Introduction to Deep Learning in Computer Vision

Danna Gurari
University of Colorado Boulder
Fall 2024

Review

- Last lecture:
  - Computer vision: origins
  - What makes computer vision hard?
  - Research in computer vision
  - Course logistics
- Assignments (Canvas)
  - New reading assignments coming out today due the next two weeks
- Questions?

Today's Topics

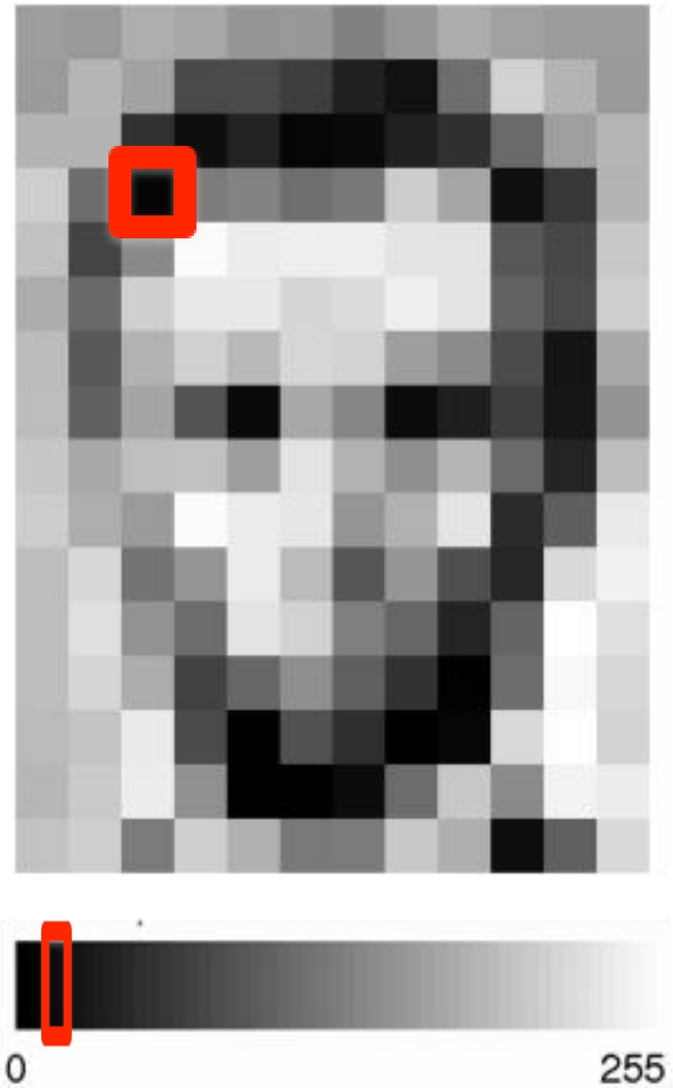
- Ways of seeing: image and video acquisition
- Evolution of computer vision (before versus after 2012)
- Fundamentals of a neural network architecture
- Training deep neural networks

Today’s Topics

- Ways of seeing: image and video acquisition
- Evolution of computer vision (before versus after 2012)
- Fundamentals of a neural network architecture
- Training deep neural networks

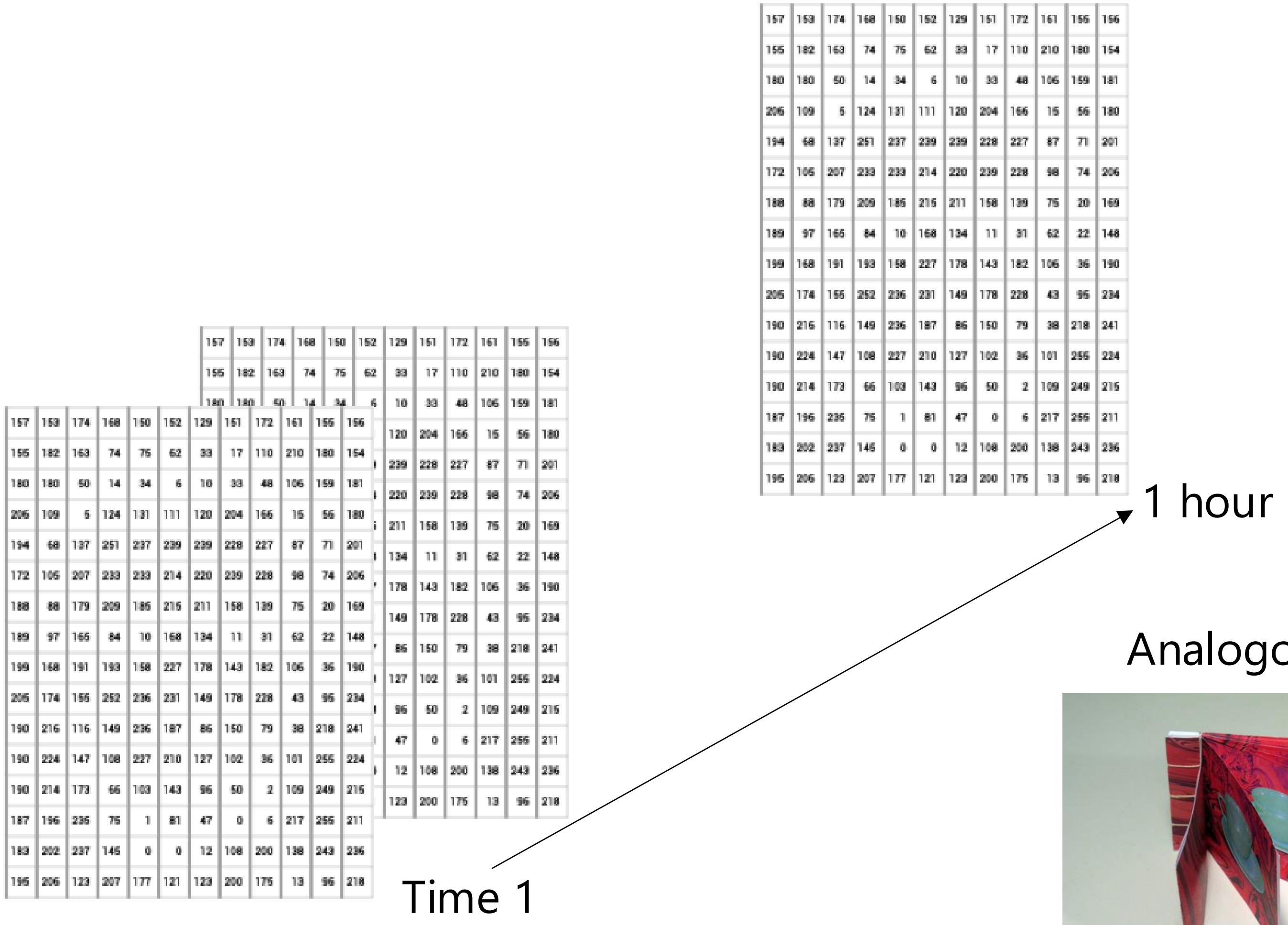
Recall What a Machine Observes: Digital Image

157	153	174	168	150	152	129	151	172	161	155	156
155	182	163	74	75	62	33	17	110	210	180	154
180	180	[illegible]	14	34	6	10	33	48	106	159	181
206	[illegible]	5	[illegible]	131	111	120	204	166	15	56	180
194	68	137	251	237	239	239	228	227	87	71	201
172	106	207	233	233	214	220	239	228	98	74	206
188	88	179	209	185	215	211	158	139	75	20	169
189	97	165	84	10	168	134	11	31	62	22	148
199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
190	216	116	149	236	187	86	150	79	38	218	241
190	224	147	108	227	210	127	102	36	101	255	224
190	214	173	66	103	143	96	50	2	109	249	215
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218



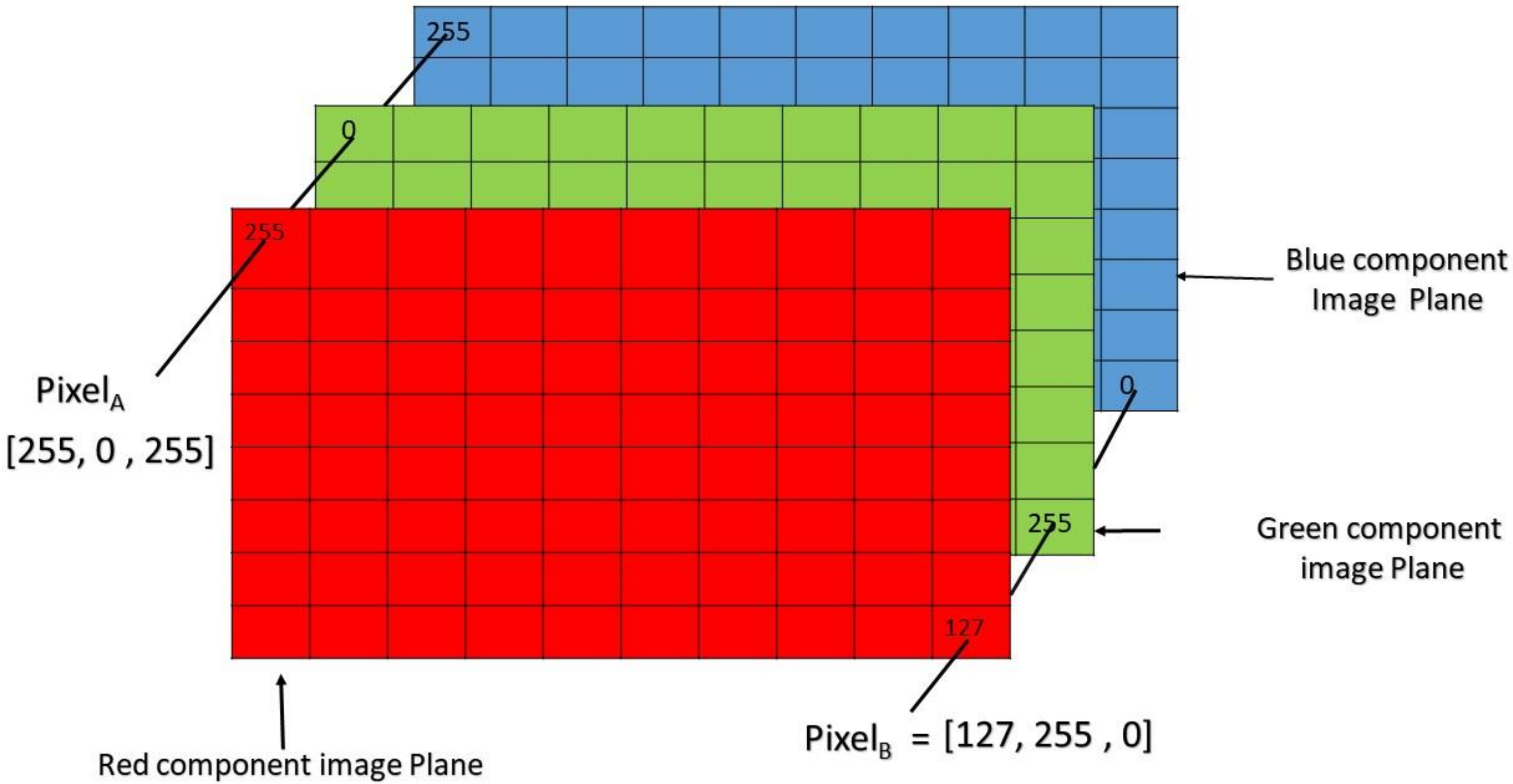
https://ai.stanford.edu/~syyeung/cvweb/tutorial1.html

Recall What a Machine Observes: Digital Video



Analogous to:

Mult-Channel Color Images; e.g., 24-bit RGB

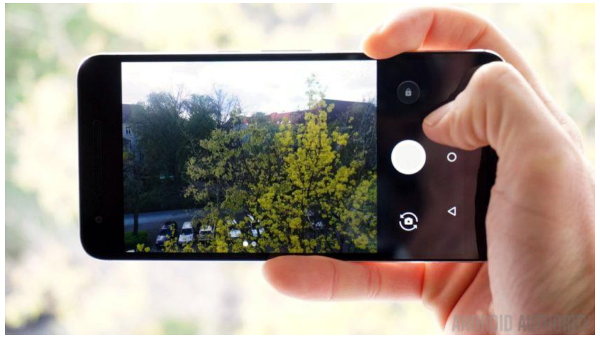


https://www.geeksforgeeks.org/matlab-rgb-image-representation/

Many Ways to Create Digital Images and Videos

Ultrasound

Infrared



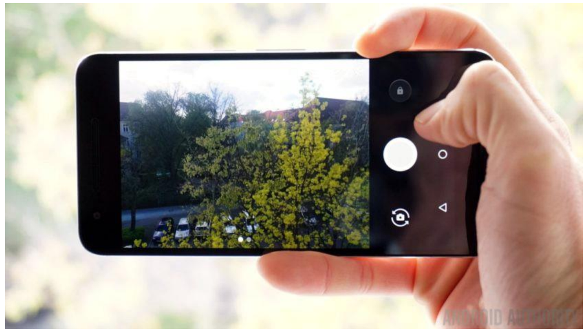
Visible

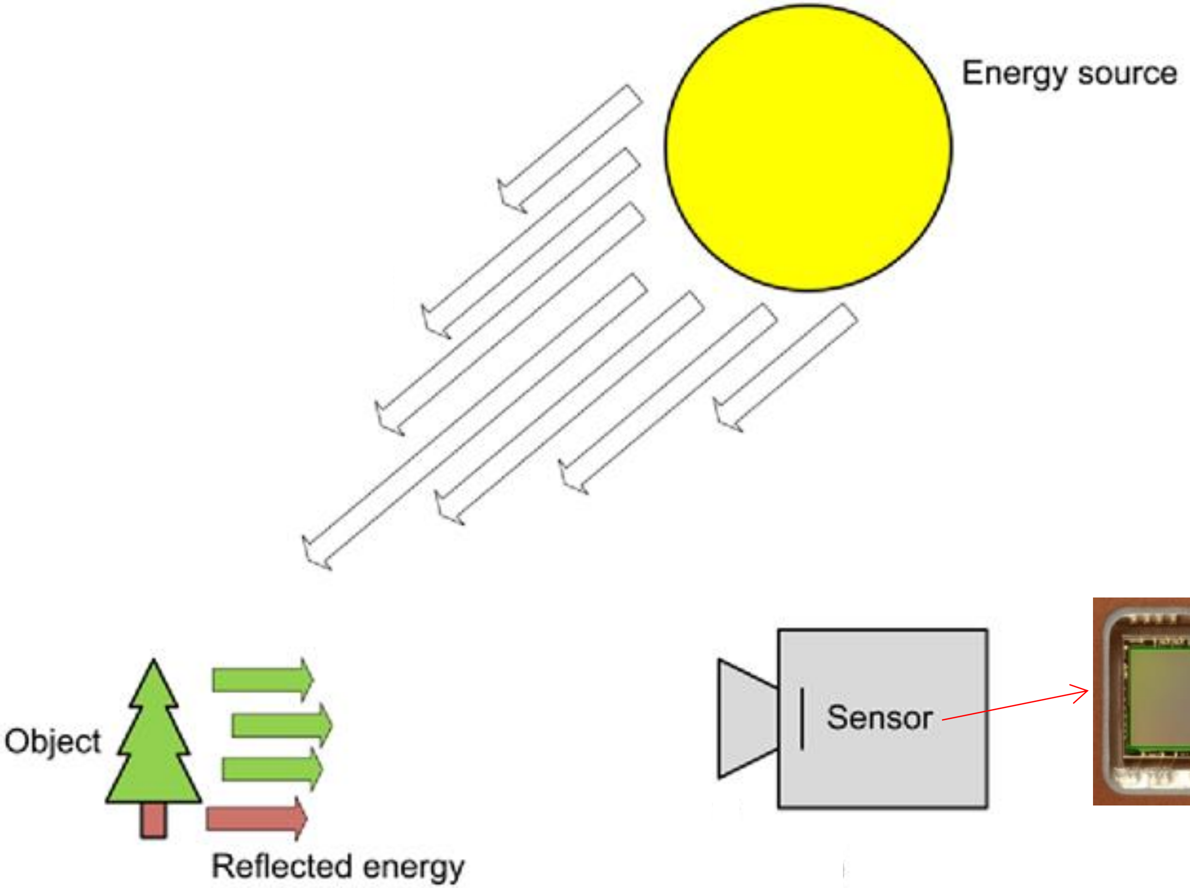
X-ray

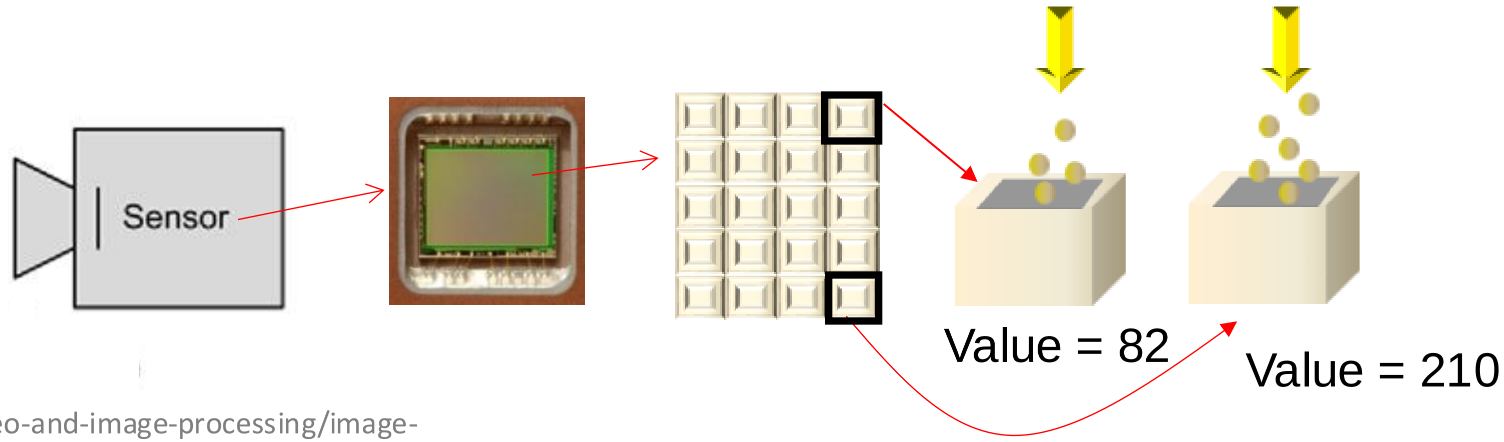
Microscopy

Many Ways to Create Digital Images and Videos

e.g., seeing what is visible to the naked human eye



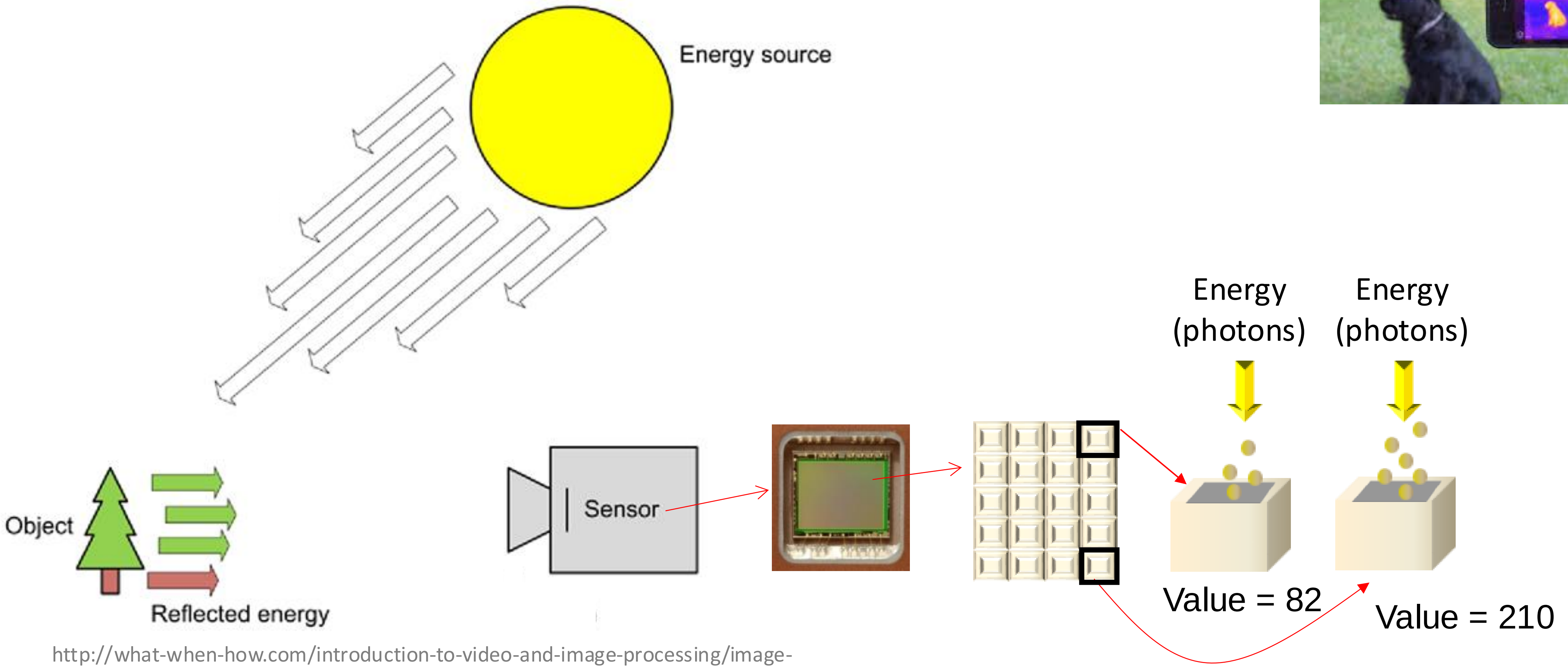




http://what-when-how.com/introduction-to-video-and-image-processing/image-acquisition-introduction-to-video-and-image-processing-part-1/

Many Ways to Create Digital Images and Videos

e.g., seeing what is invisible to the naked human eye with infrared

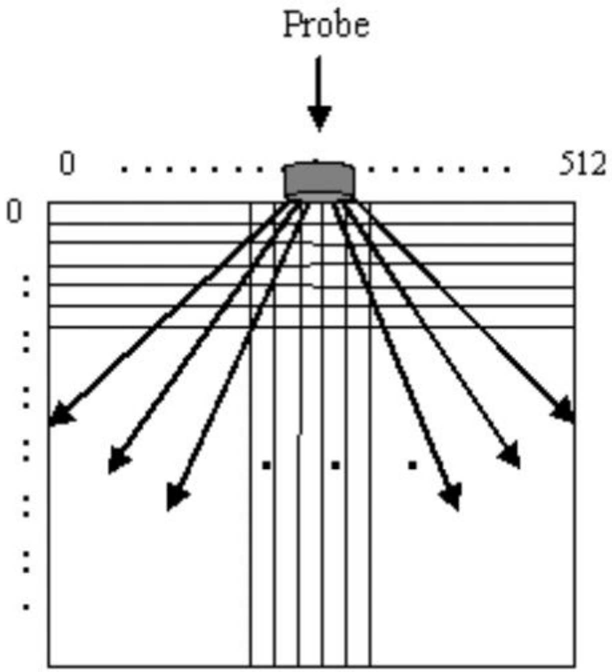


http://what-when-how.com/introduction-to-video-and-image-processing/image-acquisition-introduction-to-video-and-image-processing-part-1/

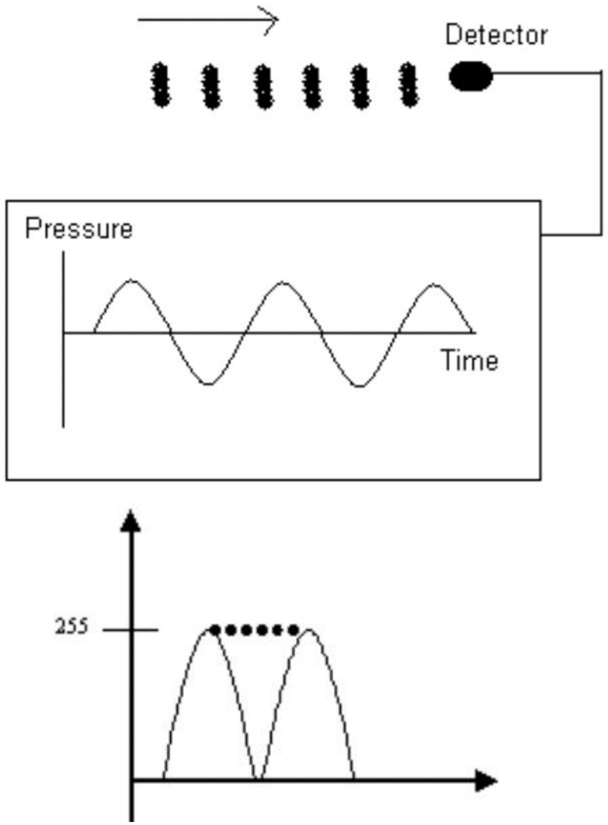
Many Ways to Create Digital Images and Videos

e.g., seeing what is invisible to the naked human eye with sound

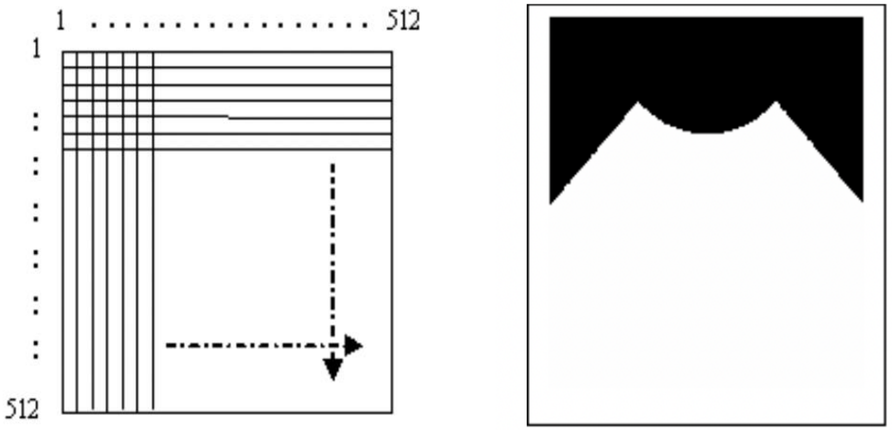
1. Sound wave generation



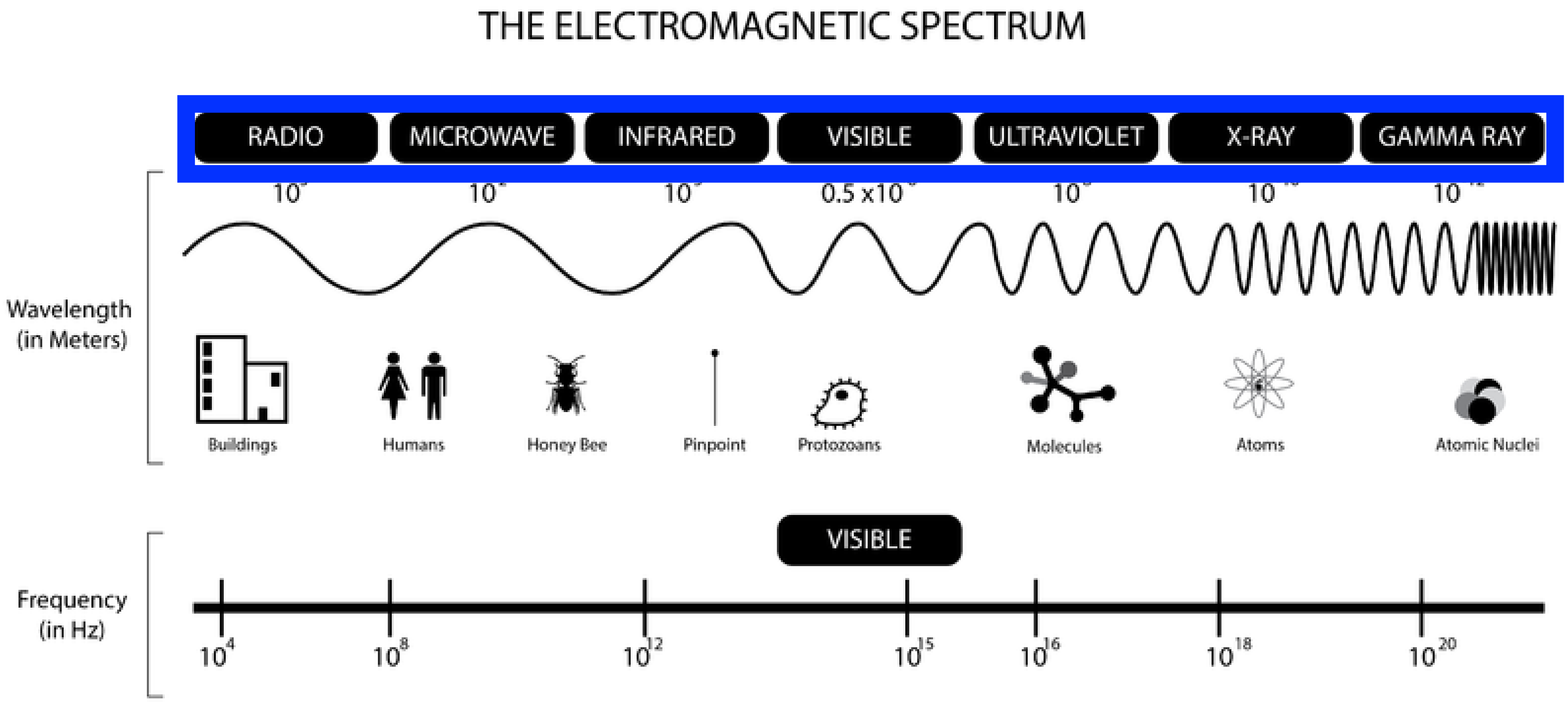
2. For each reflected sound wave, (a) record and (b) digitize to pixel values



3. Convert digitization to image



Many Ways to Create Digital Images and Videos

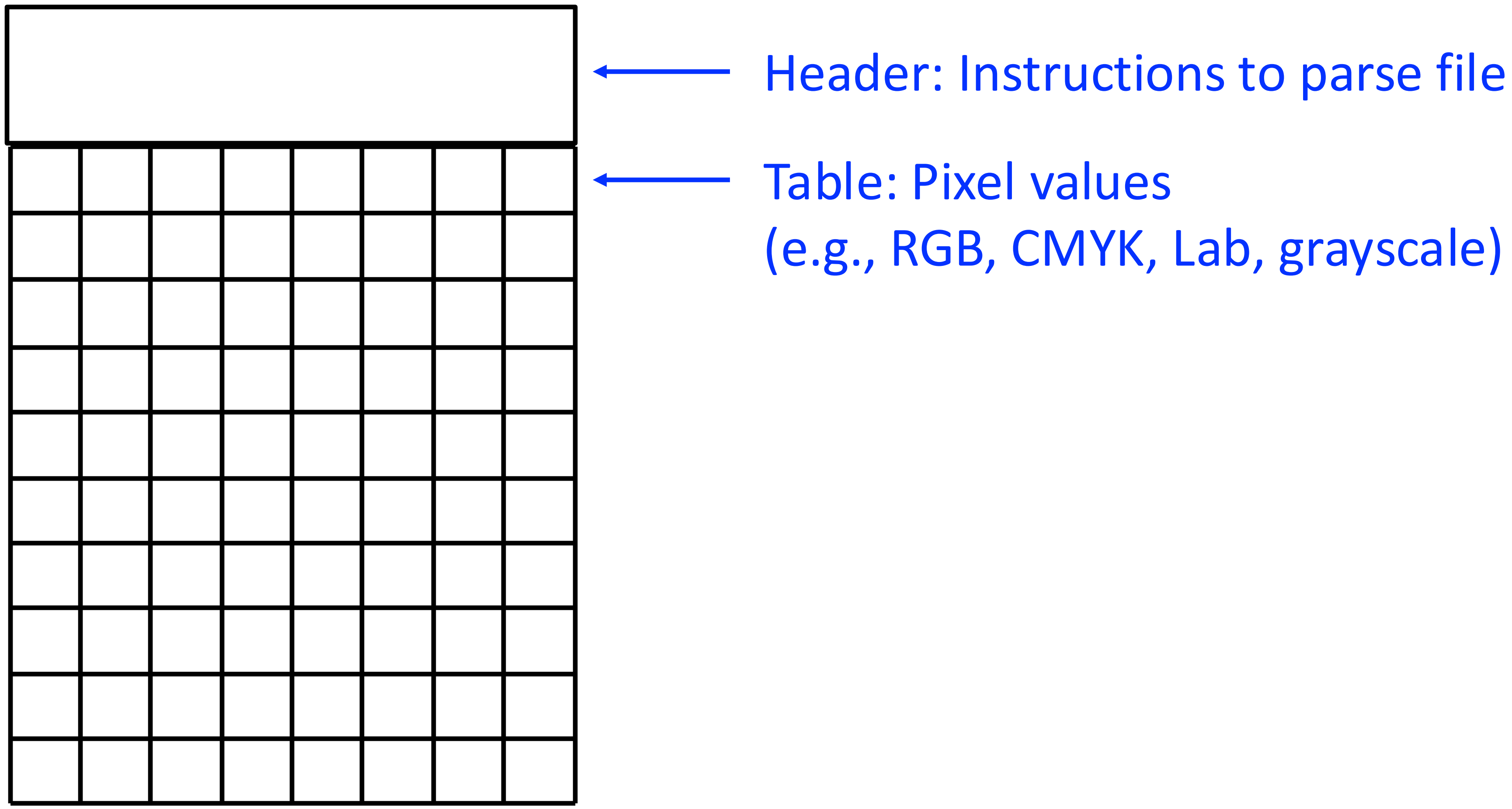


My Focus in My Career

- 2004-2005: Washington University - Ultrasound
- 2005-2007: Raytheon (NPOESS) - Satellite
- 2007-2010: Boulder Imaging - Visible & Infrared
- 2010-2015: Boston University - Microscopy
- 2015-Present: Many more types!

Many Ways to Record Digital Visual Data

e.g., Roughly, can think of file formats as headers followed by pixel values (e.g., jpg, png)



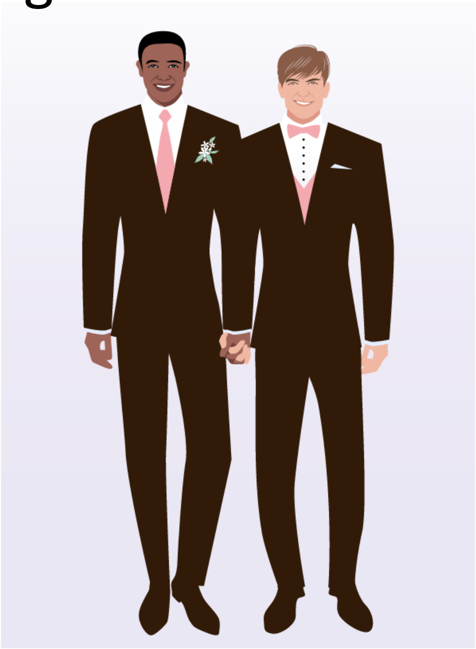
Today’s Topics

- Ways of seeing: image and video acquisition
- Evolution of computer vision (before versus after 2012)
- Fundamentals of a neural network architecture
- Training deep neural networks

Status Quo Until 2012

Algorithm Dataset

Algorithm Dataset



Algorithm Dataset

Algorithm Dataset

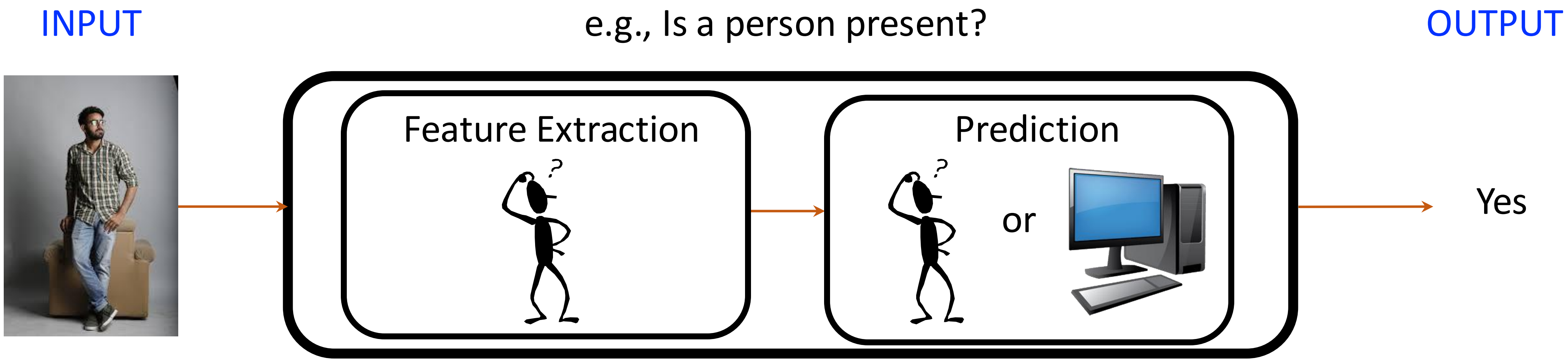
Datasets tended to be relatively small (e.g., 10s or 100s of examples)

Status Quo Until 2012: Datasets

- Authors created datasets either with their cameras, by purchasing datasets from companies, or downloading images from the Internet
- What’s wrong with such approaches?
  - Unable to perform “fair” comparison between algorithms
  - Lacks a community around a shared goal

Status Quo Until 2012: Algorithms

- An engineer manually designs methods to interpret an image



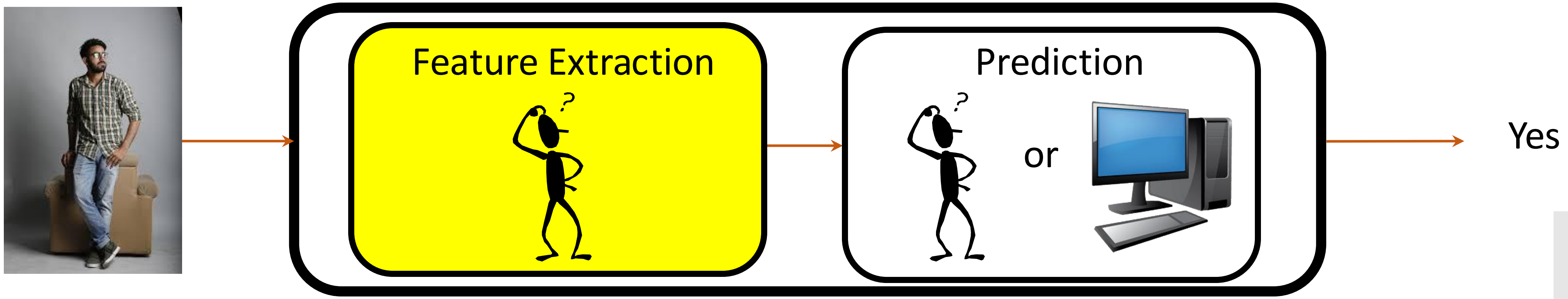
Status Quo Until 2012: Algorithms

- An engineer manually designs methods to interpret an image

INPUT

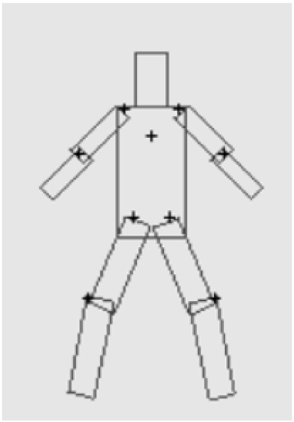
e.g., Is a person present?

OUTPUT



What features would help predict yes/no?

e.g., corners, lines, and model of expected body parts as connected shapes



e.g., Pedro F Felzenszwalb and Daniel P Huttenlocher, IJCV 2004

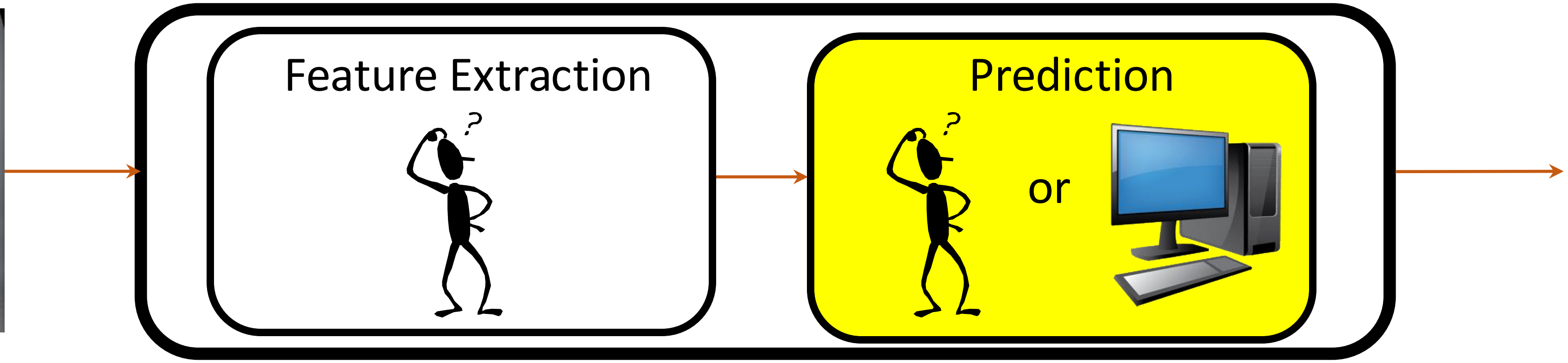
Status Quo Until 2012: Algorithms

- An engineer manually designs methods to interpret an image

INPUT

e.g., Is a person present?

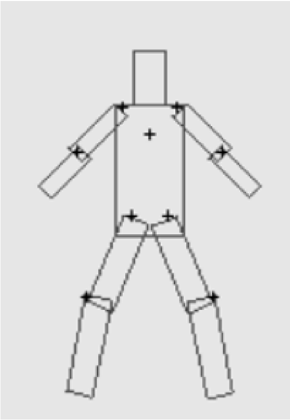
OUTPUT



Yes

What rules should be used to predict yes/no?

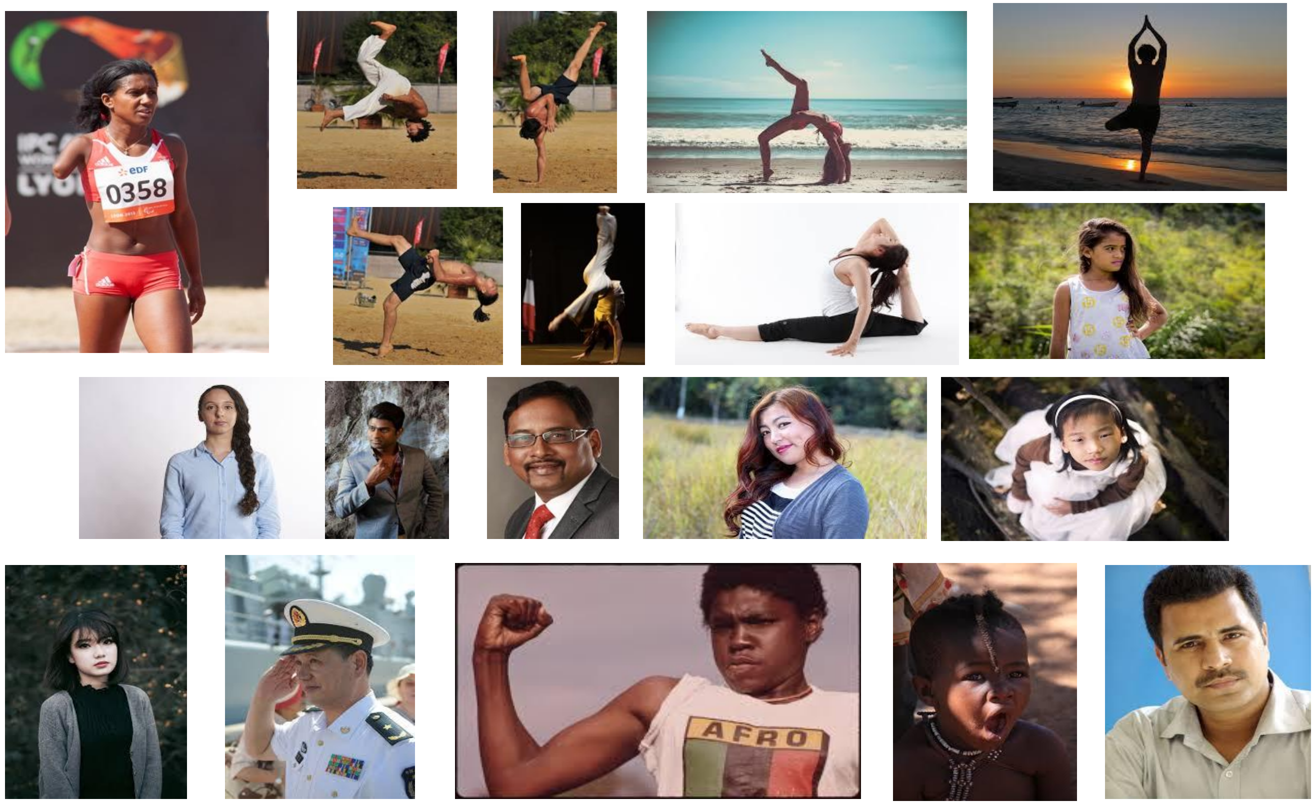
e.g., choose threshold for number of model parts detected or develop machine learning model that predicts from handcrafted features



e.g., Pedro F Felzenszwalb and Daniel P Huttenlocher, IJCV 2004

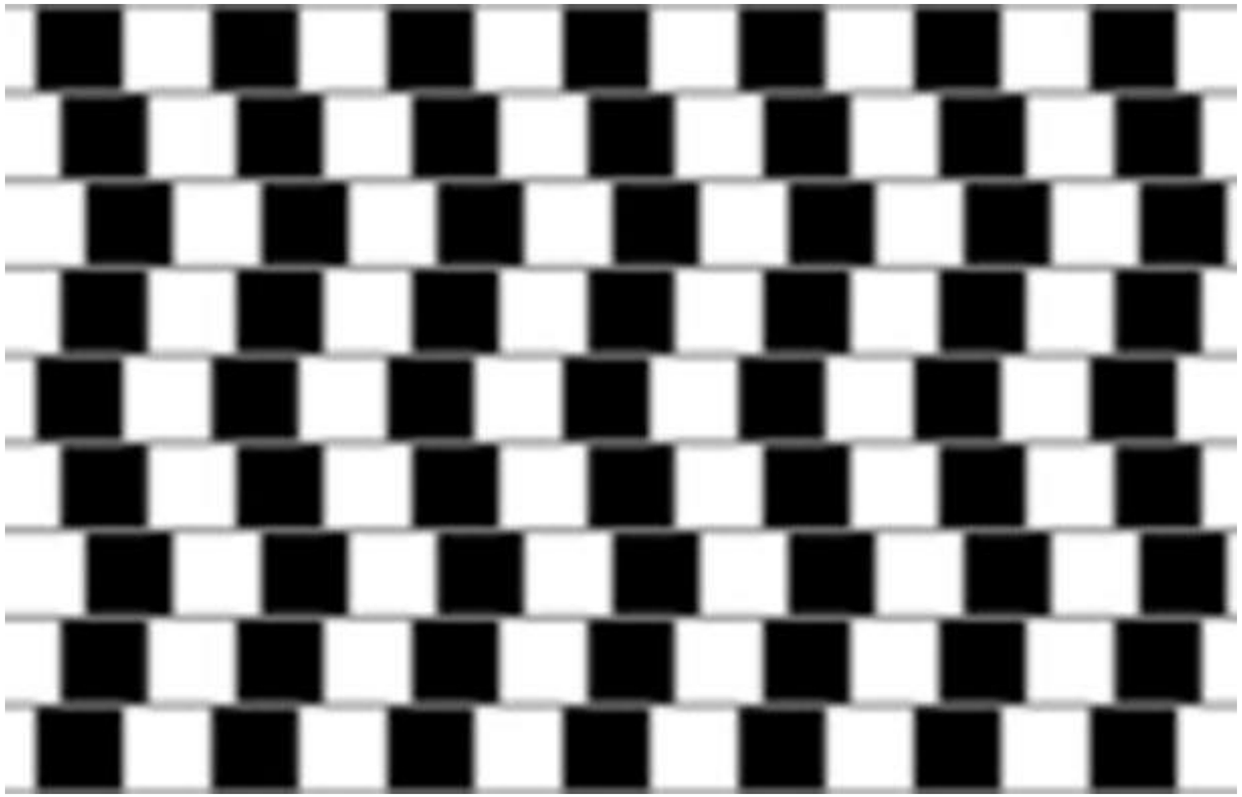
Limitations of Handcrafted Methods

- Challenging for engineers to design effective features (and rules) for ALL examples (for every computer vision problem)!



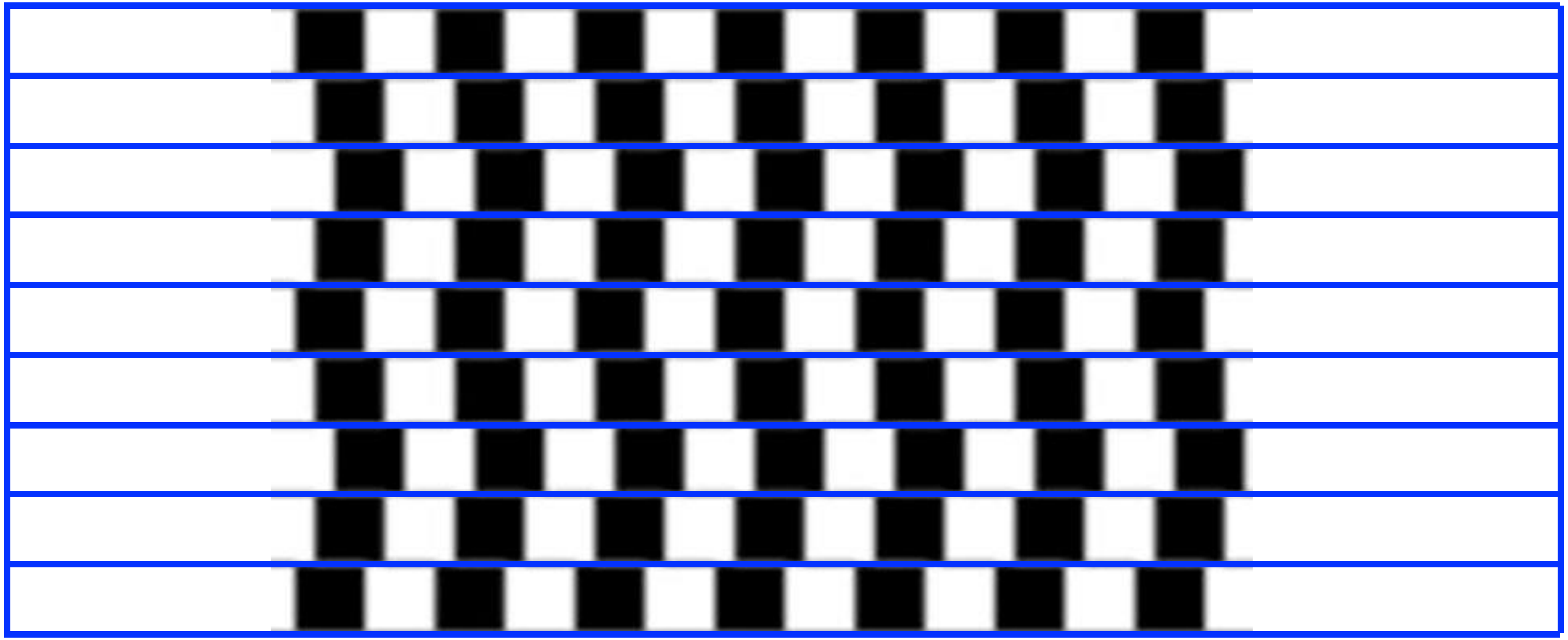
Limitations of Handcrafted Methods

e.g., are these lines parallel?



Limitations of Handcrafted Methods

e.g., are these lines parallel?

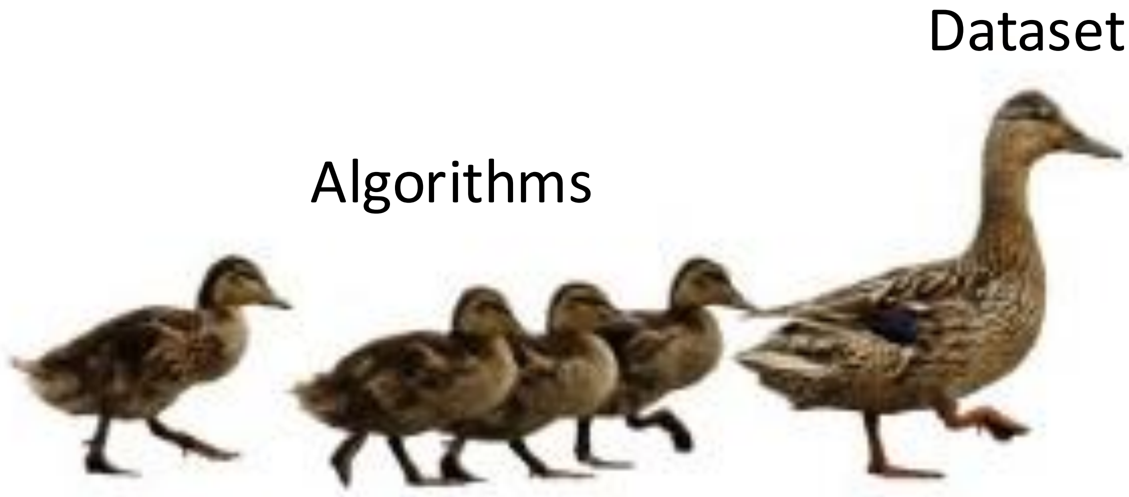


Limitations of Handcrafted Methods

1. It is hard to hand-craft a complete set of methods

2. We, as humans, may not devise the best rules for a machine since our brains (unconsciously) pre-process the data we sense

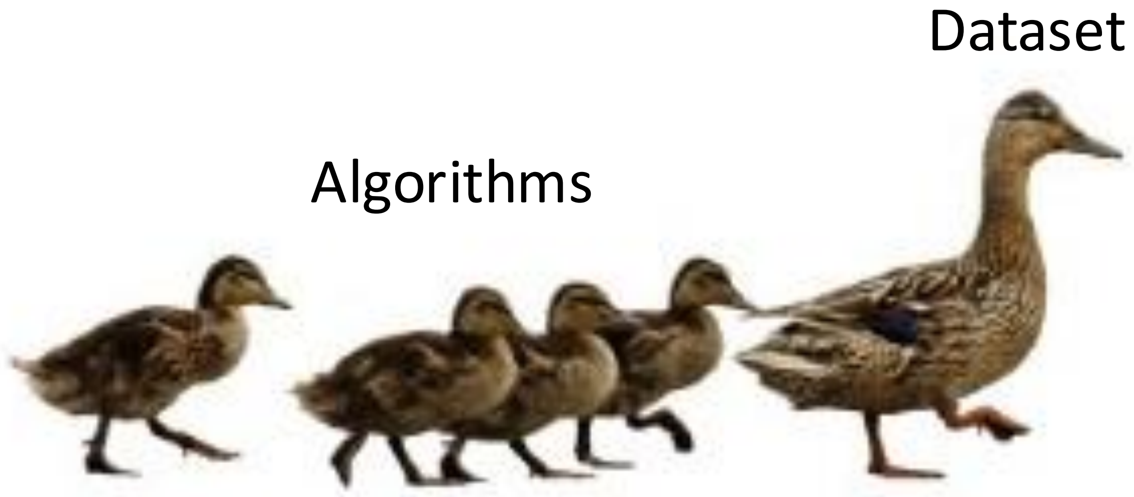
Status Quo Since 2012



Datasets tend to be large (e.g., billions or trillions of examples)

Image Source: http://larryzitnick.org/Talks/CVPR15_Dataset.pptx

Status Quo Since 2012

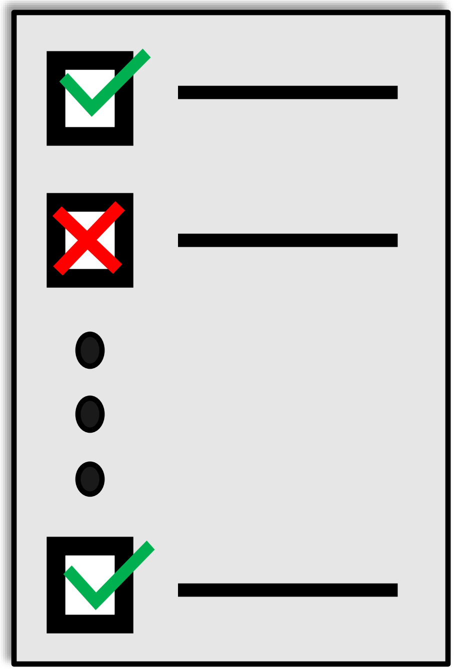


What do you think prompted this shift to large-scale datasets?

Datasets tend to be large (e.g., billions or trillions of examples)

Image Source: http://larryzitnick.org/Talks/CVPR15_Dataset.pptx

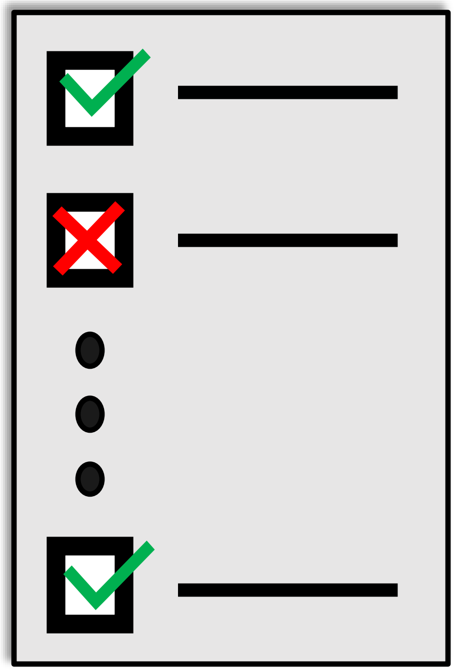
Research Since 2012: Dataset Challenges



Shutterstock

(Analogous to Tests in Schools, After Receiving Lessons)

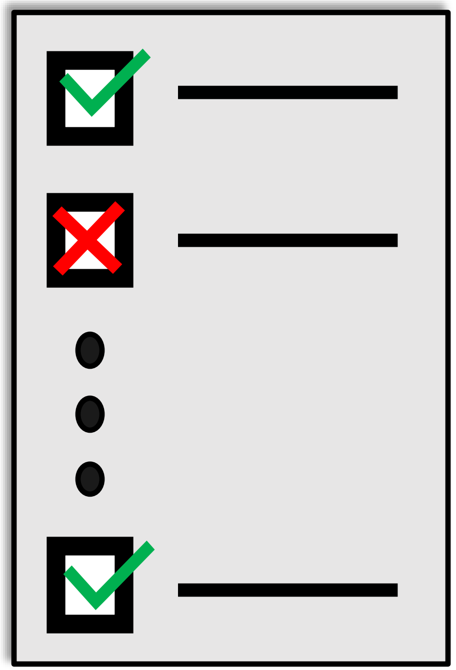
Research Since 2012: Dataset Challenges



Key ingredients:

1. Test examples that includes target results
2. Metric for assessing the similarity between each model prediction and the target result
3. New challenges for the community to tackle, evidenced by dataset analysis and model benchmarking

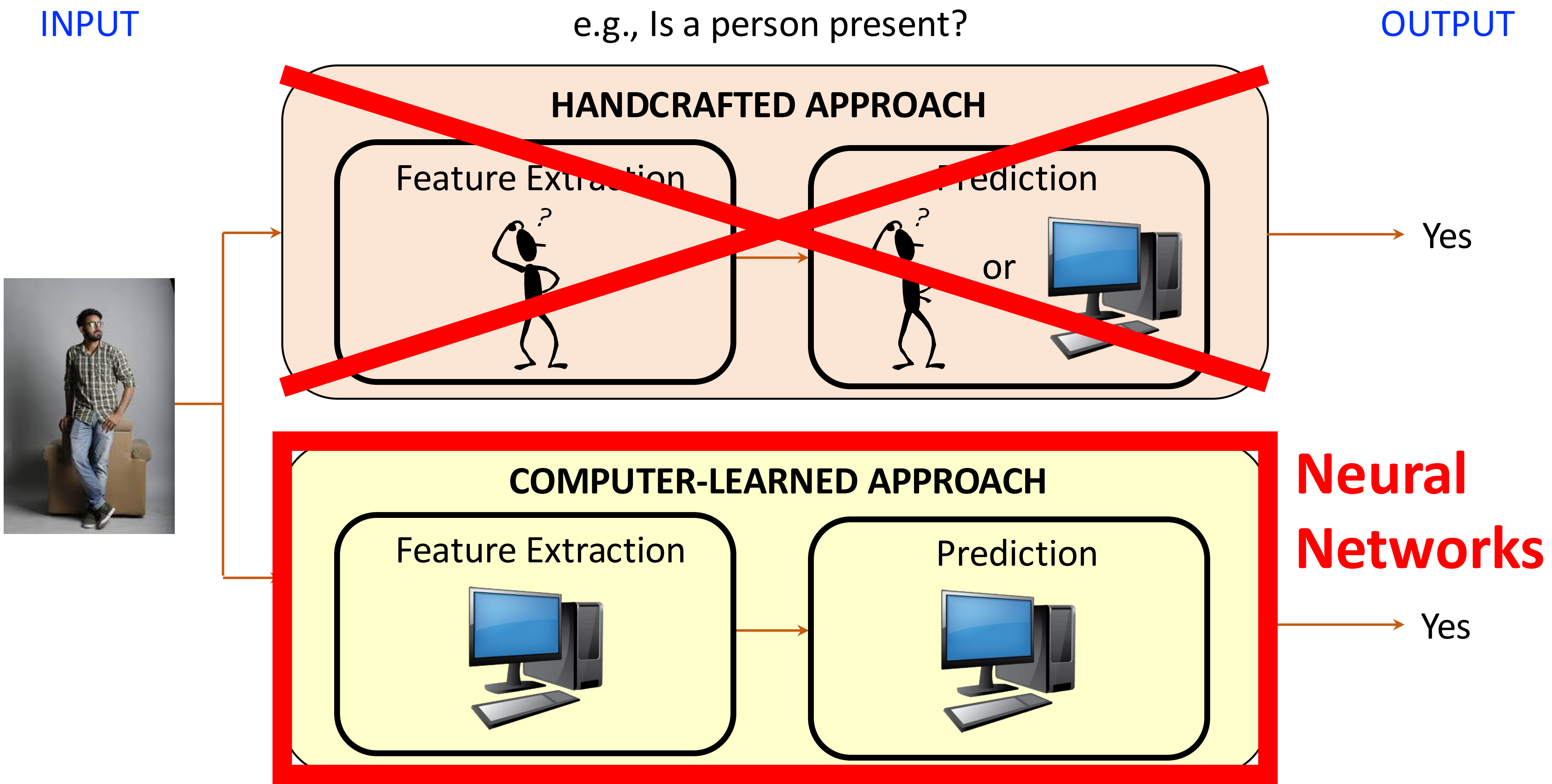
Research Since 2012: Dataset Challenges



Many public dataset challenges and datasets:

- Google Dataset Search
- Kaggle
- Amazon’s AWS datasets
- UC Irvine Machine Learning Repository
- Quora.com
- Reddit
- Dataportals.org
- Opendatamonitor.eu
- Quandl.com

Research Since 2012: Algorithms



Today’s Topics

- Ways of seeing: image and video acquisition
- Evolution of computer vision (before versus after 2012)
- Fundamentals of a neural network architecture
- Training deep neural networks

Inspiration: Animal's Computing Machinery

Neuron

- basic unit in the nervous system for receiving, processing, and transmitting information; e.g., messages such as…

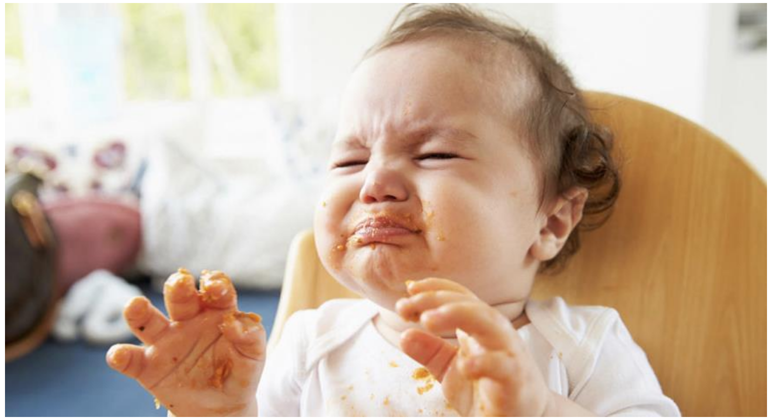
"hot"

https://www.clipart.email/clipart/dont-touch-hot-stove-clipart-73647.html

"loud"

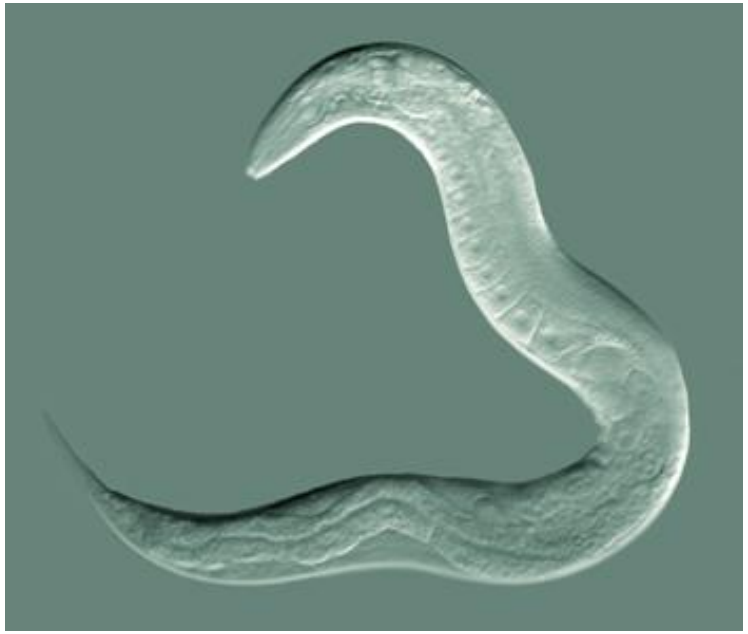
https://kisselpaso.com/if-the-sun-city-music-fest-gets-too-loud-there-is-a-phone-number-you-can-call-to-complain/

"spicy"



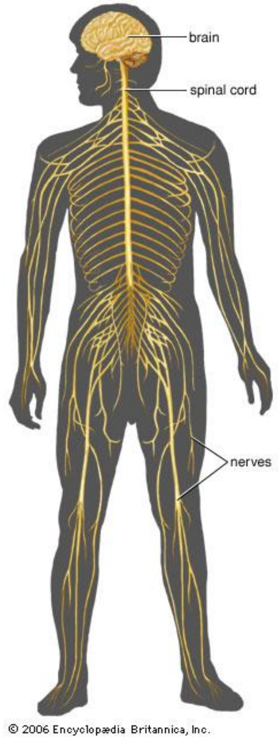
https://www.babycenter.com/404_when-can-my-baby-eat-spicy-foods_1368539.bc

Inspiration: Animal's Computing Machinery



https://en.wikipedia.org/wiki/Nematode#/media/File:CelegansGoldsteinLabUNC.jpg

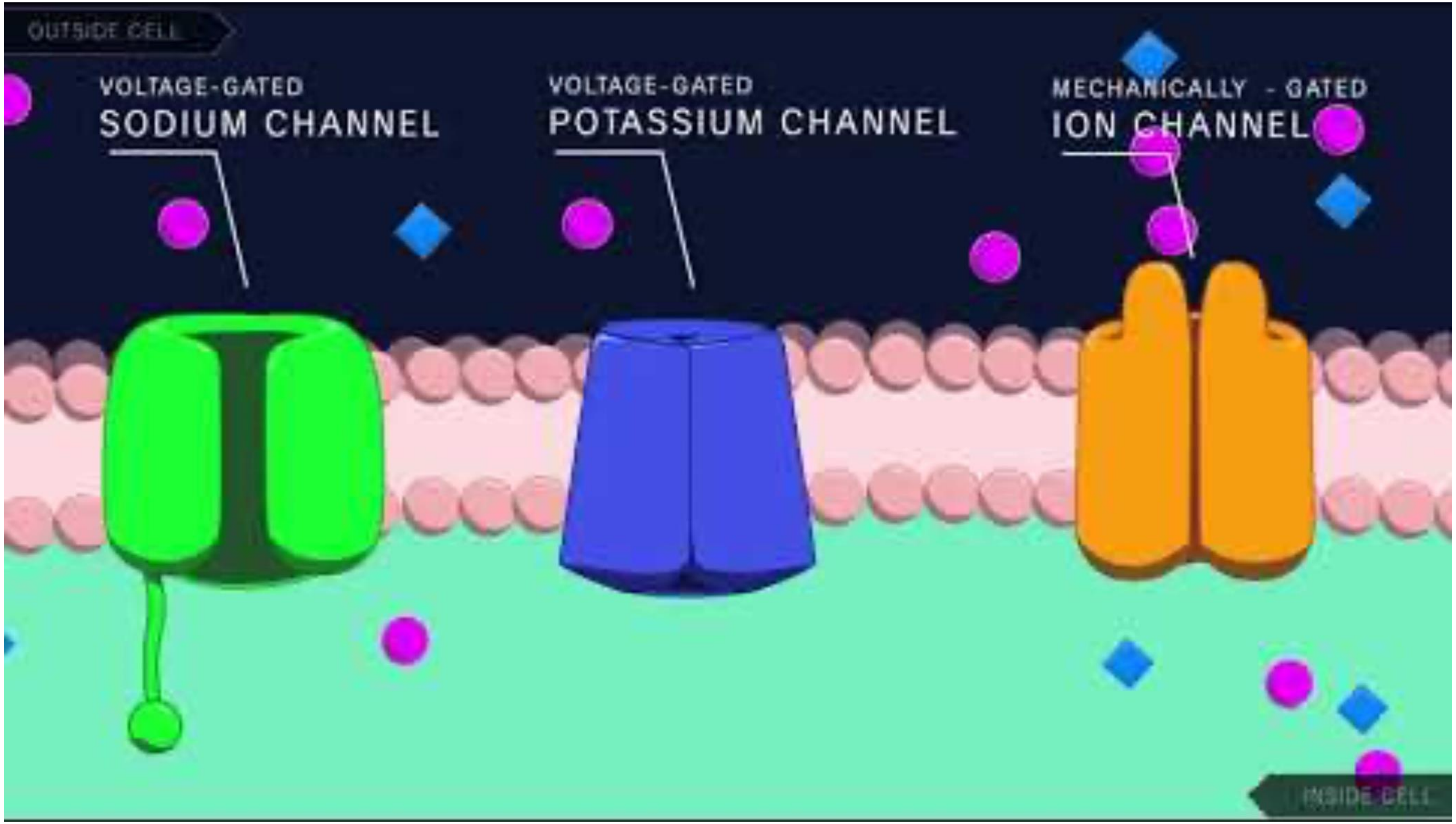
Nematode worm: 302 neurons



https://www.britannica.com/science/human-nervous-system

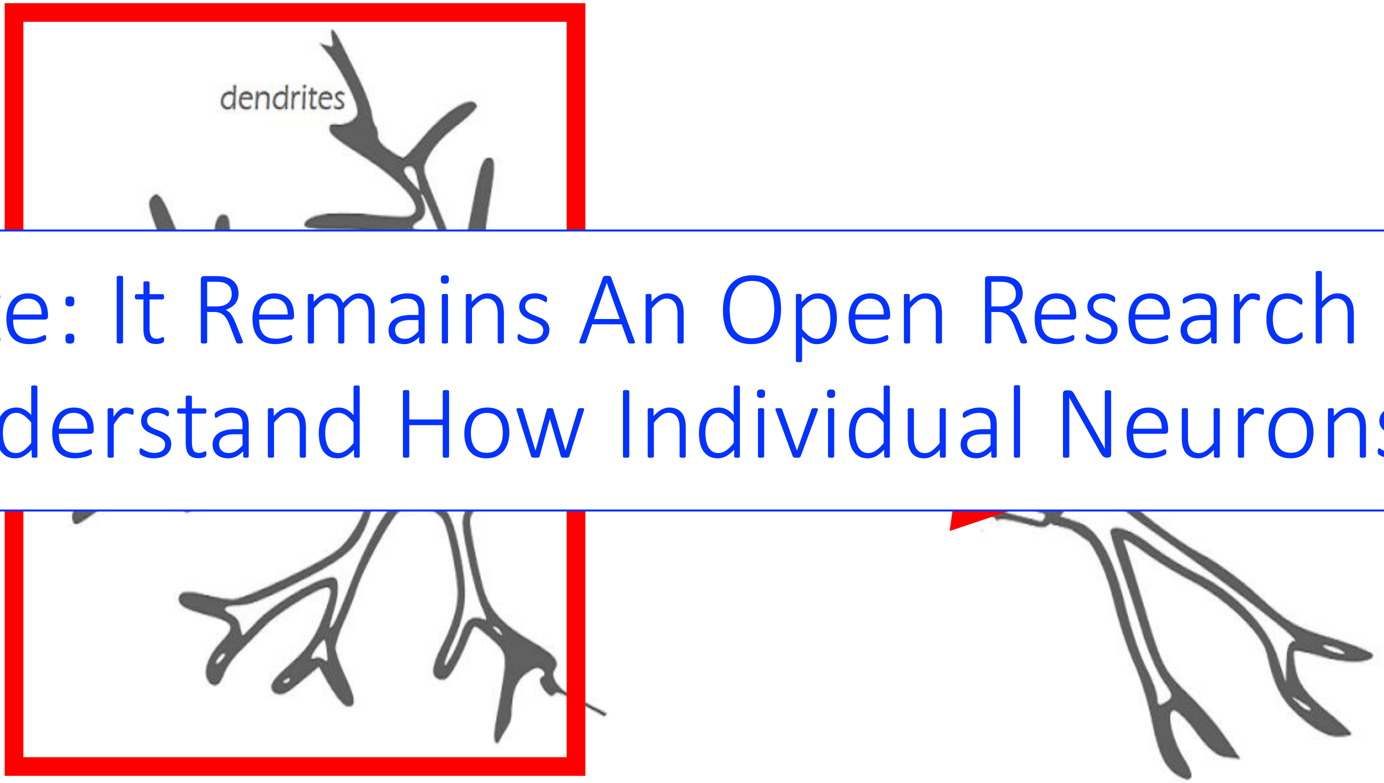
Human: ~100 billion neurons in a brain
(& 100+ trillions connections/synapses)

Inspiration: Animal’s Computing Machinery



https://www.youtube.com/watch?v=oa6rvUJlg7o

Inspiration: Basic Understanding of Neurons

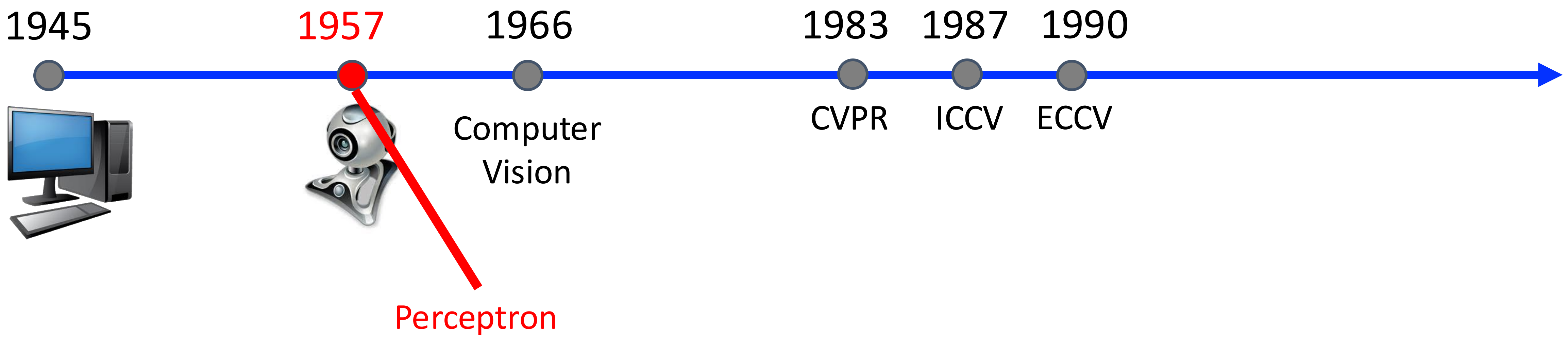


Sidenote: It Remains An Open Research Problem to Understand How Individual Neurons Work

- When the input signals exceed a certain threshold within a short period of time, a neuron "fires"
- Neuron "firing" is an "all-or-none" process, where either a signal is sent or nothing happens

Image Source: https://becominghuman.ai/introduction-to-neural-networks-bd042ebf2653

Origins of Neural Networks: Artificial Neurons



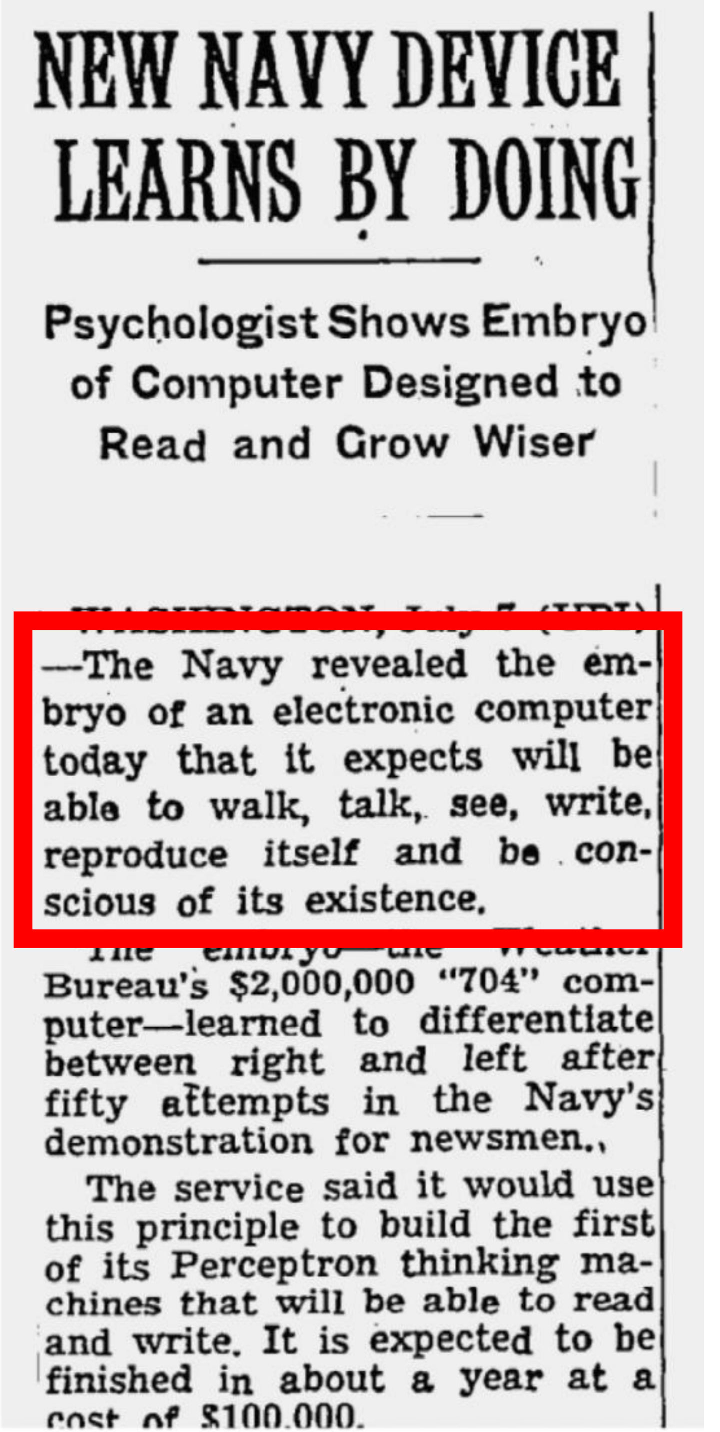
Perceptron: Innovator and Vision

Frank Rosenblatt
(Psychologist)

https://en.wikipedia.org/wiki/Frank_Rosenblatt

New York Times article, July 8, 1958 :

https://www.nytimes.com/1958/07/08/archives/new-navy-device-learns-by-doing-psychologist-shows-embryo-of.html



NEW NAVY DEVICE LEARNS BY DOING

Psychologist Shows Embryo of Computer Designed to Read and Grow Wiser

WASHINGTON, July 7 (UPI) —The Navy revealed the embryo of an electronic computer today that it expects will be able to walk, talk, see, write, reproduce itself and be conscious of its existence.

The embryo—the Weather Bureau's $2,000,000 "704" computer—learned to differentiate between right and left after fifty attempts in the Navy's demonstration for newsmen.

The service said it would use this principle to build the first of its Perceptron thinking machines that will be able to read and write. It is expected to be finished in about a year at a cost of $100,000.

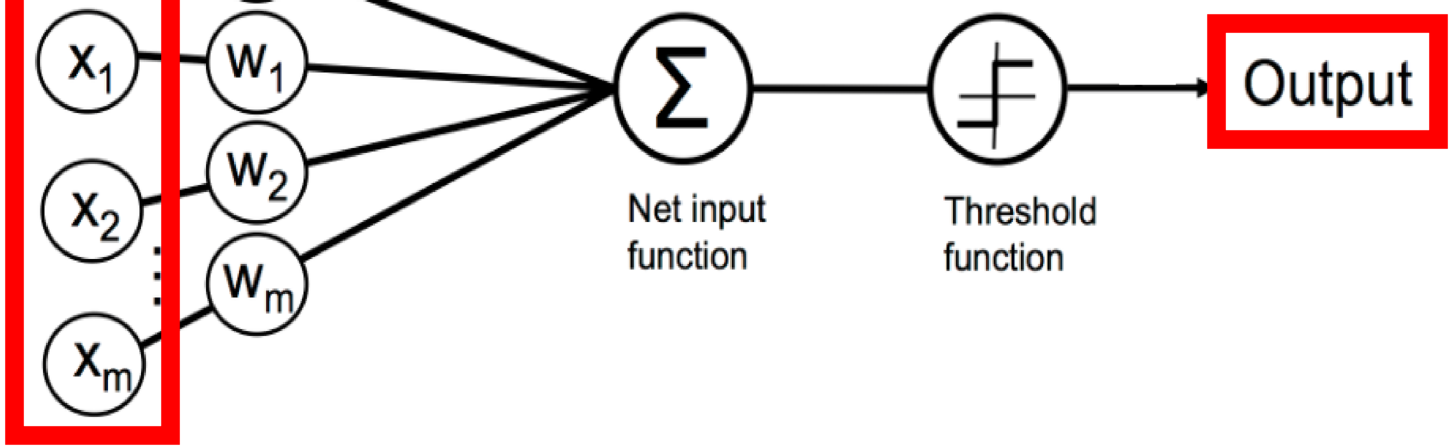
Perceptron (Artificial Neuron)

- weights (W) are learned
- outputs 1 or 0 (mimics neurons by “firing” only when sum exceeds threshold)

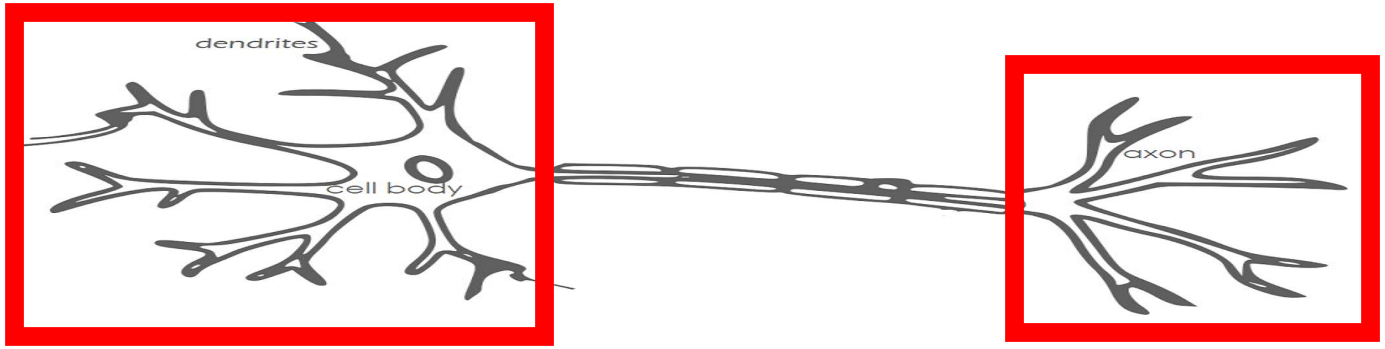
“Input signals”

“Output signal”

Artificial Neuron:



Biological Neuron:



Python Machine Learning; Raschka & Mirjalili

Image Source: https://becominghuman.ai/introduction-to-neural-networks-bd042ebf2653

Fall of Perceptron (Artificial Neuron)

XOR = “Exclusive Or”
- Input: two binary values x_1 and x_2
- Output:
  - 1, when exactly one input equals 1
  - 0, otherwise

x_1	x_2	x_1 XOR x_2
0	0	?
0	1	?
1	0	?
1	1	?

Marvin Minsky and Seymore Papert, Perceptrons, MIT Press, 1969

Fall of Perceptron (Artificial Neuron)

XOR = "Exclusive Or"
- Input: two binary values x_1 and x_2
- Output:
  - 1, when exactly one input equals 1
  - 0, otherwise

x_1	x_2	x_1 XOR x_2
0	0	?
0	1	?
1	0	?
1	1	?

Marvin Minsky and Seymore Papert, Perceptrons, MIT Press, 1969

Fall of Perceptron (Artificial Neuron)

XOR = “Exclusive Or”
- Input: two binary values x_1 and x_2
- Output:
  - 1, when exactly one input equals 1
  - 0, otherwise

x_1	x_2	x_1 XOR x_2
0	0	0
0	1	?
1	0	?
1	1	?

Marvin Minsky and Seymore Papert, Perceptrons, MIT Press, 1969

Fall of Perceptron (Artificial Neuron)

XOR = "Exclusive Or"

- Input: two binary values x_1 and x_2
- Output:
  - 1, when exactly one input equals 1
  - 0, otherwise

x_1	x_2	x_1 XOR x_2
0	0	0
0	1	1
1	0	?
1	1	?

Marvin Minsky and Seymore Papert, Perceptrons, MIT Press, 1969

Fall of Perceptron (Artificial Neuron)

XOR = “Exclusive Or”
- Input: two binary values x_1 and x_2
- Output:
  - 1, when exactly one input equals 1
  - 0, otherwise

x_1	x_2	x_1 XOR x_2
0	0	0
0	1	1
1	0	1
1	1	?

Marvin Minsky and Seymore Papert, Perceptrons, MIT Press, 1969

Fall of Perceptron (Artificial Neuron)

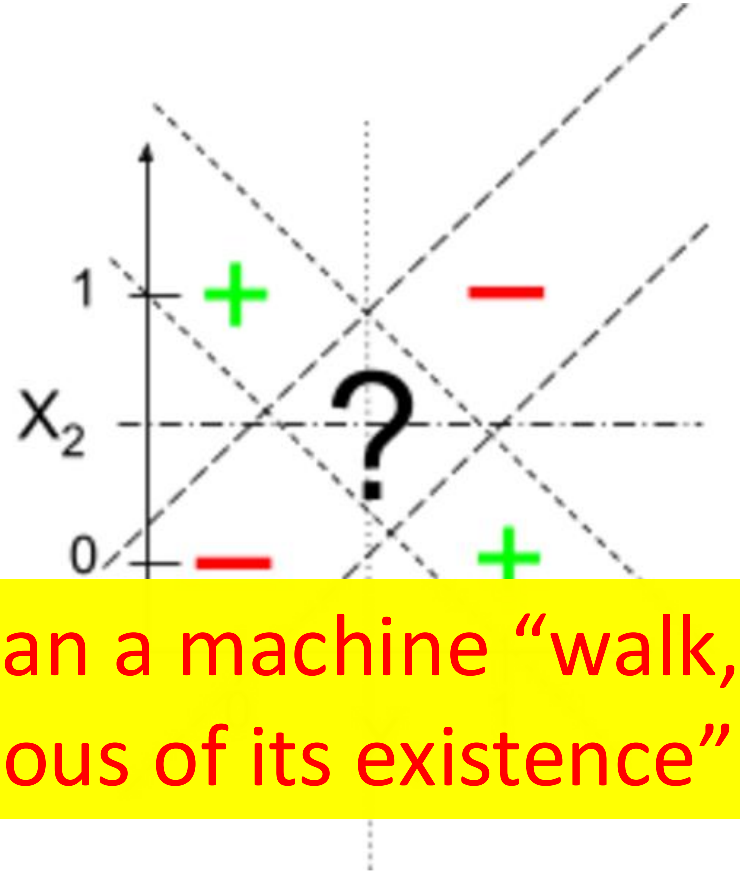
XOR = “Exclusive Or”
- Input: two binary values x_1 and x_2
- Output:
    - 1, when exactly one input equals 1
    - 0, otherwise

x_1	x_2	x_1 XOR x_2
0	0	0
0	1	1
1	0	1
1	1	0

Marvin Minsky and Seymore Papert, Perceptrons, MIT Press, 1969

Fall of Perceptron (Artificial Neuron)

A Perceptron cannot solve XOR problem and so separate 1s from 0s (it's a linear function):



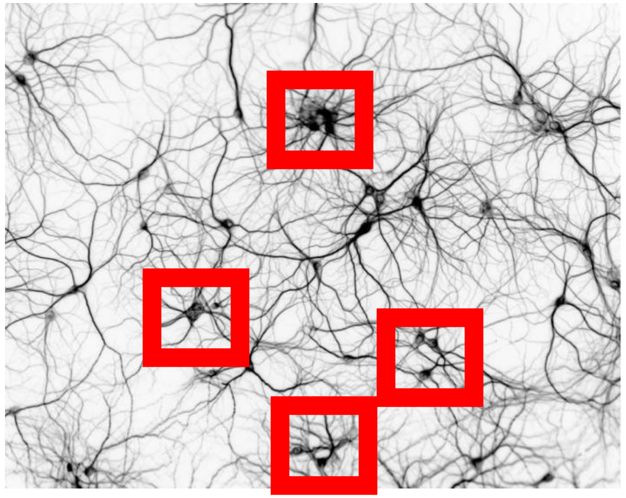
x_1	x_2	x_1 XOR x_2
0	0	0
0	1	1
1	0	1
1	1	0

How can a machine "walk, talk, see, write, reproduce itself and be conscious of its existence" when it can't solve the XOR problem?

Marvin Minsky and Seymore Papert, Perceptrons, MIT Press, 1969

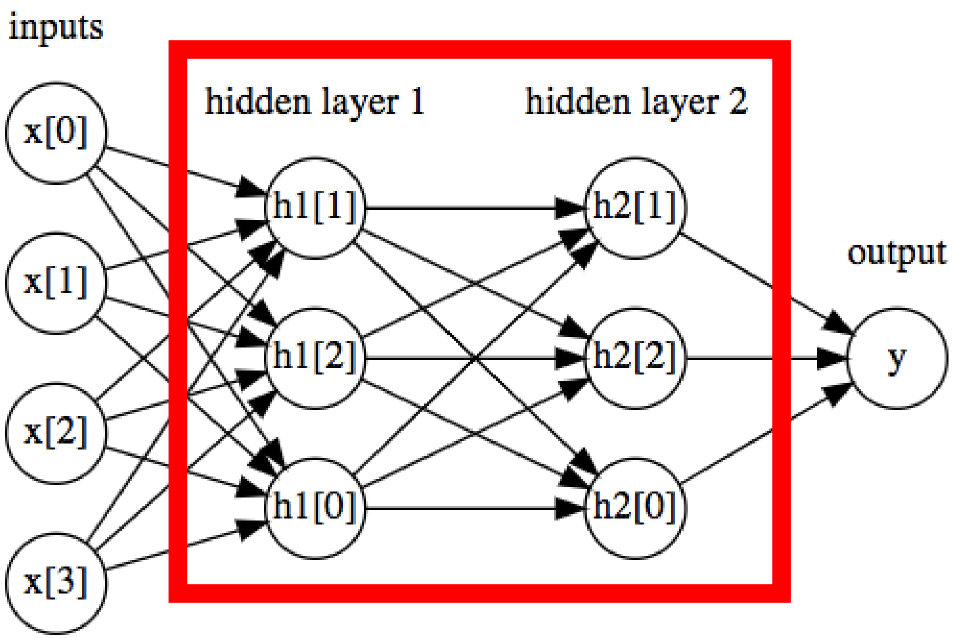
Idea: Use Connected Neurons (i.e., Neural Networks) to Transform Input into Features Useful for Prediction

Biological Neural Network:



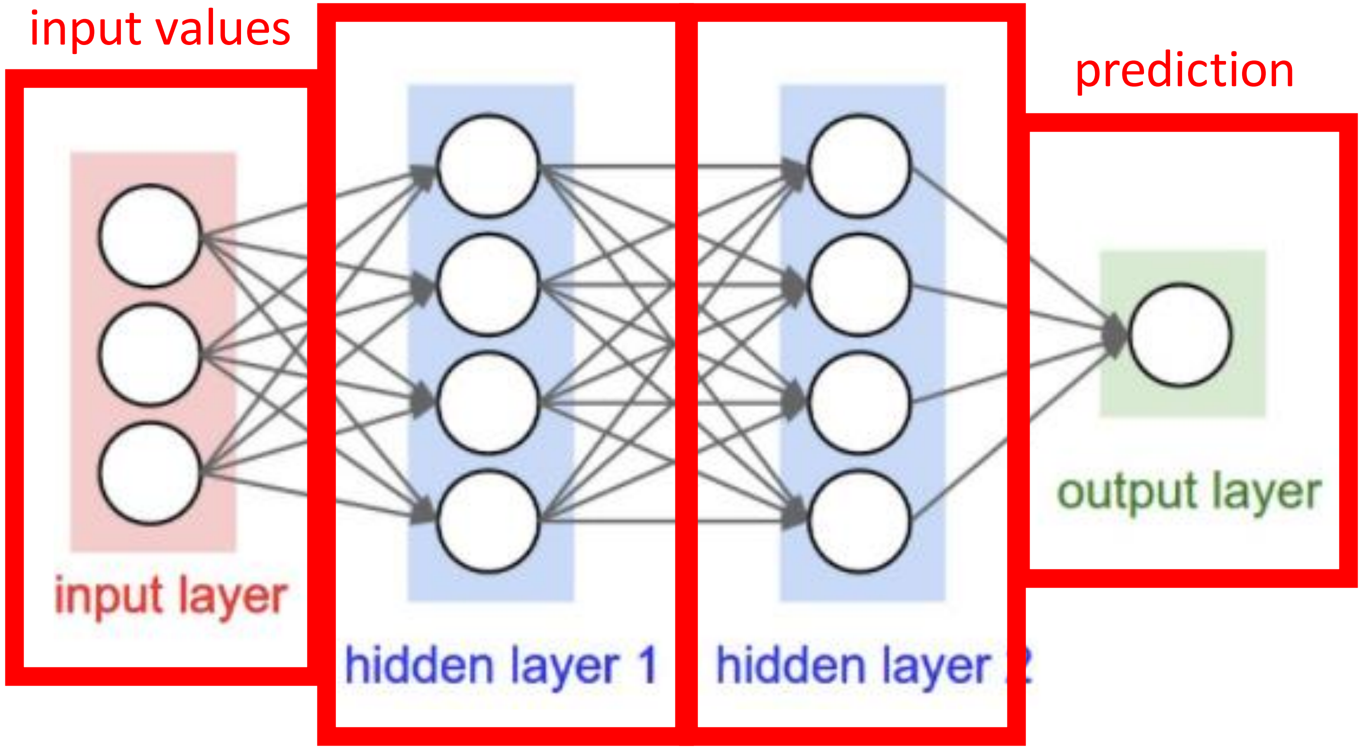
http://www.rzagabe.com/2014/11/03/an-introduction-to-artificial-neural-networks.html

Artificial Neural Network:



https://github.com/amueller/introduction_to_ml_with_python/blob/master/02-supervised-learning.ipynb

Neural Network

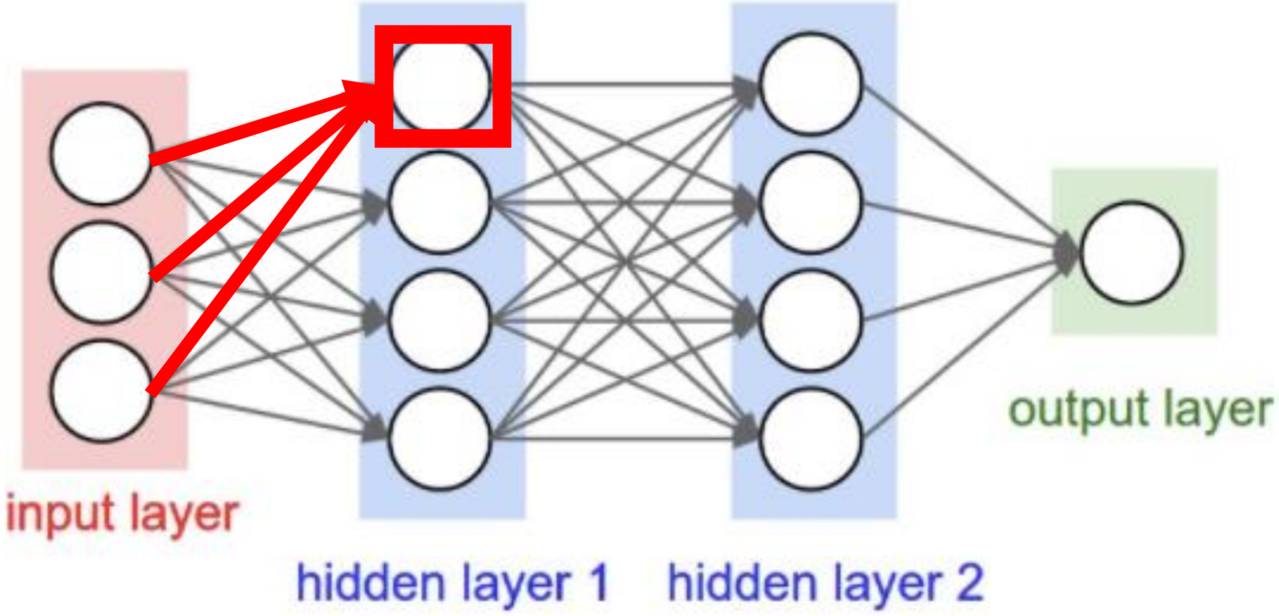


each "hidden layer" uses outputs of units (i.e., neurons) and provides them as inputs to other units (i.e., neurons)

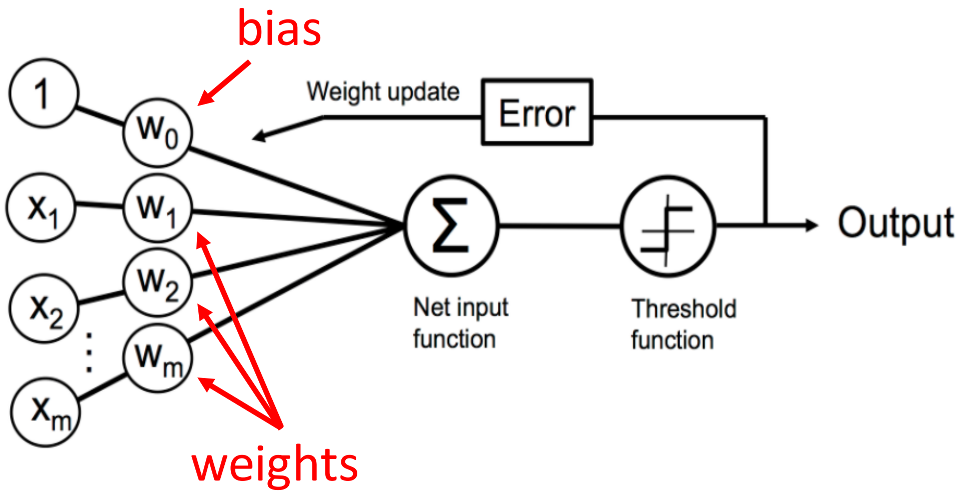
This is a 3-layer neural network (i.e., count number of hidden layers plus output layer)

http://cs231n.github.io/neural-networks-1/

Neural Network



- How does this relate to a perceptron?

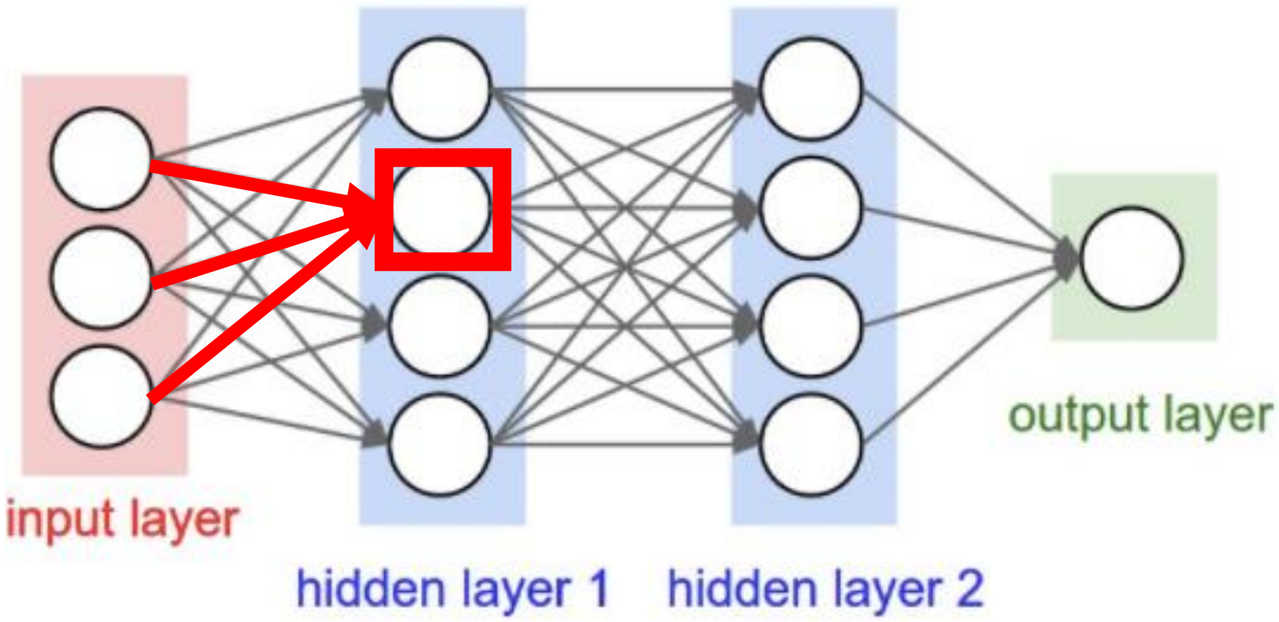


- Unit: computes a weighted sum and applies an activation function

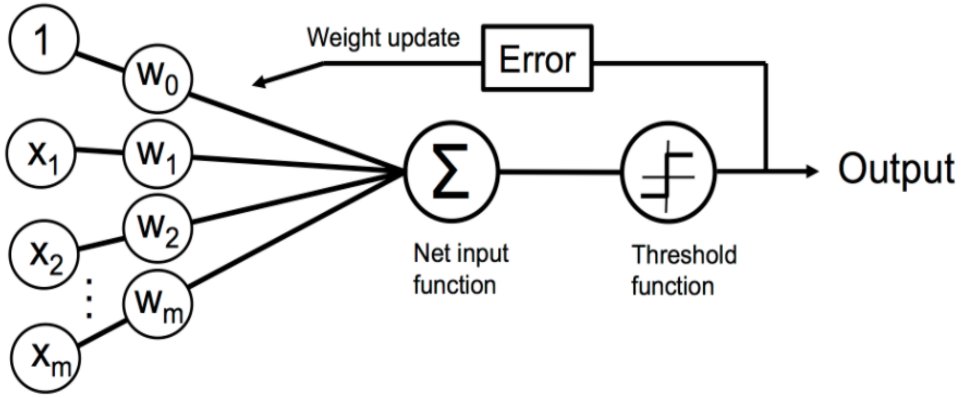
Python Machine Learning; Raschka & Mirjalili

http://cs231n.github.io/neural-networks-1/

Neural Network



- How does this relate to a perceptron?

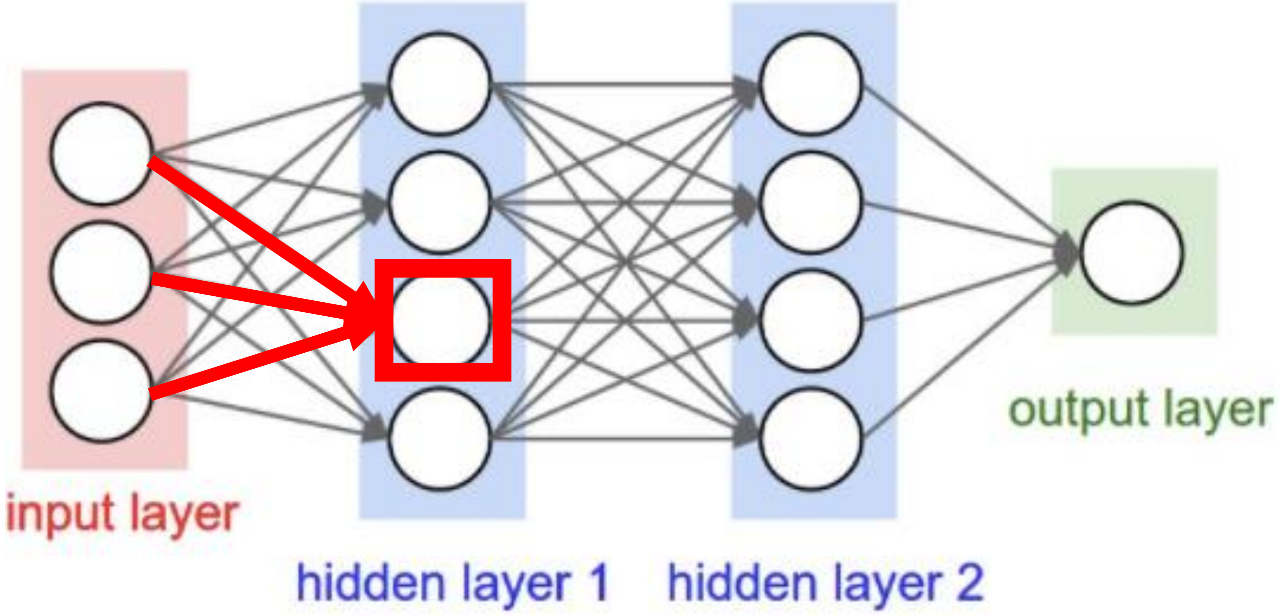


- Unit: computes a weighted sum and applies an activation function

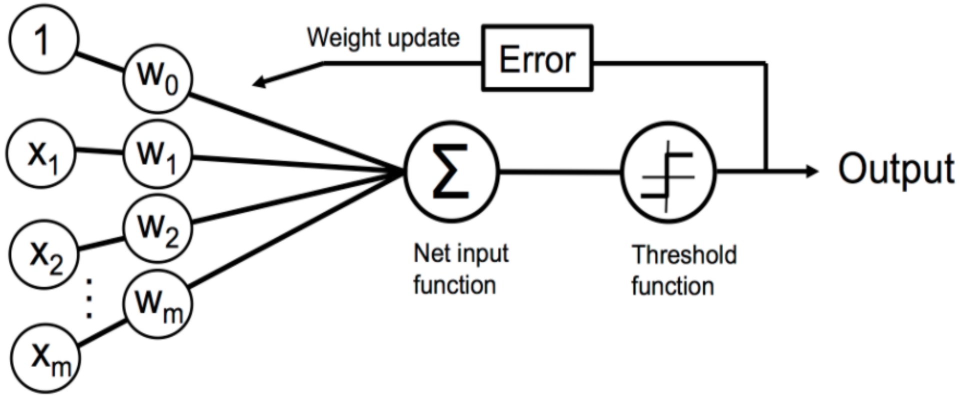
Python Machine Learning; Raschka & Mirjalili

http://cs231n.github.io/neural-networks-1/

Neural Network



- How does this relate to a perceptron?

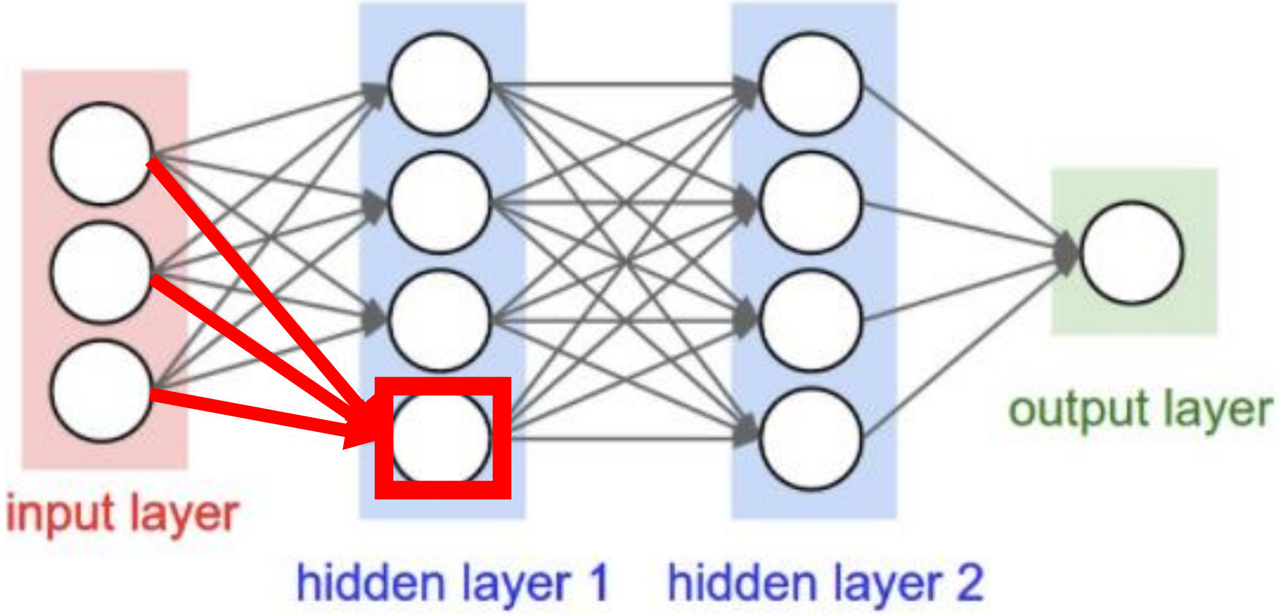


- Unit: computes a weighted sum and applies an activation function

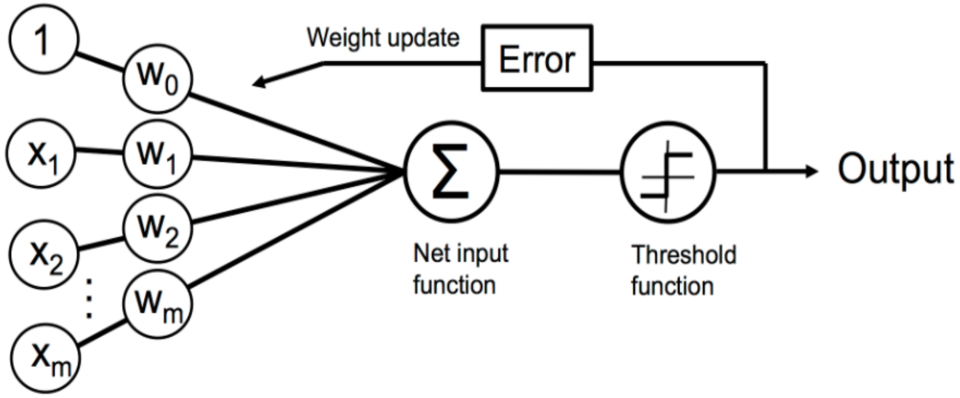
Python Machine Learning; Raschka & Mirjalili

http://cs231n.github.io/neural-networks-1/

Neural Network



- How does this relate to a perceptron?

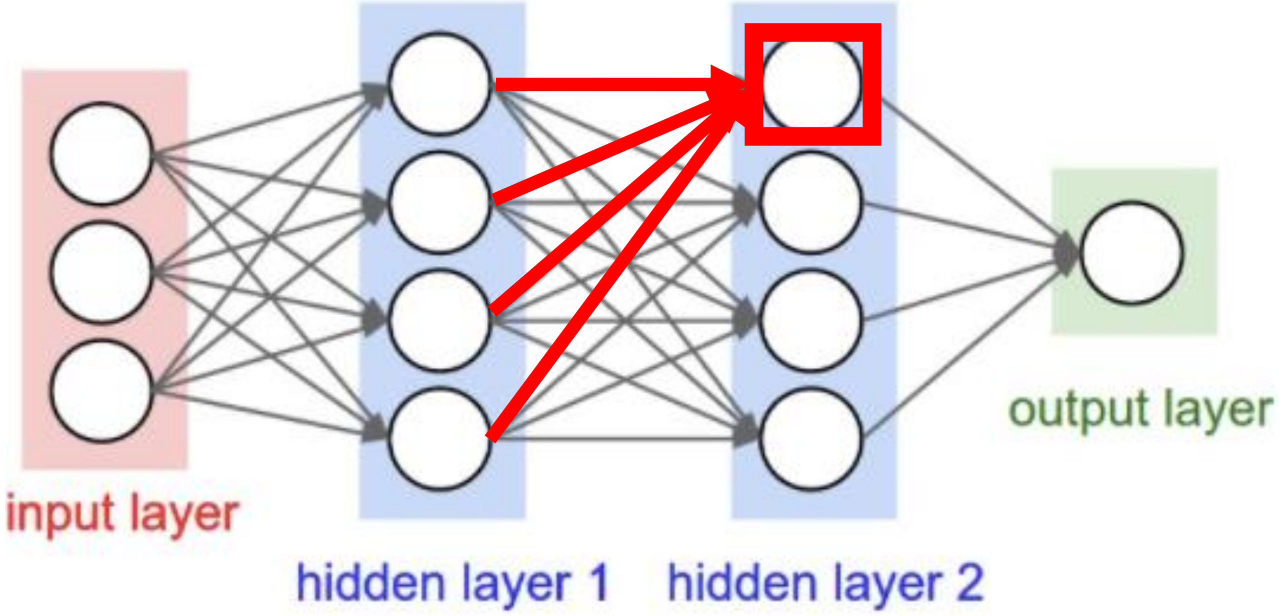


- Unit: computes a weighted sum and applies an activation function

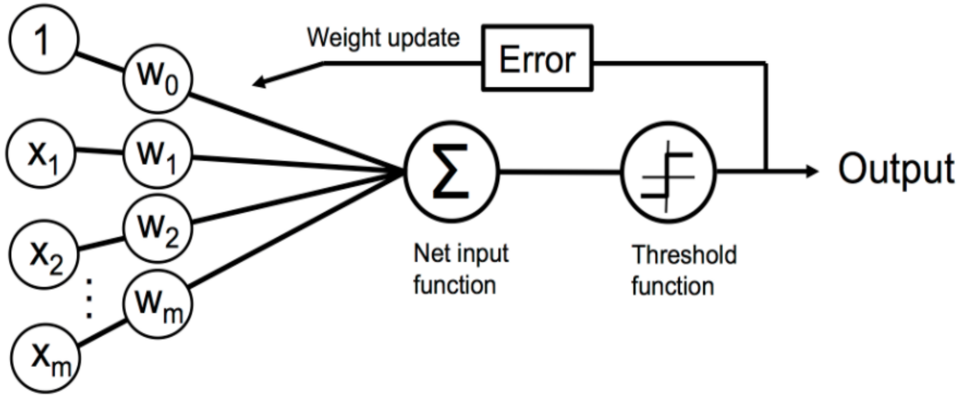
Python Machine Learning; Raschka & Mirjalili

http://cs231n.github.io/neural-networks-1/

Neural Network



- How does this relate to a perceptron?

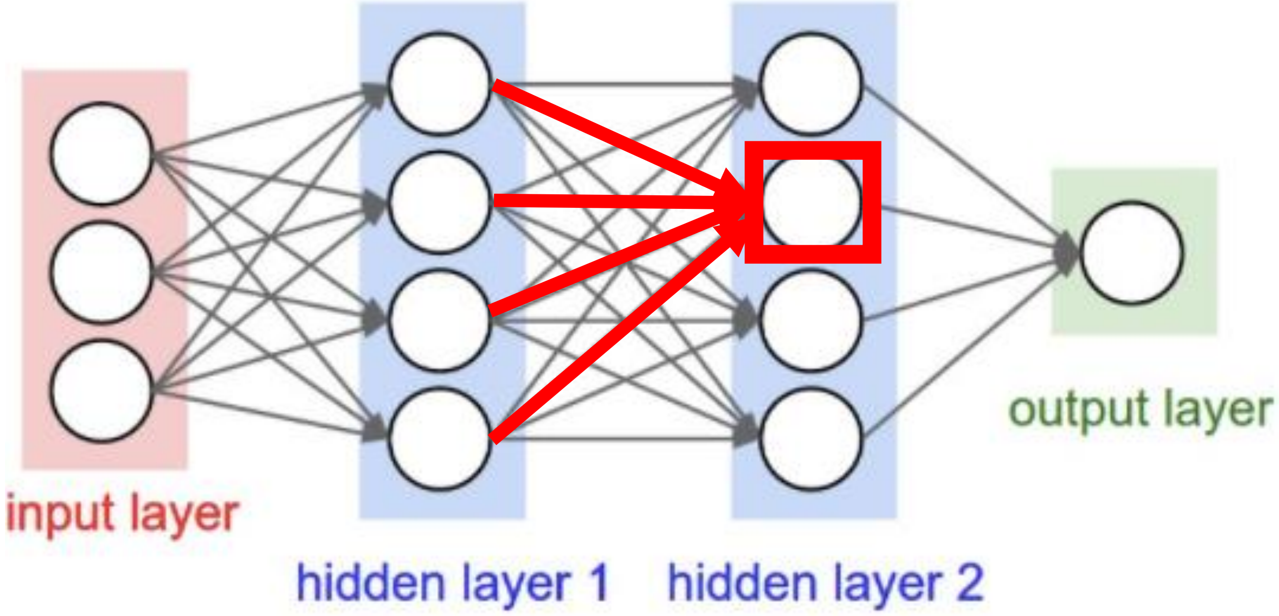


- Unit: computes a weighted sum and applies an activation function

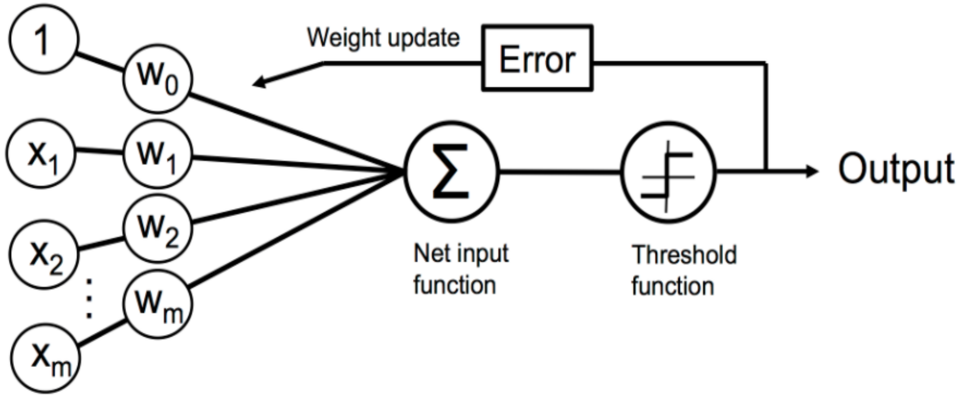
Python Machine Learning; Raschka & Mirjalili

http://cs231n.github.io/neural-networks-1/

Neural Network



- How does this relate to a perceptron?

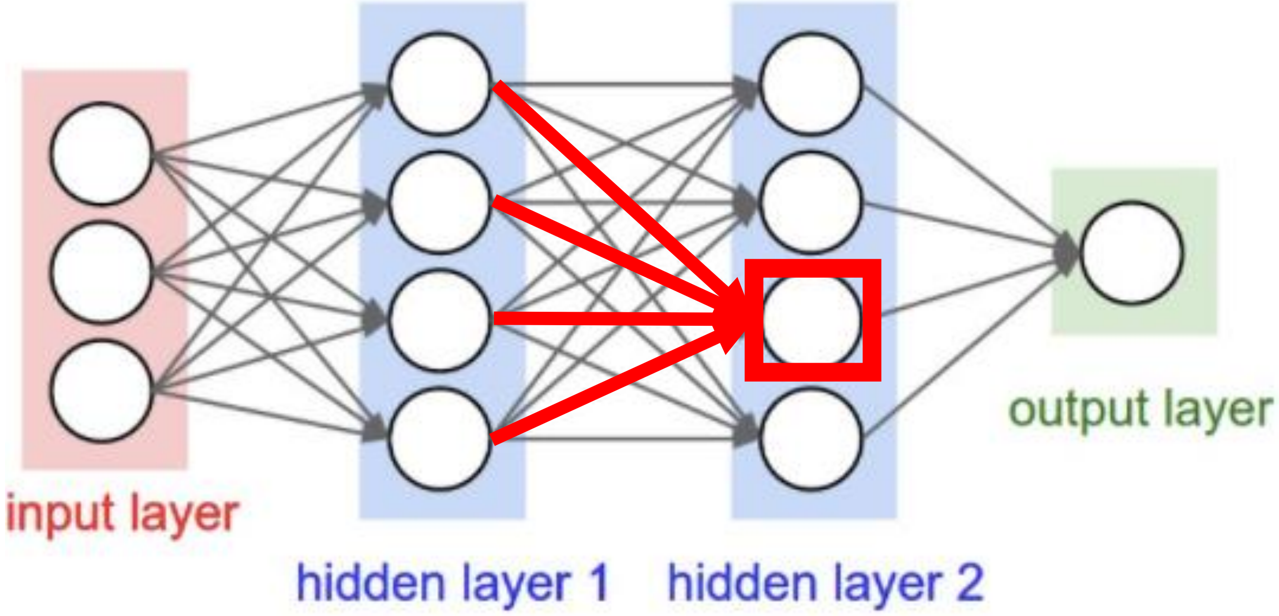


- Unit: computes a weighted sum and applies an activation function

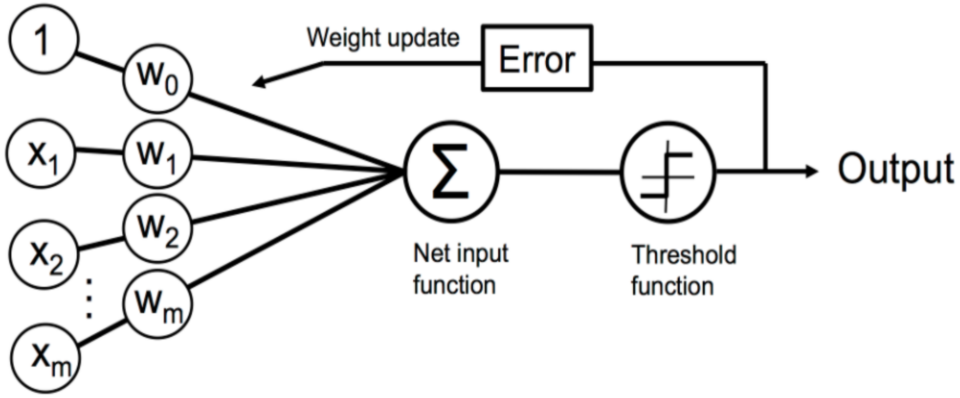
Python Machine Learning; Raschka & Mirjalili

http://cs231n.github.io/neural-networks-1/

Neural Network



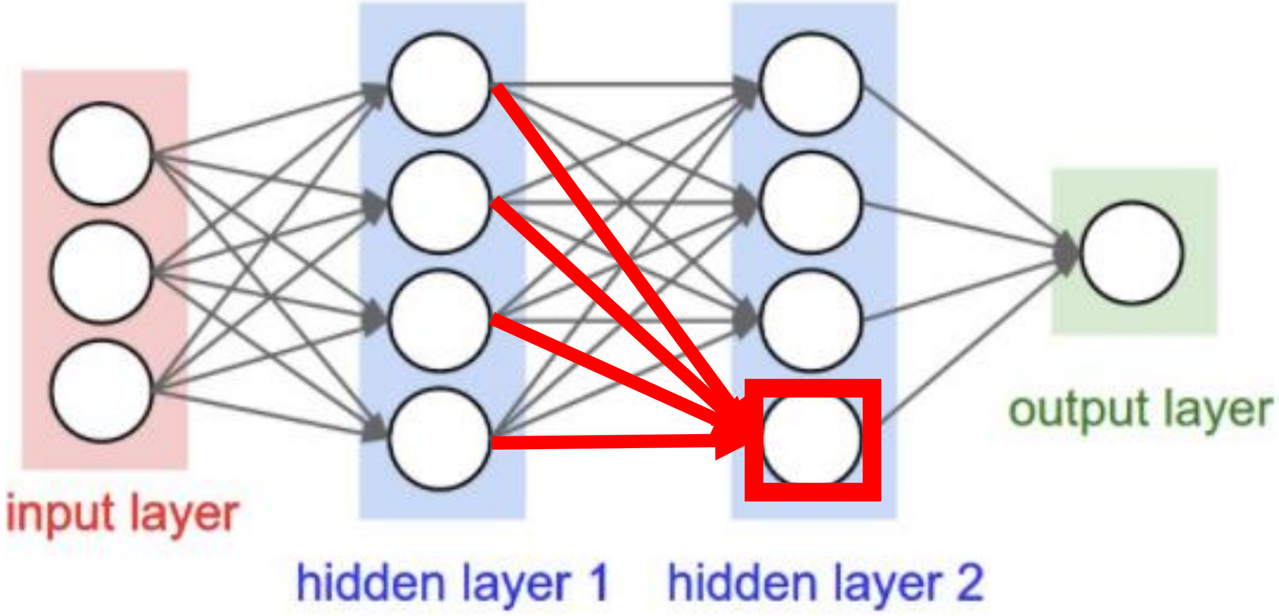
- How does this relate to a perceptron?



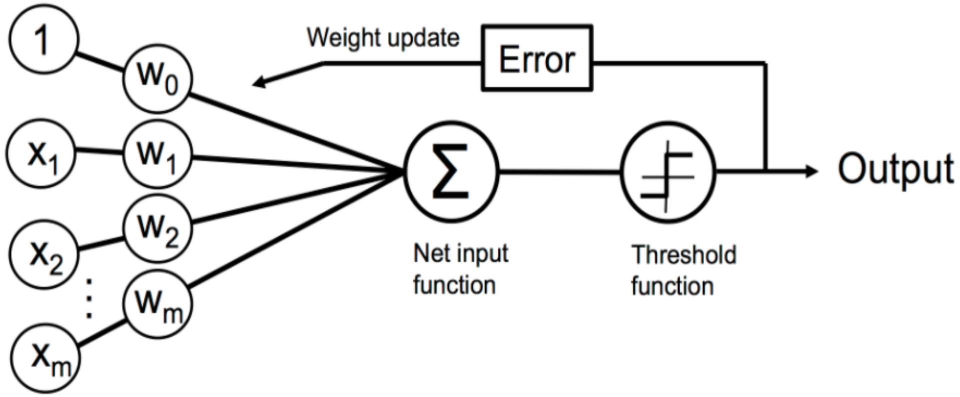
- Unit: computes a weighted sum and applies an activation function

Python Machine Learning; Raschka & Mirjalili
http://cs231n.github.io/neural-networks-1/

Neural Network



- How does this relate to a perceptron?

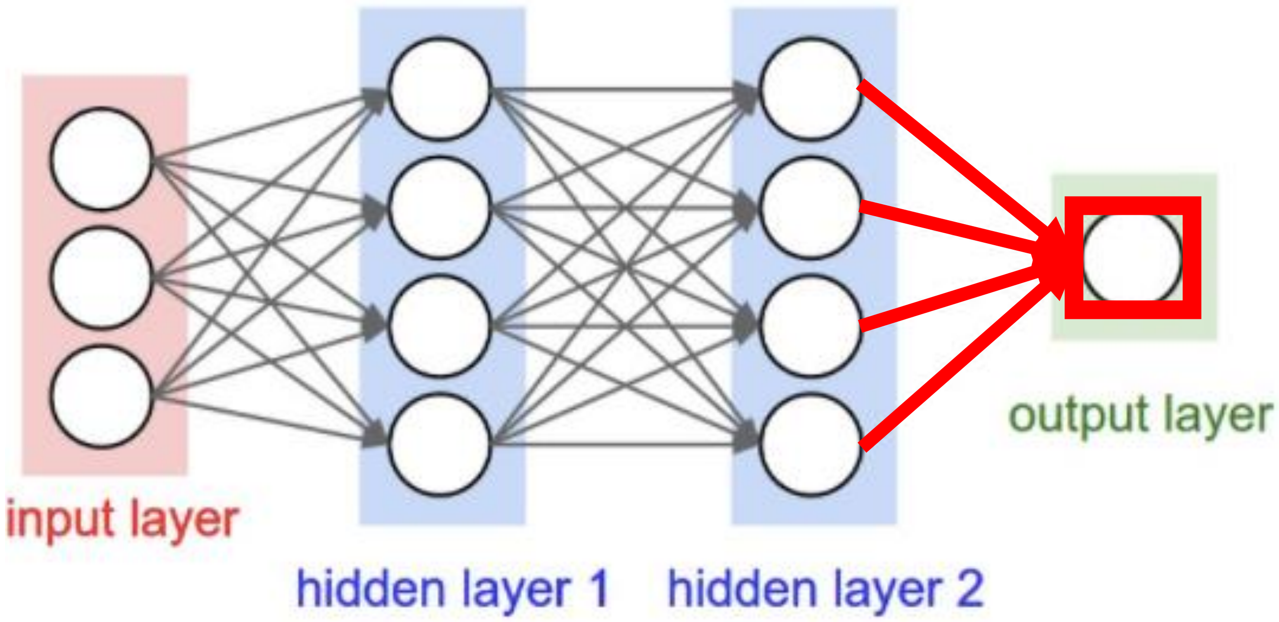


- Unit: computes a weighted sum and applies an activation function

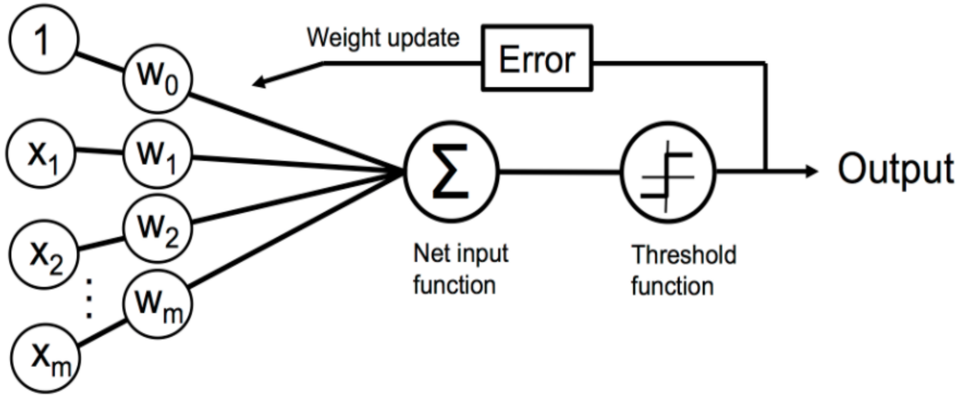
Python Machine Learning; Raschka & Mirjalili

http://cs231n.github.io/neural-networks-1/

Neural Network



- How does this relate to a perceptron?

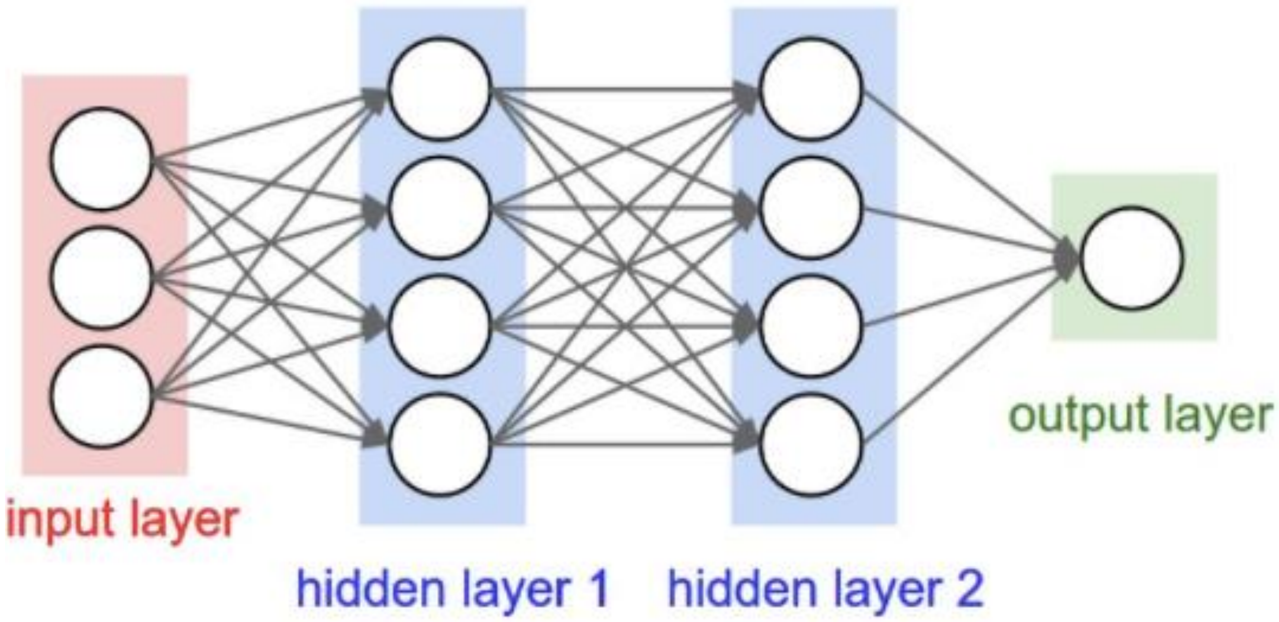


- Unit: computes a weighted sum and applies an activation function

Python Machine Learning; Raschka & Mirjalili

http://cs231n.github.io/neural-networks-1/

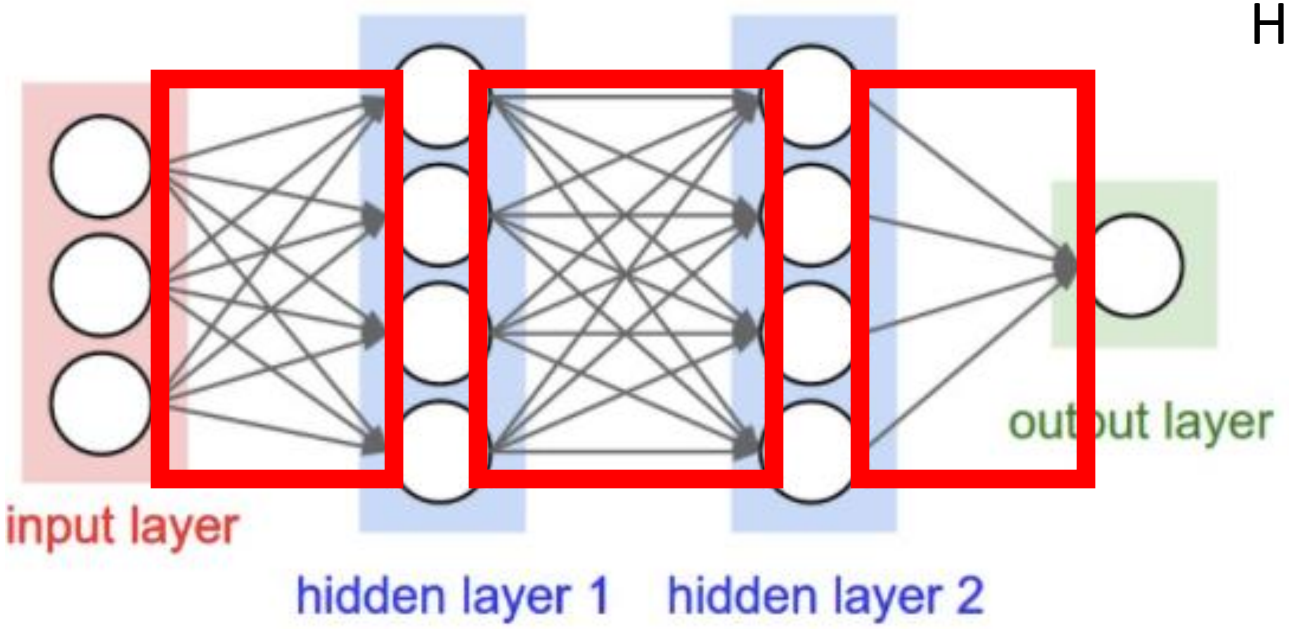
Neural Network



- **Training goal: learn model parameters**
- Layers are called "hidden" because algorithm decides how to use each layer to produce its output

http://cs231n.github.io/neural-networks-1/

Neural Network

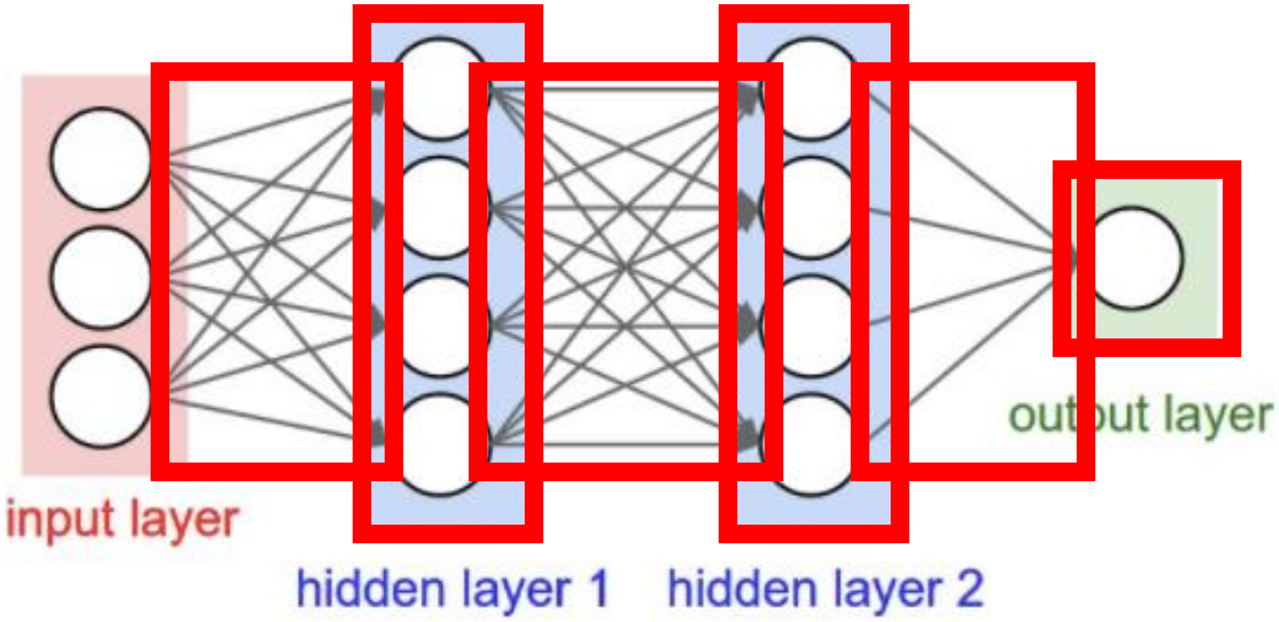


How many weights are in this model?

- Input to Hidden Layer 1:
  - 3x4 = 12
- Hidden Layer 1 to Hidden Layer 2:
  - 4x4 = 16
- Hidden Layer 2 to Output Layer
  - 4x1 = 4
- Total:
  - 12 + 16 + 4 = 32

http://cs231n.github.io/neural-networks-1/

Neural Network



How many parameters are there to learn?

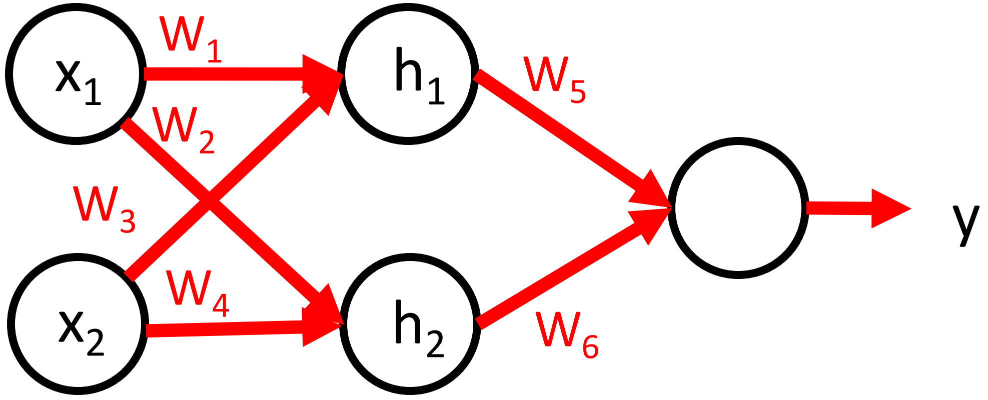
- Number of weights:
  - 32
- Number of biases:
  - 4 + 4 + 1 = 9
- Total
  - 41

http://cs231n.github.io/neural-networks-1/

Hidden Layers Alone Are NOT Enough to Model Non-Linear Functions

Key Observation: feedforward networks are just functions chained together

e.g.,



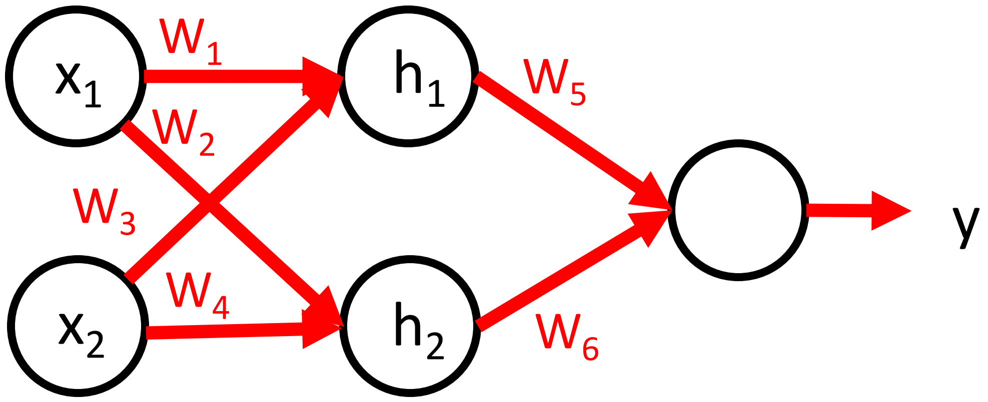
- What is function for h_1?
  - $h_1 = w_1x_1 + w_3x_2 + b_1$
- What is function for h_2?
  - $h_2 = w_2x_1 + w_4x_2 + b_2$
- What is function for y?
  - $y = h_1w_5 + h_2w_6 + b_3$
  - $y = (w_1x_1 + w_3x_2 + b_1)w_5 + (w_2x_1 + w_4x_2 + b_2)w_6 + b_3$
  - $\boxed{y = w_1w_5x_1 + w_3w_5x_2 + w_5b_1 + w_2w_6x_1 + w_4w_6x_2 + w_6b_2 + b_3}$

A chain of LINEAR functions at any depth is still a LINEAR function!

Hidden Layers Alone Are NOT Enough to Model Non-Linear Functions

Key Observation: feedforward networks are just functions chained together

e.g.,



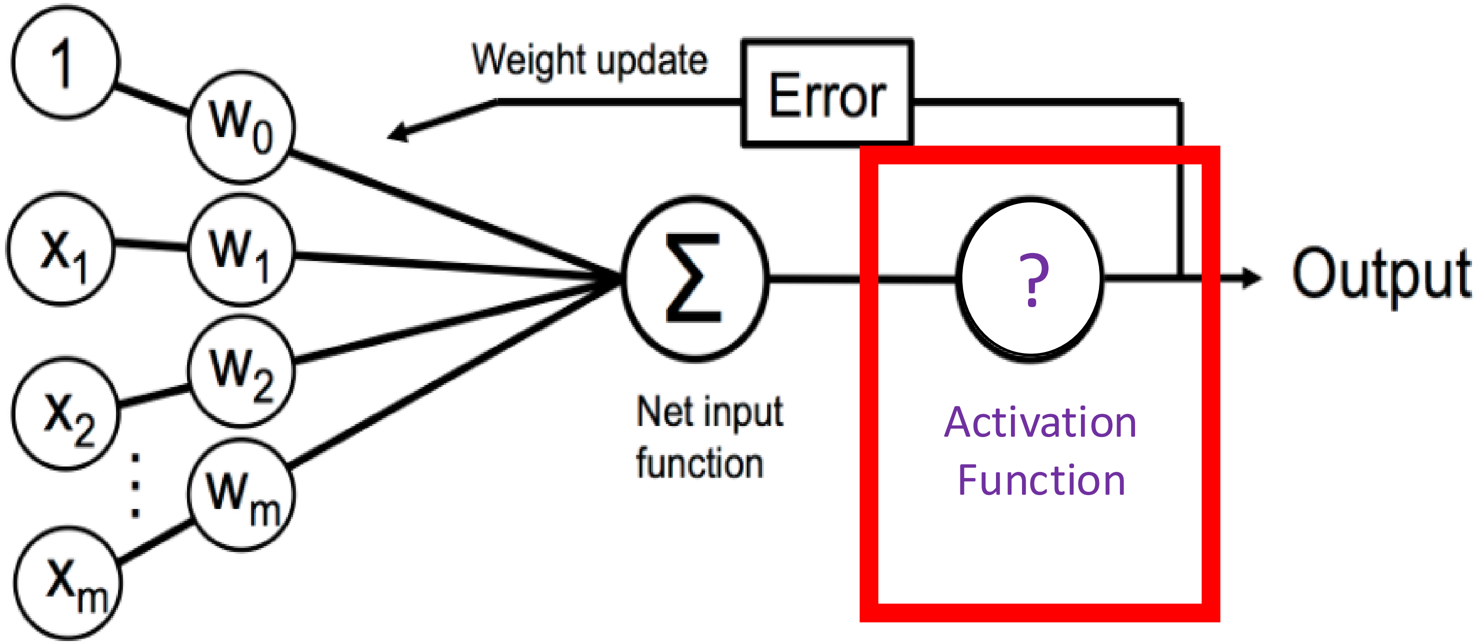
- What is function for h_1?
  - $h_1 = w_1x_1 + w_3x_2 + b_1$
- What is function for h_2?
  - $h_2 = w_2x_1 + w_4x_2 + b_2$
- What is function for y?
  - $y = \underbrace{h_1w_5} + \underbrace{h_2w_6} + b_3$

Constant x linear function = linear function

A chain of LINEAR functions at any depth is still a LINEAR function!

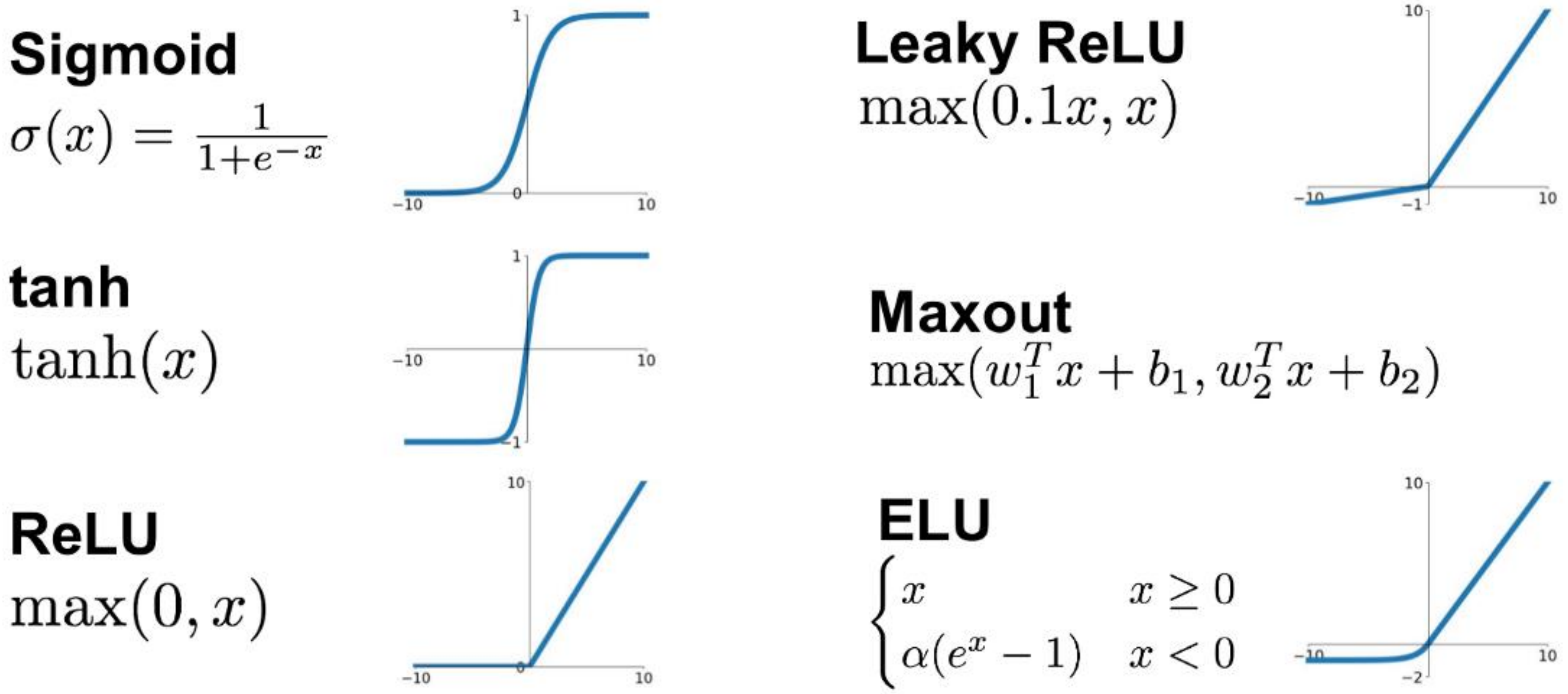
Add Non-Linear Activation Functions

- Each unit applies a non-linear “activation” function to the weighted input to mimic a neuron firing



Python Machine Learning; Raschka & Mirjalili

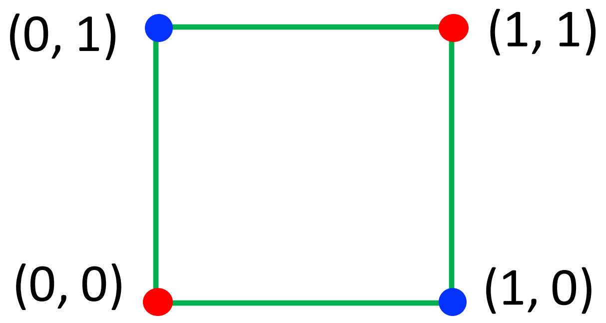
Add Non-Linear Activation Functions; e.g.,

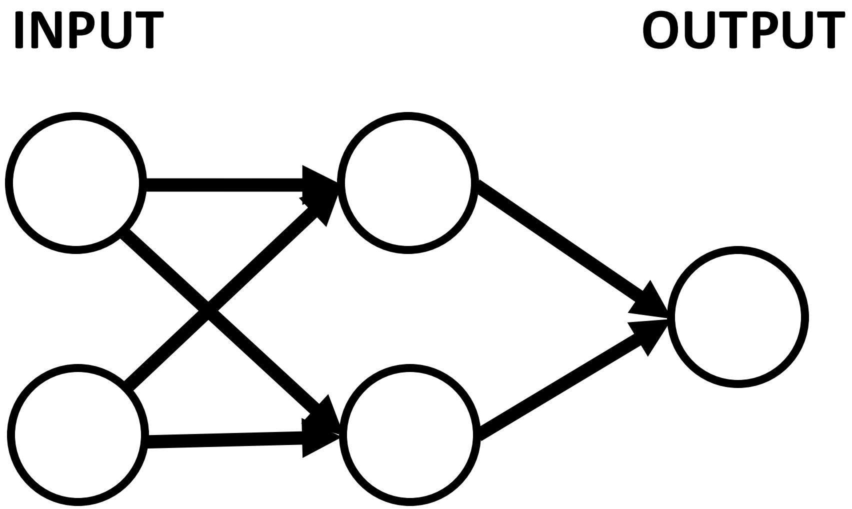


Source: https://www.linkedin.com/pulse/activation-functions-neural-networks-leonardo-calderon-j-/

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:

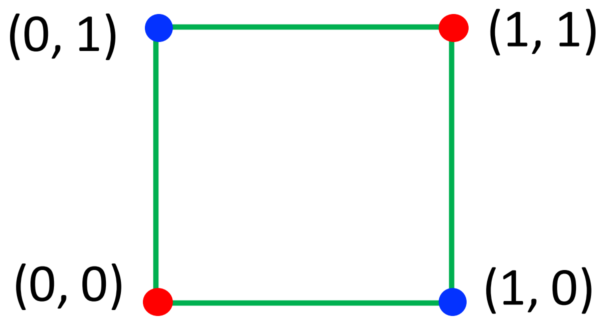




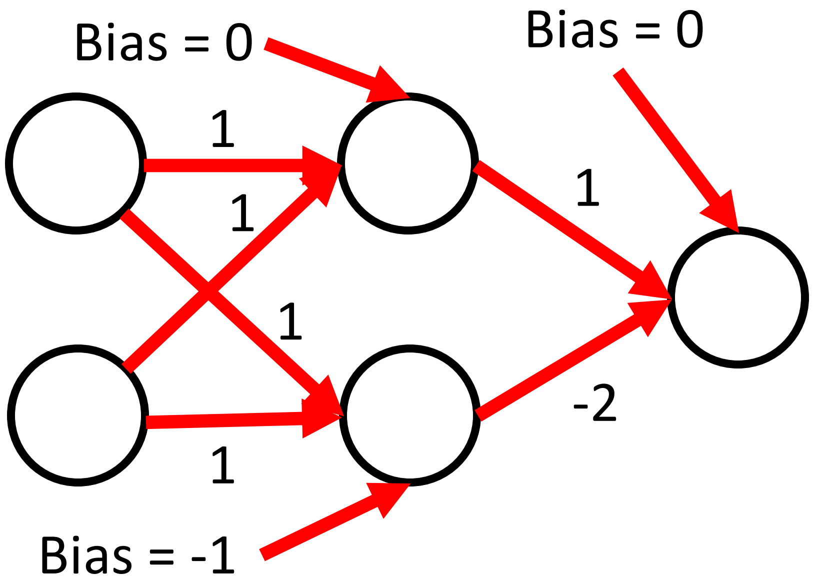
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



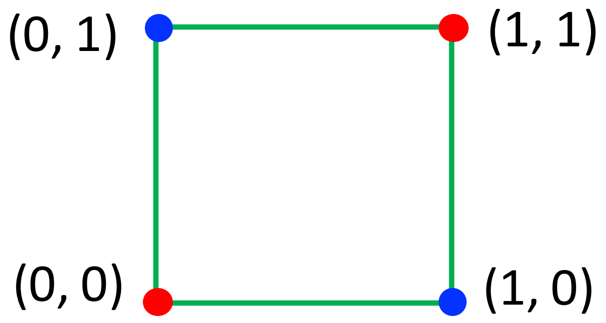
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



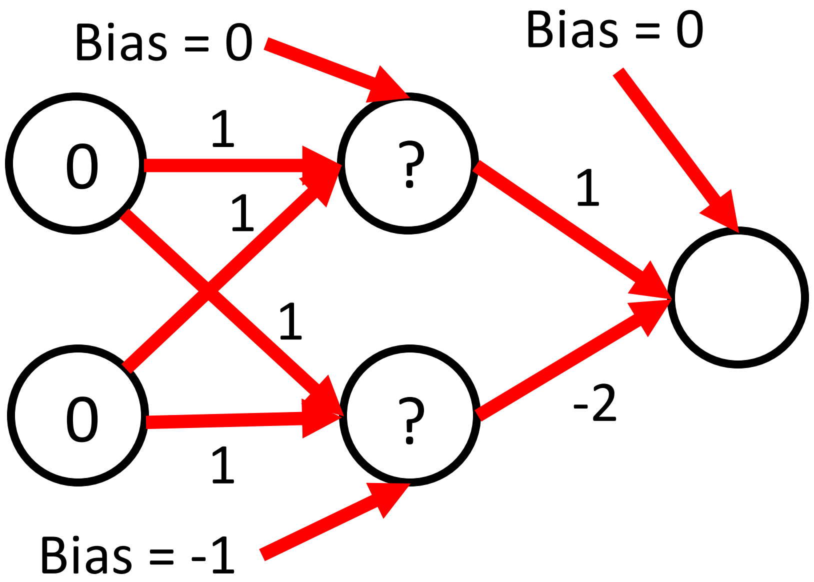
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



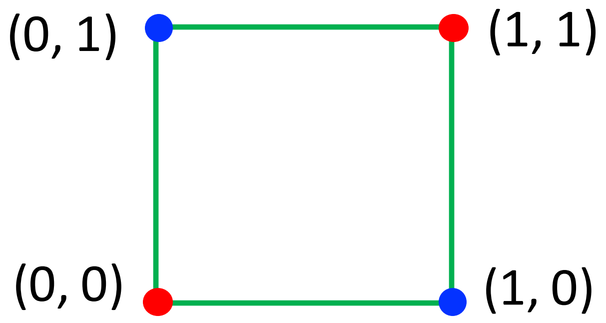
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



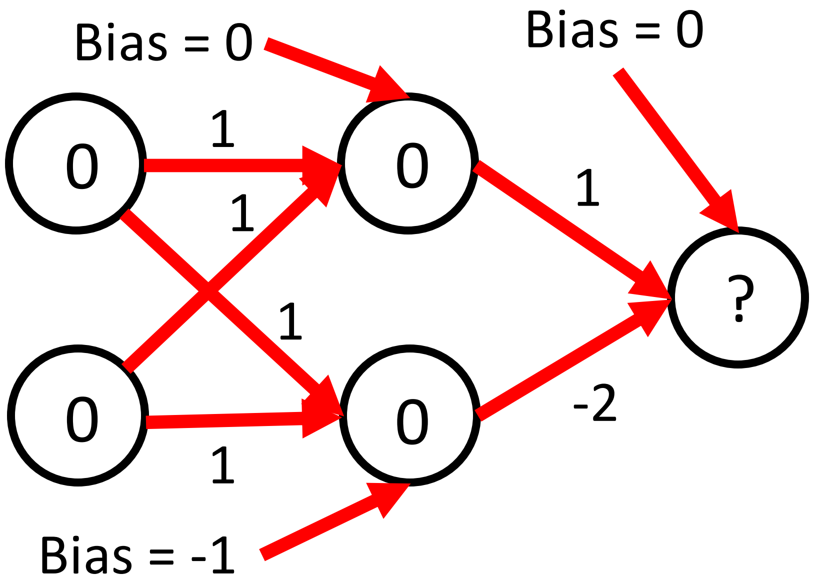
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



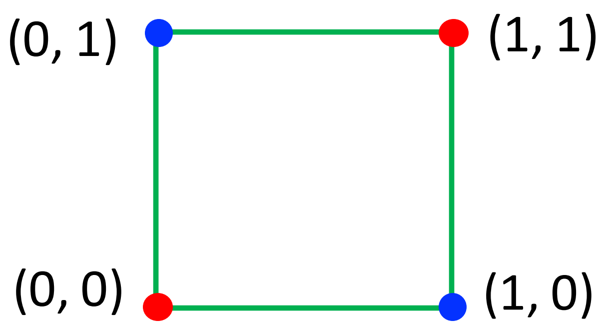
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



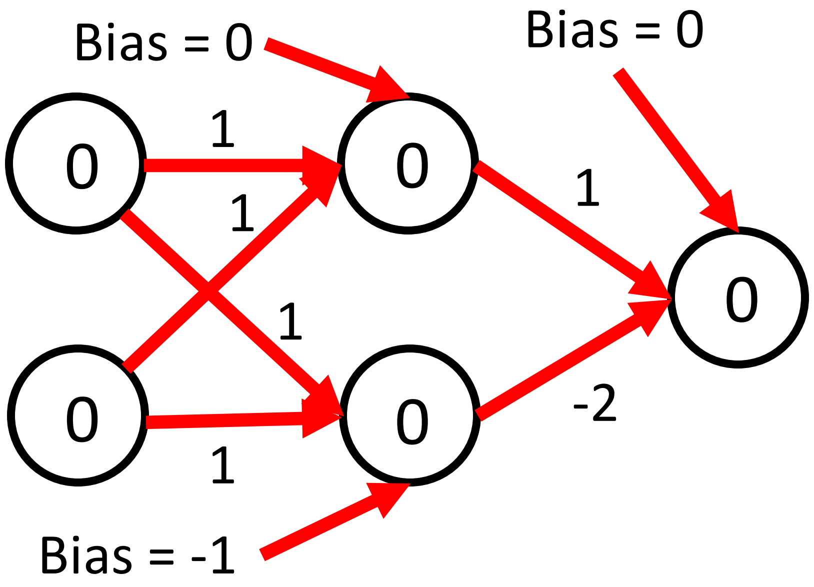
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



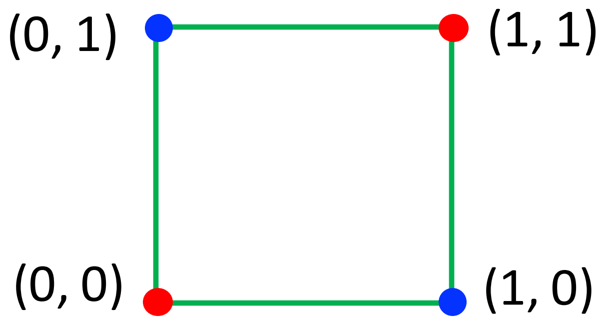
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



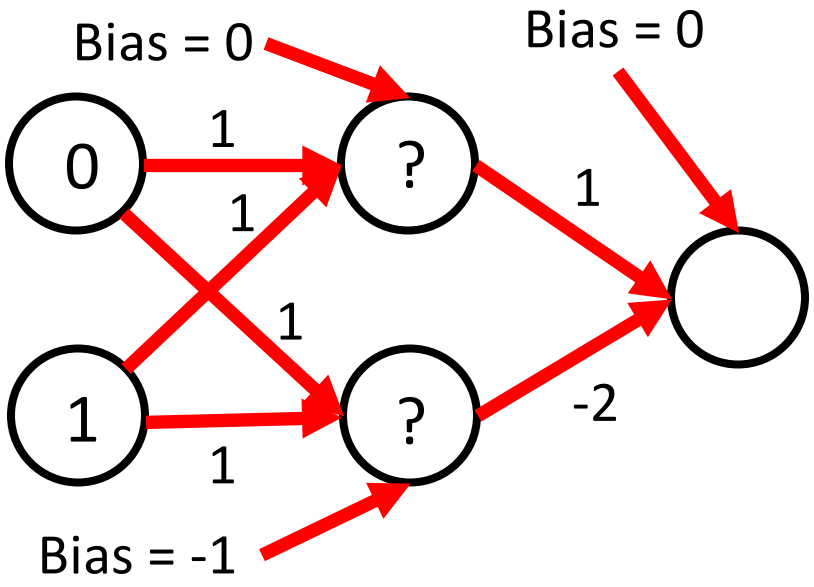
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



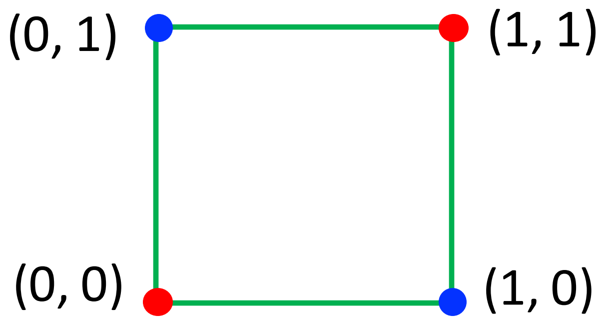
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



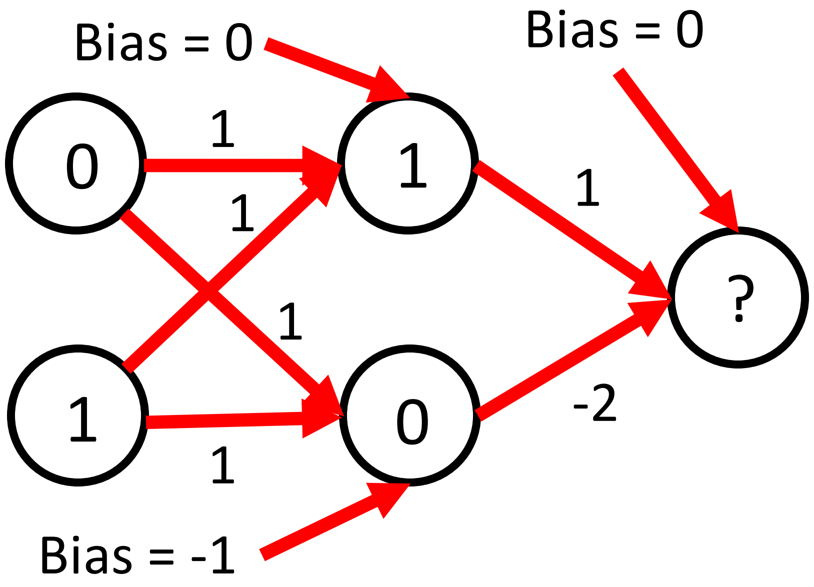
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



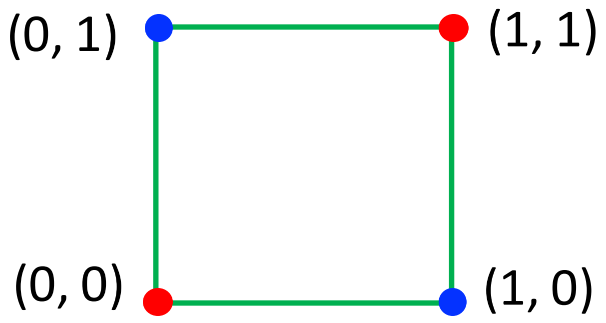
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



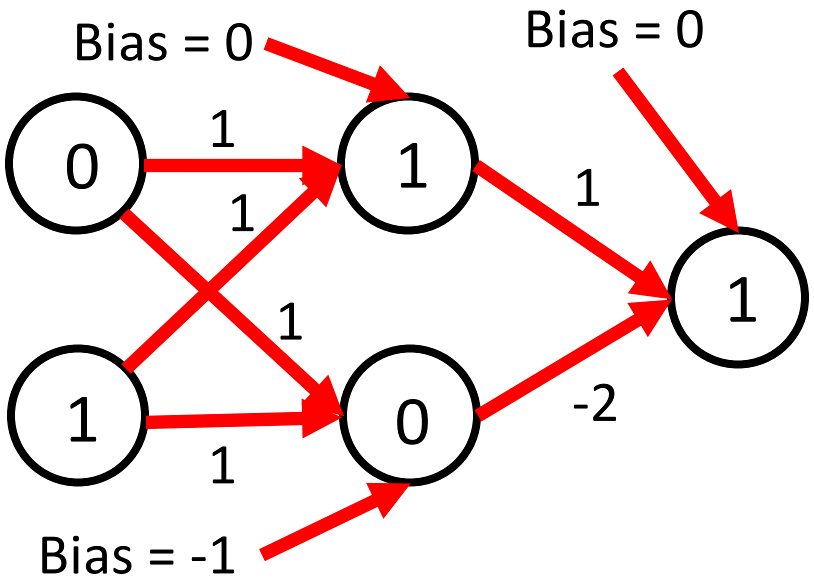
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



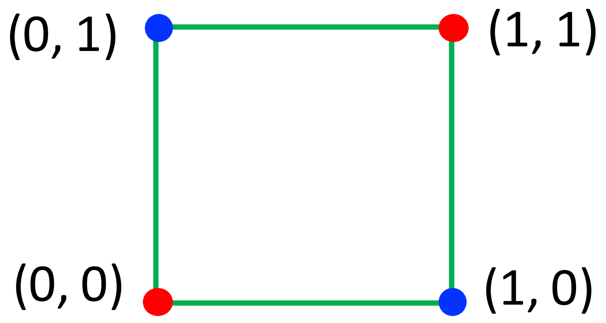
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



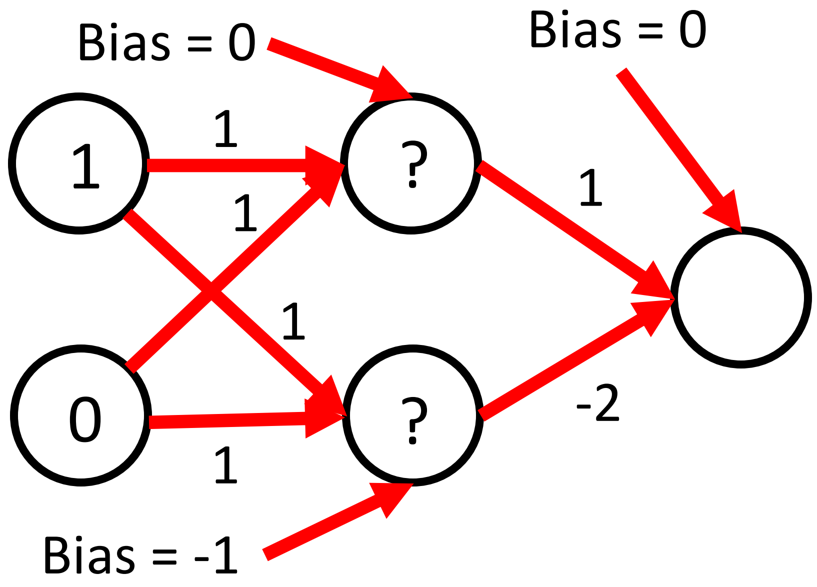
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



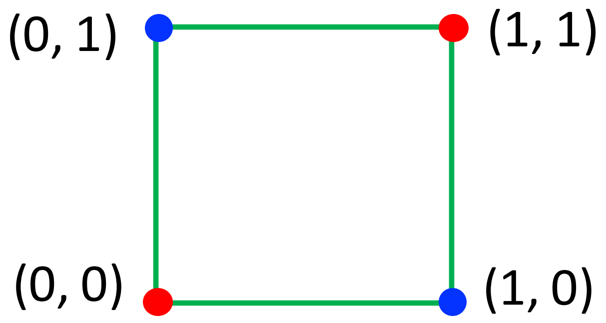
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



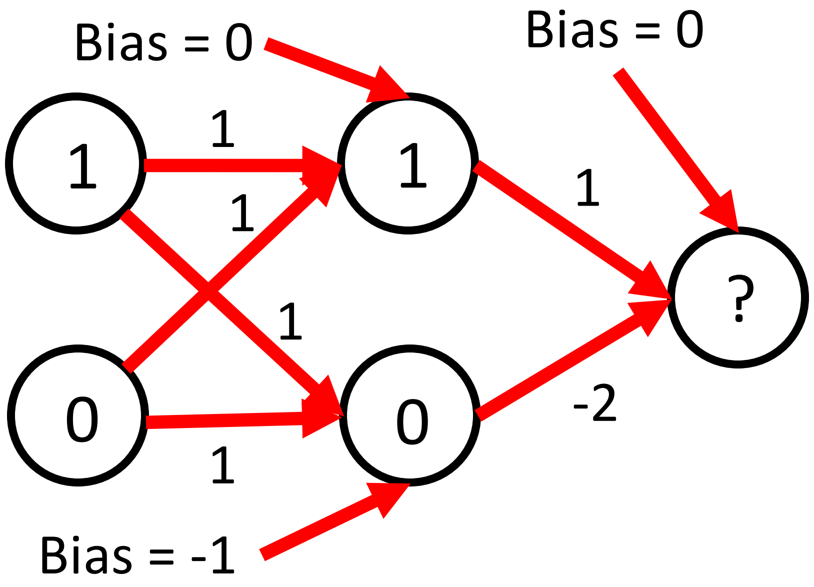
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



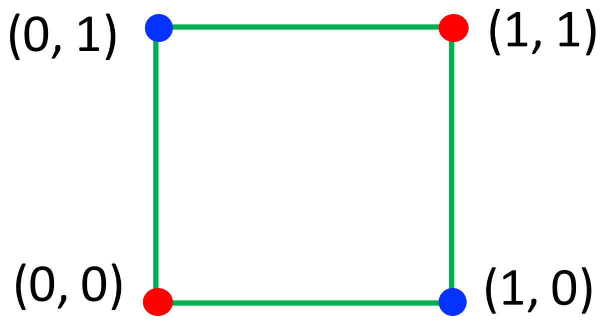
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



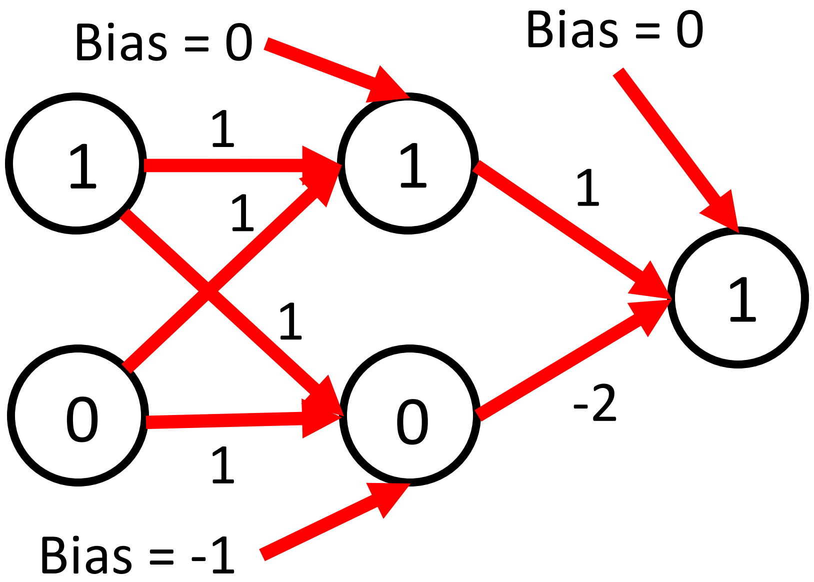
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



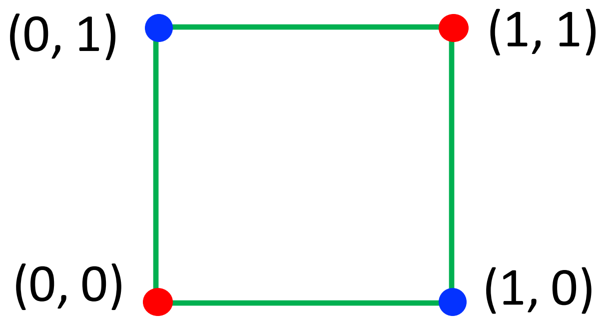
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



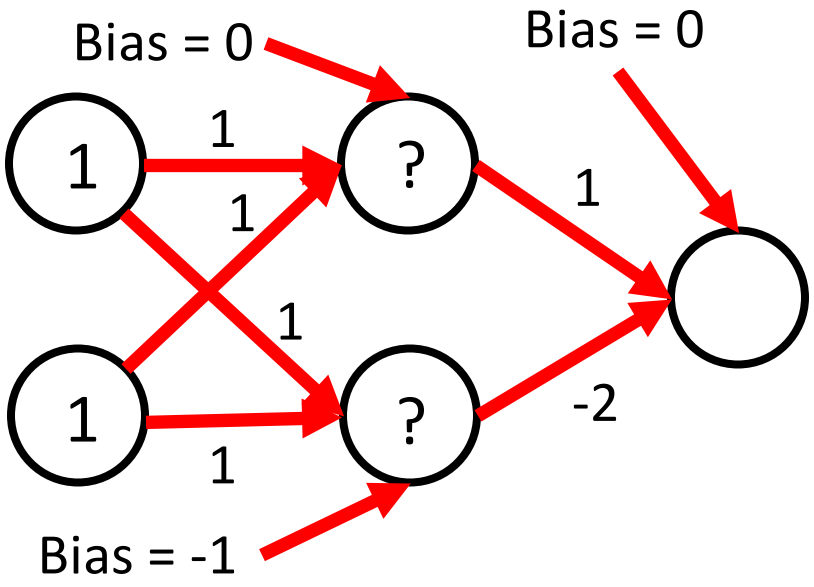
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
$\boxed{1}$	$\boxed{0}$	$\boxed{1}$
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



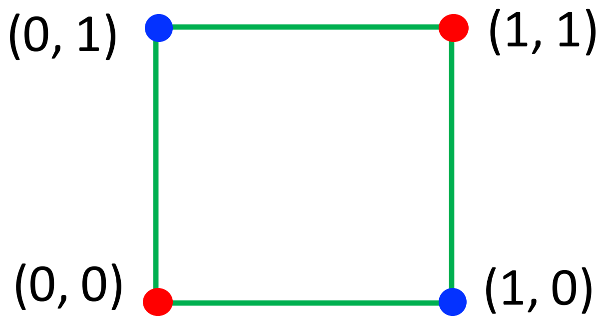
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



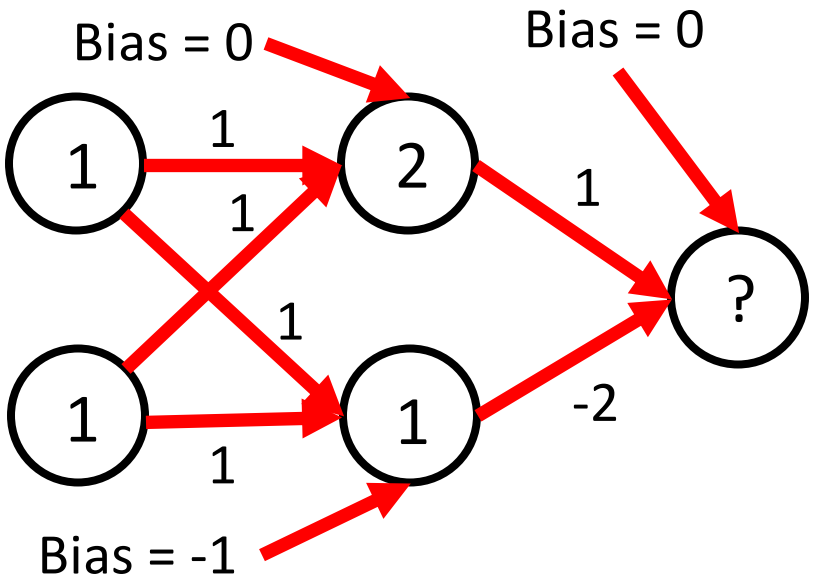
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



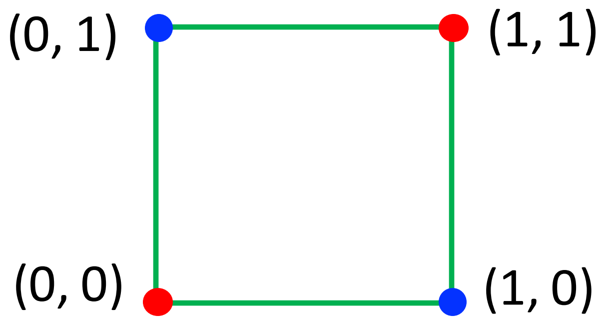
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



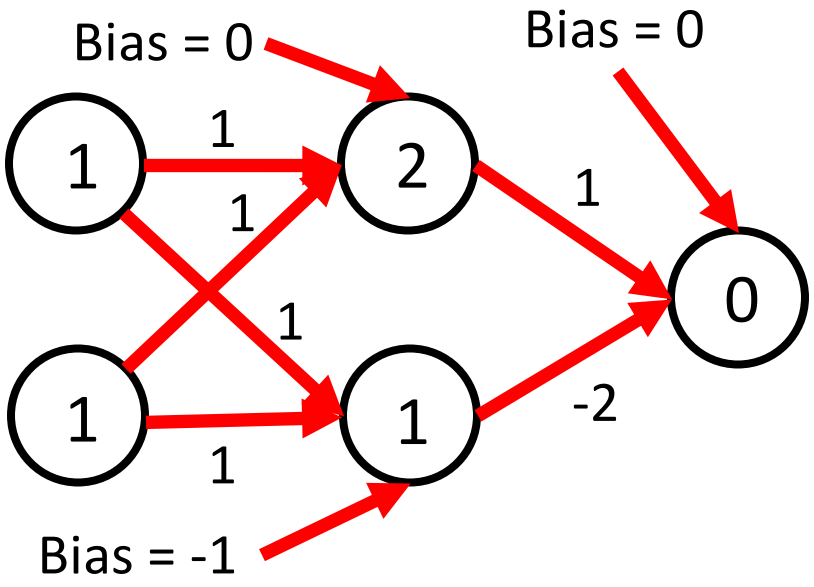
INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



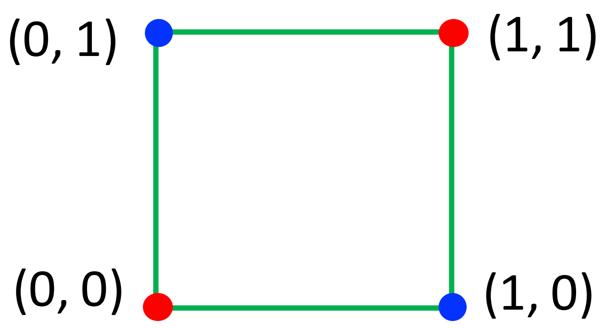
- Approach: ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with these parameters:



INPUT		OUTPUT
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

Non-Linear Example: Revisiting XOR problem

- Non-linear function: separate 1s from 0s:



- Approach: Use ReLU activation function ($\mathrm{ReLU}(z) = \max(0, z)$) with this model:

Neural networks can solve XOR problem…

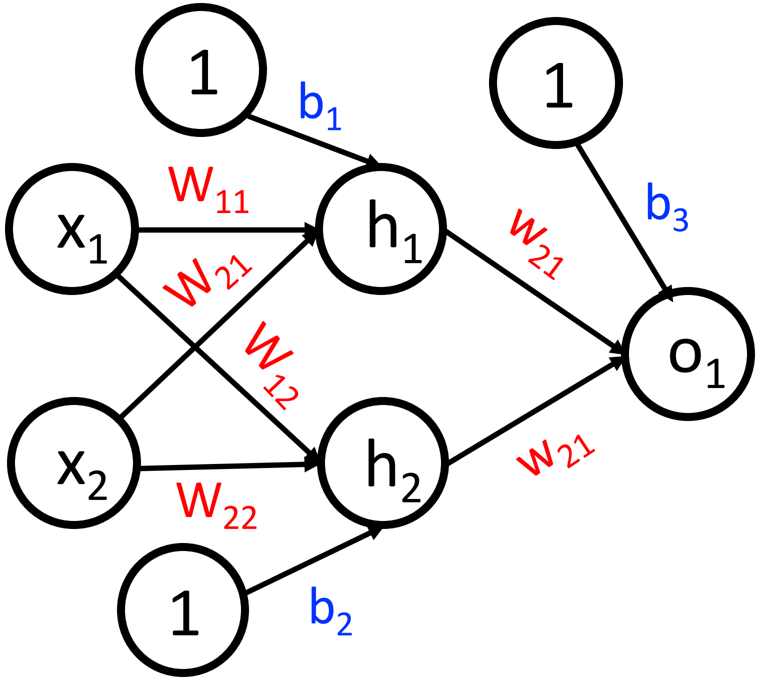
and so model non-linear functions!

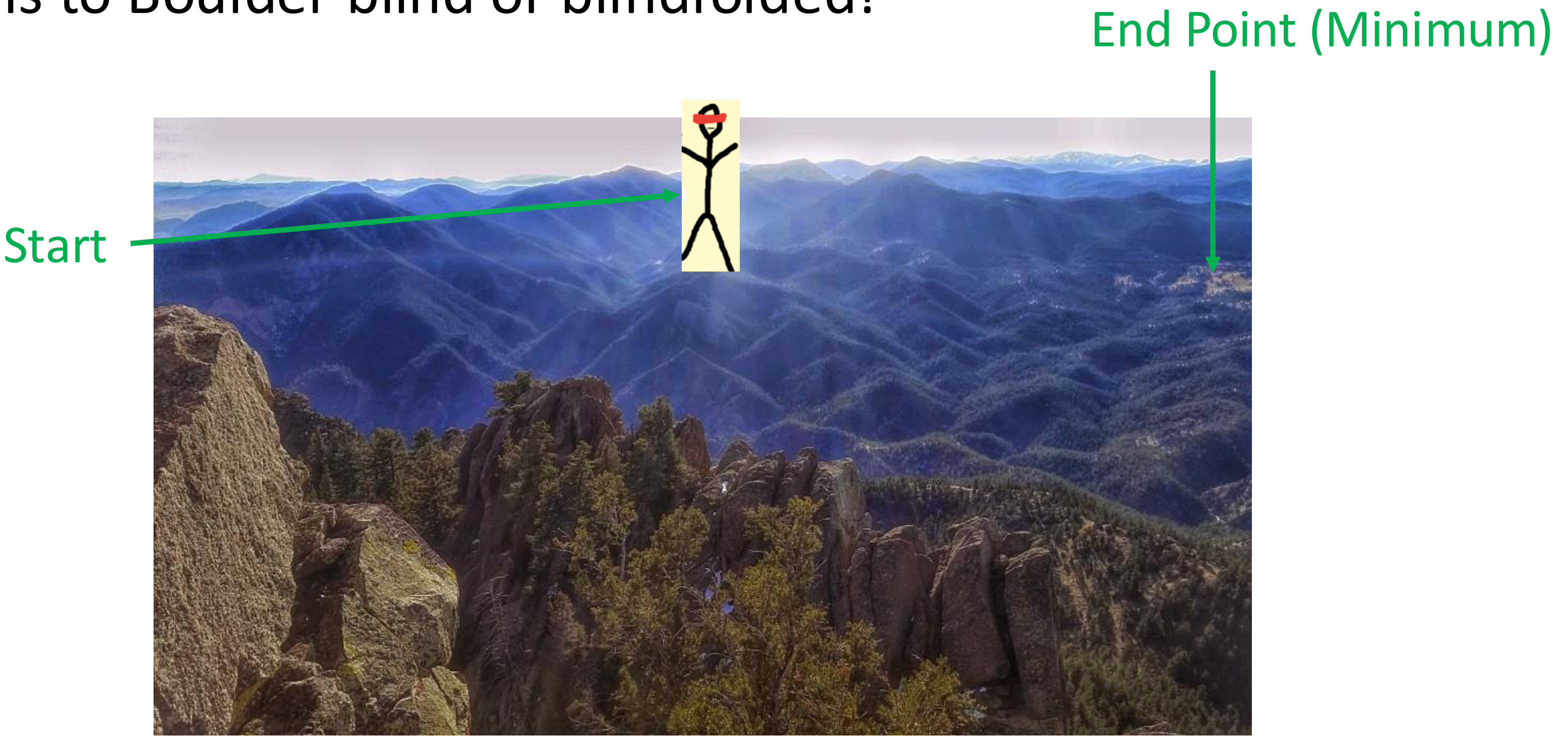
Today’s Topics

- Ways of seeing: image and video acquisition
- Evolution of computer vision (before versus after 2012)
- Fundamentals of a neural network architecture
- Training deep neural networks

Gradient Descent: Approach

- Repeatedly show a neural network examples to decide how to modify its parameters (e.g., weights and biases) so it better converts inputs to match desired outputs (performance error is measured by an objective/loss function)
- Analogy: hike from mountains to Boulder blind or blindfolded!





Gradient Descent: Intuition

- Repeat:
  1. Guess
  2. Calculate error
- e.g., learn linear model for converting kilometers to miles when only observing the input “miles” and output “kilometers”

Miles → [Kilometers = miles x constant] → Kilometers

Gradient Descent: Intuition

- Repeat:
  1. $\boxed{\text{Guess}}$
  2. Calculate error
- e.g., learn constant multiplier to convert US dollars to Israeli shekels

$10 → Shekels = dollars x constant

Gradient Descent: Intuition

- Repeat:
  1. Guess
  2. Calculate error
- e.g., learn constant multiplier to convert US dollars to Israeli shekels

$10 → Shekels = dollars x constant → Error = Guess - Correct

Gradient Descent: Intuition

- Repeat:
  1. $\boxed{\text{Guess}}$
  2. Calculate error
- e.g., learn constant multiplier to convert US dollars to Israeli shekels

$$\$10 \longrightarrow \boxed{\text{Shekels = dollars x constant}}$$

Gradient Descent: Intuition

- Repeat:
  1. Guess
  2. Calculate error
- e.g., learn constant multiplier to convert US dollars to Israeli shekels

$10 → Shekels = dollars x constant → Error = Guess - Correct

Gradient Descent: Intuition

- Repeat:
  1. Guess
  2. Calculate error
- e.g., learn constant multiplier to convert US dollars to Israeli shekels

$10 → Shekels = dollars x constant

Gradient Descent: Intuition

- Repeat:
  1. Guess
  2. $\boxed{\text{Calculate error}}$
- e.g., learn constant multiplier to convert US dollars to Israeli shekels

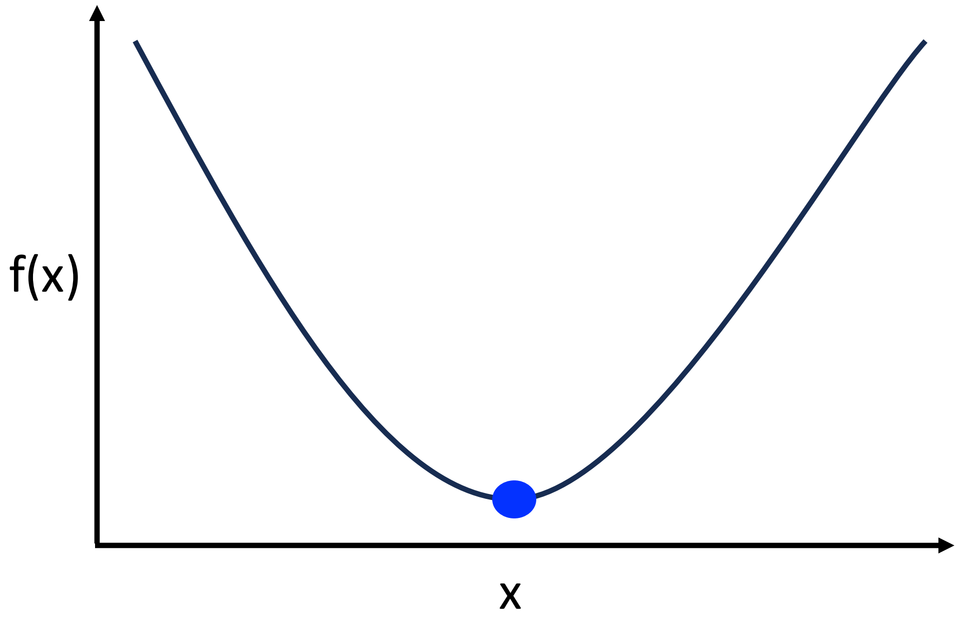
$10 → Shekels = dollars x constant → Error = Guess - Correct

- Idea: repeatedly adjust constant (i.e., model parameter) to try to reduce the error

Gradient Descent: Possible Scenarios

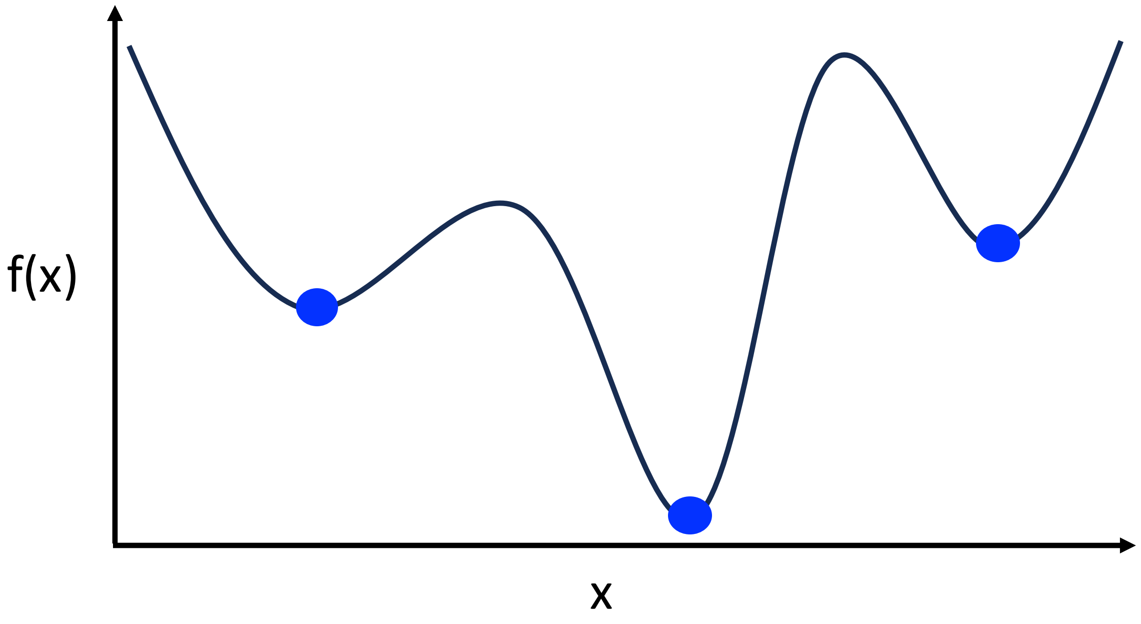
(simple 1-dimensional plots)

Convex Functions (one minimum)



Currency conversion example

Non-Convex Functions (multiple minima)



Our focus: deep learning

Gradient Descent: Objective Functions

Many options exist!

e.g., minimize the squared error (aka, L2 loss, quadratic loss) between prediction and ground truth

Mean taken over *n* instances

$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2$$

True value

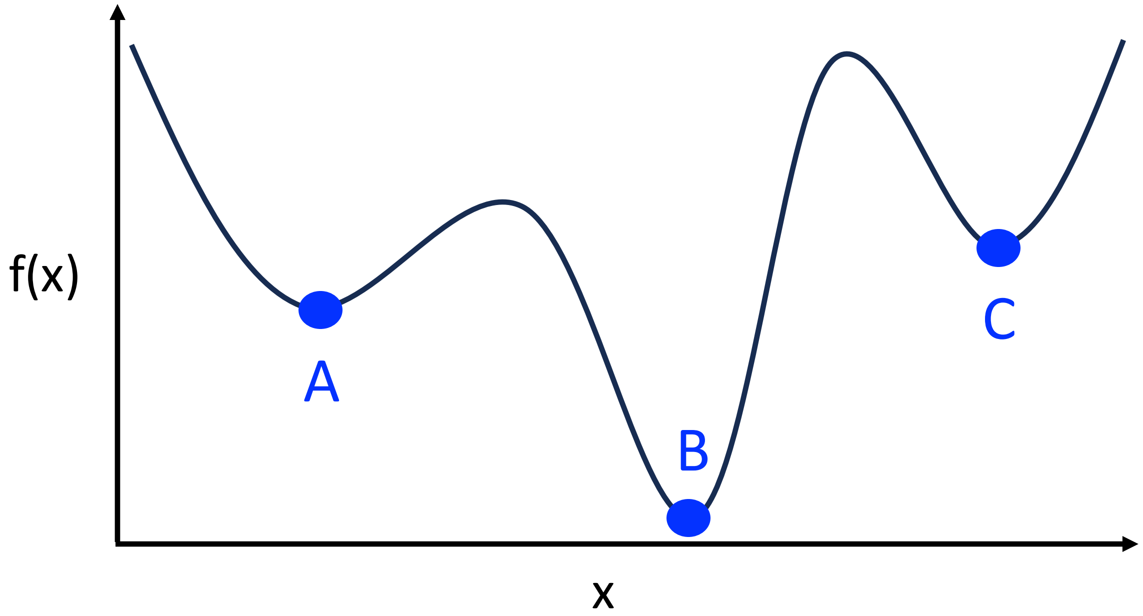
Predicted value

What is the minimum possible value?

- 0: all predictions are correct

Gradient Descent: Definitions

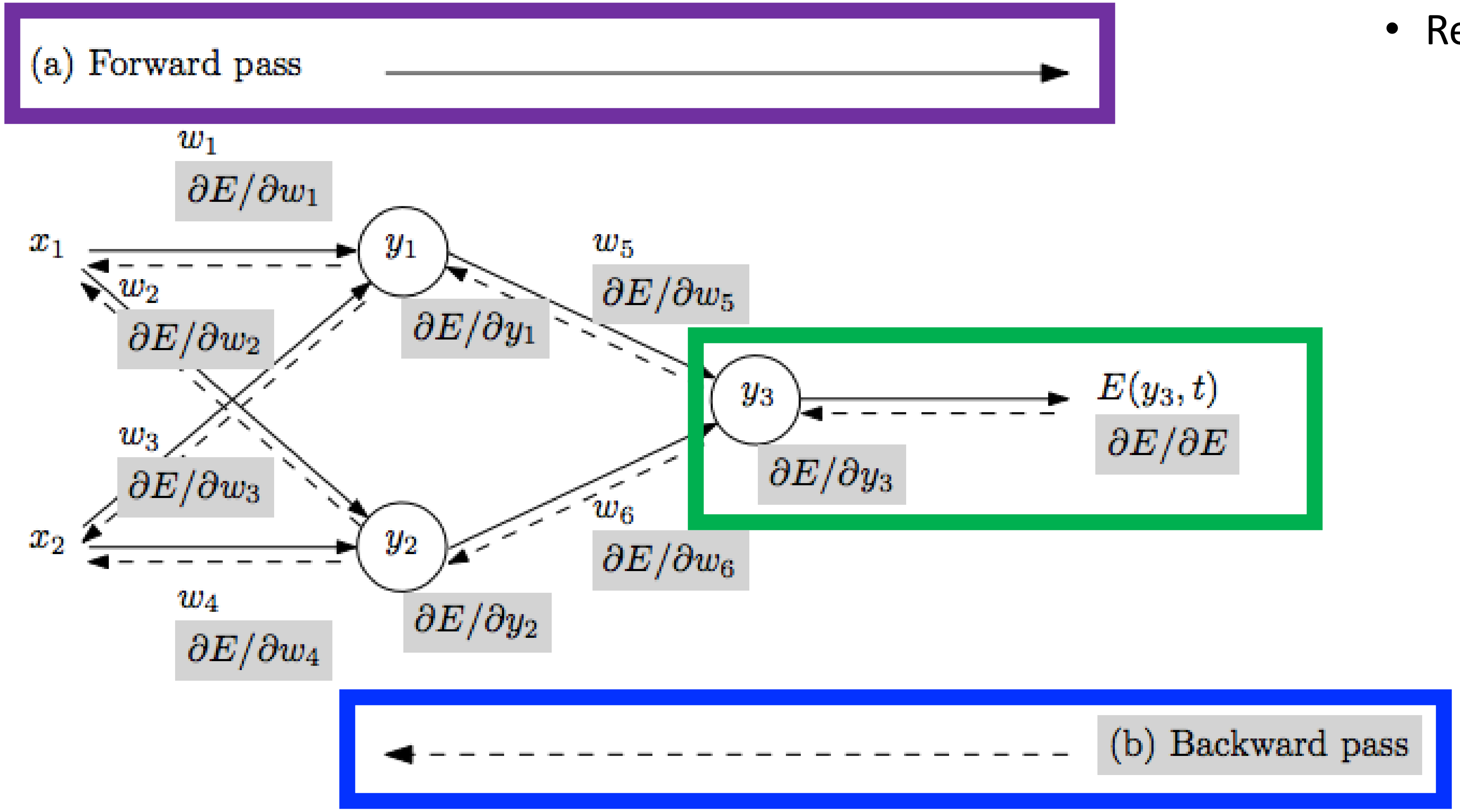
- **Gradient:** a vector indicating how a slight change to each function variable in ***x*** increases the output ***f(x)*** (partial derivatives when there are multiple variables)
- Recall, a derivative indicates the slope (rise/run) of the function at any point
- **Gradient descent**: to ***minimize*** the function, iteratively step in opposite direction of gradient (i.e., descent rather than ascent)



Which letter(s) show global minima?

Which letter(s) show local minima?

Gradient Descent: Implementation



- Repeat until stopping criterion met:
  1. **Forward pass**: propagate training data through model to make predictions
  2. **Error quantification**: measure dissatisfaction with a model's predictions on training data
  3. **Backward pass**: using predicted output, calculate gradients backward to assign blame to each model parameter
  4. Update each parameter using calculated gradients

Figure from: Atilim Gunes Baydin, Barak A. Pearlmutter, Alexey Andreyevich Radul, Jeffrey Mark Siskind; Automatic Differentiation in Machine Learning: a Survey; 2018

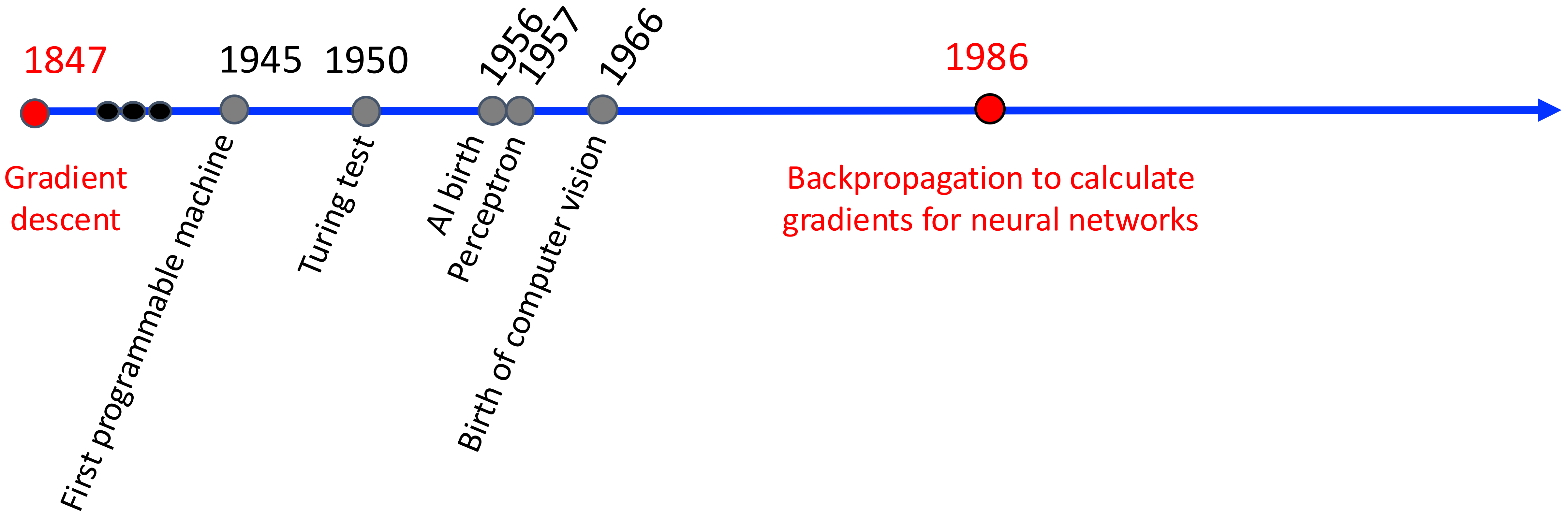
Gradient Descent: Implementation

Key challenge: calculating gradients

Solution: backpropagation

- Repeat until stopping criterion met:
  1. **Forward pass**: propagate training data through model to make predictions
  2. **Error quantification**: measure dissatisfaction with a model's predictions on training data
  3. **Backward pass**: using predicted output, calculate gradients backward to assign blame to each model parameter
  4. Update each parameter using calculated gradients

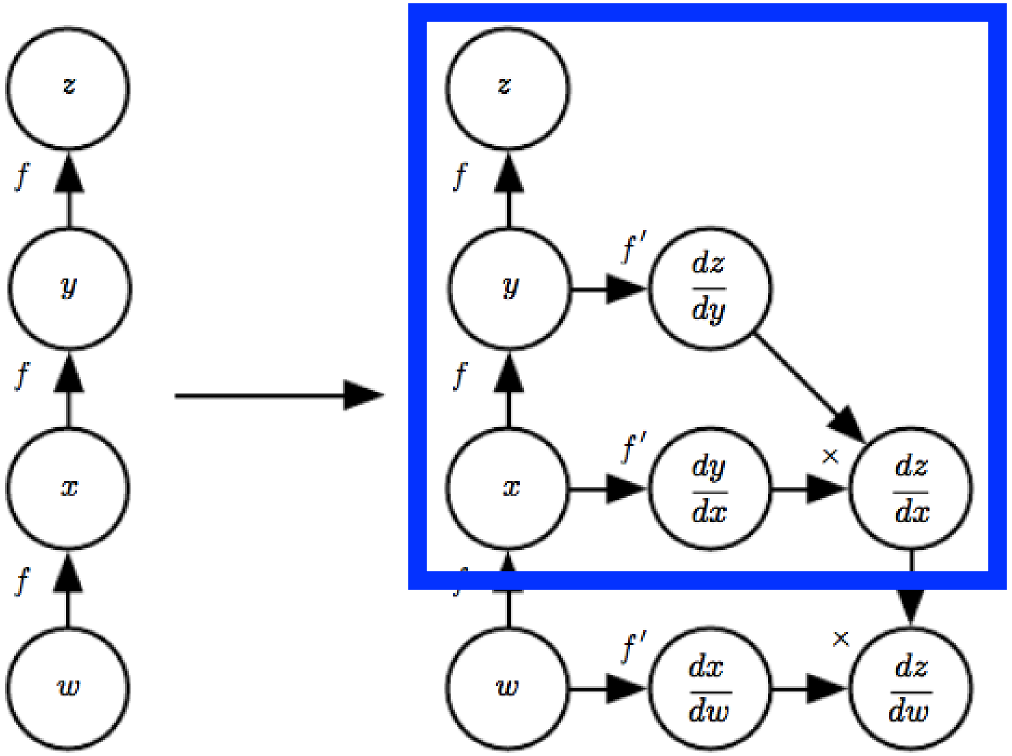
Gradient Descent: Implementation



D. Rulhart, G. Hinton, and R. Williams, Learning Internal Representations by Error Propagation, 1986.

Backpropagation Basics: Chain Rule

- **Idea**: compute gradient on loss function to inform how to nudge model parameters to reduce loss
- **Key observation**: networks are functions connected in a chain



$$x = f(w),\ y = f(x),\ z = f(y)$$

Chain rule of calculus: can compute all derivatives from top to bottom using only local derivative information at each node;

e.g.,

$$\frac{dz}{dx} = \frac{dz}{dy}\frac{dy}{dx}$$

Ian Goodfellow, Yoshua Bengio, and Aaron Courville; Deep Learning, 2016.

Backpropagation Basics: Chain Rule

- **Idea**: compute gradient on loss function to inform how to nudge model parameters to reduce loss
- **Key observation**: networks are functions connected in a chain

Intuitive example: how much faster is my husband compared to my daughter? (dz/dx)

my husband travels twice as fast as my son (dz/dy)

my son travels three times as fast as my daughter (dy/dx)

$$x = f(w),\ y = f(x),\ z = f(y)$$

Chain rule of calculus: can compute all derivatives from top to bottom using only local derivative information at each node;

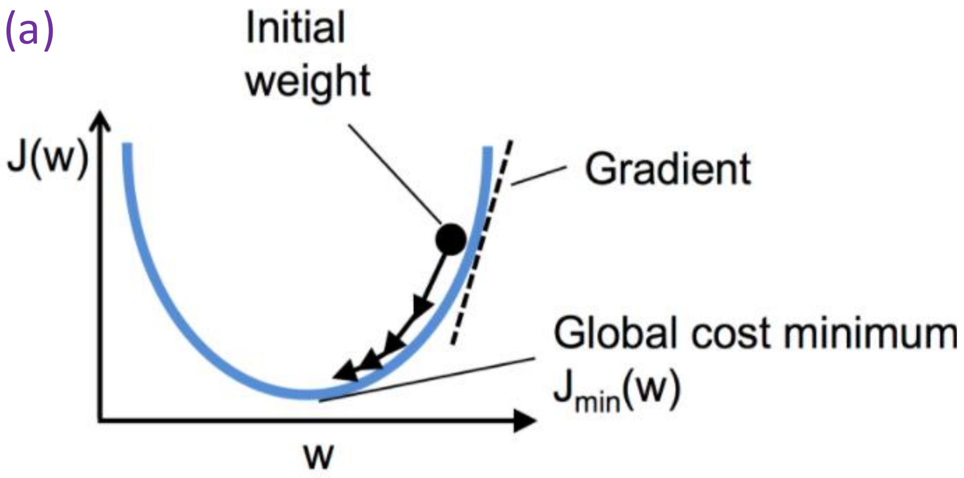
e.g.,

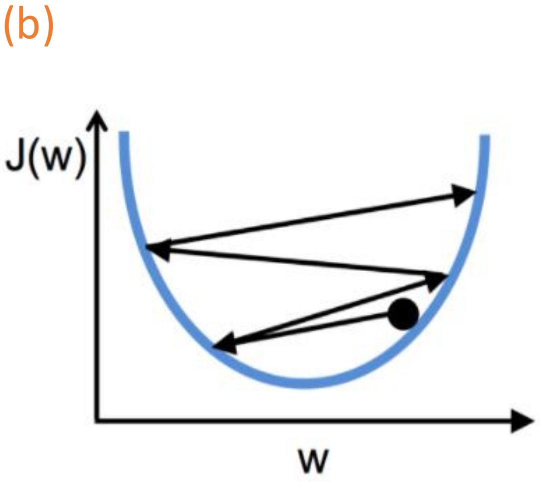
$$\frac{dz}{dx} = \frac{dz}{dy}\frac{dy}{dx}$$

Ian Goodfellow, Yoshua Bengio, and Aaron Courville; Deep Learning, 2016.

Gradient Descent: How Much to Update?

- Many ways to use the gradients
- Basic choice: Step size / learning rate
  - (a) When rate is too small, convergence to good solution is slow
  - (b) When rate is too large, convergence to good solution is impossible





- Repeat until stopping criterion met:
  1. **Forward pass**: propagate training data through model to make predictions
  2. **Error quantification**: measure dissatisfaction with a model's predictions on training data
  3. **Backward pass**: using predicted output, calculate gradients backward to assign blame to each model parameter
  4. Update each parameter using calculated gradients

https://github.com/rasbt/python-machine-learning-book-2nd-edition/blob/master/code/ch02/ch02.ipynb

Gradient Descent: Implementation

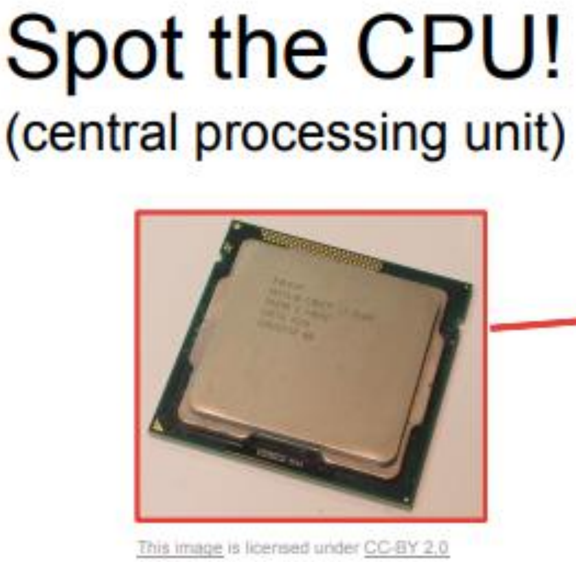
For excellent step-by-step tutorial, watch this video:

https://www.youtube.com/watch?v=VMj-3S1tku0

Critical Foundation for Training: Hardware

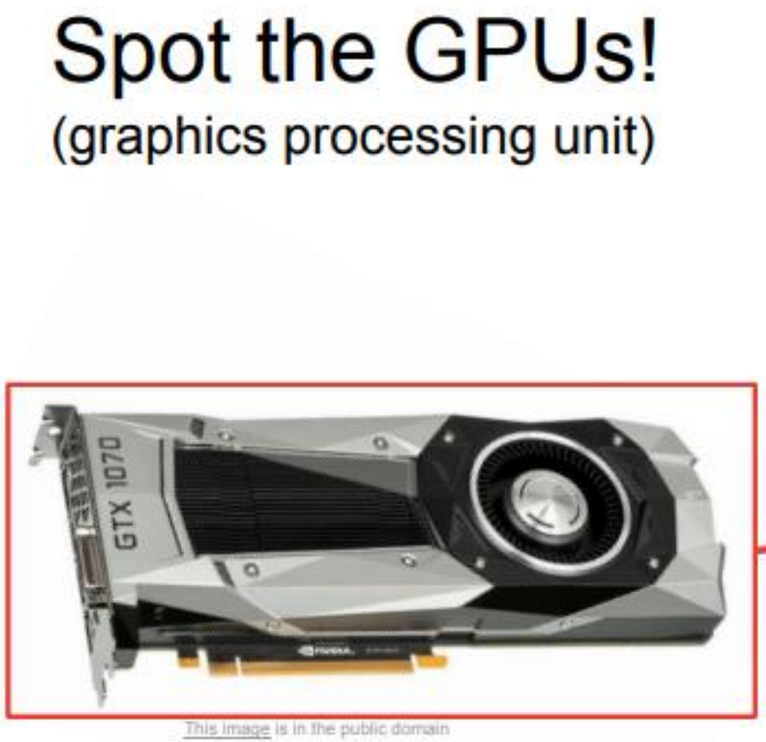
Idea: Train Algorithms Using
GPUs (think Porsche) Instead of CPUs (think Golf Cart)

Hardware: CPU versus GPU



http://cs231n.stanford.edu/slides/2018/cs231n_2018_lecture08.pdf

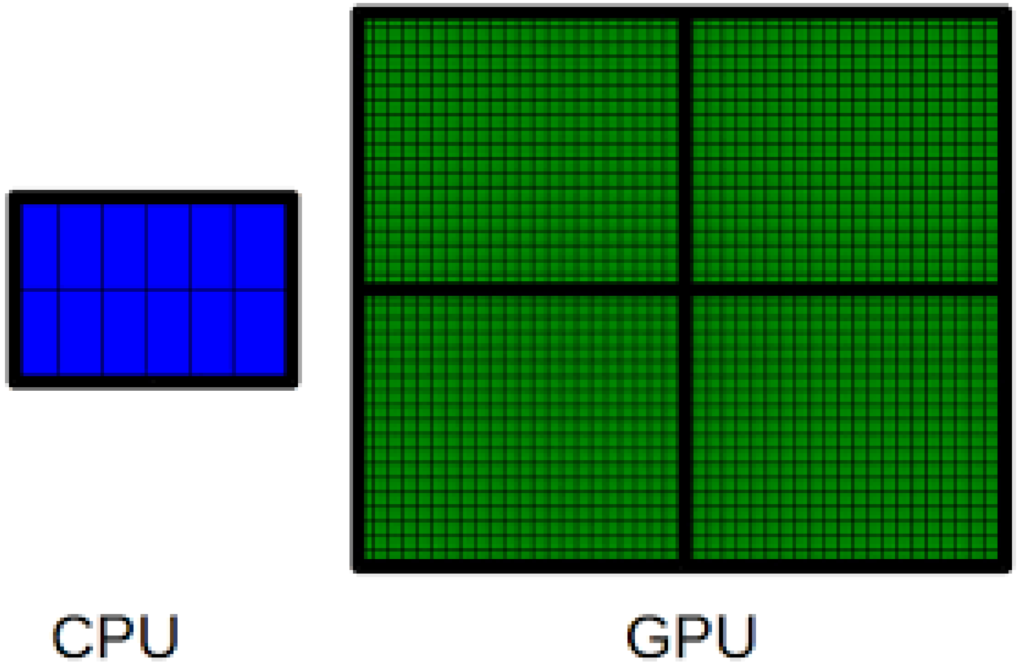
Hardware: CPU versus GPU



http://cs231n.stanford.edu/slides/2018/cs231n_2018_lecture08.pdf

Hardware: CPU versus GPU

- Graphical Processing Units: accelerates computational workloads due to MANY more processing cores



https://www.researchgate.net/figure/The-main-difference-between-CPUs-and-GPUs-is-related-to-the-number-of-available-cores-A_fig7_273383346

Rise of “Deep Learning” Open Source Platforms

torch (Collobert et al.) — 2011

theano (Bastien et al.) — 2012

Caffe (Jia et al.) — 2013

2014

Keras

TensorFlow™ (Abadi et al.) — 2015

2016

PYTORCH (Paszke et al.) — 2017

idiap RESEARCH INSTITUTE

Université de Montréal

Berkeley UNIVERSITY OF CALIFORNIA

Google

Popular for the research community

GPU Machines: Rent Versus Buy?

Rent from Cloud

(e.g., Microsoft Azure):

Instance	Core(s)	RAM	Temporary storage	GPU	Pay as you go with AHB
ND96asr A100 v4	96	900 GiB	6,500 GiB	8x A100 (NVlink)	$27.197/hour

Buy:

Lambda Bare Metal

- 4-8x NVIDIA A100 SXM4 GPUs
- Install in your Datacenter or Lambda Colo
- Customize CPU, RAM, Storage & Network
- Delivered in 2-4 weeks

Starting at

$ 89,283.00

Coding Tutorial Demo:

- Use Google Colab to create and train a neural network with PyTorch

Today’s Topics

- Ways of seeing: image and video acquisition
- Evolution of computer vision (before versus after 2012)
- Fundamentals of a neural network architecture
- Training deep neural networks

The End