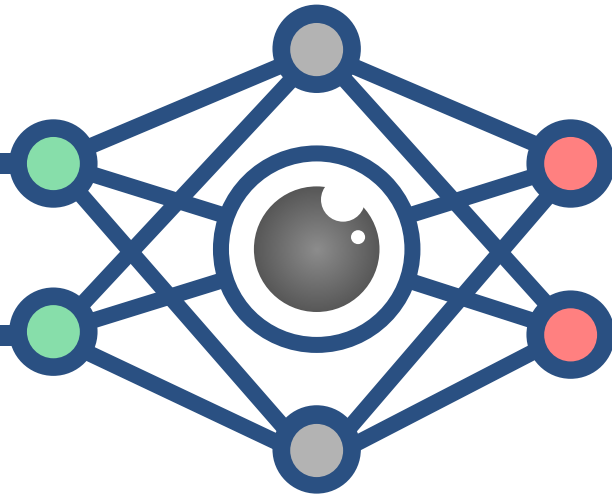


CS3485

Deep Learning for Computer Vision



Lec 3: The Multilayer Perceptron and Intro to Deep Learning

Announcements

■ Lab1:

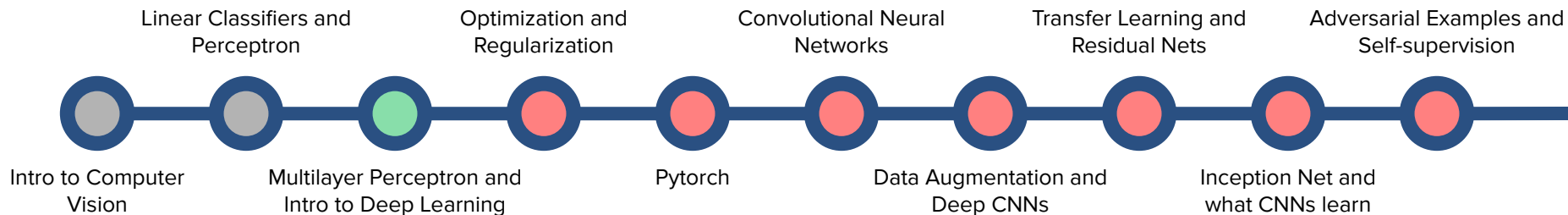
- A little issue with the website, but now it's solved, and you can find it in our [assignments](#) menu and on Canvas
- Report submission should be done on Canvas.
- Let me know if you find any issues or if the instructions are not clear enough.

■ Waitlist:

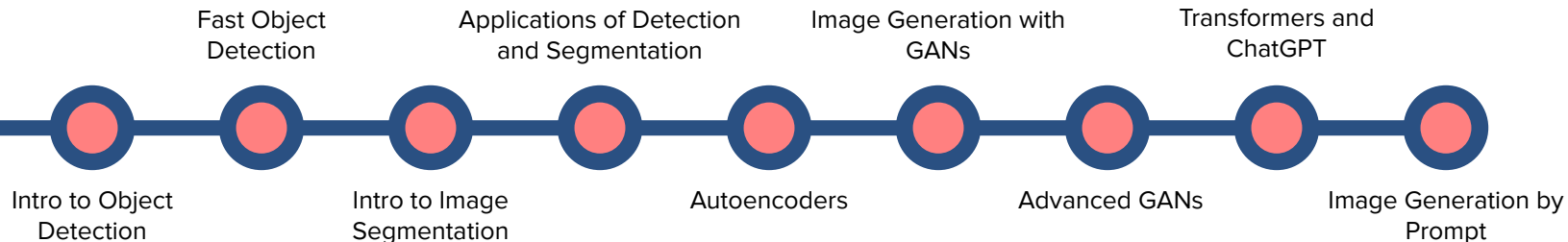
- We decided not to over enroll this class this time.
- We'll potentially offer this course again next semester (and give “over enrolling preference” for the students who tried to get in this semester, but couldn't).

(Tentative) Lecture Roadmap

Basics of Deep Learning



Computer Vision Tasks



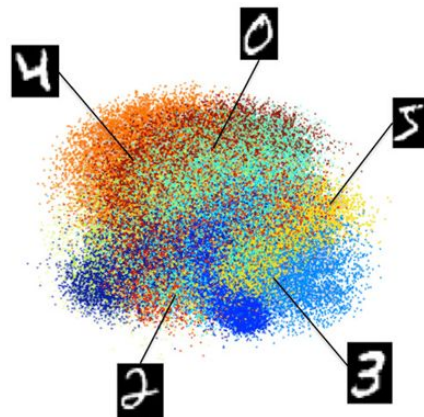
Limitations of the Perceptron Model

- Last time we saw that the Perceptron Model is useful to **model linear classifiers** and the Perceptron Algorithm is efficient at **learning the parameters** of the model.
- They, however, have two main limitations in terms of its applicability to most realistic datasets (like MNIST, on the right):
 - a. The model can only perform **binary classification**, i.e., handle datasets with two classes,
 - b. The algorithm expects the data to be **linearly separable**.
- Today we'll improve the Perceptron Model, so it can tackle both of the above issues.
- This new model, **the Multilayer Perceptron**, will form the basis for Deep Learning algorithms.

MNIST Dataset



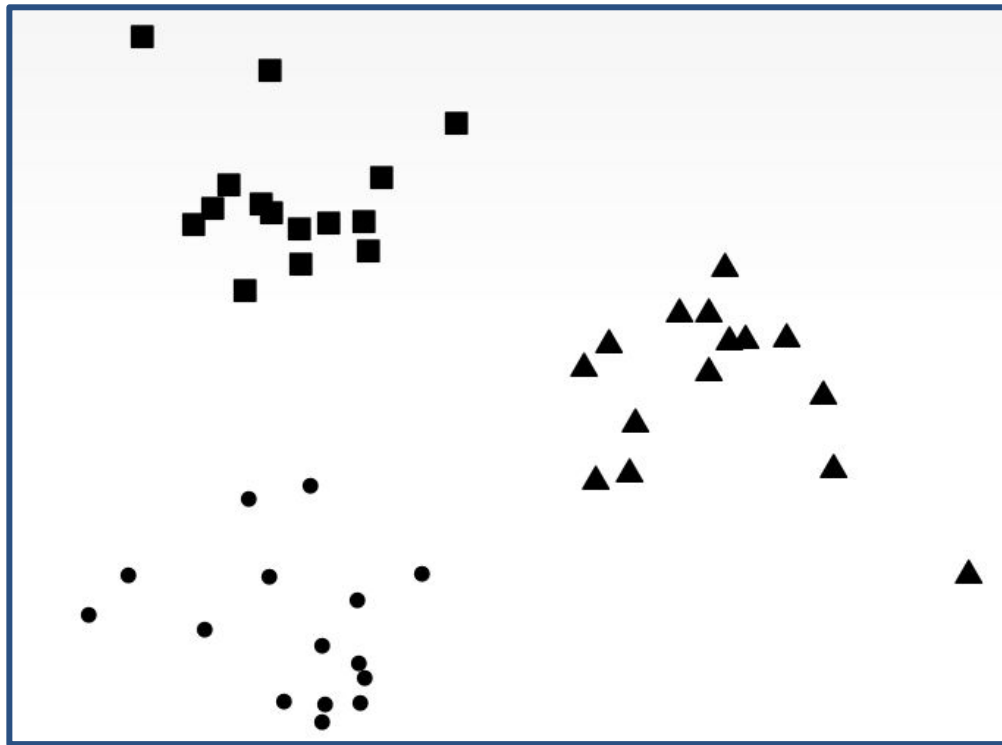
MNIST Dataset Projected in 2D



Multiclass Problems

- For the purpose of this course, assume that the Perceptron model our best solution* for **binary** classification problems.
- Now consider the problem of **classifying the points on the right into 3 classes**: squares, triangles and circles?
- How can we use only the Perceptron to do it?

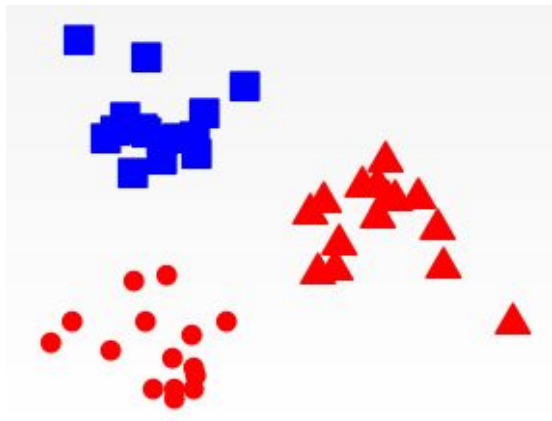
* In fact, there are many better algorithms for binary classification using linear classifiers than the perceptron, such as Support Vector Machines.



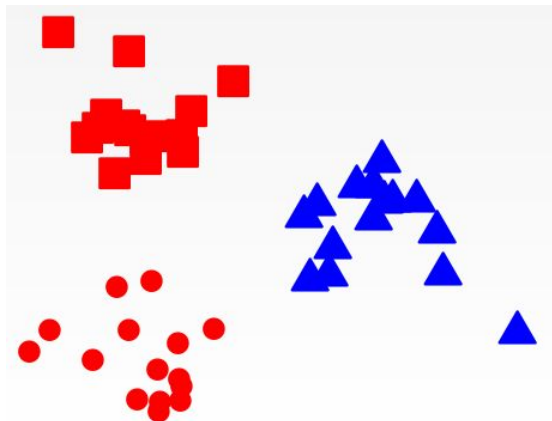
Multiclass Problems

- We can use three classifiers!

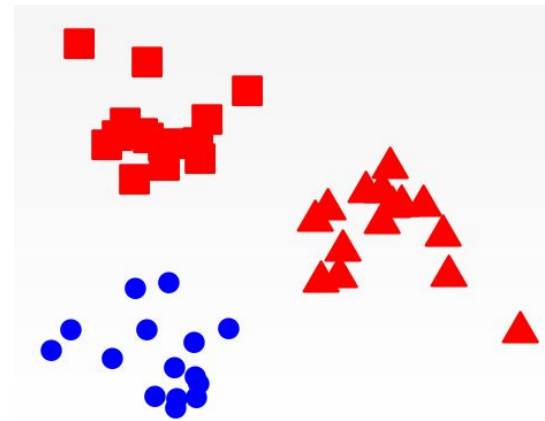
1. Is this a square?



2. Is this a triangle?



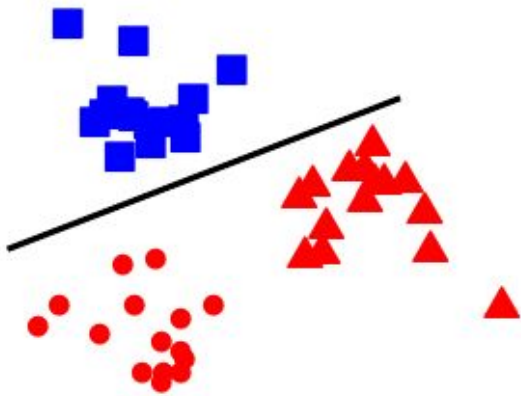
3. Is this a circle?



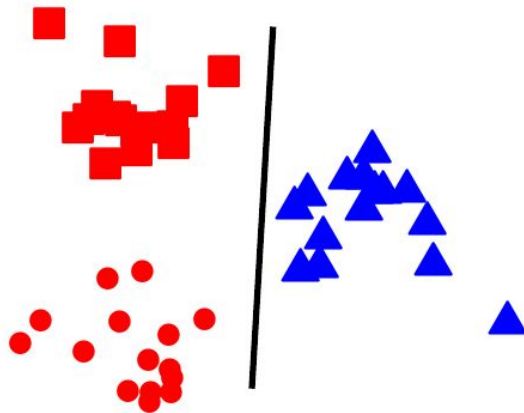
Multiclass Problems

- We can use three classifiers!

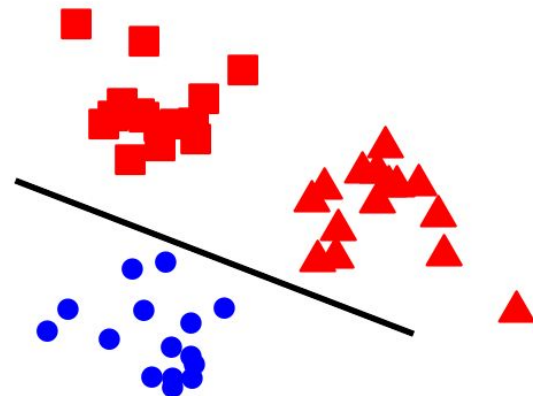
1. Is this a square?



2. Is this a triangle?

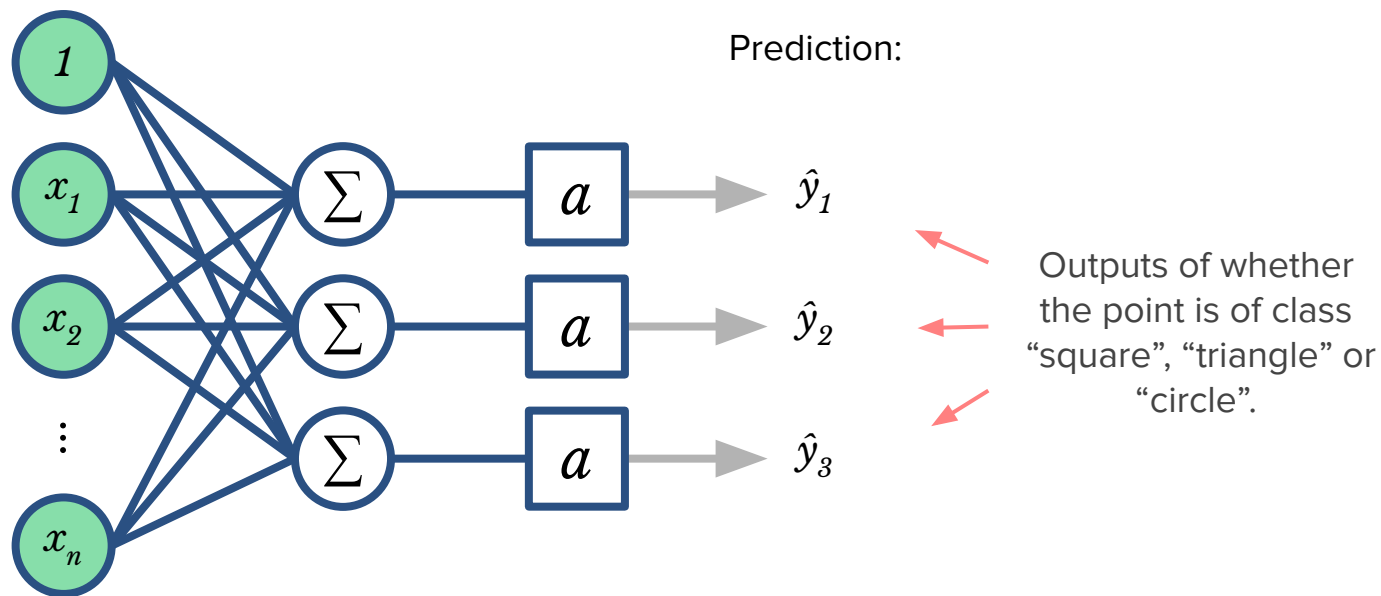


3. Is this a circle?



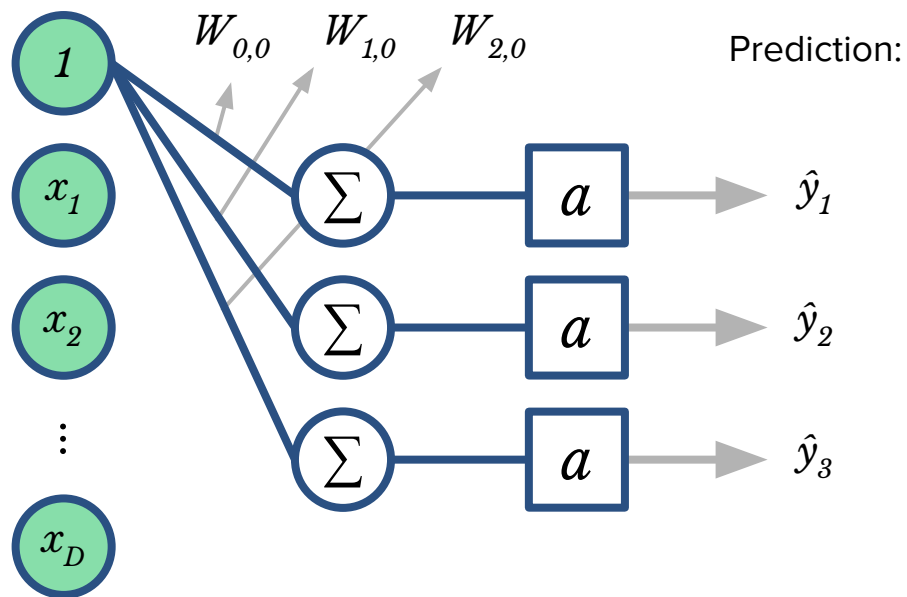
Multiclass perceptron

- We have a perceptron (or **neuron/unit**) for each class, so we can represent them as:



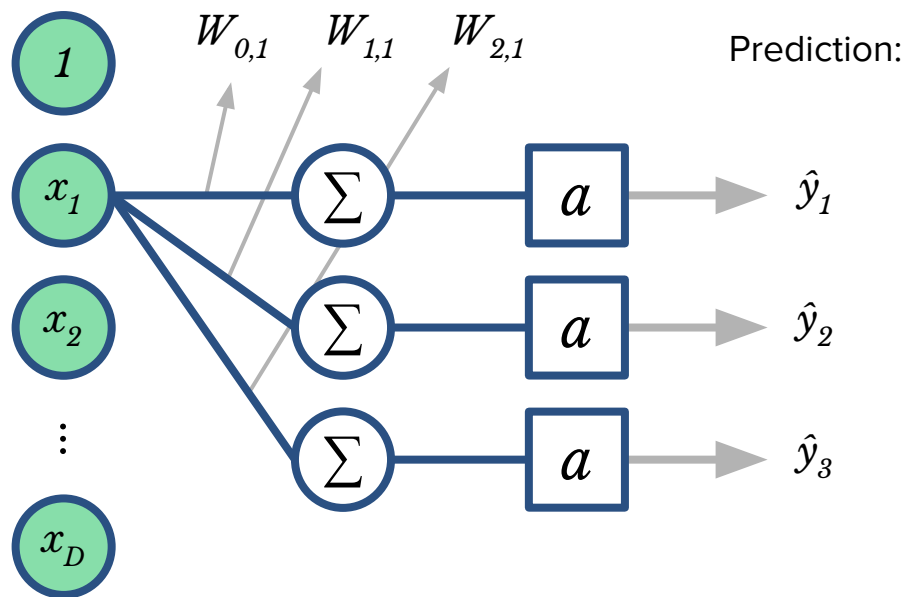
Multiclass perceptron

- Now each weight set of each neuron will be an entry of a $\mathcal{Z} \times (D+1)$ **matrix of weights** W .



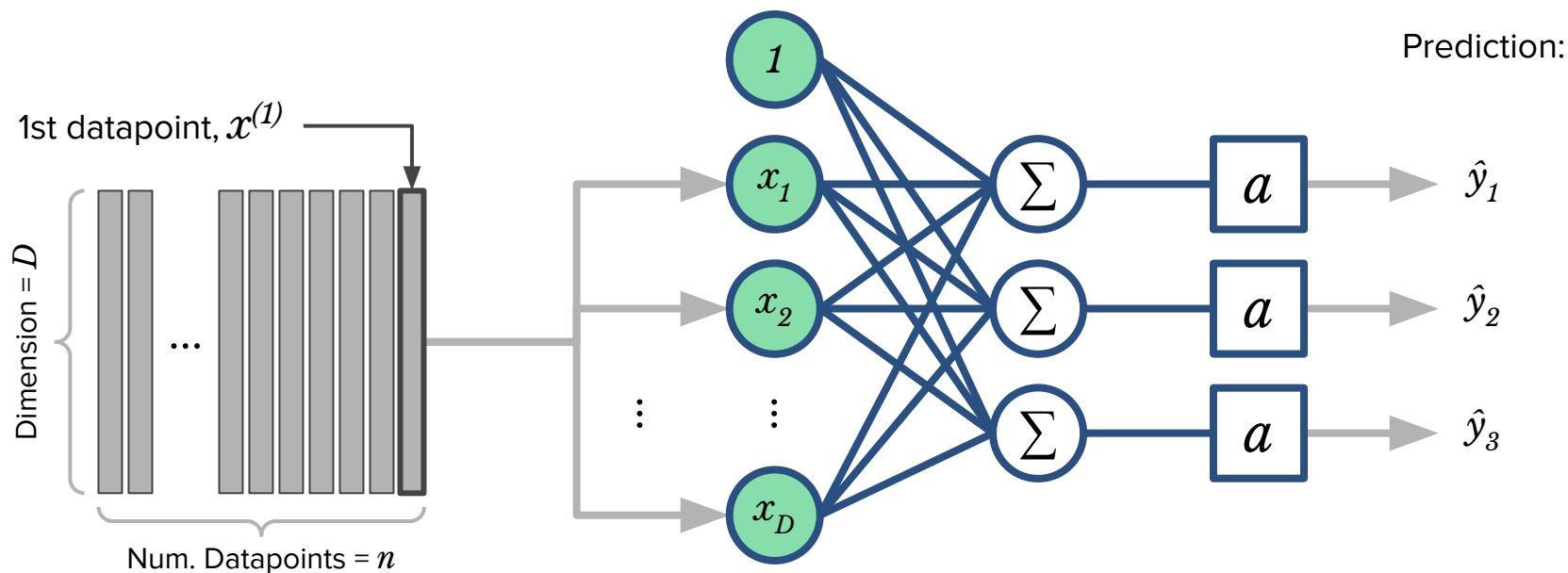
Multiclass perceptron

- Now each weight set of each neuron will be an entry of a $3 \times (D+1)$ **matrix of weights** W .



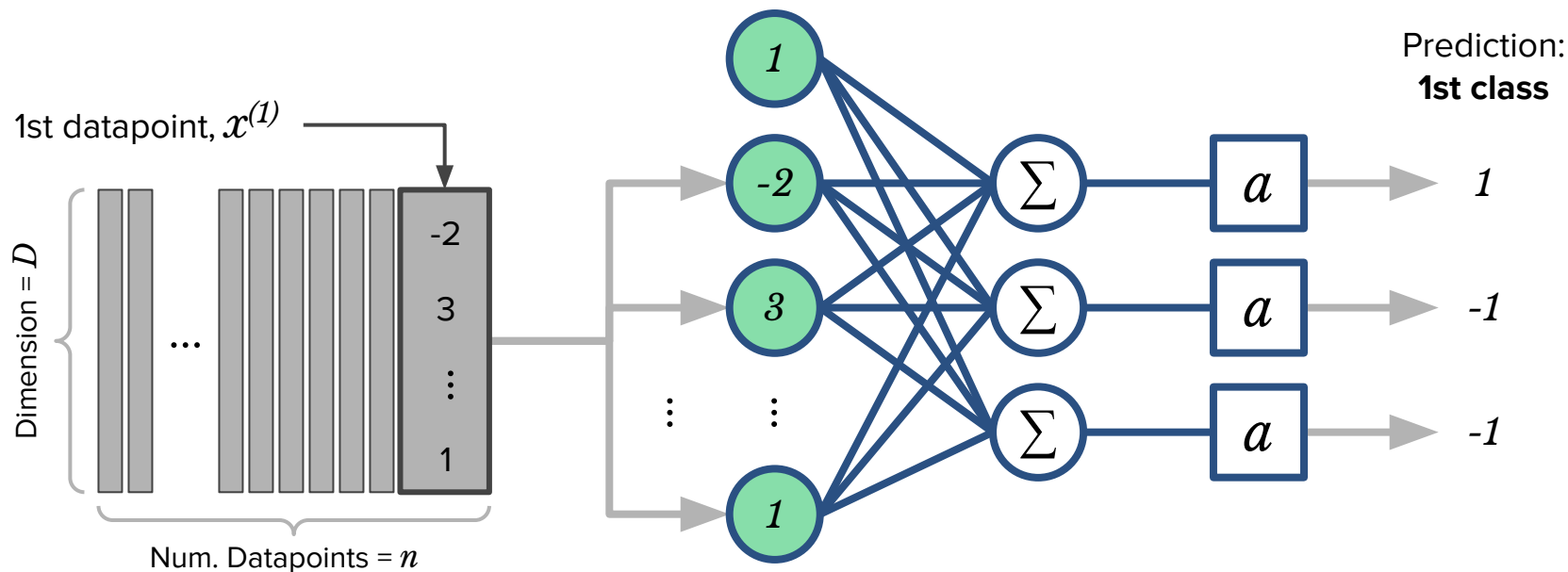
Multiclass perceptron

- Assuming we trained the three perceptrons, we can do a forward pass on them:



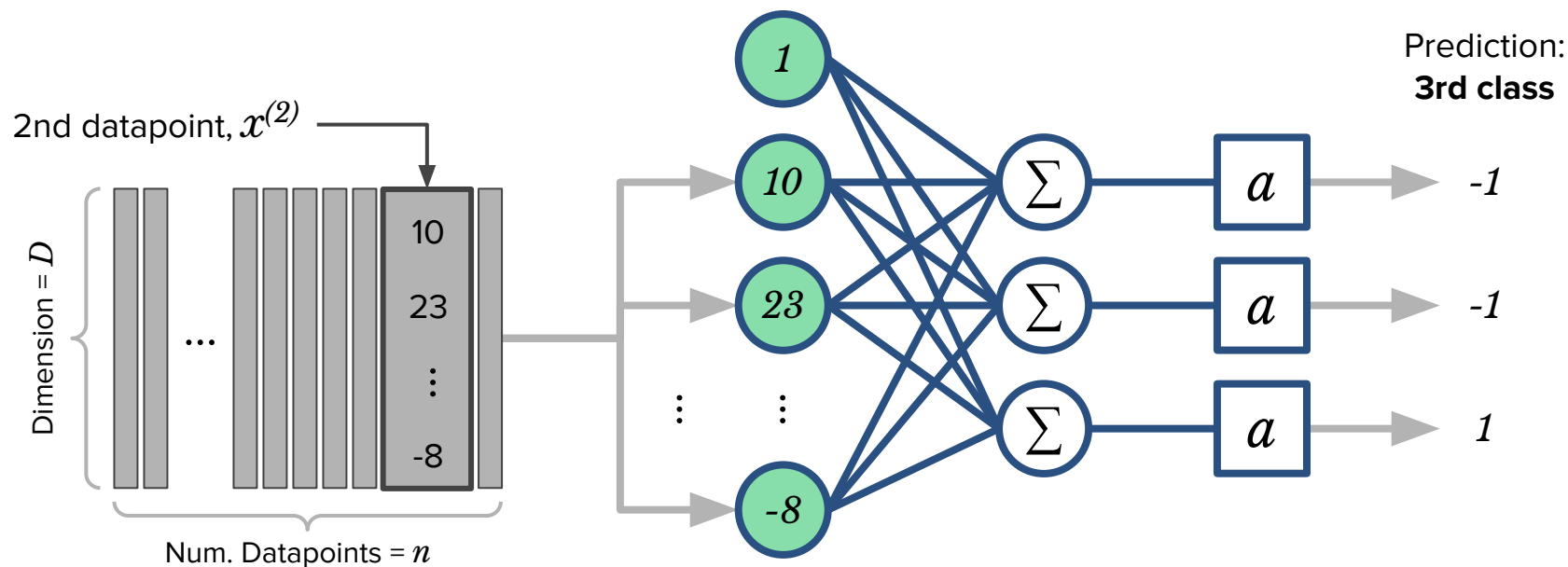
Multiclass perceptron

- Assuming we trained the three perceptrons, we can do a forward pass on them:



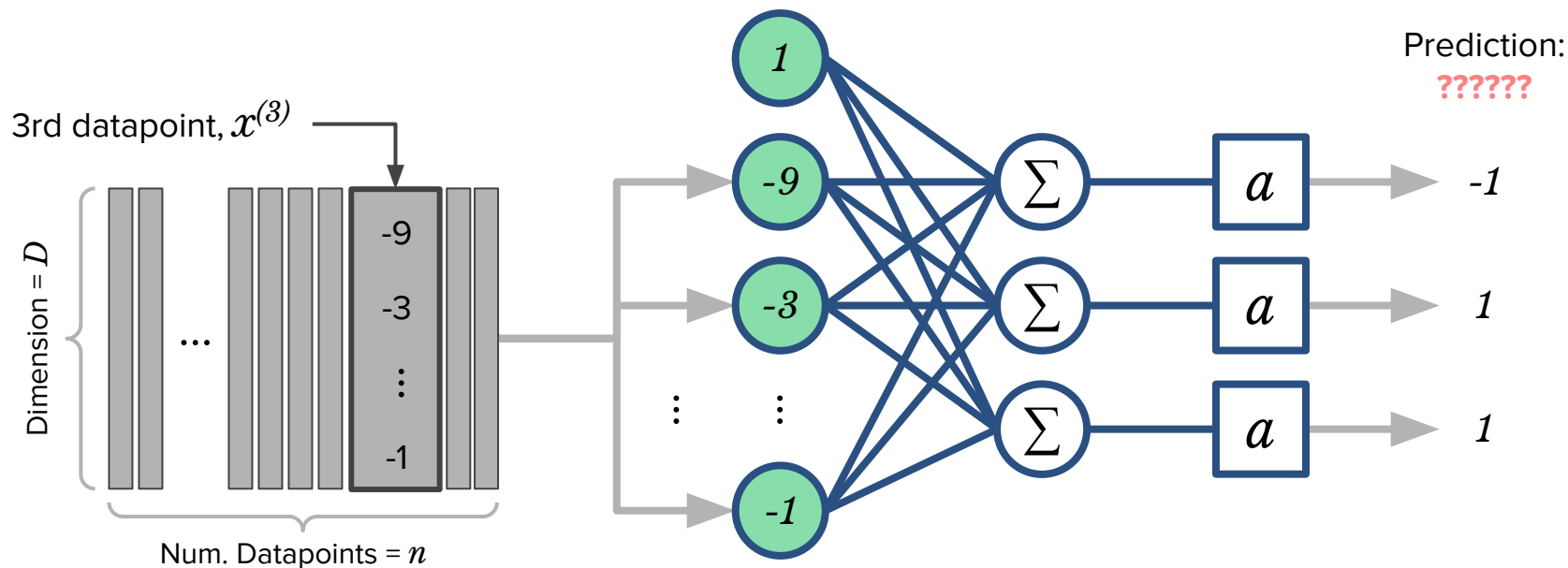
Multiclass perceptron

- Assuming we trained the three perceptrons, we can do a forward pass on them:



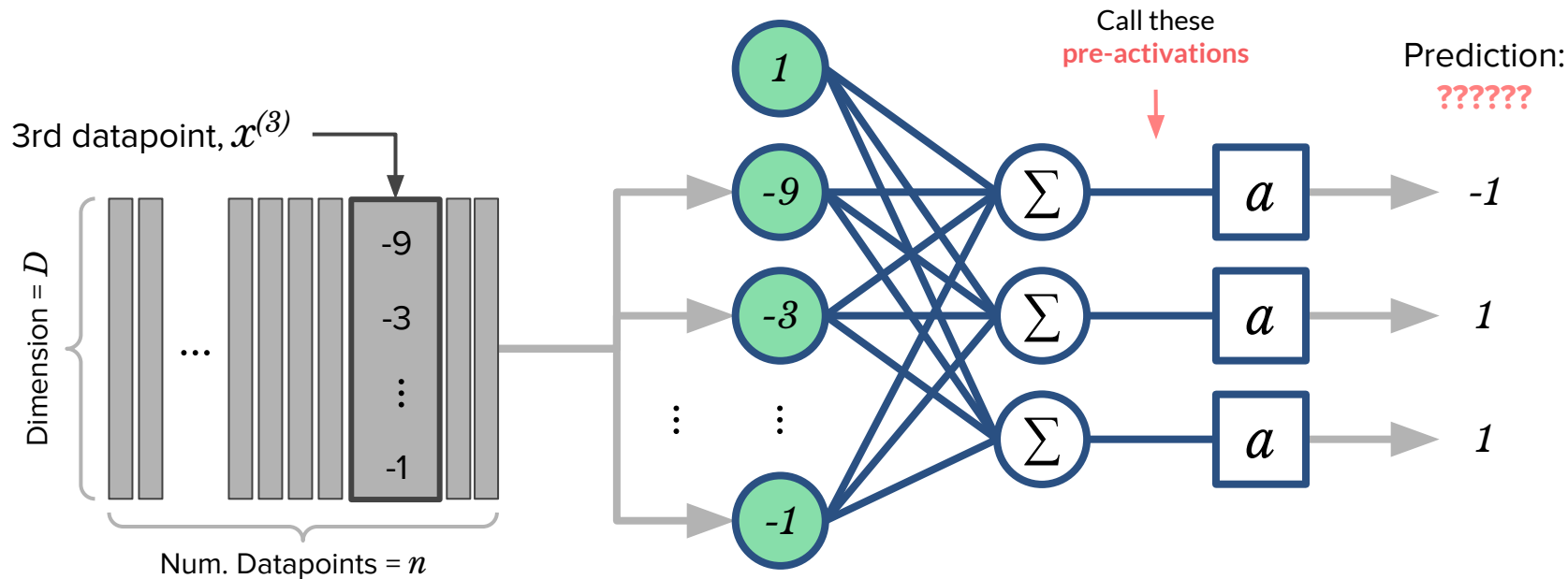
Multiclass perceptron

- What do we do when there is ambiguity?



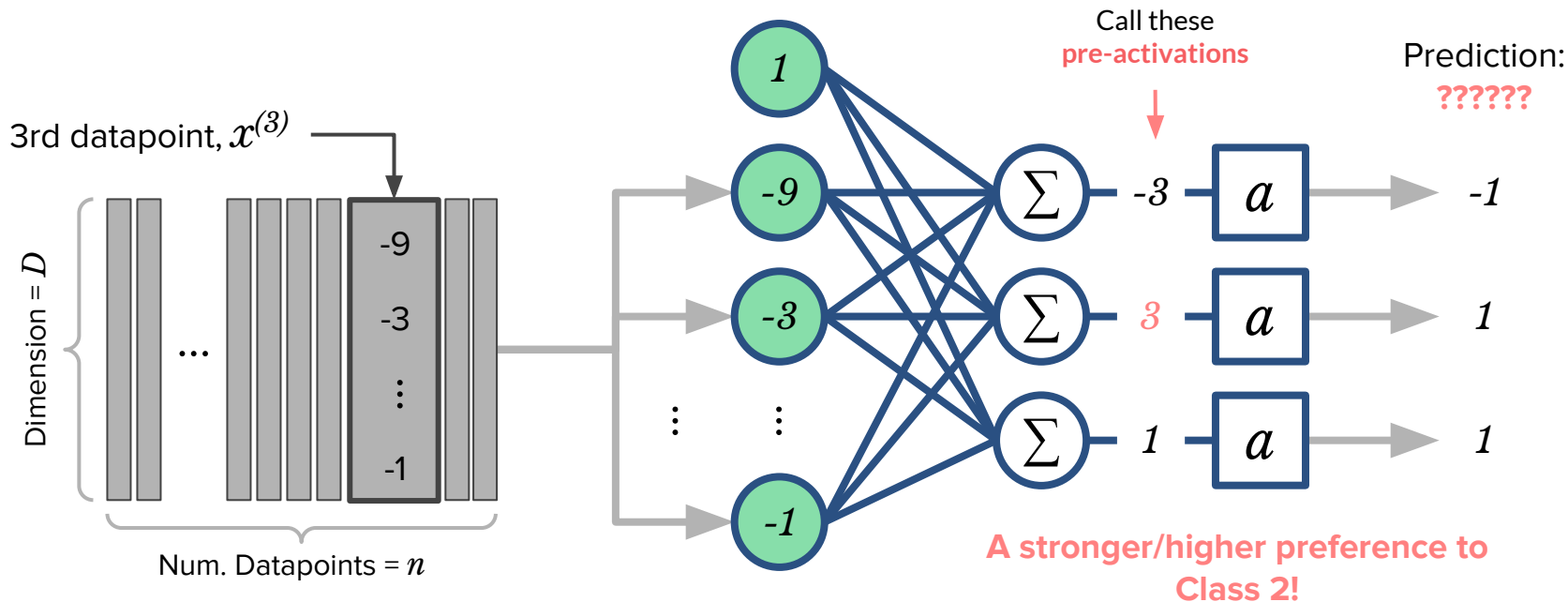
Multiclass perceptron

- What do we do when there is ambiguity?



Multiclass perceptron

- Via pre-activations (also called **logits**), we can check the class that the point “prefers” the most.



The Softmax Function

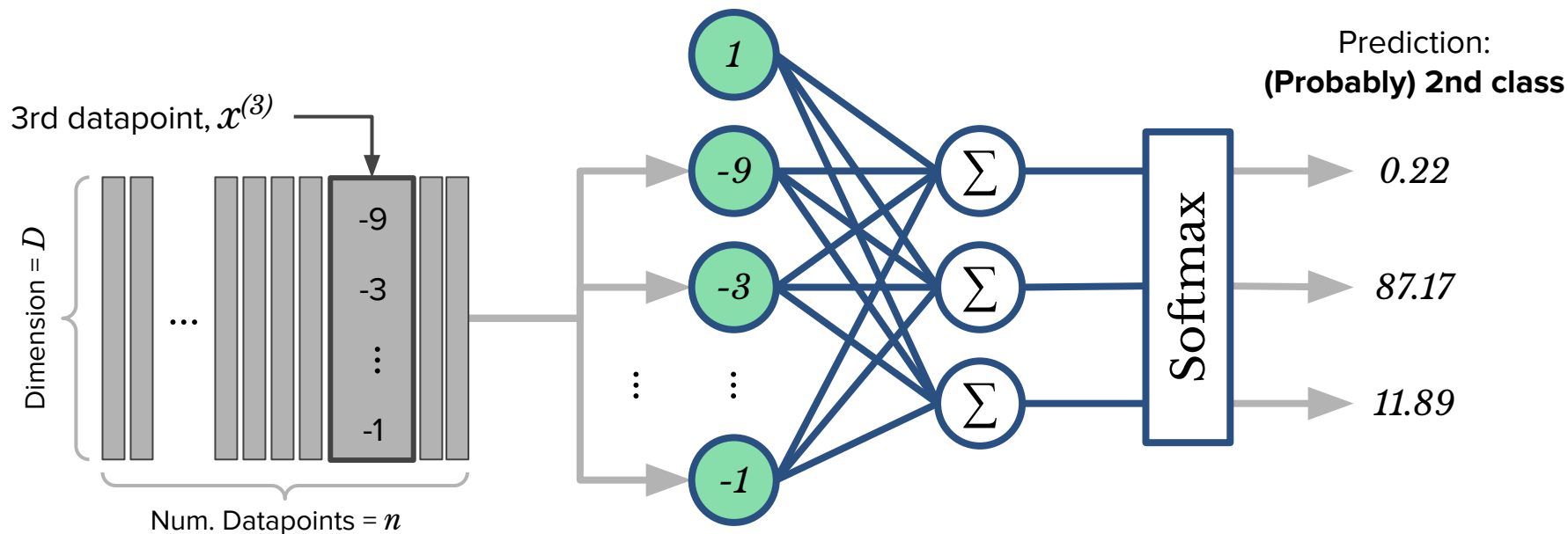
- Using **pre-activations** seems like a great way to avoid ambiguities, but they are set up is not ideal to compare them to the real classes (*as we'll see later*).
- A better approach would be to transform them into a **probability distribution** (i.e. make them all positive and summing to 1).
- Call the pre-activations $\mathbf{z} = [z_1, z_2, \dots, z_K]$. One way to turn \mathbf{z} into a distribution is via the **softmax** function:

$$\text{softmax}(z_i) = \frac{\exp(z_i)}{\sum_{c=1}^K \exp(z_c)}$$

- The $\exp()$ function turns the \mathbf{z} 's into positive numbers.
 - The normalization makes the resulting numbers sum to 1.
- *Example:* $\mathbf{z} = [-3, 3, 1] \rightarrow \text{softmax}(\mathbf{z}) = [0.22, 87.89, 11.89]$
- In practice, we replace the perceptrons' activation functions by a softmax operation.

Multiclass perceptron with softmax

- With softmax the softmax operation, we have now the following model:



One-hot Encoding

- If the input of the model is called x , its output can be computed using the **multiclass perceptron formula**:

$$\hat{y} = \text{softmax}(Wx)$$

- We need to assess how good is the output of our model (say, $\hat{y} = [0.22, 87.89, 11.89]$) for a point x in relation to the true label of that point y (which can be “circle”).
- In Neural Networks, we use a **one-hot encoding** of the true labels, so we can compare them to our predictions.

- If we have K classes, the one-hot encoding of the labels will be vectors of K dimensions, **mostly made of zeros except at the dimension corresponding to the label value, where it is one.**

- *Example:* in our dataset, we may have

$$y_1 = \text{“Triangle”} \rightarrow y_1 = [1, 0, 0]$$

$$y_2 = \text{“Square”} \rightarrow y_2 = [0, 0, 1]$$

$$y_3 = \text{“Circle”} \rightarrow y_3 = [0, 1, 0]$$

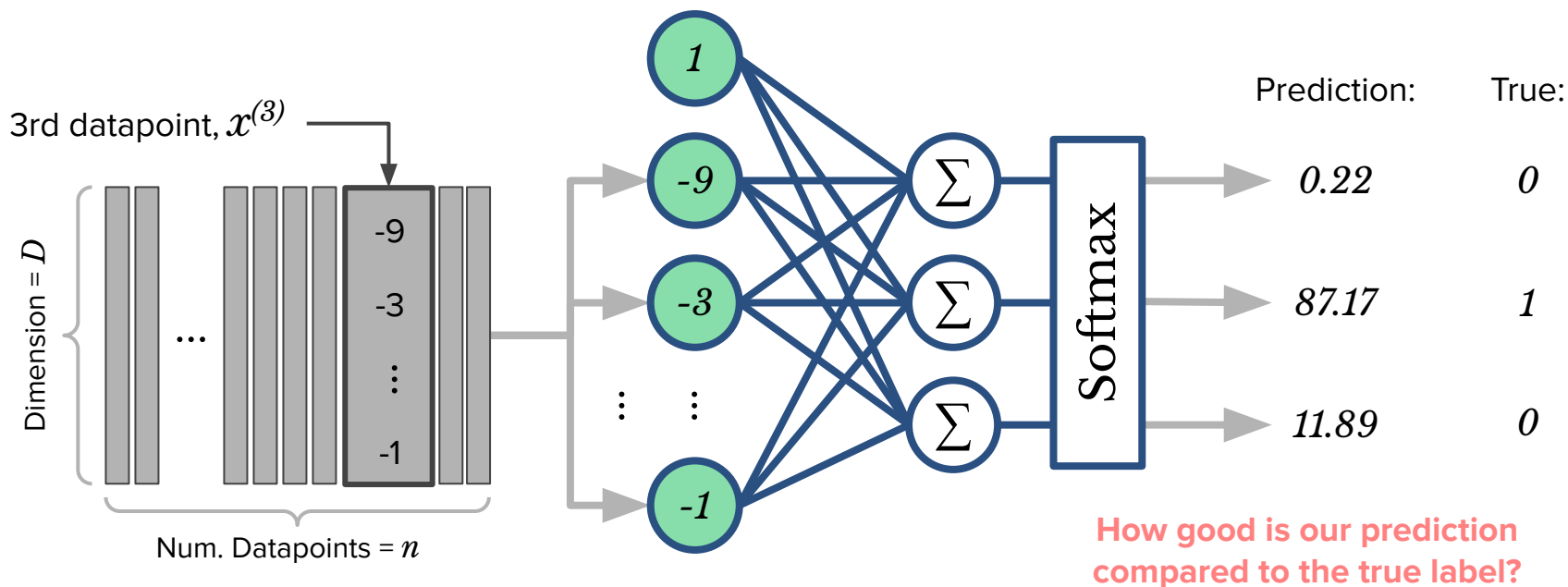
...

$$y_n = \text{“Square”} \rightarrow y_n = [0, 0, 1]$$

- These encodings are also distributions (made of positive numbers that sum to 1)!

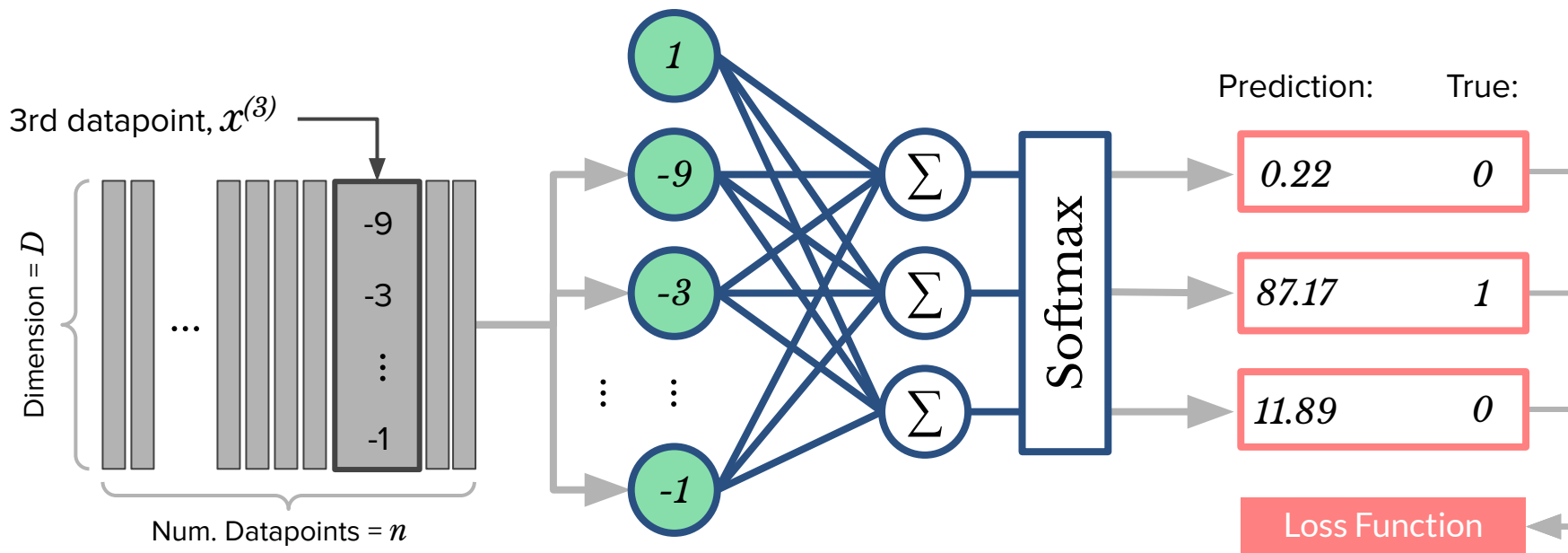
Multiclass perceptron with softmax

- Say the third point's true label is "circle", which is encoded as $[0, 1, 0]$:



Multiclass perceptron with softmax

- We can now compare our prediction to the true label using a **loss function**.



Loss functions

- We need a set of weights that achieves the **best classification performance**.
- To that end, we can then use **loss (or cost) functions** $l(\hat{y}, y)$, that compares how similar our prediction \hat{y} is to the true one-hot encoded label y .
- One of the most used loss functions* for multiclass problems is the **cross-entropy loss**:

$$l(\hat{y}, y) = -y^\top \log(\hat{y}) = -\sum_{j=1}^K y_j \log(\hat{y}_j)$$

- If we have a labeled dataset of size n , we can consider the **average loss** $L(\theta)$ on it:

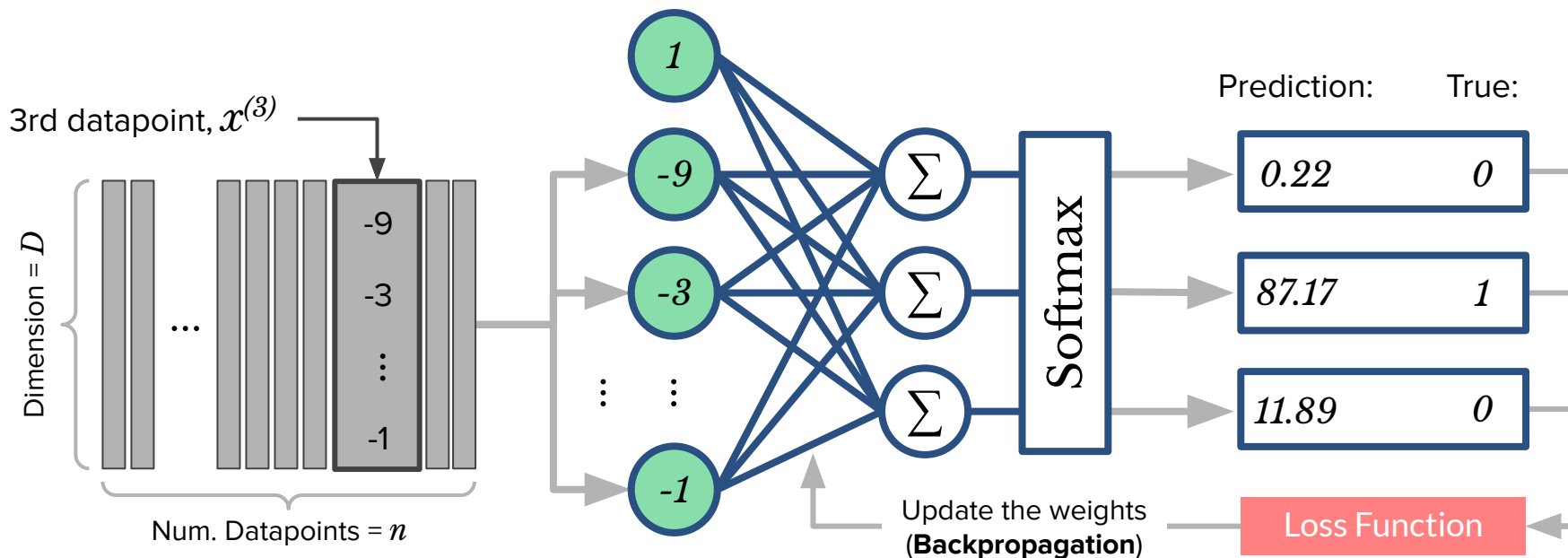
$$L(\theta) = \frac{1}{n} \sum_{i=1}^n l(\hat{y}^{(i)}, y^{(i)})$$

where θ represents all the parameters (weights, in the case of the perceptron or in Deep Learning generally speaking) used to compute \hat{y} from x (*more on it next time*).

* There are many other losses used in Deep learning, and we'll see them as we go.

Multiclass perceptron with softmax

- We use the loss value to update the weights and improve the classifier (*more next time*).



Exercise (*In pairs*)

- How many weights are there to learn if we have input data in D dimensions and K classes in the output of our multiclass perceptron?
- Compute the cross-entropy loss for the following pairs true label/prediction (assume you only have these three data points in your dataset):

- True labels:

$$y_1 = [1, 0, 0], y_2 = [0, 1, 0], y_3 = [0, 0, 1]$$

- Predictions:

$$\hat{y}_1 = [1, 0, 0], \hat{y}_2 = [0.1, 0.8, 0.1], \hat{y}_3 = [1/3, 1/3, 1/3]$$

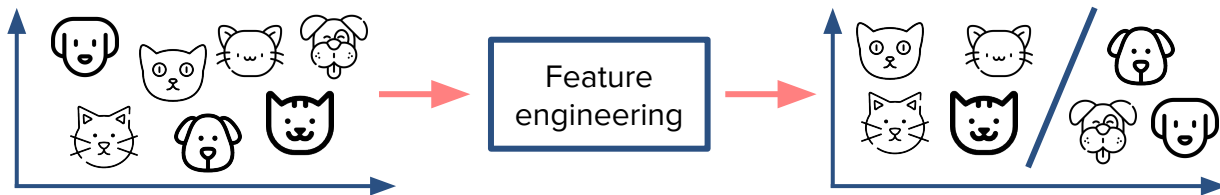
- Repeat the above exercise using the **Squared Error** loss*:

$$l(\hat{y}, y) = \|y - \hat{y}\|_2^2 = \sum_{j=1}^K (y_j - \hat{y}_j)^2$$

*The dataset's Average Loss $L(\theta)$ when using the squared error loss is the famous **Mean Squared Error (MSE) loss**.

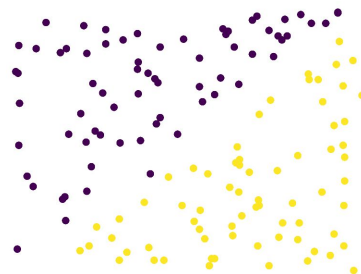
Learning Representations

- Multiclass Perceptrons are still not performant when the classes are non-linearly separable (as on the right).
- Traditionally, this problem would be solved by **handcrafting a feature transformation** that would make the data separable:

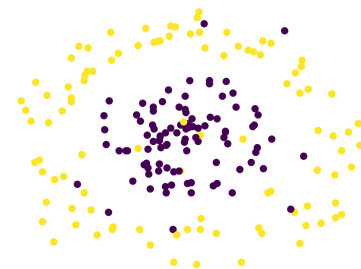


- *Example:* a feature that easily separates cats and dogs is the “*ear pointiness*”. We could **represent** cats and dogs by that.
- In Deep Learning, we aim at **learning these representations** from a labeled dataset.
- To achieve that goal, we have to “evolve” our perceptrons.

Linearly Separable

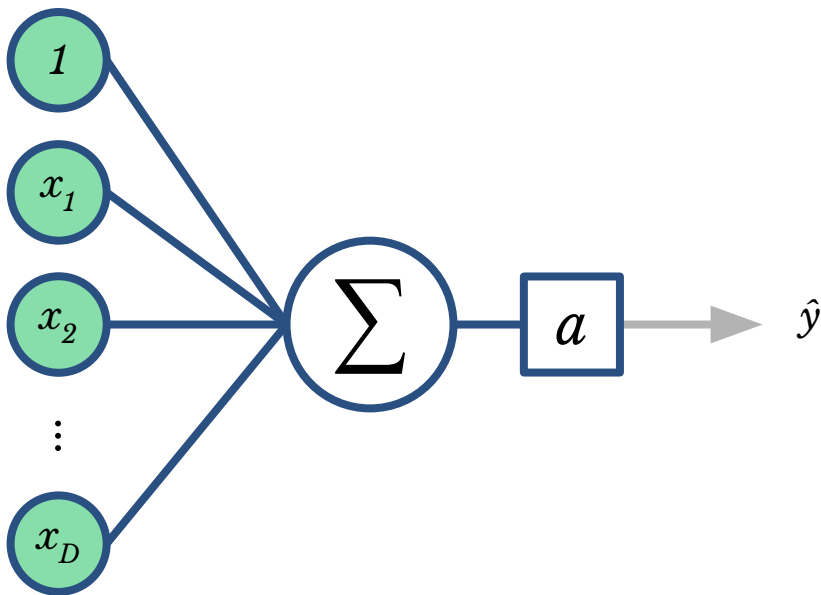


Non-Linearly Separable



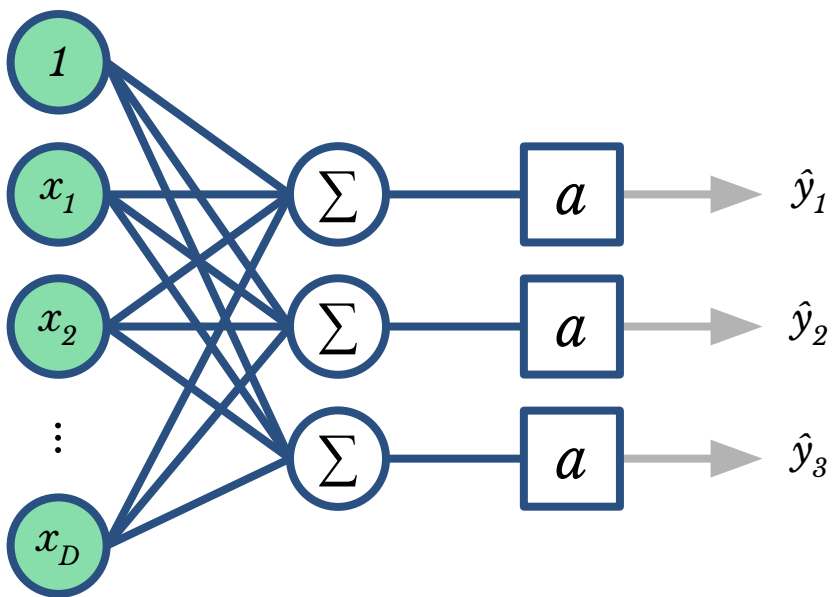
Perceptron Evolution

- The first perceptron had *1* neuron and only handled binary linearly separable problems.



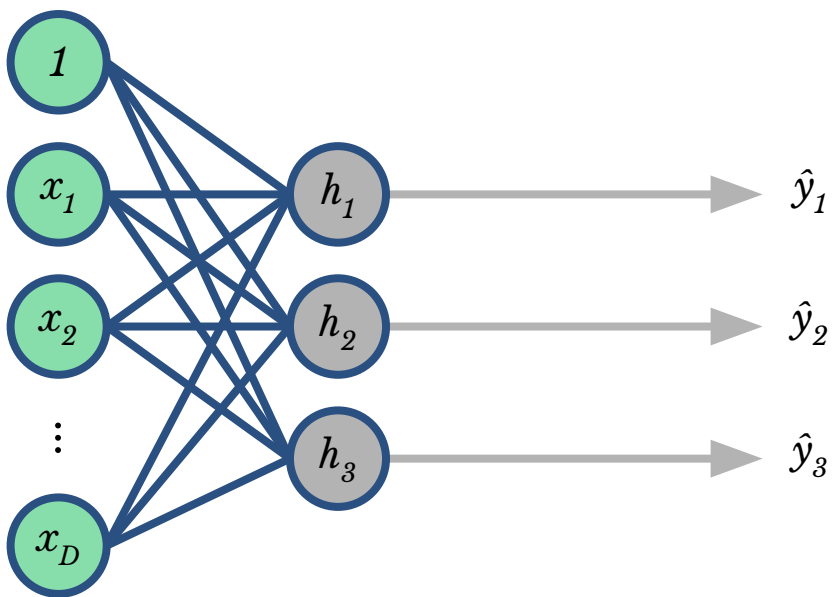
Perceptron Evolution

- Staking up some neurons, we were able to “solve” multiclass problems.



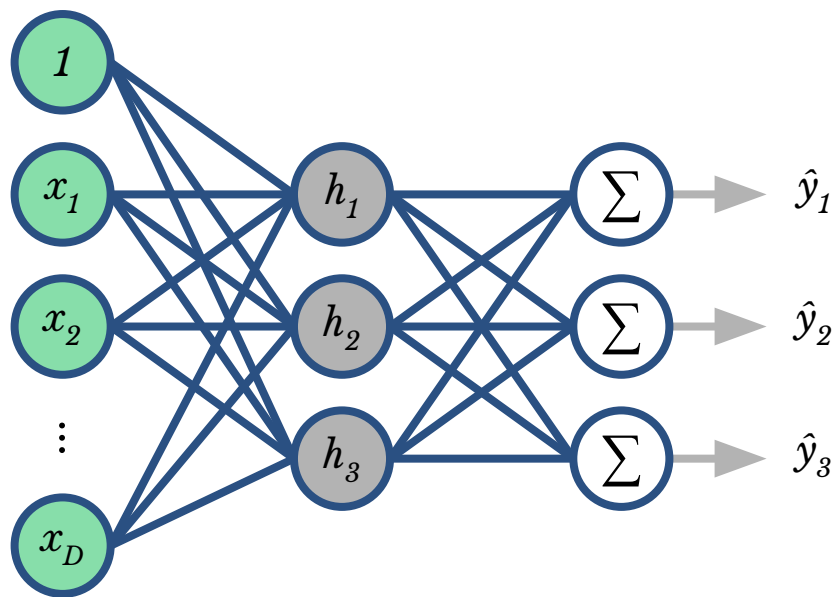
Perceptron Evolution

- We could, however, consider the outputs of the neurons as a “transformed” input ...



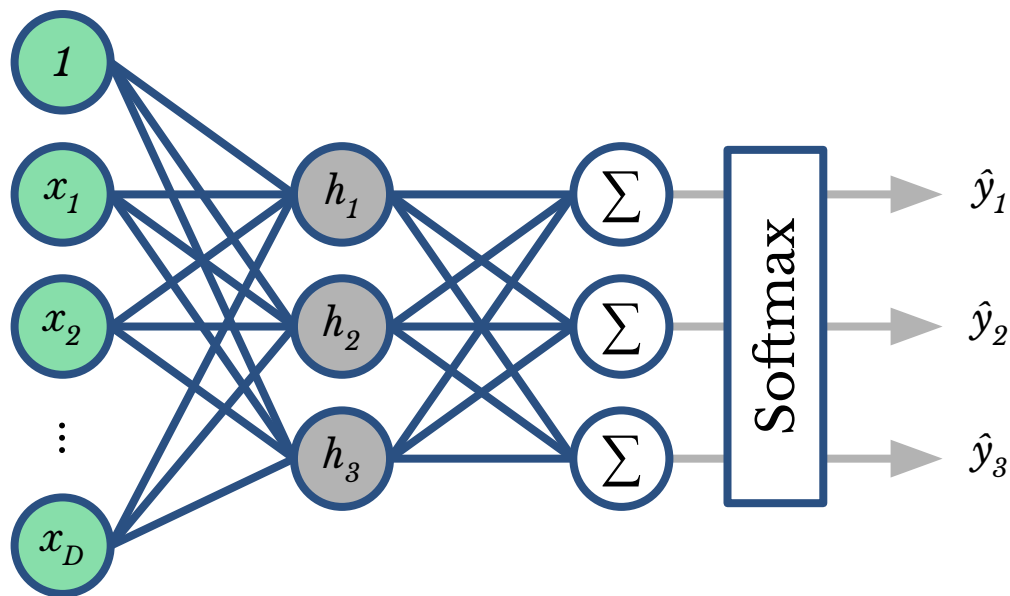
Perceptron Evolution

- ... and the pass this new data into new sums, like what we did to x , ...



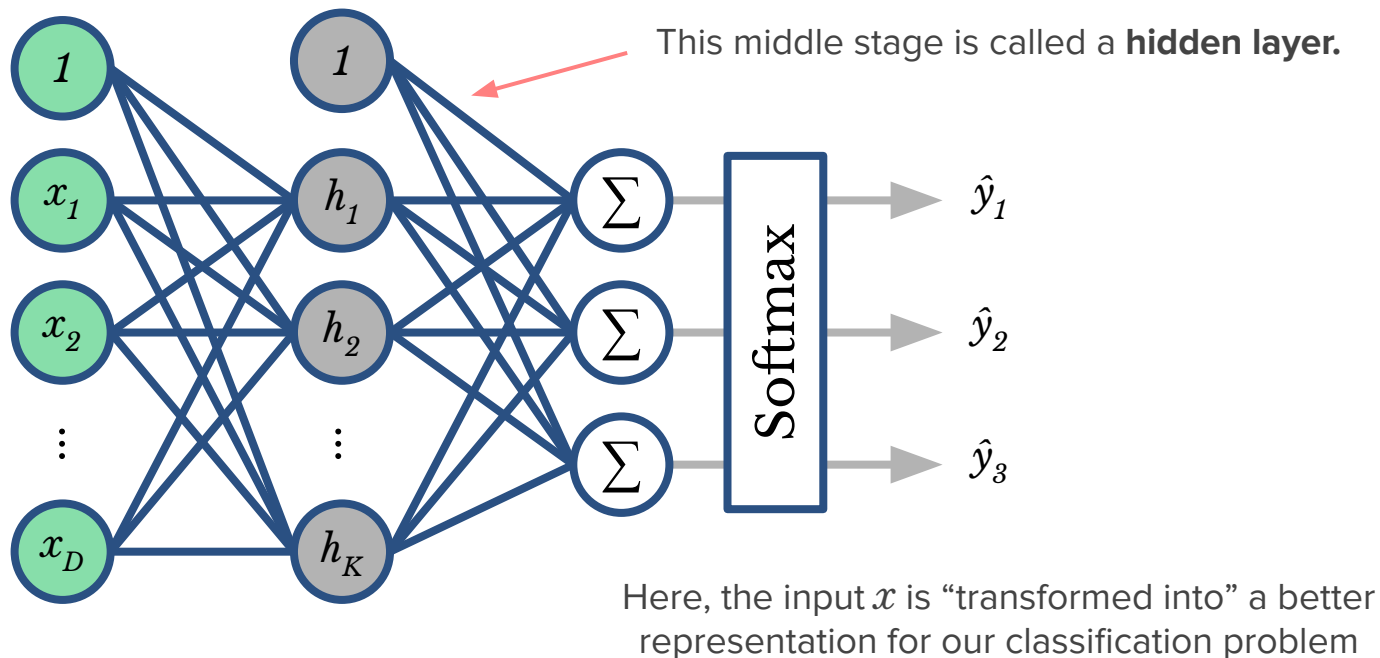
Perceptron Evolution

- ... and only then make the results of the sums go through the softmax function.



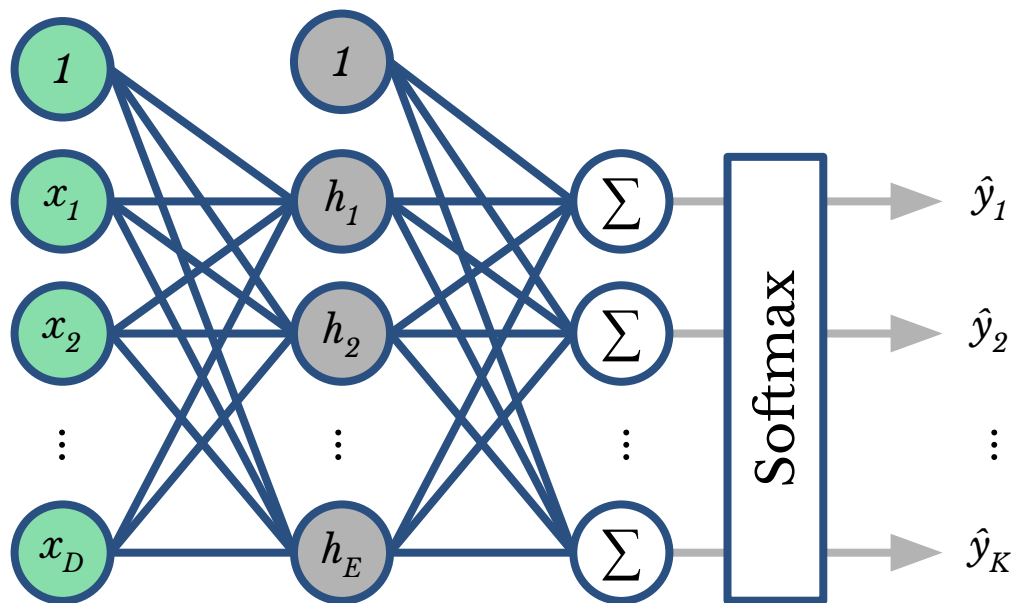
Perceptron Evolution

- We don't need to have only 3 neurons in the middle, and we can also add a bias term.



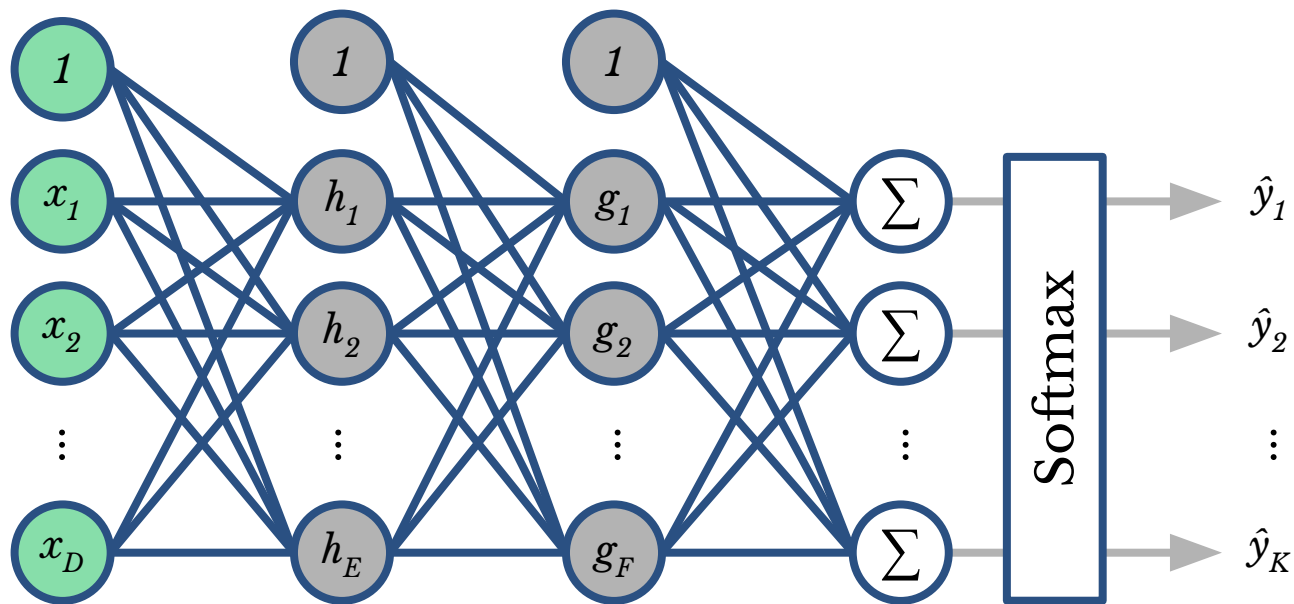
Perceptron Evolution

- This same idea can be expanded for the cases when we have any number of classes.



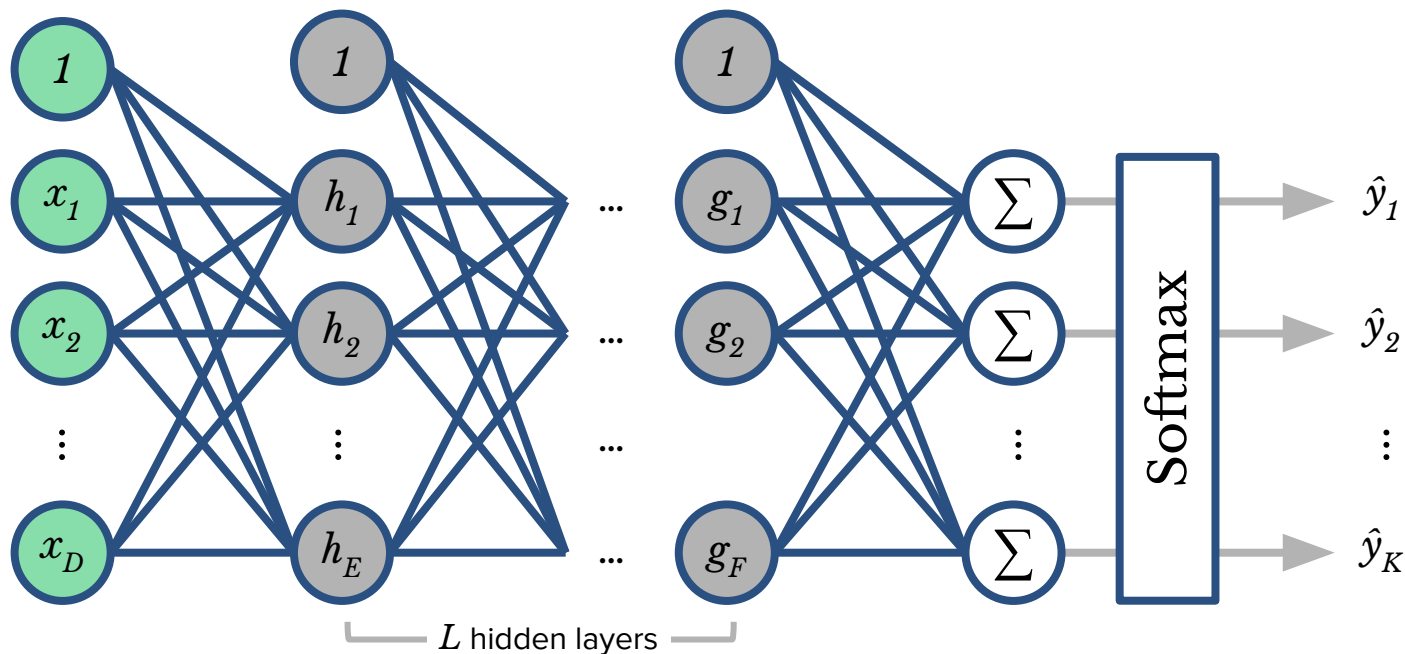
Perceptron Evolution

- Nobody will stop us from adding another hidden layer.



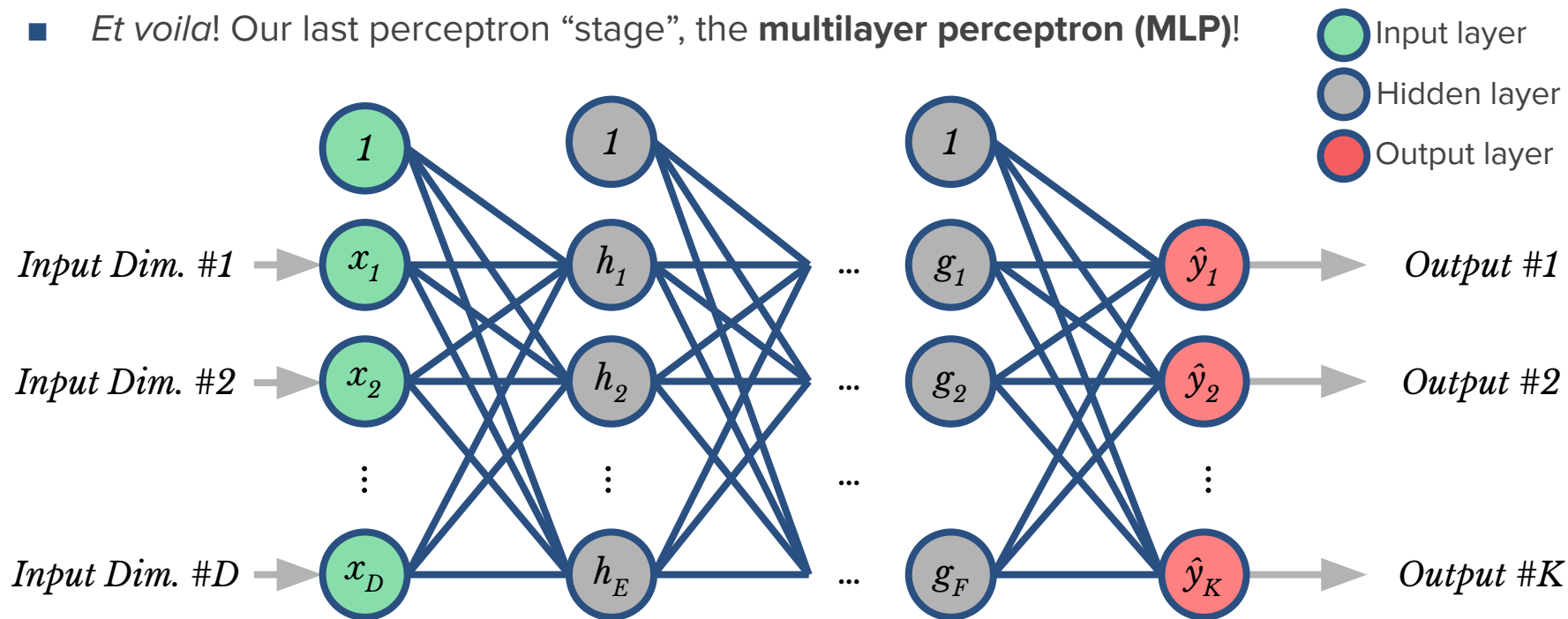
Perceptron Evolution

- Or in fact, as many hidden layers as we need.



Multilayer Perceptron

- *Et voila!* Our last perceptron “stage”, the **multilayer perceptron (MLP)**!



Mathematically Speaking...

- The previous illustrations are useful for intuition, but we need to **describe the MLP mathematically**, so we can find the best weights for them (*more on that next time*).
- Let's first recall the simple multiclass perceptron. Calling its weight matrix W_0 , we have:

$$\hat{y} = \text{softmax}(W_0 x)$$

- When we added the first hidden layer, we changed the above formula to:

$$\hat{y} = \text{softmax}(W_1 a(W_0 x))$$

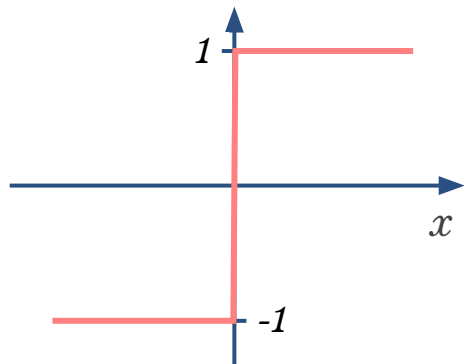
where a is the activation function applied to each of the outputs of the previous layer, i.e., if $W_0 x = [10, 20, 5]$, $a(W_0 x) = [a(10), a(20), a(5)]$.

- With L hidden layers now, we have the following expression MLP's output:

$$\hat{y} = \text{softmax}(W_L a(W_{L-1} \cdots a(W_0 x) \cdots))$$

Other Activation Functions

- The activation function we've used is the **sign**(x) function:

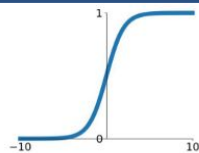


- It is, however, not great for backpropagation, as we shall see in next class, and it does not perform well in practice.

- Two more suitable activations are the sigmoid and the hyperbolic tangent (\tanh), as they are **smooth** versions of the the sign function:

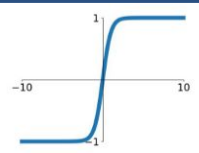
Sigmoid

$$\sigma(x) = \frac{1}{1+e^{-x}}$$



tanh

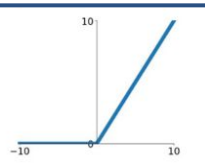
$$\tanh(x)$$



- The most widely used activation is the Rectified Linear Unit (ReLU):

ReLU

$$\max(0, x)$$



which, despite not smooth, works well in practice.

Hands-on Neural Networks

- How good is this new network to solve non-linearly separable classification problems?
- We'll see this in practice using a function from **Python's `sklearn` library!**
- First, we create* our dataset, called “blobs”:

```
from sklearn.datasets import make_blobs
X, y = make_blobs(n_samples=400, centers=4,
                  cluster_std=2, random_state=10)
```

- Then, we split* our dataset in training and test using the function “`train_test_split`” from `sklearn`:

```
from sklearn.model_selection import train_test_split
X_train, X_test, y_train, y_test = train_test_split(X, y,
                                                    test_size=0.4, random_state=2)
```

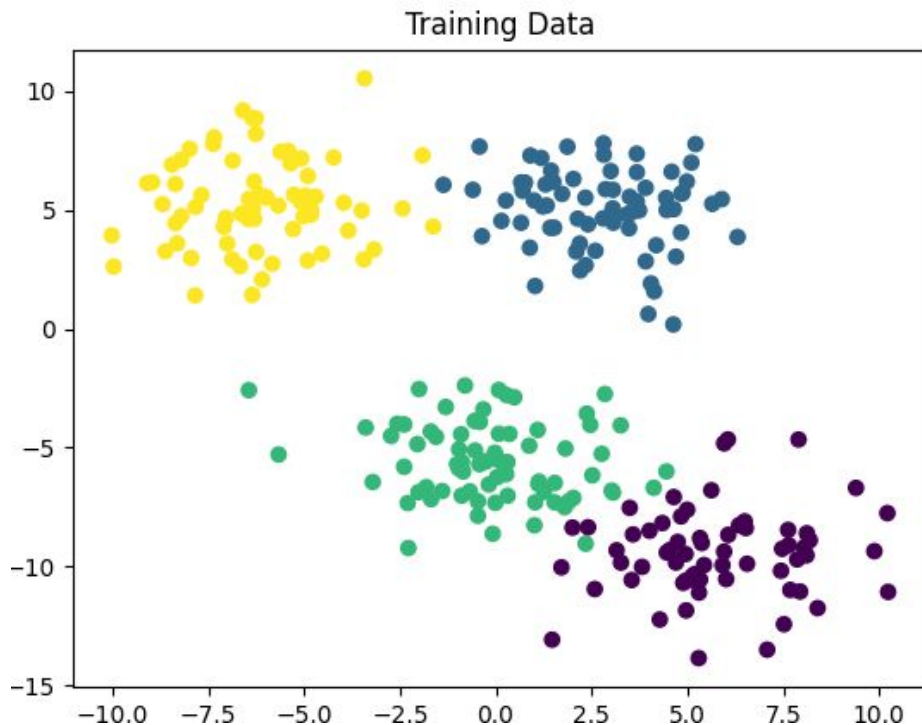
* In both functions we set the random states to those values, so you can reproduce the exact same results as in here.

Hands-on Neural Networks

- As it is usually a good practice, we then visualize the training data:

```
import matplotlib.pyplot as plt
plt.scatter(X_train[:, 0],
            X_train[:, 1],
            c=y_train)
plt.title("Training Data")
plt.show()
```

- Notice that, despite the classes being somewhat well defined, this is **not** a linearly separable dataset.
- Therefore, we should use a multilayer perceptron here.



Hands-on Neural Networks

- Now we can train a Multilayer Perceptron Classifier using `MLPClassifier`:

```
from sklearn.neural_network import MLPClassifier
clf = MLPClassifier(hidden_layer_sizes=5, random_state=10)
clf.fit(X_train, y_train) # This command trains the MLP on the training data
```

- In this example, we only have **one hidden layer with 5 neurons***.

```
np.set_printoptions(suppress=True,
                    precision=2)
print(clf.predict_proba(X_test[0:3, :]))
print(clf.predict(X_test[0:3, :]))
print(y_test[0:3])
print(clf.score(X_test, y_test))
```

```
[[0.84 0.04 0.13 0.  ]
 [0.07 0.26 0.03 0.64]
 [0.22 0.22 0.26 0.29]]
[0 3 3]
[0 3 1]
0.7416666666666667
```

- Not bad, as a random classification would have around $1/4 = 0.25\%$ accuracy.

* Here are the functions we are using: `predict_proba` gives the softmax response to each dataset, `predict` gives the predicted class for the listed points accord to `predict_proba`, and `score` outputs the overall accuracy of the classifier.

Hands-on Neural Networks

- Let's see if we can improve this result by changing the number of neurons:

```
from sklearn.neural_network import MLPClassifier
clf = MLPClassifier(hidden_layer_sizes=10, random_state=10)
clf.fit(X_train, y_train)
```

- Now we have **one hidden layer with 10 neurons**. Let's see how it performs:

```
np.set_printoptions(suppress=True,
                    precision=2)
print(clf.predict_proba(X_test[0:3, :]))
print(clf.predict(X_test[0:3, :]))
print(y_test[0:3])
print(clf.score(X_test, y_test))
```

```
[[0.97 0.    0.03 0.   ]
 [0.    0.01 0.    0.99]
 [0.02 0.97 0.01 0.   ]]
[0 3 1]
[0 3 1]
0.9416666666666667
```

- Much better! Notice how the predictions' probabilities are more “certain” of what class these points should belong to!

Hands-on Neural Networks

- Now, let's more layers, instead of just more neurons in one layer:

```
from sklearn.neural_network import MLPClassifier
clf = MLPClassifier(hidden_layer_sizes=(20, 10), random_state=10)
clf.fit(X_train, y_train)
```

- Now we have **two hidden layers with 20 and 10 neurons**, resp. So, it performs like:

```
np.set_printoptions(suppress=True,
                    precision=2)
print(clf.predict_proba(X_test[0:3, :]))
print(clf.predict(X_test[0:3, :]))
print(y_test[0:3])
print(clf.score(X_test, y_test))
```

```
[[1.  0.  0.  0. ]
 [0.  0.01 0.01 0.99]
 [0.  0.99 0.  0. ]]
[0 3 1]
[0 3 1]
0.9833333333333333
```

- Almost perfect! And the softmax probabilities are almost sure about their predictions!
- But, how long did “fit” take to run?

Hands-on Neural Networks

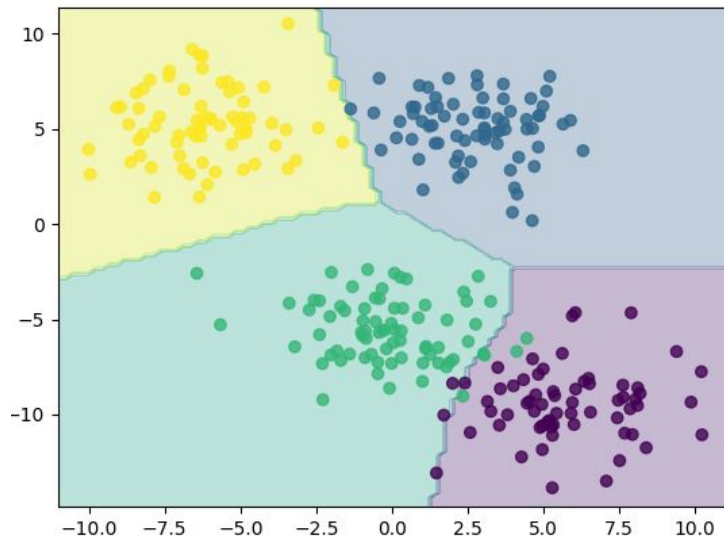
- We can also visualize the decision boundaries using the function:

```
def plot_decision_boundaries(X, y, model_class, **model_params):  
    model = model_class(**model_params, random_state=10)  
    model.fit(X, y)  
  
    x_min, x_max = X[:, 0].min() - 1, X[:, 0].max() + 1  
    y_min, y_max = X[:, 1].min() - 1, X[:, 1].max() + 1  
  
    h = .01 * np.mean([x_max - x_min, y_max - y_min])  
    xx, yy = np.meshgrid(np.arange(x_min, x_max, h), np.arange(y_min, y_max, h))  
    Z = model.predict(np.c_[xx.ravel(), yy.ravel()]).reshape(xx.shape)  
  
    plt.contourf(xx, yy, Z, alpha=0.3)  
    plt.scatter(X[:, 0], X[:, 1], c=y, alpha=0.8)  
    plt.show()
```

Hands-on Neural Networks

- Now we can visualize the training data with the decision boundary:

```
plot_decision_boundaries(X_train, y_train, MLPClassifier,  
                        hidden_layer_sizes=(20, 10))
```



Exercise (*In pairs*)

Click here to open code in Colab 

- How many weights we need to learn if or MLP has *3* layers with *10*, *5* and *20* neurons, respectively, and we have points of dimension *100*, belonging to *3* different classes?
- Run the Multilayer Perceptron on the following datasets

```
from sklearn.datasets import make_moons  
X, y = make_moons(n_samples=200, noise=0.05)
```

```
from sklearn.datasets import make_circles  
X, y = make_circles(n_samples=200, noise=0.05)
```

- Try different numbers of MLP layers and neurons.
- Compute the score of each classification.
- Visualize the decision boundaries in each case using `plot_decision_boundaries`.