

EECS 545: Machine Learning

Lecture 11. Neural Networks and Deep Learning

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02/19/2024



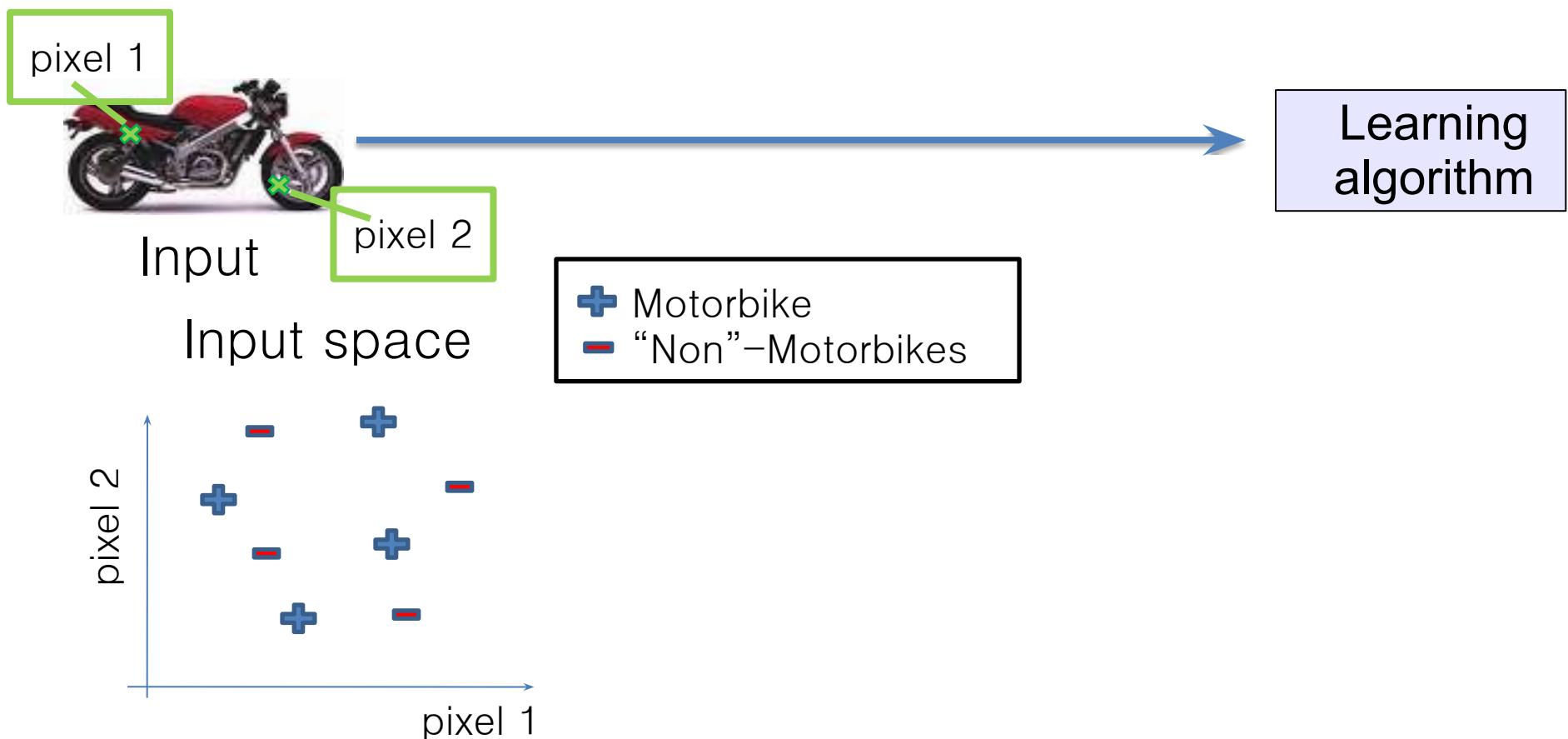
Logistics

- HW3 is released (due 03/05/24)
 - We highly recommend you start ASAP.

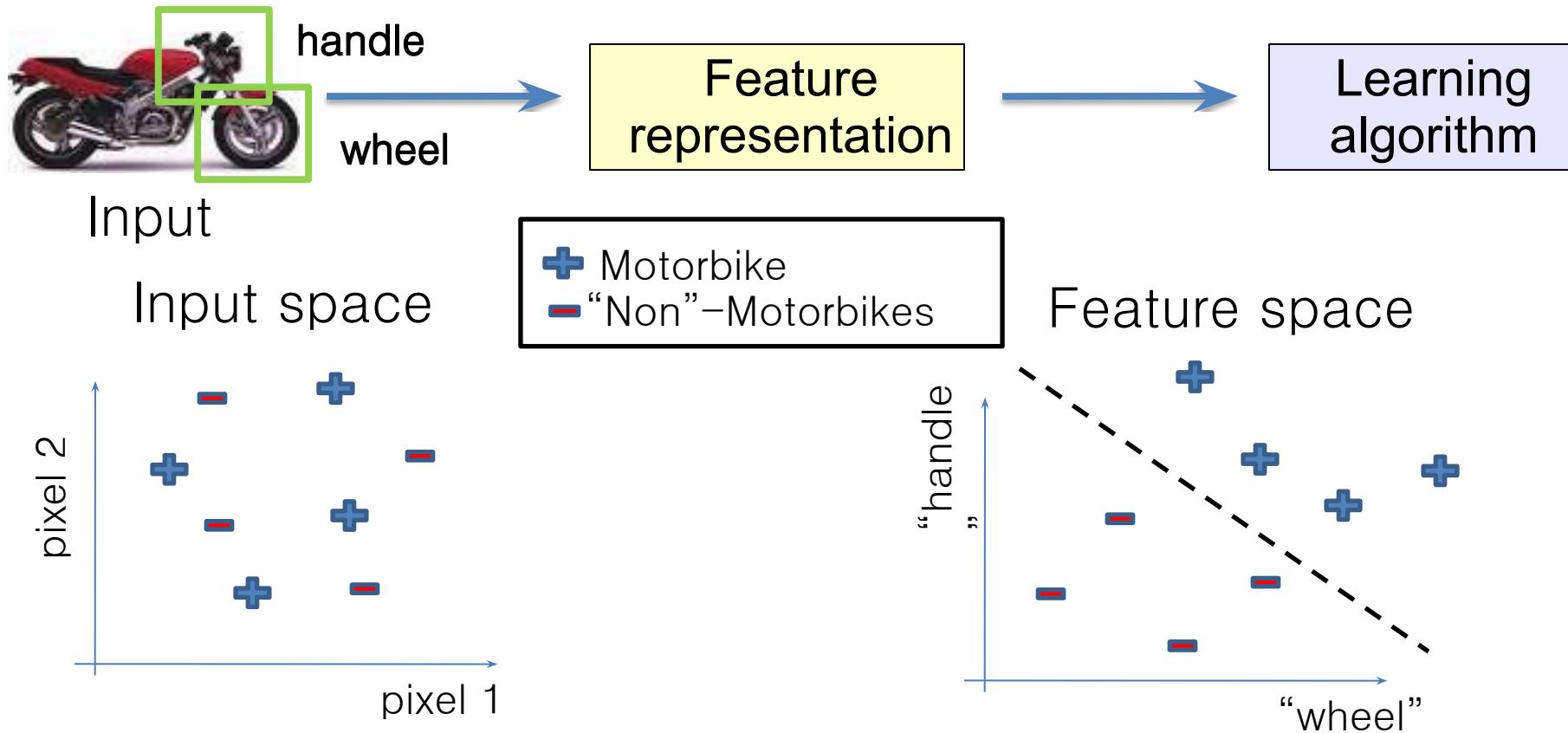
Representing Data

- The success of machine learning applications relies on having a good representation of the data.
- Machine learning practitioners put lots of efforts in “feature engineering”.
- How can we develop good representations **automatically**?

Feature representations

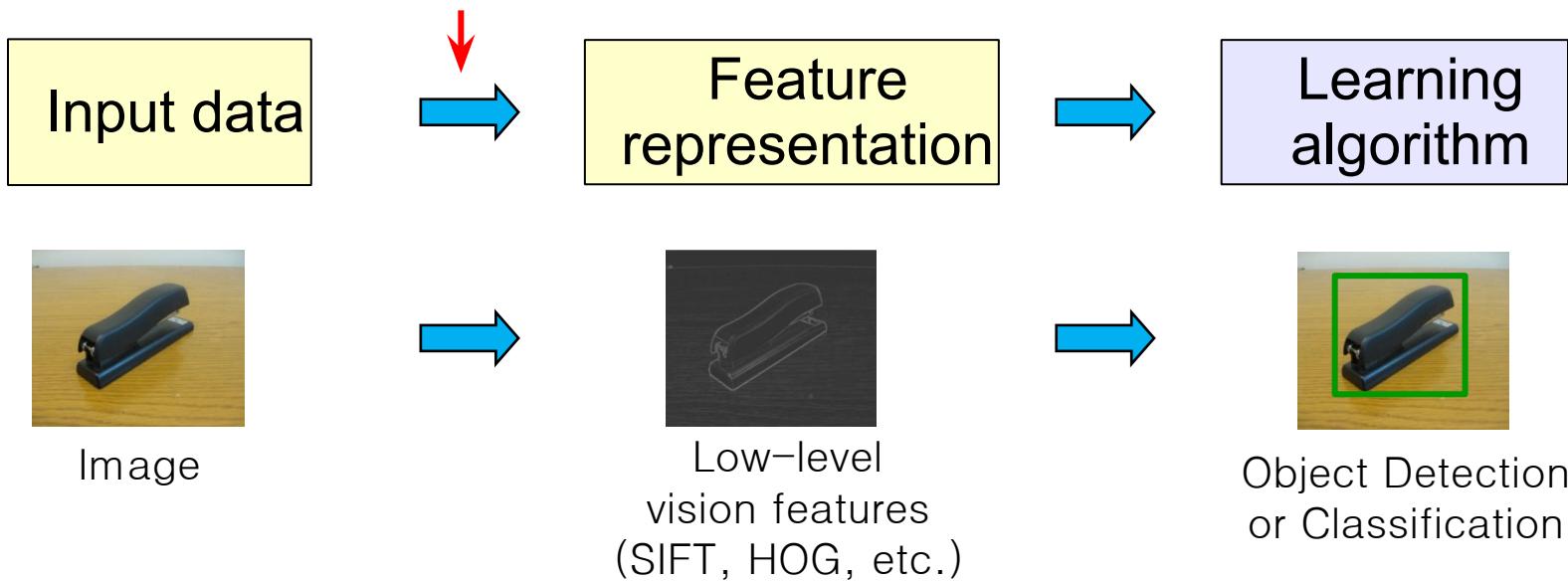


Feature representations

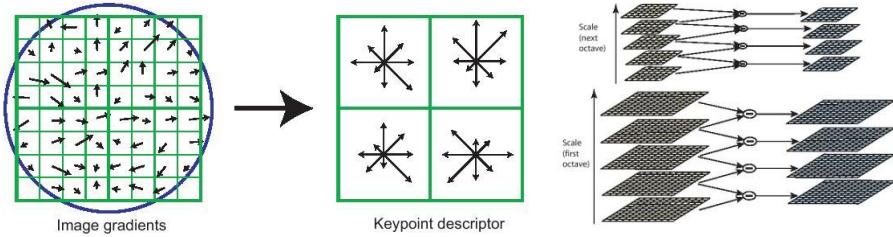


How is computer perception done?

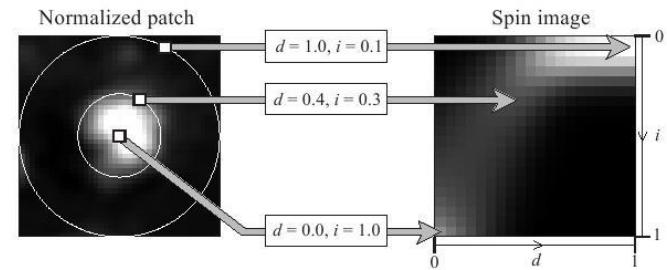
State-of-the-art:
“hand-crafting”



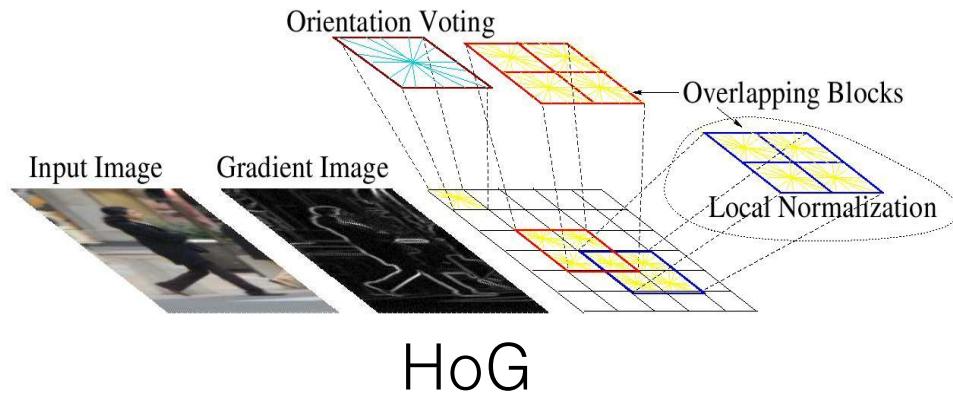
Computer Vision Features



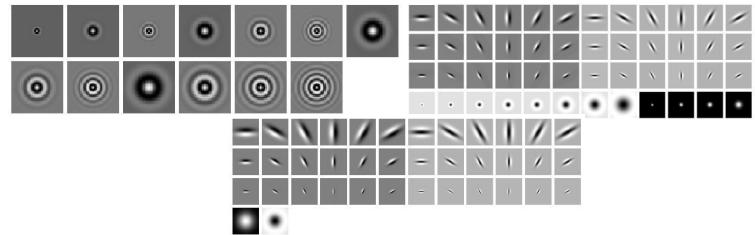
SIFT



Spin image



HoG



Textons

Issues with hand-crafted Features

(in Computer Vision, Speech Recognition, etc.)

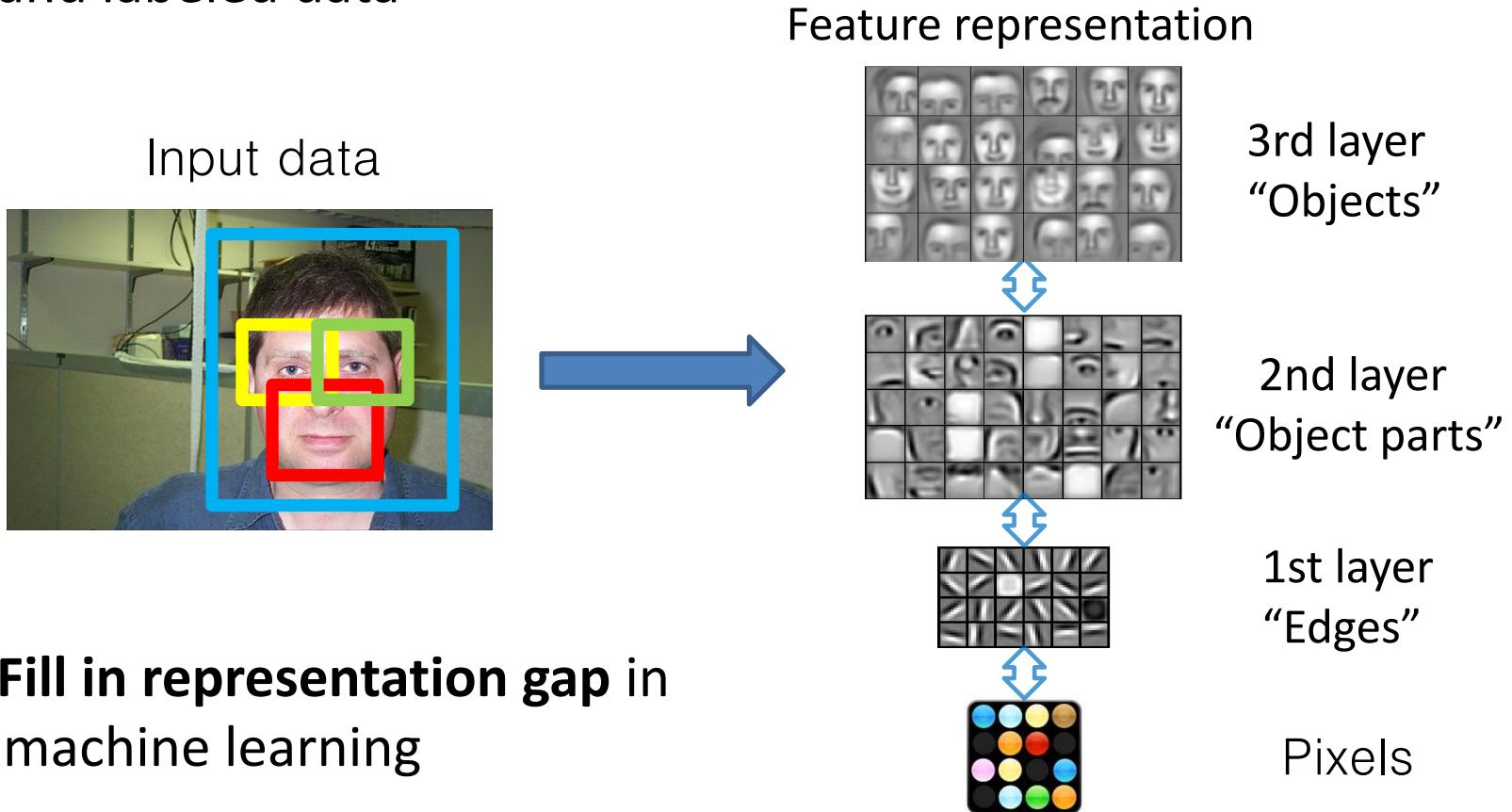
- Need expert knowledge
- Requires time-consuming hand-tuning
- (Arguably) a key limiting factor in advancing the state-of-the-art

Learning Feature Representations

- Key idea of Deep Learning:
 - Learn multiple levels of representation of increasing complexity/abstraction.
 - The representations can be learned in both **supervised** and/or **unsupervised** settings.
 - These features can be used for downstream tasks.

Example: Learning Feature Hierarchy

1. Efficiently learn **useful attributes (features)** from unlabeled and labeled data



2. **Fill in representation gap** in machine learning

Taxonomy of machine learning methods

Supervised

- Support Vector Machine
- Logistic Regression
- Perceptron
- Deep Neural Network
- Convolutional Neural Network*
- Recurrent Neural Network*

Shallow

- Denoising Autoencoder
- Restricted Boltzmann machine*
- Sparse coding*

Deep

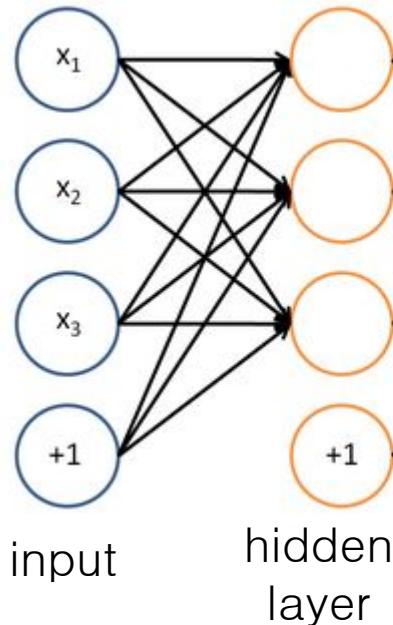
- Variational Autoencoder*
- Generative Adversarial Network
- Transformers*
- Diffusion Models*
- Deep Belief Network, Deep Boltzmann

Unsupervised

* both supervised and unsupervised versions exist

Neural network

- Neural network: similar to running several logistic regressions at the same time
- If we feed a vector of inputs through a bunch of logistic regression functions, then we get a vector of outputs

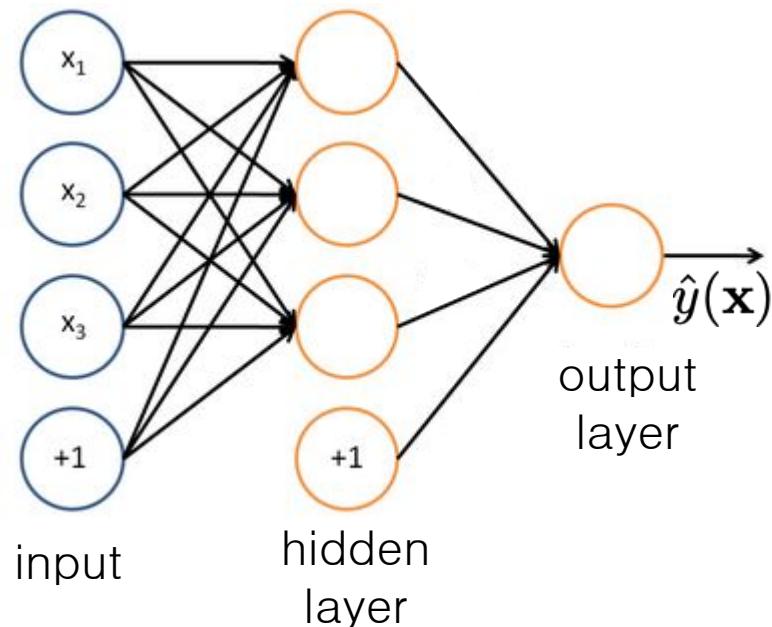


But we don't have to decide ahead of time what variables these logistic regressions are trying to predict!

Slide Credit: Yoshua Bengio

Neural network

- ... which we can feed into another logistic regression function



and it is the training criterion that will decide what those intermediate binary target variables should be, so as to make a good job of predicting the targets for the next layer, etc.

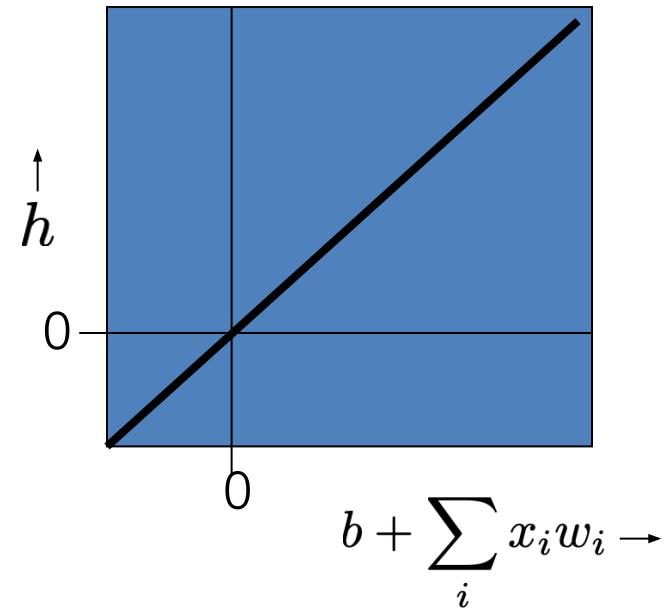
Slide Credit: Yoshua Bengio

Types of Neurons: Linear Neurons

- These are simple but limited in terms of representation power
 - e.g., composition of linear layers is still a linear function
 - If we can make them learn we **may** get insight into more complicated neurons.

$$h = b + \sum_i x_i w_i$$

bias i^{th} input
↓ ↓
output
↑
index over
input connections
weight on
 j^{th} input



Slide Credit: Geoff Hinton

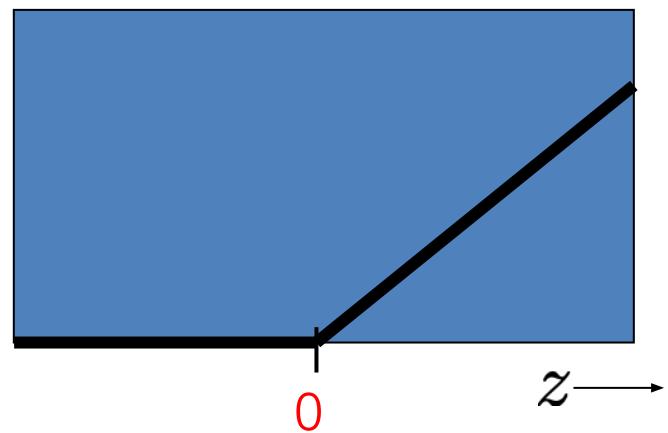
Rectified Linear (linear threshold) Neurons

- They compute a **linear** weighted sum of their inputs.
- The output is a **non-linear** function of the total input.

$$z = b + \sum_i x_i w_i$$

$$h = \begin{cases} z & \text{if } z > 0 \\ 0 & \text{otherwise} \end{cases}$$

h

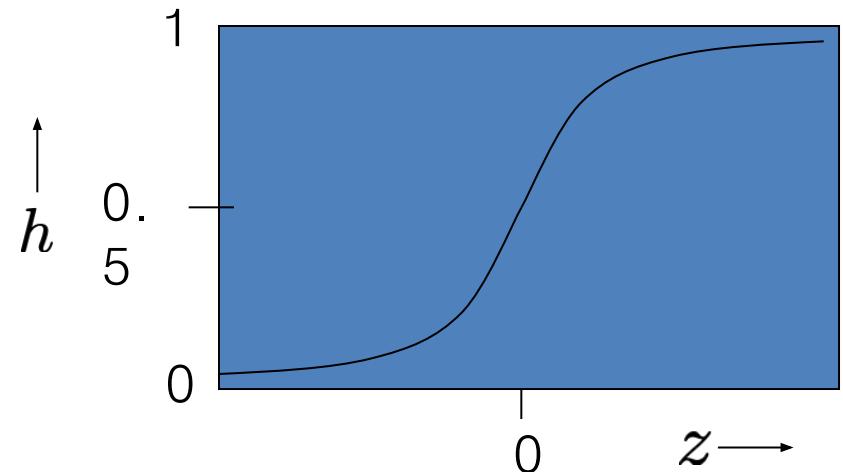


Sigmoid (logistic) neurons

- These give a real-valued output that is a smooth and bounded function of their total input.
 - They have nice derivatives which make learning easy

$$z = b + \sum_i x_i w_i$$

$$h = \frac{e^z}{1 + e^z} = \frac{1}{1 + e^{-z}}$$



Tanh neurons

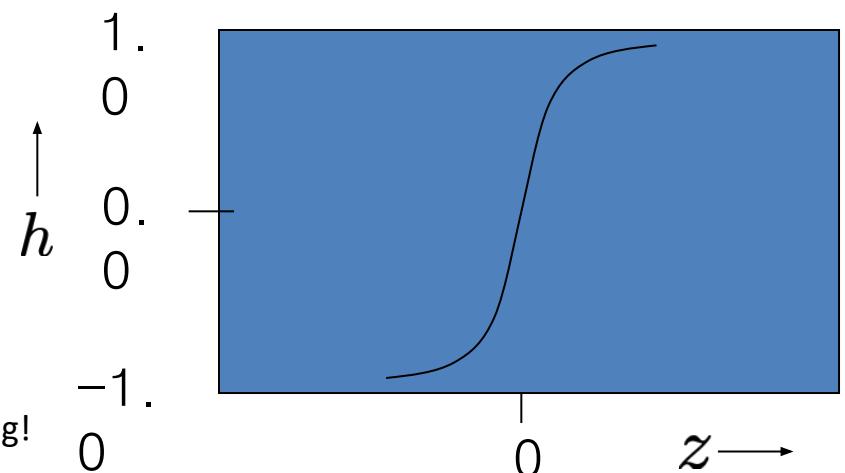
- These give a real-valued output that is a smooth and bounded function of their total input. Output range: (-1, 1)
 - larger gradient than Sigmoid

$$z = b + \sum_i x_i w_i$$

$$h = \tanh(z) = \frac{e^z - e^{-z}}{e^z + e^{-z}}$$

Note: tanh and sigmoid is equivalent after shifting and scaling!

$$\sigma(z) = \frac{1}{2} + \frac{1}{2} \tanh\left(\frac{z}{2}\right) \quad \text{or} \quad \tanh(z) = 2\sigma(2z) - 1$$



Softmax neurons

- These give a real-valued output that is a smooth and bounded function of their total input.
 - The outputs sum up to 1 (useful for classification problems)
 - They have nice derivatives which make learning easy

$$z_k = b^k + \sum_i x_i w_i^k$$

\mathbf{w}^k is the weight vector for the k-th output
 b^k is the bias for the k-th output

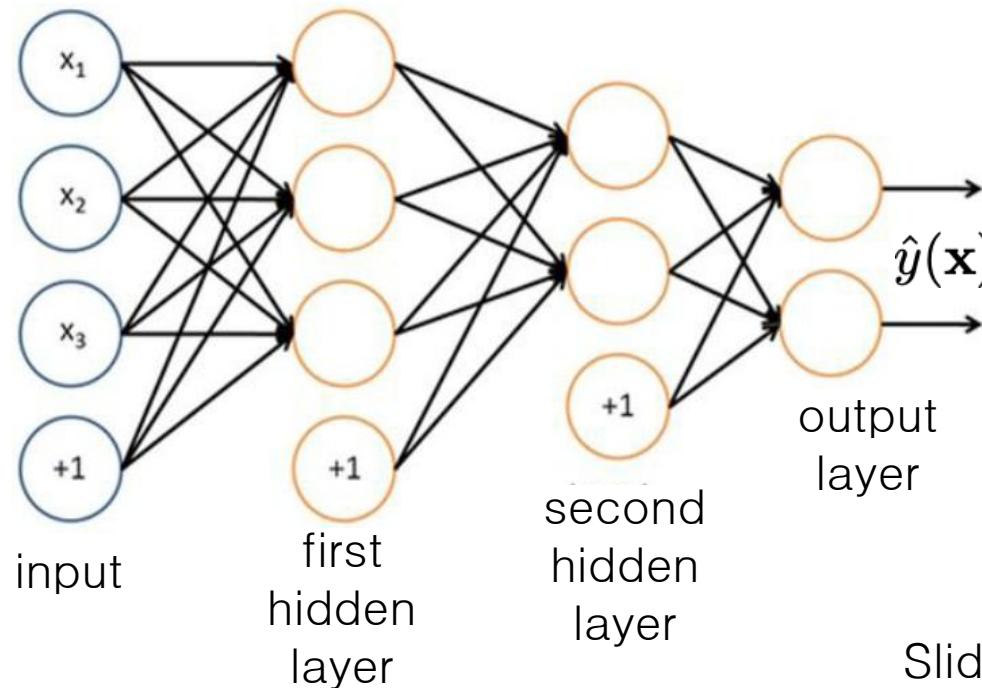
$$h_j = \frac{e^{z_j}}{\sum_k e^{z_k}}$$

Recall:

This softmax function is a generalization of logistic (sigmoid) function.

Multilayer neural networks

- We can construct a multilayer neural network by defining the network connectivity and (nonlinear or linear) activation functions.
 - Sigmoid nonlinearity for hidden layers
 - Softmax for the output layer



Training Neural Network

- Repeat until convergence

(\mathbf{x}, \mathbf{y}) : Sample an example (or a mini-batch) from data

$\hat{\mathbf{y}} \leftarrow f(\mathbf{x}; \theta)$: Forward propagation

Compute $\mathcal{L}(\mathbf{y}, \hat{\mathbf{y}})$

$\nabla_{\theta} \mathcal{L}$: Backward propagation

$\theta \leftarrow \theta - \alpha \nabla_{\theta} \mathcal{L}$: Update weights using (stochastic) gradient descent

Overview of backpropagation

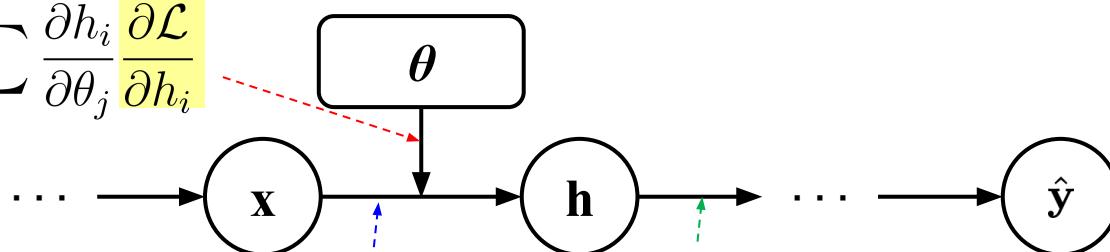
- Recall: Deep Neural Network represents a complex function with nested, composite functions (represented by layer-wise operation and nonlinearity, etc.)
- Q. How can we compute the gradient of the complex function?
- A. Backpropagation:
 - Computing gradient via **chain rule** for compositional function
 - The chain rule can be expressed as a **local computation**
 - Think about it as a **computational graph**

Backpropagation

- Denote $\mathbf{x} \in \mathbb{R}^D$, $\mathbf{h} \in \mathbb{R}^N$, $\theta \in \mathbb{R}^M$ as the input, output and parameter of a layer.
- It is non-trivial to derive the gradient of loss w.r.t. parameters in intermediate layers, but we can derive a recursion rule for the gradient.

“gradient w.r.t. parameters”
(to be used for SGD update)

$$\frac{\partial \mathcal{L}}{\partial \theta_j} = \sum_i \frac{\partial h_i}{\partial \theta_j} \frac{\partial \mathcal{L}}{\partial h_i}$$



$$\frac{\partial \mathcal{L}}{\partial x_k} = \sum_i \frac{\partial h_i}{\partial x_k} \frac{\partial \mathcal{L}}{\partial h_i}$$

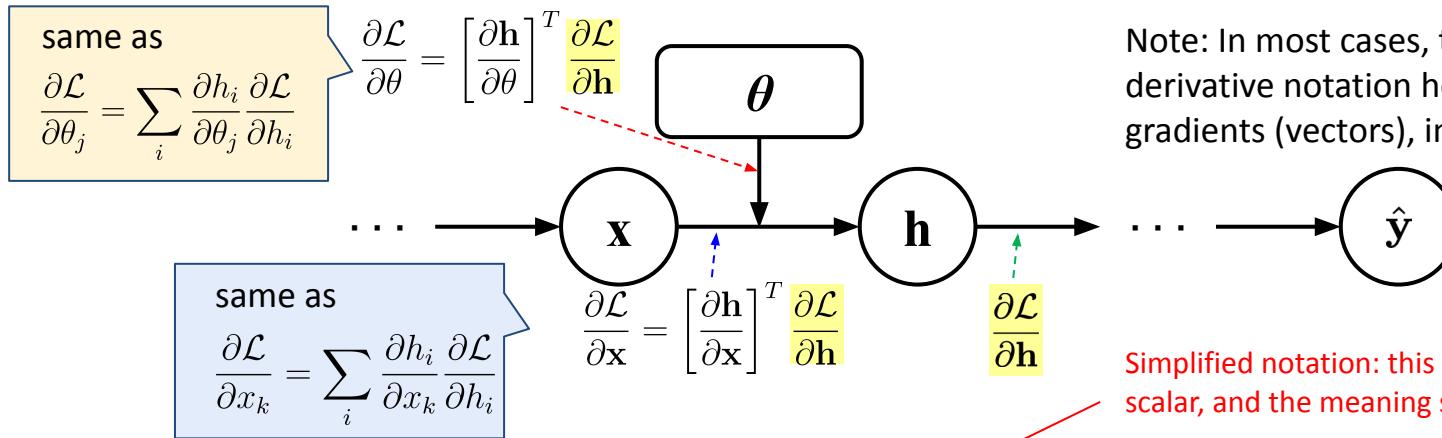
$$\nabla_{\mathbf{h}} \mathcal{L} = \left[\frac{\partial \mathcal{L}}{\partial h_1}, \dots, \frac{\partial \mathcal{L}}{\partial h_N} \right]^T$$

“gradient w.r.t. input” (to be propagated
to lower layers in backprop recursion)

“gradient w.r.t. hidden layer above” (given)

Backpropagation: vectorized formula

- Denote $\mathbf{x} \in \mathbb{R}^D$, $\mathbf{h} \in \mathbb{R}^N$, $\theta \in \mathbb{R}^M$ as the input, output and parameters
- It is non-trivial to derive the gradient of loss w.r.t. parameters in intermediate layers, but we can derive a recursion rule for the gradient.



Note: In most cases, the short-hand partial derivative notation here is Jacobian (matrices) or gradients (vectors), instead of scalars.

Simplified notation: this denotes a vector or matrix, not a scalar, and the meaning should be clear from the context.

Note: $\frac{\partial \mathcal{L}}{\partial \mathbf{h}} = \nabla_{\mathbf{h}} \mathcal{L}$: $N \times 1$ vector (gradient vector)

$\frac{\partial \mathbf{h}}{\partial \theta} = \nabla_{\theta} \mathbf{h}$: $N \times M$ matrix (Jacobian matrix); i.e. $\left[\frac{\partial \mathbf{h}}{\partial \theta} \right]_{i,j} = \frac{\partial h_i}{\partial \theta_j}$

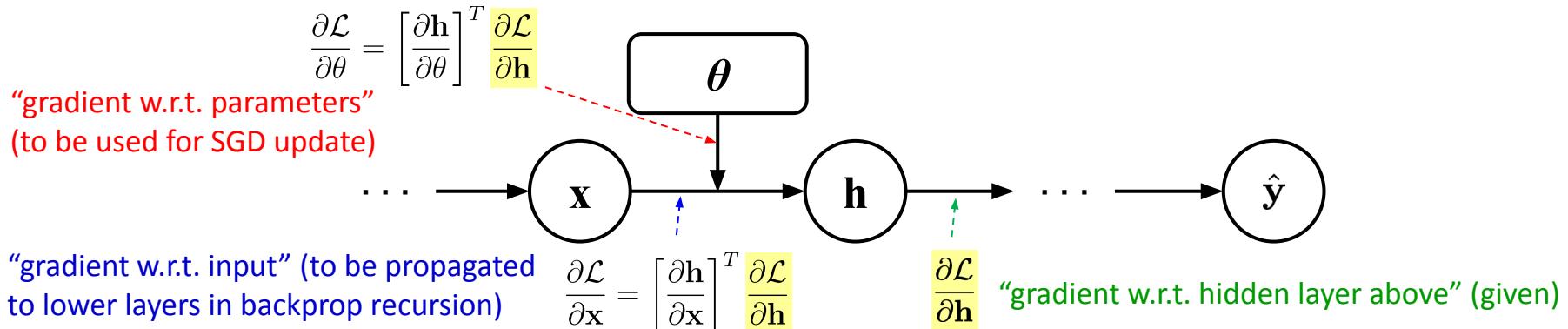
$\frac{\partial \mathcal{L}}{\partial \theta} = \nabla_{\theta} \mathcal{L}$: $M \times 1$ vector (gradient vector)

$\frac{\partial \mathbf{h}}{\partial \mathbf{x}} = \nabla_{\mathbf{x}} \mathbf{h}$: $N \times D$ matrix (Jacobian matrix); i.e. $\left[\frac{\partial \mathbf{h}}{\partial \mathbf{x}} \right]_{i,j} = \frac{\partial h_i}{\partial x_j}$

$\frac{\partial \mathcal{L}}{\partial \mathbf{x}} = \nabla_{\mathbf{x}} \mathcal{L}$: $D \times 1$ vector (gradient vector)

Backpropagation

- Denote x, h, θ is the input, output and parameter of a layer.
- It is non-trivial to derive the gradient of loss w.r.t. parameters in intermediate layers, but we can derive a recursion rule for the gradient.



- Assuming that $\frac{\partial \mathcal{L}}{\partial h}$ is given, use the **chain rule** to compute the gradients.



- Repeat recursion backwards (until reaching the bottom layers).

Backpropagation: Examples (NN with 1-hidden layer for regression)

Forward Propagation

- Example: a network with 1 hidden layer

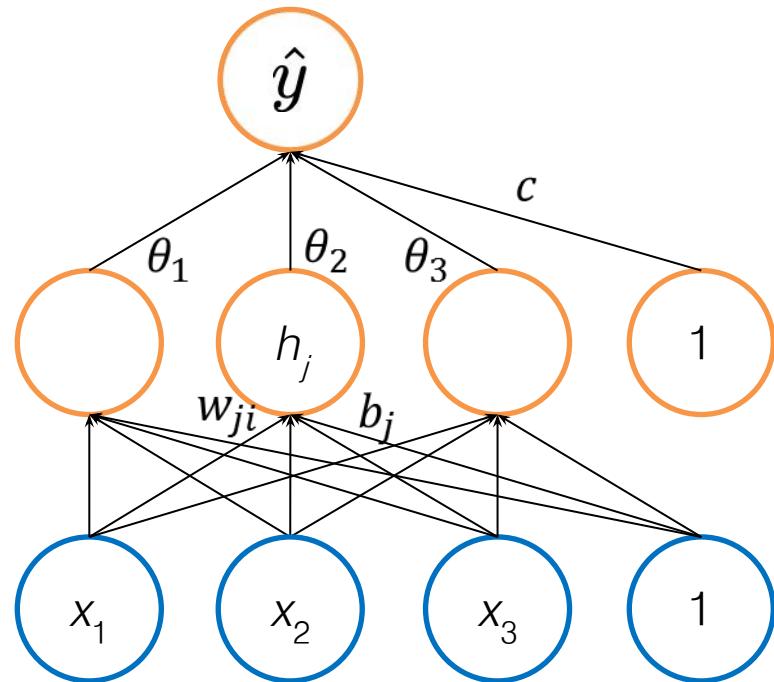
- Input: \mathbf{x}
- Output: \hat{y}
- Target: y
- Loss function: square error $(\hat{y} - y)^2$

Hidden
layer

$$h_j = f\left(\sum_i w_{ji}x_i + b_j\right)$$

Output

$$\hat{y} = \sum_j \theta_j h_j + c$$



Forward Propagation

- Example: a network with 1 hidden layer

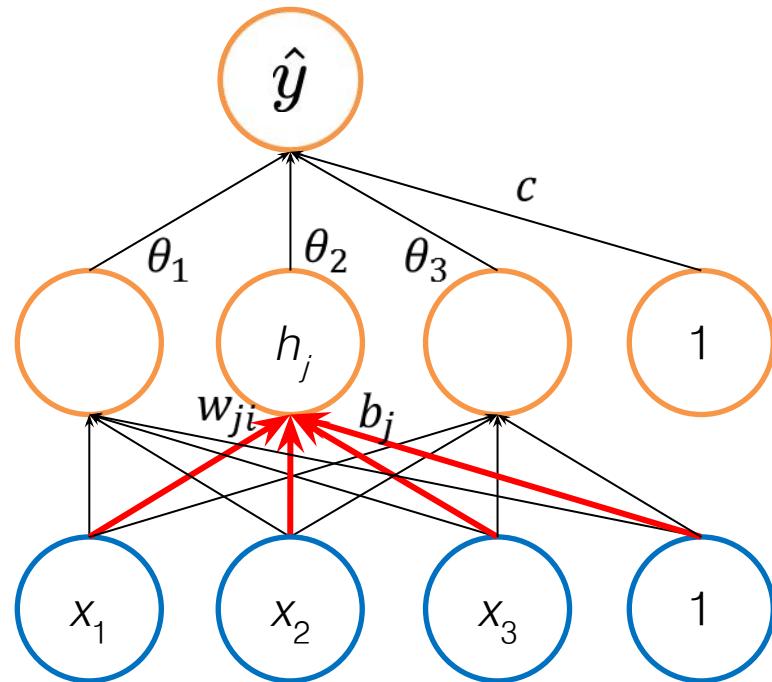
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Forward Propagation

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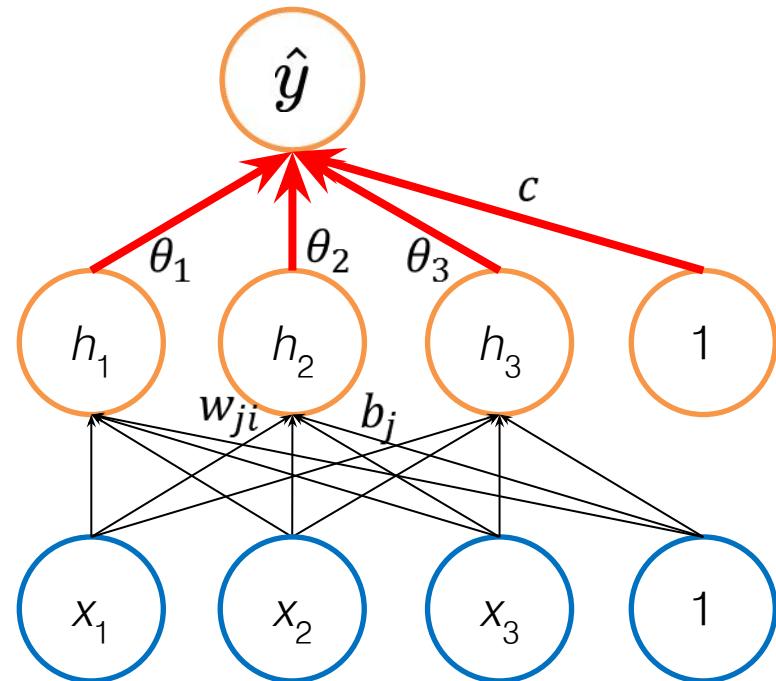
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Hidden
layer

$$h_j = f\left(\sum_i w_{ji}x_i + b_j\right)$$

Output

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Backpropagation

$$h_j = f\left(\sum_i w_{ji}x_i + b_j\right), \forall j$$
$$\hat{y} = \sum_j \theta_j h_j + c$$

- Goal: Compute gradient w.r.t. parameters $\{W, b, \theta, c\}$ $\mathcal{L} = (\hat{y} - y)^2$
- Main idea: Apply a chain rule recursively!

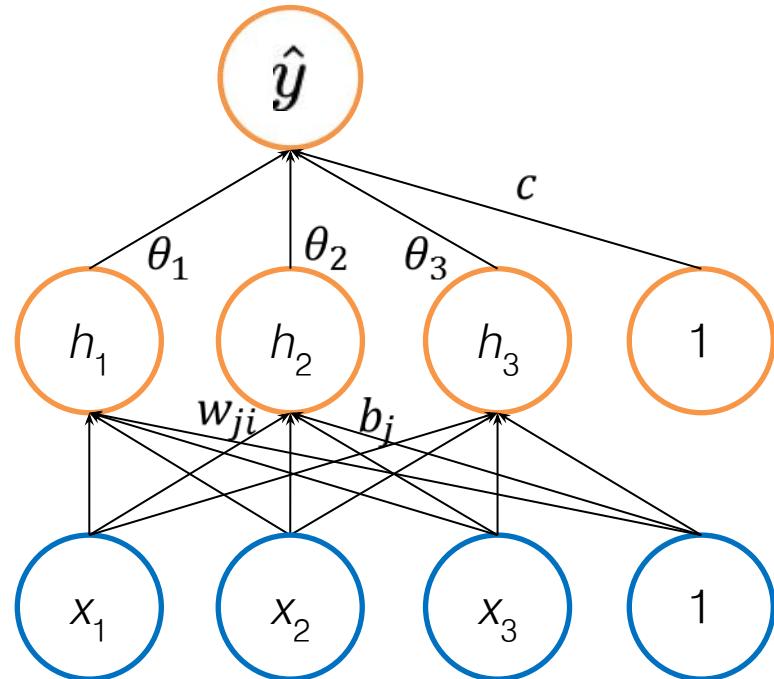
$$\frac{\partial \mathcal{L}}{\partial \hat{y}} = 2(\hat{y} - y)$$

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$$\frac{\partial \mathcal{L}}{\partial w_{ji}} = \frac{\partial h_j}{\partial w_{ji}} \frac{\partial \mathcal{L}}{\partial h_j} = f' x_i \frac{\partial \mathcal{L}}{\partial h_j}$$

where $f' = f'\left(\sum_i w_{ji}x_i + b_j\right)$

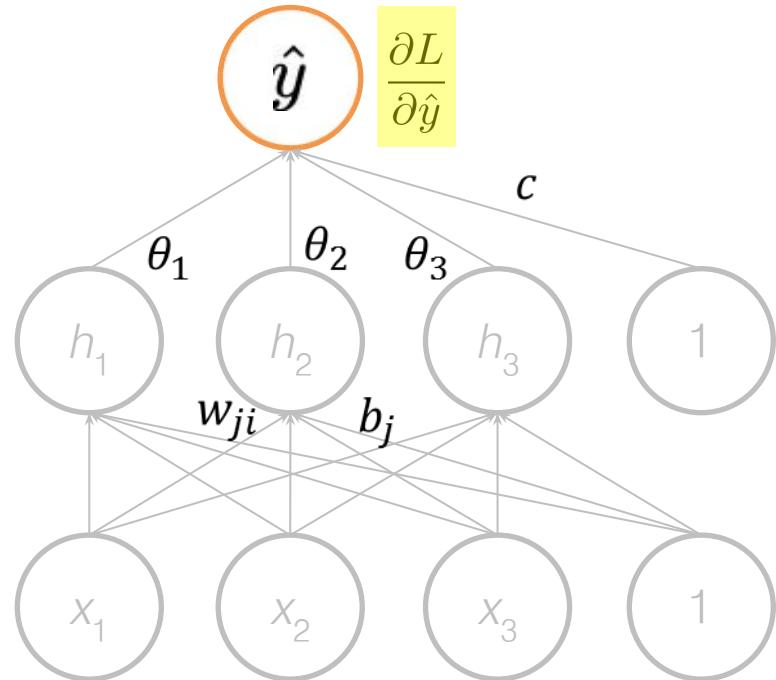


Backpropagation

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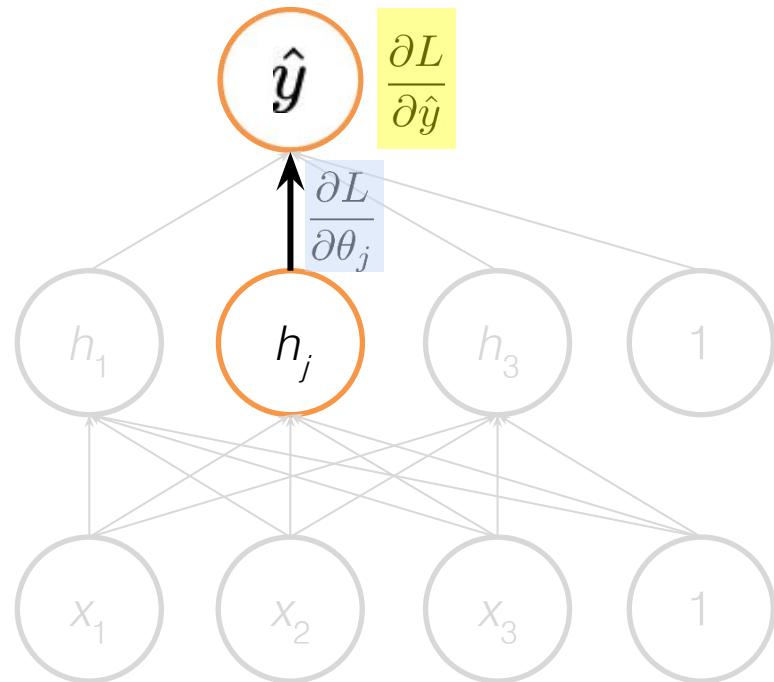
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Backpropagation

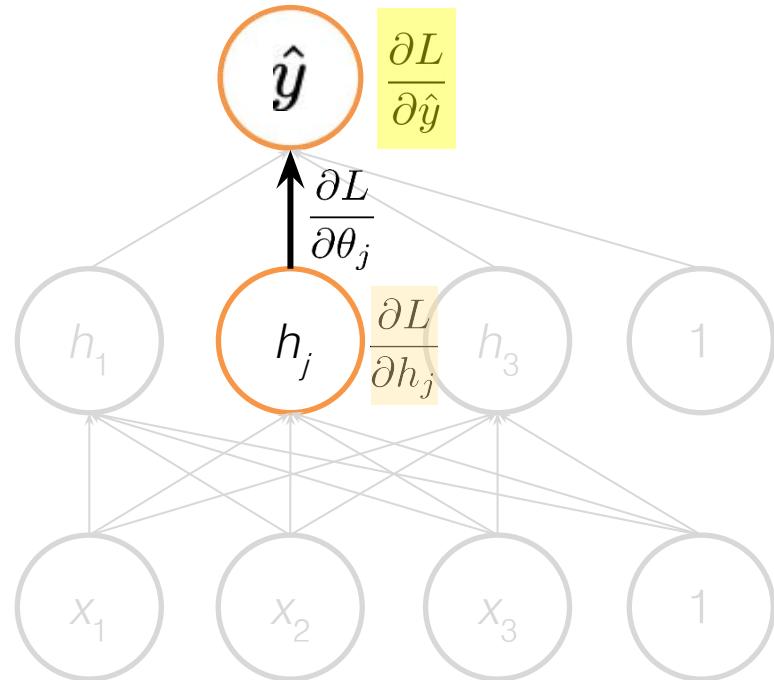
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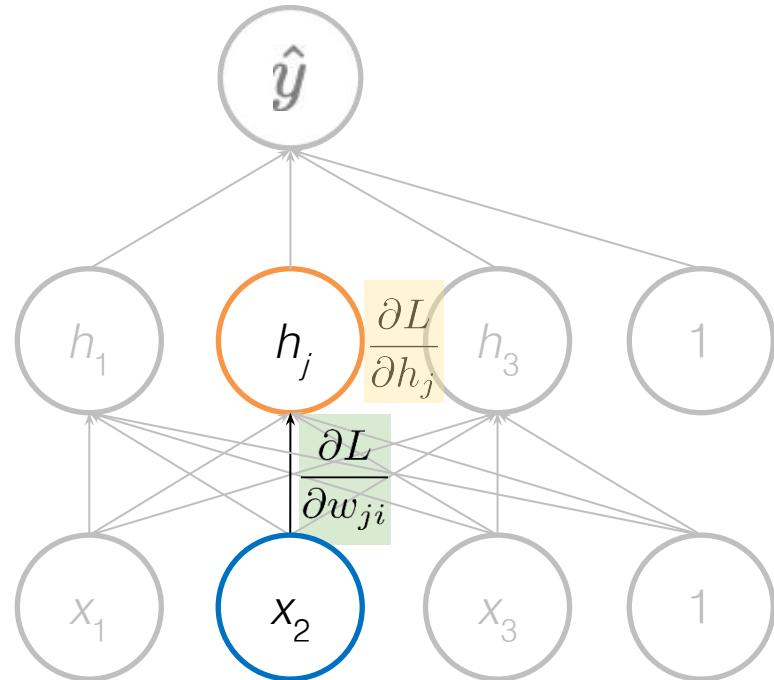
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Backpropagation: examples (NN with 2-hidden layer for regression)

Multilayer neural network

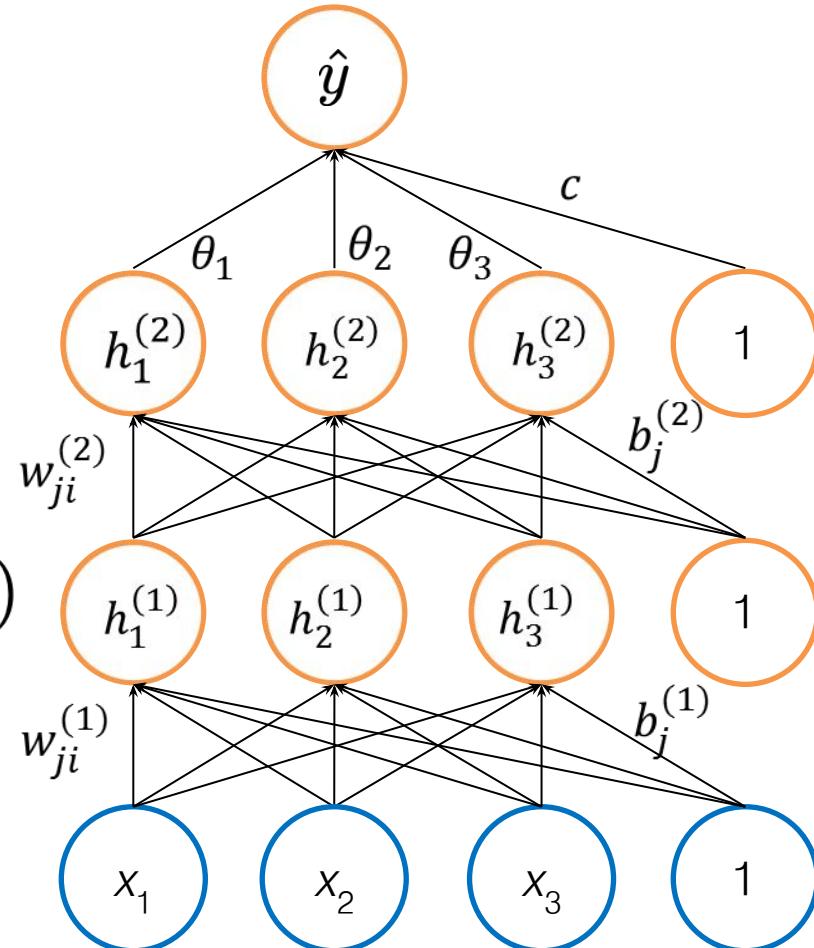
- Example: a network with 2 hidden layers

- Input: \mathbf{x}
- Output: \hat{y}
- Target: y
- Loss function: square error $(\hat{y} - y)^2$

First hidden layer $h_j^{(1)} = f(\sum_i w_{ji}^{(1)} x_i + b_j^{(1)})$

Second hidden layer $h_j^{(2)} = f(\sum_i w_{ji}^{(2)} h_i^{(1)} + b_j^{(2)})$

Output $\hat{y} = \sum_j \theta_j h_j^{(2)} + c$

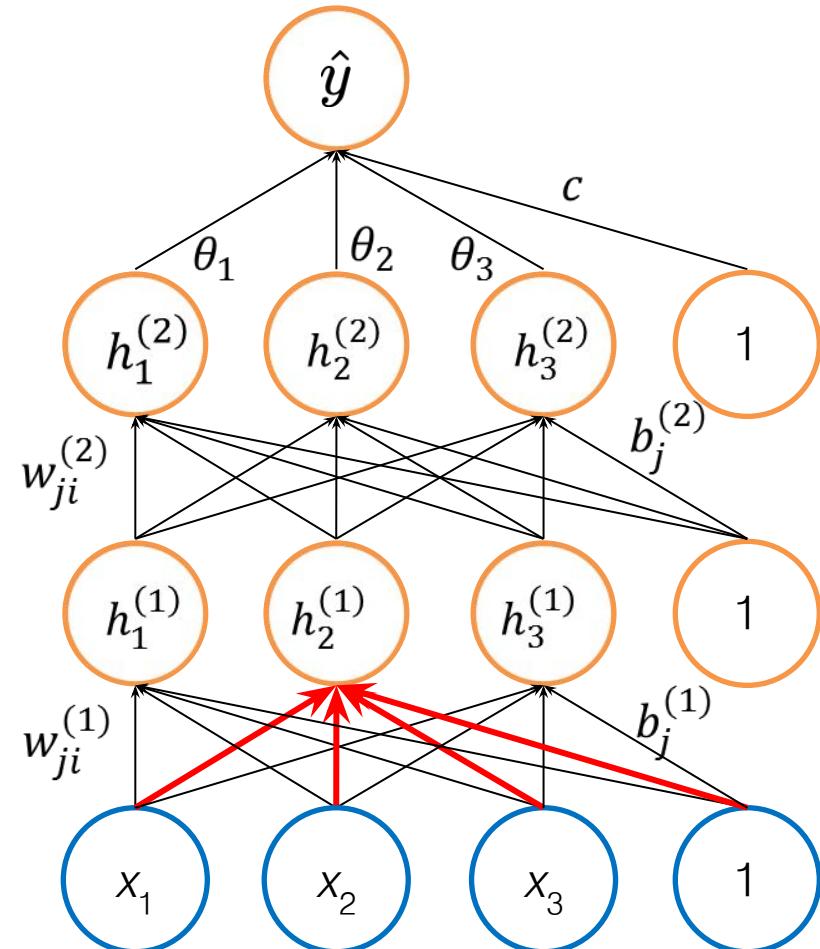


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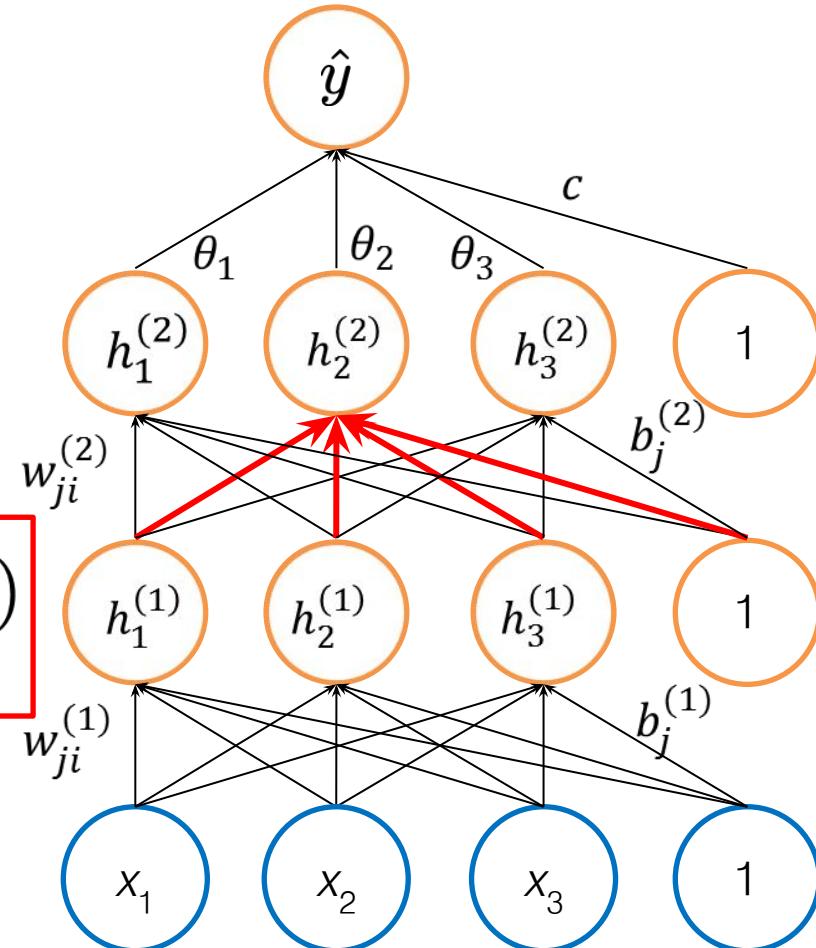
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Multilayer neural network

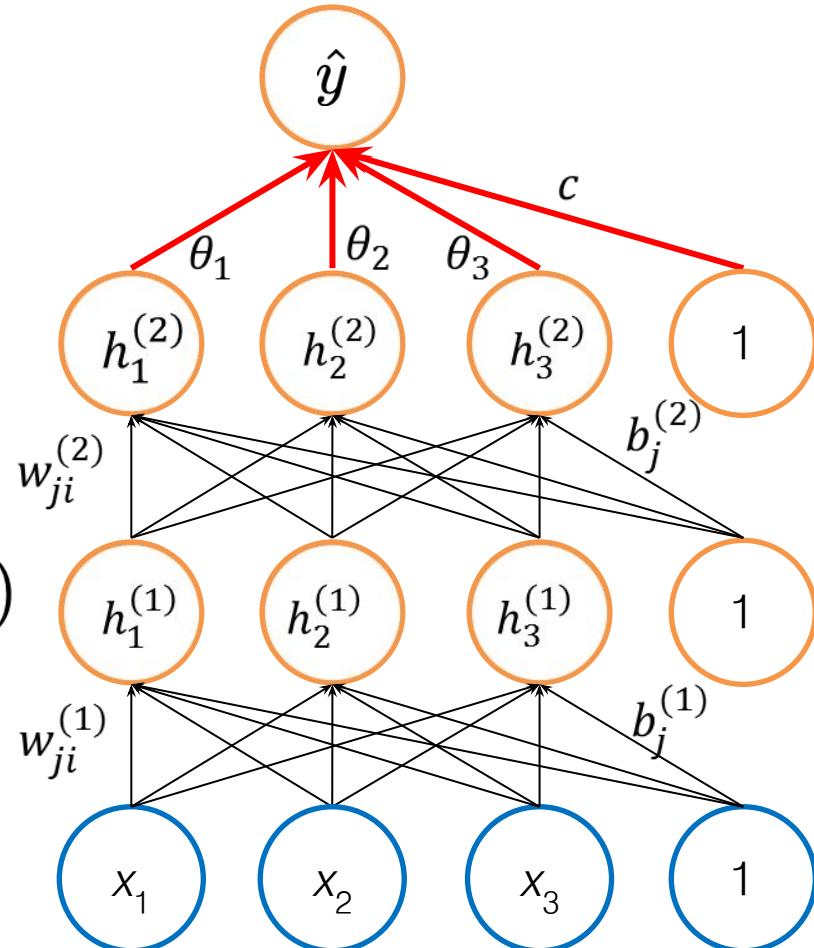
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Output $\hat{y} = \sum_j \theta_j h_j^{(2)} + c$



Backpropagation: Compute gradient w.r.t. parameters $\{W^{(1)}, W^{(2)}, b^{(1)}, b^{(2)}, \theta, c\}$

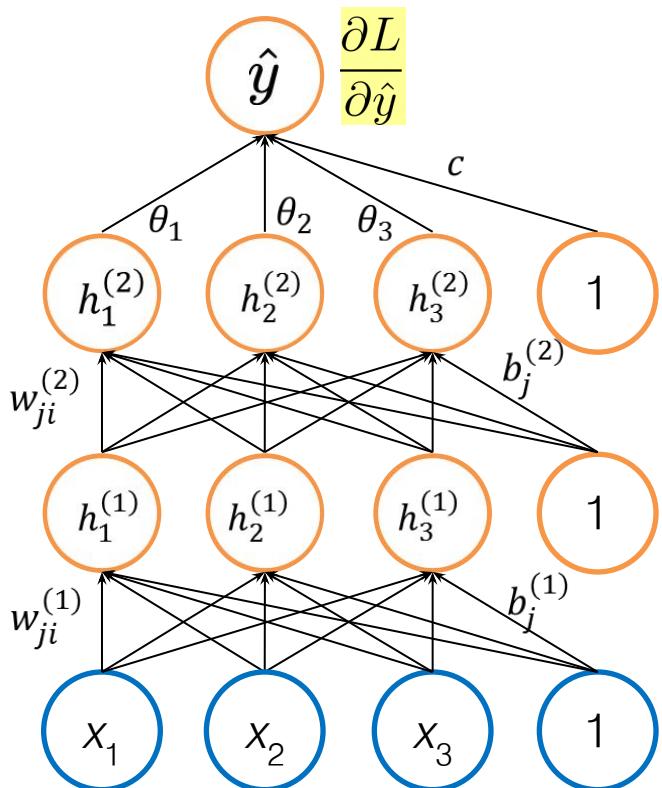
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$$\hat{y} = \sum_j \theta_j h_j^{(2)} + c$$

$$\mathcal{L} = (\hat{y} - y)^2$$



Backpropagation: Compute gradient w.r.t. parameters $\{W^{(1)}, W^{(2)}, b^{(1)}, b^{(2)}, \theta, c\}$

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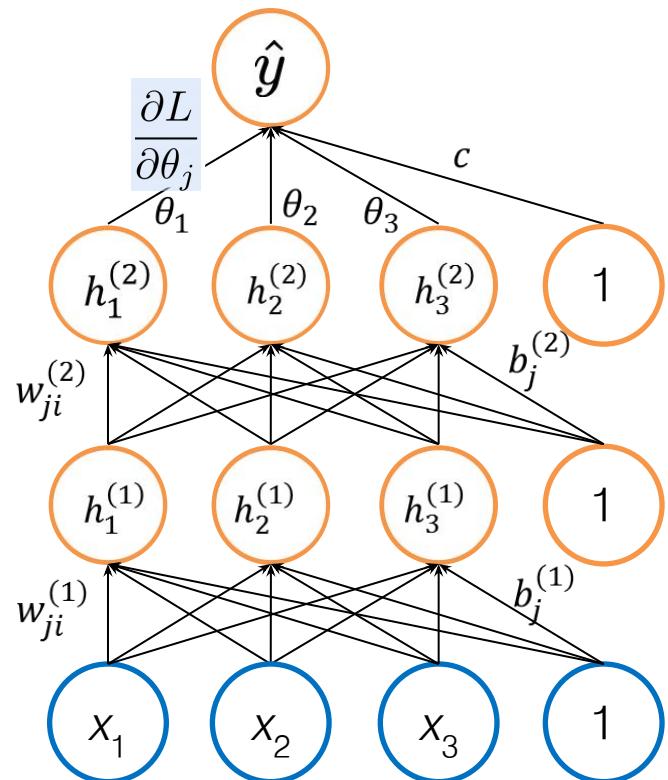
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Backpropagation: Compute gradient w.r.t. parameters $\{W^{(1)}, W^{(2)}, b^{(1)}, b^{(2)}, \theta, c\}$

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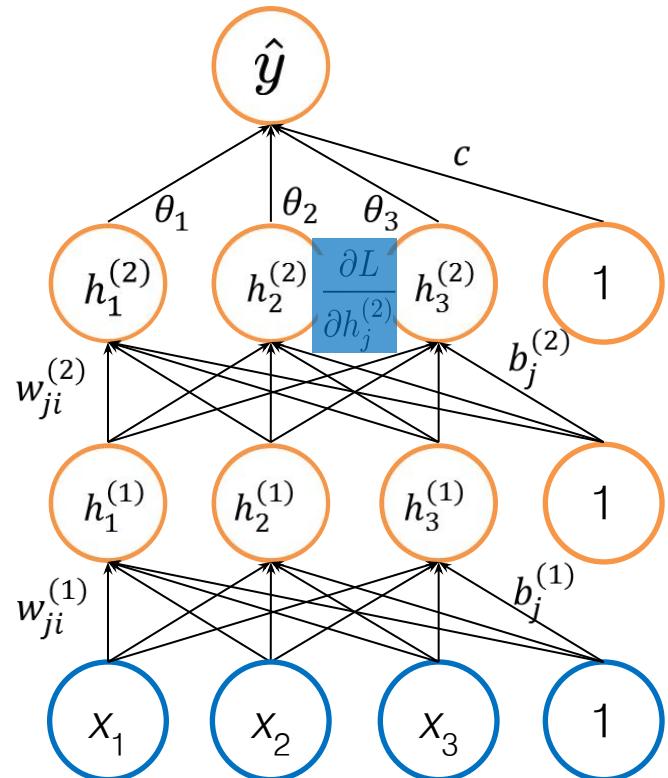
$$\frac{\partial \mathcal{L}}{\partial h_j^{(2)}} = \frac{\partial \hat{y}}{\partial h_j^{(2)}} \frac{\partial \mathcal{L}}{\partial \hat{y}} = \theta_j \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

$$h_j^{(1)} = f(\sum_i w_{ji}^{(1)} x_i + b_j^{(1)}), \forall j$$

$$h_j^{(2)} = f(\sum_i w_{ji}^{(2)} h_i^{(1)} + b_j^{(2)}), \forall j$$

$$\hat{y} = \sum_j \theta_j h_j^{(2)} + c$$

$$\mathcal{L} = (\hat{y} - y)^2$$



Backpropagation: Compute gradient w.r.t. parameters $\{W^{(1)}, W^{(2)}, b^{(1)}, b^{(2)}, \theta, c\}$

$$\frac{\partial \mathcal{L}}{\partial \hat{y}} = 2(\hat{y} - y)$$

$$\frac{\partial \mathcal{L}}{\partial \theta_j} = \frac{\partial \hat{y}}{\partial \theta_j} \frac{\partial \mathcal{L}}{\partial \hat{y}} = h_j^{(2)} \frac{\partial \mathcal{L}}{\partial \hat{y}}$$

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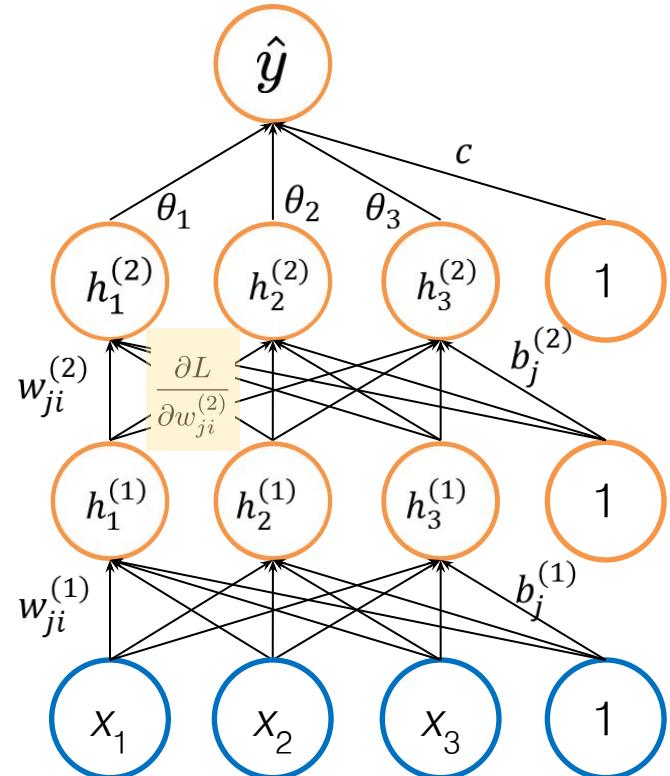
$$\frac{\partial \mathcal{L}}{\partial w_{ji}^{(2)}} = \frac{\partial h_j^{(2)}}{\partial w_{ji}^{(2)}} \frac{\partial \mathcal{L}}{\partial h_j^{(2)}} = f'(z_j^{(2)}) h_i^{(1)} \frac{\partial \mathcal{L}}{\partial h_j^{(2)}}$$

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Backpropagation: Compute gradient w.r.t. parameters $\{W^{(1)}, W^{(2)}, b^{(1)}, b^{(2)}, \theta, c\}$

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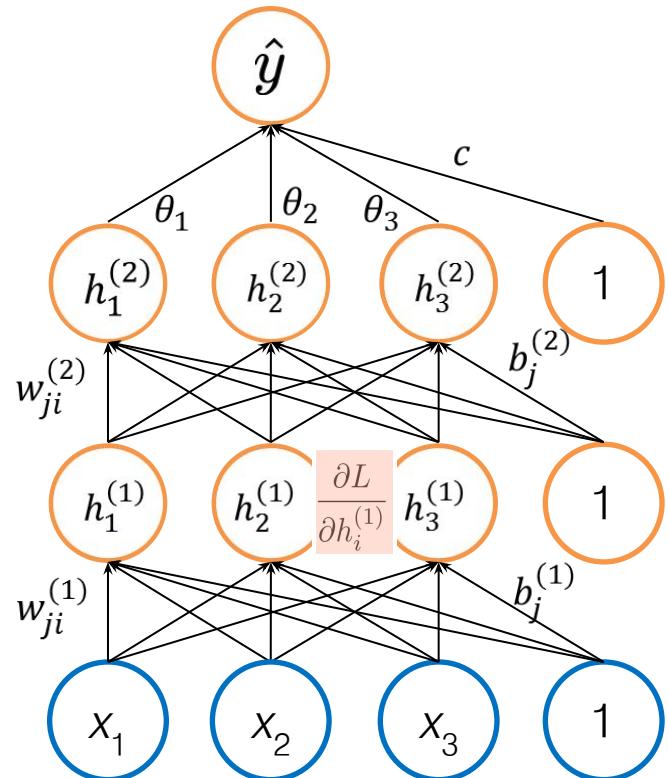
$$\frac{\partial \mathcal{L}}{\partial h_i^{(1)}} = \sum_j \frac{\partial h_j^{(2)}}{\partial h_i^{(1)}} \frac{\partial \mathcal{L}}{\partial h_j^{(2)}} = \sum_j f'(z_j^{(2)}) w_{ji}^{(2)} \frac{\partial \mathcal{L}}{\partial h_j^{(2)}}$$

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$$\frac{\partial \mathcal{L}}{\partial h_i^{(1)}} = \sum_j \frac{\partial h_j^{(2)}}{\partial h_i^{(1)}} \frac{\partial \mathcal{L}}{\partial h_j^{(2)}} = \sum_j f'(z_j^{(2)}) w_{ji}^{(2)} \frac{\partial \mathcal{L}}{\partial h_j^{(2)}}$$

$$\frac{\partial \mathcal{L}}{\partial w_{ik}^{(1)}} = \frac{\partial h_i^{(1)}}{\partial w_{ik}^{(1)}} \frac{\partial \mathcal{L}}{\partial h_i^{(1)}} = f'(z_i^{(1)}) x_k \frac{\partial \mathcal{L}}{\partial h_i^{(1)}}$$

where $z_j^{(2)} = \sum_i h_i^{(1)} w_{ji}^{(2)} + b_j^{(2)}$

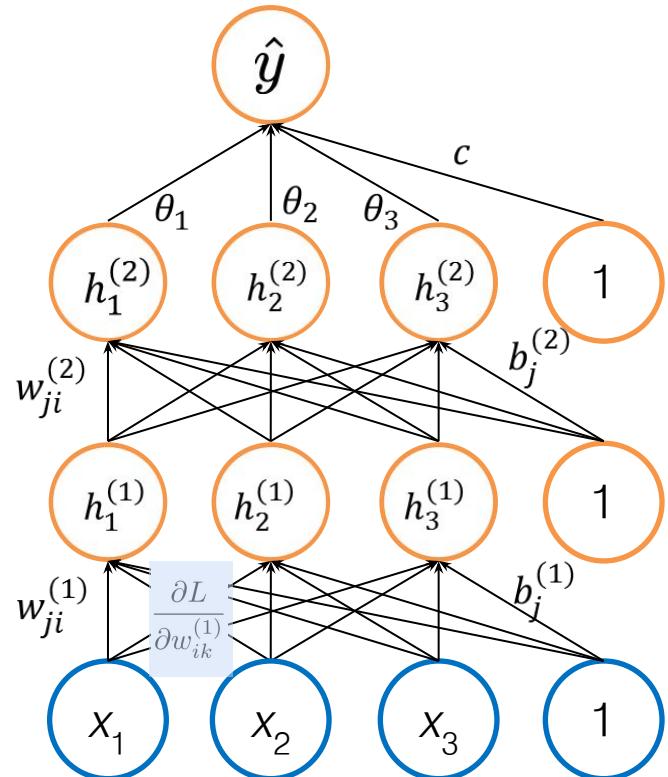
$$z_i^{(1)} = \sum_k x_k w_{ik}^{(1)} + b_i^{(1)}$$

$$h_j^{(1)} = f(\sum_i w_{ji}^{(1)} x_i + b_j^{(1)}), \forall j$$

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$$\mathcal{L} = (\hat{y} - y)^2$$



Backpropagation: examples
(NN with 1-hidden layer for classification)

Forward Propagation

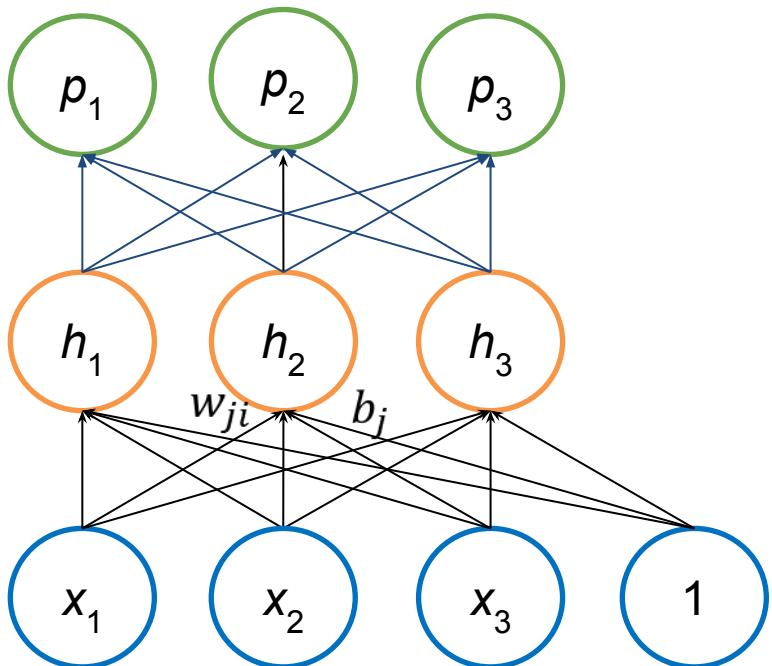
- Example: a network with 1 hidden layer

- Input: \mathbf{x}
- Output: \mathbf{p}
- Target: \mathbf{y} (one-hot vector)

- Loss function: cross entropy $-\sum_i y_i \log p_i$

Hidden layer $h_j = f\left(\sum_i w_{ji}x_i + b_j\right)$

Output $p_i = \frac{e^{h_i}}{\sum_k e^{h_k}}$



Forward Propagation

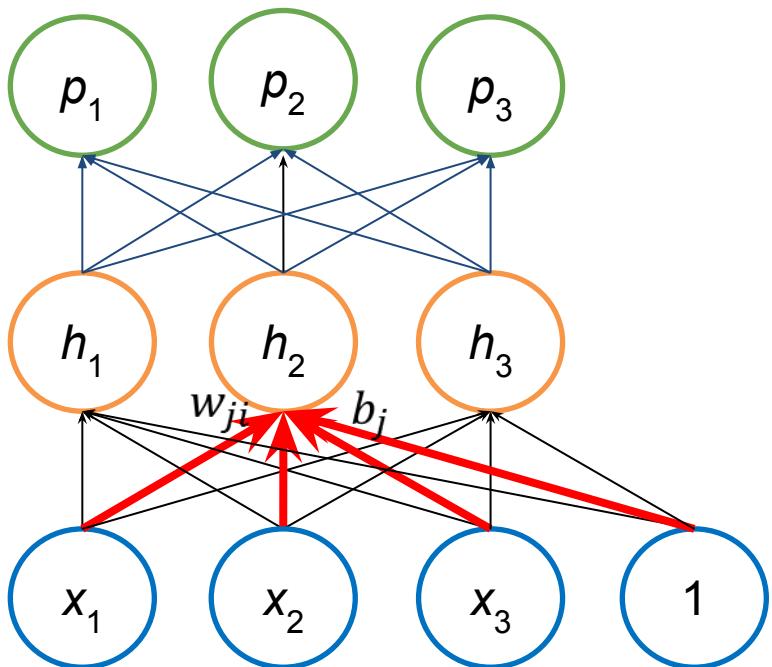
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Forward Propagation

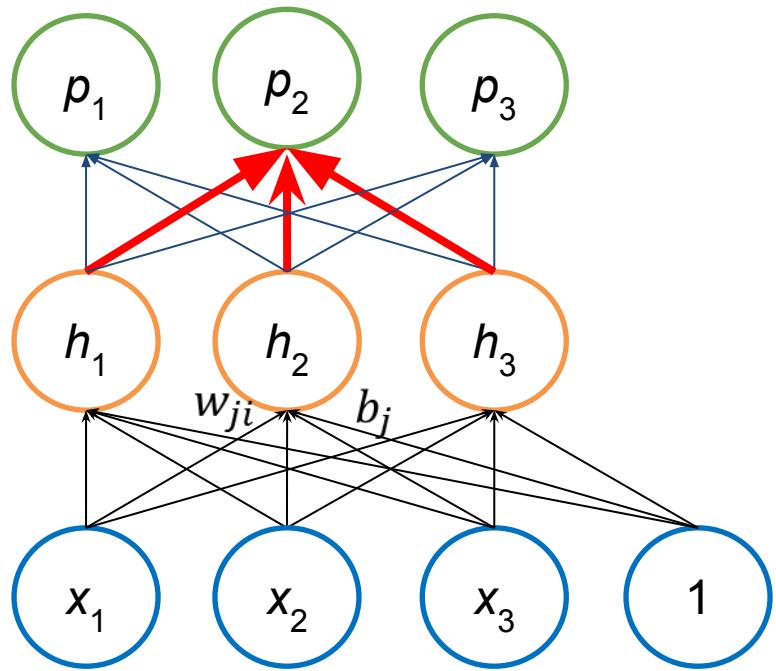
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- Output: \mathbf{p}
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- Loss function: cross entropy $-\sum_i y_i \log p_i$

Hidden layer $h_j = f\left(\sum_i w_{ji}x_i + b_j\right)$

Output $p_i = \frac{e^{h_i}}{\sum_k e^{h_k}}$



Backpropagation

- **Example: a network with 1 hidden layer**

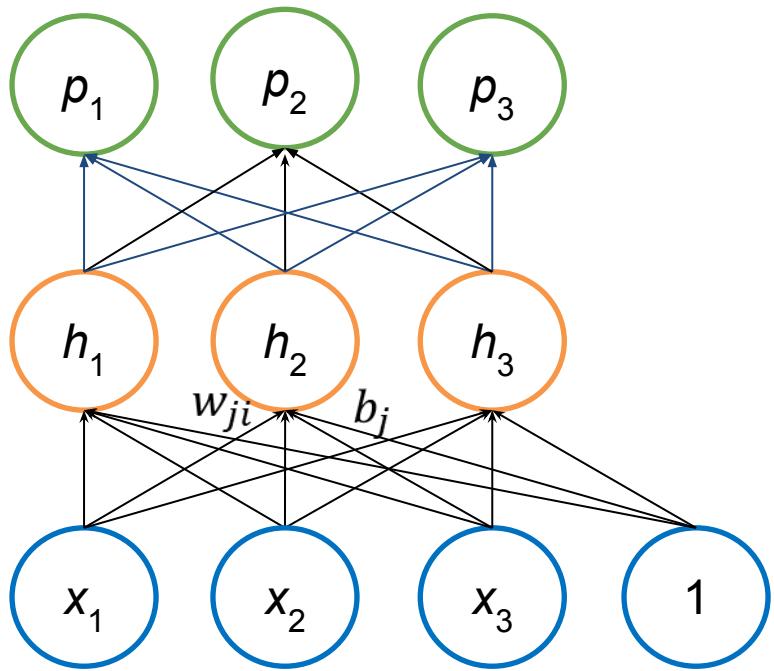
- Goal: Compute Gradients w.r.t parameters $\{W, b\}$
- Main Idea: Apply Chain Rule recursively

$$\begin{aligned}\mathcal{L} &= - \sum_i y_i \log p_i = - \sum_i y_i \log \frac{e^{h_i}}{\sum_k e^{h_k}} \\ &= - \sum_i y_i h_i + (\sum_i y_i) \log(\sum_k e^{h_k}) \\ &= \log(\sum_k e^{h_k}) - \sum_k y_k h_k\end{aligned}$$

$$\frac{\partial \mathcal{L}}{\partial h_j} = \frac{e^{h_j}}{\sum_k e^{h_k}} - y_j = p_j - y_j$$

$$\frac{\partial \mathcal{L}}{\partial w_{ji}} = \frac{\partial h_j}{\partial w_{ji}} \frac{\partial \mathcal{L}}{\partial h_j} = f' x_i \frac{\partial \mathcal{L}}{\partial h_j}$$

where $f' = f'(\sum_i w_{ji} x_i + b_j)$

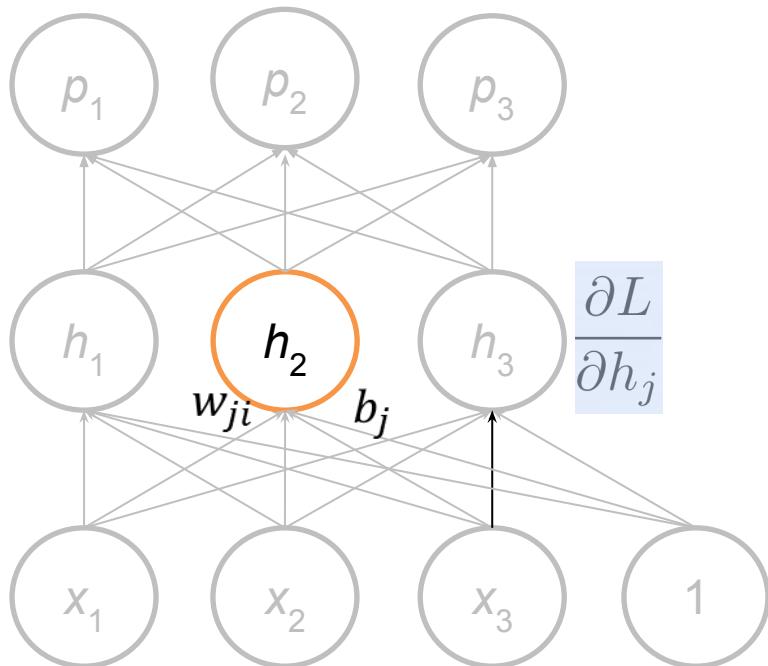


Backpropagation

- **Example: a network with 1 hidden layer**
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 - Main Idea: Apply Chain Rule recursively

$$\begin{aligned}\mathcal{L} &= - \sum_i y_i \log p_i = - \sum_i y_i \log \frac{e^{h_i}}{\sum_k e^{h_k}} \\ &= - \sum_i y_i h_i + (\sum_i y_i) \log(\sum_k e^{h_k}) \\ &= \log(\sum_k e^{h_k}) - \sum_k y_k h_k\end{aligned}$$

$$\frac{\partial \mathcal{L}}{\partial h_j} = \frac{e^{h_j}}{\sum_k e^{h_k}} - y_j = p_j - y_j$$



Backpropagation

- **Example: a network with 1 hidden layer**

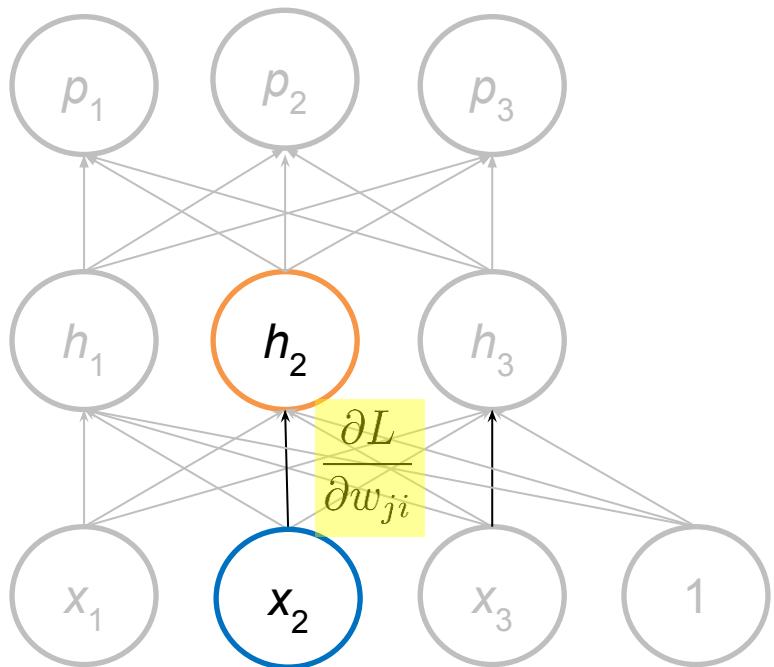
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$$\frac{\partial \mathcal{L}}{\partial w_{ji}} = \frac{\partial h_j}{\partial w_{ji}} \frac{\partial \mathcal{L}}{\partial h_j} = f' x_i \frac{\partial \mathcal{L}}{\partial h_j}$$

where $f' = f'(\sum_i w_{ji} x_i + b_j)$

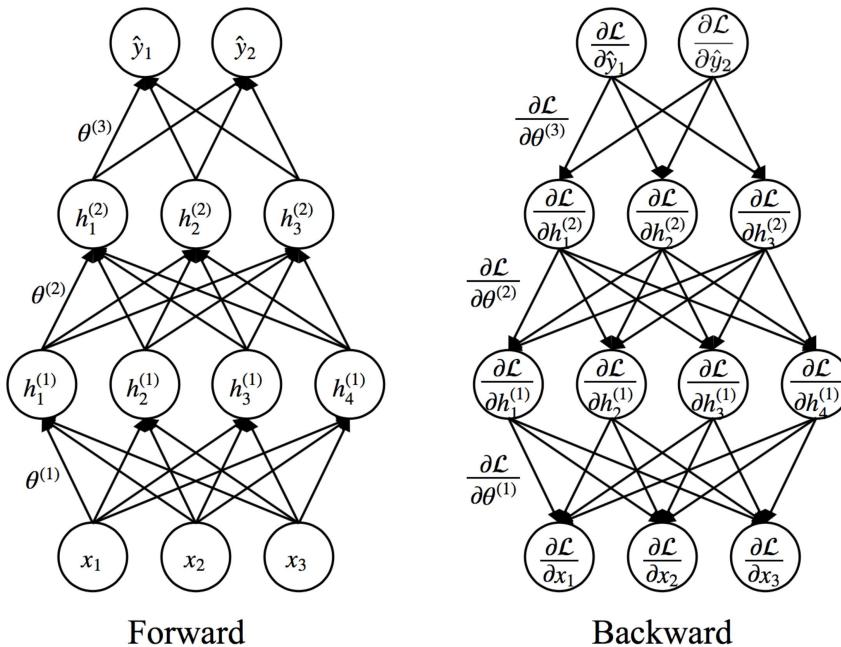


Deep Neural Networks

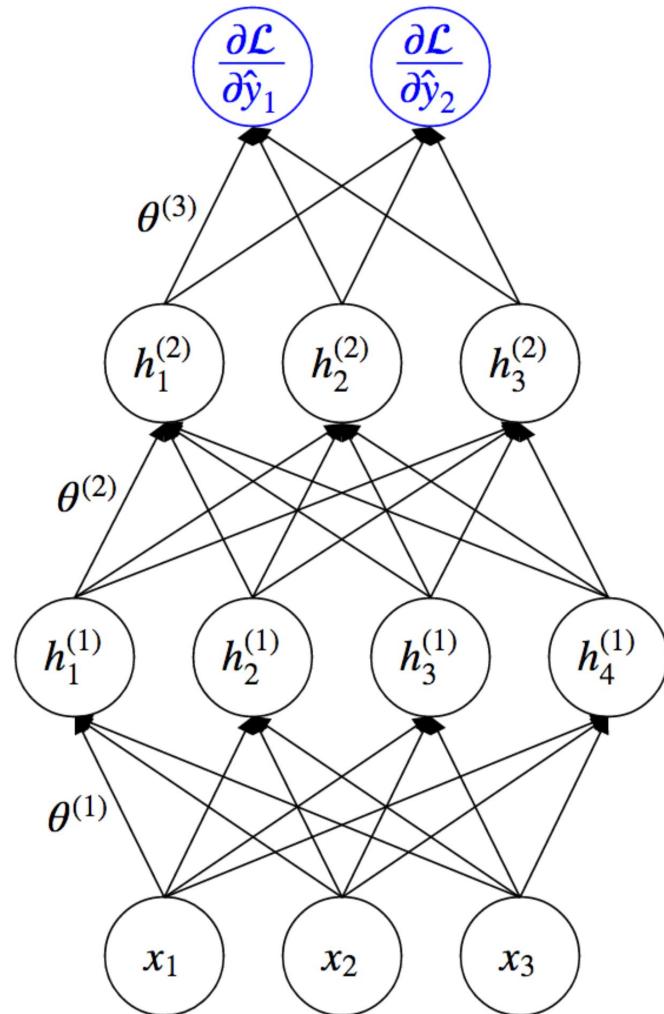
- Construction is straightforward: recursively stacking the blocks of layers
- Computing gradient is straightforward (via back propagation)
 - For general formula, see Bishop's book.

Backpropagation for deep neural nets

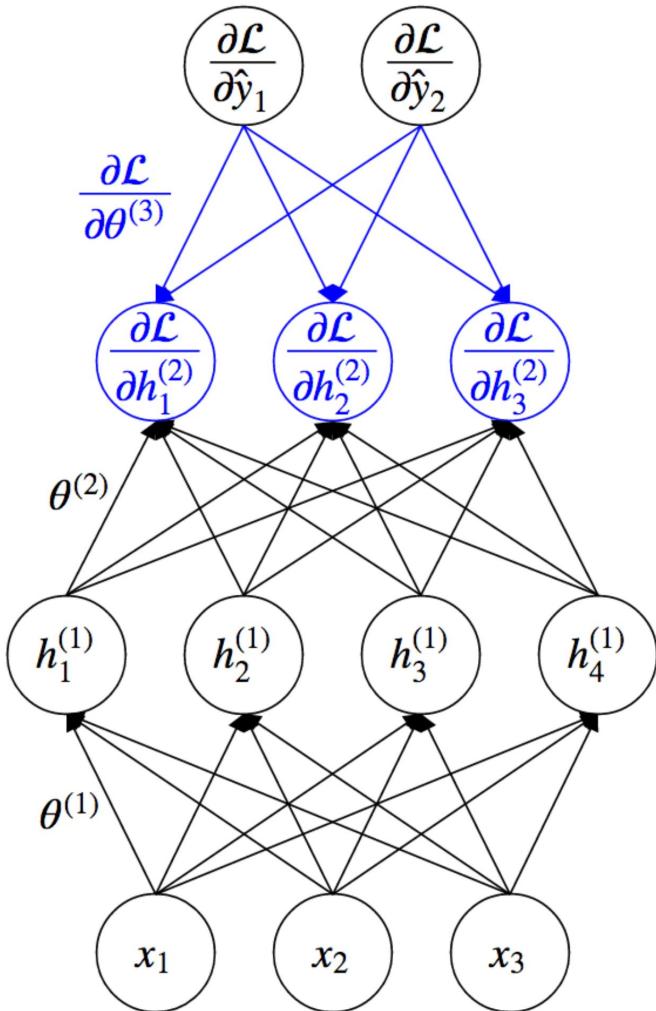
- Computing gradient via **chain rule** for compositional function
- The chain rule can be expressed as a **local computation**
- Think of it as a **computational graph**



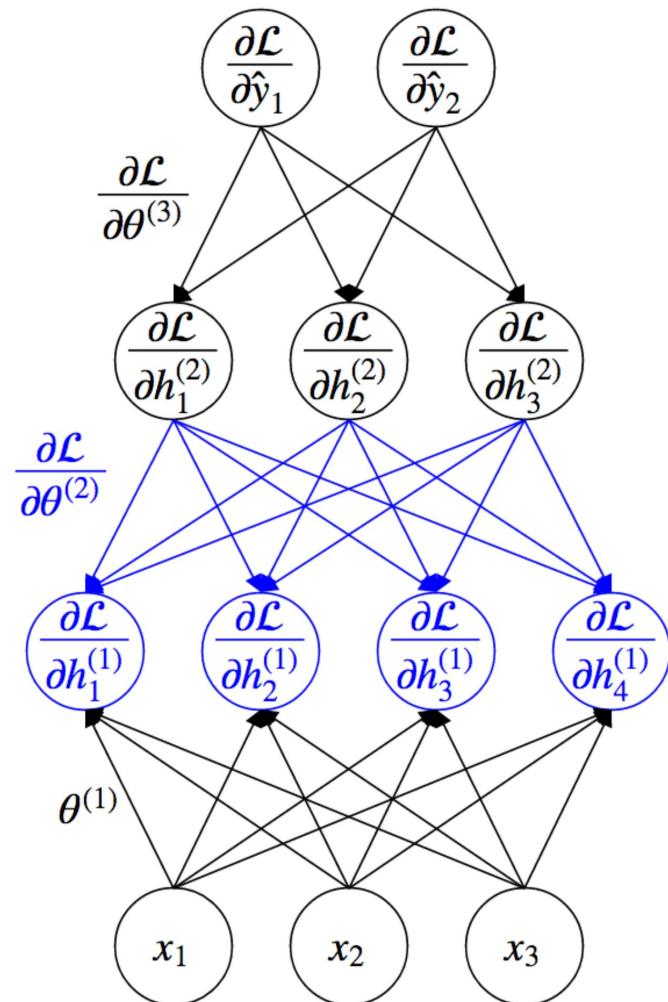
Backpropagation (for deep neural nets)



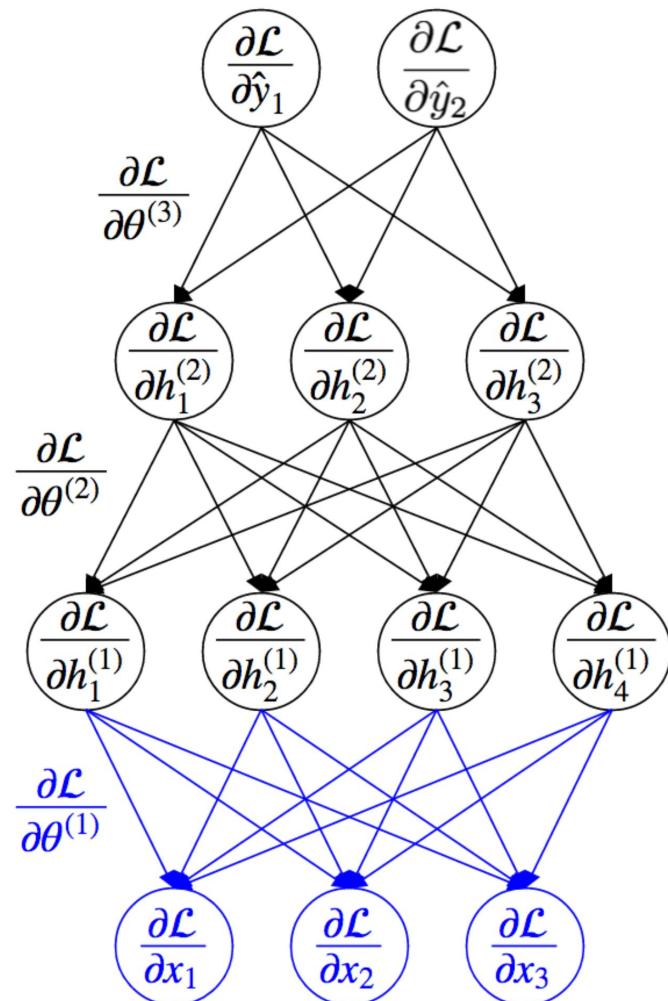
Backpropagation (for deep neural nets)



Backpropagation (for deep neural nets)



Backpropagation (for deep neural nets)



Back-Propagation Algorithm: Recap

- Compute $\nabla_y \mathcal{L} = \left[\frac{\partial \mathcal{L}}{\partial y_1}, \dots, \frac{\partial \mathcal{L}}{\partial y_n} \right]^T$ directly from the loss function.
- For each layer (from top to bottom) with output \mathbf{h} , input \mathbf{x} , and weights \mathbf{W} ,
 - Assuming that $\nabla_{\mathbf{h}} \mathcal{L}$ is given, compute gradients using the **chain rule** as:

$$\nabla_{\mathbf{W}} \mathcal{L} = [\nabla_{\mathbf{W}} \mathbf{h}]^T \nabla_{\mathbf{h}} \mathcal{L} \quad \nabla_{\mathbf{x}} \mathcal{L} = [\nabla_{\mathbf{x}} \mathbf{h}]^T \nabla_{\mathbf{h}} \mathcal{L}$$

“gradient w.r.t. parameters”

(to be used for SGD update)

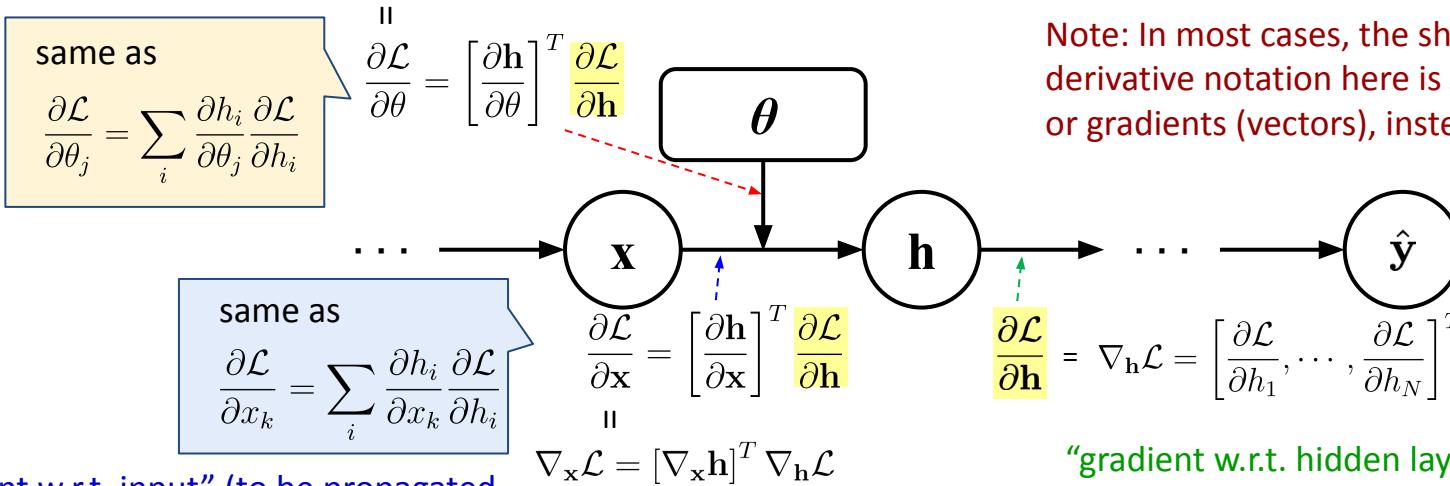
$$\nabla_{\mathbf{W}} \mathcal{L} = [\nabla_{\mathbf{W}} \mathbf{h}]^T \nabla_{\mathbf{h}} \mathcal{L}$$

same as

$$\frac{\partial \mathcal{L}}{\partial \theta_j} = \sum_i \frac{\partial h_i}{\partial \theta_j} \frac{\partial \mathcal{L}}{\partial h_i}$$

$$\frac{\partial \mathcal{L}}{\partial \theta} = \left[\frac{\partial \mathbf{h}}{\partial \theta} \right]^T \frac{\partial \mathcal{L}}{\partial \mathbf{h}}$$

Note: In most cases, the short-hand partial derivative notation here is Jacobian (matrices) or gradients (vectors), instead of scalars.



“gradient w.r.t. input” (to be propagated to lower layers in backprop recursion)

“gradient w.r.t. hidden layer above” (given)

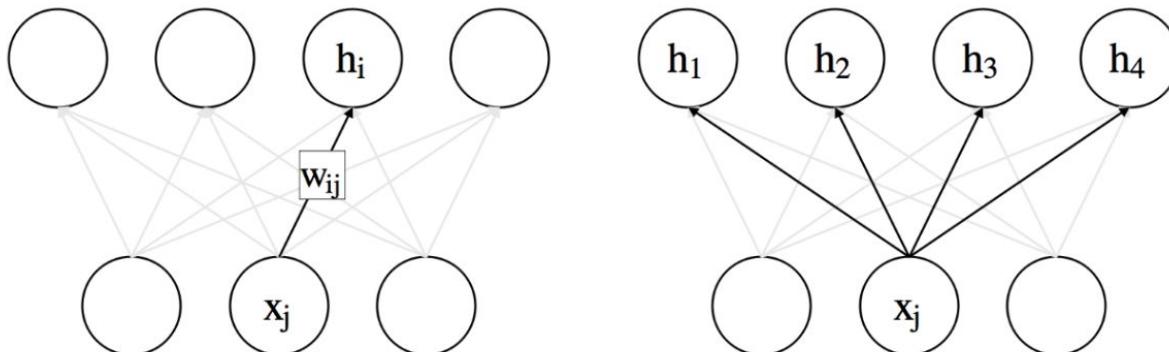
Practice: Linear

- Forward: $h_i = \sum_j w_{ij}x_j + b_i \iff \mathbf{h} = \mathbf{W}\mathbf{x} + \mathbf{b}$
- Gradient w.r.t parameters

$$\frac{\partial \mathcal{L}}{\partial w_{ij}} = \frac{\partial \mathcal{L}}{\partial h_i} \frac{\partial h_i}{\partial w_{ij}} = \frac{\partial \mathcal{L}}{\partial h_i} x_j \iff \nabla_{\mathbf{W}} \mathcal{L} = \nabla_{\mathbf{h}} \mathcal{L} \mathbf{x}^{\top}$$

- Gradient w.r.t inputs

$$\frac{\partial \mathcal{L}}{\partial x_j} = \sum_i \frac{\partial \mathcal{L}}{\partial h_i} \frac{\partial h_i}{\partial x_j} = \sum_i \frac{\partial \mathcal{L}}{\partial h_i} w_{ij} \iff \nabla_{\mathbf{x}} \mathcal{L} = \mathbf{W}^{\top} \nabla_{\mathbf{h}} \mathcal{L}$$



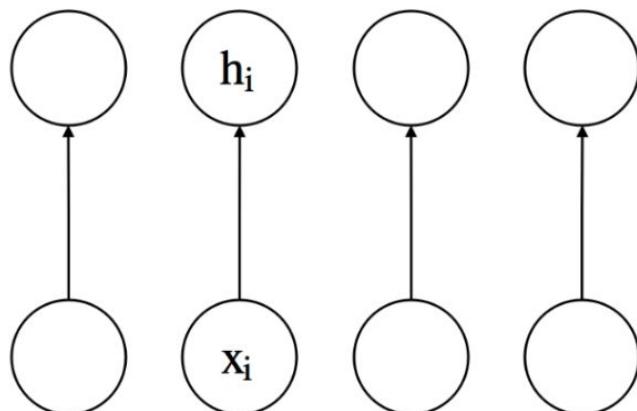
Note: In the lecture, we use column vector notation.
However, PyTorch / NumPy typically uses row vector notation
(please also see the note in the HW4).

Practice: Non-Linear Activation (Sigmoid)

- Forward: $h_i = \sigma(x_i) = \frac{1}{1 + \exp(-x_i)} \iff \mathbf{h} = \sigma(\mathbf{x})$
- Gradient w.r.t inputs

$$\frac{\partial \mathcal{L}}{\partial x_i} = \frac{\partial \mathcal{L}}{\partial h_i} \frac{\partial h_i}{\partial x_i} = \frac{\partial \mathcal{L}}{\partial h_i} \sigma(x_i)(1 - \sigma(x_i)) = \frac{\partial \mathcal{L}}{\partial h_i} h_i(1 - h_i)$$

$$\nabla_{\mathbf{x}} \mathcal{L} = \nabla_{\mathbf{h}} \mathcal{L} \odot \mathbf{h} \odot (1 - \mathbf{h})$$

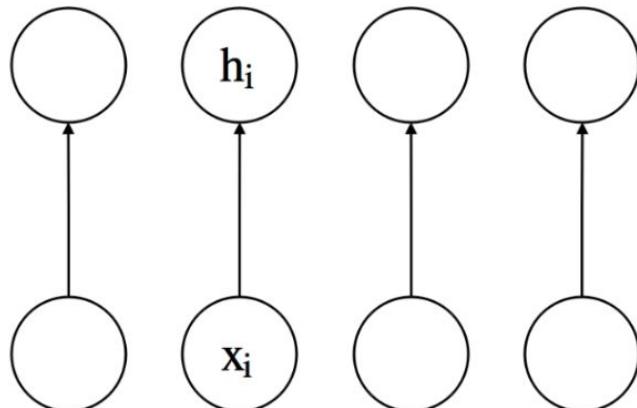


Practice: Non-Linear Activation (tanh)

- Forward: $h_i = \tanh(x_i) = \frac{\exp(x_i) - \exp(-x_i)}{\exp(x_i) + \exp(-x_i)} \iff \mathbf{h} = \tanh(\mathbf{x})$
- Gradient w.r.t inputs

$$\frac{\partial \mathcal{L}}{\partial x_i} = \frac{\partial \mathcal{L}}{\partial h_i} \frac{\partial h_i}{\partial x_i} = \frac{\partial \mathcal{L}}{\partial h_i} (1 - \tanh^2(x_i)) = \frac{\partial \mathcal{L}}{\partial h_i} (1 - h_i^2)$$

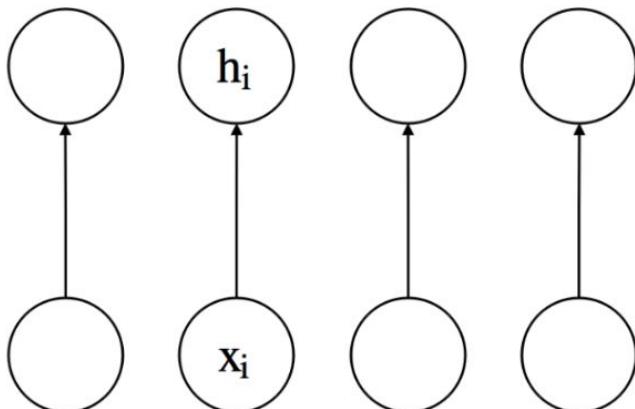
$$\nabla_{\mathbf{x}} \mathcal{L} = \nabla_{\mathbf{h}} \mathcal{L} \odot (1 - \mathbf{h} \odot \mathbf{h})$$



Practice: Non-Linear Activation (ReLU)

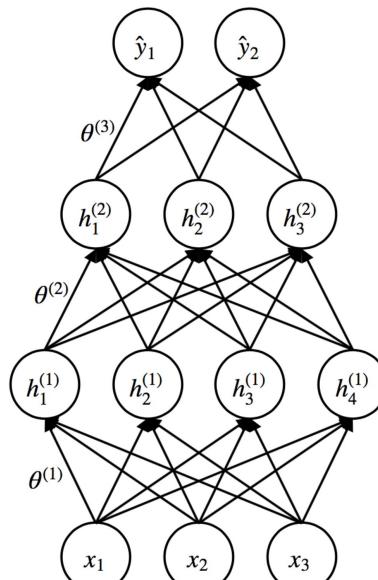
- Forward: $h_i = \text{ReLU}(x_i) = \max(x_i, 0) \iff \mathbf{h} = \text{ReLU}(\mathbf{x})$
- Gradient w.r.t inputs

$$\frac{\partial \mathcal{L}}{\partial x_i} = \frac{\partial \mathcal{L}}{\partial h_i} \frac{\partial h_i}{\partial x_i} = \begin{cases} \frac{\partial \mathcal{L}}{\partial h_i} & x_i > 0 \\ 0 & x_i < 0 \end{cases}$$

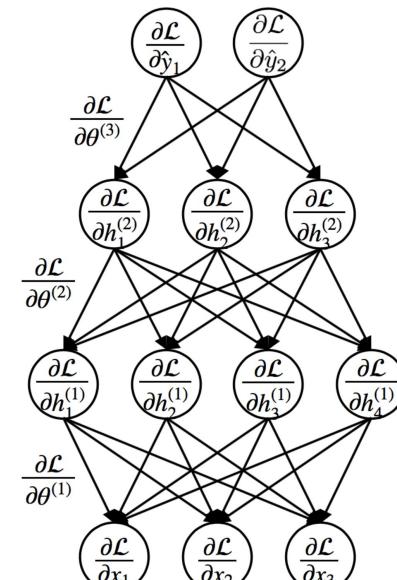


Backpropagation for deep neural nets

- Computing gradient via **chain rule** for compositional function
- The chain rule can be expressed as a **local computation**
- Think of it as a **computational graph**



Forward



Backward

Problems with Back Propagation

- Gradient is progressively getting more diluted
 - Below top few layers, correction signals can be significantly reduced
- Easy to get stuck in local minima
 - Especially since they start out far from ‘good’ regions (i.e., random initialization)

Back Propagation & Amount of Data

- Typically requires lots of labeled data
- Given limited amounts of labeled data, training via backpropagation does not work well
 - Deep networks trained with backpropagation (without any sort of unsupervised pretraining) sometimes perform worse than shallow networks – Overfitting
- However, when there is a large amount of labeled data, backpropagation works surprisingly well.
 - Example of success: Convolutional Neural Networks trained from ImageNet classification (~1M labeled images from 1000 classes)

Any feedback (about lecture, slide, homework, project, etc.)?

(via anonymous google form: <https://forms.gle/MPrZkBvx668CRWRt8>)



Change Log of lecture slides:

<https://docs.google.com/document/d/e/2PACX-1vR7IWYfoLOKlrH2vacdF2VwwN35w1kO18sEEtB2U1Sk-4QgxBshy9rQOEc9vbIHhOIHVc9at-yKEKV/pub>