

EECE 571F: Advanced Topics in Deep Learning

Lecture 1: Introduction to Deep Learning

Renjie Liao

University of British Columbia

Winter, Term 2, 2025

Course Information

- Course website: <https://lrjconan.github.io/UBC-EECE571F-DL-Structures/>
- Cutting-edge topics in deep learning with structures (not an introduction!!!)
- Assumes basic knowledge about machine learning, deep learning
 - View relevant textbooks/courses on the website
- Assumes basic knowledge about linear algebra, calculus, probability
- Assumes proficiency in deep learning libraries: PyTorch, JAX, Tensorflow
 - Self-learning through online tutorials, e.g. <https://pytorch.org/tutorials/>

Course Information

- Two sections: Mon. & Wed. 13:30 to 3:00pm,
Room 208, West Mall Swing Space Building (SWNG)
Office hour: 2:00pm to 3:00pm, Tue., KAIS 3047 (Ohm)
- TA: Yuanpei Gao (yuanpeig@student.ubc.ca)



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- TA: Yuanpei Gao (yuanpeig@student.ubc.ca)
- Half lectures and half paper presentations. All lectures will be delivered in person without recording unless notified otherwise.
- Use Piazza for discussion & questions (actively answering others' questions get you bonuses) and Canvas for submitting reports.

<https://piazza.com/ubc.ca/winterterm2025/eece571f>

Course Information

- Expectation & Grading (More info on the website)
 - [30%] Paper presentation
 - [10%] Project proposal, due Feb. 22
 - [10%] Project presentations, around last two weeks
 - [10%] Peer-review report of project presentations, due Apr. 10
 - [40%] Project report and code, due Apr. 15
 - [3%] Extra bonus for participation
- You are encouraged to team up (up to 4 members) for projects

Course Information

- How to get free GPUs for your course project?

1. **Google Colab:** <https://research.google.com/colaboratory/>

Google Colab is a web-based iPython Notebook service that has access to a free Nvidia K80 GPU per Google account.

2. **Google Compute Engine:** <https://cloud.google.com/compute>

Google Compute Engine provides virtual machines with GPUs running in Google's data center. You get \$300 free credit when you sign up.

- Strategy of using GPUs

1. Debug models on small datasets (subsets) using CPUs or low-end GPUs until they work
2. Launch batch jobs on high-end GPUs to tune hyperparameters

Course Scope

- Brief Intro to Deep Learning

Course Scope

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- Geometric Deep Learning
 - Deep Learning Models for Sets and Sequences: Deep Sets & Transformers
 - Deep Learning Models for Graphs: Message Passing & Graph Convolution GNNs
 - Group Equivariant Deep Learning

Course Scope

- Brief Intro to Deep Learning
- Geometric Deep Learning
 - Deep Learning Models for Sets and Sequences: Deep Sets & Transformers
 - Deep Learning Models for Graphs: Message Passing & Graph Convolution GNNs
 - Group Equivariant Deep Learning
- Probabilistic Deep Learning
 - Auto-regressive models, Large Language Models (LLMs), Deep RL
 - Variational Auto-Encoders (VAEs) and Generative Adversarial Networks (GANs)
 - Flow models
 - Diffusion/Score based models

Outline

- Brief Introduction & History & Application
- Basic Deep Learning Models
 - Multi-Layer Perceptron (MLP)
 - Convolutional Neural Network (CNN)
 - Recurrent Neural Network (RNN)
- Objective Function
- Learning Algorithm: Back-propagation
- Limitations

Outline

- **Brief Introduction & History & Application**
- Basic Deep Learning Models
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What is Deep Learning?

- Definition from Wikipedia:

Deep learning (also known as deep structured learning) is part of a broader family of machine learning methods based on artificial neural networks with representation learning.

- Key Aspects:

Data: Large (supervised) datasets, e.g., ImageNet (14 million+ annotated images)

Model: Deep (i.e., many layers) neural networks, e.g., ResNet-152

Learning algorithm: Back-propagation (BP), i.e., stochastic gradient descent (SGD)

Brief History of Deep Learning (Connectionism)

- Artificial Neurons (McCulloch and Pitts 1943)
- Hebbian Rule: Cells that fire together wire together (Donald Hebb 1949)
- Perceptron (Frank Rosenblatt 1958)
- Discovery of orientation selectivity and columnar organization in the visual cortex (Hubel and Wiesel, 1959)
- Neocognitron (first Convolutional Neural Network, Fukushima 1979)
- Hopfield networks (Hopfield 1982)
- Boltzmann machines (Hinton, Sejnowski 1983)
- Backpropagation (Linnainmaa 1970, Werbos 1974, Rumelhart, Hinton, Williams 1986)
- First application of BP to Neocognitron-like CNNs (LeCun et al. 1989)
- Long-short term memory (Hochreiter, Schmidhuber 1997)

Brief History of Deep Learning (Connectionism)

- Deep belief networks (DBN) (Hinton et al., 2006)
- Breakthrough in speech recognition (Dahl et al. 2010)
- Breakthrough in computer vision: AlexNet (Krizhevsky et al. 2012), ResNet (He et al. 2016)
- Breakthrough in games: DQN (Minh, 2015), AlphaGO (2016)
- Breakthrough in natural language processing: Seq2seq (Sutskever et al. 2014), Transformers (Vaswani et al. 2017), GPT-3 (Brown et al. 2020)
- Breakthrough in protein structure prediction: AlphaFold (2020)

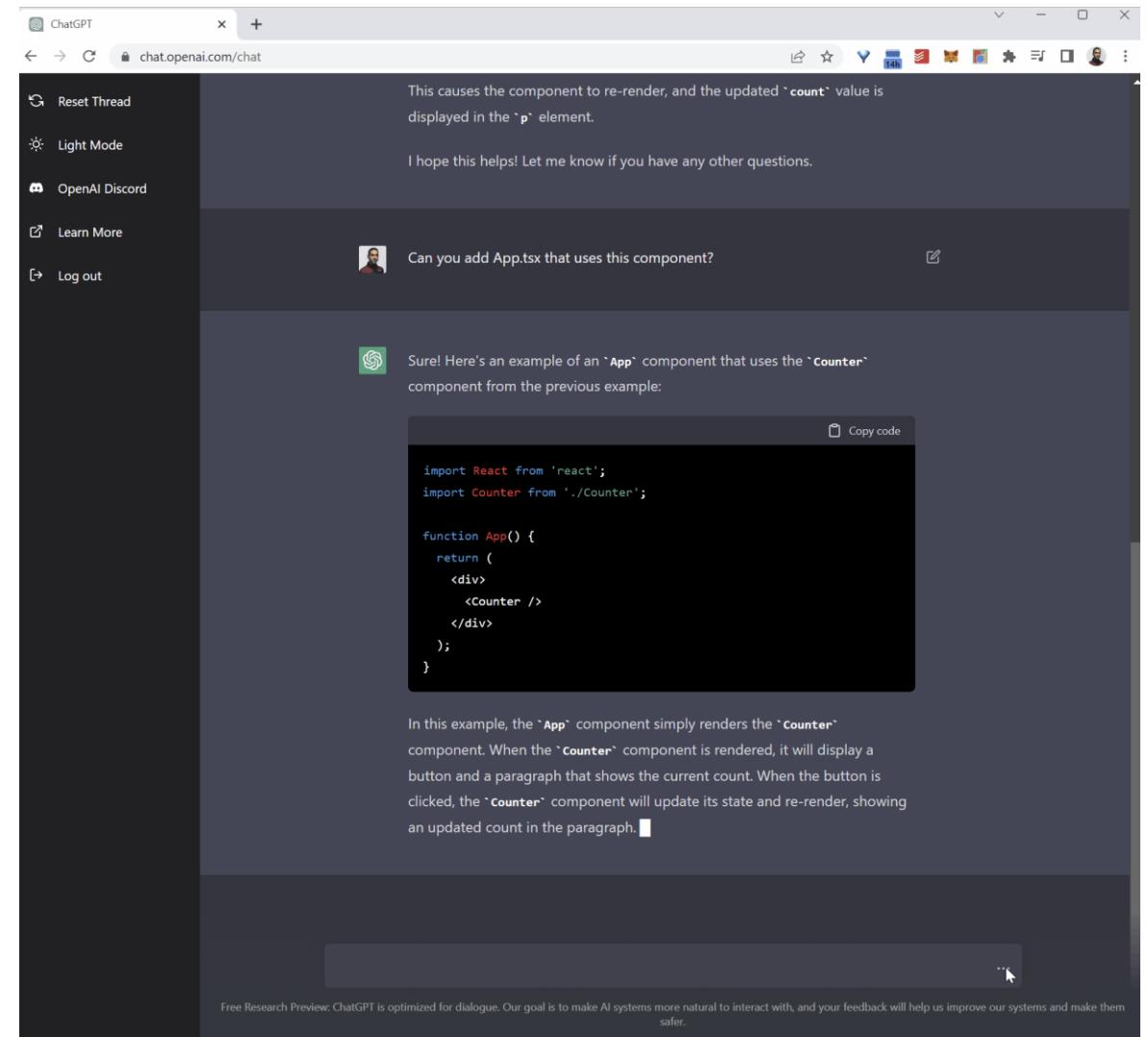
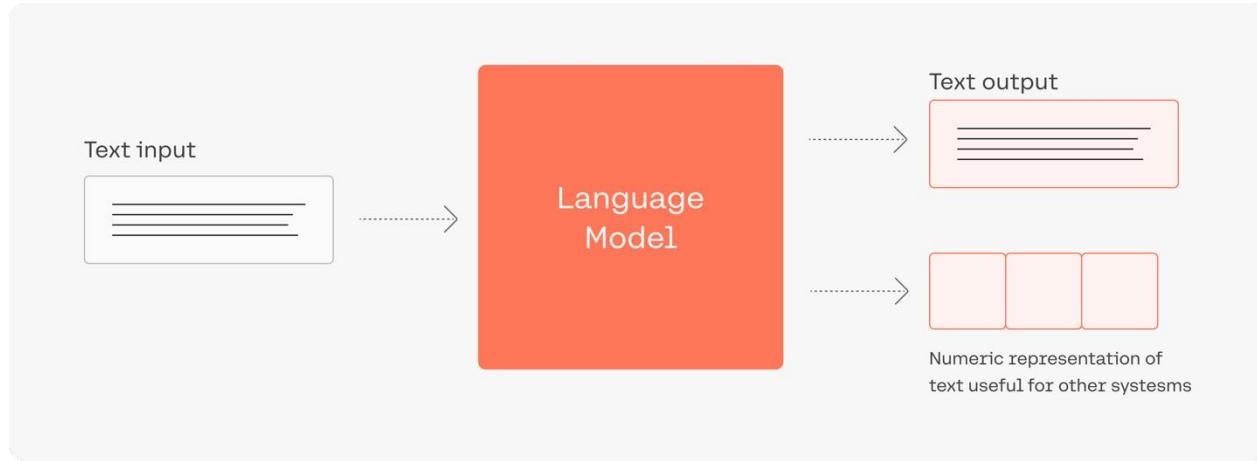
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The future depends on some graduate student who is deeply suspicious of everything I have said.

- Geoffrey Hinton

Applications of Deep Learning

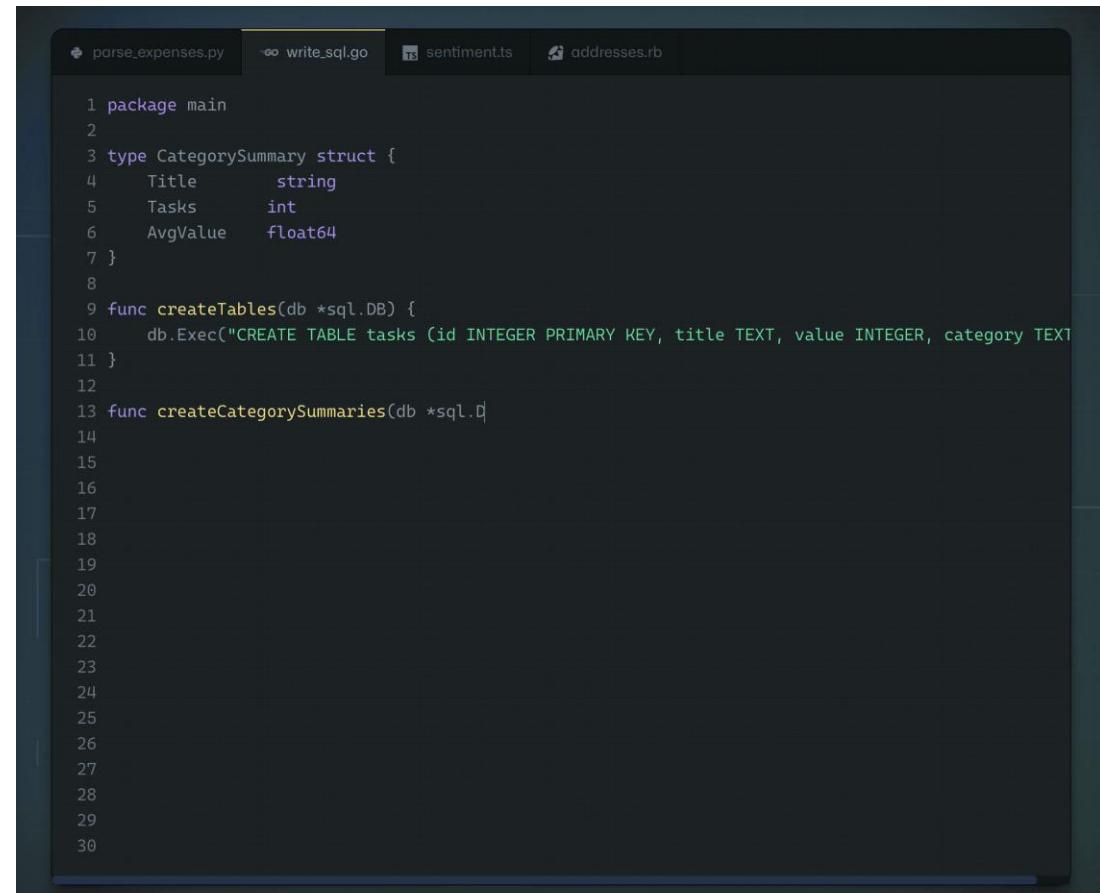
Large Language Models (LLMs)



Applications of Deep Learning

Text/Program Generation

◀ Matt Shumer (matt@othersideai.com), 1 CC

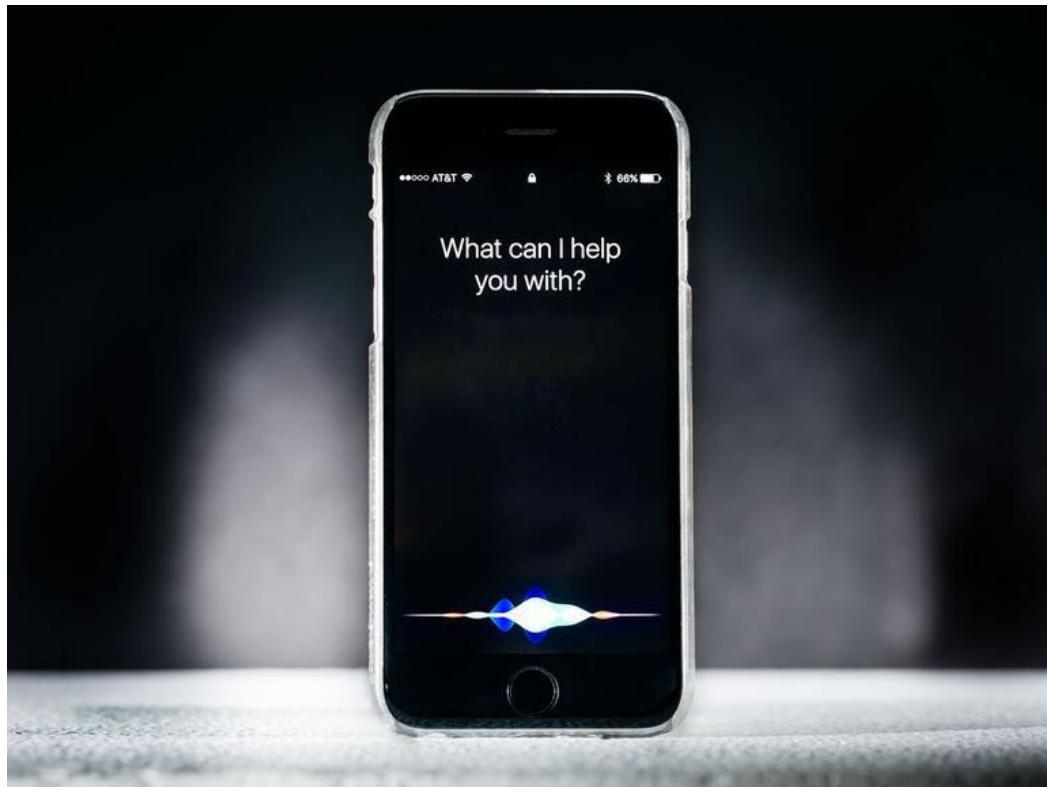


```
1 package main
2
3 type CategorySummary struct {
4     Title      string
5     Tasks      int
6     AvgValue   float64
7 }
8
9 func createTables(db *sql.DB) {
10    db.Exec("CREATE TABLE tasks (id INTEGER PRIMARY KEY, title TEXT, value INTEGER, category TEXT")
11 }
12
13 func createCategorySummaries(db *sql.D...
```

OTHERSIDEAI 

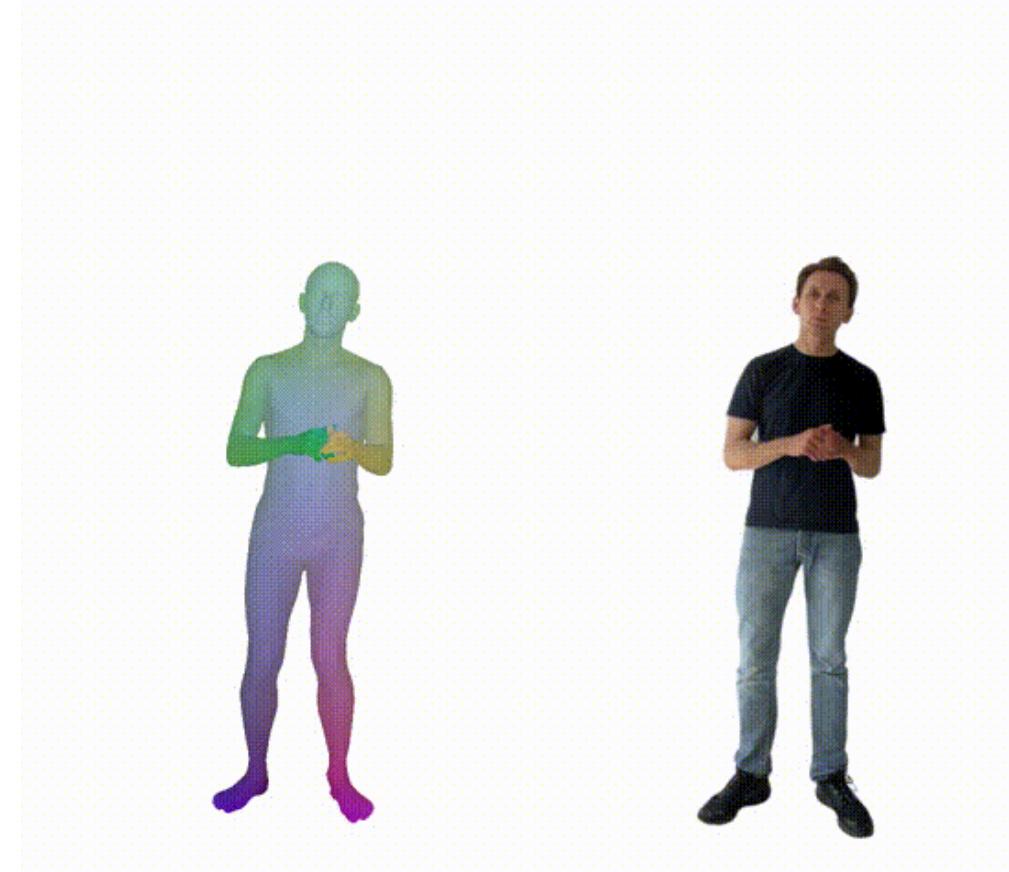
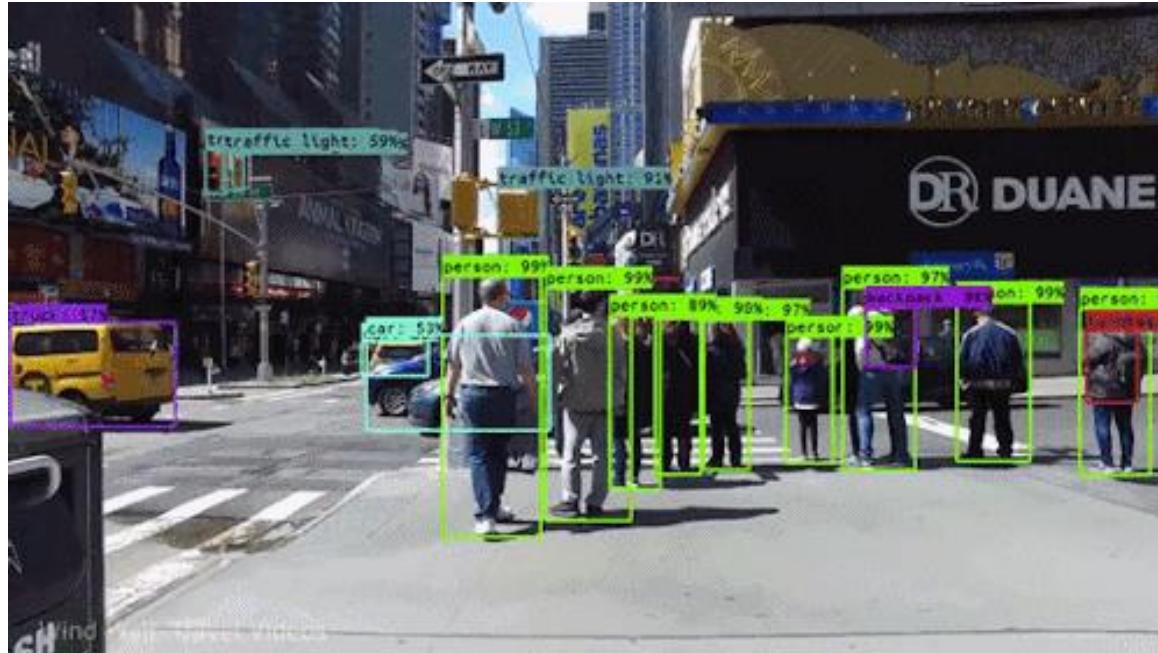
Applications of Deep Learning

Speech Recognition, Personal Assistants



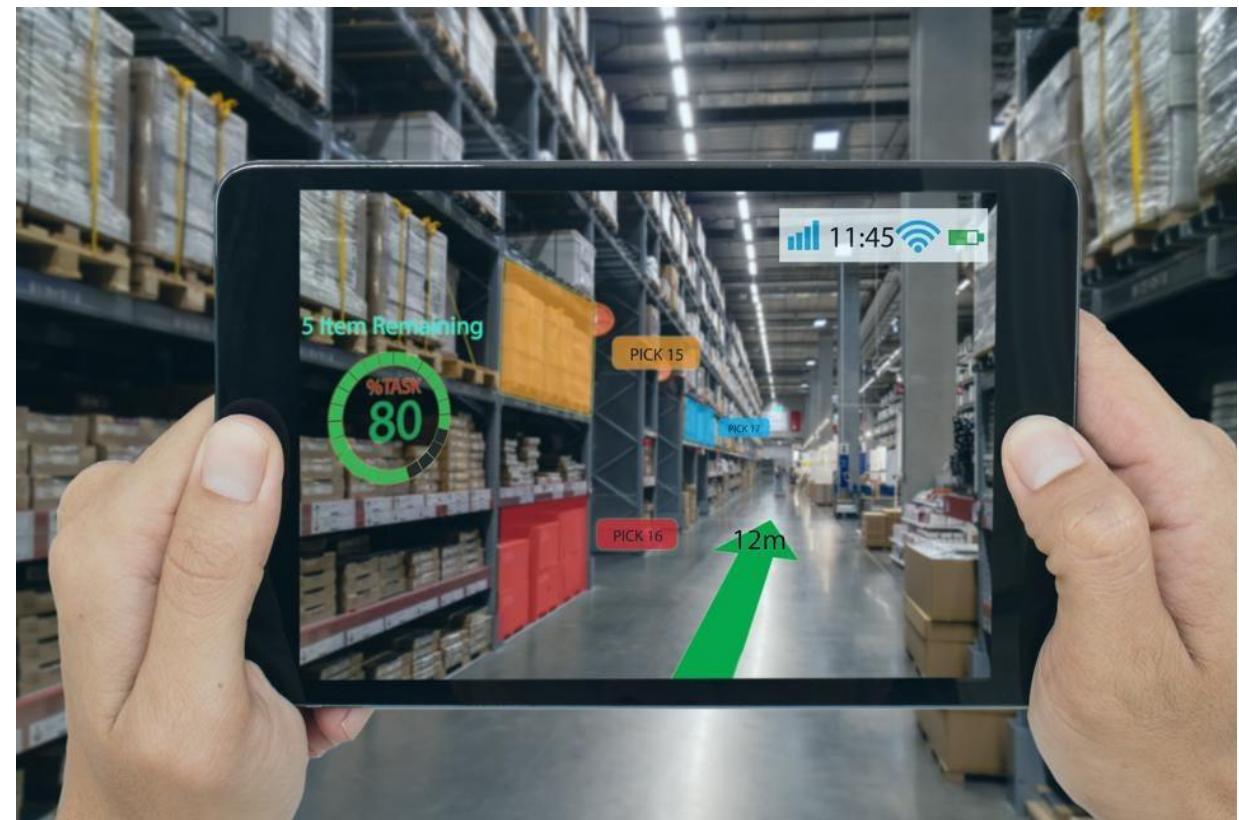
Applications of Deep Learning

Computer Vision/Graphics, e.g., Object detection, Rendering



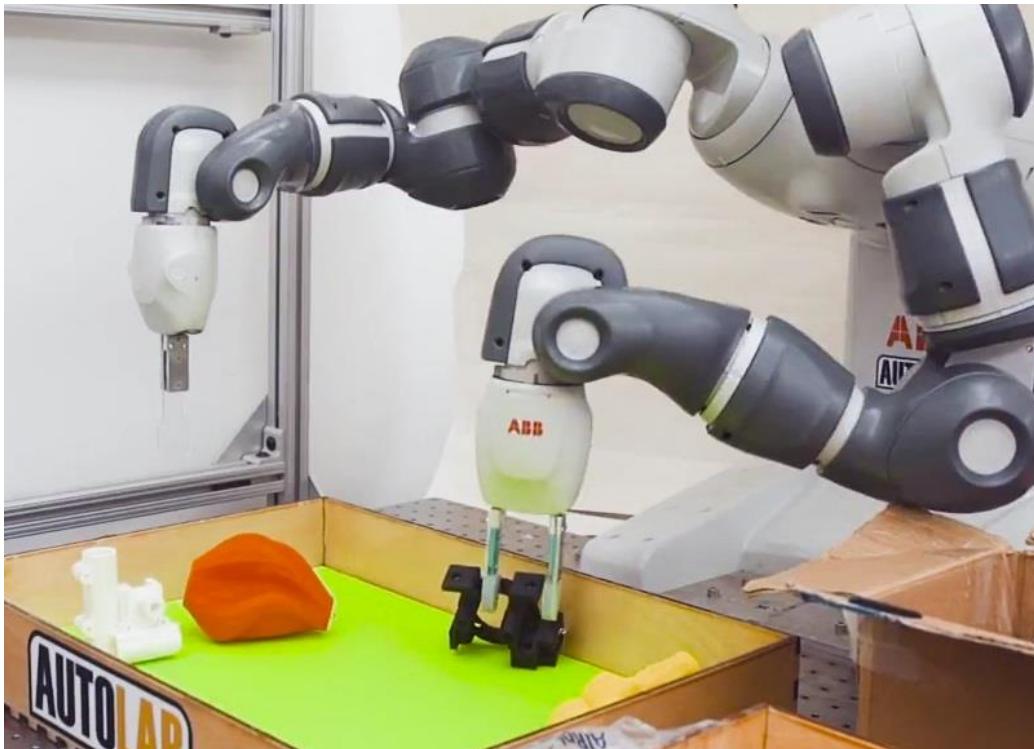
Applications of Deep Learning

Virtual/Augmented Reality



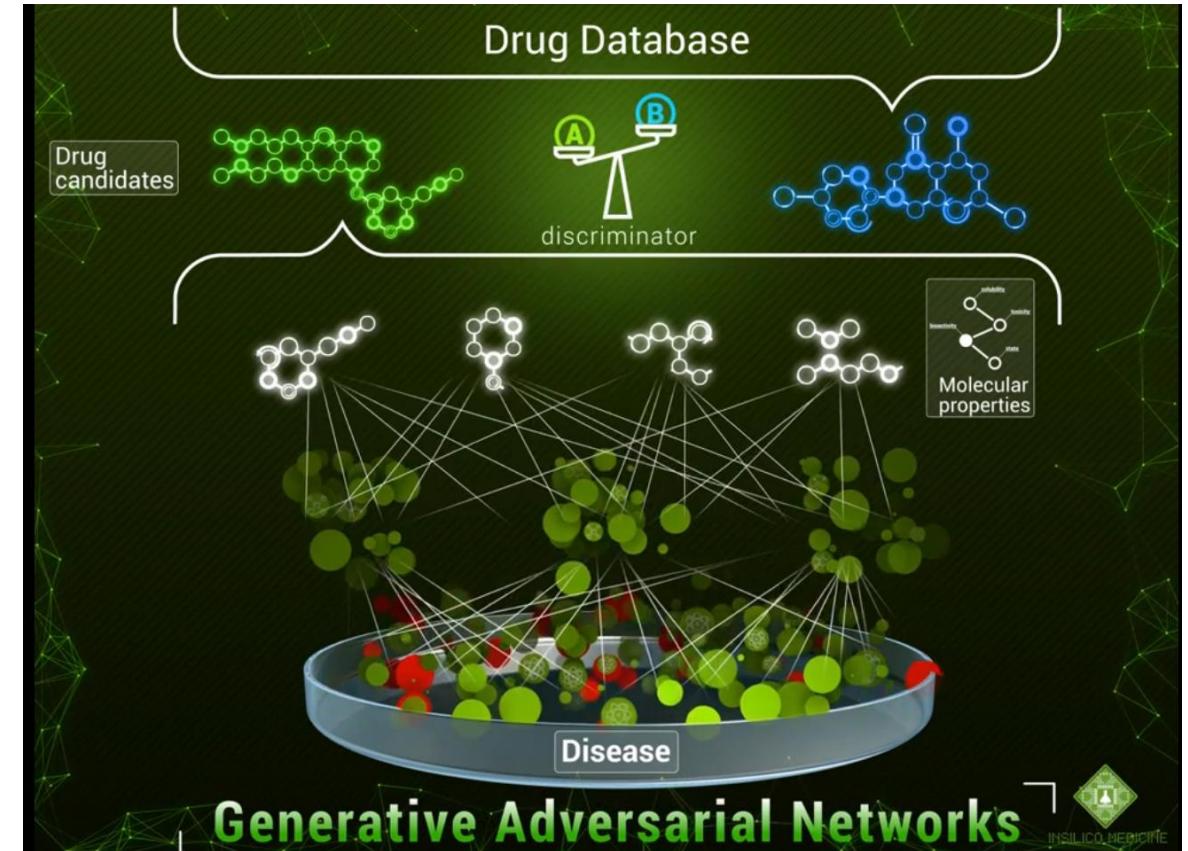
Applications of Deep Learning

Robotics, Autonomous Driving



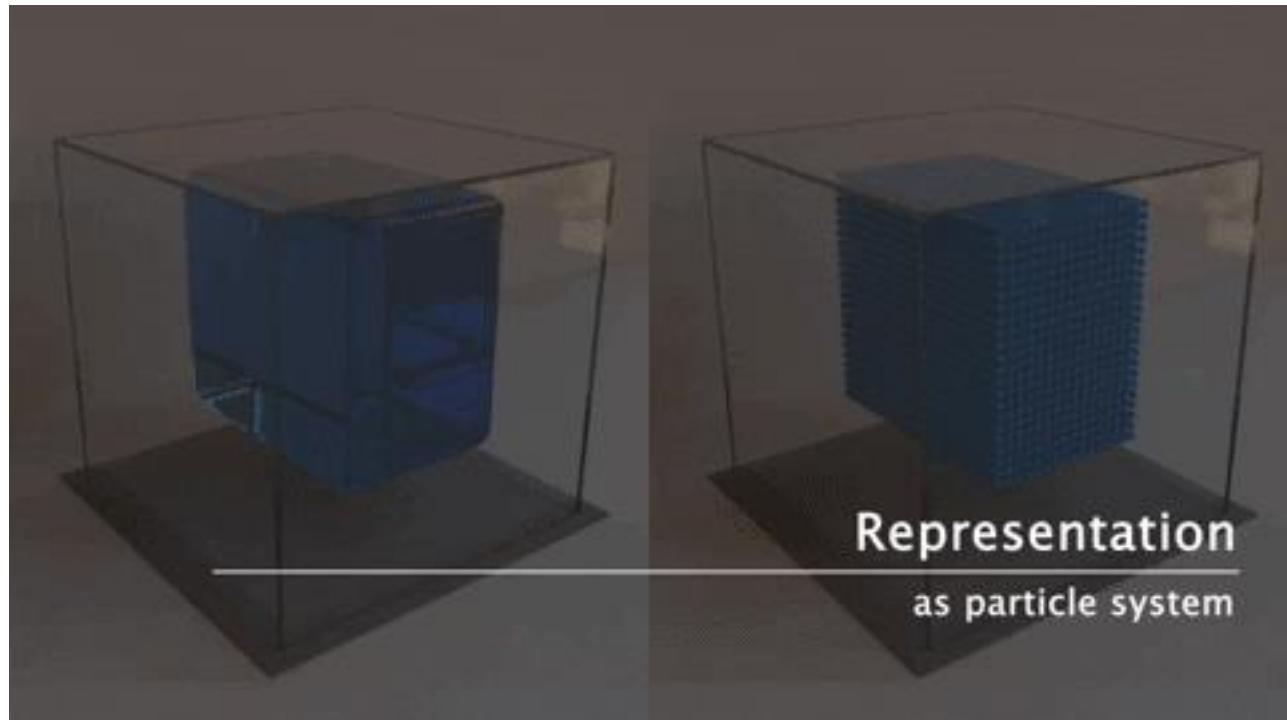
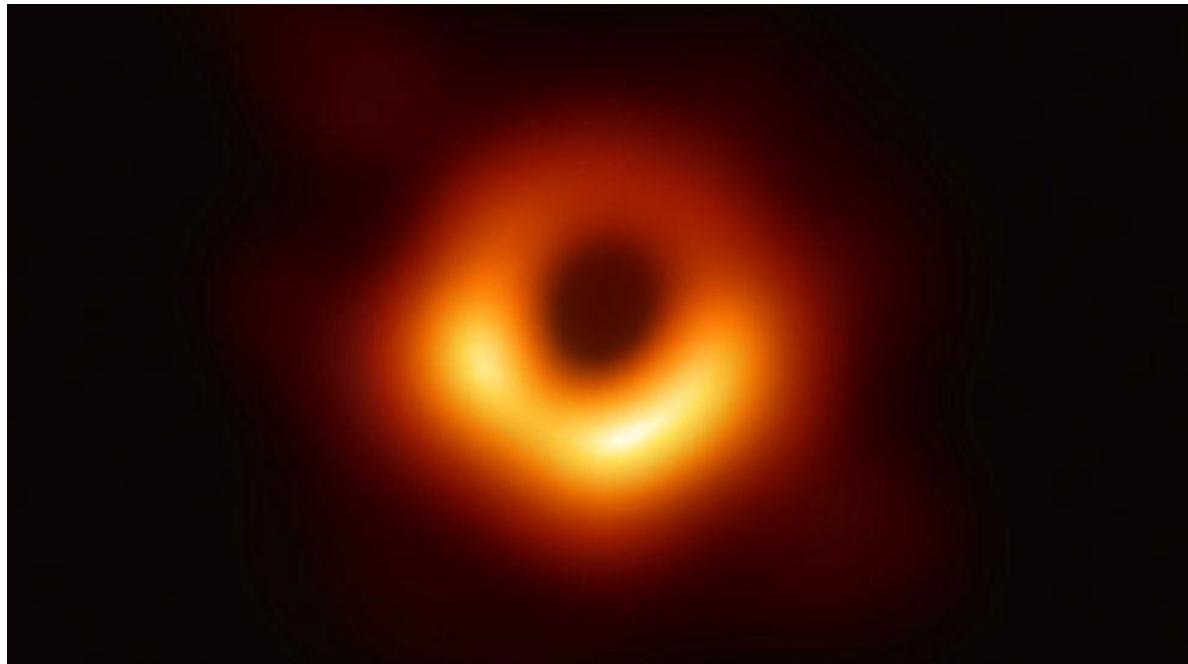
Applications of Deep Learning

Protein structure prediction, Drug discovery



Applications of Deep Learning

Black Holes, Physics Simulation

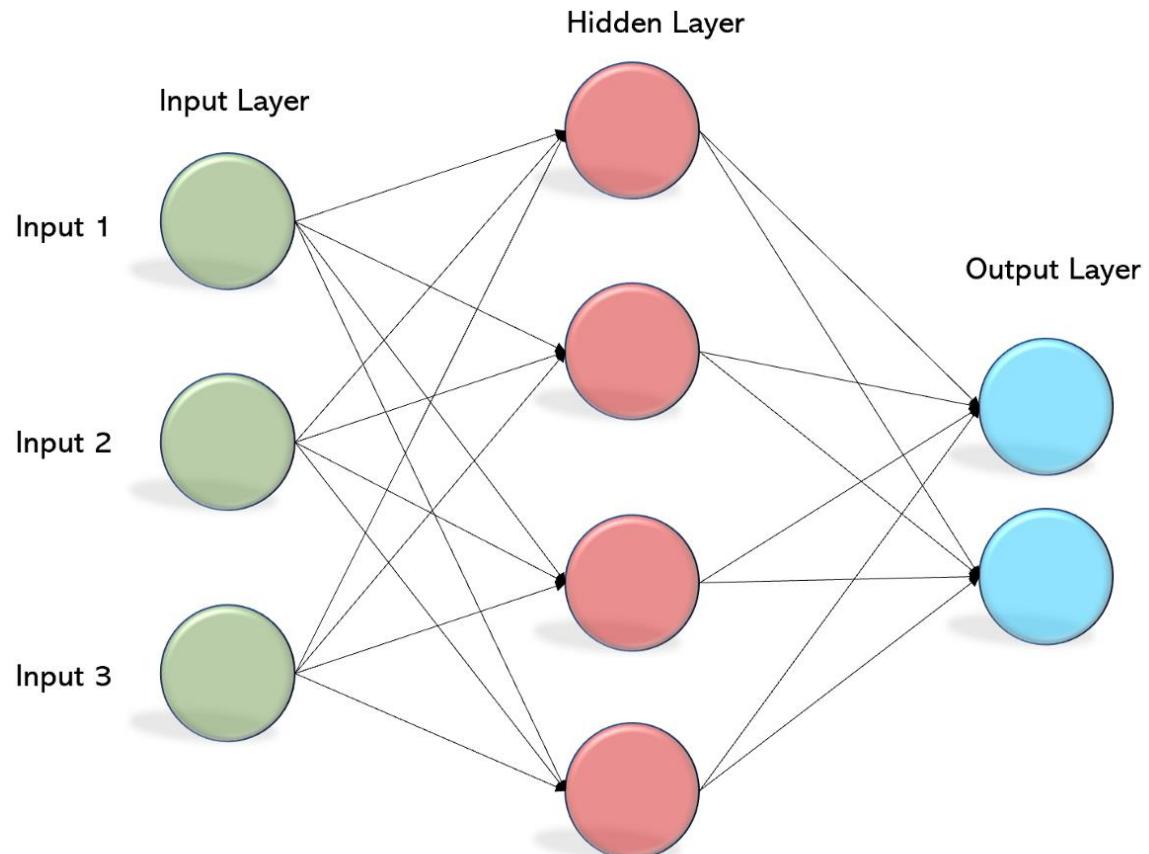


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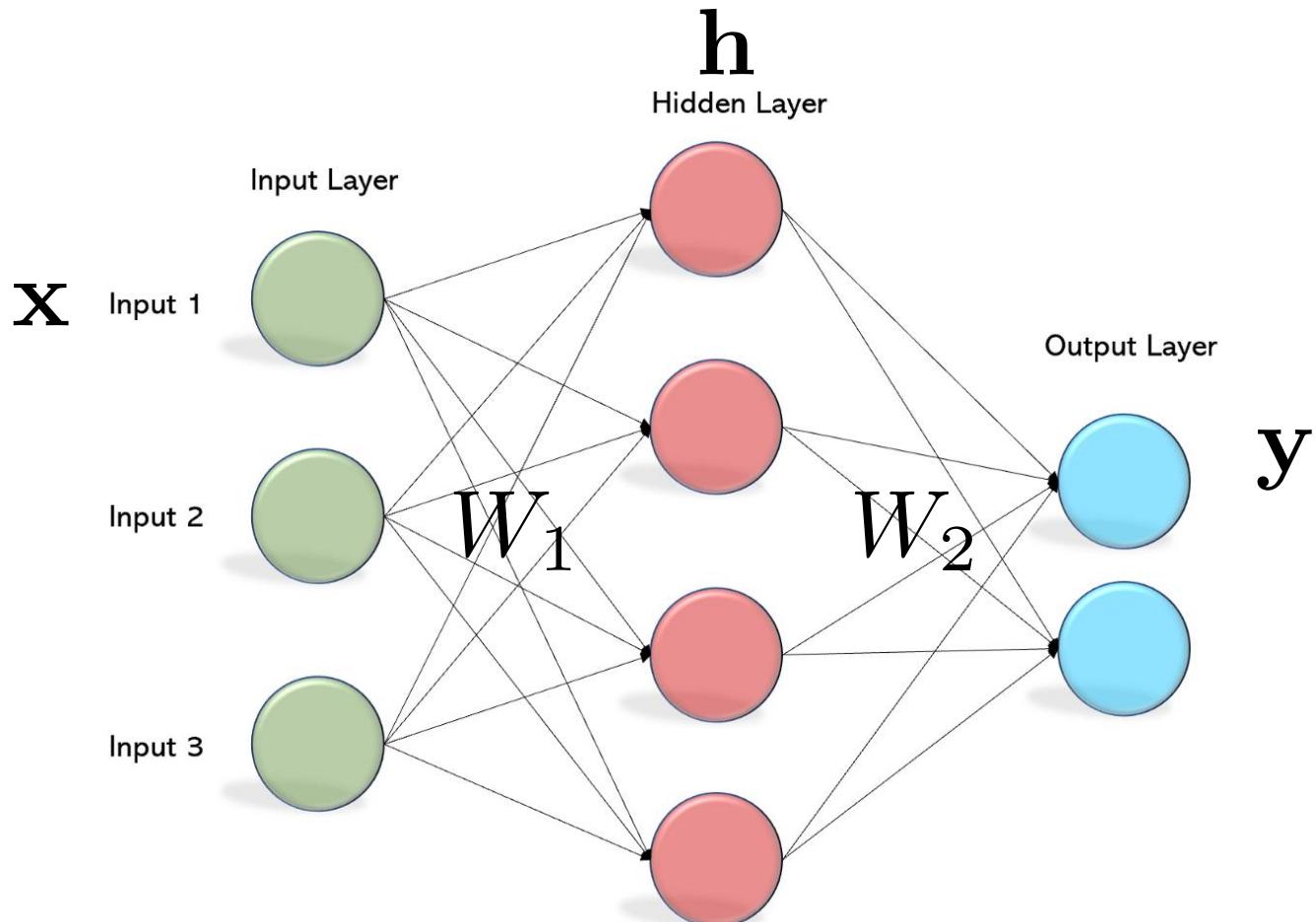
Basic Deep Learning Models

Multi-Layer Perceptron (MLP)



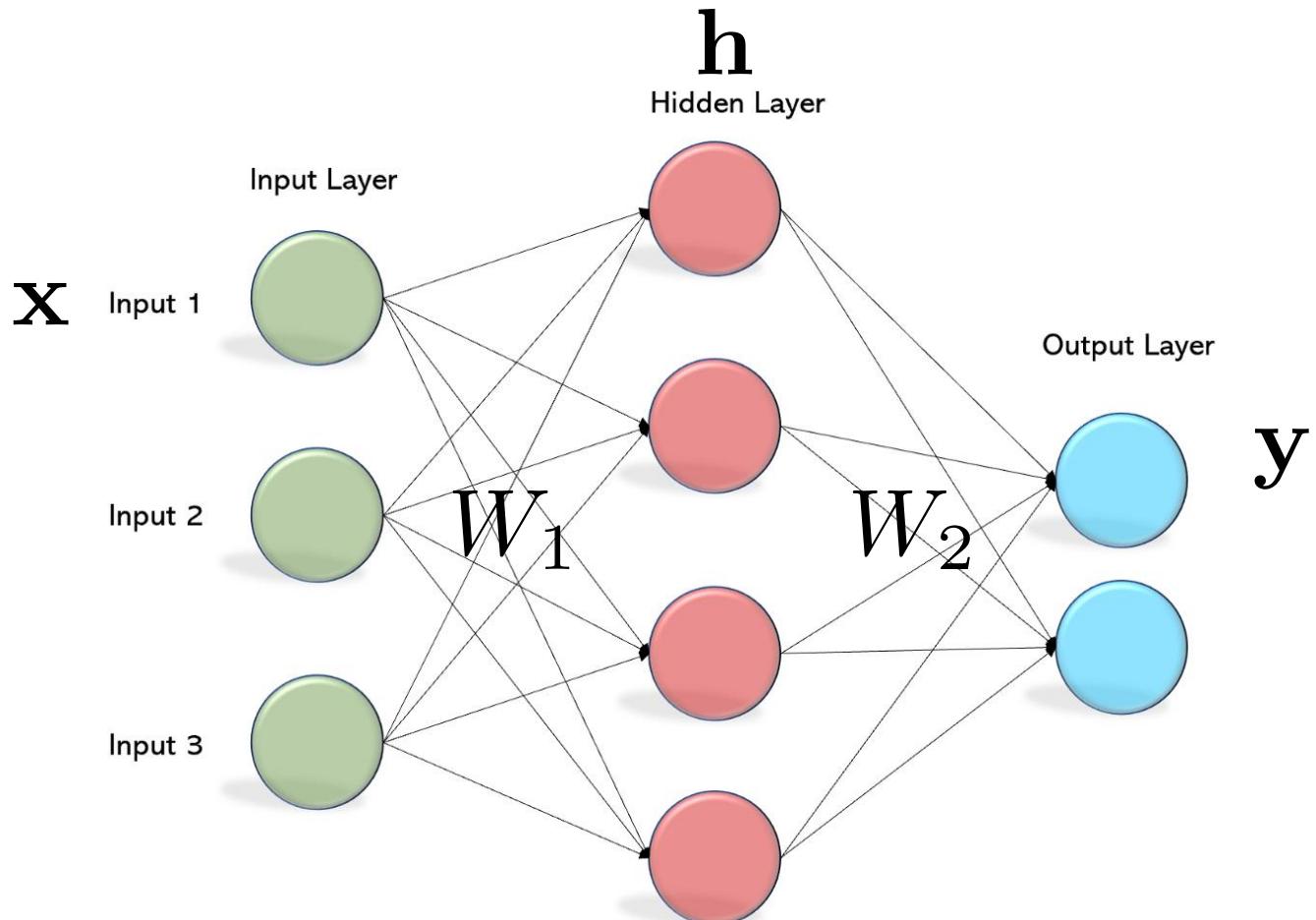
Basic Deep Learning Models

Multi-Layer Perceptron (MLP)



Basic Deep Learning Models

Multi-Layer Perceptron (MLP)

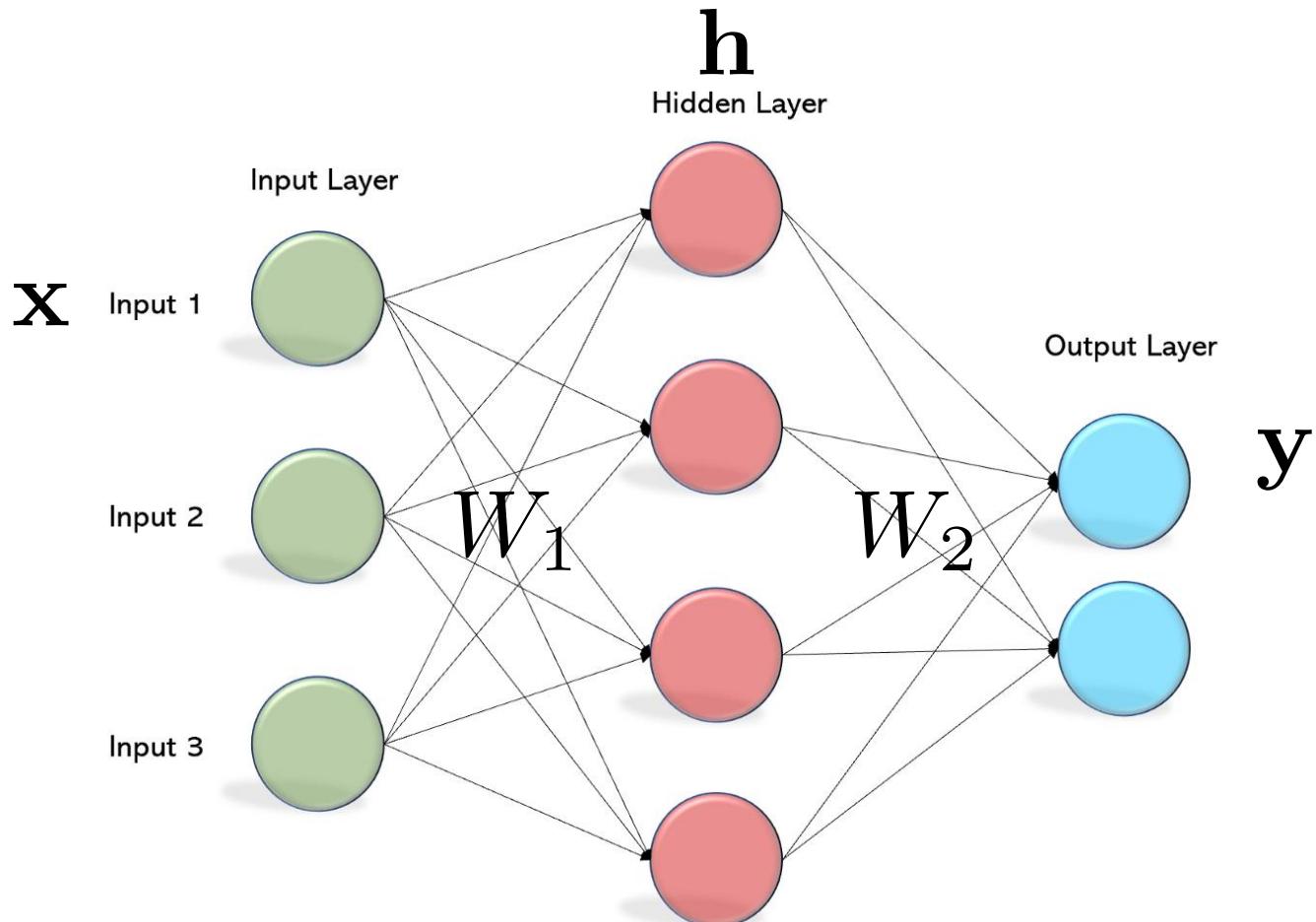


$$\mathbf{h} = \sigma(\mathbf{W}_1 \mathbf{x})$$

$$\mathbf{y} = \mathbf{W}_2 \mathbf{h}$$

Basic Deep Learning Models

Multi-Layer Perceptron (MLP)



$$\mathbf{h} = \sigma(W_1 \mathbf{x})$$

$$\mathbf{y} = W_2 \mathbf{h}$$

ReLU: $\sigma(\mathbf{h}) = \max(\mathbf{h}, 0)$

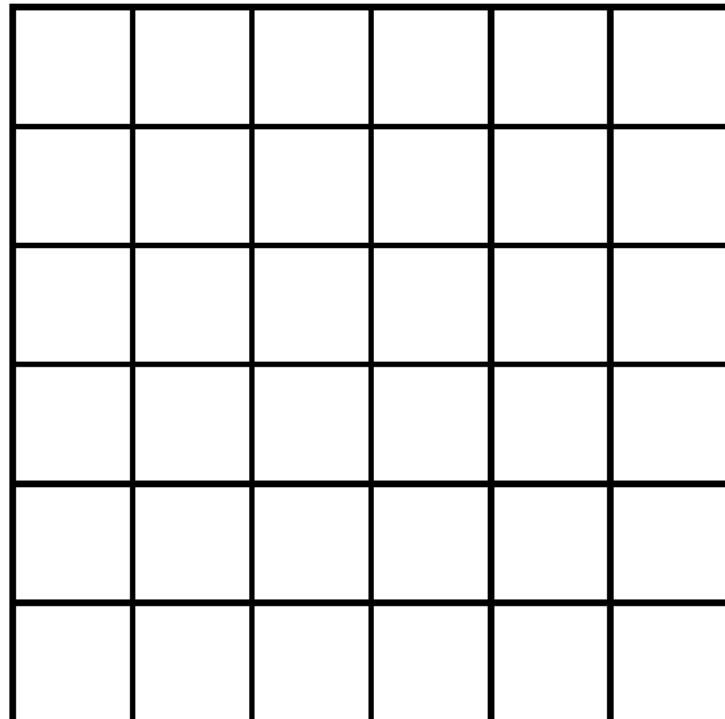
Sigmoid: $\sigma(\mathbf{h}) = \frac{1}{1 + \exp(-\mathbf{h})}$

Tanh, Softplus, ELU, ...

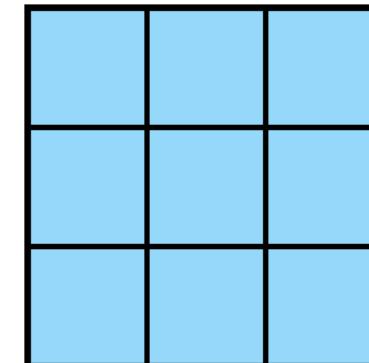
Basic Deep Learning Models

Convolutional Neural Network (CNN)

Convolution (Discrete)



Image



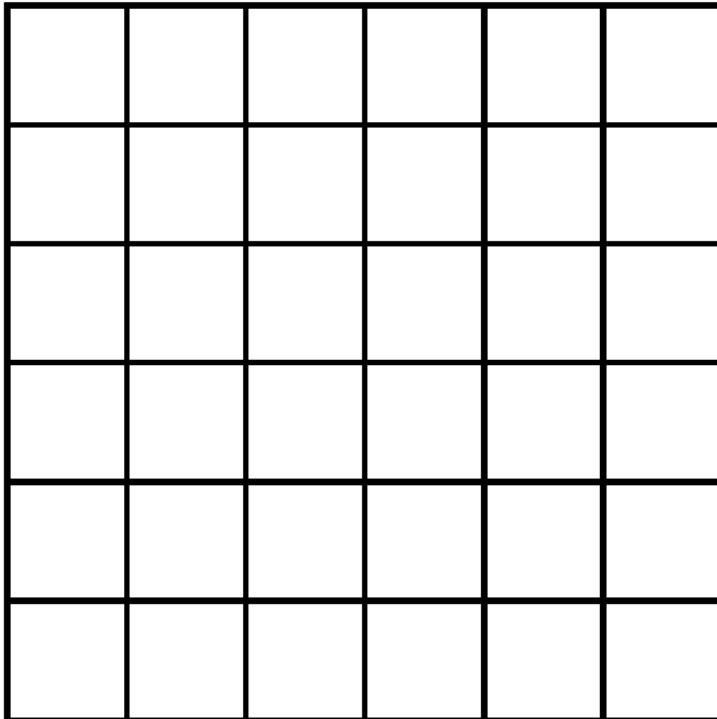
Convolutional Filter

Basic Deep Learning Models

Convolutional Neural Network (CNN)

Convolution (Discrete)

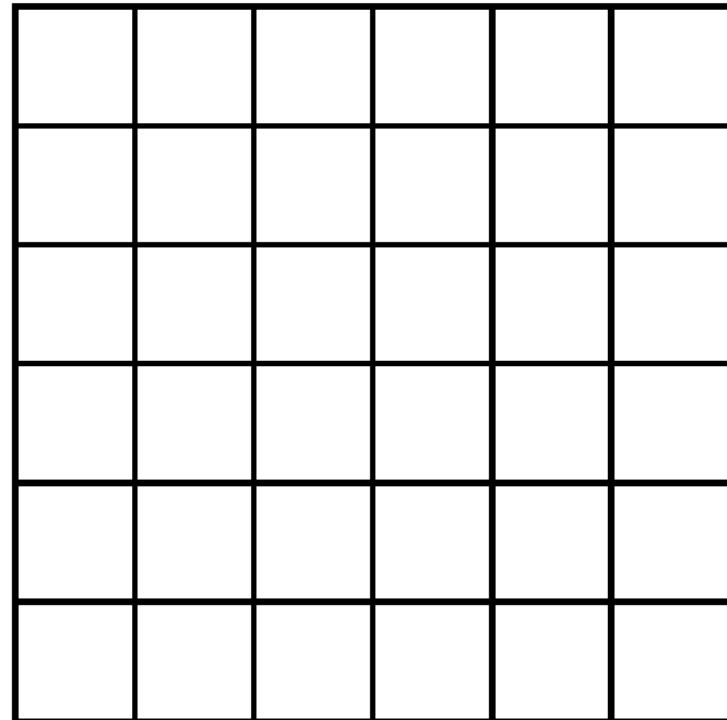
$$\mathbf{y}_{i,j} = \sum_{m=1}^K \sum_{n=1}^K W_{m,n} \mathbf{x}_{i+m-\lceil K/2 \rceil, j+n-\lceil K/2 \rceil}$$



Basic Deep Learning Models

Convolutional Neural Network (CNN)

Convolution (Discrete)



$$\mathbf{y}_{i,j} = \sum_{m=1}^K \sum_{n=1}^K W_{m,n} \mathbf{x}_{i+m-\lceil K/2 \rceil, j+n-\lceil K/2 \rceil}$$

Convolution \Leftrightarrow Matrix Multiplication

Matrix Multiplication View I

1D Convolution (Discrete) \Leftrightarrow Matrix Multiplication

Filter \Rightarrow Toeplitz matrix (diagonal-constant)

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1D Convolution (Discrete) \Leftrightarrow Matrix Multiplication

Filter \Rightarrow Toeplitz matrix (diagonal-constant)

$$y = h * x = \begin{bmatrix} h_{\lfloor m/2 \rfloor + 1} & h_{\lfloor m/2 \rfloor + 2} & \cdots & h_m & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\ h_{\lfloor m/2 \rfloor} & h_{\lfloor m/2 \rfloor + 1} & \cdots & h_{m-1} & h_m & 0 & \cdots & \cdots & \cdots & 0 \\ \vdots & \vdots \\ h_1 & h_2 & \cdots & \cdots & \cdots & \cdots & h_m & 0 & \cdots & 0 \\ 0 & h_1 & h_2 & \cdots & \cdots & \cdots & \cdots & h_m & \cdots & 0 \\ \vdots & \vdots \\ 0 & 0 & \cdots & \cdots & \cdots & 0 & h_1 & h_2 & \cdots & h_{\lfloor m/2 \rfloor + 2} \\ 0 & 0 & \cdots & \cdots & \cdots & \cdots & 0 & h_1 & \cdots & h_{\lfloor m/2 \rfloor + 1} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{bmatrix}$$

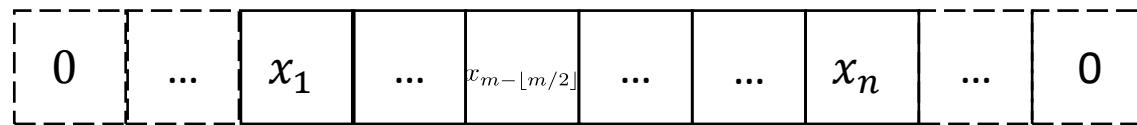
Matrix Multiplication View I

1D Convolution (Discrete) \Leftrightarrow Matrix Multiplication

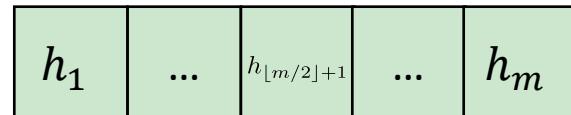
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Input x



Filter h



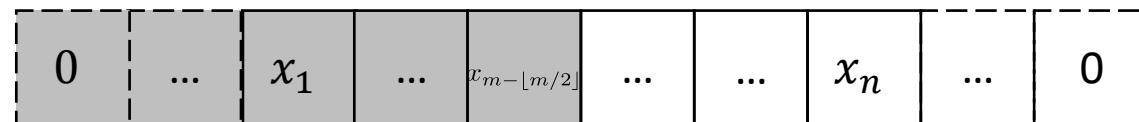
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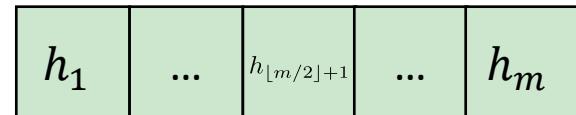
Filter \Rightarrow Toeplitz matrix (diagonal-constant)

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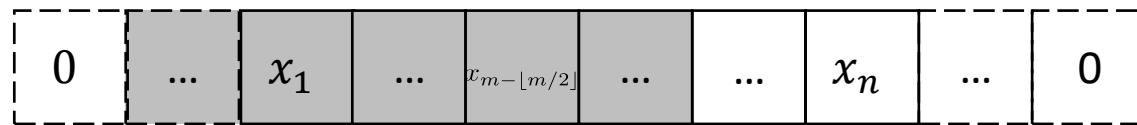
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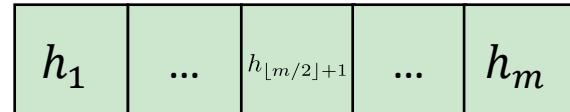
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Input x



Filter h



Matrix Multiplication View I

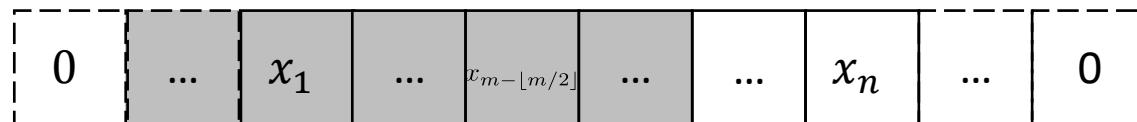
1D Convolution (Discrete) \Leftrightarrow Matrix Multiplication

Filter \Rightarrow Toeplitz matrix (diagonal-constant)

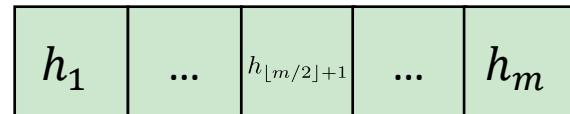
It could be very sparse (e.g., when $n \gg m$!)

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Input x



Filter h



Matrix Multiplication View II

1D Convolution (Discrete) \Leftrightarrow Matrix Multiplication

Data \Rightarrow Toeplitz matrix (diagonal-constant)

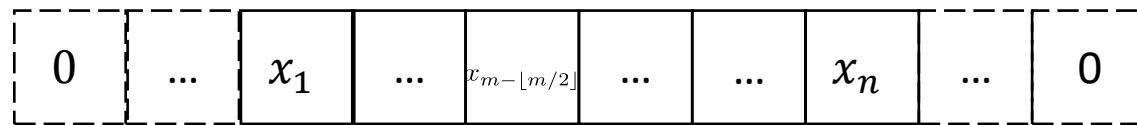
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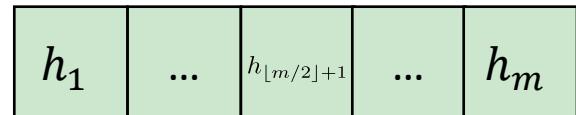
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$$y^\top = (h * x)^\top = [h_m \ h_{m-1} \ \cdots \ h_3 \ h_2 \ h_1] \begin{bmatrix} x_{m-\lfloor m/2 \rfloor} & x_{m-\lfloor m/2 \rfloor+1} & \cdots & x_m & x_{m+1} & \cdots & 0 & 0 \\ \vdots & \vdots & \cdots & x_{m-1} & x_m & \cdots & \vdots & \vdots \\ x_1 & x_2 & \cdots & \vdots & x_{m-1} & \cdots & x_n & 0 \\ 0 & x_1 & \cdots & \vdots & \vdots & \cdots & x_{n-1} & x_n \\ \vdots & 0 & \cdots & \vdots & \vdots & \cdots & \vdots & \vdots \\ 0 & 0 & \cdots & x_1 & x_2 & \cdots & x_{n-\lfloor m/2 \rfloor+1} & x_{n-\lfloor m/2 \rfloor} \end{bmatrix}$$

Input x



Filter h



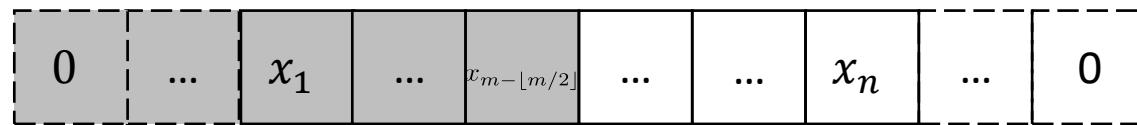
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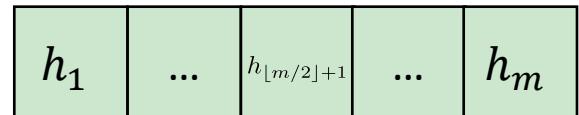
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Input x



Filter h



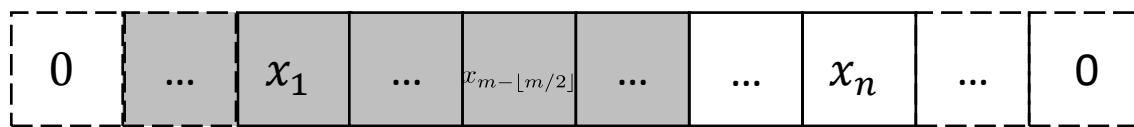
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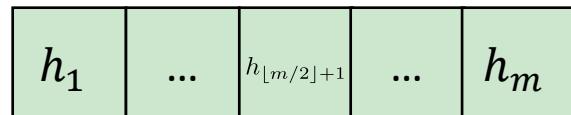
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Input x



Filter h



Matrix Multiplication View II

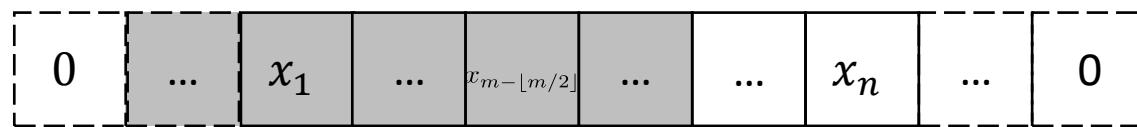
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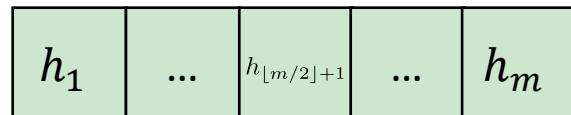
It could be dense (e.g., when $n \gg m$)!

$$y^\top = (h * x)^\top = [h_m \ h_{m-1} \ \dots \ h_3 \ h_2 \ h_1] \begin{bmatrix} x_{m-\lfloor m/2 \rfloor} & x_{m-\lfloor m/2 \rfloor+1} & \dots & x_m & x_{m+1} & \dots & 0 & 0 \\ \vdots & \vdots & \dots & x_{m-1} & x_m & \dots & \vdots & \vdots \\ x_1 & x_2 & \dots & \vdots & x_{m-1} & \dots & x_n & 0 \\ 0 & x_1 & \dots & \vdots & \vdots & \dots & x_{n-1} & x_n \\ \vdots & 0 & \dots & \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & 0 & \dots & x_1 & x_2 & \dots & x_{n-\lfloor m/2 \rfloor+1} & x_{n-\lfloor m/2 \rfloor} \end{bmatrix}$$

Input x



Filter h



Matrix Multiplication View II

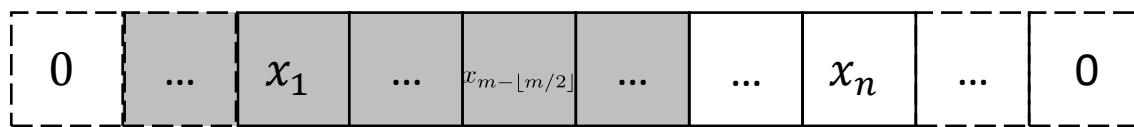
1D Convolution (Discrete) \Leftrightarrow Matrix Multiplication

Data \Rightarrow Toeplitz matrix (diagonal-constant)

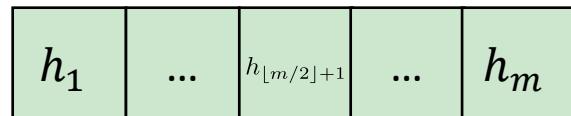
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This version is typically implemented on GPUs!

Matrix Multiplication View II

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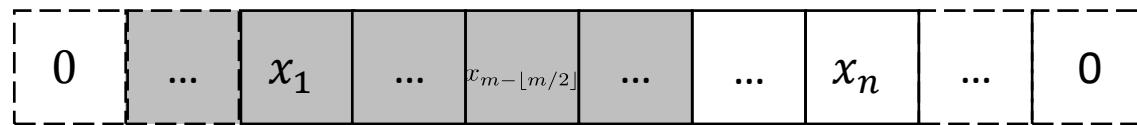
This equivalence holds for 2D and other higher-order convolutions!

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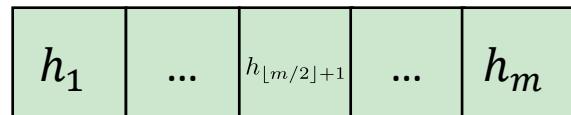
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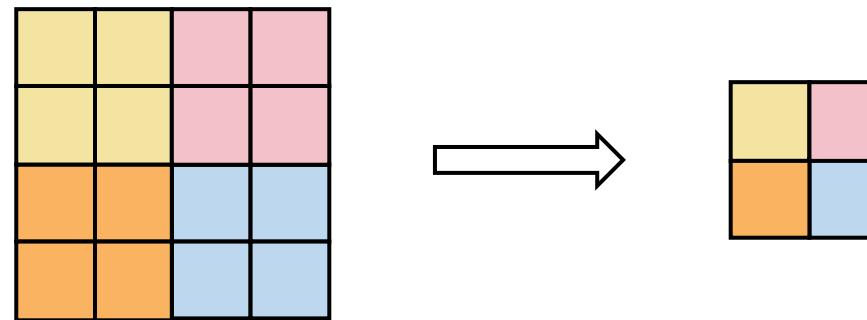


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Basic Deep Learning Models

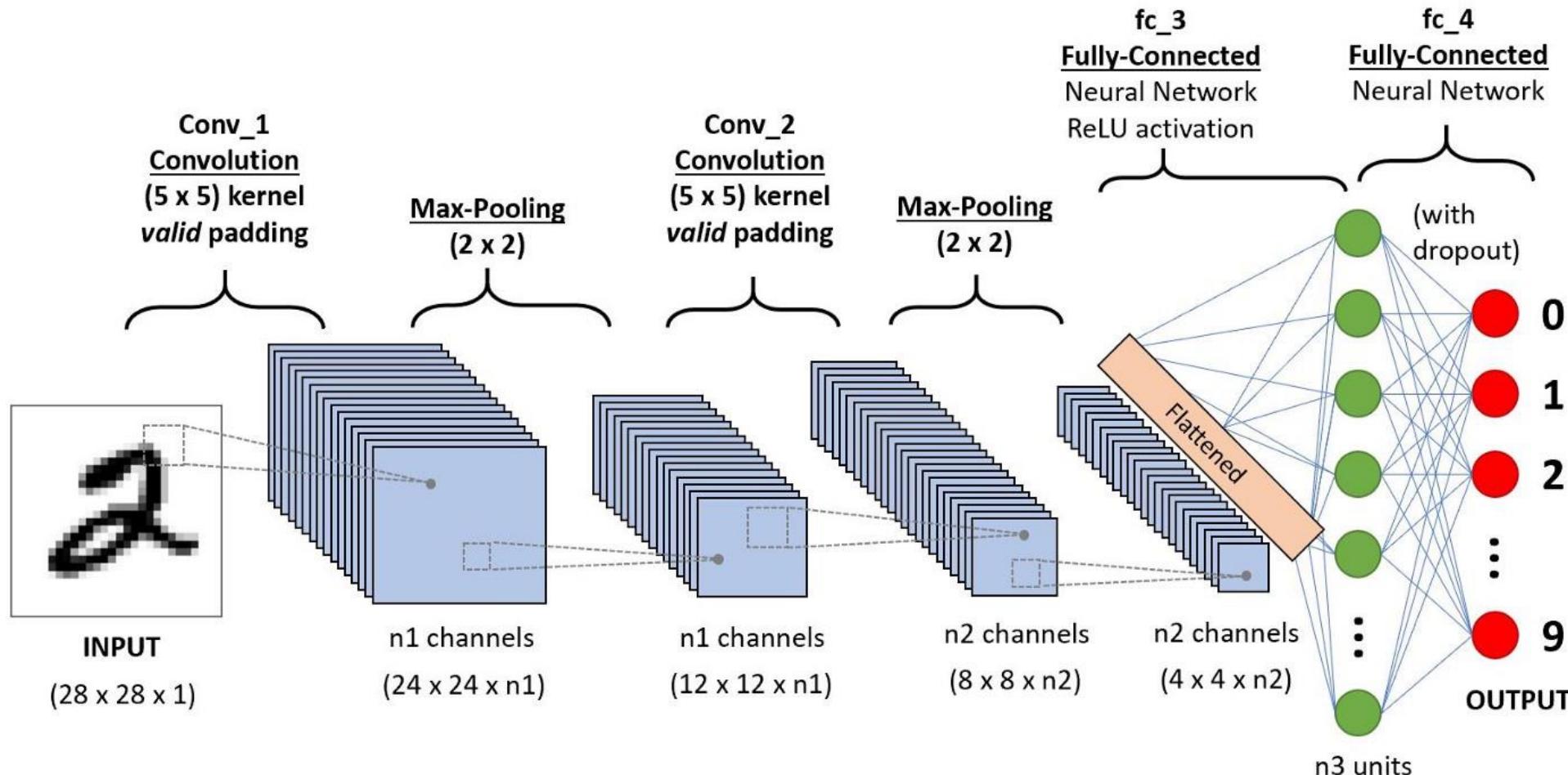
Convolutional Neural Network (CNN)

Pooling (e.g., 2X2)



Basic Deep Learning Models

Convolutional Neural Network (CNN)



Basic Deep Learning Models

Recurrent Neural Network (RNN)

Same neural network gets reused many times!

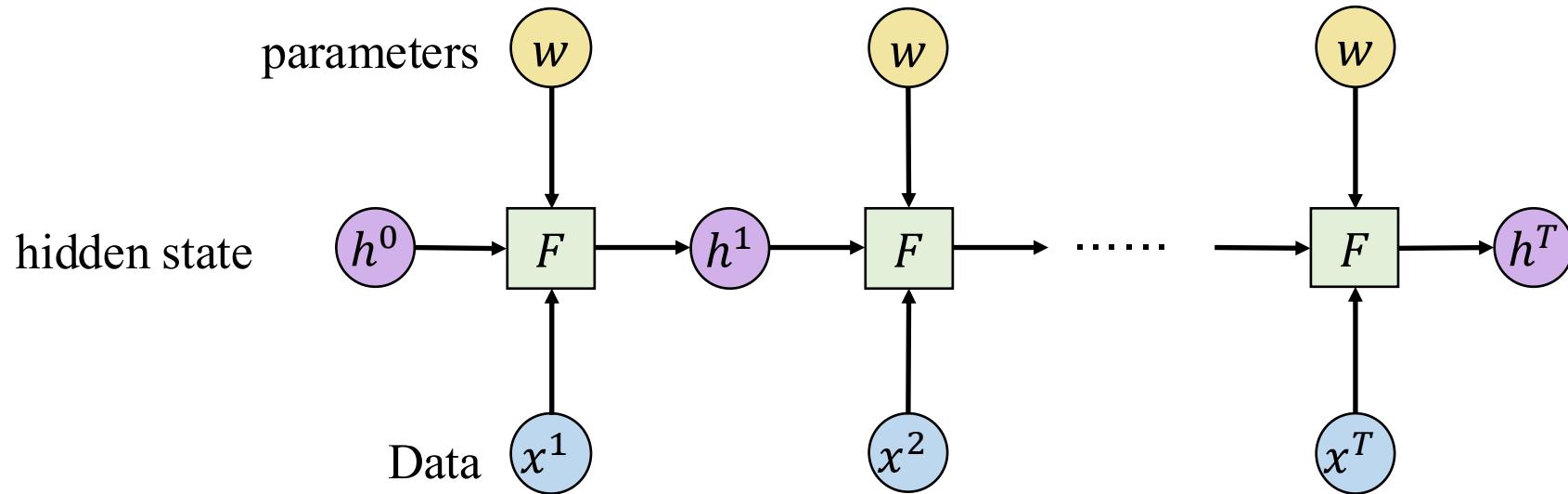
$$\mathbf{h}^t = F(\mathbf{x}^t, \mathbf{h}^{t-1}, W)$$

Basic Deep Learning Models

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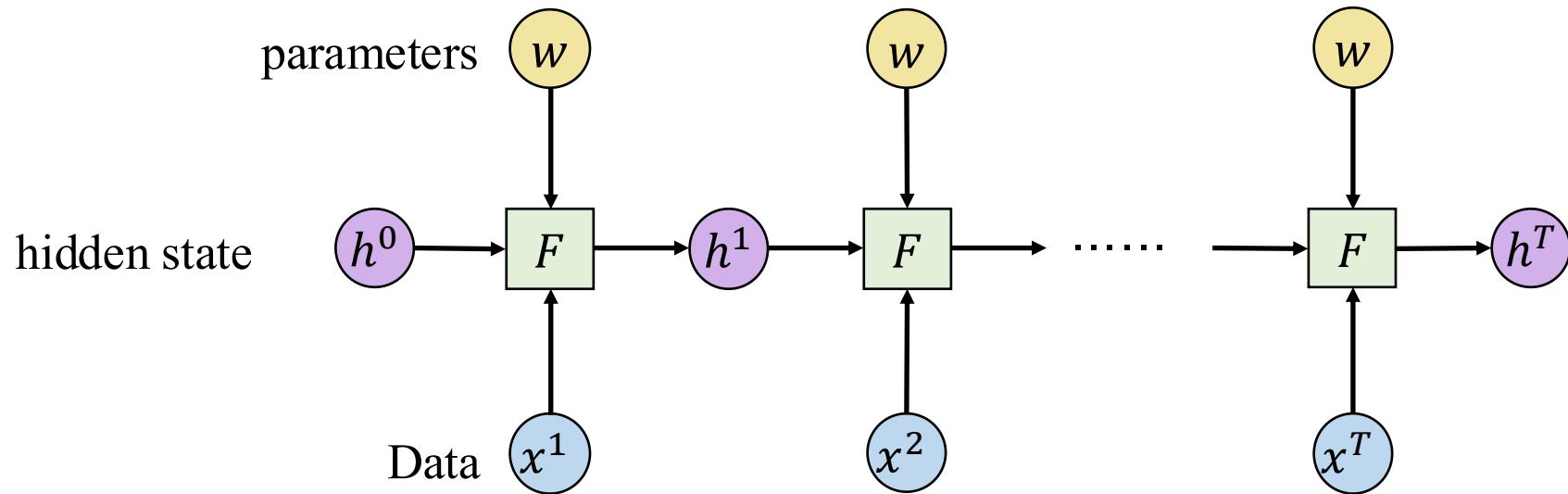


Basic Deep Learning Models

Recurrent Neural Network (RNN)

Same neural network gets reused many times!

$$\mathbf{h}^t = F(\mathbf{x}^t, \mathbf{h}^{t-1}, W)$$



F could be any neural network!

Outline

- Brief Introduction & History & Application
- Basic Deep Learning Models
 - Multi-Layer Perceptron (MLP)
 - Convolutional Neural Network (CNN)
 - Recurrent Neural Network (RNN)
- **Objective Function**
- Learning Algorithm: Back-propagation
- Limitations

Objective (Loss) Function

- Supervised Learning

Given (data, label), we want to minimize empirical risk/loss

Loss = Function(label, model(data))

Objective (Loss) Function

- Supervised Learning **Empirical Risk Minimization (ERM)!**

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Cross-Entropy Loss:

$$\ell(p, q) = - \sum_{i=1}^K p_i \log q_i$$

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- Supervised Learning

Empirical Risk Minimization (ERM)!

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Cross-Entropy Loss:

$$\ell(p, q) = - \sum_{i=1}^K p_i \log q_i$$

- Regression

Mean-Squared Error (MSE):

$$\ell(\mathbf{x}, \mathbf{y}) = \frac{1}{K} \|\mathbf{x} - \mathbf{y}\|_2^2$$

Objective (Loss) Function

Unsupervised/Self-supervised Learning

Only data is given

Objective (Loss) Function

Unsupervised/Self-supervised Learning

Only data is given

- Likelihood (Autoregressive models)
- Reconstruction Loss (Auto-encoders)
- Contrastive Loss (noise contrastive estimation, self-supervised learning)
- Min-max Loss (Generative adversarial networks)

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.....

Designing a good objective function itself is a challenging research question!

Objective (Loss) Function

- **"Pure" Reinforcement Learning (cherry)**

- ▶ The machine predicts a scalar reward given once in a while.
- ▶ **A few bits for some samples**

- **Supervised Learning (icing)**

- ▶ The machine predicts a category or a few numbers for each input
- ▶ Predicting human-supplied data
- ▶ **10→10,000 bits per sample**

- **Unsupervised/Predictive Learning (cake)**

- ▶ The machine predicts any part of its input for any observed part.
- ▶ Predicts future frames in videos
- ▶ **Millions of bits per sample**

- **(Yes, I know, this picture is slightly offensive to RL folks. But I'll make it up)**



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Learning algorithm is about **credit assignment**

Assign credits based on contribution \Leftrightarrow Adjust parameters based on loss

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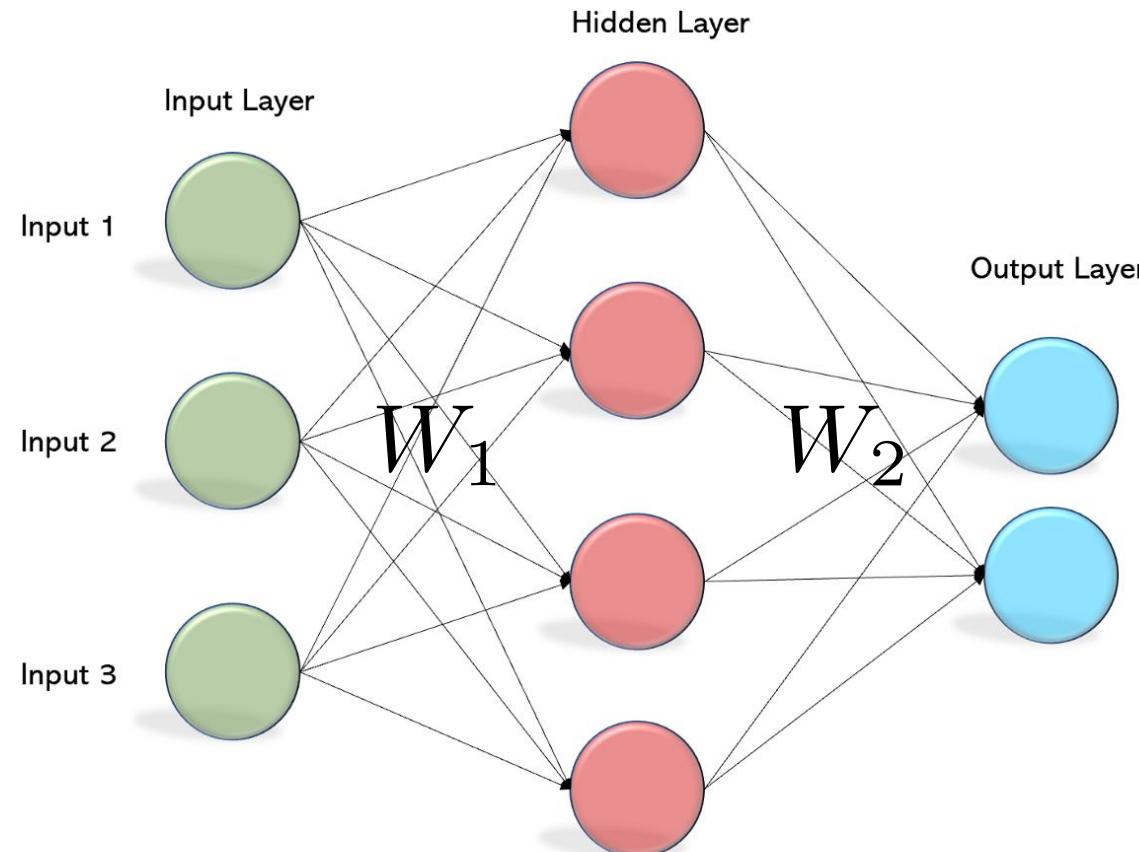
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Back-propagation (BP) = SGD in the context of deep learning

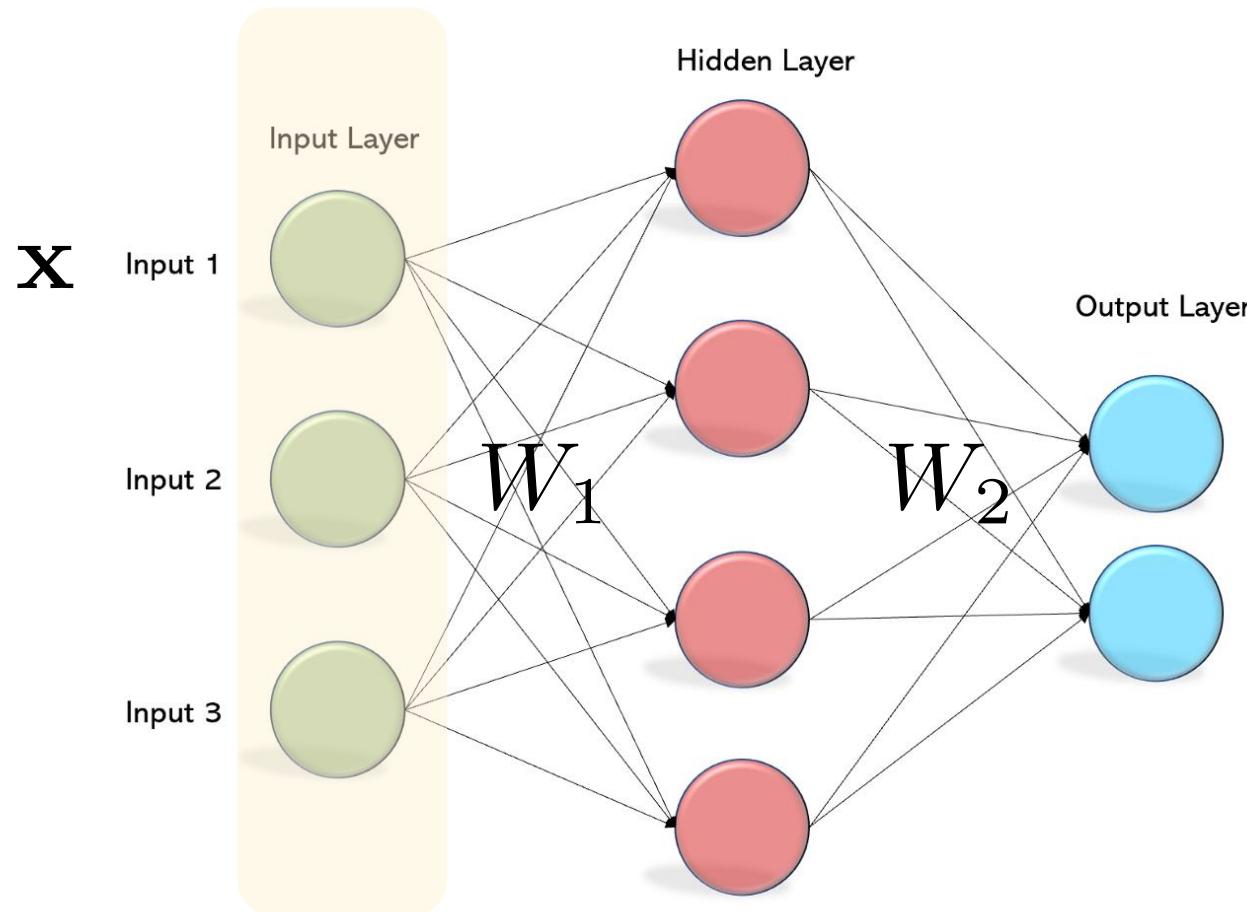
Back-Propagation

Multi-Layer Perceptron (MLP)



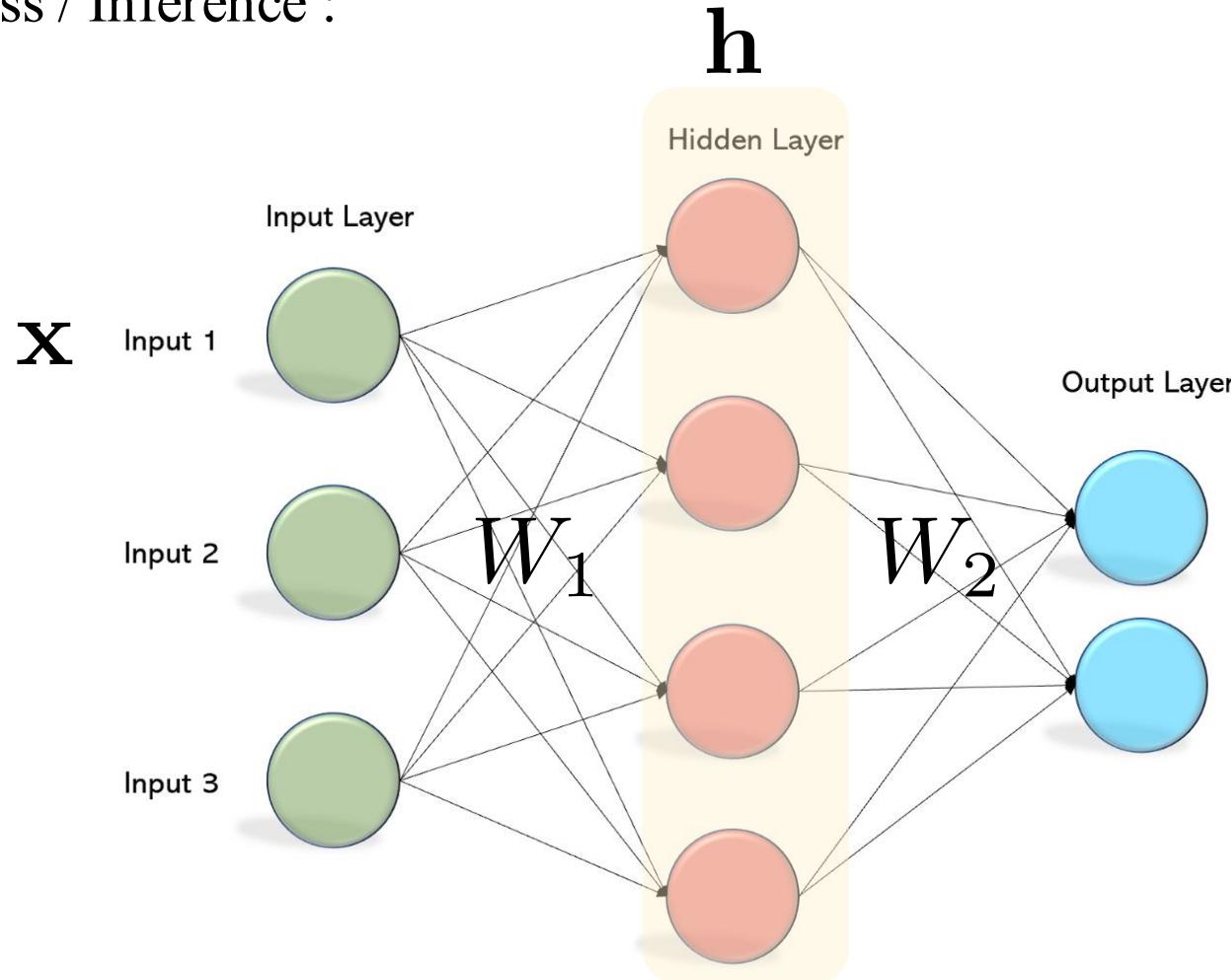
Back-Propagation

Forward Pass / Inference :



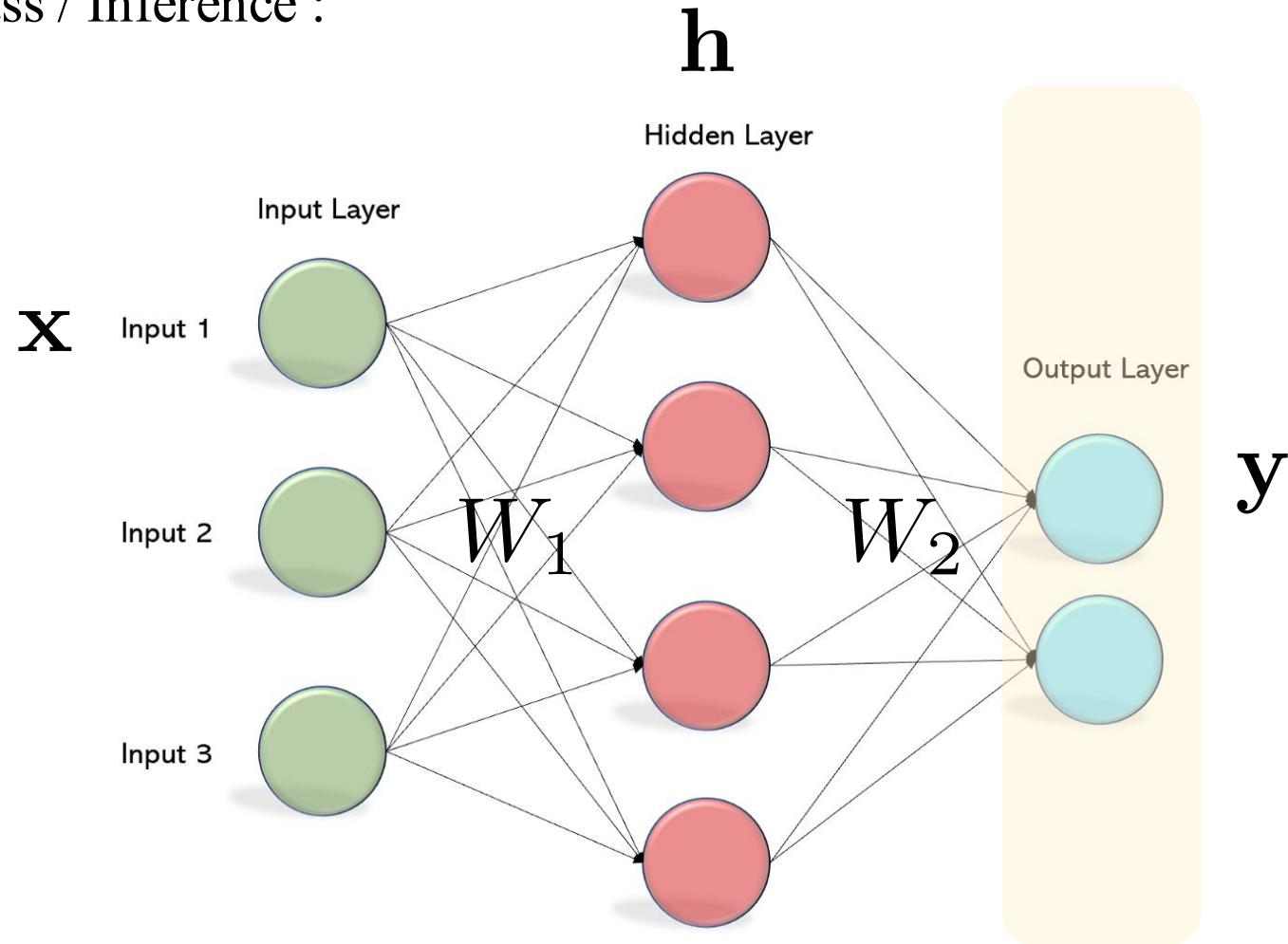
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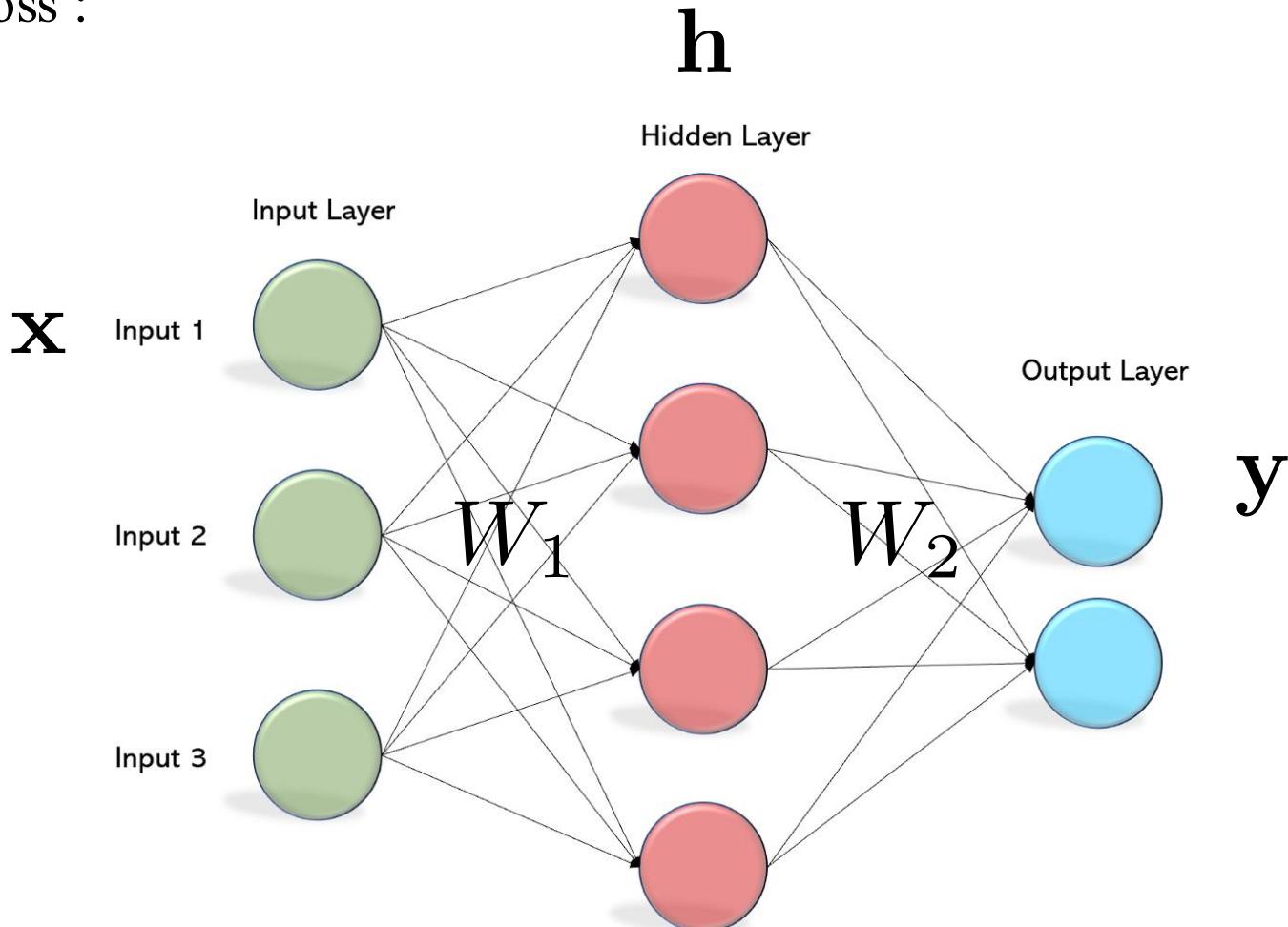
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Back-Propagation

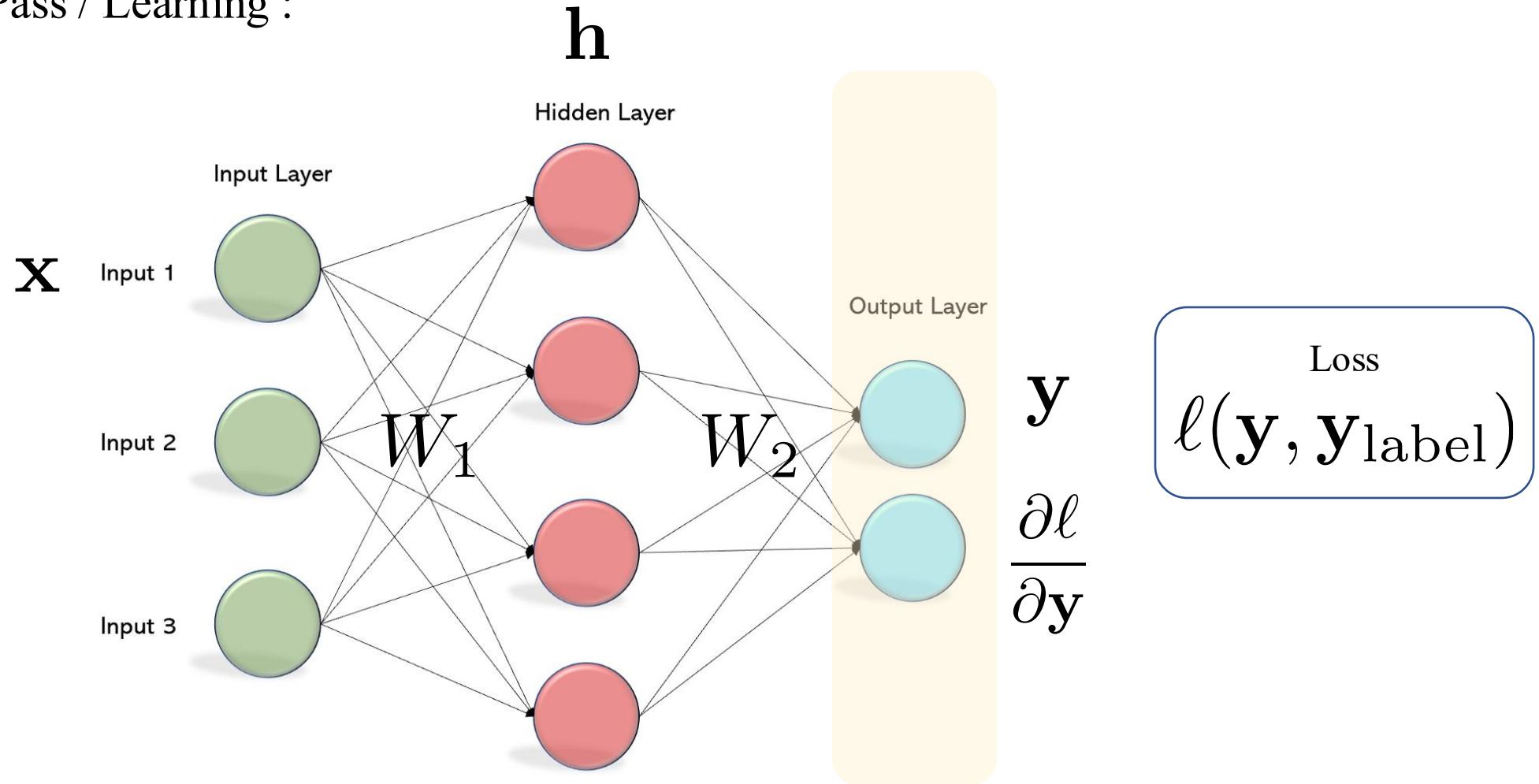
Compute Loss :



Loss
 $\ell(\mathbf{y}, \mathbf{y}_{\text{label}})$

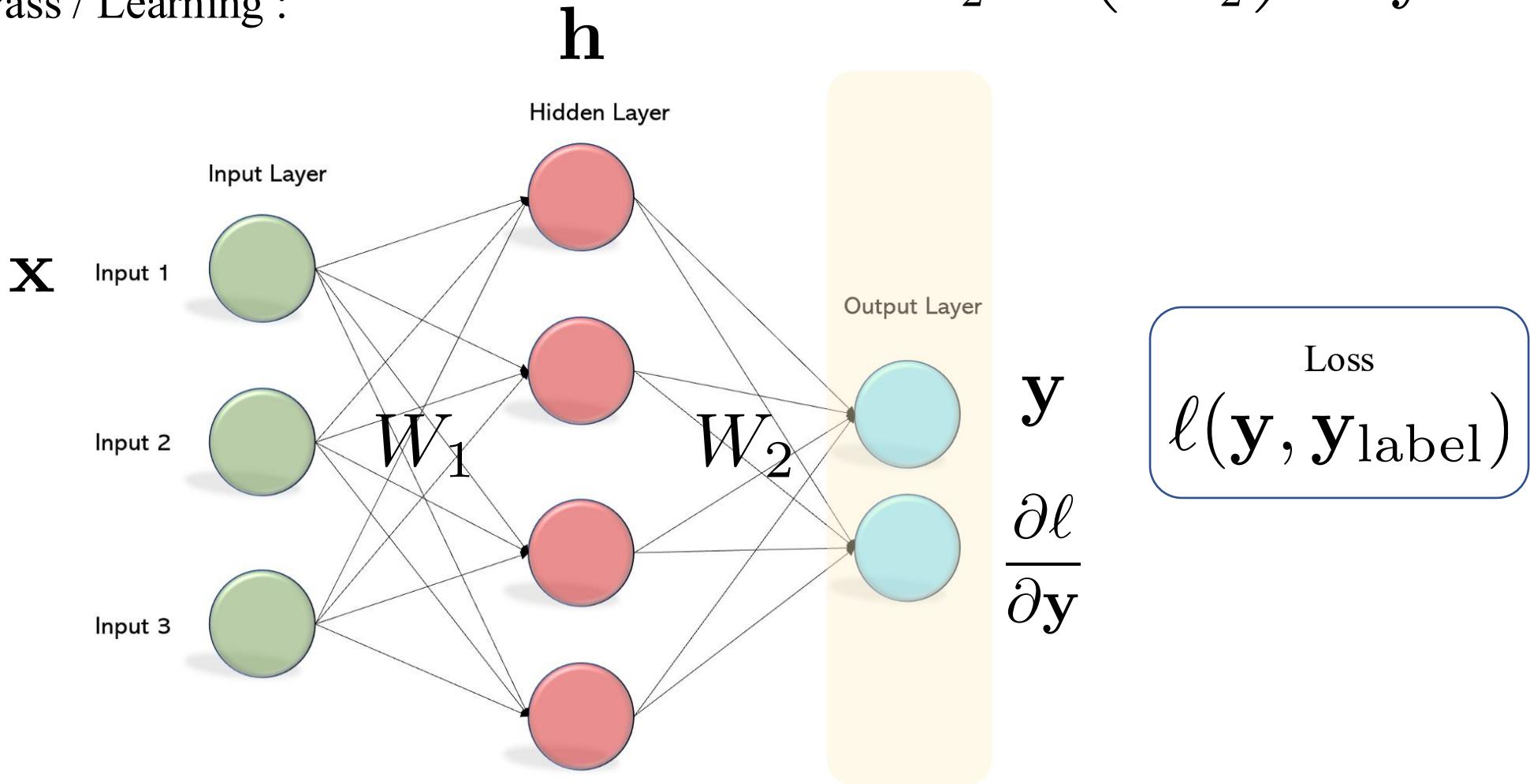
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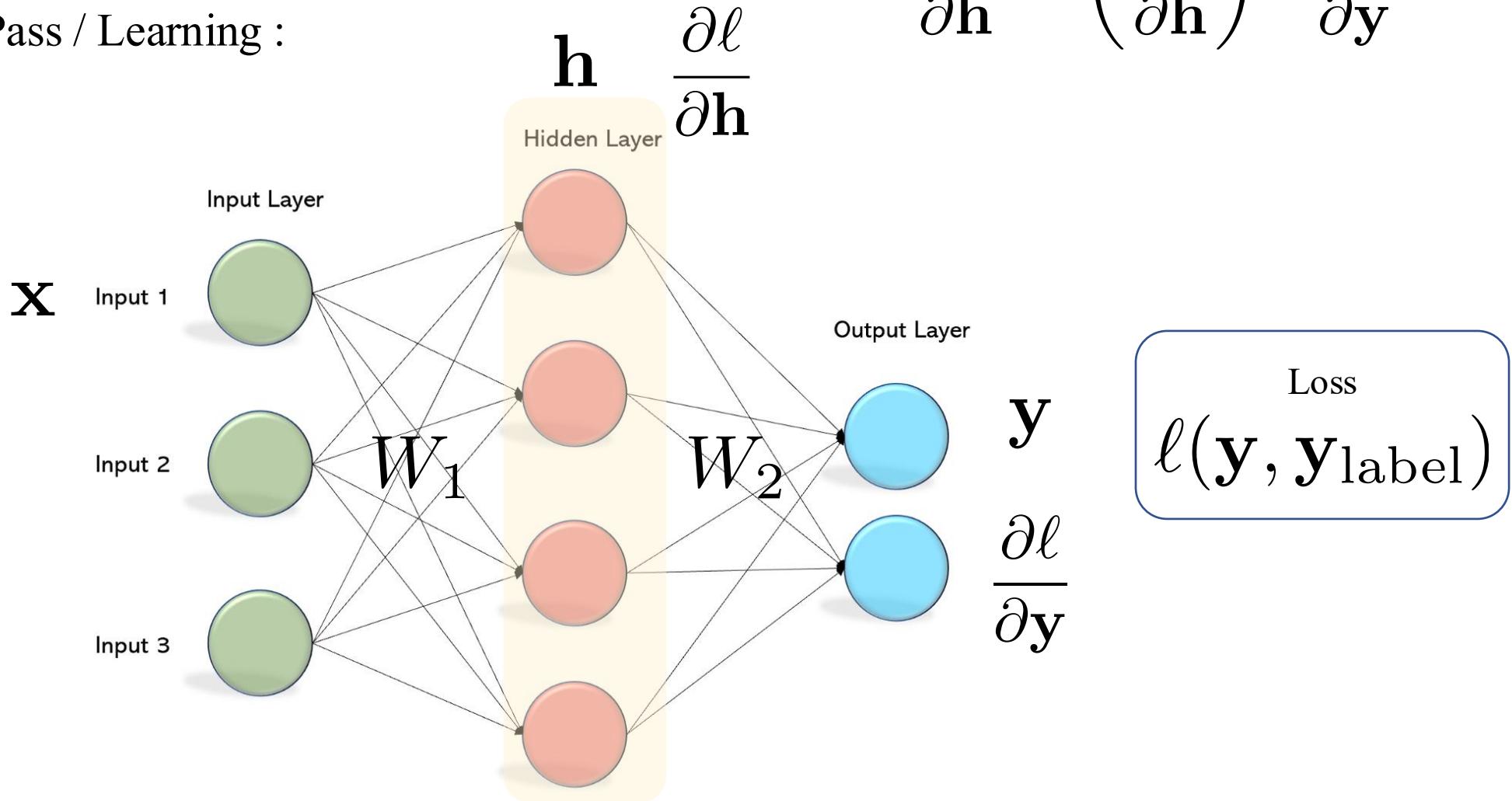
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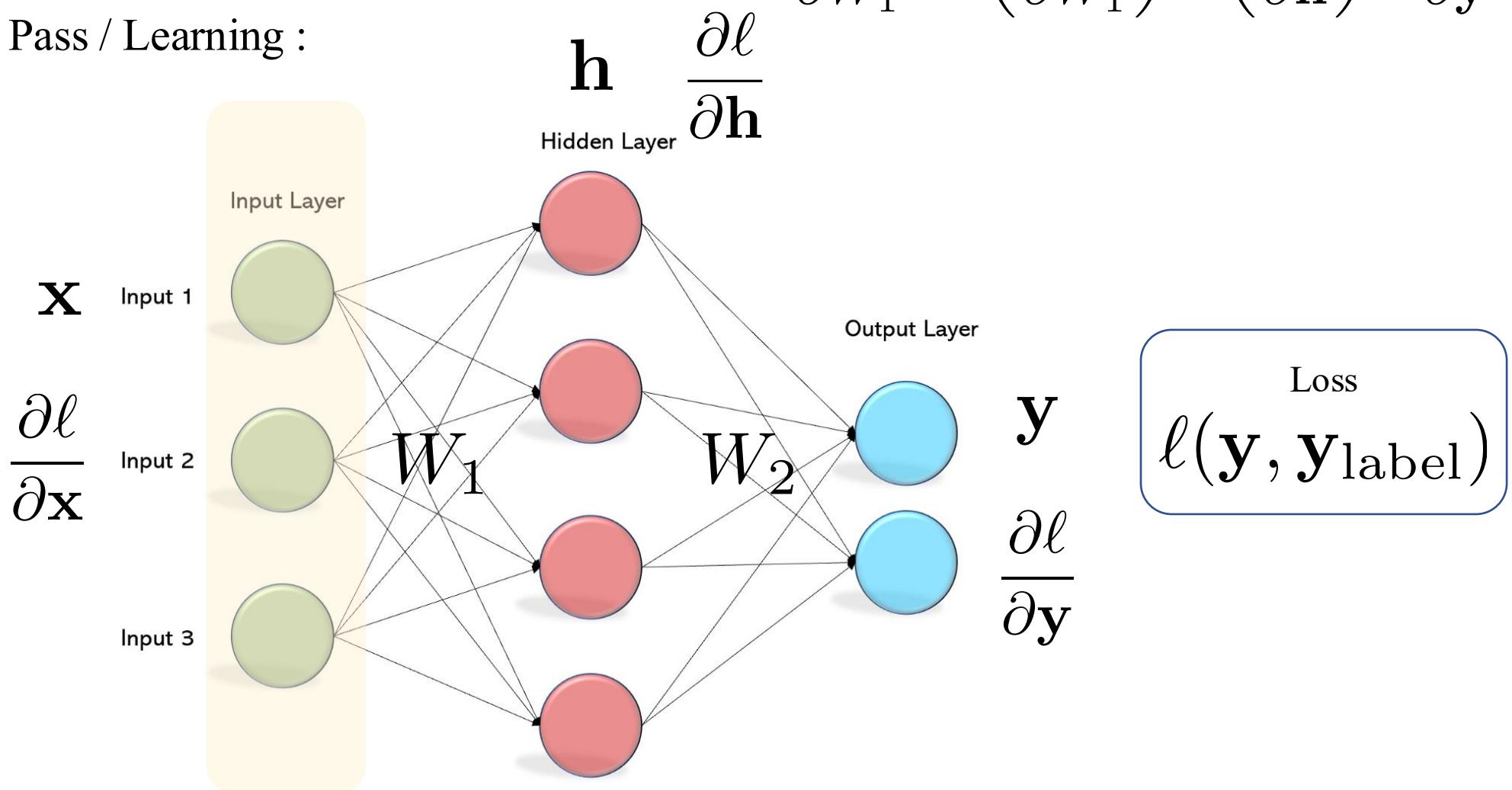
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- MLPs/CNNs are restricted to data with fixed size
 - Each sample needs to have the same size
- RNNs can deal with varying-size data
 - Only presented as sequences
- Learned representations do not explicitly encode structures of data
 - Hard to interpret and manipulate

Questions?