Key Concepts in Image Processing and Analysis

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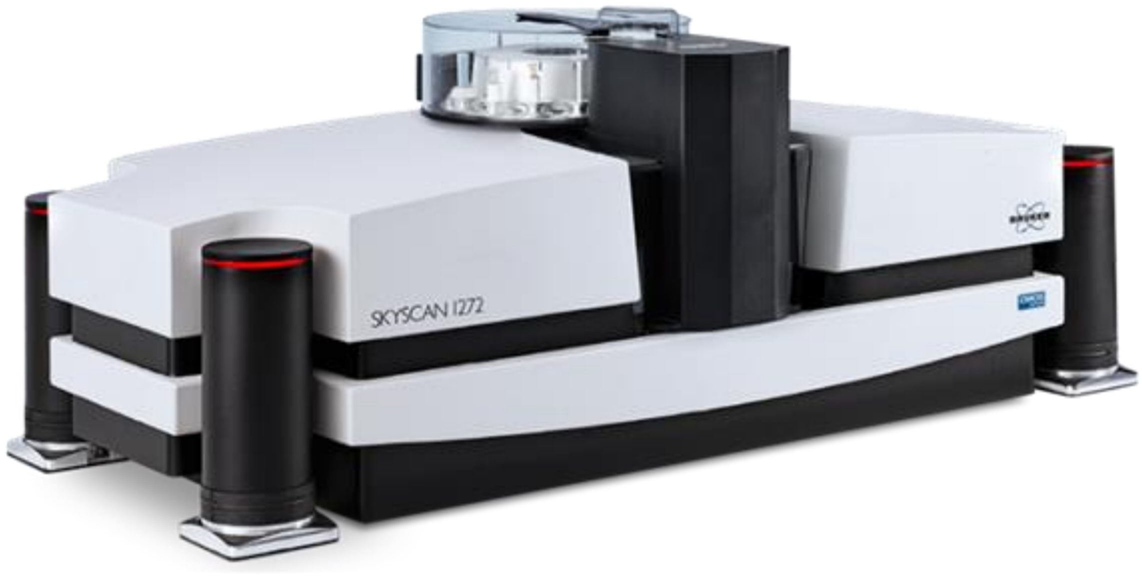
SCRI Ex-vivo MicroCT System



Bruker Skyscan 1272 (with sample changer)

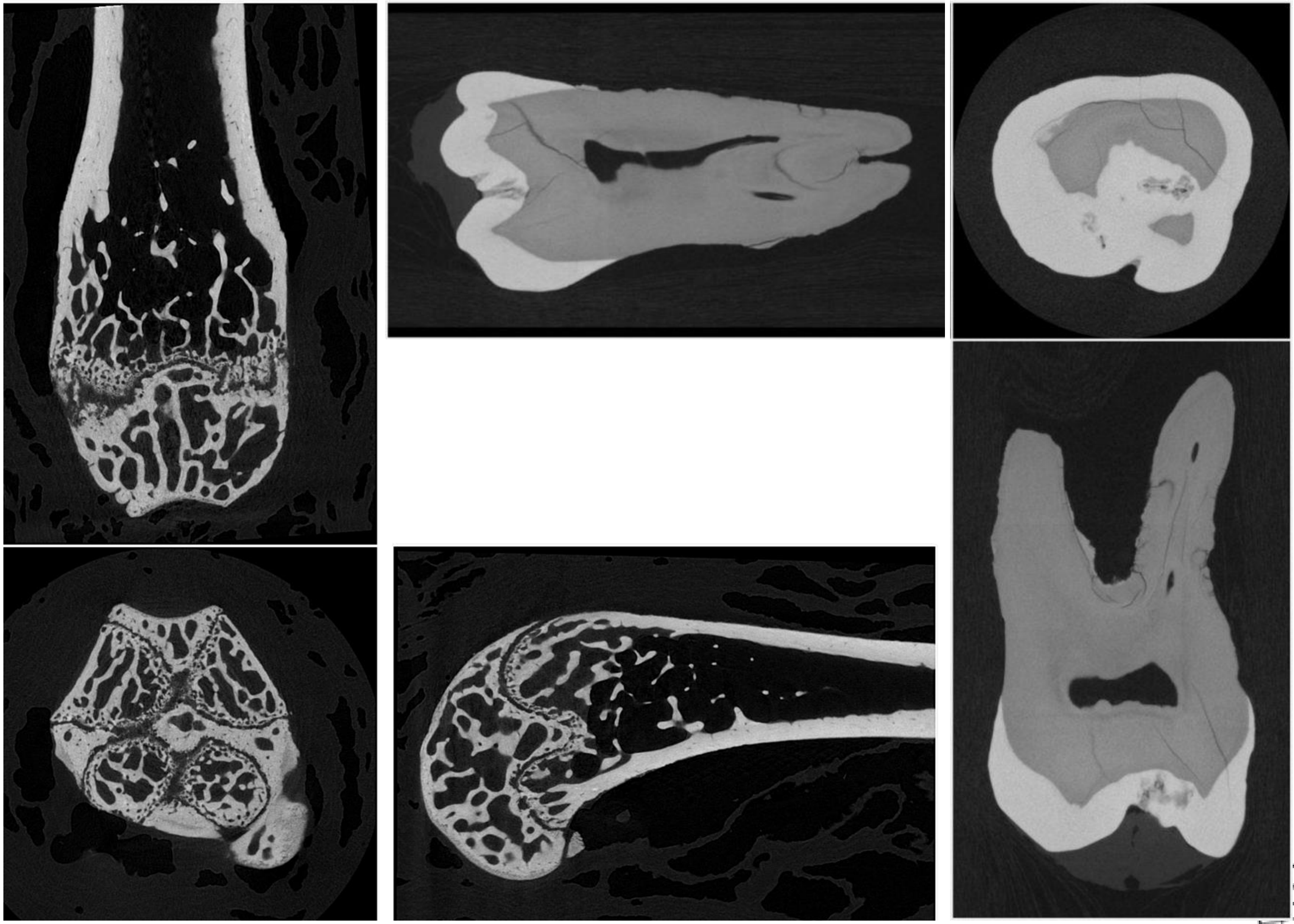
1-50 micron isotropic resolution

Max FoVs: @1um ~9-11mm

@50um ~60-65mm

Instrument Website: **http://bit.ly/SCRI_MicroCT**

MicroCT is ideal for volumetric imaging of mineralized tissue:



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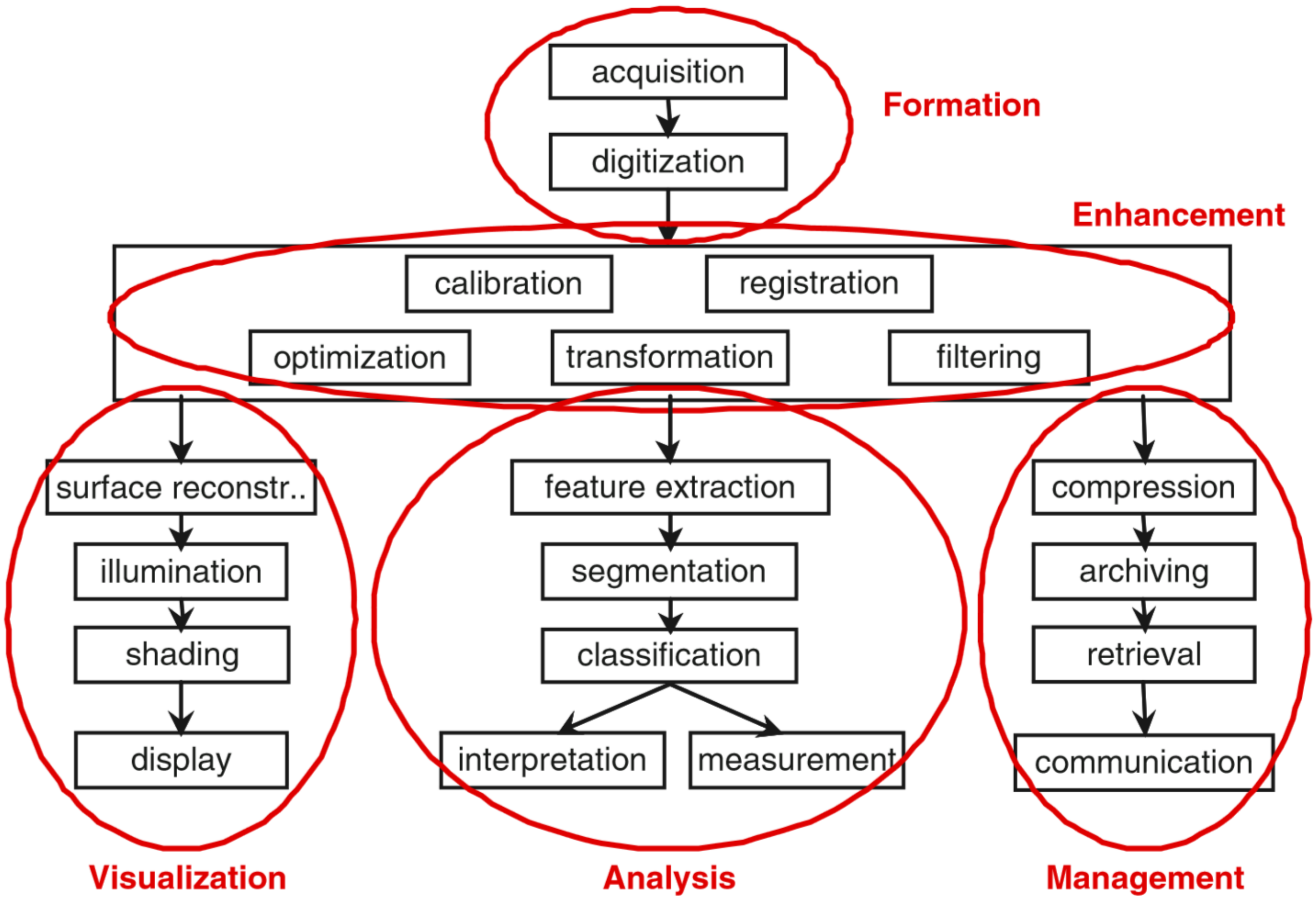
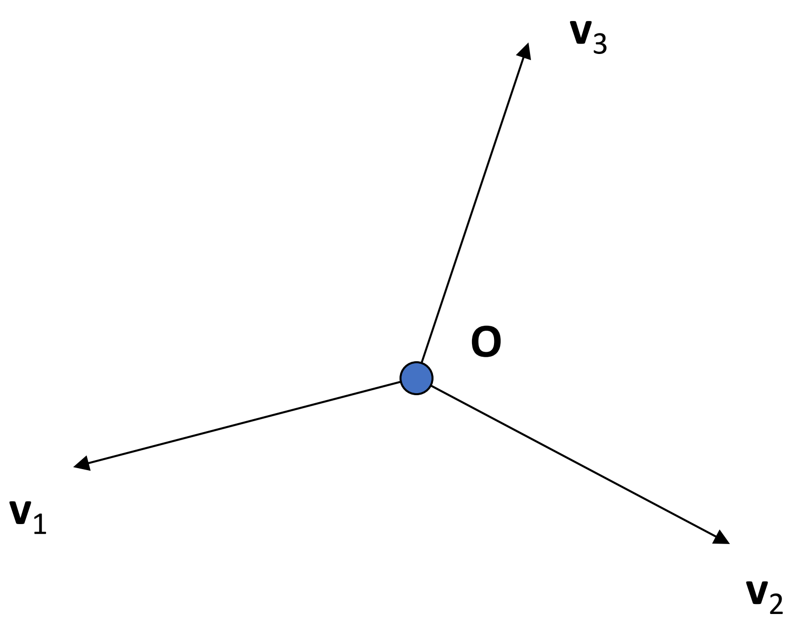
3D imaging conceptual workflow



Outline

- Image Formation
  - Coordinate systems
  - Digitization and quantization
  - Resolution
- Image Enhancement
  - Filtering and transformations
  - Registration
- Image Analysis
  - Segmentation

What is a Coordinate System?



A *coordinate system* for a three-dimensional space is a point **O** called the *origin* along with three linearly independent vectors $\mathbf{v}_1$, $\mathbf{v}_2$, and $\mathbf{v}_3$.

Linearly independent here means no two of the vectors are parallel and the three vectors do not all lie in the same plane.

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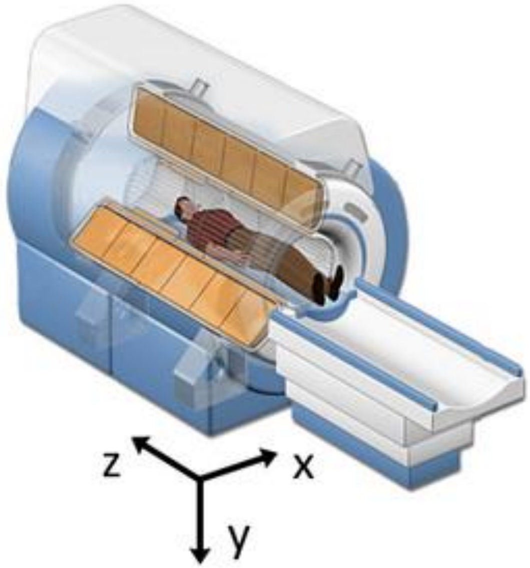
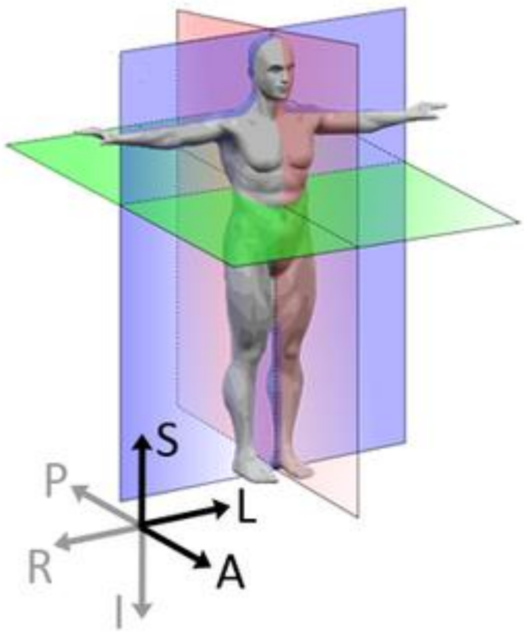
Coordinate Systems



World Coordinate System



Anatomical Coordinate System

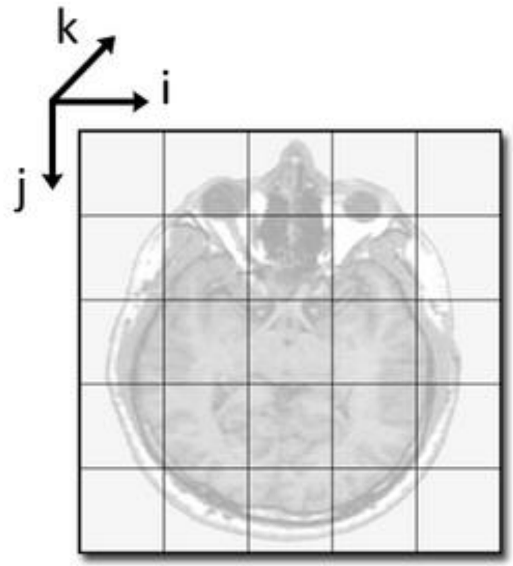


Image Coordinate System

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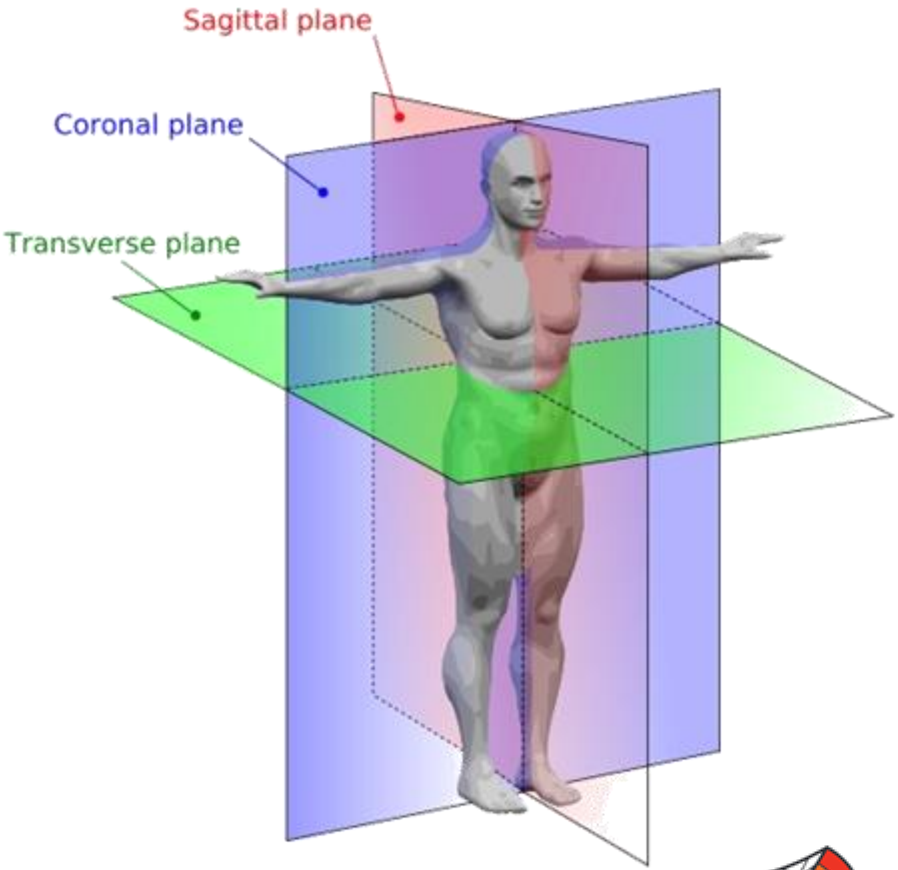
Anatomical coordinate system

This space consists of three planes to describe the standard anatomical position of a human:

- ***axial plane*** is parallel to the ground and separates the head (Superior) from the feet (Inferior)
- ***coronal plane*** is perpendicular to the ground and separates the front from (Anterior) the back (Posterior)
- ***sagittal plane*** separates the Left from the Right



This coordinate system is fixed with respect to the scan table and the object or subject being scanned. Different medical applications use different definitions of this 3D basis

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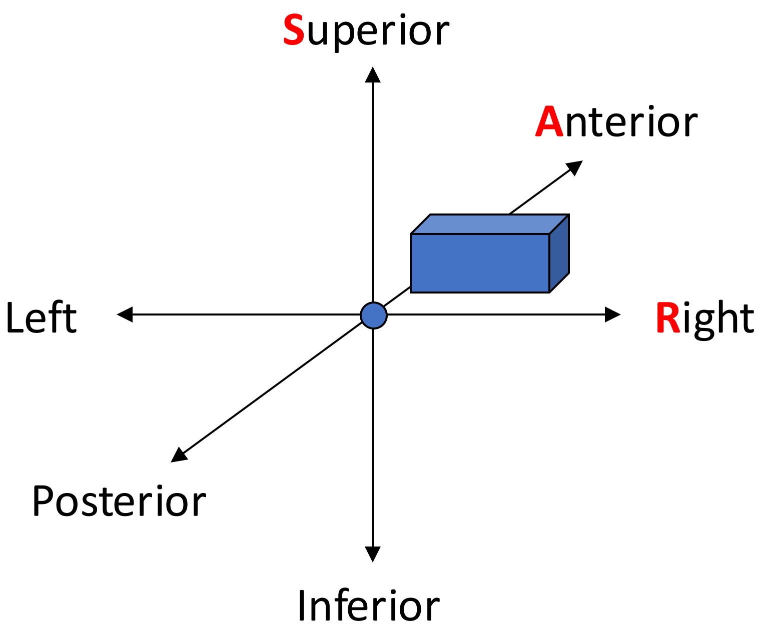
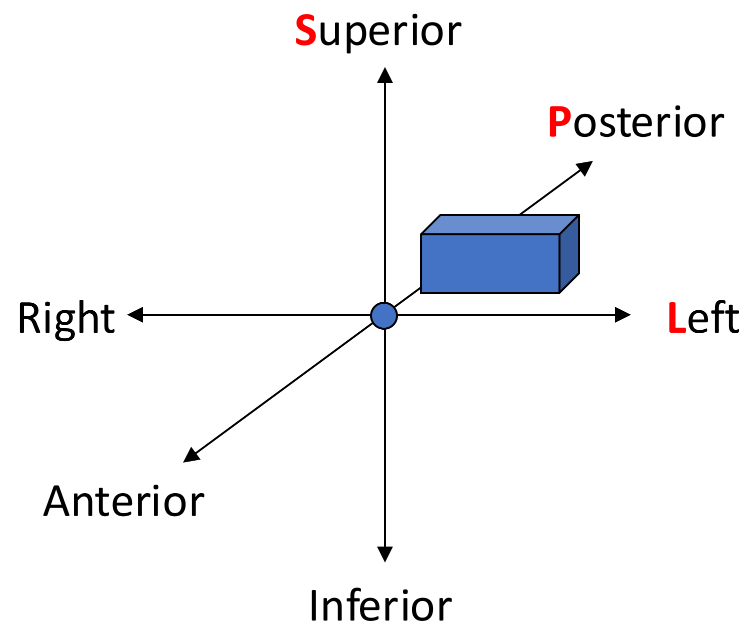
Anatomical coordinate system: RAS vs LPS



RAS (Right, Anterior, Superior): 3D Slicer



LPS (Left, Posterior, Superior): DICOM images, ITK toolkit

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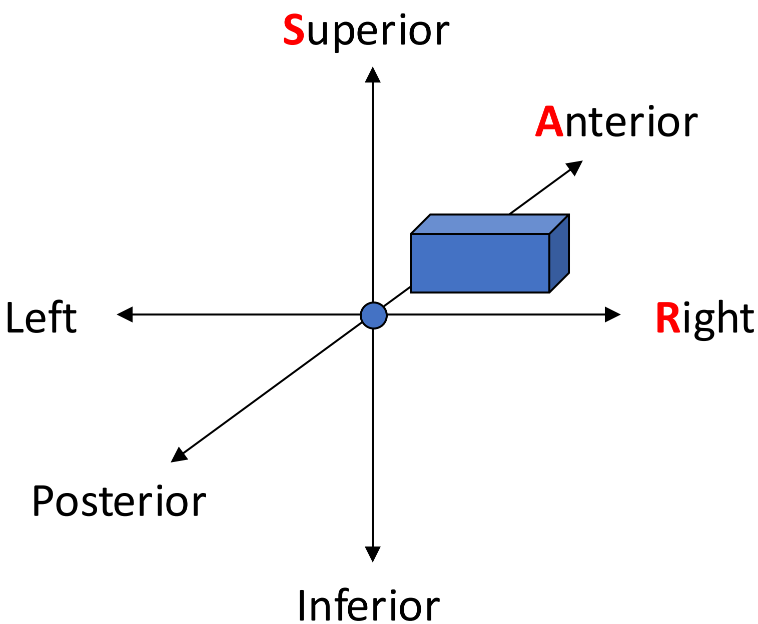
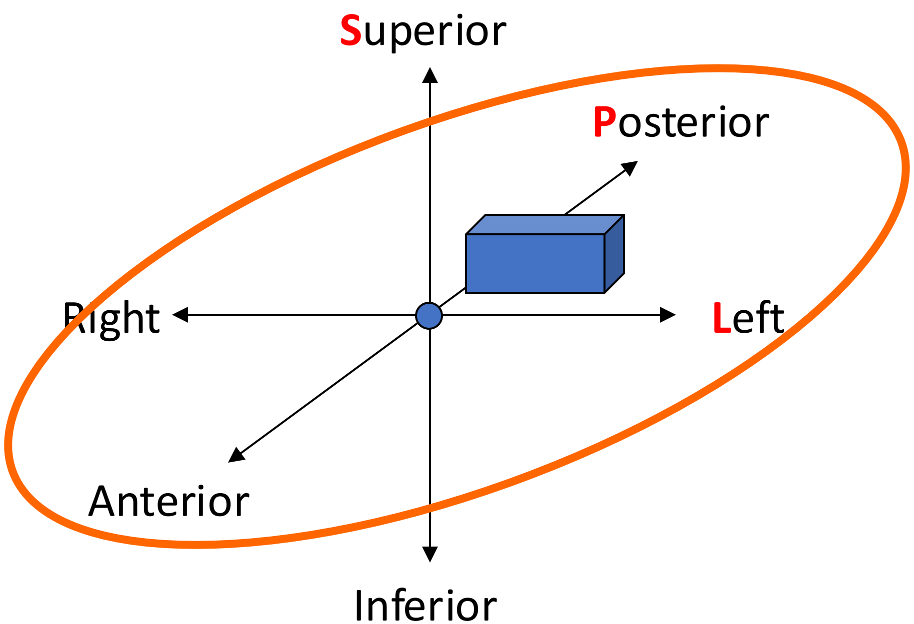
Anatomical coordinate system: RAS vs LPS





RAS (Right, Anterior, Superior):
3D Slicer

LPS (Left, Posterior, Superior):
DICOM images, ITK toolkit

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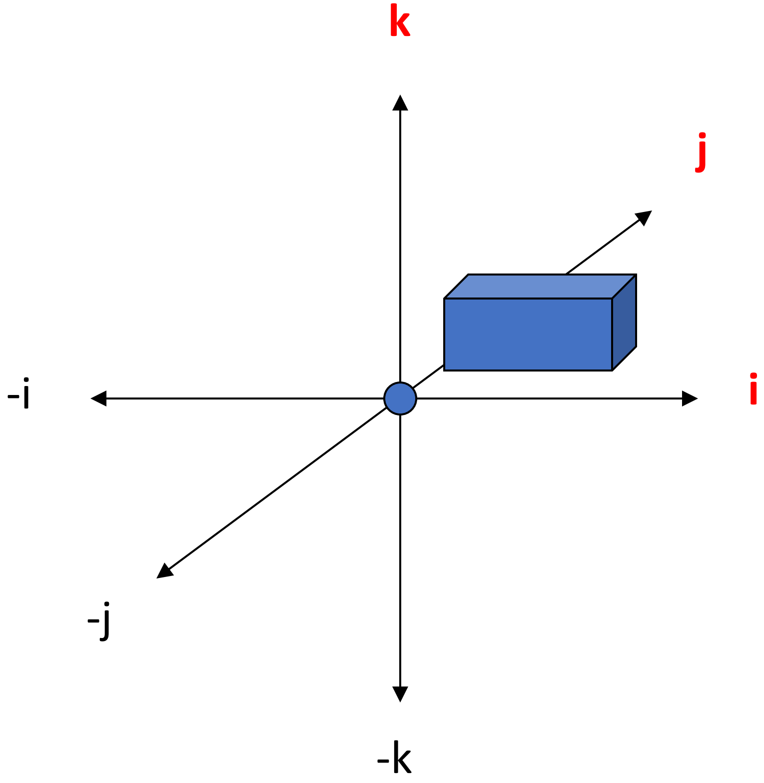
The IJK Image Coordinate System

Every medical scanner has its own coordinate system called the *IJK coordinate system*. The IJK coordinate system represents the actual rectangular prism of data that is scanned, instead of the position of the scan table

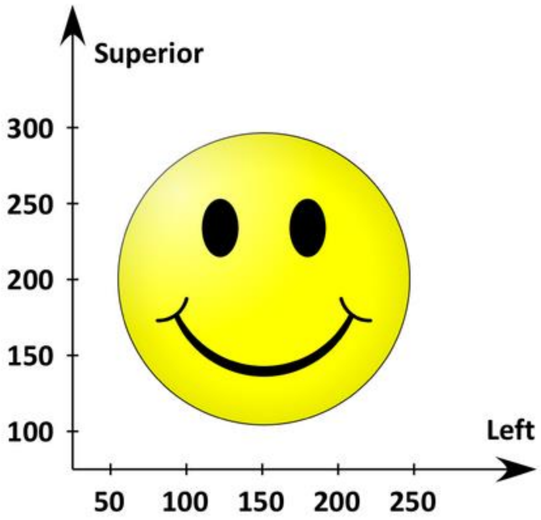


Coordinate System Conversion

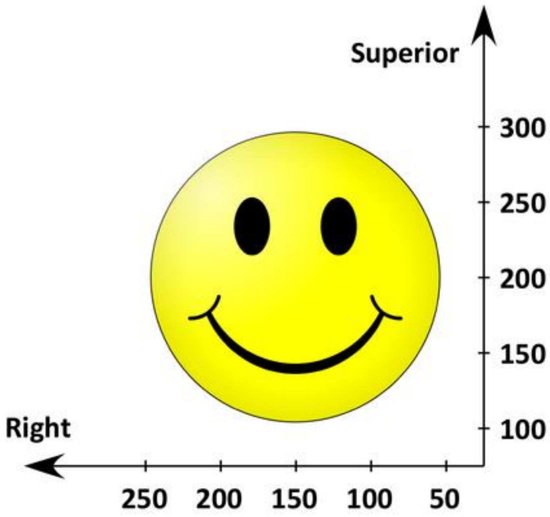
We frequently need to convert between coordinate systems, such as RAS and IJK.

The mapping from one coordinate system to another is a 3D *affine transformation*: a sequence of transformations consisting of a shear, a reflection, a rotation, a scaling, and a translation.

What do all of these mean



LPS Anatomical space



RAS Anatomical space

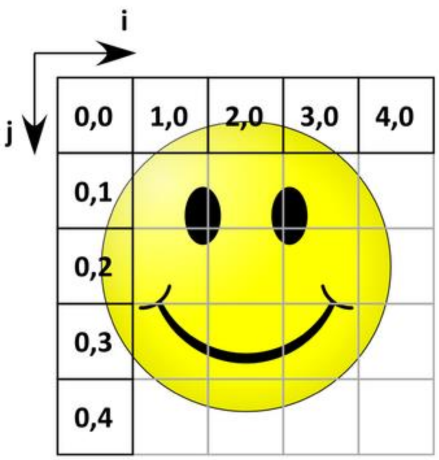
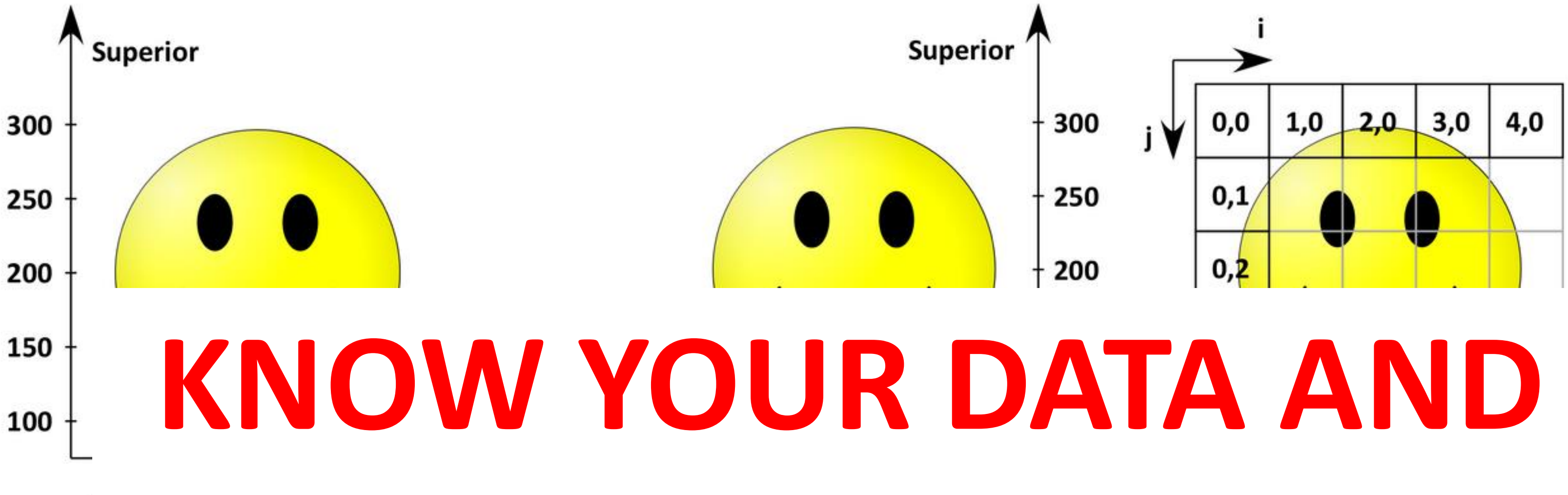


Image Coordinate System

What do all of these mean



LP

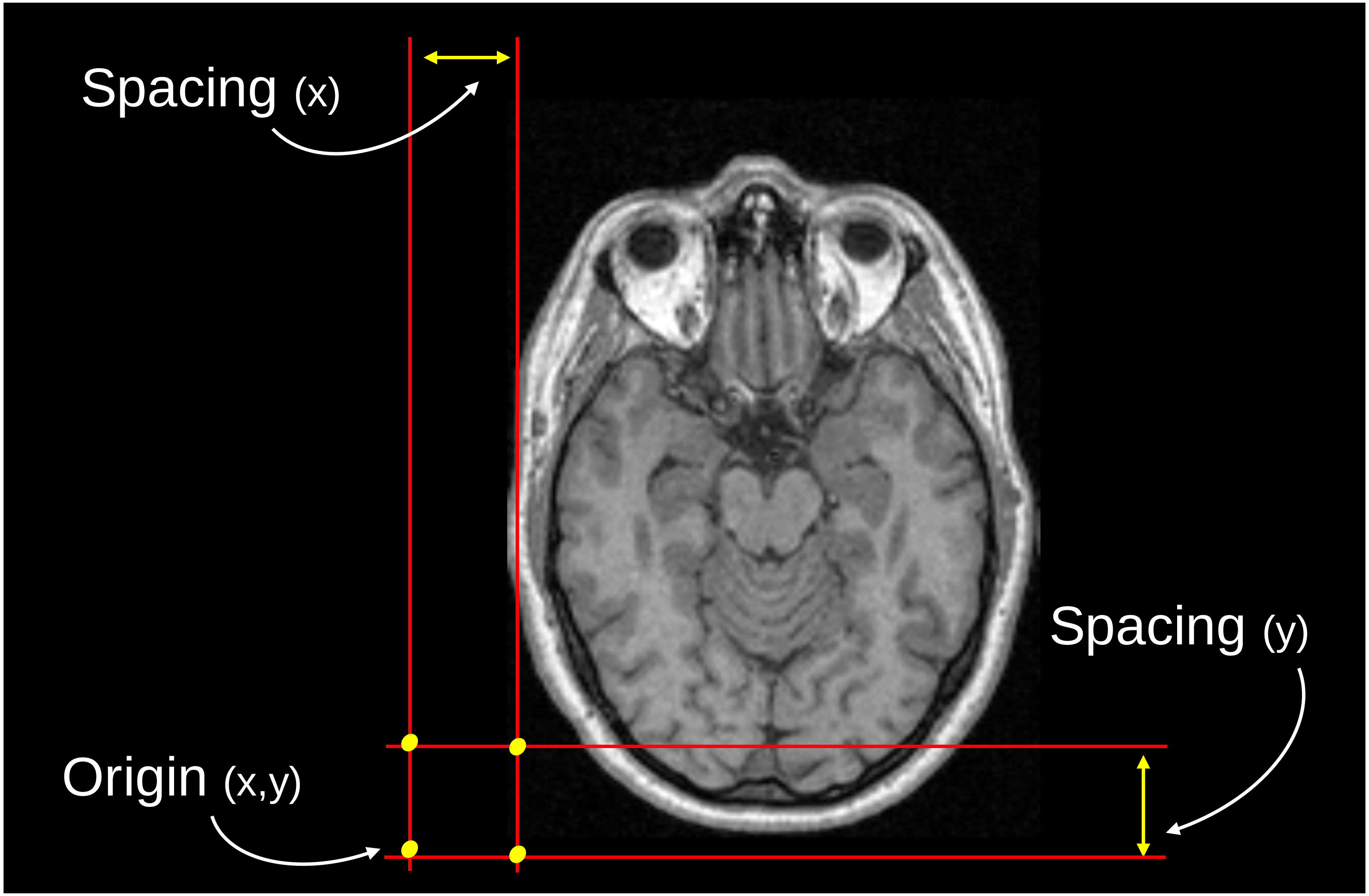
KNOW YOUR DATA AND SOFTWARE

tem

What is an image?

An image is a sampling of a continuous field using a discrete grid

What is an image?



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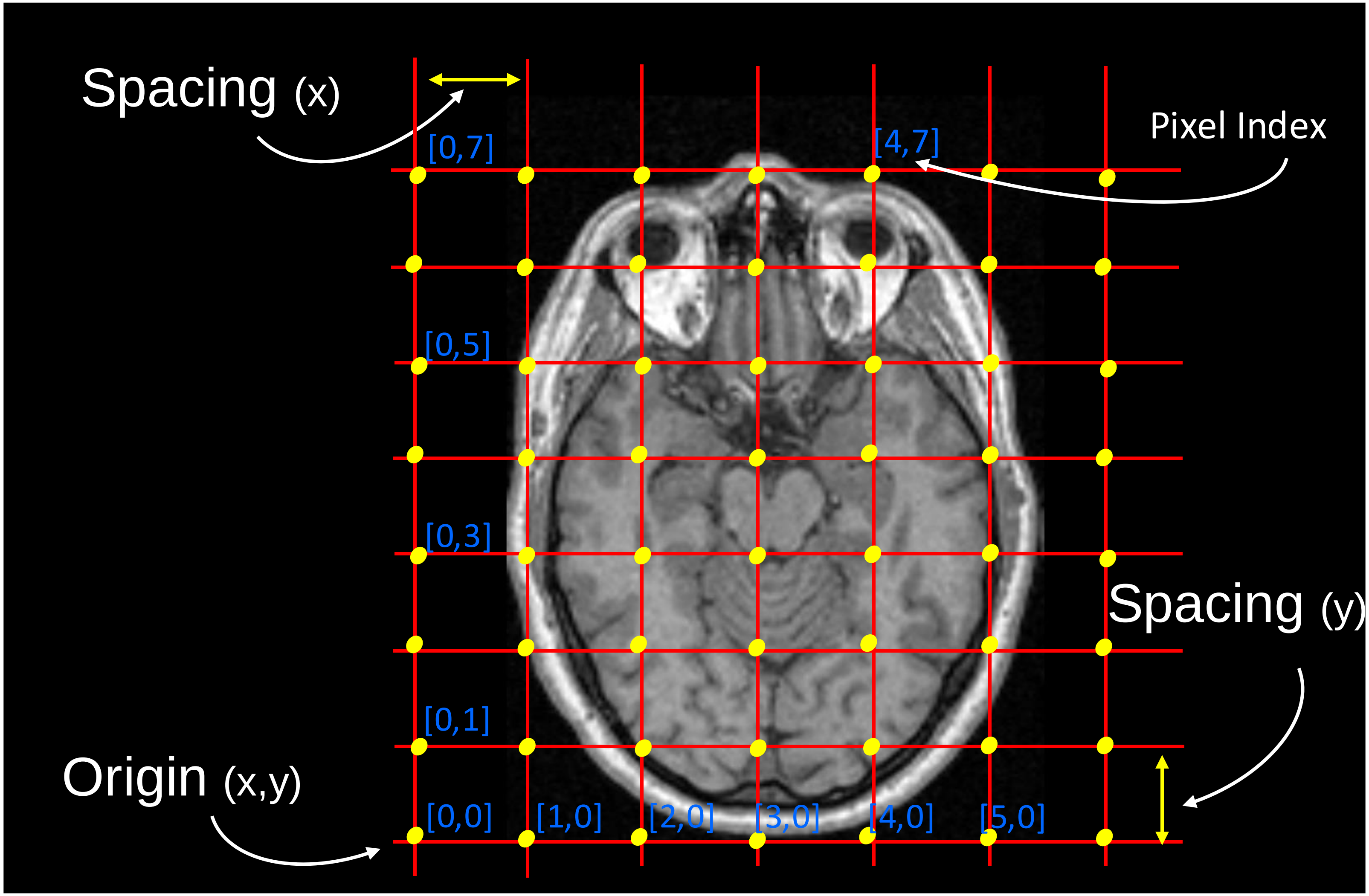
What is an image?



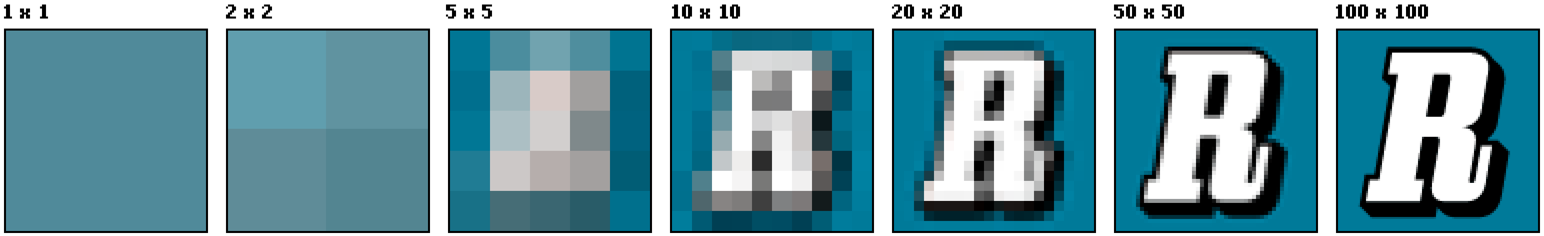
Digitization

- Digital image processing implies the discrete nature of images.
- Values in an image are samples on a pixel (2D) or voxel matrix (3D)
- Digitization applies to both sampling (resolution) and the value range (quantification)

Resolution

Resolution is the capability of sensor to observe or measure the smallest object clearly with distinct boundaries. MicroCT scanners have resolutions from sub-micron range to 10s of microns (1000 micron = 1 mm).

Pixel is unit of digital image. How big of a physical structure a pixel represents depends on the resolution (i.e. resolution and pixel size are inversely proportional).



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Resolution in 3D

Similar to pixel**, voxel is a unit of digital volume:**

Resolution in each dimension is not necessarily identical: That’s especially true for medical imaging, where the sampling in Z is a lot coarser than X and Y (i.e. they take far fewer slices, but within a slice you see everything you need to see in high-detail). In this case the voxels are said to be **ANISOTROPIC**.

If all dimensions are identical then the voxels are **ISOTROPIC**

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Bits and Bytes

- A “bit” is the smallest unit of storage, storing either a 0 or 1
- n bits yield 2^ndistinct patterns

Number of bits	Different Patterns	Number of Patterns
1	0, 1	=2
2	00, 01, 10, 11	=4
3	000, 001, 010, 011 100, 101, 110, 111	=8

- One byte = collection of 8 bits
- All storage (memory or disk) is measured in bytes
  - Kilobyte, KB, ~ 1 thousand bytes
  - Megabyte, MB, ~ 1 million bytes
  - Gigabyte, GB, ~ 1 billion bytes
  - Terabyte, TB, ~ 1 trillion bytes
  - Petabyte, PB, ~1000 trillion bytes

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Quantization

- Quantization refers to the discretization of the value range
  - Grayscale image: 8 bits (256 possible states)
  - Color image: 24 bits (16,777,216 possible states)
  - Medical CT scans: 12 bits (4,096 possible states)

6 bit (64 values) 3 bit (8 values) 2 bit (4 values)

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Quantization and image size and memory needed

You have a CT scan of a human subject that is **256 pixels wide**, **256 pixels high**, and consists of **256 slices** and the image depth is **16 bit**.

How big is this data set?

Quantization and image size

You have a CT scan of a human subject that is **256 pixels wide**, **256 pixels high**, and consists of **256 slices** and the image depth is **16 bit**.

How big is this data set?

8 bit = 1 byte

$$256 \times 256 \times 256 \times (16/8) = 33{,}554{,}432 \text{ Bytes}$$
$$\sim 32\text{MB}$$

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So what do those mean to me?

As a general rule, you need at least **4-6 times as large RAM** than your dataset.

If you want to visualize your dataset in full resolution, you need **a GPU** that has at least **1.2 times as large VRAM** than your dataset.

A typical high-resolution microCT dataset is **1024 x 1024 x 1024** in dimensions.

If image depth is 8 bit this = **1024MB or 1GB**

So in case of 1GB volume, you need at least 6GB of RAM and a GPU with 1.5GB of VRAM.

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Memory Limitations:

You might have 100s of GB of RAMs but you are still getting **Out Of Memory (OOM)** errors:

- **Memory fragmentation:** The available memory isn’t **contiguous**, but consists of many small fragments. This results in out of memory errors the OS reports that the sufficient memory is available.

- Slicer allocated image as large arrays. This memory address needs to be contiguous. If it cannot find a chunk to fit it, it may throw OOM.

Image compression

Goal: Reduce the amount of data required to represent the information in a digital image

- Can be lossy or lossless
- Eliminates redundancy in the data:
  - Coding: optimize number of bits required to code information in image
  - Interpixel: exploit correlations between neighboring pixels
  - Psychovisual: discard data that is perceptually insignificant

Has no impact when the data is loaded into the memory.
Compression is only relevant when saving to disk.

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What format NOT to use?

JPEG

Or any other lossy compression format. Why are we doing all this work if we are going to throw them out when we save?

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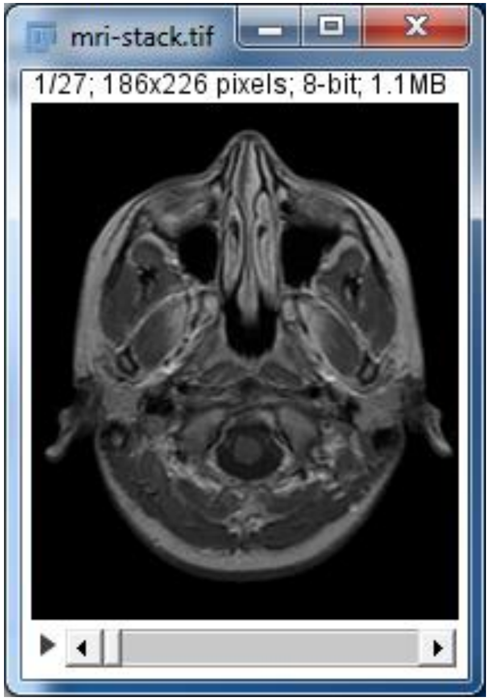
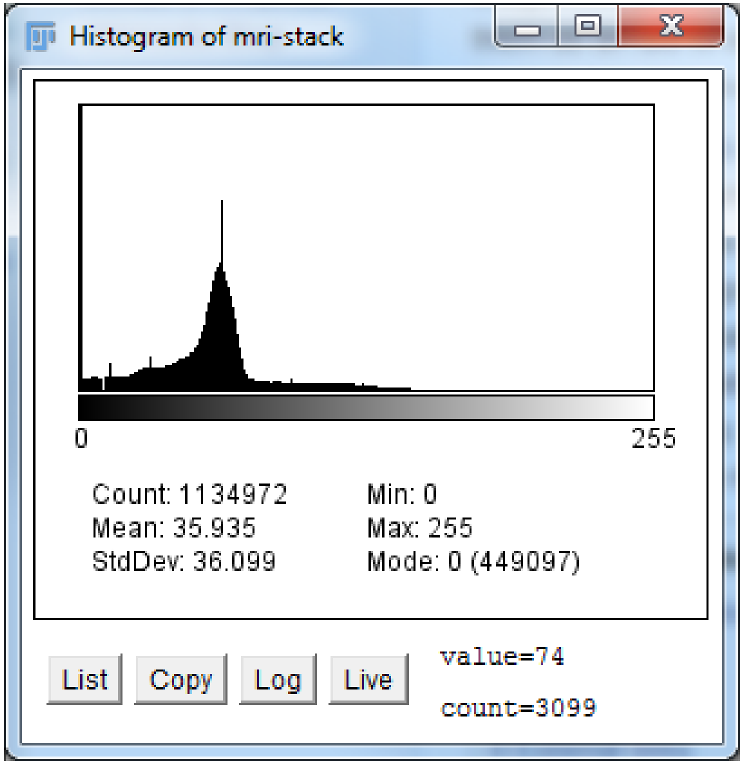
Image enhancement

- Image enhancements are low-level operations that are preformed without knowledge of the content of an image
- Why?
  - Remove noise
  - Sharpen image, etc.
- Examples
  - Histogram transformations
  - Convolution
  - Mathematical morphology
  - Registration

Image Histogram

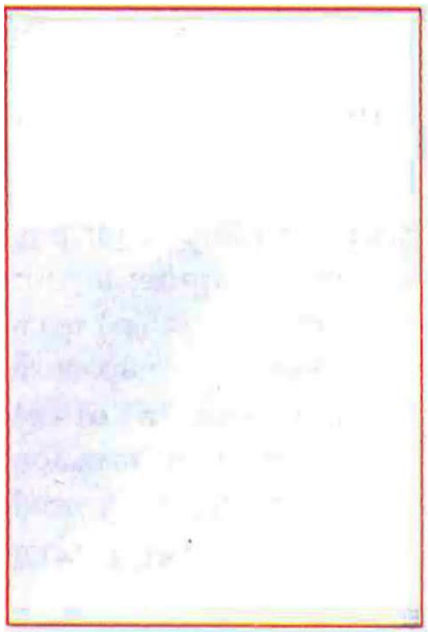
An image histogram shows the frequency distribution of the pixel values (in this context grayscale) in a digital image. It plots the number of pixels for each tonal value.



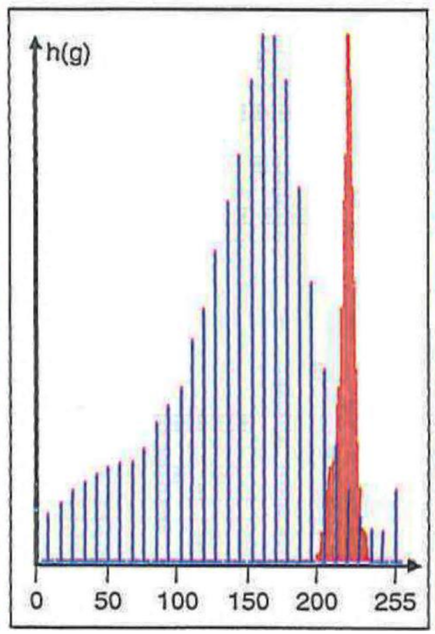


Histogram transformation

- Simple pixel transforms can be defined using the histogram
- In this example the gray scale values of the image in (A) are stretched, resulting in the improved contrast in (C)



A. Original image



B. Original and stretched histograms

C. Enhanced image

Image filtering

Modify the intensity values of a pixel based on a function of the intensity values from a local neighborhood around that pixel.

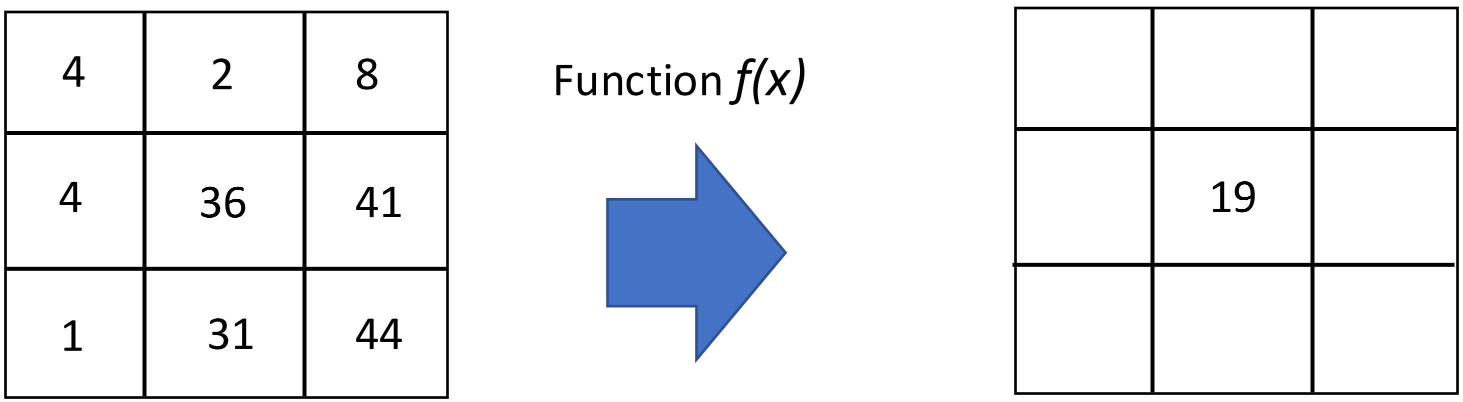


Image filtering

Modify the intensity values of a pixel based on a function of the intensity values from a local neighborhood around that pixel.

4	2	8
4	36	41
1	31	44

Function *f(x)*

	19	

$$f(x) = \frac{1}{n}\sum_{i}^{n} x_i$$

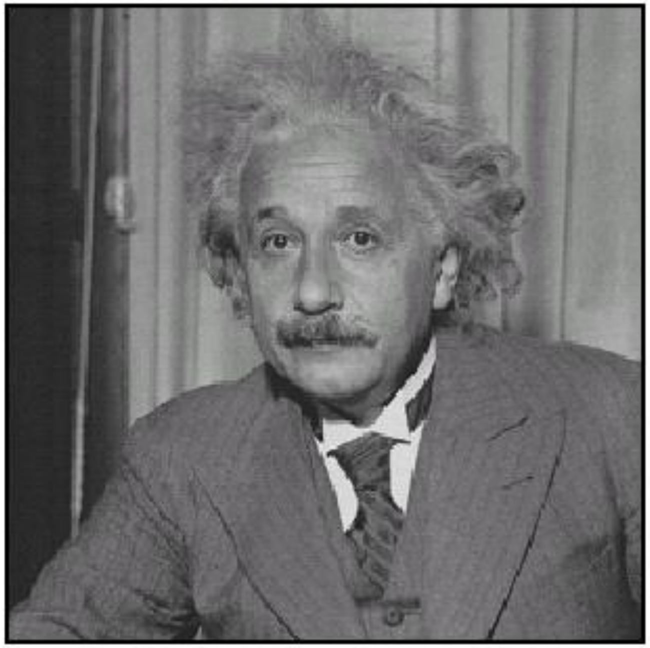
Mean filtering/ moving average

Removes sharp features

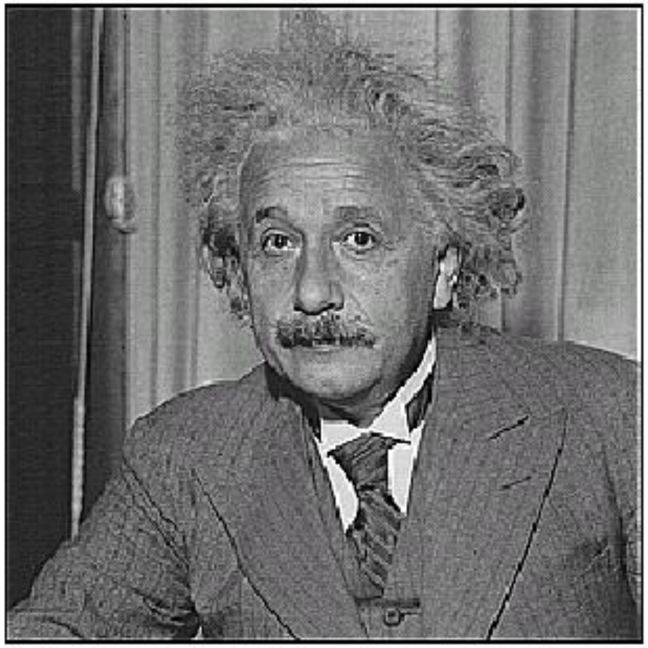
Smoothing with a mean filter

Sharpening

Sharpening function $g(x) = 2x - f(x), \qquad f(x) = \frac{1}{n}\sum_i^n x_i$



before



after

Mathematical morphology

- Set of logical operations performed primarily on binary images
- Frequently used to clean up shapes after pixel–based segmentation

- Binary mathematical morphology consists of two basic operations

  - **Dilation: based on logical AND**
  - **Erosion: based on logical OR**

  and several composite relations

  - **Closing: dilation followed by erosion**
  - **Opening: erosion followed by dilation**
  - **Skeleton: erosion with various structuring elements**

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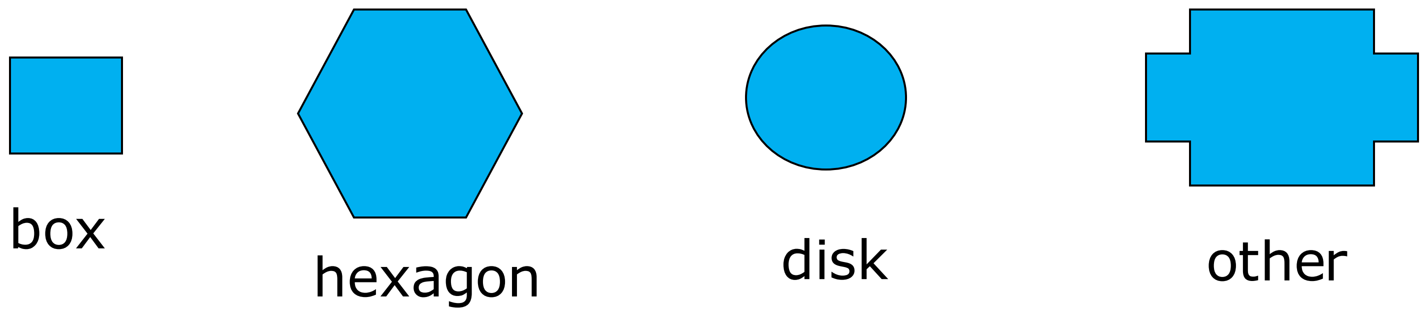
Structuring Elements

A structuring element is a shape mask used in the basic morphological operations.

They can be any shape and size that is digitally representable, and each has an origin.

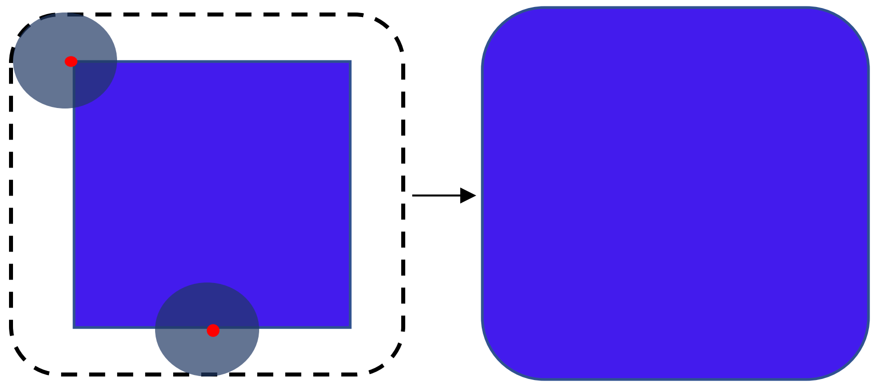


Dilation

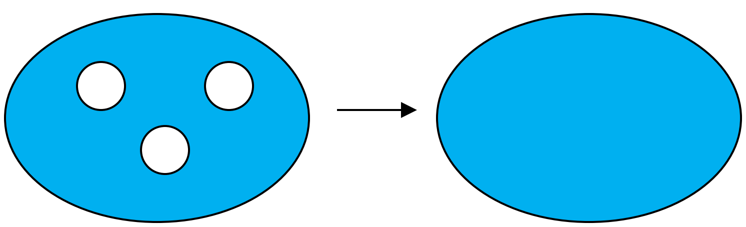
Dilation **expands** the connected sets of 1s of a binary image.

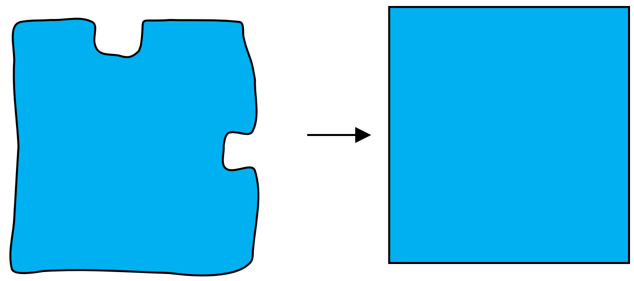
It can be used for

1. growing features



2. filling holes and gaps





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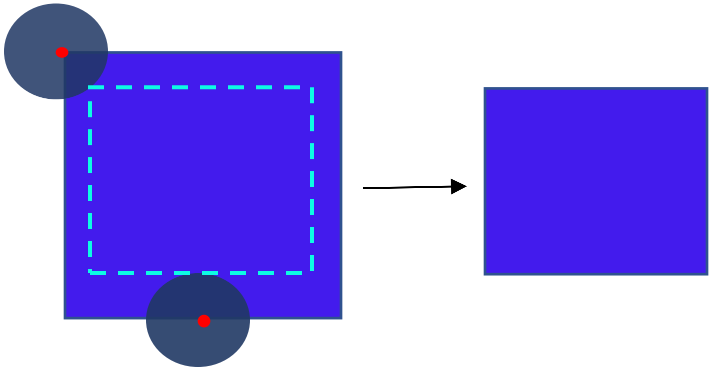
Erosion

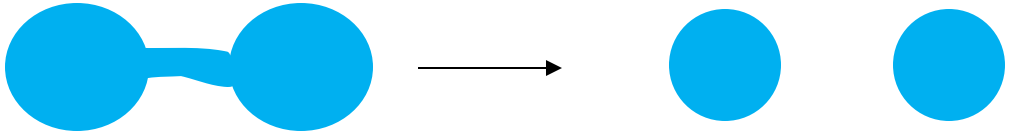
Erosion **shrinks** the connected sets of 1s of a binary image.

It can be used for



1. shrinking features

2. Removing bridges, branches and small protrusions



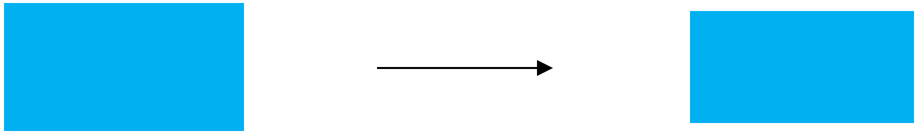
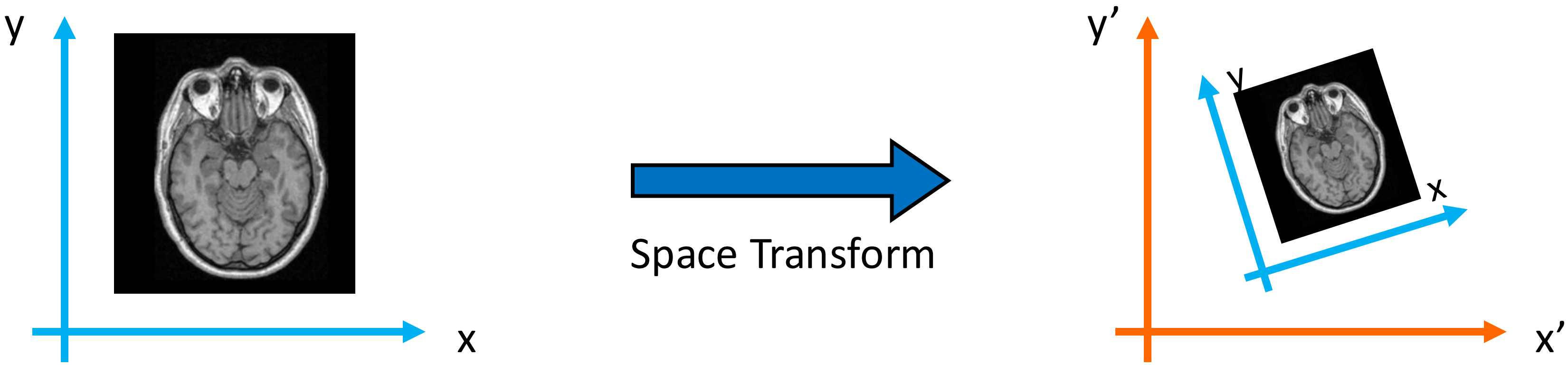


Image Registration

- Registration can be used to obtain a correspondence between images such that a change in measured dimensions can be quantified.
- The moving image will be resampled into the fixed image coordinate system



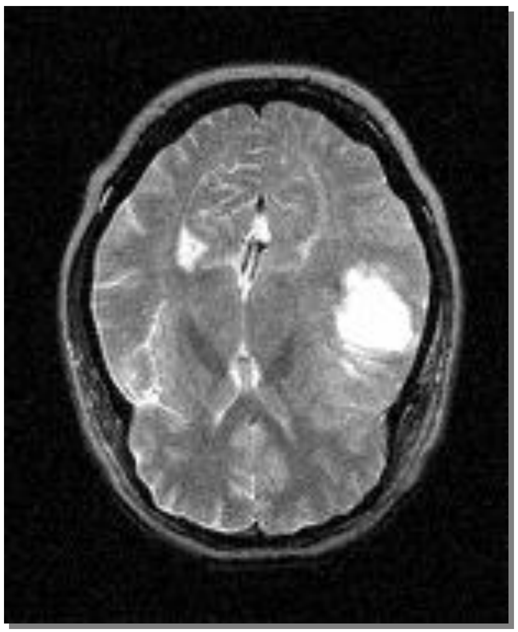
Physical coordinates of fixed image

Physical coordinates of moving image

- The space transformation can be rigid or non-rigid (more on this later)

Multimodal registration

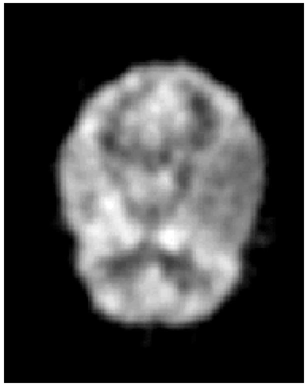
MRI-T2



256 x 256 pixels

Space Transform

PET

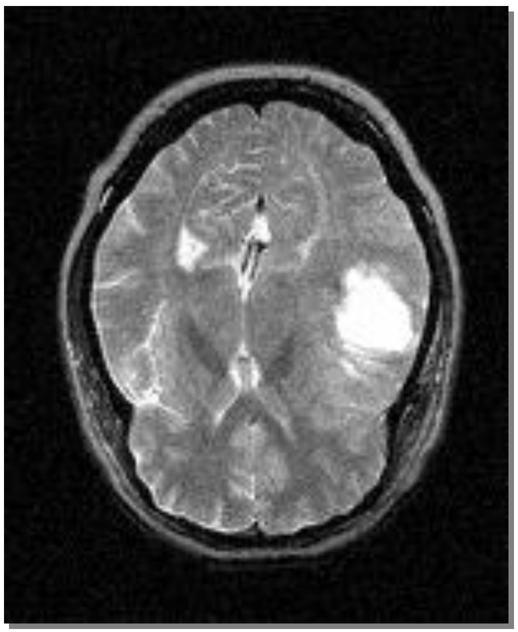


128 x 128 pixels

Images from the project: “Retrospective Image Registration Evaluation”,
NIH, Project No. 8R01EB002124-03, Principal Investigator, J. Michael Fitzpatrick, Vanderbilt University, Nashville, TN.

Multimodal registration

MRI-T2



256 x 256 pixels

Transform

PET

128 x 128 pixels

Do not register images in pixel space
Pixel spacing needs to be specified

Images from the project: "Retrospective Image Registration Evaluation",
NIH, Project No. 8R01EB002124-03, Principal Investigator, J. Michael Fitzpatrick, Vanderbilt University, Nashville, TN.

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Segmentation

- Dividing an image into connected regions based on the content of the image

- Regions of an image segmentation should be uniform and homogenous with respect to some characteristic, such as gray tone, color or texture and should differ significantly with respect to adjacent regions

- Techniques include
  - Thresholding
  - Grow from seeds
  - Watershed filter
  - Fast marching filter

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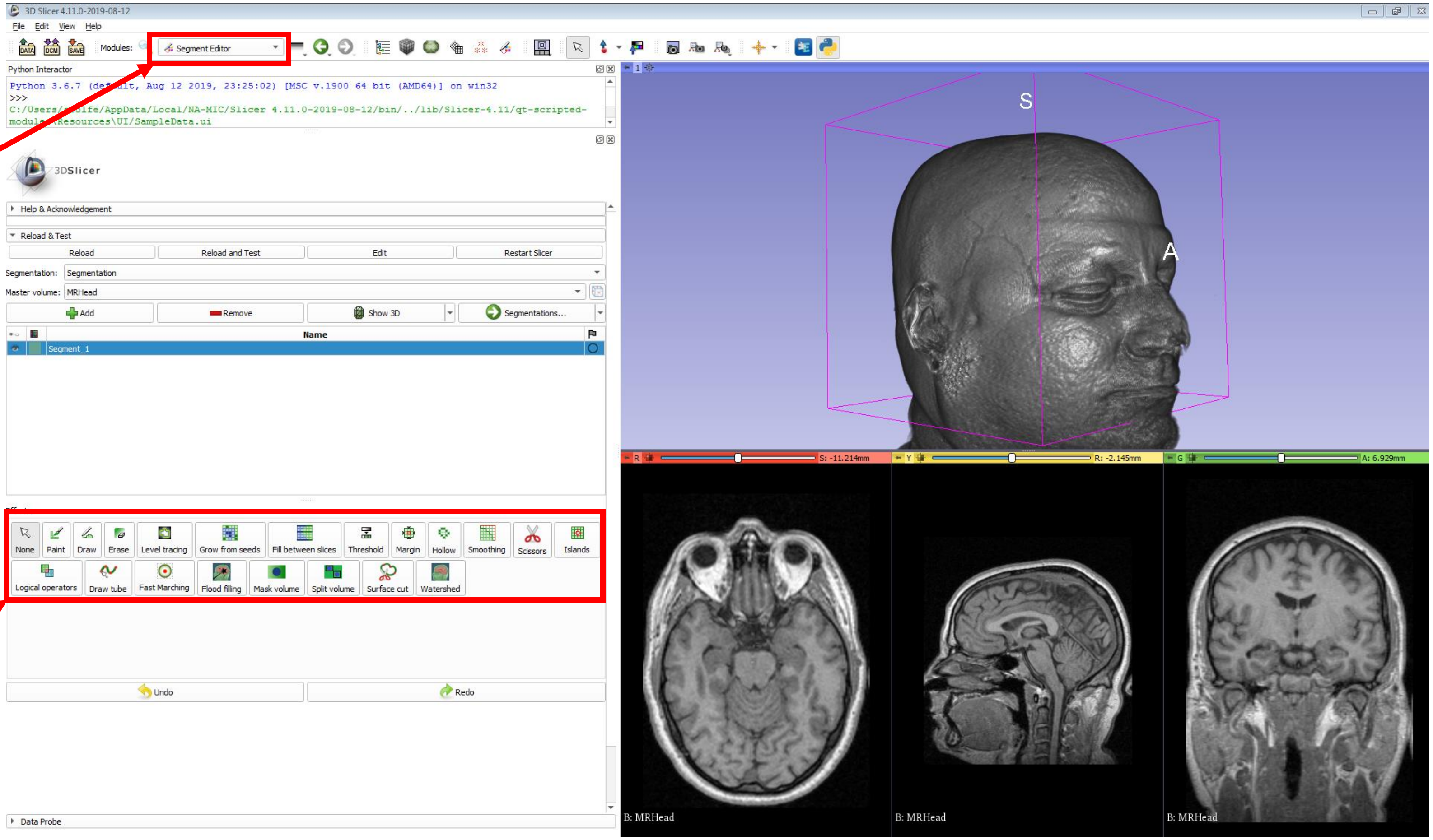
Segmentation tools available in 3D Slicer



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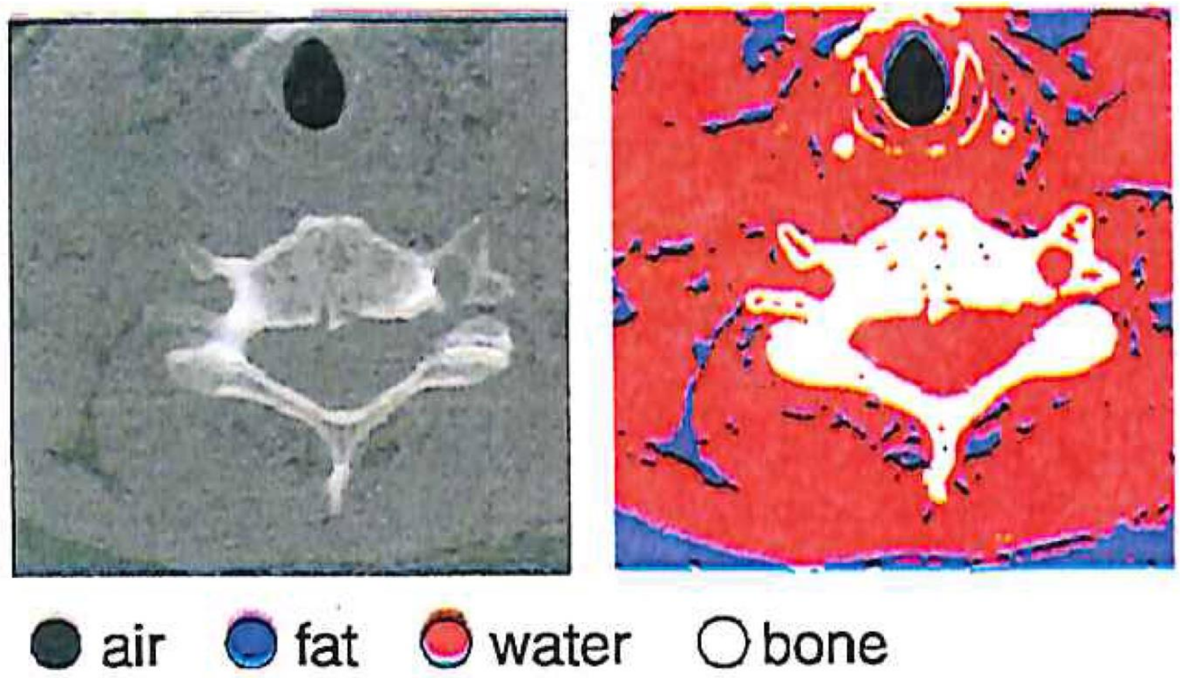
Thresholding

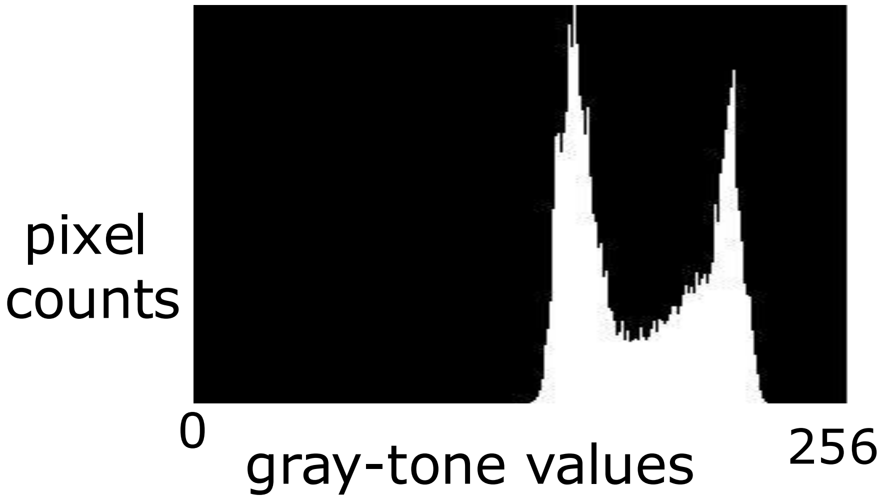
- Assigning labels to pixel intensity ranges
- Can be static or dynamic
- Static: known value ranges for types of tissue in CT scans



Segmentation in CT relying on Hounsfield Units (HU) which define a window of values for each tissue type

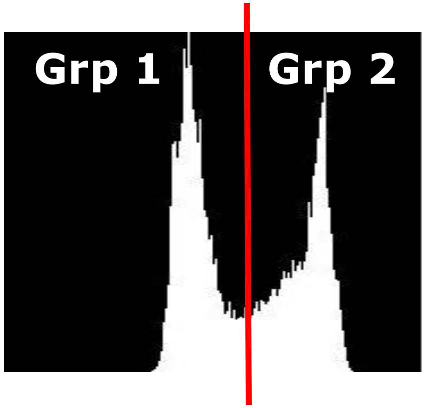
Histogram-Directed Thresholding

How can we use a histogram to separate an image into 2 (or several) different regions?



Is there a single clear threshold? 2? 3?

Automatic Thresholding: Otsu's Method



Assumption: the histogram is bimodal

Method: find the threshold t that minimizes the weighted sum of within-group variances for the two groups that result from separating the gray tones at value t.

Note: In practice, this operator works very well for true bimodal distributions and not too badly for others.

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Thresholding Example

original gray tone image

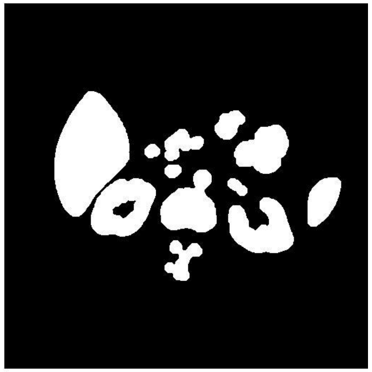
Binary image after threshold is applied

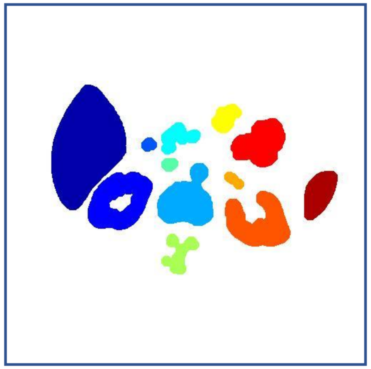
Connected Components Labeling

- Identify and then analyze each connected set of pixels.
- The connected components operation takes in a binary image and produces a labeled image in which each pixel has the integer label of either the background (0) or a component.


original grayscale image

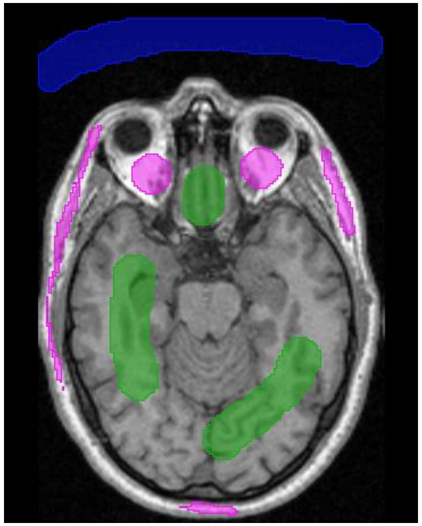

binary image after threshold applied


binary image after morphology

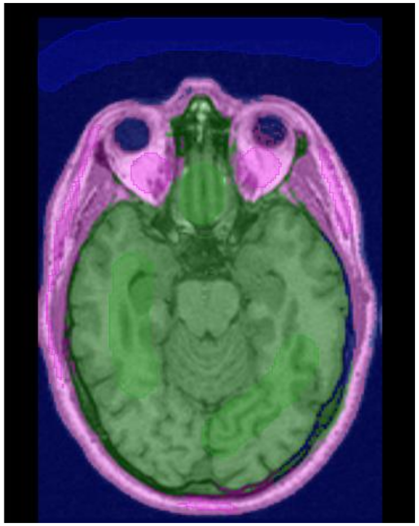

connected components

Grow from seeds

- Region growing techniques start with one pixel of a potential region and try to grow it by adding adjacent pixels till the pixels being compared are too dissimilar
- Can include a priori knowledge of the scene by taking a set of seed pixels can be chosen from the image
- A statistical tests used to decide which pixels can be added to a region



User provided seeds



Segmentation grown from seeds

SLICERMORPH