

Deep Learning & Applied AI

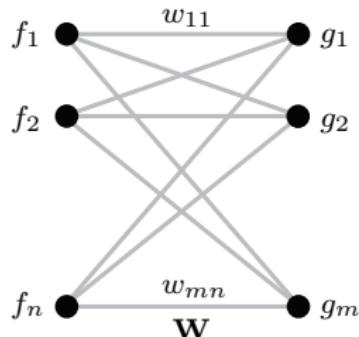
Convolutional neural networks

Emanuele Rodolà
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SAPIENZA
UNIVERSITÀ DI ROMA

Neural network (NN)



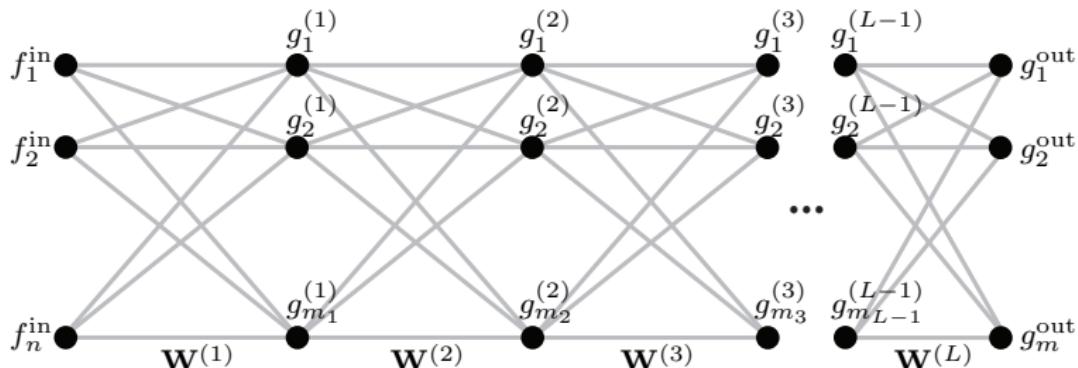
Single linear layer

Linear layer
$$g_\ell = \sigma \left(\sum_{\ell'=1}^n f_{\ell'} w_{\ell, \ell'} \right) \quad \ell = 1, \dots, m$$
 $\ell' = 1, \dots, n$

Activation, e.g. $\sigma(x) = \max\{x, 0\}$ rectified linear unit (ReLU)

Parameters layer weights \mathbf{W} (including bias)

Neural network (NN)



Deep neural network consisting of L layers

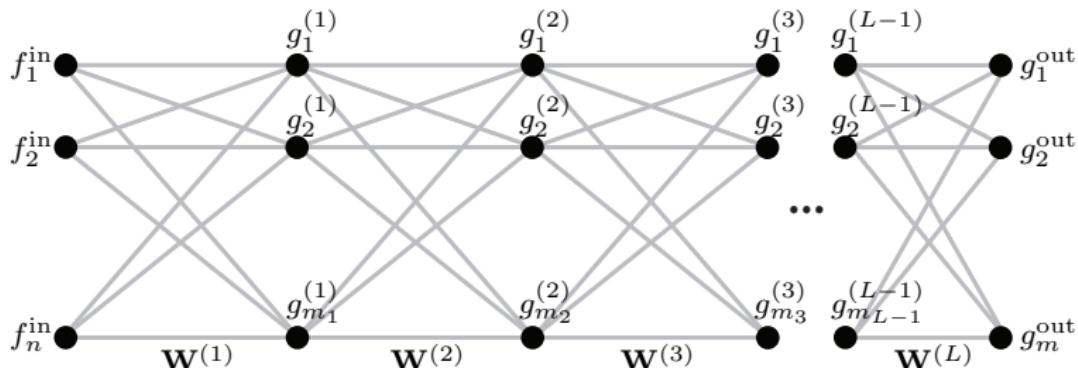
Linear layer

$$g_\ell^{(k)} = \sigma \left(\sum_{\ell'=1}^{m_{k-1}} g_{\ell'}^{(k-1)} w_{\ell,\ell'}^{(k)} \right) \quad \ell = 1, \dots, m_k \quad \ell' = 1, \dots, m_{k-1}$$

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Parameters weights of all layers $\mathbf{W}^{(1)}, \dots, \mathbf{W}^{(L)}$ (including biases)

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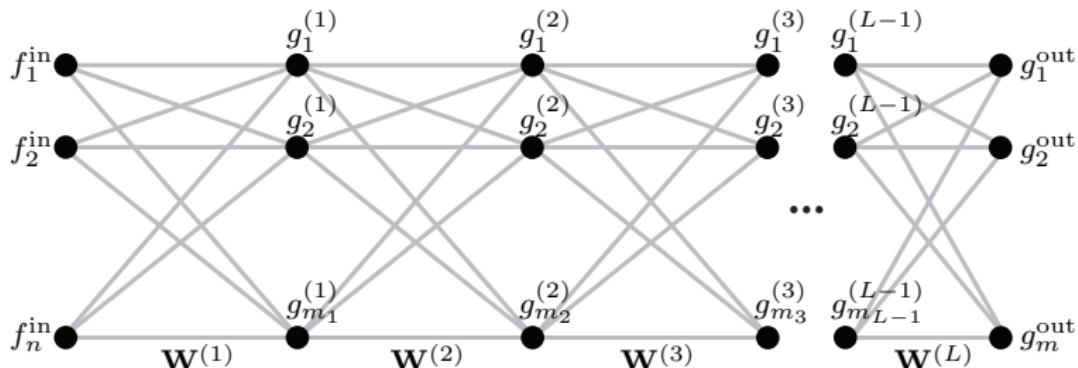
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Linear layer $\quad \mathbf{g}^{(k)} = \sigma(\mathbf{W}^{(k)} \mathbf{g}^{(k-1)})$

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Net output $\quad \mathbf{g}^{\text{out}} = \sigma(\dots \mathbf{W}^{(2)} \sigma(\mathbf{W}^{(1)} \mathbf{f}^{\text{in}}))$

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The need for priors

Deep feed-forward networks are provably **universal**.

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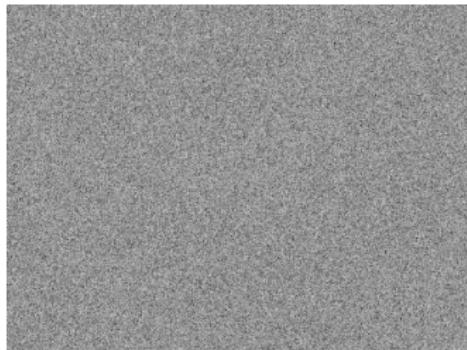
We need additional priors as a (partial) remedy to the above.

Look for “universal” priors that are task-independent to some extent.

Task-independent priors must come with the data.

Structure as a strong prior

Key insight: Data often carries **structural priors** in terms of repeating patterns, compositionality, locality, ...



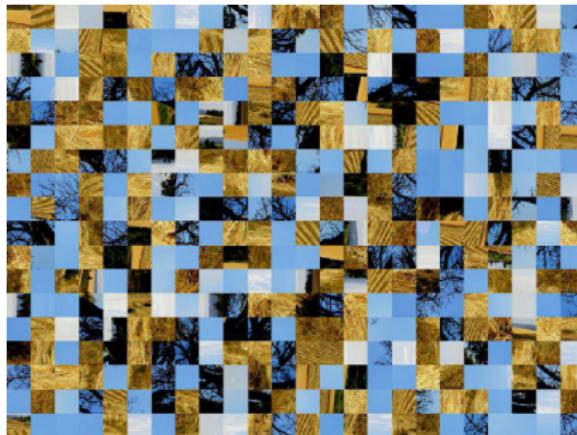
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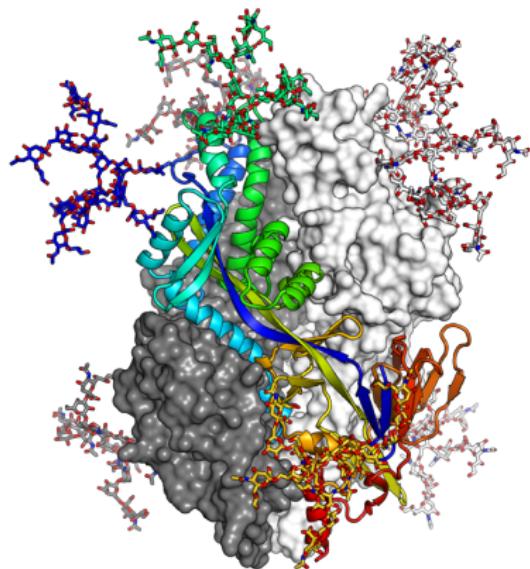
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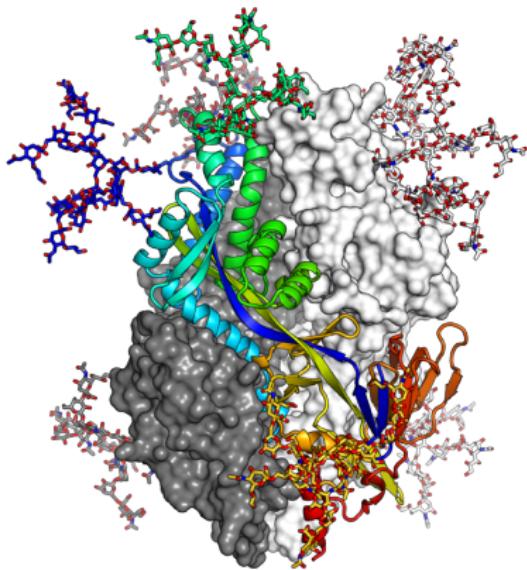
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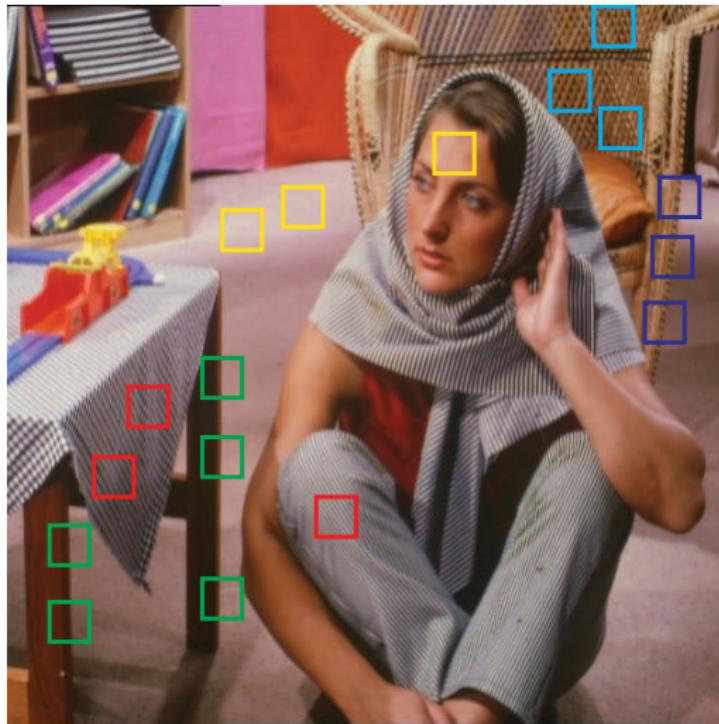
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Take advantage of the **structure** of the data.

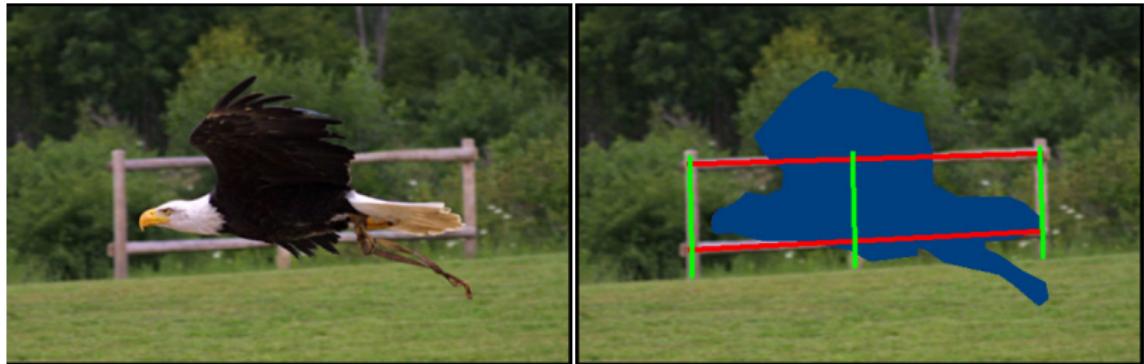
Self-similarity

Data tends to be **self-similar** across the domain:



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Define the (linear!) **translation operator** \mathcal{T} along vector $v \in \mathbb{R}^2$ as:

$$\mathcal{T}_v f(x) = f(x - v)$$



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Therefore, it is desirable to enforce **translation invariance**:

$$\mathcal{C}(\mathcal{T}_v f) = \mathcal{C}(f) \quad \forall f, \mathcal{T}_v$$

where \mathcal{C} is a classification functional.

Deformation invariance

Other types of invariance are possible.

Invariance to [partiality](#) and [isometric deformations](#):



In many cases, invariance can be directly injected into the network.
Today we concentrate on [translation](#) invariance.

Hierarchy and compositionality

Translation invariance is desirable [across multiple scales](#):



We expect [local features](#) to be invariant to their location in the image:

$$z(\mathcal{T}_v p) = z(p) \quad \forall p, \mathcal{T}_v$$

where p are image patches of variable size.

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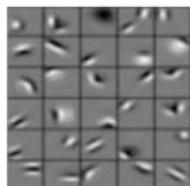
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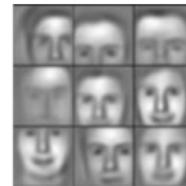
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scale 1

scale n

Convolutional neural networks (CNN)

Data is often composed of hierarchical, local, shift-invariant patterns.

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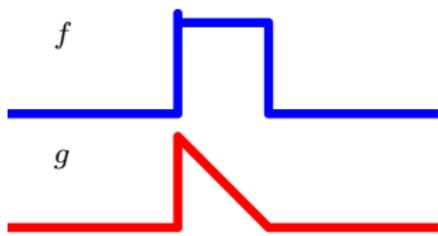
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CNNs directly exploit this fact as a prior.

Convolution

Given two functions $f, g : [-\pi, \pi] \rightarrow \mathbb{R}$ their **convolution** is a function:

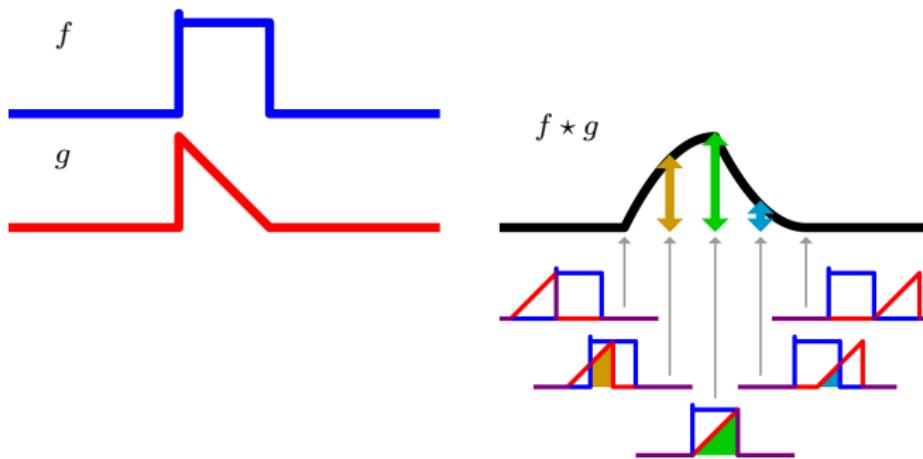
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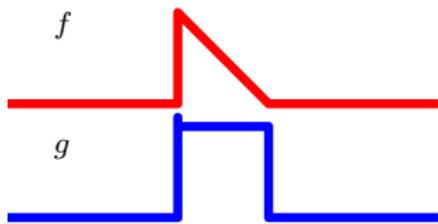
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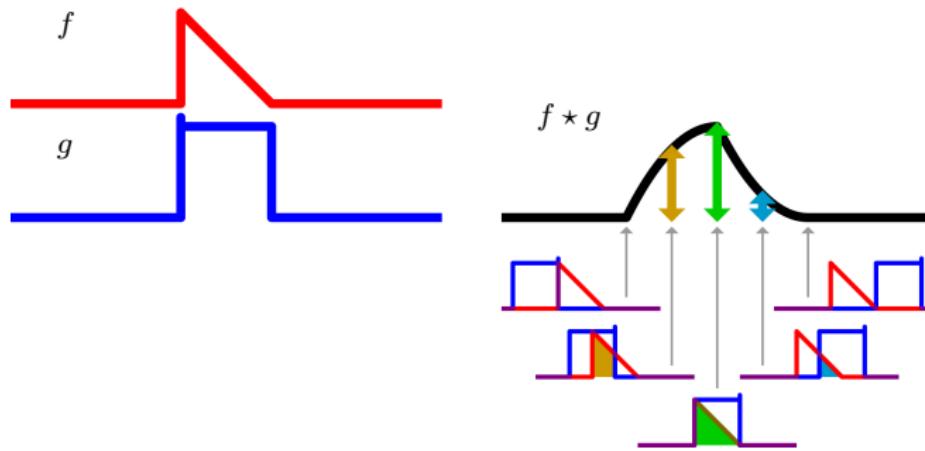
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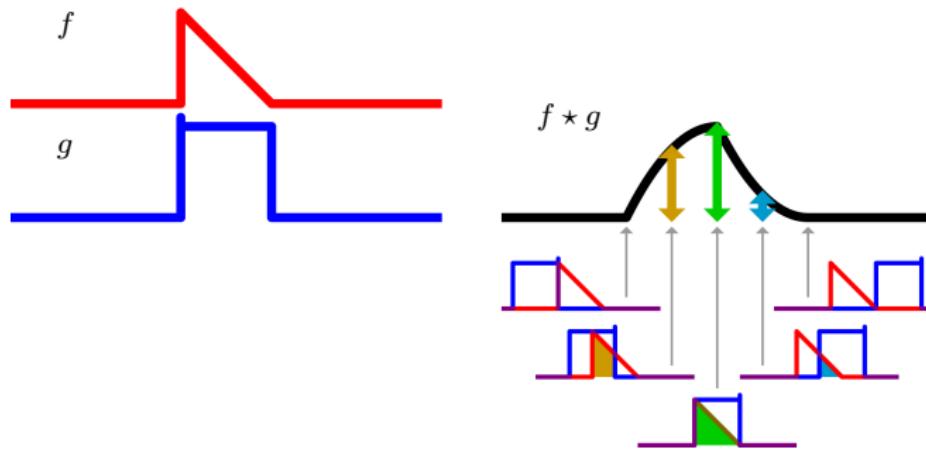
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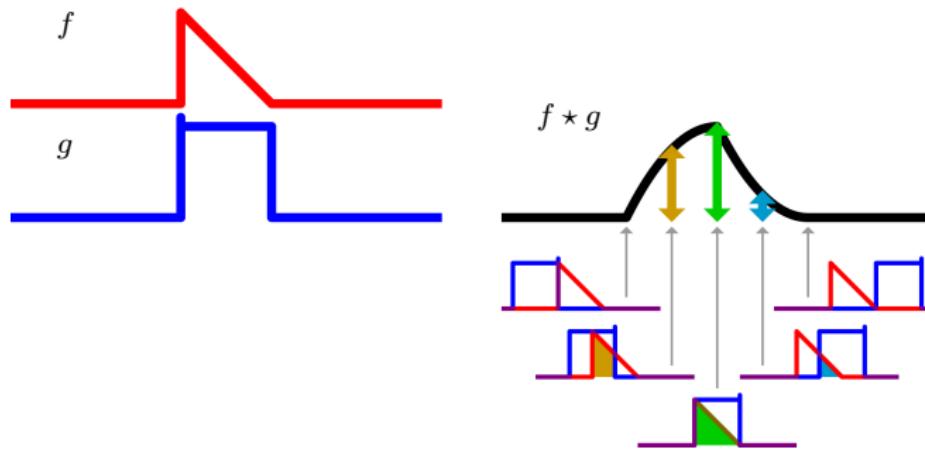
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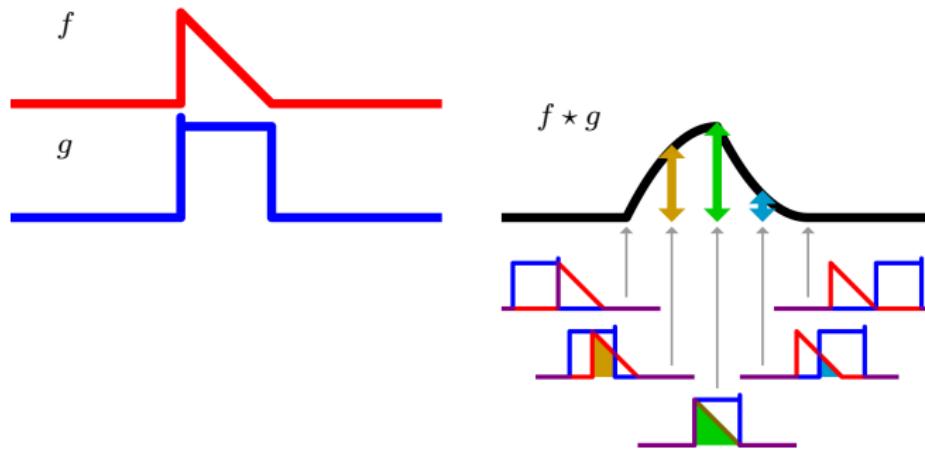
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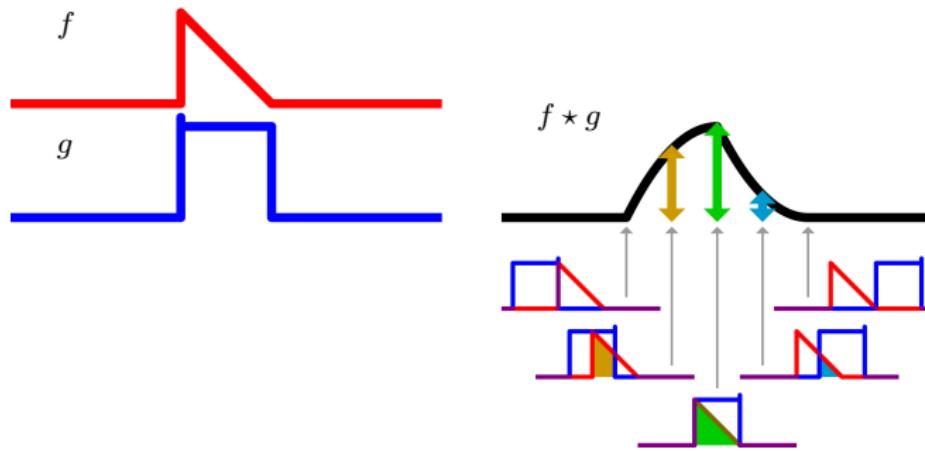
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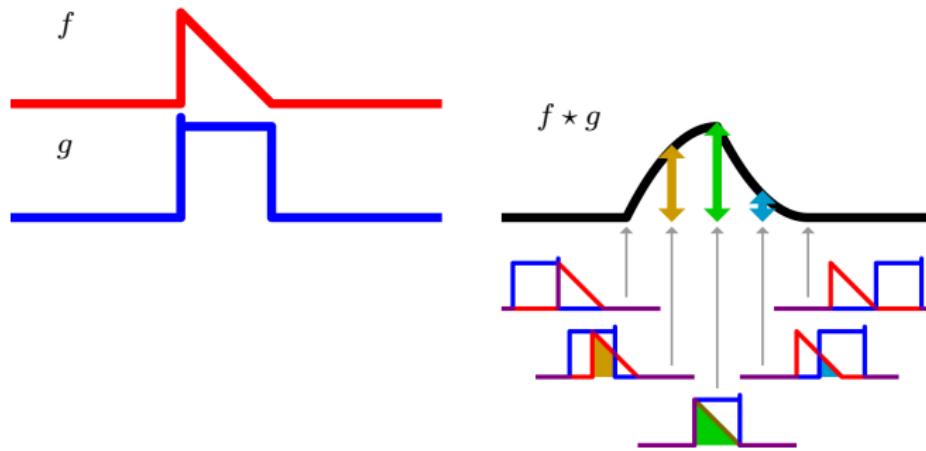
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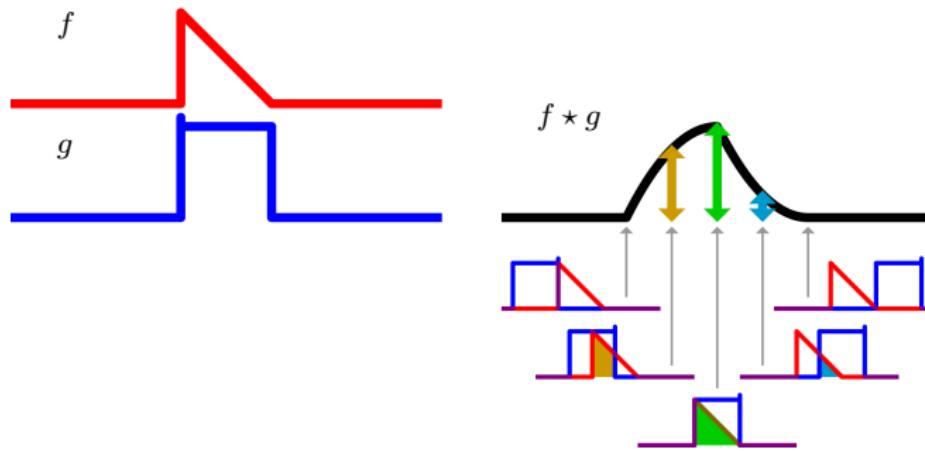
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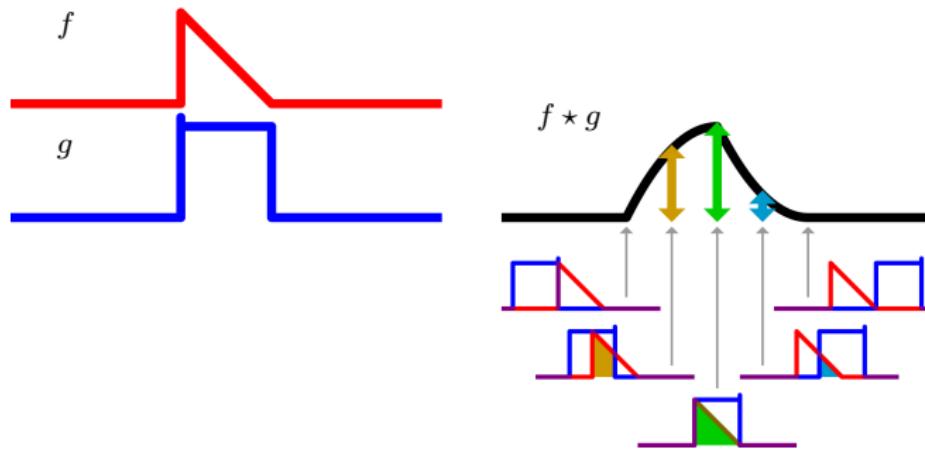
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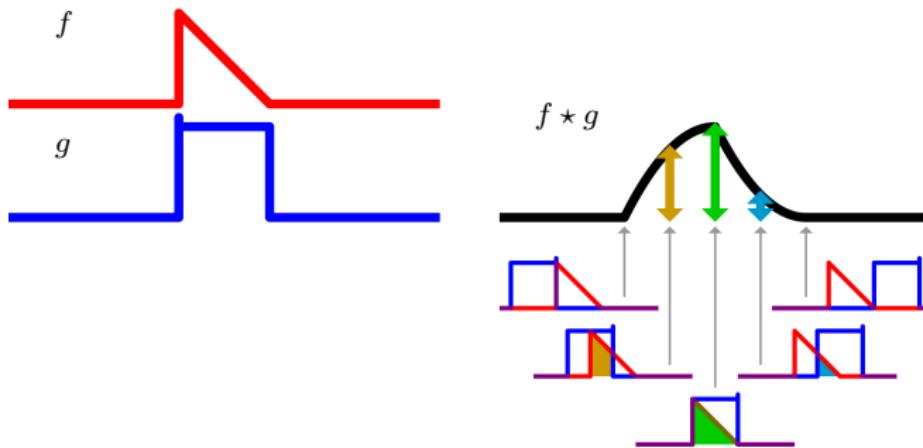
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Convolution: Commutativity

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Further, convolution is **shift-equivariant** (or **translation-equivariant**):

$$f(x - x_0) \star g(x) = (f \star g)(x - x_0)$$

Convolution: Shift-equivariance



shift
 \Rightarrow



convolve
 \Downarrow



shift
 \Rightarrow



Convolution: Shift-equivariance



shift
⇒



convolve
↓



shift
⇒



In fact, equivariance is a **defining property** of convolutions.

(any linear operator that is shift-equivariant, is a convolution)

Convolution: Linearity

We can see convolution as the application of a **linear** operator \mathcal{G} :

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Translation **equivariance** can then be phrased as:

$$\mathcal{G}(\mathcal{T}f) = \mathcal{T}(\mathcal{G}f)$$

i.e., the convolution and translation operators **commute**.

Discrete convolution

In the **discrete setting**, we deal with vectors \mathbf{f}, \mathbf{g} .

We define the **convolution sum**:

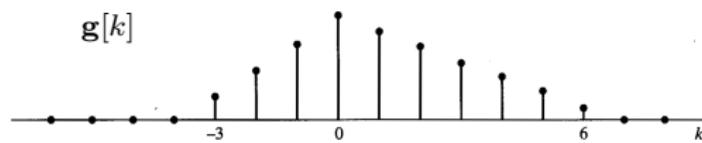
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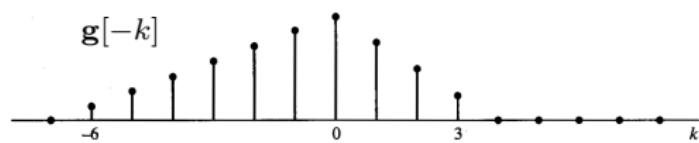


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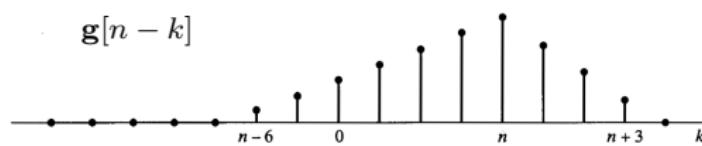


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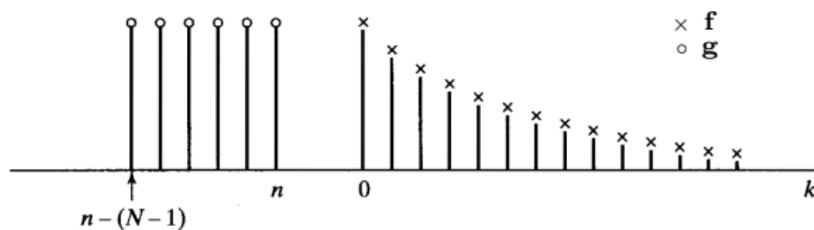


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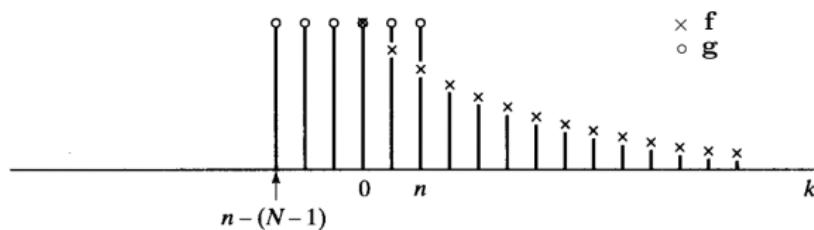


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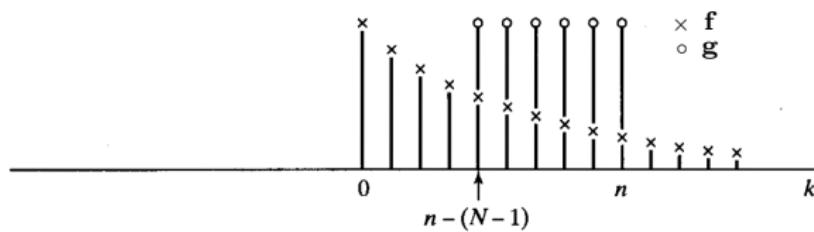


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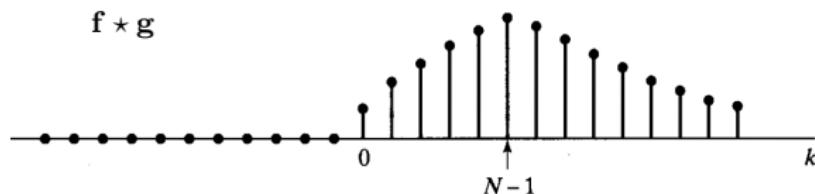


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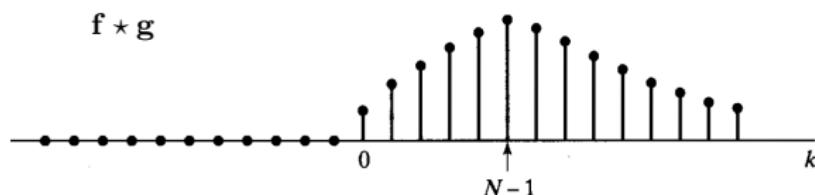


Discrete convolution

In the **discrete setting**, we deal with vectors \mathbf{f}, \mathbf{g} .

We define the **convolution sum**:

$$(\mathbf{f} * \mathbf{g})[n] = \sum_{k=-\infty}^{\infty} \mathbf{f}[k]\mathbf{g}[n-k]$$



The specific discretization depends on the **boundary conditions**.

In the example above, \mathbf{f} was **zero-padded** in order for the products to be well defined for all shifts.

Discrete convolution

On 2D domains (e.g. RGB images $f : \mathbb{R}^2 \rightarrow \mathbb{R}^3$), for each channel:

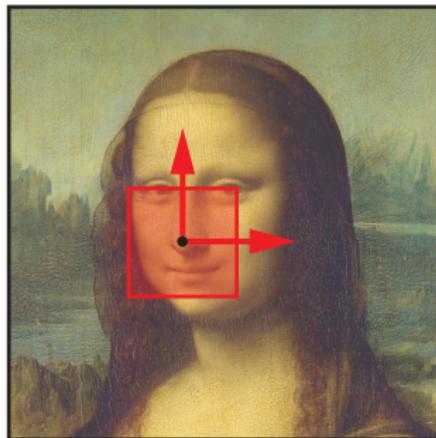
$$(\mathbf{f} \star \mathbf{g})[m, n] = \sum_k \sum_{\ell} \mathbf{f}[k, \ell] \mathbf{g}[m - k, n - \ell]$$

Discrete convolution

On 2D domains (e.g. RGB images $f : \mathbb{R}^2 \rightarrow \mathbb{R}^3$), for each channel:

$$(\mathbf{f} \star \mathbf{g})[m, n] = \sum_k \sum_{\ell} \mathbf{f}[k, \ell] \mathbf{g}[m - k, n - \ell]$$

We get the classical interpretation in terms of a moving window:

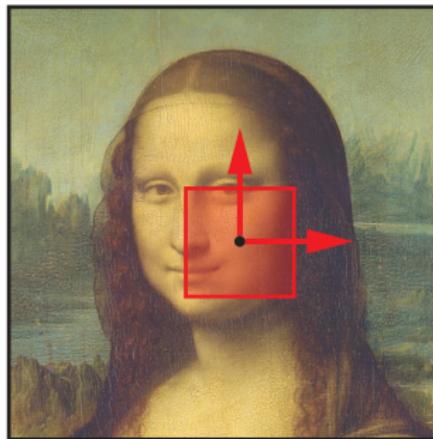


Discrete convolution

On 2D domains (e.g. RGB images $f : \mathbb{R}^2 \rightarrow \mathbb{R}^3$), for each channel:

$$(\mathbf{f} \star \mathbf{g})[m, n] = \sum_k \sum_{\ell} \mathbf{f}[k, \ell] \mathbf{g}[m - k, n - \ell]$$

We get the classical interpretation in terms of a moving window:



Boundary conditions and stride

No padding: The convolution kernel is directly applied within the boundaries of the underlying function (an image in this example).

The result of the convolution is a smaller image.

Boundary conditions and stride

Full zero-padding: The domain is enlarged and padded with zeroes. The convolution kernel is applied within the (now larger) boundaries.

The result of the convolution is a larger image.

Boundary conditions and stride

Arbitrary zero-padding, with stride: The domain is enlarged and padded with zeroes, but not enough to capture the boundary pixels. Further, each discrete step skips one pixel.

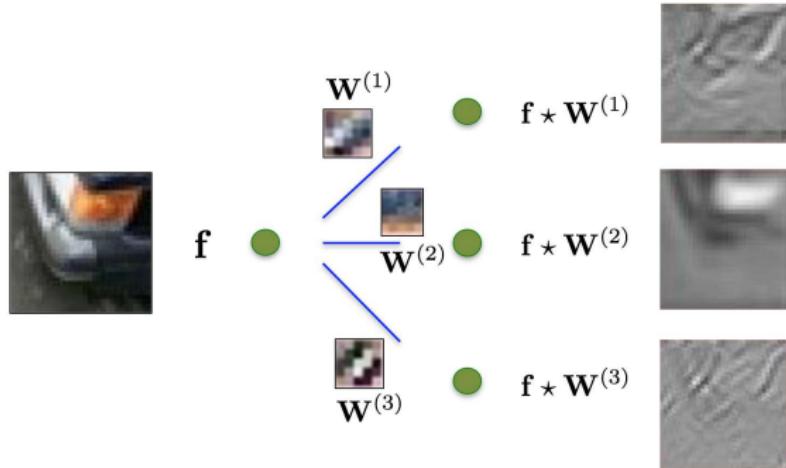
The result is the same as no stride followed by downsampling.

CNN vs. MLP

We are replacing the large matrices of MLPs with small [local filters](#).

CNN vs. MLP

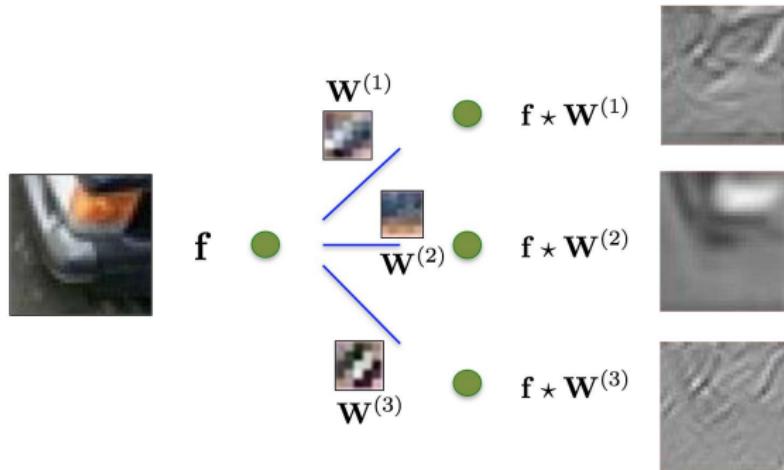
We are replacing the large matrices of MLPs with small **local filters**.



- $O(1)$ parameters per filter; huge gain compared to the MLP.

CNN vs. MLP

We are replacing the large matrices of MLPs with small **local filters**.



- $O(1)$ parameters per filter; huge gain compared to the MLP.
- Filter weights are applied across the entire image \Rightarrow weight sharing, which implements the notion of self-similarity and shift-equivariance.

Sparse interactions

Fully-connected layer:

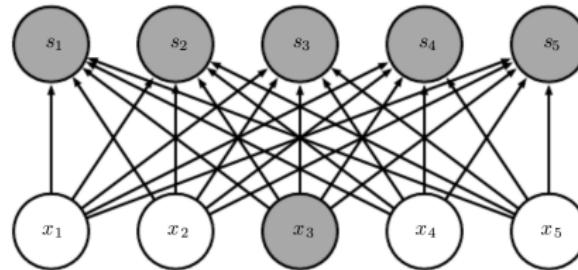


Image: Goodfellow et al, 2016

Sparse interactions

Fully-connected layer:

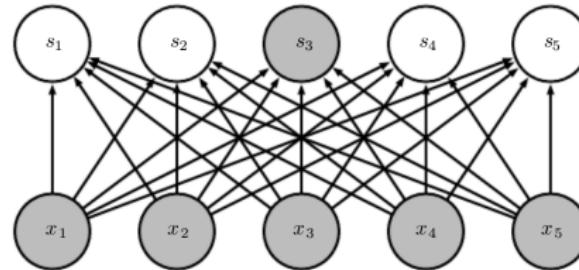
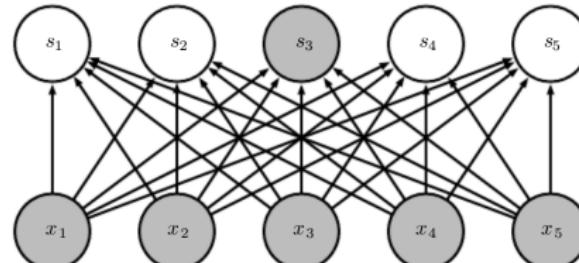


Image: Goodfellow et al, 2016

Sparse interactions

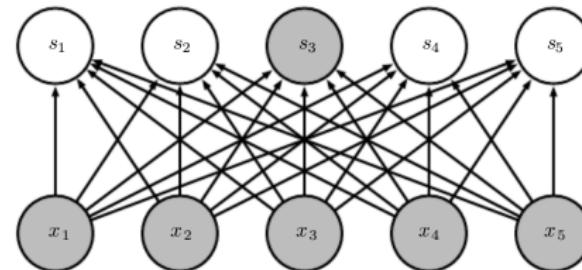
Fully-connected layer:



each edge is a different weight

Sparse interactions

Fully-connected layer:



each edge is a different weight

Convolutional layer:

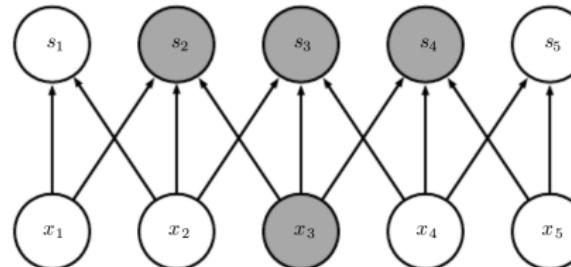
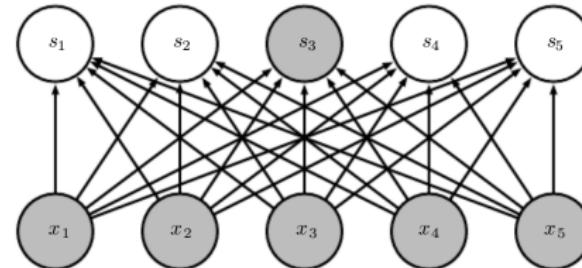


Image: Goodfellow et al, 2016

Sparse interactions

Fully-connected layer:



each edge is a different weight

Convolutional layer:

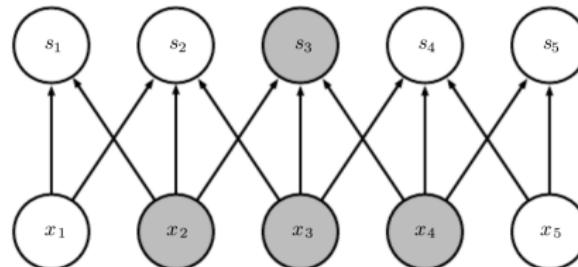
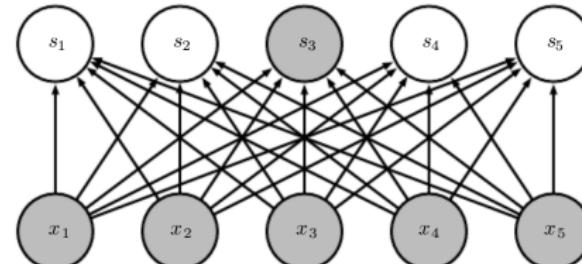


Image: Goodfellow et al, 2016

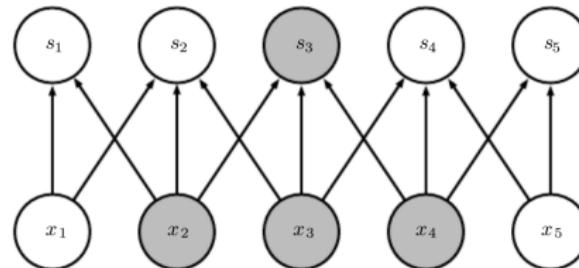
Sparse interactions

Fully-connected layer:



each edge is a different weight

Convolutional layer:



the outgoing edges have the same weights
for each input variable (**weight sharing**)

Image: Goodfellow et al, 2016

Pooling

At deep layers, filters interact with larger portions of the input.

3	3	2	1	0	0
3	3	2	1	0	0
3	3	2	1	0	0
3	3	3	2	0	0
3	3	2	1	0	0
3	2	1	1	0	0

Input data

$$\begin{matrix} * & \quad & = \\ \begin{matrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{matrix} & \quad & \begin{matrix} \text{Filter} \end{matrix} \end{matrix}$$

6	8	6	3	1	0
9	13	10	5	2	0
9	14	11	6	3	0
9	13	11	6	2	0
8	13	10	5	3	0
6	7	5	3	1	0

Feature map

Pooling

At deep layers, filters interact with larger portions of the input.

3	3	2	1	0	0
3	3	2	1	0	0
3	3	2	1	0	0
3	3	3	2	0	0
3	3	2	1	0	0
3	2	1	1	0	0

Input data



1	0	1
0	1	0
1	0	1

Filter



6	8	6	3	1	0
9	13	10	5	2	0
9	14	11	6	3	0
9	13	11	6	2	0
8	13	10	5	3	0
6	7	5	3	1	0

Feature map

13	10	2
14	11	3
13	10	3

Max pooling

Pooling

At deep layers, filters interact with larger portions of the input.

3	3	2	1	0	0
3	3	2	1	0	0
3	3	2	1	0	0
3	3	3	2	0	0
3	3	2	1	0	0
3	2	1	1	0	0

Input data



1	0	1
0	1	0
1	0	1

Filter

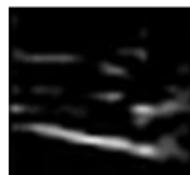


6	8	6	3	1	0
9	13	10	5	2	0
9	14	11	6	3	0
9	13	11	6	2	0
8	13	10	5	3	0
6	7	5	3	1	0

Feature map

13	10	2
14	11	3
13	10	3

Max pooling

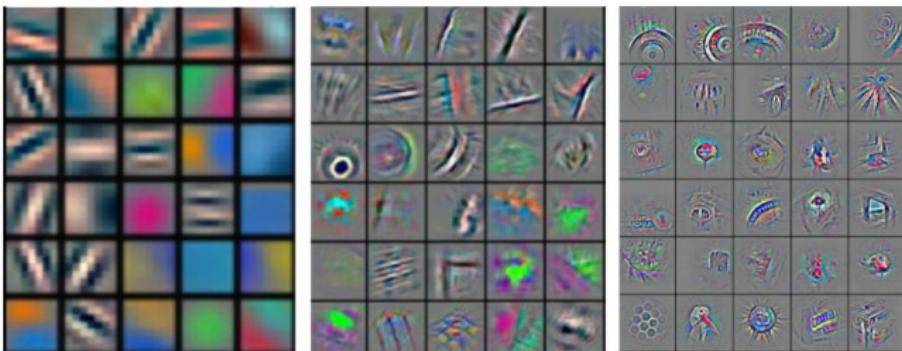


2x2 Max
pooling

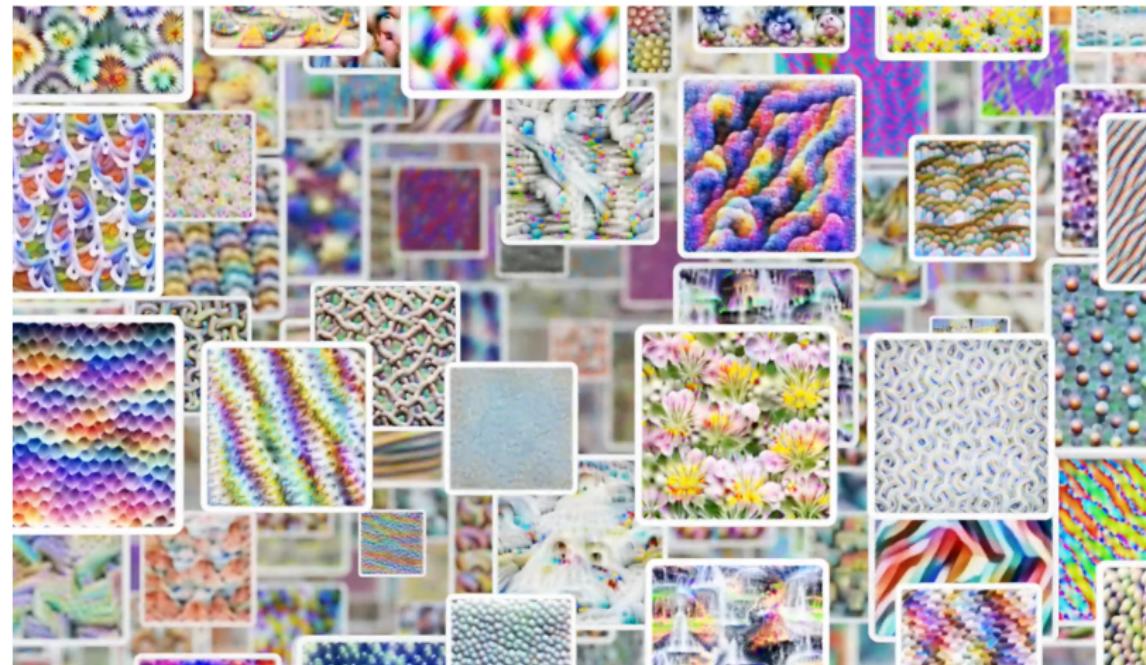


This allows to capture complicated **non-local interactions** via simple building blocks that only describe sparse interactions.

Learned features



Learned features



<https://openai.com/blog/microscope/>

Suggested reading

Convolution animations, including variants:

https://github.com/vdumoulin/conv_arithmetic

Seminal paper on CNN, seen as a set of feature detectors:

<http://yann.lecun.com/exdb/publis/pdf/lecun-89e.pdf>