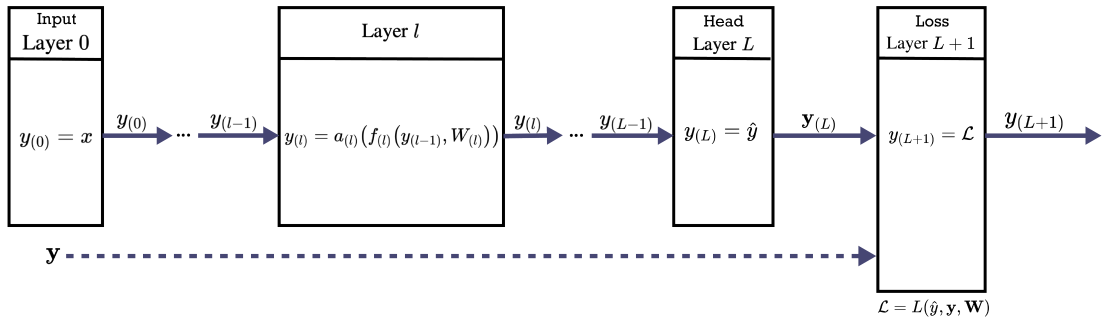
Inside a layer: Units/Neurons

Notation 1

Layer l, for $1 \le l \le L$:

- Produces output vector $\mathbf{y}_{(l)}$
- $\mathbf{y}_{(l)}$ is a vector of $n_{(l)}$ synthetic features
$$n_{(l)} = ||\mathbf{y}_{(l)}||$$
- Takes as input $\mathbf{y}_{(l-1)}$, the output of the preceding layer

- Layer L will typically implement Regression or Classification
- The first $(L-1)$ layers create synthetic features of increasing complexity
- We will use layer $(L+1)$ to compute a Loss


Input
Layer 0
$y_{(0)} = x$
$y_{(0)}$
$y_{(l-1)}$
Layer l
$y_{(l)} = a_{(l)}(f_{(l)}(y_{(l-1)}, W_{(l)}))$
$y_{(l)}$
$y_{(L-1)}$
Head
Layer L
$y_{(L)} = \hat{y}$
$\mathbf{y}_{(L)}$
Loss
Layer $L+1$
$y_{(L+1)} = \mathcal{L}$
$y_{(L+1)}$
$\mathbf{y}$
$\mathcal{L} = L(\hat{y}, \mathbf{y}, \mathbf{W})$

The input $\mathbf{x}$

- Is called "layer 0"
- $\mathbf{y}_{(0)} = \mathbf{x}$

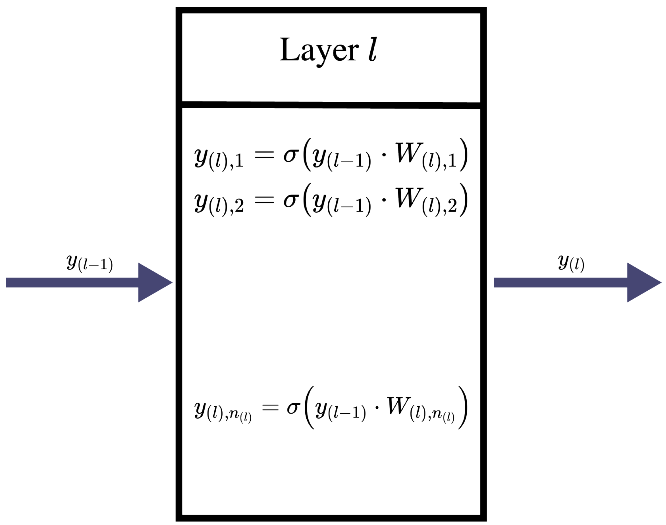
The output $\mathbf{y}_{(L-1)}$ of the penultimate layer $(L-1)$

- Becomes the input of a Classifier/Regression model at layer L

Our first layer type: the Fully Connected/Dense Layer

Let's look inside layer l (of a particular type called *Fully Connected* or *Dense*)

Layer


Layer l
$y_{(l),1} = \sigma\left(y_{(l-1)} \cdot W_{(l),1}\right)$
$y_{(l),2} = \sigma\left(y_{(l-1)} \cdot W_{(l),2}\right)$
$y_{(l),n_{(l)}} = \sigma\left(y_{(l-1)} \cdot W_{(l),n_{(l)}}\right)$
$y_{(l-1)}$
$y_{(l)}$

- Input vector of $n_{(l-1)}$ features: $\mathbf{y}_{(l-1)}$
- Produces output vector or $n_{(l)}$ features $\mathbf{y}_{(l)}$
- Feature j defined by the function

$$\mathbf{y}_{(l),j} = \sigma(\mathbf{y}_{(l-1)} \cdot \mathbf{W}_{(l),j})$$

Each feature $\mathbf{y}_{(l),j}$ is produced by a *unit* (*neuron*)

- There are $n_{(l)}$ units in layer l
- The units are *homogenous*
    - same input $\mathbf{y}_{(l-1)}$ to every unit
    - same functional form for every unit
    - units differ only in $\mathbf{W}_{(l),j}$

Units are also sometimes refered to as *Hidden Units*

- They are internal to a layer.
- From the standpoint of the Input/Output behavior of a layer, the units are "hidden"

The functional form

$$\mathbf{y}_{(l),j} = \sigma(\mathbf{y}_{(l-1)} \cdot \mathbf{W}_{(l),j})$$

is called a *Dense* or *Fully Connected* unit.

It is called Fully connected since

- each unit takes as input $\mathbf{y}_{(l-1)}$, **all** $n_{(l-1)}$ outputs of the preceding layer

The *Fully Connected* part can be better appreciated by looking at a diagram of the connectivity of a *single* unit producing a *single* feature.

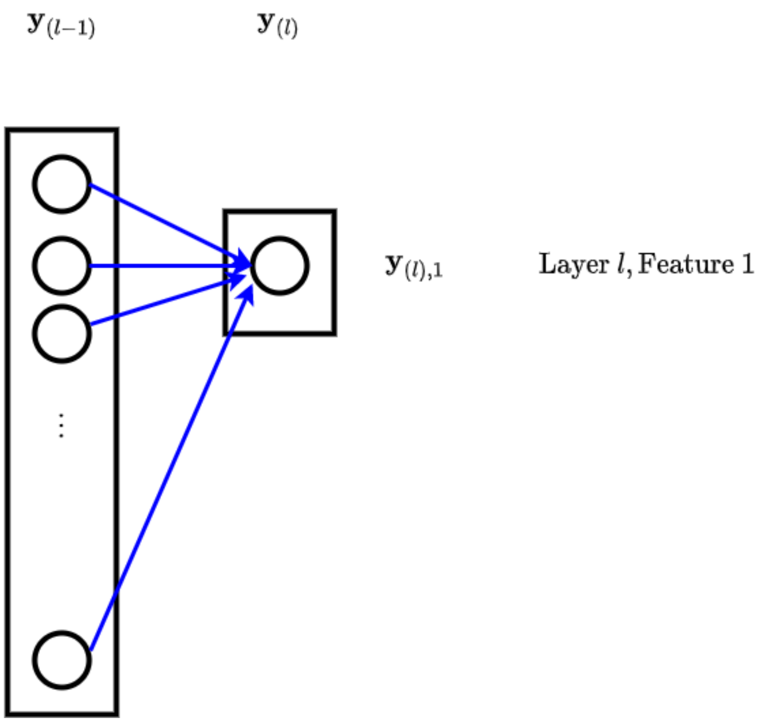
A Fully Connected/Dense Layer producing a *single* feature at layer l computes

$$\mathbf{y}_{(l),1} = a_{(l)}(\mathbf{y}_{(l-1)} \cdot \mathbf{W}_{(l),1})$$

A function, $a_{(l)}$, is applied to the dot product

- It is called an *activation function*
- A very common choice for activation function is the sigmoid σ

Fully connected unit, single feature

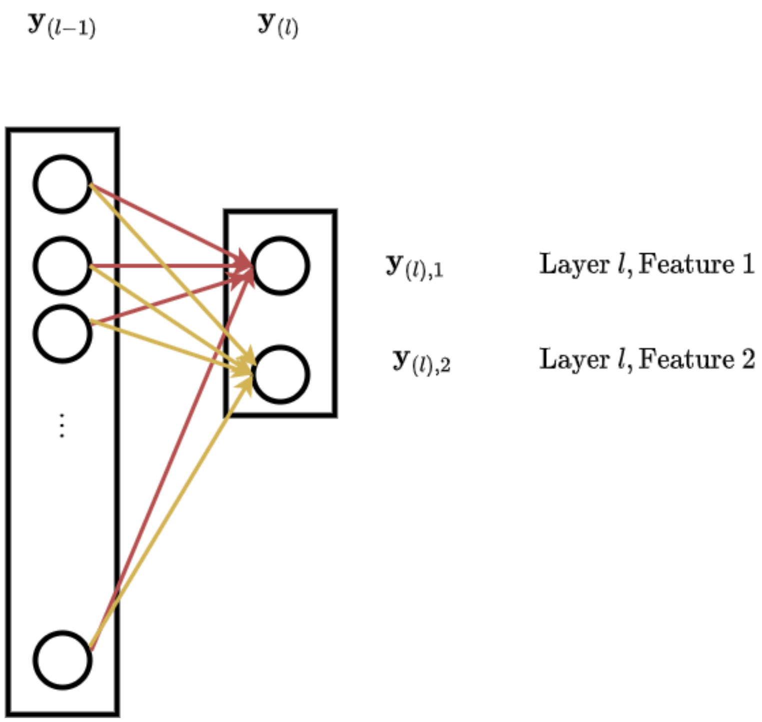


The edges into the single unit of layer l correspond to $\mathbf{W}_{(l),1}$.

A Fully Connected/Dense Layer with multiple units producing *multiple* feature at layer l computes

$$\mathbf{y}_{(l),j} = a_{(l)}(\mathbf{y}_{(l-1)} \cdot \mathbf{W}_{(l),j})$$

Fully connected, two features



The edges into each unit of layer l correspond to

- $\mathbf{W}_{(l),1}, \mathbf{W}_{(l),2} \cdots$
- Separate colors for each units/row of $\mathbf{W}$

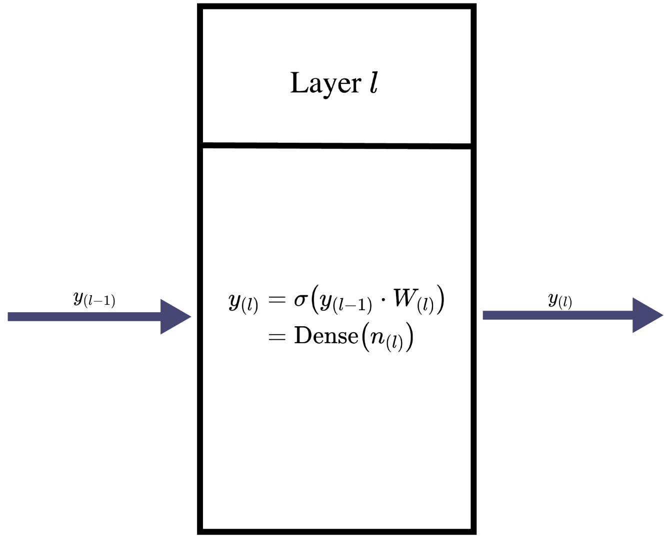
Each unit $\mathbf{y}_{(l),j}$ in layer l creates a new feature using pattern$\mathbf{W}_{(l),j}$

The functional form is of

- A dot product $\mathbf{y}_{(l-1)} \cdot \mathbf{W}_{(l),j}$
    - Which can be thought of matching input $\mathbf{y}_{(l-1)}$ against pattern $\mathbf{W}_{(l),j}$
- Fed into an activation function $a_{(l)}$
    - Here, $a_{(l)} = \sigma$, the *sigmoid* function we have previously encountered in Logistic Regression.

Because the units are homogeneous, we can depict it as

Layer


Layer l
$y_{(l-1)}$
$y_{(l)} = \sigma\left(y_{(l-1)} \cdot W_{(l)}\right)$
$= \mathrm{Dense}\left(n_{(l)}\right)$
$y_{(l)}$

where

- $\mathbf{y}_{(l)}$ is a vector of length $n_{(l)}$
- $\mathbf{W}_{(l)}$ is a matrix
    - $n_{(l)}$ rows
    - $\mathbf{W}_{(l)}^{(j)} = \mathbf{W}_{(l),j}$

Written with the shorthand `Dense(` n_l `)`

We will introduce other types of layers.

- Most will be homogeneous
- Not all will be fully Connected
- The dot product will play a similar role

Non-linear activation

The sigmoid function σ may be the *most significant part* of the functional form

- The dot product is a *linear* operation
- The outputs of sigmoid are *non-linear* in its inputs

So the sigmoid induces a non-linear transformation of the features $\mathbf{y}_{(l-1)}$

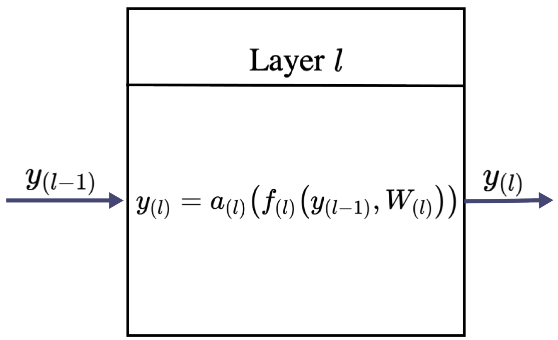
The outer function $a_{(l)}$ which applies a non-linear transformation to linear inputs

- Is called an *activation function*
- Sigmoid is one of several activation functions we will study

- The operation of a layer does not always need to be a dot production
- The activation function of a layer need not always be the sigmoid

More generically we write a layer as

Layers



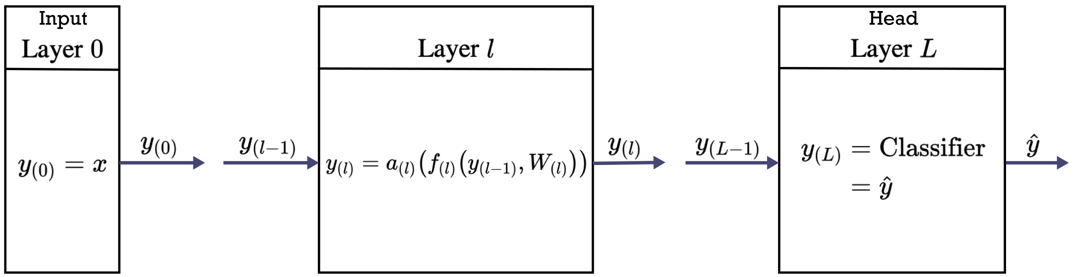
$$\mathbf{y}_{(l)} = \boldsymbol{a}_{(l)}\left(\boldsymbol{f}_{(l)}(\mathbf{y}_{(l-1)}, \mathbf{W}_{(l)})\right)$$

where

- $\boldsymbol{f}_{(l)}$ is a function of $\mathbf{y}_{(l)-1}$ and $\mathbf{W}_{(l)}$
- $\boldsymbol{a}_{(l)}$ is an activation function

So our multi-layer Neural Network (using Dense layers) looks like

Layers


Input
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$y_{(0)}$
$y_{(l-1)}$
Layer l
$y_{(l)} = a_{(l)}(f_{(l)}(y_{(l-1)}, W_{(l)}))$
$y_{(l)}$
$y_{(L-1)}$
Head
Layer L
$y_{(L)} = \text{Classifier}$
$= \hat{y}$
$\hat{y}$

Pattern matching

We again meet our old friend: the dot product.

We have argued that the dot product is nothing more than pattern matching

- $\mathbf{W}_{(l),j}$ is a pattern
- That layer l is trying to match against layer $(l-1)$ output $\mathbf{y}_{(l-1)}$

What then, is the role of the Sigmoid activation in the Dense layer ?

The Sigmoid

- **converts the intensity of the match (the dot product)**
- **into the range $[\mathbf{0}, \mathbf{1}]$**
- **which we can interpret as a *probability* that**
    - **the input**
    - **matches the pattern**

At the two extremes $\mathbf{0}$ and $\mathbf{1}$, the Sigmoid output can be interpreted as a binary test

```
Does the input match the pattern ?
```

In [4]:

```
print("Done")
```

```
Done
```