Deep learning for plant root image analysis

Bioinformatic tools

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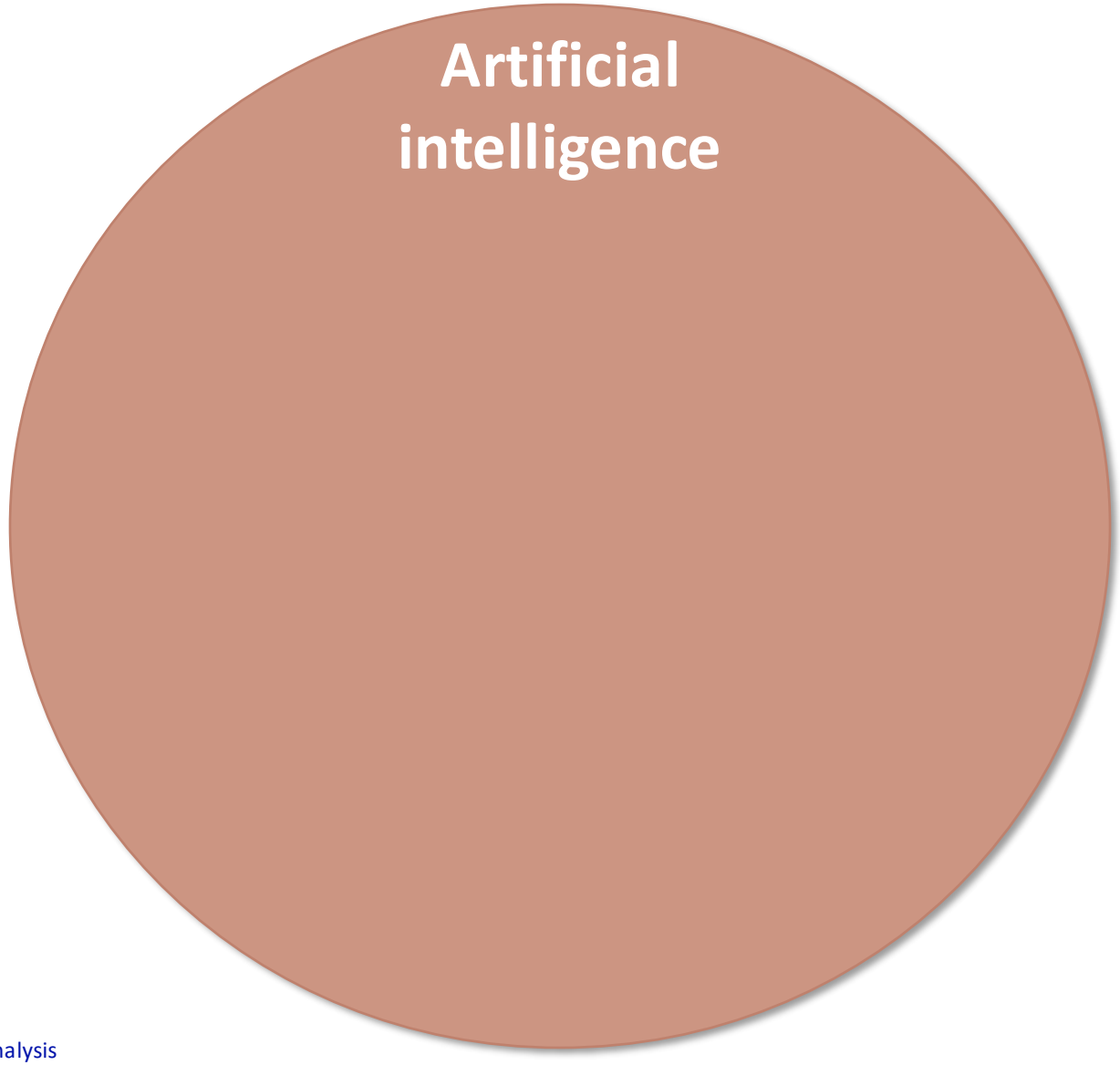
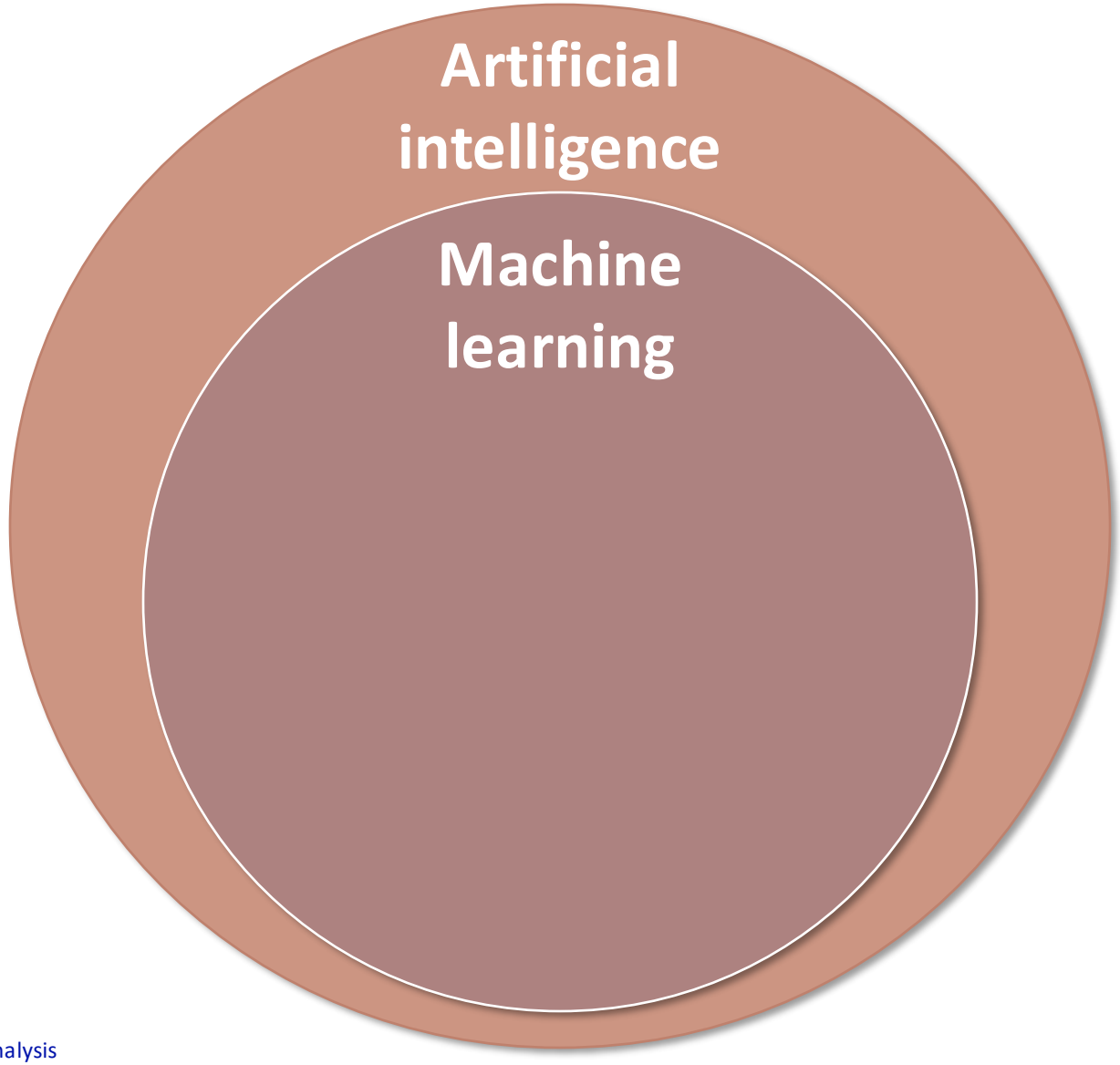
Introduction to AI

AI, machine learning, deep learning, what are we talking about?



A science whose goal is to enable machines to perform tasks that humans accomplish using their intelligence.

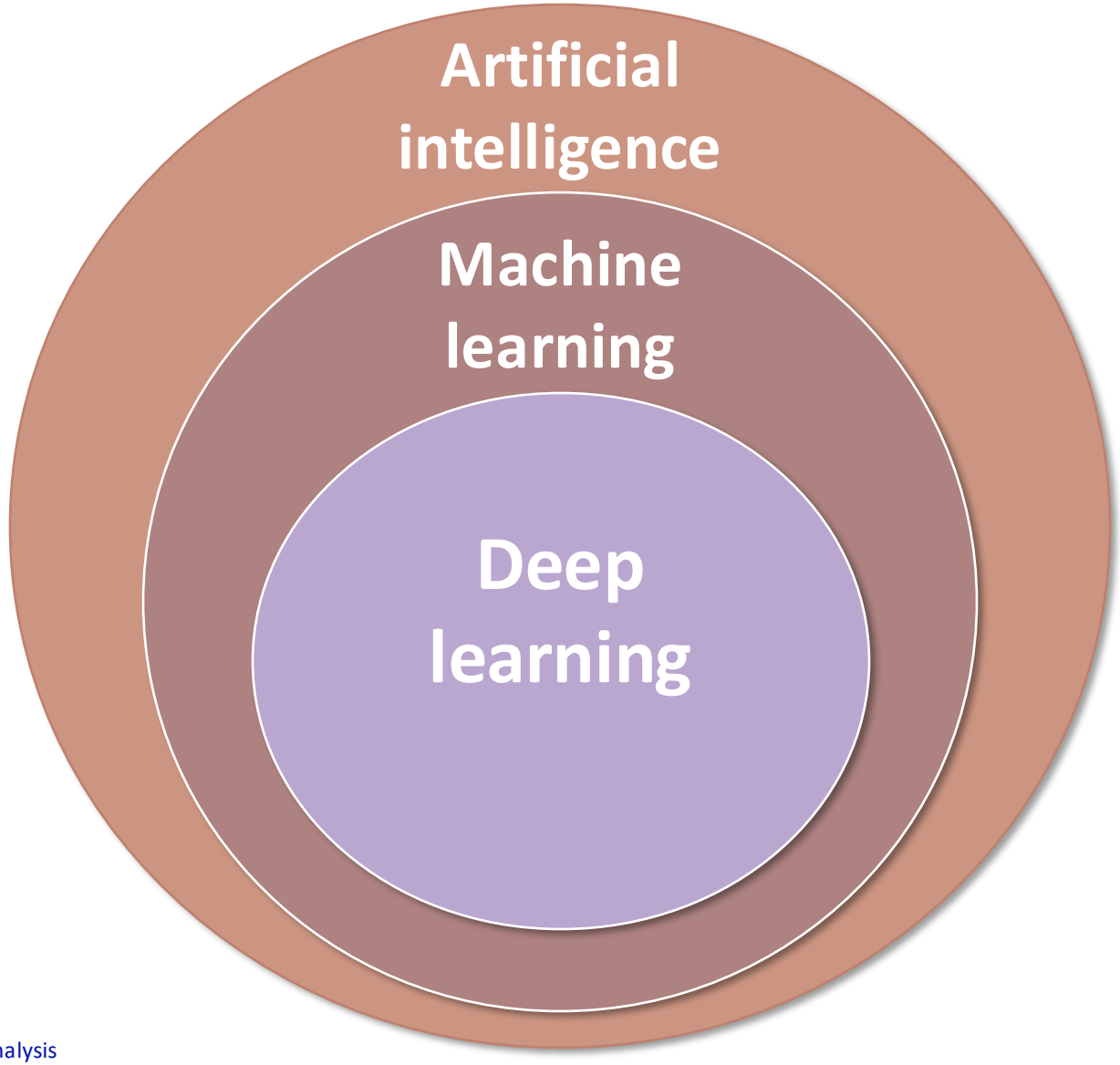
AI, machine learning, deep learning, what are we talking about?



Machine learning (ML) is a branch of artificial intelligence that enables computers to learn **without being explicitly programmed**.(1959)

Machine learning works on the basis of **examples**. It uses algorithms to statistically analyze data and **identify patterns**. These patterns are then used to predict results, gain a better understanding of the processes that generate this data, or make decisions.

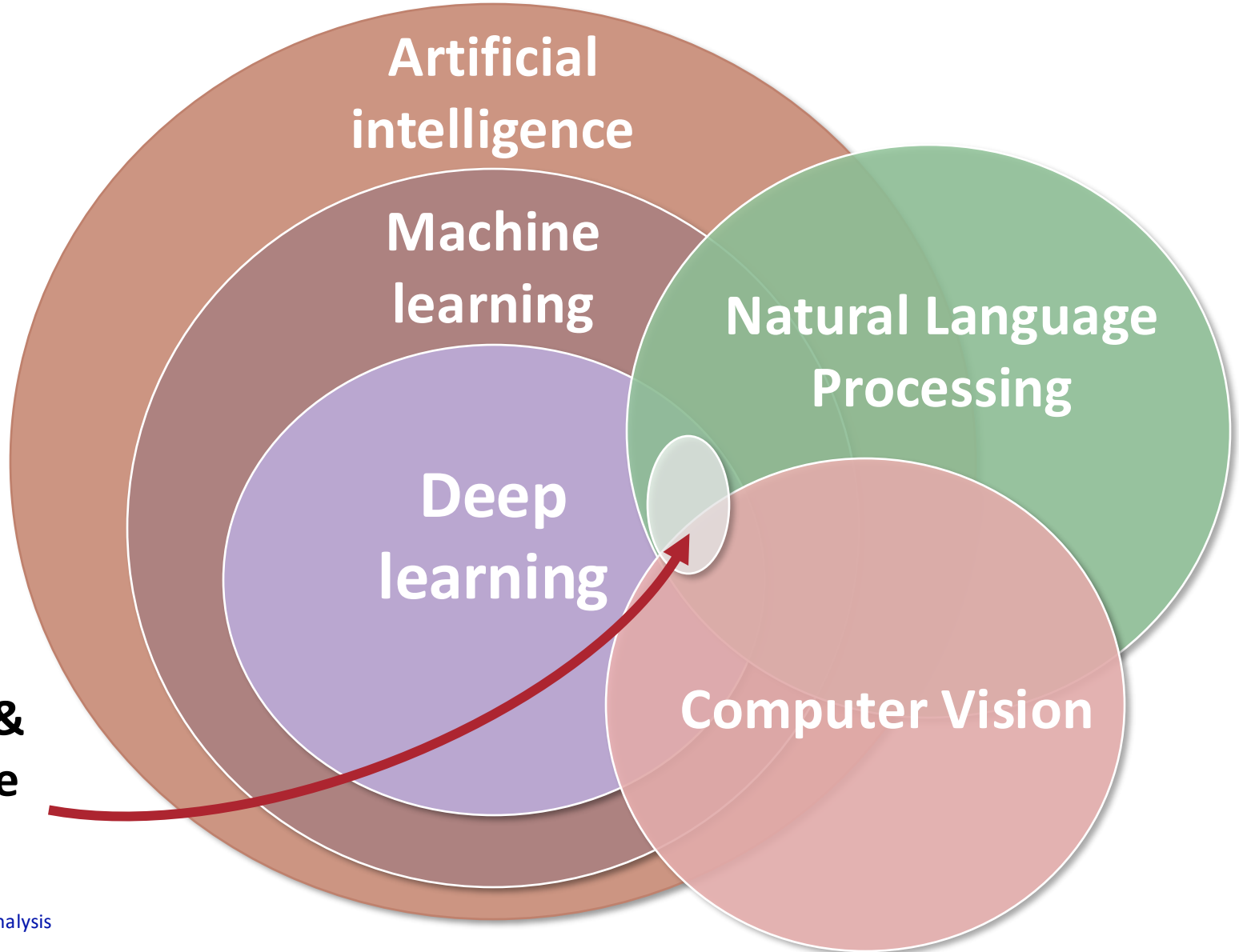
AI, machine learning, deep learning, what are we talking about?



Deep learning (DL) is a subset of machine learning. It uses **artificial neural networks** (ANNs), algorithms inspired by the functioning of the human brain, imitating the way neurons send signals to each other. These neurons are organized into interconnected layers with a certain level of depth. Each level of depth helps to optimize and refine the accuracy of the results.

Deep learning algorithms are well suited to solving complex problems. They **require a large volume of data** and therefore a great amount of computing power to process it.

AI, machine learning, deep learning, what are we talking about?



Generative AI & Large Language Models

How does machine learning work? Generalization, predicting data...

Diameter (cm)	Height (m)
10	2,8
17	4,6
14	4,0
9	2,6
21	5,8
25	6,9
31	8,8
12	3,4
23	6,6
32	9
31	8,7
11	3
13	3,8

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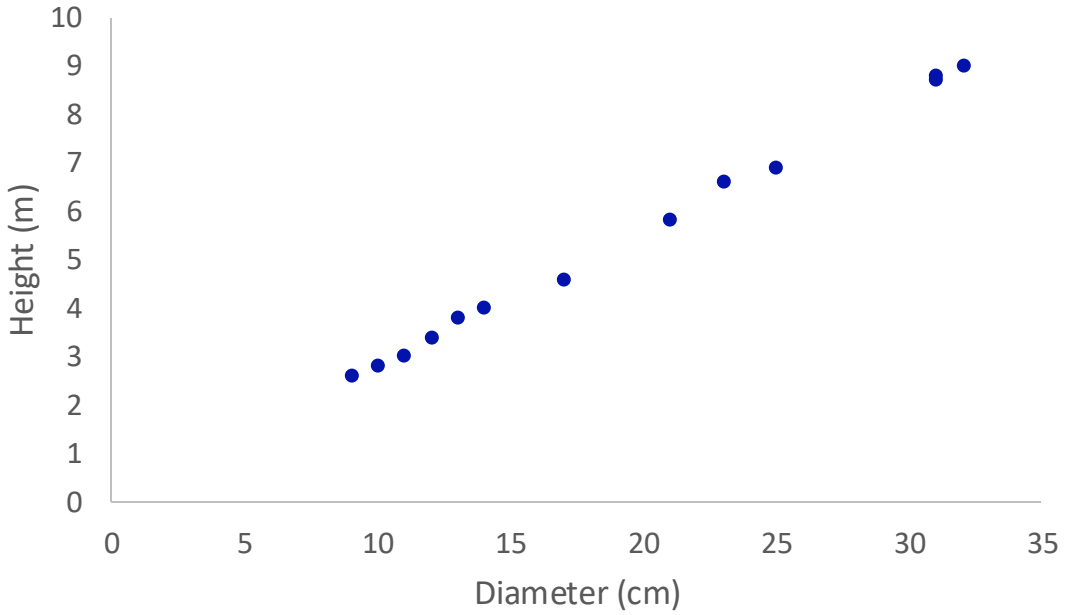

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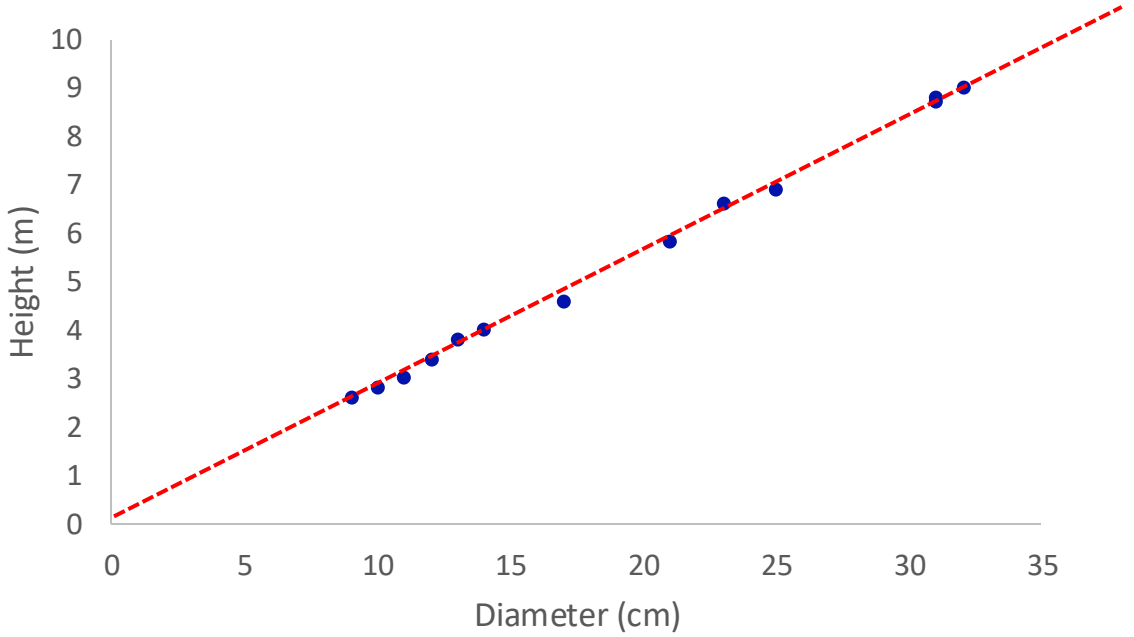
11	3
13	3,8



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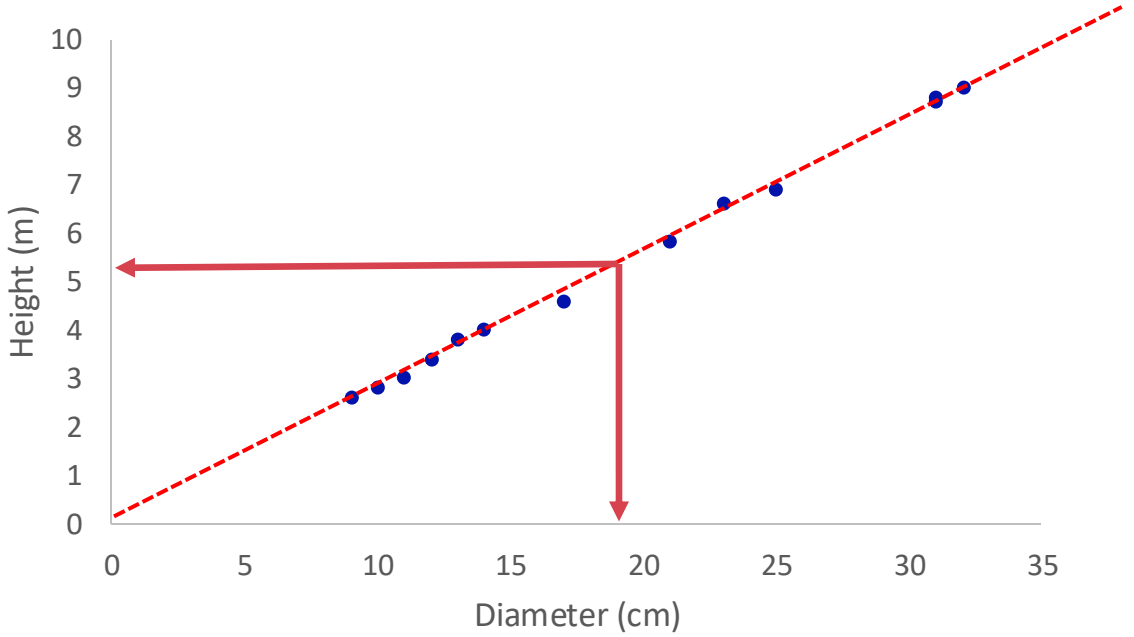
23	6,6
32	9
31	8,7
11	3
13	3,8
19	?



How does machine learning work? Generalization, predicting data...

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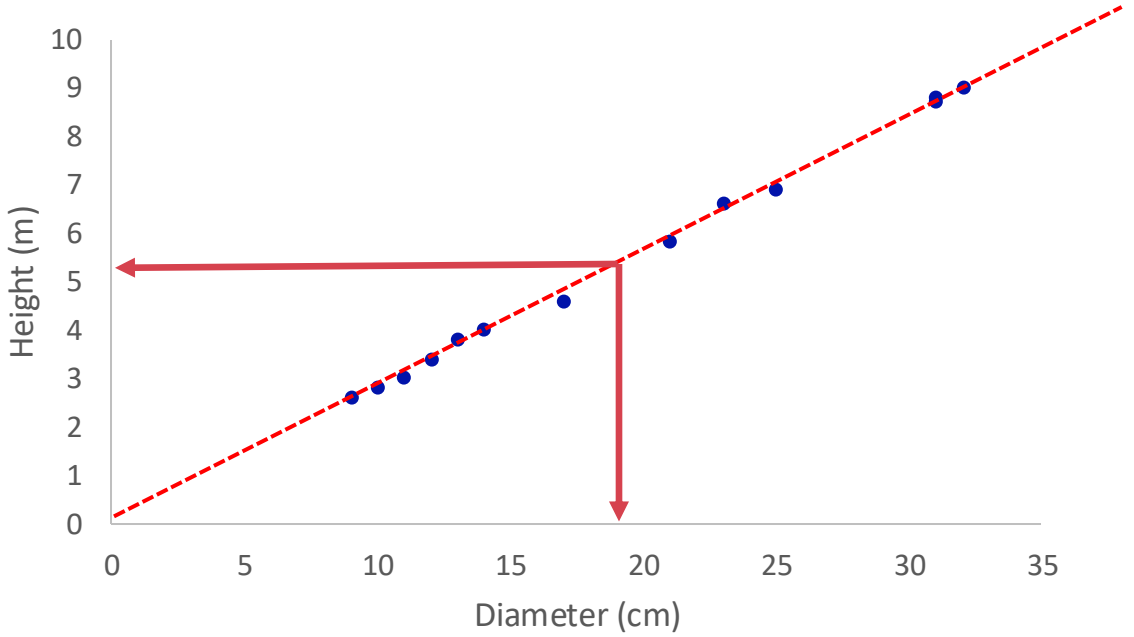
23	6,6
32	9
31	8,7
11	3
13	3,8
19	?



Data (observation) → links between data → generalisation, prediction

How does machine learning work? Generalization, predicting data...

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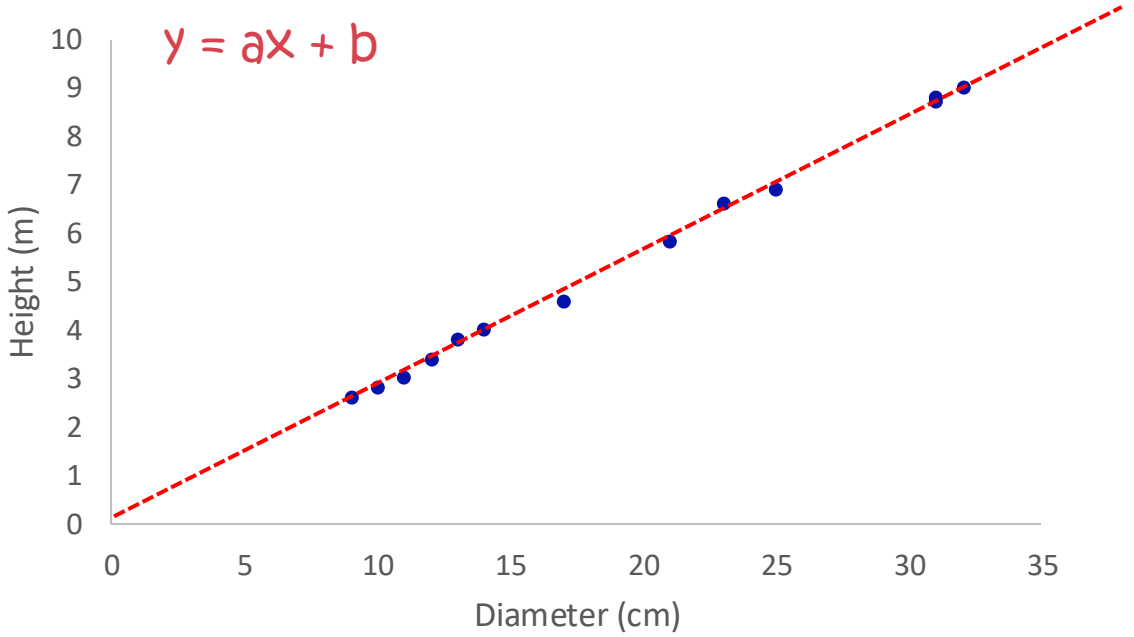
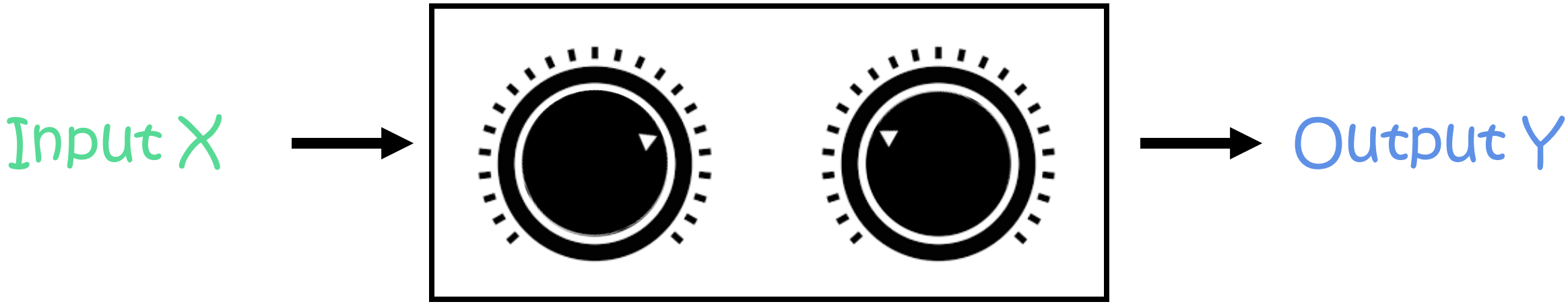


a

b

How does machine learning work? Generalization, predicting data...

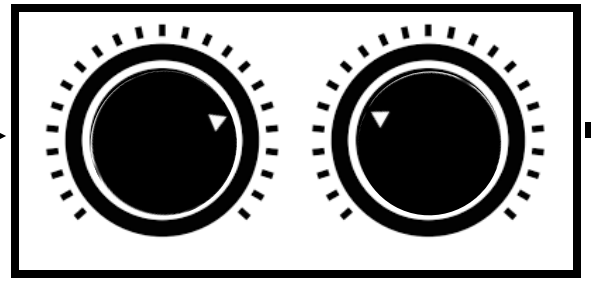
X	Y
...	...
...	...
...	...
...	...
...	...



Learning phase

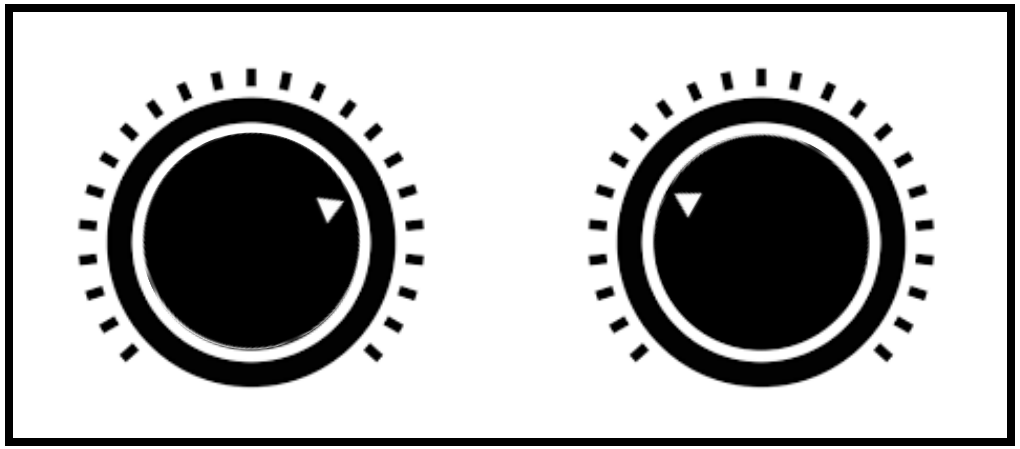
Exemple of the Facebook feed algorithm

Who posted?
When?
Nature
Subject
Reactions
from others
...



Will you like, click, comment, interact...?

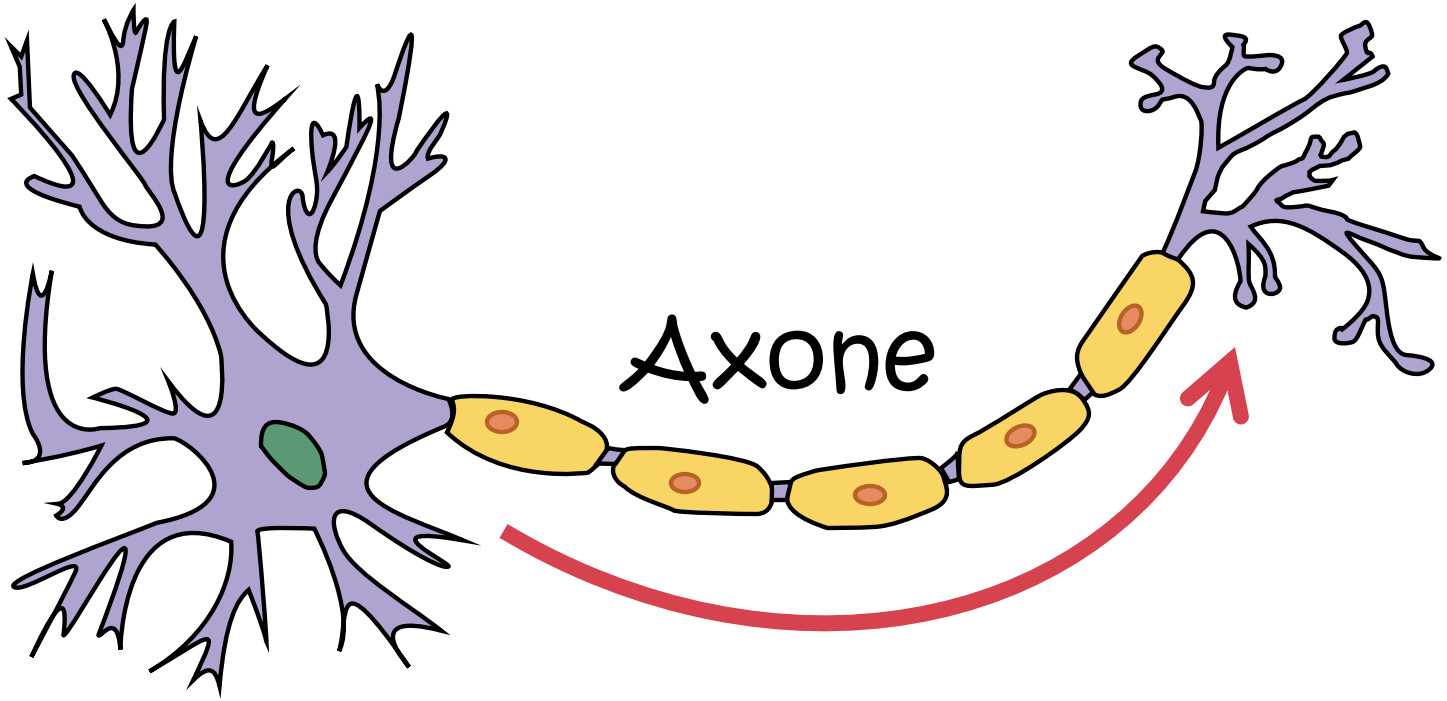
Image recognition



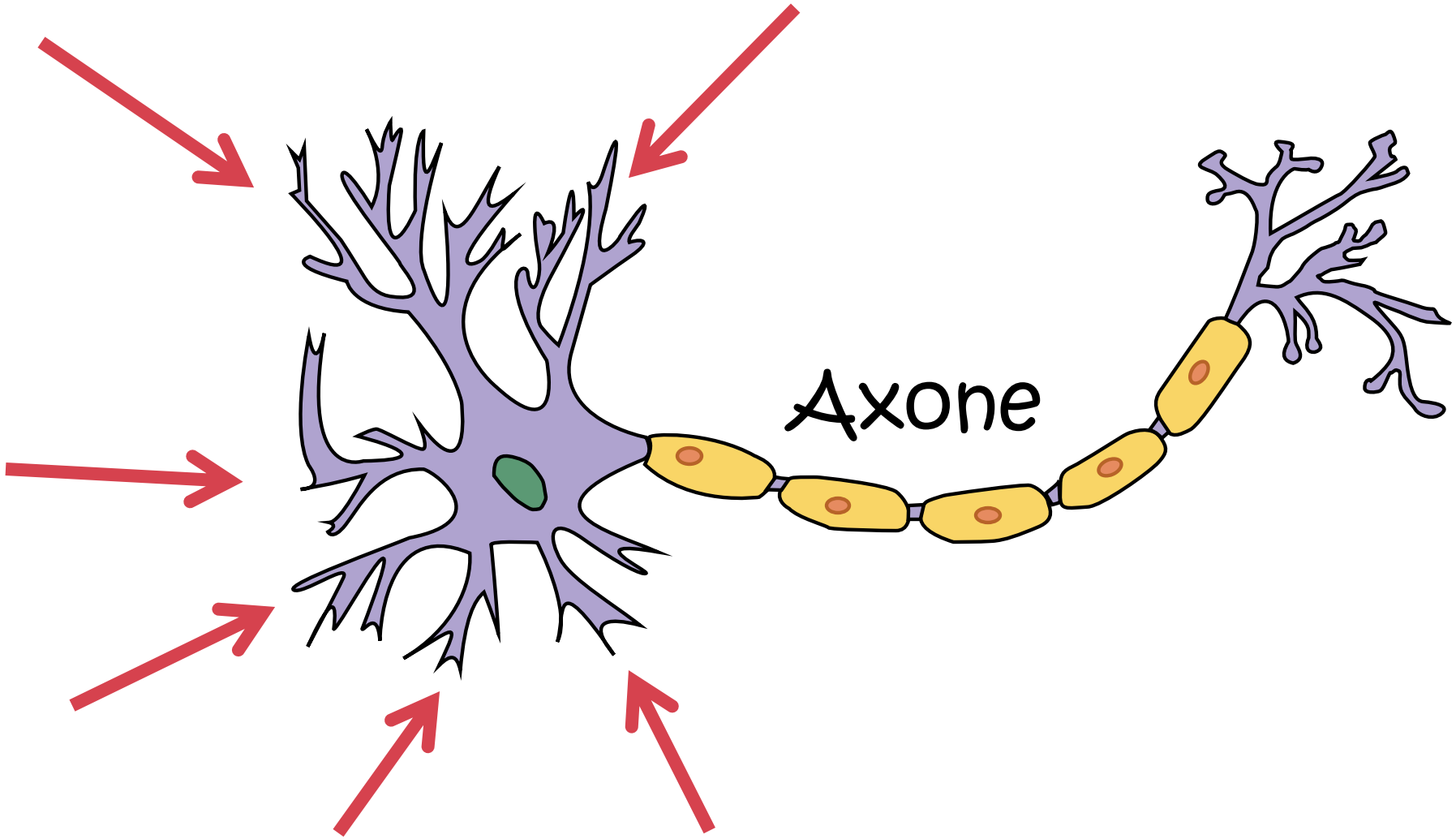
Learning phase

Flower?
Heron?
Lamp?
Robot?
…

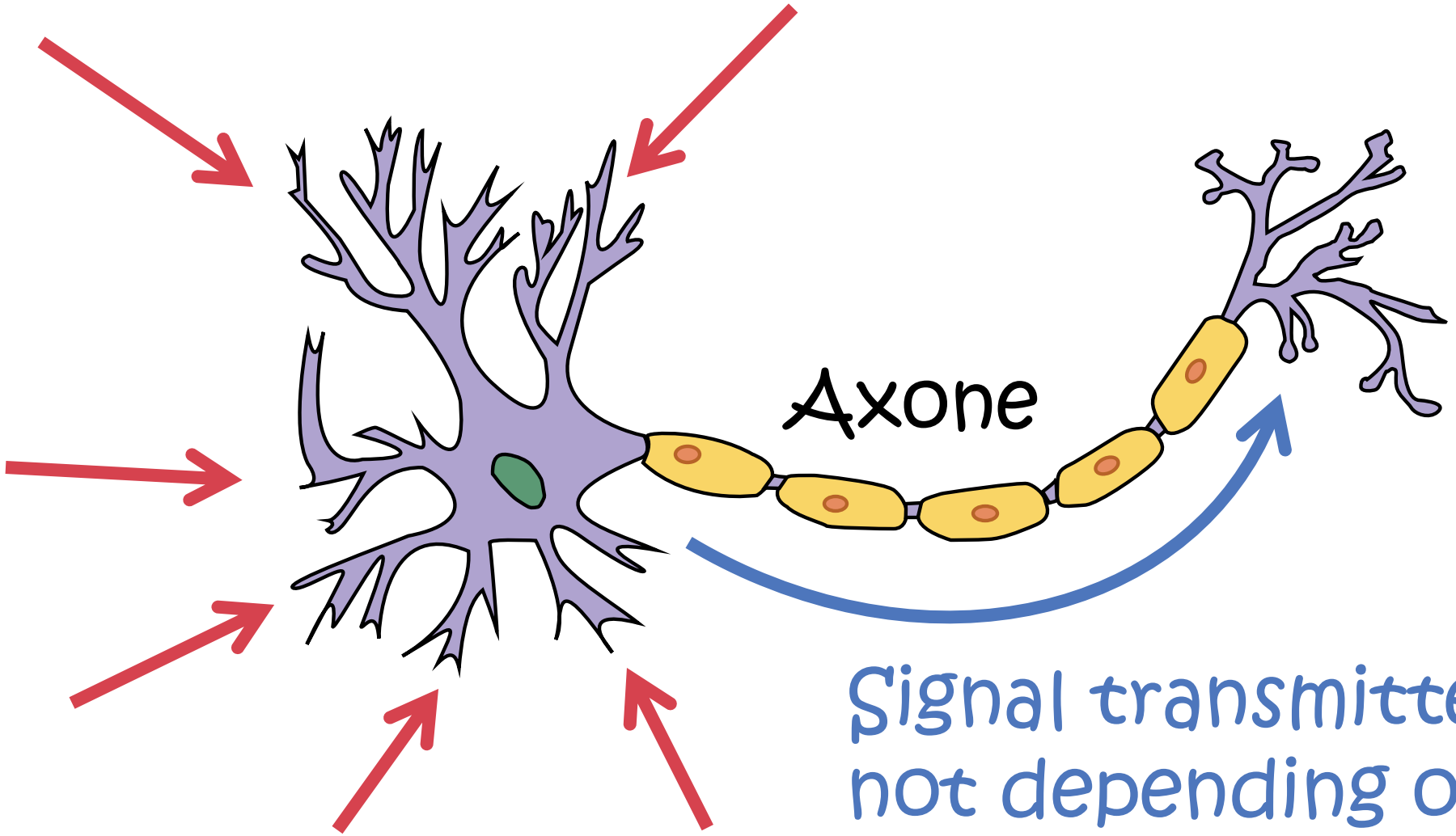
Biological neuron



Biological neuron

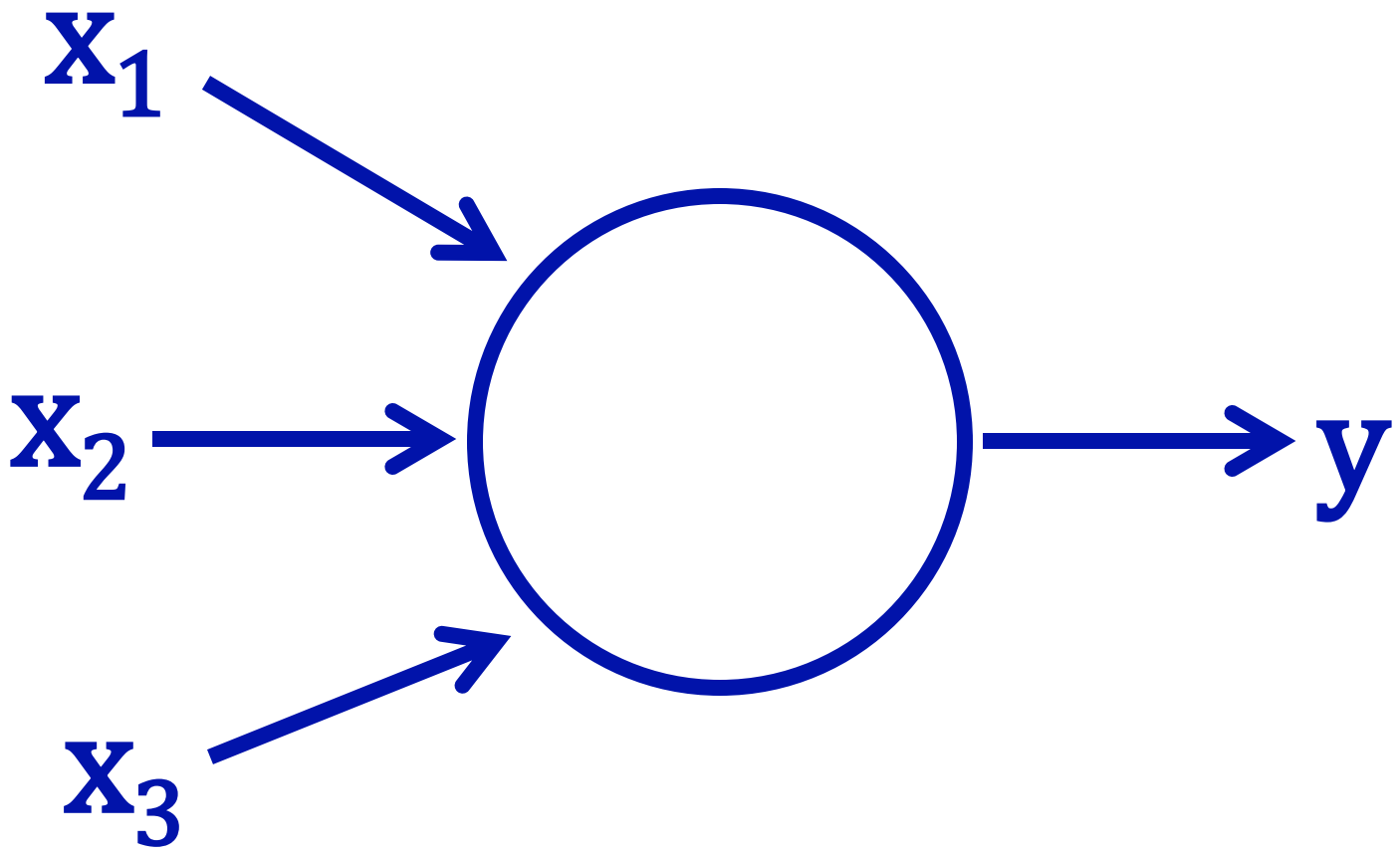


Biological neuron

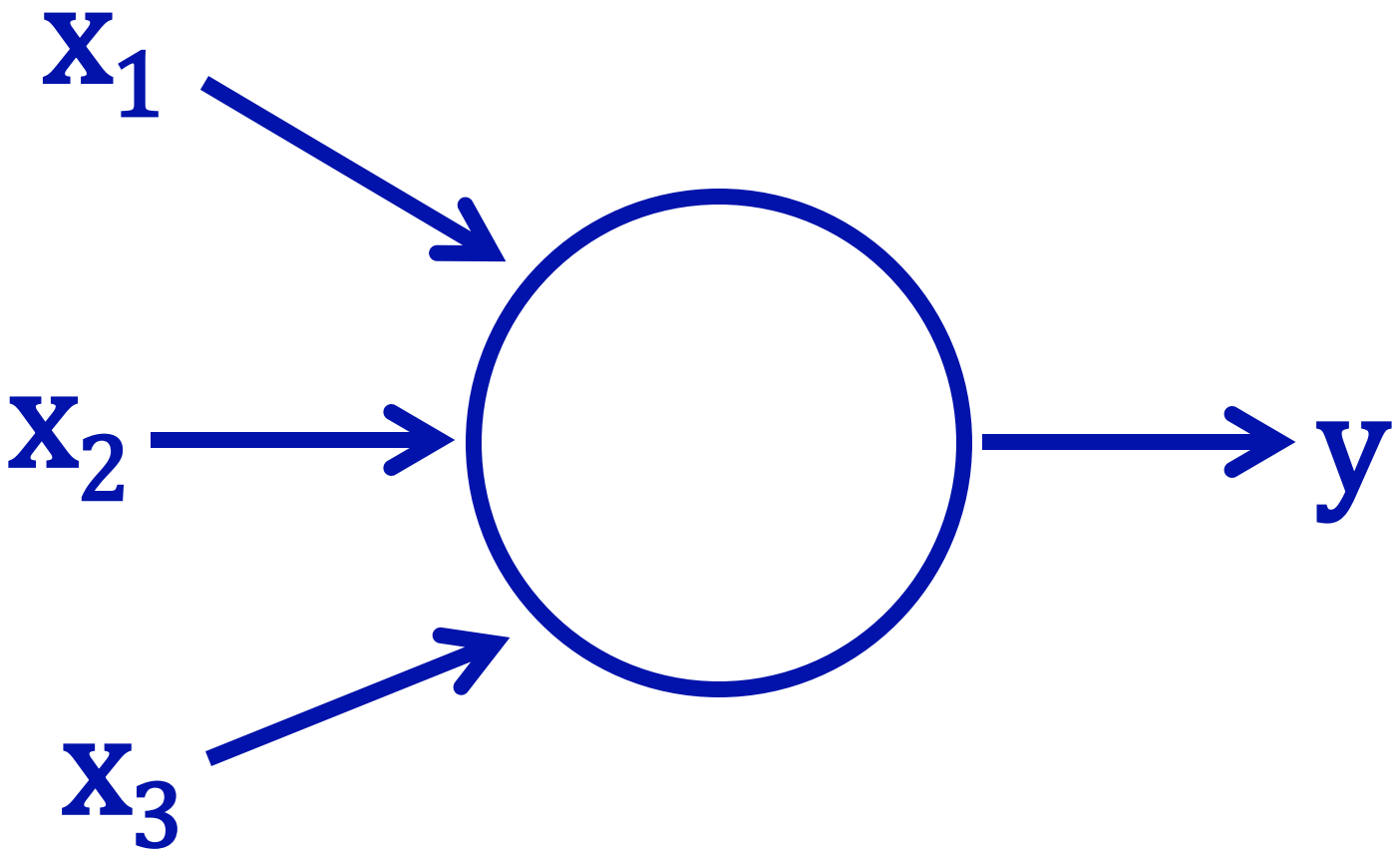


Signal transmitted or not depending on the information received

Artificial neuron

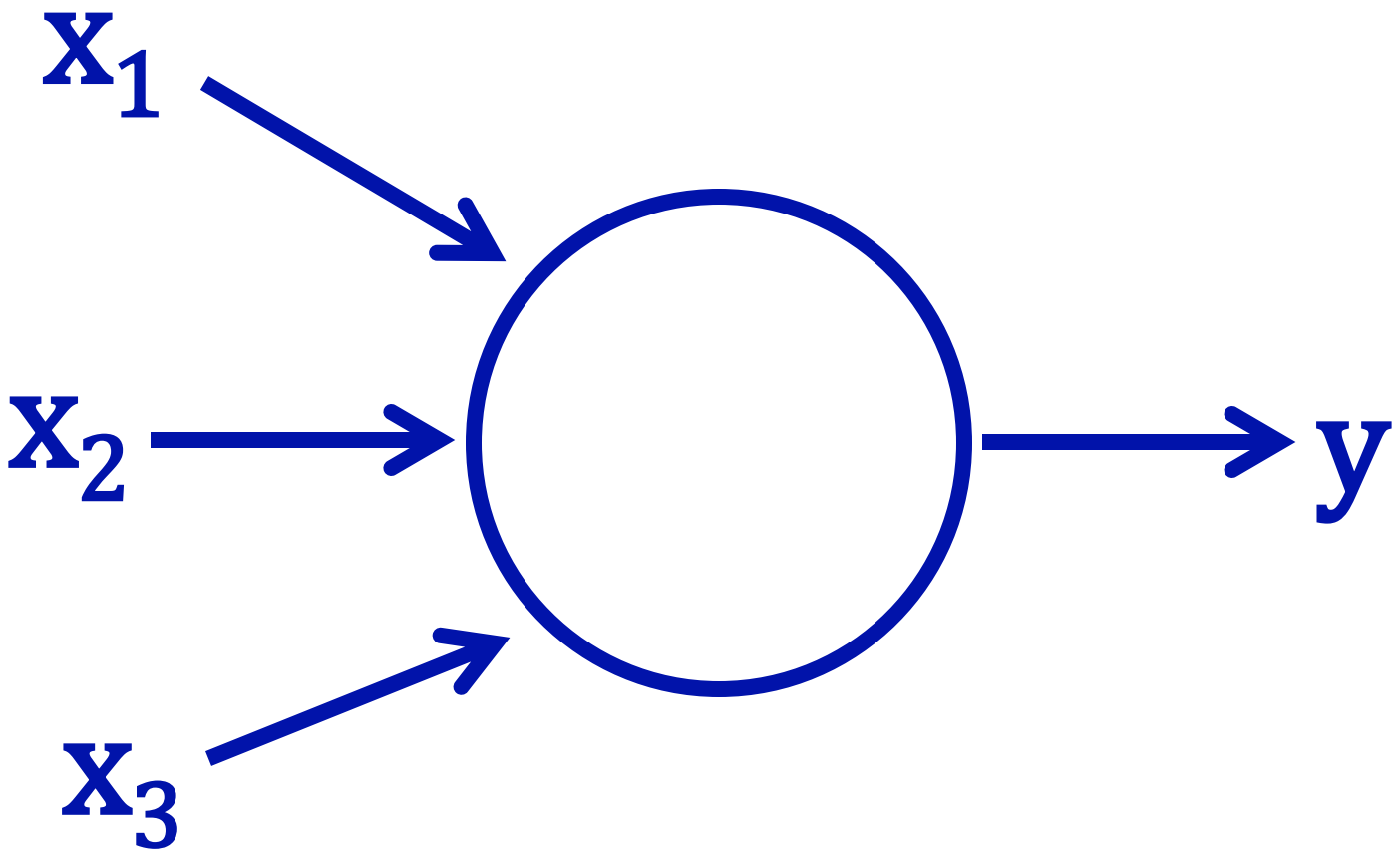


Artificial neuron



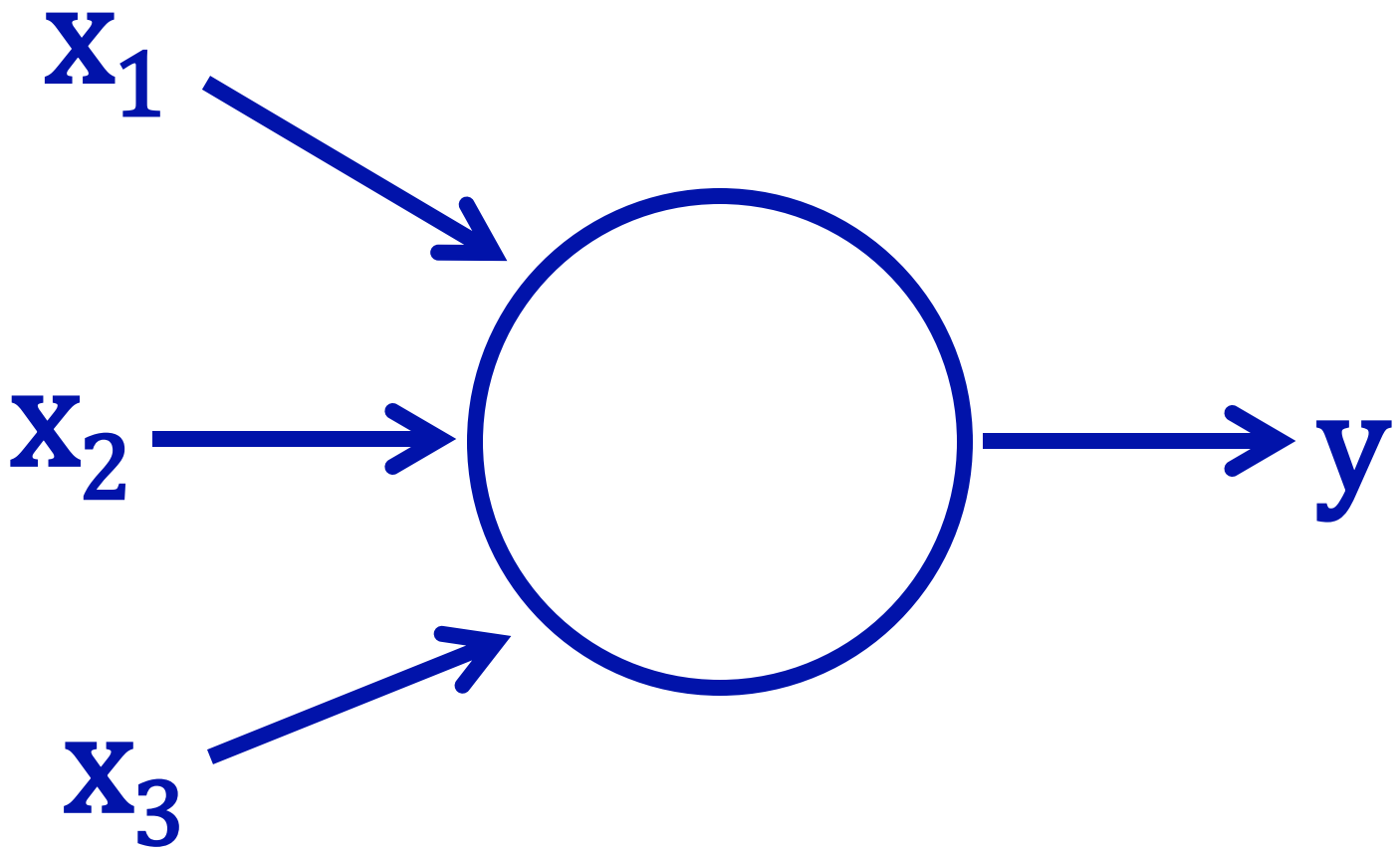
$$x_1 + \quad x_2 + \quad x_3$$

Artificial neuron



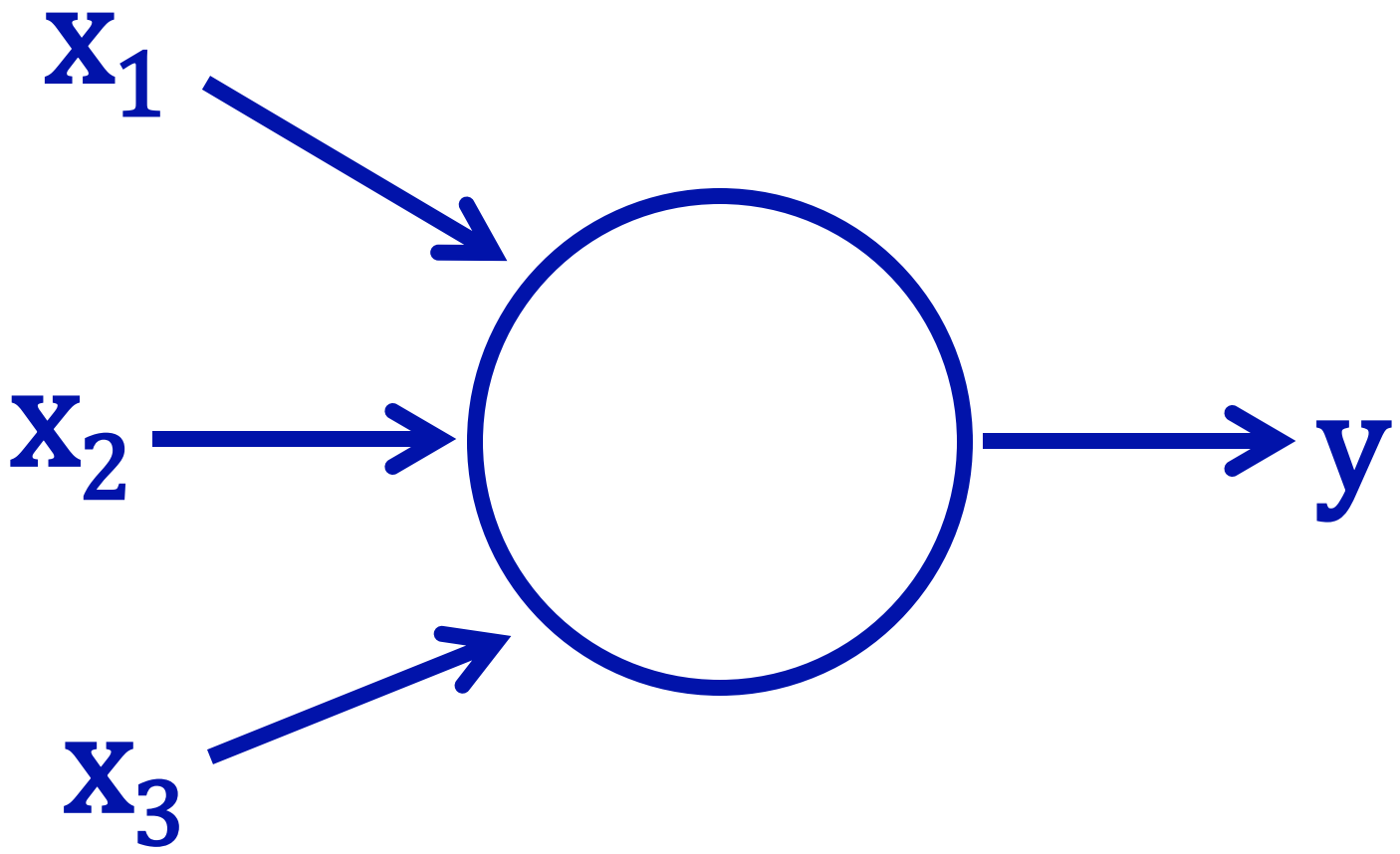
$$p_1x_1+p_2x_2+p_3x_3$$

Artificial neuron



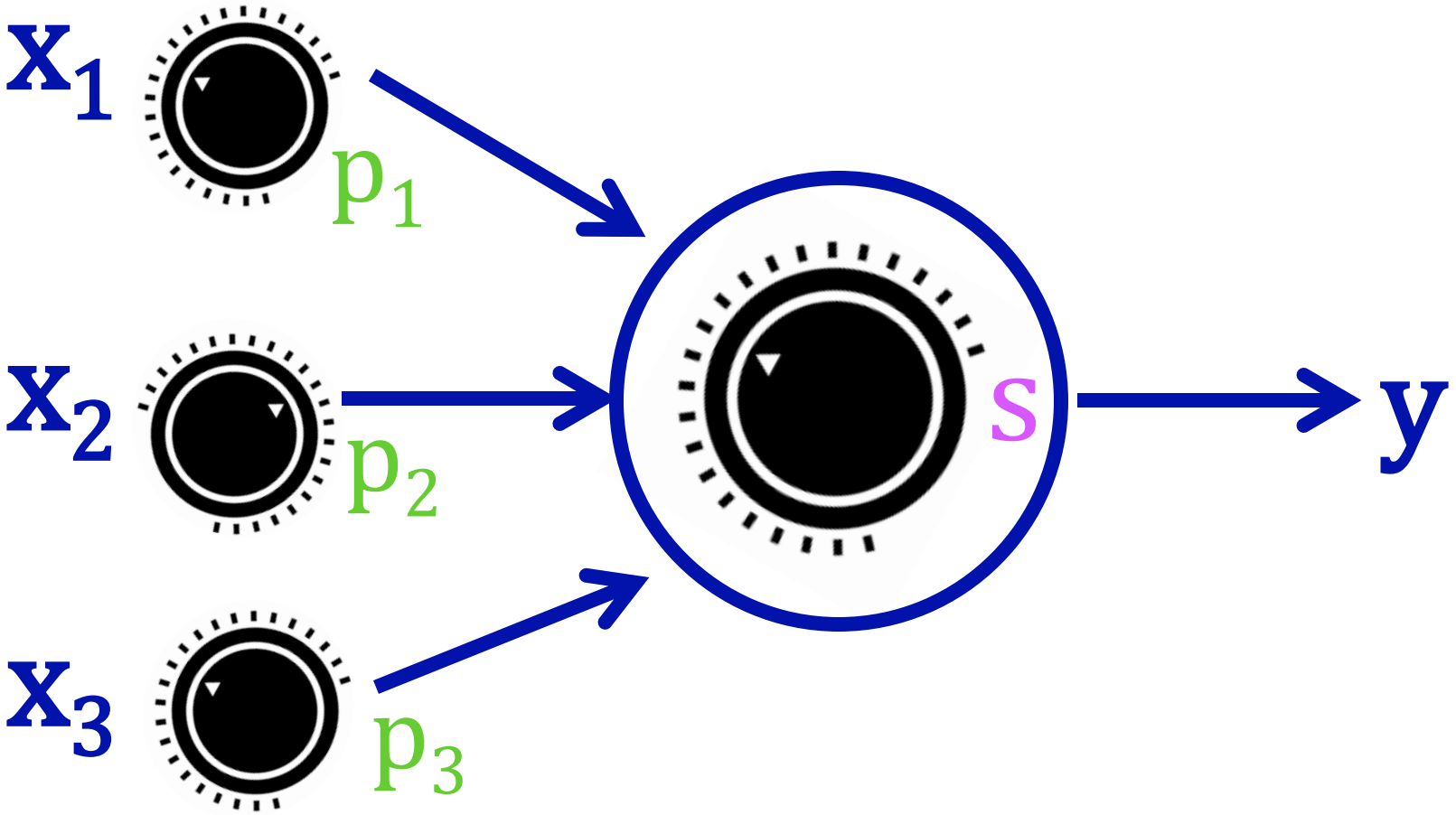
$$p_1x_1 + p_2x_2 + p_3x_3 > s \; ? \rightarrow y = 1$$

Artificial neuron



$$p_1x_1+p_2x_2+p_3x_3 > s \;?\rightarrow y = 1$$
$$< s \;?\rightarrow y = 0$$

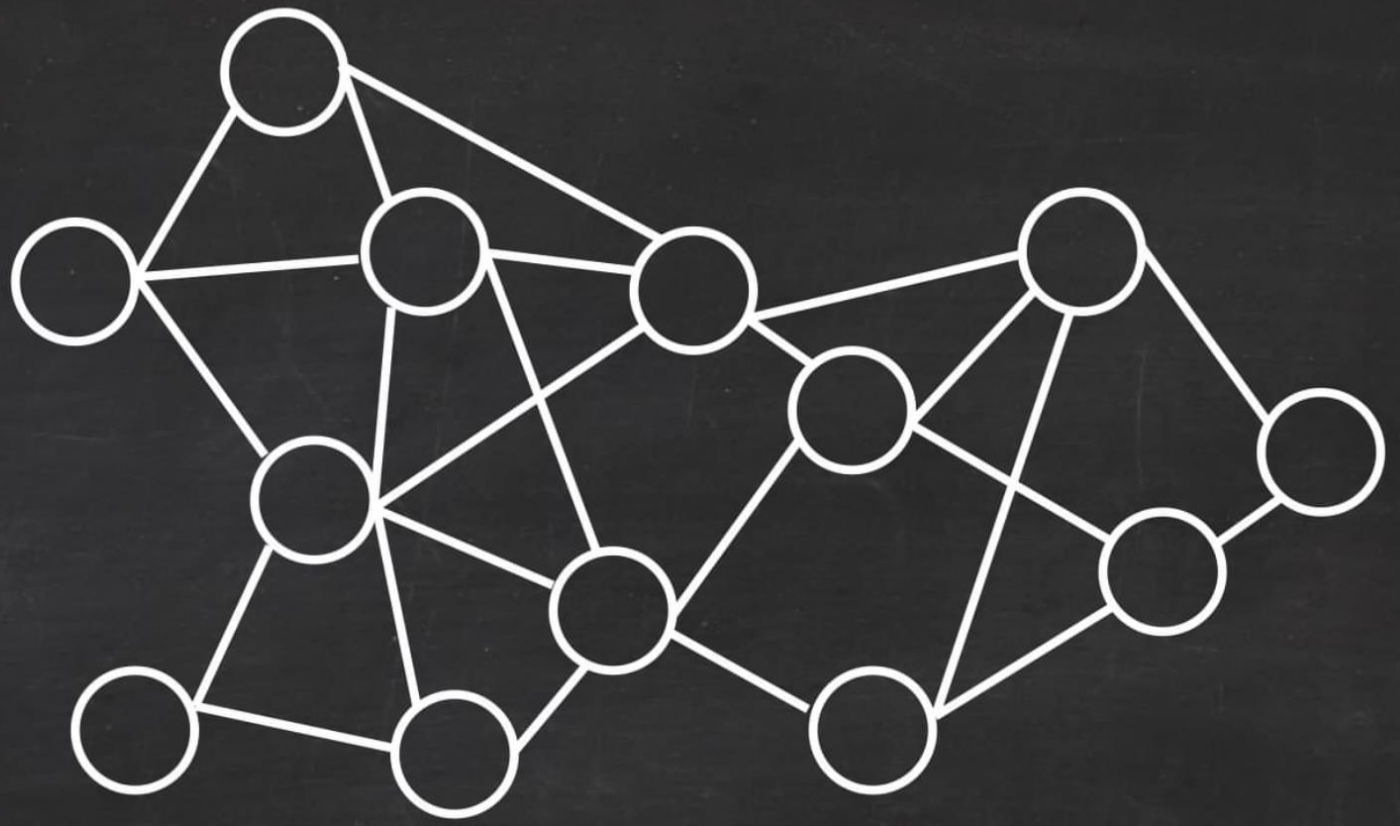
Artificial neuron



$$p_1x_1+p_2x_2+p_3x_3 > s \; ? \rightarrow y = 1$$

$$< s \; ? \rightarrow y = 0$$

Neural network (artificial)



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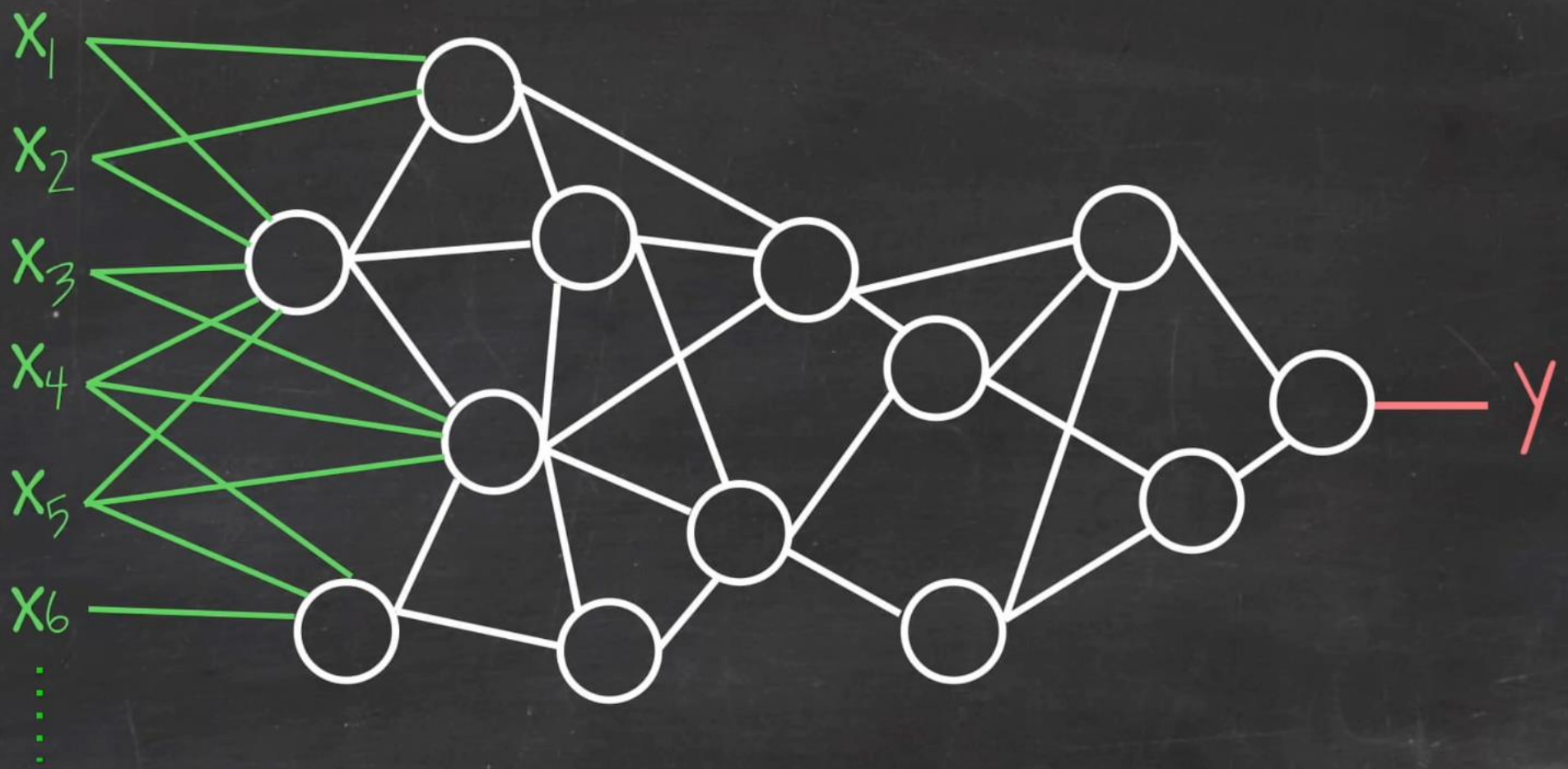

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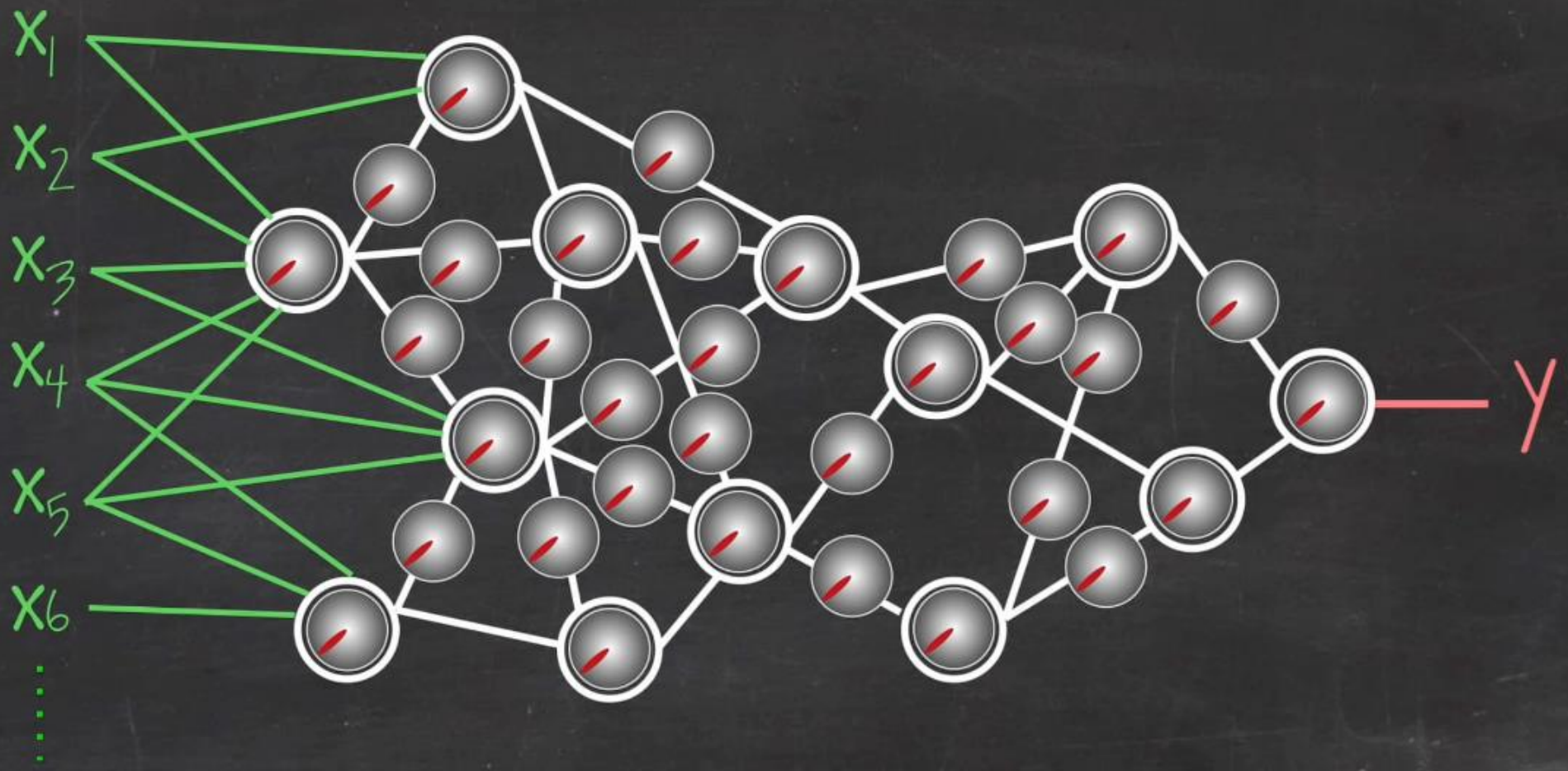
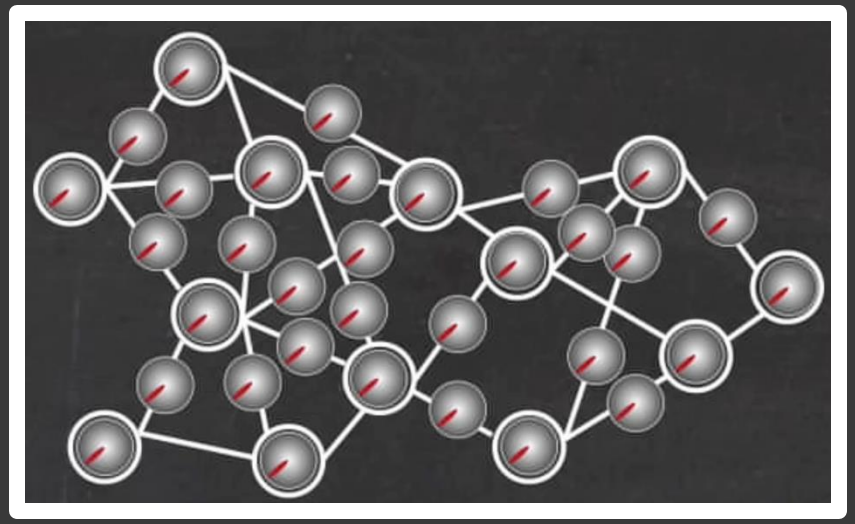


Learning phase

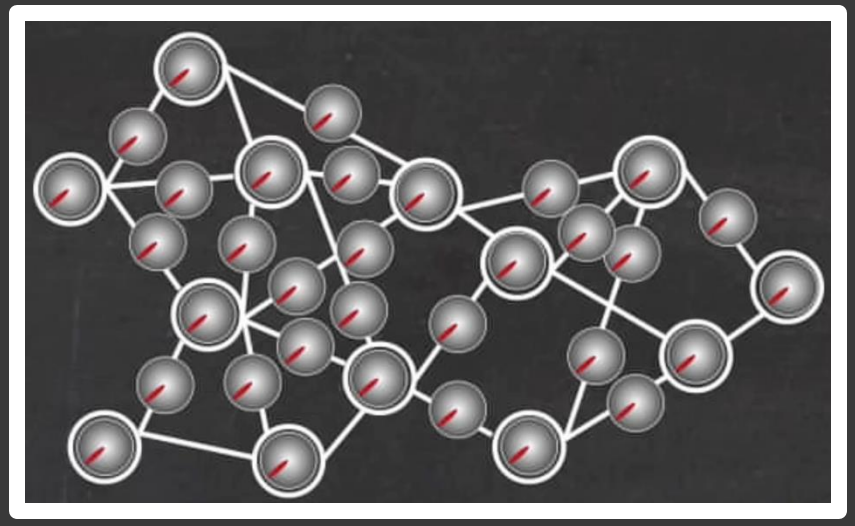
Input
X



Output
Y

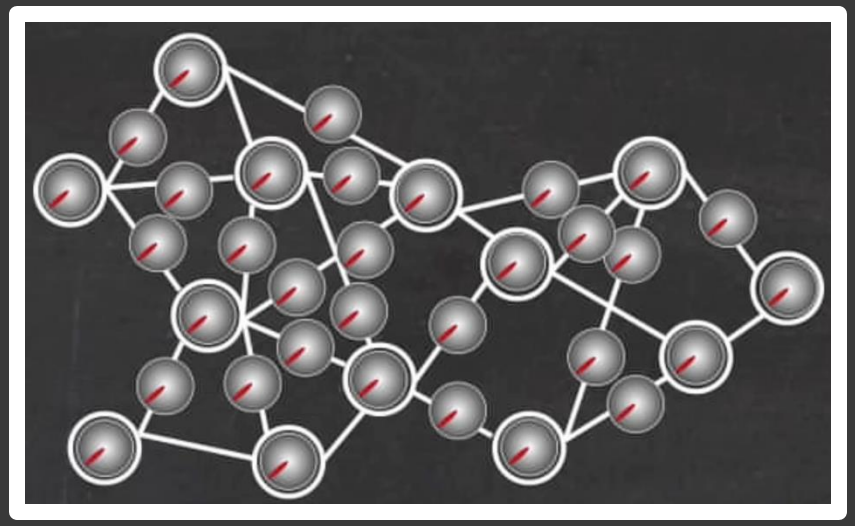
Learning phase

Input
X



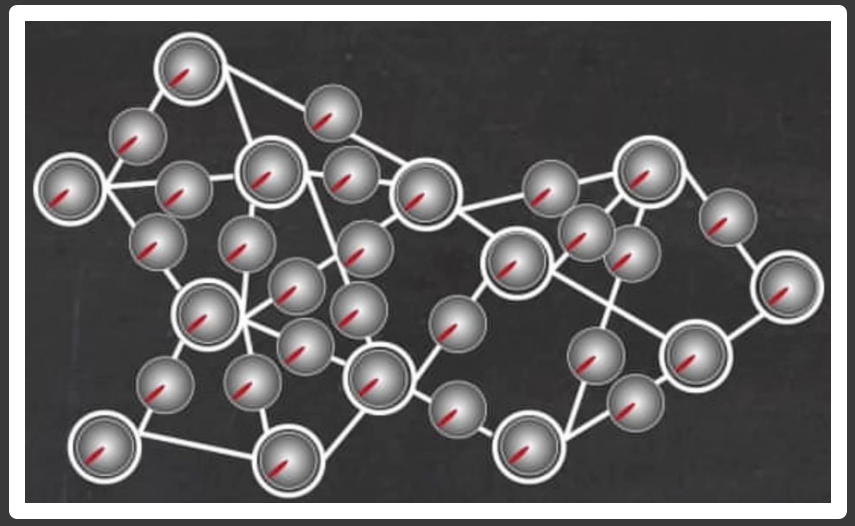
Output
Y

New
entry
X



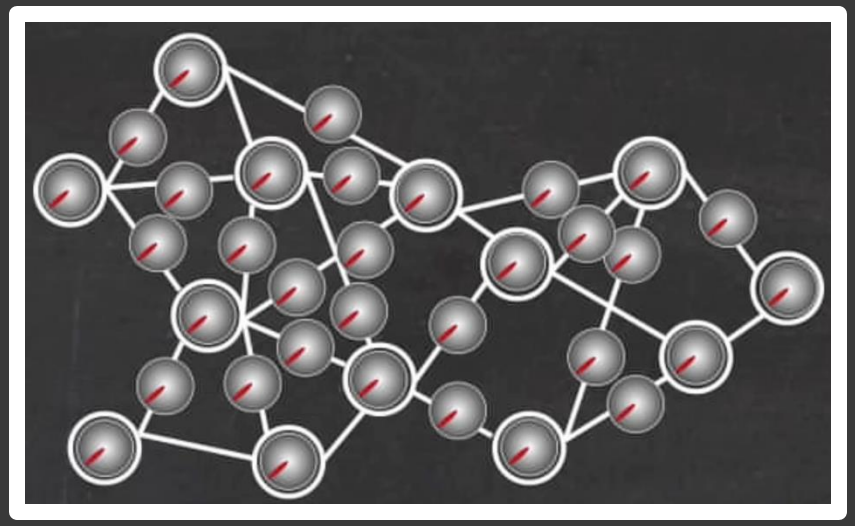
Learning phase

Input
X



Output
Y

New
entry
X



Y
prediction

But how many neurons are needed?

What is their best arrangement?

But how many neurons are needed?

What is their best arrangement?

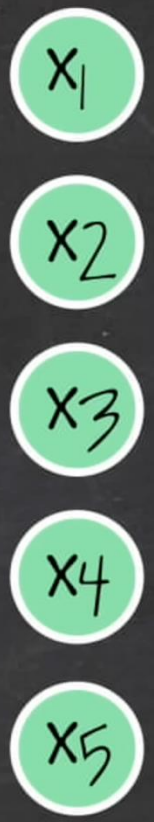
There are 100 billion neurons in our brain.

But how many neurons are needed?

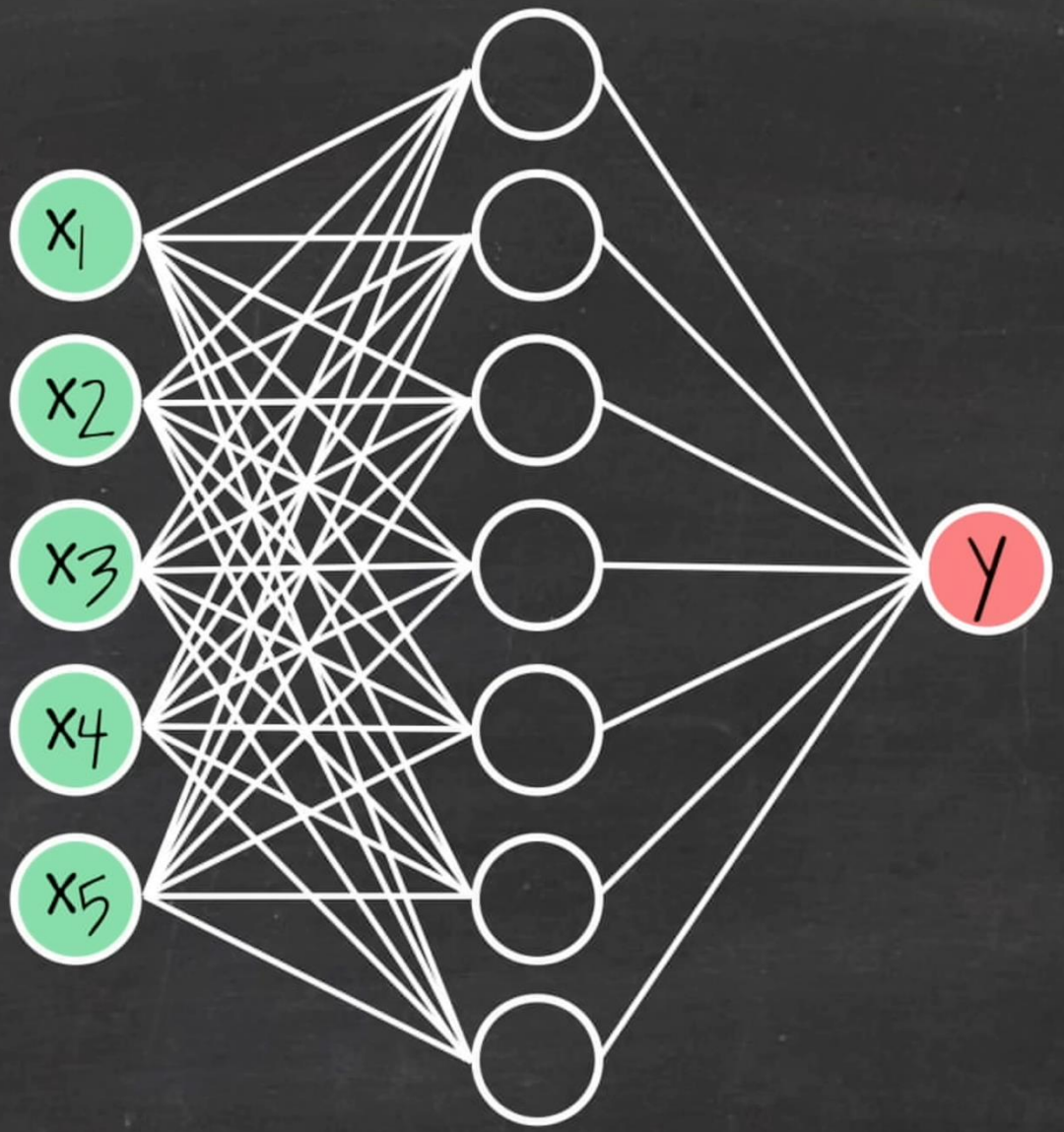
What is their best arrangement?

There are 100 billion neurons in our brain.

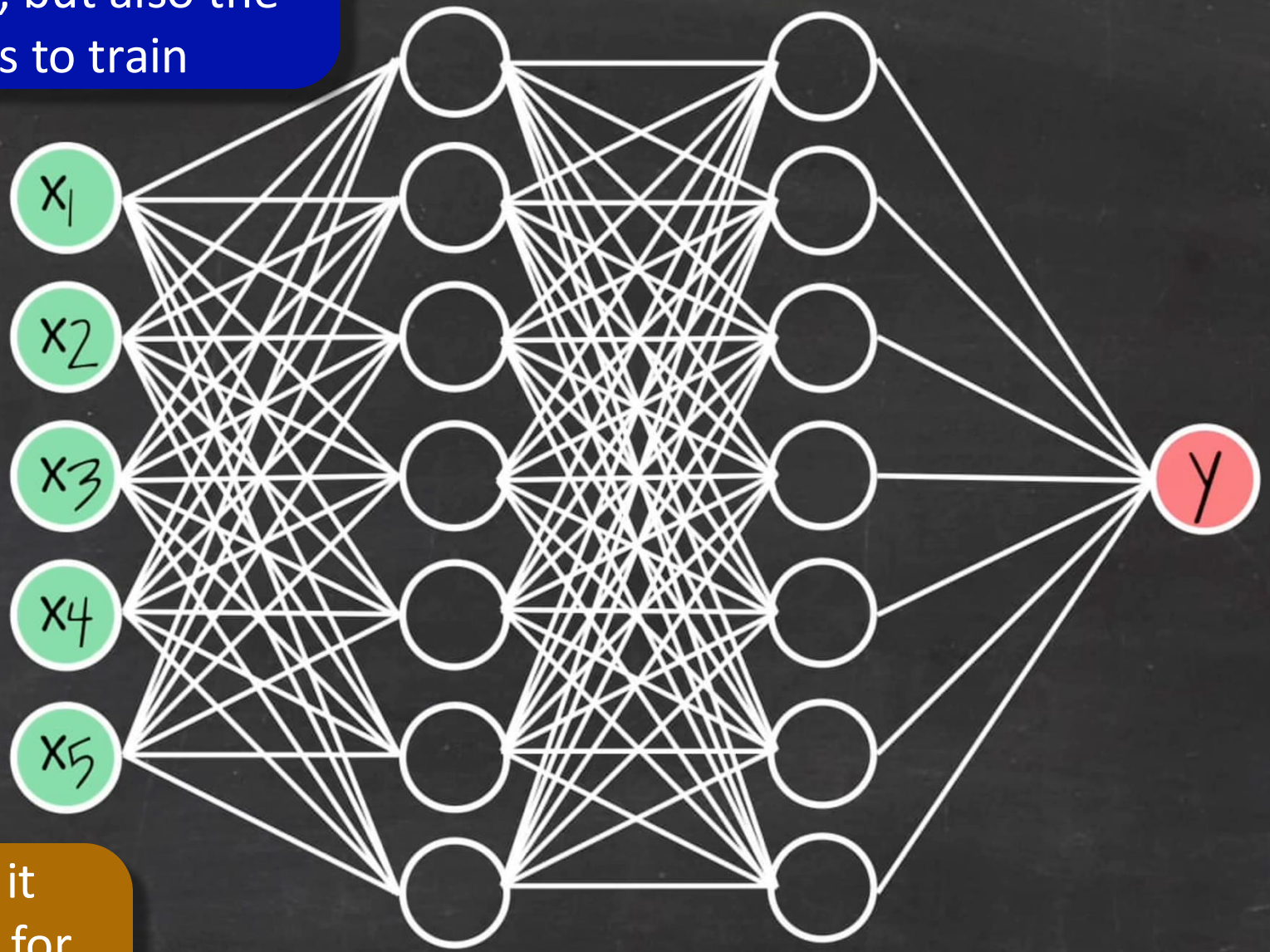
Several thousand synapses per neuron, meaning several million billion connections. That's too much for a simple computer


x1
x2
x3
x4
x5


x1
x2
x3
x4
x5
y


x1
x2
x3
x4
x5
y

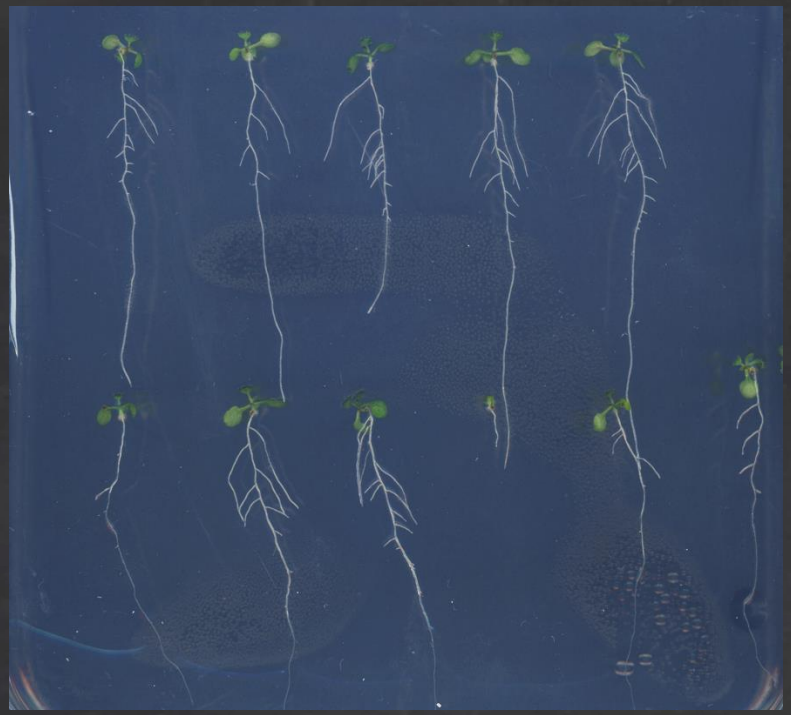
The more neurons there are, the more powerful the algorithm is, but also the more complicated it is to train



For simple algorithms, it works very well. But not for image analysis

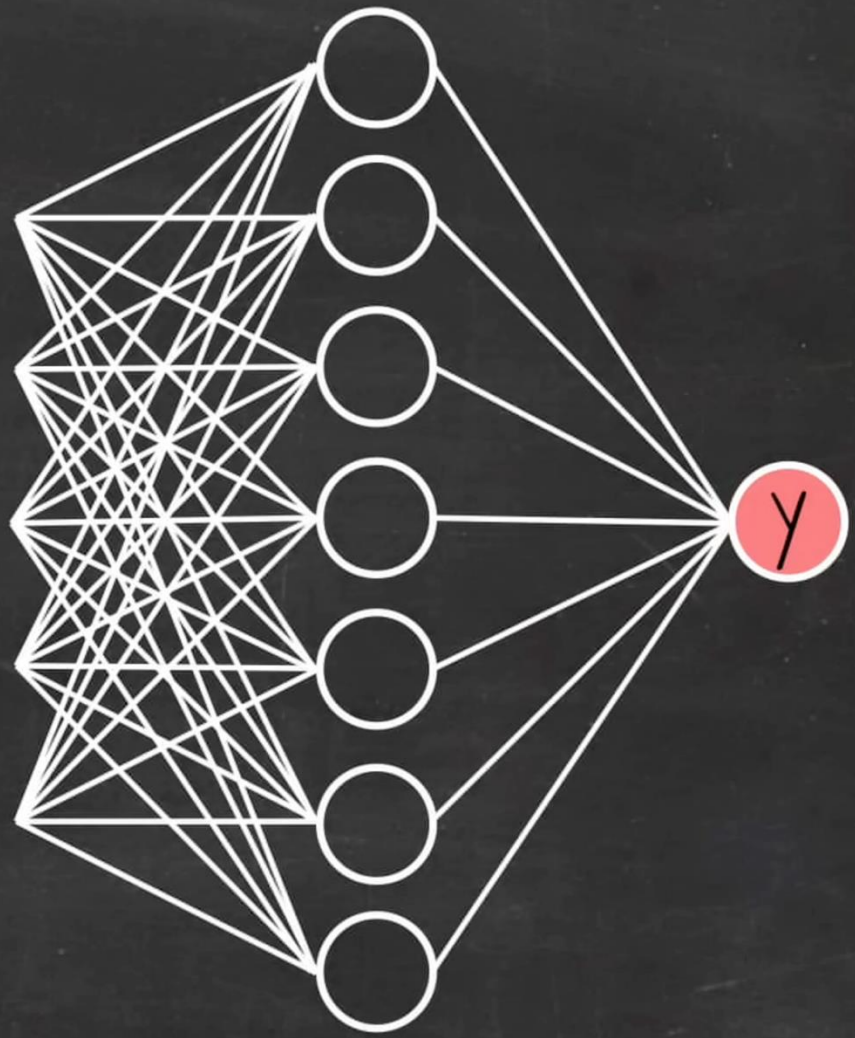
Image recognition is quickly limited (**machine learning**, not deep learning)

Image 5 000 x 5 000

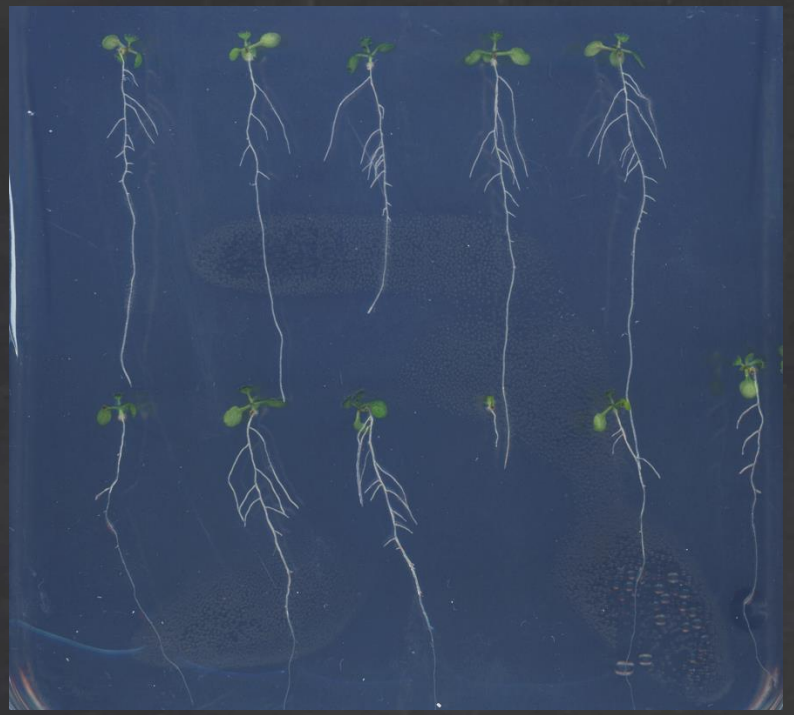


25000000 in number of input

?



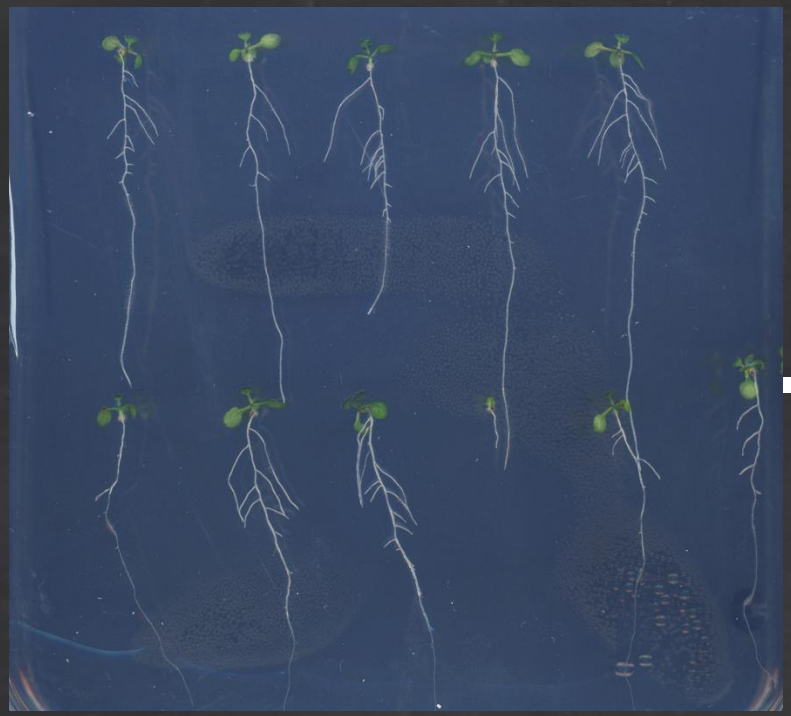
Recognition of plant organs (**machine learning**, not deep learning)



Algorithme

Leaves
Roots
Plate
Seeds

Recognition of plant organs. (**machine learning**, not deep learning)



Raw images or slightly modified images

Feature extraction algorithm

List of features

Recognition by a neural network

Recognition of plant organs. First extracts **hand-crafted image features** (Color/Intensity, Edge, Texture, etc)

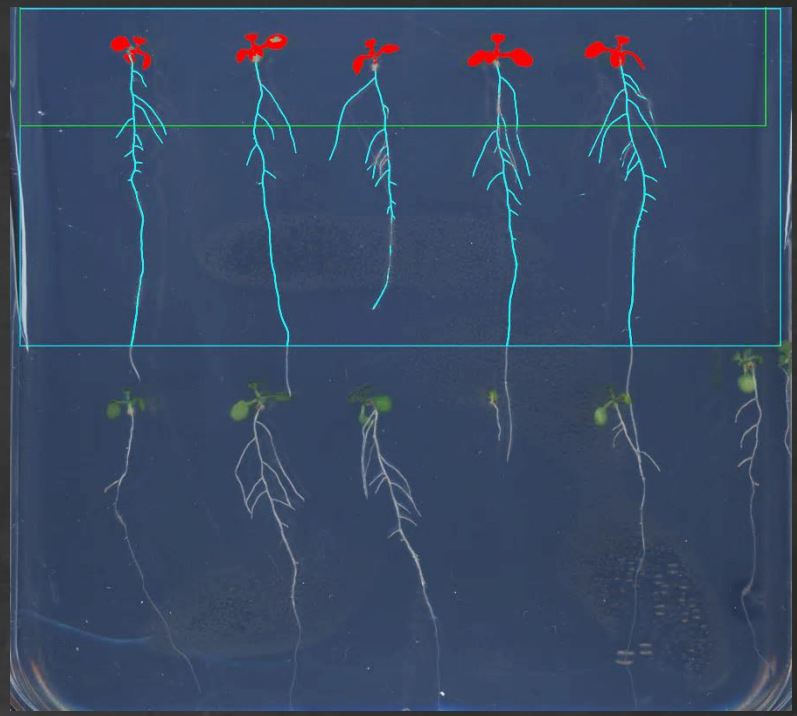
	Color / intensity	Edge	Texture
Leaves	chlorophyll green, brighter veins, darker lamina, patches, color gradients, smooth inner texture	leaf contour, serrated or smooth margin, vein borders, midrib edges, reticulated network edges	reticulated vein network pattern, mesophyll granularity, directional anisotropy from venation
Roots	strong contrast vs background, pale white/yellow roots, thin uniform structures, inner root homogeneity, high signal contrast	fine thin edges, forks, junctions, crossings, broken edges, root branching points	tubular tissue texture, smooth cortex interior, fine micro-texture (root hairs), fiber-like directionality, multiscale branching texture
Plate	uniform intensity, low variance, smooth gradient, glare, shadow zones, light/dark background, homogeneous region	circular border, plate ring edge, sharp transition background/air or background/casing	smooth, isotropic, low structural complexity, background noise sometimes granular but weak directionality
Seeds	brown/cream tone, darker seed coat, uniform inner color, oval colored blob, seed clusters, embryo vs background contrast	elliptical contour, seed coat border, hilum edge, cluster boundaries, clean air/background transition	coarse striated or rough seed coat pattern, repetitive grooves, mottled coat texture, cluster texture when seeds overlap

Test with ilastik

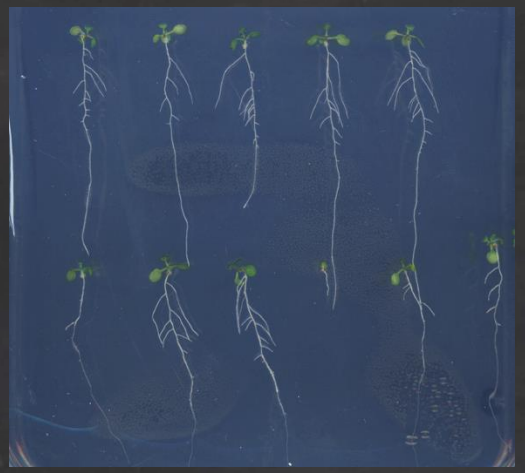
- Random Forest classifier based on the pixel labels
- This is classical machine learning, similar to methods used before deep neural networks became mainstream
- Runs fast even without a strong GPU
- Great for interactive segmentation and small datasets

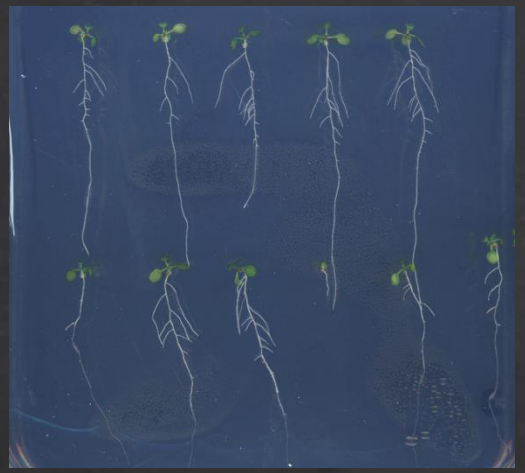
Root branching recognition

Algorithme



Recognition of plant ramification (**deep learning**, not machine learning)



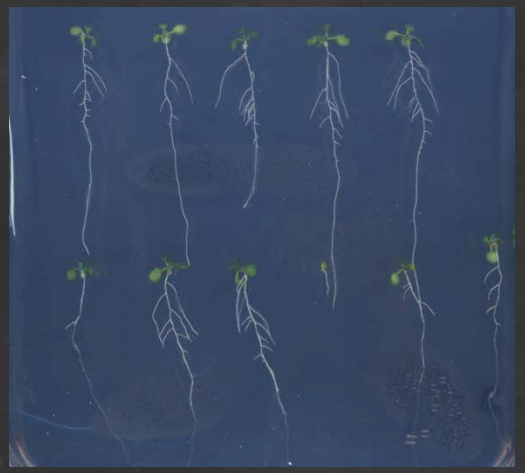


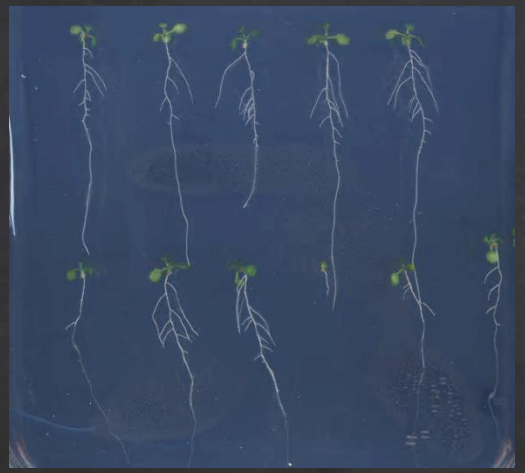
Feature extraction algorithm

Machine learning

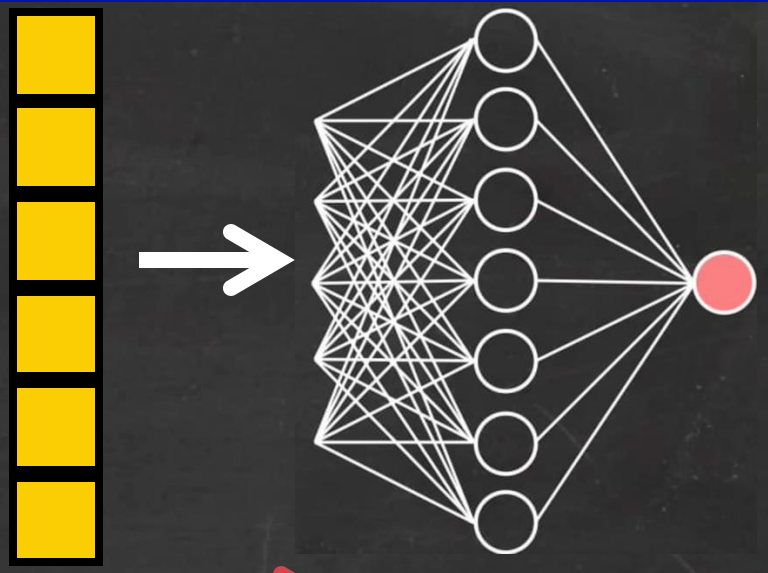
Deep learning

Recognition of plant ramification (**deep learning**, not machine learning)



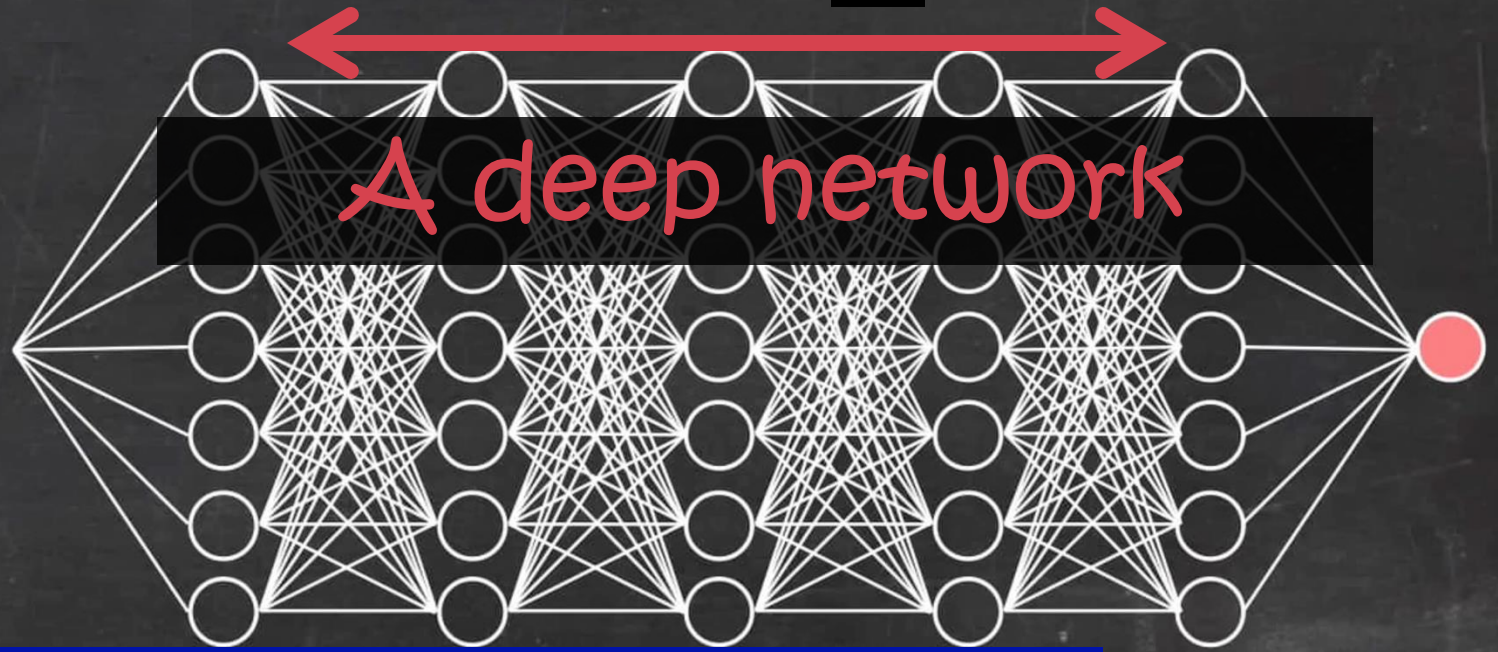


Feature extraction algorithm



Machine learning

A deep network



Deep learning

Yann Le Cun
(1989)

Machine leargning algorithm for image recognition

Large Scale Visual Recognition Challenge

2010		
1.	NEC	28%
2.	XRCE	34%
3.	ISIL	45%
4.	UCI	47%
5.	Hminmax	54%

↑ Error rate

Yann Le Cun
(1989)

Machine leargning algorithm for image recognition

Large Scale Visual Recognition Challenge

2010	
1. NEC	28%
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3. ISIL	45%
4. UCI	47%
5. Hminmax	54%

2011	
1. XRCE	26%
2. Uv A	31%
3. ISI	36%
4. NII	50%

Yann Le Cun
(1989)

Machine leargning algorithm for image recognition

Deep learning algorithm

Large Scale Visual Recognition Challenge

2010		
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2011		
1.	XRCE	26%
2.	Uv A	31%
3.	ISI	36%
4.	NII	50%

2012		
1.	SuperVision	16%
2.	ISI	26%
3.	VGG	27%
4.	XRCE	27%
5.	Uv A	30%

Yann Le Cun
(1989)

Machine leargning algorithm for image recognition

Deep learning algorithm

Large Scale Visual Recognition Challenge

2010

1.	NEC	28%
2.	XRCE	34%
3.	ISIL	45%
4.	UCI	47%
5.	Hminmax	54%

2011

1.	XRCE	26%
2.	Uv A	31%
3.	ISI	36%
4.	NII	50%

2012

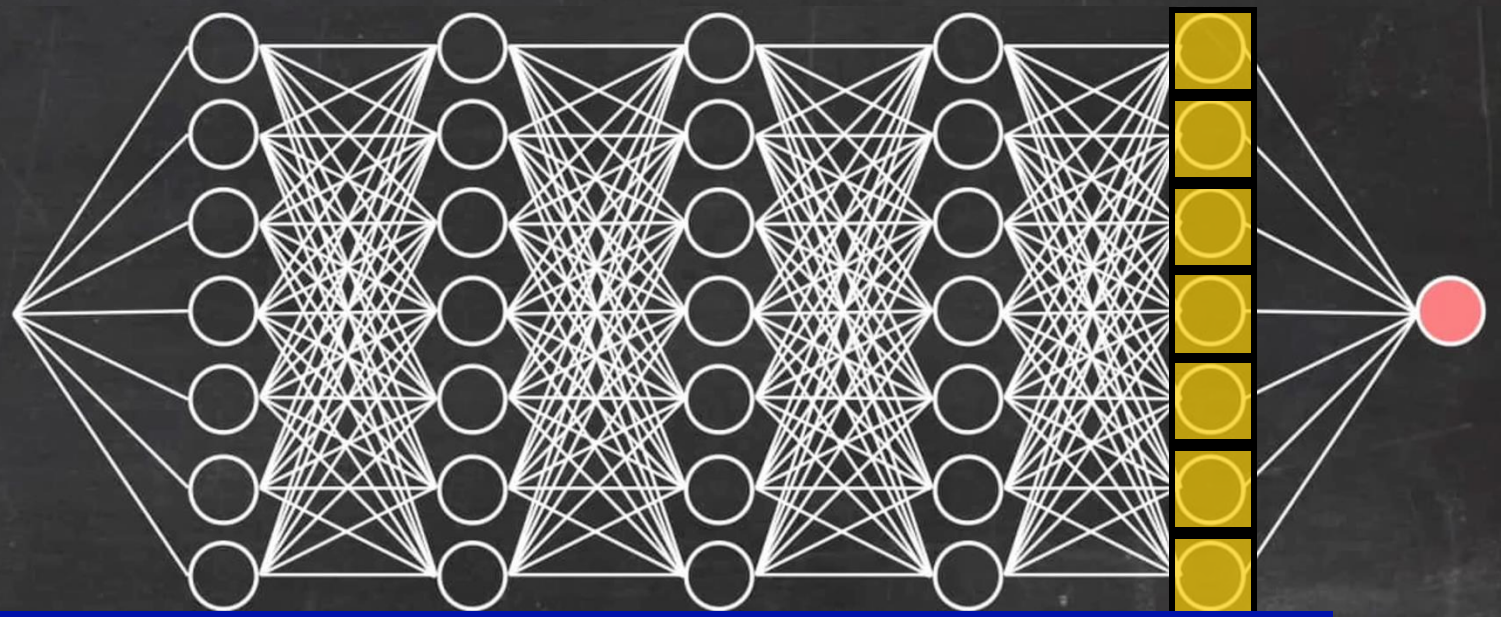
1.	SuperVision	16%
2.	ISI	26%
3.	VGG	27%
4.	XRCE	27%
5.	Uv A	30%

2013

1.	Clarifai	12%
2.	NUS	13%
3.	ZeilerFergus	13%
4.	A.Howard	13%
5.	OverFeat	14%

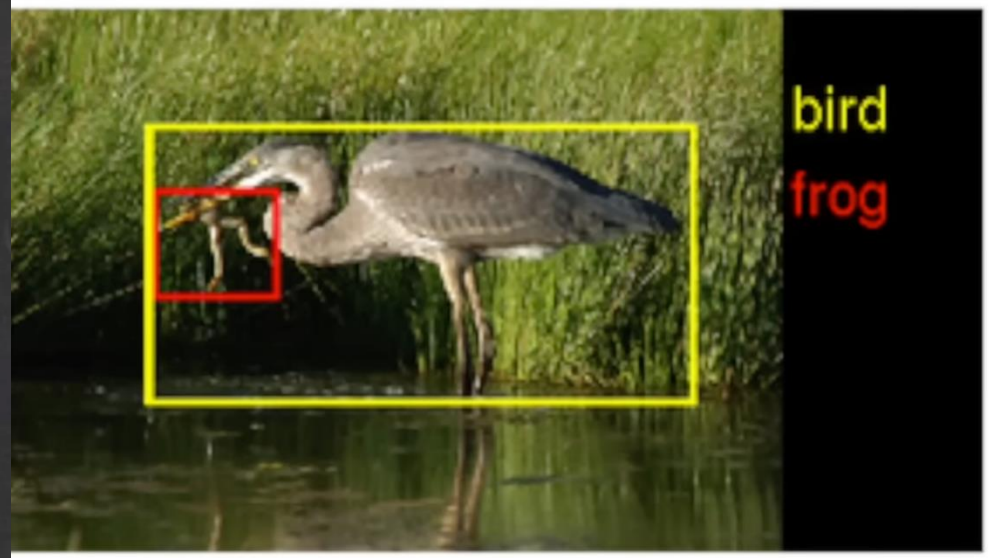
Why does deep learning finally work?

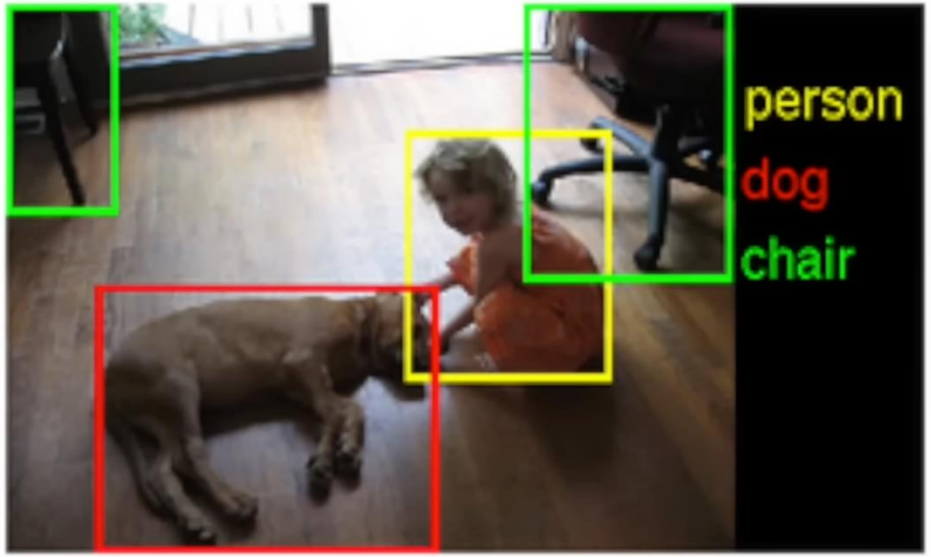
- Better understanding of the importance of network architecture
- Greater computing power than before (GPU)
- More accessible databases (ImageNet)

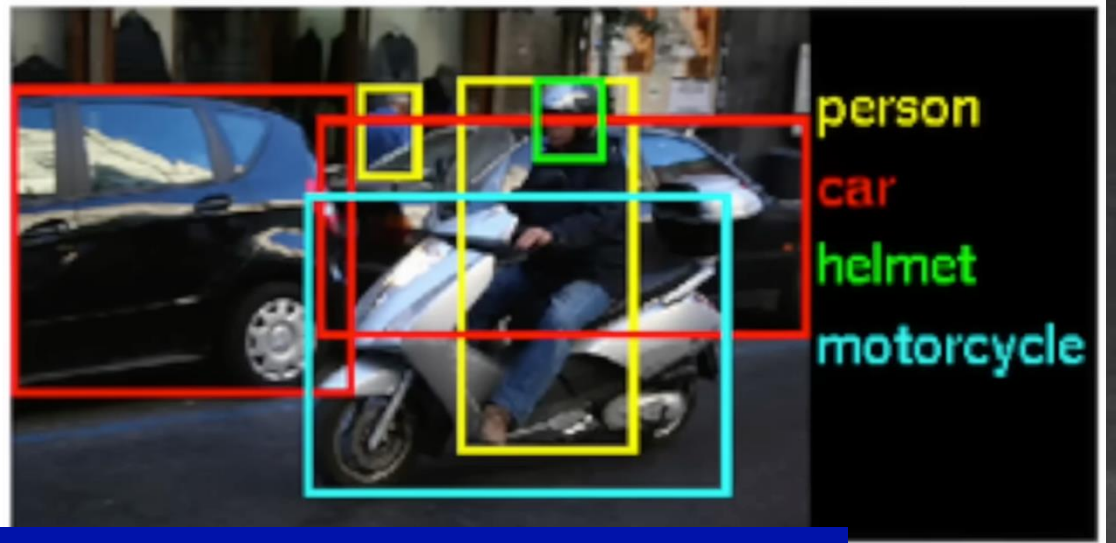


Deep learning

Example of image recognition using Deeplearning







Sometimes a few errors appear…

Hairdryer ?

Camel ?

Deep learning with U-Net

How U-Net works:

2 key ideas behind U-Net:

1. **Understand the image context (where roots, leaves, seeds are)**
2. **Locate fine details precisely (thin root pixels, tissue boundaries)**

Unlike classical methods, U-Net:
learns its own features automatically from raw pixels
does *not rely on the user defining edge or texture manually*

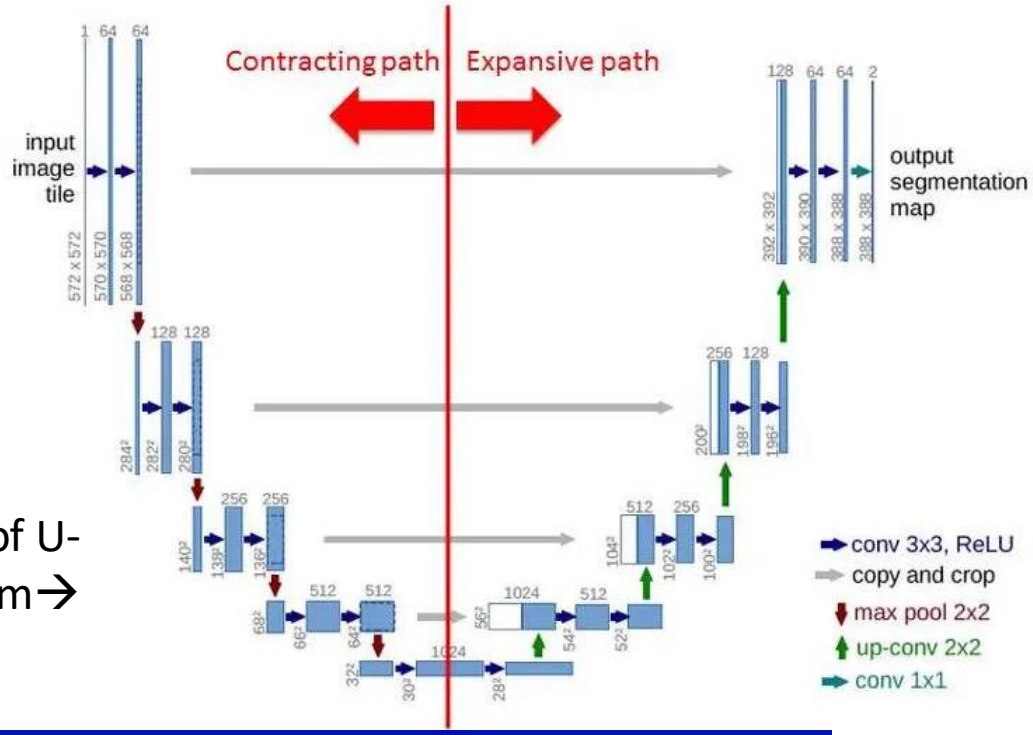
Unlike classical ML, U-Net learns its own features directly from pixel data through backpropagation

Training workflow

Typical steps when using a U-Net model:

- Input images
- Marked the areas that are considered to be ramifications
- Neural network learns to map image → mask
- Output = segmentation of new images

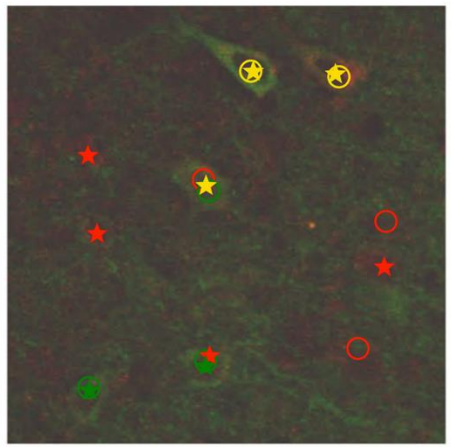
Network architecture of U-Net algorithm→



nature methods
BRIEF COMMUNICATION
https://doi.org/10.1038/s41592-018-0261-2

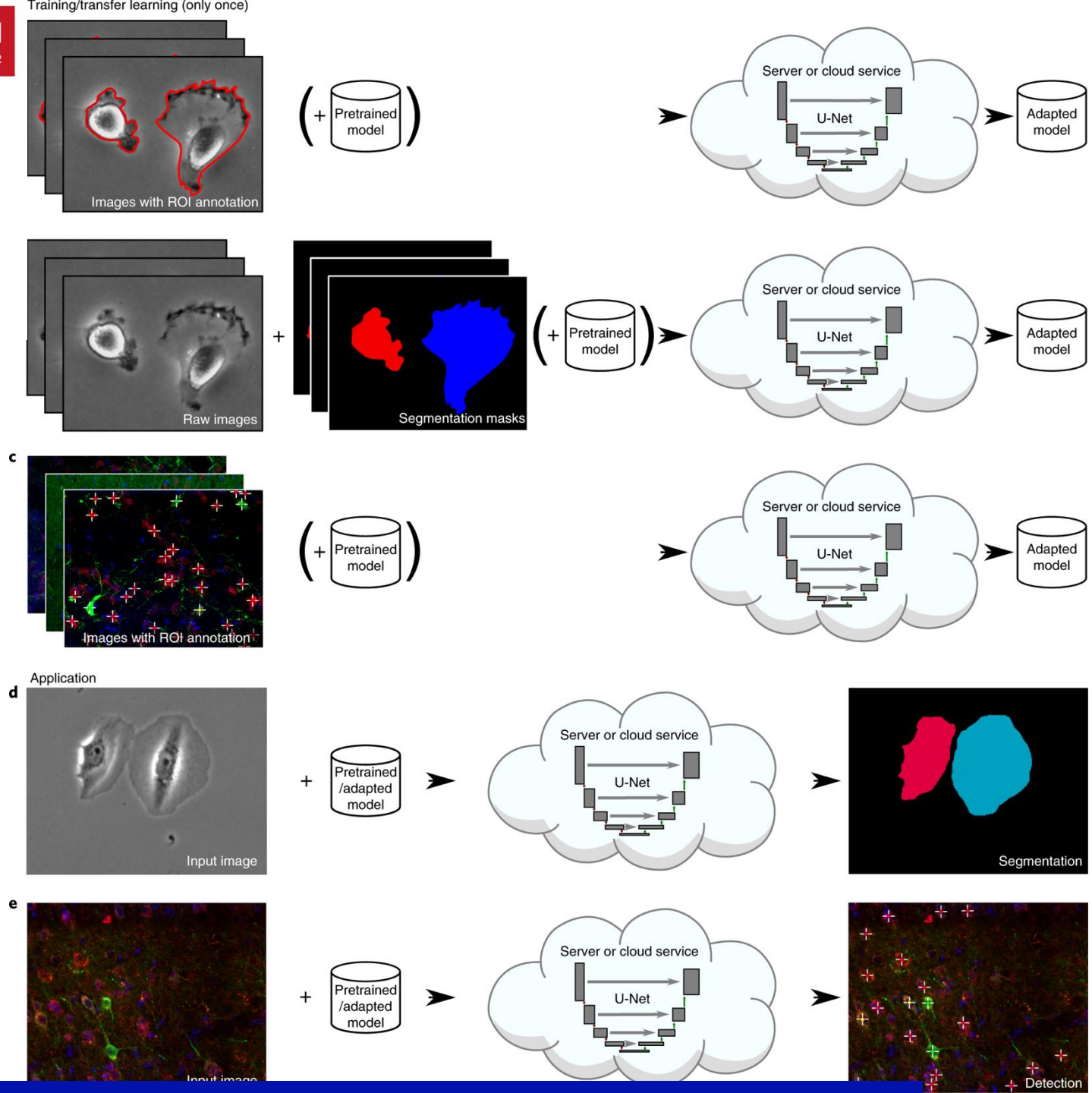
U-Net: deep learning for cell counting, detection, and morphometry

Thorsten Falk[1,2,3,19], Dominic Mai[1,2,4,15,19], Robert Bensch[1,2,16,19], Özgün Çiçek[1], Ahmed Abdulkadir[1,5], Yassine Marrakchi[1,2,3], Anton Böhm[1], Jan Deubner[6,7], Zoe Jäckel[6,7], Katharina Seiwald[6], Alexander Dovzhenko[8,17], Olaf Tietz[8,17], Cristina Dal Bosco[8], Sean Walsh[8,17], Deniz Saltukoglu[2,4,9,10], Tuan Leng Tay[7,11,12], Marco Prinz[2,3,11], Klaus Palme[2,8], Matias Simons[2,4,9,13], Ilka Diester[6,7,14], Thomas Brox[1,2,3,7] and Olaf Ronneberger[1,2,18]*



○ Human expert
★ U-Net

— Antibody only
— eYFP only
— Colocalization



Deep learning to find plant branching patterns with U-Net

Scan

Deep learning to find plant branching patterns with U-Net

Scan → Preprocessing (image alignment)

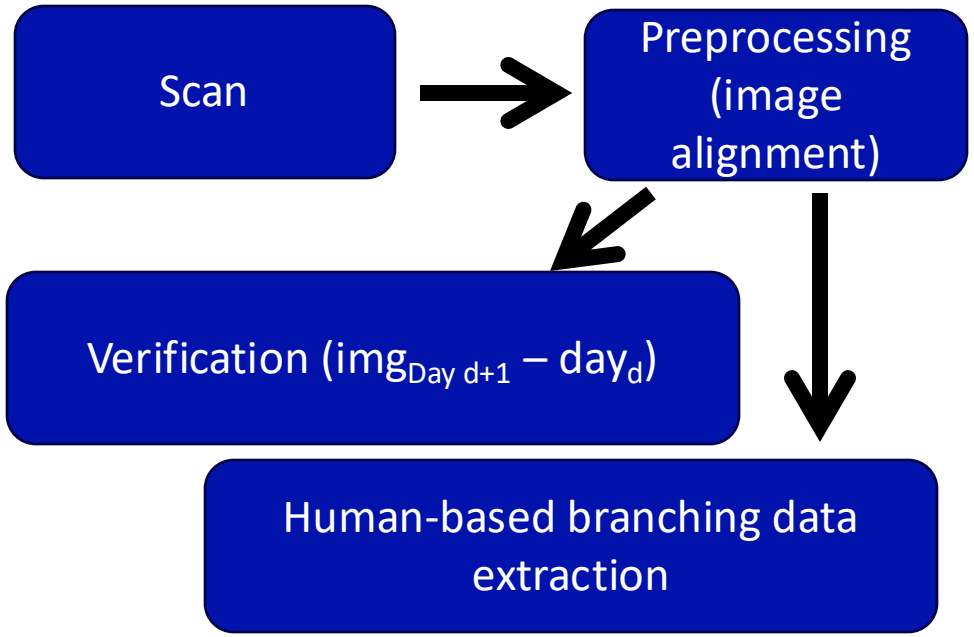
Image Alignment Example

LearnOpenCV.com

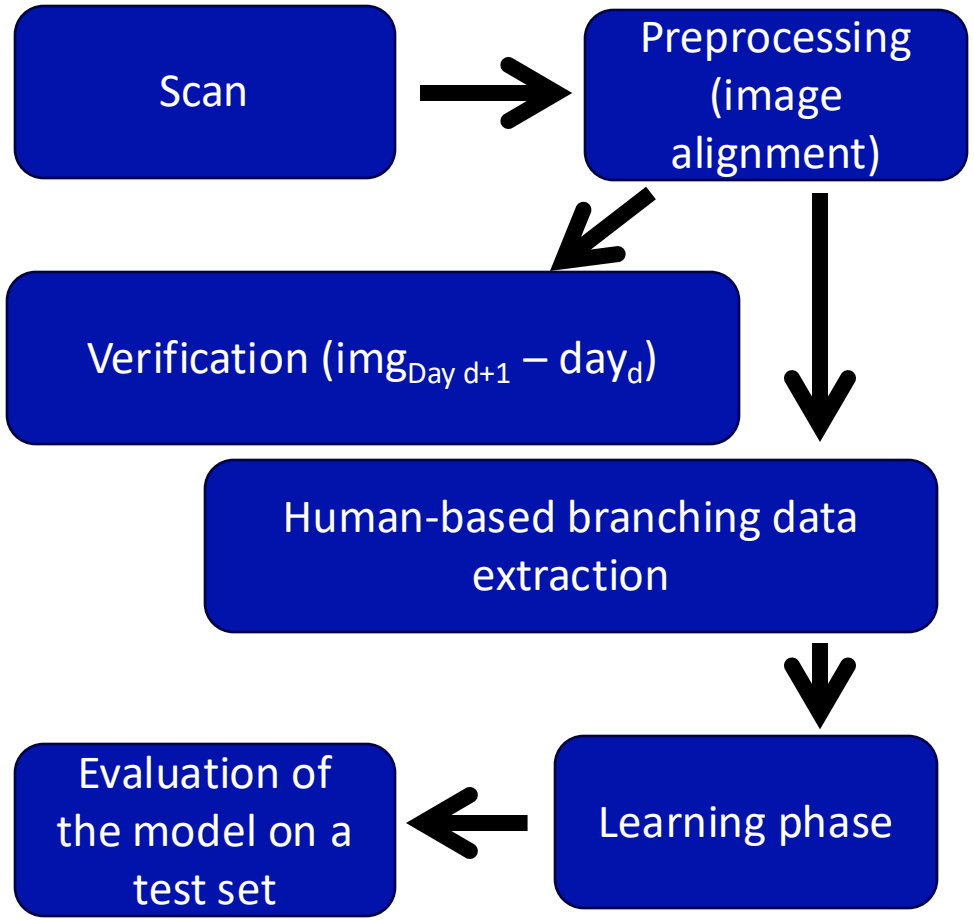
Deep learning to find plant branching patterns with U-Net

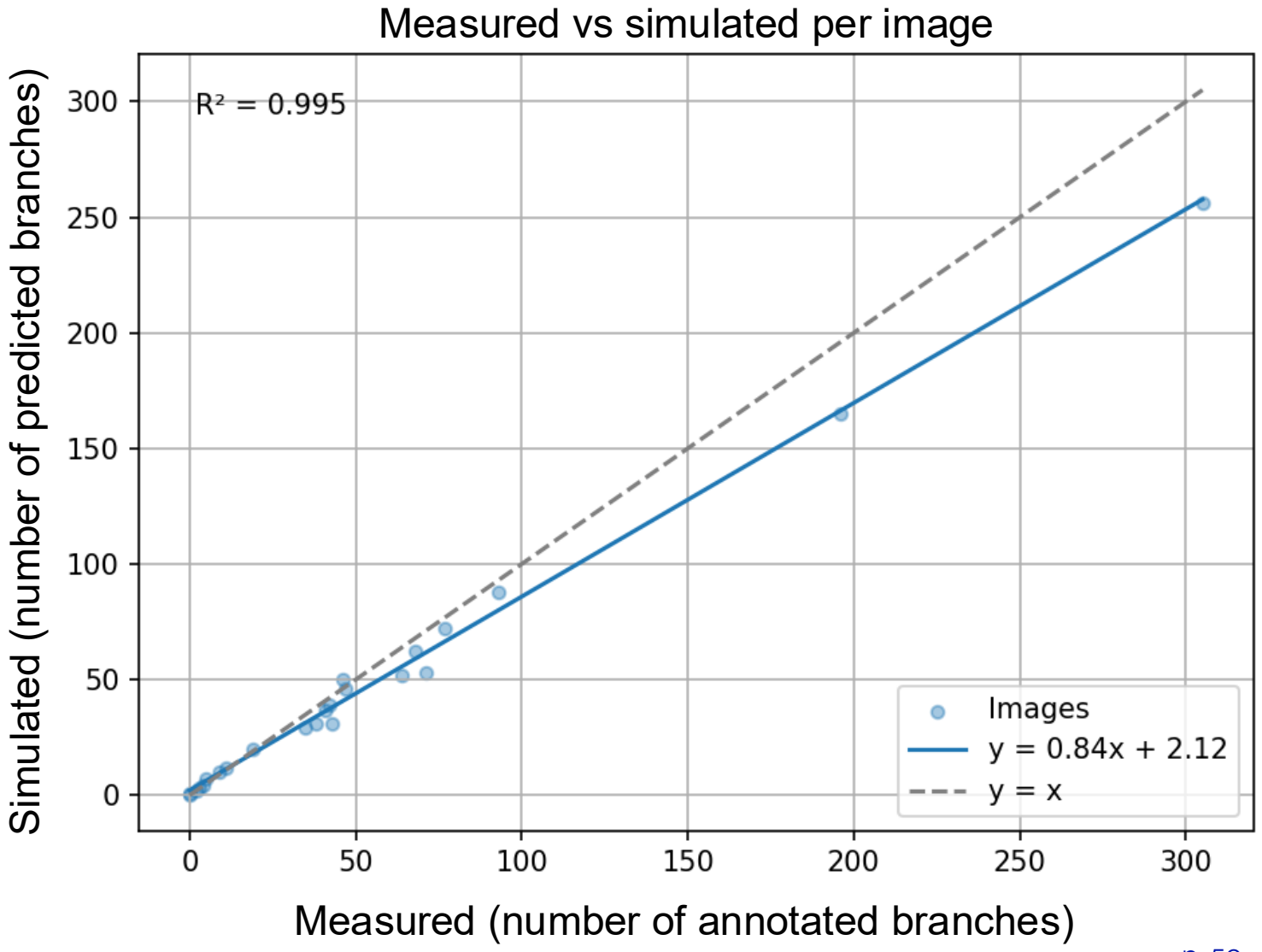
Scan → Preprocessing (image alignment) → Verification ($img_{Day\ d+1} - day_d$)

Deep learning to find plant branching patterns with U-Net

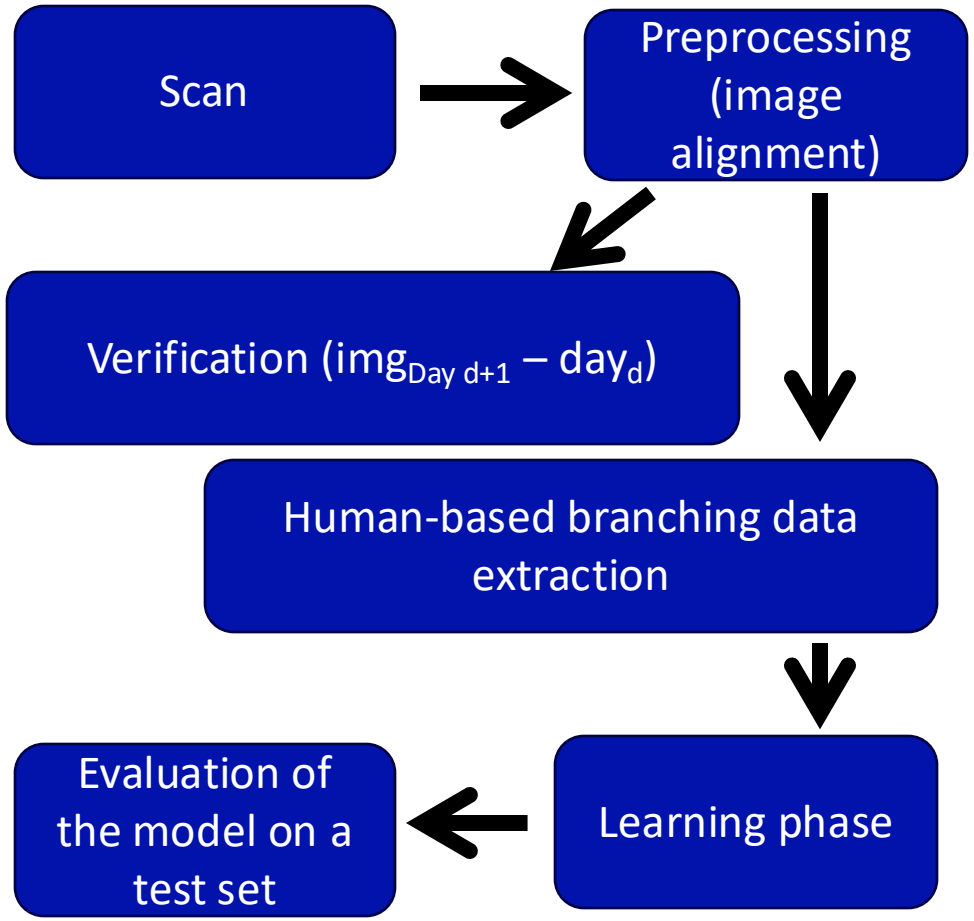


Deep learning to find plant branching patterns with U-Net





Deep learning to find plant branching patterns with U-Net

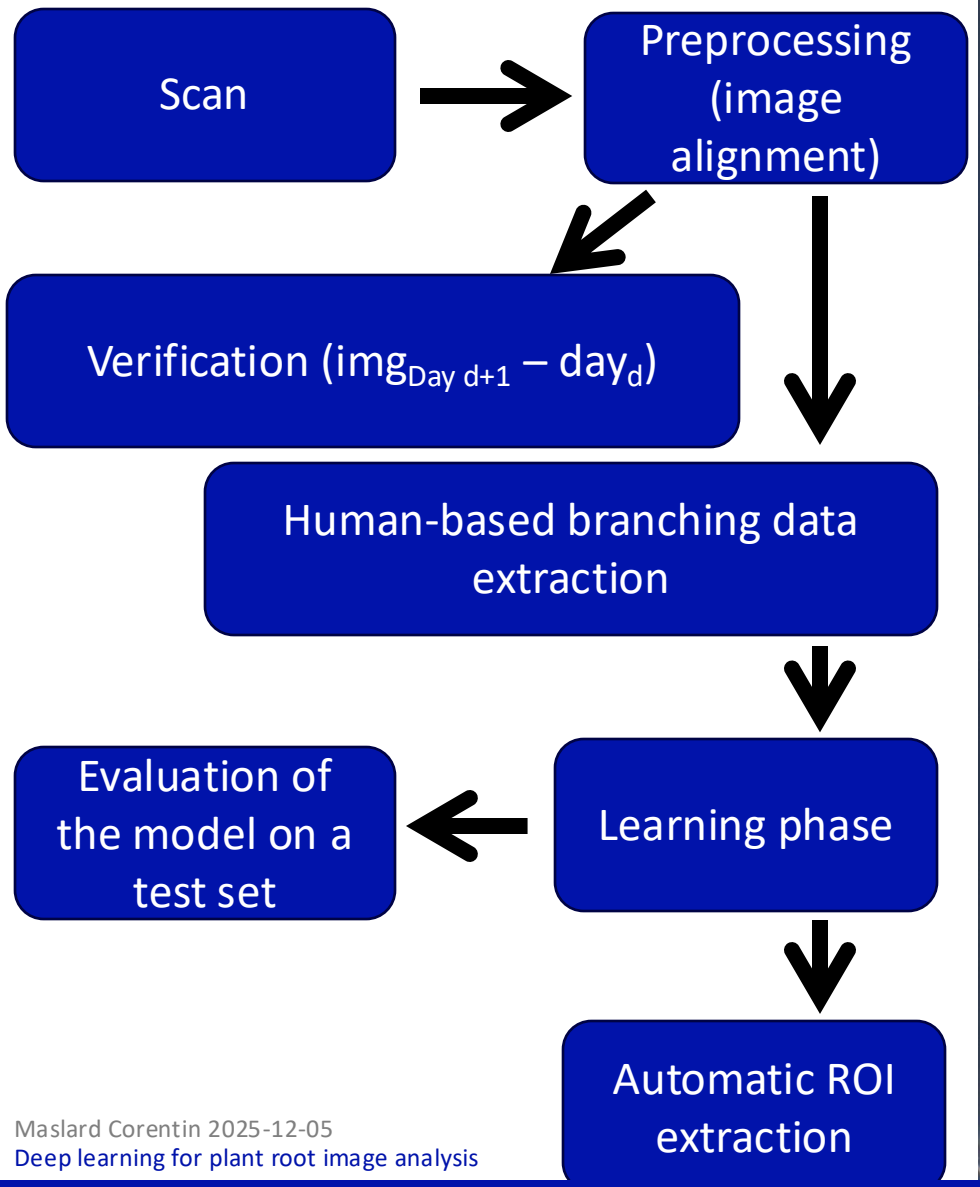


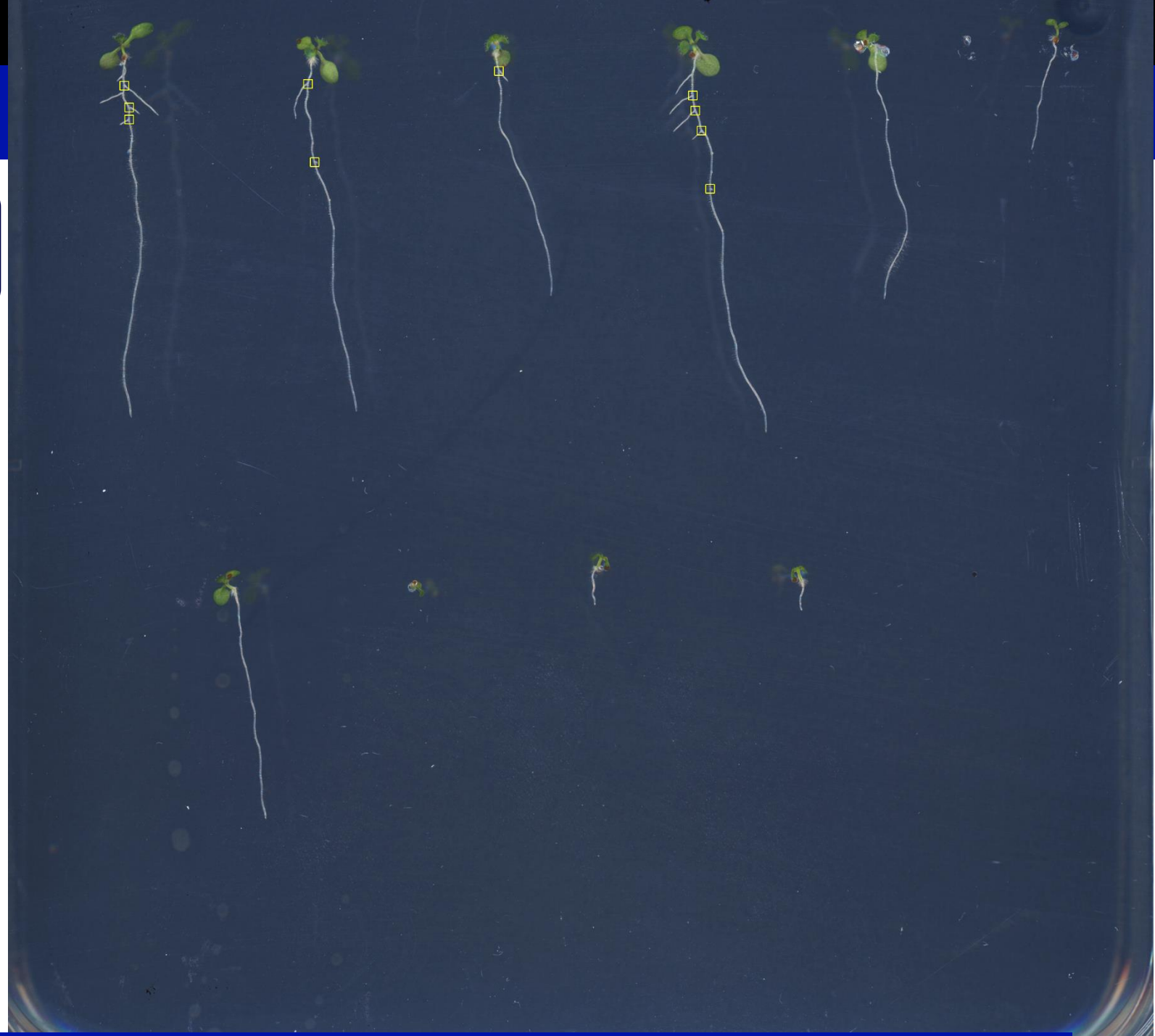
Annotation of the ROI by a human

Prediction of the ROI

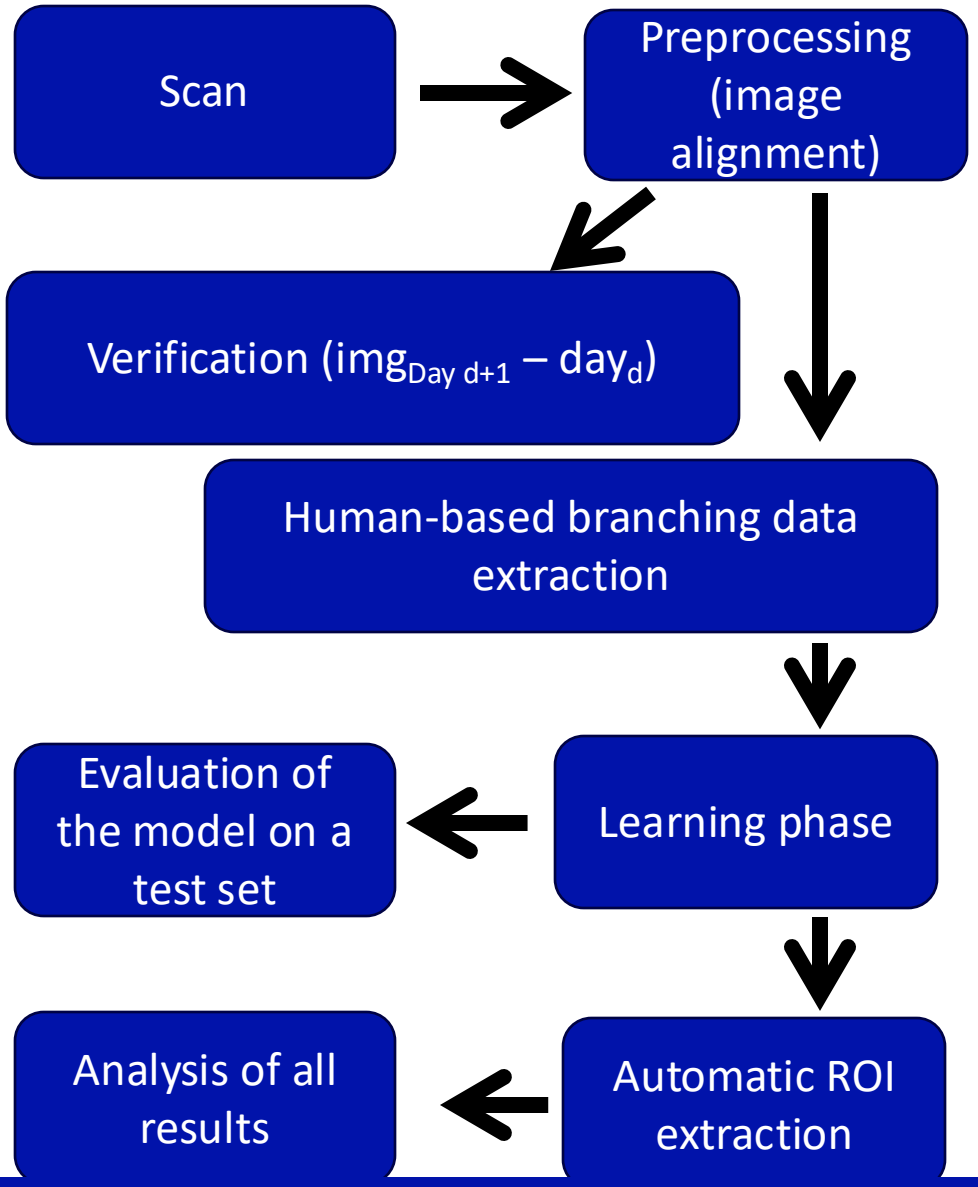
Here we have only given the model 20 images for training.

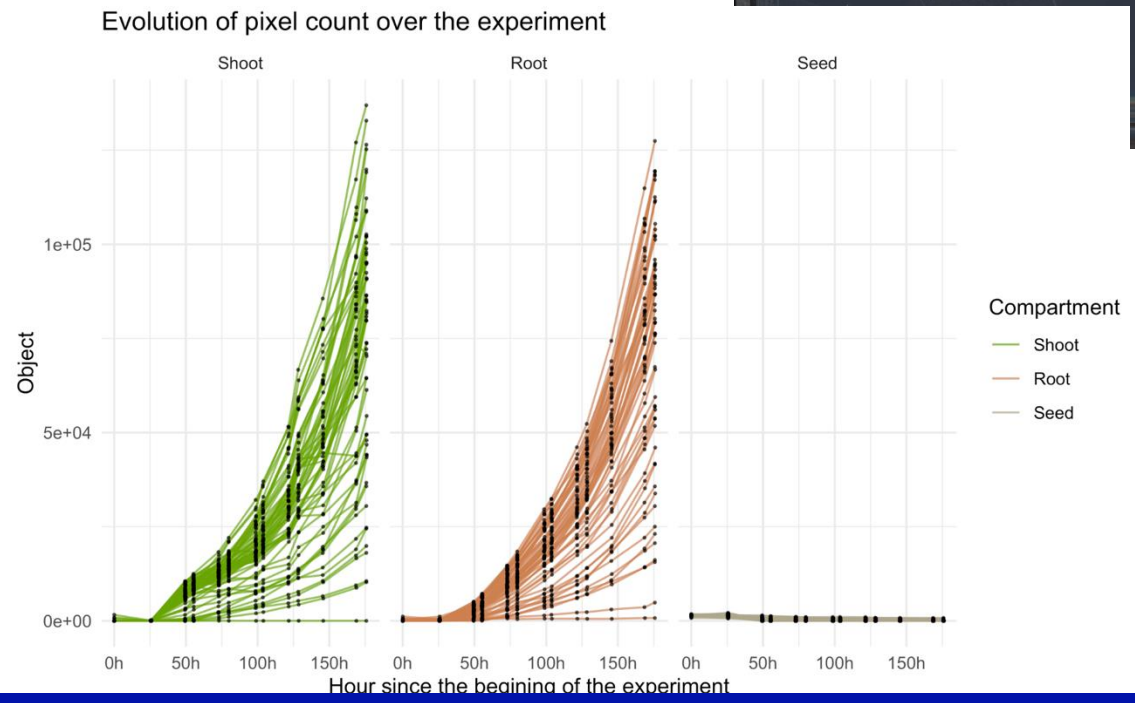
Deep learning to find plant branching patterns with U-Net





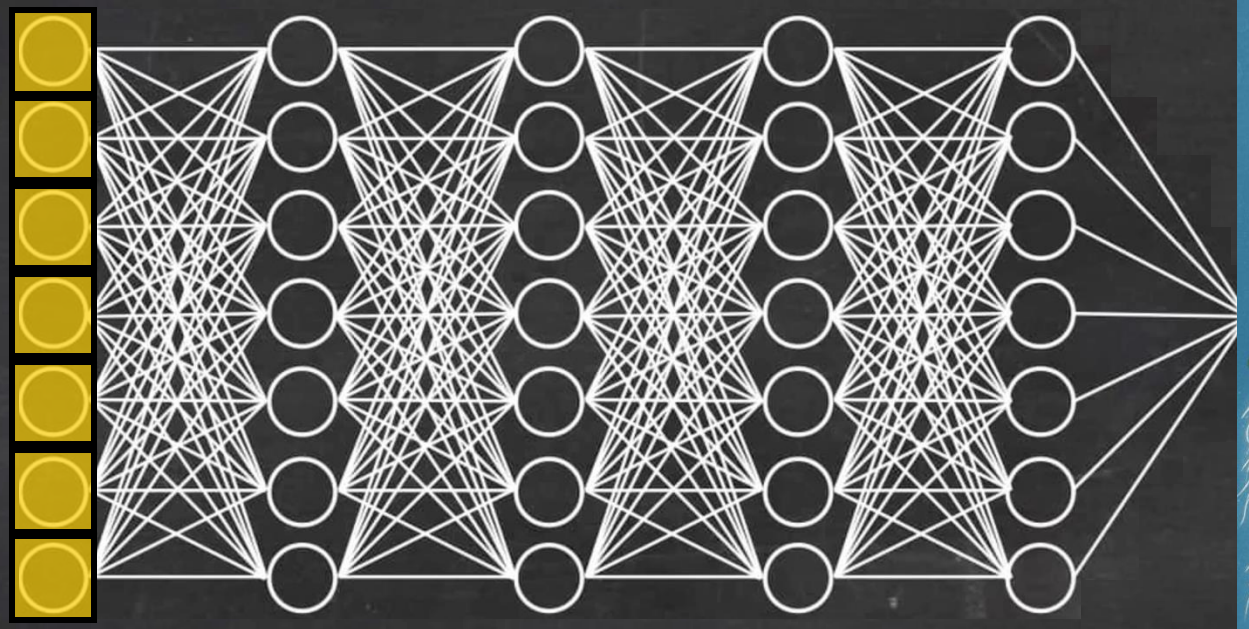
Deep learning to find plant branching patterns with U-Net





Bonus: How work generative models ? just by returning the network

Values of essential features



Invented images

To go further

Inspiring talks & lectures

- Ted talk by Fei-Fei Li on the future of ai and computer vision
- Advanced academic lectures by Yann Le Cun at the Collège de France

Courses & tutorials

- Deep learning specialization by Andrew Ng
- practical deep learning courses on fast.ai

Tools & frameworks for image and root analysis

classical machine learning: scikit-learn
computer vision: opencv
deep learning:
    tensorflow
    pytorch
    keras

Here you can find the slides from this presentation →

Generate with: https://www.qrcode-monkey.com/#

- Feel free to reach out if you need help designing or optimizing image-analysis or deep-learning pipelines
- For more information and code examples, check my personal website if needed.