

## Convolutional Neural Networks

We will extend our framework to include the building blocks for modern Convolutional Neural Networks (CNNs). To this end, we will add initialization schemes improving our results, advanced optimizers and the two iconic layers making up CNNs, the convolutional layer and the max-pooling layer. To ensure compatibility between fully connected and convolutional layers, we will further implement a flatten layer. Of course we want to continue implementing the layers ourselves and the usage of machine learning libraries is still not allowed.

### 1 Initializers

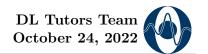
Initialization is critical for non-convex optimization problems. Depending on the application and network, different initialization strategies are required. A popular initialization scheme is named Xavier or Glorot initialization. Later an improved scheme specifically targeting ReLU activation functions was proposed by Kaiming He.

#### Task:

Implement four <u>classes</u> Constant, UniformRandom, Xavier and He in the file "Initializers.py" in folder "Layers". Each of them has to provide the <u>method</u> initialize(weights\_shape, fan\_in, fan\_out) which <u>returns</u> an initialized tensor of the desired shape.

- Implement all four initialization schemes. Note the following:
  - The **Constant** class has a <u>member</u> that determines the constant value used for weight initialization. The value can be passed as a constructor argument, with a default of 0.1.
  - The support of the uniform distribution is the interval [0,1).
  - Have a look at the exercise slides for more information on Xavier and He initializers.
- Add a <u>method</u> initialize(weights\_initializer, bias\_initializer) to the <u>class</u> FullyConnected reinitializing its weights. Initialize the bias separately with the bias\_initializer. Remember that the bias is usually also stored in the weights matrix.
- Refactor the <u>class</u> **NeuralNetwork** to receive a **weights\_initializer** and a **bias\_initializer** upon construction.
- Extend the <u>method</u> append\_layer(layer) in the <u>class</u> NeuralNetwork such that it initializes trainable layers with the stored initializers.

You can verify your implementation using the provided testsuite by providing the commandline parameter **TestInitializers**.



### 2 Advanced Optimizers

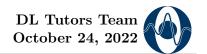
More advanced optimization schemes can increase speed of convergence. We implement a popular per-parameter adaptive scheme named Adam and a common scheme improving stochastic gradient descent called momentum.

#### Task:

Implement the <u>classes</u> **SgdWithMomentum** and **Adam** in the file "Optimizers.py" in folder "Optimization". These classes all have to provide the <u>method</u> calculate\_update(weight\_tensor, gradient\_tensor).

- The **SgdWithMomentum** constructor receives the **learning\_rate** and the **momentum\_rate** in this order.
- The Adam constructor receives the learning\_rate, mu and rho, exactly in this order. In literature mu is often referred as  $\beta_1$  and rho as  $\beta_2$ .
- Implement for both optimizers the <u>method</u> calculate\_update(weight\_tensor, gradient\_tensor) as it was done with the basic SGD Optimizer.

You can verify your implementation using the provided testsuite by providing the commandline parameter **TestOptimizers2**.



# 3 Flatten Layer

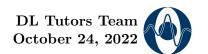
Flatten layers reshapes the multi-dimensional input to a one dimensional feature vector. This is useful especially when connecting a convolutional or pooling layer with a fully connected layer.

#### Task:

Implement a <u>class</u> **Flatten** in the file "Flatten.py" in folder "Layers". This class has to provide the <u>methods</u> **forward(input\_tensor)** and **backward(error\_tensor)**.

- Write a <u>constructor</u> for this class, receiving no arguments.
- Implement a <u>method</u> forward(input\_tensor), which reshapes and returns the input\_tensor.
- Implement a <u>method</u> backward(error\_tensor) which reshapes and returns the error\_tensor.

You can verify your implementation using the provided testsuite by providing the commandline parameter **TestFlatten**.



# 4 Convolutional Layer

While fully connected layers are theoretically well suited to approximate any function they struggle to efficiently classify images due to extensive memory consumption and overfitting. Using convolutional layers, these problems can be circumvented by restricting the layer's parameters to local receptive fields.

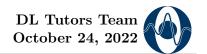
#### Task:

Implement a <u>class</u> Conv in the file "Conv.py" in folder "Layers". This class has to provide the <u>methods</u> forward(input\_tensor) and backward(error\_tensor).

- Write a <u>constructor</u> for this class, receiving the <u>arguments</u> **stride\_shape**, **convolution\_shape** and **num\_kernels** defining the operation. Note the following:
  - this layer has trainable parameters, so set the inherited <u>member</u> trainable accordingly.
  - stride\_shape can be a single value or a tuple. The latter allows for different strides in the spatial dimensions.
  - **convolution\_shape** determines whether this object provides a 1D or a 2D convolution layer. For 1D, it has the shape [c, m], whereas for 2D, it has the shape [c, m, n], where c represents the number of input channels, and m, n represent the spatial extent of the filter kernel.
  - num\_kernels is an integer value.

Initialize the parameters of this layer uniformly random in the range [0, 1).

- To be able to test the gradients with respect to the weights: The <u>members</u> for <u>weights</u> and <u>biases</u> should be named **weights** and **bias**. Additionally provide two <u>properties</u>: **gradient\_weights** and **gradient\_bias**, which return the gradient with respect to the weights and bias, after they have been calculated in the backward-pass.
- Implement a <u>method</u> **forward(input\_tensor)** which returns a tensor that serves as the **input\_tensor** for the next layer. Note the following:
  - The input layout for 1D is defined in b, c, y order, for 2D in b, c, y, x order. Here, b stands for the batch, c represents the channels and x, y represent the spatial dimensions.
  - You can calculate the output shape in the beginning based on the input\_tensor and the stride\_shape.
  - Use zero-padding for convolutions/correlations ("same" padding). This allows input and output to have the same spatial shape for a stride of 1.



Make sure that 1×1-convolutions and 1D convolutions are handled correctly.

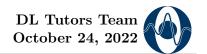
<u>Hint:</u> Using correlation in the forward and convolution/correlation in the backward pass might help with the flipping of kernels.

<u>Hint 2:</u> The scipy package features a n-dimensional convolution/correlation.

<u>Hint 3:</u> Efficiency trade-offs will be necessary in this scope. For example, striding may be implemented wastefully as subsampling *after* convolution/correlation.

- Implement a <u>property</u> **optimizer** storing the optimizer for this layer. Note that you need two copies of the optimizer object if you handle the <u>bias</u> separately from the other weights.
- Implement a <u>method</u> **backward(error\_tensor)** which updates the parameters using the **optimizer** (if available) and returns the **error\_tensor** which returns a tensor that servers as **error\_tensor** for the next layer.
- Implement a <u>method</u> initialize(weights\_initializer, bias\_initializer) which reinitializes the weights by using the provided initializer objects.

You can verify your implementation using the provided testsuite by providing the command-line parameter **TestConv**. For further debugging purposes we provide optional unittests in "SoftConvTests.py". Please read the instructions there carefully in case you need them.



### 5 Pooling Layer

Pooling layers are typically used in conjunction with the convolutional layer. They reduce the dimensionality of the input and therefore also decrease memory consumption. Additionally, they reduce overfitting by introducing a degree of scale and translation invariance. We will implement max-pooling as the most common form of pooling.

#### Task:

Implement a <u>class</u> **Pooling** in the file "Pooling.py" in folder "Layers". This class has to provide the <u>methods</u> forward(input\_tensor) and backward(error\_tensor).

- Write a constructor receiving the <u>arguments</u> **stride\_shape** and **pooling\_shape**, with the same ordering as specified in the convolutional layer.
- Implement a <u>method</u> forward(input\_tensor) which returns a tensor that serves as the input\_tensor for the next layer. Hint: Keep in mind to store the correct information necessary for the backward pass.
  - Different to the convolutional layer, the pooling layer must be implemented only for the 2D case.
  - Use "valid"-padding for the pooling layer. This means, unlike to the convolutional layer, don't apply any "zero"-padding. This may discard border elements of the input tensor. Take it into account when creating your output tensor.
- Implement a <u>method</u> backward(error\_tensor) which returns a tensor that serves as the error\_tensor for the next layer.

You can verify your implementation using the provided testsuite by providing the commandline parameter **TestPooling**.

# 6 Test, Debug and Finish

Now we implemented everything.

### Task:

Debug your implementation until every test in the suite passes. You can run all tests by providing no commandline parameter. To run the unittests you can either execute them with python in the terminal or with the dedicated unittest environment of PyCharm. We recommend the latter one, as it provides a better overview of all tests. For the automated computation of the bonus points achieved in one exercise, run the unittests with the bonus flag in a terminal, with

# python3 NeuralNetworkTests.py Bonus

or set in PyCharm a new "Python" configuration with Bonus as "Parameters". Notice, in some cases you need to set your src folder as "Working Directory". More information about PyCharm configurations can be found here  $^1$ .

Make sure you don't forget to upload your submission to StudOn. Use the dispatch tool, which checks all files for completeness and zips the files you need for the upload. Try

python3 dispatch.py --help

to check out the manual. For dispatching your folder run e.g.

python3 dispatch.py -i ./src\_to\_implement -o submission.zip

and upload the .zip file to StudOn.

<sup>&</sup>lt;sup>1</sup>https://www.jetbrains.com/help/pycharm/creating-and-editing-run-debug-configurations.html