

Convolutional Neural Networks

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- A Bit of History
- Main Ideas and Motivation
- Definition of Convolution
- Working with Channels
- Working with Bias
- Parameters of Convolutions
- Additional Operations and Layers in CNNs
- Typical Architectures of CNNs
- Training CNNs with Back-Propagation
- What Make CNNs Work?

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Convolutional Neural Networks (CNNs) are very old models:

- Neocognitron [Fukushima, 1980] incorporated most of the elements in modern CNNs, but with a different approach
- Time-Delay Neural Networks [Lang and Hinton, 1988, Lang et al., 1990] are one-dimensional versions of CNNs applied to time series, trained with back-propagation
- Convolutional (Neural) Networks are described for the first time in [LeCun et al., 1989]

A Bit of History

CNNs were some of the first neural networks to be used in commercial applications:

- AT&T developed a CNN for reading checks [LeCun et al., 1998], and by the end of the 1990s this system was reading over 10% of all checks in the USA
- Microsoft deployed several OCR and handwriting recognition systems based on CNNs [Simard et al., 2003]
- More information: [LeCun et al., 2010]

More recently, CNNs have attracted much attention because the winner models of several important contests were based on CNNs (the first one was the 2012 ImageNet object recognition challenge <http://www.image-net.org/challenges/LSVRC/2012/results.html>)

Since then they are widely used, mainly for image recognition tasks

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A (simple) definition: **CNNs are Neural Networks that compute a convolution instead of a matrix multiplication in at least one of their layers**

The convolution operation implicitly leads to:

- **Sparse interactions** (sparse connectivity)
- **Weight sharing**

with the aim of obtaining **translation invariance** (be able to find a pattern in any place of the input)

Typically, the convolution operation is combined with other operations, such as **non-linear transformation** and **pooling**

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Definition of Convolution

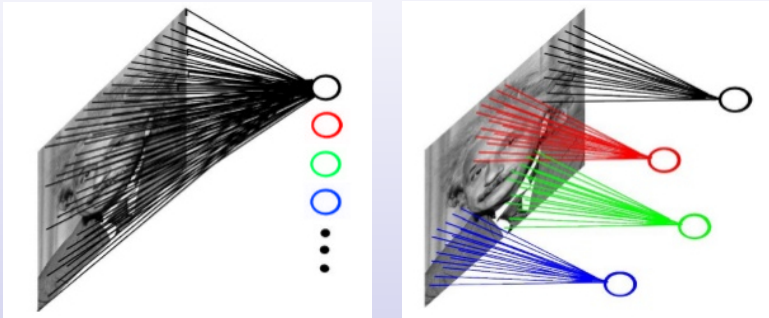


Figure 1: Difference between classical MLP and CNN hidden units

With a convolution, the **same weights** are used to compute output values in **different and small parts** of the input

Definition of Convolution

Mathematical definition of the convolution of two functions F , W :

$$C(t) = (F * W)(t) = \int_{-\infty}^{\infty} F(t-x) W(x) dx = \int_{-\infty}^{\infty} F(x) W(t-x) dx$$

Interpretation: We can think that the convolution $(F * W)(t)$ as

- An expectation / weighted average (by W) of F around t
- The matching of two functions F and W at every t

Discrete convolution used in 2D CNNs (*cross-correlation*):

$$C(n, m) = (I * K)(n, m) = \sum_i \sum_j I(n + i, m + j) K(i, j)$$

where

- I is the **input**, K is the **feature detector** or **filter** or **kernel** (the weights) and C is the **feature map** (the output)
- The sum is defined over all valid values

Viewing the Convolution in a Classical FNN

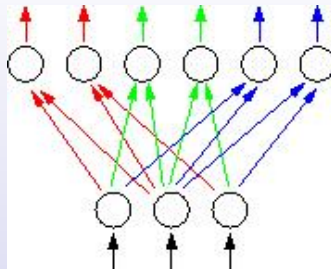


Figure 2: Viewing CNNs as Classical FNNs

Note that we have:

- **Sparse interactions** (sparse connectivity)
- **Weight sharing**

with the aim of obtaining **translation invariance**

Much less parameters than a standard fully connected network

Viewing the Convolution in a Classical FNN

A convolutional operation is similar to a **local receptive field** with shared weights

The previous figure shows that **discrete convolution can be seen as a multiplication by a matrix with restrictions**:

- Equal weights in different units
- Zeros for several weights

Although it is not used in practice (it would be very inefficient) it allows to understand it as a classical Feed-forward Neural Network (FNN) and **apply standard techniques (back-propagation, for example) in a natural way**

Obviously, it needs to **reshape** the input data (e.g., an image) to a vector

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Working with Channels

In real data sets, there are additional dimensions where we do not want to apply the convolution operation:

- 1D: Multi-dimensional time series (for example, animations of “skeletons”, where the data is described by the angles of each joint in the skeleton)
- 2D: Color images (each pixel is a rgb vector)
- 3D: Color volumetric data (for example, medical rgb CT scans)

These additional dimensions are usually called **channels** (also referred to as the **depth** of the input)

How does the convolution operate with channels?

Working with Channels

For example, in 2D color images (3 channels), we have:

- The input is a $N \times M \times 3$ tensor
- Every filter K_f is a $A \times B \times 3$ tensor
- The convolution of the input image I and the filter K_f is a $N \times M \times 1$ tensor (a matrix), where each component is (we do not apply the convolution to the channels, sum over them):

$$C_{K_f}(n, m) = \sum_{i=1}^A \sum_{j=1}^B \sum_{k=1}^3 I(n+i, m+j, k) K_f(i, j, k)$$

- Every filter “outputs an image of just one channel”: If we have F filters, the output of the convolutional layer is a $N \times M \times F$ tensor, where the third component has the convolutions of the image with every filter:

$$C(n, m, f) = C_{K_f}(n, m)$$

Therefore, **the outputs of a convolutional layer, in turn, are also reshaped in a structure with channels**, so that it can be used as the input of a new convolutional layer:

- The number of dimensions of the original image ($N \times M$) is constant (approximately, see below) between adjacent convolutional layers
- The number of output channels of a convolutional layer is the number of filters of that layer (F)

This **allows to construct deep CNNs in a natural way**

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We can add some bias terms to the convolution

How do they operate?

Typically, we will have one bias per channel in the output and one bias per filter, shared across all locations in the convolution:

$$C_{K_f}(n, m) = \sum_{i=1}^A \sum_{j=1}^B \sum_{k=1}^3 (I(n+i, m+j, k) K_f(i, j, k) + b_f(k))$$

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Parameters of Convolutions

The first parameter is, obviously, **the size of the filter** $A \times B$

With the previous definition of convolution, the size of the output of the convolution of a $N \times M$ image with an $A \times B$ filter is exactly $(N - A + 1) \times (M - B + 1)$, since only valid positions can be used to compute the convolution

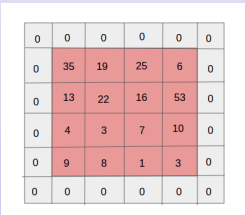
We may want:

- On the one hand, to have the possibility to obtain outputs with the same size than the original one by adding zeros (**Zero-padding**)
- On the other hand, reduce the computational cost by removing (or not computing) some of the outputs of the convolution (**Stride**)

Parameters of Convolutions: Zero-padding

The most common settings for Zero-padding are

- When Zero-padding = *valid*, the convolution is only allowed to visit positions where the entire filter is entirely within the image (and therefore reducing the size of the output)
- When Zero-padding = *same*, zeros are added at the borders so that the size of the output is equal to the input (every pixel contributes to the same number of convolutions)



0	0	0	0	0	0
0	35	19	25	6	0
0	13	22	16	53	0
0	4	3	7	10	0
0	9	8	1	3	0
0	0	0	0	0	0

Figure 3: Convolution with Zero-padding

Parameters of Convolutions: Stride

The easiest and most common way to reduce the outputs of a convolution is to sample only every s pixels in each direction

It is a **downsampled convolution**:

$$C(n, m) = \sum_i \sum_j I(n + i \times s, m + j \times s) K(i, j)$$

The parameter s is the *stride* of the downsampled convolution

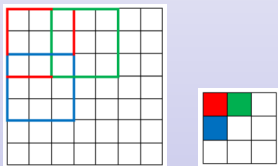


Figure 4: Convolution with Stride = 2

Some information is lost, but the computations are cheaper

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Additional Operations and Layers in CNNs

Note that CNNs can handle **inputs of variable size**: applying each filter at different positions depending on the size of the input (similar to the stride parameter)

CNNs may have other types of operations and layers:

- Non-linearities: apply a non-linear transformation to the output of the convolution (sigmoidal, ReLU,...)
- **Pooling layers** (see next slide)
- Fully connected layers: standard layers (typically on top of the convolutional layers)

Additional Operations and Layers in CNNs: Pooling layers

Pooling layers **replace the output of the network at a certain rectangle with a summary statistic of its contents**

The most common pooling functions are:

- Max-pooling: the output is the maximum value
- Average-pooling: the output is the mean value

Parameters of the pooling operation:

- The size of the rectangle (typically 2×2)
- The stride (typically 2)

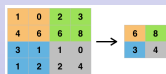


Figure 5: Max-pooling of size 2×2 and stride = 2

Additional Operations and Layers in CNNs: Pooling layers

Pooling layers are used to **reduce the spatial size of the representation and the number of parameters**, thus reducing the amount of computation in the network

For example, with a pooling of size of 2×2 and stride 2 the number of elements is reduced to 25% of its original size

Additionally, it makes the representation approximately invariant to small variations of the input (for example, if we translate the input by a small amount, the change in the values of the outputs will be small)

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Typical Architectures of CNNs

In summary, in a CNN we can find:

- Convolutional layers
- Non-linearity layers (transformations of the convolution)
- Pooling layers
- Fully connected layers

Note that **we have separated the aggregation function (the convolution) and the activation function** of standard MLPs

Typically:

- A pooling layer is inserted after several Convolutional + Non-linearity layers (**deep feature learning/extraction**)
- Fully connected layers are the output layers of the network (typically for **classification/discrimination**)

Typical Architectures of CNNs

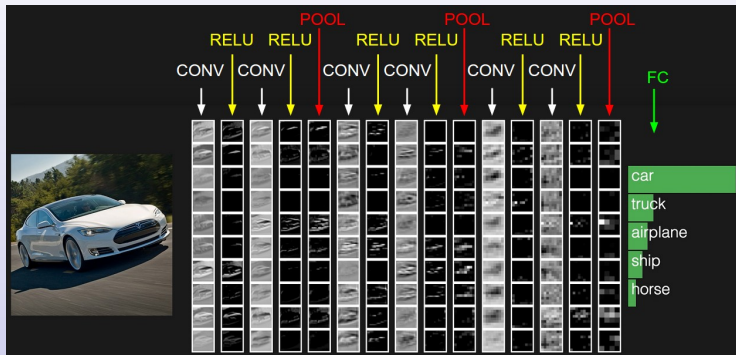


Figure 6: Typical architecture of a CNN (layers)

Typical Architectures of CNNs

What about the sizes? A common practice is to divide the size of the inputs by a factor and multiply the depth by another factor, forming a pyramid

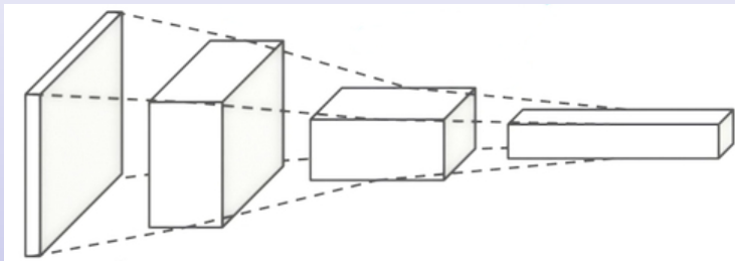


Figure 7: Typical architecture of a CNN (sizes)

Several Famous Architectures of CNNs

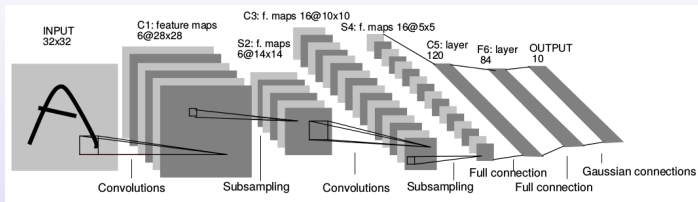


Figure 8: LeNet-5 architecture [LeCun et al., 1998]

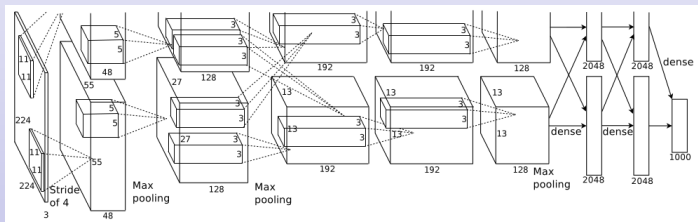


Figure 9: AlexNet architecture [Krizhevsky et al., 2012]

Several Famous Architectures of CNNs

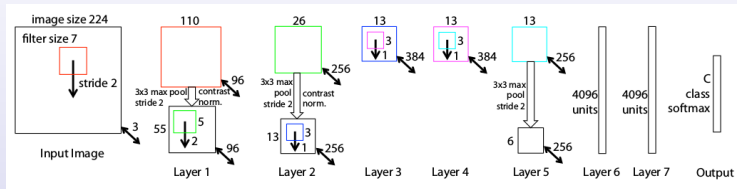


Figure 10: ZFNet architecture [Zeiler and Fergus, 2014]

More famous CNNs:

<http://cs231n.github.io/convolutional-networks>

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Training CNNs with Back-Propagation

Since CNNs can be viewed as classical FNNs (see above), back-propagation can be easily applied to CNNs:

- For shared weights in convolutional layers, the derivative is the sum of the back-propagated derivatives
- For non-linearities, the derivative back-propagates as usual
- For pooling layers, the derivative is back-propagated according to the type of pooling and forward propagations (max-pooling only propagates the derivative of the maximum element, etc)
- For fully connected layers, the derivative back-propagates as usual

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What Make CNN Work?

Basically, the joint interaction of a number of ingredients:

- Good initialization of the weights [Glorot and Bengio, 2010]
- Non-saturated activation functions, such as Rectified Linear Units (ReLUs) $f(x) = \max(0, x)$ (or any of its variants) [Nair and Hinton, 2010, Glorot et al., 2011]
- Adaptive learning rates (RMSProp, Adagrad,...) [Tieleman and Hinton, 2012, Duchi et al., 2011]
- Strong regularization techniques, such as dropout [Srivastava et al., 2014] or other tricks, such as batch normalization [Ioffe and Szegedy, 2015] or local contrast normalization
- High performance resources (GPUs, supercomputers)
- A large set of labeled examples
- Data where the convolution operation make sense
- etc

What Make CNN Work?

A comparative analysis of several CNN architectures from different points of view:

- Accuracy
- Number of parameters
- Memory usage
- Computational complexity
- Inference time

can be found in [Bianco et al., 2018]

That's it!

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