

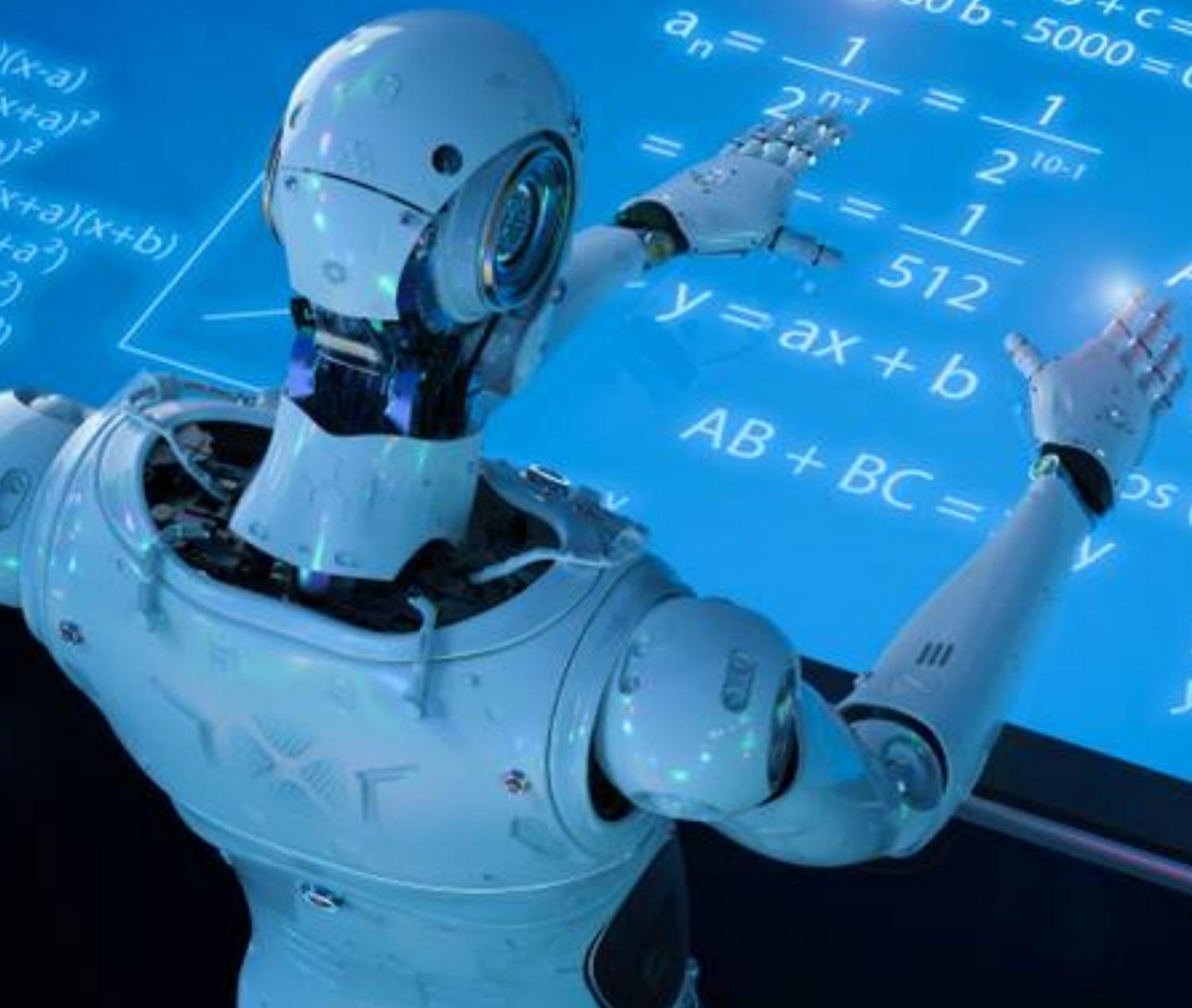


Deep Learning From Scratch

Bruno Gonçalves

www.data4sci.com

<https://github.com/DataForScience/DeepLearning>



Question

<https://github.com/DataForScience/DeepLearning>

• Where are you located?

• Europe

• Asia

• Africa

• US

• Canada

• Latin America

• Oceania

Question

<https://github.com/DataForScience/DeepLearning>

- What's your job title?

- Data Scientist

- Statistician

- Data Engineer

- Researcher

- Business Analyst

- Software Engineer

- Other

Question

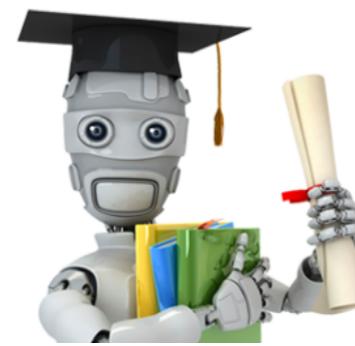
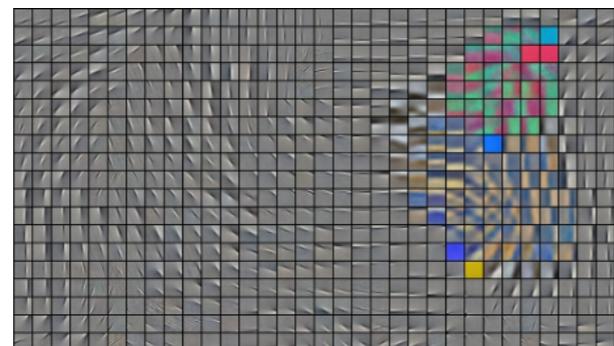
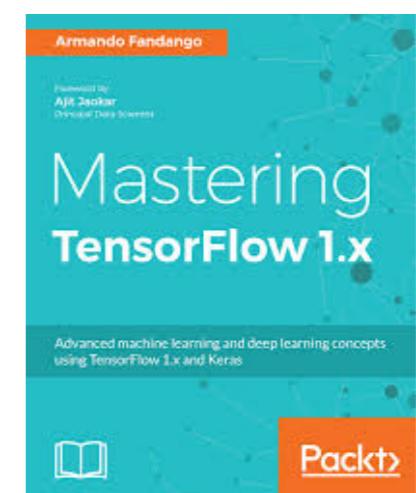
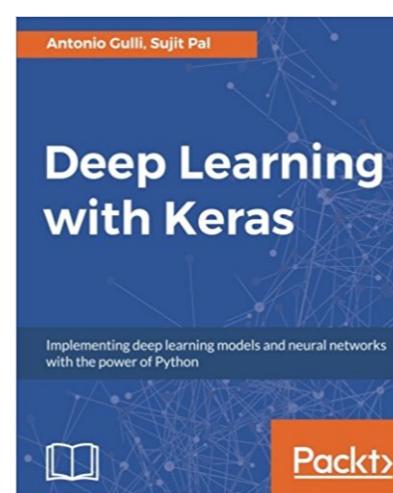
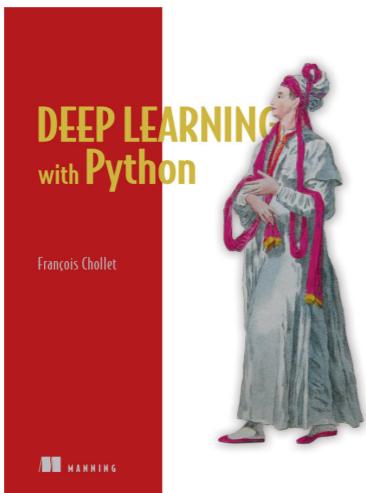
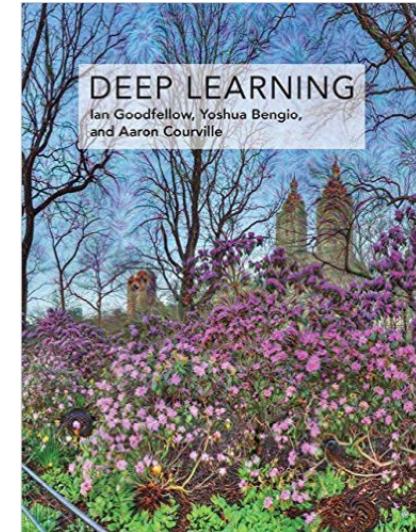
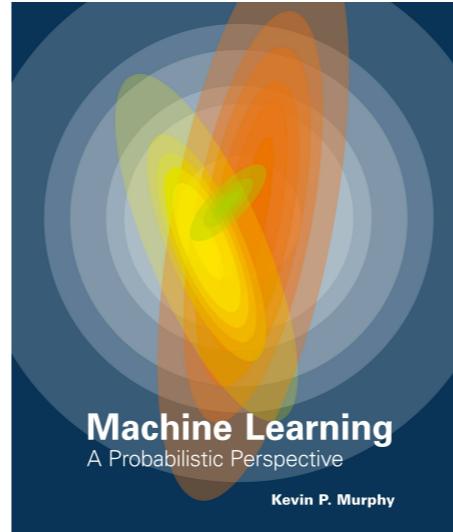
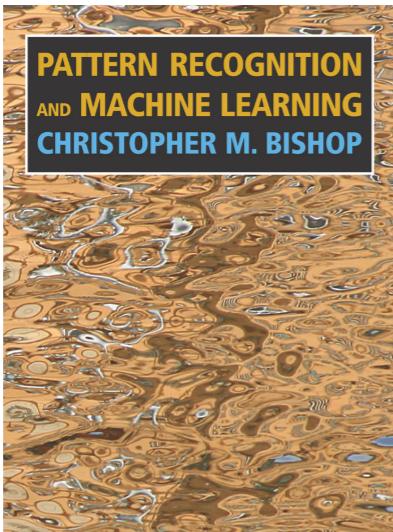
<https://github.com/DataForScience/DeepLearning>

- How experienced are you in Python?

- Beginner (<1 year)
- Intermediate (1 -5 years)
- Expert (5+ years)

References

<https://github.com/DataForScience/DeepLearning>

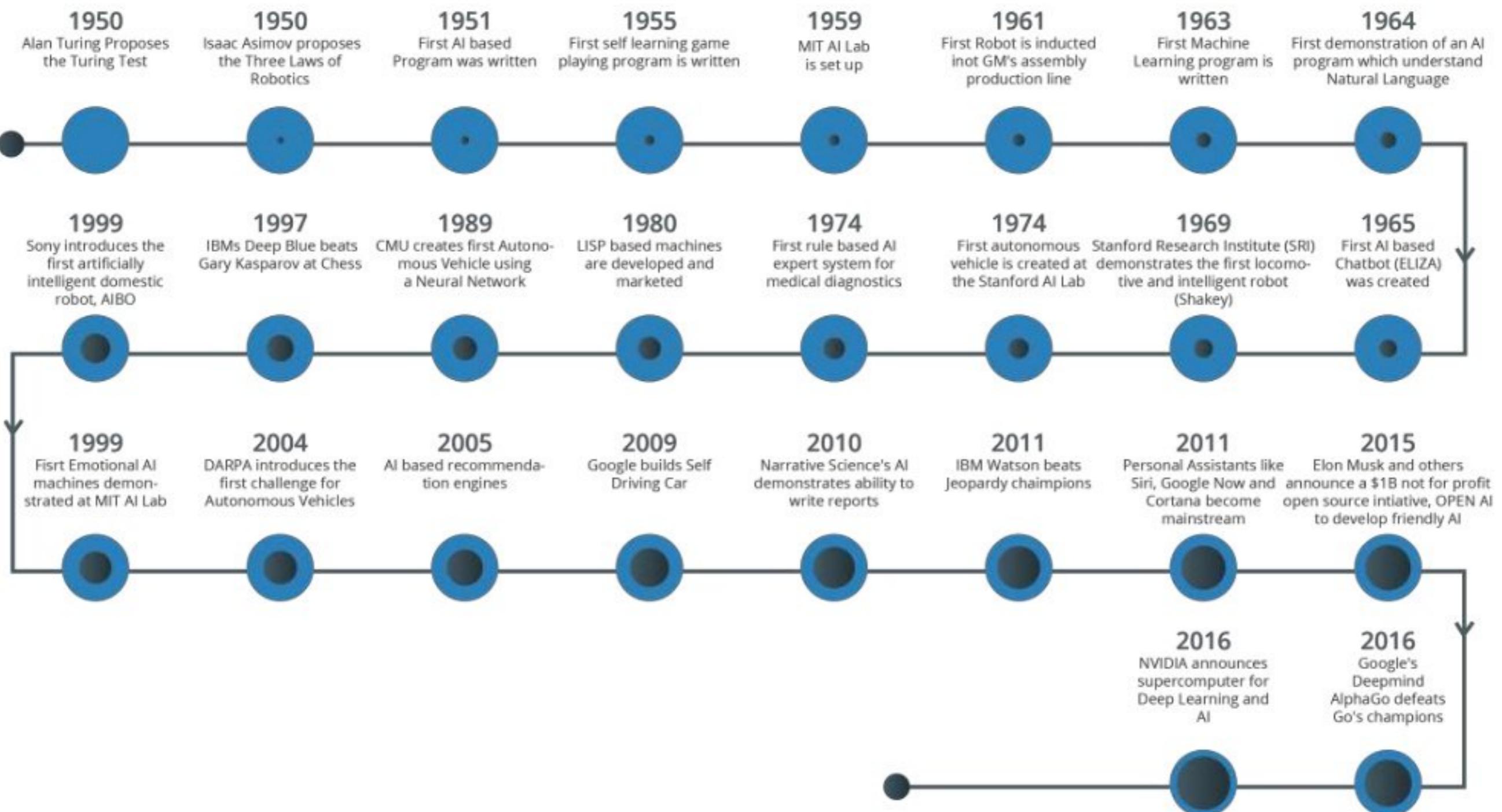


Requirements

<https://github.com/DataForScience/DeepLearning>



AI Key Milestone Events



Machine Learning



3 Types of Machine Learning

<https://github.com/bmtgoncalves/Neural-Networks/>

- Supervised Learning

- Predict output given input
- Training set of known inputs and outputs is provided

- Unsupervised Learning

- Autonomously learn an good representation of the dataset
- Find clusters in input

- Reinforcement Learning

- Learn sequence of actions to maximize payoff
- Discount factor for delayed rewards



3 Types of Machine Learning

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Optimization Problem

<https://github.com/bmtgoncalves/Neural-Networks/>

- (Machine) Learning can be thought of as an optimization problem.

- Optimization Problems have 3 distinct pieces:

- The constraints

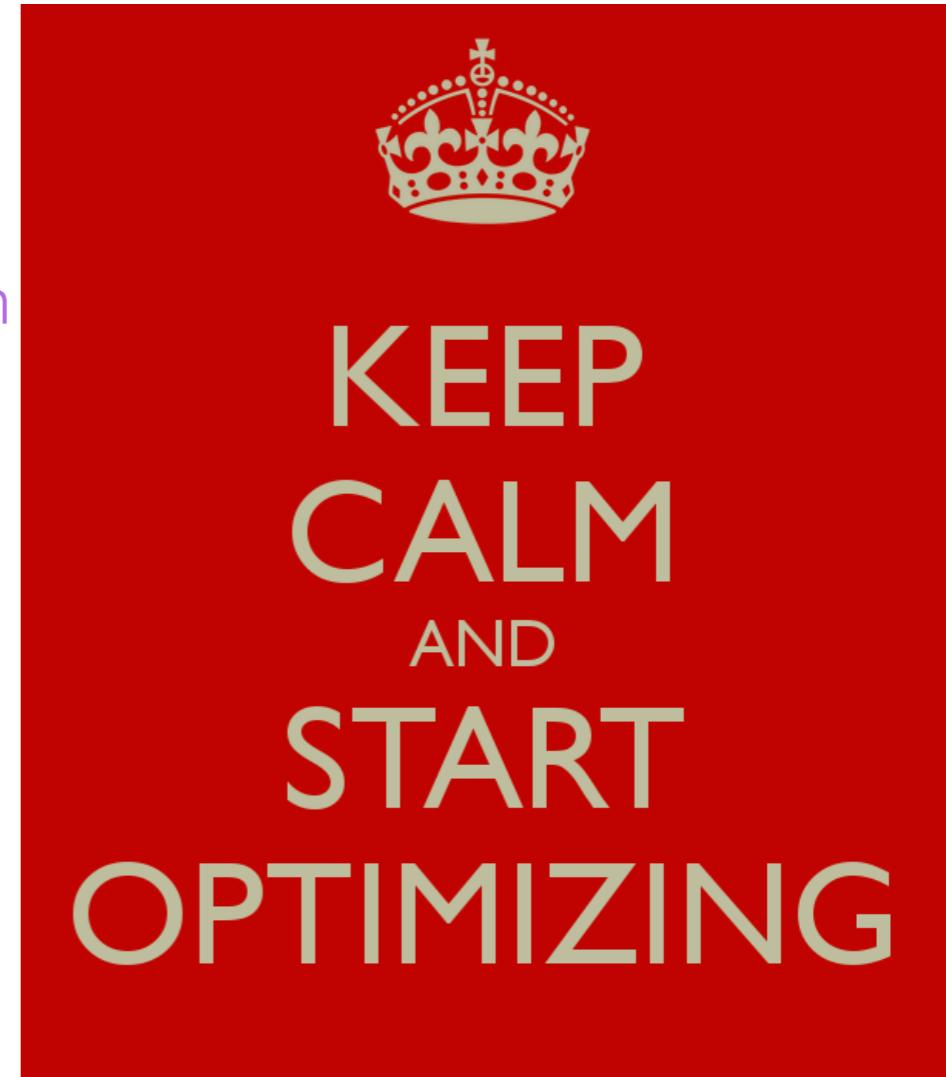
Problem Representation

- The function to optimize

Prediction Error

- The optimization algorithm.

Gradient Descent



Supervised Learning



Supervised Learning - Regression

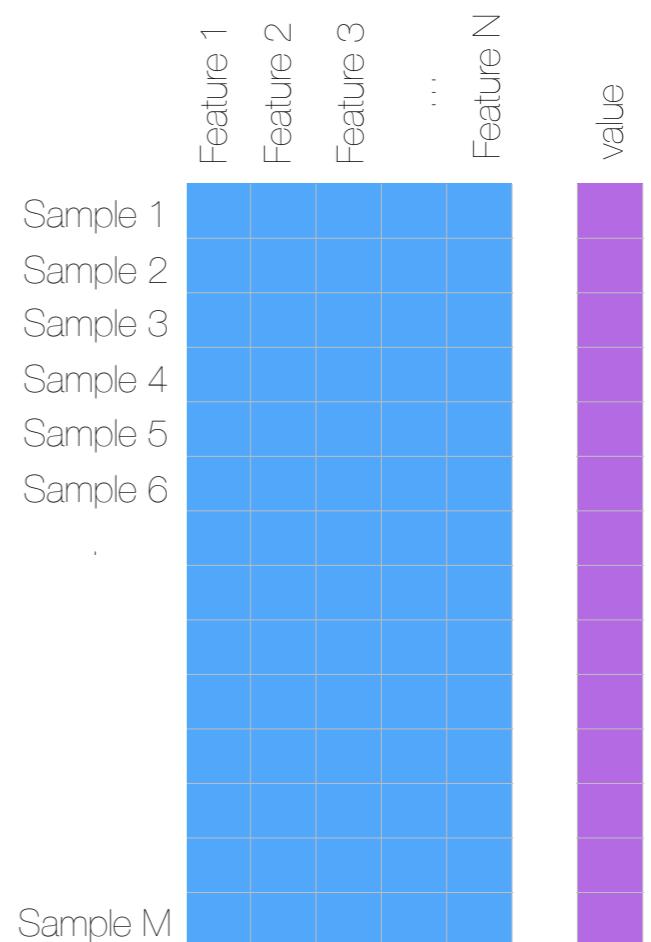
- Dataset formatted as an **MxN** matrix of **M** samples and **N** features
- Each sample corresponds to a specific **value** of the target variable
- The goal of **regression** is to predict or approximate the value of a function at previously unseen points

- Two fundamental types of problems:
 - **Regression (continuous output value)**
 - Classification (discrete output value)

| | Feature 1 | Feature 2 | Feature 3 | ... | Feature N |
|----------|-----------|-----------|-----------|-----|-----------|
| Sample 1 | | | | | |
| Sample 2 | | | | | |
| Sample 3 | | | | | |
| Sample 4 | | | | | |
| Sample 5 | | | | | |
| Sample 6 | | | | | |
| Sample M | | | | | |

Supervised Learning - Regression

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 - Linear Regression
 - Neural Networks

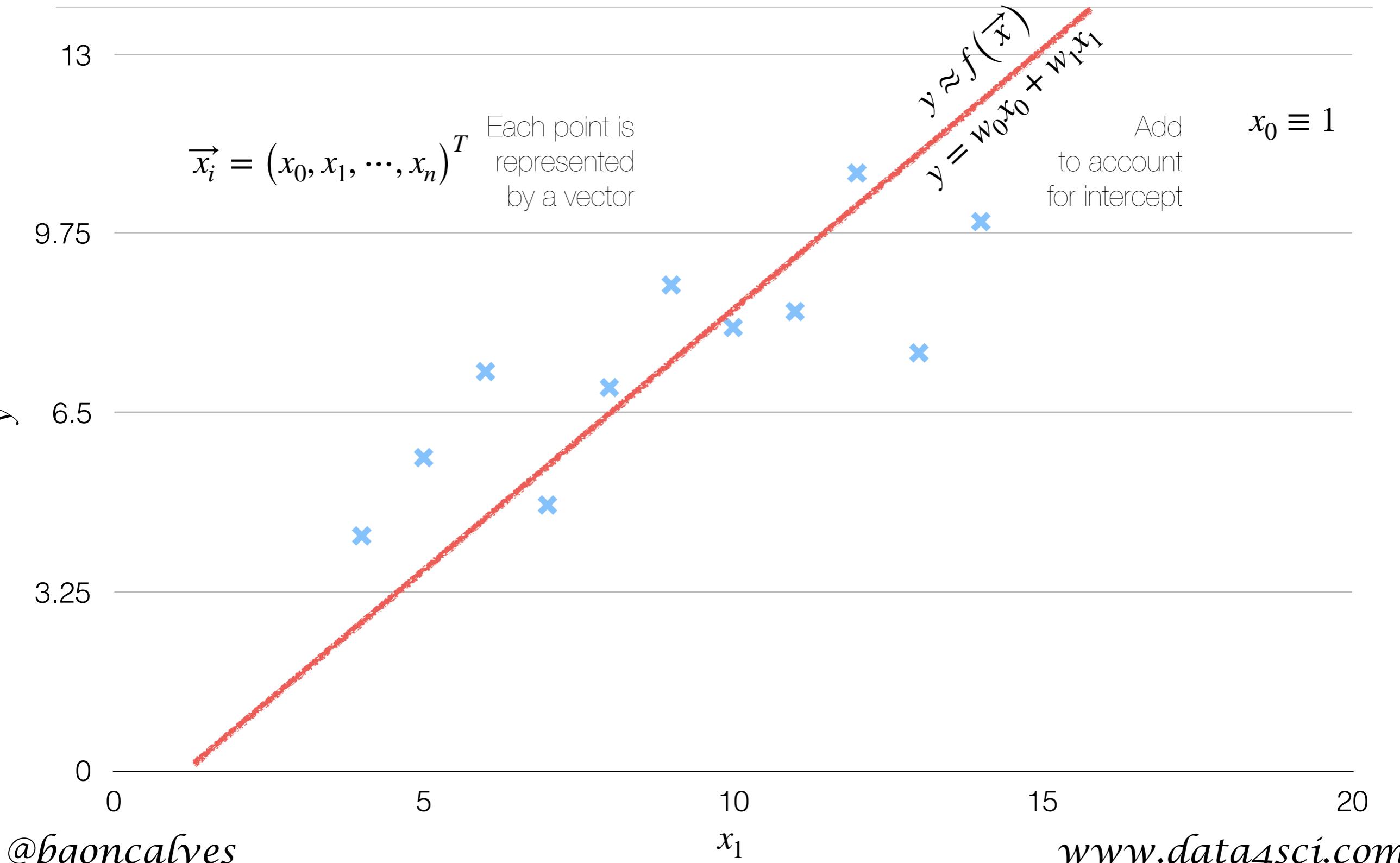


Supervised Learning - Regression

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| Sample 6 | | | | | | |
| Sample M | | | | | | |

Linear Regression



Linear Regression

- We are assuming that our functional dependence is of the form:

$$f(\vec{x}) = w_0 + w_1 x_1 + \cdots + w_n x_n \equiv X \vec{w}$$

- In other words, at each step, our **hypothesis** is:

$$h_w(X) = X \vec{w} \equiv \hat{y}$$

and it imposes a **Constraint** on the solutions that can be found.

- We quantify how far our hypothesis is from the correct value using an **Error Function**:

$$J_w(X, \vec{y}) = \frac{1}{2m} \sum_i [h_w(x^{(i)}) - y^{(i)}]^2$$

or, vectorially:

$$J_w(X, \vec{y}) = \frac{1}{2m} [X \vec{w} - \vec{y}]^2$$

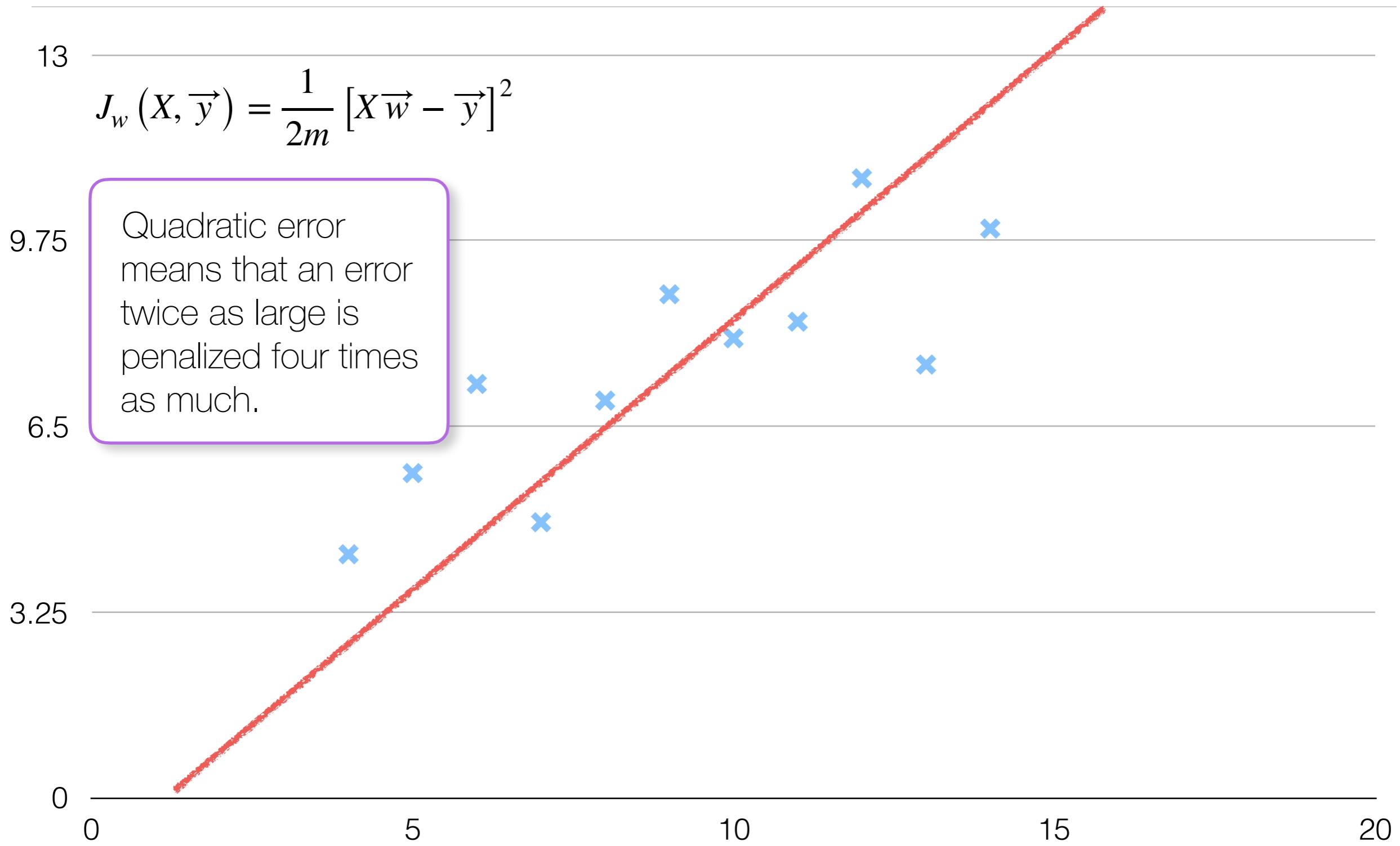


| | Feature 1 | Feature 2 | Feature 3 | ... | Feature N | value |
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| Sample 3 | | | | | | |
| Sample 4 | | | | | | |
| Sample 5 | | | | | | |
| Sample 6 | | | | | | |
| . | | | | | | |
| X | | | | | | |
| y | | | | | | |
| Sample M | | | | | | |

Geometric Interpretation

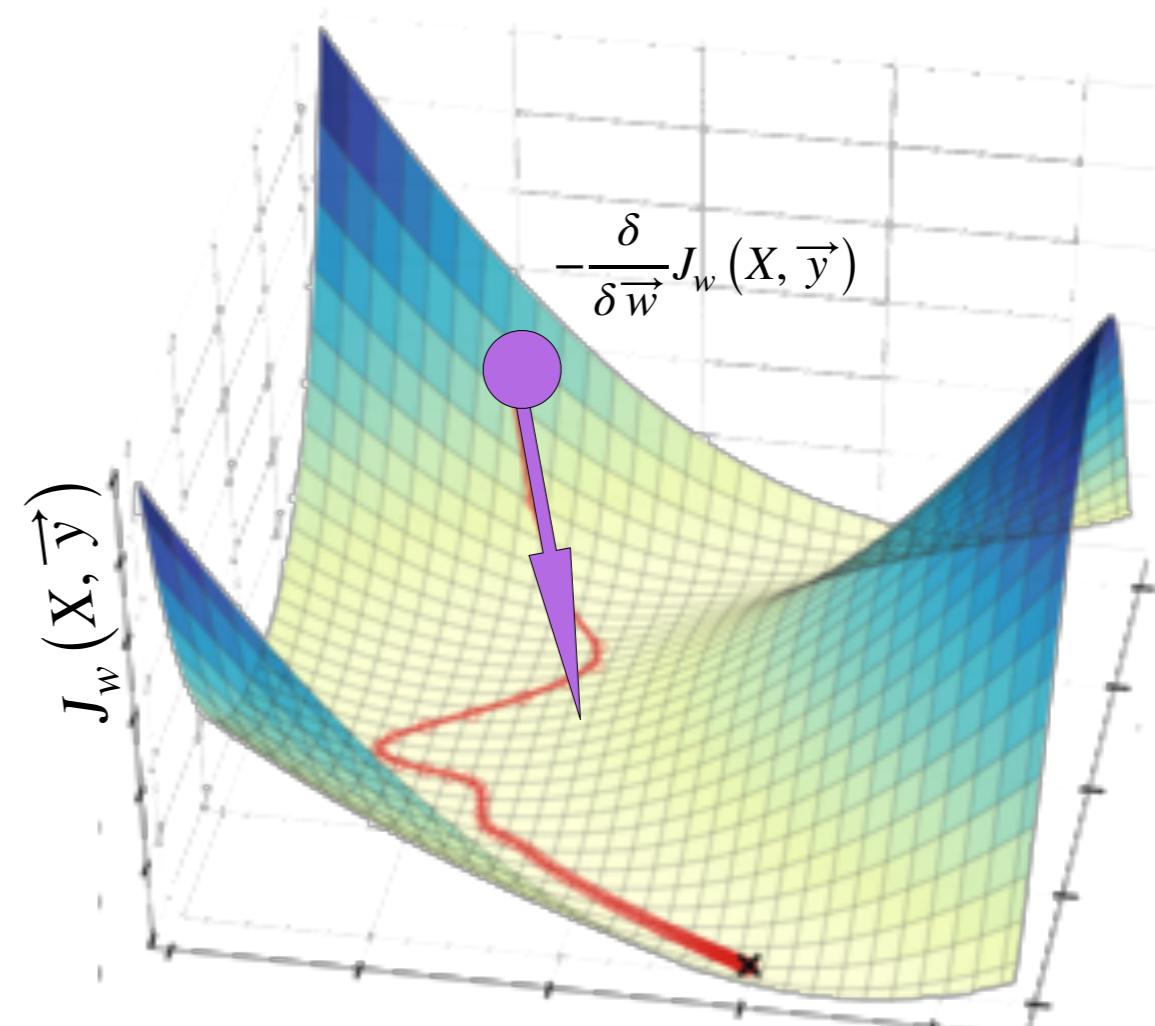
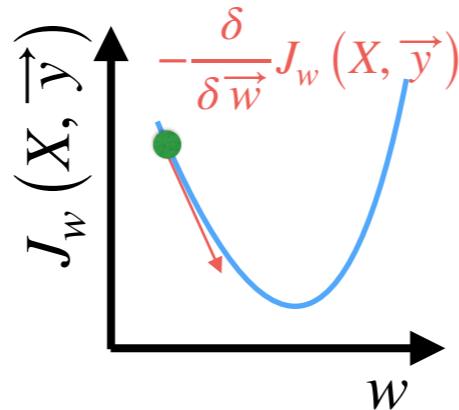
$$J_w(X, \vec{y}) = \frac{1}{2m} [X\vec{w} - \vec{y}]^2$$

Quadratic error means that an error twice as large is penalized four times as much.



Gradient Descent

- **Goal:** Find the minimum of $J_w(X, \vec{y})$ by varying the components of \vec{w}
- **Intuition:** Follow the slope of the error function until convergence



Algorithm:

- Guess $\vec{w}^{(0)}$ (initial values of the parameters)

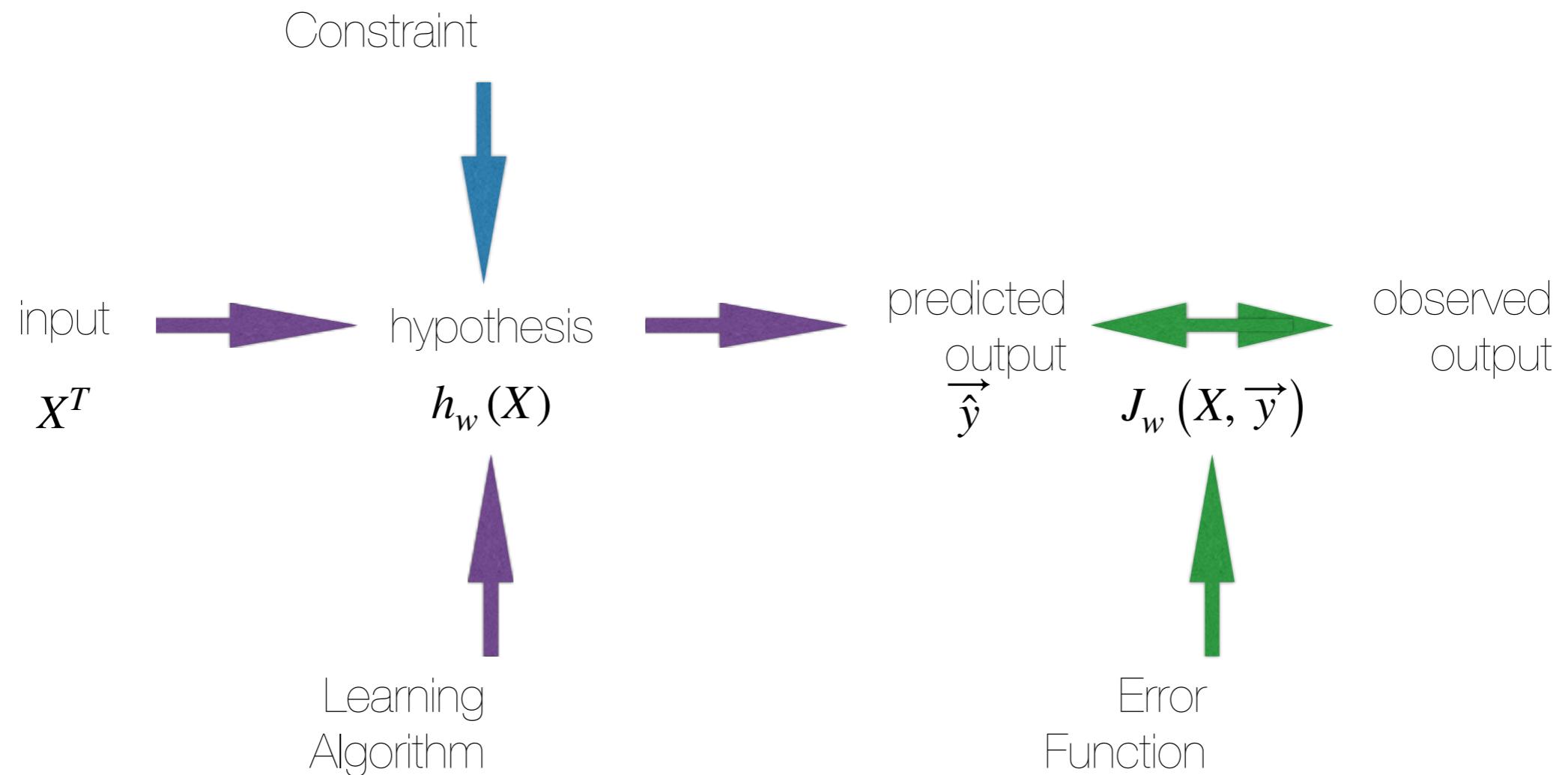
step size

- Update until "convergence":

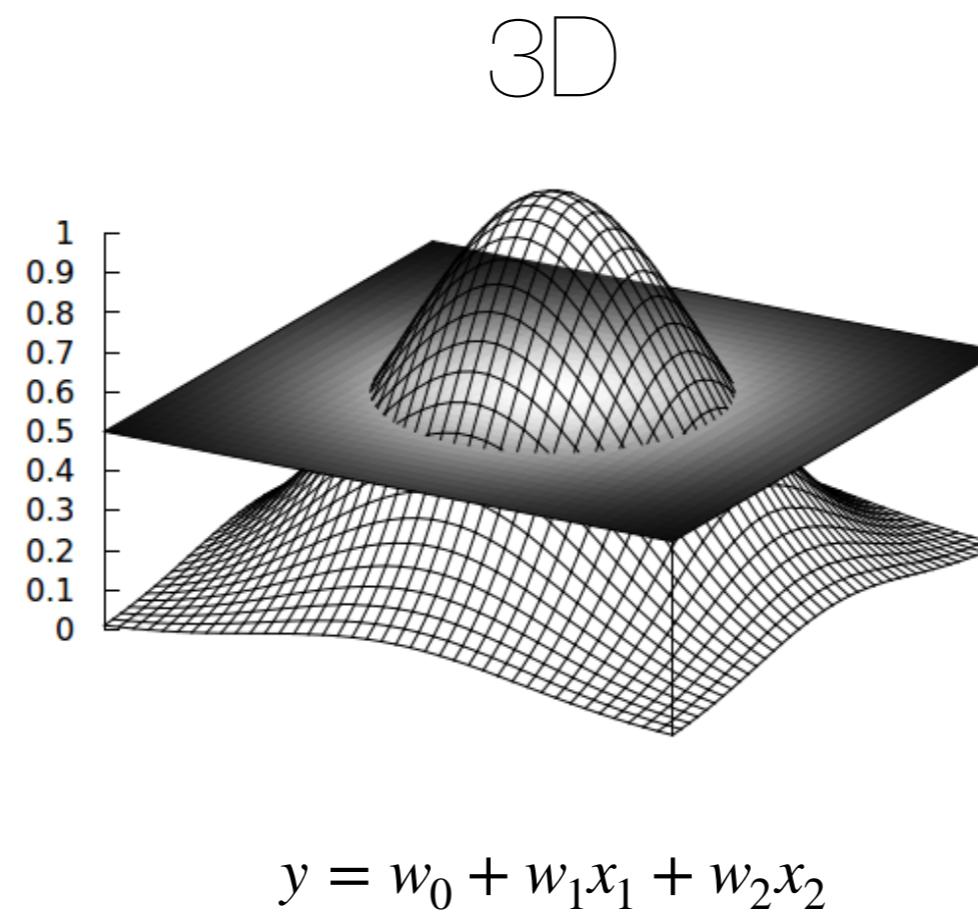
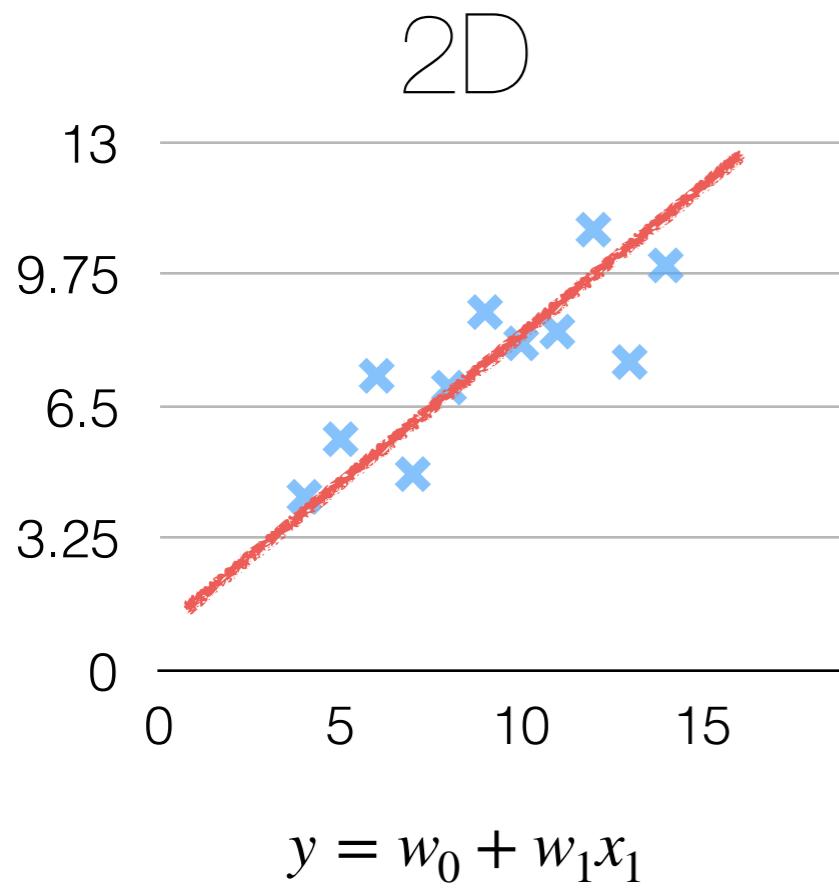
$$w_j = w_j - \alpha \frac{\delta}{\delta w_j} J_w(X, \vec{y})$$

$$\frac{\delta}{\delta w_j} J_w(X, \vec{y}) = \frac{1}{m} X^T \cdot (h_w(X) - \vec{y})$$

Learning Procedure



Geometric Interpretation



Finds the hyperplane that splits the points in two such that the errors on each side balance out

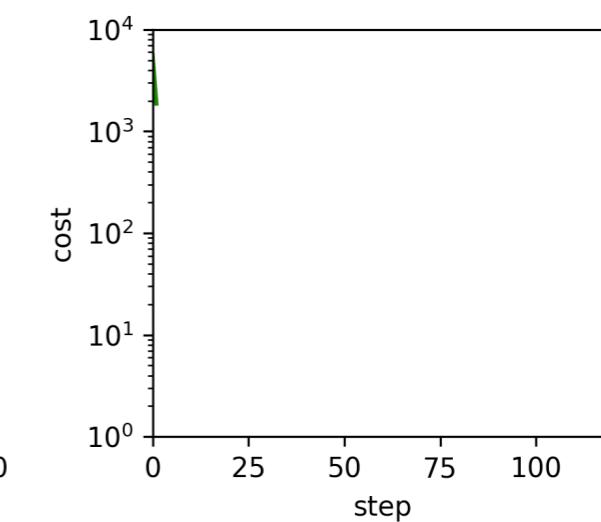
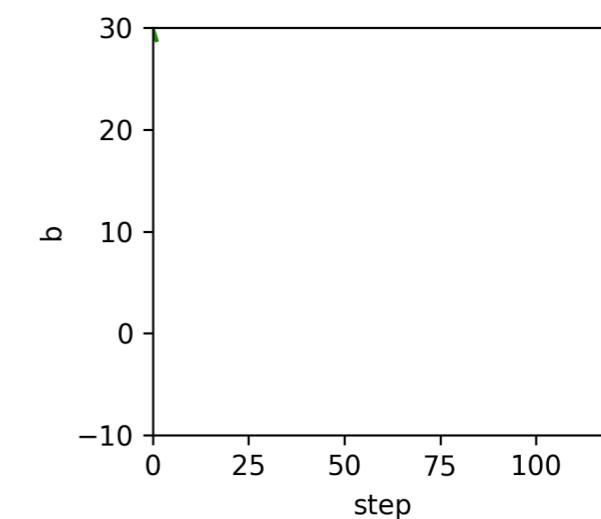
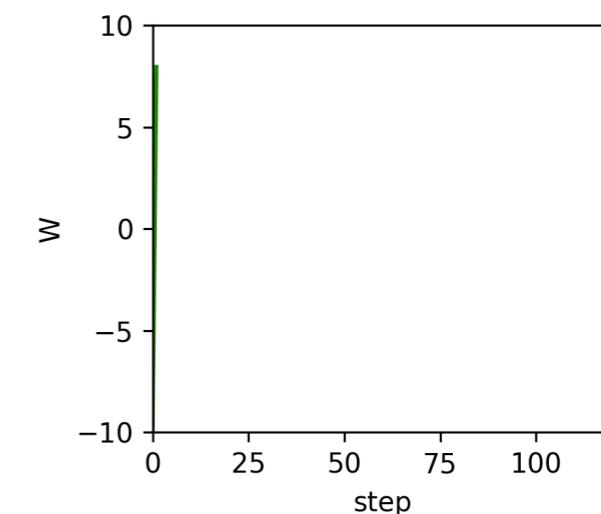
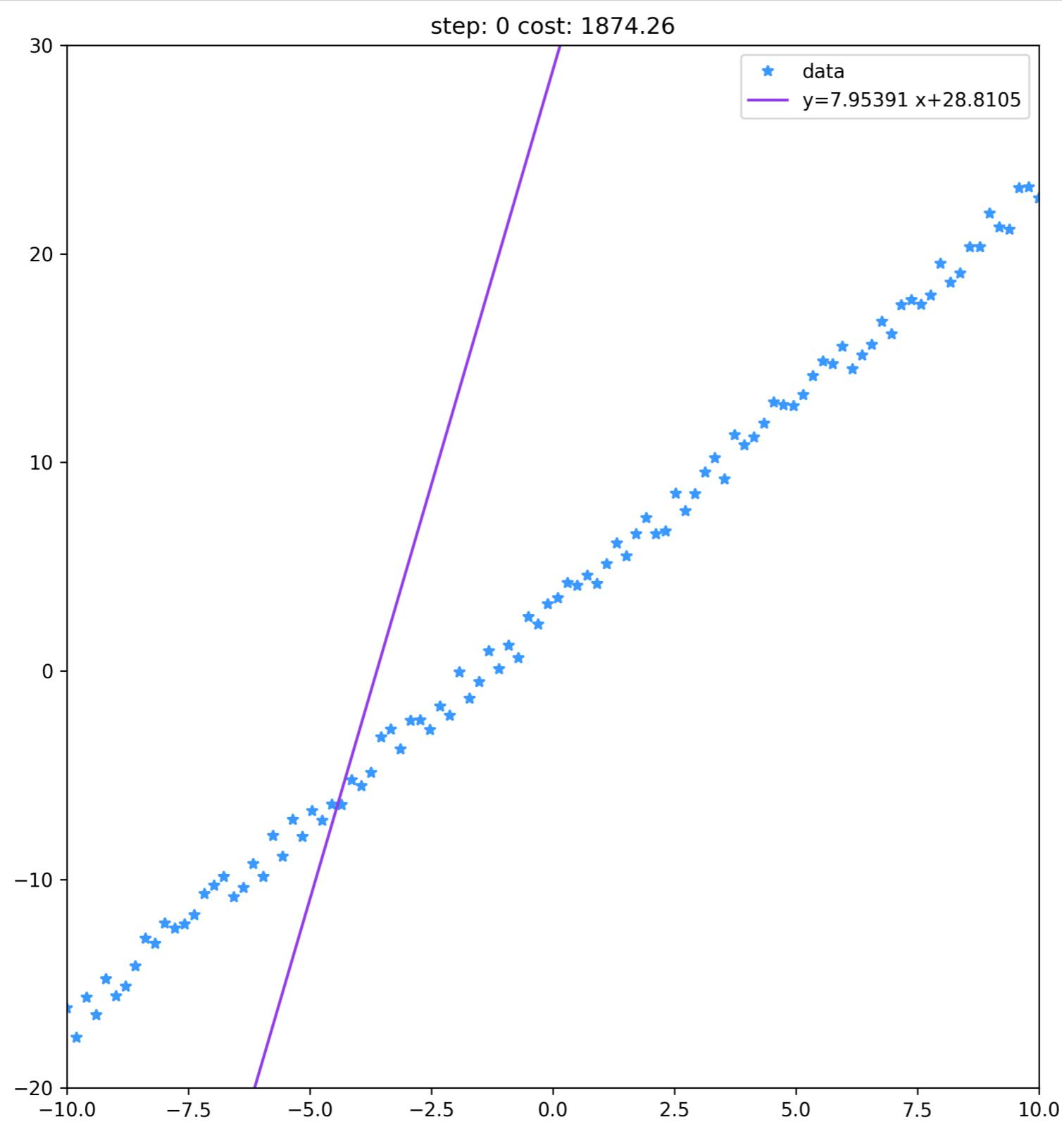
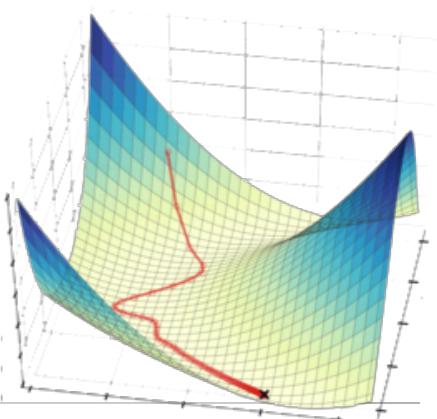
Add to account for intercept

$$x_0 \equiv 1$$

Code - Linear Regression

<https://github.com/DataForScience/DeepLearning>

Linear Regression



Supervised Learning - Classification

- Dataset formatted as an $N \times M$ matrix of N samples and M features
- Each sample belongs to a specific **class** or has a specific **label**.
- The goal of classification is to predict to which class a previously unseen sample belongs to by learning defining regularities of each class
 - Logistic Regression
 - Neural Networks
- Two fundamental types of problems:
 - Regression (continuous output value)
 - Classification (discrete output value)

| | Feature 1 | Feature 2 | Feature 3 | ... | Feature M | label |
|----------|-----------|-----------|-----------|-----|-----------|-------|
| Sample 1 | | | | | | |
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| Sample 3 | | | | | | |
| Sample 4 | | | | | | |
| Sample 5 | | | | | | |
| Sample 6 | | | | | | |
| ... | | | | | | |
| Sample N | | | | | | |

Logistic Regression (Classification)

- Not actually regression, but rather Classification
- Predict the probability of instance belonging to the given class:

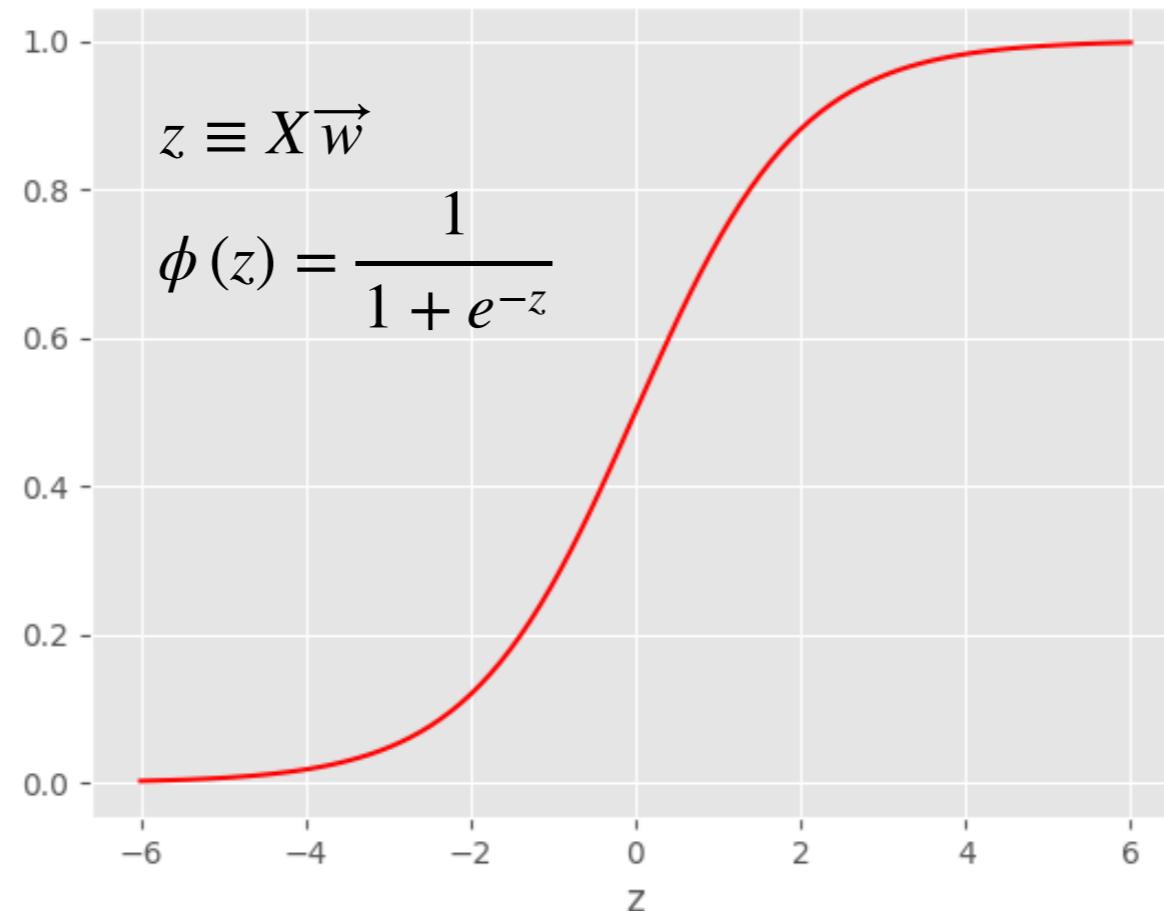
$$h_w(X) \in [0,1]$$

- Use **sigmoid/logistic** function to map weighted inputs to $[0,1]$

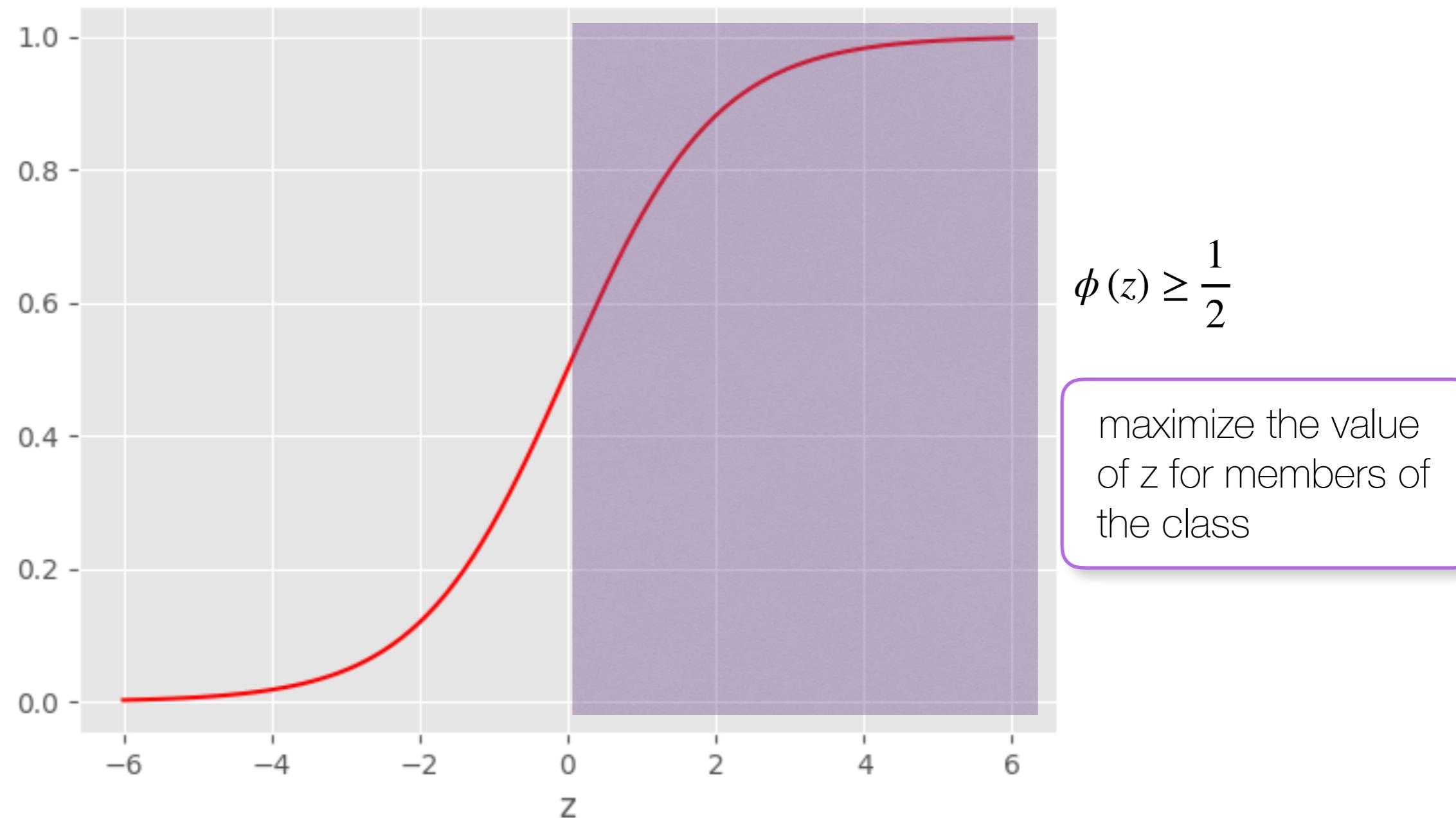
$$h_w(X) = \phi(X\vec{w})$$

1 - part of the class
0 - otherwise

z encapsulates all the parameters and input values



Geometric Interpretation



Logistic Regression

- **Error Function** - Cross Entropy

$$J_w(X, \vec{y}) = -\frac{1}{m} \left[y^T \log(h_w(X)) + (1-y)^T \log(1-h_w(X)) \right]$$

measures the “distance” between two probability distributions

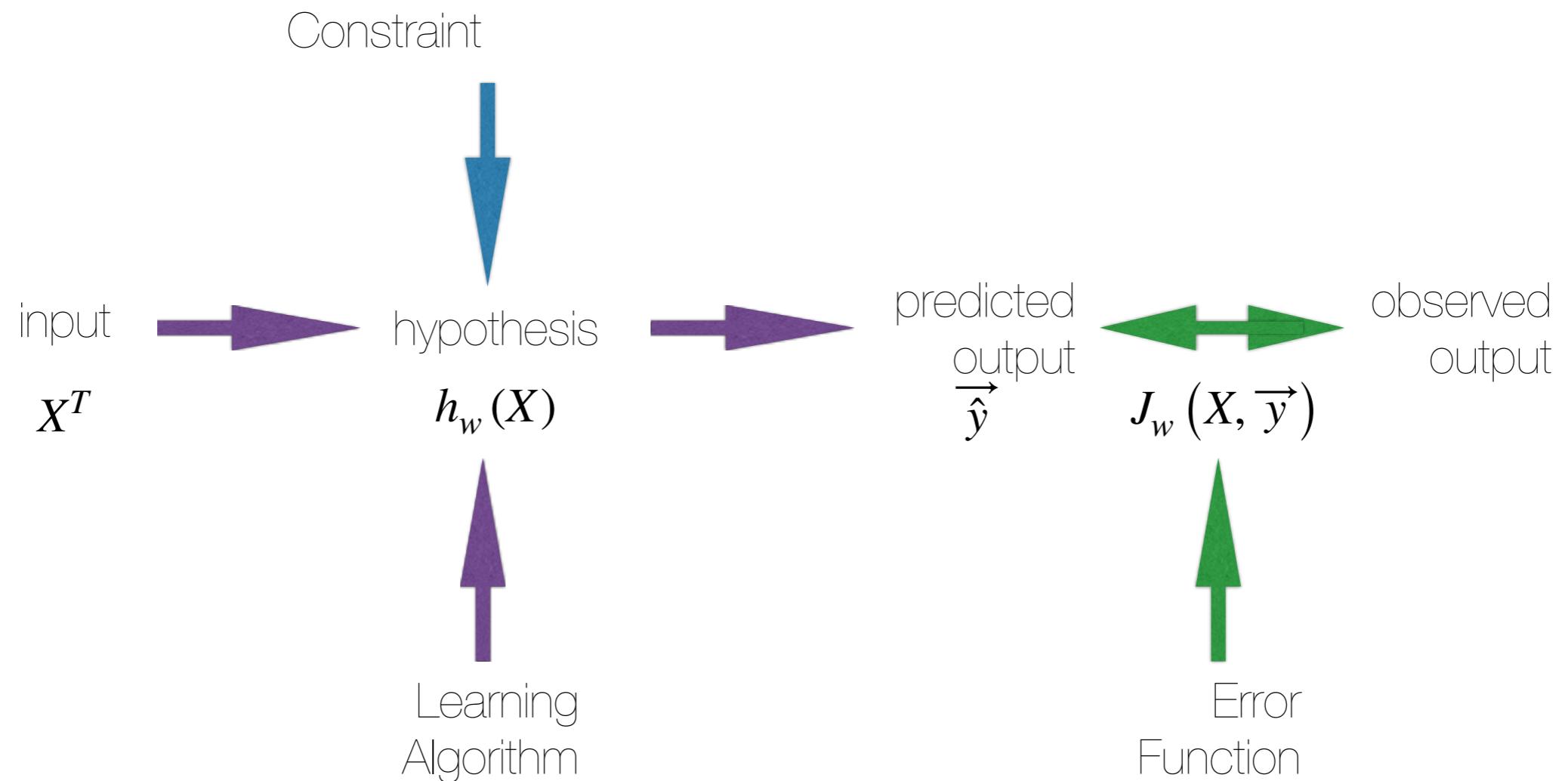
$$h_w(X) = \frac{1}{1 + e^{-X^T w}}$$

- Effectively **treating the labels as probabilities** (an instance with label=1 has Probability 1 of belonging to the class).
- **Gradient** - same as Logistic Regression

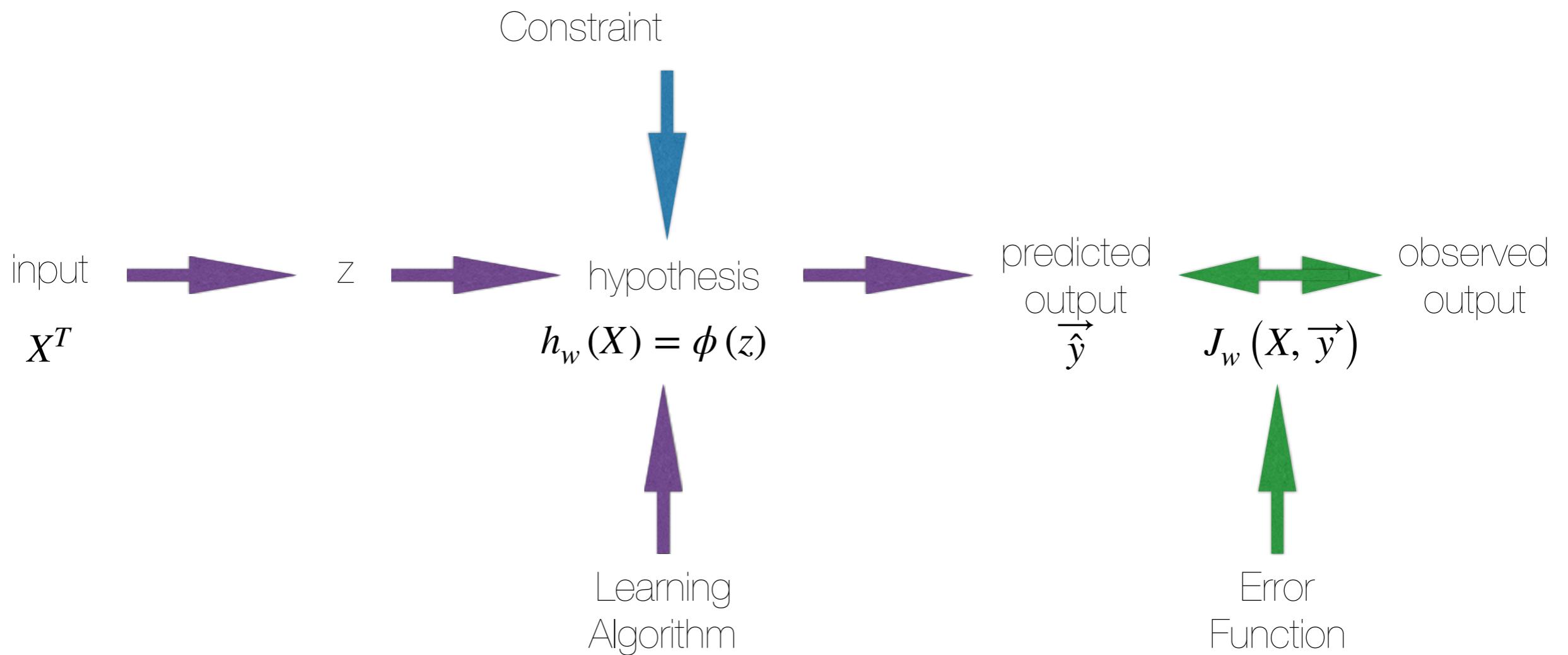
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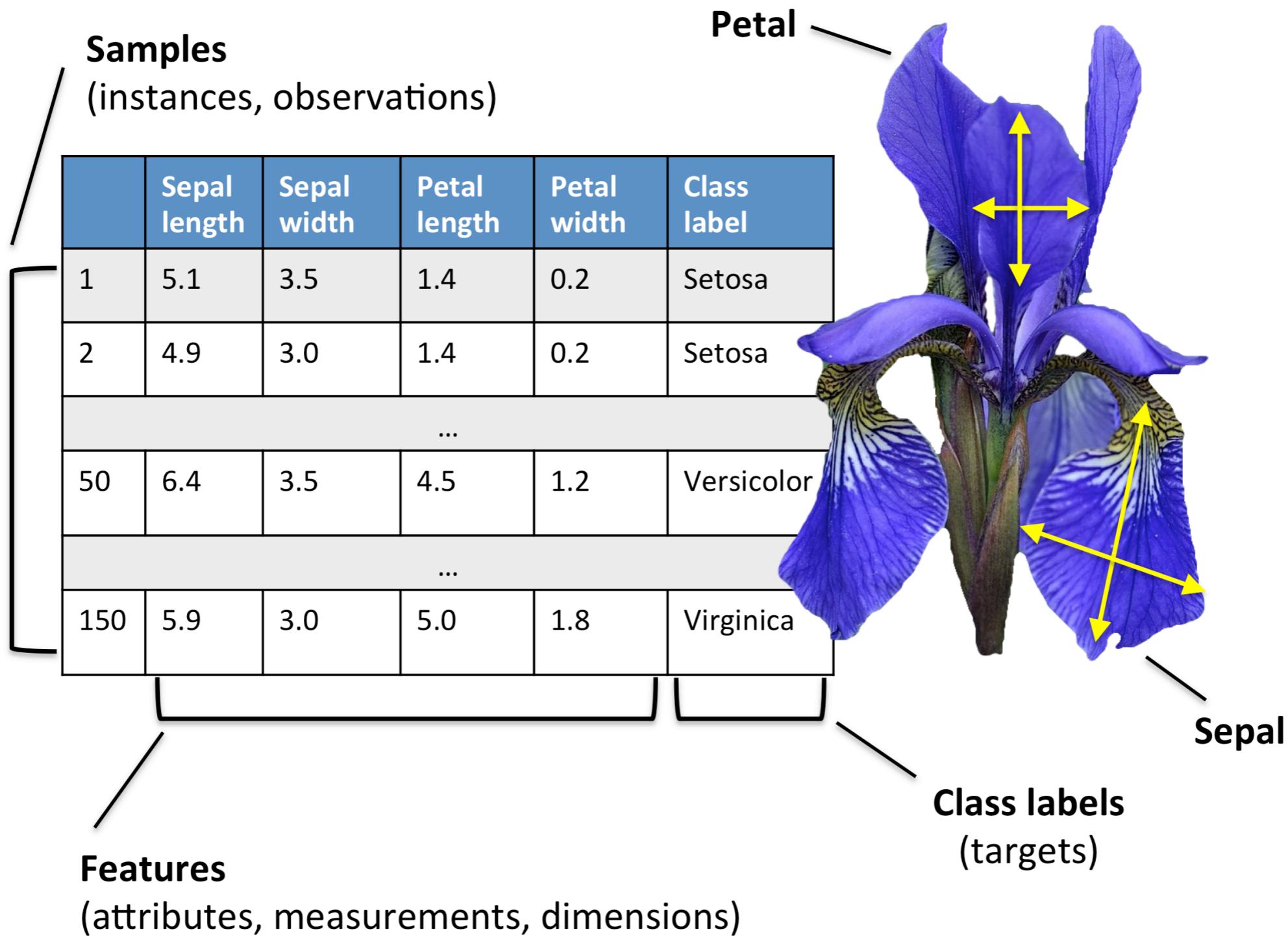
Learning Procedure



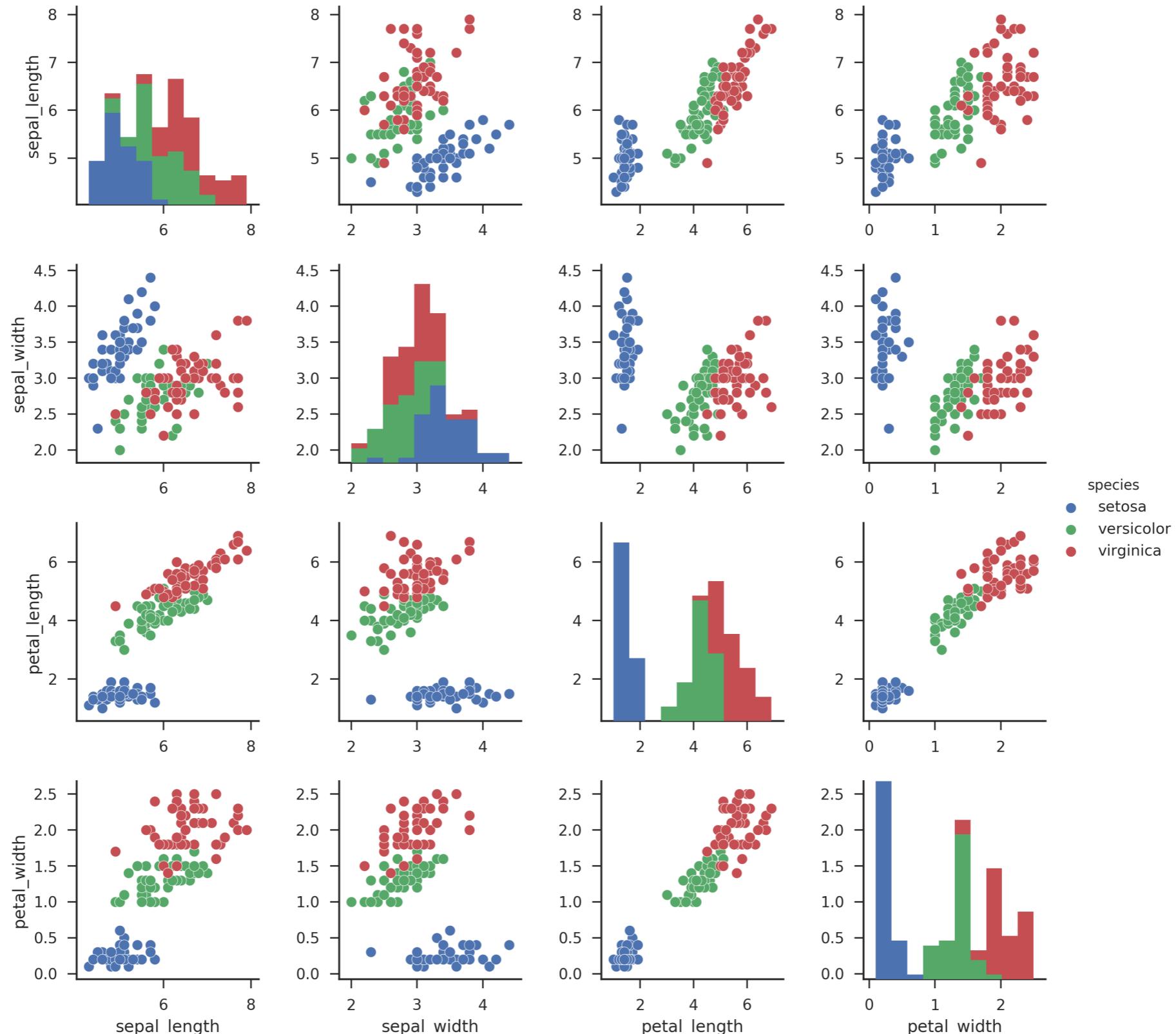
Learning Procedure



Iris dataset



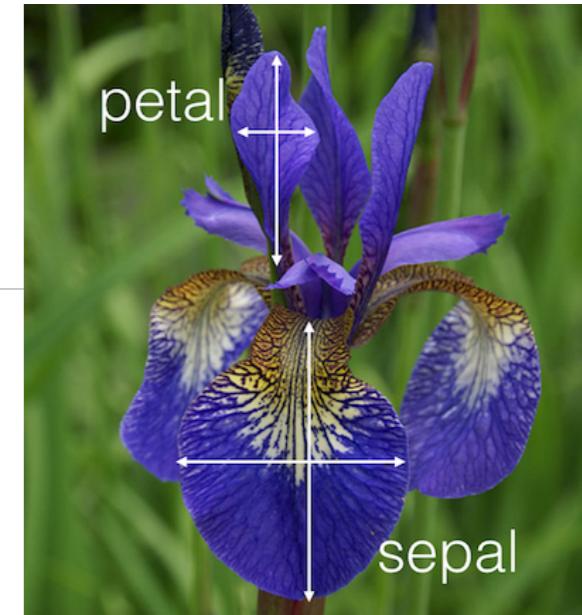
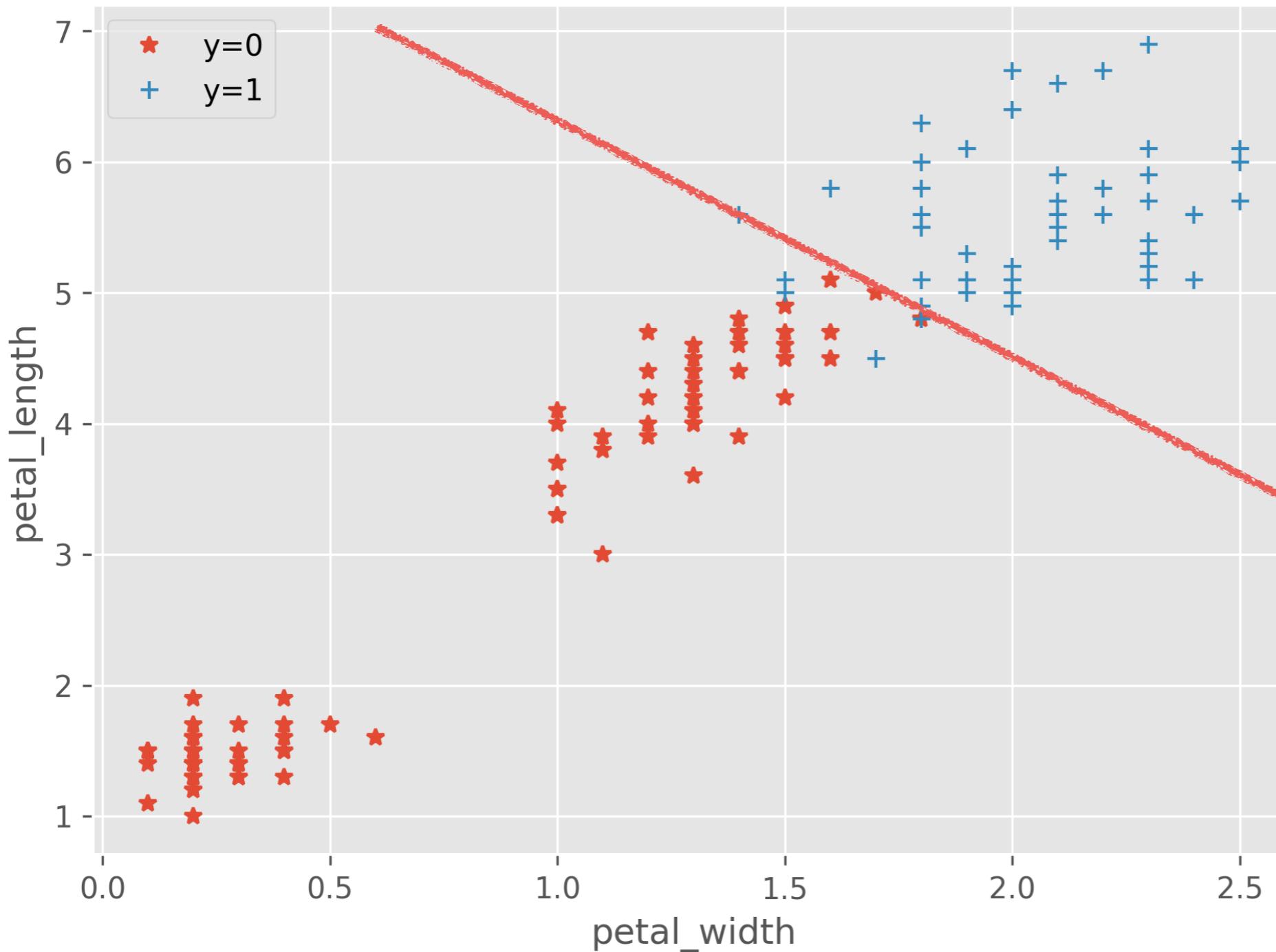
Iris dataset



Code - Logistic Regression

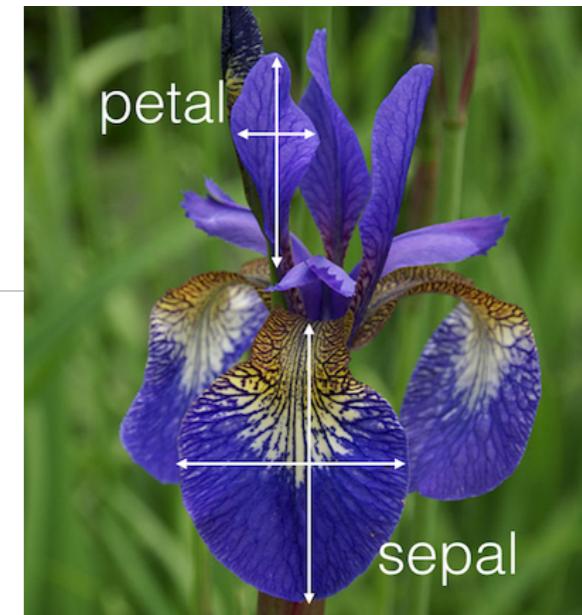
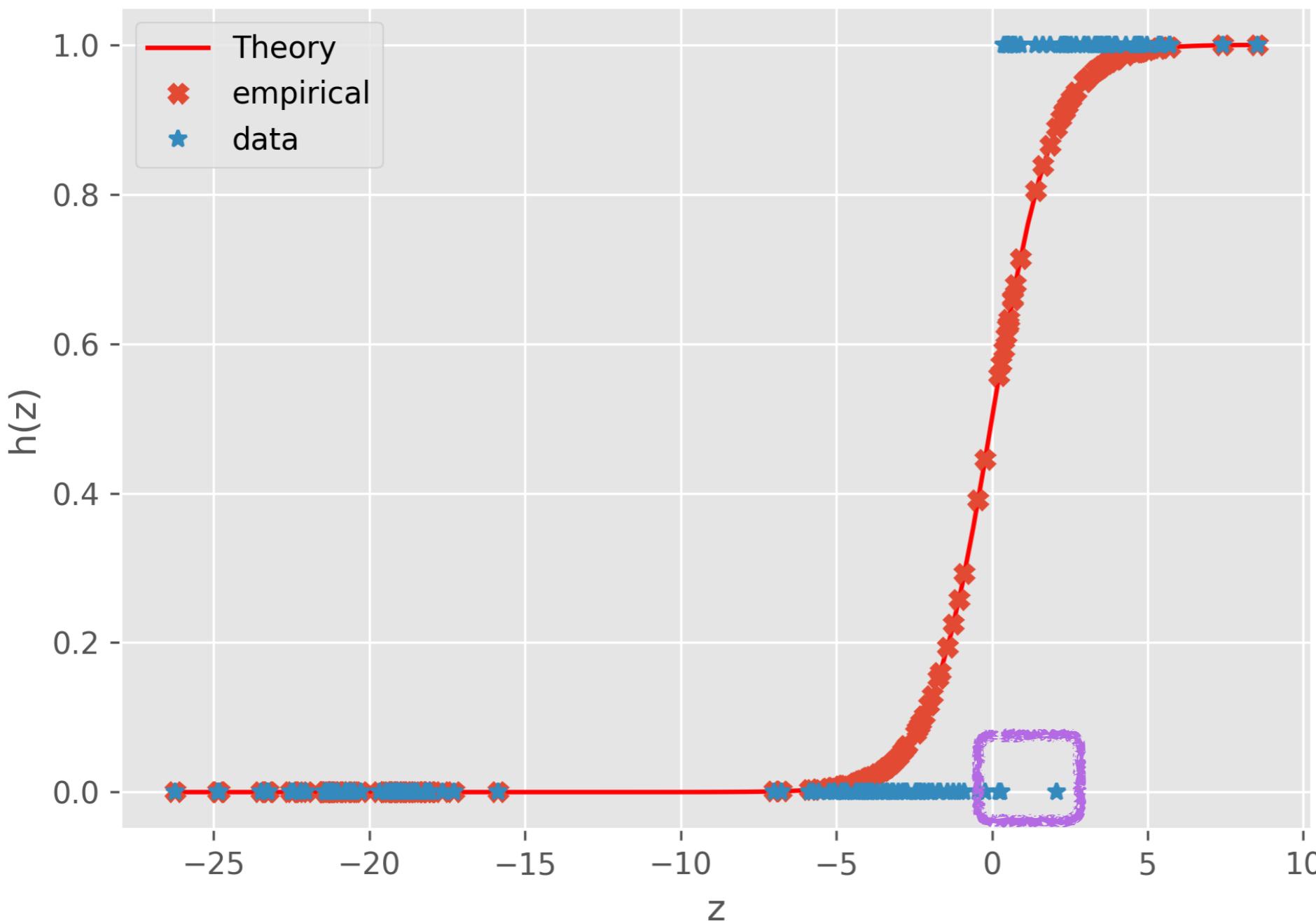
<https://github.com/DataForScience/DeepLearning>

Logistic Regression



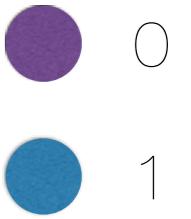
Logistic Regression

Logistic Regression



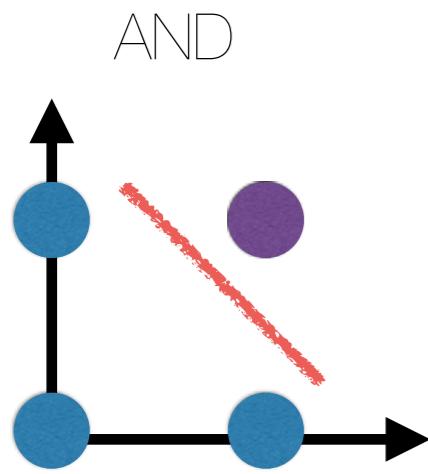
Practical Considerations

- So far we have looked at very idealized cases. Reality is never this simple!
- In practice, many details have to be considered:
 - Data normalization
 - Overfitting
 - Hyperparameters
 - Bias, Variance tradeoffs
 - etc...

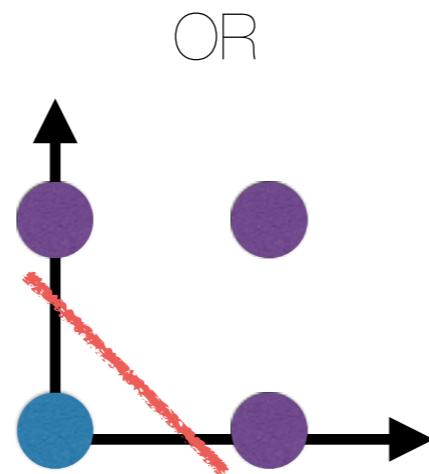


Linear boundaries

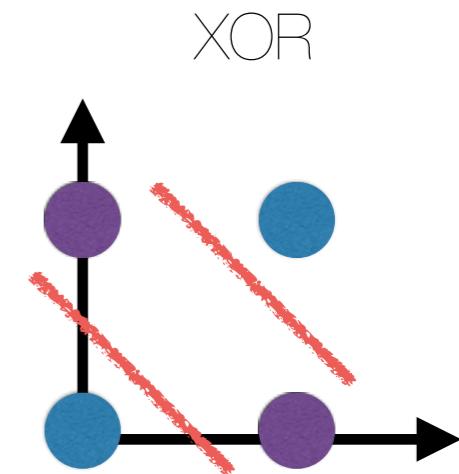
- Both Linear Regression and Logistic Regression rely on hyperplanes to separate the data points. Unfortunately, this is not always possible:



Possible



Possible



Impossible

Data Normalization

<https://github.com/bmtgoncalves/Neural-Networks/>

- The range of raw data values can vary widely.
- Using feature with very different ranges in the same analysis can cause numerical problems.
Many algorithms are linear or use euclidean distances that are heavily influenced by the numerical values used (cm vs km, for example)
- To avoid difficulties, it's common to rescale the range of all features in such a way that each feature follows within the same range.
- Several possibilities:
 - Rescaling - $\hat{x} = \frac{x - x_{min}}{x_{max} - x_{min}}$
 - Standardization - $\hat{x} = \frac{x - \mu_x}{\sigma_x}$
 - Normalization - $\hat{x} = \frac{x}{\|x\|}$
- In the rest of the discussion we will assume that the data has been normalized in some suitable way

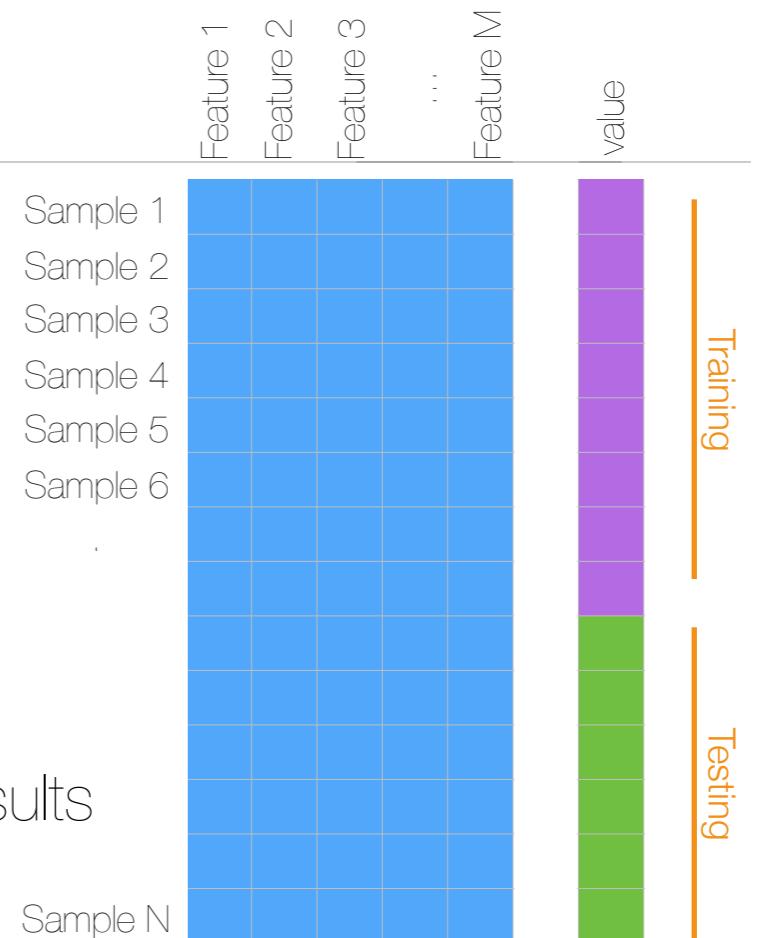
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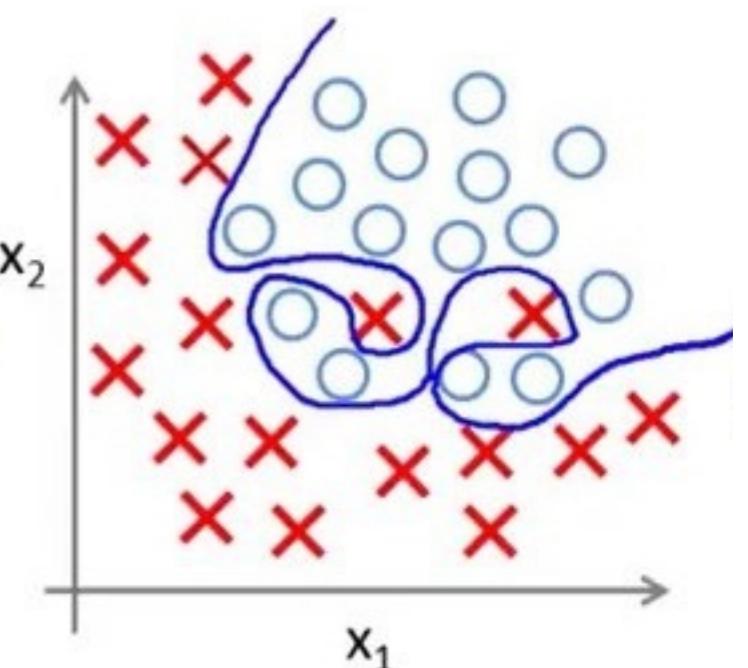
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Supervised Learning - Overfitting

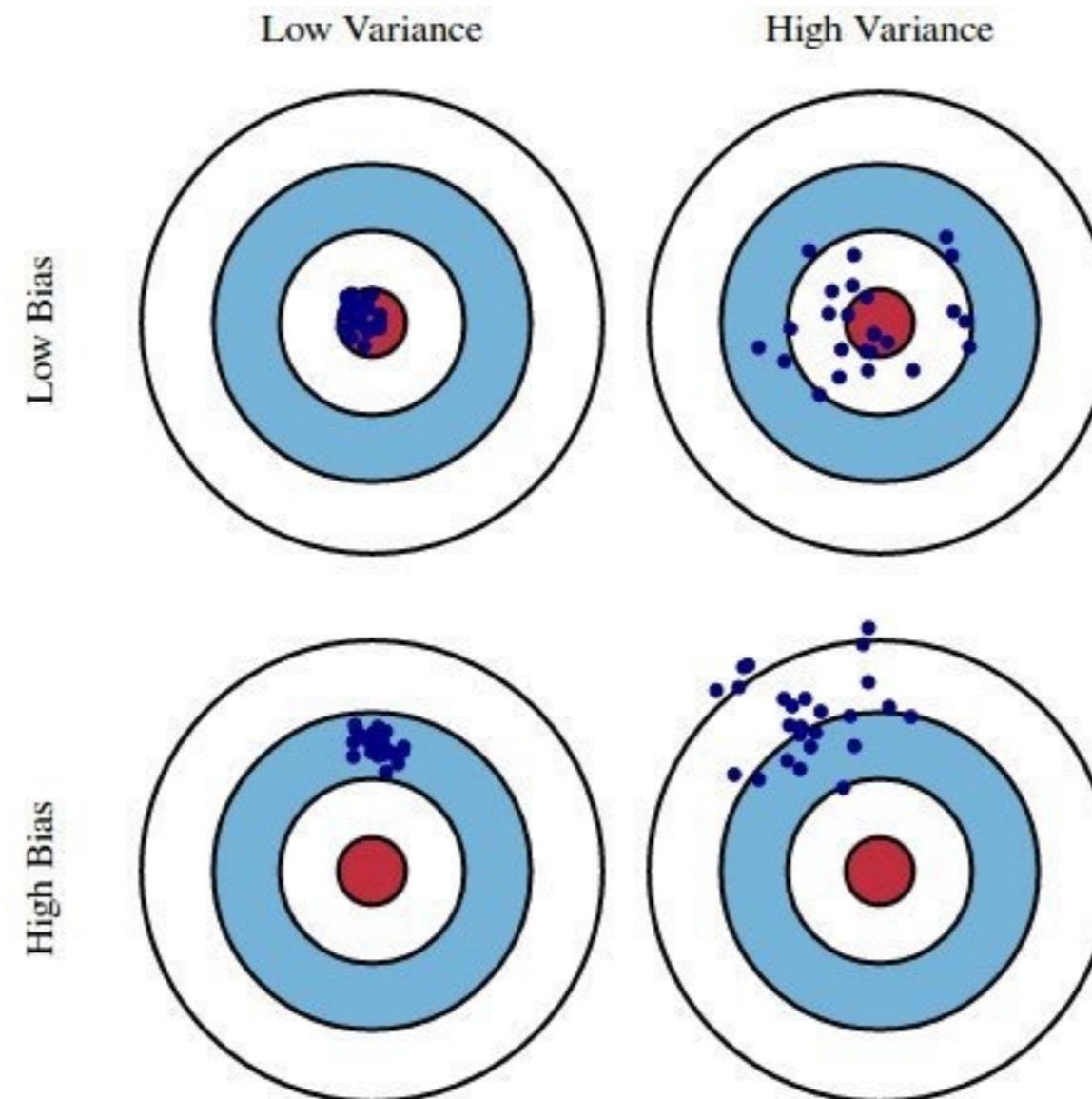
- "Learning the noise"
- "**Memorization**" instead of "generalization"
- How can we prevent it?
 - Split dataset into two subsets: **Training** and **Testing**
 - Train model using only the **Training** dataset and evaluate results in the previously unseen **Testing** dataset.



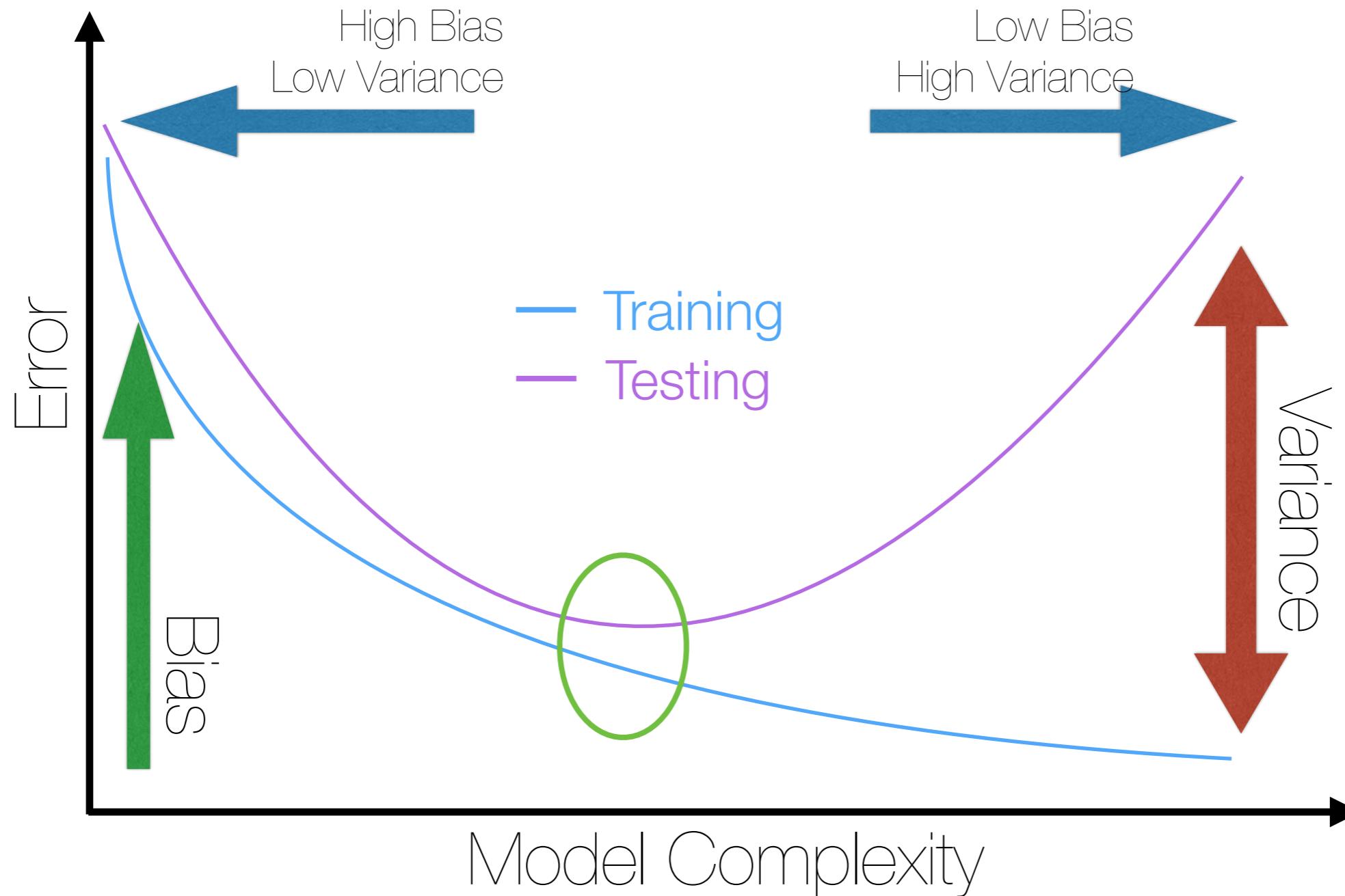
- Different heuristics on how to split:
 - Single split
 - k-fold cross validation: split dataset in **k** parts, train in **k-1** and evaluate in **1**, repeat **k** times and average results.



Bias-Variance Tradeoff



Bias-Variance Tradeoff



Comparison

- Linear Regression

$$z = X \vec{w}$$

$$h_w(X) = \phi(Z)$$

- Logistic Regression

$$z = X \vec{w}$$

$$h_w(X) = \phi(Z)$$

Map features to a continuous variable

Compare prediction with reality

$$\phi(Z) = Z$$

$$\phi(Z) = \frac{1}{1 + e^{-Z}}$$

Predict based on continuous variable



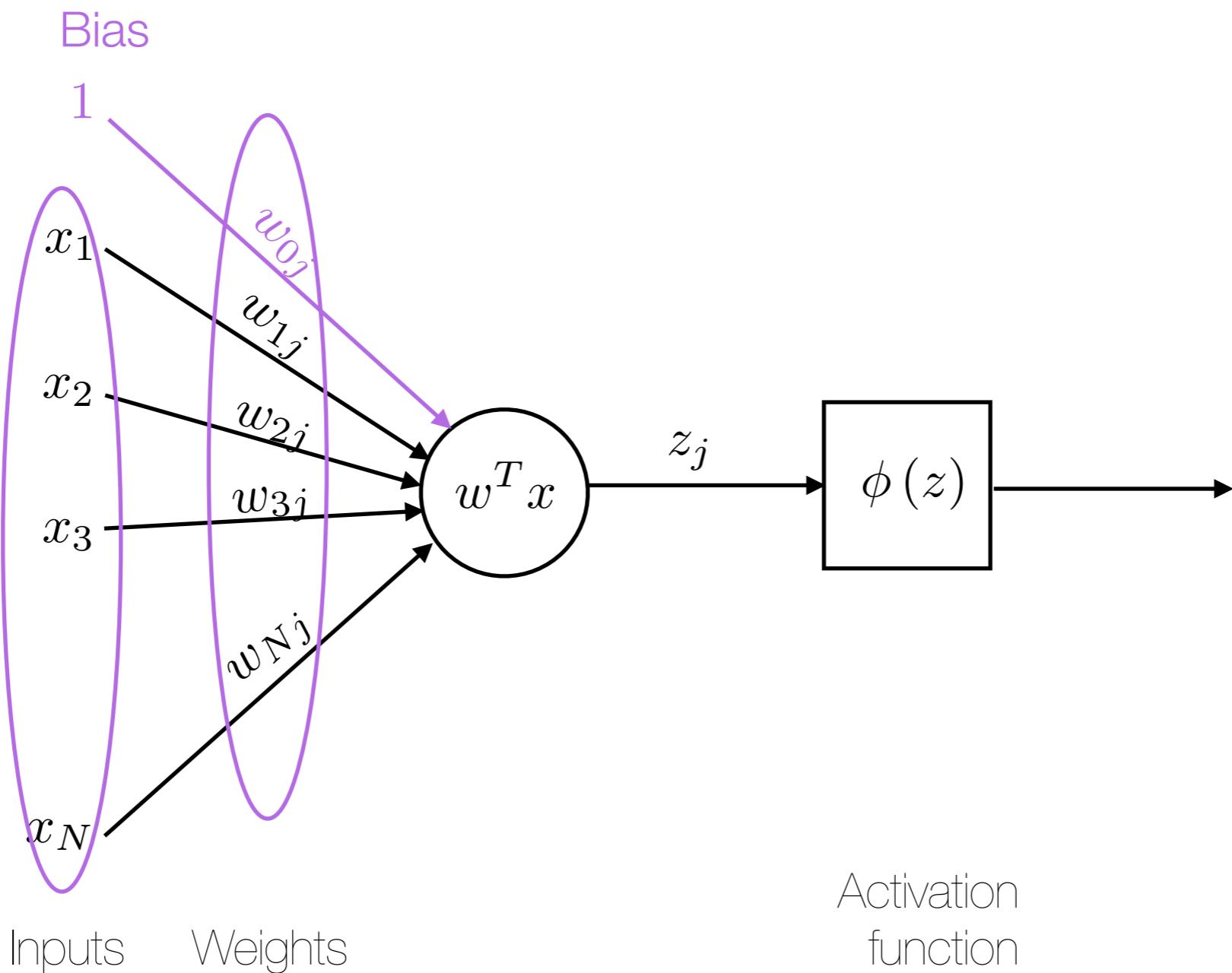
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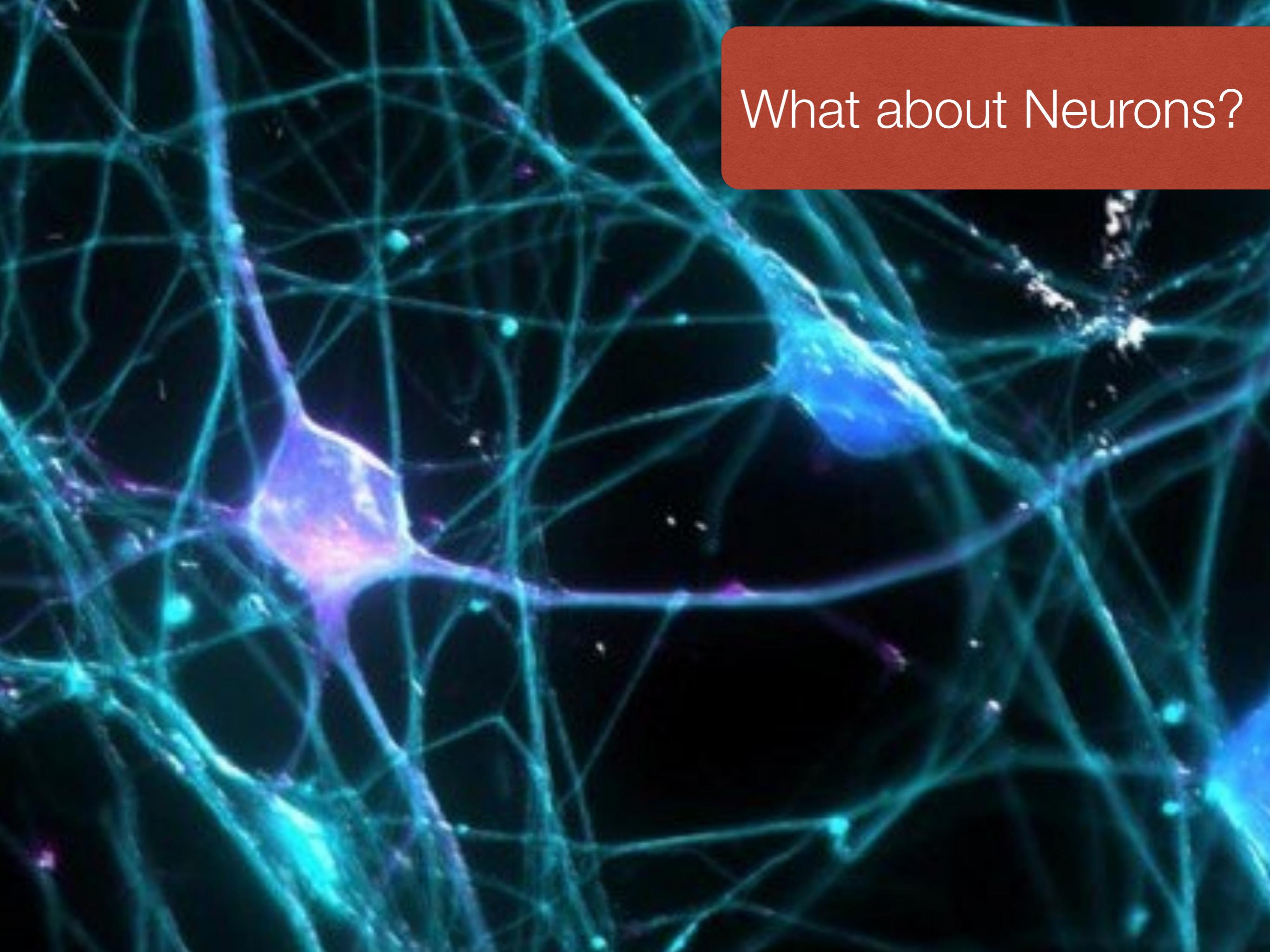
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$$\frac{\delta}{\delta w_j} J_w(X, \vec{y}) = \frac{1}{m} X^T \cdot (h_w(X) - \vec{y})$$

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Similar Structure



A dense network of glowing blue and purple neurons against a dark background.

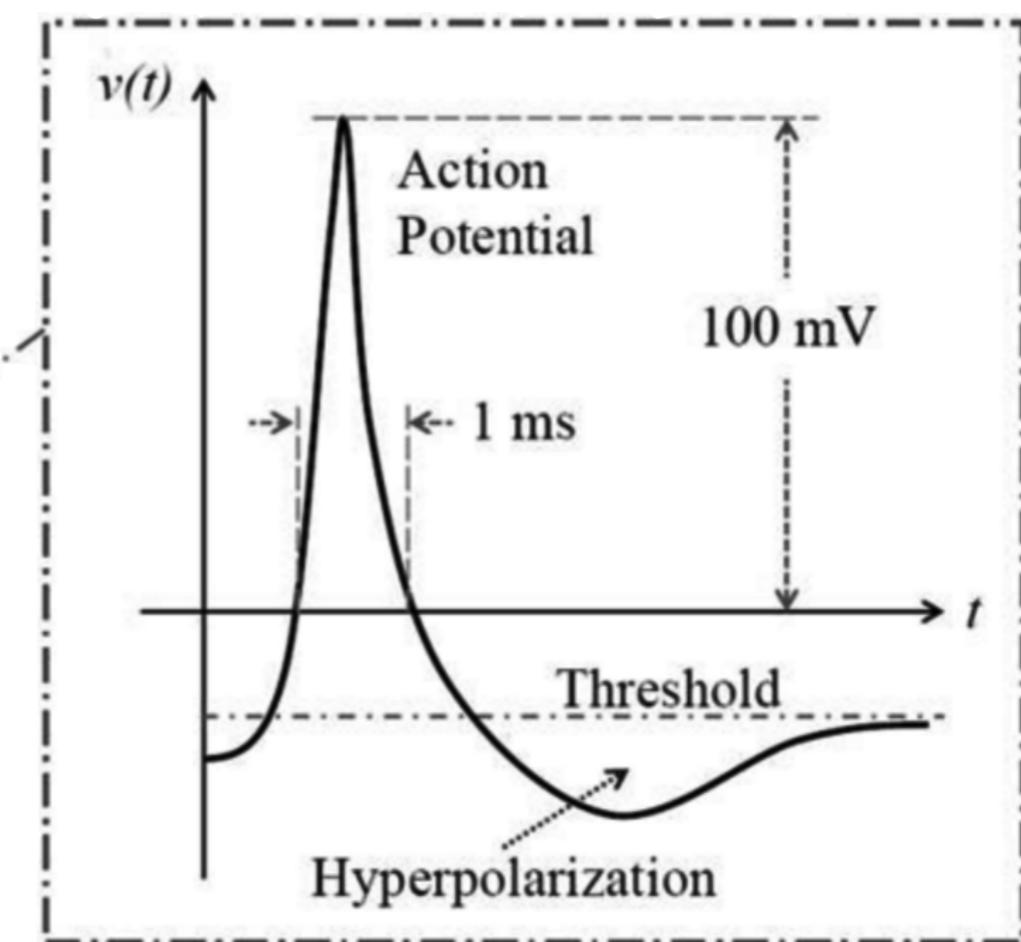
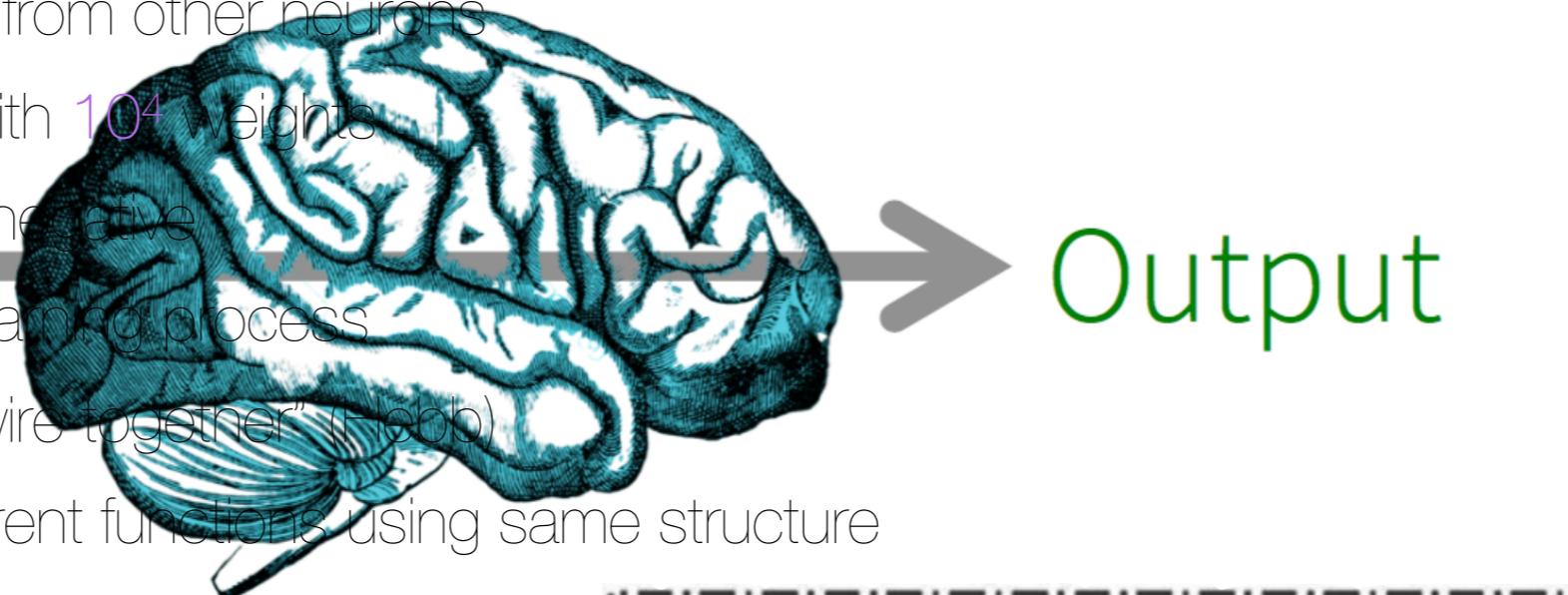
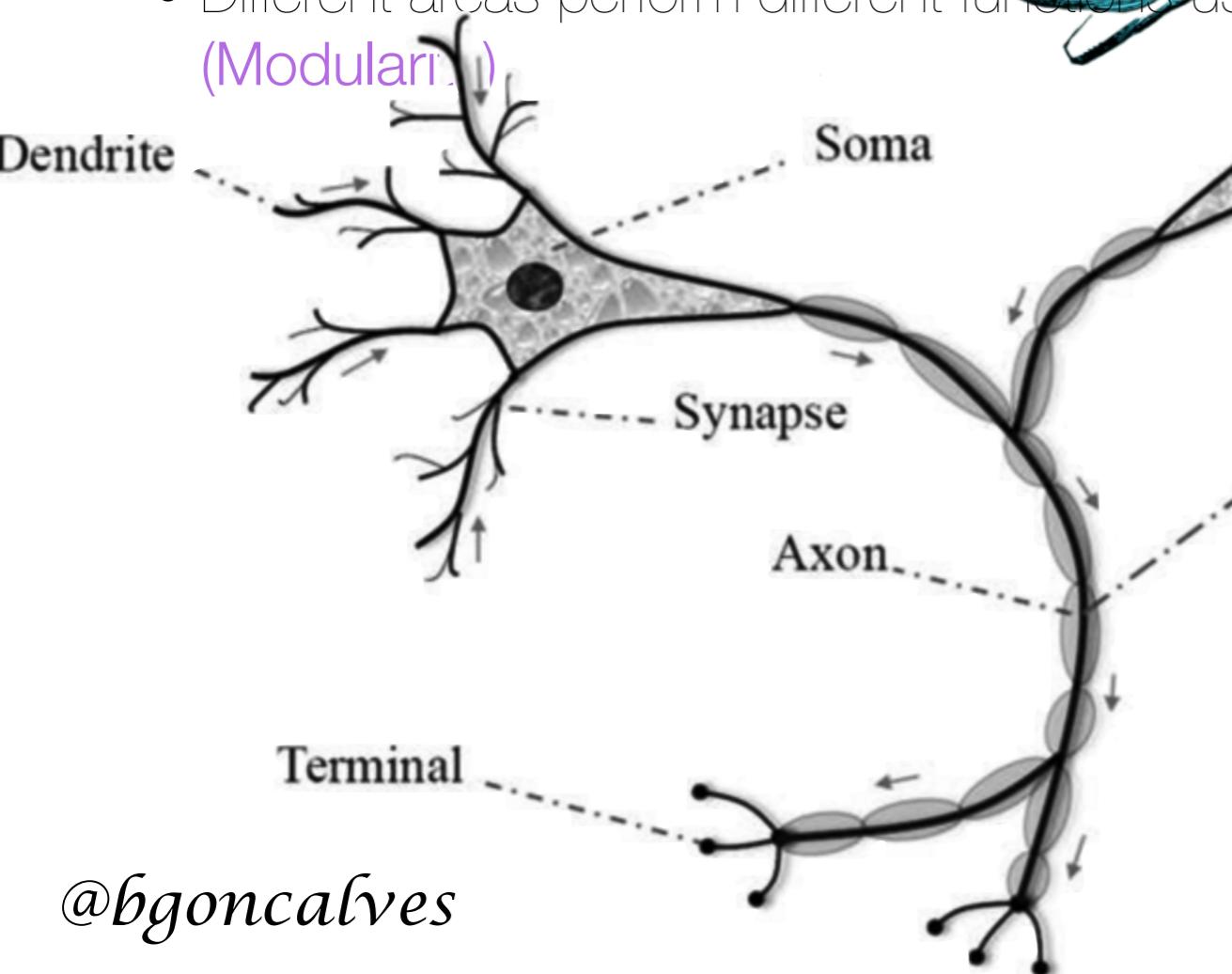
What about Neurons?

How the Brain “Works” (Cartoon version)

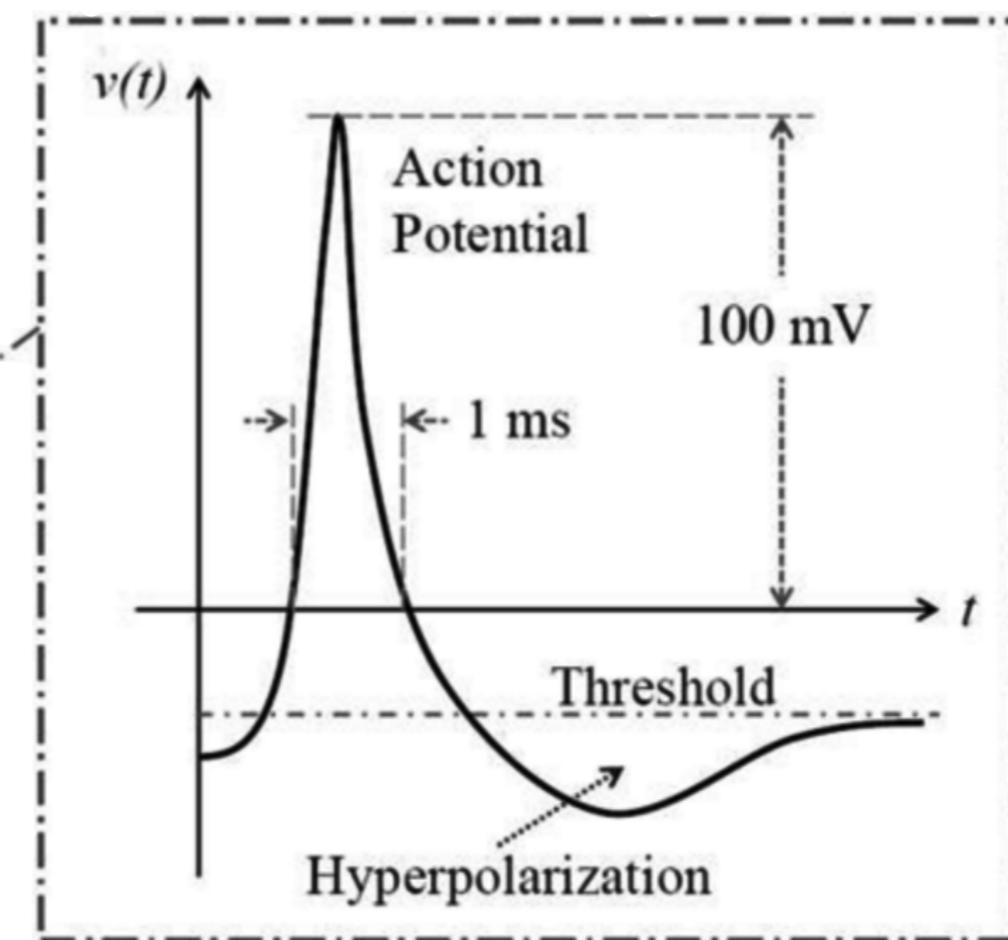
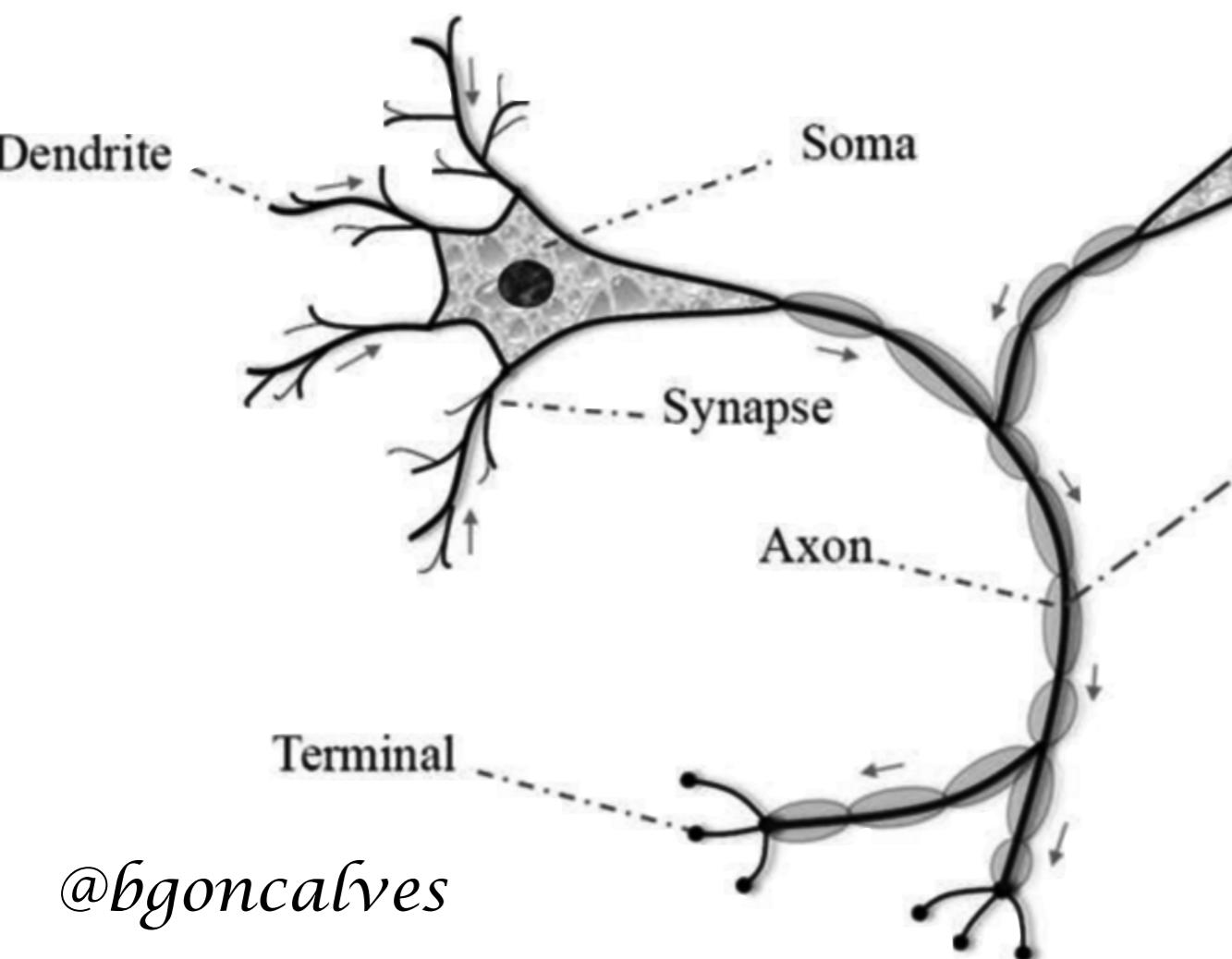
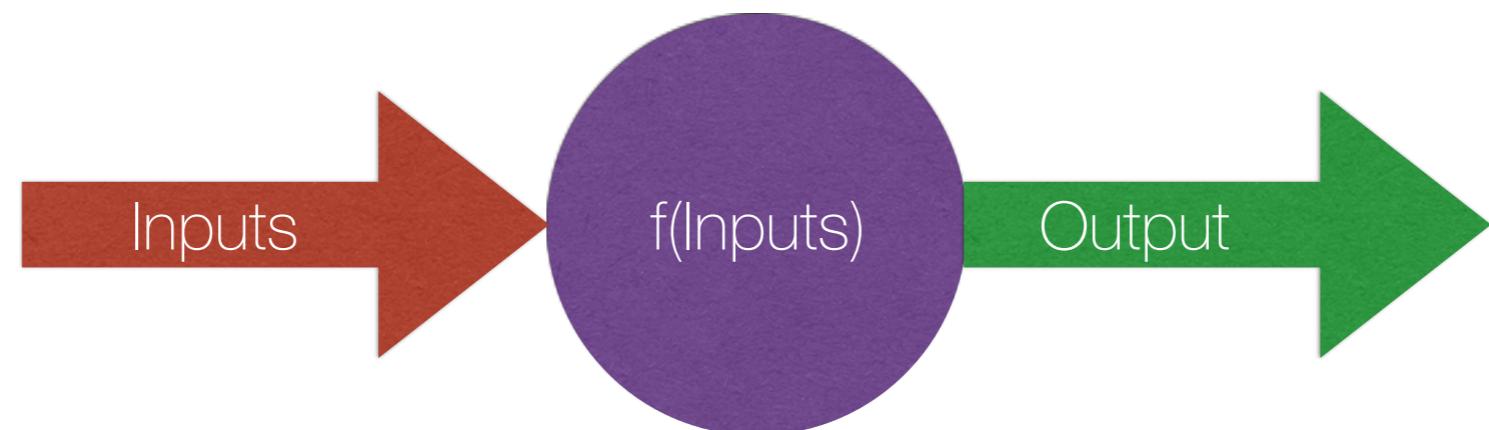


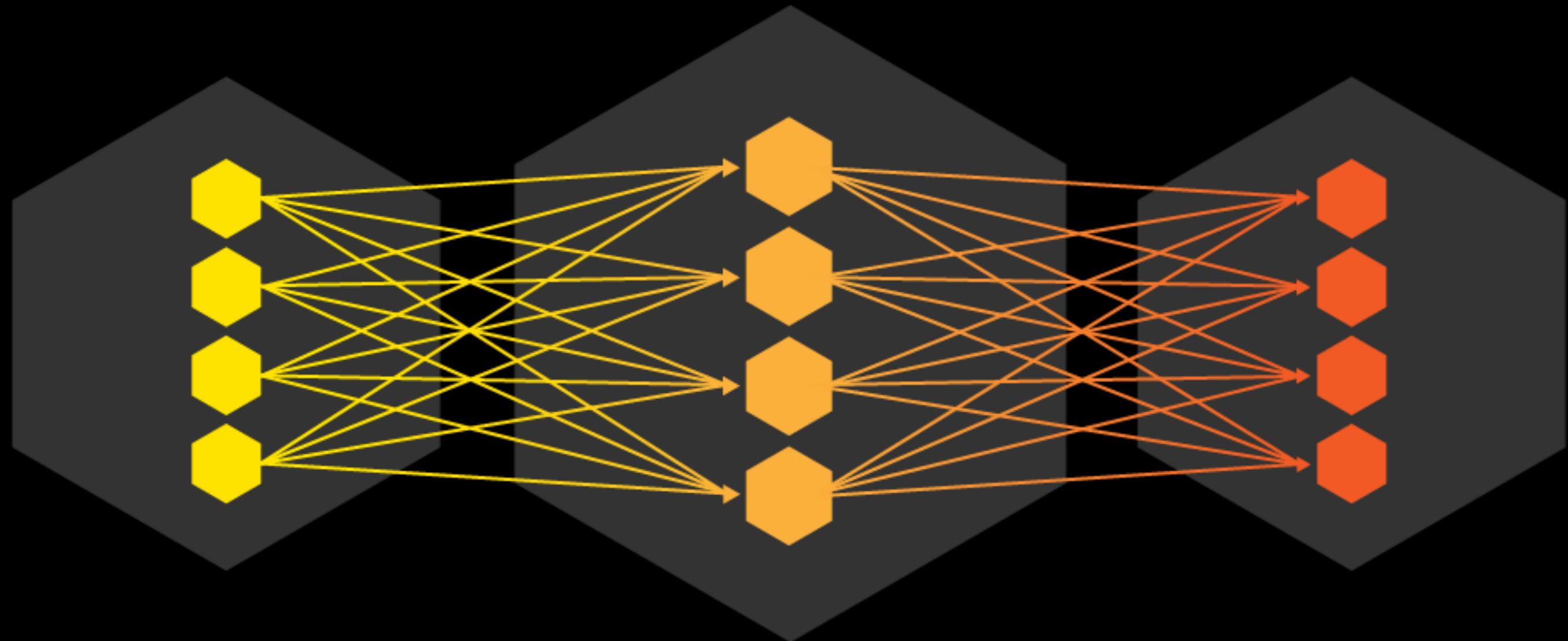
How the Brain “Works” (Cartoon version)

- Each neuron receives input from other neurons
- 10^{11} neurons, each with 10^4 weights
- Weights can be positive or negative
- Weights adapt during the learning process
- “neurons that fire together wire together” (Hebb)
- Different areas perform different functions using same structure
(Modular)



How the Brain “Works” (Cartoon version)





INPUT TERMS

FEATURES
PREDICTIONS
ATTRIBUTES
PREDICTABLE VARIABLES

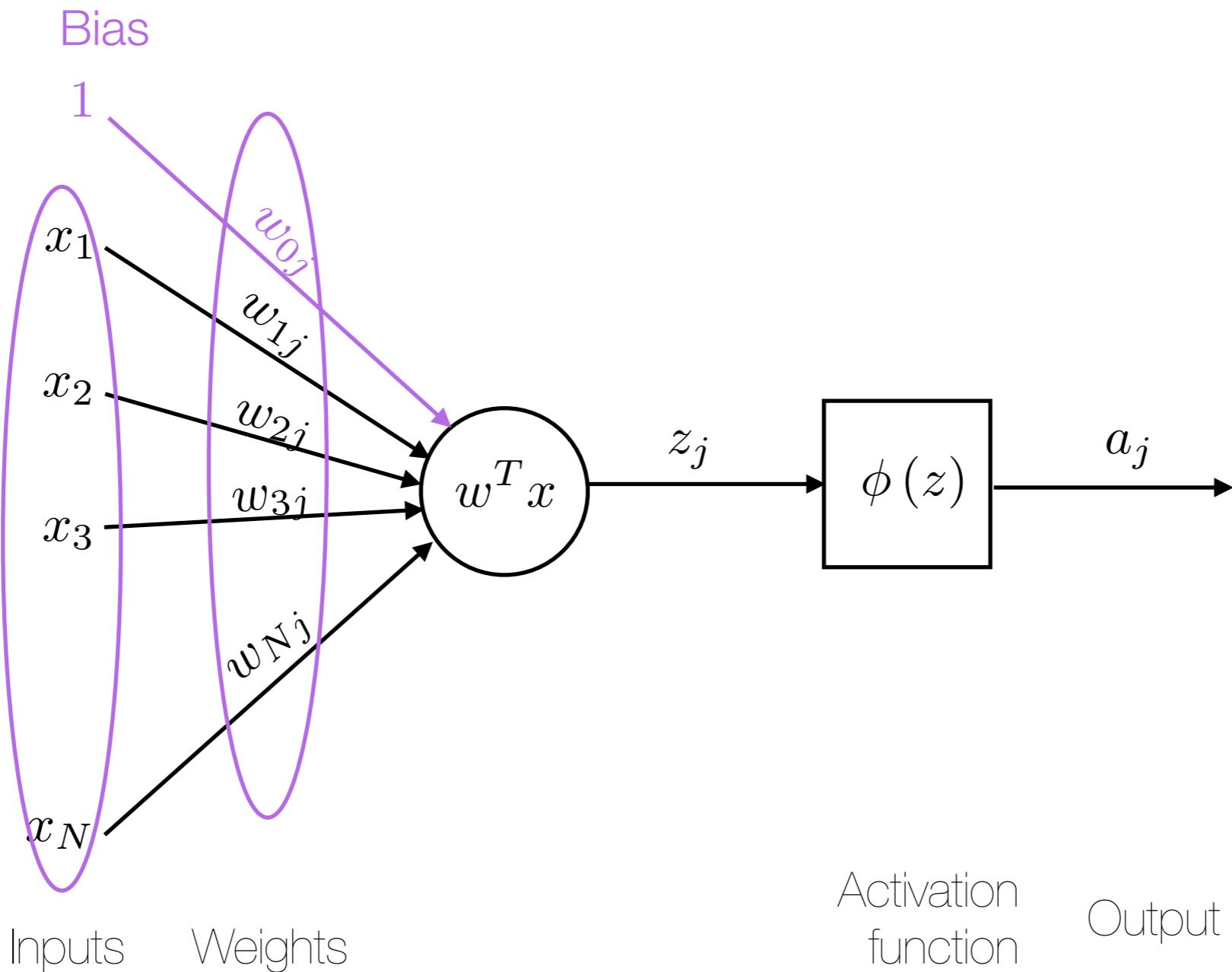
MACHINE

ALGORITHMS
TECHNIQUES
MODELS

OUTPUT TERMS

CLASSES
RESPONSES
TARGETS
DEPENDANT VARIABLES

Perceptron



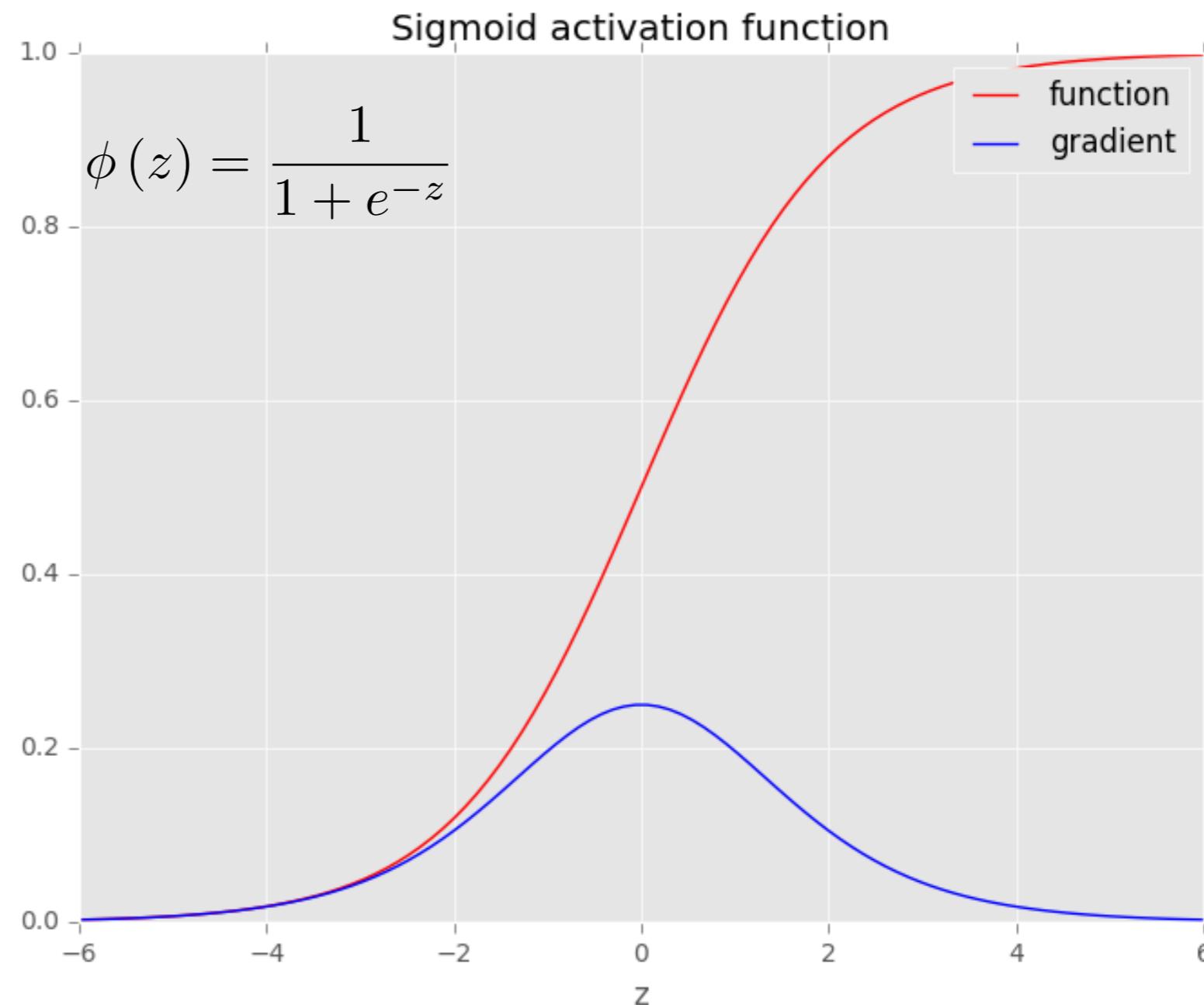
Activation Function

<http://github.com/bmtgoncalves/Neural-Networks>

- Non-Linear function
- Differentiable
- non-decreasing
- Compute new sets of features
- Each layer builds up a more abstract representation of the data

Activation Function - Sigmoid

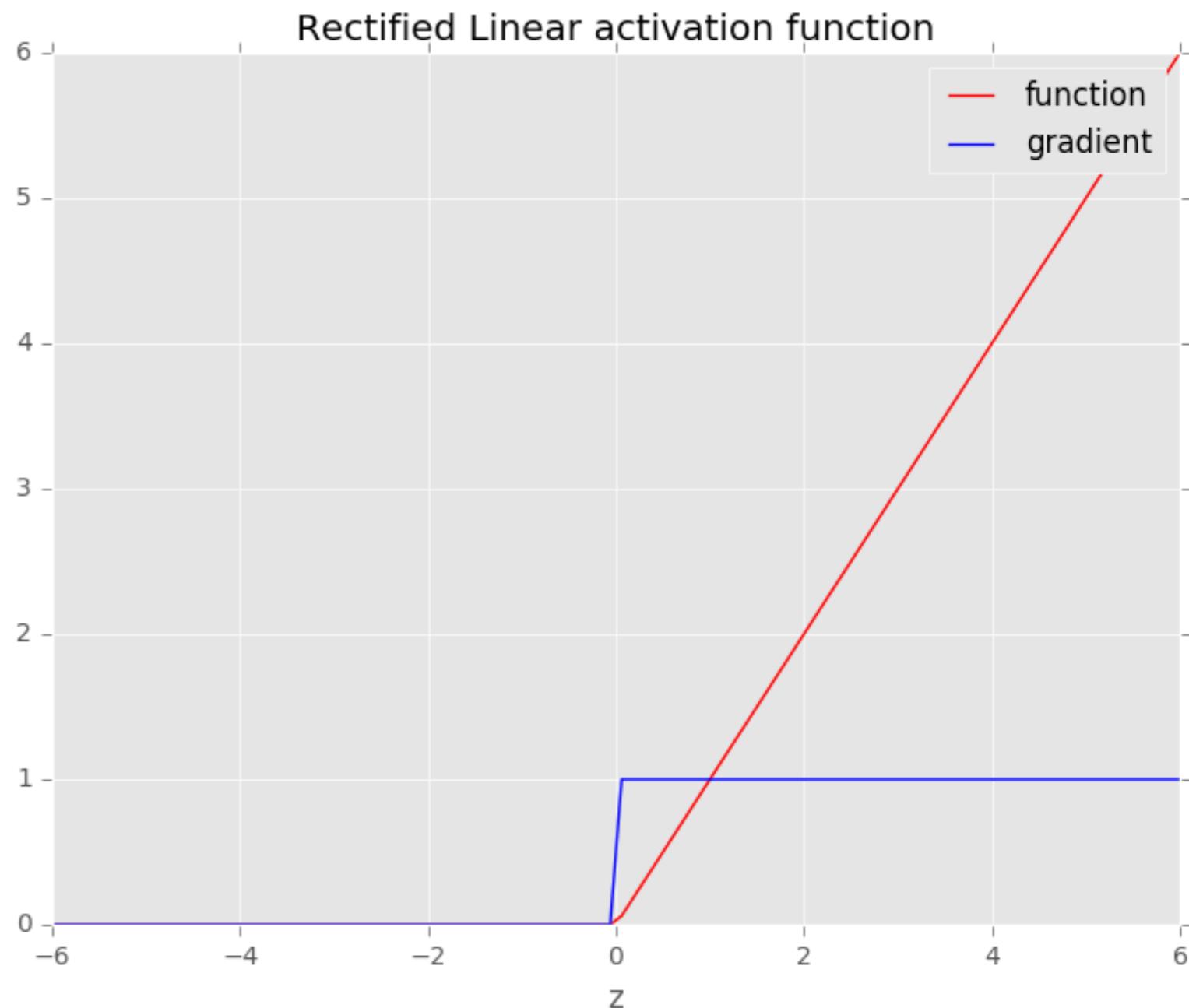
- Non-Linear function
- Differentiable
- non-decreasing
- Compute new sets of features
- Each layer builds up a more abstract representation of the data
- Perhaps the **most common**



Activation Function - ReLu

<http://github.com/bmtgoncalves/Neural-Networks>

- Non-Linear function
- Differentiable
- non-decreasing
- Compute new sets of features
- Each layer builds up a more abstract representation of the data
- Results in **faster learning** than with sigmoid



Activation Function - tanh

<http://github.com/bmtgoncalves/Neural-Networks>

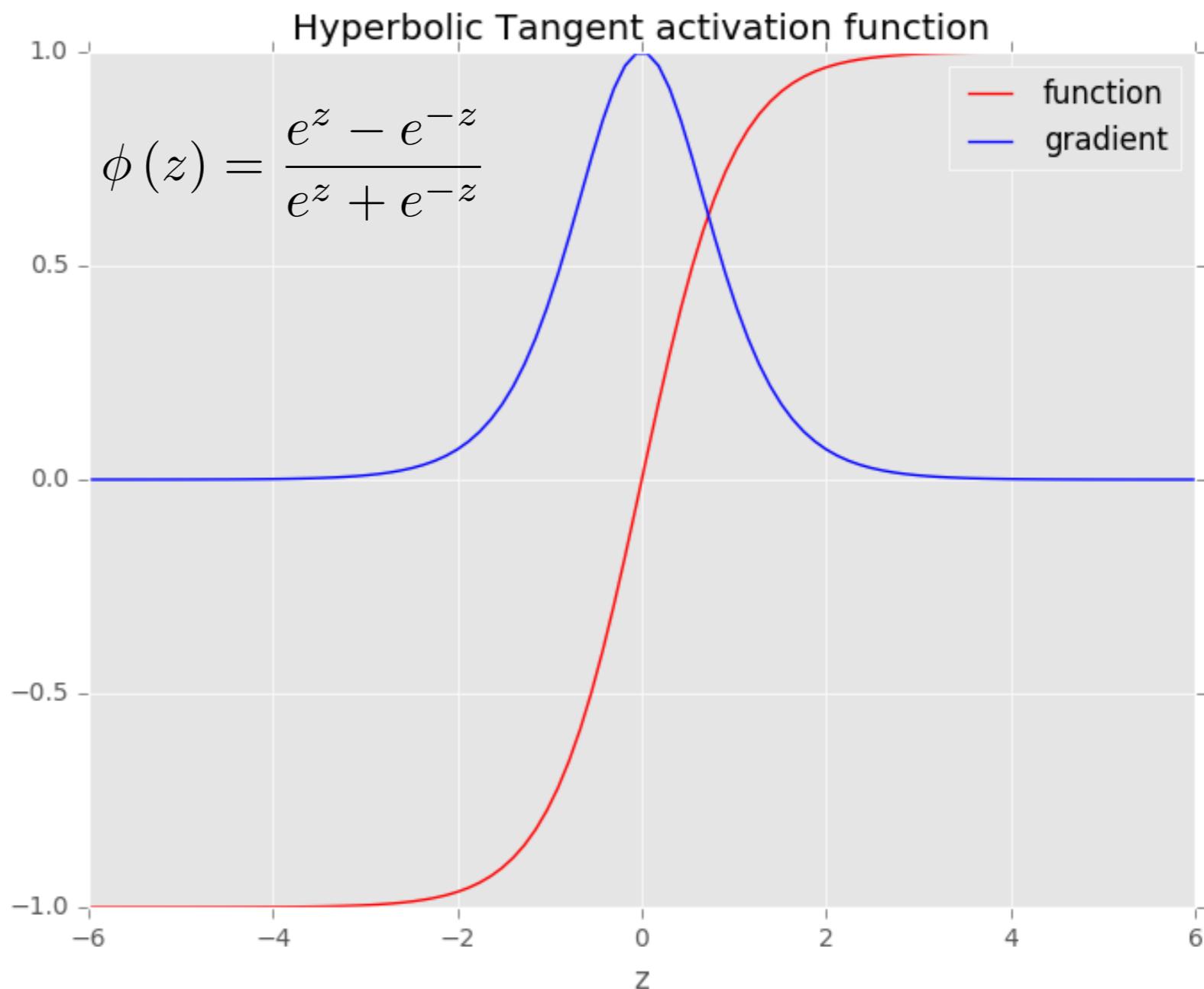
- Non-Linear function

- Differentiable

- non-decreasing

- Compute new sets of features

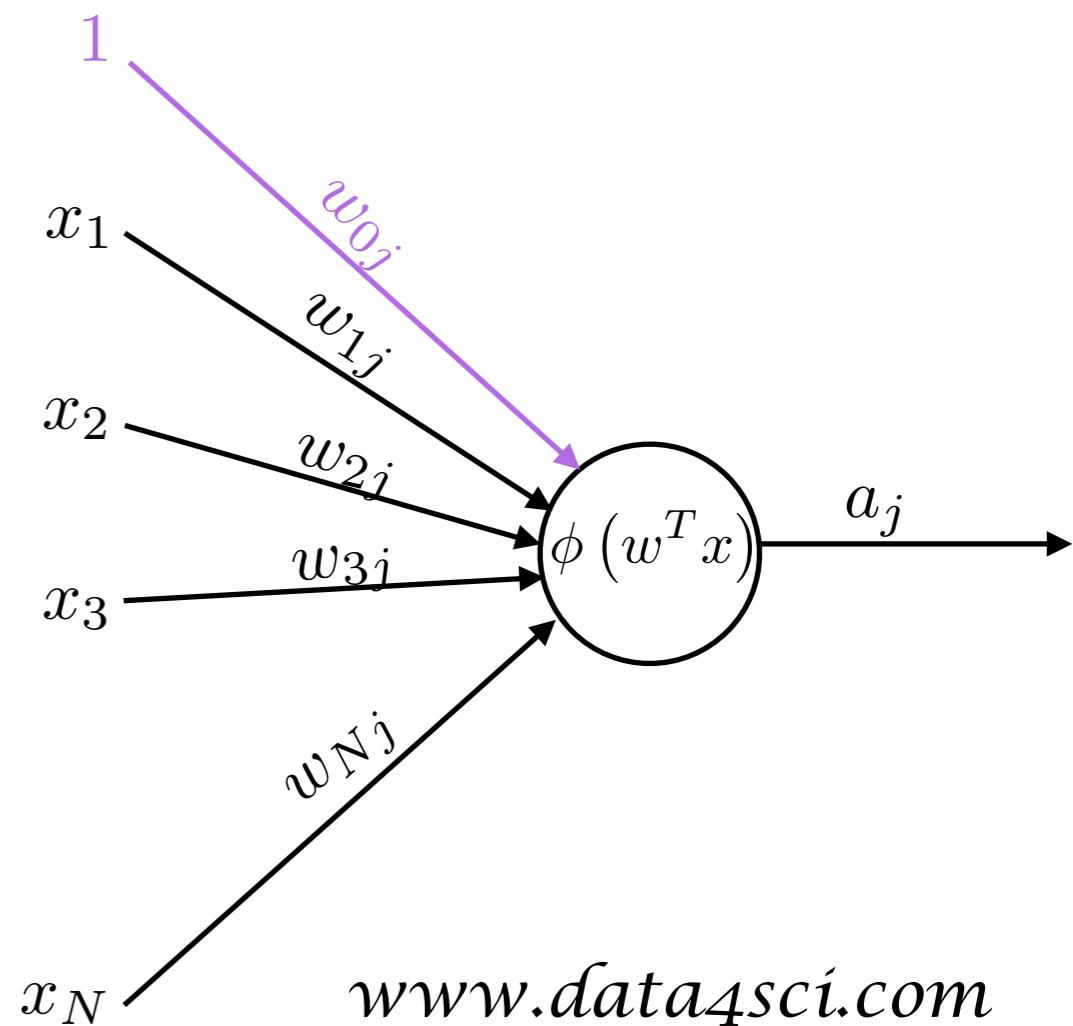
- Each layer builds up a more abstract representation of the data



Perceptron - Forward Propagation

- The output of a perceptron is determined by a sequence of steps:
 - obtain the inputs
 - multiply the inputs by the respective weights
 - calculate value of the activation function
 - (map activation value to predicted output)

$$a_j = \phi(\omega^T x)$$



Perceptron - Forward Propagation

<http://github.com/bmtgoncalves/Neural-Networks>

```
def forward(Theta, X, active):
    N = X.shape[0]

    # Add the bias column
    X_ = np.concatenate((np.ones((N, 1)), X), 1)

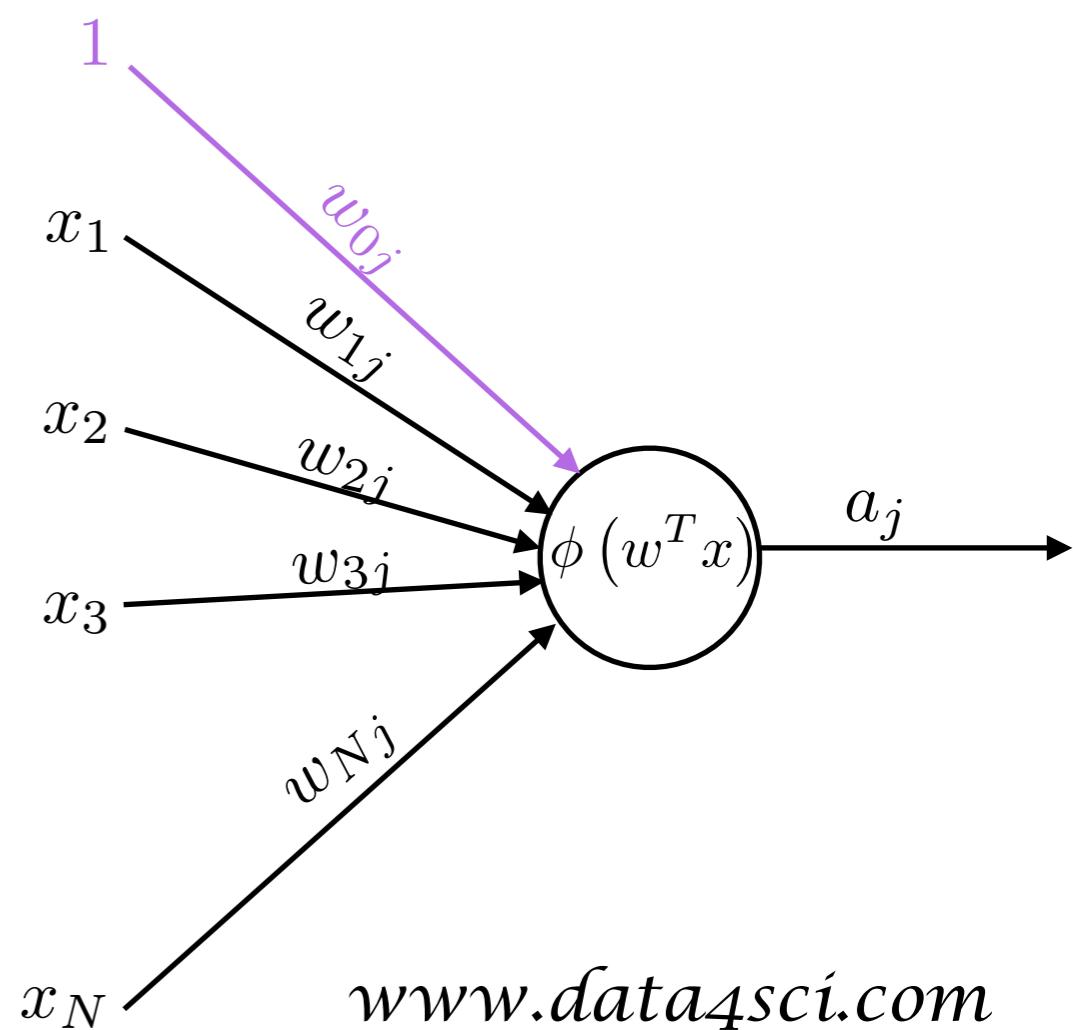
    # Multiply by the weights
    z = np.dot(X_, Theta.T)

    # Apply the activation function
    a = active(z)

    return a
```

Perceptron - Training

- Training Procedure:
 - If correct, do nothing
 - If output incorrectly outputs 0, add input to weight vector
 - if output incorrectly outputs 1, subtract input to weight vector
- Guaranteed to converge, if a correct set of weights exists
- Given enough features, perceptrons can learn almost anything
- Specific Features used limit what is possible to learn

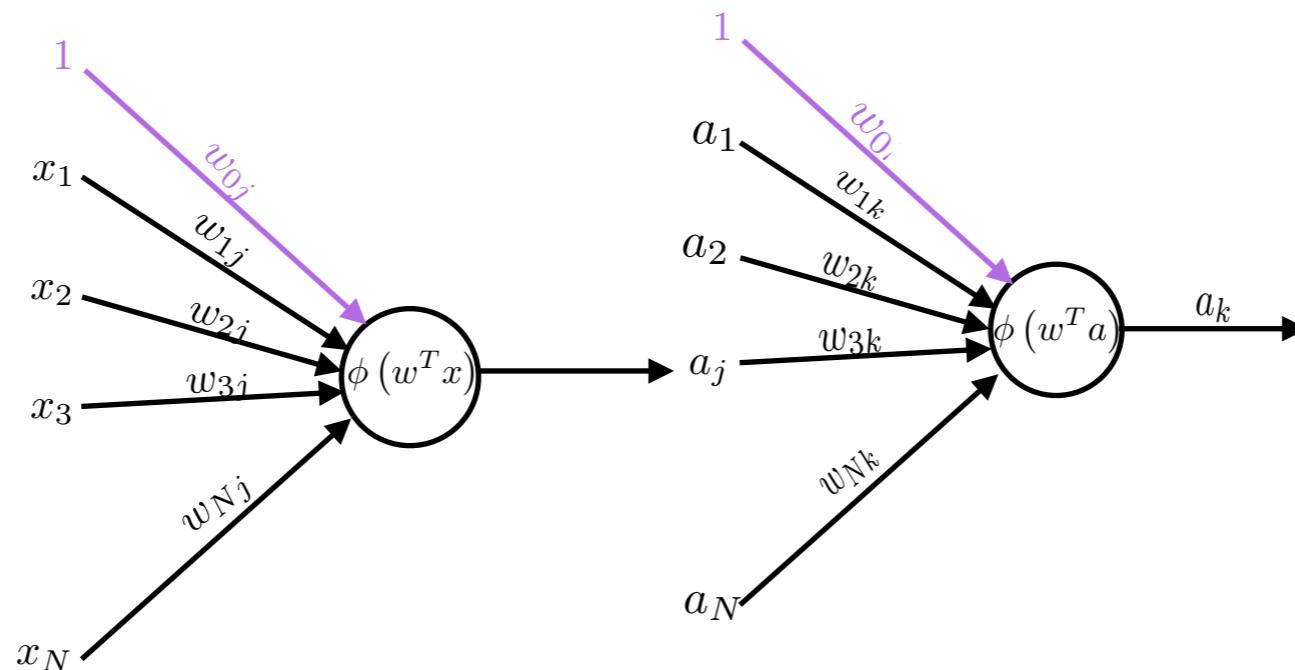


Code - Forward Propagation

<https://github.com/DataForScience/DeepLearning>

Forward Propagation

- The output of a perceptron is determined by a sequence of steps:
 - obtain the inputs
 - multiply the inputs by the respective weights
 - calculate output using the activation function
- To create a multi-layer perceptron, you can simply use the output of one layer as the input to the next one.



- But how can we propagate back the errors and update the weights?

Loss Functions

- For learning to occur, we must quantify how far off we are from the desired output. There are two common ways of doing this:
 - Quadratic error function:
- Cross Entropy

$$E = \frac{1}{N} \sum_n |y_n - a_n|^2$$
$$J = -\frac{1}{N} \sum_n \left[y_n^T \log a_n + (1 - y_n)^T \log (1 - a_n) \right]$$

The **Cross Entropy** is complementary to **sigmoid** activation in the output layer and improves its stability.

Regularization

- Helps keep weights relatively small by adding a penalization to the cost function.
- Two common choices:

$$\hat{J}_w(X) = J_w(X) + \lambda \sum_{ij} |w_{ij}| \quad \text{"Lasso"}$$

$$\hat{J}_w(X) = J_w(X) + \lambda \sum_{ij} w_{ij}^2 \quad \text{L2}$$

- Lasso helps with feature selection by driving less important weights to zero

Backward Propagation of Errors (BackProp)

- BackProp operates in two phases:
 - Forward propagate the inputs and calculate the deltas
 - Update the weights
- The error at the output is a **weighted average difference** between predicted output and the observed one.
- For inner layers there is no “real output”!

BackProp

- Let $\delta^{(l)}$ be the error at each of the total L layers:

- Then:

$$\delta^{(L)} = h_w(X) - y$$

- And for every other layer, **in reverse order**:

$$\delta^{(l)} = W^{(l)T} \delta^{(l+1)} * \phi^\dagger(z^{(l)})$$

- Until:

$$\delta^{(1)} \equiv 0$$

as there's no error on the input layer.

- And finally:

$$\Delta_{ij}^{(l)} = \Delta_{ij}^{(l)} + a_j^{(l)} \delta_i^{(l+1)}$$

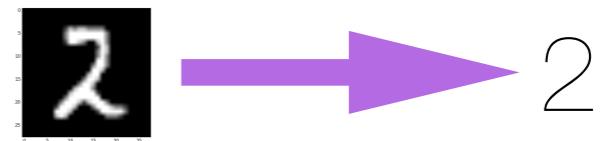
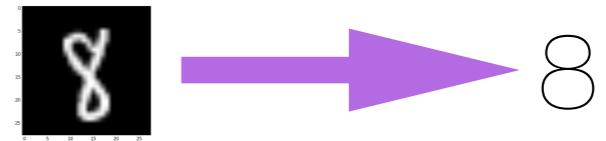
$$\frac{\partial}{\partial w_{ij}^{(l)}} J_w(X, \vec{y}) = \frac{1}{m} \Delta_{ij}^{(l)} + \lambda w_{ij}^{(l)}$$

A practical example - MNIST

<http://github.com/yann-lecun/MNIST>

THE MNIST DATABASE of handwritten digits

[Yann LeCun](#), Courant Institute, NYU
[Corinna Cortes](#), Google Labs, New York
[Christopher J.C. Burges](#), Microsoft Research, Redmond



A practical example - MNIST

<http://yann.lecun.com/exdb/mnist/>

<http://github.com/bmtgoncalves/Neural-Networks>

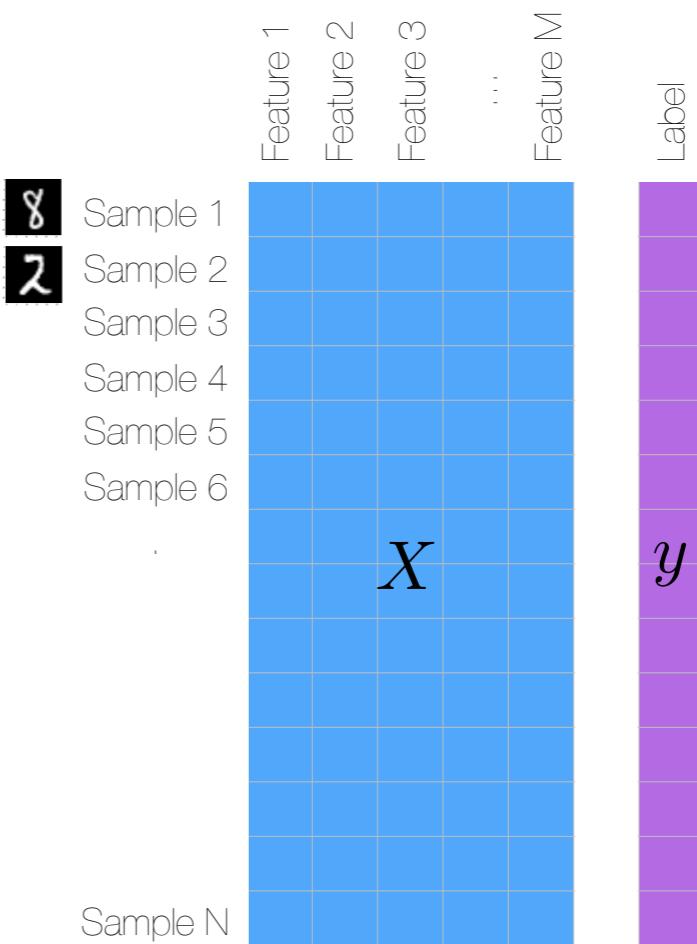
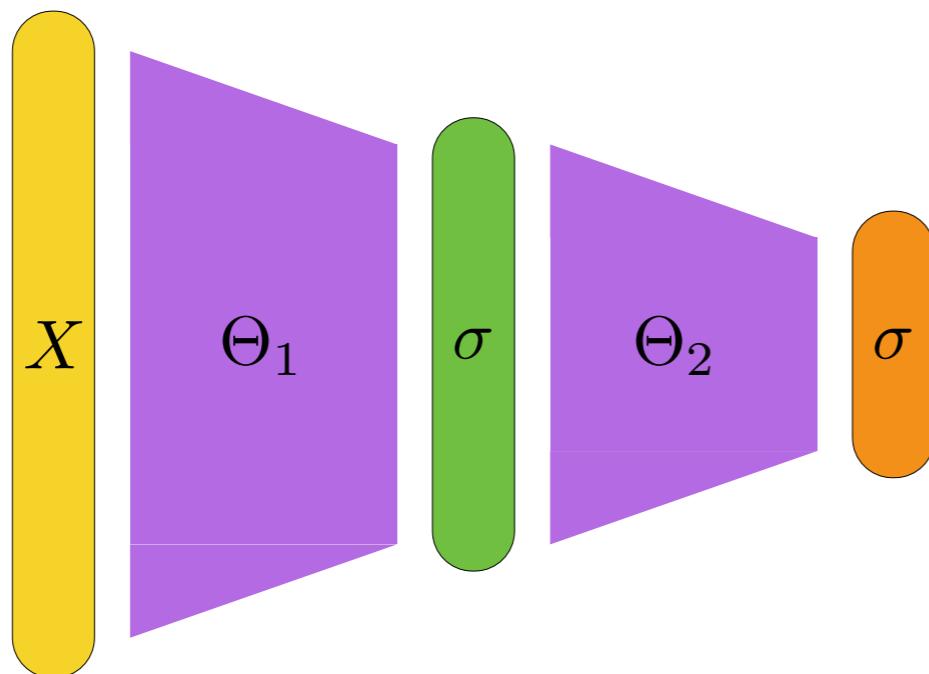
THE MNIST DATABASE

of handwritten digits

[Yann LeCun](#), Courant Institute, NYU

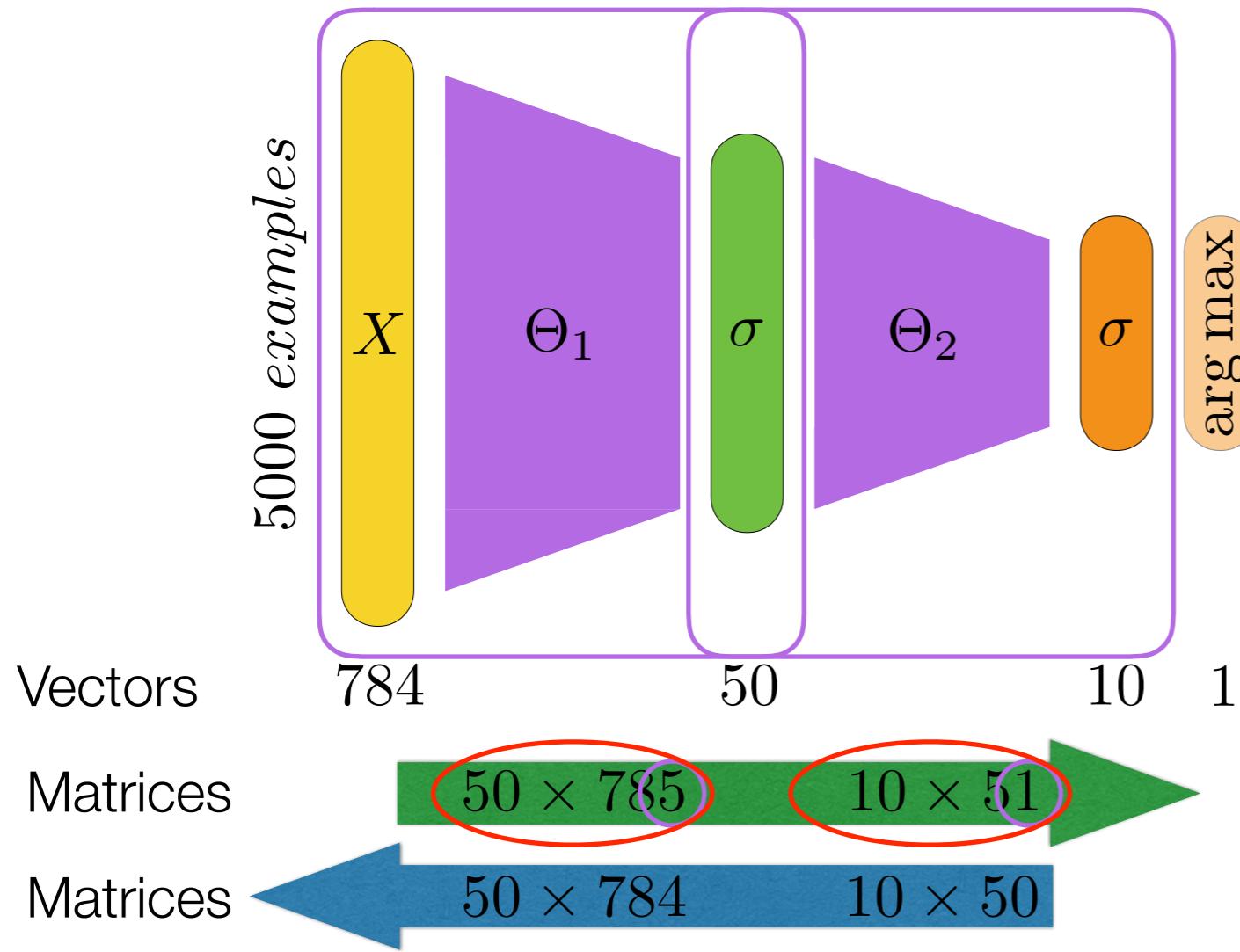
[Corinna Cortes](#), Google Labs, New York

[Christopher J.C. Burges](#), Microsoft Research, Redmond



A practical example - MNIST

<http://github.com/bmtgoncalves/Neural-Networks>



```
def forward(Theta, X, active):  
    N = X.shape[0]  
  
    # Add the bias column  
    X_ = np.concatenate((np.ones((N, 1)), X), 1)  
  
    # Multiply by the weights  
    z = np.dot(X_, Theta.T)  
  
    # Apply the activation function  
    a = active(z)  
  
    return a
```

Forward Propagation

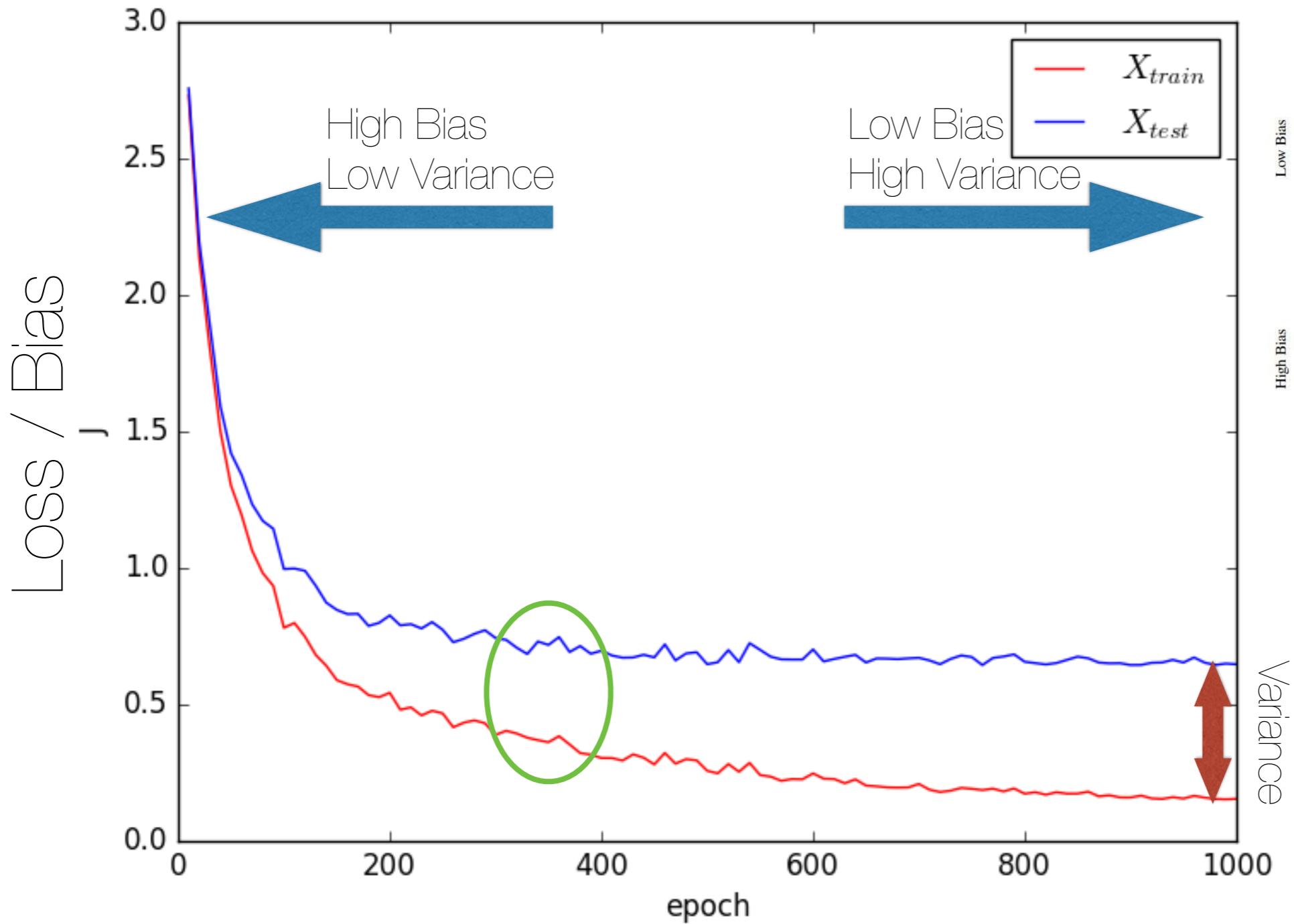
Backward Propagation

```
def predict(Theta1, Theta2, X):  
    h1 = forward(Theta1, X, sigmoid)  
    h2 = forward(Theta2, h1, sigmoid)  
  
    return np.argmax(h2, 1)
```

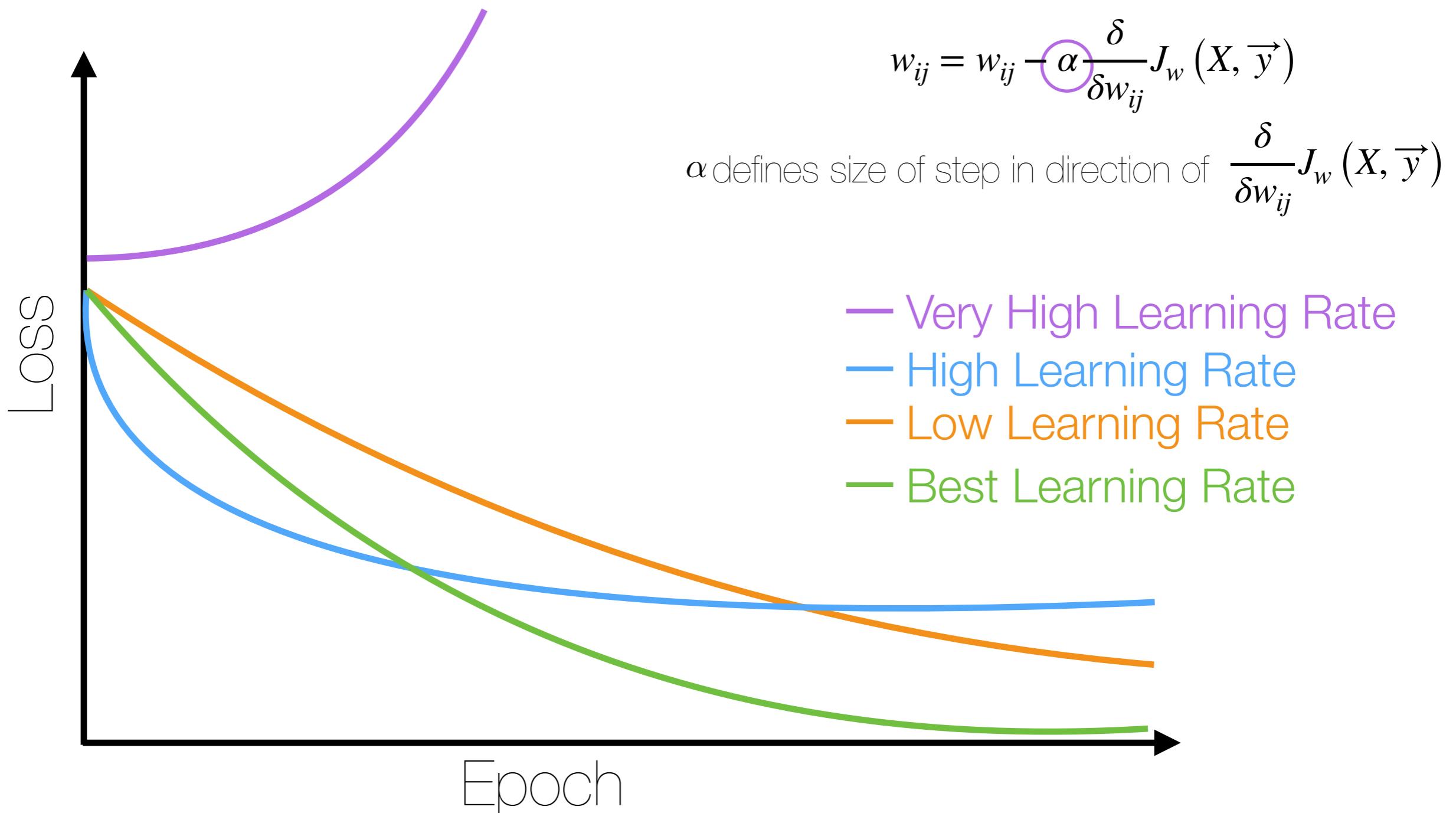
Code - Simple Network

<https://github.com/DataForScience/DeepLearning>

Bias-Variance Tradeoff



Learning Rate



Tips

- **online learning** - update weights after **each** case
 - might be useful to update model as new data is obtained
 - subject to fluctuations
- **mini-batch** - update weights after a "**small**" number of cases
 - batches should be balanced
 - if dataset is redundant, the gradient estimated using only a fraction of the data is a good approximation to the full gradient.
- **momentum** - let gradient change the **velocity** of weight change instead of the value directly
- **rmsprop** - divide learning rate for each weight by a **running average** of "recent" gradients

Generalization

- Neural Networks are extremely modular in their design with
- Fortunately, we can write code that is also modular and can easily handle arbitrary numbers of layers
- Let's describe the structure of our network as a list of weight matrices and activation functions
- We also need to keep track of the gradients of the activation functions so let us define a simple class:

```
class Activation(object):
    def f(z):
        pass

    def df(z):
        pass

class Linear(Activation):
    def f(z):
        return z

    def df(z):
        return np.ones(z.shape)

class Sigmoid(Activation):
    def f(z):
        return 1./(1+np.exp(-z))

    def df(z):
        h = Sigmoid.f(z)
        return h*(1-h)
```

Generalization

- Now we can describe our simple MNIST model with:

```
Thetas = []
Thetas.append(init_weights(input_layer_size, hidden_layer_size))
Thetas.append(init_weights(hidden_layer_size, num_labels))

model = []

model.append(Thetas[0])
model.append(Sigmoid)
model.append(Thetas[1])
model.append(Sigmoid)
```

- Where **Sigmoid** is an object that contains both the sigmoid function and its gradient as was defined in the previous slide.

Generalization - Forward propagation

```
def forward(Theta, X, active):
    N = X.shape[0]

    # Add the bias column
    X_ = np.concatenate((np.ones((N, 1)), X), 1)

    # Multiply by the weights
    z = np.dot(X_, Theta.T)

    # Apply the activation function
    a = active.f(z)

    return a

def predict(model, X):
    h = X.copy()
```

```

def backprop(model, X, y):
    M = X.shape[0]

    Thetas = model[0::2]
    activations = model[1::2]
    layers = len(Thetas)

    K = Thetas[-1].shape[0]
    J = 0
    Deltas = []

    for i in range(layers):
        Deltas.append(np.zeros(Thetas[i].shape))

    deltas = [0, 0, 0, 0]

    for i in range(M):
        As = []
        Zs = [0]
        Hs = [X[i]]
        # Forward propagation, saving intermediate results
        As.append(np.concatenate(([1], Hs[0]))) # Input layer

        for l in range(1, layers+1):
            Zs.append(np.dot(Thetas[l-1], As[l-1]))
            Hs.append(activations[l-1].f(Zs[l]))
            As.append(np.concatenate(([1], Hs[l])))

    y0 = one_hot(K, y[i])

    # Cross entropy
    J -= np.dot(y0.T, np.log(Hs[2])) + np.dot((1-y0).T, np.log(1-Hs[2]))

    # Calculate the weight deltas
    deltas[layers] = Hs[layers]-y0

    for l in range(layers-1, 1, -1):
        deltas[l] = np.dot(Thetas[l-1].T, deltas[l+1])[1:]*activations[l-1].df(Zs[l-1])
        Deltas[l] += np.outer(deltas[l+1], As[l])

    J /= M
    grads = []
    grads.append(Deltas[0]/M)
    grads.append(Deltas[1]/M)

return [J, grads]

```

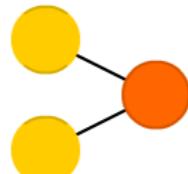
Code - Modular Network

<https://github.com/DataForScience/DeepLearning>

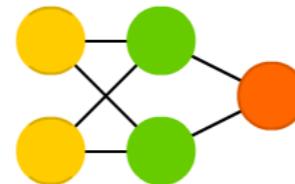
Neural Network Architectures

- (○) Backfed Input Cell
- (○) Input Cell
- (△) Noisy Input Cell
- (●) Hidden Cell
- (○) Probabilistic Hidden Cell
- (△) Spiking Hidden Cell
- (●) Output Cell
- (○) Match Input Output Cell
- (●) Recurrent Cell
- (○) Memory Cell
- (△) Different Memory Cell
- (●) Kernel
- (○) Convolution or Pool

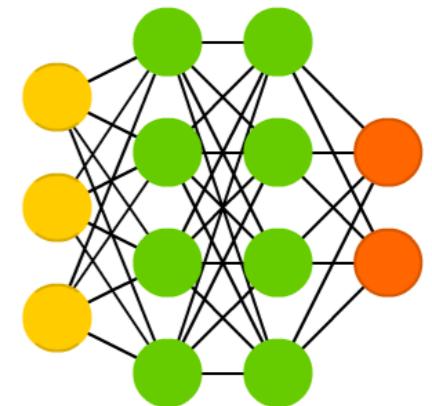
Perceptron (P)



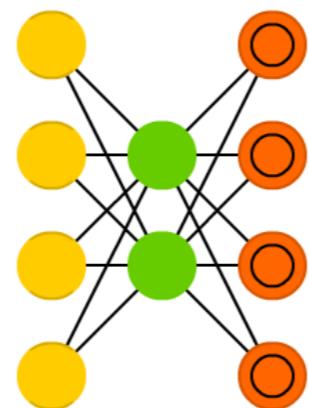
Feed Forward (FF)



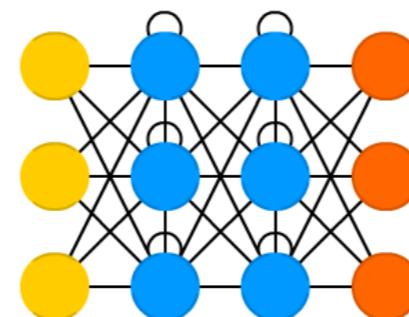
Deep Feed Forward (DFF)



Auto Encoder (AE)

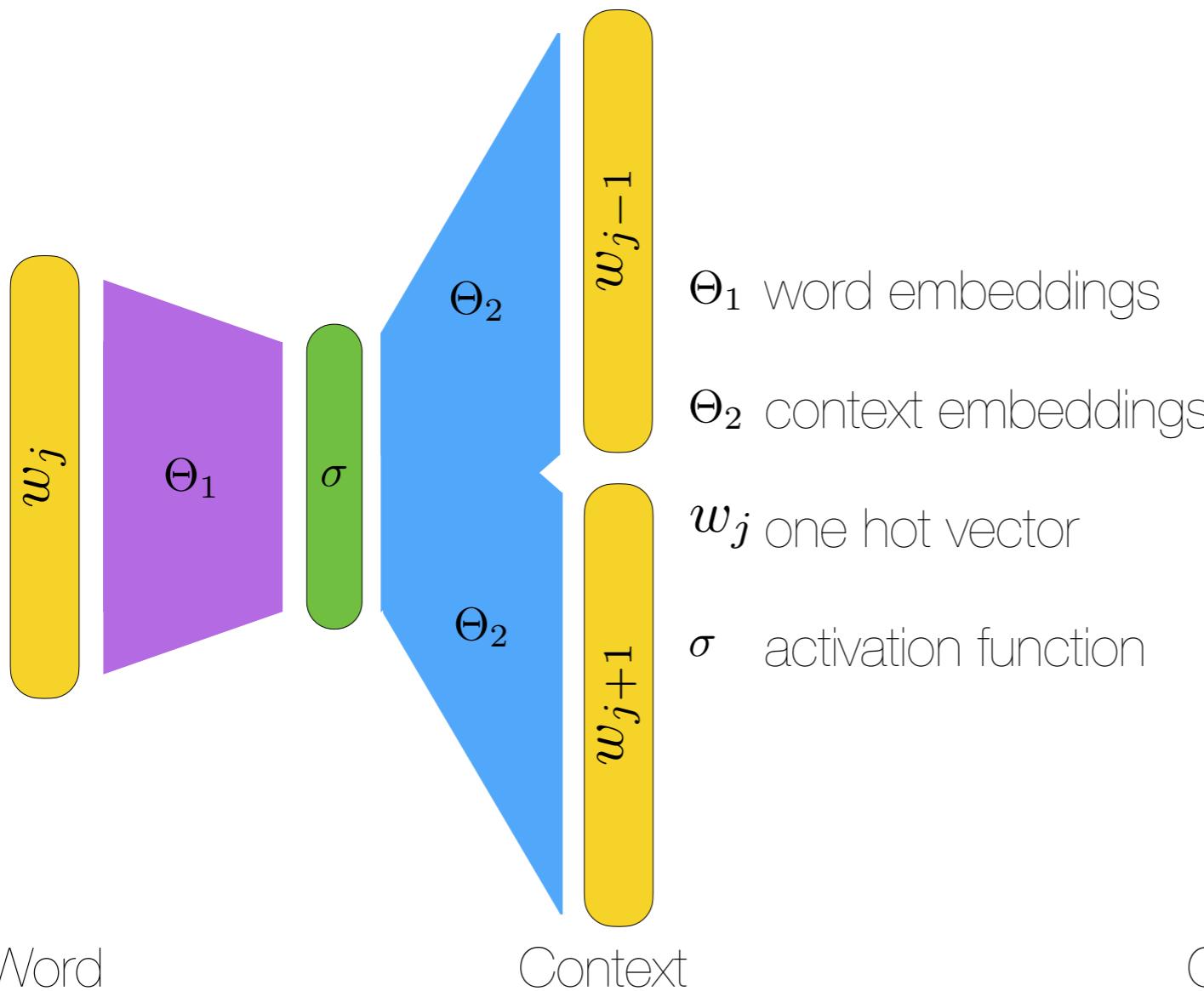


Recurrent Neural Network (RNN)



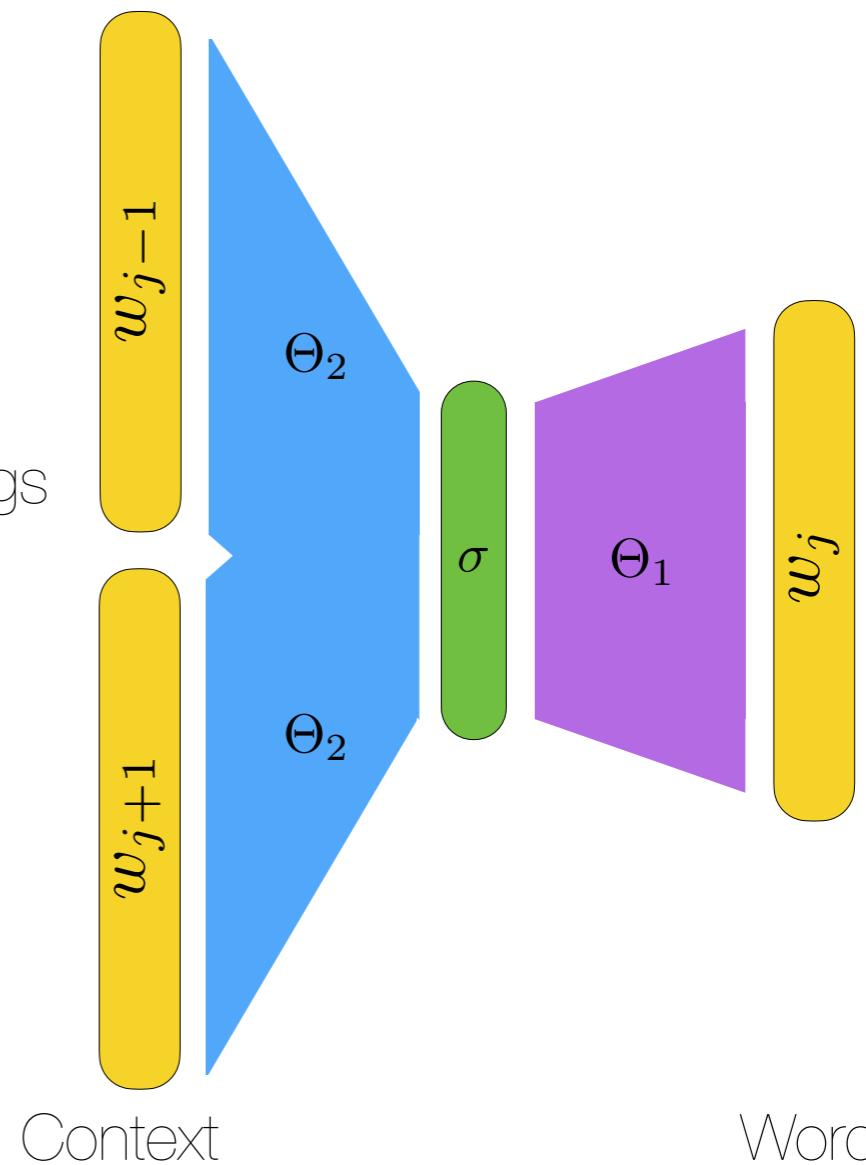
Skipgram

$$\max p(C|w)$$

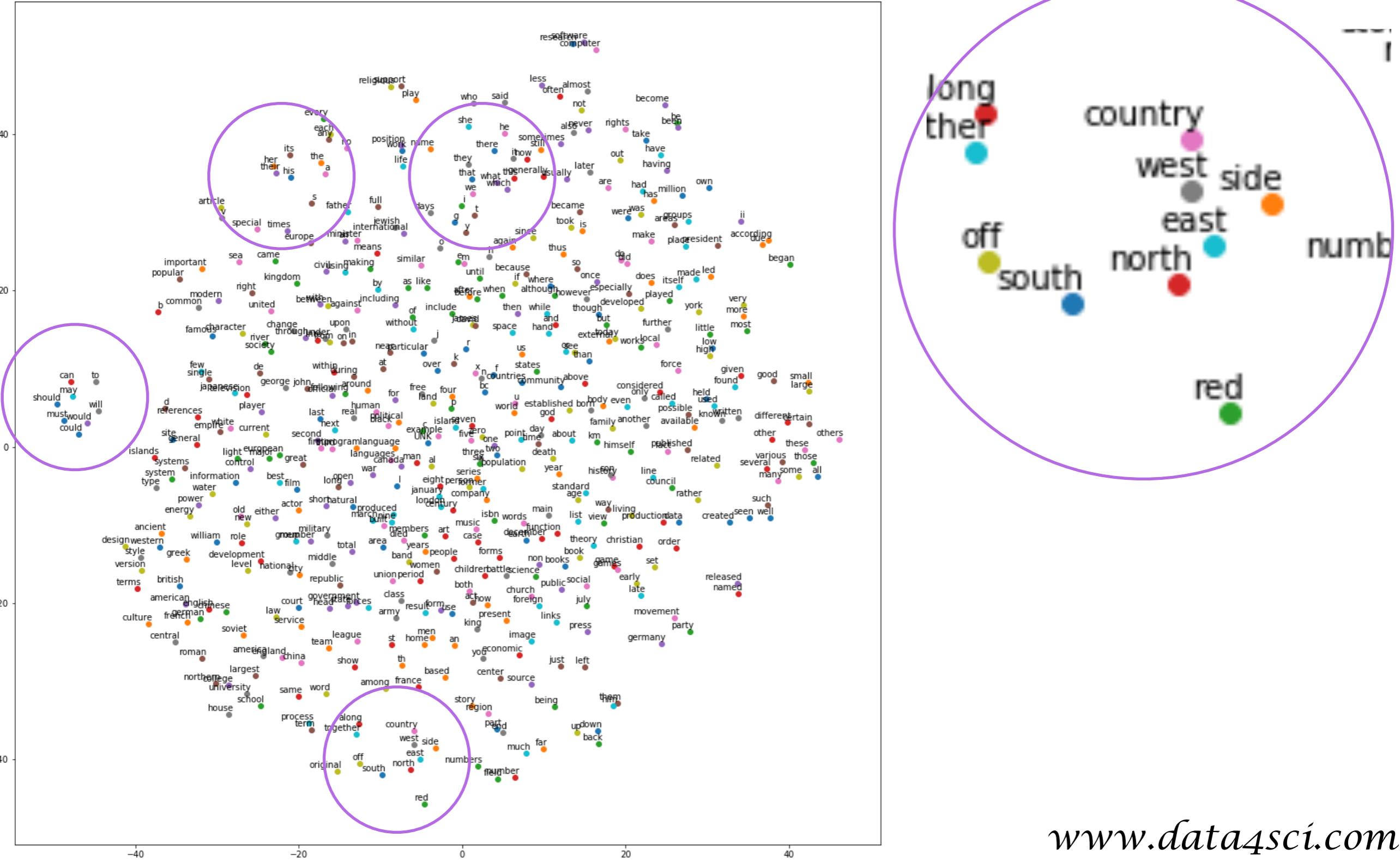


Continuous Bag of Words

$$\max p(w|C)$$



Visualization





"You shall know a word by the company it keeps"
(J. R. Firth)

Analogies

- The embedding of each word is a function of the context it appears in:

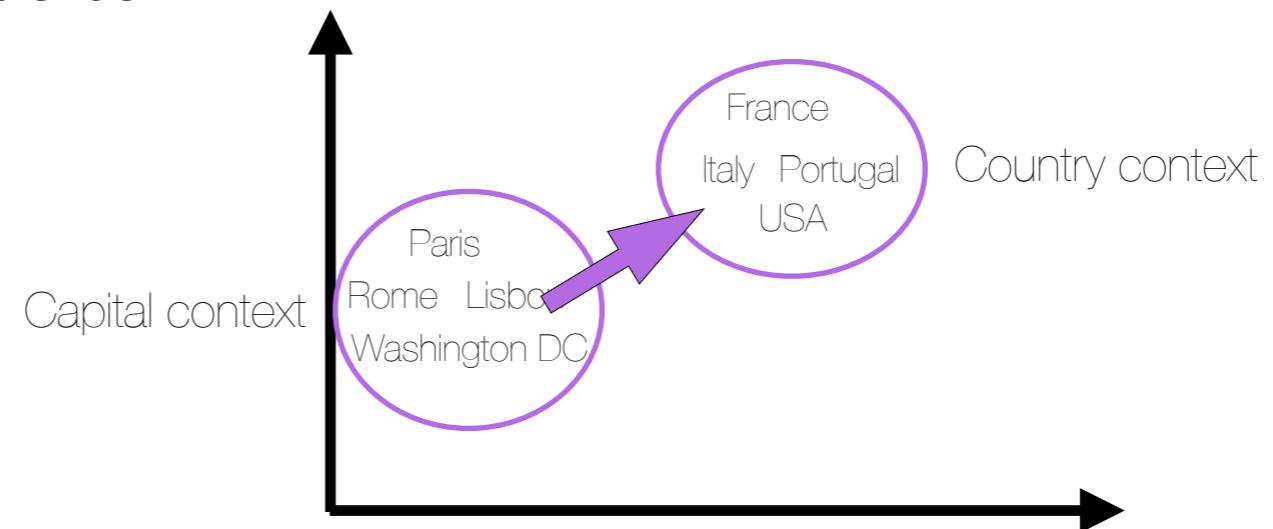
$$\sigma(\text{red}) = f(\text{context}(\text{red}))$$

- words that appear in similar contexts will have similar embeddings:

$$\text{context}(\text{red}) \approx \text{context}(\text{blue}) \implies \sigma(\text{red}) \approx \sigma(\text{blue})$$

- "Distributional hypothesis" in linguistics

Geometrical relations
between contexts imply
semantic relations
between words!



$$\sigma(\text{France}) - \sigma(\text{Paris}) + \sigma(\text{Rome}) = \sigma(\text{Italy})$$

$$\vec{b} - \vec{a} + \vec{c} = \vec{d}$$

Analogies

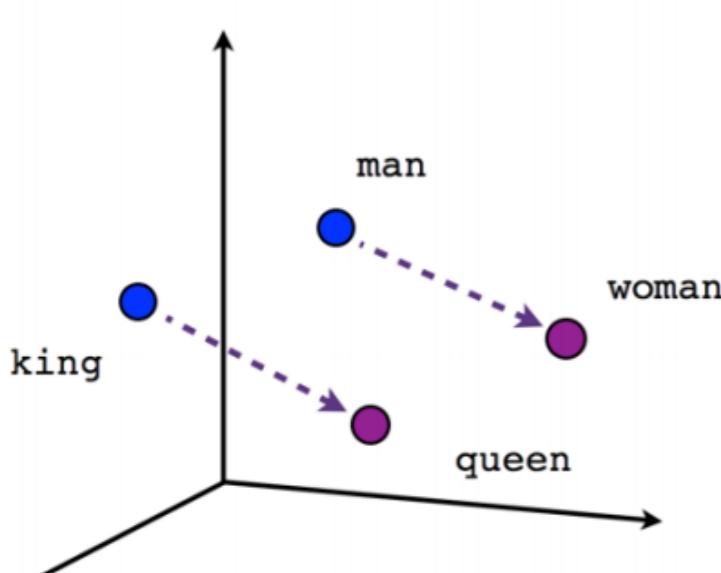
<https://www.tensorflow.org/tutorials/word2vec>

What is the word **d** that is most **similar** to **b** and **c** and most **dissimilar** to **a**?

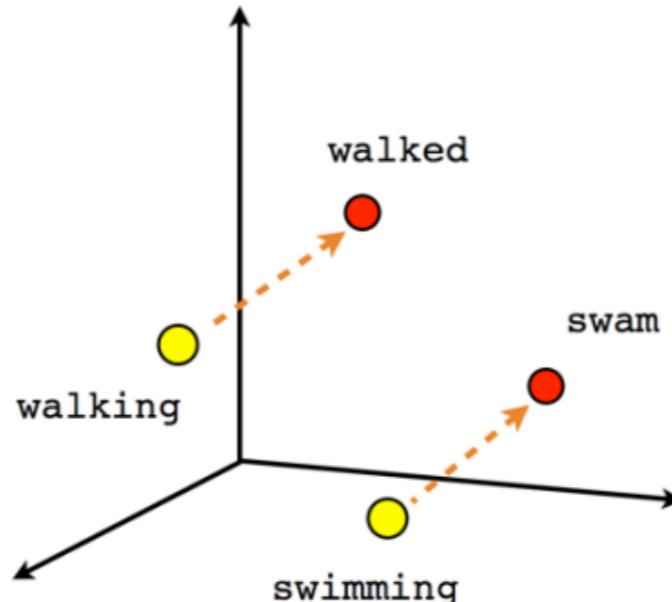
$$\vec{b} - \vec{a} + \vec{c} = \vec{d}$$

$$d^\dagger = \operatorname{argmax}_x \frac{(\vec{b} - \vec{a} + \vec{c})^T}{\|\vec{b} - \vec{a} + \vec{c}\|} \vec{x}$$

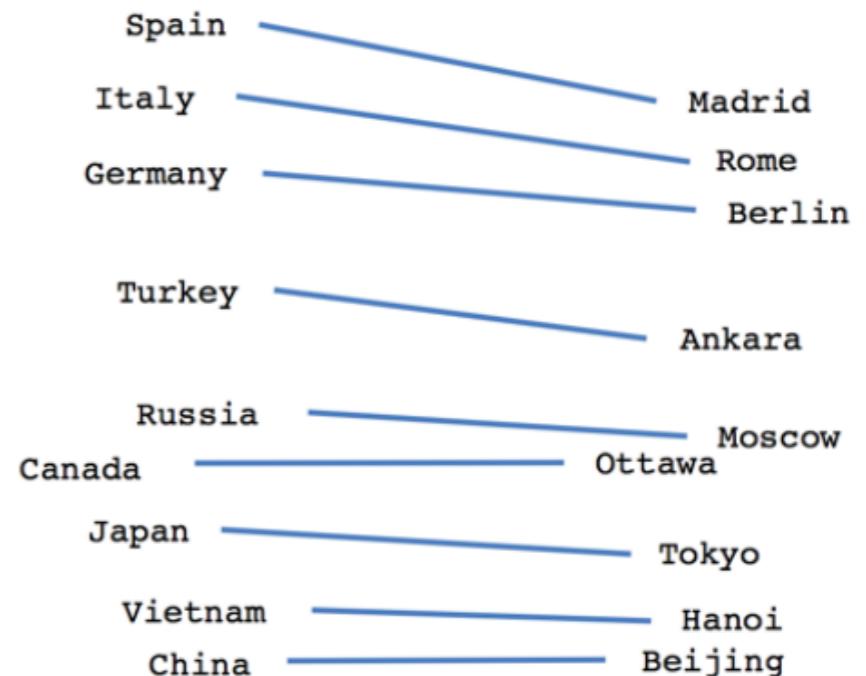
$$d^\dagger \sim \operatorname{argmax}_x (\vec{b}^T \vec{x} - \vec{a}^T \vec{x} + \vec{c}^T \vec{x})$$



Male-Female

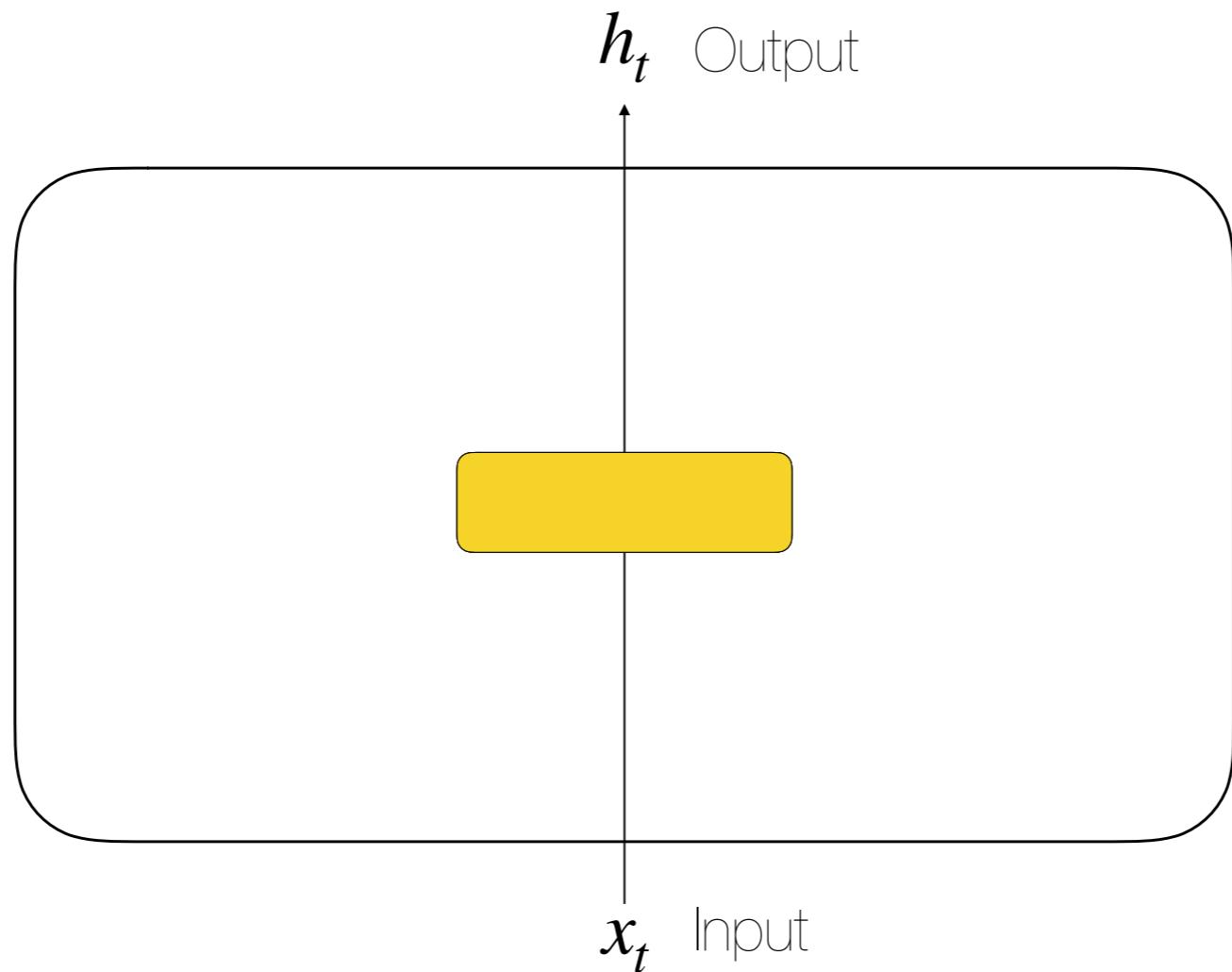


Verb tense



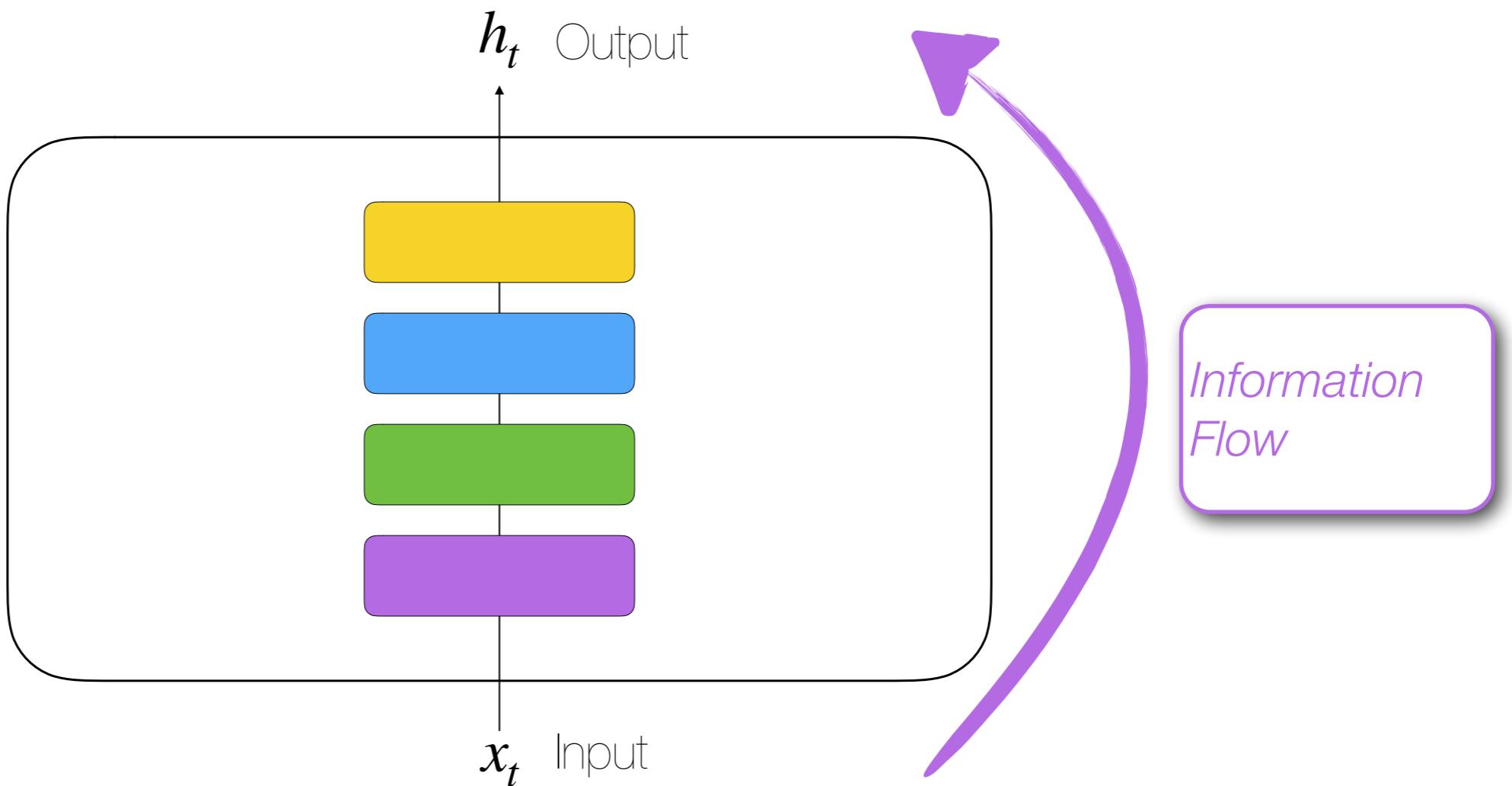
Country-Capital

Feed Forward Networks



$$h_t = f(x_t)$$

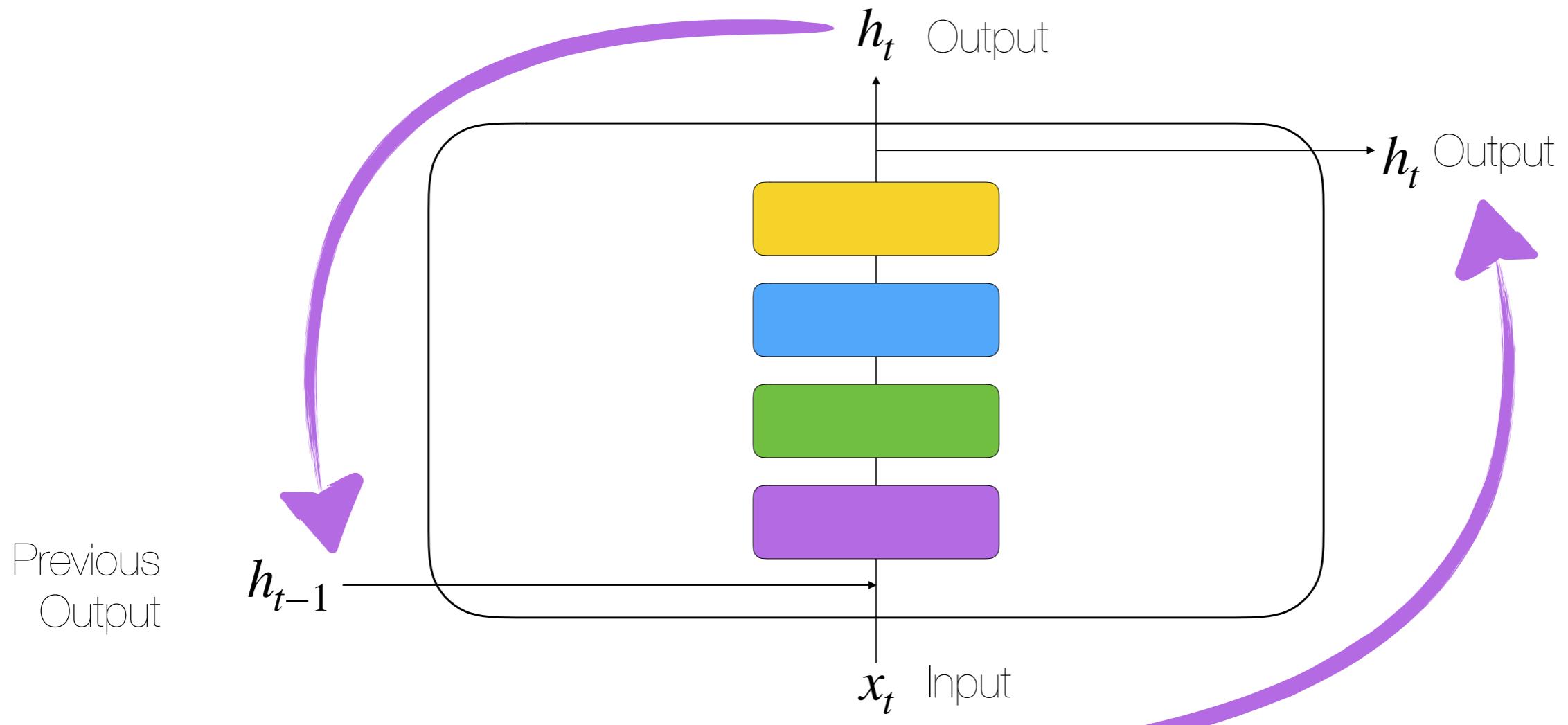
Feed Forward Networks



$$h_t = f(x_t)$$

Information
Flow

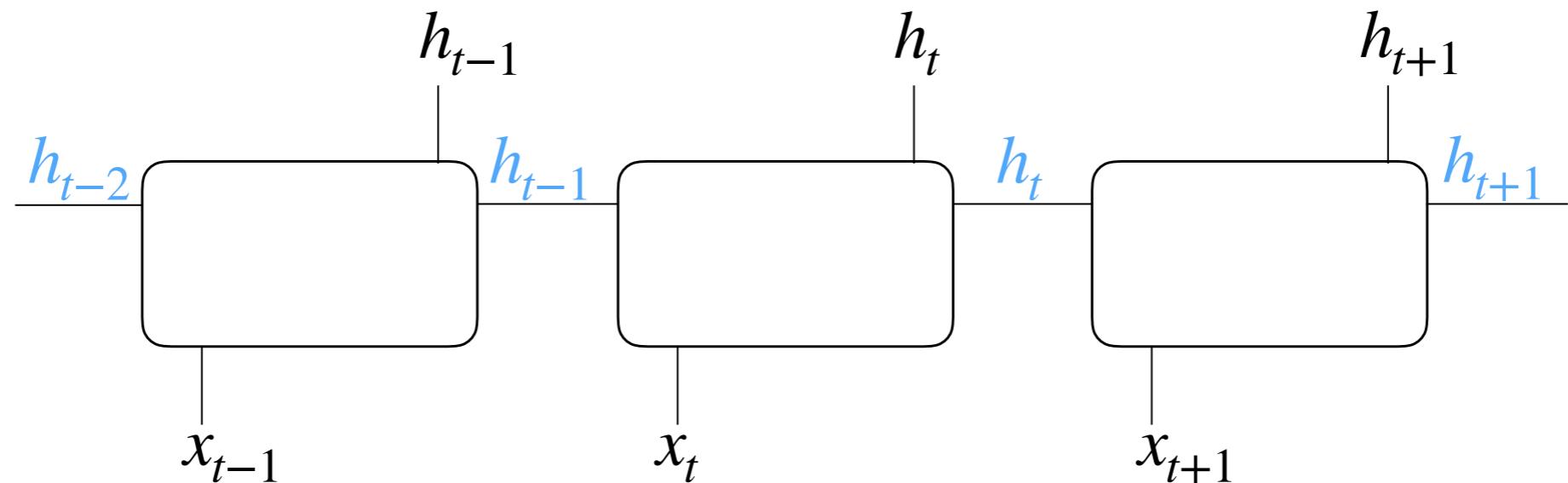
Recurrent Neural Network (RNN)



$$h_t = f(x_t, h_{t-1})$$

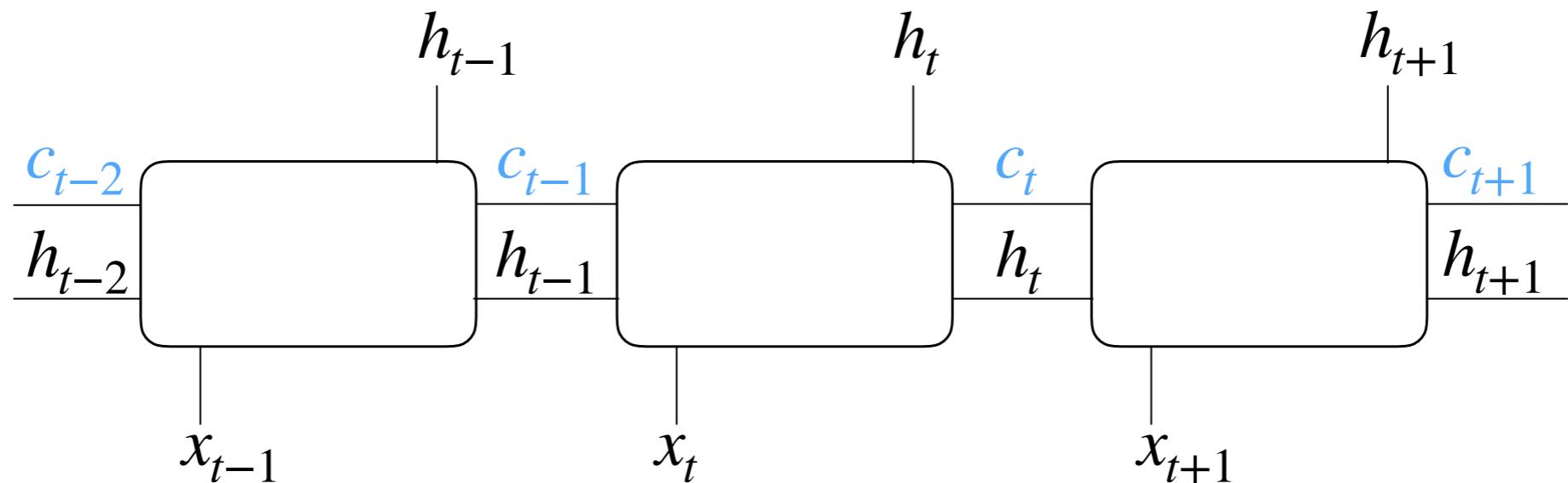
Recurrent Neural Network (RNN)

- Each output depends (implicitly) on all previous **outputs**.
- Input sequences generate output sequences (**seq2seq**)

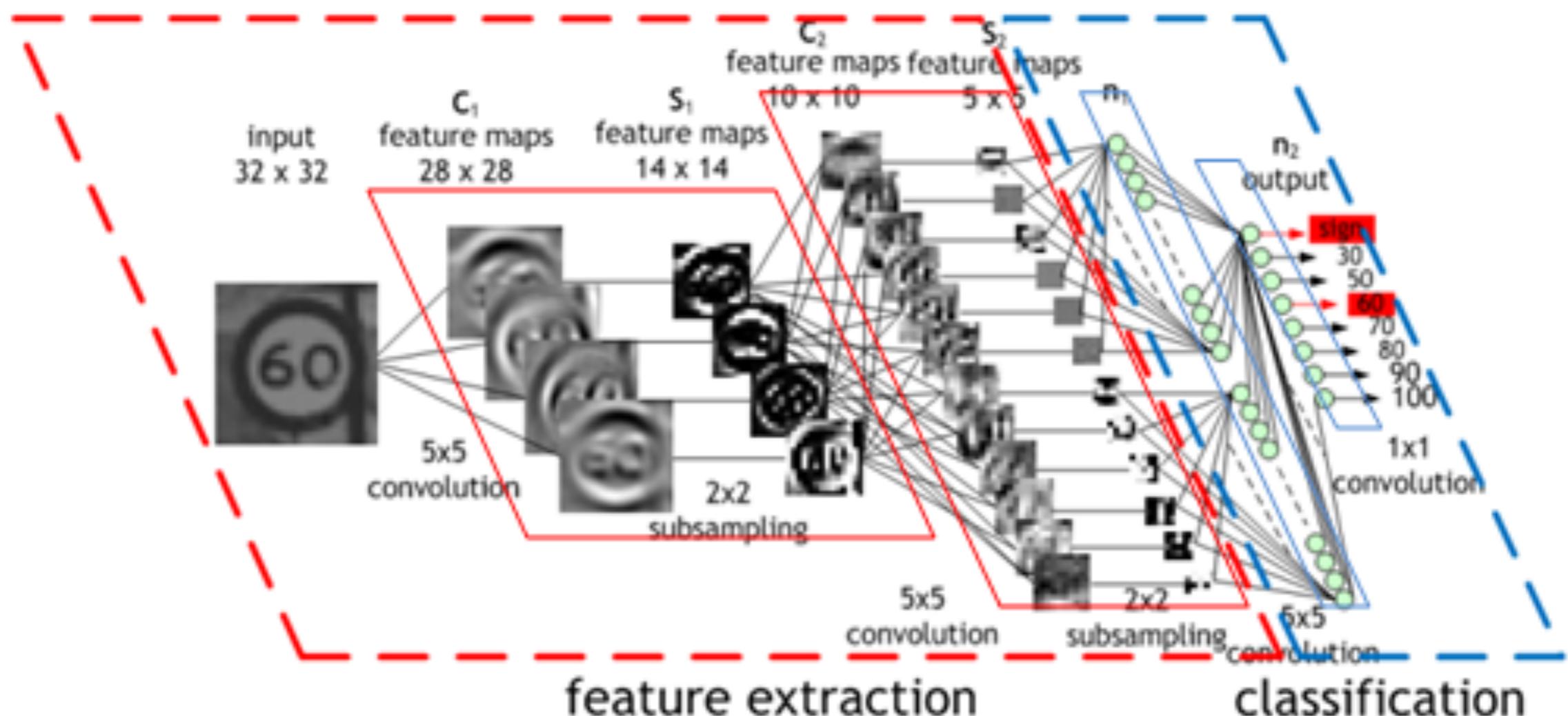


Long-Short Term Memory (LSTM)

- What if we want to keep explicit information about previous states (**memory**)?
- How much information is kept, can be controlled through gates.
- LSTMs were first introduced in **1997** by Hochreiter and Schmidhuber



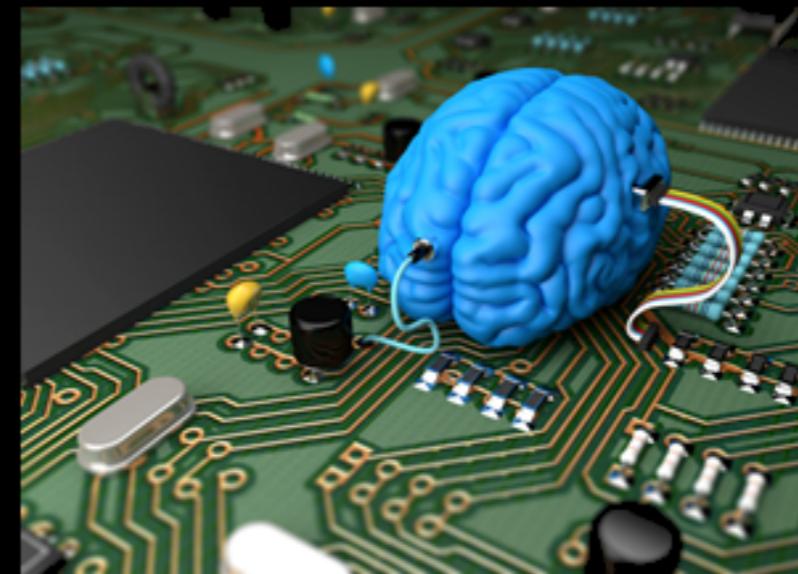
Convolutional Neural Networks



Deep Learning



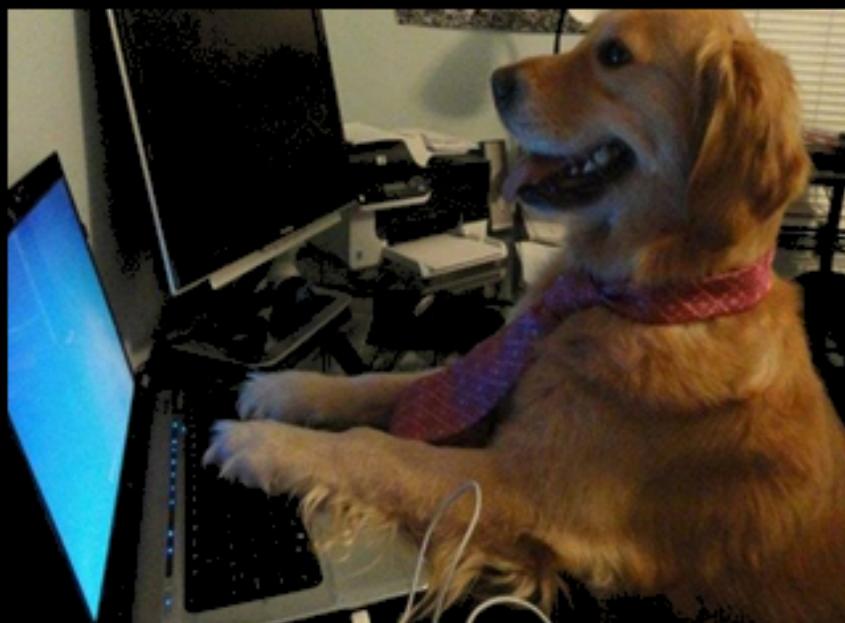
What society thinks I do



What my friends think I do



What other computer
scientists think I do



What mathematicians think I do

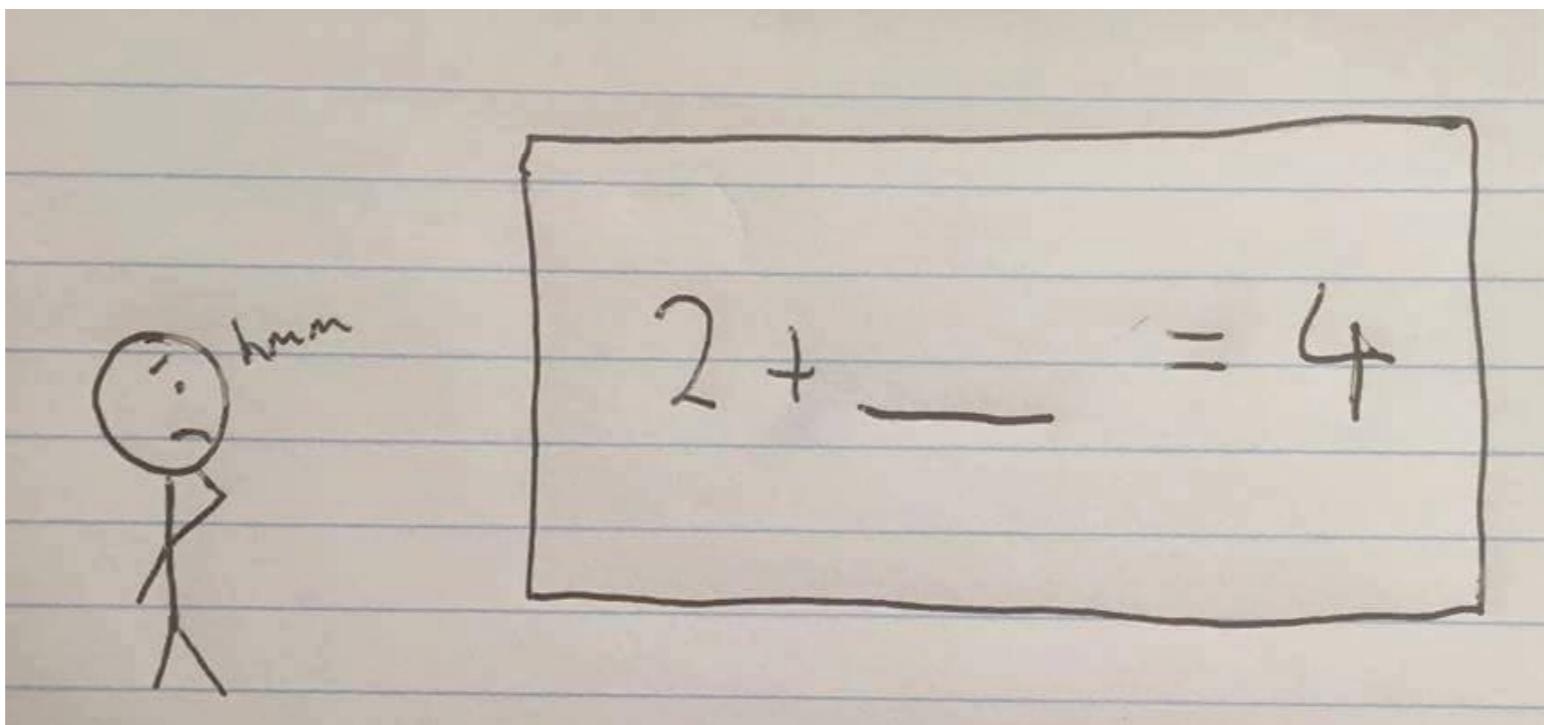


What I think I do

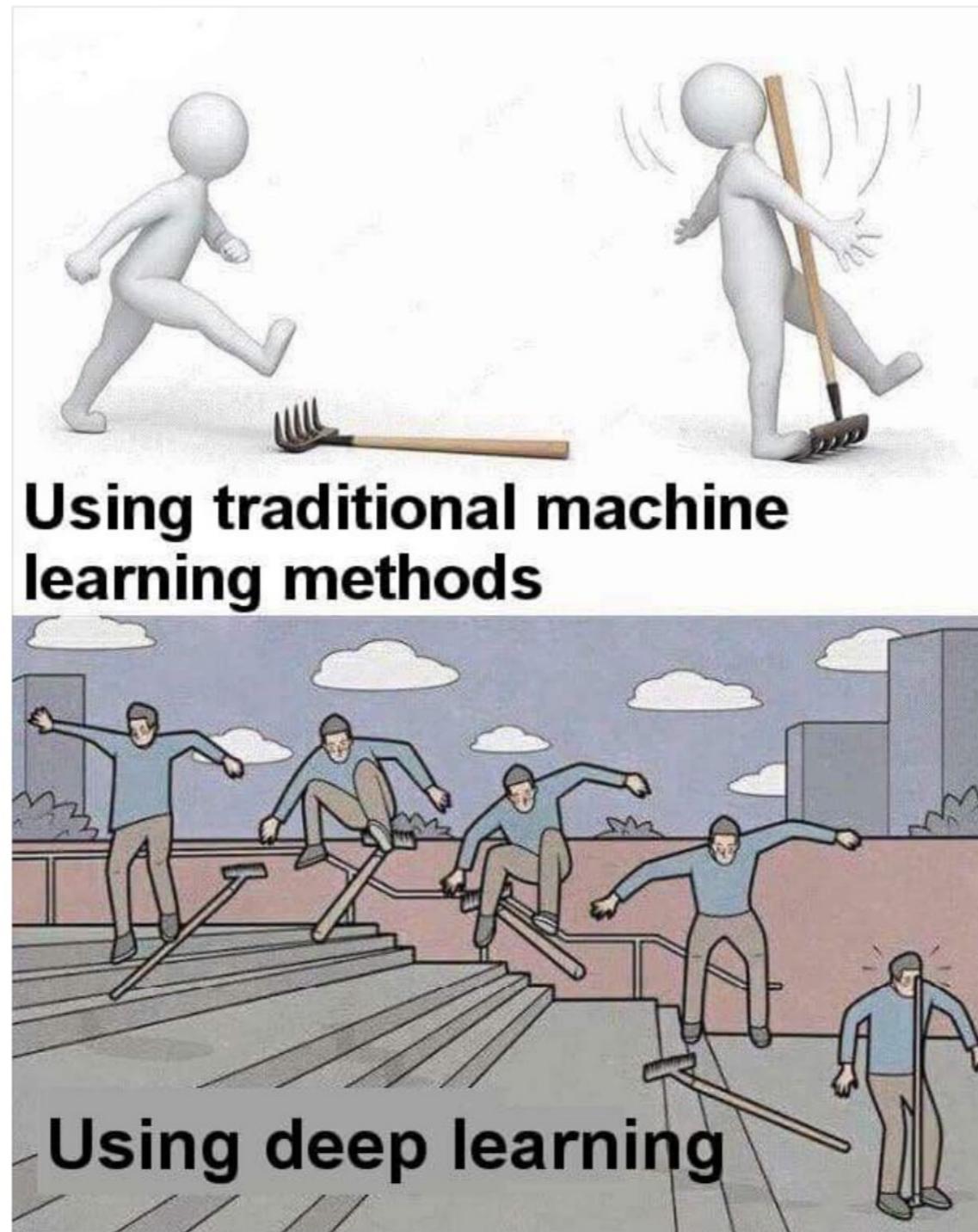
```
In [1]:  
import keras  
Using TensorFlow backend.
```

What I actually do

Interpretability



“Deep” learning



Webinars



Natural Language Processing (NLP) from Scratch

- May 6, 2019 5am-9am (PST)

Data Visualization with matplotlib and seaborn

- Jun 4, 2019 8am-12pm (PST)

