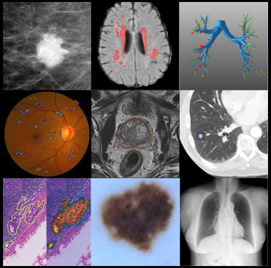

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# *Deep Learning for 3D Medical Image Analysis*

## Lecture 1: Introduction

Thursday February 6, 2025

**Jelmer Wolterink**

**Mathematics of Imaging & AI group**

# Why medical imaging

There are many reasons to acquire a medical image

- *Diagnosis*: To detect if there is something ‘off‘ in the patient
- *Screening*: To identify patients with disease
- *Monitoring*: To see if disease is stable/progressing
- *Treatment planning*: To determine which treatment to take
- *Peroperative*: To provide additional information during surgery
- *Prognosis*: To predict outcomes of disease/treatment
- …

Also, histopathology, dermatology, ophthalmology, ...

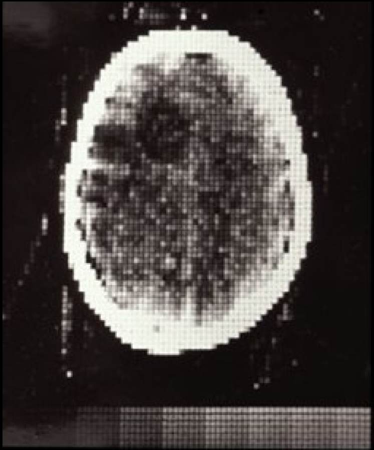
# Why this course?

1632: Rembrandt van Rijn – De anatomische les van Dr. Nicolaes Tulp

# Why this course?

1896: One of the first X-rays by Wilhelm Röntgen

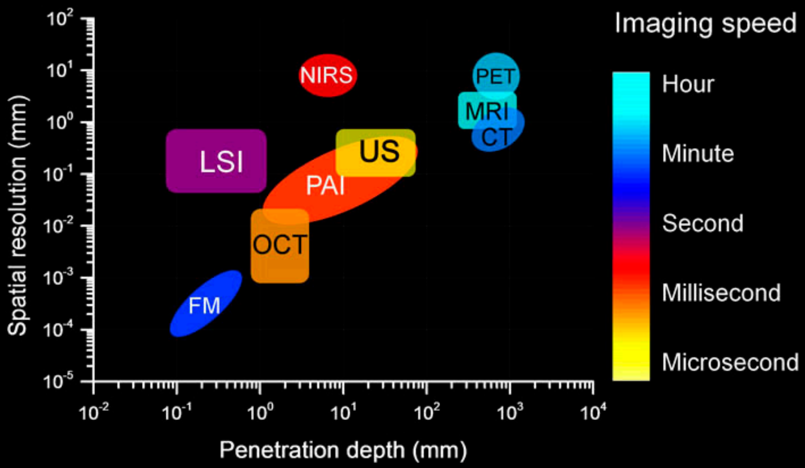
# Why this course?



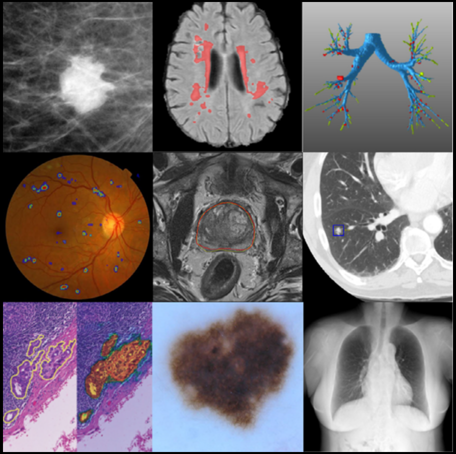
1971: First CT

2021: 4D CT angiograpy

# Imaging modalities



# Medical image analysis



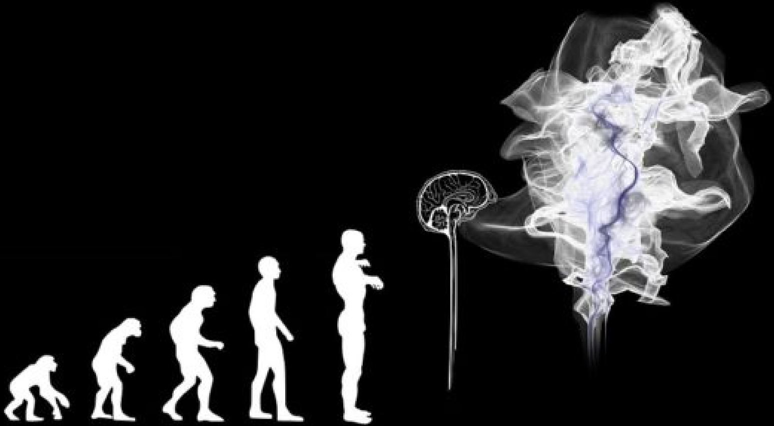
# Growing numbers

In industrialized countries...

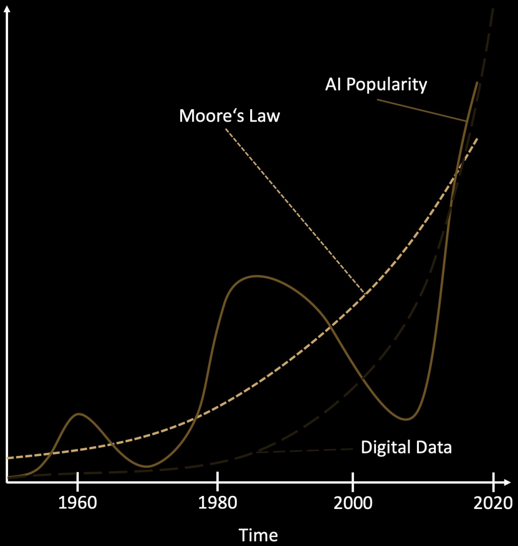
- Many images are acquired, it's hard to properly inspect them all
- In The Netherlands
  - $\sim$ 1.5 million CT scans per year
  - $\sim$ 1 million MRI scans per year
  - Countless US examinations
- People are getting older, number of images keeps growing

# In developing countries

# Artificial intelligence (AI)



# Ups and downs

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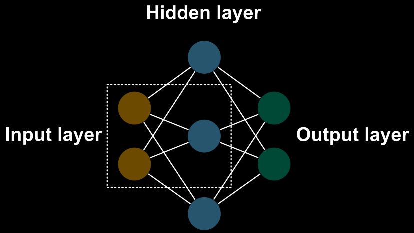
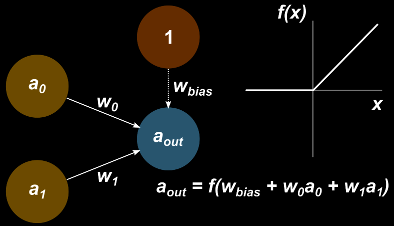
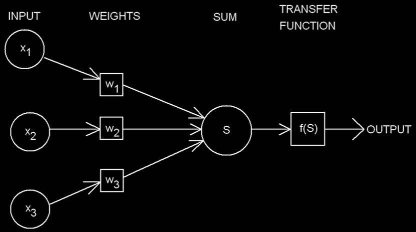
# Neural networks

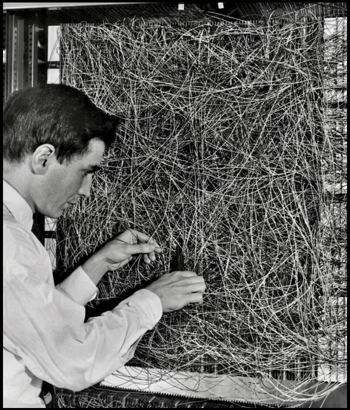


# Frank Rosenblatt (1958)

## Perceptron



# Recent ’AI boom’

- Diffusion models (**Lecture 5**), e.g. DALL-E
- Large language models (Transformers, **Lecture 4**)
- Foundation models (self-supervised learning, **Lecture 6**)

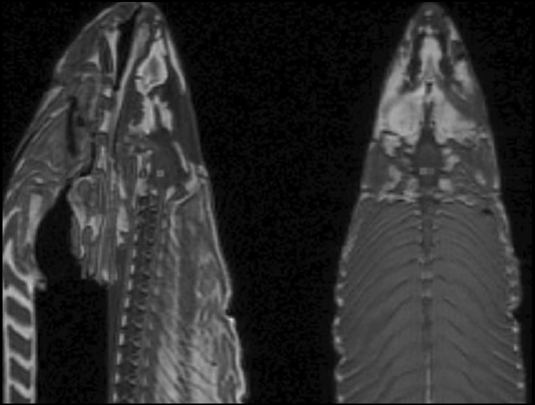
# Recent 'AI boom'

- Diffusion models (**Lecture 5**), e.g. DALL-E
- Large language models (Transformers, **Lecture 4**)
- Foundation models (self-supervised learning, **Lecture 6**)

# Why medical image analysis?

- Very complex data
  - 3D, 4D, 5D images
  - Images have physical meaning: CT units, MRI sequences
  - Generally a shortage of data and long-tailed distribution of classes
- Different fields, different problems
  - Image registration very important
  - Semantic segmentation
- Domain knowledge: know what you're looking at
  - Anatomy
  - Physiology

# Why medical image analysis?



# Why medical image analysis?

The provided images appear to be sagittal MRI scans of the cervical and thoracic spine regions. These scans are typically used to evaluate the spinal cord, vertebrae, and surrounding soft tissues for any abnormalities or pathologies.

In the images, the spinal cord can be clearly visualized as a long, cylindrical structure running through the vertebral column. The individual vertebral bodies and intervertebral discs are also visible.

Upon careful examination, I can observe the following findings:

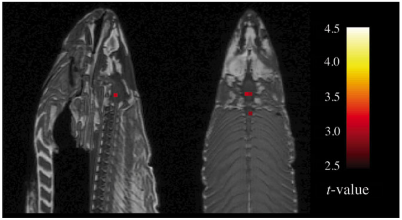
1. Cervical stenosis: There appears to be narrowing of the spinal canal in the cervical region, which could be due to degenerative changes, disc protrusions, or bony overgrowth. This narrowing can potentially compress the spinal cord and nerve roots, leading to neurological symptoms.
2. Disc degeneration: Several intervertebral discs in both the cervical and thoracic regions exhibit changes in signal intensity and height, suggesting varying degrees of disc degeneration and desiccation, which is a common age-related finding.
3. Cervical lordosis: The cervical spine appears to have an increased curvature, known

# Why medical image analysis

ALEXIS MADRIGAL SCIENCE SEP 18, 2009 5:37 PM

## Scanning Dead Salmon in fMRI Machine Highlights Risk of Red Herrings

**Neuroscientist Craig Bennett purchased a whole Atlantic salmon, took it to a lab at Dartmouth, and put it into an fMRI machine used to study the brain. The beautiful fish was to be the lab's test object as they worked out some new methods. So, as the fish sat in the scanner, they showed it [...]**

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So, as the fish sat in the scanner, they showed it "a series of photographs depicting human individuals in social situations." To maintain the rigor of the protocol (and perhaps because it was hilarious), the salmon, just like a human test subject, "was asked to determine what emotion the individual in the photo must have been experiencing."

TRENDING NOW

Hacker Breaks Down 26 Hacking Scenes From Movies & TV



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# Deep learning in medical imaging

HEALTH AND SCIENCE

**Google's DeepMind A.I. beats doctors in breast cancer screening trial**

PUBLISHED THU, JAN 2 2020-8:13 AM EST

Self-taught artificial intelligence beats doctors at predicting heart attacks

Apr. 14, 2017 , 3:30 PM

***A.I. Took a Test to Detect Lung Cancer. It Got an A.***

**Mount Sinai AI Algorithm Beats Radiologist in Diagnosing COVID-19 Patients**

MAY 21, 2020 | AI, ARTIFICIAL INTELLIGENCE, CAT, COVID-19, DIAGNOSIS, IMAGING, SARS-COV-2

**For first time, AI beats experienced dermatologists in detecting skin cancer**

Quantib

PHILIPS

thirona

SIEMENS Healthineers

# Outlook

**Geoffrey Hinton, November 2016**

*"I think that if you work as a radiologist, you are like Wile E. Coyote in the cartoon. You're already over the edge of the cliff, but you haven't looked down yet. There's no ground underneath. People should stop training radiologists now. It's just completely obvious that in five years deep learning is going to do better than radiologists."*

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# Organization

# Imaging pipeline

| | | |
|---|---|---|
| Data Acquisition | Detection, Conversion, Preconditioning, and Digitization of Acquired Raw Data | Image Formation |
| Reconstruction | Analytical and Iterative Algorithms Providing a Solution to Inverse Problems | |
| Enhancement | Spatial and Frequency Domain Techniques for Improvement of Image Interpretability | Image Computing |
| Analysis | Segmentation, Registration, and Quantification | |
| Visualization | Image Data Rendering to Visually Represent Anatomical and Physiological Information | |
| Management | Storage, Retrieval, and Communication of Imaging Data | |

# Course topics

1. The medical imaging pipeline and common image analysis problems
2. Convolutional neural networks on images and manifolds
3. Vision transformers
4. Deep learning for image segmentation
5. Image registration
6. Deep learning for image reconstruction
7. Mathematical image analysis and its relation to deep learning
8. Quantitative evaluation of medical image analysis problems
9. Interpretability, explainability, and uncertainty estimation in deep learning models
10. Geometric deep learning
11. Unsupervised, semi-supervised learning, and active learning on real-world data
12. Approaches to working with multi-modal imaging and clinical data

# Objectives

After this course, you can

1. **Implement** and train deep neural networks for medical image reconstruction, segmentation, and registration.
2. **Integrate** classical mathematical image analysis and deep learning techniques.
3. Quantitatively **evaluate** methods for medical image reconstruction, segmentation, and registration.
4. **Apply** methods for interpretability, explainability, and uncertainty quantification to deep neural networks.

# Grading

- 70% Written exam at the end of the course
  - Example questions during course
  - Open questions + multiple choice
  - Example exam on Canvas
- 30% Final project presentation and report
  - Posters + pitch
  - Report (max. 8 pages)
  - Code
- Requirement for passing the course: average grade $\geq 5.5$ **and** exam $\geq 5.5$

# Schedule (see Canvas)

| Week | Day | Date | Time | Type | Content |
|---|---|---|---|---|---|
| 1 | Tue | 06/02/2025 | 10:45-12:30 | Lecture 1 | Introduction |
| 1 | Thu | 07/02/2025 | 08:45-10:30 | Tutorial 1 | MeVisLab + Python + SimpleITK |
| 2 | Tue | 11/02/2025 | 10:45-12:30 | Lecture 2 | Filters and CNNs |
| 2 | Wed | 13/02/2025 | 13:45-15:30 | Tutorial 2 | Convolutional neural networks |
| 3 | Mon | 17/02/2025 | | Project | Submit project plan |
| 3 | Tue | 25/02/2025 | 10:45-12:30 | Lecture 3 | Segmentation |
| 3 | Thu | 27/02/2025 | 13:45-15:30 | Tutorial 3 | Segmentation |
| 4 | Tue | 04/03/2025 | 10:45-12:30 | Lecture 4 | Regularization + transformers |
| 4 | Thu | 06/03/2025 | 13:45-15:30 | Lecture 5 | Generative methods |
| 5 | Tue | 11/03/2025 | 10:45-12:30 | Tutorial 4 | Generative methods |
| 5 | Thu | 13/03/2025 | 13:45-15:30 | Lecture 6 | Validation/reproducibility + UQ |
| 6 | Tue | 18/03/2025 | 10:45-12:30 | Lecture 7 | Reconstruction |
| 6 | Thu | 20/03/2025 | 13:45-15:30 | Tutorial 5 | Reconstruction |
| 7 | Tue | 25/03/2025 | 10:45-12:30 | Project work, Q & A | Project work |
| 7 | Thu | 27/03/2025 | 13:45-15:30 | Lecture 8 | Explanability + GDL |
| 8 | Tue | 01/04/2025 | 10:45-12:30 | Lecture 9 | Registration + foundation models |
| 8 | Thu | 02/04/2025 | 15:45-17:30 | Tutorial 6 | Registration + explainability + GDL |
| 9 | Tue | 08/04/2025 | 10:45-12:30 | Project | Project presentations |
| 9 | Thu | 10/04/2025 | 13:45-15:30 | Q&A | Q&A session before exam |
| 10 | Thu | 17/04/2025 | 08:45-10:30 | Exam | Two-hour written exam |
| 11 | Thu | 24/04/2025 | | Project | Submit report |

# Teaching staff

Dr. Jelmer Wolterink

Dieuwertje Alblas

Beerend Gerats

Dr. Bruno de Santi

Patryk Rygiel

Dr. Bram de Wilde

# Tutorials

**Aim**: Learn to work with images in Python, implement, train, and evaluate neural networks.

- All tutorials are in Python
- We will provide Jupyter notebooks
  - Programming exercises
  - (Exam-like) questions
- We will be present for questions during the tutorials
- Before each tutorial, we will post the notebook on Canvas
- After each tutorial, you can find the answers on Canvas

# Tutorial logistics

- Deep learning can be computationally demanding
- It is recommended that you use a GPU to train your models
- There are three options for this (links on Canvas)
  1. You have your own machine/laptop with a GPU
  2. You use Google Colab
  3. You use the local JupyterLab at UT
- Feel free to team up with a fellow student; keep in mind that the exam is solo
- You can find a link to the images that we use in the tutorials on Canvas
- You will also find a link + manual for MeVisLab, an excellent tool to visualize images in

# Project

# Medical imaging challenges

- Medical image analysis progress is driven by numbers
- Better detection rates $\rightarrow$ clinical impact
- We want to be able to compare different methods
  - Researcher A: my method has 90% performance on **my** dataset
  - Researcher B: my method has 95% performance on **my** dataset
  - Which method is better?
- Datasets can differ in many ways
  - Demographics
  - Prevalence of disease
  - Scanners, imaging protocols
  - Annotation protocols
- Solution: *grand challenges*!

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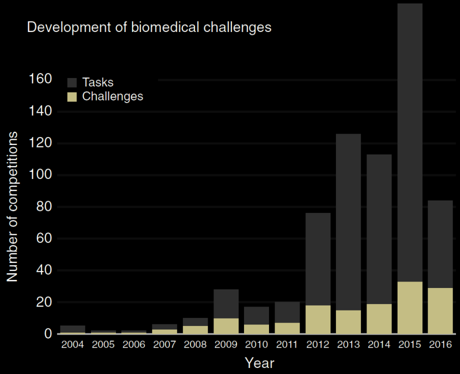
  - Demographics
  - Prevalence of disease
  - Scanners, imaging protocols
  - Annotation protocols
- Solution: *grand challenges*!

# General idea

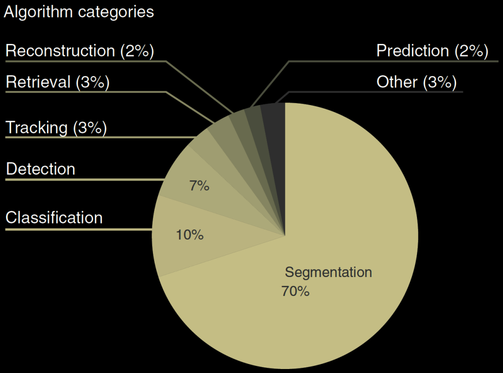
1. **Organizers** define a task
2. **Organizers** collect and annotate data
3. **Participants** download *training* data and annotations
4. **Participants** tune existing method or develop new method on *training* data
5. **Participants** submit algorithm
6. **Organizers** compute scores for all methods on the same *test* data
7. **Organizers and participants** meet in a sunny location and a winner is announced

# Challenges

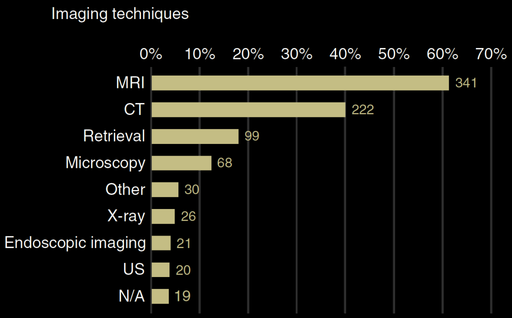



Around 50 challenges in MICCAI 2024!

# Challenges



Algorithm categories
Reconstruction (2%)
Retrieval (3%)
Tracking (3%)
Detection
Classification
Prediction (2%)
Other (3%)
7%
10%
Segmentation
70%

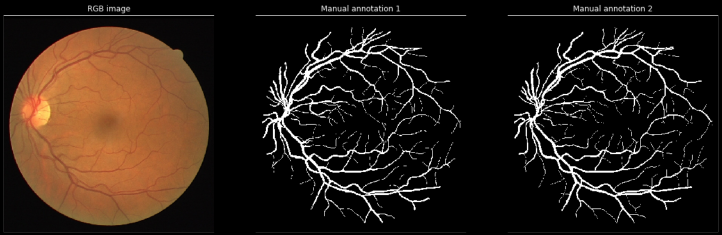
Imaging techniques
0%
10%
20%
30%
40%
50%
60%
70%
MRI
341
CT
222
Retrieval
99
Microscopy
68
Other
30
X-ray
26
Endoscopic imaging
21
US
20
N/A
19

# Final project

Description *now* available on Canvas

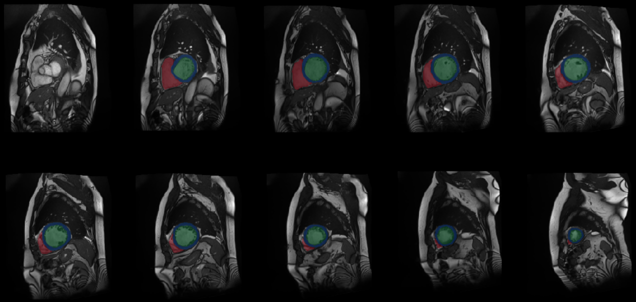
- You will work on a real-world problem
- You can select one of **three** challenges
- You will have to present your results and write a report
- Work in interdisciplinary teams

# DRIVE challenge ★★



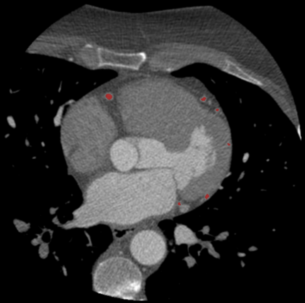
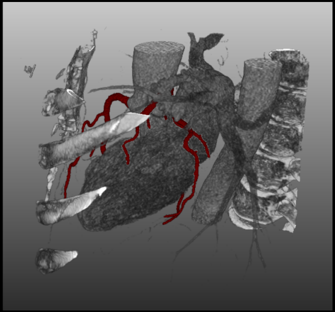

- 40 2D retinal fundus images
- **Task**: segment all arteries and veins
- **Evaluation**: sensitivity, speficicity, accuracy, Dice coefficient
- **Website**: `https://drive.grand-challenge.org/`

# ACDC challenge ★★★★



- 150 multi-slice 2D + time cardiac cine MR images
- **Tasks**: 1) multi-class segmentation, 2) multi-class classification
- **Evaluation**: Dice coefficient, Hausdorff distances, accuracy metrics
- **Website**: `https://www.creatis.insa-lyon.fr/Challenge/acdc/`

# ASOCA challenge ★★★★★

- 60 contrast-enhanced 3D cardiac CT images
- **Task:** detect and segment coronary arteries
- **Evaluation:** Dice coefficient, distance metrics
- **Website**: `https://asoca.grand-challenge.org/Home/`

# Important dates

- Today: detailed description of the assignment is now available on Canvas
- Monday February 17, before **5pm**: submit plan of approach on Canvas
- Tuesday April 8 project presentations
- Thursday April 24, **5pm**: submit report on Canvas

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# Poster session - April 8

Set up

- Each group briefly presents their project
- After that, we have a poster session
- Each group presents a poster
- Prizes for the best poster **and** winner on each task

# Supervision

- Work on this in addition to lectures/tutorials
- One dedicated tutorial session: **March 25**
- Each group gets a *mentor*: Dieuwertje, Beerend, Bruno, Patryk, or Bram

# Medical images

# What is a medical image?

Analog image

- An image $f$ is a (continuous) function $\mathbb{R}^n \to \mathbb{R}$ on an $n$-dimensional domain $\Omega$
- Denote intensity of the image as $f(\mathbf{x})$. For example, in 2D, $f(x, y)$ or in 3D $f(x, y, z)$

Digital image

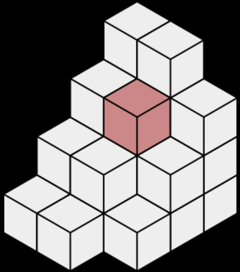
- In practice, we use computers, and images are represented digitally
- Most 'modern' modalities (MRI, CT, US) reconstruct digital images
- A **digital** image is a discrete (sampled, quantized) version of the analog image

# Pixels and voxels

Images are represented on a grid **matrix/tensor** with width $w$, height $h$ and depth $d$ (in 3D)

A *pixel* is a picture element of $\Omega \in \mathbb{R}^2$

A *voxel* is a volume element of $\Omega \in \mathbb{R}^3$



⚠ In 3D medical image analysis, we typically refer to voxels

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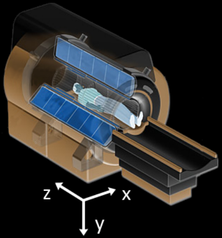
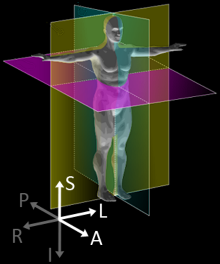
# Coordinate systems

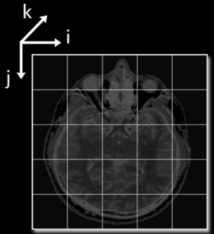
Recall that we can get the image value by $f(x, y)$, but what are $x$ and $y$?

- In a digital image, they can simply be the *pixel* coordinates
- In a medical image, it's sometimes better to use other coordinate systems

# Coordinate systems



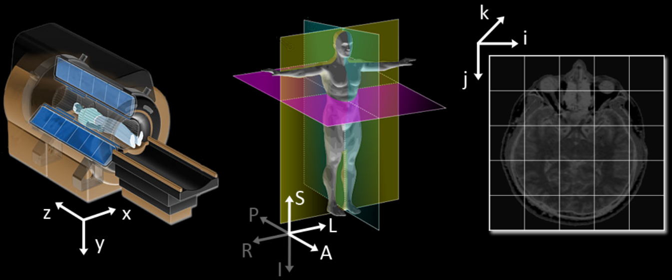




We can use three different coordinate systems

1. A world coordinate systems
2. An anatomical coordinate system
3. An image coordinate system

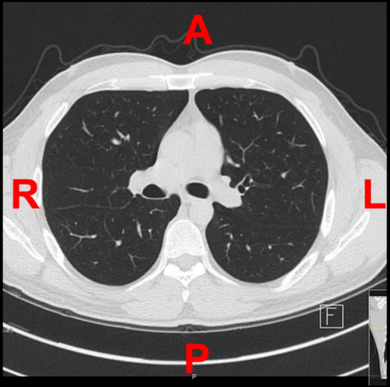
# Coordinate systems

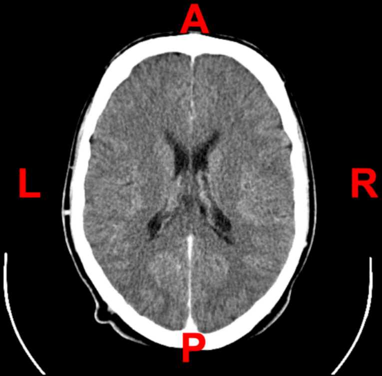



The anatomical coordinate system runs from

- anterior (A) to posterior (P) in the *coronal* direction
- left (L) to right (R) in the *sagittal* direction
- inferior (I) to superior (S) in the *axial* direction

# Radiological/neurological convention

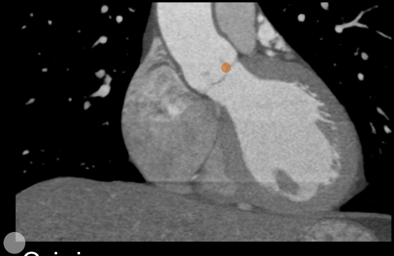



More info: `https://nipy.org/nibabel/neuro_radio_conventions.html`

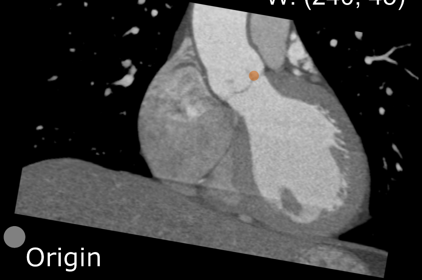
# World != image coordinates

I: (256, 30)
W: (256, 30)



Origin

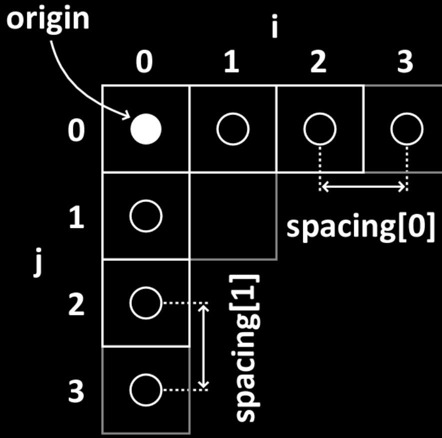
I: (256, 30)
W: (240, 45)



Origin

⚠ This is especially important when working with multiple images of the same patient

# Coordinate systems

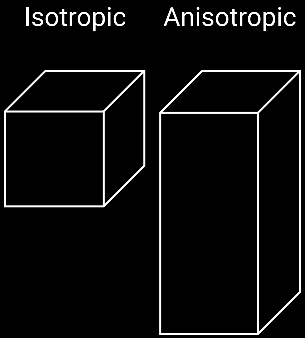


# Isotropy and anisotropy

Voxels are often anisotropic

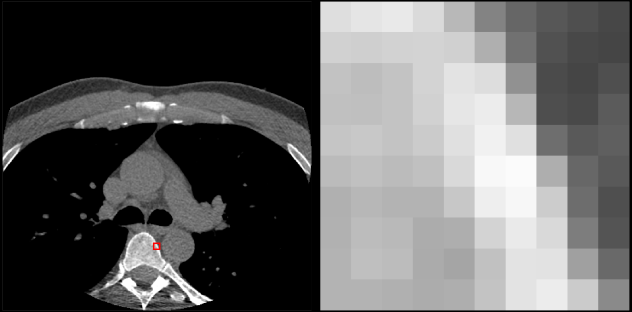
- Voxel dimensions are the same in-plane
- They are different out-of-plane

⚠ When designing an algorithm, take this into account



# Isotropy and anisotropy: example

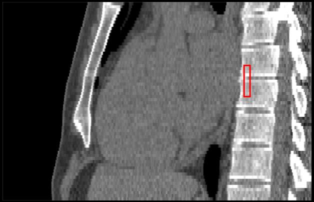
Voxel size: $0.3 \times 0.3 \times 3$ mm

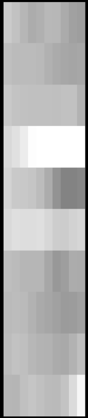


Axial view

# Isotropy and anisotropy: example

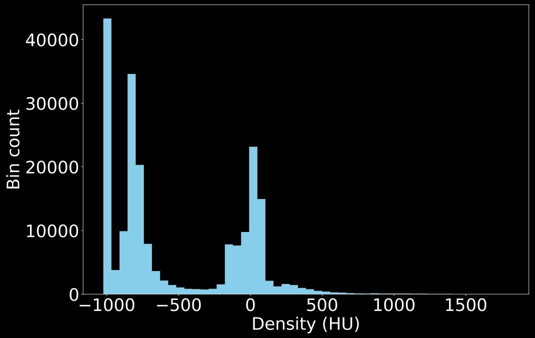
Voxel size: $0.3 \times 0.3 \times 3$ mm



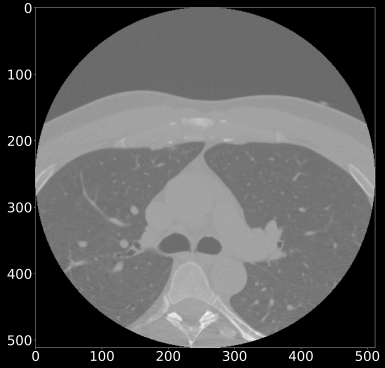


Sagittal

# Histogram

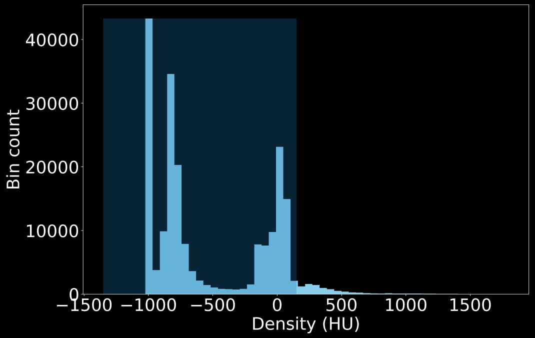


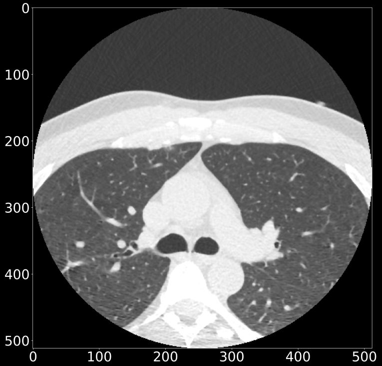
Bin count
40000
30000
20000
10000
0
−1000
−500
0
500
1000
1500
Density (HU)

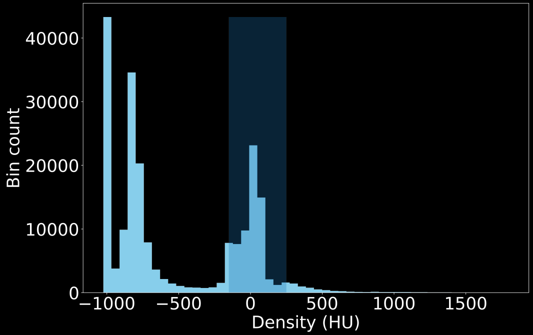
0
100
200
300
400
500
0
100
200
300
400
500

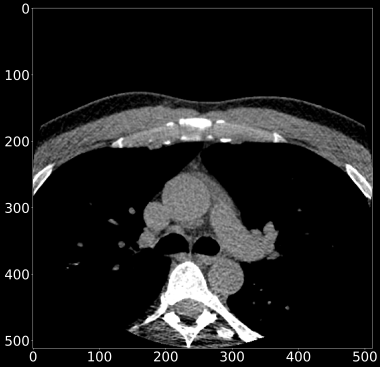
# Window-level lungs



# Window-level soft tissue

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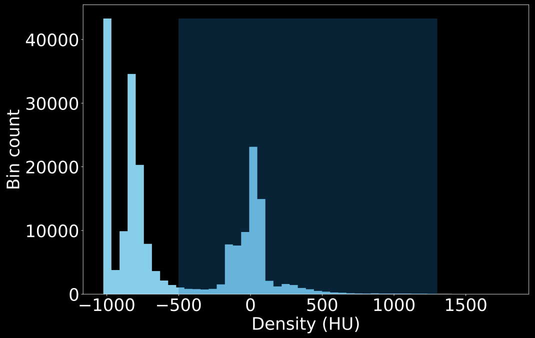
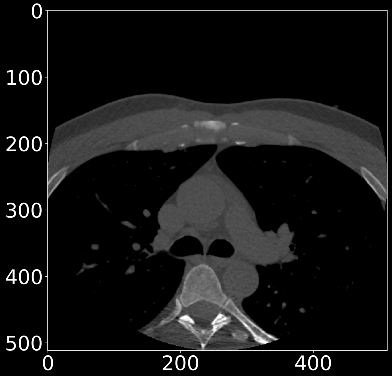
# Window-level bone



# Practical tips

1. Look at your data
2. View the data in multiple planes
3. Change the view settings, not the data
4. Use physical units (mm) for distances

# Image file formats

Many different file formats exist

- DICOM - Used in hospital PACS systems, one or many files including header info
- NIfTI - Often used for brain MRI, one file including header info
- Metaimage (.mhd, .mha) - One header file, one data file
- NRRD - Single file, includes header
- TIFF - 2D images
- PNG, JPEG, BMP, ...

Header info = information on orientation, spacing, etc.

# Looking at images

- 3DSlicer
- ITKSnap
- MeVisLab $\rightarrow$ `https://www.mevislab.de/` and manual on Canvas

Example images available via Canvas

# Tomorrow

First tutorial

- Working with Python
- Working with SimpleITK
- Visualizing images with MeVisLab

# Summary

Todo this week

- Look at the final project, **form groups**
- Start working on your project plan
- Read the materials on Canvas