Quantitative Big Imaging - Bimodal experiments

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CONTENTS

This is the lecture notes for the 10th lecture of the Quantitative big imaging class given during the spring semester 2021 at ETH Zurich, Switzerland.

0.1 Bimodal experiments

```
%reload_ext autoreload
%autoreload 2
import numpy as np
import seaborn as sns
import matplotlib.pyplot as plt
import itertools
import numpy as np
import skimage.io as io
from scipy import linalg
import matplotlib as mpl
from sklearn import mixture
import pandas as pd

plt.rcParams["figure.figsize"] = (8, 8)
plt.rcParams["figure.dpi"] = 100
plt.rcParams["font.size"] = 14
plt.rcParams['font.family'] = ['sans-serif']
plt.rcParams['font.sans-serif'] = ['DejaVu Sans']
plt.style.use('default')
sns.set_style("whitegrid", {'axes.grid': False})
```

0.1.1 Literature / Useful References

Books

General:

- John C. Russ, "The Image Processing Handbook",(Boca Raton, CRC Press)

Fusion specific:

- Mitchell, H.B., "Data Fusion: Concepts and Ideas", Springer Verlag, 2012.
- Mitchel, H.B., "Image Fusion - Theories, Techniques and Applications", Springer Verlag, 2010.
- T. Stathaki, "Image fusion", Academic Press, 2008
- Goshtasby, A. Ardeshir, "Image Registration Principles, Tools and Methods", Springer Verlag, 2012
- *Xiao, G., Bavirisetti, D.P., Liu, G., Zhang, X., "Image Fusion", Springer Verlag

Software engineering

- Okken, B., Python testing with pytest
- Wuttke, J. et al.Guidelines for collaborative software development, 2022.

0.1.2 Previously on QBI ...

- Image Enhancement
- Highlighting the contrast of interest in images
- Minimizing Noise
- Understanding image histograms
- Automatic Methods
- Component Labeling
- Single Shape Analysis
- Complicated Shapes
- Dynamic Experiments
- Image registration
- Statistics
- Plotting

0.1.3 Outline

- Motivation (Why and How?)
- Scientific Goals
- Image fusion
- Bivariate segmentation
- Software engineering for repeatability

0.2 Imaging modalities

0.2.1 Some imaging experiments and their challenges

- Segmentation accuracy
- Estimate water content
- Segmentation accuracy
- Material classification
- Estimate water content
- Dimensional changes
- Penetration power

- Ambiguous readings

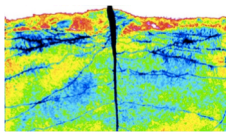


Fig. 1: In the soil the graylevels are often ambiguous.

Fig. 2: Studies of the cultural heritage.

0.2.2 Reasons to select an imaging modality?

Reasons to select or reject a specific imaging method

- Good transmission
- Good contrast
- Relevant features visible
- Materials can be identified
- Low transmission
- Low contrast
- Not all features visible
- Ambiguous response

Until now, we only collected image features from a single modality.

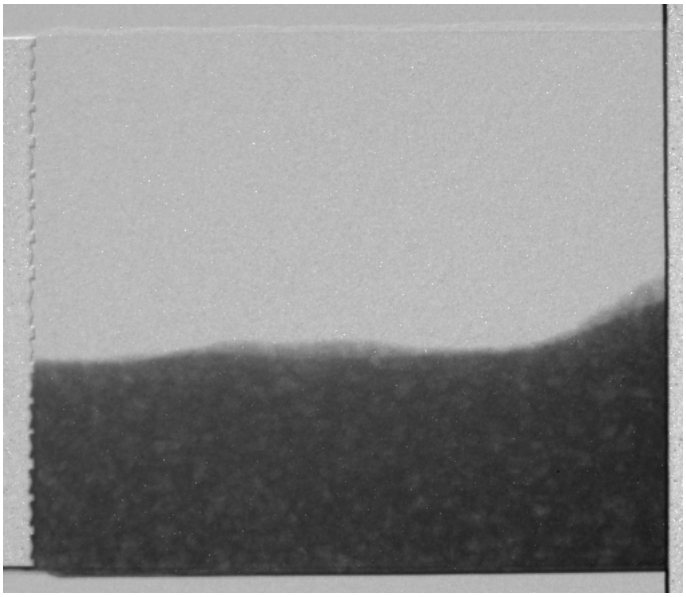


Fig. 3: Dimensional changes in porous media.

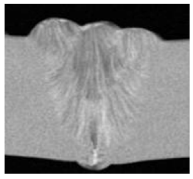


Fig. 4: Material science with material mixes.

0.2.3 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.

Fig. 5: The multispectral glasses from the movie 'National Treasure'.

The players of an imaging experiment

Fig. 6: An imaging experiment is only successful when all aspects are considered.

0.2.4 Some considered modalities - Neutrons and X-rays

In material science it often relevant to combine imagning with neutrons and X-rays. The reason is the complementarity between the two modalities. Simply put, neutrons are often sensitive to low-z materials while x-rays are more sensitive to high-z materials. Combining the two modalities is of particular interest when the sample is a mix of high and low-z materials.

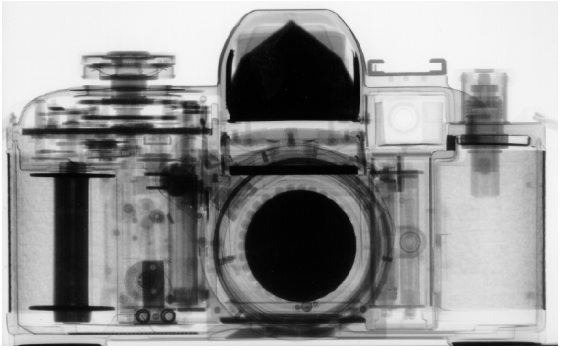


Fig. 7: Neutron radiography of a camera.

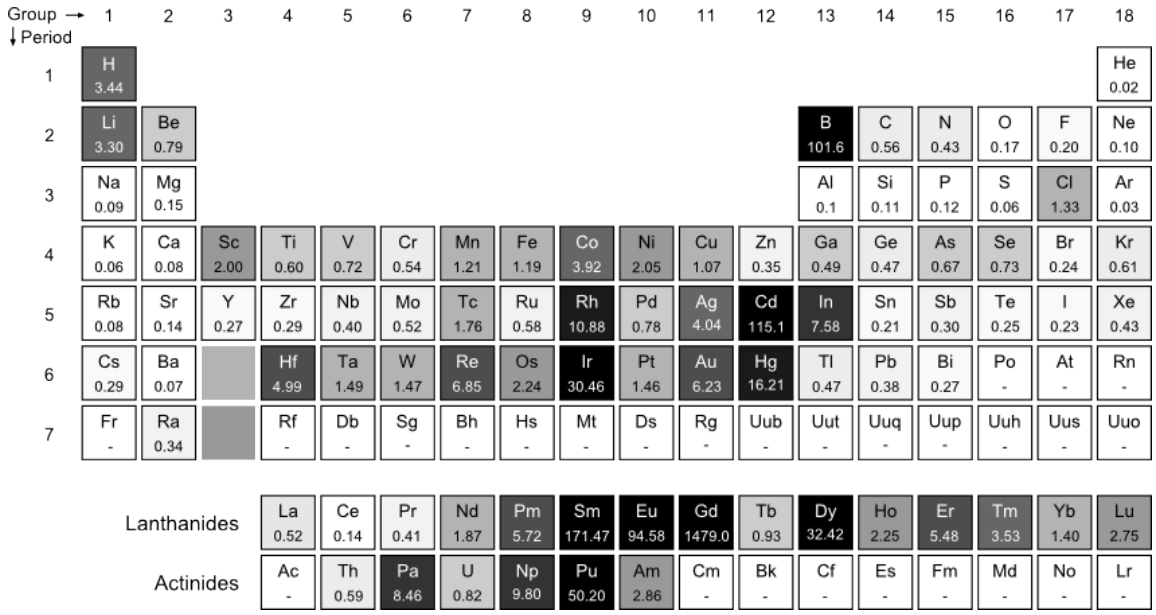


Fig. 8: Attenuation coefficients for thermal neutrons.

0.2.5 Some considered modalities for medical imaging

Imaging is widely used in medical applications. There are also many different imaging modalities available, each revealing it own particular information.

The modalities also differ in the resolution that can be achived. Therefore, it makes sense to combine the modalities to increase the understanding of provided information.

Du et al. 2015

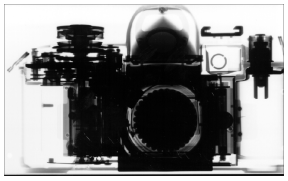


Fig. 9: X-ray radiography of a camera.

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 -

Fig. 10: Attenuation coefficients for 125keV X-rays.

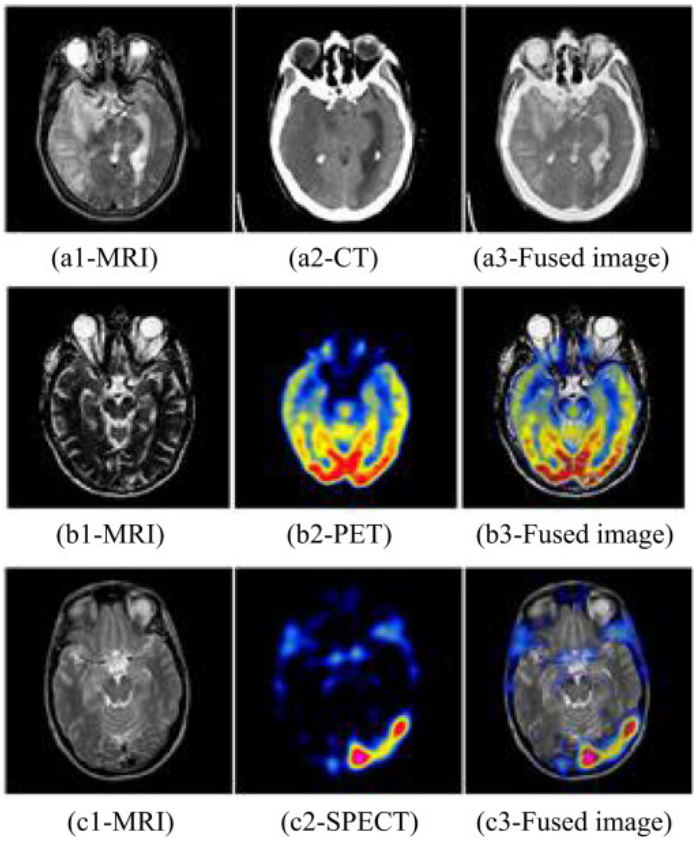


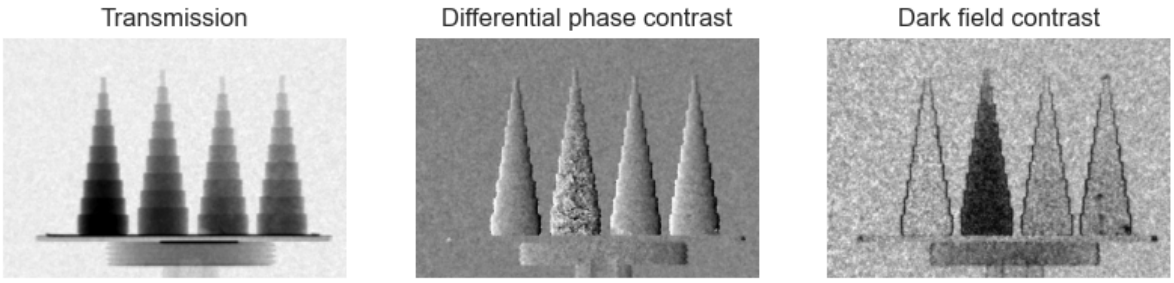
Fig. 11: Combining different medical imaging modalities.

0.2.6 Some considered modalities - Grating interferometry

Grating interferometry is an imaging technique that exploits the wave property of the beam. This makes it possible to extract more information than the traditional transmission image. These are

- The phase contrast - measures the phase shift of the beam to provide better contrast than the tranmission in some cases.
- The dark field contrast - is related to the scattered bream and can probe clusters of sample features that a much smaller than the resolution of the imaging system.

```
fig,ax=plt.subplots(1,3,figsize=(10,5))
ax[0].imshow(io.imread("figures/nGI_TI.png"));  ax[0].set_title('Transmission');
 ↪          ax[0].axis('off')
ax[1].imshow(io.imread("figures/nGI_DPC.png")); ax[1].set_title('Differential phase
 ↪contrast'); ax[1].axis('off')
ax[2].imshow(io.imread("figures/nGI_DFI.png")); ax[2].set_title('Dark field contrast
 ↪');         ax[2].axis('off');
```



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

0.2.7 Some considered modalities - Spectroscopic imaging

- Material analysis
- Selector calibration

S. Peetermans

0.2.8 Other modalities and dimensionality

The information can also be provided as few localized points

- Single point measurements
- Surface information
- Single radiographs vs CT data

to provide

- Temperature

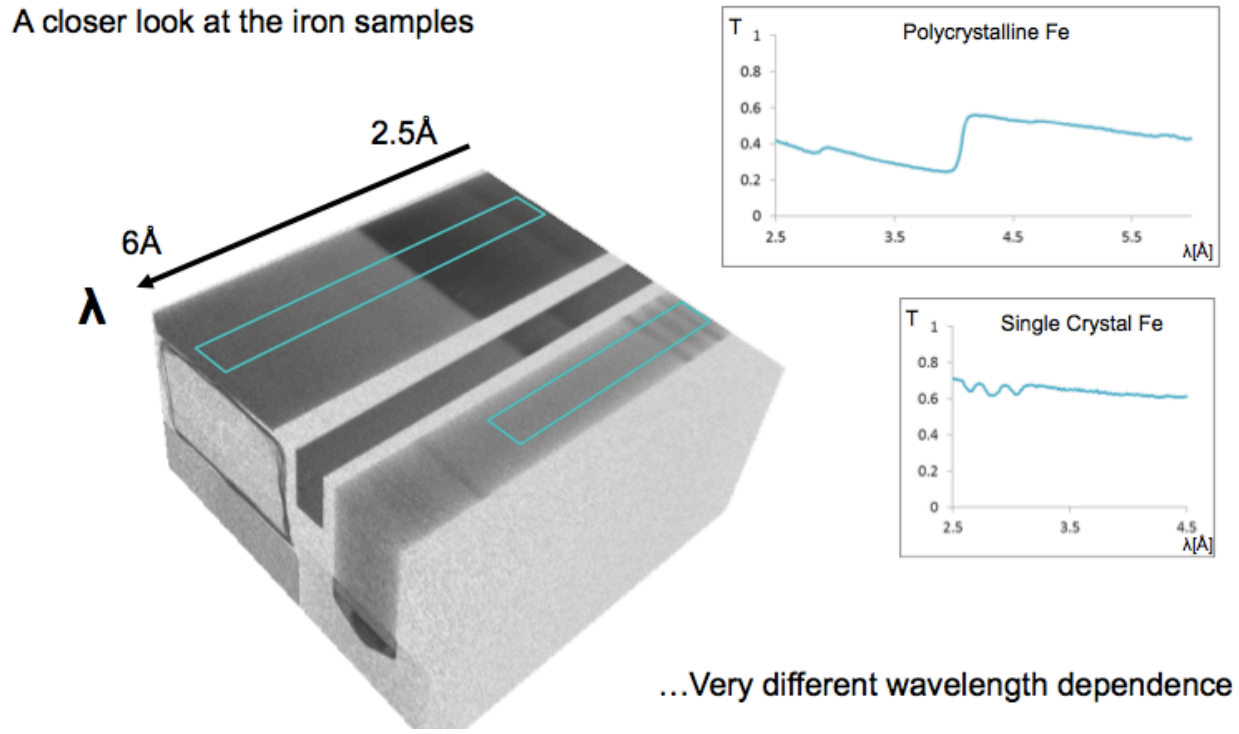


Fig. 12: Neutron energy scan through a piece of iron.

- Flowrate
- Pressure

0.3 Data and image fusion

0.3.1 Definition

The theory, techniques and tools which are used for

- combining sensor data, or data derived from sensory data,
- into a common representational format.

0.3.2 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

0.3.3 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:** A single fusion method may not give the final result - combination

Select strategy

The fusion strategy determined by:

- Sample composition
- Experiment objectives
- Condition of the data

Levels of fusion

Input	Output	Description
Data	Data	Input data is smoothed/filtered/segmented
Data	Feature	The pixels are reduced to features using multiple sources.
Feature	Feature	Input features are reduced in number, or new features are generated by fusing input features.
Feature	Decision	Input features are fused together to give output decision.
Decision	Decision	Multiple input decisions are fused together to give a final output decision. e.g. Random forest

0.4 Image fusion workflow

Image fusion is the process to combine images from different modalities with the aim to enhance the information compared the images individually. This process has serveral steps and the fusion can be done on several levels of abstraction.

Mitchel, 2010, Goshtasby, 2012

0.4.1 Catastrophic fusion

Definition

The combination perform worse than the individual modalities… don't fuse because you can!

Catastrofic fusion can be caused by:

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

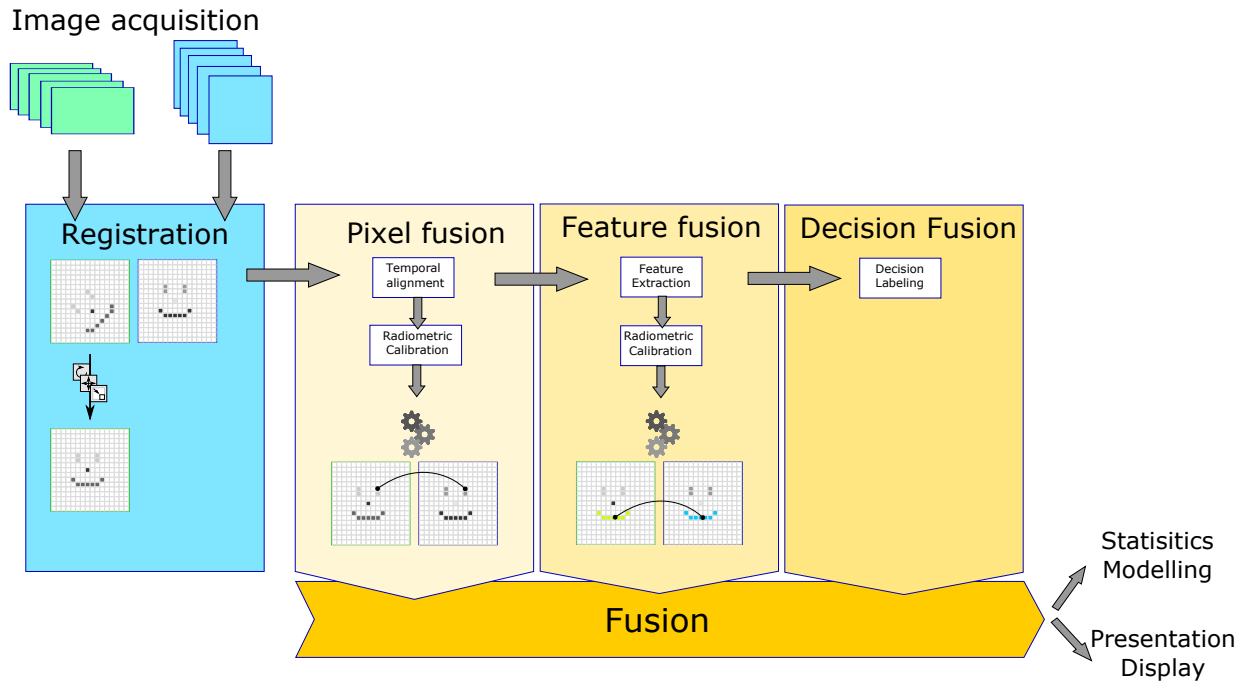


Fig. 1: Flow chart showing how image fusion can be done

Fig. 2: More chefs don't always mean better soup, the same applies to data fusion. Chose your source combination and fusion metods carefully.

0.4.2 Image registration

From last weeks lecture: A series of affine transformations to bring images on the same grid.

The process

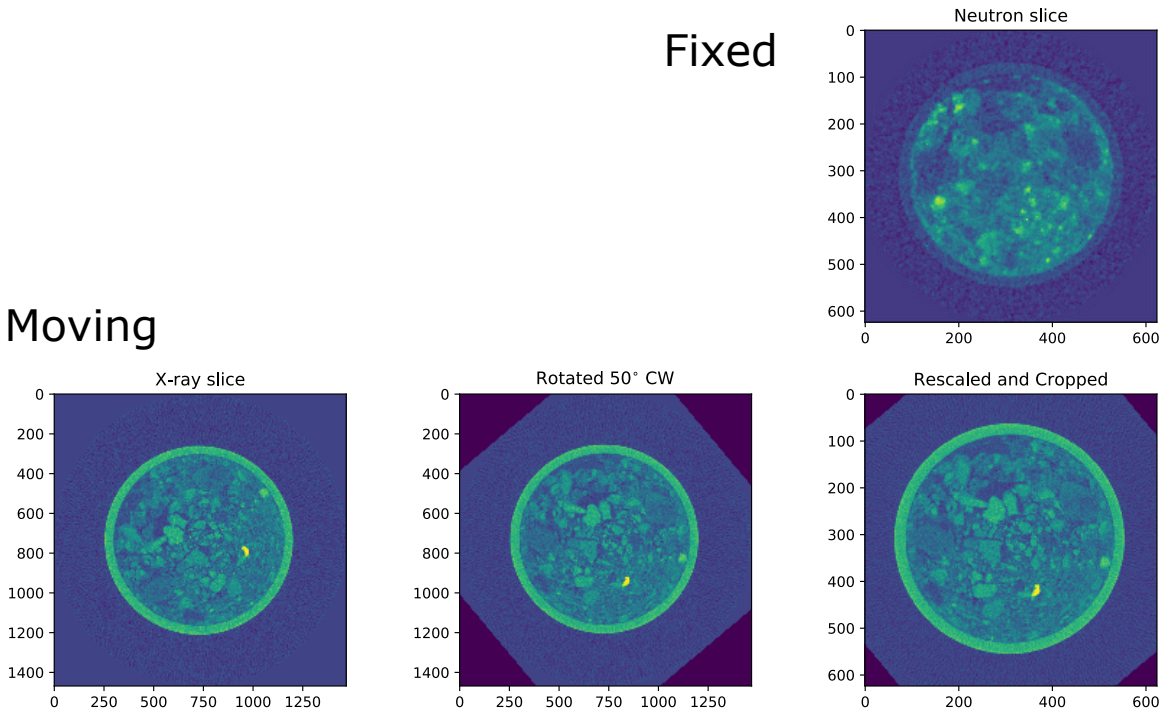


Fig. 3: Registration optimizes the scale, rotation, and position of an image compared to a fixed reference.

0.4.3 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

0.5 Qualitative fusion: Registration and covisualization

Use e.g. VG Studio or 3DSlicer to

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

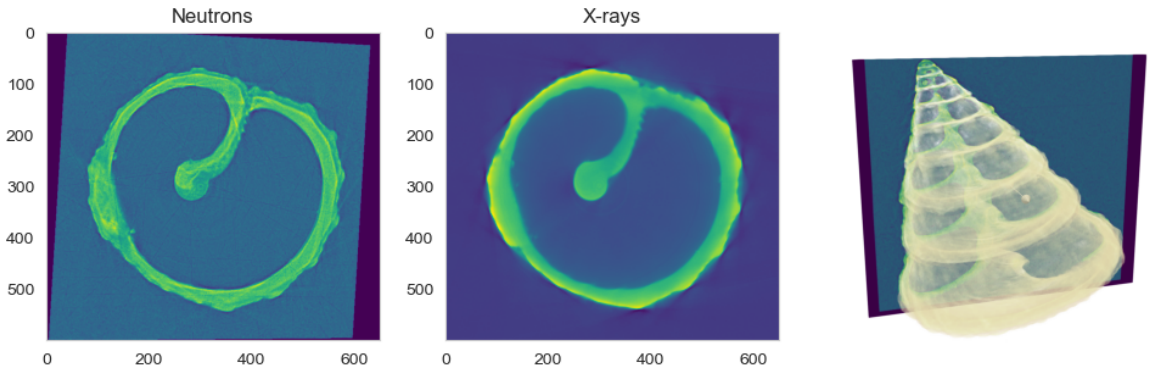
Fig. 1: The sword from lake Zug as seen with neutrons.

Fig. 2: The sword from lake Zug as seen with X-rays.

Mannes et al., 2015

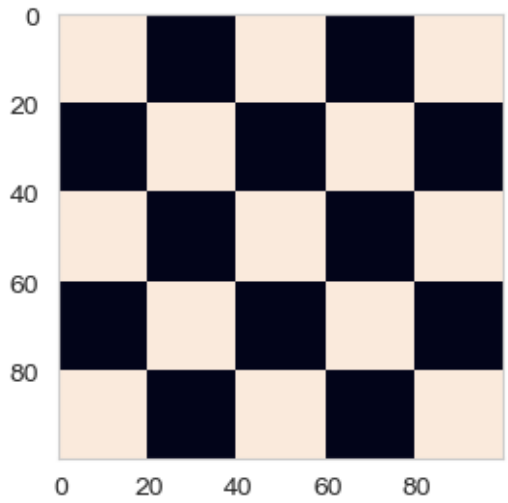
0.5.1 Let's load some test data

```
imgA=np.load('data/shellN.npy')
imgB=np.load('data/shellX.npy')
fig,(ax1,ax2,ax3) = plt.subplots(1,3,figsize=(12,5))
ax1.imshow(imgA,cmap='viridis'), ax1.set_title('Neutrons')
ax2.imshow(imgB,cmap='viridis'), ax2.set_title('X-rays');
ax3.imshow(plt.imread('figures/snailshellNeutron.png')); ax3.axis('off');
```



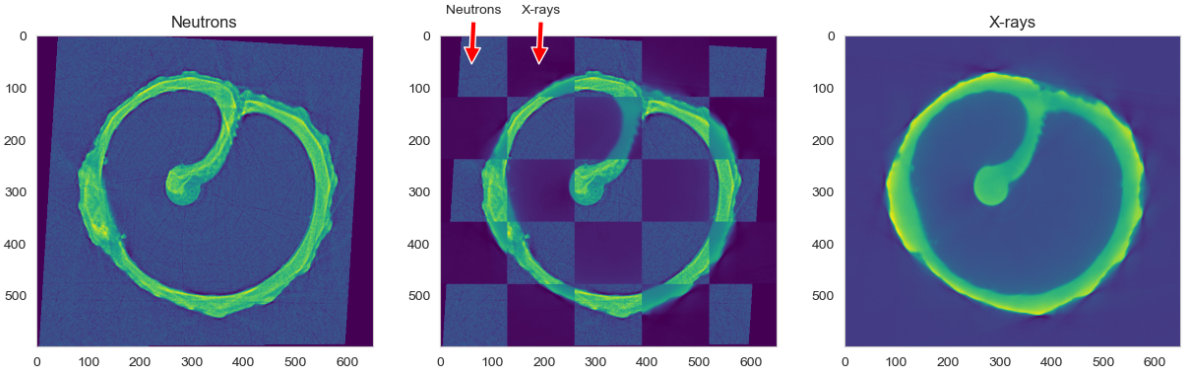
0.5.2 Visualization techniques - Checker board

```
def checkerBoard(imgA,imgB,tiles=10) :
    if imgA.shape != imgB.shape :
        raise Exception('Image have different sizes')

    dims     = imgA.shape
    tileSize = (dims[0]//tiles,dims[1]//tiles)

    mix = np.zeros(dims)

    for r in np.arange(0,tiles) :
        for c in np.arange(0,tiles) :
            if (c+r) % 2 :
                mix[(r*tileSize[0]):((r+1)*tileSize[0]),
 ↪(c*tileSize[1]):((c+1)*tileSize[1])]= imgB[(r*tileSize[0]):((r+1)*tileSize[0]),
 ↪(c*tileSize[1]):((c+1)*tileSize[1])]
            else :
                mix[(r*tileSize[0]):((r+1)*tileSize[0]),
 ↪(c*tileSize[1]):((c+1)*tileSize[1])]= imgA[(r*tileSize[0]):((r+1)*tileSize[0]),
 ↪(c*tileSize[1]):((c+1)*tileSize[1])]

    return mix
plt.figure(figsize=(3,3))
plt.imshow(checkerBoard(np.ones((100,100)),np.zeros((100,100)),tiles=5),interpolation=
 ↪'none');
```



Try checker board with images

```
fig,(ax1,ax2,ax3)=plt.subplots(1,3,figsize=(15,5))
ax1.imshow(imgA,cmap='viridis',vmin=10000,vmax=60000), ax1.set_title('Neutrons')
ax2.imshow(checkerBoard(imgA,imgB,tiles=5),cmap='viridis',vmin=10000,vmax=60000);
ax2.annotate('Neutrons',
             xy=(60, 60), xycoords='data',
             xytext=(0.1, 1.1), textcoords='axes fraction',
             arrowprops=dict(facecolor='red', shrink=0.05),
             horizontalalignment='center', verticalalignment='top')
ax2.annotate('X-rays',
             xy=(190, 60), xycoords='data',
             xytext=(0.3, 1.1), textcoords='axes fraction',
             arrowprops=dict(facecolor='red', shrink=0.05),
             horizontalalignment='center', verticalalignment='top')
ax3.imshow(imgB,cmap='viridis'), ax3.set_title('X-rays');
```



0.5.3 Visualization techniques - Color channel mixing

With two or three modalities, we can visualize the mix using the RGB color channels:

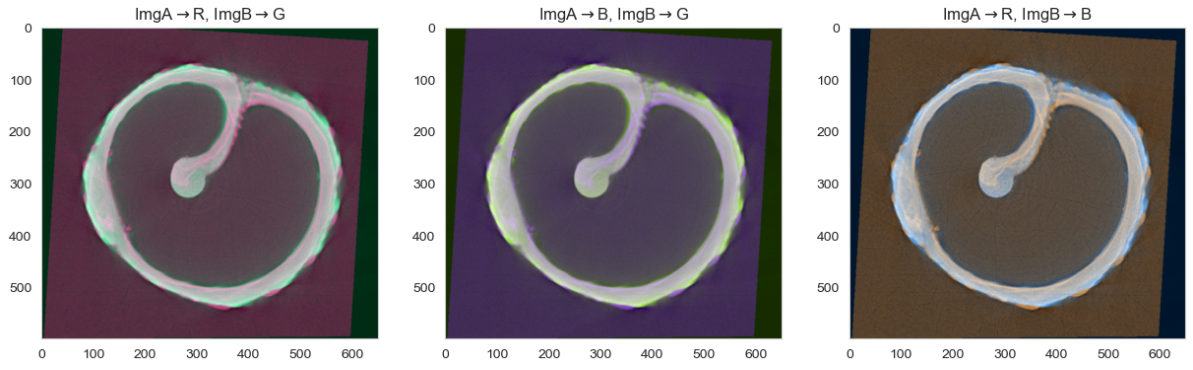
$$\begin{cases} R & modality_A \\ G & modality_B \\ B & \frac{modality_A + modality_B}{2} \end{cases}$$

some intensity scaling may be needed for best result.

Implementation of channel mixing

```
def channelMix(imgA,imgB, order=(0,1,2)) :
    imgAN=(imgA-imgA.min())/(imgA.max()-imgA.min())
    imgBN=(imgB-imgB.min())/(imgB.max()-imgB.min())

    rgb=np.zeros((imgA.shape[0],imgA.shape[1],3));
    rgb[:,:,order[0]]=imgAN
    rgb[:,:,order[1]]=imgBN
    rgb[:,:,order[2]]=0.5*(imgAN+imgBN)

    return rgb
```

```
fig,(ax1,ax2,ax3)=plt.subplots(1,3,figsize=(15,6))
ax1.imshow(channelMix(imgA,imgB,order=(0,1,2))), ax1.set_title(r'ImgA$\rightarrow$R,␣
↪ImgB$\rightarrow$G');
ax2.imshow(channelMix(imgA,imgB,order=(2,1,0))), ax2.set_title(r'ImgA$\rightarrow$B,␣
↪ImgB$\rightarrow$G');
ax3.imshow(channelMix(imgA,imgB,order=(0,2,1))), ax3.set_title(r'ImgA$\rightarrow$R,␣
↪ImgB$\rightarrow$B');
```



0.6 Bimodal segmentation

0.6.1 Histogram of single modality

When you do experiments with a single modiality, you only obtain a single histogram. The modes of the histogram may merge into a single mode if the SNR is too low to separate the feature classes. This leads to a large amount of miss-classifications. The blue region between the histogram peaks in Figure 1 represents the area of ambiguous decisions.

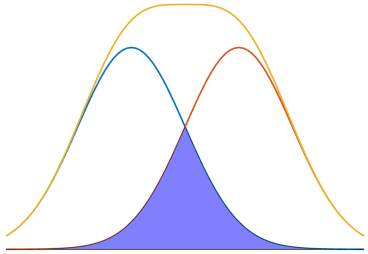


Fig. 1: Histogram of two classes using modality *A*.

0.6.2 Individual histograms of two modalities

Now we may conclude that the first modality we looked at doesn't provide sufficient information to make a reliable segmentation. Therefore, we go to a second modality. Unfortunately, this modality has the same low class separability as you can see in Figure 2. This time the two classes have different responses and the histogram modes have swapped compared to Figure 1.

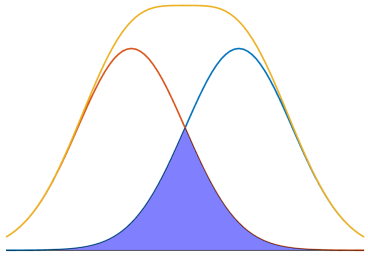


Fig. 2: Histogram of two classes using modality *B*.

So the conclusion is that we don't get much closer to our segmented image using these modalities individually.

0.6.3 Bivariate histogram

Now, if we start combining the two modalities, we start seeing the benefit of using more than one modality. The bivariate histogram, which we already have looked at in previous lectures is a great way to visualize how two variables depend on each other.

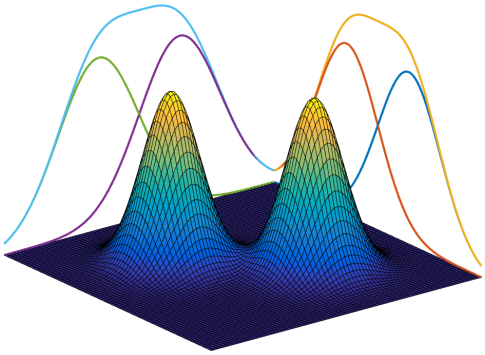


Fig. 3: A bivariate histogram of modalities A and B.

In the histogram show in Figure 3, we see that there is a clear separation between class A and B that could be easily thresholded.

Example: Roots in soil

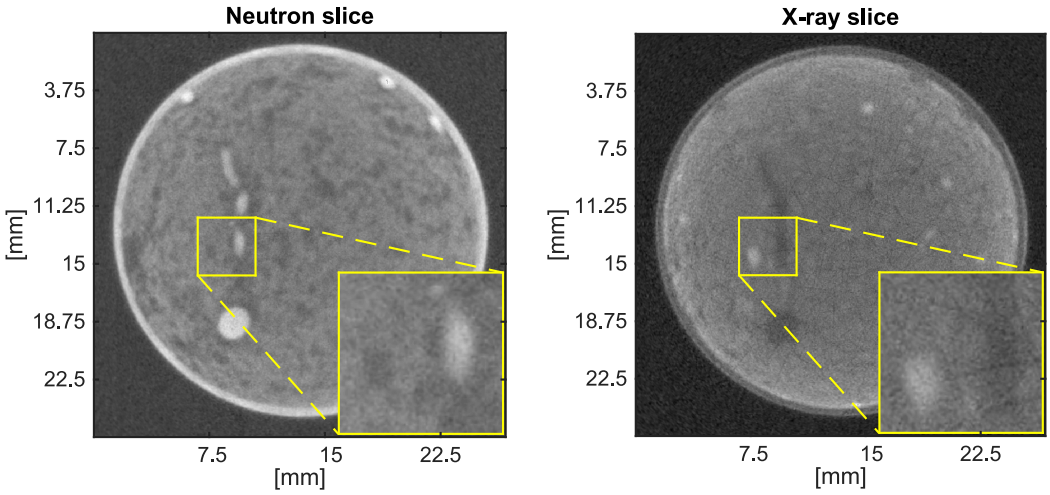


Fig. 4: Tomography slices of a soil sample with roots.

Kaestner et al., 2016

Bivariate histogram of roots

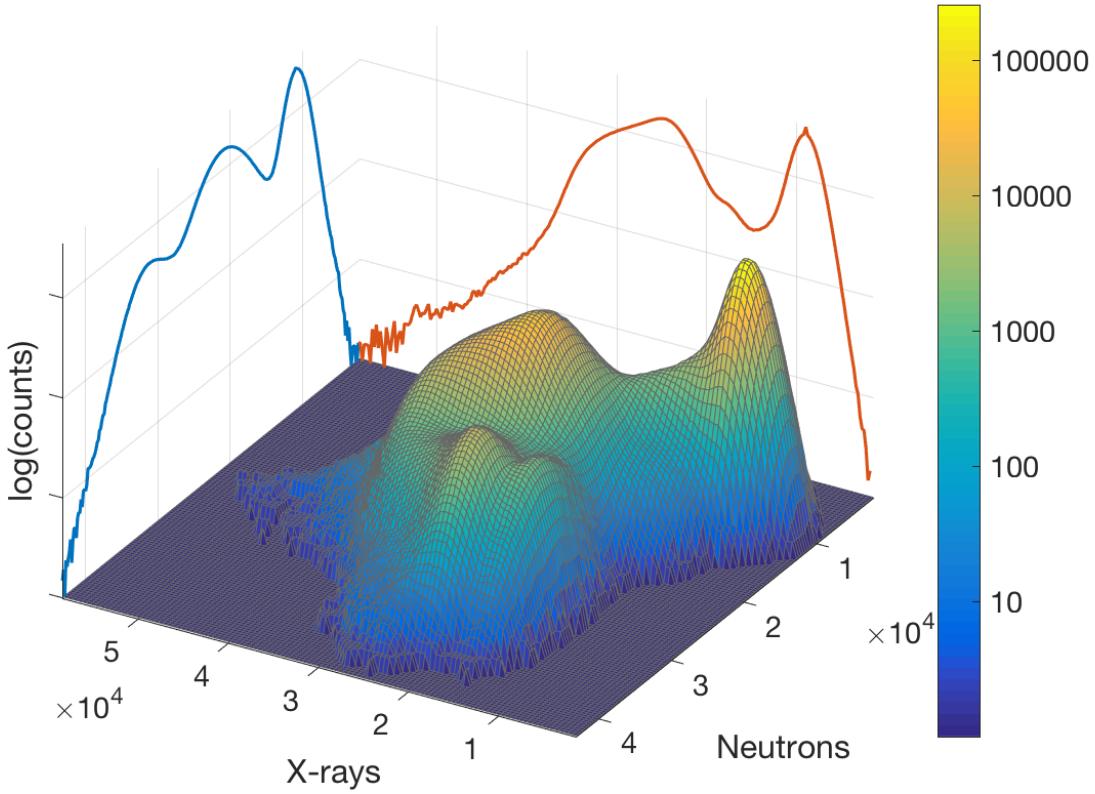


Fig. 5: Bivariate histogram of the root images in Figure 4

0.6.4 Segmentation methods

Data

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

Classes

The N classes are described by: $\begin{cases} \mathcal{H}_1 : p(?_1, \Sigma_1) \\ \mathcal{H}_2 : p(?_2, \Sigma_2) \\ \vdots \\ \mathcal{H}_N : p(?_N, \Sigma_N) \end{cases}$ $

Duda, Hart, and Stork, 2001

0.6.5 Previous segmentation methods

In this class we have already looked into many different ways to perform the segmentation on images. These are methods that are well suited for segmenting bi- or multivariate data:

- k-means
- k-NN
- Regression
- Neural networks

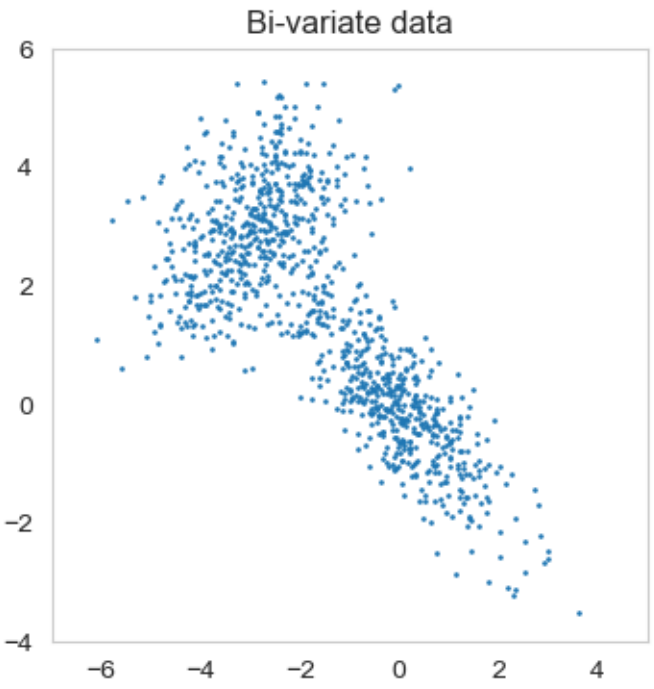
0.6.6 Gaussian mixture model

With Gaussian distribution we can describe the bivariate histogram using: $$p(\theta) = \sum_1^N \phi_i \, \mathcal{N}(?_i, \Sigma_i)$$

- μ_i - vector with averages for each class.
- Σ_i - covariance matrix for each class.
- ϕ_i - mixing coefficient.

```
# Number of samples per component
n_samples = 500

# Generate random sample, two components
np.random.seed(0)
C1 = np.array([[1, -0.5], [-0.5, 1]])
C2 = np.array([[1, 0.25], [0.25, 1]])
X = np.r_[np.dot(np.random.randn(n_samples, 2), C1), np.dot(np.random.randn(n_samples,
 ↪ 2),C2) + np.array([-3, 3])]
```

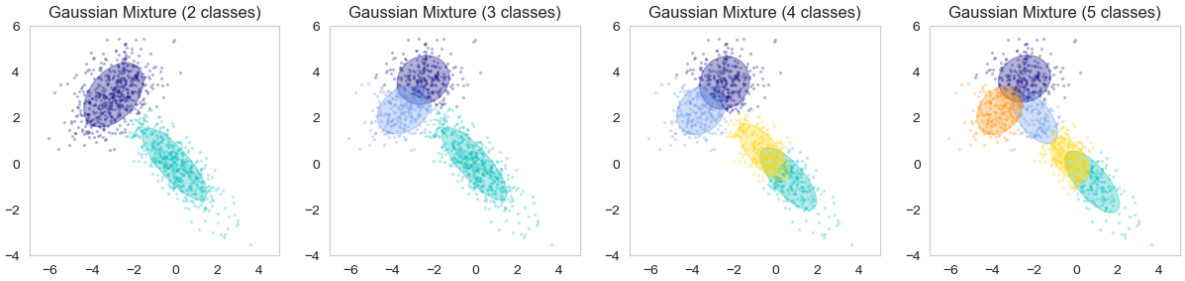
```
plt.figure(figsize=[4,4])
plt.scatter(X[:,0],X[:,1],0.8)
plt.xlim(-7., 5.),plt.ylim(-4., 6.)
plt.title('Bi-variate data');
```




```
def plot_results(X, Y_, means, covariances, title, ax, showShape=True,␣
↪showCenter=False):
    color_iter = itertools.cycle(['navy', 'c', 'cornflowerblue', 'gold',
                                  'darkorange'])

    for i, (mean, covar, color) in enumerate(zip(
            means, covariances, color_iter)):
        v, w = linalg.eigh(covar)
        v = 2. * np.sqrt(2.) * np.sqrt(v)
        u = w[0] / linalg.norm(w[0])
        # as the DP will not use every component it has access to
        # unless it needs it, we shouldn't plot the redundant
        # components.
        if not np.any(Y_ == i):
            continue
        ax.scatter(X[Y_ == i, 0], X[Y_ == i, 1],2, color=color,alpha=0.2)

        # Plot an ellipse to show the Gaussian component
        if showShape :
            angle = np.arctan(u[1] / u[0])
            angle = 180. * angle / np.pi  # convert to degrees
            ell = mpl.patches.Ellipse(mean, v[0], v[1], angle=180. + angle,␣
↪color=color)
            ell.set_clip_box(ax.bbox)
            ell.set_alpha(0.3)
            ax.add_artist(ell)

        if showCenter :
            ax.plot(mean[0],mean[1],'ro')

    ax.set_xlim(-7., 5.)
    ax.set_ylim(-4., 6.)
    ax.set_title(title)
```

Gaussian mixture model fitting

```
fig, axes = plt.subplots(1,4,figsize=(15,3))
# Fit a Gaussian mixture with EM using five components
for i,ax in zip(np.arange(0,len(axes.ravel())),axes.ravel()) :
    classes = i+2
    gmm = mixture.GaussianMixture(n_components=classes,random_state=0, covariance_
↪type='full').fit(X)

    plot_results(X, gmm.predict(X), gmm.means_, gmm.covariances_,
             title='Gaussian Mixture ({} classes)'.format(classes), ax=ax)
```



0.6.7 Classification distances

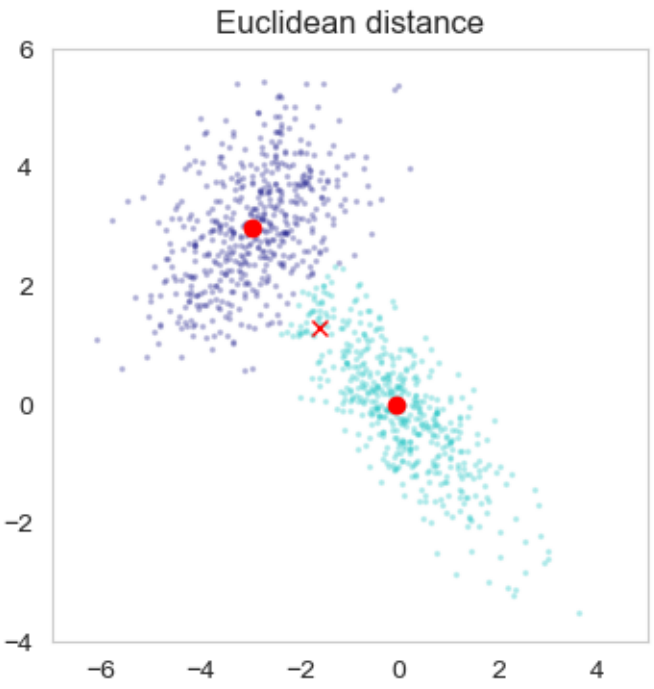
For a set of multivariate normal distributions $p_i = \mathcal{N}(\mu_i, \Sigma_i)$

We can find the nearest neighbor class using the following distances

Euclidean

Distance between two points $$D_E = \sqrt{(x-\mu_1)^T \cdot (x-\mu_1)}$$

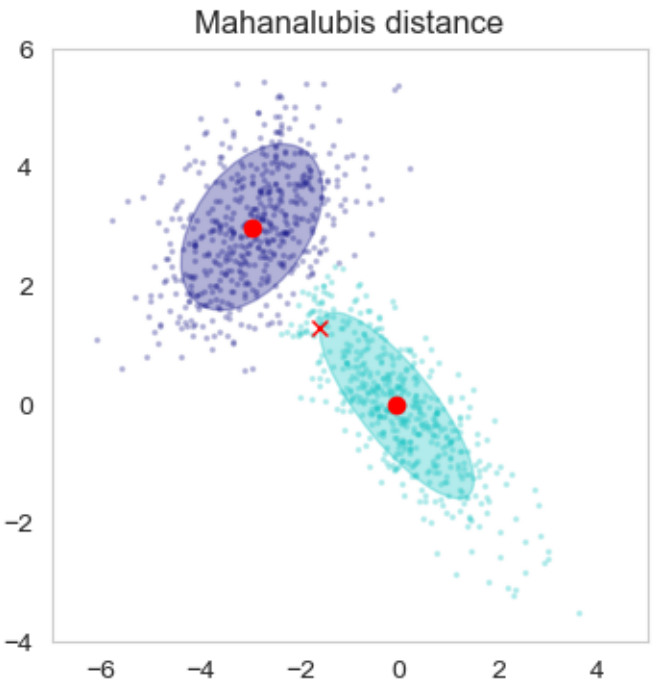
```
gmm = mixture.GaussianMixture(n_components=2, covariance_type='full').fit(X)
m=[-1.6,1.3]
fig,ax1=plt.subplots(1,figsize=(4,4))

plot_results(X, gmm.predict(X), gmm.means_, gmm.covariances_,
             'Euclidean distance',ax1, showShape=False,showCenter=True)
ax1.plot(-1.6,1.3,'rx');
```



Mahanalubis

Distance from class i to point x $D_M = \sqrt{(x-\mu_i)^T \Sigma_i (x-\mu_i)}$

```
gmm = mixture.GaussianMixture(n_components=2, covariance_type='full').fit(X)
m=[-1.6,1.3]
fig,ax2=plt.subplots(1,figsize=(4,4))

plot_results(X, gmm.predict(X), gmm.means_, gmm.covariances_,
             'Mahanalubis distance'.format(2),ax2, showCenter=True)
ax2.plot(-1.6,1.3,'rx');
```

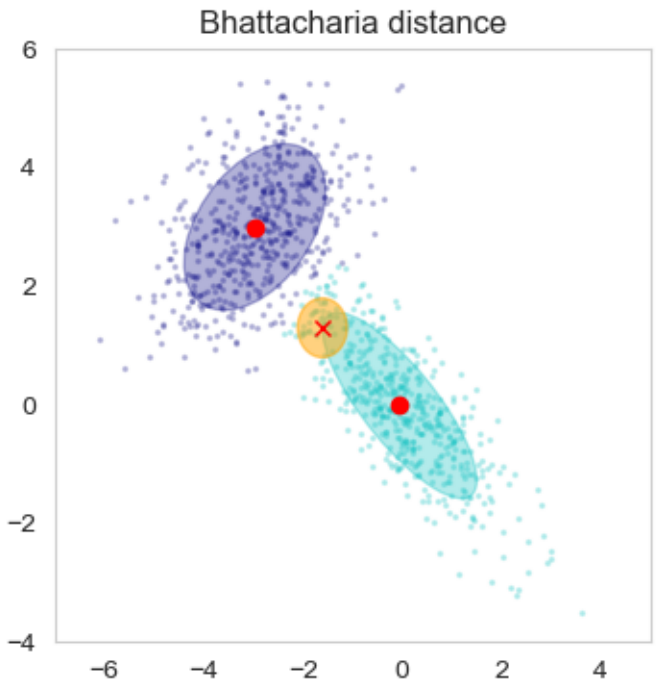


Bhattacharia

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

Assign the point to the class with shortest distance.

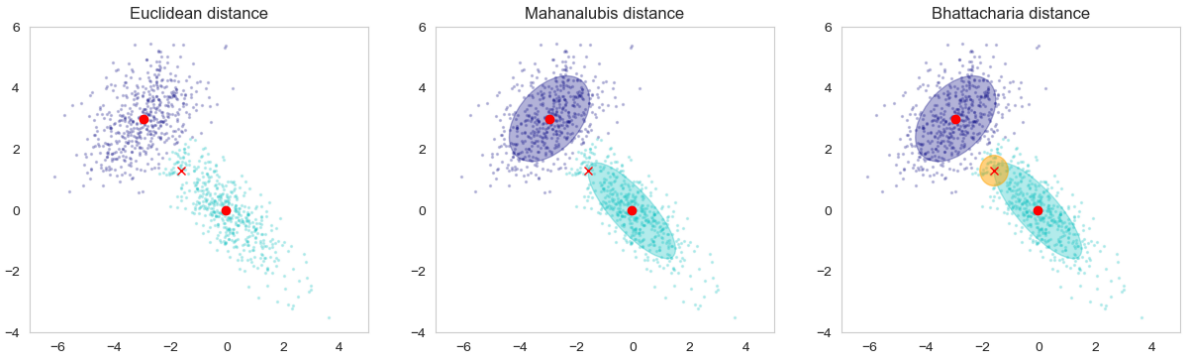
```
gmm = mixture.GaussianMixture(n_components=2, covariance_type='full').fit(X)
m=[-1.6,1.3]
fig,ax3=plt.subplots(1,figsize=(4,4))

plot_results(X, gmm.predict(X), gmm.means_, gmm.covariances_,
             'Bhattacharia distance'.format(2),ax3, showCenter=True)
v=1
ell = mpl.patches.Ellipse(m, v, v, angle=0, color='orange')
ell.set_clip_box(ax3.bbox)
ell.set_alpha(0.5)
ax3.add_artist(ell)
ax3.plot(m[0],m[1],'rx');
```



0.6.8 Graphical presentation of the different distances

```
gmm = mixture.GaussianMixture(n_components=2, covariance_type='full').fit(X)
m=[-1.6,1.3]
fig,(ax1,ax2,ax3)=plt.subplots(1,3,figsize=(15,4))

plot_results(X, gmm.predict(X), gmm.means_, gmm.covariances_,
             'Euclidean distance',ax1, showShape=False,showCenter=True)
ax1.plot(-1.6,1.3,'rx')
plot_results(X, gmm.predict(X), gmm.means_, gmm.covariances_,
             'Mahanalubis distance'.format(2),ax2, showCenter=True)
ax2.plot(-1.6,1.3,'rx')

plot_results(X, gmm.predict(X), gmm.means_, gmm.covariances_,
             'Bhattacharia distance'.format(2),ax3, showCenter=True)
v=1
ell = mpl.patches.Ellipse(m, v, v, 0, color='orange')
ell.set_clip_box(ax3.bbox)
ell.set_alpha(0.5)
ax3.add_artist(ell)
ax3.plot(m[0],m[1],'rx');
```

```
/var/folders/hj/l3z3z7bj663f4wp4vlx69lt40000nw/T/ipykernel_39014/1990464347.py:15:␣
 ↪MatplotlibDeprecationWarning: Passing the angle parameter of __init__()␣
 ↪positionally is deprecated since Matplotlib 3.6; the parameter will become␣
 ↪keyword-only two minor releases later.
  ell = mpl.patches.Ellipse(m, v, v, 0, color='orange')
```



0.6.9 Segmentation by Euclidean distance

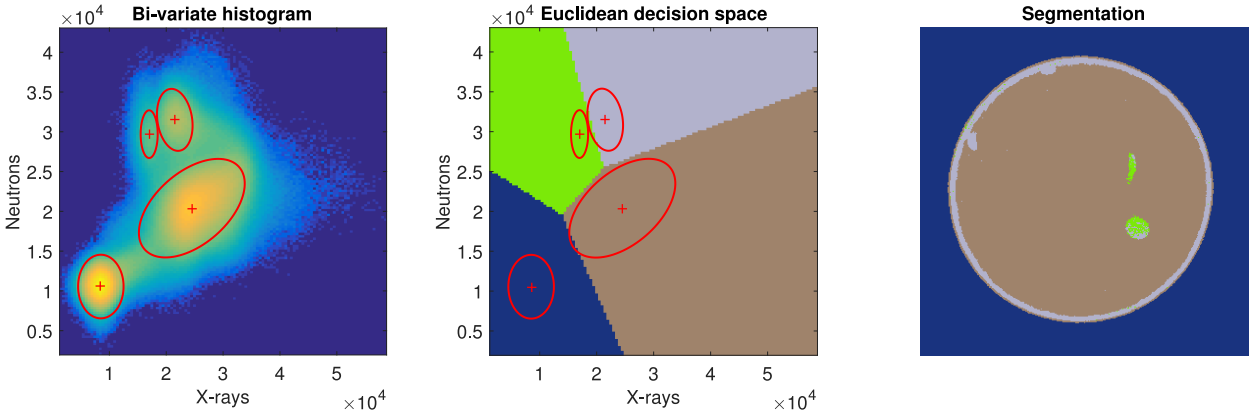


Fig. 6: Segmenting the root image in

Kaestner et al., 2016

0.7 Bivariate estimation: Working with attenuation coefficients

0.7.1 Beer-Lamberts law

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

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

0.7.2 Equation system

$$\sum_{i=1}^{N} \Sigma_i \, x_i = q_N$$
$$\sum_{i=1}^{N} \mu_i \, x_i = q_X$$

- attn coeff known → estimate lengths.
- More pixels → more materials.

0.8 Beyond multi modal experiments

Many bimodal experiments are done separately.

There many reasons for this, two are:

- Limited resources
- Scanners at different locations

This is often the case in medical imaging where the hospitals have different dedicated machines for each modality. It is also not always that the patient is scan using all relevant modalities at the same time, but different modalities are used at different stages of the therapy.

This is also a common approach in materials science and ex situ imaging. The home laboratory may own their own X-ray CT scanner but they need to got to a large scale facility to obtain more information with further modalities.

Next steps:

- Dynamic experiments

Last week we looked into the topic of dynamic experiments. The use of bimodal imaging is also very relevant in dynamic experiments. The observed samples and processes often change shape when you introduce a liquid, apply a preasure, etc. These shape changes are often more visible in one modality than the other. Ideally, you will have a system where one modality is sensitive to dimensional changes while the other is sensity the changes in mixing ratios and other process related parameters.

- Combined setups

Combined setups all simultaneous acquisition using two modalities. This has the advantage that you can perform dynamic experiments.

Figure 3 show a setup for bimodal neutron and X-ray imaging. The system has two difference beam geometries neutrons uses parallel beam and X-rays a cone beam. The beams are also at oblique angles and mostly also resulting in different resolutions, there it is a first requirement that the resulting iamges are registered before any analysis can be performed.

0.9 Some software engineering

Repeatable workflows require some software engineering skills

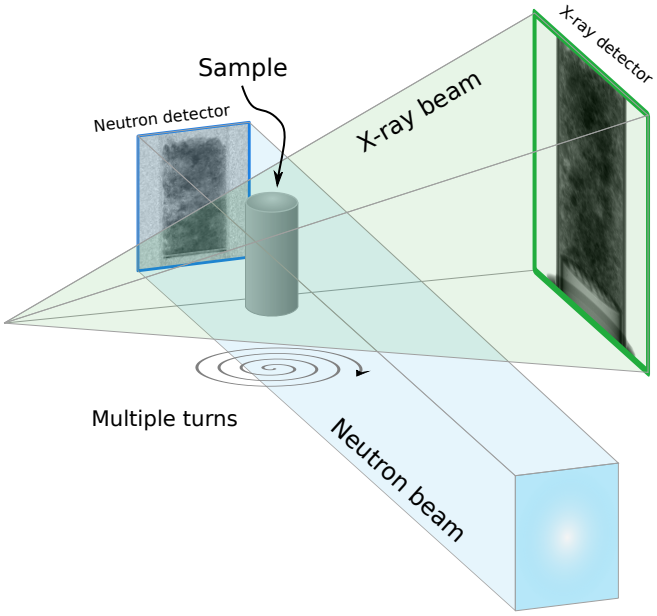


Fig. 1: The outline of a bimodal imaging system for neutrons and X-rays.

0.9.1 Repeatable workflows

From lecture 8

Repeatability requires that your code:

- is testable
- has a tracked history
- is reviewed
- is documented

… and keep track of bugs and new ideas in an issue manager.

Tools to support reproducible workflows

Use a repository

History management

Use automated tests

Guarantees unit functionality

Use a build server

Combines repository and tests

0.9.2 How to organize the code

Notebooks are good for prototyping … but are not good for

- structuring/maintenance
- repositories
- portability/sharing
- testing

Save functions in .py files which are imported

Your functions are saved in a file 'mylib.py'

```
import mylib

mylib.myfunction(1234)
```

Reload during development

```
import importlib
importlib.reload(mylib)
```

0.9.3 API Documentation

API documentation is a minimum!

Doc string in python

```
def fancy_function(value) :
    """ Description: Makes fantastic calculations

    Parameters:
    value (int): Description of argument

    Returns:
    int: Returning value

    """
    return 42+value

help(fancy_function)
```

```
Help on function fancy_function in module __main__:

fancy_function(value)
    Description: Makes fantastic calculations

    Parameters:
    value (int): Description of argument

    Returns:
    int: Returning value
```

Doxygen for many languages

https://www.doxygen.nl

0.9.4 Unit Testing

In computer programming, unit testing is a method by which individual units of source code, sets of one or more computer program modules together with associated control data, usage procedures, and operating procedures, are tested to determine if they are fit for use.

- Intuitively, one can view a unit as the smallest testable part of an application
- Unit testing is possible with every language
- Most (Java, C++, Matlab, R, Python) have built in support for automated testing and reporting

Computational science: … Error

0.9.5 Unit Testing - design

The first requirement for unit testing to work well is to have your code divided up into small independent parts (functions)

What to test?

- Each part can then be tested independently (unit testing)
  - If the tests are well done, units can be changed and tested independently
  - Makes upgrading or expanding tools *easy*
- The entire path can be tested (integration testing)
  - Catches mistakes in integration or *glue*

How to test

- The *happy path* - check what it is supposed to do
- To **provoke** your code - provide data that will fail execution

Test data

Ideally with realistic but simulated test data

0.9.6 Example

Given the following function `function vxCnt=countVoxs(inImage)`

We can write the following tests:

testEmpty2d

```
assert countVoxs(zeros(3,3)) == 0
```

testEmpty3d

```
assert countVoxs(zeros(3,3,3)) == 0
```

testDiag2d

```
assert countVoxs(eye(3)) == 3
```

0.9.7 Unit Testing: Example

Given the following function `function shapeTable=shapeAnalysis(inImage)`

We should decompose the function into sub-components with single tasks:

```
from graphviz import Digraph
dot = Digraph()
dot.edge('shapeAnalysis(inImage)', 'componentLabel(inImage)'), dot.edge(
 ↪'shapeAnalysis(inImage)', 'analyzeObject(inObject)')
dot.edge('analyzeObject(inObject)','countVoxs(inObject)'),     dot.edge(
 ↪'analyzeObject(inObject)','calculateCOV(inObject)')
dot.edge('analyzeObject(inObject)','calcShapeT(covMat)'),      dot.edge(
 ↪'analyzeObject(inObject)','calcOrientation(shapeT)')
dot.edge('analyzeObject(inObject)','calcAnisotropy(shapeT)')
dot
```

```
<graphviz.graphs.Digraph at 0x16882af40>
```

0.9.8 Unit Testing in Python

PyTest

Packages like PyTest are

- well suited for larger projects
- you make a set of specific tests for each module
- run each time the project is updated.

0.9.9 Unit testing examples from Scikit Image

https://github.com/scikit-image/scikit-image/tree/master/skimage

- Test Watershed
- Test Connected Components

```
class TestWatershed(unittest.TestCase):
    eight = np.ones((3, 3), bool)

    def test_watershed01(self):
        "watershed 1"
        data = np.array([[0, 0, 0, 0, 0, 0, 0],
                         [0, 0, 0, 0, 0, 0, 0],
                         [0, 0, 0, 0, 0, 0, 0],
                            [0, 1, 1, 1, 1, 1, 0],
                            [0, 1, 0, 0, 0, 1, 0],
                            [0, 1, 0, 0, 0, 1, 0],
                            [0, 1, 0, 0, 0, 1, 0],
                            [0, 1, 1, 1, 1, 1, 0],
                            [0, 0, 0, 0, 0, 0, 0],
                            [0, 0, 0, 0, 0, 0, 0]], np.uint8)
        markers = np.array([[ -1, 0, 0, 0, 0, 0, 0],
                            [0, 0, 0, 0, 0, 0, 0],
                            [0, 0, 0, 0, 0, 0, 0],
                               [  0, 0, 0, 0, 0, 0, 0],
                               [  0, 0, 0, 0, 0, 0, 0],
                               [  0, 0, 0, 1, 0, 0, 0],
                               [  0, 0, 0, 0, 0, 0, 0],
                               [  0, 0, 0, 0, 0, 0, 0],
                               [  0, 0, 0, 0, 0, 0, 0],
                               [  0, 0, 0, 0, 0, 0, 0]],
                             np.int8)
        out = watershed(data, markers, self.eight)
        expected = np.array([[-1, -1, -1, -1, -1, -1, -1],
                       [-1, -1, -1, -1, -1, -1, -1],
                       [-1, -1, -1, -1, -1, -1, -1],
                       [-1,  1,  1,  1,  1,  1, -1],
                       [-1,  1,  1,  1,  1,  1, -1],
                       [-1,  1,  1,  1,  1,  1, -1],
                       [-1,  1,  1,  1,  1,  1, -1],
                       [-1,  1,  1,  1,  1,  1, -1],
                       [-1, -1, -1, -1, -1, -1, -1],
                       [-1, -1, -1, -1, -1, -1, -1]])
        error = diff(expected, out)
        assert error < eps
```

0.9.10 Unit testing in python - DocTests

Keep the tests in the code itself:

```
def apply_hysteresis_threshold(image, low, high):
    """Apply hysteresis thresholding to `image`.
    This algorithm finds regions where `image` is greater than `high`
    OR `image` is greater than `low` *and* that region is connected to
    a region greater than `high`.
    Parameters
    ----------
    image : array, shape (M,[ N, ..., P])
        Grayscale input image.
    low : float, or array of same shape as `image`
        Lower threshold.
    high : float, or array of same shape as `image`
        Higher threshold.
    Returns
    -------
    thresholded : array of bool, same shape as `image`
        Array in which `True` indicates the locations where `image`
        was above the hysteresis threshold.
    Examples
    --------
    >>> image = np.array([1, 2, 3, 2, 1, 2, 1, 3, 2])
    >>> apply_hysteresis_threshold(image, 1.5, 2.5).astype(int)
    array([0, 1, 1, 1, 0, 0, 0, 1, 1])
    References
    ----------
    .. [1] J. Canny. A computational approach to edge detection.
           IEEE Transactions on Pattern Analysis and Machine Intelligence.
           1986; vol. 8, pp.679-698.
           DOI: 10.1109/TPAMI.1986.4767851
    """
    low = np.clip(low, a_min=None, a_max=high)  # ensure low always below high
    mask_low = image > low
    mask_high = image > high
```

0.9.11 Unit Testing with Jupyter

Working primarily in notebooks makes regular testing more difficult but not impossible.

- If we employ a few simple tricks we can use doctesting seamlessly inside of Jupyter.
- We can make what in python is called an annotatation to setup this code.

```
import doctest
import copy
import functools

def autotest(func):
    globs = copy.copy(globals())
    globs.update({func.__name__: func})
    doctest.run_docstring_examples(
        func, globs, verbose=True, name=func.__name__)
    return func
```

A very simple test

This test will be used in a jupyter notebook.

It is implemented as a DocTest. The function is supposed to return five added to the input value. The test is implemented for the specific case with the input '5' and we expect the function to return 10.

```
@autotest
def add_5(x):
    """
    Function adds 5
    >>> add_5(5)
    10
    """
    return x+5
```

```
Finding tests in add_5
Trying:
    add_5(5)
Expecting:
    10
ok
```

The test returned 10 and DocTest concludes that the test passed with an 'ok'. This is a very simple function that already assumes you enter a number, but what would happen if we call the function with a string of a complicated object of some kind? The function should be extended with checks if the correct data type is provided, which in turn would require further tests to verify that the functionality under these conditions.

Testing an image processing algorithm

Numerical algorithms are often hard to check with unit tests. In particular, when noise is added. You can however always test the basic functionality. Below we have an example that tests wether the label function does what it is supposed to do:

1. A single object - labels 0 and 1
2. Break the object in two - labels 0-2

```
from skimage.measure import label
import numpy as np
@autotest
def simple_label(x):
    """
    Label an image
    >>> test_img = np.eye(3)
    >>> test_img
    array([[1., 0., 0.],
           [0., 1., 0.],
           [0., 0., 1.]])
    >>> simple_label(test_img)
    array([[1, 0, 0],
           [0, 1, 0],
           [0, 0, 1]])
    >>> test_img[1,1] = 0
    >>> simple_label(test_img)
    array([[1, 0, 0],
           [0, 0, 0],
```

(continues on next page)

(continued from previous page)

```
        [0, 0, 2]])
    """
    return label(x)
```

```
Finding tests in simple_label
Trying:
    test_img = np.eye(3)
Expecting nothing
ok
Trying:
    test_img
Expecting:
    array([[1., 0., 0.],
           [0., 1., 0.],
           [0., 0., 1.]])
ok
Trying:
    simple_label(test_img)
Expecting:
    array([[1, 0, 0],
           [0, 1, 0],
           [0, 0, 1]])
ok
Trying:
    test_img[1,1] = 0
Expecting nothing
ok
Trying:
    simple_label(test_img)
Expecting:
    array([[1, 0, 0],
           [0, 0, 0],
           [0, 0, 2]])
ok
```

Unit Testing Matlab

https://www.mathworks.com/help/matlab/matlab-unit-test-framework.html

Unit Testing in C++

- Google test
- Boost.test
- QTest

Test management by `CTest` from `CMake`

0.9.12 Test Driven Programming

Test Driven programming is a style or approach to programming where

1. *the tests are written before the functional code*.
2. The tests are like very concrete specifications.
3. It is easy to estimate project progress since you can automatically see how many of the tests have been passed.

You and your collaborators are clear on the utility of the system.

1. shapeAnalysis must give an anisotropy of 0 when we input a sphere
2. shapeAnalysis must give the center of volume within 0.5 pixels
3. shapeAnalysis must run on a 1000x1000 image in 30 seconds

0.9.13 Using repositories

A repository is (simply put) a backup system tailored to the needs of software development.

- Synchronizes multiple versions
- Manages development branches
- Located on a centralized server

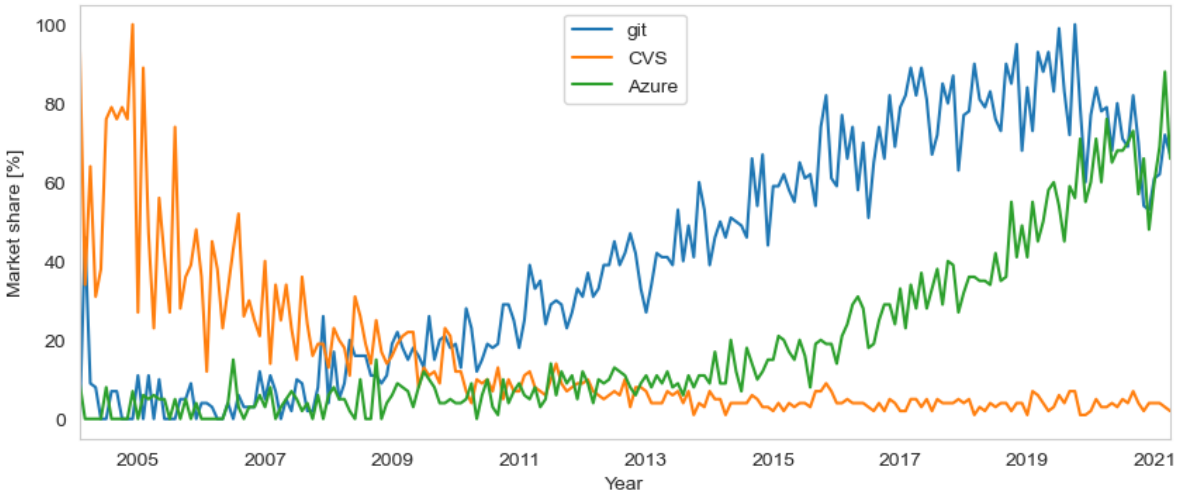
Why should I use a repository?

- It makes it easy to got back to earlier versions
- It is good for reproducibility
- Makes bug tracking easier
- Easier for a team to work on the same code (without disturbing each other)

Different repository frameworks

- **Git**
- Azure
- Subversion
- CVS

```
fig,ax=plt.subplots(1,1,figsize=(10,4))
repodf = pd.read_csv('data/repository_popularity.csv',parse_dates=['Date'],index_col=[
↪'Date'])
repodf.plot(ax=ax);
ax.set_xlabel('Year');
ax.set_ylabel('Market share [%]');
```



Git servers

There are many servers available. These services include

- Repository
- Issue tracking
- Project management (Kanban tables etc.)

Public

- GitHub
- GitLab
- BitBucket

Local

- ETH GitLab

0.9.14 Repository workflows

- Single branch (like a backup server with comments)
- Multiple branches (Recommended)

The recommended workflow when you work with a repository is to generously work with branches for each new sub task of the development. This make it easier to maintain a stable main branch that other people in the team can rely on to perform the tasks correctly and without crashing. The work in the branches are merged into the main after synchronization and review with a team mate.

GitHub tutorials

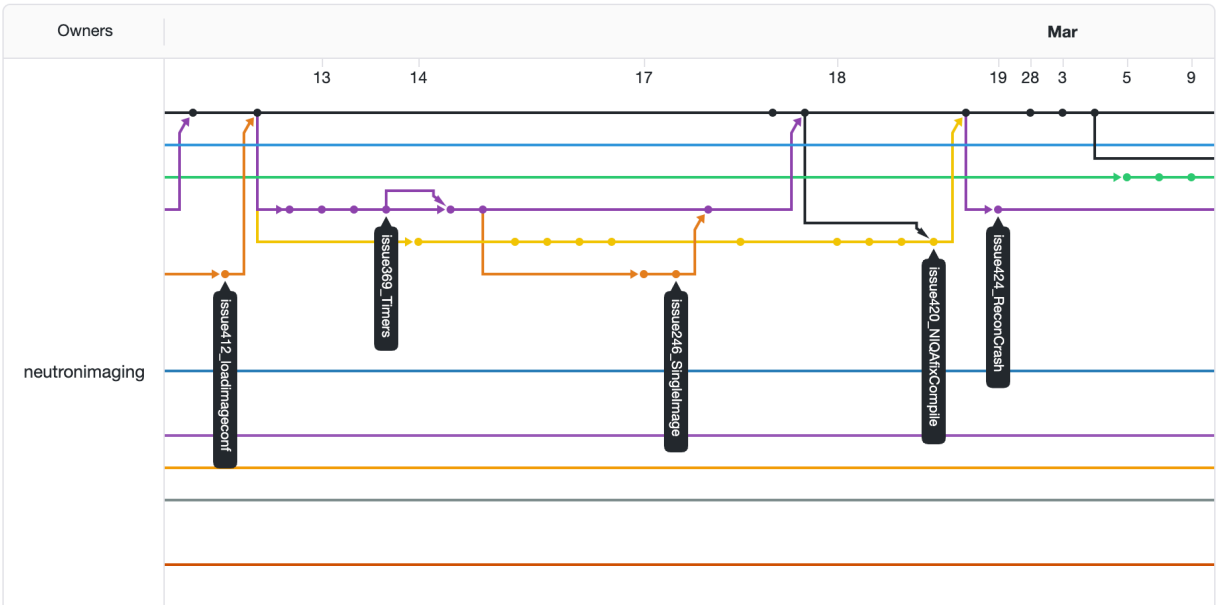


Fig. 1: A snapshot of the branch network from a git repository.

0.9.15 Continuous Integration

Conntinuous integration is the process of running tests automatically everytime changes are made.

This is possible to setup inside of many IDEs and is offered as a commercial service from companies like CircleCI and Travis.

We use them for the QBI course to make sure all of the code in the slides are correct.

Projects like scikit-image use them to ensure changes that are made do not break existing code without requiring manual checks

0.10 Summary

0.10.1 Multiple modalities

- Add more information to improve the conclusions
- Add component in the analysis and visualization
- Data fusion can be done on different levels of abstraction.

0.10.2 Software engineering

- Unit testing
- Working with repositories
- Contiuous integration