

# Neural networks

Feedforward neural network - artificial neuron

# ARTIFICIAL NEURON

**Topics:** connection weights, bias, activation function

- Neuron pre-activation (or input activation):

$$a(\mathbf{x}) = b + \sum_i w_i x_i = b + \mathbf{w}^\top \mathbf{x}$$

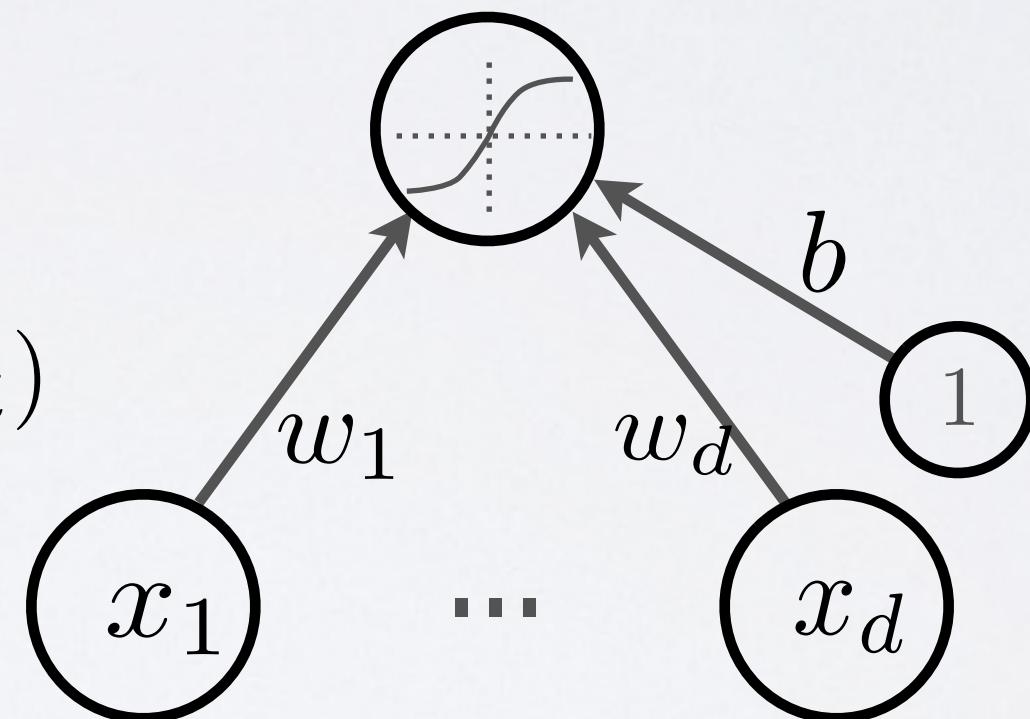
- Neuron (output) activation

$$h(\mathbf{x}) = g(a(\mathbf{x})) = g(b + \sum_i w_i x_i)$$

**w** are the connection weights

**b** is the neuron bias

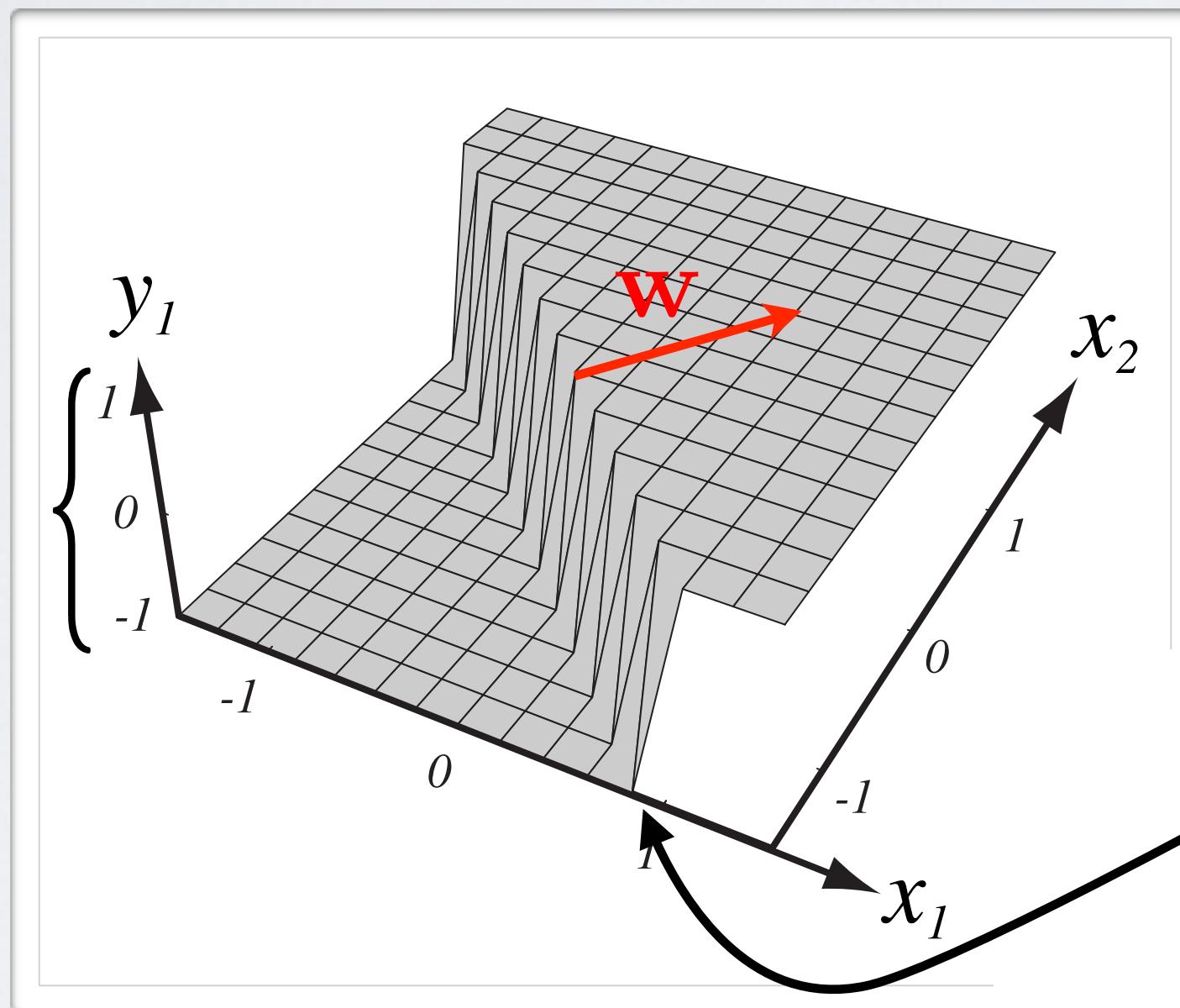
**g(·)** is called the activation function



# ARTIFICIAL NEURON

**Topics:** connection weights, bias, activation function

range determined  
by  $g(\cdot)$



bias  $b$  only  
changes the  
position of  
the riff

(from Pascal Vincent's slides)

# Neural networks

Feedforward neural network - activation function

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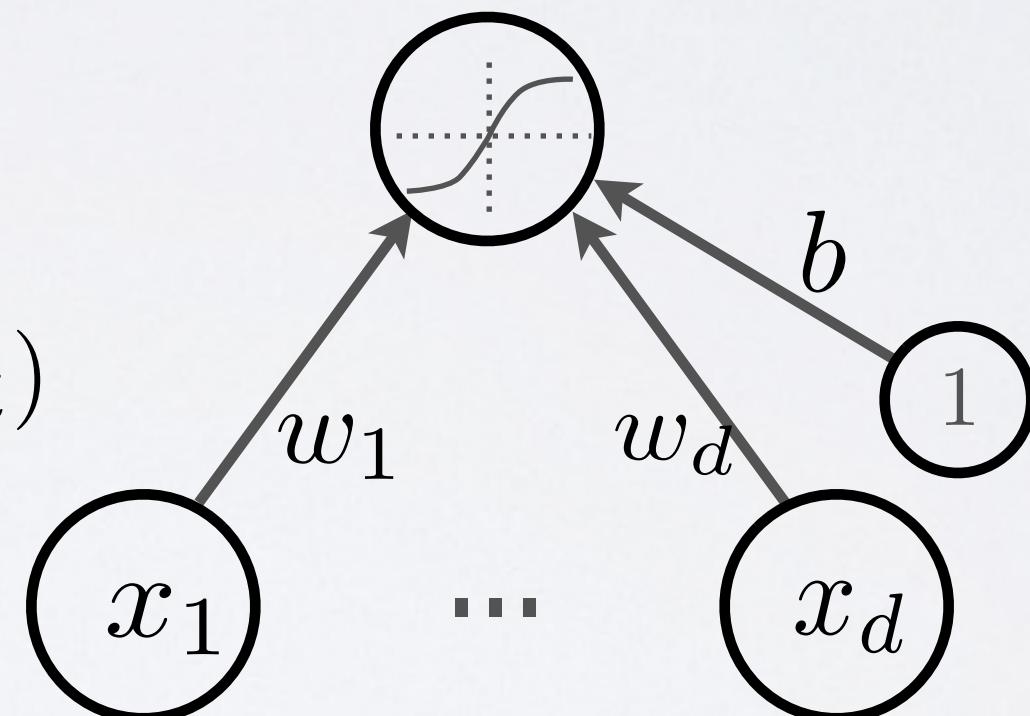
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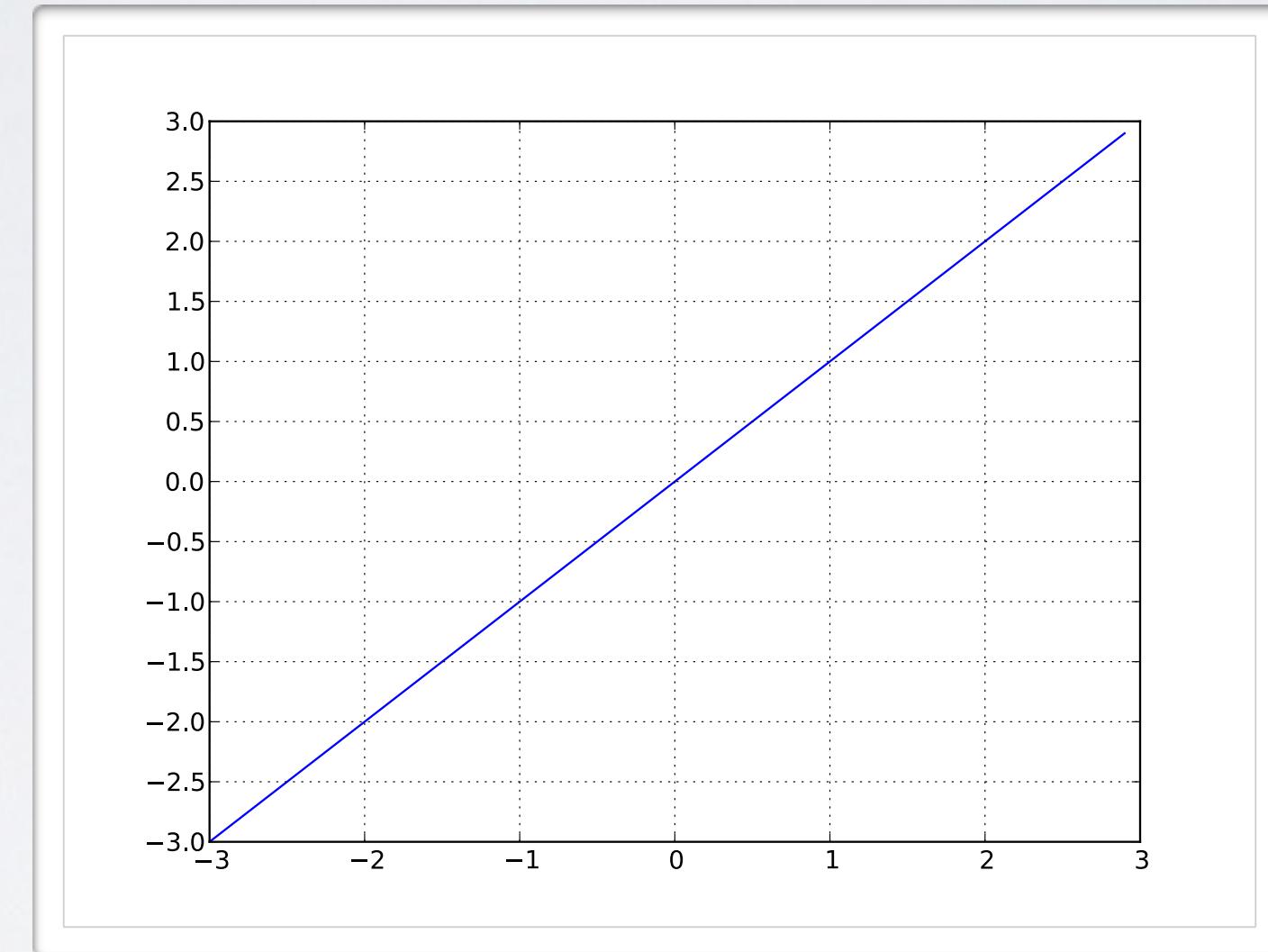
**g(·)** is called the activation function



# ACTIVATION FUNCTION

**Topics:** linear activation function

- Performs no input squashing
- Not very interesting...

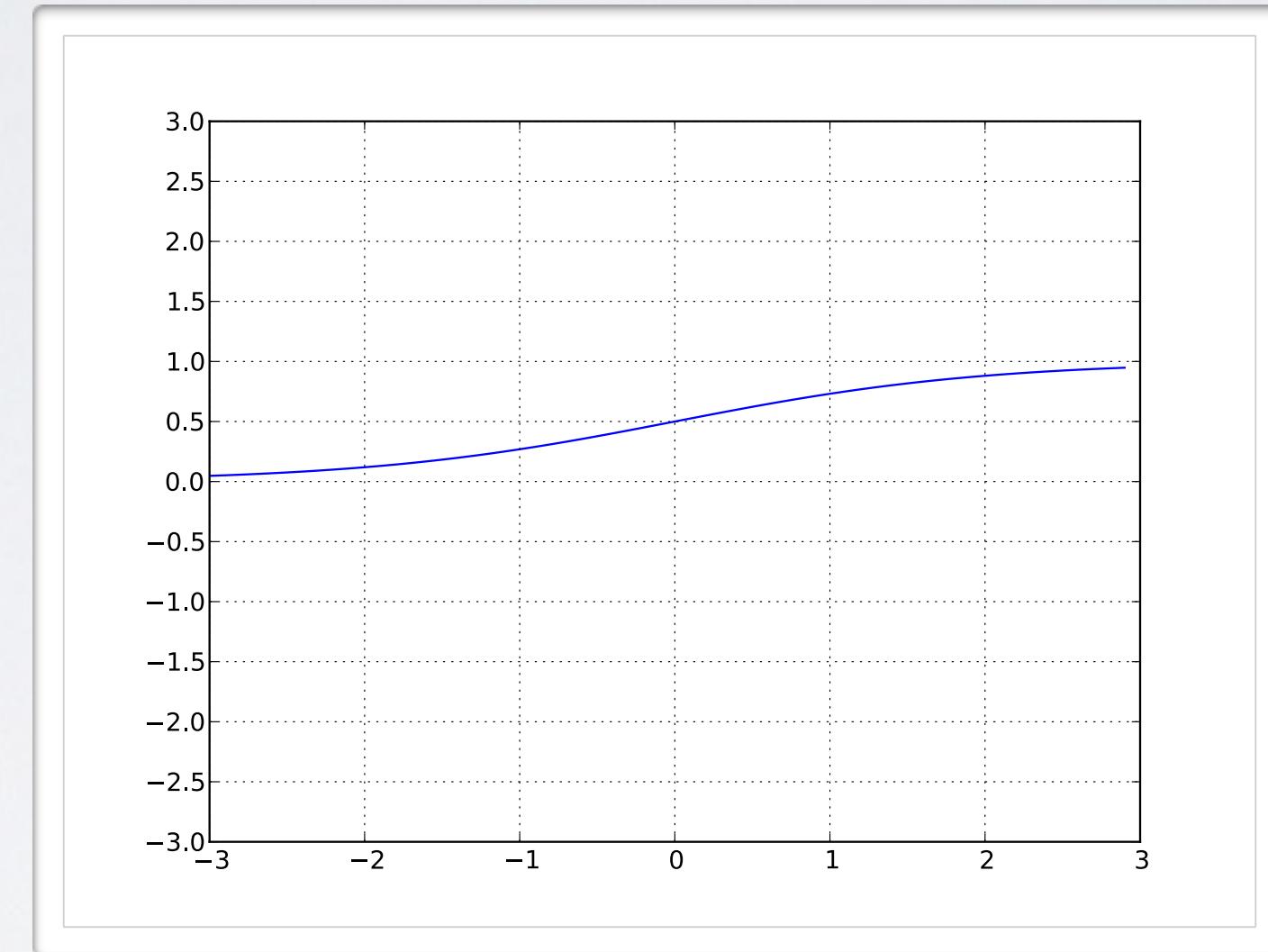


$$g(a) = a$$

# ACTIVATION FUNCTION

**Topics:** sigmoid activation function

- Squashes the neuron's pre-activation between 0 and 1
- Always positive
- Bounded
- Strictly increasing

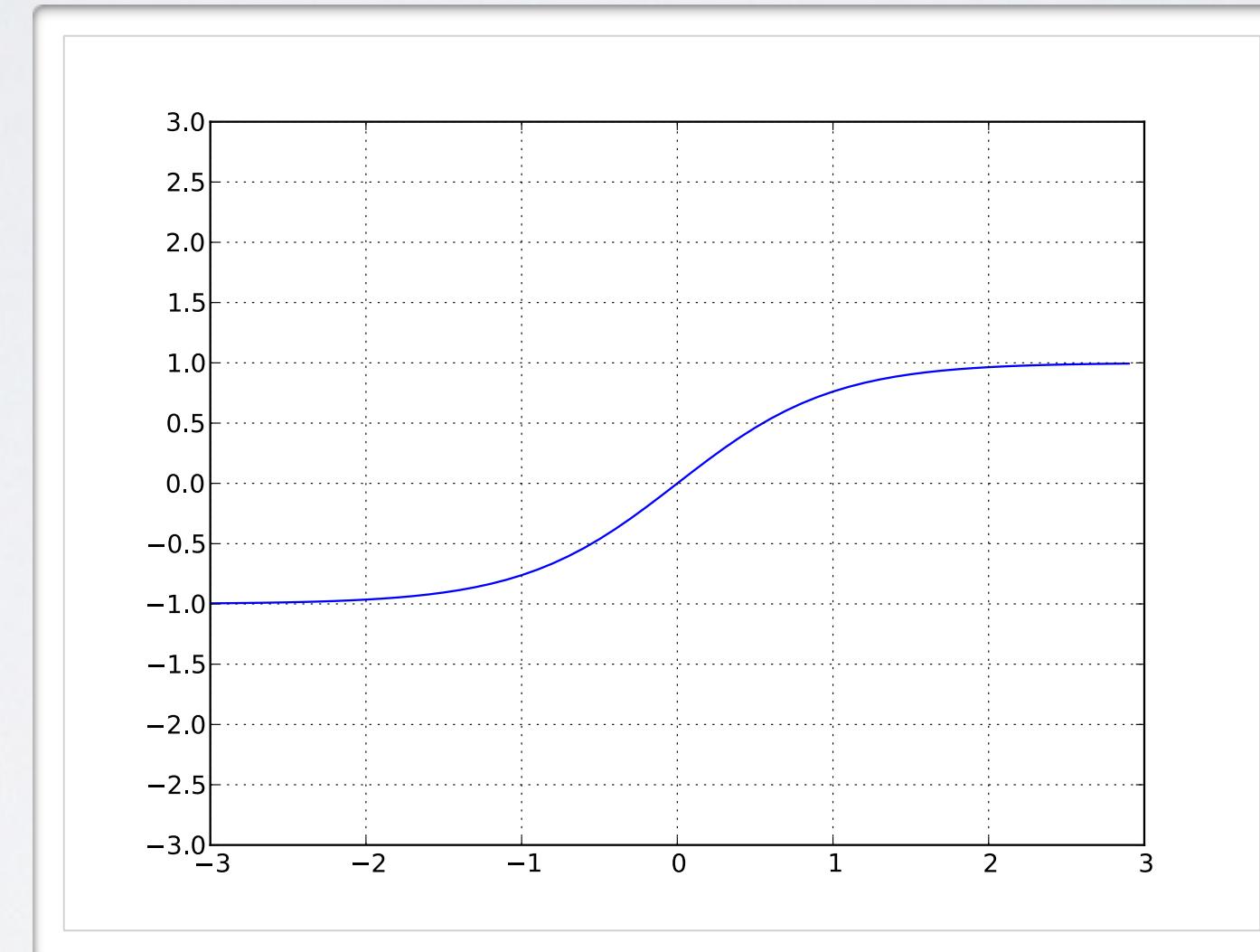


$$g(a) = \text{sigm}(a) = \frac{1}{1+\exp(-a)}$$

# ACTIVATION FUNCTION

**Topics:** hyperbolic tangent (“tanh”) activation function

- Squashes the neuron’s pre-activation between  $-1$  and  $1$
- Can be positive or negative
- Bounded
- Strictly increasing

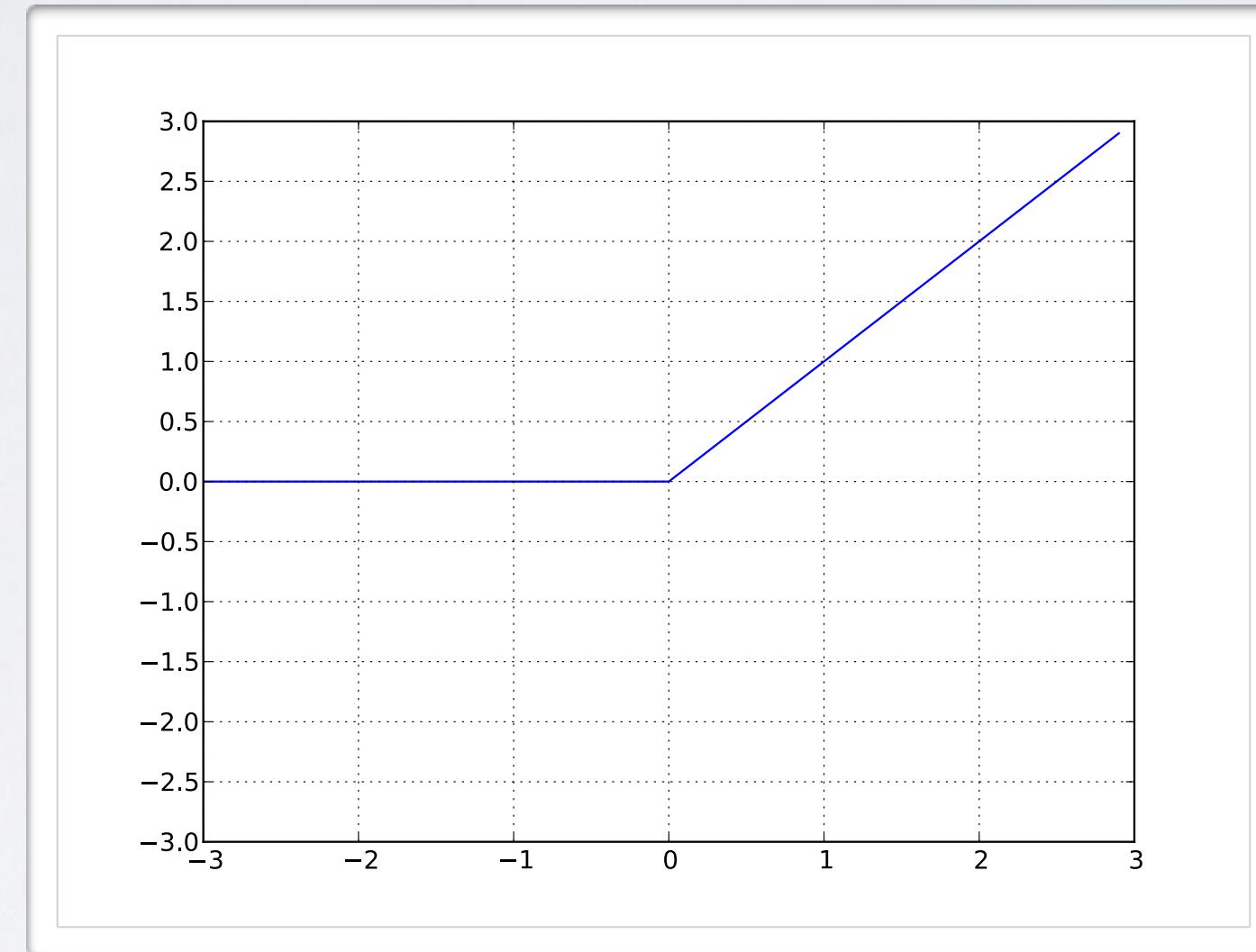


$$g(a) = \tanh(a) = \frac{\exp(a) - \exp(-a)}{\exp(a) + \exp(-a)} = \frac{\exp(2a) - 1}{\exp(2a) + 1}$$

# ACTIVATION FUNCTION

**Topics:** rectified linear activation function

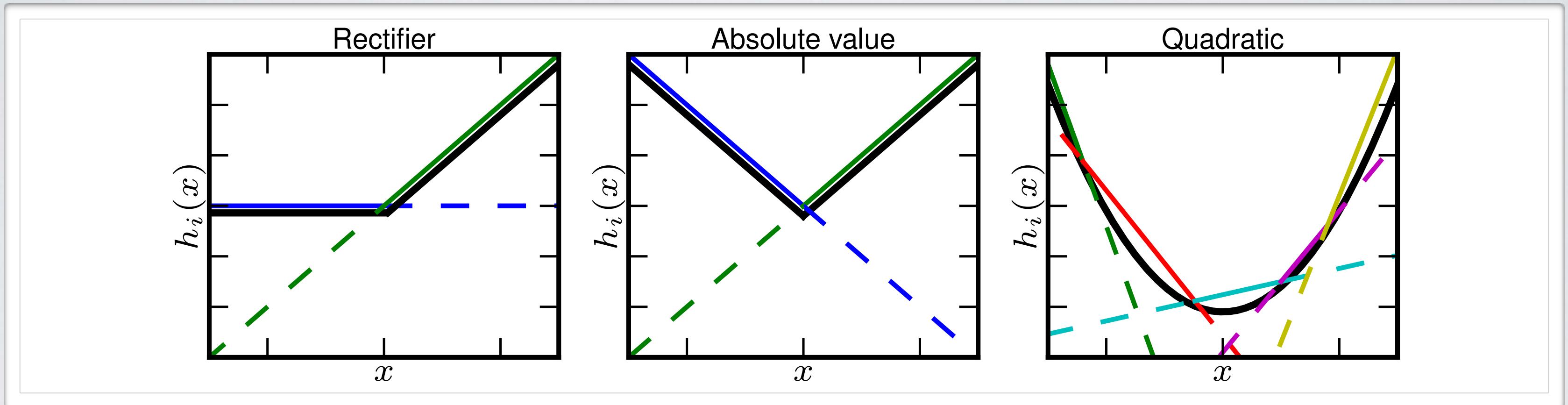
- Bounded below by 0  
(always non-negative)
- Not upper bounded
- Strictly increasing
- Tends to give neurons  
with sparse activities



$$g(a) = \text{reclin}(a) = \max(0, a)$$

# ACTIVATION FUNCTION

**Topics:** maxout activation function



- Not lower / upper bounded
- Does not give neurons with sparse activities
- But gradients are sparse

$$g(x) = \max_{j \in [1, k]} a_j$$

$$a_j = b_j + \mathbf{w}_j^T \mathbf{x}$$

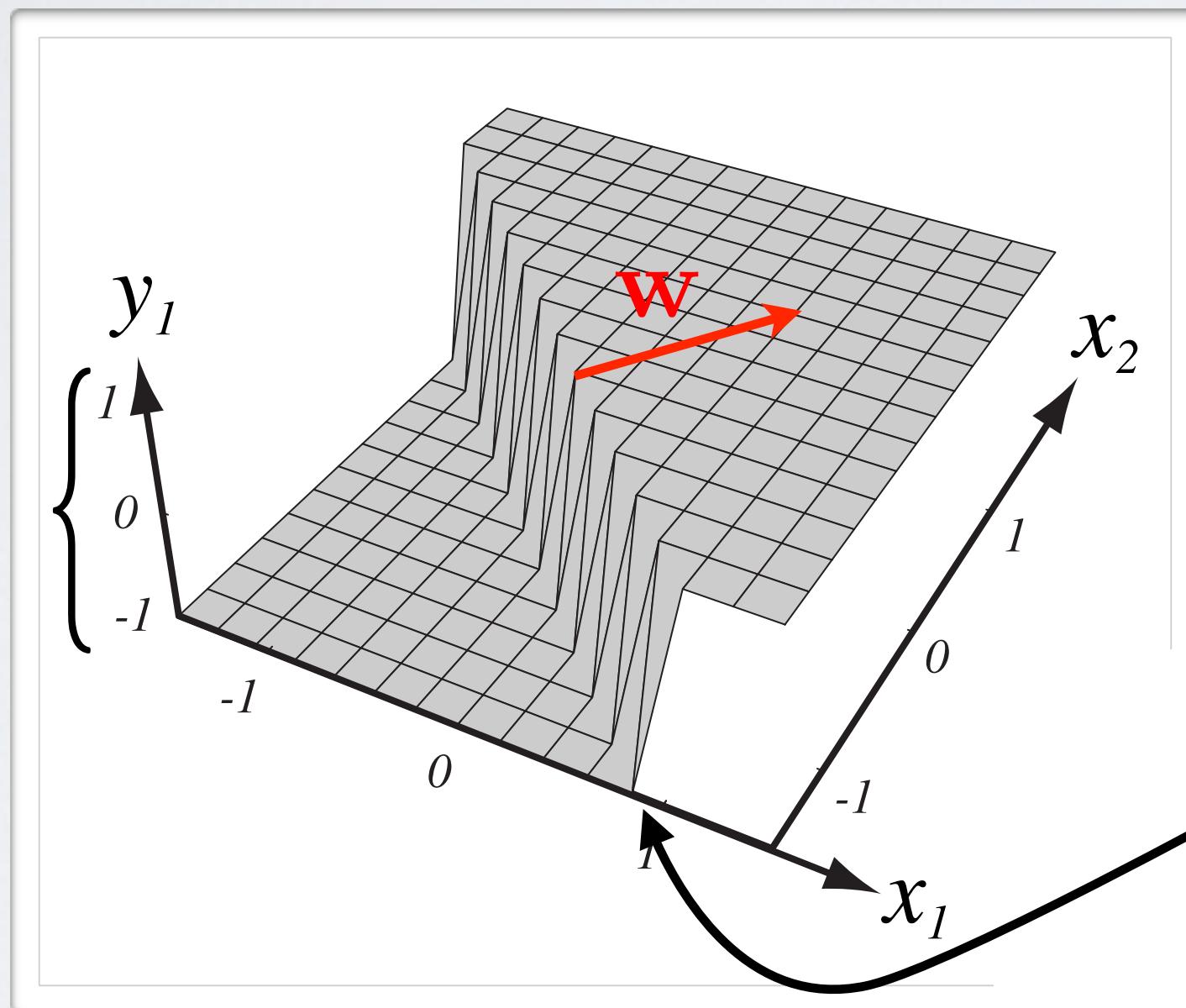
# Neural networks

Feedforward neural network - capacity of single neuron

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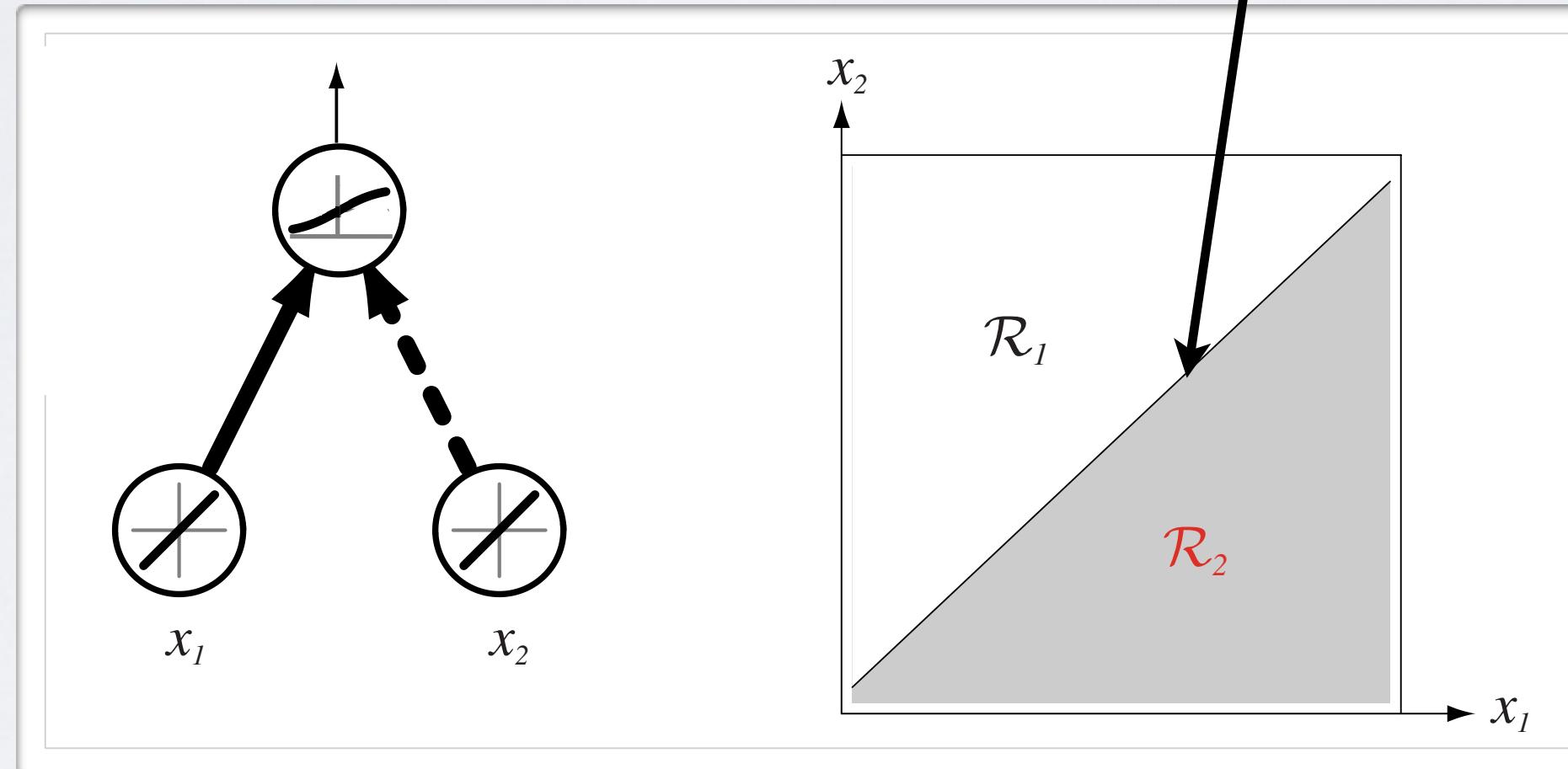
# ARTIFICIAL NEURON

**Topics:** capacity, decision boundary of neuron

- Could do binary classification:

- ▶ with sigmoid, can interpret neuron as estimating  $p(y = 1|\mathbf{x})$
- ▶ also known as logistic regression classifier
- ▶ if greater than 0.5, predict class 1
- ▶ otherwise, predict class 0

(similar idea can apply with tanh)

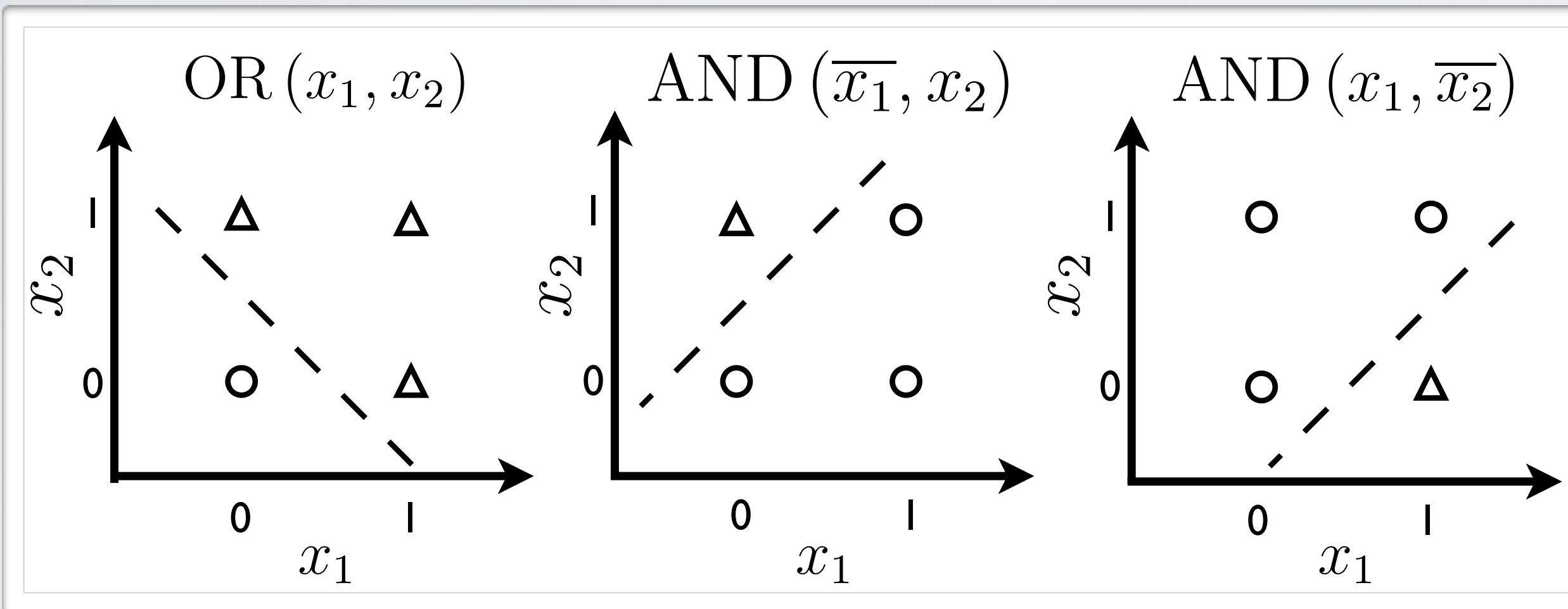


(from Pascal Vincent's slides)

# ARTIFICIAL NEURON

**Topics:** capacity of single neuron

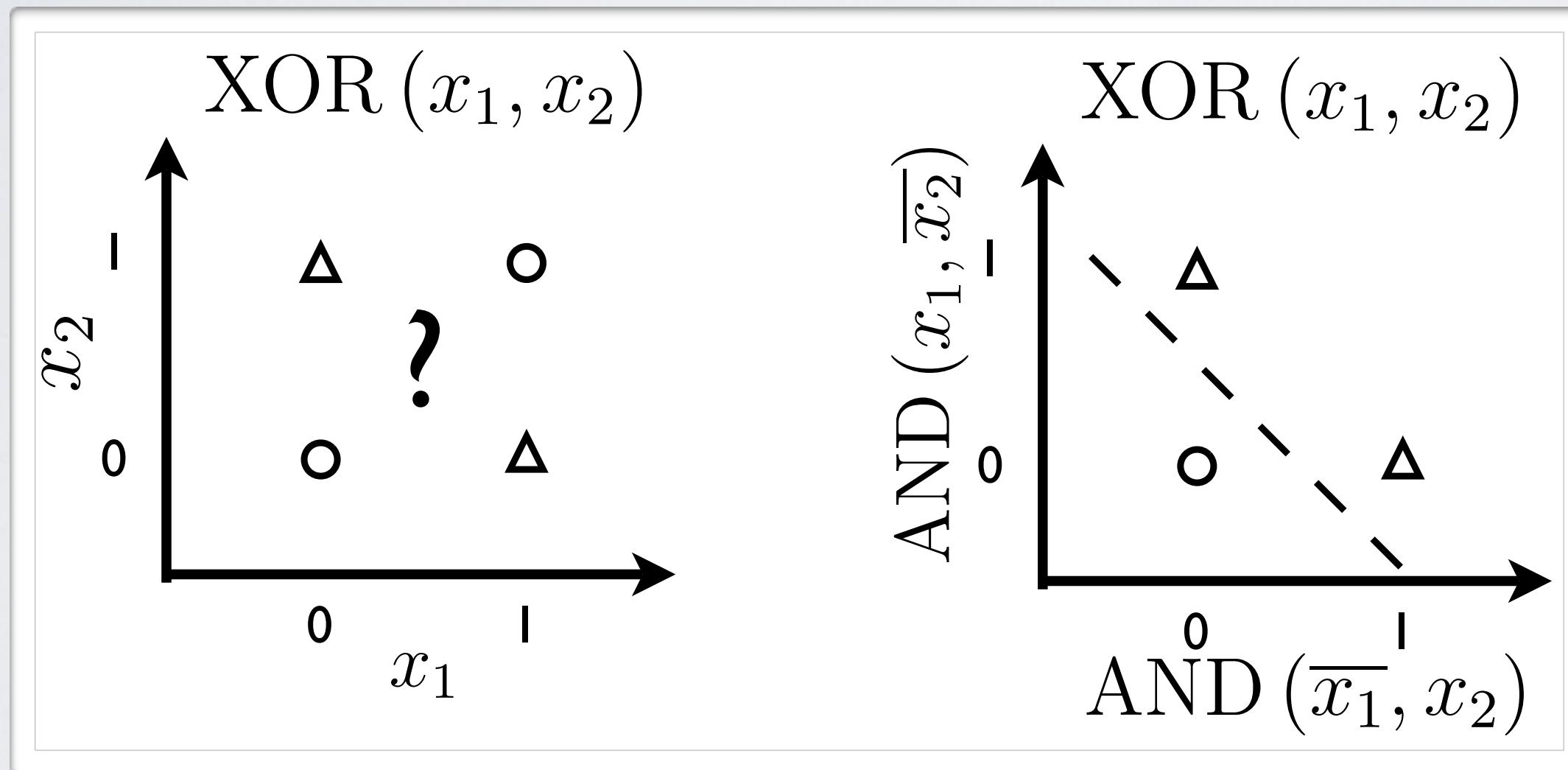
- Can solve linearly separable problems



# ARTIFICIAL NEURON

**Topics:** capacity of single neuron

- Can't solve non linearly separable problems...



- ... unless the input is transformed in a better representation

# Neural networks

Feedforward neural network - multilayer neural network

# NEURAL NETWORK

**Topics:** single hidden layer neural network

- Hidden layer pre-activation:

$$\mathbf{a}(\mathbf{x}) = \mathbf{b}^{(1)} + \mathbf{W}^{(1)}\mathbf{x}$$

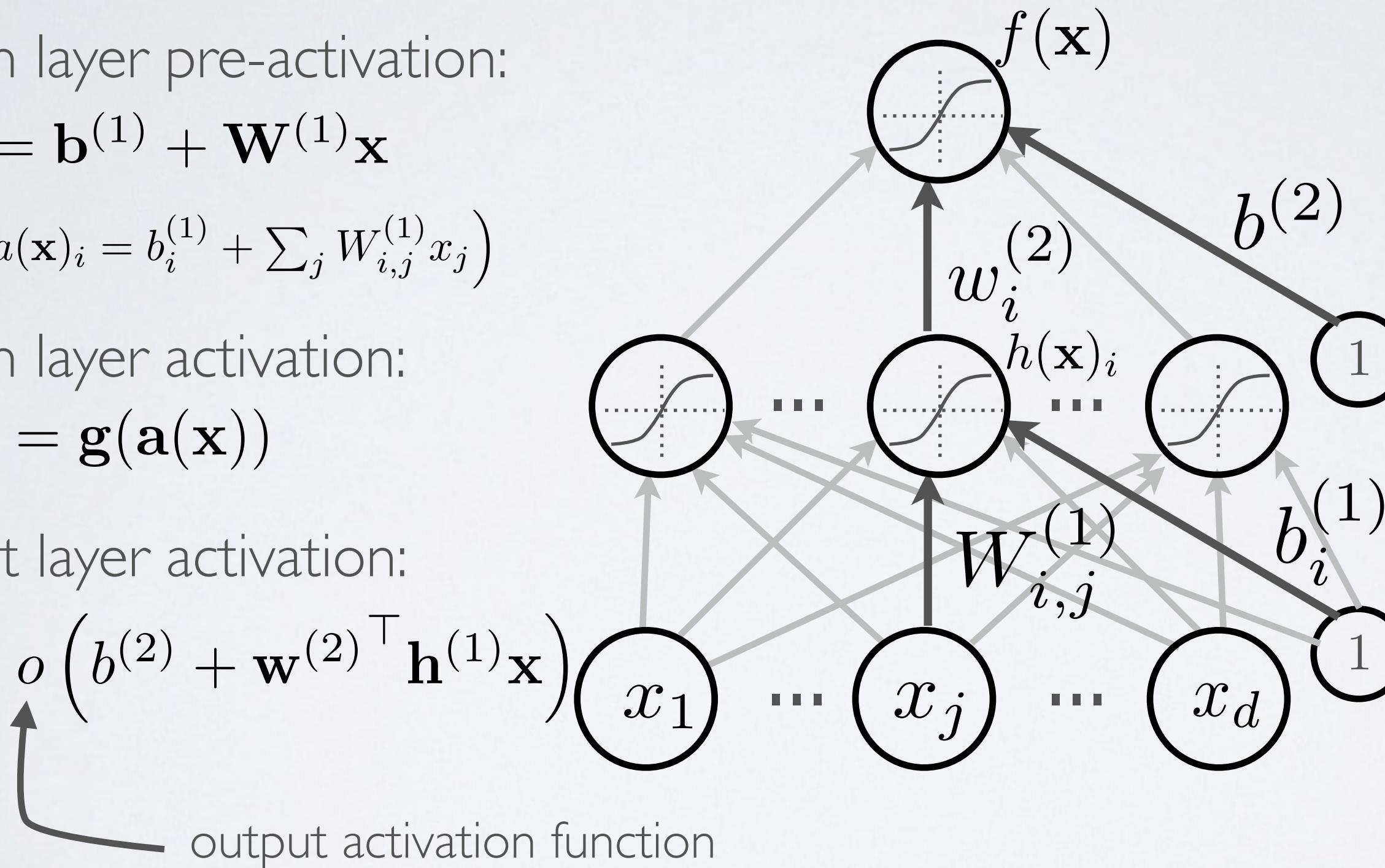
$$(a(\mathbf{x})_i = b_i^{(1)} + \sum_j W_{i,j}^{(1)} x_j)$$

- Hidden layer activation:

$$\mathbf{h}(\mathbf{x}) = g(\mathbf{a}(\mathbf{x}))$$

- Output layer activation:

$$f(\mathbf{x}) = o\left(b^{(2)} + \mathbf{w}^{(2)^\top} \mathbf{h}^{(1)} \mathbf{x}\right)$$



# NEURAL NETWORK

**Topics:** softmax activation function

- For multi-class classification:
  - ▶ we need multiple outputs (1 output per class)
  - ▶ we would like to estimate the conditional probability  $p(y = c|\mathbf{x})$
- We use the softmax activation function at the output:
$$\mathbf{o}(\mathbf{a}) = \text{softmax}(\mathbf{a}) = \left[ \frac{\exp(a_1)}{\sum_c \exp(a_c)} \cdots \frac{\exp(a_C)}{\sum_c \exp(a_c)} \right]^T$$
  - ▶ strictly positive
  - ▶ sums to one
- Predicted class is the one with highest estimated probability

# NEURAL NETWORK

**Topics:** multilayer neural network

- Could have  $L$  hidden layers:

- ▶ layer pre-activation for  $k > 0$  ( $\mathbf{h}^{(0)}(\mathbf{x}) = \mathbf{x}$ )

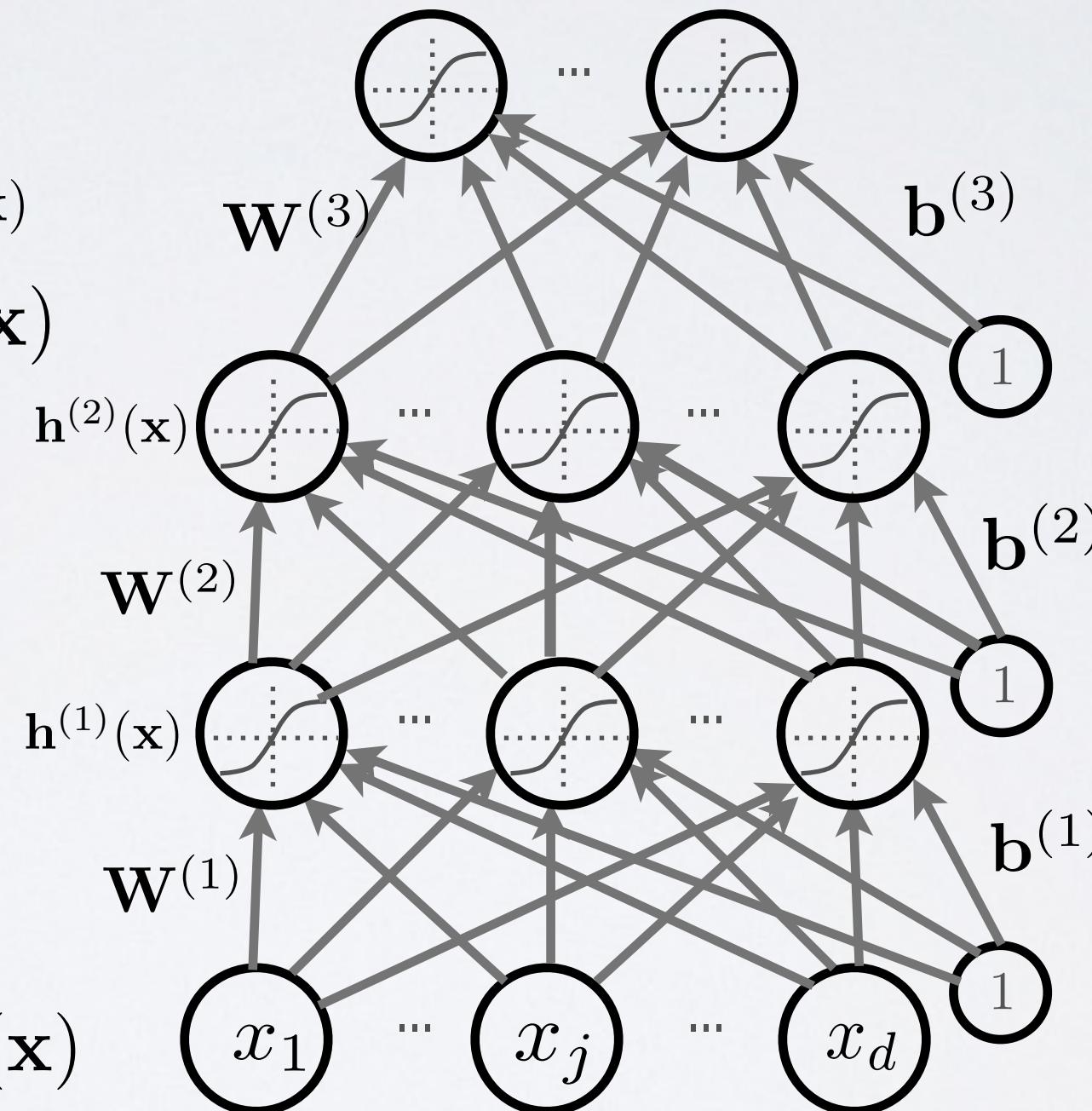
$$\mathbf{a}^{(k)}(\mathbf{x}) = \mathbf{b}^{(k)} + \mathbf{W}^{(k)} \mathbf{h}^{(k-1)}(\mathbf{x})$$

- ▶ hidden layer activation ( $k$  from 1 to  $L$ ):

$$\mathbf{h}^{(k)}(\mathbf{x}) = \mathbf{g}(\mathbf{a}^{(k)}(\mathbf{x}))$$

- ▶ output layer activation ( $k = L+1$ ):

$$\mathbf{h}^{(L+1)}(\mathbf{x}) = \mathbf{o}(\mathbf{a}^{(L+1)}(\mathbf{x})) = \mathbf{f}(\mathbf{x})$$



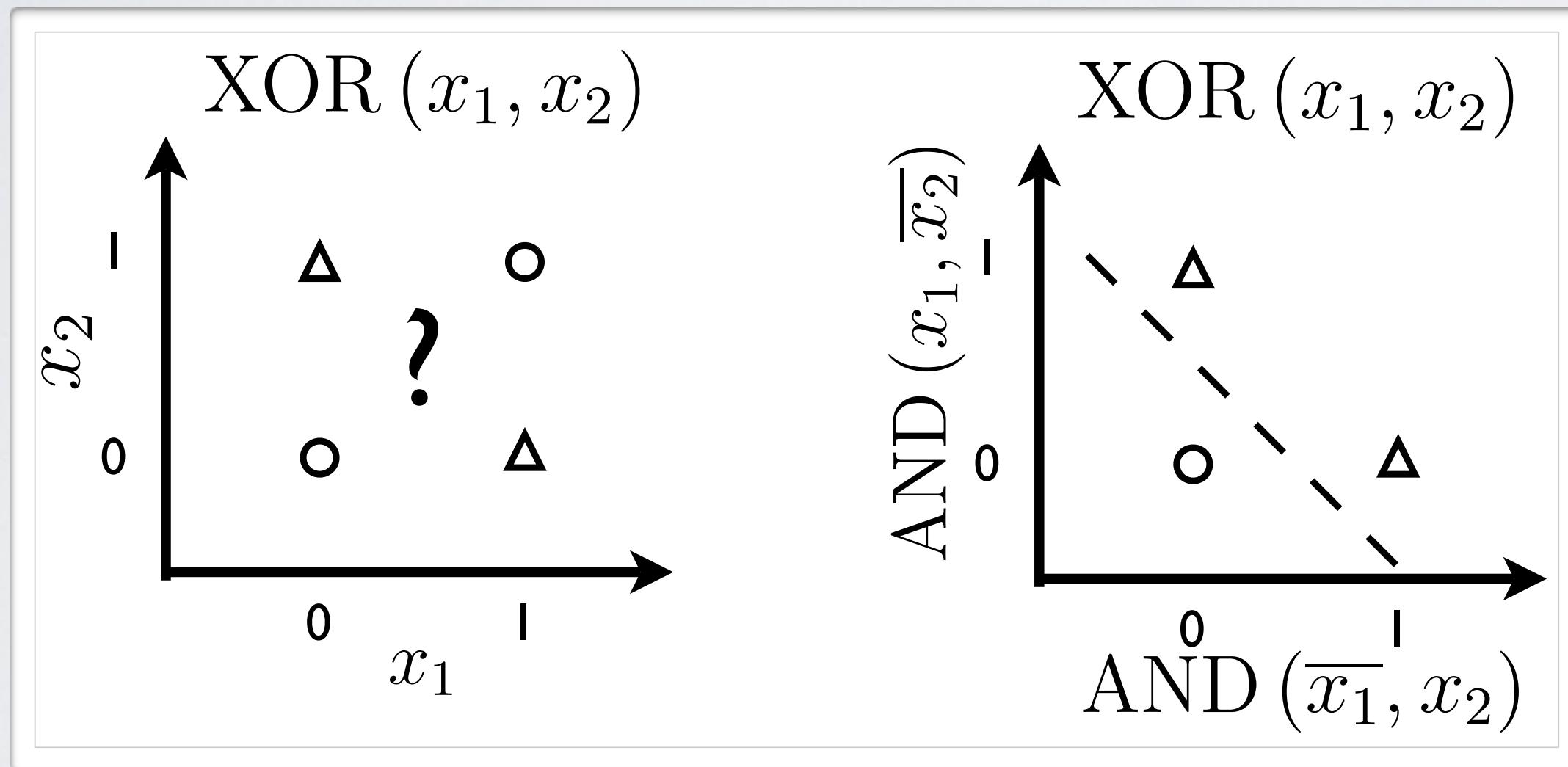
# Neural networks

Feedforward neural network - capacity of neural network

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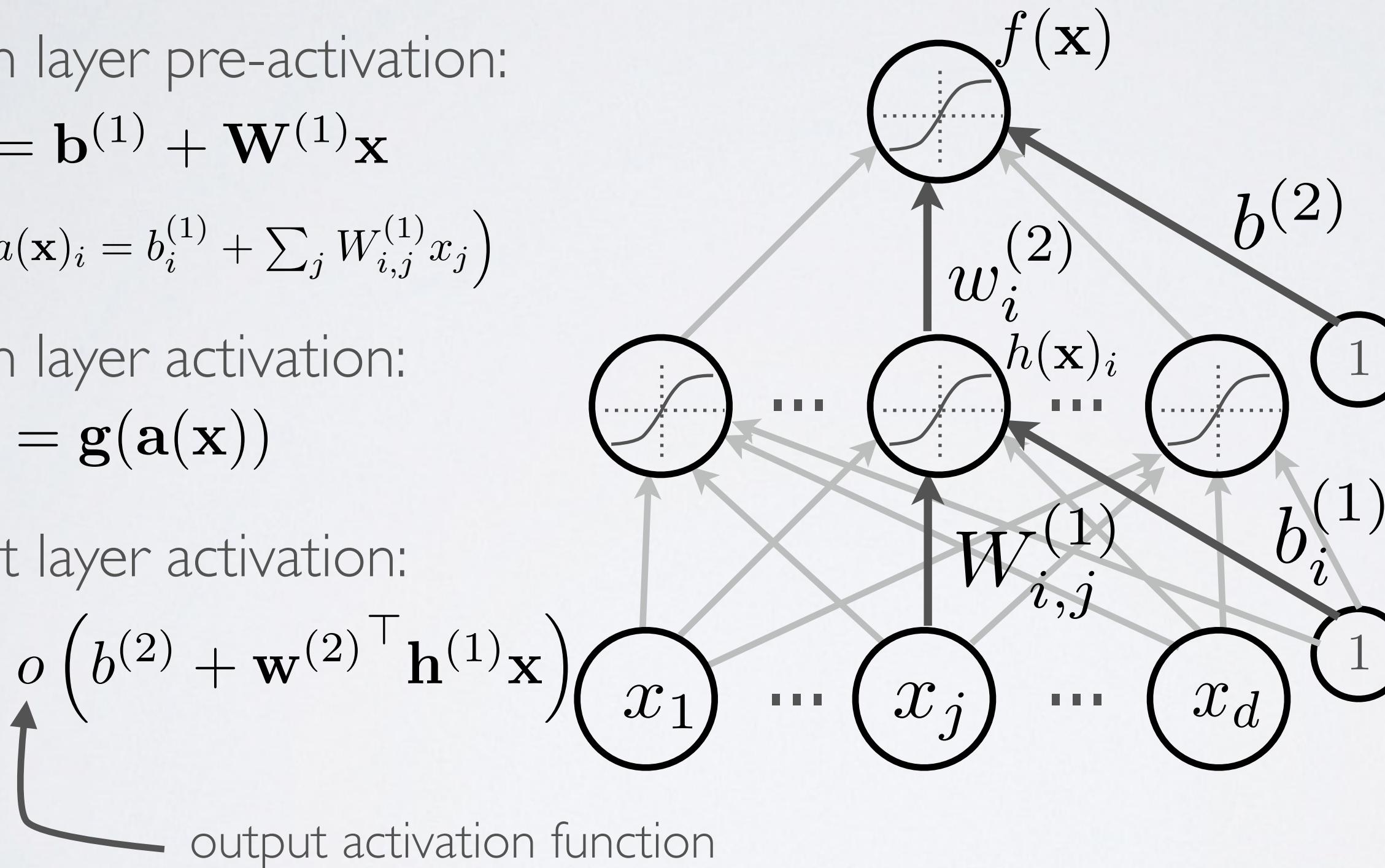
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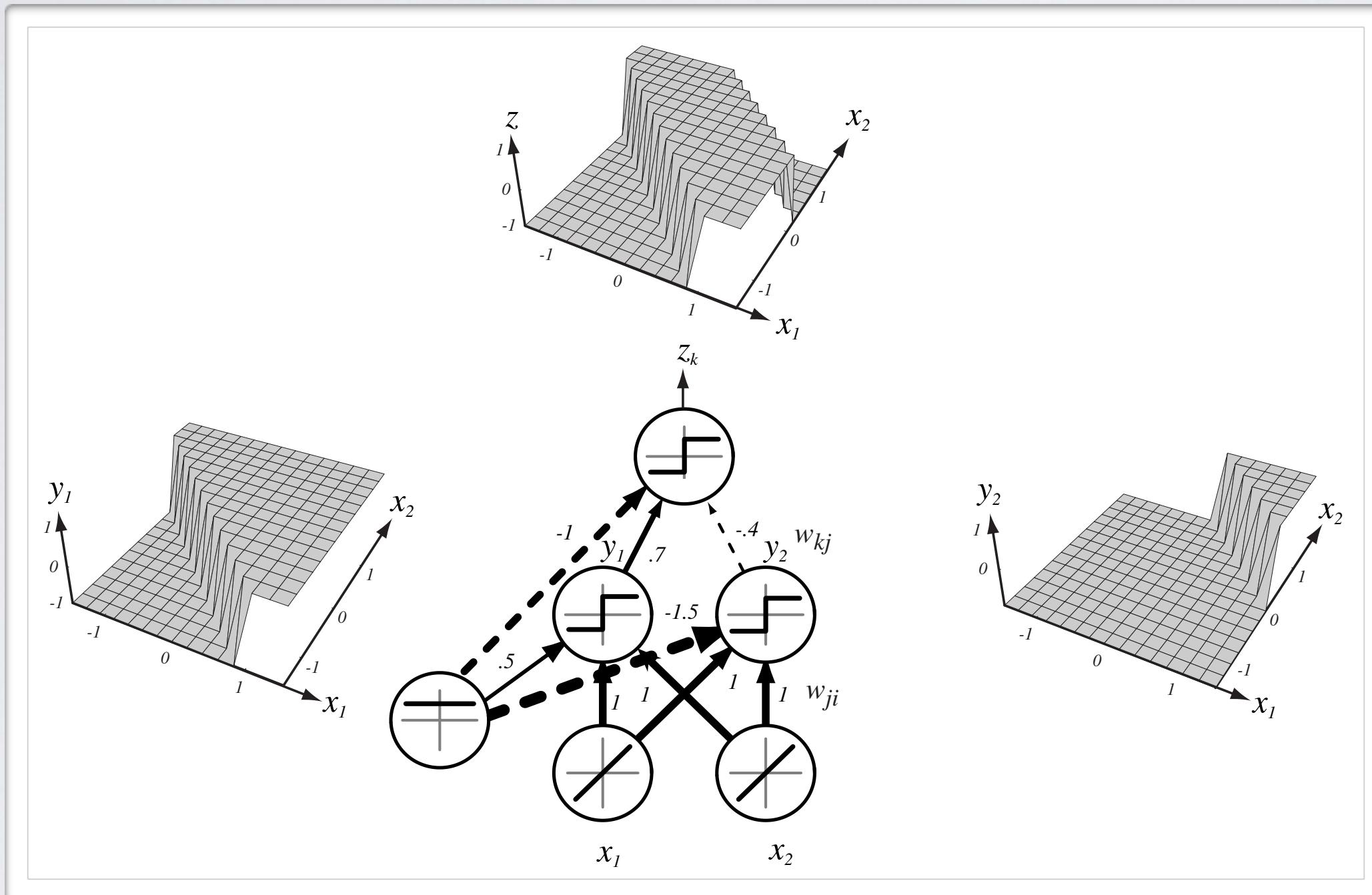
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# CAPACITY OF NEURAL NETWORK

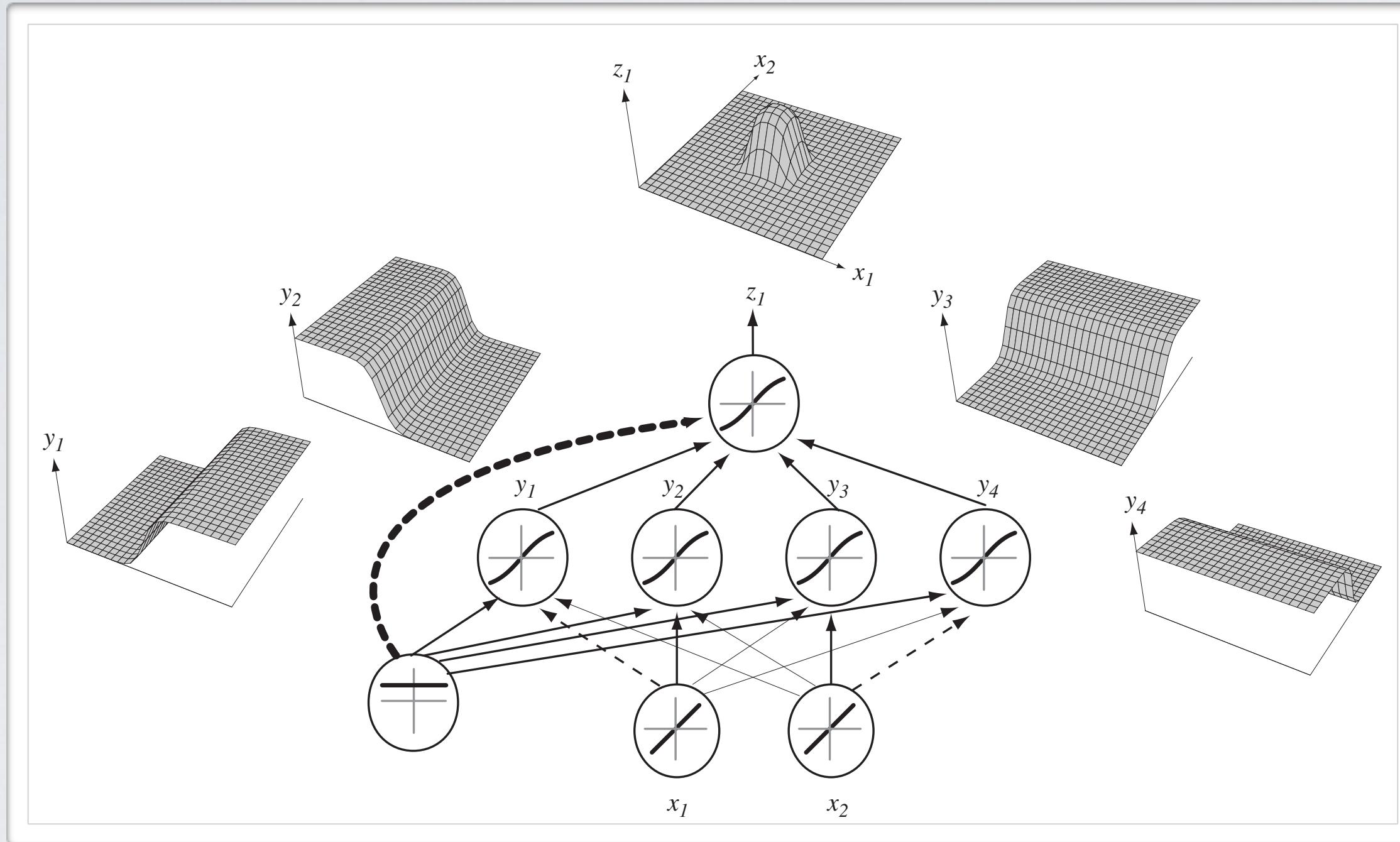
**Topics:** single hidden layer neural network



(from Pascal Vincent's slides)

# CAPACITY OF NEURAL NETWORK

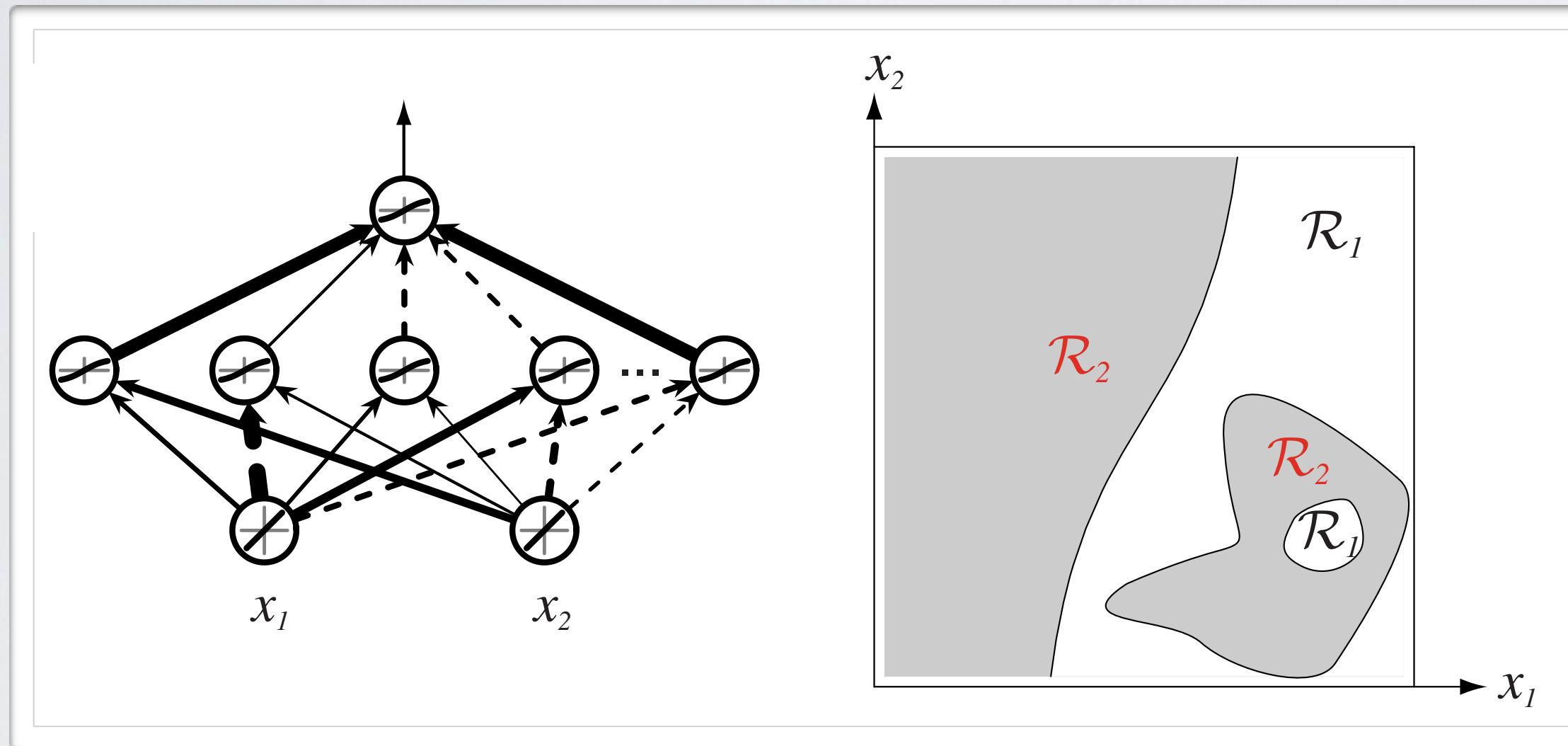
**Topics:** single hidden layer neural network



(from Pascal Vincent's slides)

# CAPACITY OF NEURAL NETWORK

**Topics:** single hidden layer neural network



(from Pascal Vincent's slides)

# CAPACITY OF NEURAL NETWORK

**Topics:** universal approximation

- Universal approximation theorem (Hornik, 1991):
  - ▶ “a single hidden layer neural network with a linear output unit can approximate any continuous function arbitrarily well, given enough hidden units”
- The result applies for sigmoid, tanh and many other hidden layer activation functions
- This is a good result, but it doesn’t mean there is a learning algorithm that can find the necessary parameter values!

# Neural networks

Feedforward neural network - biological inspiration

# NEURAL NETWORK

**Topics:** multilayer neural network

- Could have  $L$  hidden layers:

- ▶ layer pre-activation for  $k > 0$  ( $\mathbf{h}^{(0)}(\mathbf{x}) = \mathbf{x}$ )

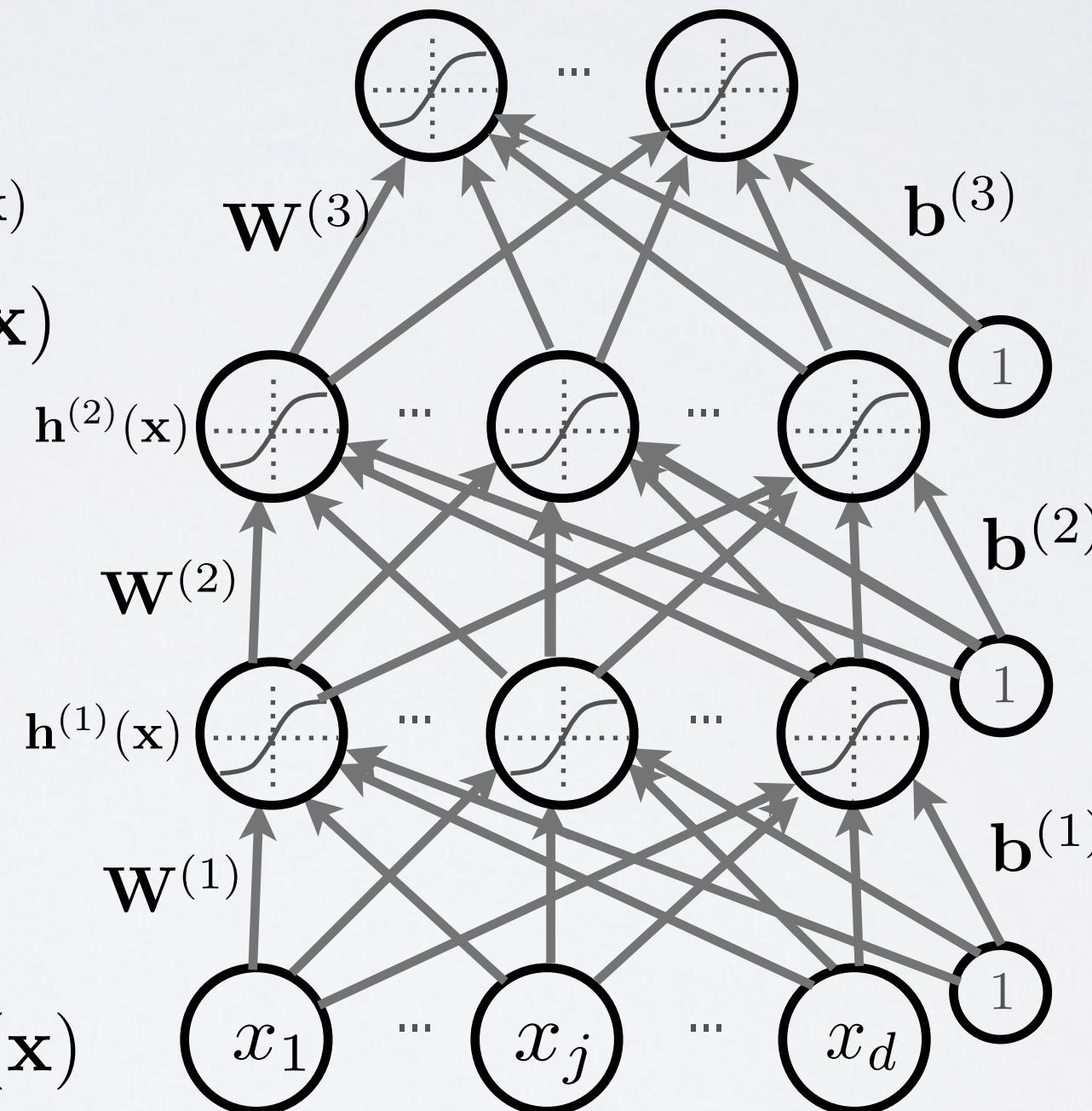
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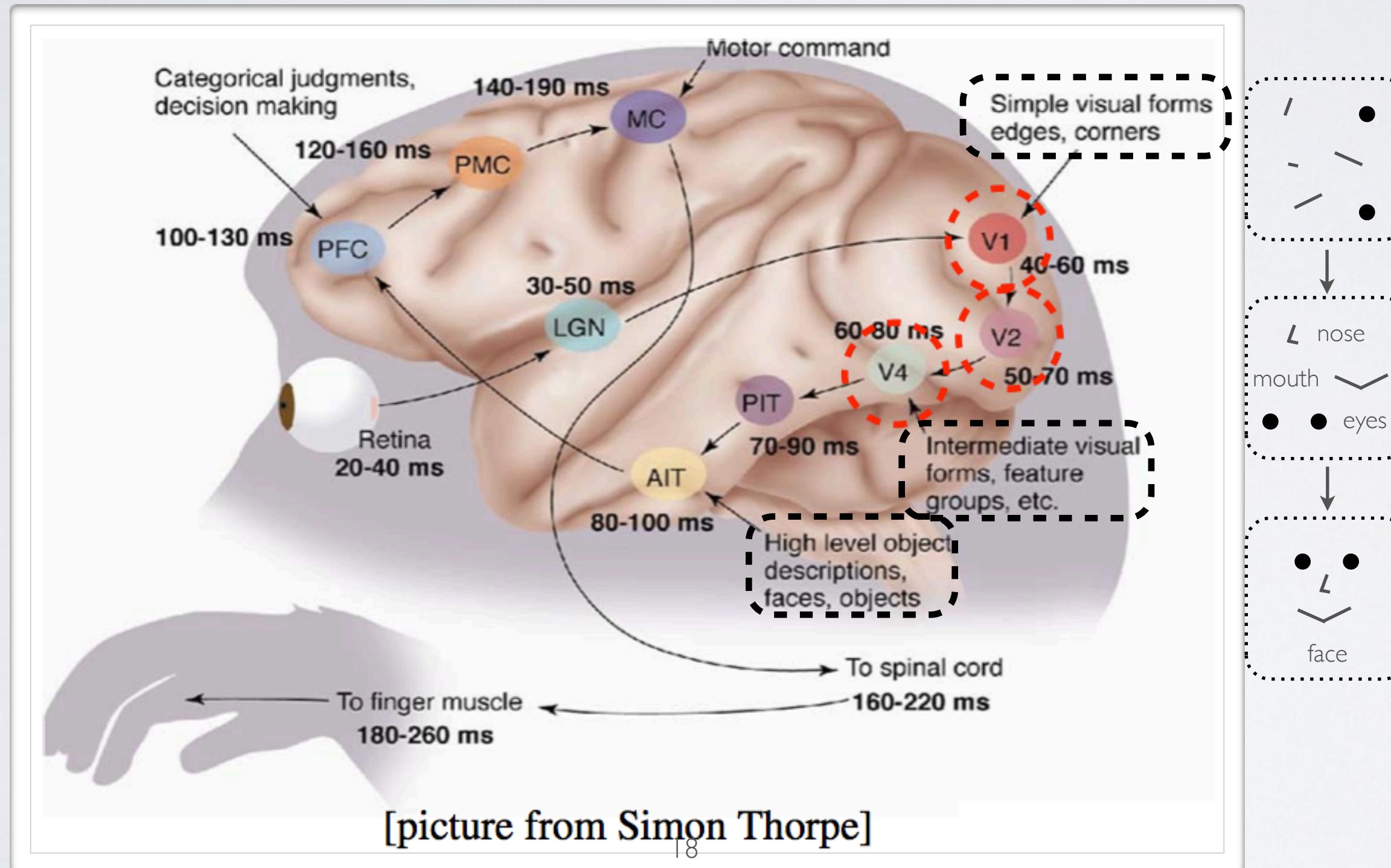
- ▶ output layer activation ( $k = L+1$ ):

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# NEURAL NETWORK

**Topics:** parallel with the visual cortex



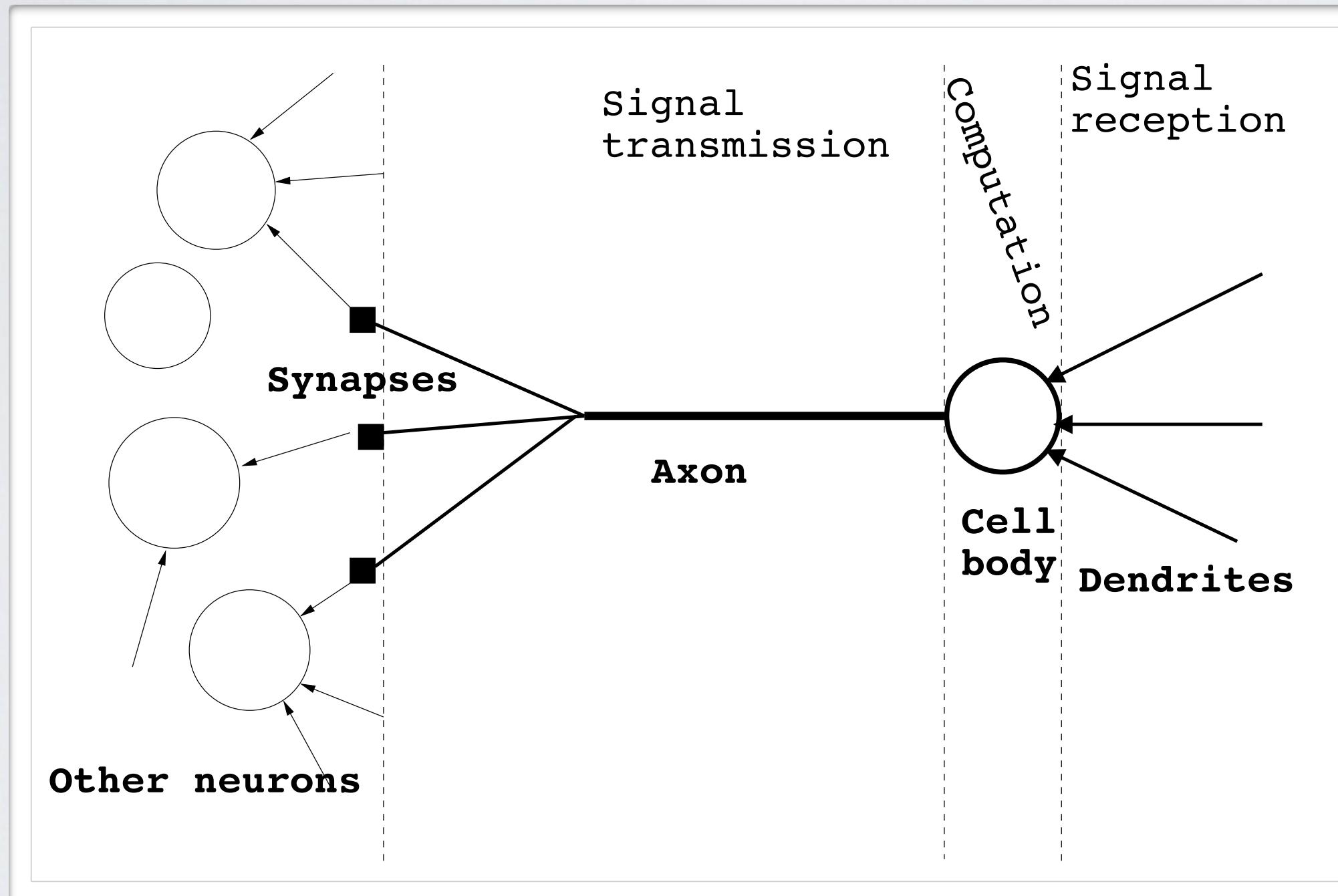
# BIOLOGICAL NEURONS

**Topics:** synapse, axon, dendrite

- We estimate around  $10^{10}$  and  $10^{11}$  the number of neurons in the human brain:
  - ▶ they receive information from other neurons through their dendrites
  - ▶ they “process” the information in their cell body (soma)
  - ▶ they send information through a “cable” called an axon
  - ▶ the point of connection between the axon branches and other neurons’ dendrites are called synapses

# BIOLOGICAL NEURONS

**Topics:** synapse, axon, dendrite



(from Hyvärinen, Hurri and Hoyer's book)

# BIOLOGICAL NEURONS

**Topics:** action potential, firing rate

- An action potential is an electrical impulse that travels through the axon:
  - ▶ this is how neurons communicate
  - ▶ it generates a “spike” in the electric potential (voltage) of the axon
  - ▶ an action potential is generated at neuron only if it receives enough (over some threshold) of the “right” pattern of spikes from other neurons
- Neurons can generate several such spikes every seconds:
  - ▶ the frequency of the spikes, called firing rate, is what characterizes the activity of a neuron
    - neurons are always firing a little bit, (spontaneous firing rate), but they will fire more, given the right stimulus

# BIOLOGICAL NEURONS

**Topics:** action potential, firing rate

- Firing rates of different input neurons combine to influence the firing rate of other neurons:
  - ▶ depending on the dendrite and axon, a neuron can either work to increase (excite) or decrease (inhibit) the firing rate of another neuron
- This is what artificial neurons approximate:
  - ▶ the activation corresponds to a “sort of” firing rate
  - ▶ the weights between neurons model whether neurons excite or inhibit each other
  - ▶ the activation function and bias model the thresholded behavior of action potentials

# BIOLOGICAL NEURONS

## **Hubel & Wiesel experiment**

<http://www.youtube.com/watch?v=8VdFf3egwfg&feature=related>