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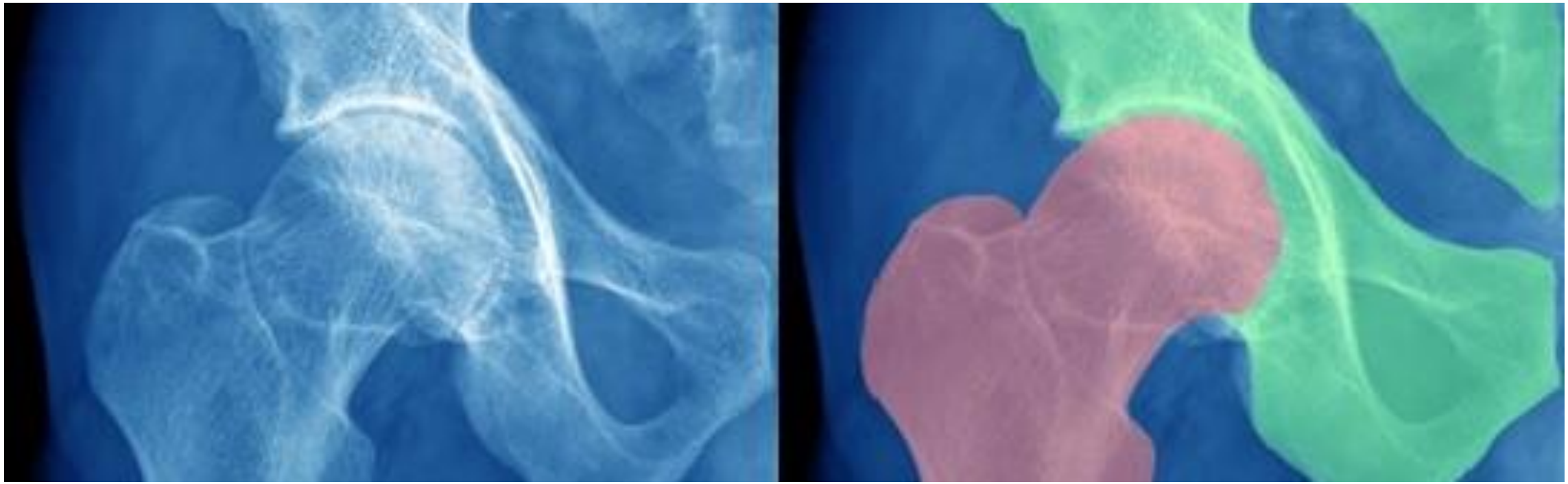
UNIVERSITY OF APPLIED SCIENCES

Image Segmentation

From top-down to bottom-up



Agenda

- Recap
- Image segmentation (focus on classical methods):
  - Gray-level Thresholding
  - Kernel & Filtering
  - Region Growing
  - Level set

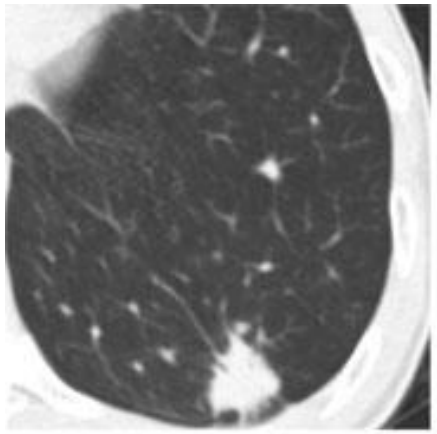
  - Edge Detection
  - Active contours

- Segmentation Evaluation:
  - DICE Coefficient
  - JACCARD Index

RECAP

Recall: ML Imaging Tasks

Classification



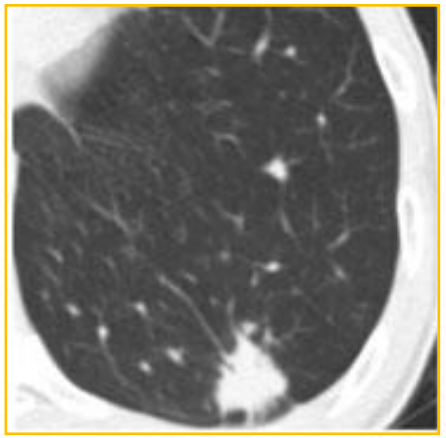
Adenocarcinoma

Adenoma

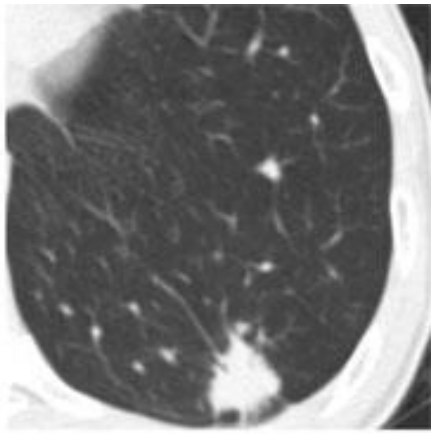
Mesothelioma

…

Detection



Segmentation



Recall: ML Imaging Tasks

Output Space & Size?

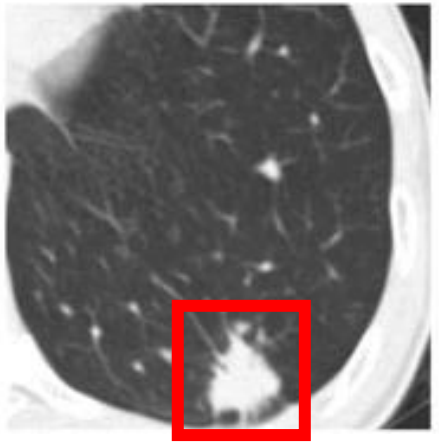
Classification	Detection	Segmentation
Multiclass: $\#\ of\ Classes$ Multilabel: 2^n	*4 numbers:* $(x_1, y_1), (x_2, y_2)$ $\mathbb{R}$	n^{w*h}

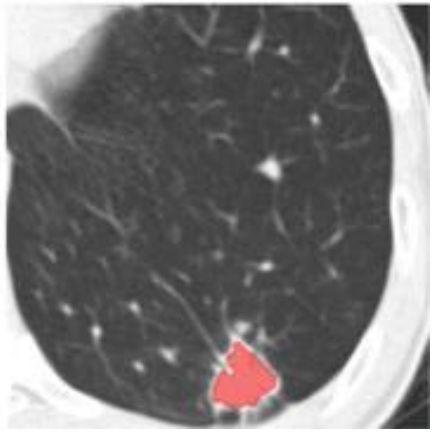
Adenocarcinoma

Adenoma

Mesothelioma

…





General Recipe for ML Modeling

- Define of the problem
- Collect (Historical) data
- (Always!) Look at the data (e.g., *analyze statistics*)
- Decide on an evaluation metric(s)
- Define Features
- Split the dataset
- Train and compare Models
- Hyperparameter tuning
- Select a model and apply (inference / predictions)

General Recipe for ML Modeling

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- Decide on an evaluation metric(s)
- Define Features
- Split the dataset
- Train and compare Models
- Hyperparameter tuning
- Select a model and apply (inference / predictions)

Decide on an evaluation metric(s)

What metrics do you know?

Decide on an evaluation metric(s)

What would you use for:				
Classification?	Regression?	Clustering?	Detection?	Segmentation?

What would you use for:

Classification?

Precision
Recall
F1-Score
Mathew's Correlation Coefficient (MCC)
ROC
AUC
Confusion Matrix

What would you use for:

Classification?

Precision
Recall
F1-Score
Mathew's Correlation Coefficient (MCC)
ROC
AUC
Confusion Matrix

What would you use for:

Classification

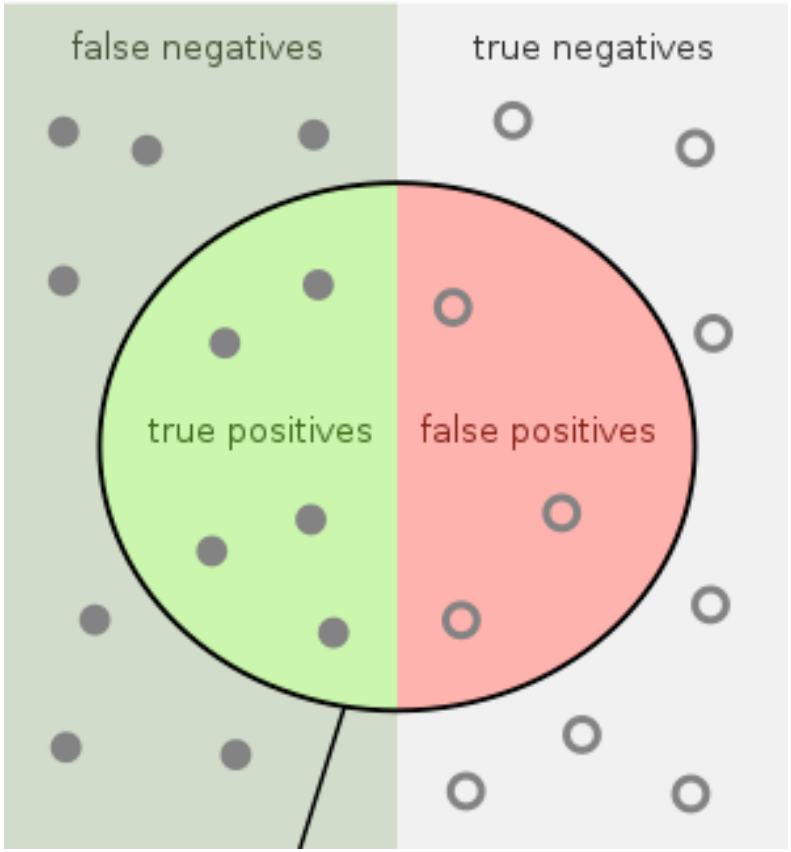
	P	N
P	TP	FP
N	FN	TN

$$Precision: \frac{TP}{TP + FP}$$

$$Recall: \frac{TP}{TP + FN}$$

$$\text{Precision} = \frac{\text{●}}{\text{●}}$$

$$\text{Recall} = \frac{\text{●}}{\text{●}}$$



What would you use for:

Classification

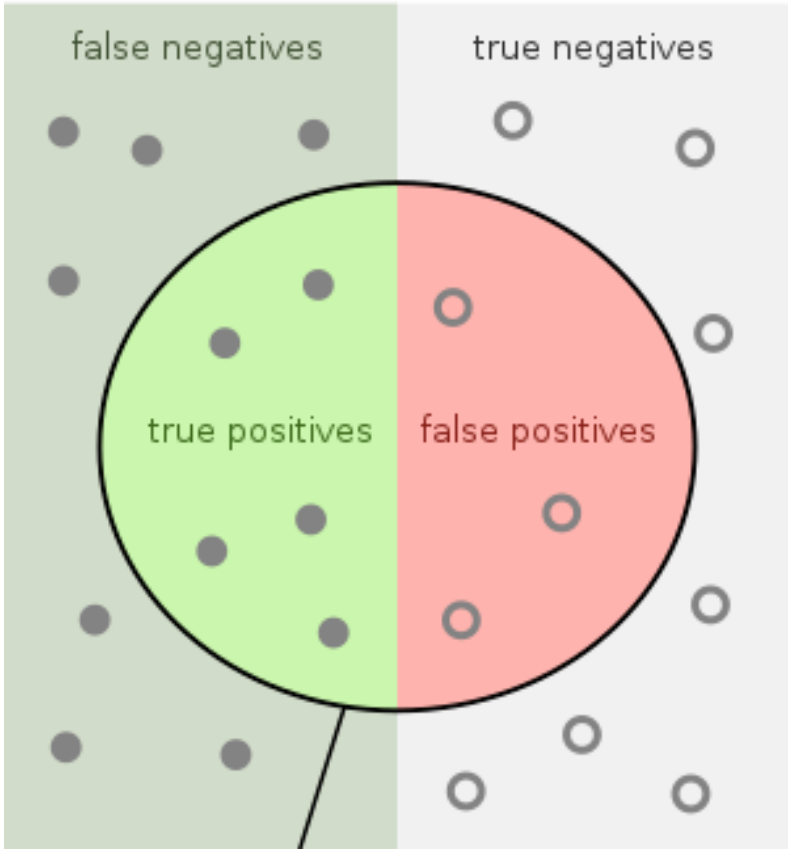
	P	N
P	TP	FP
T	FN	TN

$F1$:

$$2\frac{recall \times precision}{recall + precision}$$

$$\frac{2 \times TP}{2 \times TP + FP + FN}$$

What is missing?



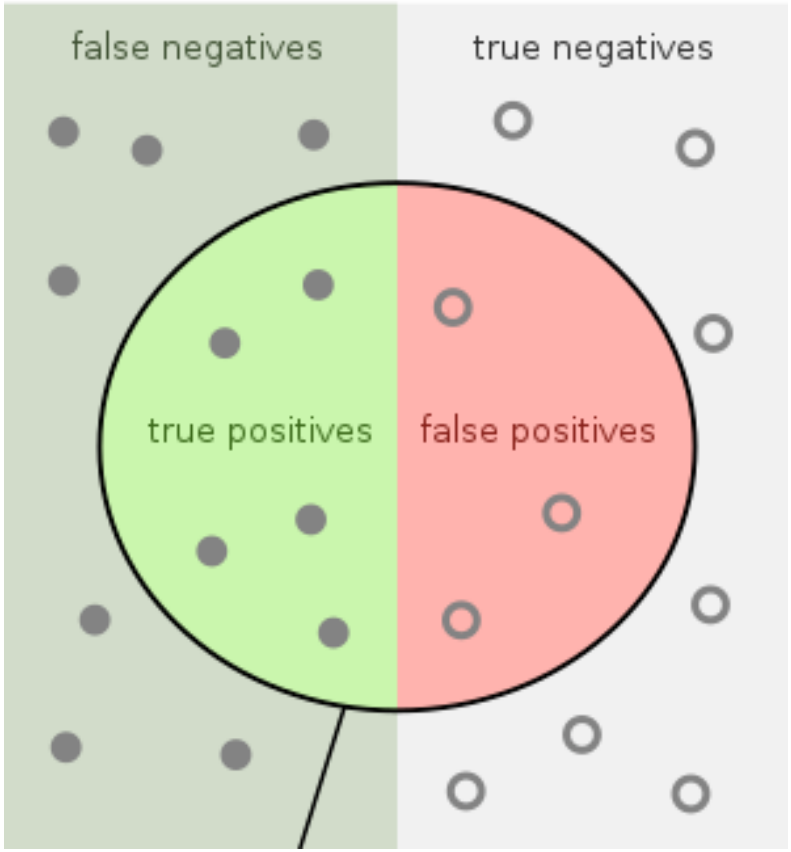
What would you use for:

Classification

	P	N
P	TP	FP
T	FN	TN

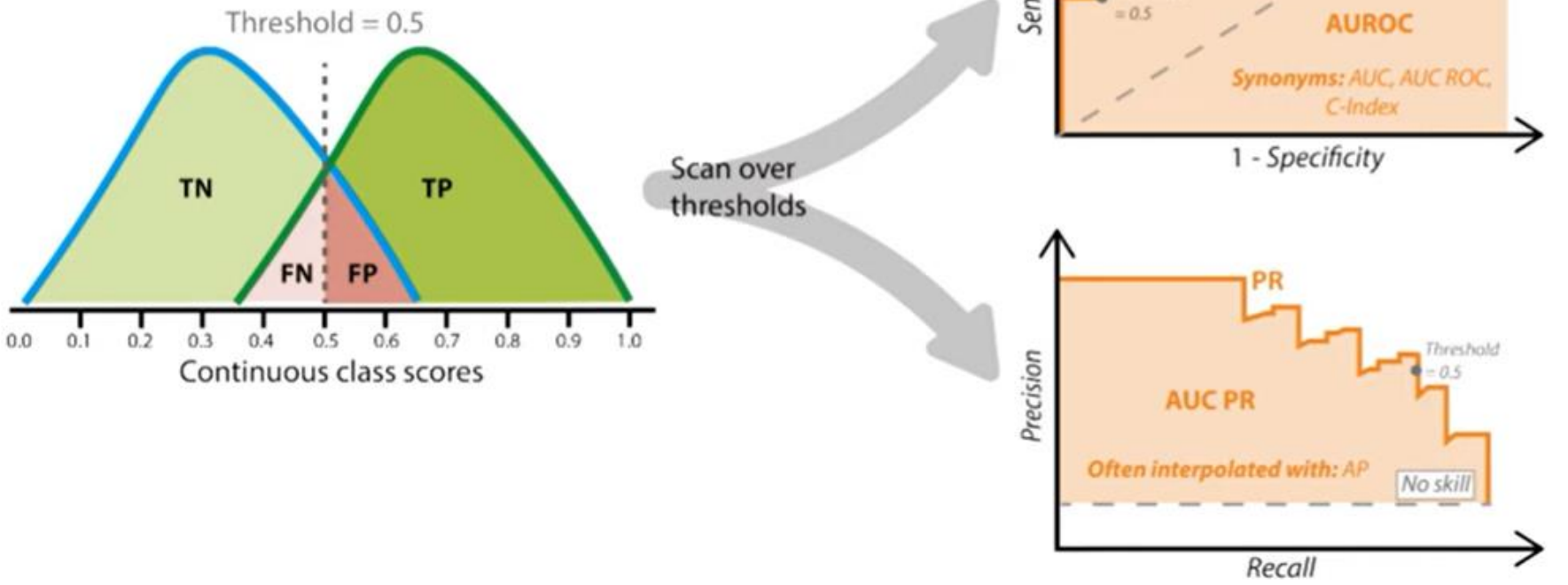
MCC:

$$\frac{TP \times TN - FP \times FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}}$$



What would you use for:

Classification



Decide on an evaluation metric(s)

What would you use for:				
Classification?	Regression?	Clustering?	Detection?	Segmentation?

What would you use for:

Regression

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y})^2$$

$$RMSE = \sqrt{MSE}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - \hat{y}|$$

Decide on an evaluation metric(s)

What would you use for:				
Classification?	Regression?	Clustering?	Detection?	Segmentation?

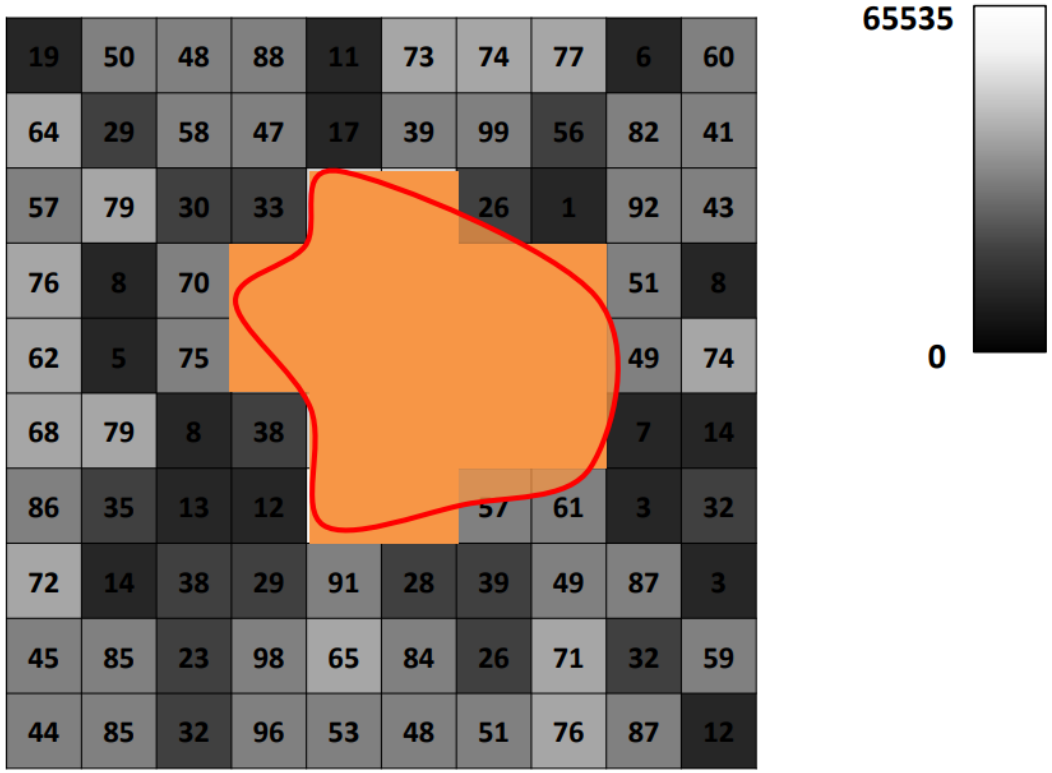
What wo

Segmen

Keep in mind:
- Images are 2D, 3D, 4D…
- Most medical images are 16-bit

Definition: Clustering image elements as "belong together"

- Partitioning
  - Divide into regions/sequences with coherent internal properties
- Grouping
  - Identify sets of coherent tokens in image

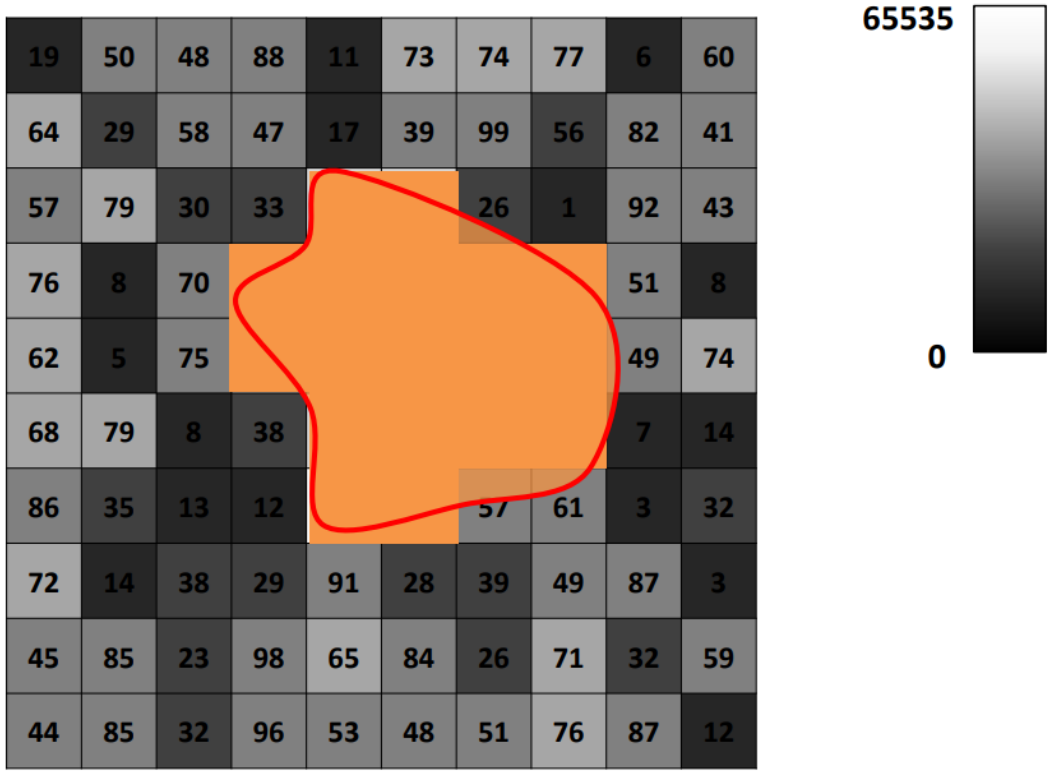


What would you use for:

Segmentation

Definition: Clustering image elements as "belong together"

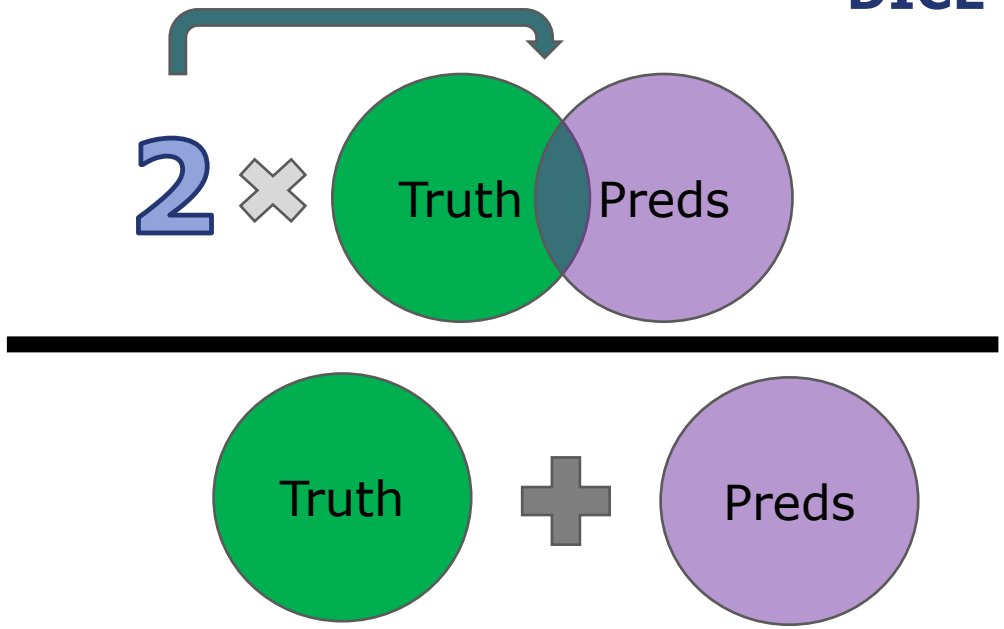
- Two approaches:
  - Pixel-wise categorial labels
  - Implicit Representations



What would you use for:

Segmentation

DICE Coefficient (F1-Score)



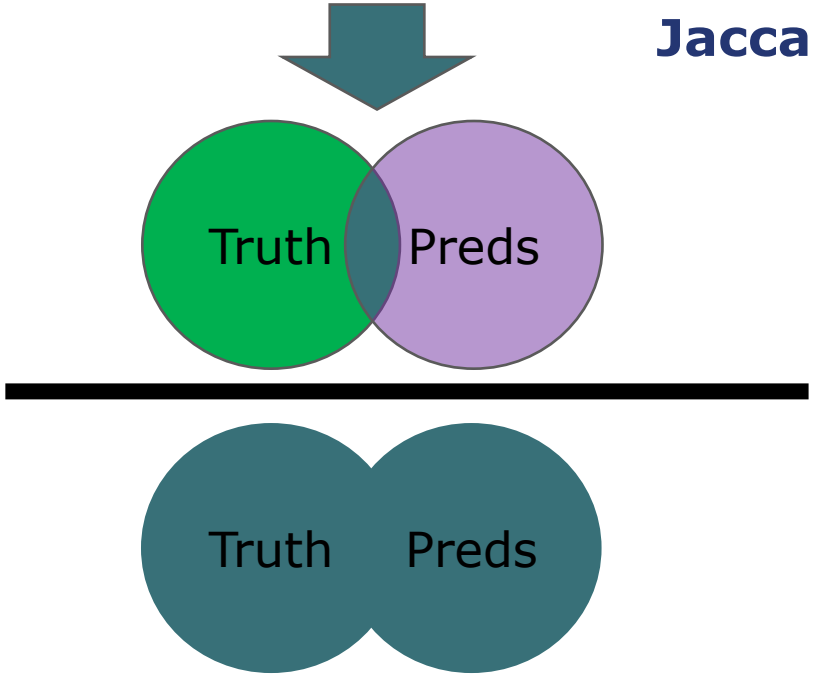
$$\frac{2 * Overlap\ Area}{Total\ Pixel\ Combined}$$

Division for normalization (to be between 0-1)

What would you use for:

Segmentation

Jaccard Index (AUC)

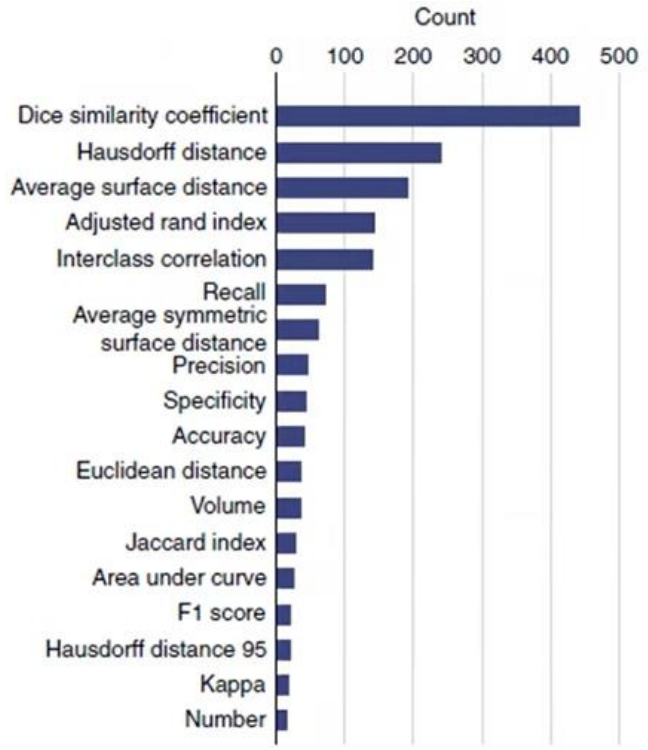


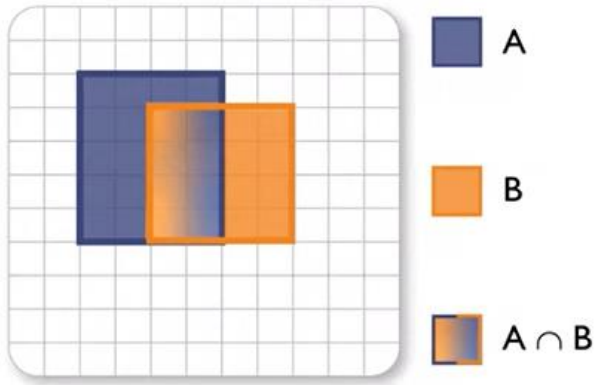
$$IOU = \frac{Overlap\ Area}{Area\ of\ Union}$$

Division for normalization (to be between 0-1)

Dice Similarity Coefficient

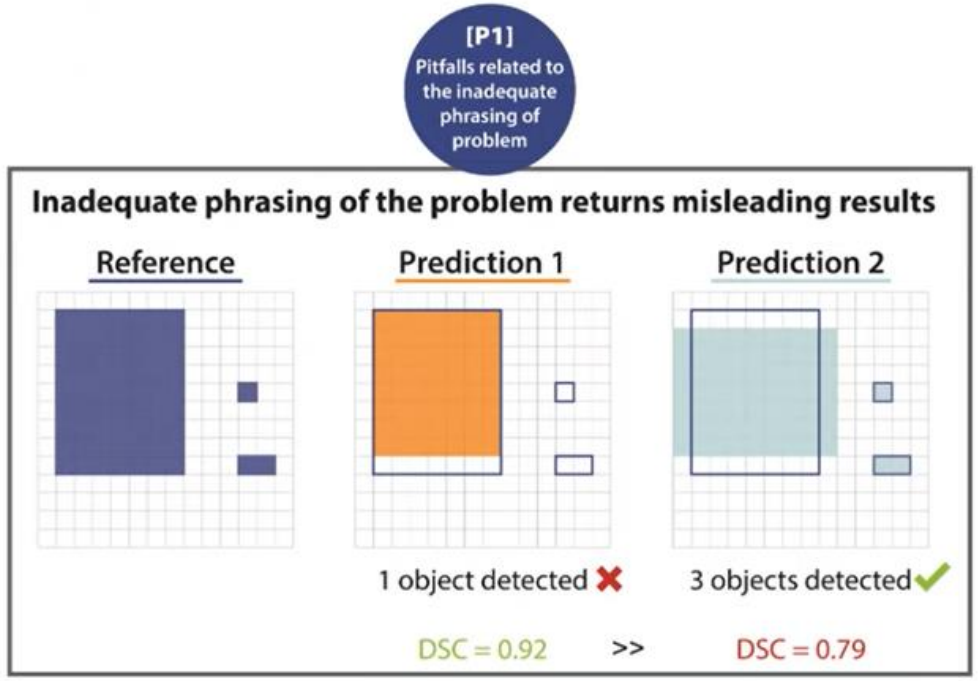
Most widely used metric





Dice Similarity Coefficient

Pitfalls: Object Detection vs. Segmentation



[2206.01653] Metrics reloaded: Recommendations for image analysis validation (arxiv.org)

Motivation

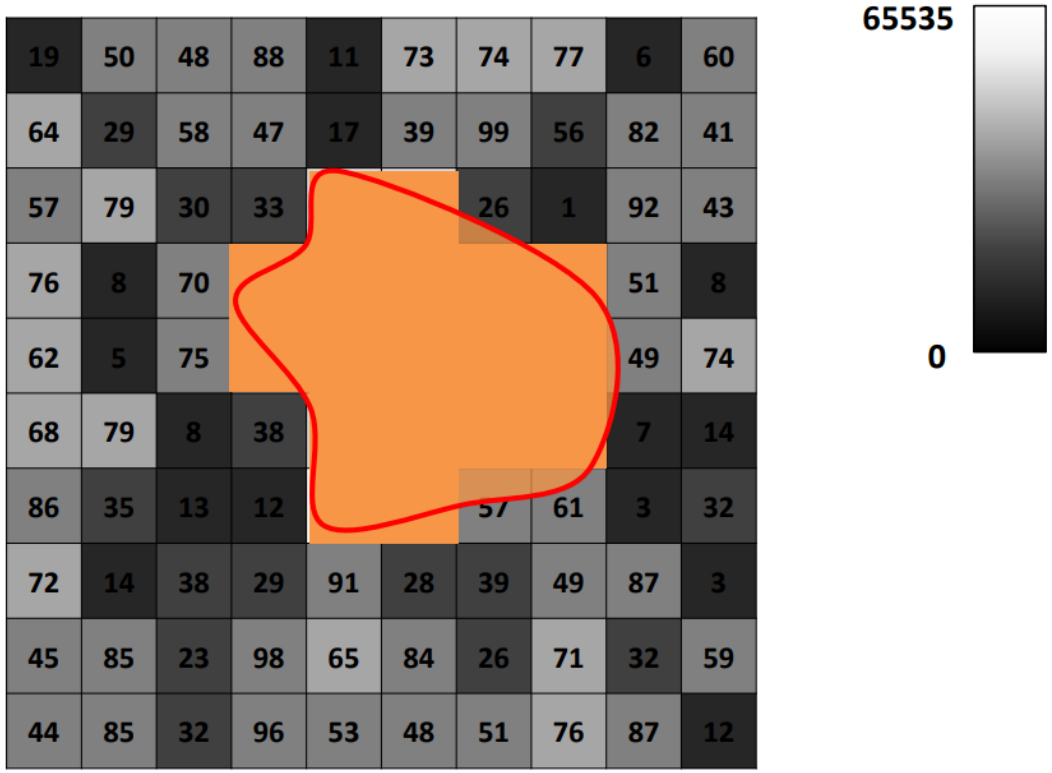
- Organ detection
  - Heart, liver, lungs in MRI / CT Scans
- Brain segmentation
  - Thalamus, hippocampus
- Quantitative Measurements
  - Ultrasound
- Image-guided surgery

What would you use for:

Segmentation

Definition: Clustering image elements as "belong together"

- Two approaches:
  - Pixel-wise categorial labels
  - Implicit Representations

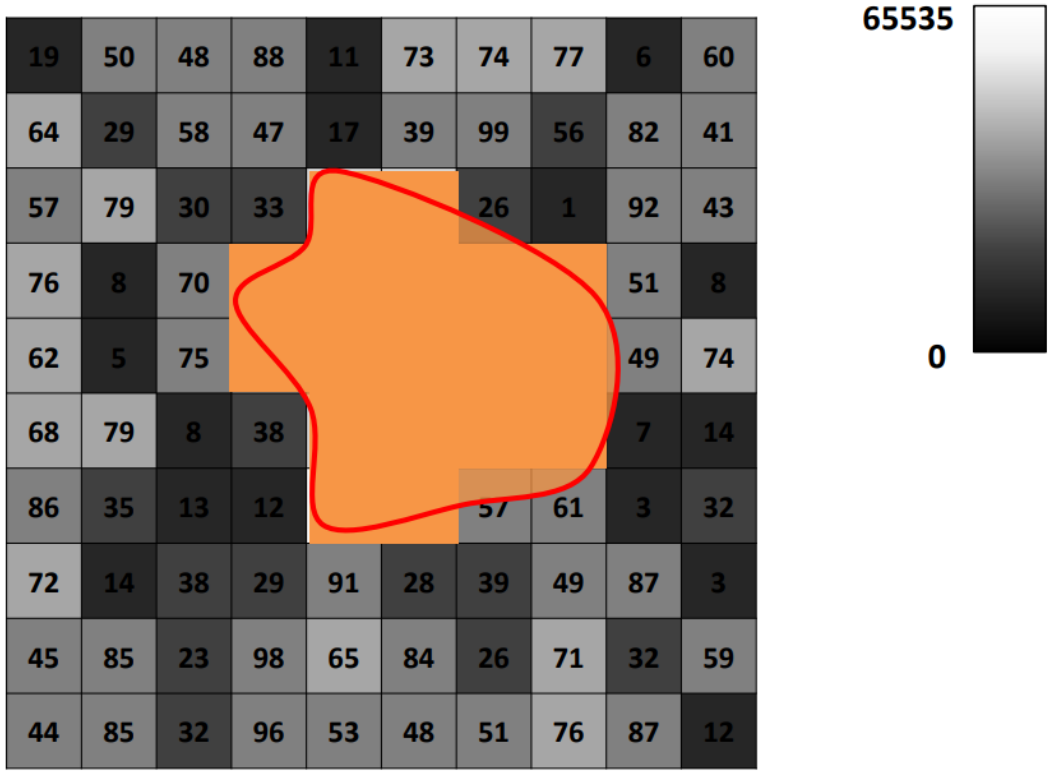


What would you use for:

Segmentation

Definition: Clustering image elements as "belong together"

- Two approaches:
  - **Pixel-wise categorial labels**
  - Implicit Representations



Pixel-wise Image Segmentation

Pixel-wise labeling is the most common representation.

Categorical labels can range from 0–N.

19	50	48	88	11	73	74	77	6	60
64	29	58	47	17	39	99	56	82	41
57	79	30	33	134	145	26	1	92	43
76	8	70	100	184	173	156	176	51	8
62	5	75	118	176	189	189	163	49	74
68	79	8	38	103	127	110	164	7	14
86	35	13	12	198	108	57	61	3	32
72	14	38	29	91	28	39	49	87	3
45	85	23	98	65	84	26	71	32	59
44	85	32	96	53	48	51	76	87	12

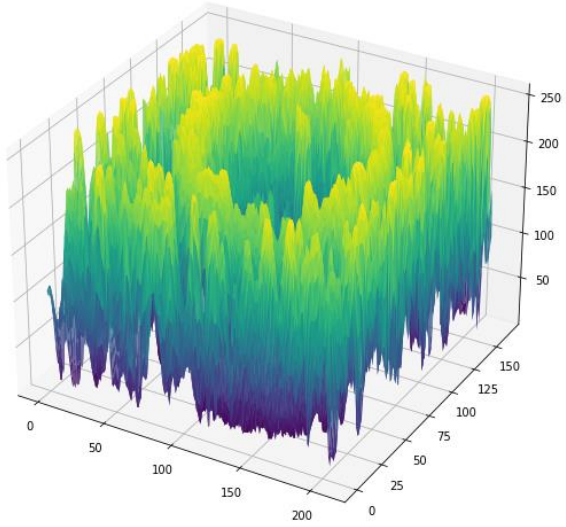
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	1	0	0	0	0
0	0	0	1	1	1	1	1	0	0
0	0	0	1	1	1	1	1	0	0
0	0	0	0	1	1	1	1	0	0
0	0	0	0	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

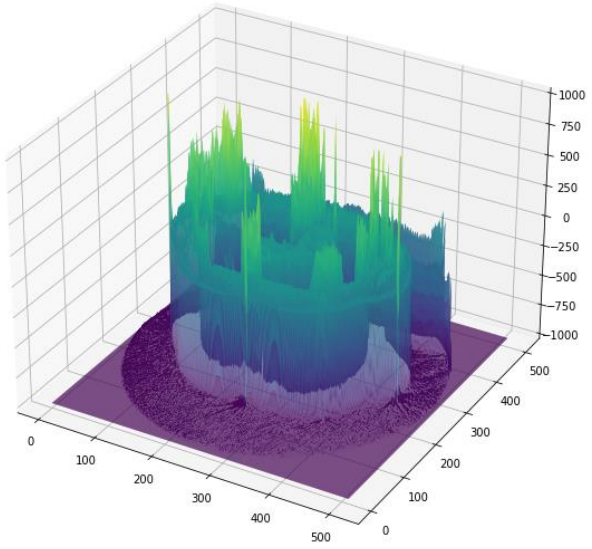
Foreground

Background

Segmentation Methods

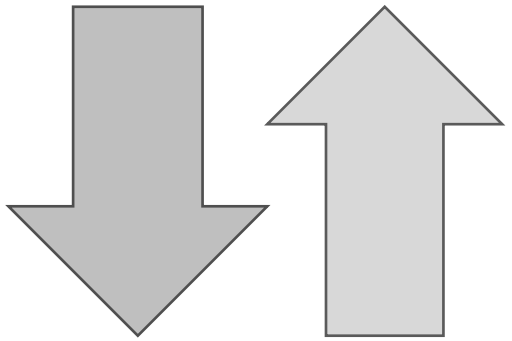
Random Taxonomy





- Based on global knowledge:
  - Histogram-Based Thresholding
- Edge-based
  - Filters
- Region-Based
  - KNN/GMM
- A combination the two
  - Edge-based and Region-Based are duals for each other.

Clustering in Vision: Grouping Pixels



Top down vs. bottom-up segmentation

- Top down: pixels belong together because they are from the same object
- Bottom up: pixels belong together because they look similar

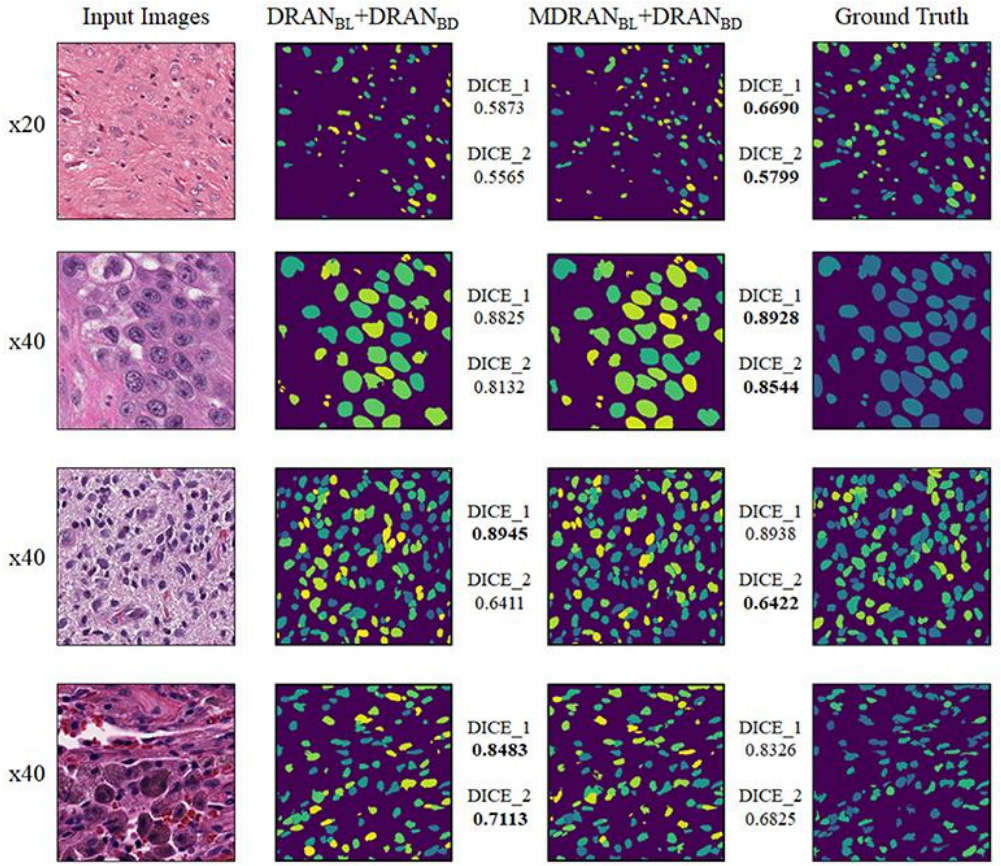
- Hard to measure success:
  - Evaluation metrics depend on the application – each measure a different aspect

  - (55) Lena Maier-Hein @ ICBINB Seminar Series – YouTube

    Shows examples where the metrics are high, but the models still miss

Segmentation via Classification (supervised)

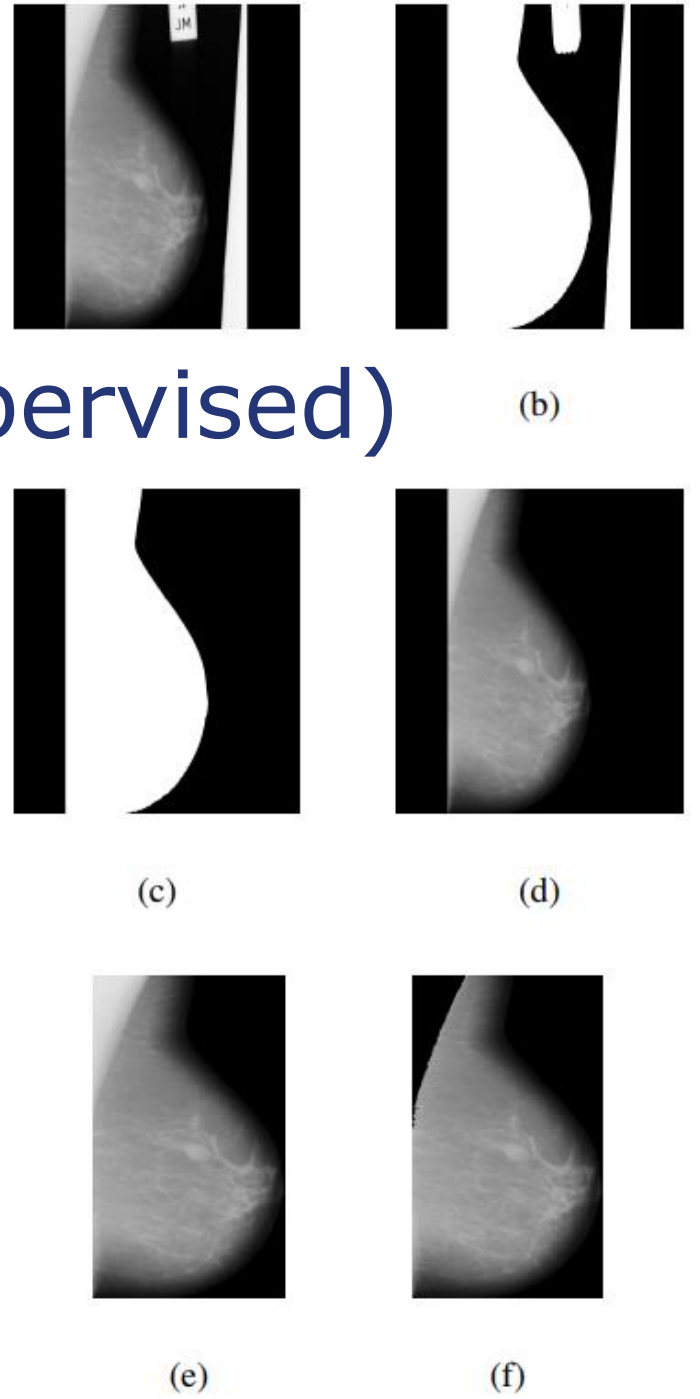
- **Classifier:**
  KNN, Support Vector Machine (SVM), NN, etc.
- **Features:**
  - Voxel value
  - Voxel position
  - Gradient magnitude
  - Neighboring values
- **Labels:**
  - Foreground/Background (binary) or Class IDs (multiclass)
- **Requires Labeled Training Data**



Segmentation via Clustering (Unsupervised)

K-Means

- **Algorithm:**
- Pick **K** feature space cluster centers at random
- While not converged
  - Assign each pixel to the nearest cluster
  - Recalculate cluster centers as the centroid of pixels in that cluster

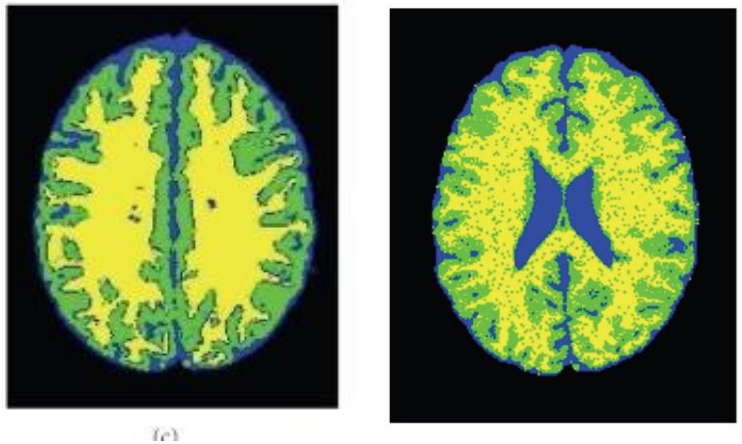


[Fully Automatic Computer-Aided Detection of Breast Cancer based on Genetic Algorithm Optimization | IEEE Conference Publication | IEEE Xplore]

Segmentation via Clustering (Unsupervised)

Gaussian Mixture Models (GMM)

- **Algorithm:**
- Pick **K** feature space cluster centers using K-Means
- Initialize Gaussians (random mean & co-variance)
- While not converged
  - Calculate the probabilities for each pixel to each Gaussian
  - Recalculate the mean and the co-variance of each Gaussian



[Multiple sclerosis lesion detection using constrained GMM and curve evolution - PubMed (nih.gov)]

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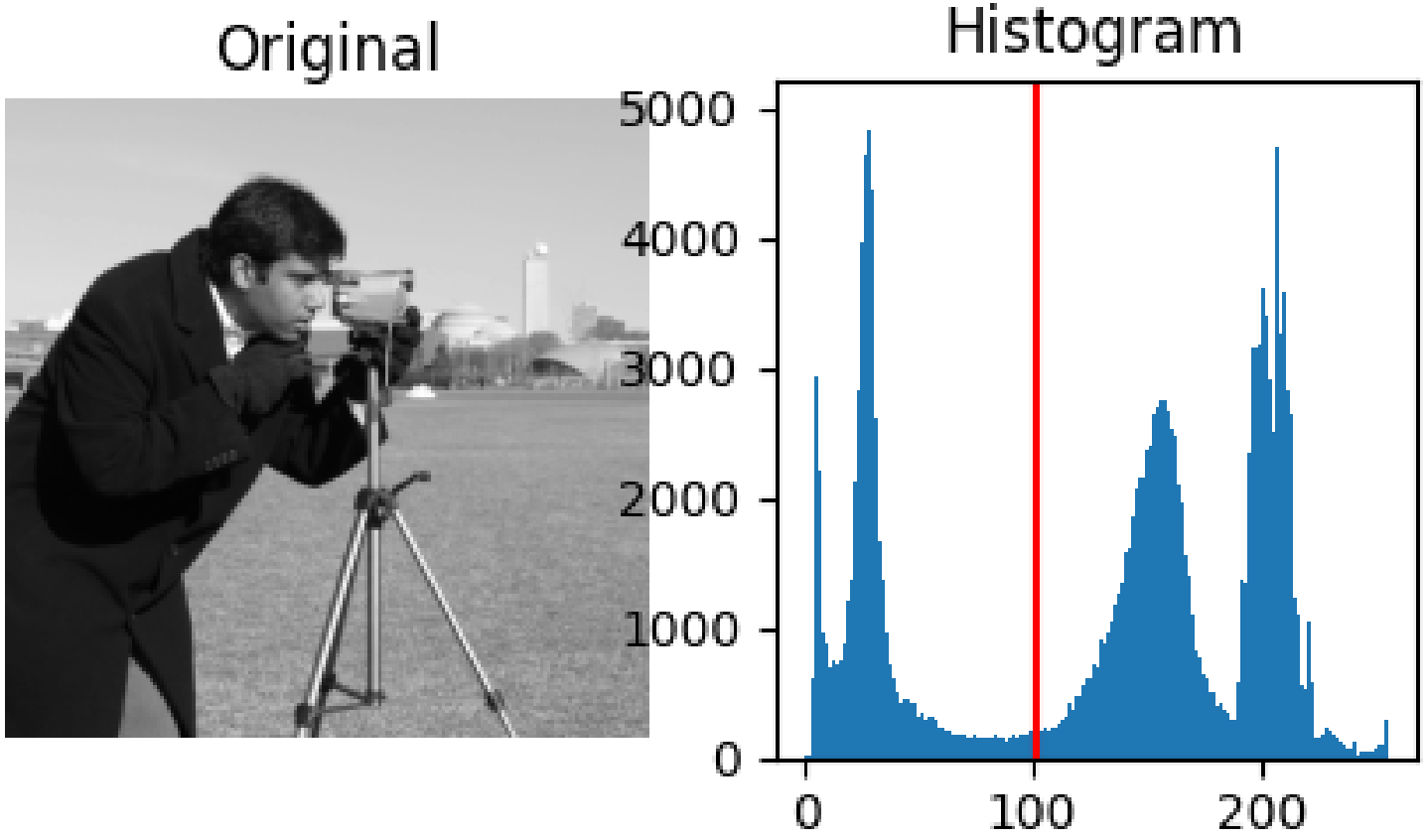
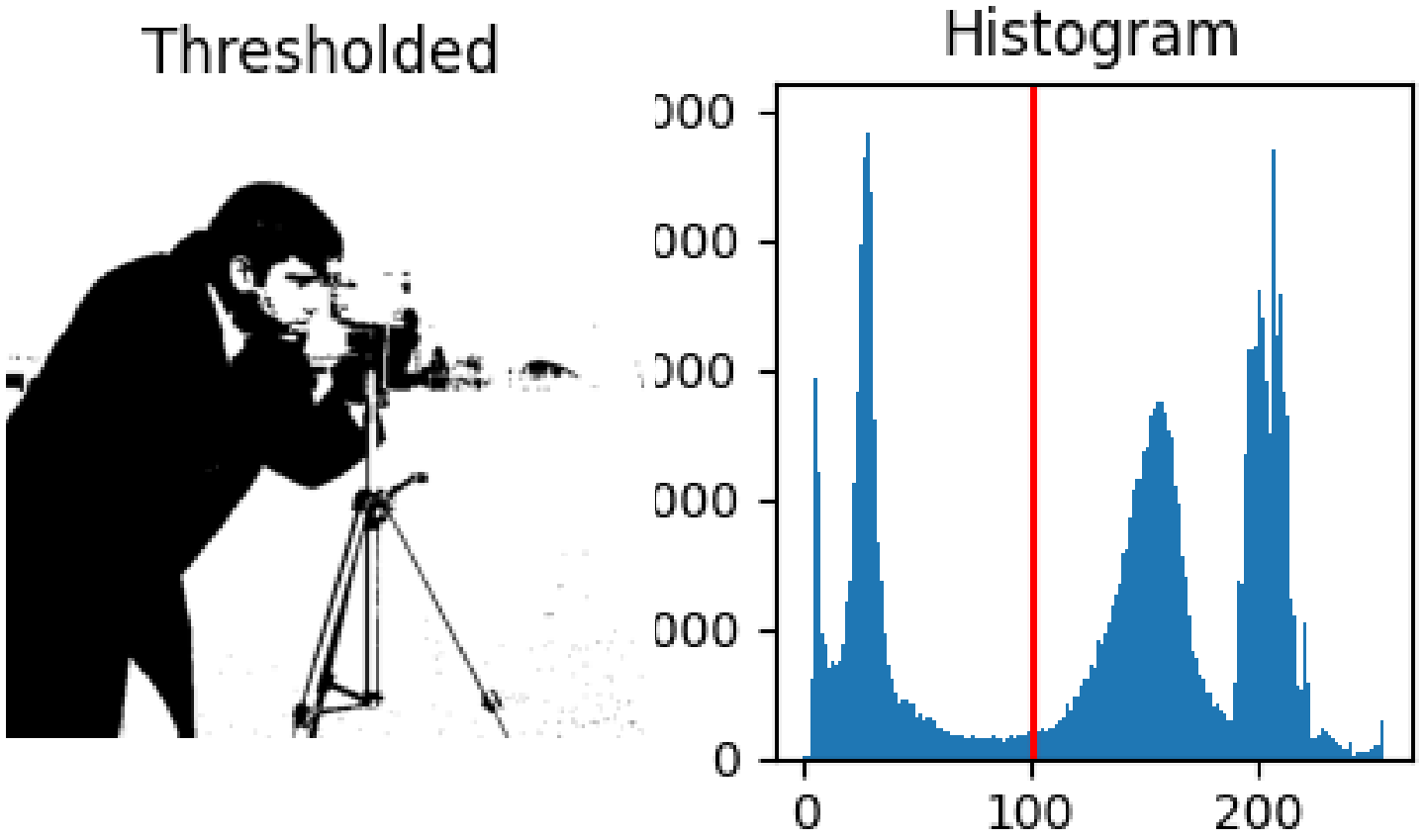
THRESHOLDING

Thresholding



Thresholding

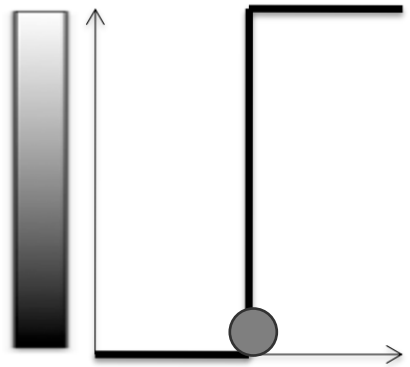


Intensity Thresholding

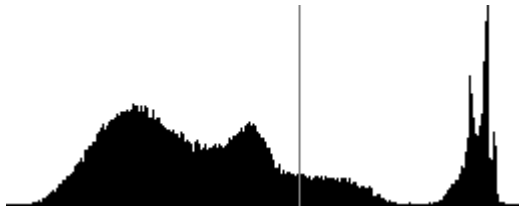
- Input: **Gray-level** images
- Output: **binary Image**
- Works best on high-contrast images

Algorithm:

- Choose a threshold pixel value T
- For every pixel
  - if pixel ≥ T, label as *foreground*
  - Else: label as *background*



But how to choose T?



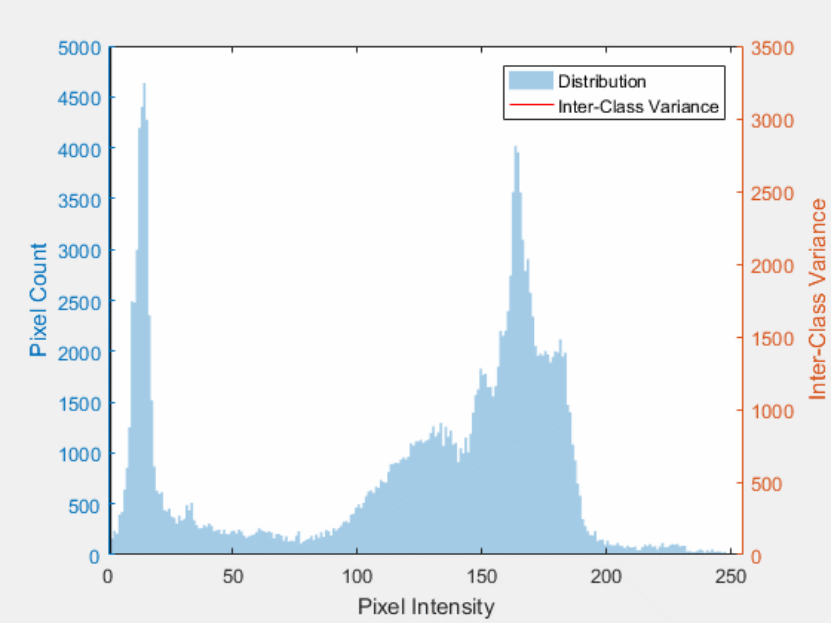
Choosing a Threshold Value

Example: Otsu's Method

Searches the point t that minimizes the *variance* of foreground and background pixel values, weighted by class probabilities*.

$$\sigma_{\omega}^2(t) = P_a(t)\ \sigma_a^2(t) + P_b(t)\sigma_b^2(t)$$

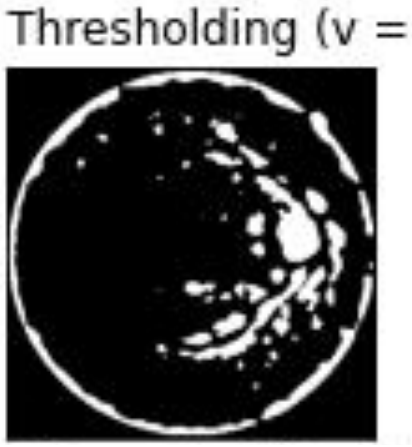
Works well for bi-modal histograms.



* **Probabilities**: count how many pixels with those colors belong to the foreground, and how many to the background

Otsu Thresholding - The Lab Book Pages

Adaptive Thresholding



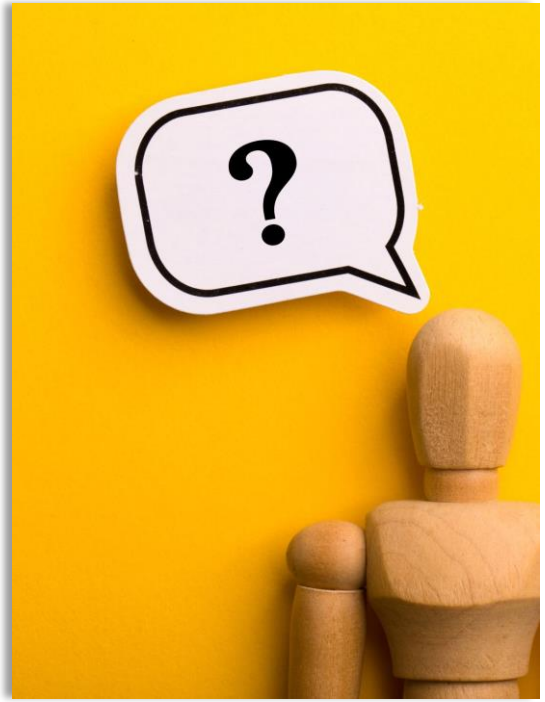
- Global Thresholding:
  - operates on the whole image
- Adaptive Thresholding:
  - Using a running-window
  - Every patch is handled on its own

Choosing a Threshold Value

- Many algorithms exist:
  - Maximum Entropy
  - Niblack
  - Li's
  - Kapur
  - Sauvola
  - Wolf …
- Often, task-dependent
  - no single perfect threshold value exists.
- Thresholding leads to multiple disconnected components (i.e., "islands")

manuelaguadomtz/pythreshold: PyThreshold is a python package featuring Numpy/Scipy implementations of state-of-the-art image thresholding algorithms. (github.com)

Thresholding



- What are your Take-Aways

Thresholding

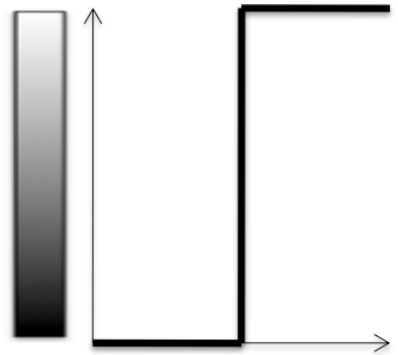
Take-Aways

- A method to detect a middle point through the image histogram
- Clusters the image to foreground/background
- Operates either globally or on a running-window

REGION-GROWING

Thresholding

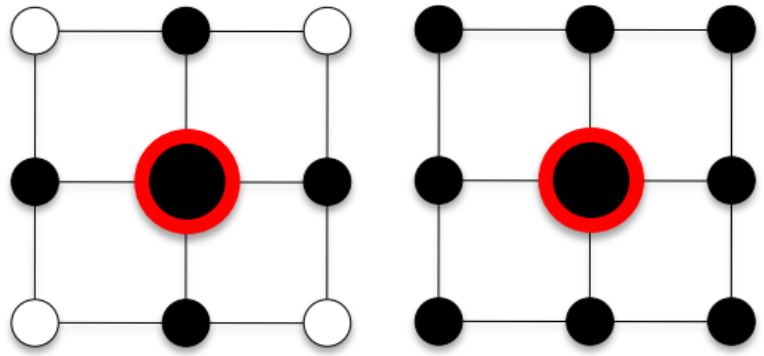
Recap



- Given a threshold level T, for every pixel:
  - If pixel ≥ T, label as *foreground*, else as *background*
- Otsu's Method
  - minimize variance of foreground and background pixel values weighted by class probabilities
- Maximum entropy
  - Maximize sum of each class's entropy: $H(t) = -\sum_i p(a_i) \log p(a_i) - \sum_i p(b_i) \log p(b_i)$
- Adaptive/local Threshold
  - Running window (same as filters)
  - Local mean, local median, Sauvola, Perwit, …

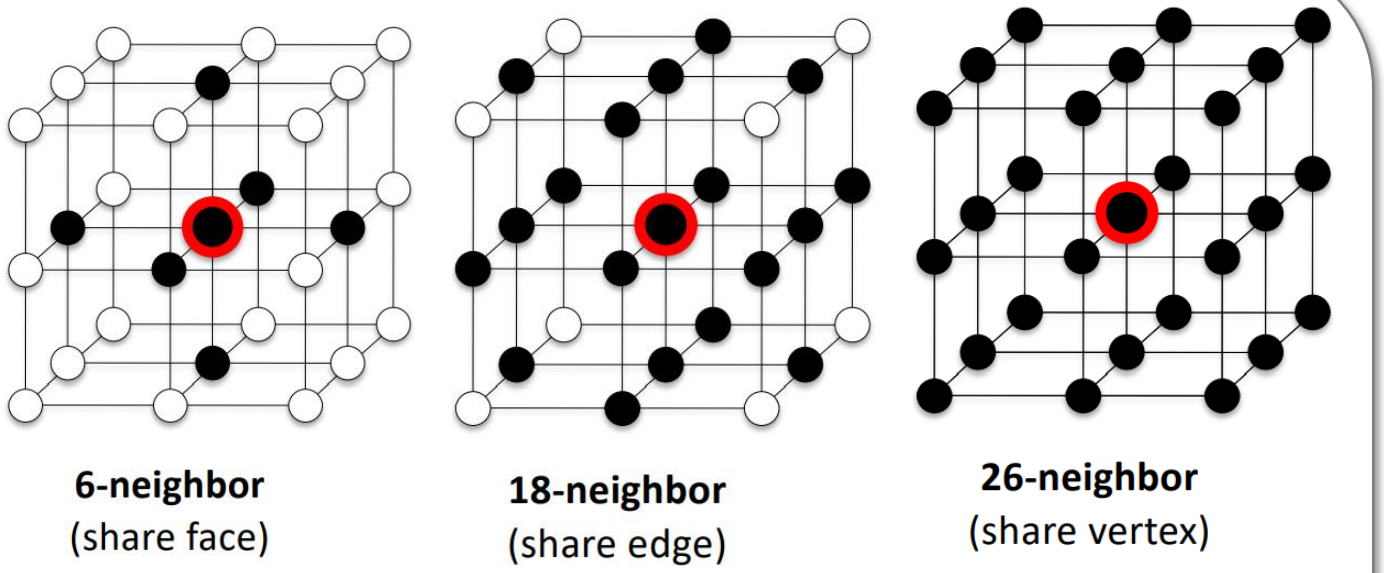
Connectivity

Defining Anatomic Regions Based on Contiguity



4-neighbor 8-neighbor

2D



6-neighbor
(share face)

18-neighbor
(share edge)

26-neighbor
(share vertex)

3D

Region-Growing

Group pixels with similar properties – finding continuous regions

Algorithm:

- Select "seed" pixels according to some criteria
  - Add to a region and push to the back of the queue
- While the queue is not empty
  - For each neighbor of the front of the queue:
    - If the neighbor meets the criteria and isn't in the region
      - add to the region and push to the back of the queue
  - Pop head of the queue

Example Implementation

Notes:
Criteria can be anything (e.g., global threshold)

* If you are familiar with Graph Theory: This is a breadth-first search

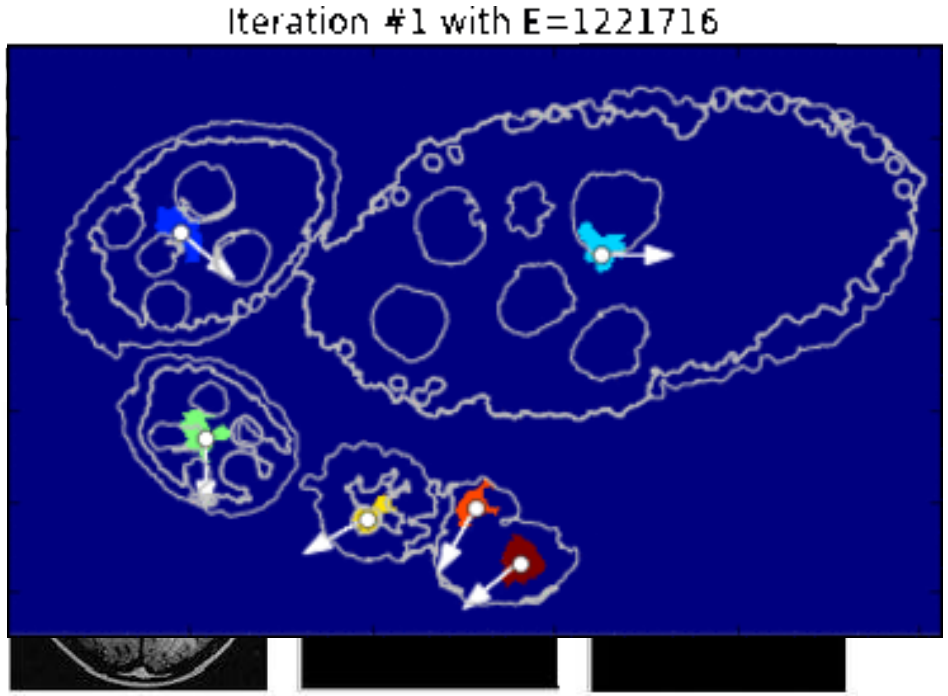


Figure 5(a). Original Image

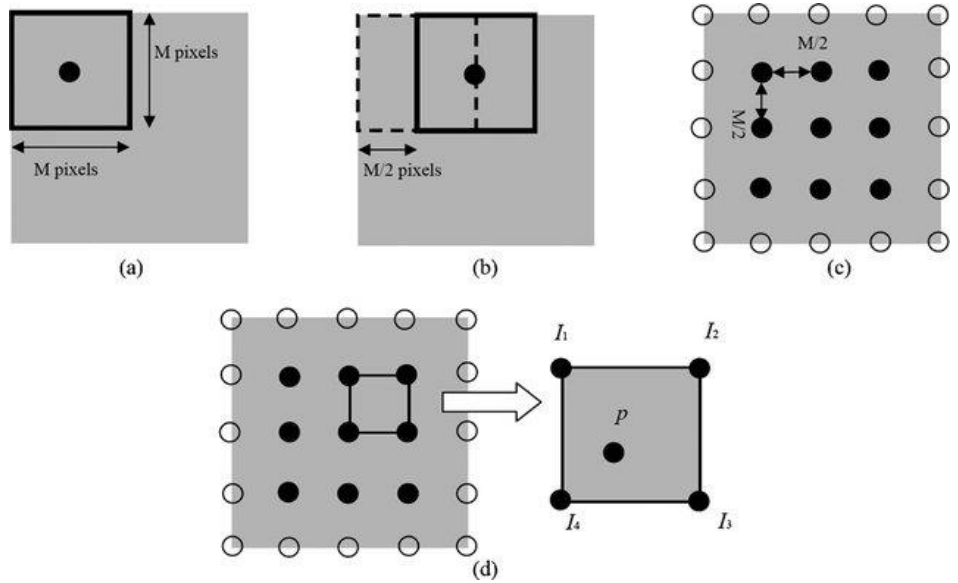
Figure 5(b). Seed points

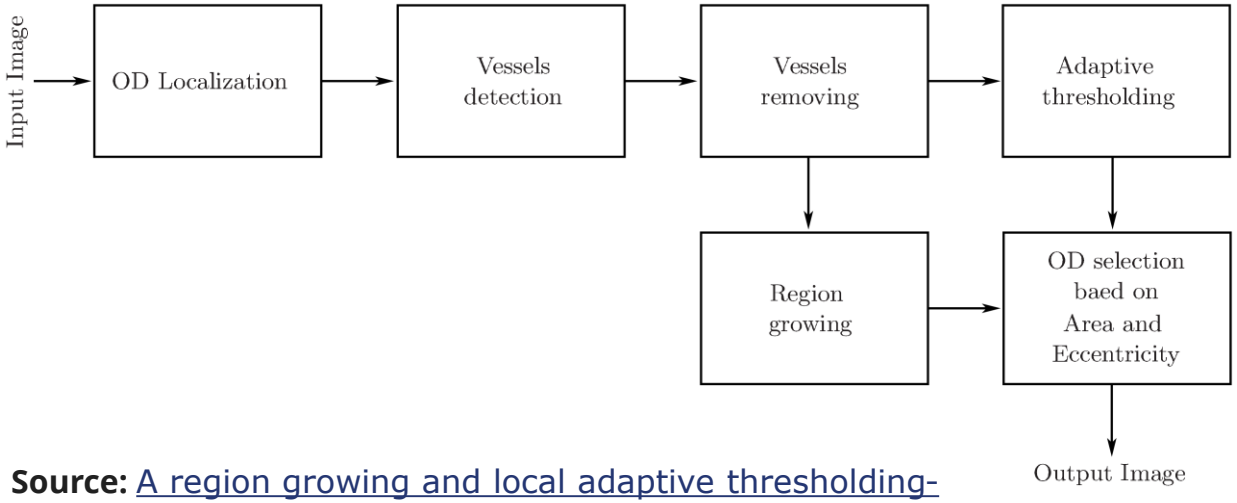
Figure 5(c). Result of Region growing

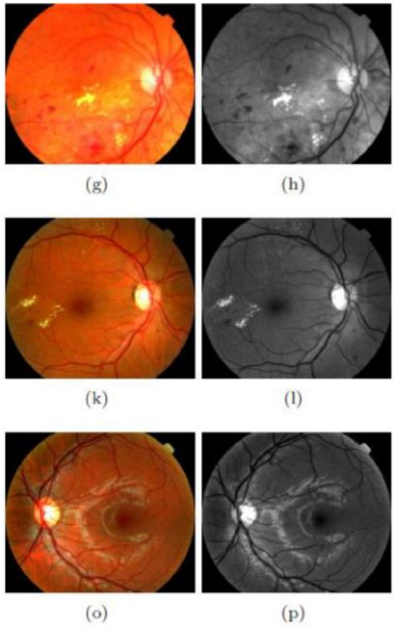
Figure 5. segmentation by Region Growing[22]

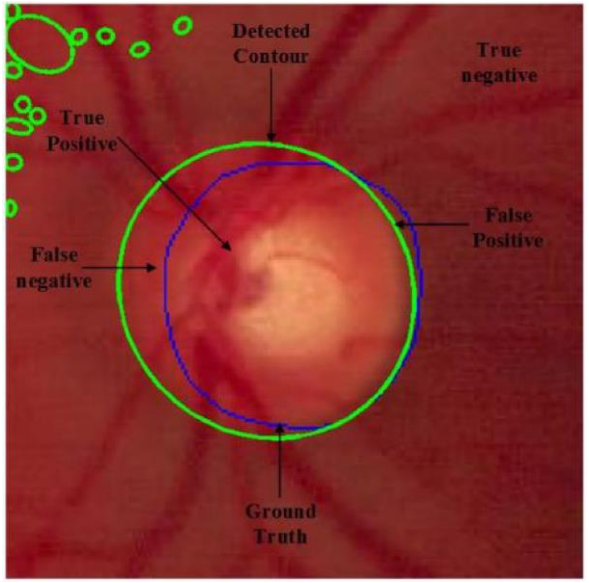
Local Adaptive Thresholding

- Calculating the thresholds separately on different regions of the image.
- Note: Regions can be chosen ‘smartly’



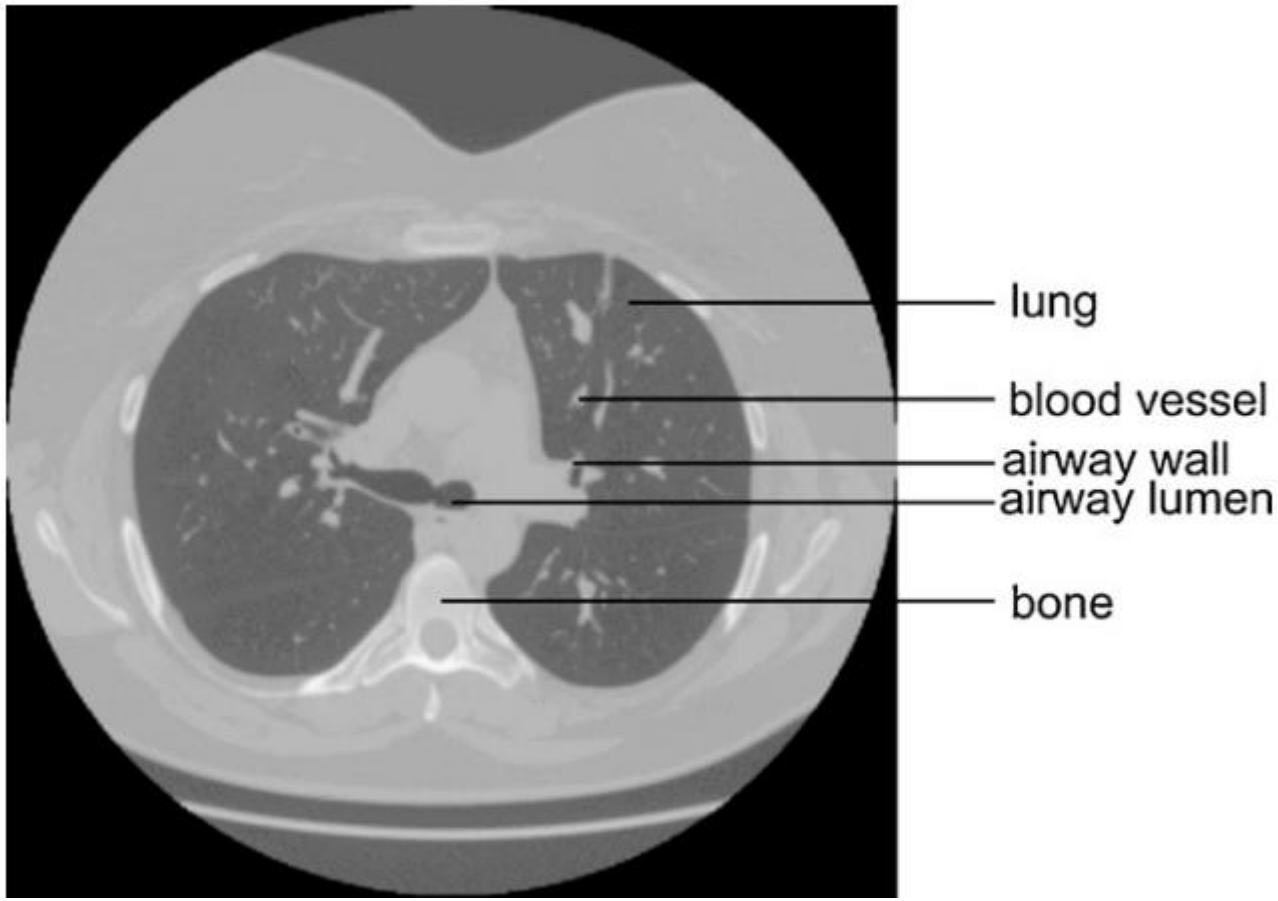


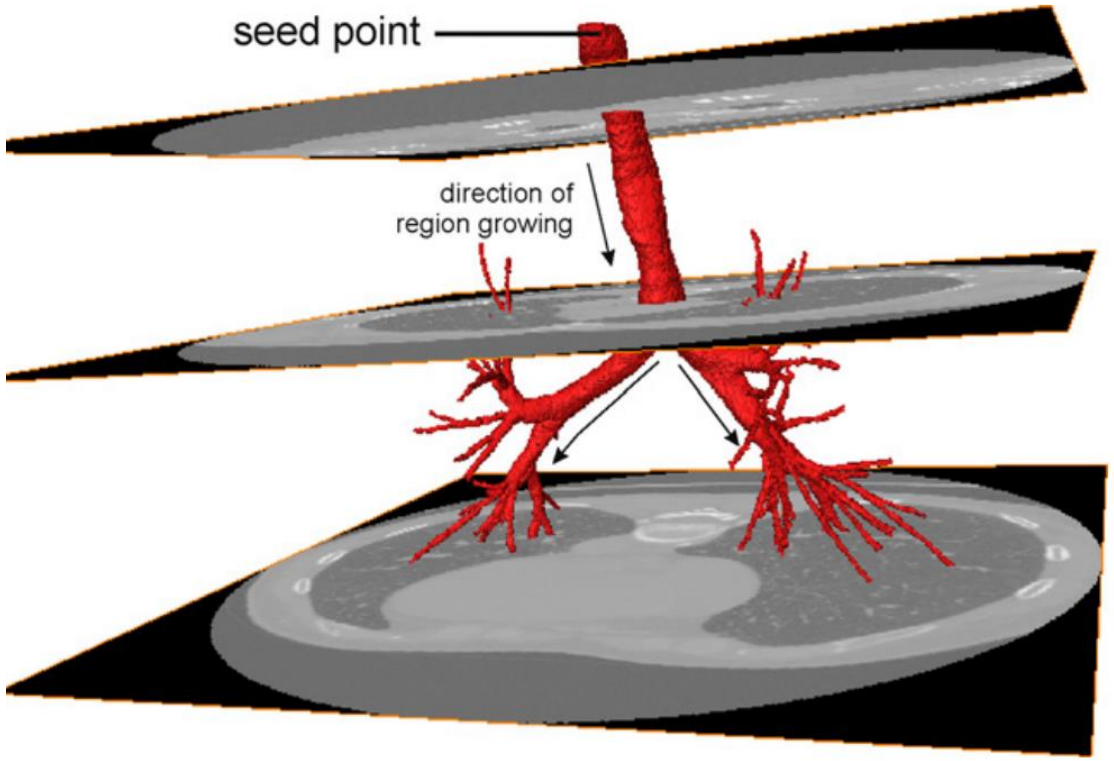




Source: A region growing and local adaptive thresholding-based optic disc detection (plos.org)

Region Growing – Best for a Continuous Region





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KERNELS & FILTERS

Kernels & Filters

Kernel – a 2 parameters function: $f(x_1, x_2)$

These parameters can be scalars or matrices

Q: Where have we met (and used) **Kernels** before in ML?

Image Kernels (Filters)

- Kernel: a fixed matrix of numbers
- Calculates an average on the image, using a *sliding window*

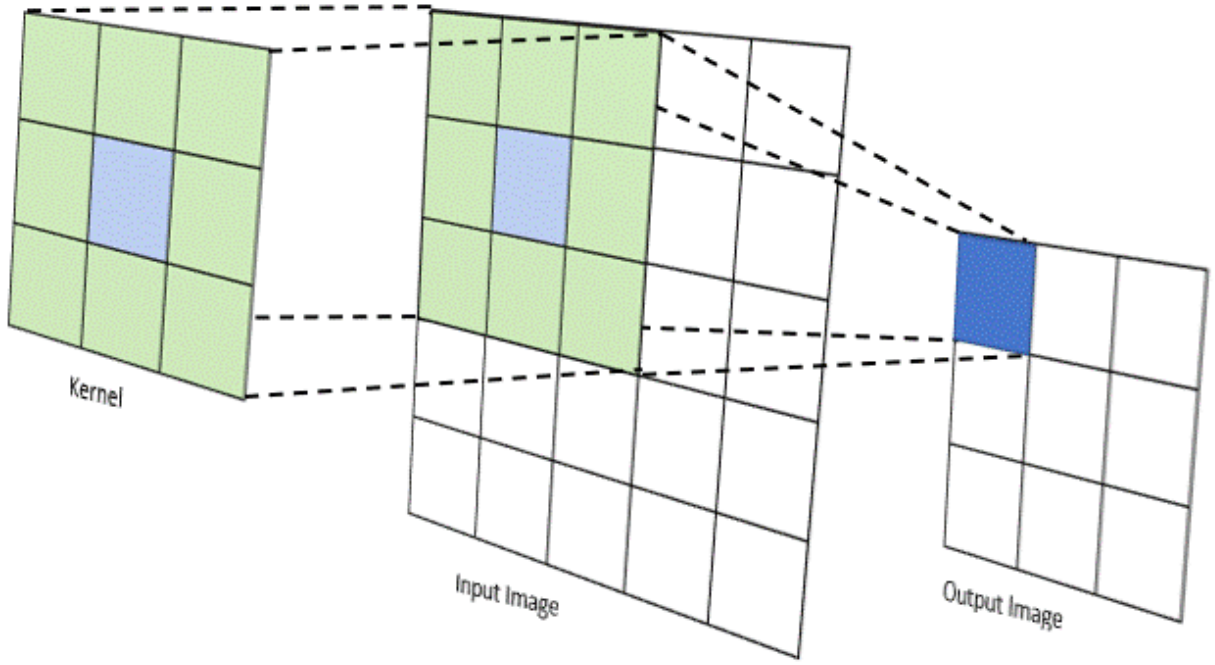
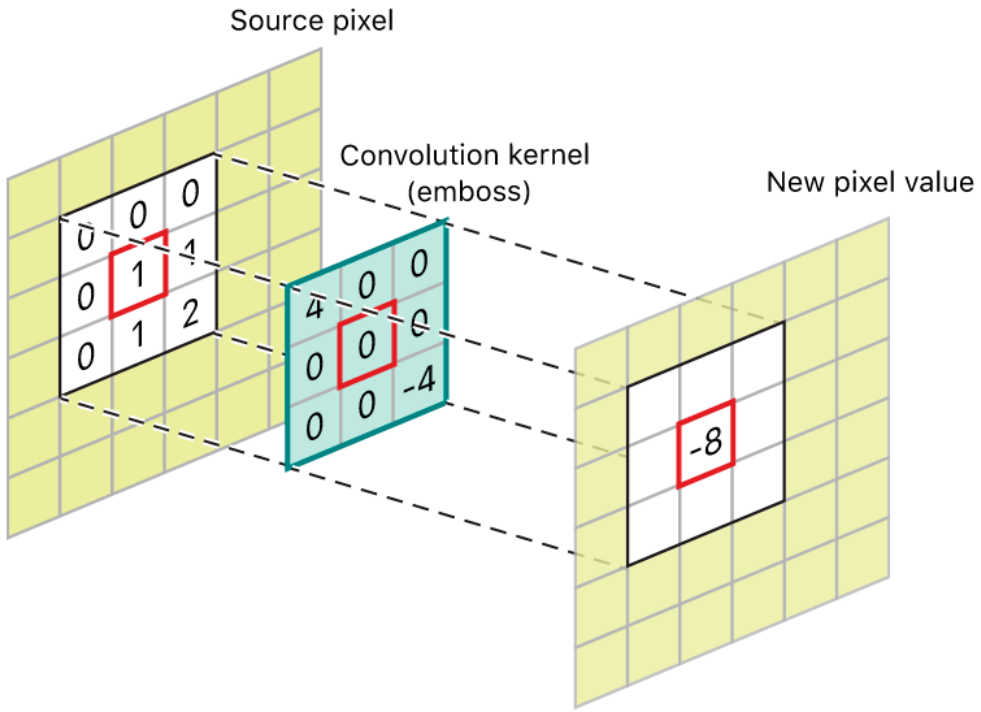


Image Kernels (Filters)

- Different Kernels exist.
  - Used for: **blur**, **sharpen**, **shift**
- It can also detect **edges**, and more.
- Try it yourself: https://setosa.io/ev/image-kernels/

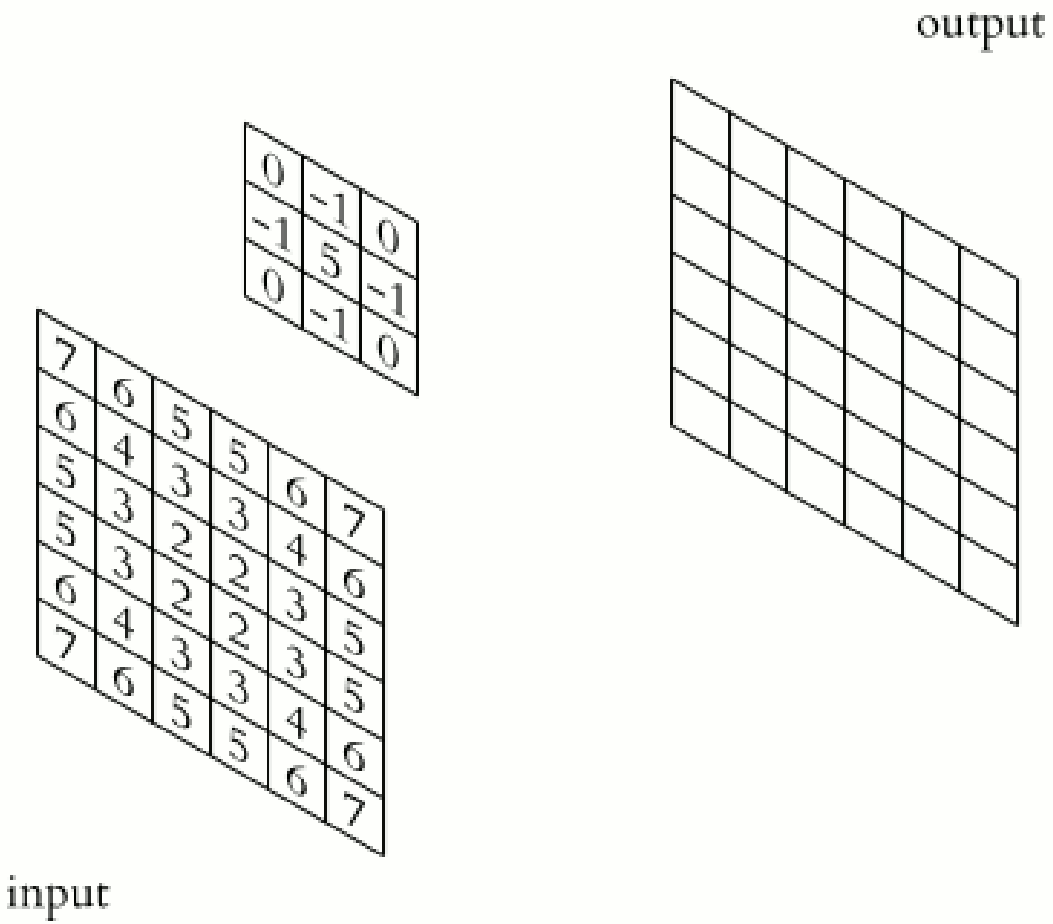


Input				Kernel			Output	
0	1	2	*	0	1	=	19	25
3	4	5		2	3		37	43
6	7	8						

Image Kernels explained visually (setosa.io)

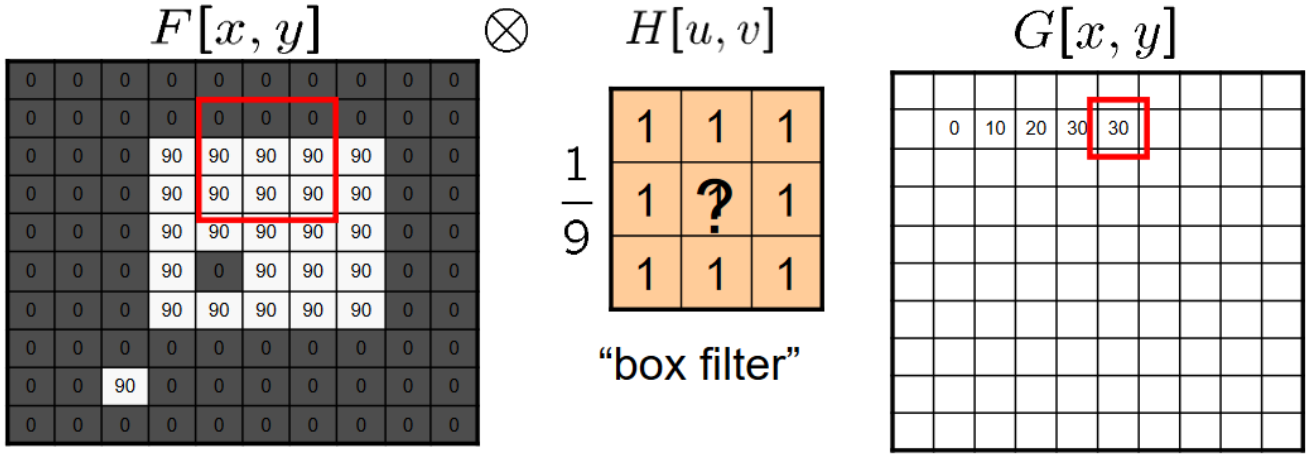
Aka “Convolution”

(we’ll meet it again in neural networks)



Averaging Filter

- What values belong in the kernel H for the moving average example?



$$G = H \otimes F$$

Removes high-frequency components from the image ("low-pass filter").

Gaussian Filters

- What if we want nearest neighboring pixels to have the most influence on the output?

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$F[x, y]$

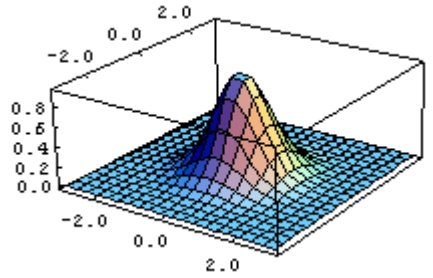
$$\frac{1}{16}$$

1	2	1
2	4	2
1	2	1

$H[u, v]$

This kernel approximates a 2d Gaussian function:

$$h(u, v) = \frac{1}{2\pi\sigma^2} e^{-\frac{u^2+v^2}{\sigma^2}}$$

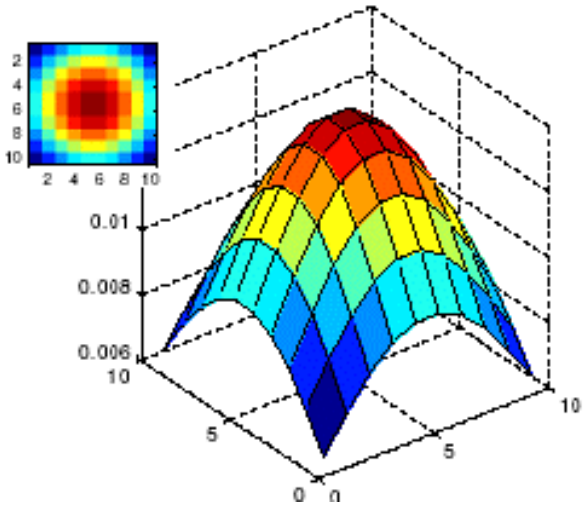


Gaussian Filters

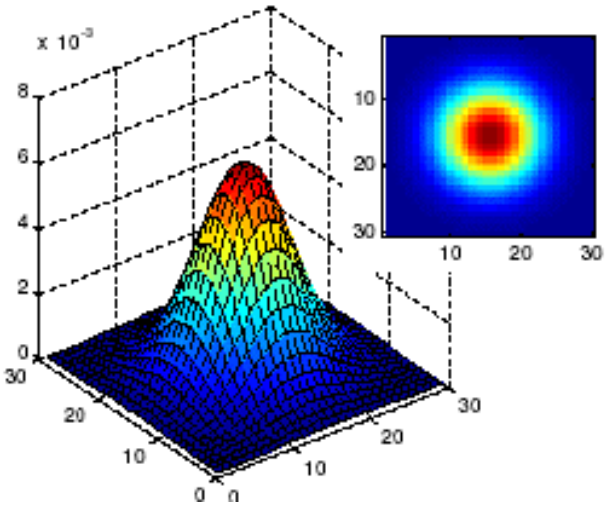
Hyperparameters affect the result: **Kernel Size**

Kernel Size - determines the range the smoothing takes into account

Note: Gaussian function has infinite support, but discrete filters use *finite* kernels



σ = 5 with 10 x 10 kernel

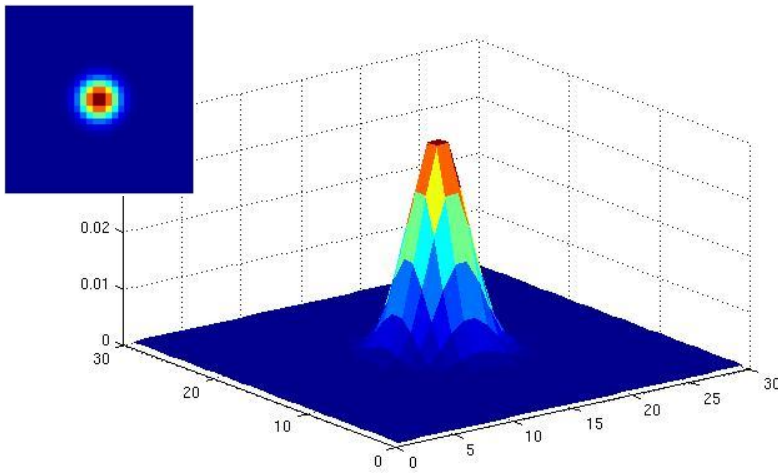


σ = 5 with 30 x 30 kernel

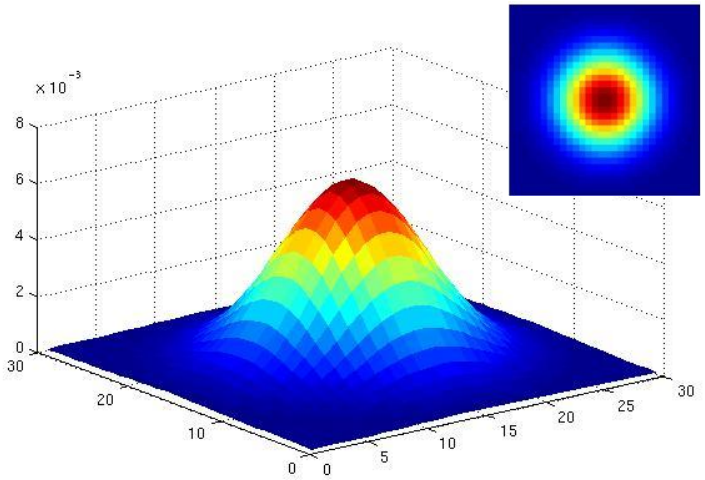
Variance of Gaussian - determines extent of smoothing

Gaussian Filters

Hyperparameters affect the result: Gaussian **Variance**



σ = 2 with 30 x 30 kernel



σ = 5 with 30 x 30 kernel

Gaussian Filter