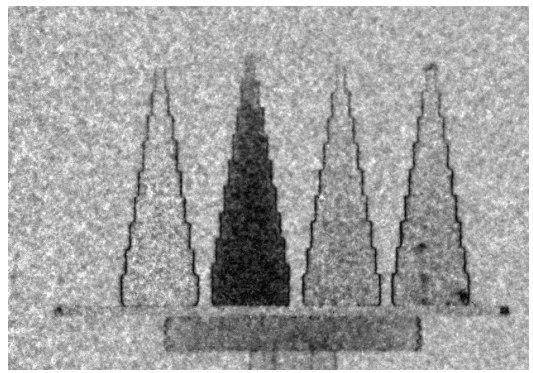
Transmission



Differential phase



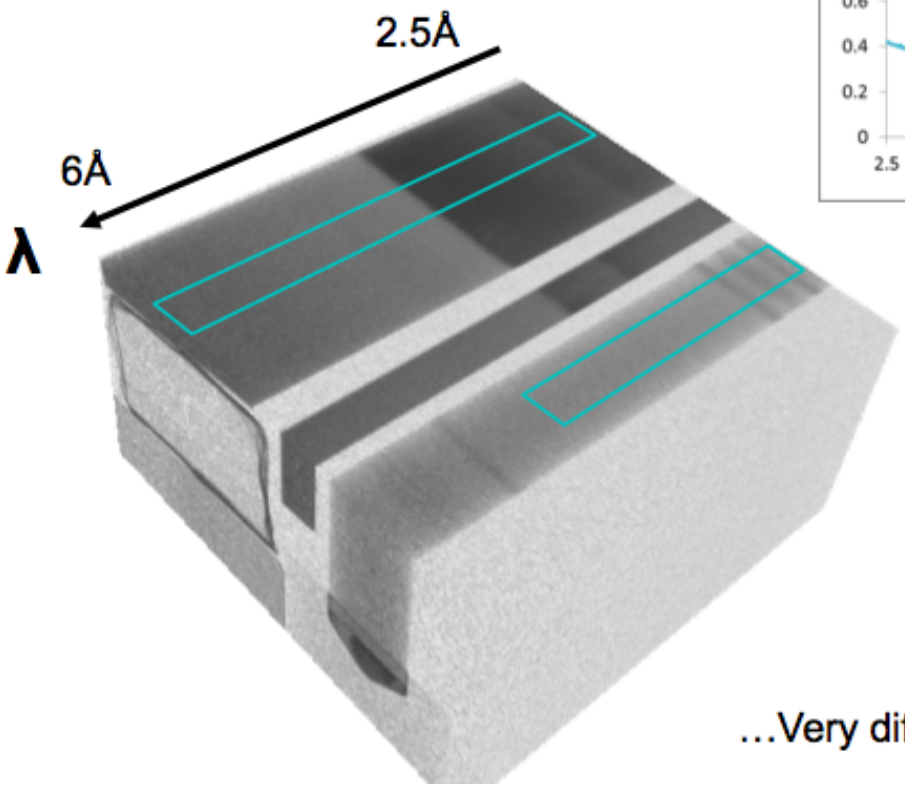
Dark field

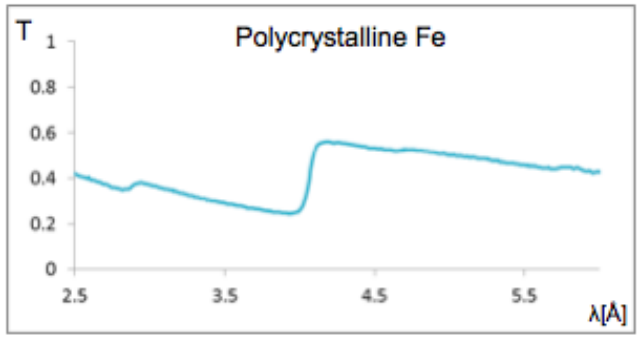


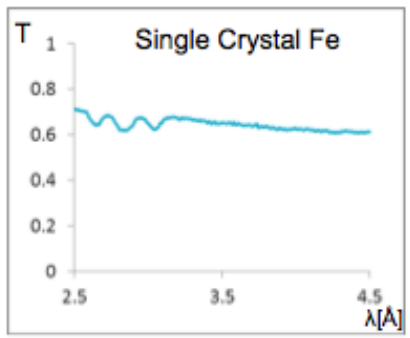
- Data comparable on pixel level
- Non-linear relation between the variables.
- Improved estimation schemes using iterative process
- Physical interpretation/motivation to fuse?

Spectroscopic imaging

A closer look at the iron samples







…Very different wavelength dependence

- Material analysis
- Selector calibration

[S. Peetermans]

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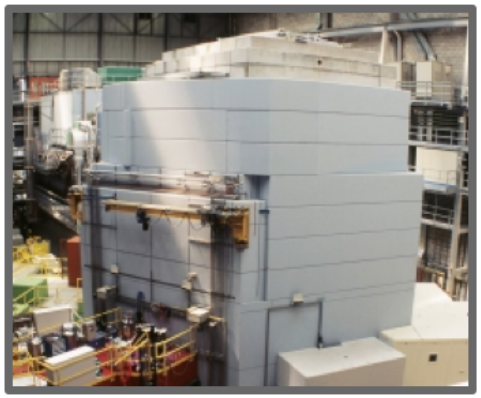
PSI

Acquisition

Different approaches to NX-imaging: Off-site



Neutrons

OR

Synchrotron

Lab-based X-ray

Pros

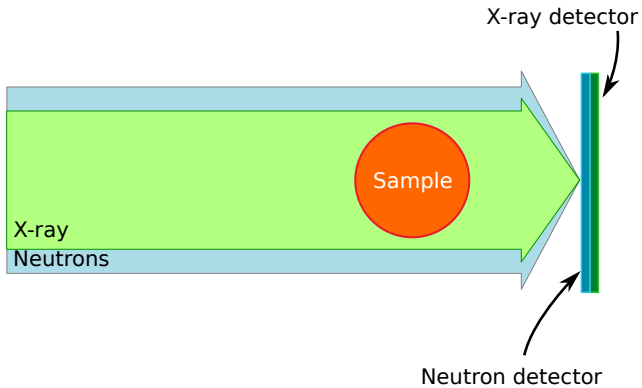
- Different resolutions
- Optimized acquisition times
- Access to equipment

Cons

- Sample transport (sample activation etc.)
- No simultaneous acquisition
- Coordination of beamtime

Different approaches to NX-imaging: On-site

Inline – NEUTRA



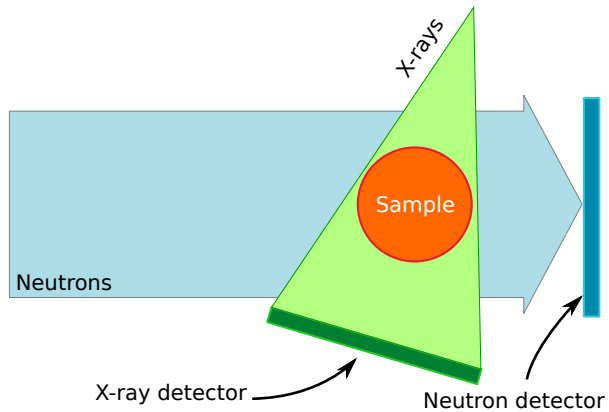
Pros

- Same detector
- Pixel-wise comparable
- Sample is not repositioned
- Strong X-ray source

Cons

- No simultaneous acquisition

Perpendicular – ICON



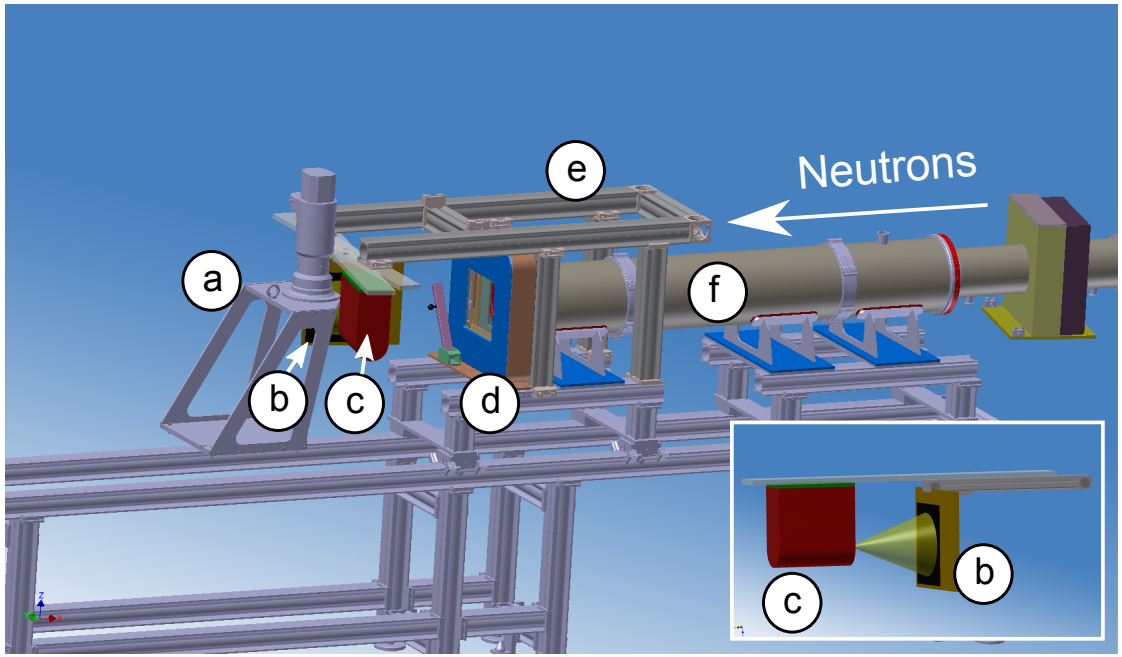
Pros

- Optimized detectors
- Magnification (X-rays)
- Simultaneous acquisition
- Sample is not repositioned

Cons

- Different coordinate systems

The NX setup at ICON



Components

- a X-ray source
- b Neutron flight tube
- c Beam limiter
- d Midi camera box
- e Maxi camera box
- f Sample environment

Neutrons

- Cold neutron spectrum
- Almost parallel beam
- Camera/Scintillator

X-rays

- 150kV, 75W source
- Cone beam (42°)
- Flat panel detector

[?]

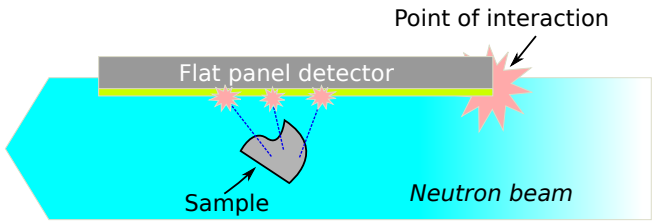
Multimodal acquisition

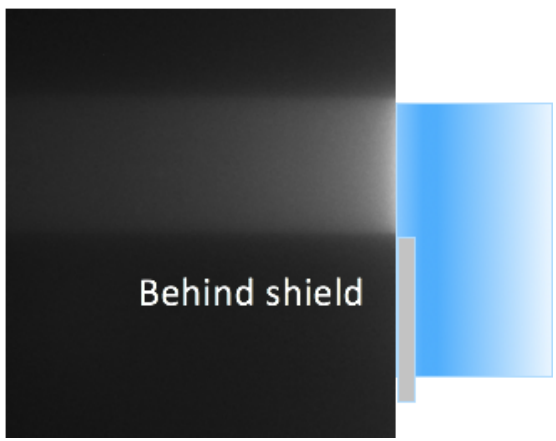
Considerations for the acquisition

Interference	The cross-talk between modalities must be minimized
Time	To observe processes – when are the data acquired.
Resolution	Resolution of the modalities
Magnification	Beam divergence of the modalities.

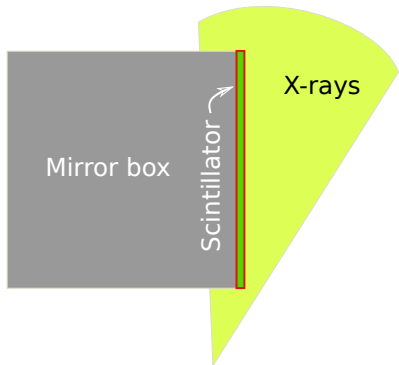
Cross-talk and the effect of shielding

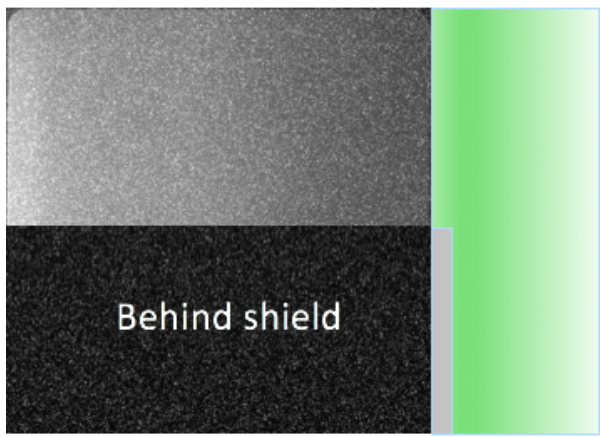
Neutrons on X-ray detector





X-rays on Neutron detector

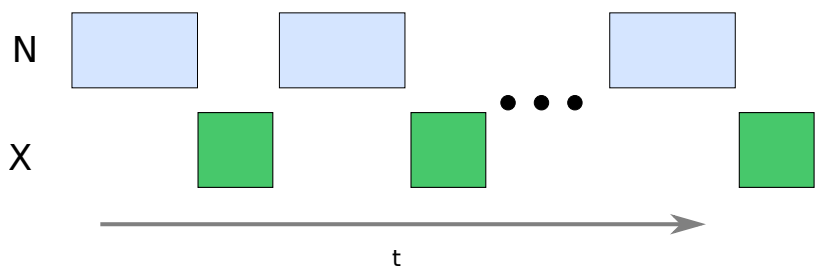




Simultaneous acquisition

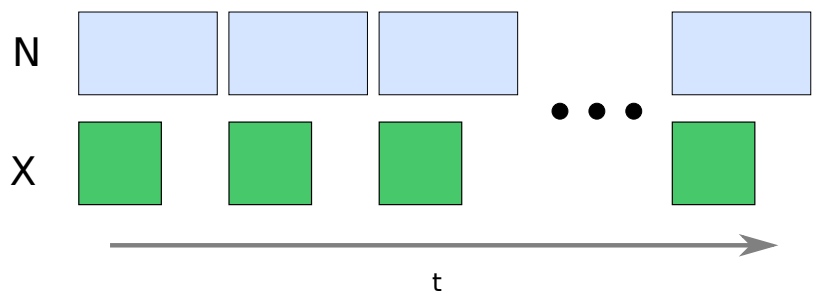
Alternating sequence

- One modality active
  - Full scan
  - Alternating
- Cross-talk is minimized
- Two acquisition position possible
- Longer delays



Parallel sequence

- Both modalities active
- Shielding required
- Single acquisition position only
- Rapid acquisition



What limits the volume rate?

Sample stage

Sample stability

Detector sensitivity

Detector frame rate

Low radiation dose – low SNR

Image fusion

What is data fusion?

Definition

The theory, techniques and tools which are used for combining sensor data, or data derived from sensory data, into a common representational format.

Aim

To improve the quality of the information, so that it is, in some sense, better than would be possible if the data sources were used individually.

[Mitchell, 2012]

Fusion approaches – no golden recipe

Fusion strategies

Multivariate fusion All data are combined using the same concept.

Augmented fusion Modalities have different functions in the fusion process.

Artifact reduction by fusion The second modality can be used to fill in the blanks.

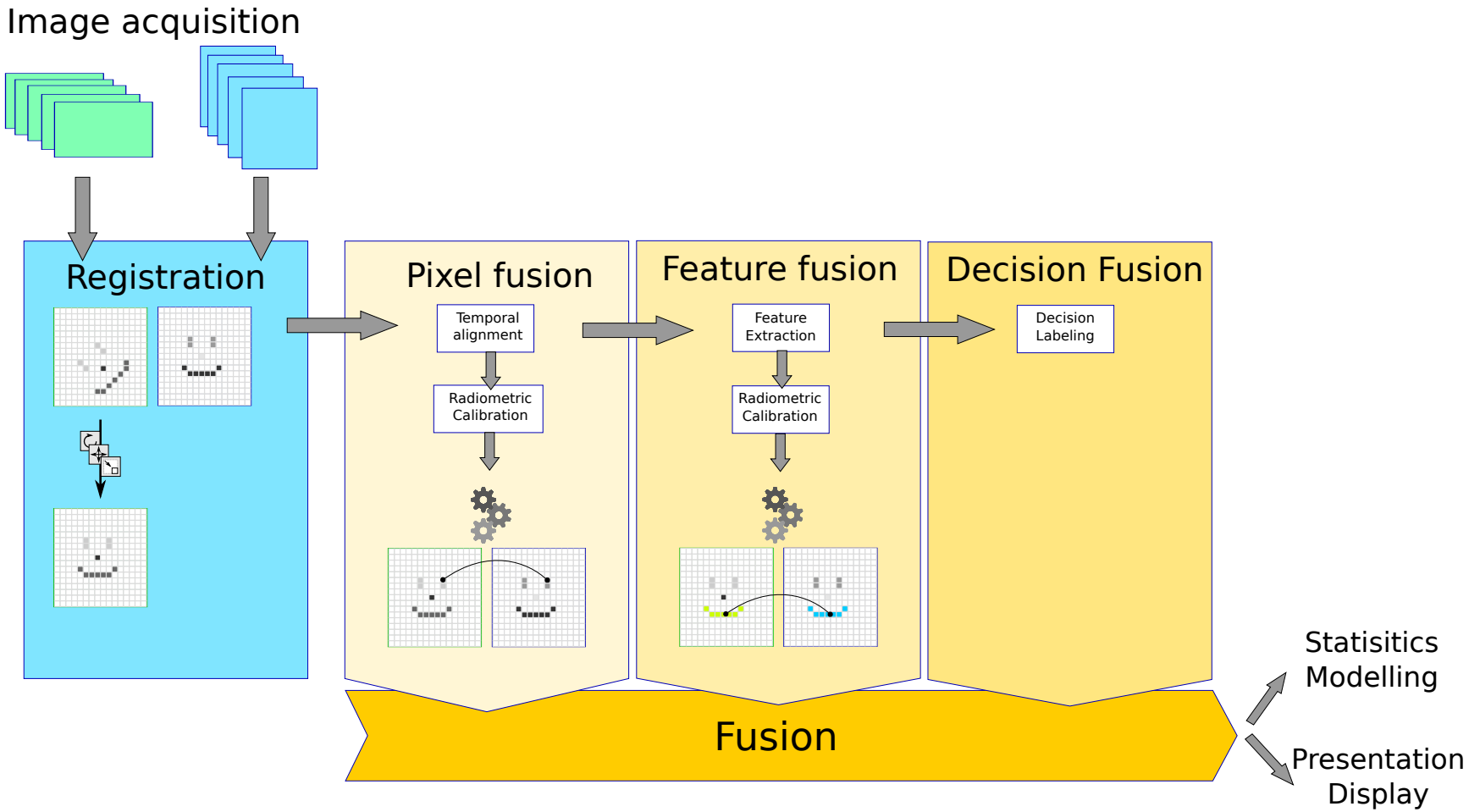
Combination One method may not give the final result – combination

Select strategy

The fusion strategy determined by:

- Sample composition
- Experiment objectives
- Condition of the data

Image fusion workflow



[Goshtasby, 2012],[Mitchell, 2010]

Catastrophic fusion

Definition

The combination perform worse than the individual modalities.

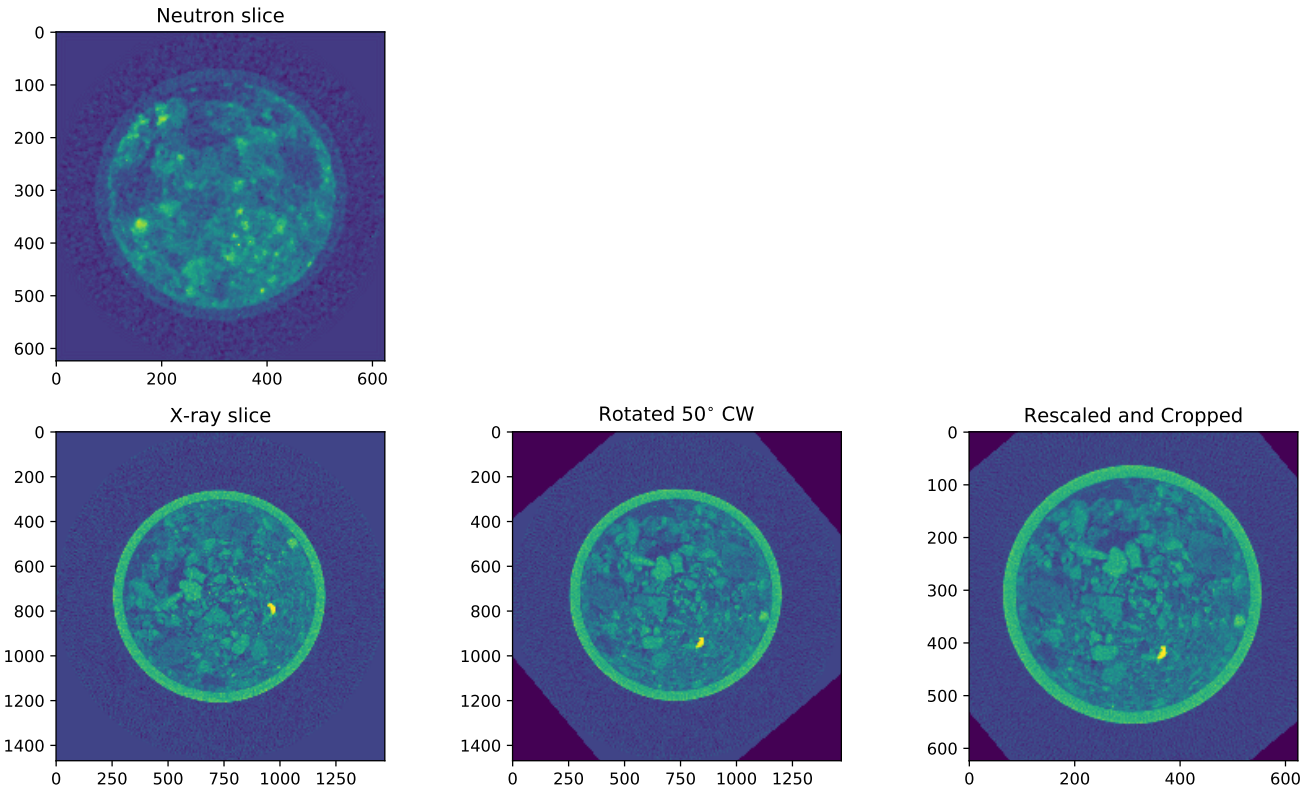
This can be caused by

- Selection of the wrong variables.
- Too complex combination.
- Sensor information canceling each other.

Image registration

The process

A series of affine transformations to bring images on the same grid.



Registration considerations

Registration is an optimization problem with many local minima.

- Manual or guided registration
  - Perform the full transformation manually
  - Identify land marks, points, lines, planes
  - Provide a coarse preregistration
- Automatic registration
  - Iterative process
  - Metrics
  - Multi-modality loose common landmarks

[Goshtasby, 2012]

Registration and covisualization

Use e.g. VG Studio to

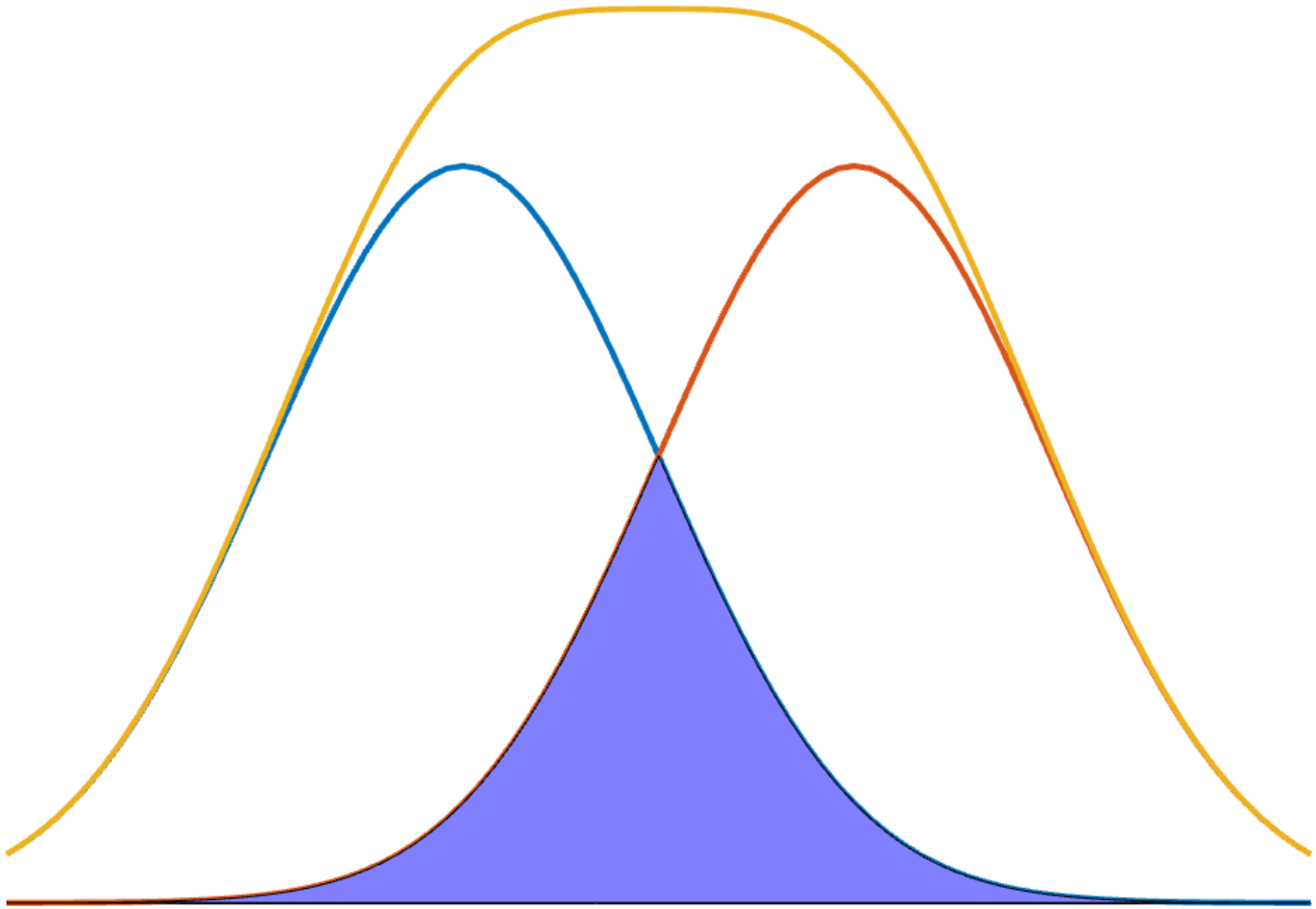
- Register data sets
- Interactive guided segmentation of the separate data sets.

Neutrons

X-rays

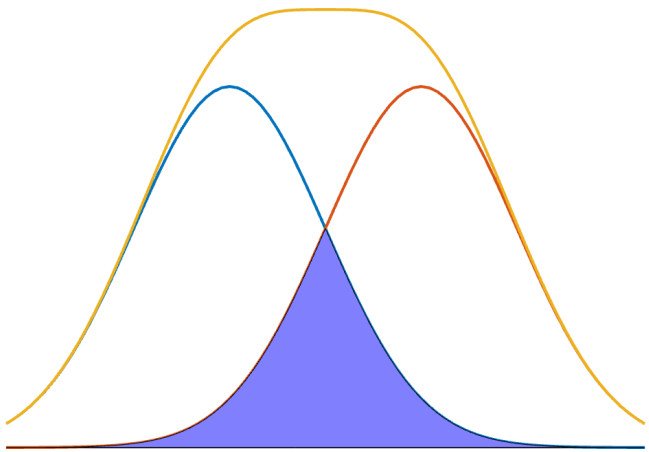
[Mannes et al., 2015]

Bimodal Segmentation – Single modality histogram

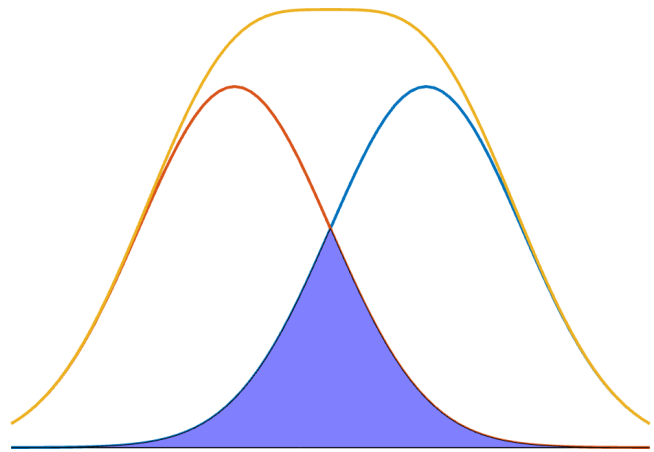


Two modalities separate

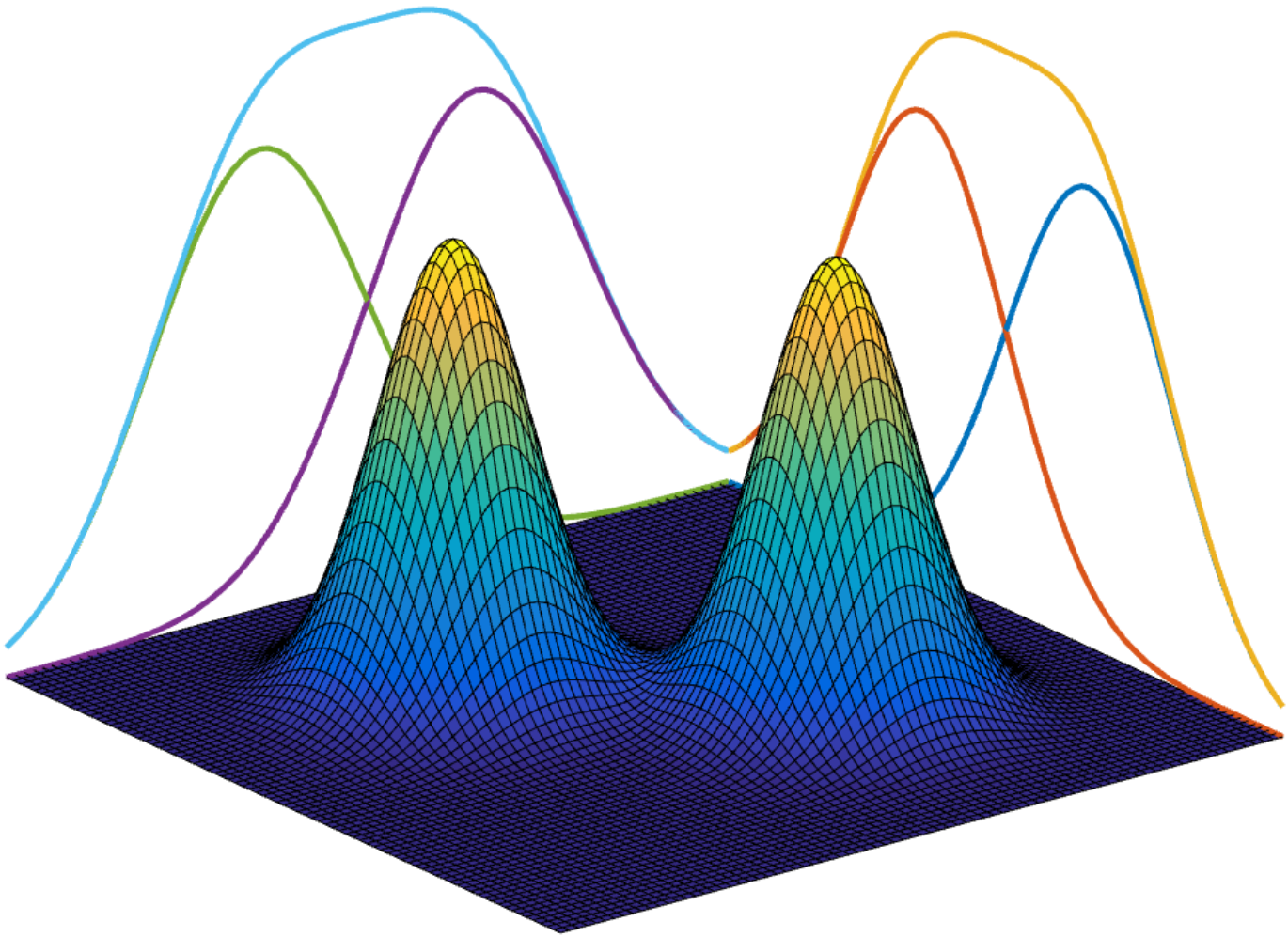
Modality A



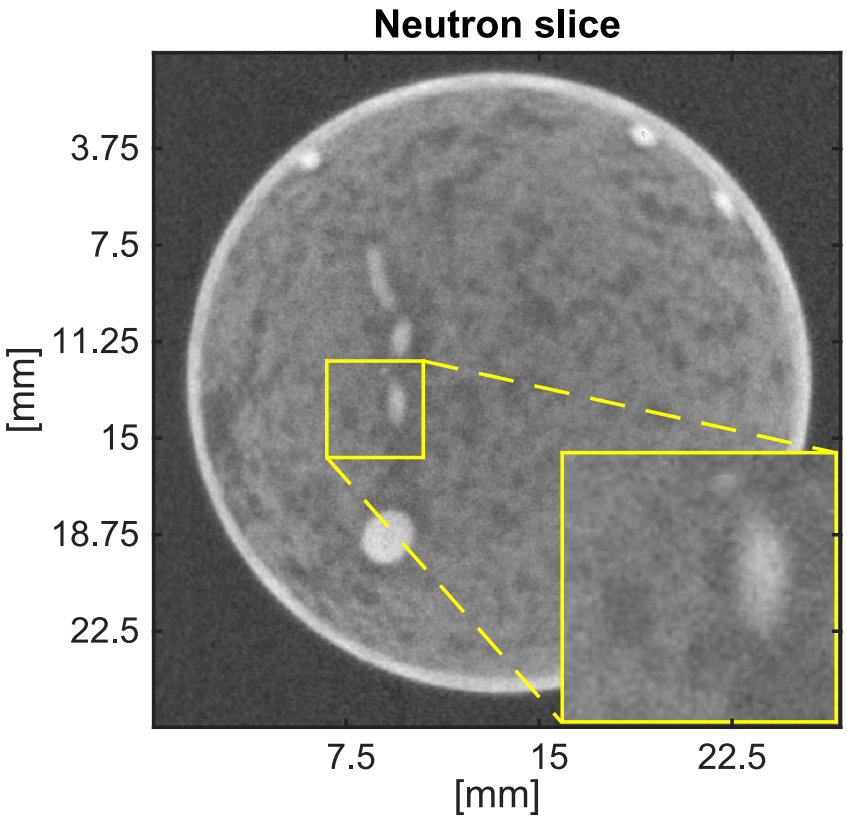
Modality B

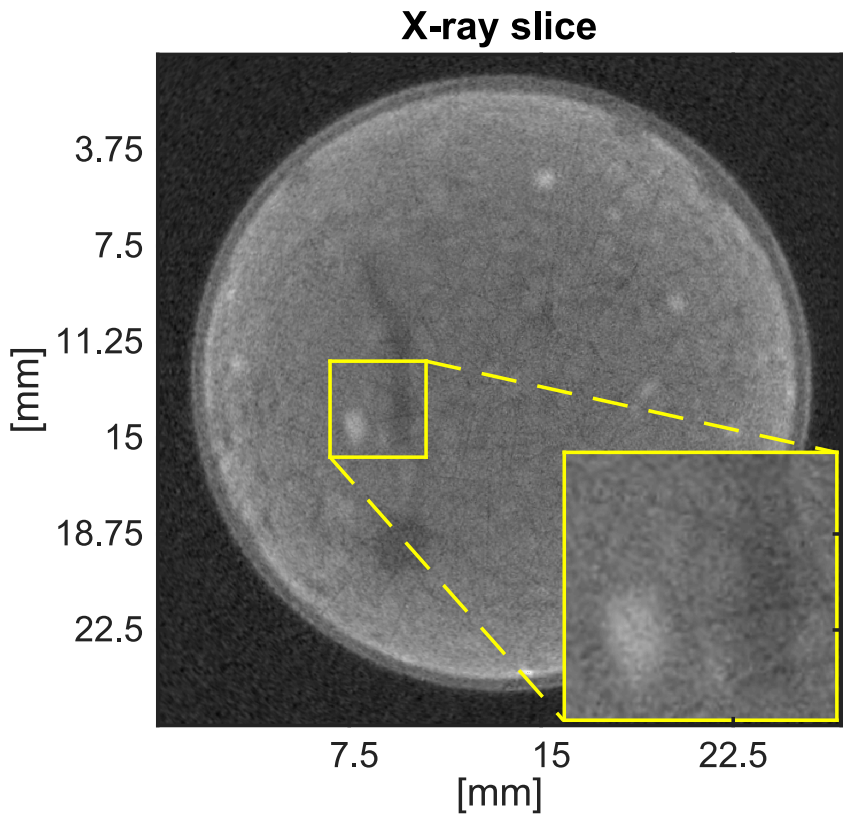


Bivariate histogram

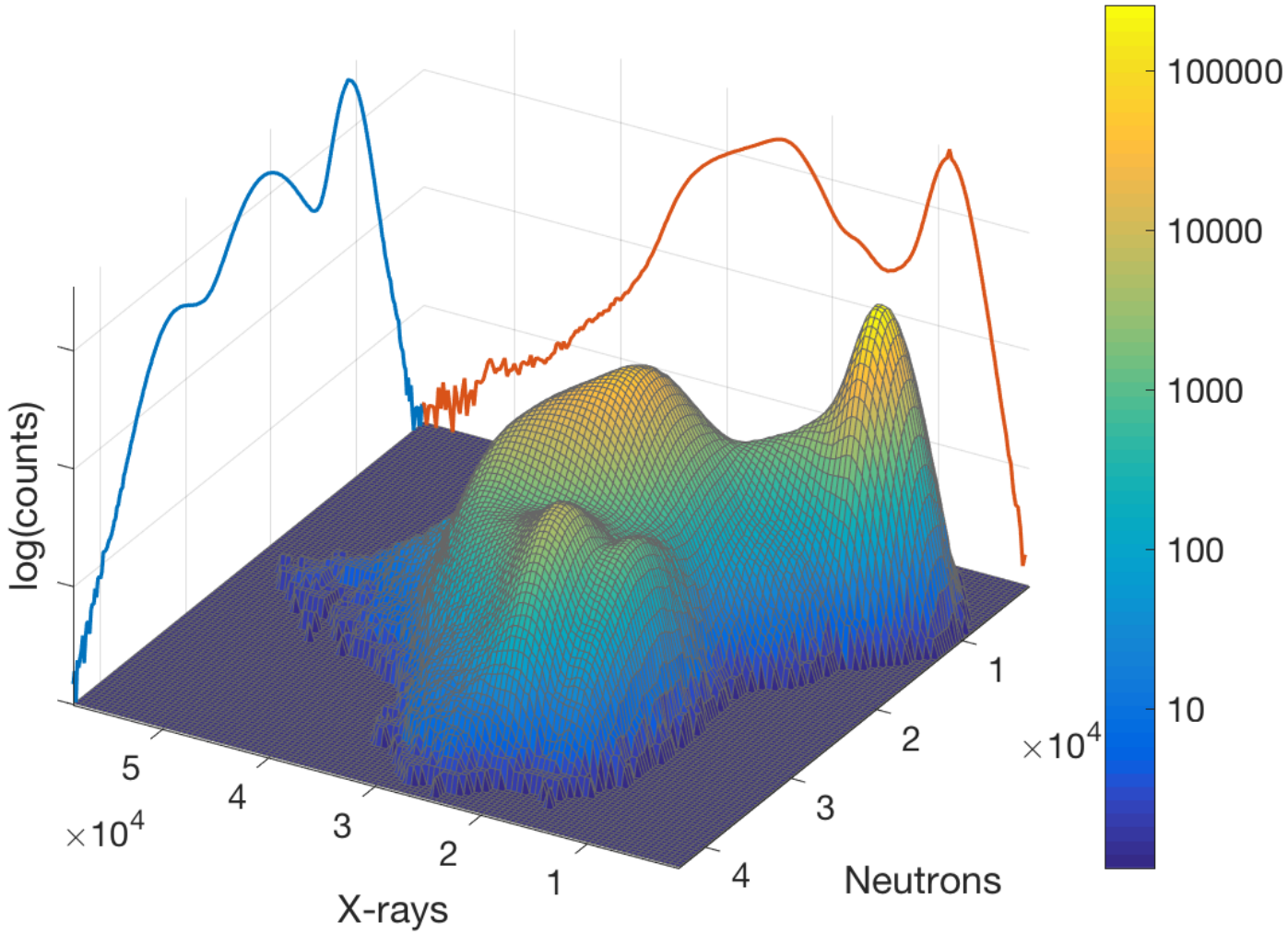


Example: Roots in soil





Bivariate histogram of roots



Classification methods

Data

- Images from M modalities $f_1, \ldots, f_M$
- Registered
- Artifact corrected

Classes

The N classes are described by:

$$\mathcal{H}_1 : p(\mu_1, \Sigma_1)$$
$$\mathcal{H}_2 : p(\mu_2, \Sigma_2)$$
$$\vdots$$
$$\mathcal{H}_N : p(\mu_N, \Sigma_N)$$

Gaussian mixture model

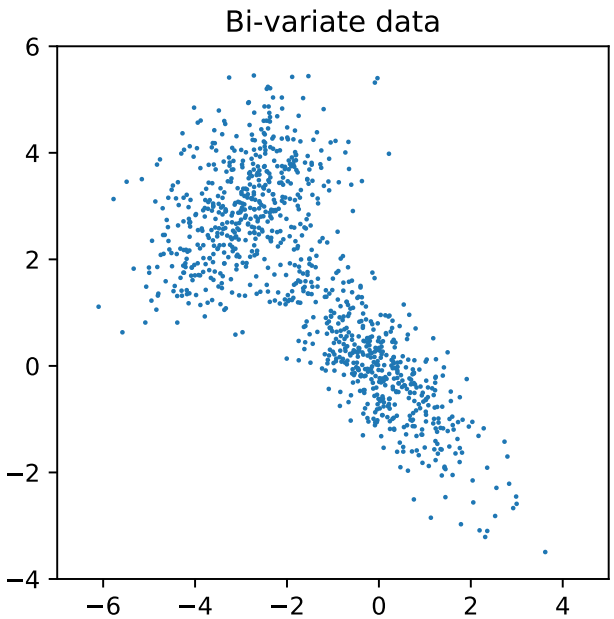
With Gaussian distribution we can describe the bivariate histogram using:

$$p(\theta) = \sum_{1}^{N} \phi \mathcal{N}(\mu_i, \Sigma_i)$$

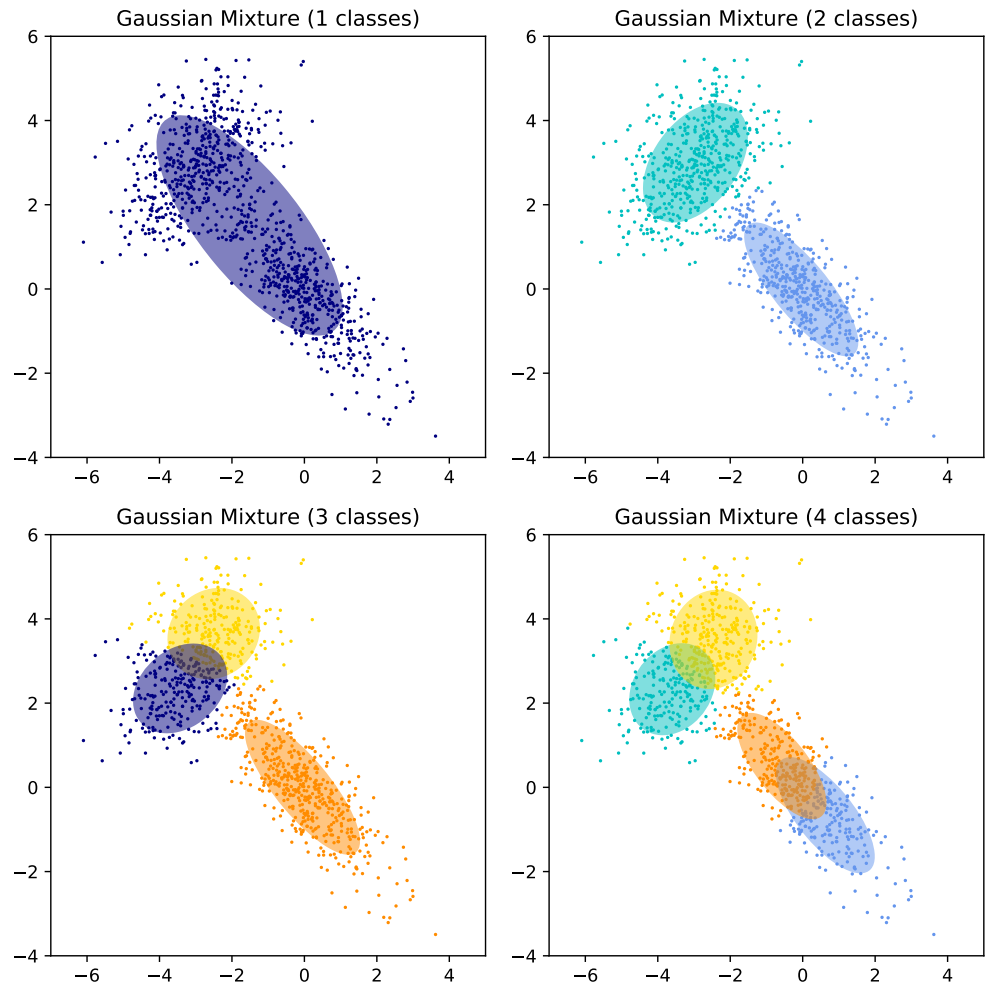
[Duda et al., 2001]

Gaussian mixture model

Bivariate data



Gaussian mixture model fitting



Classification distances

For a set of multivariate normal distributions $p_i = \mathcal{N}(\mu_i, \Sigma_i)$

Euclidean

$$D_E = \sqrt{(x - \mu_1)^T \cdot (x - \mu_1)}$$

Mahanalubis Distance from class i to point x

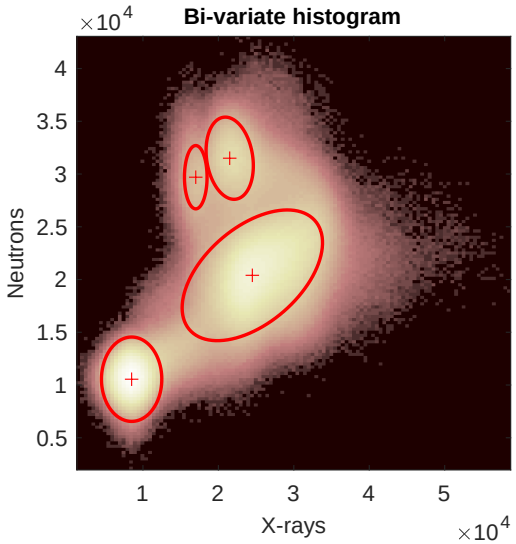
$$D_M = \sqrt{(x - \mu_i)^T \Sigma_i (x - \mu_i)}$$

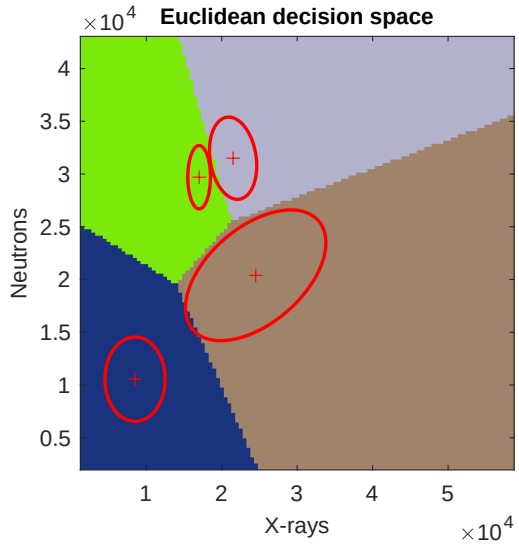
Bhattacharia Distance between two classes

$$D_B = \frac{1}{8} (\mu_1 - \mu_2)^T \Sigma (\mu_1 - \mu_2) + \frac{1}{2} \ln \left(\frac{|\Sigma|}{\sqrt{|\Sigma_1| \cdot |\Sigma_2|}} \right)$$

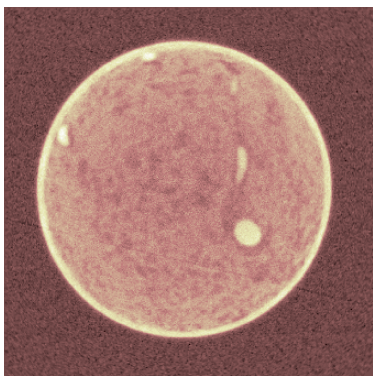
Assign the point to the class with shortest distance.

Segmentation by Euclidean distance

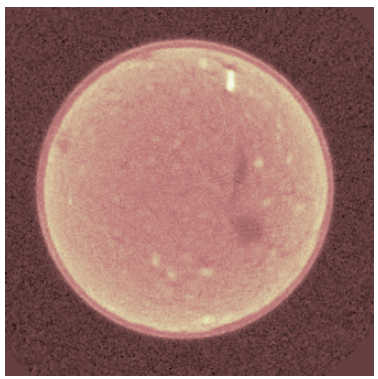




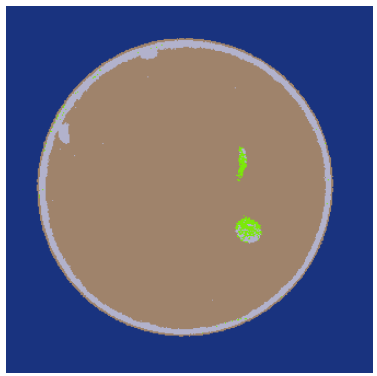
Neutrons



X-rays



Segmentation



[?]

Working with attenuation coefficients

Beer–Lamberts law

$$I = I_0 \, e^{-\frac{\rho}{A} N_A \sigma x} \tag{2}$$

- ρ Material denstity
- A Atomic weight
- σ microscopic cross section
  - Probability of interaction
  - modality dependent
- x propagation length

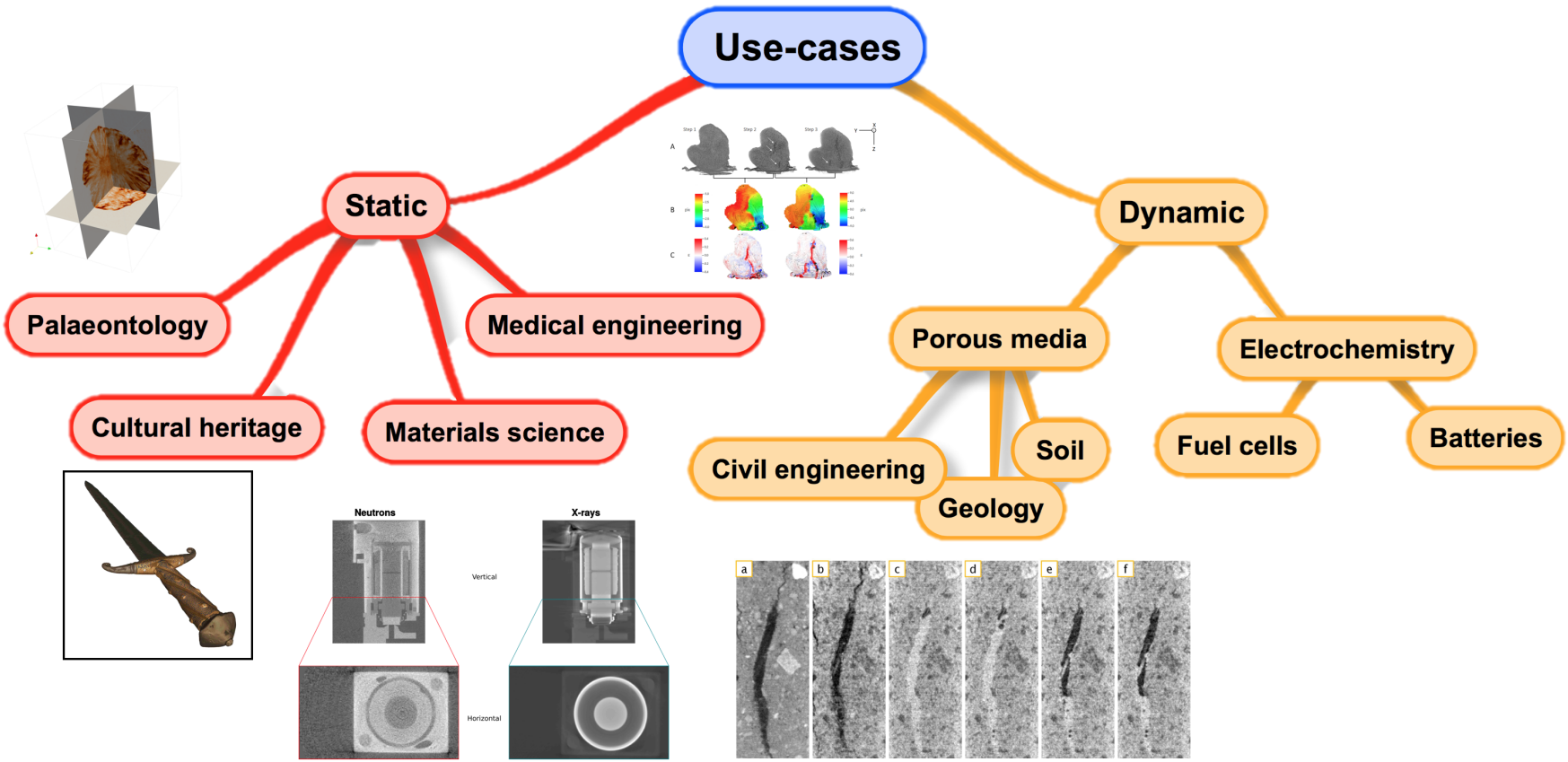
Equation system

$$\begin{aligned} \sum_{i=1}^{N} \Sigma_i \, x_i &= q_N \\ \sum_{i=1}^{N} \mu_i \, x_i &= q_X \end{aligned} \tag{3}$$

- attn coeff known $\rightarrow$ estimate lengths.
- More pixels $\rightarrow$ more materials.

Applications

Applications of bimodal imaging



Static experiments

NDT

- Function or production inspection
- Neutrons and X-rays

Medical engineering

- Bone growth with implants
- Neutrons and X-rays

Cultural heritage

- Ancient artifact inspection
- Neutrons and X-rays

Material science

- Texture contrast
- Multi energy fusion

Case study: Ancient nails – preservation of iron

Corroding nails

Desalinisation bath

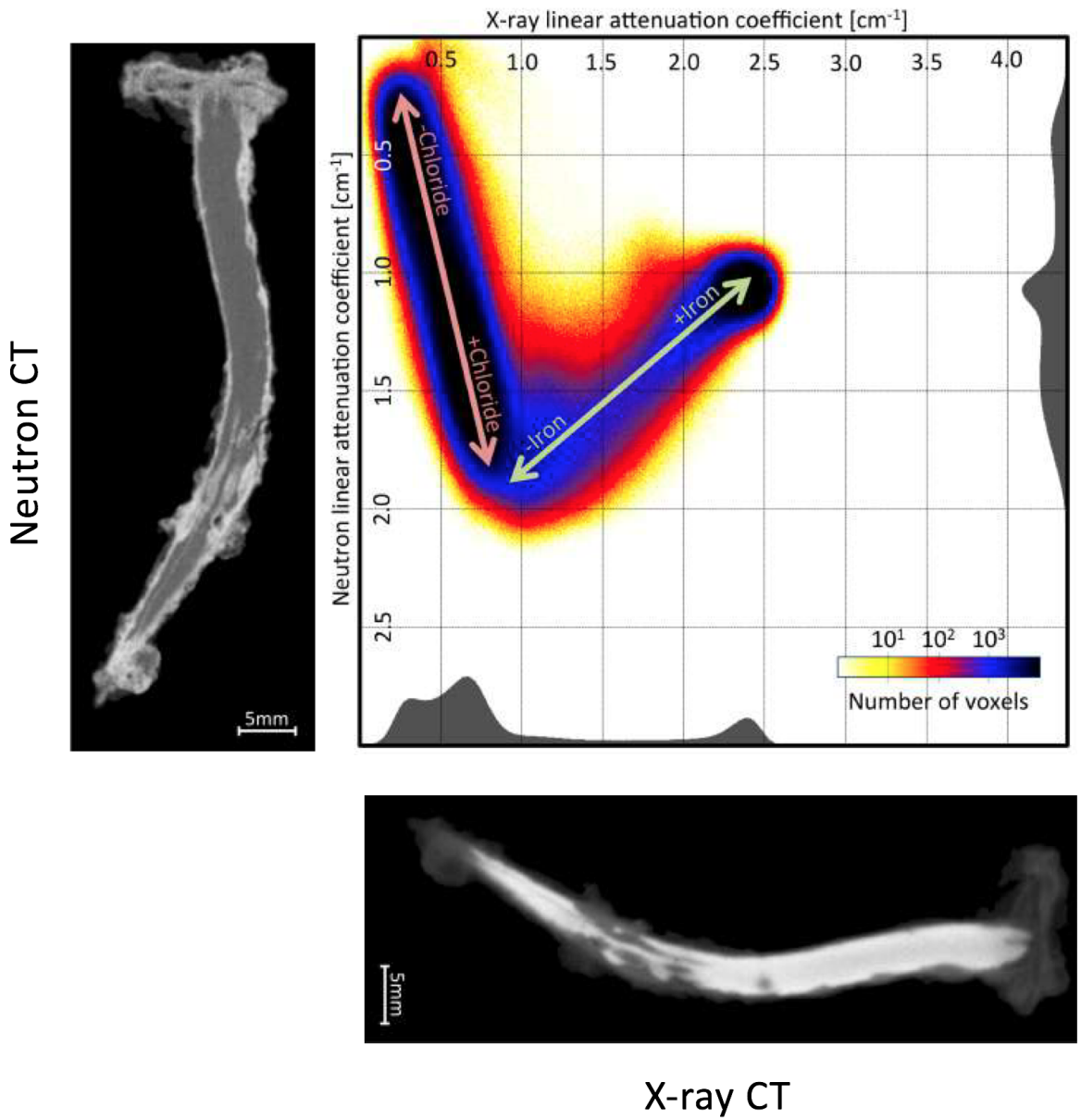
Evaluation of desalinisation process by imaging

- Corrosion products have low density but contain H
- Hard to separate components

$\Rightarrow$ Bimodal imaging helps

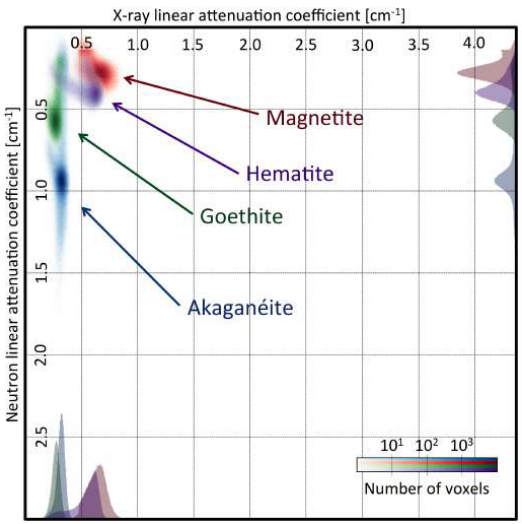
[Jacot-Guillarmod et al., 2018]

Nails – images and histogram

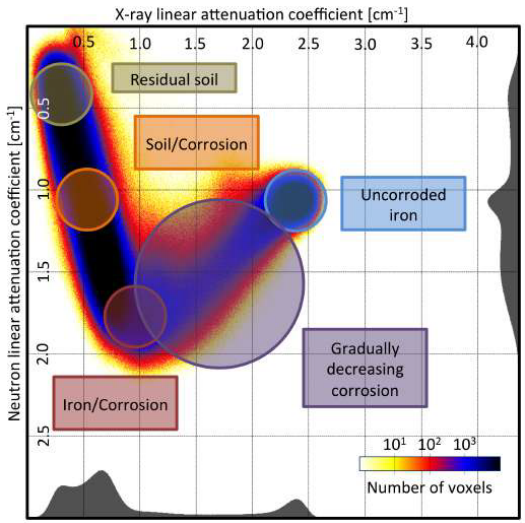


Nails – classifying regions

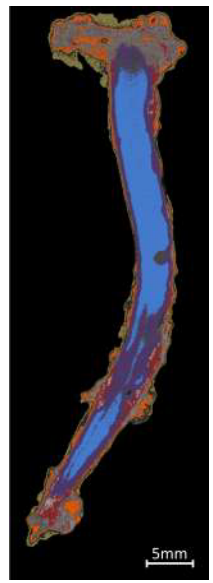
Components



Nail histogram



Classified regions



Conclusion

- Bimodal imaging made it possible to verify the effect of desalinisation.

Dynamic experiments

Porous media

- Soil and roots
- Civil engineering
- Cultural heritage/preservation

Foams

- Food
- Construction materials

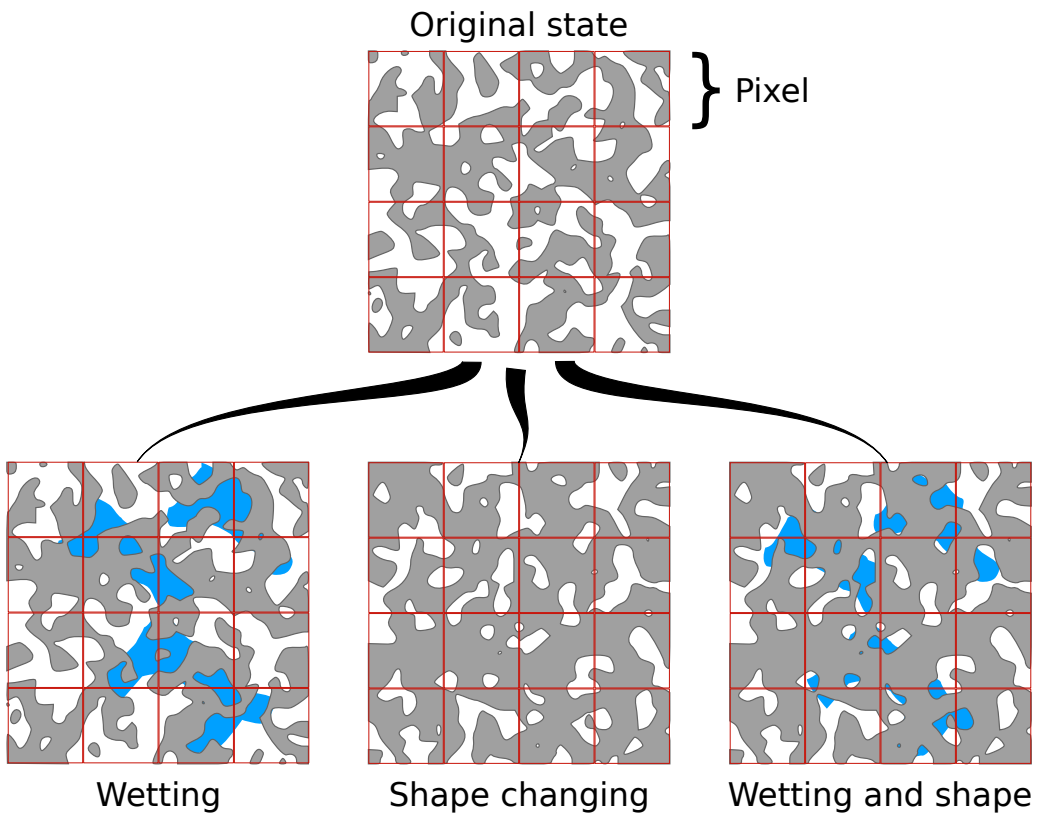
Dynamic imaging with reactive samples

The problem

- More than one component changes over time, e.g. shape and composition.
- A single modality can't tell what changed.

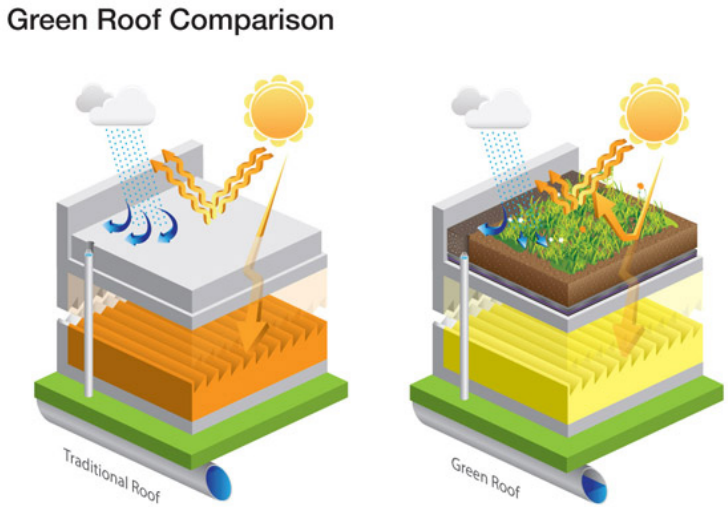
Partial volume effects

- Pore can't be resolved
- Contributions unknown
- Changes with time



Case study: Imbibition in soil

Urban vegetation



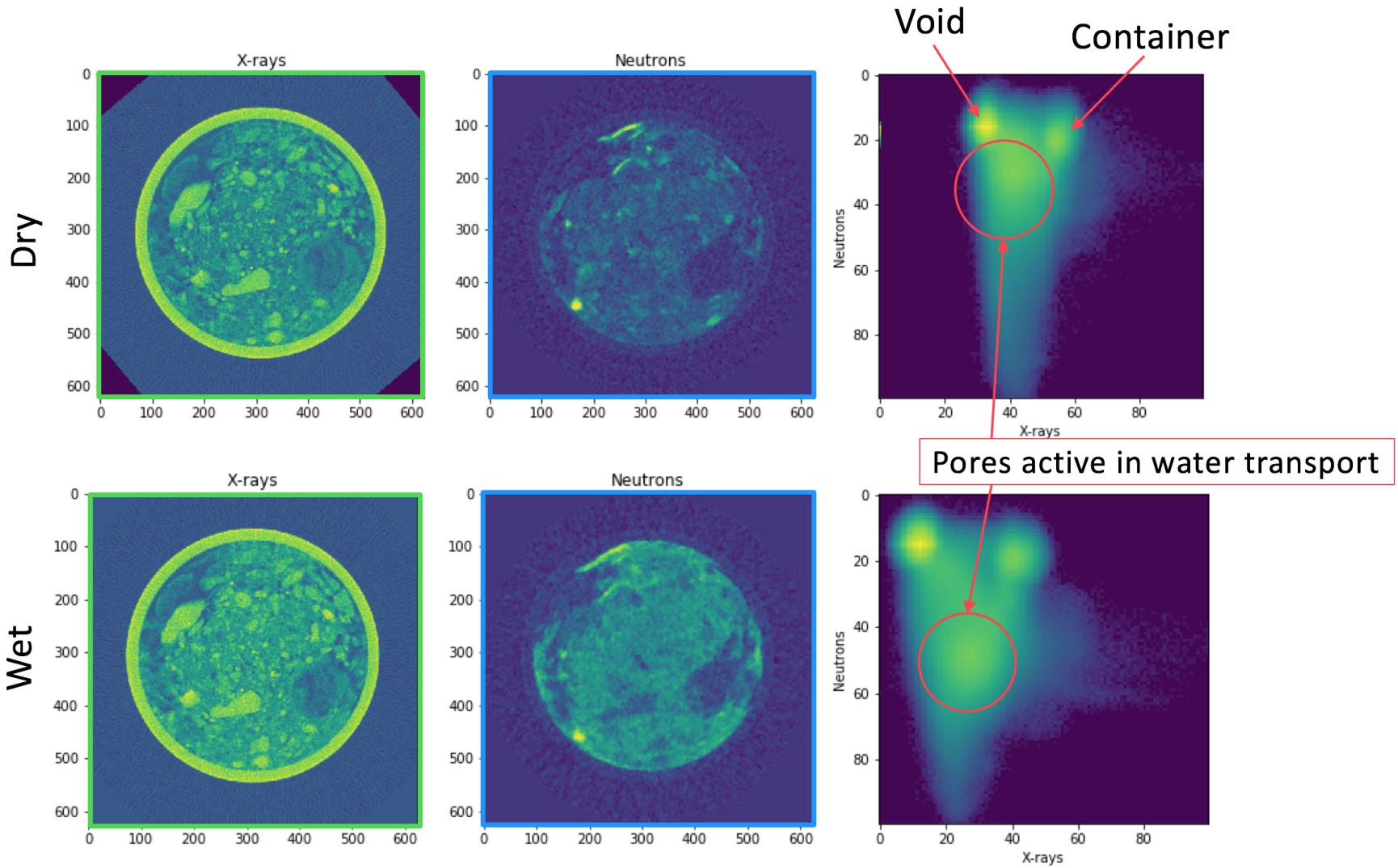
- Controls urban climate
- Controls building environment
- Reduces excess rain water

Experiment

- Early pedogenesis
- Water flow – imbibition
- Soil formation

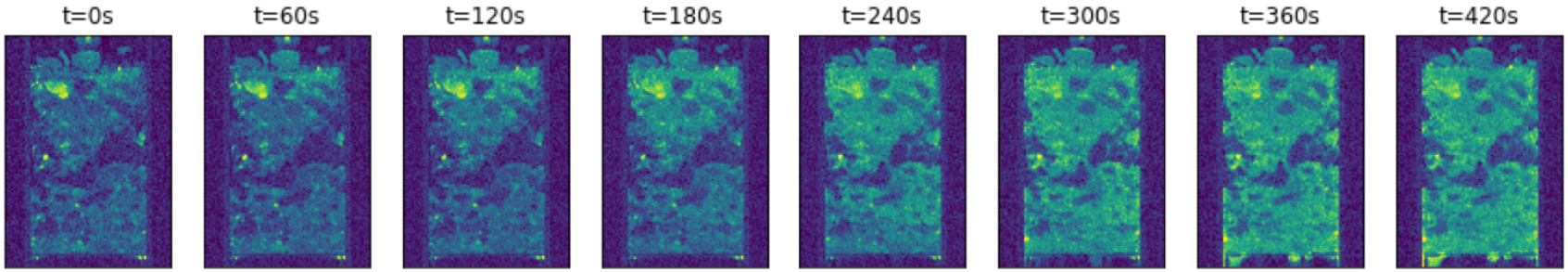
[Kaestner et al., 2018]

On-the-fly bimodal imaging

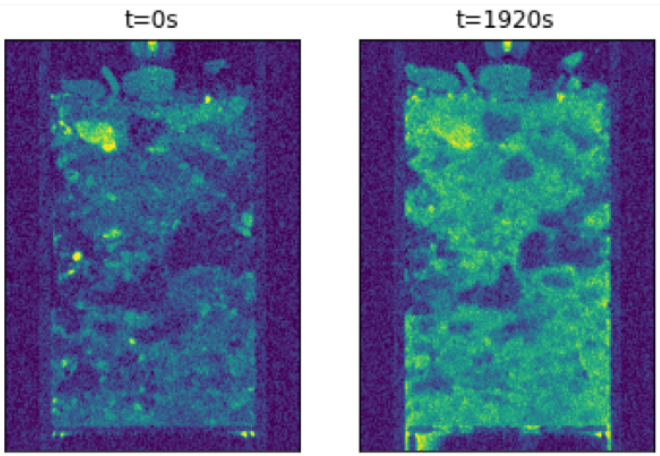


Verifying imaging performance

Wetting front



Sample swelling



Next steps

- Quantify water content
- Analyze displacements
- System modeling

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Summary and Discussion

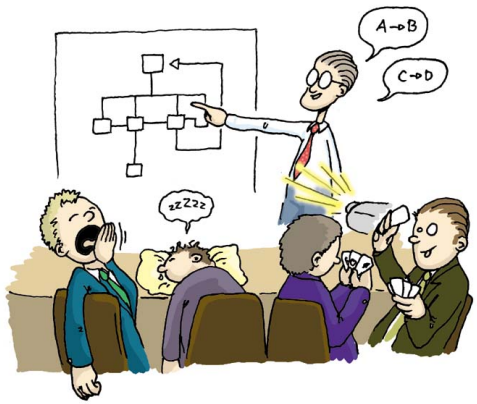
Summary

Multimodal imaging. . .

- Is a combination of several methods
- Requires planning and development of experiment strategies
  - Understanding of the underlying physics.
  - Optimized acquisition.
  - Dedicated analysis strategies.
  - Choices are application oriented.
- We have the instrumentation
- Data fusion theory exists, but needs to be explored for NI

Discussion

I'm done



Your turn

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