



Report: Deep learning final project (miniprojects)

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Dated: December 18, 2022

Abstract

This is a report on the solution of the two mini projects proposed as a final project for the course Deep Learning (14X050). The solution consists of this report and a GitHub archive containing the corresponding code ([Github Archive](#)).

Project 1

1.1 Introduction

The main goal of the first project is to compare the performance of basic neural network architectures. This is done with respect to a specific classification task where the network is supposed to predict the relationship (smaller or equal / larger) between two numbers of the MNIST dataset. A small selection from this dataset can be seen in fig. 1.

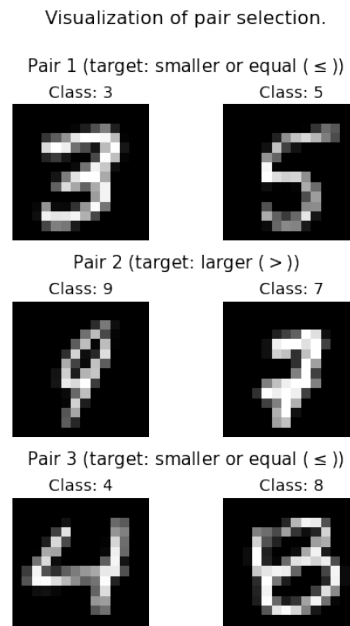


Figure 1: Small selection of inputs from the dataset where every row represents an input and the captions show the corresponding target classes.

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1.2 Architectures

For the structure of the networks, four variable architectures were chosen. For all architectures there is one version which starts with convolutional and Batchnorm layers and is followed by linear layers, another which is fully convolutional. Also, every architecture has the possibility to switch between several or one output neuron depending on whether one-hot encoded labels are used.

The fully convolutional networks are created on the basis of the mixed networks at initialization through the function `convolutionize` which is based on the `convolutionize` function [Fleuret2022] defined in the lectures. They are not transformed after training but at initialization so they are trained as fully convolutional networks. From this point on, not calling `convolutionize` will be the norm for project one. Whenever fully convolutional networks are used it will be explicitly specified.

One-hot encoding is triggered through the variable `one_hot_encoding` at initialization and is enabled for all additional functions by the same variable. From this point on, one-hot encoding will be the norm for project one. Whenever one-hot encoding is turned off it will be explicitly specified.

All architectures use ReLU as their internal activation functions and Sigmoid as their output activation. All models are initialized with 64, 64 and 32 for the number of neurons in the main branch for the hidden Linear layers.

The first implemented architecture can be seen in fig. 2 it represents the “naive” approach where the images are passed through separate convolutional layers to extract their features. The results are concatenated, flattened and passed through fully connected linear layers/convolutional layers for the actual classification. This architecture will be called “simple network” (SN) from now on.

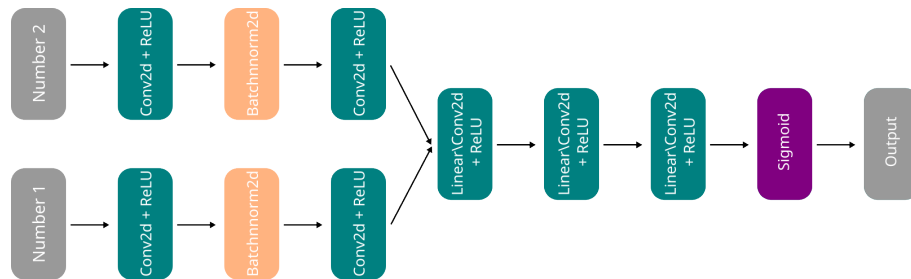


Figure 2: Diagrammatic visualization of the architecture for the simple network. (figure made using Inkscape)

Of course an architecture like fig. 2 wastes some learning potential by separating the feature extraction. Therefore an attempt on improvement is made through the architecture in fig. 3 from now on called “weight sharing network” (WSN). Here, we do the feature extraction by passing Number 1 as well as Number 2 (one after the other) through the first two convolutional layers, then concatenate and continue.

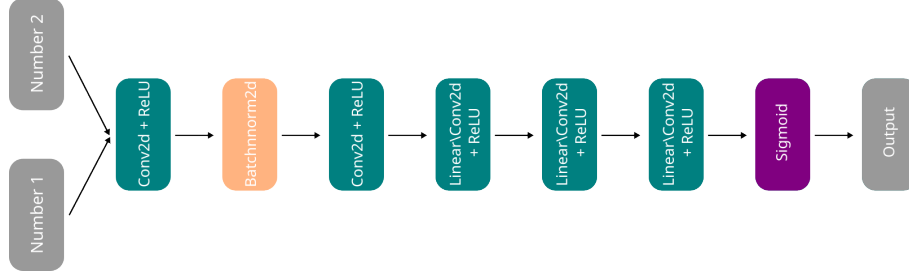


Figure 3: Diagrammatic visualization of the architecture for the weight sharing network. (figure made using Inkscape)

The following two architectures rely on the concept of auxiliary classifiers as described in [Szegedy2014]. The basic idea is to branch of the main architecture at some point to do the same or another classification with an additional architecture. This part is also trained and the loss is added (usually multiplied by a some fraction smaller than one) to the loss of the main branch. This part is usually discarded when evaluating the model.

Figure 4 takes the most simple approach to this concept by branching of and trying to perform the same classification as the main branch and will therefore be called “Simple auxiliary classifier model” (SAUX) from now on.

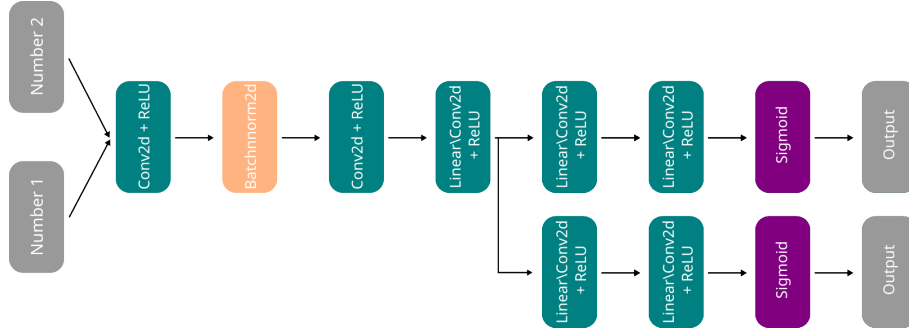


Figure 4: Diagrammatic visualization of the architecture for the simple auxiliary neural network. (figure made using Inkscape)

Another approach could be to use the information about the classes of the respective numbers from the MNIST. Figure 5 introduces this concept by having an auxiliary classifier branch just after the initial feature extraction to find the classes of the respective numbers. This architecture will be called “auxiliary classifier using classes” (CAUX) from now on.

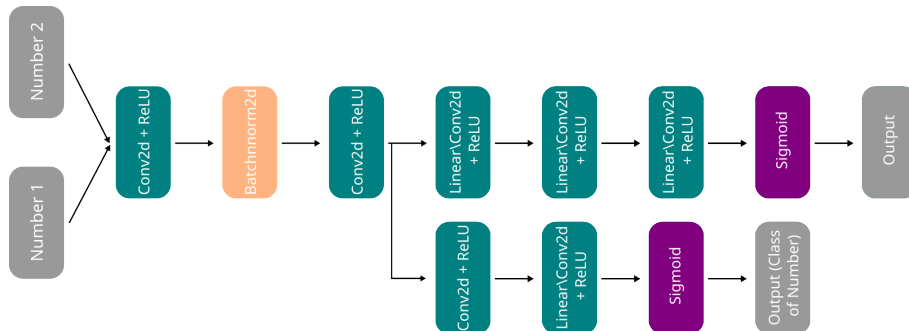


Figure 5: Diagrammatic visualization of the architecture for the auxiliary neural network using the numbers classes. (figure made using Inkscape)

For both auxiliary architectures the modification specified at the start of this section are also imposed on the auxiliary classifiers. Both architectures keep the structure of the WSN for the initial feature extraction.

1.3 Training

All the Architectures were trained for 100 epochs, which was repeated for 150 times while logging the test accuracy to calculate its mean values and corresponding standard deviations for that experiment. The actual training and testing is performed by the `Teacher` class which stores the train and test data and whose methods are the actual train and test function of the model. The whole process for the analysis is performed by the `run_analysis` function which returns the mean and the standard deviation for use in further analysis or visualization. All models with one-hot encoding were trained using the `CrossEntropyLoss` optimizer and all the models without one-hot encoding were trained using the `MSELoss` optimizer.

All models were trained with a learning rate of 0.01 and a batch size of 50. These parameters remained fixed for the whole analysis in project one to keep the results as comparable as possible.

1.4 Results

As a starting point the different architectures are compared in their standard forms (one-hot encoding and not fully convolutional) as specified in section 1.2. The results of this comparison can be seen in fig. 6.

Figure 6a shows the WSN performing better on average than the SN. Not only does it reach a higher value at the end of the training, it also has a steeper slope for the evolution of the test accuracy. This development is consistent with the ideas behind the WSN explained in section 1.2.

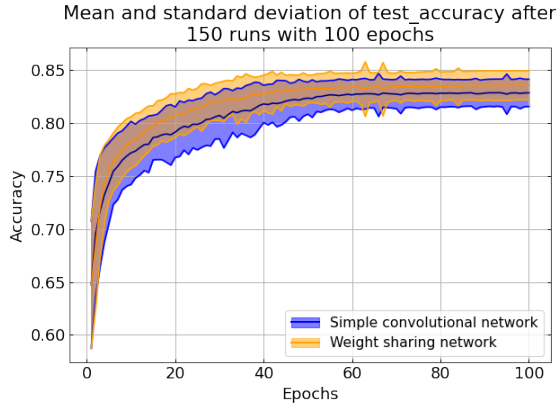
The WSN is then compared to the SAUX with the result of them having nearly indistinguishable performance in the comparison fig. 6b.

Figure 6c shows the comparison between SAUX and CAUX, where SAUX seems to perform better overall, with both architectures starting out very similar but the SAUX plateauing less aggressively. This result is unexpected as intuitively the introduction of additional information should boost the performance on the test set.

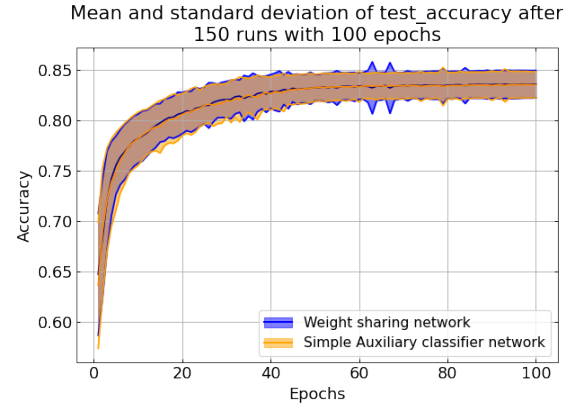
The next group of comparisons in fig. 7 shows the performance of the networks from fig. 6 against their fully convolutional equivalent. Sadly no significant improvement in performance is observable. A reason for that might be that the networks are not taking full advantage of the possibilities of the convolutional layers as they are mere translations of the mixed architectures.

In contrast the switch to non-one-hot encoding visible in fig. 8 led to better performance of the SN, WSN and SAUX with the most significant improvement for the SN and barely significant for the WSN. The CAUX was unable to learn any significant structure from the dataset without one-hot encoding. This is probably due to the fact that while one output neuron might be well suited for a binary output, having ten classes differentiated using one output neuron is more difficult. For the CAUX a mixed structure (main branch fully convolutional and auxiliary classifier unchanged) could be a better solution.

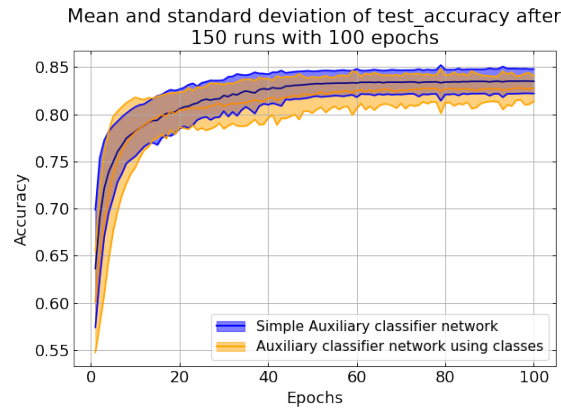
With the knowledge from figs. 7 and 8 only two comparisons are required to decide on the best performing network of this analysis. Namely the comparisons between the models without one-hot encoding as shown in fig. 9. We can conclude that, by a small margin the SAUX without one-hot encoding delivered on average the best results for the architectures tested in this analysis.



(a) Simple network

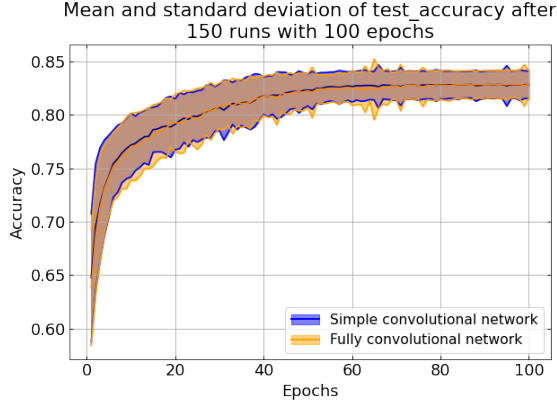


(b) Weight sharing network

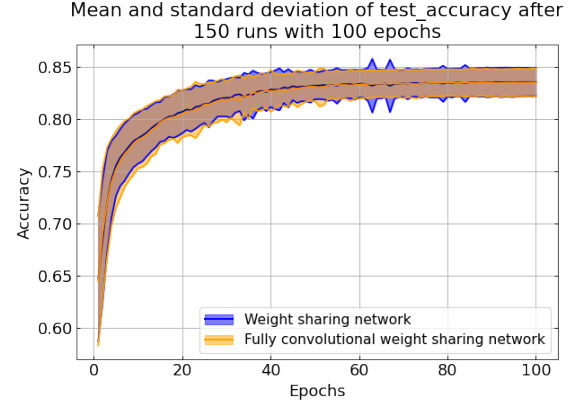


(c) Simple auxiliary classifier network

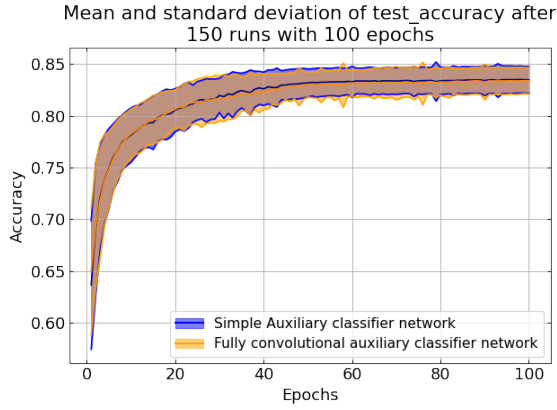
Figure 6: The mean and standard deviation of the test accuracy compared over the course of 100 epochs calculated for 150 trials. For the architectures in their standard form.



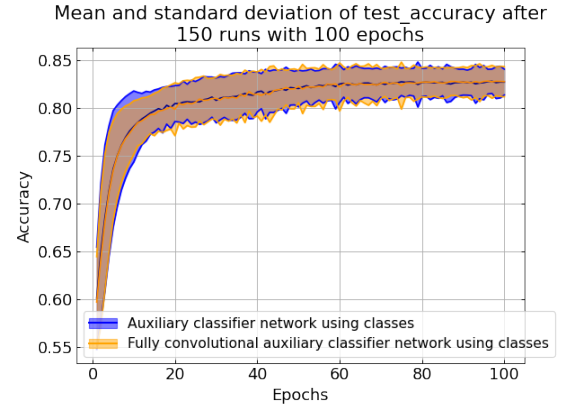
(a) Simple network



(b) Weight sharing network

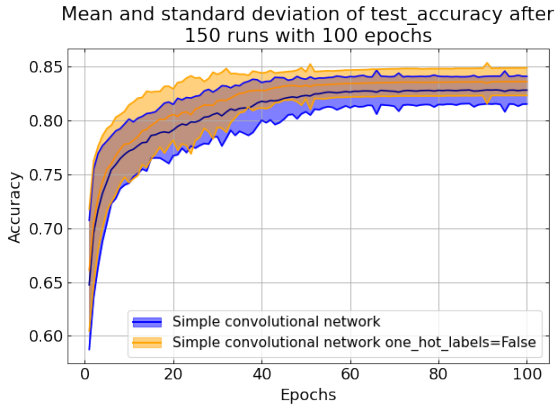


(c) Simple auxiliary classifier network

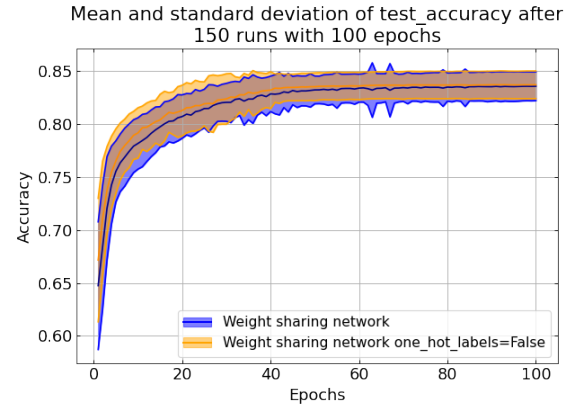


(d) Auxiliary classifier network (number classes)

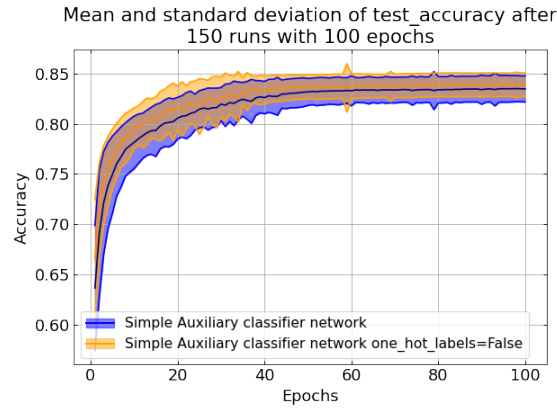
Figure 7: The mean and standard deviation of the test accuracy compared over the course of 100 epochs calculated for 150 trials. For the architectures in their standard form.



(a) Simple network

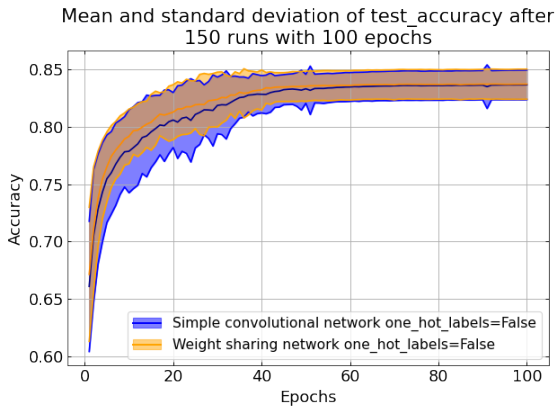


(b) Weight sharing network

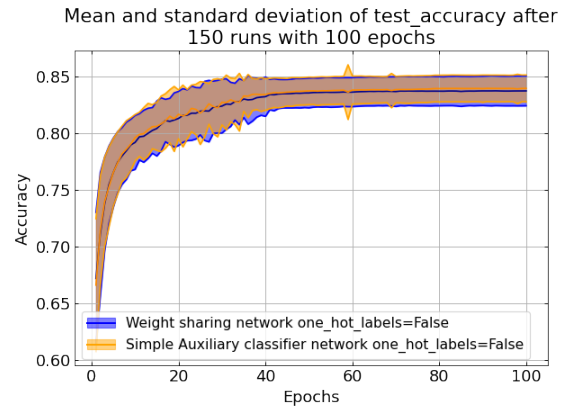


(c) Simple auxiliary classifier network

Figure 8: The mean and standard deviation of the test accuracy compared over the course of 100 epochs calculated for 150 trials. For the architectures in their standard form.



(a) Simple network



(b) Weight sharing network

Figure 9: The mean and standard deviation of the test accuracy compared over the course of 100 epochs calculated for 150 trials. For the architectures in their standard form.

1.5 Conclusion

Four different base architectures and their modifications were tested during this project. In the case of one-hot encoding the best performing models are WSN and SAUX with nearly indistinguishable performance. In the case of non-one-hot encoding the best performing architecture found was SAUX.

In both cases CAUX performed worse than SAUX and WSN which is surprising but might be changed with a more sophisticated architecture for this type of classifier.

No significant improvement was found using fully convolutional architectures but as explained in section 1.4 the networks as proposed in section 1.2 do not take full advantage of the possibilities provided by the convolutional layers.

For this specific task not-one-hot encoding lead to better performance for all networks except CAUX.

Project 2

2.1 Introduction

The goal of this project is to create a framework for constructing neural networks. Here, only the tensor functionalities of the PyTorch library should be used, especially not making use of the `torch.nn` module and the autograd functions of Pytorch.

There are five modules that have to be implemented: Linear (fully connected layer), ReLU, Tanh, Sequential and LossMSE.

To test the framework, a model with 2 input neurons at least three hidden layers of 25 neurons and 1 output neuron is created and trained on a test dataset.

The dataset used for testing is a standard choice in machine learning. Points are created uniformly over a subspace of \mathbb{R} then all points inside a specified circle are classified as target 1 and outside the circle they are classified as target 0. For this project the circle is specified to have a radius of $\frac{1}{\sqrt{2\pi}}$ centered at $x = 0.5$ and $y = 0.5$. The subspace is chosen to be $[0, 1]^2$. An example of the created dataset is visualized in fig. 10

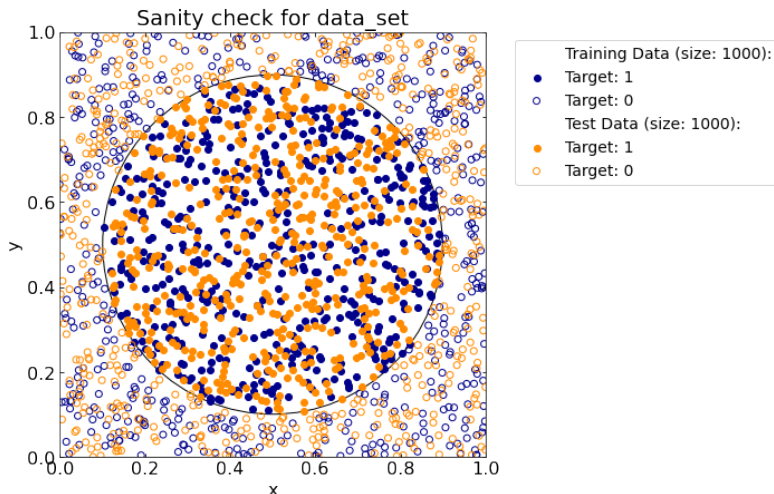


Figure 10: Test dataset for Project 2. Points inside a circle of radius $\frac{1}{\sqrt{2\pi}}$ centered at $x = 0.5$ and $y = 0.5$ are classified as target 1 and outside the circle they are classified as target 0. Points are uniformly generated over $[0, 1]^2$.

2.2 The framework

2.2.1 Base

As a Base Class

```
1 class Module:
2     def __init__(self):
3         self.has_params = False
4         self.device = torch.device('cpu')
5
6     # Defining __call__ method to keep the easy syntax for the forward prop
7     def __call__(self, *input):
8         return self.forward(*input)
9
10    def forward(self, input):
11        raise NotImplementedError
12
13    def backward(self, gradwrtoutput):
14        raise NotImplementedError
15
16    def params(self):
17        return []
18
```

was implemented as suggested in the task. The `__call__` function was defined to be able to call the method `forward` with object().

Building on that, the following classes were constructed:

```
1 class Activation(Module):
2
3     def __call__(self, input):
4         self.x = self.forward(input)
5         return self.x
6
7     def backward(self, prev_layer, grad, loss = False):
8         if loss:
9             return torch.einsum("ik,jk->ij", prev_layer.derivative(self.x, activation=True), grad)
10        else:
11            return torch.einsum("ik,jk->ji", prev_layer.derivative(self.x, activation=True), grad)
12
13    def to_device(self, device):
14        self.device = device
15
16    class Optimizer(Module):
17        def __init__(self, lr, batch_size, device=None):
18            super().__init__()
19            self.lr = torch.tensor([lr])
20            self.has_params = True
21            self.batch_size = torch.tensor([batch_size])
22
23        def params(self):
24            return [self.lr]
25
26        def to_device(self, device):
27            self.lr = self.lr.to(device)
28            self.batch_size = self.batch_size.to(device)
29            self.device = device
30
31
32    class Loss(Module):
33        def __init__(self, target):
34            self.target = target # I choose this initialization to make the loss compatible with the Backpropagation
35
36
37    class Model(Module):
38        """Base class for defining general models"""
39
40        def __init__(self):
41            super().__init__()
42            self.has_params = True
43
44        def save(self, filename, path=None):
45            if path == None:
```

```

46     with open(os.path.join(os.path.curdir, "saved_models", filename + ".pkl"), 'wb') as f:
47         pickle.dump(self, f)
48     else:
49         try:
50             with open(path + filename + ".pkl", 'wb') as f:
51                 pickle.dump(self, f)
52         except:
53             raise Exception("Please enter a valid path when using the optional path argument!")
54
55

```

They should allow too add new activations, losses, optimizers and more complex models than Sequential more quickly if needed. The model class provides a method `save` to store a model using the pickle library. The model can then be loaded into a variable using the `load_model` function.

All Modules posses a method `to_device` which transfers all their parameters to the specified device and changes the parameter `Module.device` to the specified device and therefore enabling CUDA support for the framework. All Modules posses a forward and a backward method except for Loss and Optimizer. All classes that can act as layers of a network, and the loss are implemented with a method that returns their derivative.

Forward pass

The forward pass for the modules is fairly straight forward as the definitions of the required functions are well known and can just be translated into code from the literature [Fleuret2022, Goodfellow-et-al-2016]. With the only addition that the respective results are stored inside the class object for later use in the backward pass. Two forward methods might be worth mentioning. For the Tanh it is implemented using a second class for Sigmoid as they are closely related and also in this case the Sigmoid function is already implemented too without additional effort.

```

1     class Sigmoid(Activation):
2
3     def forward(self, input):
4         return 1/(1+torch.exp(-input))
5
6     def derivative(self, input, activation = False):
7         if activation:
8             raise Exception("Chaining of two activation functions directly after one another!")
9
10        return self.forward(input) * (1 - self.forward(input))
11
12    class Tanh(Activation):
13
14    def __init__(self):
15        super().__init__()
16        self.sigmoid = Sigmoid()
17
18    def forward(self, input):
19        return 2 * self.sigmoid.forward(2 * input) - 1
20
21    def derivative(self, input, activation = False):
22        if activation:
23            raise Exception("Chaining of two activation functions directly after one another!")
24
25        return 4 * self.sigmoid.derivative(2*input) # chain rule
26

```

And the forward propagation of Sequential, which is just the chaining of all the individual forward calls.

```

1     def forward(self, input):
2         for layer in self.layers:
3             input = layer(input)
4
5         return input
6

```

In contrast the backward propagation is way more nuanced. The general equations can be found in various resources like [Fleuret2022, Goodfellow-et-al-2016]. For the case of the sequential model a more or less simple implementation is possible. Except for the first step of the backward propagation, which includes the loss at every step corresponding to a layer, the gradient (of at least one parameter) is calculated using only the derivative of the previous layer, the gradient of the previous layer and the forward pass result of the current layer (the direction being backwards in the graph).

Therefore we can make use of the already implemented derivative method and pass the previous layer as well as the gradient of its backward pass to the backward method of the current layer and use the information that has been stored during the forward pass. With one addition: When two Linear layers follow each other, the previous one returns 1 as its derivative. In that way we can account for most possible architectures that can be created using Sequential.

Then for the linear layer the backward pass is implemented as:

```

1  def backward(self, prev_layer, grad):
2  self.db = prev_layer.derivative(self.s) * grad
3  #self.db = torch.einsum("ik,jk->ij", prev_layer.derivative(self.s), grad)
4  self.dw = torch.einsum("ik,ij->ikj", self.db, self.x)
5  return self.db
6
```

The activation backward pass is implemented as:

```

1  def backward(self, prev_layer, grad, loss = False):
2  if loss:
3  return torch.einsum("ik,jk->ij", prev_layer.derivative(self.x, activation=True), grad)
4  else:
5  return torch.einsum("ik,jk->ji", prev_layer.derivative(self.x, activation=True), grad)
6
```

To get the backward pass for the whole Sequential model we use these methods in the Sequential.backward method:

```

1  def backward(self, loss): # the loss functions will be initialized with target, they get one parameter as an ↵
    instance which will be the output
2
3  grads = [torch.tensor([1]).unsqueeze(1).to(self.device)] # makes the Backprop of the loss work even if the ↵
    output layers is not an activation
4  self.layers.append(loss)
5  self.layers = self.layers[::-1]
6
7  for i in range(1, len(self.layers)):
8  if i == 1:
9  grads.append(self.layers[i].backward(self.layers[i-1], grads[i-1], loss = True))
10 else:
11 grads.append(self.layers[i].backward(self.layers[i-1], grads[i-1]))
12
13
14 self.layers = self.layers[::-1]
15 self.layers = self.layers[:-1] # reformat the layer variable
16 grads = grads[1:]
17 grads = grads[::-1]
18 return grads
19
```

After the gradient is calculated the models parameters need to be updated. As Linear is the only layer with parameters in this example, the update_params function is implemented for this module:

```

1  def update_params(self, optimizer):
2  if self.bias:
3  self.b -= optimizer(self.db)
4  self.w -= optimizer(self.dw)

```

The model Sequential has a method `update_params` which calls the `update_params` of all layers with parameters (i.e. only linear layers in this case).

Which concludes the basic tools needed to build a simple sequential neural network.

2.3 Training

Inside of every training function there is the sequence of calculating the output, doing the backward pass and updating the parameters of the model. In this framework as specified in section 2.2 this routine is:

```

1  output = model(inputs)
2
3  optim = nn.SGD(lr, inputs.shape[0])
4  optim.to_device(self.device)
5
6  loss = nn.MSE(targets)
7
8  grads = model.backward(loss)
9  model.update(optim)
10
```

The framework was set up in a way such that whenever parameters inside the model are changed during training, this is done by a method of the model itself, as this seemed most intuitive. As opposed to `torch.nn` where the backward pass is performed by the loss function object and the update is performed by the optimizer object.

The Teacher class as well as the `run_analysis` function are reused from Project 1 in a slightly modified form.

The Model is trained for 50000 epochs with a learning rate of 0.0001 and a batch size of 100 for a total of 50 trials to estimate the mean and standard deviation. The architecture is build to meet the requirements as described in section 2.1 exactly, with Tanh as the first activation function and ReLU for the rest (as this showed the most promising learning behaviour for small numbers of epochs).

The loss is the MSE loss and the optimizer is SGD.

2.4 Results

The network was created and moved to the GPU. With the Training setup as in section 2.3 the network needed a large number of epochs but reached a relatively high accuracy. The development of the test accuracy can be seen in fig. 11

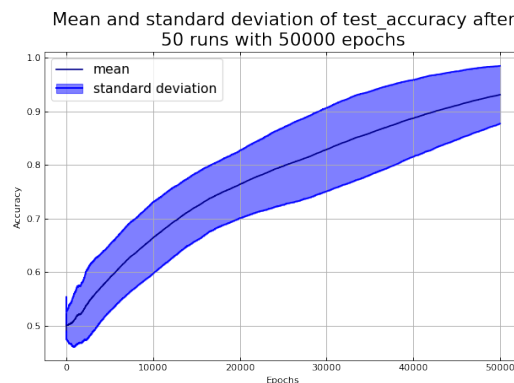


Figure 11: Mean and standard deviation for the test accuracy of the network after training for 50000 epochs with a learning rate of 0.0001 and a batch size of 100 for a total of 50 trials.

2.5 Conclusion

A framework including all of the required modules was implemented. Using this framework a network meeting the requirements laid down in section [2.1](#) was created. The network needed a large number of epochs to perform reasonably well on the test set but was able to reach a relatively high degree of accuracy.