



# Introduction to Deep Learning and Transfer Learning



## Input/output

- **Goal:** infer a function from an input (often tensor) space to an output (often tensor) space,  $\mathbf{y} = f(\mathbf{x})$ ,
- **Example:** input can be an image, output a vector where the largest value indicate the category the image belongs to.

## Error/Loss

- **Loss  $\mathcal{L}$ :** nonnegative measure of the discrepancy between expected output  $\hat{\mathbf{y}}$  and obtained output  $\mathbf{y}$ .
- **Example:** output should be  $[0, 1]$  but is  $[0.2, 0.8]$ .

## Parameters

- $f = f_{\mathbf{w}}$  contains **parameters  $\mathbf{W}$**  to be trained,
- In most cases, an ideal  $f_{\mathbf{w}}$  exists but is **hard to find in practice**,
- Learning is a **regression ill-posed** problem.

2022-02-07

## Introduction to Deep Learning and Transfer Learning

└ Global formalism

Loss: it's a way to tell the model when it is wrong and train the model accordingly. The model contains parameters (model weights and bias) and usually, given a task, an optimal set of parameters exist but again finding it is ill posed problem (many solutions exists)

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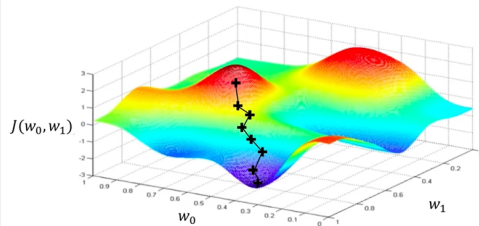
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- **Loss:**  $J(\mathbf{W}) = \sum_i \mathcal{L}(f(\mathbf{x}^{(i)}, \mathbf{W}), \mathbf{y}^{(i)}), i = \text{examples}$
- Model parameters:  $\mathbf{W}^* = \text{argmin}(J(\mathbf{W}))$

## Training Algorithm

- Randomly Initialize model weights
- Compute Gradient of the Loss  $\frac{\partial J(\mathbf{W})}{\partial \mathbf{W}}$
- Update weights  $\mathbf{W} \leftarrow \mathbf{W} - \eta \frac{\partial J(\mathbf{W})}{\partial \mathbf{W}}$
- Repeat until convergence



from MIT course [introtodeeplearning.com](https://introtodeeplearning.com)

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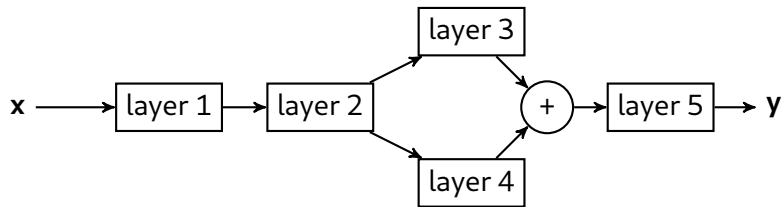
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The total loss  $J$  (Empirical Risk, Objective function) is the average of Loss for each input/example and the optimal model parameters are those that minimize it. But how to find them? In other words, how to train the model? Here is a simplified description of the training algorithm at the base of modern DL, gradient descent. Repeat until reaching a local minimum (as illustrated in the figure for a simple example where we have only 2 parameters. We'll see that the function becomes much more complicated for millions of parameters -modern neural networks.)

## Main idea

- **Compositional Approach:** Instead of directly mapping  $\mathbf{x}$  to  $\mathbf{y}$ , express solutions as an assembly of simple mathematical functions called **layers**
- **End-to-end learning:** Tune all atomic functions together
- **Training:** Backpropagate throughout the architecture (to compute the gradient of the loss wrt all layers parameters)



2022-02-07

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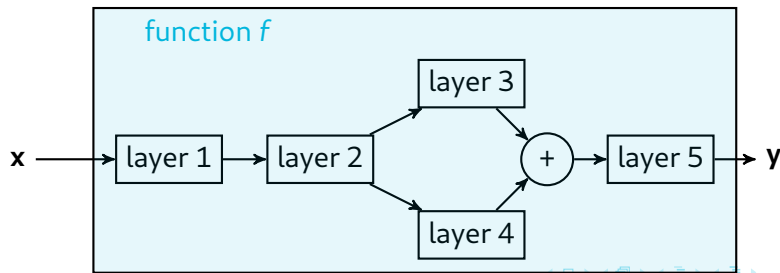
The small diagram shows an input  $x$  entering a box labeled 'layer 1'. The output of 'layer 1' goes into a box labeled 'layer 2'. From 'layer 2', the path splits into two parallel branches: a box labeled 'layer 3' and a box labeled 'layer 4'. The outputs of 'layer 3' and 'layer 4' are combined at a summation node (represented by a circle with a '+'). The output of this summation node then enters a box labeled 'layer 5', which produces the final output  $y$ .

DL at its core is the ability to learn higher and higher level representations or features from data in an end-to-end fashion. How? By means of a compositional approach of simple mathematical functions (layers). Representations are useful to interpret data: ideally the final representation should be easy to deal with (to classify, to generate data from...). What is new about DL is that we do that in an end-to-end fashion starting from raw data. Also, in DL, we use deep architectures with hidden layers to approximate any complex function  $f$ . So the fundamental blocks of NN are layers, each layer has its own parameters (weights and bias) that need to be trained.

# Deep learning

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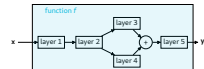
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└ Deep learning

Deep learning

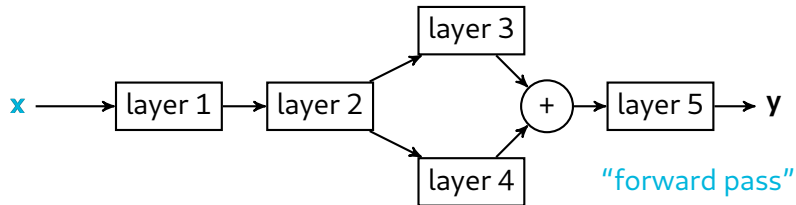
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2022-02-07

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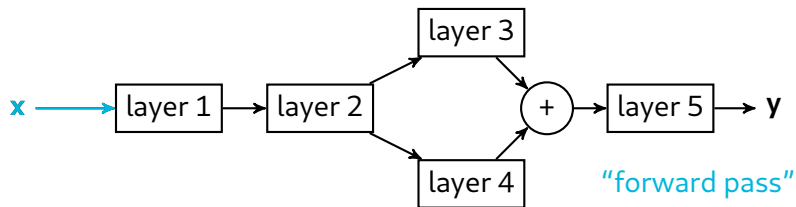
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As we have seen the model is trained by calculating the gradient of the loss wrt to each layer parameters. How do we calculate gradients? Using backpropagation: efficient way to compute the gradient of the loss with respect to different layers parameters, using the derivative chain rule. The model weights are then updated with the rule we have seen  $\mathbf{W} \leftarrow \mathbf{W} - \eta \frac{\partial J(\mathbf{W})}{\partial \mathbf{W}}$  so that those responsible for producing the right output are increased, and the other decreased.



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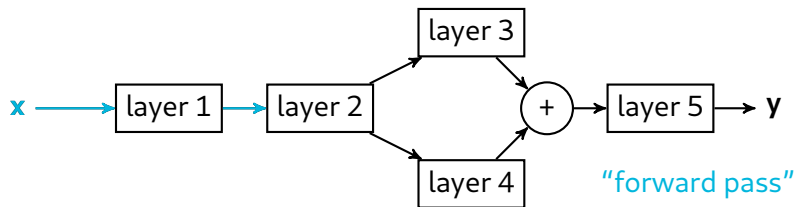
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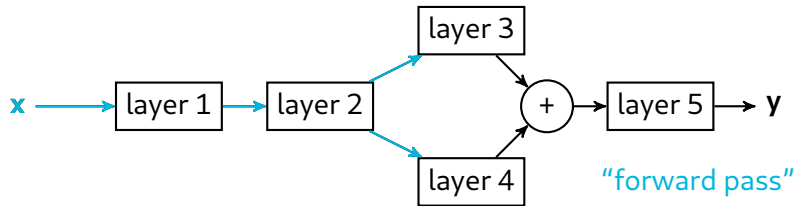
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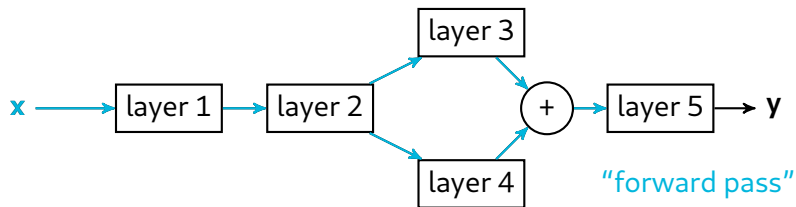
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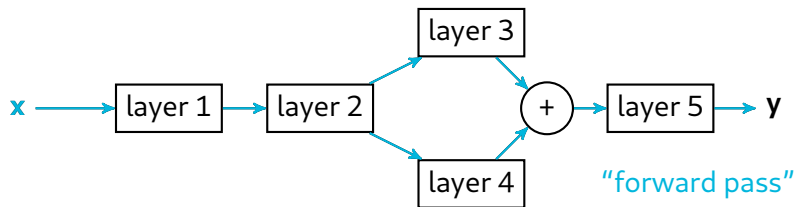
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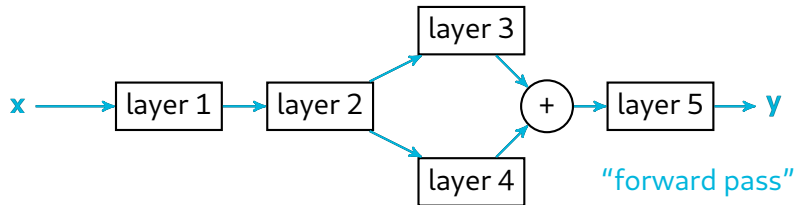
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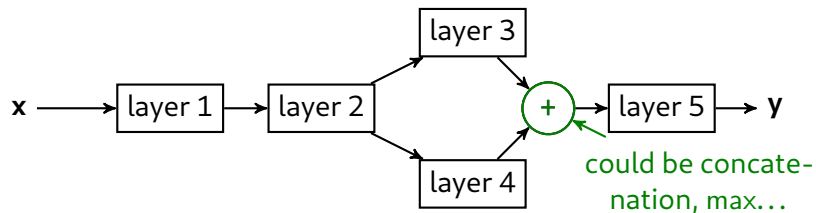
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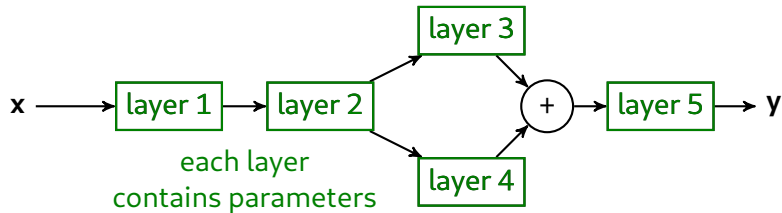
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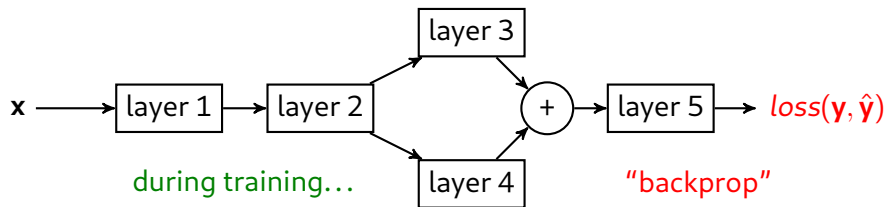
A small diagram of a deep learning architecture with 5 layers. It starts with an input  $x$  entering a box labeled 'layer 1'. An arrow points from 'layer 1' to 'layer 2'. From 'layer 2', two arrows branch out to 'layer 3' and 'layer 4'. Both 'layer 3' and 'layer 4' have arrows pointing to a circular node containing a plus sign '+'. An arrow from this node points to 'layer 5', which finally outputs  $y$ . Below the first three layers, the text 'each layer contains parameters' is written in green.

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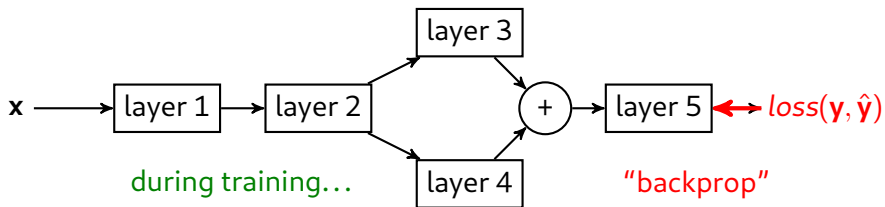
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The small diagram shows an input  $x$  passing through layer 1, then layer 2, which branches into layer 3 and layer 4. These merge at a summation node (+), followed by layer 5, resulting in the loss  $loss(y, \hat{y})$ . The forward pass is labeled "during training..." and the backward pass is labeled "backprop".

As we have seen the model is trained by calculating the gradient of the loss wrt to each layer parameters. How do we calculate gradients? Using backpropagation: efficient way to compute the gradient of the loss with respect to different layers parameters, using the derivative chain rule. The model weights are then updated with the rule we have seen  $\mathbf{W} \leftarrow \mathbf{W} - \eta \frac{\partial J(\mathbf{W})}{\partial \mathbf{W}}$  so that those responsible for producing the right output are increased, and the other decreased.

## Main idea

- **Compositional Approach:** Instead of directly mapping  $\mathbf{x}$  to  $\mathbf{y}$ , express solutions as an assembly of simple mathematical functions called **layers**
- **End-to-end learning:** Tune all atomic functions together
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2022-02-07

## Introduction to Deep Learning and Transfer Learning

└ Deep learning

Deep learning

Main idea

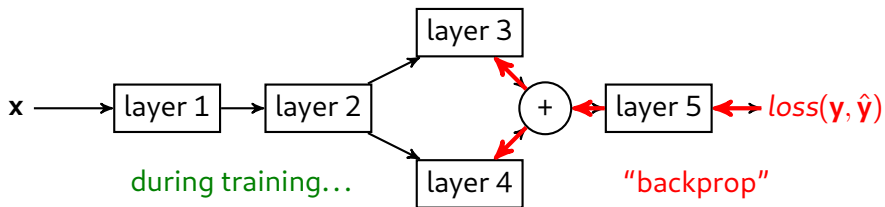
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The small diagram shows an input  $x$  passing through layer 1, layer 2, layer 3, layer 4, and layer 5. Layer 2 branches into layer 3 and layer 4, which merge at a summation node (+). The output of layer 5 is compared with the target  $y$  to calculate the loss  $loss(y, \hat{y})$ . The forward pass is labeled "during training..." in green, and the backward pass is labeled "backprop" in red.

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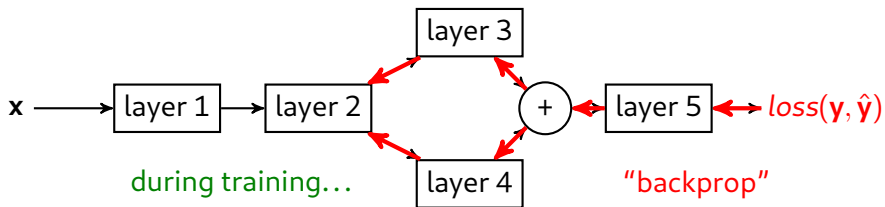
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The small diagram shows an input  $x$  entering 'layer 1', which connects to 'layer 2'. 'layer 2' connects to both 'layer 3' and 'layer 4'. The outputs of 'layer 3' and 'layer 4' are combined at a summation node (a circle with a '+'). The output of this node goes to 'layer 5', which outputs the loss function  $loss(y, \hat{y})$ . Red arrows indicate the backpropagation path from the loss back through 'layer 5', the summation node, and then through 'layer 3' and 'layer 4' back to 'layer 2'. The text 'during training...' is written in green below 'layer 1', and '"backprop"' is written in red below the summation node.

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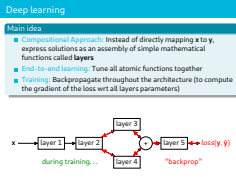
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## Introduction to Deep Learning and Transfer Learning

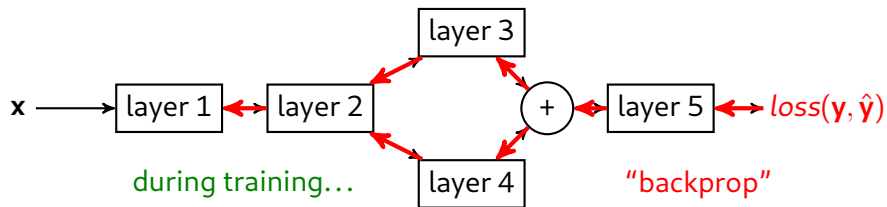
└ Deep learning



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## Introduction to Deep Learning and Transfer Learning

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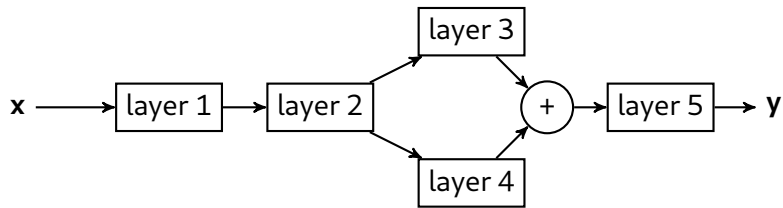
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A small version of the diagram described above, showing the flow from input  $x$  through layers 1, 2, 3, 4, 5 to a loss function, with forward (red) and backward (green) passes indicated.

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# Some additional details

## Layers

- $\mathbf{x} \mapsto h(\mathbf{W}\mathbf{x} + \mathbf{b})$ .
  - $h$  is a nonlinear parameterwise function (often without parameters),
  - $\mathbf{W}$  is a tensor:
    - Can be agnostic of the structure: **fully-connected layers**,
    - Can be structure-dependent: **convolutional layers**.

## Introduction to Deep Learning and Transfer Learning

### Some additional details

Non linearity: approximate complex functions! Otherwise combination of linear transformations.

# Some additional details

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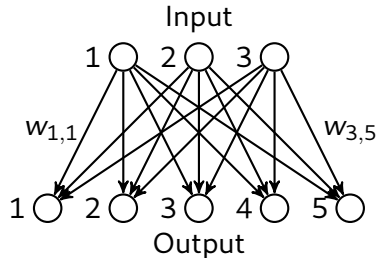
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### Fully connected layer



$$\begin{pmatrix} w_{1,1} & w_{1,2} & w_{1,3} & w_{1,4} & w_{1,5} \\ w_{2,1} & w_{2,2} & w_{2,3} & w_{2,4} & w_{2,5} \\ w_{3,1} & w_{3,2} & w_{3,3} & w_{3,4} & w_{3,5} \end{pmatrix}$$

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Fully connected layer

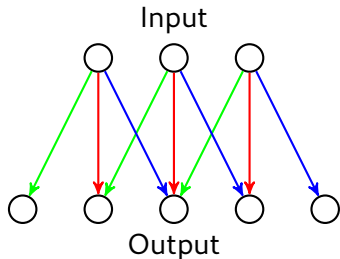
A small diagram of a fully connected layer with 3 input nodes and 5 output nodes, similar to the one in the main slide.

# Some additional details

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## Convolutional layer



$$\begin{pmatrix} w_1 & w_2 & w_3 & 0 & 0 & 0 \\ 0 & w_4 & w_5 & w_6 & 0 & 0 \\ 0 & 0 & w_7 & w_8 & w_9 & 0 \end{pmatrix}$$

Some additional details

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Layers

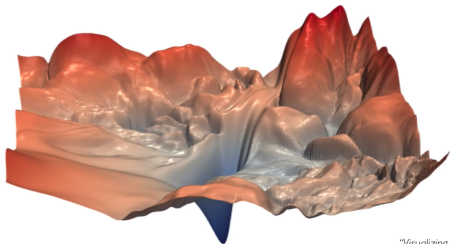
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Convolutional layer

Diagram illustrating a convolutional layer. The input layer has three nodes, and the output layer has five nodes. The connections are colored: green, red, and blue. The green connections represent the first filter (weights  $w_1, w_2, w_3$ ), the red connections represent the second filter (weights  $w_4, w_5, w_6$ ), and the blue connections represent the third filter (weights  $w_7, w_8, w_9$ ). The output nodes are connected to the input nodes in a way that shows the sliding window of the convolution operation.

## Some additional details

### Training Neural Networks is Difficult



"Visualizing the loss landscape of neural nets". Dec 2017.

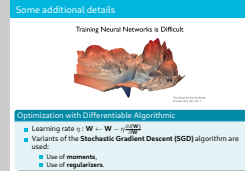
### Optimization with Differentiable Algorithmic

- Learning rate  $\eta$  :  $\mathbf{W} \leftarrow \mathbf{W} - \eta \frac{\partial J(\mathbf{W})}{\partial \mathbf{W}}$
- Variants of the **Stochastic Gradient Descent (SGD)** algorithm are used:
  - Use of **moments**,
  - Use of **regularizers**.

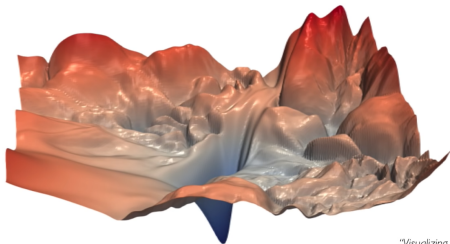
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### └ Some additional details

Training a NN is a challenging task: this picture represents the loss landscape of a typical DL network with million of parameters, something very different from the version we have seen before for 2 parameters, extremely complex and with many local minima. Optimization depends of different factors but one of the most crucial one is the learning rate (the fraction of the gradient that is subtracted from the loss) as it determines the convergence of the SGD: it should be large enough to avoid local minima, but small enough to converge. Most of modern implementation use an adaptive lr (increase, decrease during training): try out different adaptive schemes during the lab! Also different optimizers, all variants of SGD can be explored. To increase generalization (or in other words, avoid overfitting) different regularizations techniques. Momentum: help reduce variance: accumulates a decaying moving average of past gradients so the gradient step depends on how aligned past gradients are



## Training Neural Networks is Difficult



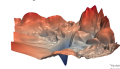
"Visualizing the loss landscape of neural nets". Dec 2017.

### Batches

- To accelerate computations, inputs are often treated **concurrently** using small **batches**.

### Some additional details

Backprop is computationally intensive if performed for each data example. One way to accelerate computation is to compute the gradient of batches (or small group) of training examples. This also gives a better estimate of the gradient, allows for parallelization and higher lr. Of course there is a tradeoff between higher speed (large batches) and better generalization: batch size is a hyperparameter itself. Recap: batch: gradient step, epoch: iteration over the entire dataset (ensemble of batches)



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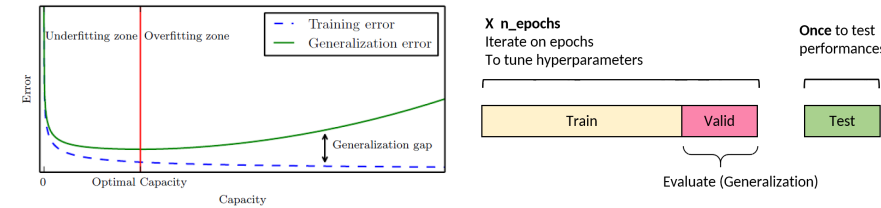
# Generalization vs Overfitting

## Learning Objectives

- Reduce the training error AND reduce the gap between training and **generalization error** (error on new inputs)
- Avoid **overfitting**, increase generalization for better performances on test set

## Validation Set

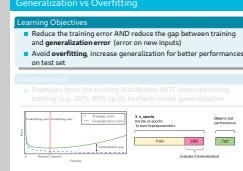
- Examples from the training distribution NOT observed during training (e.g. 20%, 80% sp lit) to check model generalization



2022-02-07

## Introduction to Deep Learning and Transfer Learning

### Generalization vs Overfitting



All these hyperparameters choices and regularization techniques have the objective to increase generalization or reduce overfitting. The typical model learning curves are showed in the left figure. In the left area when both train and generalization error are high we are in an underfitting regime: the model is not able to express the complexity of the dataset. When the gap between the generalization error and the train error increases we are specializing to much on the dataset (Overfitting regime). One way to assess this is to evaluate the performance on a validation set (split as figure on the right) and one popular regularization technique is the early stopping: stop training at the inflection point. There are many other regularization techniques (dropout: randomly set some model units to zero, also increases robustness; normalization of inputs, batch norm: normalization for intermediate features deeper in the network.)

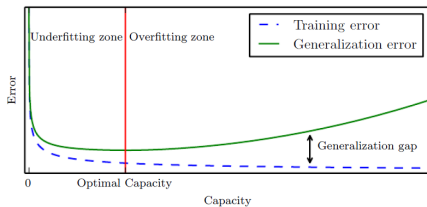
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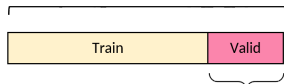
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X n\_epochs  
Iterate on epochs  
To tune hyperparameters



Once to test  
performances



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## Introduction to Deep Learning and Transfer Learning

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**Generalization vs Overfitting**

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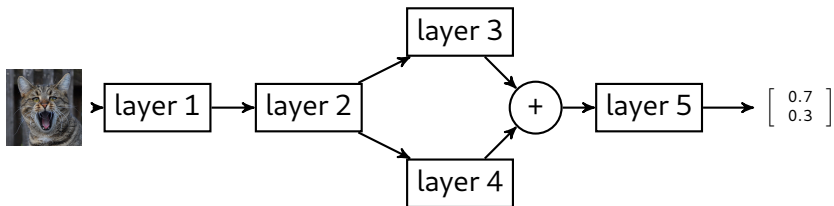
The small graph on the right shows the same concepts as the larger one. The workflow diagram below it shows 'Train' and 'Valid' phases in a single box, followed by a 'Test' phase in a separate box.

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# The case of deep learning in classification

## Inputs/outputs

- Often: inputs are **raw signals** or **feature vectors**,
- Often: outputs are vectors which **highest value** indicate the **category of the input**.



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└ The case of deep learning in classification

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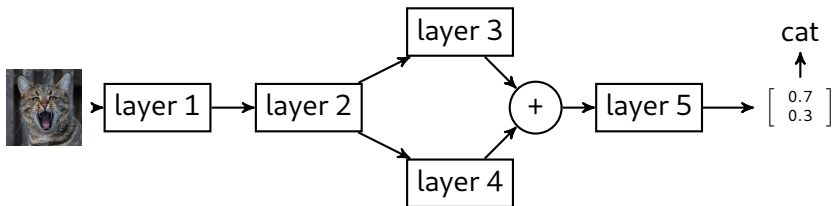
Softmax to generate a probability from numbers. Cross Entropy Loss (Shannon 50 years ago) compare how different the predicted and labels distribution are.



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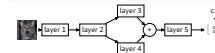
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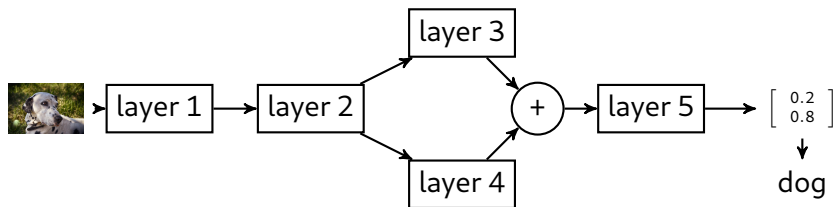


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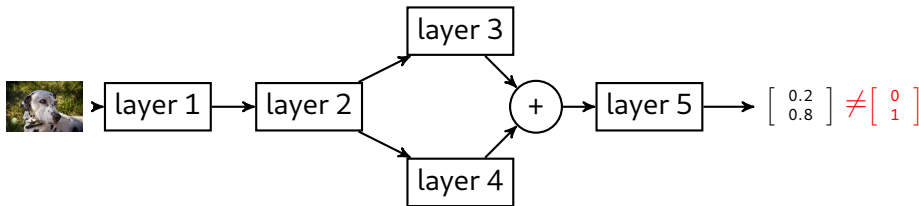


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## Loss and targets

- Labels are encoded as one-hot-bit vectors and called **targets**,
- Outputs are **softmaxed**:  $y_i \leftarrow \exp(\mathbf{y}_i) / \sum_j \exp(\mathbf{y}_j)$ ,
- Loss is typically **cross-entropy**:  $-\log(\hat{\mathbf{y}}^\top \mathbf{y})$ .

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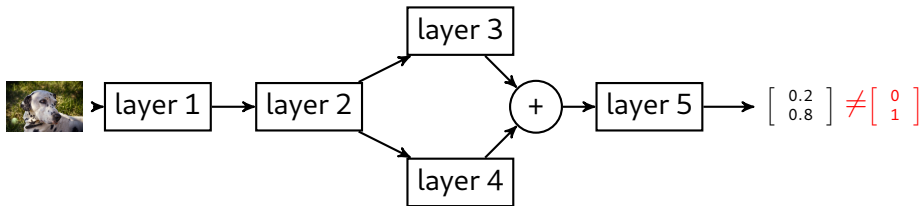
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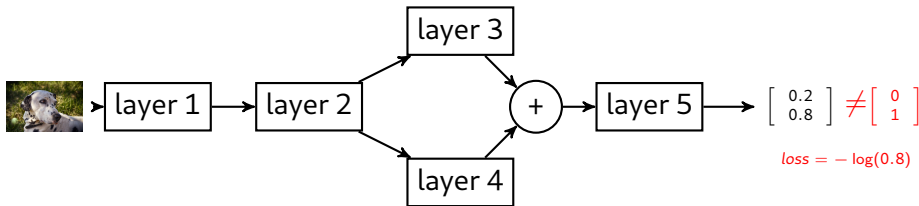
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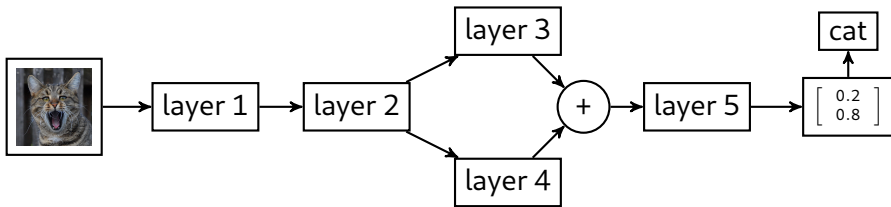
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# Transfer Learning and fine-tuning

Idea: use **feature vectors** from a **backbone** (pretrained) network to train a **downstream** classifier.

## Two usecases

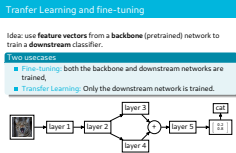
- **Fine-tuning:** both the backbone and downstream networks are trained,
- **Transfer Learning:** Only the downstream network is trained.



## Introduction to Deep Learning and Transfer Learning

### Transfer Learning and fine-tuning

An idea that is extensively applied in computer vision and more generally in DL is transfer learning. Consist in exploiting the knowledge of a network pretrained on a large dataset to adapt it for a novel, usually smaller and more specialized dataset/ classification task on dataset. 2 ways: Fine tuning: retrain for a few epochs the whole network on the novel dataset.

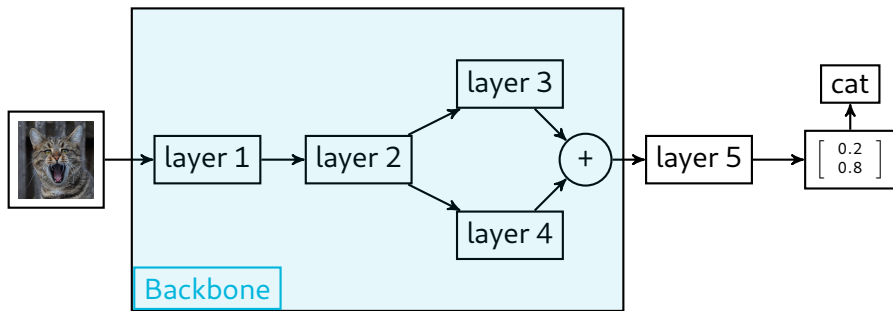


# Transfer Learning and fine-tuning

Idea: use **feature vectors** from a **backbone** (pretrained) network to train a **downstream** classifier.

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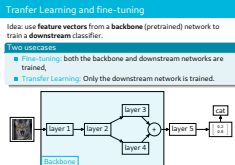
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## Introduction to Deep Learning and Transfer Learning

└ Transfer Learning and fine-tuning

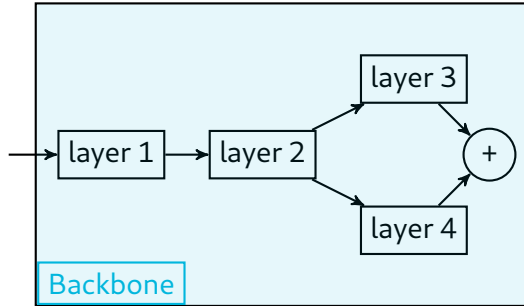


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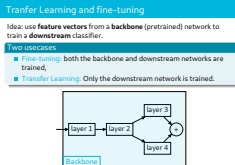
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## Introduction to Deep Learning and Transfer Learning

└ Transfer Learning and fine-tuning



Transfer Learning: chop out from the pretrained network the last dense/fully connected layers: this part is frozen and called backbone and only the final layer(s) are retrained on the novel dataset.

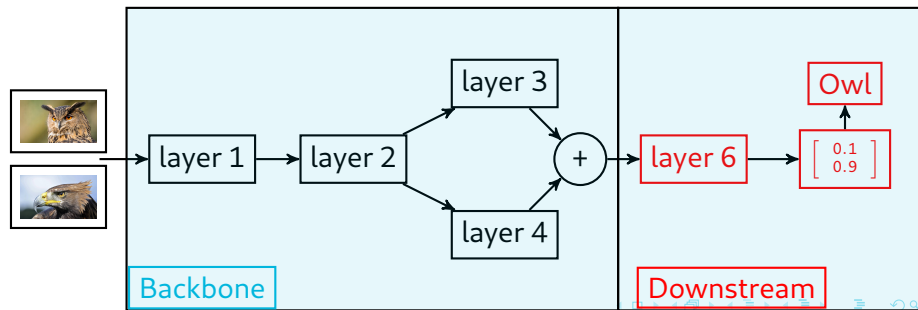


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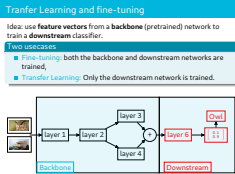
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## Introduction to Deep Learning and Transfer Learning

└ Transfer Learning and fine-tuning



These two techniques can obviously be combined! And are very useful to specialise the network for a precise task like for instance classifying birds, using a backbone trained on a big CV dataset such as ImageNet.

## Architecture

- Number of layers
- Architecture choice (e.g. ResNet, DenseNet, VGG, ...)

## Training

- Learning rate and scheduling
- Regularization (e.g. weight decay)
- Choice of optimizer (e.g. SGD)

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# Lab Session 1 and assignment

## Introduction to Deep Learning

- Introduction to Deep Learning in Pytorch
- Train a full DL model from scratch
- Train a downstream model using transfer learning

## Project 1 (oral presentation)

Explore one of the following architectures : ResNet, DenseNet, PreActResNet, VGG.

You have to prepare a 10 minutes (+5 min Q&A) presentation for session 2, in which you explain :

- Description of the architecture
- Hyperparameter search and results
- Study the compromise between architecture size, performance and training time.

2022-02-07

## Introduction to Deep Learning and Transfer Learning

└ Lab Session 1 and assignment

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