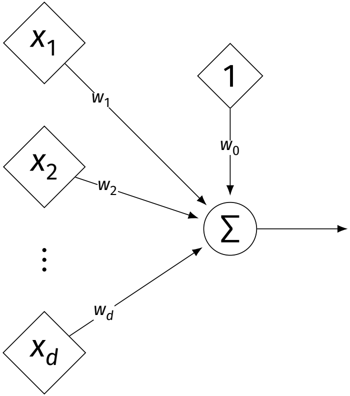
DSC 140B
Representation Learning

Lecture 11 | Part 1

Neural Networks

Linear Models

$$H(\vec{x}) = w_0 + w_1 x_1 + \ldots + w_d x_d$$



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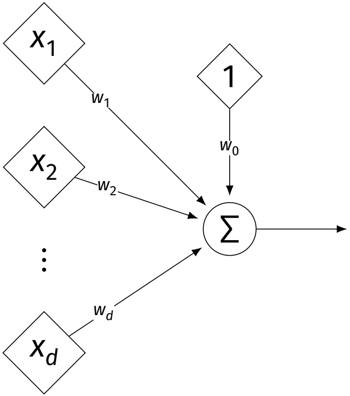
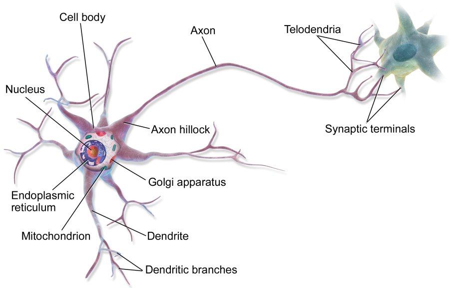
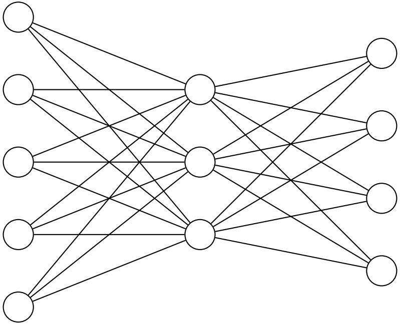




The Brain

- The brain is a **network** of neurons.
  - The **output** of a neuron is used as an **input** to others.

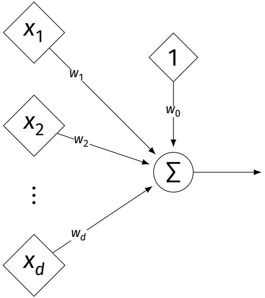


Idea: Neural Networks

- Replace brain's neurons with linear models.
- Connect them together into a **neural network**.
  - Output of one linear model is used as input to others.

A Simple Neural Network

- The simplest neural network is the one we've already seen: one neuron.



A Simple Neural Network

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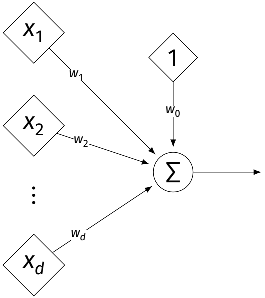
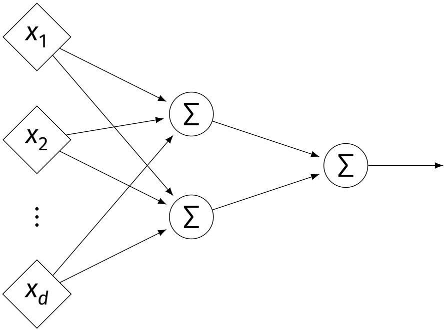


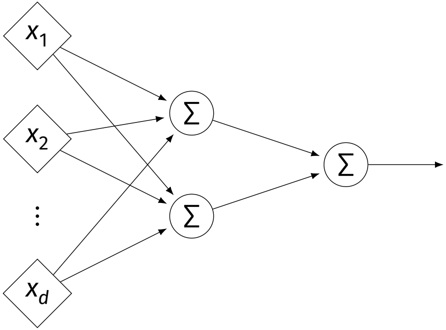
- A linear regression model is a neural network with one neuron.

Another Neural Network



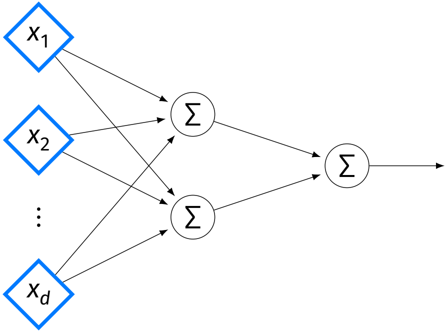
Another Neural Network

- Neural nets have **layers**.



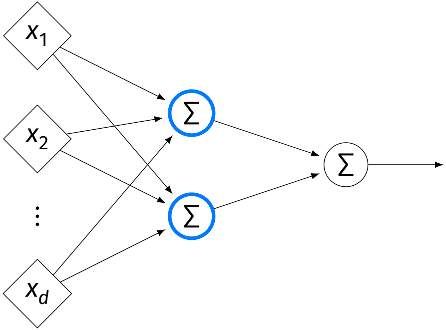
Another Neural Network

- The **input** layer (one node per feature).



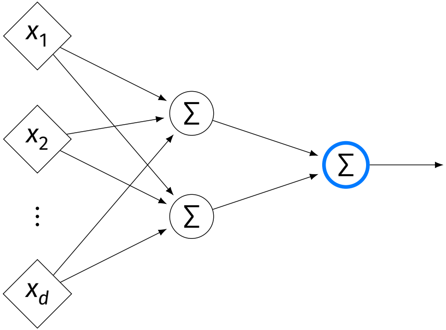
Another Neural Network

- Zero or more **hidden** layers.



Another Neural Network

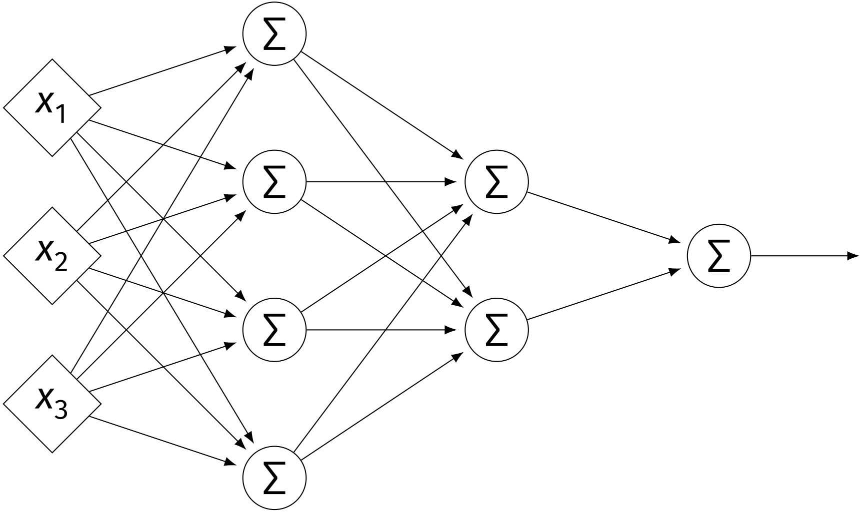
- The **output** layer (one node per output).



Architecture

- Can have more than one hidden layer.
  - A network is “**deep**” if it has >1 hidden layer.
- Hidden layers can have different number of neurons.

Neural Network (Two Hidden Layers)

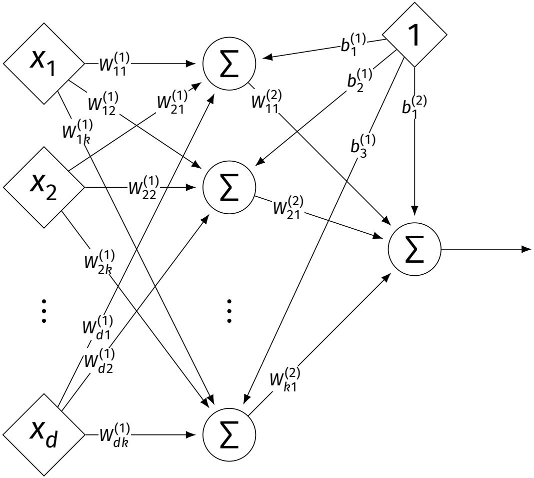


Network Weights

- Each edge in a NN has a weight that can be learned.
- Like a linear model, a NN is **totally determined** by its weights.
- But there are often many more weights to learn!

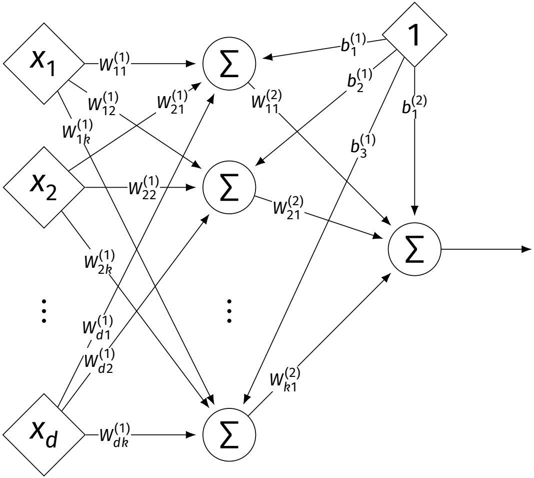
Notation

- Input is layer #0.
- $W_{jk}^{(i)}$ denotes weight of connection between neuron *j* in layer (*i* – 1) and neuron *k* in layer *i*
- Layer weights are 2-d arrays.



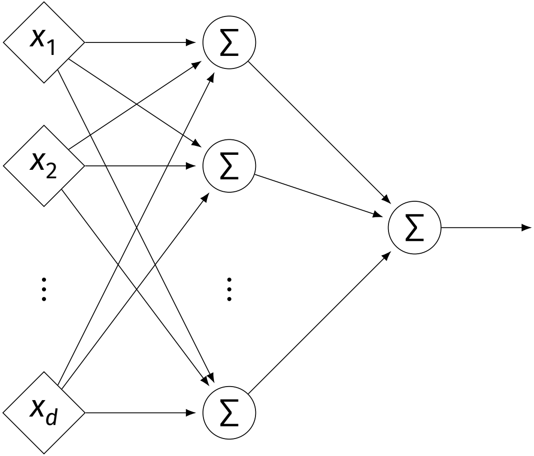
Notation

- Each hidden/output neuron gets a “dummy” input of 1.
- jth node in ith layer assigned a bias weight of $b_j^{(i)}$
- Biases for layer are a vector: $\vec{b}^{(i)}$

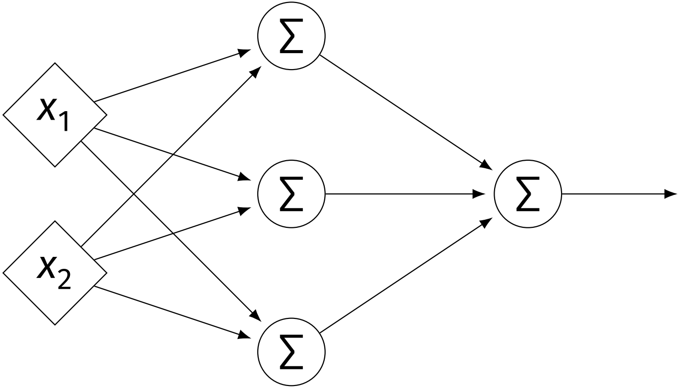


Notation

- Typically, we will not draw the weights.
- We will not draw the dummy input, too, but it is there.



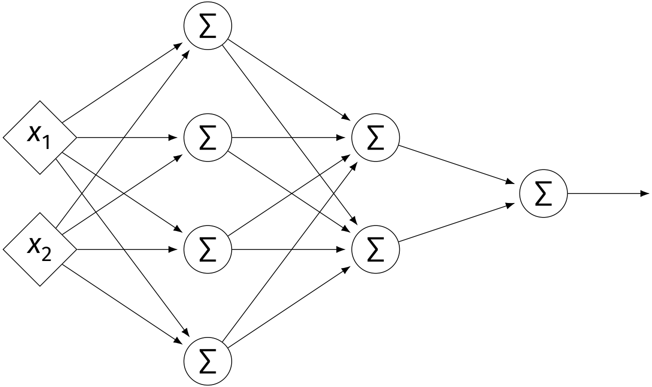
Example



$$W^{(1)} = \begin{pmatrix} 2 & -1 & 0 \\ 4 & 5 & 2 \end{pmatrix} \quad W^{(2)} = \begin{pmatrix} 3 \\ 2 \\ -4 \end{pmatrix}$$

$$\vec{b}^{(1)} = (3, -2, -2)^T \quad \vec{b}^{(2)} = (-4)^T$$

Example



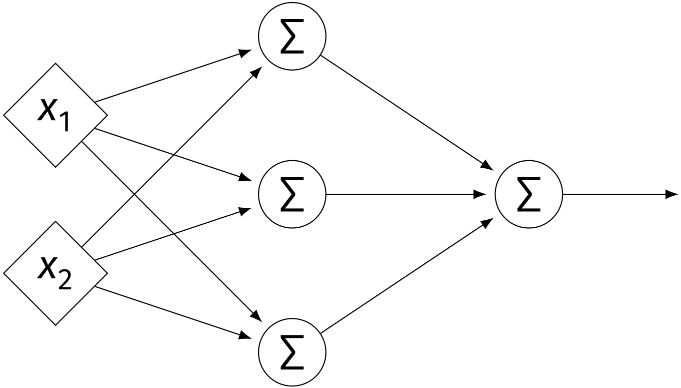
$$W^{(1)} = \begin{pmatrix} 2 & -1 & -3 & 0 \\ 4 & 5 & -7 & 2 \end{pmatrix} \quad W^{(2)} = \begin{pmatrix} 1 & 2 \\ -4 & 3 \\ -6 & -2 \\ 3 & 4 \end{pmatrix} \quad W^{(3)} = \begin{pmatrix} -1 & 5 \end{pmatrix}$$

$$\vec{b}^{(1)} = (3, 6, -2, -2)^T \quad \vec{b}^{(2)} = (-4, 0)^T \quad \vec{b}^{(3)} = (1)^T$$

Evaluation

- These are "**fully-connected, feed-forward**" networks with one output.
- They are functions $H(\vec{x}) : \mathbb{R}^d \to \mathbb{R}^1$
- To evaluate $H(\vec{x})$, compute result of layer i, use as inputs for layer $i + 1$.

Example



- $\vec{x} = (3, -1)^T$
- $z_1^{(1)} =$
- $z_2^{(1)} =$
- $z_3^{(1)} =$
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$W^{(1)} = \begin{pmatrix} 2 & -1 & 0 \\ 4 & 5 & 2 \end{pmatrix}$ $W^{(2)} = \begin{pmatrix} 3 \\ 2 \\ -4 \end{pmatrix}$ $\vec{b}^{(1)} = (3, -2, -2)^T$ $\vec{b}^{(2)} = (-4)^T$

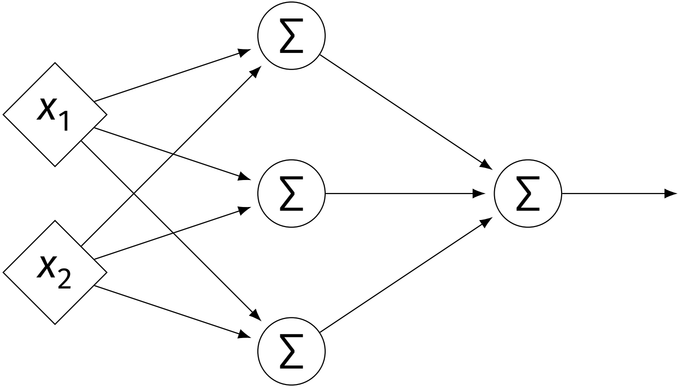
Exercise

What is the output of the network on the previous slide?

Evaluation as Matrix Multiplication

- Let $z_j^{(i)}$ be the output of node j in layer i.
- Make a vector of these outputs: $\vec{z}^{(i)} = (z_1^{(i)}, z_2^{(i)}, \ldots)^T$
- Observe that $\vec{z}^{(i)} = \left[W^{(i)}\right]^T \vec{z}^{(i-1)} + \vec{b}^{(i)}$

Example



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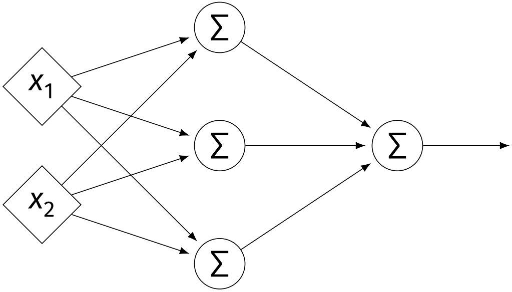
Each Layer is a Function

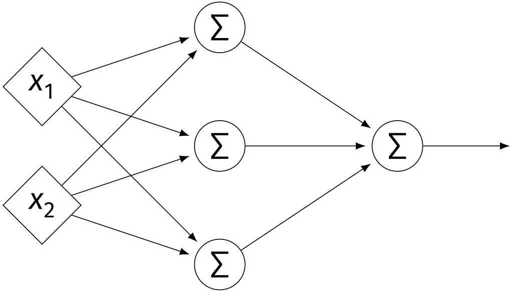
- We can think of each layer as a function mapping a vector to a vector.

- $H^{(1)}(\vec{z}) = \left[W^{(1)}\right]^T \vec{z} + \vec{b}^{(1)}$
  - $H^{(1)} : \mathbb{R}^2 \to \mathbb{R}^3$
- $H^{(2)}(\vec{z}) = \left[W^{(2)}\right]^T \vec{z} + \vec{b}^{(2)}$
  - $H^{(2)} : \mathbb{R}^3 \to \mathbb{R}^1$



NNs as Function Composition

- The full NN is a composition of layer functions.



$$H(\vec{x}) = H^{(2)}(H^{(1)}(\vec{x})) = \left[W^{(2)}\right]^T \underbrace{\left(\left[W^{(1)}\right]^T \vec{x} + \vec{b}^{(1)}\right)}_{\vec{z}^{(1)}} + \vec{b}^{(2)}$$

NNs as Function Composition

- In general, if there k hidden layers:

$$H(\vec{x}) = H^{(k+1)}\left(\cdots H^{(3)}\left(H^{(2)}\left(H^{(1)}(\vec{x})\right)\right)\cdots\right)$$

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Lecture 11 | Part 2

Activation Functions

The Power of NNs

- Our goal in connecting linear models together was to build a more powerful model.
- These neural networks must be more powerful than linear models, right?

The Power of NNs

- Our goal in connecting linear models together was to build a more powerful model.
- These neural networks must be more powerful than linear models, right?
- **Well, no**... not as they are currently defined.

Theorem

If $f(x)$ is a linear function, and $g(x)$ is a linear function, then $f(g(x))$ is again a linear function.

Result

- Our neural networks are just compositions of linear functions.

- The NNs we have seen so far are all equivalent to linear models!

$$H(\vec{x}) = \vec{w} \cdot \text{Aug}(\vec{x})$$

- For NNs to be more useful, we will need to add **non-linearity**.

Activations

- So far, the output of a neuron has been a linear function of its inputs:

$$w_0 + w_1 x_1 + w_2 x_2 + \dots$$

- Can be arbitrarily large or small.
- But real neurons are **activated** non-linearly.
  - E.g., saturation.

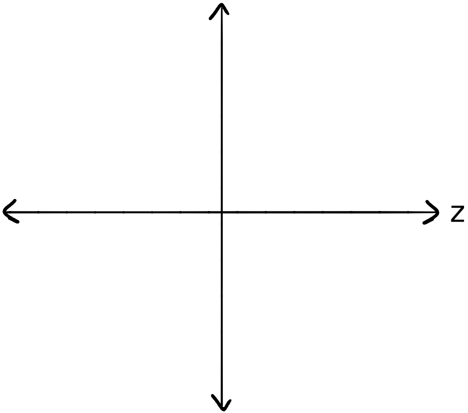
Idea

- To add nonlinearity, we will apply a non-linear **activation function** g to the output of **each** hidden neuron (and sometimes the output neuron).

Linear Activation

- The **linear** activation is what we've been using.

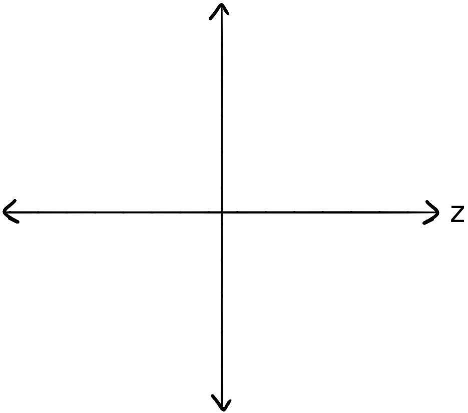
$$\sigma(z) = z$$



Sigmoid Activation

- The **sigmoid** models saturation in many natural processes.

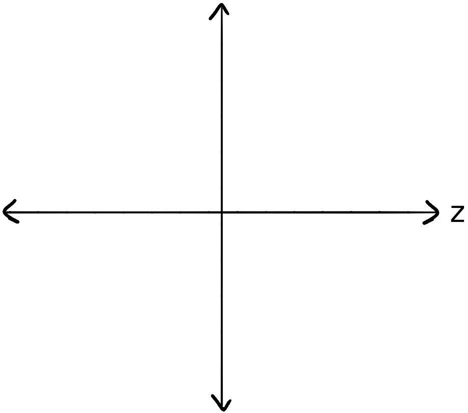
$$\sigma(z) = \frac{1}{1 + e^{-z}}$$



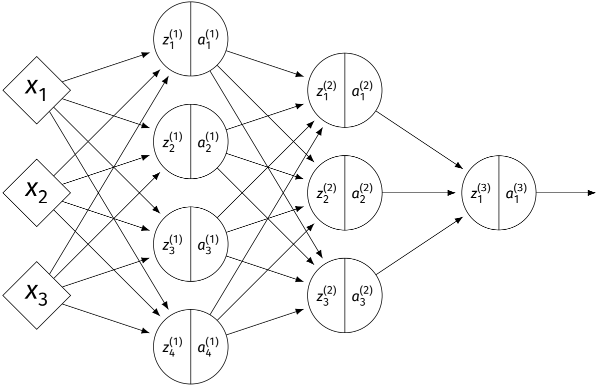
ReLU Activation

- The **Rectified Linear Unit (ReLU)** tends to work better in practice.

$$g(z) = \max\{0, z\}$$

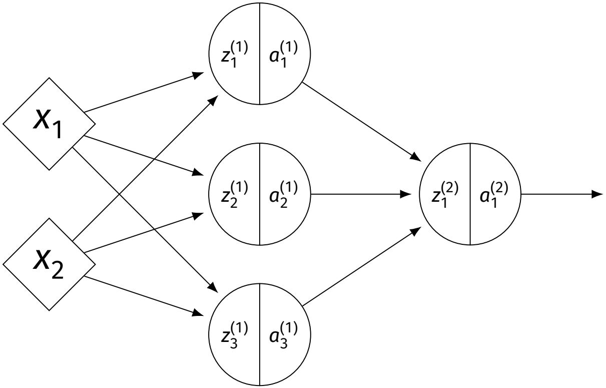


Notation



- $z_j^{(i)}$ is the linear activation before g is applied.
- $a_j^{(i)} = g(z^{(i)})$ is the actual output of the neuron.

Example



- g = ReLU
- Linear output
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- $a_1^{(1)} =$
- $z_2^{(1)} =$
- $a_2^{(1)} =$
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Output Activations

- The activation of the output neuron(s) can be different than the activation of the hidden neurons.
- In classification, **sigmoid** activation makes sense.
- In regression, **linear** activation makes sense.

Main Idea

A neural network with linear activations is a linear model. If non-linear activations are used, the model is made non-linear.

DSC 140B
Representation Learning

Lecture 11 | Part 3

Demo

Feature Map

- We have seen how to fit non-linear patterns with linear models via **basis functions** (i.e., a feature map).

$$H(\vec{x}) = w_0 + w_1\phi_1(\vec{x}) + \ldots + w_k\phi_k(\vec{x})$$

- These basis functions are fixed **before** learning.

- **Downside:** we have to choose $\vec{\phi}$ somehow.

Learning a Feature Map

- **Interpretation:** The hidden layers of a neural network **learn** a feature map.

Each Layer is a Function

- We can think of each layer as a function mapping a vector to a vector.

- $H^{(1)}(\vec{z}) = \left[W^{(1)}\right]^T \vec{z} + \vec{b}^{(1)}$
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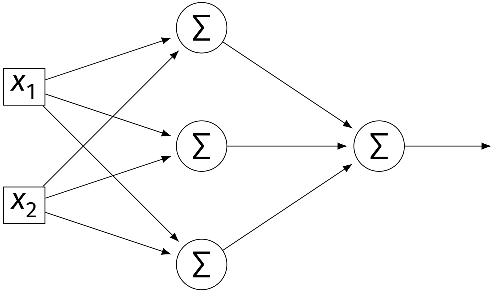
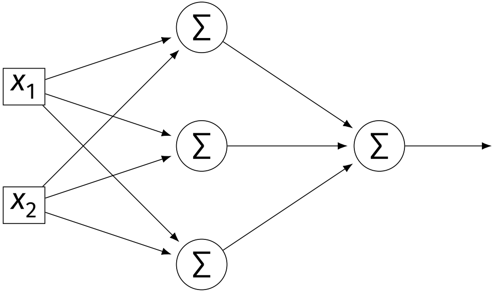


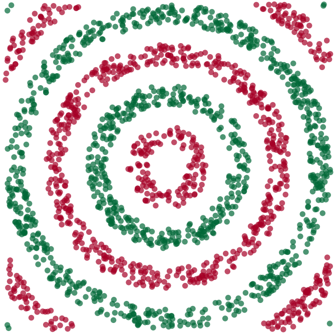
Each Layer is a Function

- The hidden layer performs a feature map from $\mathbb{R}^2$ to $\mathbb{R}^3$.
- The output layer makes a prediction in $\mathbb{R}^3$.
- **Intuition:** The feature map is learned so as to make the output layer's job "easier".



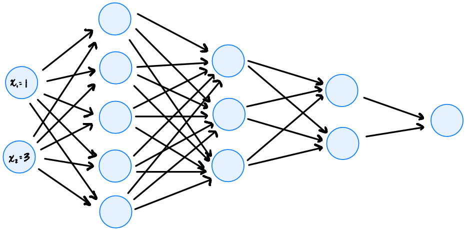
Demo

- Train a deep network to classify the data below.
- Hidden layers will learn a new feature map that makes the data linearly separable.

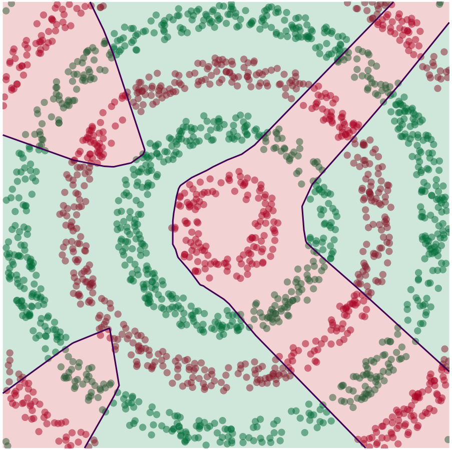


Demo

- We'll use three hidden layers, with last having two neurons.
- We can see this new representation!
- Plug in $\vec{x}$ and see activations of last hidden layer.



Learning a New Representation



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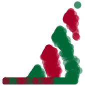

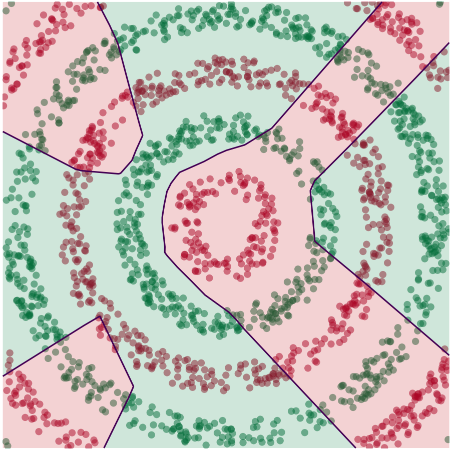

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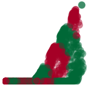

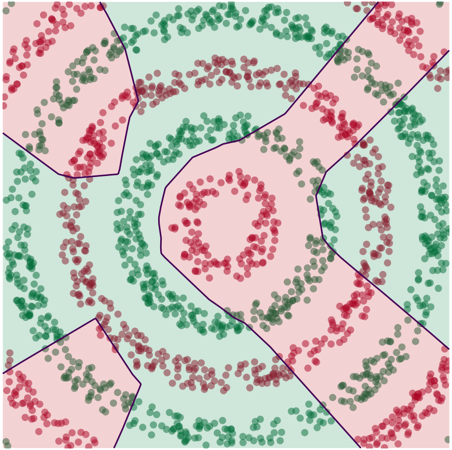

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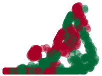

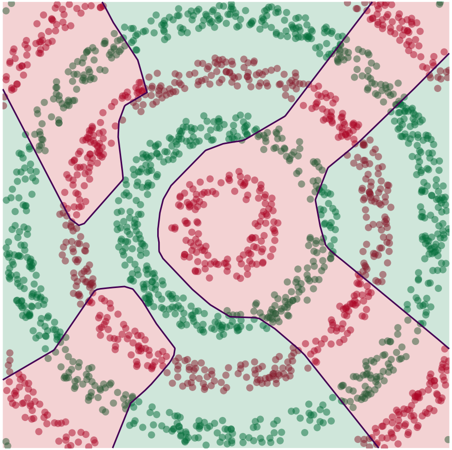

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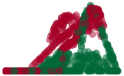

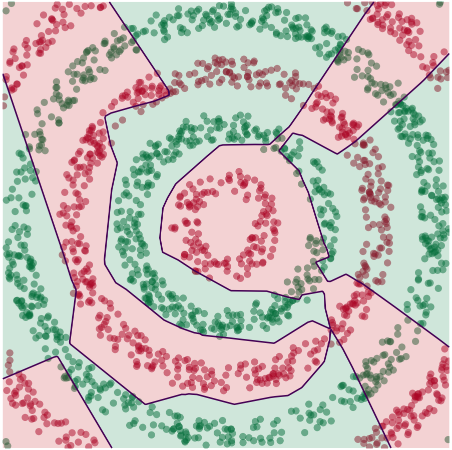

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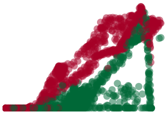

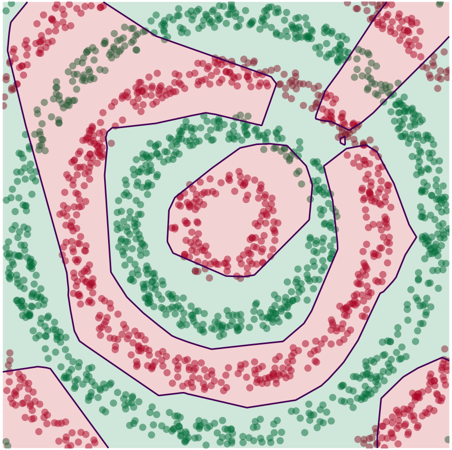

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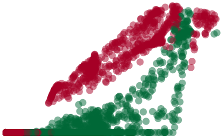

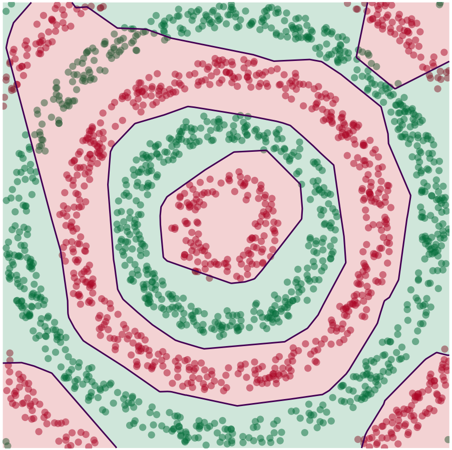

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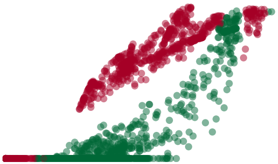

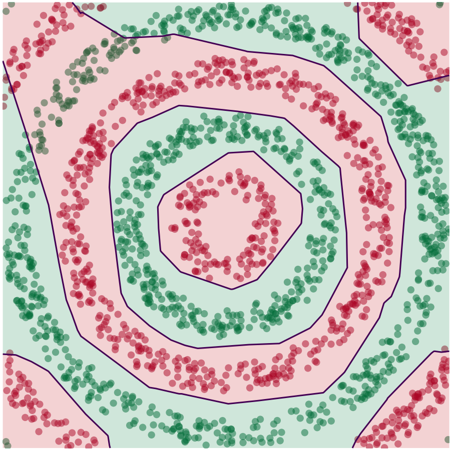

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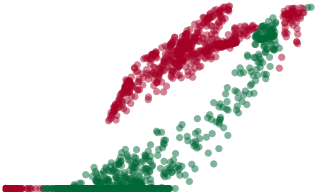

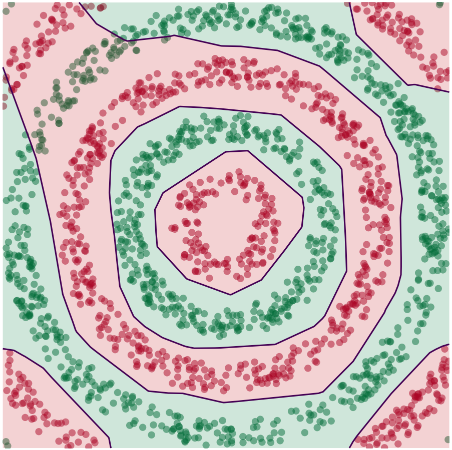

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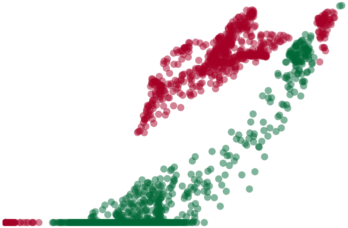
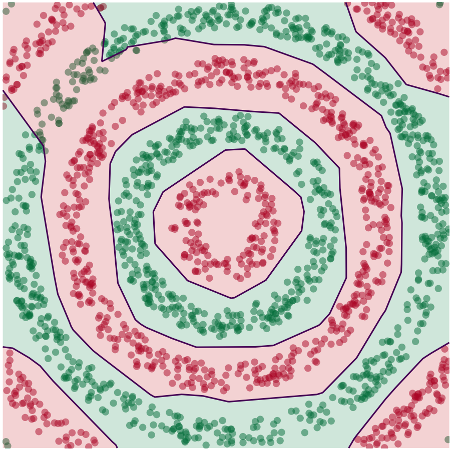
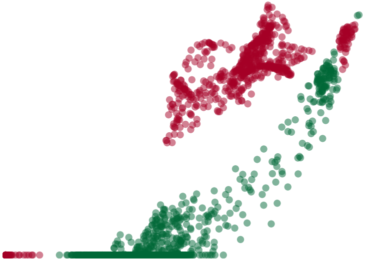
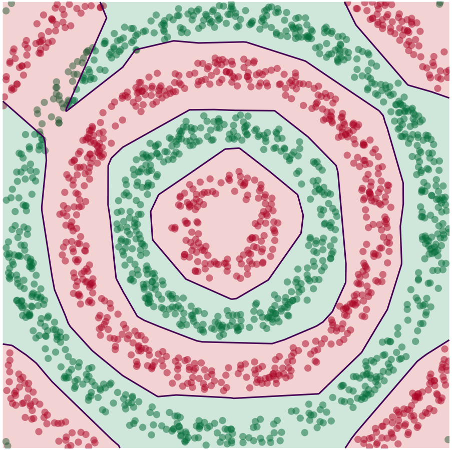


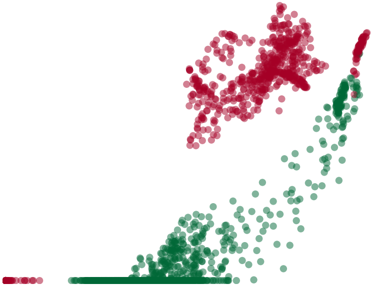


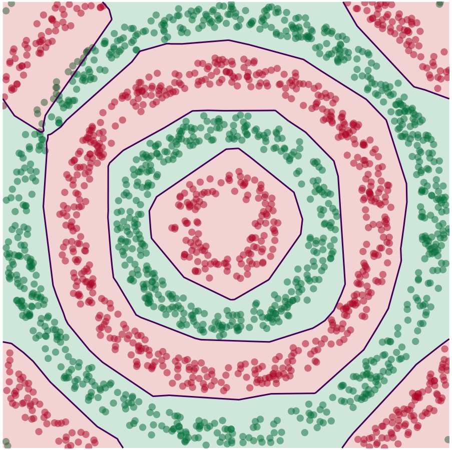
Learning a New Representation



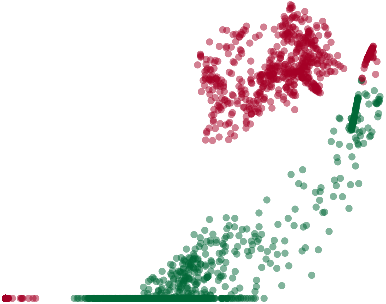


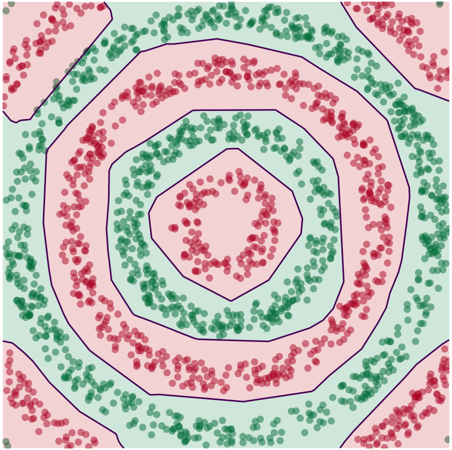
Learning a New Representation



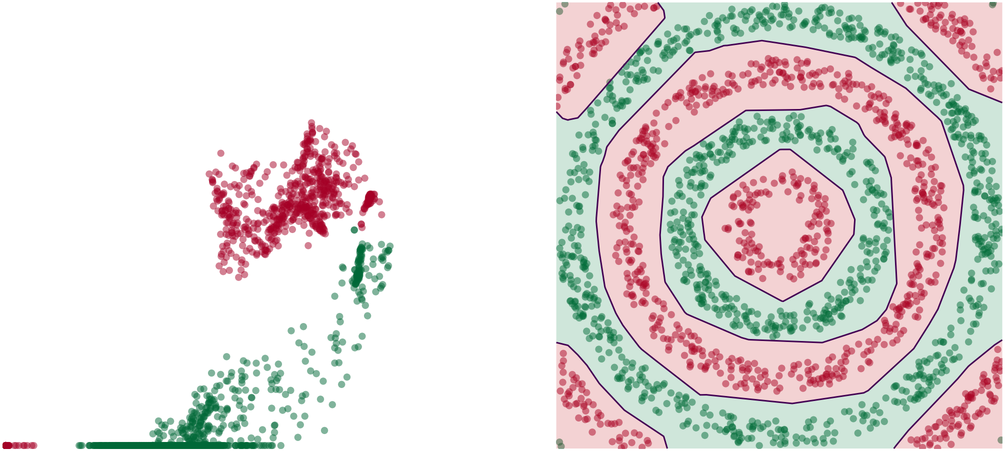


Learning a New Representation

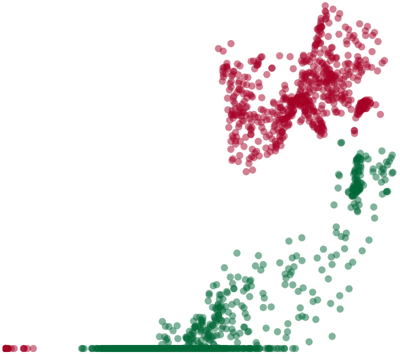


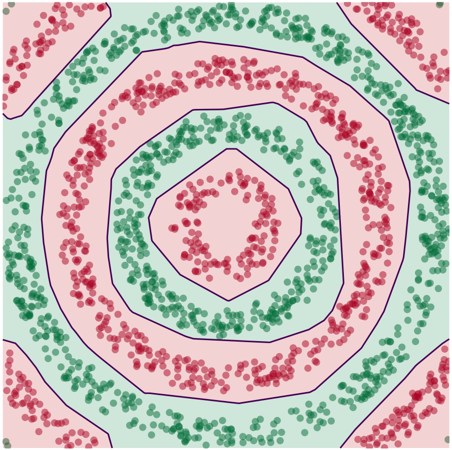


Learning a New Representation

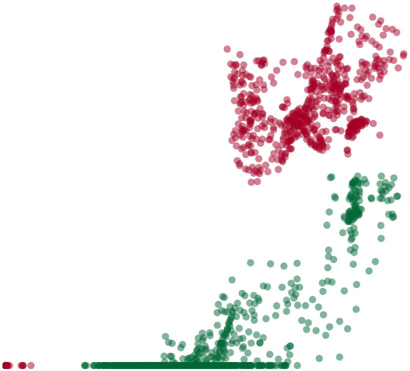


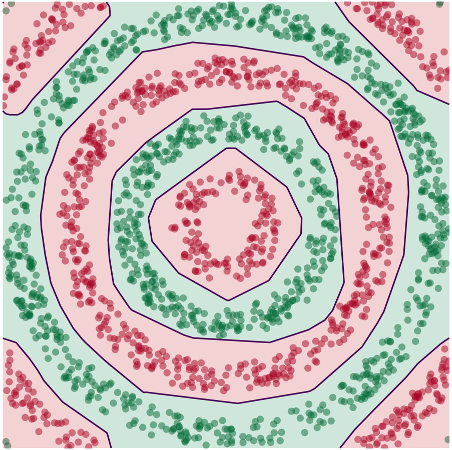
Learning a New Representation



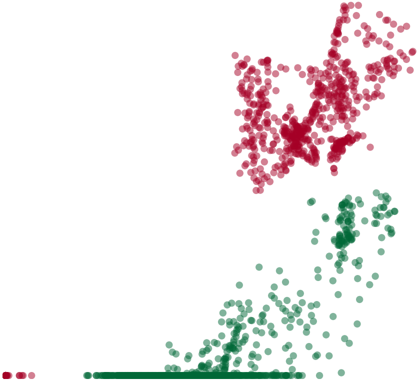


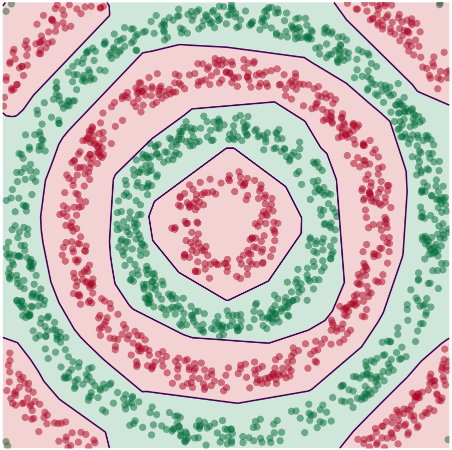
Learning a New Representation



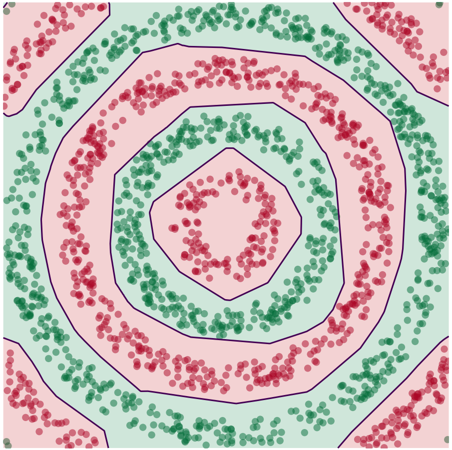


Learning a New Representation

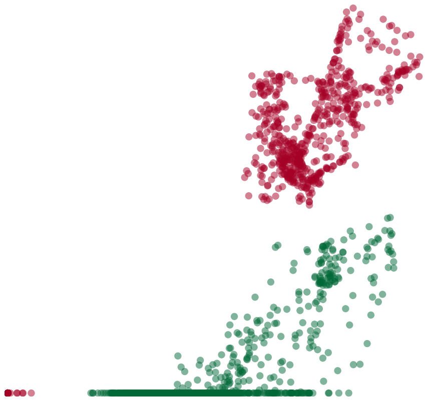


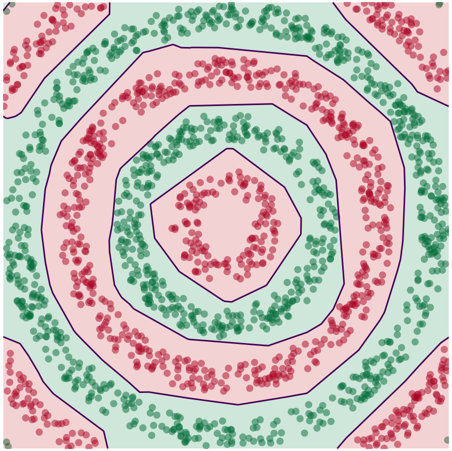


Learning a New Representation



Learning a New Representation





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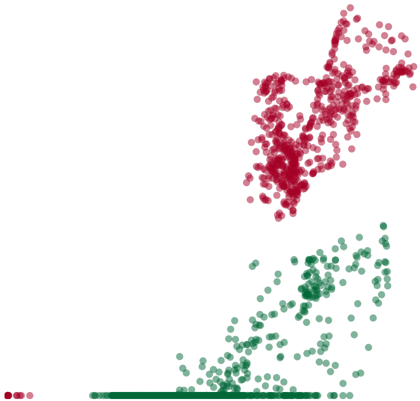

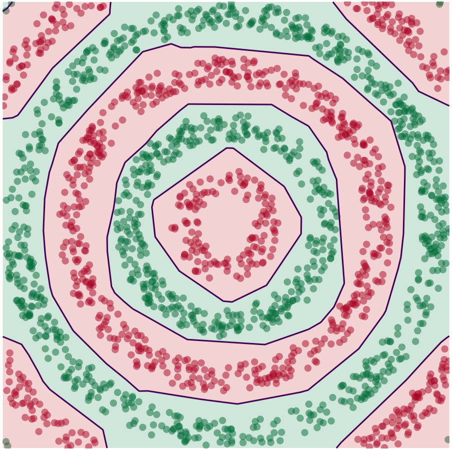

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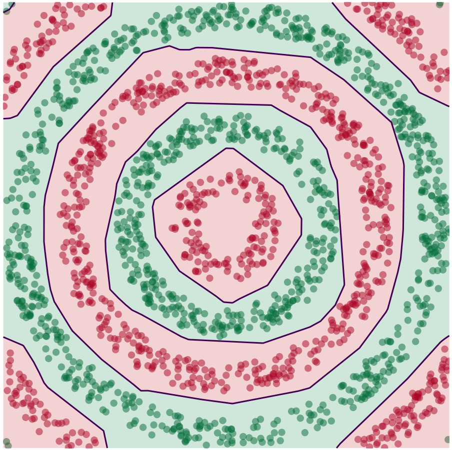
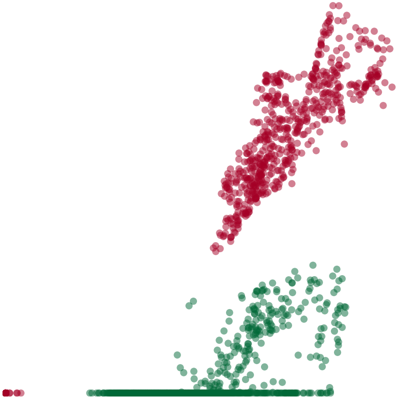
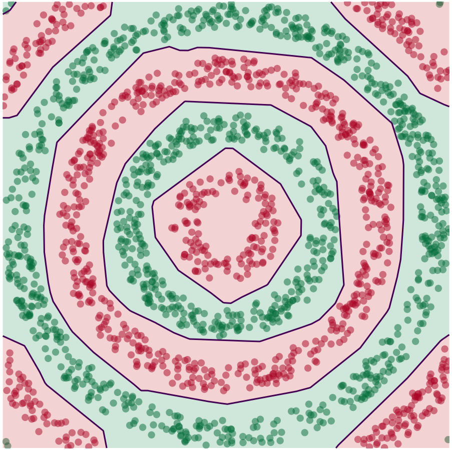
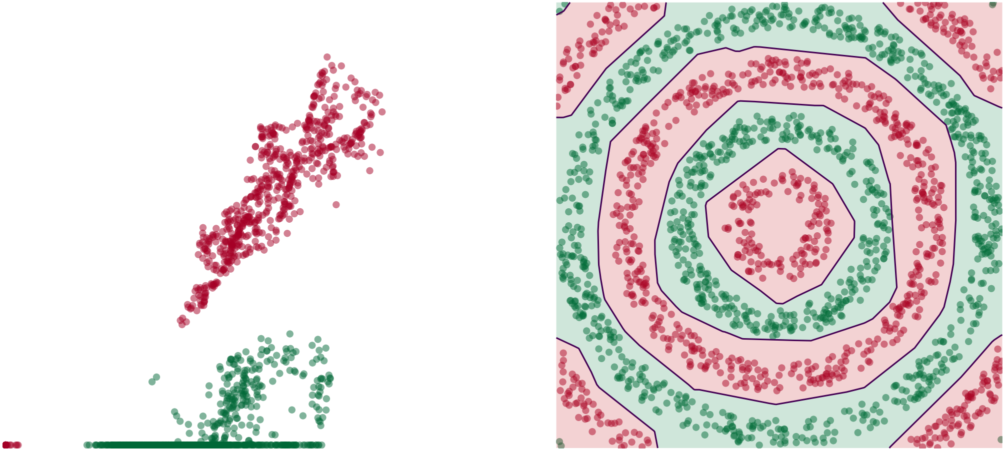


Learning a New Representation

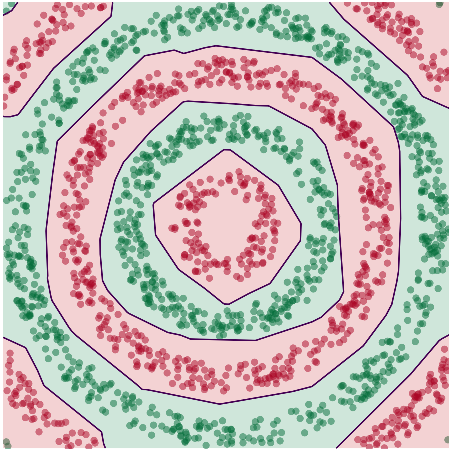




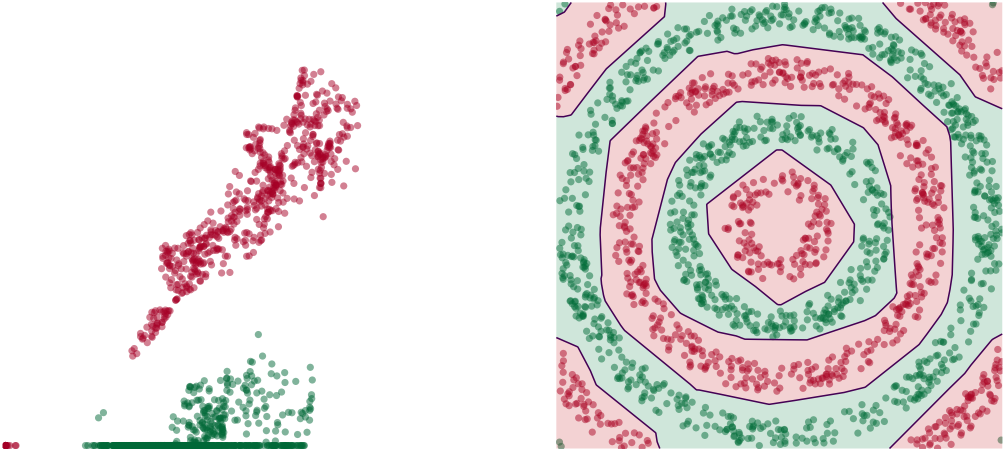
Learning a New Representation



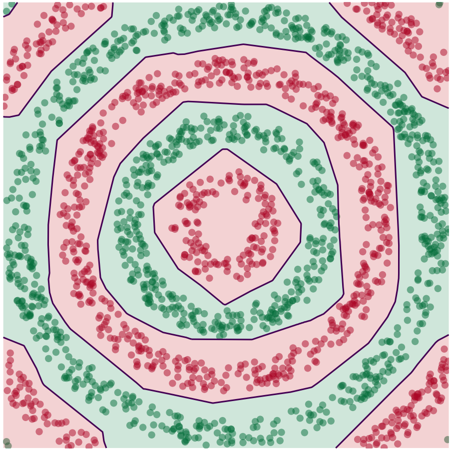
Learning a New Representation



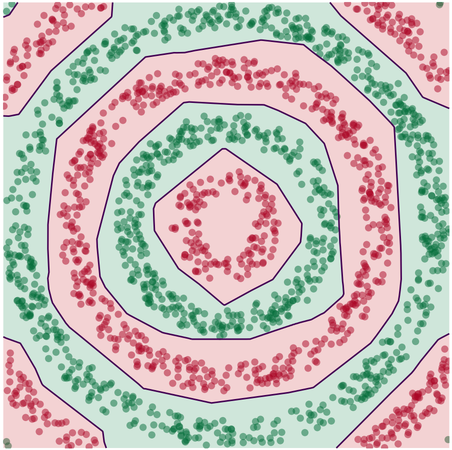
Learning a New Representation



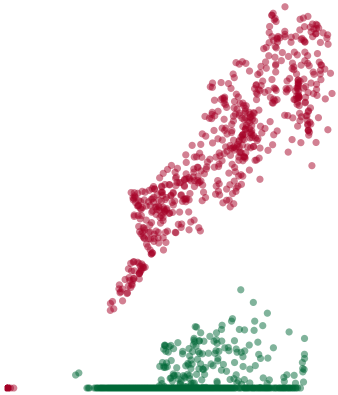
Learning a New Representation

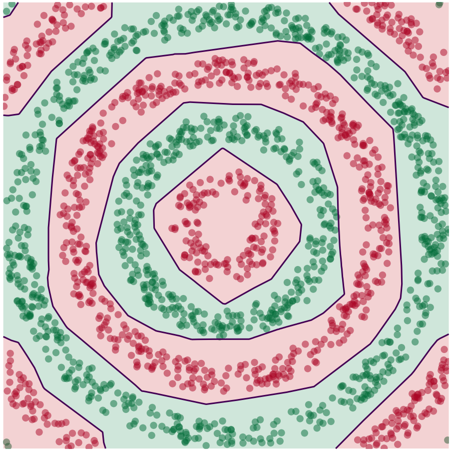


Learning a New Representation

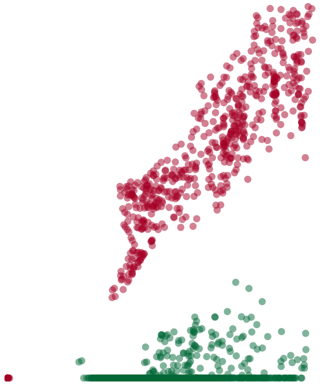


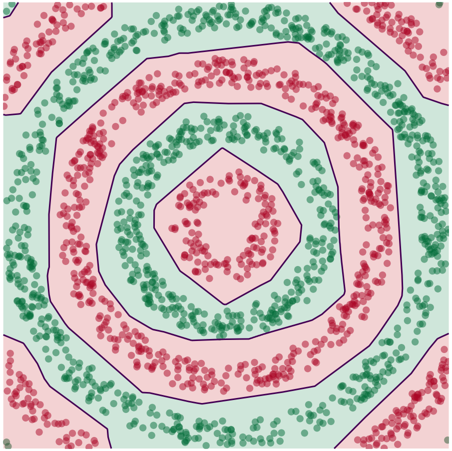
Learning a New Representation



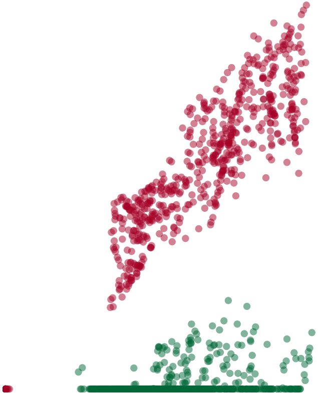


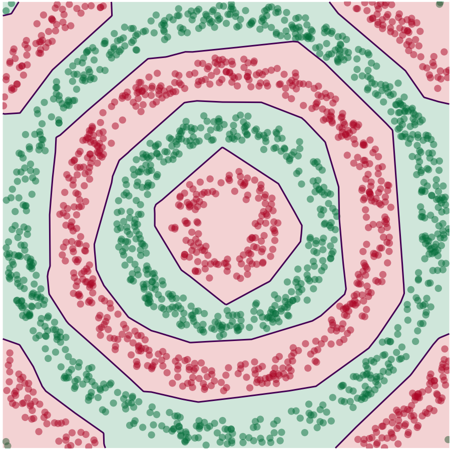
Learning a New Representation





Learning a New Representation





Deep Learning

- The NN has learned a new **representation** in which the data is easily classified.

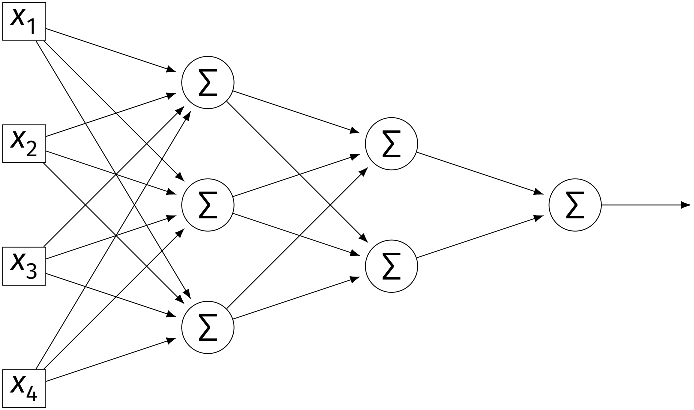
DSC 140B
Representation Learning

Lecture 11 | Part 4

Training Neural Networks

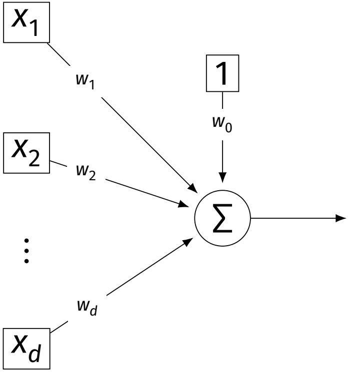
Training

- How do we learn the weights of a (deep) neural network?



Remember...

- How did we learn the weights in linear least squares regression?



Empirical Risk Minimization

0. Collect a training set, $\{(\vec{x}^{(i)}, y_i)\}$
1. Pick the form of the prediction function, H.
2. Pick a loss function.
3. Minimize the empirical risk w.r.t. that loss.

Remember: Linear Least Squares

1. Pick the form of the prediction function, H.
   - E.g., linear: $H(\vec{x}; \vec{w}) = w_0 + w_1 x_1 + \ldots + w_d x_d = \text{Aug}(\vec{x}) \cdot \vec{w}$
2. Pick a loss function.
   - E.g., the square loss.
3. Minimize the empirical risk w.r.t. that loss:

$$R_{\text{sq}}(\vec{w}) = \frac{1}{n} \sum_{i=1}^{n} (H(\vec{x}^{(i)}) - y_i)^2 = \frac{1}{n} \sum_{i=1}^{n} (\text{Aug}(\vec{x}^{(i)}) \cdot \vec{w} - y_i)^2$$

Minimizing Risk

- To minimize risk, we often use **vector calculus**.
  - Either set $\nabla_{\vec{w}} R(\vec{w}) = 0$ and solve...
  - Or use gradient descent: walk in opposite direction of $\nabla_{\vec{w}} R(\vec{w})$.

- Recall, $\nabla_{\vec{w}} R(\vec{w}) = (\partial R / \partial w_0, \partial R / \partial w_1, \ldots, \partial R / \partial w_d)^T$

In General

- Let ℓ be the loss function, let $H(\vec{x};\vec{w})$ be the prediction function.

- The empirical risk:

$$R(\vec{w}) = \frac{1}{n}\sum_{i=1}^{n} \ell(H(\vec{x}^{(i)};\vec{w}), y_i)$$

- Using the chain rule:

$$\nabla_{\vec{w}} R(\vec{w}) = \frac{1}{n}\sum_{i=1}^{n} \frac{\partial \ell}{\partial H} \nabla_{\vec{w}} H(\vec{x}^{(i)};\vec{w})$$

Gradient of H

- To minimize risk, we want to compute $\nabla_{\vec{w}} R$.
- To compute $\nabla_{\vec{w}} R$, we want to compute $\nabla_{\vec{w}} H$.
- This will depend on the form of H.

Example: Linear Model

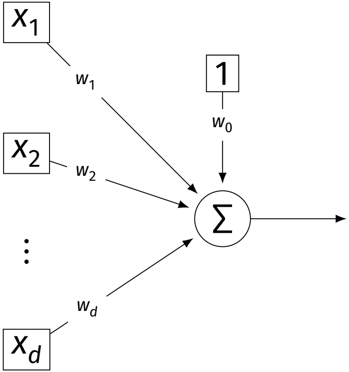
- Suppose H is a linear prediction function:

$$H(\vec{x};\vec{w}) = w_0 + w_1 x_1 + \ldots + w_d x_d$$

- What is $\nabla_{\vec{w}} H$ with respect to $\vec{w}$?

Example: Linear Model

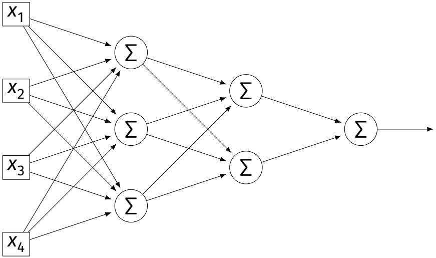
- Consider $\partial H / \partial w_1$:



Example: Neural Networks

- Suppose H is a neural network (with nonlinear activations).

- What is ∇H?
  - It's more complicated...



Parameter Vectors

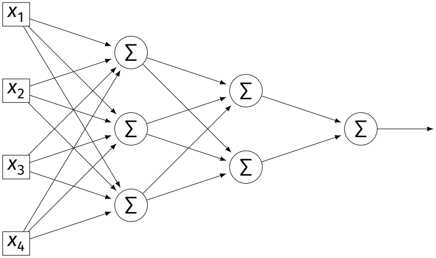
- It is often useful to pack all of the network's weights into a **parameter vector**, $\vec{w}$.
- Order is arbitrary:

$$\vec{w} = (W_{11}^{(1)}, W_{12}^{(1)}, \ldots, b_1^{(1)}, b_2^{(1)}, W_{11}^{(2)}, W_{12}^{(2)}, \ldots, b_1^{(2)}, b_2^{(2)}, \ldots)^T$$

- The network is a function $H(\vec{x}; \vec{w})$.
- Goal of learning: find the "best" $\vec{w}$.

Gradient of Neural Network

- $\nabla_{\vec{w}} H$ is a vector-valued function.
- Plugging a data point, $\vec{x}$, and a parameter vector, $\vec{w}$, into $\nabla_{\vec{w}} H$ "evaluates the gradient", results in a vector, same size as $\vec{w}$.



Today

- **Backpropagation**: a strategy for computing ∇H when H is a neural network.

DSC 140B
Representation Learning

Lecture 11 | Part 5

The Chain Rule

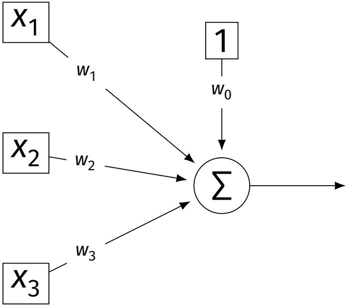
The Gradient

- The **gradient** $\nabla_{\vec{w}} H$ is the vector of partial derivatives of H with respect to each weight in $\vec{w}$:

$$\nabla_{\vec{w}} H = \left(\frac{\partial H}{\partial w_0}, \frac{\partial H}{\partial w_1}, \ldots, \frac{\partial H}{\partial w_d} \right)^T$$

- A partial derivative, $\partial H / \partial w_i$, measures the change in H due to a change in w_i.

Example: Linear Model



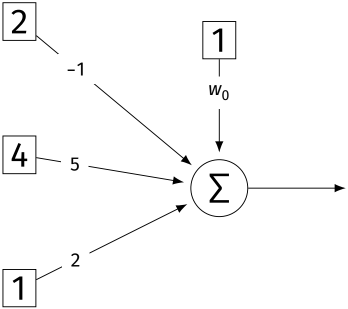
- Consider $\partial H / \partial w_1$:

$$\begin{aligned}
\frac{\partial H}{\partial w_1} &= \frac{\partial}{\partial w_1}(w_0 + w_1 x_1 + w_2 x_2 + \ldots + w_d x_d) \\
&= 0 + x_1 + 0 + \ldots + 0 \\
&= x_1
\end{aligned}$$

Exercise

Suppose the input to H is $\vec{x} = (2, 4, 1)^T$.

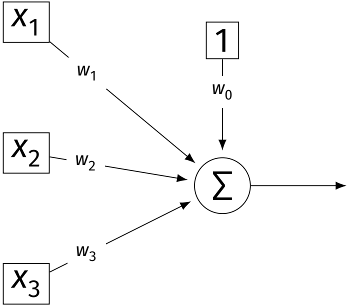
How much does H change if we increase w_2 by 1?



Exercise

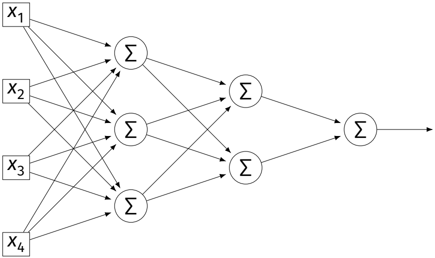
Suppose the input to H is $\vec{x} = (x_1, x_2, x_3)^T$.

What is $\partial H / \partial w_2$?



Neural Networks

- When H is a neural network, $\nabla_{\vec{w}} H$ is more complicated.

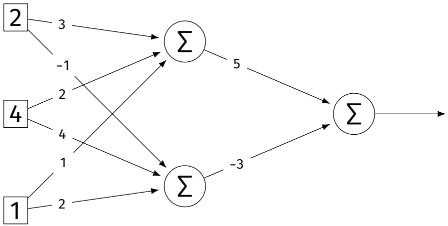


A "Simple" Strategy

- However, there is a **simple** strategy for computing $\nabla_{\vec{w}} H$ when H is a neural network.
- We will derive it via examples.

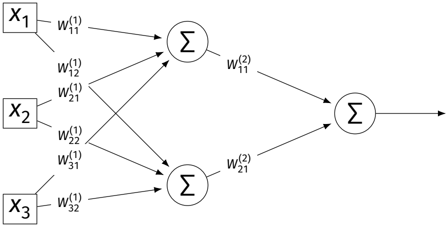
Exercise

Now suppose H is the neural network shown below and $\vec{x} = (2, 4, 1)^T$. How much does H change if we increase $W_{11}^{(2)}$ by 1?



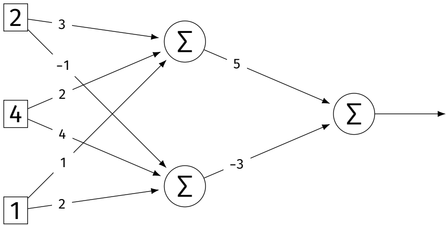
Exercise

Suppose H is the neural network shown below and $\vec{x} = (x_1, x_2, x_3)^T$. What is $\partial H / \partial W_{11}^{(2)}$?



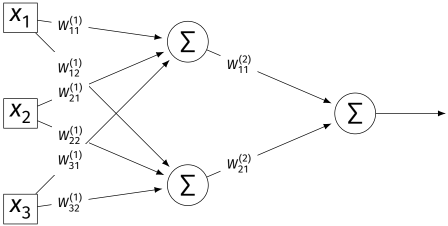
Exercise

Suppose H is the neural network shown below and $\vec{x} = (2, 4, 1)^T$. How much does H change if we increase $W_{11}^{(1)}$ by 1?



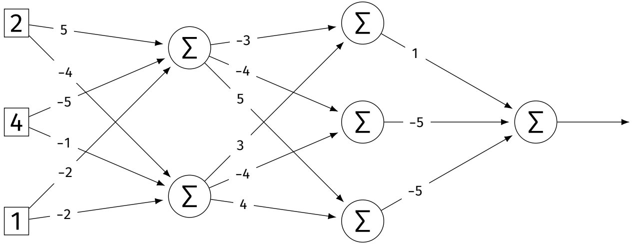
Exercise

Suppose H is the neural network shown below and $\vec{x} = (x_1, x_2, x_3)^T$. What is $\partial H / \partial W_{11}^{(1)}$?

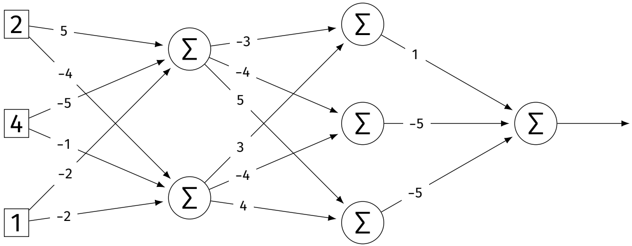


Exercise

Suppose H is the neural network shown below and $\vec{x} = (2, 4, 1)^T$. How much does H change if we increase $W_{11}^{(1)}$ by 1?



Solution



$\Delta H =$

$\Delta z_1^{(2)} =$

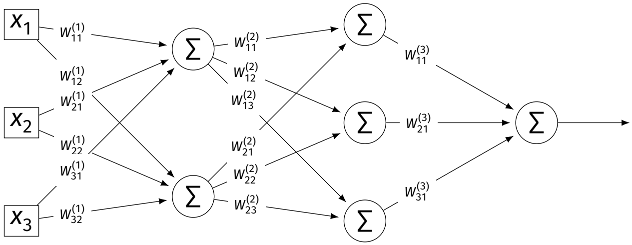
$\Delta z_2^{(2)} =$

$\Delta z_3^{(2)} =$

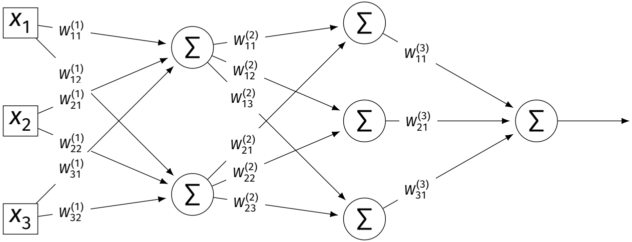
$\Delta z_1^{(1)} =$

Exercise

Suppose H is the neural network shown below and $\vec{x} = (x_1, x_2, x_3)^T$. What is $\partial H / \partial W_{11}^{(1)}$?



Solution



x_1
x_2
x_3
$w_{11}^{(1)}$
$w_{12}^{(1)}$
$w_{21}^{(1)}$
$w_{22}^{(1)}$
$w_{31}^{(1)}$
$w_{32}^{(1)}$
$w_{11}^{(2)}$
$w_{12}^{(2)}$
$w_{13}^{(2)}$
$w_{21}^{(2)}$
$w_{22}^{(2)}$
$w_{23}^{(2)}$
$w_{11}^{(3)}$
$w_{21}^{(3)}$
$w_{31}^{(3)}$
Σ

Chain Rule

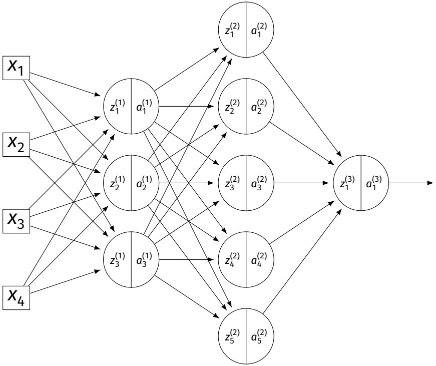
- We are rediscovering the **chain rule**.
- Example: if $H(x) = f_1(f_2(f_3(x)))$, then

$$\frac{\partial H}{\partial x} = \frac{\partial f_1}{\partial f_2} \cdot \frac{\partial f_2}{\partial f_3} \cdot \frac{\partial f_3}{\partial x}$$

Activations?

- So far, we have only considered linear activations.
- What happens if we have nonlinear activations?

Example



- Consider $\partial H / \partial W_{11}^{(1)}$.
- Let g be the activation function.

A Better Way

- Computing the gradient is straightforward...
- But can involve a lot of repeated work.
- **Backpropagation** is an algorithm for efficiently computing the gradient of a neural network.