

Exercise III: Convolutional and Recurrent Neural Networks

Short summary

In this exercise you will:

- Train CNNs for a binary classification problem
- Visualize how CNNs interprets the data
- Train CNNs for two 3-class classification problem
- Train a RNN on a time series prediction problem
- Visualize RNN hidden node activities

In this lab we will look at network architectures that are designed to handle specific kinds of data. Convolutional Neural Networks for image processing and Recurrent Neural Networks for time series processing

Deadline for submitting the report: See Canvas assignment.

The data

Digits "5" and "6" from the MNIST database used for a binary classification problem.

A dataset consisting of circles, rectangles or triangles, that can be read using the *loadImagesCRT* function.

A dataset consisting of three different types of rectangles, squares, "horizontal" rectangles and "vertical" rectangles. This data can be read using the *loadImagesR3* function.

A dataset consisting of pairs of times series. The input time series is a train of rectangle pulses, and the output is triangles, i.e. an up-ramp followed by a down-ramp. For more details see the cell *Ex4-1*. The task is to train a recurrent network that predicts the triangle time series from the pulse time series.

The exercises

As for the previous labs all exercises are found below.

The different 'Cells'

This notebook contains several cells with python code, together with the markdown cells (like this one) with only text. Each of the cells with python code has a "header" markdown cell with information about the code. The table below provides a short overview of the code cells.

#	CellName	CellType	Comment
1	Init	Needed	Sets up the environment
2	Data	Needed	Loading images for the CNN exercise
3	PlotImg	Information	View some of the images
4	Stats	Needed	Compute classification results
5	Visualization	Needed	Visualize layers of a CNN
6	Ex1	Exercise	For question 1-2
7	Ex2	Exercise	For question 3
8	Ex3	Exercise	For question 4-5
9	Ex4-1	Exercise	For question 6-9
10	Ex4-2	Exercise	For question 6-9
11	Ex4-3	Exercise	For question 6-9

In order for you to start with the exercise you need to run all cells with the CellType "Needed". The very first time you start with this exercise we suggest that you enter each of the needed cells, read the cell instruction and run the cell. It is important that you do this in the correct order, starting from the top and work your way down the cells. Later when you have started to work with the notebook it may be easier to use the command "Run All" found in the "Cell" dropdown menu.

Writing the report

First the report should be written within this notebook. We have prepared the last cell in this notebook for you where you should write the report. The report should contain 4 parts:

- Name:
- Introduction: A **few** sentences where you give a small introduction of what you have done in the lab.
- Answers to questions: For each of the questions provide an answer. It can be short answers or longer ones depending on the nature of the questions, but try to be effective in your writing.
- Conclusion: Summarize your findings in a few sentences.

It is important that you write the report in this last cell and **not** after each question!

Last but not least

Have fun again!

CellName: Init (#1)

CellType: Needed

Cell instruction: Initializing the libraries

In the cell below, we import all the libraries that are needed for this exercises.

Run the cell by entering into the cell and press "CTRL Enter".

```
In [1]: import numpy as np
import tensorflow as tf
import time

from tensorflow import keras
from tensorflow.keras.models import Model, Sequential
from tensorflow.keras.layers import Dense, Dropout, Flatten, Input, Activation
from tensorflow.keras.layers import Conv2D, MaxPooling2D
from tensorflow.keras.layers import TimeDistributed
from tensorflow.keras.layers import Lambda, concatenate
from tensorflow.keras.layers import LSTM, GRU, SimpleRNN, RNN

from tensorflow.keras.optimizers import SGD, Adam, RMSprop, Nadam
from tensorflow.keras import backend as K

from sklearn.metrics import *

import matplotlib
import matplotlib.pyplot as plt

2022-12-30 11:22:45.236622: I tensorflow/core/platform/cpu_feature_guard.cc:193] This TensorFlow binary is optimized with oneAPI Deep Neural Network Library (oneDNN) to use the following CPU instructions in performance-critical operations: AVX2 FMA
To enable them in other operations, rebuild TensorFlow with the appropriate compiler flags.
```

CellName: Data (#2)

CellType: Needed

Cell instruction: Function for getting images for the CNN exercises

This cell defines the functions that obtain the images needed for the CNN exercise.

Note: Make sure the "crt-trn/" and "crt-tst/" folders are available in the same directory as this notebook file when you actually call these functions. Otherwise, the files files are not found.

Run the cell by entering into the cell and press "CTRL Enter".

```
In [2]: def load_pics(folder, N):
    import imageio
    imgs = []
    for i in range(N):
        img = imageio.imread(folder+"img_{:05}.png".format(i+1))
```

```

        ch = img[:, :, 0]
        imgs.append(ch)
    return np.array(imgs)

def load_labels(fn):
    return np.loadtxt(fn, usecols=(0, 1, 2))

def loadImagesCRT():
    base = "./"
    trainpic = load_pics(base + "crt-trn/", 500)
    valpic = load_pics(base + "crt-val/", 1000)
    ntrain, width, height = trainpic.shape

    xtrain = (trainpic/np.float32(255)).reshape(500, width, height, 1)
    xval = (valpic/np.float32(255)).reshape(1000, width, height, 1)

    ytrain = load_labels(base+"crt-trn_trg.csv")
    #ytrain = ytrain[:N]
    yval = load_labels(base+"crt-val_trg.csv")

    return xtrain, ytrain, xval, yval, width, height

def loadImagesR3():
    base = "./"
    trainpic = load_pics(base + "r3-trn/", 500)
    valpic = load_pics(base + "r3-val/", 1000)
    ntrain, width, height = trainpic.shape

    xtrain = (trainpic/np.float32(255)).reshape(500, width, height, 1)
    xval = (valpic/np.float32(255)).reshape(1000, width, height, 1)

    ytrain = load_labels(base+"r3-trn_trg.csv")
    #ytrain = ytrain[:500]
    yval = load_labels(base+"r3-val_trg.csv")

    return xtrain, ytrain, xval, yval, width, height

def loadMNIST56():
    xtrain, ytrain, xval, yval = np.load("mnist56.npy", allow_pickle=True)
    width, height = xtrain.shape[1:3]
    return xtrain, ytrain, xval, yval, width, height

```

CellName: PlotImg (#3)

CellType: Information

Cell instruction: Show some of the images

Here we look at the first ten pictures in the training set, and their respective targets. You can select the dataset to look at by uncomment the correct line.

Run the cell by entering into the cell and press "CTRL Enter".

```
In [3]: xTrn, dTrn, xVal, dVal, width, height = loadMNIST56()
#xTrn, dTrn, xVal, dVal, width, height = loadImagesCRT()
#xTrn, dTrn, xVal, dVal, width, height = loadImagesR3()

rndSel = np.random.randint(500, size=10)
plt.figure(1, figsize=(15,10))
```

```

plt.imshow(xTrn[rndSel,:,:].swapaxes(0,1).reshape(width,10*height),cmap="gray")
plt.axis("off")
plt.show()

print("Targets:")
print(dTrn[rndSel])

```



Targets:

[0. 1. 0. 1. 0. 0. 0. 0. 1. 0.]

CellName: Stats (#4)

CellType: Needed

Cell instruction: Get binary and 3-class classification results

This cell just defines functions that we can call to compute som performance measures for binary and 3-class classification problems.

Run the cell by entering into the cell and press "CTRL Enter".

```
In [4]: def binary_pred_stats(ytrue, ypred, threshold=0.5):
    one_correct = np.sum((ytrue==1)*(ypred > threshold))
    zero_correct = np.sum((ytrue==0)*(ypred <= threshold))
    sensitivity = one_correct / np.sum(ytrue==1)
    specificity = zero_correct / np.sum(ytrue==0)
    accuracy = (one_correct + zero_correct) / len(ytrue)
    return sensitivity, specificity, accuracy

def plot_confusion_matrix(cm,
                          target_names,
                          title='Confusion matrix',
                          cmap=None,
                          normalize=True):

    import itertools

    accuracy = np.trace(cm) / float(np.sum(cm))
    misclass = 1 - accuracy

    if cmap is None:
        cmap = plt.get_cmap('Blues')

    plt.figure(figsize=(8, 6))
    plt.imshow(cm, interpolation='nearest', cmap=cmap)
    plt.title(title)
    plt.colorbar()
    #plt.ylim([-0.5, cm.shape[0]-0.5])

    if target_names is not None:
        tick_marks = np.arange(len(target_names))
        plt.xticks(tick_marks, target_names, rotation=45)
        plt.yticks(tick_marks, target_names)

    if normalize:
        cm = cm.astype('float') / cm.sum(axis=1)[:, np.newaxis]
```

```

thresh = cm.max() / 1.5 if normalize else cm.max() / 2
for i, j in itertools.product(range(cm.shape[0]), range(cm.shape[1])):
    if normalize:
        plt.text(j, i, "{:0.4f}".format(cm[i, j]),
                  horizontalalignment="center",
                  color="white" if cm[i, j] > thresh else "black")
    else:
        plt.text(j, i, "{:,}").format(cm[i, j]),
                  horizontalalignment="center",
                  color="white" if cm[i, j] > thresh else "black")

plt.tight_layout()
plt.ylabel('True label')
plt.xlabel('Predicted label\naccuracy={:0.4f}; misclass={:0.4f}'.format(
plt.show()

def multi_stat_3(model = None, x_test = None, y_test = None, lbl = None):
    y_pred = model.predict(x_test, verbose=0)
    print(lbl, ' log_loss: ', log_loss(y_test, y_pred, eps=1e-15))

    y_true = y_test.argmax(axis=1)
    y_pred = y_pred.argmax(axis=1)
    print(lbl, ' accuracy: ', (y_pred==y_true).mean(), '\n')

    target_names = ['class {}'.format(i+1) for i in range(3)]

    confuTst = confusion_matrix(y_true, y_pred)
    plot_confusion_matrix(cm = confuTst,
                          normalize = False,
                          target_names = target_names,
                          title = "Confusion Matrix: " + lbl)

```

CellName: Visualization (#5)

CellType: Needed

Cell instruction: Function that can visualize the different layers of a CNN

This cell is feeding an image through a CNN and stores the intermediate values. It plots the different layers (filtered images) either before or after maxpooling.

Run the cell by entering into the cell and press "CTRL Enter".

```
In [5]: def layerVisaliztion(model,
                         indata,
                         target,
                         idx=10,
                         post_pool = False):

    # The prediction for the test case
    #idx_pred = model.predict(indata)[idx,0]
    #print('True label: = {:0.1f}, Prediction = {:0.8f}'.format(idx_pred, ta

    print('Prediction: ', model.predict(indata)[idx])
    print('Target      : ', target[idx])
```

```

kind = MaxPooling2D if post_pool else Conv2D
outs = [l.output for l in model.layers if isinstance(l, kind)]
intermediate = K.function([model.layers[0].input], outs)

states = [indata[idx:idx+1]] + intermediate([indata[idx:idx+1]])
plt.figure(figsize=(18,12))
for k,s in enumerate(states):
    plt.figure(figsize=(18,12))
    plt.subplot(len(outs)+1,1,k+1)
    pics = s[0]
    pics = np.rollaxis(pics,2,0)
    rows = 2 if pics.shape[0] > 8 else 1
    cols = pics.shape[0]//rows
    pad = pics.shape[0]-rows*cols
    if pad > 0:
        padding = np.zeros_like(pics, shape=(rows-pad,) + pics.shape[1:])
        pics = np.concatenate([pics, padding])
        cols = cols + 1
    imgshape = pics.shape[1:]
    pics = pics.reshape((rows,cols)+imgshape)
    pics = pics.swapaxes(1,2)
    pics = pics.reshape((pics.shape[0]*pics.shape[1], pics.shape[2]*pics
extent = (0,cols*imgshape[0], 0,rows*imgshape[1]))
plt.imshow(pics,cmap='gray',extent=extent)
for r in range(1,rows):
    plt.plot([0,cols*imgshape[0]], [r*imgshape[1], r*imgshape[1]], c
for c in range(1,cols):
    plt.plot([c*imgshape[0], c*imgshape[0]], [0,rows*imgshape[1]], c

```

CellName: Ex1 (#6)

CellType: Exercise

Cell instruction: Instructions for question 1-2

CNN for image classification

In this first exercise you are going to train a CNN that can separate between numbers "5" and "6" from the mnist dataset (mnist56 dataset). We are going to use 2000 training images and 1850 validation images. To start with we have a proposed CNN that can solve this problem. It consists of the following:

- First convolutional layer consisting of 4 kernels of size 3x3, with ReLU activation
- Maxpooling of size 2x2
- Second convolutional layer of 4 kernels of size 3x3, with ReLU activation
- Maxpooling of size 2x2
- Special layer *Flatten()*, just transforms the all of the max pooled filter outputs to a linear vector of outputs
- *Dense* layer, meaning a fully connected MLP layer, to 10 hidden nodes, again ReLU activation
- Final output layer consisting of one single output node with sigmoid activation function because we have a binary classification problem.

The default is to use *stride* = 1 and no *padding*.

Question 1

Make sure you understand the definition of the CNN model in the cell below and train it.

What is your validation set performance in terms of the accuracy?

Question 2

This image classification problem should be relatively easy since a "5" has some distinct differences from a "6". Experiment with the architecture of the CNN model and try to make it smaller (in terms of the number of trainable parameters), but with the same almost perfect validation accuracy (>98%). **How many parameters do you have in your trimmed model? What is your architecture?**

Hint: There is of course very many ways you can make a smaller architecture. You do not need to test all of them!

```
In [16]: # Load the dataset, MNIST-56
x_trn, d_trn, x_val, d_val, width, height = loadMNIST56()

# The size of the images
input_shape = (width, height, 1)

# Define the CNN ex1
ex1 = Sequential()

# First conv layer
ex1.add(Conv2D(3, kernel_size=(3, 3), activation='relu', input_shape=input_s
ex1.add(MaxPooling2D(pool_size=(3, 3)))

# Second conv layer
ex1.add(Conv2D(3, kernel_size=(3, 3), activation='relu'))
ex1.add(MaxPooling2D(pool_size=(3, 3)))

# Fully connected MLP layers
ex1.add(Flatten())
ex1.add(Dense(5, activation='relu'))

# Output layer
ex1.add(Dense(1, activation='sigmoid'))

# We use cross entropy error and the adam optimizer
adam = Adam(learning_rate=0.005)
ex1.compile(loss='binary_crossentropy', optimizer=adam, metrics=['accuracy'])
ex1.summary()

# Now train the ex1
estimator_ex1 = ex1.fit(x_trn, d_trn,
                        validation_data=(x_val, d_val),
                        epochs=30,
                        batch_size=64,
                        verbose=0)

# Training history
plt.figure()
plt.ylabel('Loss / Accuracy')
plt.xlabel('Epoch')
for k in estimator_ex1.history.keys():
    plt.plot(estimator_ex1.history[k], label = k)
plt.legend(loc='best')
```

```

plt.show()

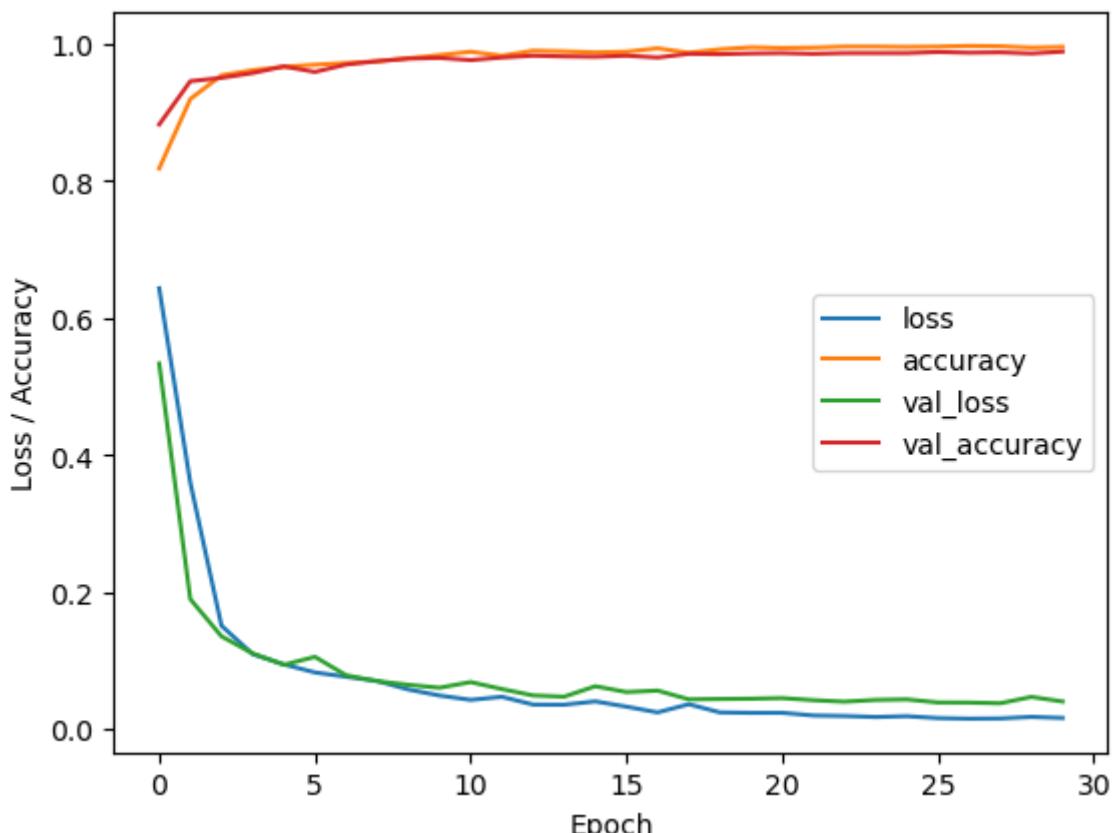
# Get the training predictions and results for those
d_trn_pred = ex1.predict(x_trn)[:,0]
sens, spec, acc = binary_pred_stats(d_trn, d_trn_pred)
print('training: Accuracy = {:.4f}, Sensitivity = {:.4f}, Specificity = {:.4f}'

# Get the validation predictions and the results for those
d_val_pred = ex1.predict(x_val)[:,0]
sens, spec, acc = binary_pred_stats(d_val, d_val_pred)
print('validation: Accuracy = {:.4f}, Sensitivity = {:.4f}, Specificity = {:.4f}

```

Model: "sequential_9"

Layer (type)	Output Shape	Param #
<hr/>		
conv2d_17 (Conv2D)	(None, 26, 26, 3)	30
max_pooling2d_17 (MaxPooling2D)	(None, 8, 8, 3)	0
conv2d_18 (Conv2D)	(None, 6, 6, 3)	84
max_pooling2d_18 (MaxPooling2D)	(None, 2, 2, 3)	0
flatten_9 (Flatten)	(None, 12)	0
dense_14 (Dense)	(None, 5)	65
dense_15 (Dense)	(None, 1)	6
<hr/>		
Total params: 185		
Trainable params: 185		
Non-trainable params: 0		



```
63/63 [=====] - 0s 4ms/step
training: Accuracy = 0.9970, Sensitivity = 0.9980, Specificity = 0.9960

58/58 [=====] - 0s 5ms/step
validation: Accuracy = 0.9892, Sensitivity = 0.9875, Specificity = 0.9910
```

CellName: Ex2 (#7)

CellType: Exercise

Cell instruction: Instructions for question 3

You are now going to take a look into the CNN model. There are many attempts to visualize how the CNN model is making classifications. We will here just look at the different layer outputs given an input image. The function 'layerVisualization', found in cell #5 does the following:

- Use one selected image from the supplied dataset.
- Make a forward pass through the CNN remembering all intermediate values.
- Plot all of the "filters" for each of the layers.
- One can select to plot before or after the MaxPooling.

You pass the model that you want to visualize to the 'layerVisualization' function. If you do not change the names in cell (Ex1) it will be 'ex1'.

Question 3

Train a CNN for the "5" vs "6" problem! As a suggestion use the following CNN

3x(3x3 kernel)-maxpool-3x(3x3 kernel)-maxpool-(Flatten)-Dense(5)-Dense(1)

Make sure that your trained model gives good validation results (i.e. > 95% accuracy). Having such a model, you can run the cell below. There are two parameters you need to specify, *idx* and *post_pool*. The *post_pool* variable can be set to *True* meaning that filters will be shown after MaxPooling. The image to show is selected by the *idx* variable. As an example, the following values represent,

- *idx=1* number "6"
- *idx=2* number "5"
- *idx=3* another number "6"
- *idx=5* another number "5"

Can you find and describe some property in the filters that makes sense when it comes to separating "5" from "6"?

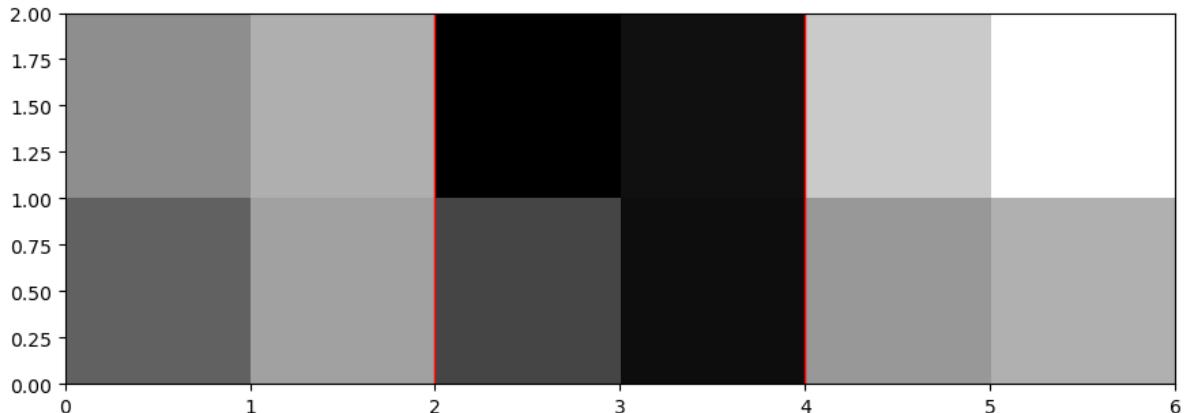
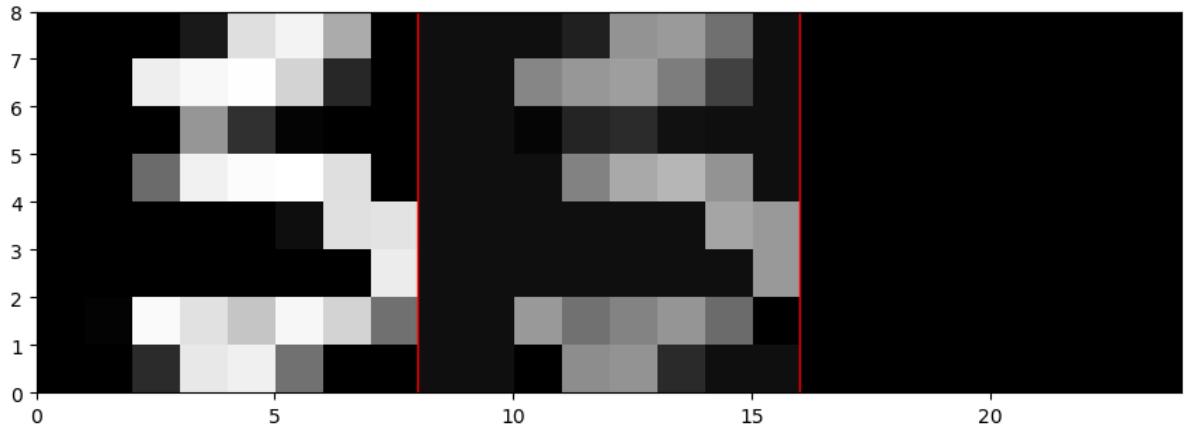
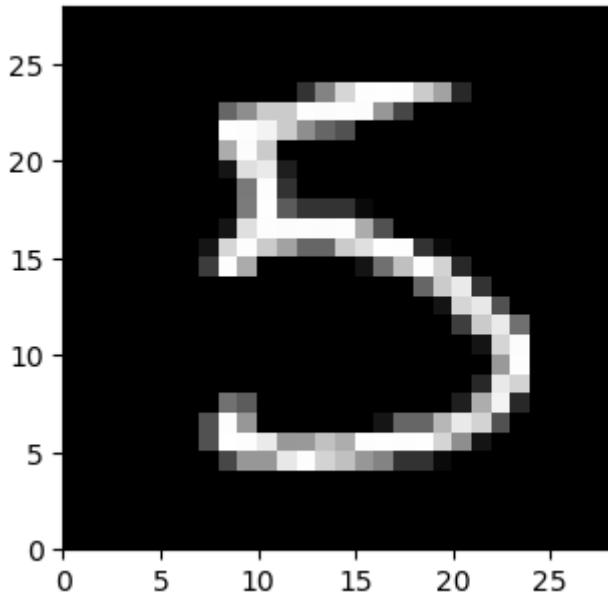
Hint! If you repeat the training you most likely get a new network and other filters!

```
In [24]: # Show before or after MaxPooling
post_pool = True

# The test image to look at
idx = 2
```

```
# Call the visualization method, giving the model and the validation data to  
layerVisaliztion(ex1, x_val, d_val, idx, post_pool)
```

```
58/58 [=====] - 0s 4ms/step  
Prediction: [8.99182e-06]  
Target : 0.0  
<Figure size 1800x1200 with 0 Axes>
```



CellName: Ex3 (#8)

CellType: Exercise

Cell instruction: Instructions for question 4-5

CNN for image classification

In this exercise you are going to train a CNN that can separate between circles/squares/triangles found in the CRT dataset, and the three different types of rectangles found in the R3 dataset. You will use 500 training images and 1000 validation images. Code is provided for loading the data, training the model and presenting the result. Your task is to define the actual CNN model and see how it performs. For the following two questions you can optimize the model based on the validation performance. Here we assume that 1000 validation images are many enough for "model selection overtraining bias" to be small.

Question 4

Define your own CNN model for classifying the images in the CRT data into three classes. **Provide the details of your CNN model and present the validation result.**

Hint: Remember the difference between a binary classifier and a multi-class classifier!

Question 5

Define your own CNN model for classifying the images in the R3 data into three classes. **Provide the details of your CNN model and present the validation result. Why is this a more difficult problem than Question 4?**

Bonus task

The bonus tasks are provided if you have extra time and want to continue to explore the CNNs. **These tasks are not required for the course and does not influence any grading.**

You can use the *layerVisualization* method also for above models (Q4 and Q5). It will show you the different filter outputs. Again try to understand the features the different filter learn to separate between circles-triangles-rectangles, or the rectangles for the R3 data set.

```
In [56]: # Load the CRT dataset (Question 4)
#x_trn, d_trn, x_val, d_val, width, height = loadImagesCRT()

# Load the R3 dataset (Question 5)
x_trn, d_trn, x_val, d_val, width, height = loadImagesR3()

print('Training data input shape: ', x_trn.shape)
print('Training data output shape: ', d_trn.shape)
print('Validation data input shape: ', x_val.shape)
print('Validation data output shape: ', d_val.shape)

# The size of the images
input_shape = (width, height, 1)

# Define the CNN ex3
ex3 = Sequential()

#
# YOUR CODE HERE
# First conv layer
```

```

ex3.add(Conv2D(3, kernel_size=(3, 3), activation='relu', input_shape=input_s
ex3.add(MaxPooling2D(pool_size=(3, 3)))

# Second conv layer
ex3.add(Conv2D(3, kernel_size=(3, 3), activation='relu'))
ex3.add(MaxPooling2D(pool_size=(3, 3)))

# Fully connected MLP layers
ex3.add(Flatten())
ex3.add(Dense(10, activation='relu'))

# Output layer
ex3.add(Dense(3, activation='softmax'))

# We use cross entropy error and the adam optimizer
adam = Adam(learning_rate=0.003)
ex3.compile(loss='categorical_crossentropy', optimizer=adam, metrics=[ 'accuracy'])
ex3.summary()

# Now train the ex3
estimator_ex3 = ex3.fit(x_trn, d_trn,
                        validation_data=(x_val, d_val),
                        epochs=50,
                        batch_size=50,
                        verbose=0)

# Training history
plt.figure()
plt.ylabel('Loss / Accuracy')
plt.xlabel('Epoch')
for k in estimator_ex3.history.keys():
    plt.plot(estimator_ex3.history[k], label = k)
plt.legend(loc='best')
plt.show()

# Training result
multi_stat_3(ex3, x_trn, d_trn, 'Training')

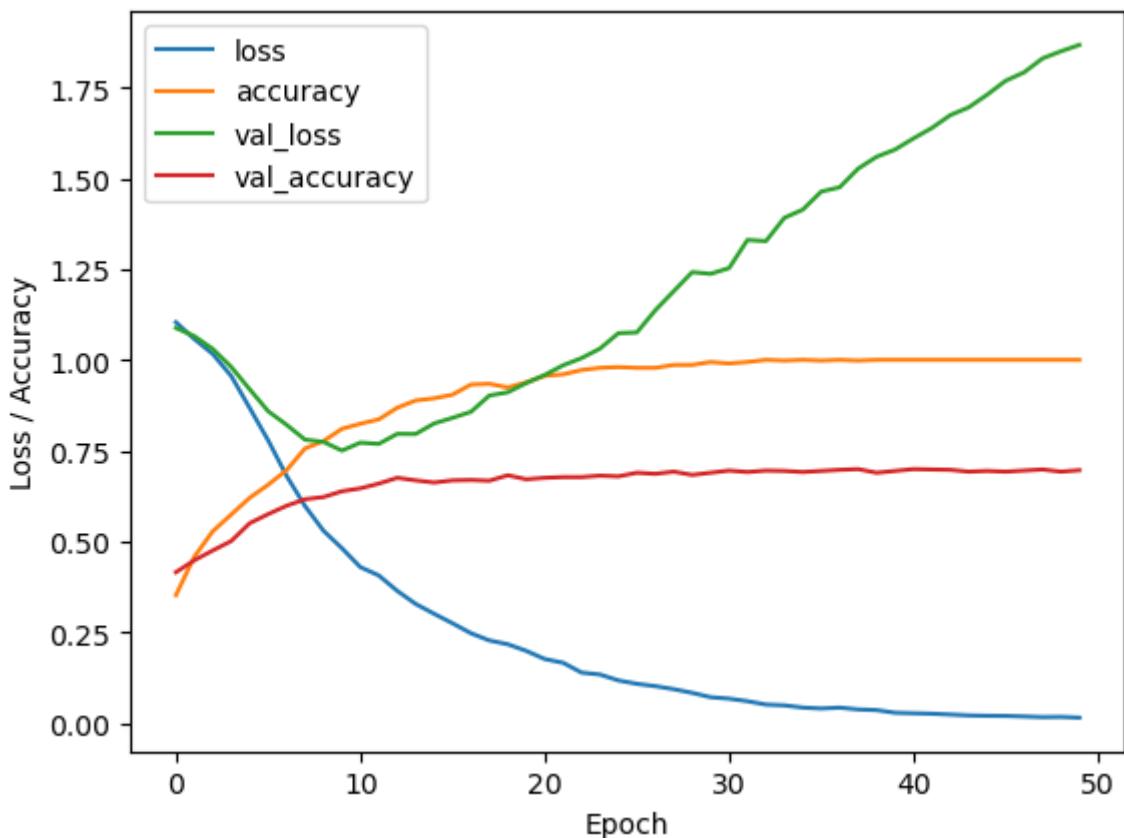
# Validation result
multi_stat_3(ex3, x_val, d_val, 'Validation')

/var/folders/bq/myp7pv7d2kx50tbcnmg3pjgm0000gn/T/ipykernel_11804/3241759781.py:5: DeprecationWarning: Starting with ImageIO v3 the behavior of this function will switch to that of iio.v3.imread. To keep the current behavior (and make this warning disappear) use `import imageio.v2 as imageio` or call `imageio.v2.imread` directly.
    img = imageio.imread(folder+"img_{:05}.png".format(i+1))

```

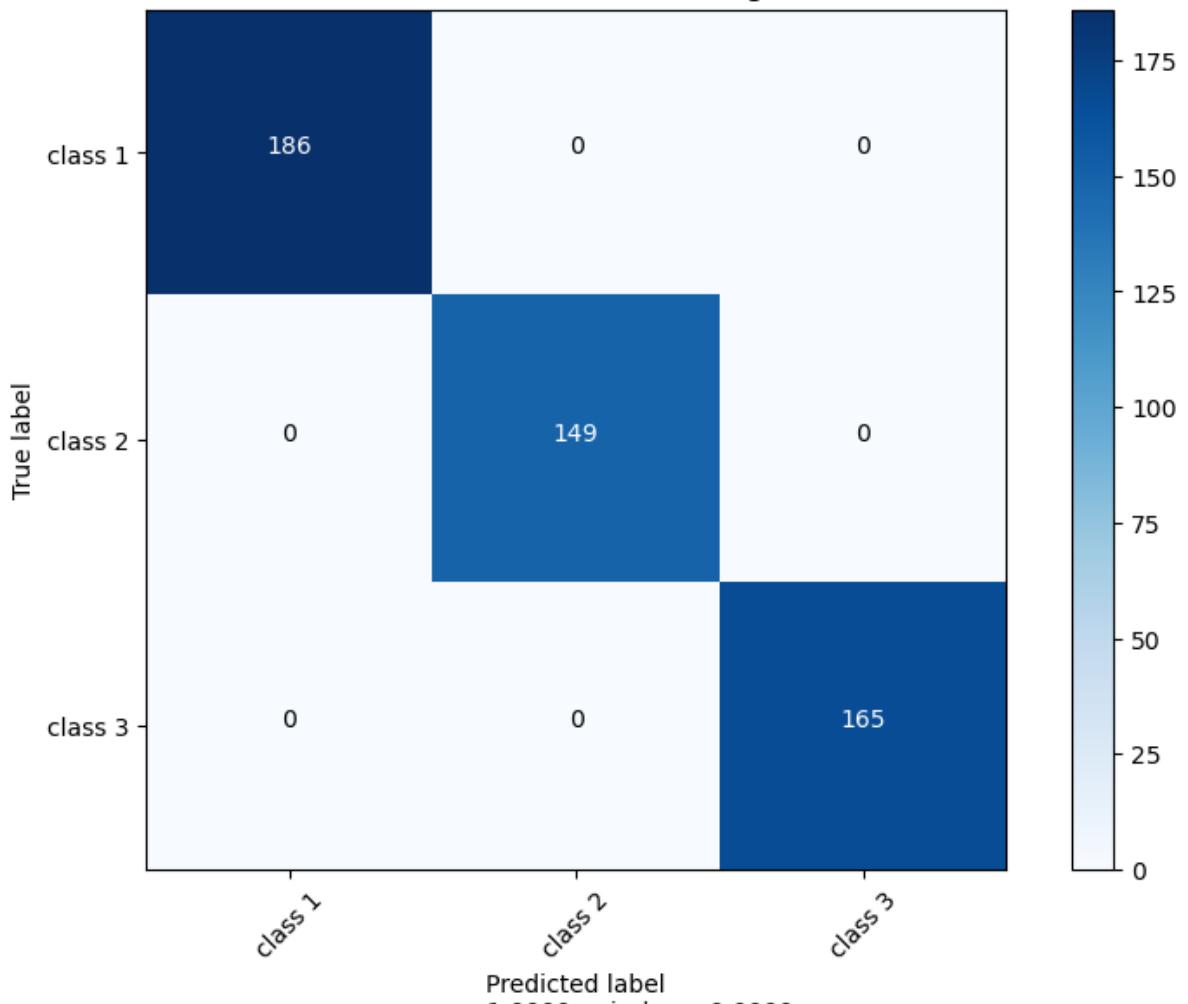
Training data input shape: (500, 64, 64, 1)
 Training data output shape: (500, 3)
 Validation data input shape: (1000, 64, 64, 1)
 Validation data output shape: (1000, 3)
 Model: "sequential_35"

Layer (type)	Output Shape	Param #
<hr/>		
conv2d_70 (Conv2D)	(None, 62, 62, 3)	30
max_pooling2d_67 (MaxPooling2D)	(None, 20, 20, 3)	0
conv2d_71 (Conv2D)	(None, 18, 18, 3)	84
max_pooling2d_68 (MaxPooling2D)	(None, 6, 6, 3)	0
flatten_31 (Flatten)	(None, 108)	0
dense_60 (Dense)	(None, 10)	1090
dense_61 (Dense)	(None, 3)	33
<hr/>		
Total params: 1,237		
Trainable params: 1,237		
Non-trainable params: 0		

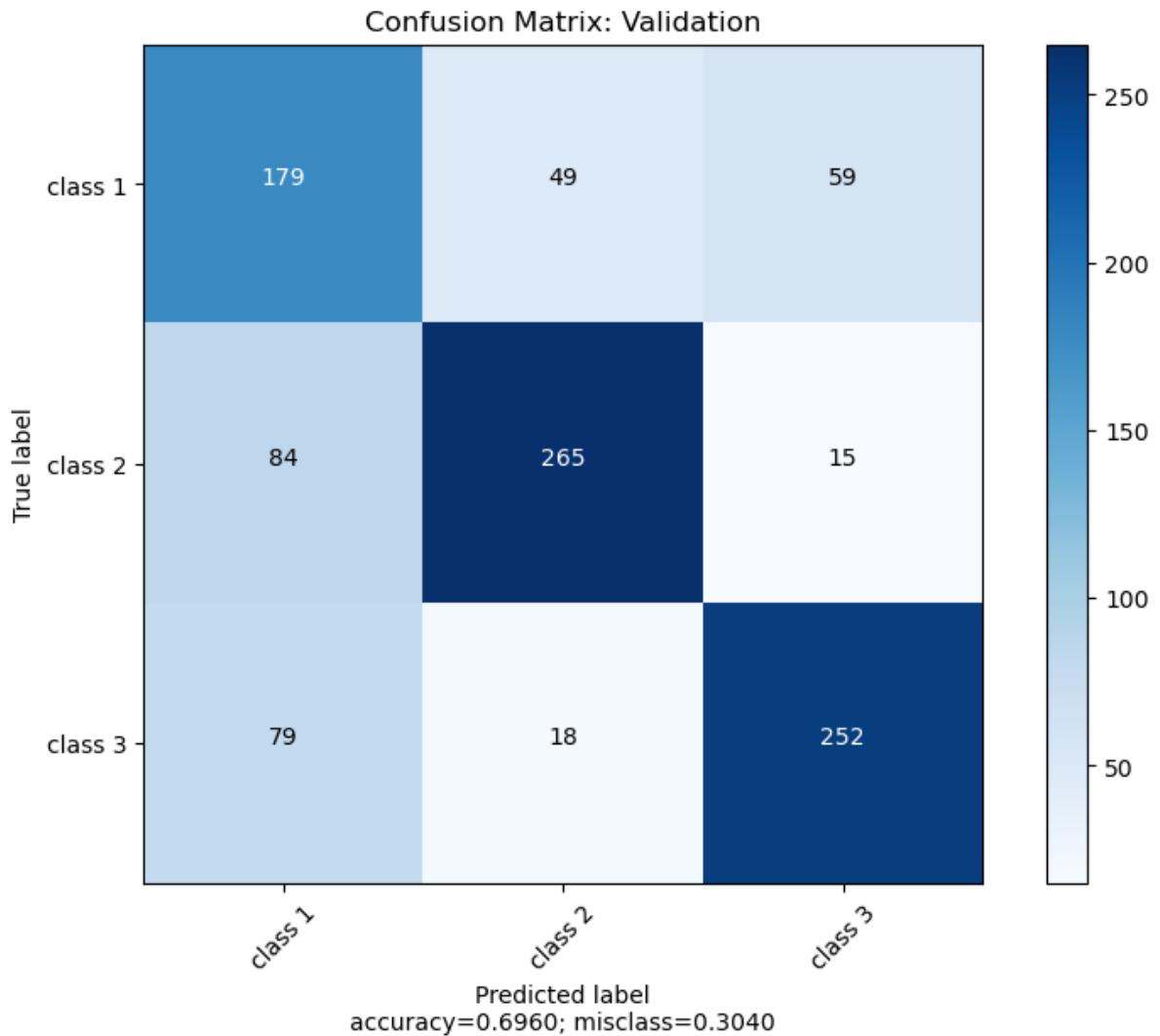


Training log_loss: 0.013137920730167195
 Training accuracy: 1.0

Confusion Matrix: Training



Validation log_loss: 1.8674451073507212
Validation accuracy: 0.696

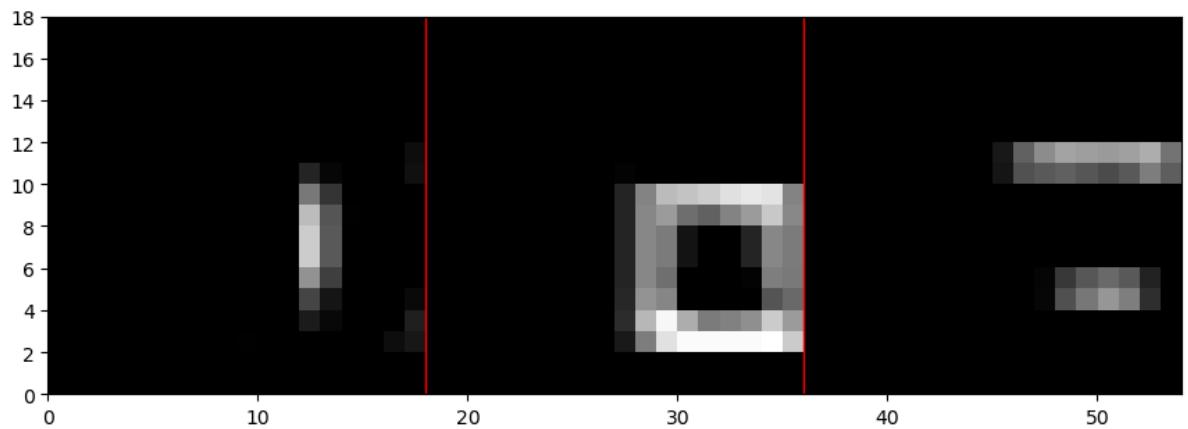
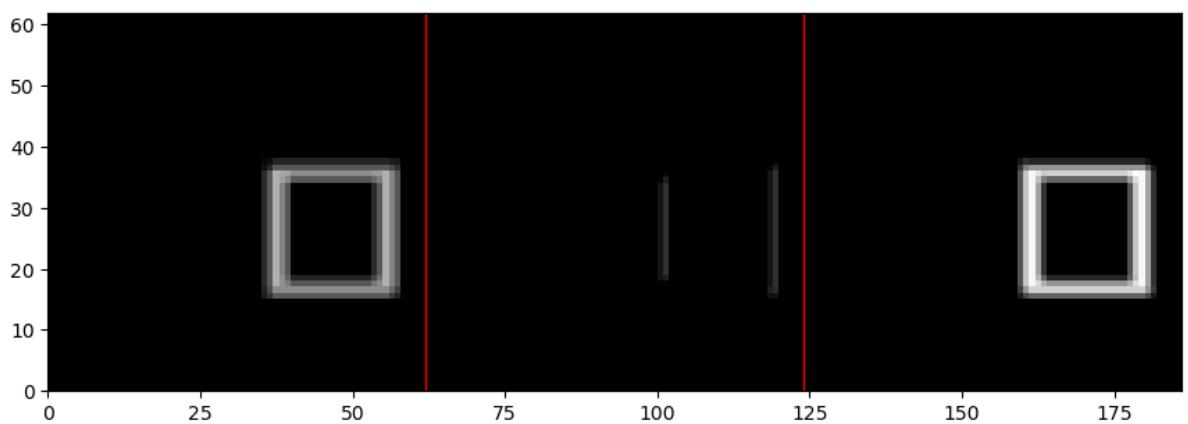
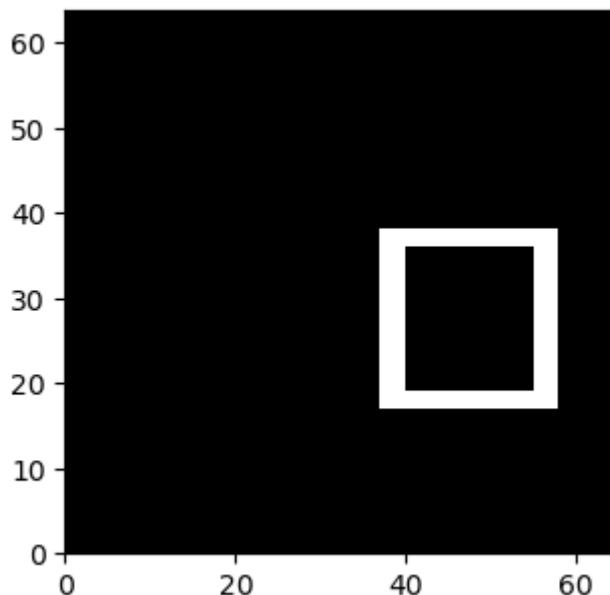


```
In [60]: # Show before or after MaxPooling
post_pool = False

# The test image to look at
idx = 8

# Call the visualization method, giving the model and the test data to select
layerVisaliztion(ex3, x_val, d_val, idx, post_pool)

32/32 [=====] - 0s 14ms/step
Prediction: [9.999988e-01 4.745644e-07 7.113031e-07]
Target      : [1. 0. 0.]
<Figure size 1800x1200 with 0 Axes>
```



In []:

CellName: Ex4-1 (#9)

CellType: Exercise

Cell instruction: Instructions for question 6-9

RNN as a pulse converter

We will now look at recurrent networks! **Note:** This exercise is divided into three cells. The actual questions for this part can be found in cell *Ex4-3* below.

Loading and visualizing the data

The cell below loads the training data and the validation data from existing binary python files and plots one set of training/validation data, both the input sequence and the target sequence. Run the cell by entering into the cell and press "CTRL Enter".

How is data generated? The input sequence consists of square pulses with varying length and height. The waiting time between the pulses is also varying within some predefined ranges. The lower limit is 2 times the length of the previous pulse. The target triangle pulse sequence is built from the input sequence as follows:

- the triangle pulse starts when the input square pulse have ended.
- the width of the triangle (at the base) is twice the width of the square pulse.
- the height of the triangle is the same as the height of the square pulse.

The task is now to learn this mapping using a recurrent neural network. There are 500 input/target sequences in the training data and 500 in the validation data.

```
In [68]: # Load data from files
x_trn,d_trn= np.load("pulsedata1-trn.npy")
x_val,d_val = np.load("pulsedata1-val.npy")

print('Training data input shape: ', x_trn.shape)
print('Training data output shape: ', d_trn.shape)
print('Validation data input shape: ', x_val.shape)
print('Validation data output shape: ', d_val.shape)

# If this is set to True, then we have the reverse problem. Input triangle p
if True:
    d_trn,x_trn = x_trn[:,::-1],d_trn[:,::-1]
    d_val,x_val = x_val[:,::-1],d_val[:,::-1]

ns,tlen = x_trn.shape
t = np.arange(tlen)

# The training / test case to look at
i = 3

# Plot
plt.figure(figsize=(15,10))
plt.subplot(4,1,1)
plt.plot(t,x_trn[i,:])
plt.legend(['Training, input sequence'], loc=0)

plt.subplot(4,1,2)
plt.plot(t,d_trn[i,:])
plt.legend(['Training, target sequence'], loc=0)

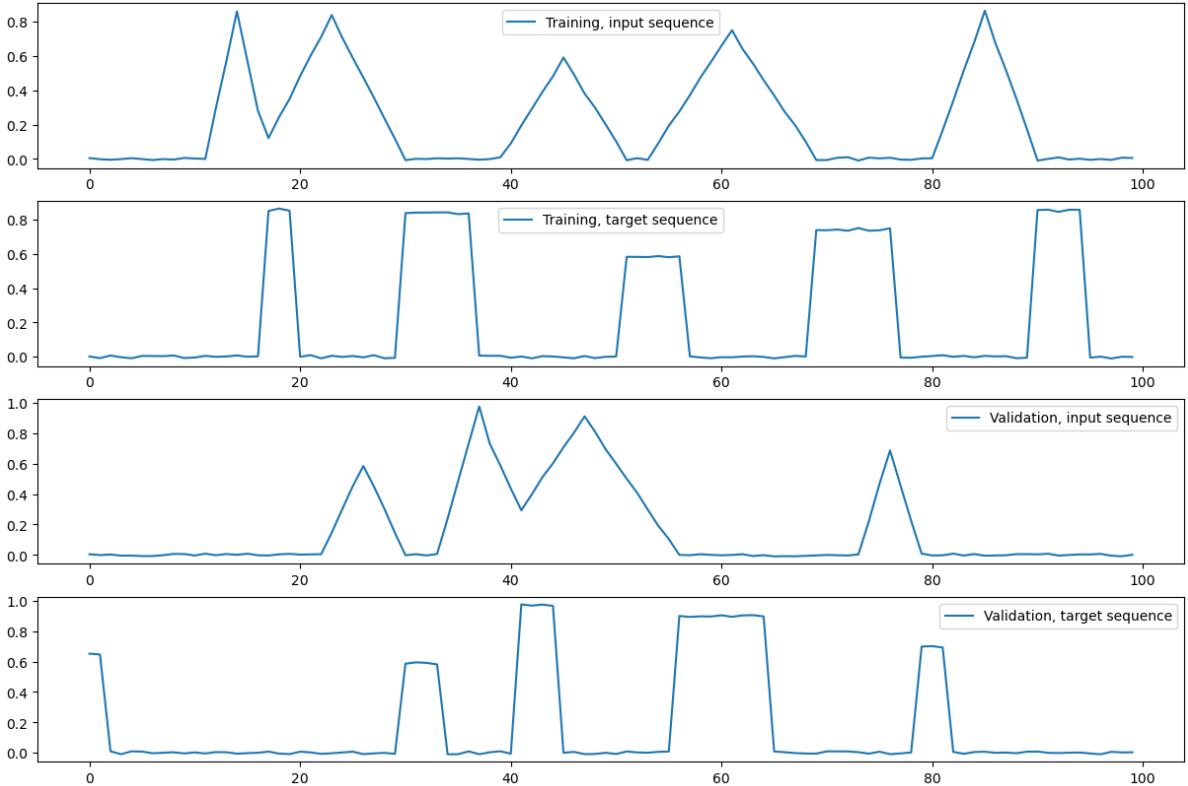
plt.subplot(4,1,3)
plt.plot(t,x_val[i,:])
plt.legend(['Validation, input sequence'], loc=0)

plt.subplot(4,1,4)
```

```
plt.plot(t,d_val[i,:])
plt.legend(['Validation, target sequence'], loc=0)
```

Training data input shape: (500, 100)
 Training data output shape: (500, 100)
 Validation data input shape: (500, 100)
 Validation data output shape: (500, 100)

Out [68]:

**CellName:** Ex4-2 (#10)**CellType:** Exercise**Cell instruction:** Instructions for question 6-9

RNN as a pulse converter

Define the model and train

Here we are going to setup the model and train it. There are three different models to choose from:

- SimpleRNN: Simple feedback weights where the output from a node is feeding back to itself. For several hidden nodes there are feedback weights to all other nodes in the layer.
- LSTM: The LSTM unit
- GRU: The GRU unit

The standard choice of activation function is *tanh*, but you can also test *relu*. When it comes to training this model we are going to use a possible truncated BPTT approach. The support in Keras for doing this is somewhat limited so here it is implemented

manually. In short we have 500 training sequences and we define a mini-batch size mb that selects mb of these sequences to train using the normal stochastic gradient descent idea. Then we have a variable $batchlen$ that is the length of the sequence to use in truncated BPTT. The default values for these are $mb=20$ and $batchlen=50$. If you want to train without the truncated BPTT approach put $batchlen=100$.

During training we print the normalized training and validation error. Normalized means here that the loss (=MSE) is divided by the variance of the target signal. That means that a normalized error of 1 is poor, but below 0.1 (or so) the error is much smaller than the signal itself.

What you need to do in this cell is to define your model and train it.

In [83]:

```
%time
ns,tlen = x_trn.shape

# Parameters defining the mini-batch size and
# the sequence length for truncated BPTT
mb = 20
batchlen = 50

# The network type
#net = SimpleRNN
net = GRU
#net = LSTM

# Number of hidden nodes
nh1 = 25

# This is only if you would like to add an additional hidden layer. See below
nh2 = 25

# The activation function
#activation = 'tanh'
activation = 'relu'

# The number of epochs
nE = 40

# Start defining the model
nmb = ns//mb
ntsteps = tlen//batchlen

model = Sequential()
model.add(net(nh1,
              batch_input_shape=(mb,batchlen,1),
              stateful=True,
              return_sequences=True,
              activation=activation))

# Uncomment this line if you want to add an additional hidden layer

model.add(TimeDistributed(Dense(1)))
model.add(TimeDistributed(Dense(1)))

adam = Adam(learning_rate=0.003)
model.compile(optimizer=adam, loss='mean_squared_error')
model.summary()

# Now the training part
```

```

trnTrgVar = np.var(d_trn[:, :])    # Variance for train target signal
valTrgVar = np.var(d_val[:, :])    # Variance for validation target signal
ndone = 0

print('Epoch', 'Time/Epoch', 'Trn-Err', 'Val-Err')
for ne in range(nE):
    t0 = time.time()
    sumlossTrn = 0
    for batch in range(nmb):
        i1, i2 = batch * mb, (batch + 1) * mb
        model.reset_states()
        for tstep in range(ntsteps):
            t1, t2 = tstep * batchlen, (tstep + 1) * batchlen
            loss = model.train_on_batch(x_trn[i1:i2, t1:t2], d_trn[i1:i2])
            sumlossTrn += loss
    meanlossTrn = sumlossTrn / (nmb * ntsteps)

    # Validation error
    sumlossVal = 0
    for batch in range(nmb):
        i1, i2 = batch * mb, (batch + 1) * mb
        model.reset_states()
        for tstep in range(ntsteps):
            t1, t2 = tstep * batchlen, (tstep + 1) * batchlen
            loss = model.evaluate(x_val[i1:i2, t1:t2], d_val[i1:i2, t1:t2])
            sumlossVal += loss
    meanlossVal = sumlossVal / (nmb * ntsteps)
    t1 = time.time()
    ndone += 1
    print(ndone, "    {:.2f}          {:.5f}    {:.5f}" .format(t1 - t0, meanlos

```

Model: "sequential_54"

Layer (type)	Output Shape	Param #
gru_15 (GRU)	(20, 50, 25)	2100
time_distributed_21 (TimeDistributed)	(20, 50, 1)	26
time_distributed_22 (TimeDistributed)	(20, 50, 1)	2
<hr/>		
Total params: 2,128		
Trainable params: 2,128		
Non-trainable params: 0		

Epoch	Time/Epoch	Trn-Err	Val-Err
1	5.21	0.80683	0.58685
2	3.91	0.52648	0.45716
3	3.89	0.41676	0.34696
4	3.88	0.32201	0.28871
5	4.18	0.27694	0.25919
6	4.02	0.24903	0.22901
7	3.92	0.22636	0.20775
8	3.94	0.20715	0.18888
9	3.97	0.19213	0.17416
10	3.92	0.17786	0.16638
11	3.96	0.16822	0.15788
12	4.04	0.14868	0.15416
13	3.95	0.14360	0.13412
14	3.96	0.13049	0.14340
15	4.43	0.12653	0.14346
16	3.92	0.12924	0.11050
17	3.95	0.12666	0.12718
18	3.94	0.11479	0.10989
19	3.96	0.11276	0.11633
20	3.93	0.10994	0.11236
21	3.89	0.10417	0.10619
22	3.92	0.10689	0.10672
23	3.96	0.10239	0.11155
24	3.99	0.10073	0.09226
25	3.92	0.09519	0.09537
26	3.95	0.09399	0.09286
27	3.97	0.09923	0.09617
28	3.96	0.09397	0.08706
29	3.94	0.09115	0.08423
30	3.96	0.10051	0.09136
31	4.26	0.08650	0.08286
32	4.00	0.08701	0.08197
33	3.98	0.08768	0.08056
34	4.04	0.08319	0.08107
35	3.99	0.08777	0.09253
36	3.98	0.08598	0.09667
37	4.00	0.08349	0.08503
38	3.96	0.08529	0.08897
39	4.08	0.08359	0.09082
40	3.96	0.08294	0.09330

CPU times: user 3min 14s, sys: 17 s, total: 3min 31s

Wall time: 2min 40s

CellName: Ex4-3 (#11)

CellType: Exercise

Cell instruction: Instructions for question 6-9

RNN as a pulse converter

Plot the result

In this cell we just plot the result for one of the first mb (minibatch size) test sequences. You can select which of these ones by an index (see the code). Also, the last graph shows the hidden node activation for all of the hidden nodes. **Note:** For the GRU and simpleRNN models this is all of the hidden activity there is, but for the LSTM there is also the memory signal. That one is not shown!

Questions

We are now finally at the point of asking questions. Whenever you define a new model and train it, you need to run the cell below in order to show the result for the newly trained model.

Hint! For all of the questions below you are going to train different models. Keep an eye on how the training error is developing. If you see large fluctuations, you may want to change the learning rate. The default value of 0.003 should be OK for most trainings.

Question 6

(Just to get started!) Define a simpleRNN model with 5 hidden nodes and train it for about 20 epochs. **What validation error do you obtain?**

Hint 1: The validation error can be found during "training" as the error for the last epoch.
Hint 2: You may have to train a couple of times to make sure that you did not end up in a "bad" local minima the first time.

Question 7

Test different models! Train the three different models (one hidden layer only) with the approximately the same number of trainable weights (around 150-200) and decide which of them that works best? **So, out of the three different models, simpleRNN, GRU and LSTM, which one worked best using the same number weights?**

Question 8

Interpretation! You are now going to interpret the hidden node outputs. Remember that the actual output for each time is a linear combination of the hidden node outputs. As said before you can see the hidden nodes output in the last plot. Note that the weights in the dense layer can have different signs so that hidden nodes outputs can be linearly combined with both positive and negative signs. Train a GRU model with 3 hidden nodes for about 20 epochs. **Try to explain what the different hidden nodes are detecting.**

Comment: This is of course a question with no definite true answer. We just want you to interpret what the different nodes are doing.

Question 9

If you look at the top of cell *Ex4-1* you can, by changing False -> True, define the reverse problem (see top of the code cell). That is, input is the triangle pulse and target is the square pulse. This should be a more difficult problem! **Why? Present a RNN model that can "solve" this reverse problem (i.e. below 0.1 in test error).**

Hint: Here you can experiment with two hidden layers of LSTM/GRU/SimpleRNN nodes

```
In [67]: xshow = x_val[:mb]
dshow = d_val[:mb]
dout = np.zeros((mb,tlen))
hidden1 = np.zeros((mb,tlen,nh1))
hidden2 = np.zeros((mb,tlen,nh2))

rnn1 = model.layers[0]
rnn2 = model.layers[1]

#dense = model.layers[-1]
#sign = K.sign(dense.layer.kernel)[None,None,:,:0]
if len(model.layers) > 2 :
    intermediate = K.function([rnn1.input], [rnn1.output, rnn2.output])
else :
    intermediate = K.function([rnn1.input], [rnn1.output])

for tstep in range(ntsteps):
    t1,t2 = tstep*batchlen,(tstep+1)*batchlen
    inp = xshow[:,t1:t2,None]
    if len(model.layers) > 2 :
        hi,hi2 = intermediate([inp])
        hidden2[:,t1:t2,:,:] = hi2
    else :
        hi, = intermediate([inp])
        hidden1[:,t1:t2,:,:] = hi
    yi = model.predict(xshow[:,t1:t2,None])
    dout[:,t1:t2] = yi[:, :, 0]

t = np.arange(tlen)

# Selection of validation sequence, valid range is [0,mb]
i = 0

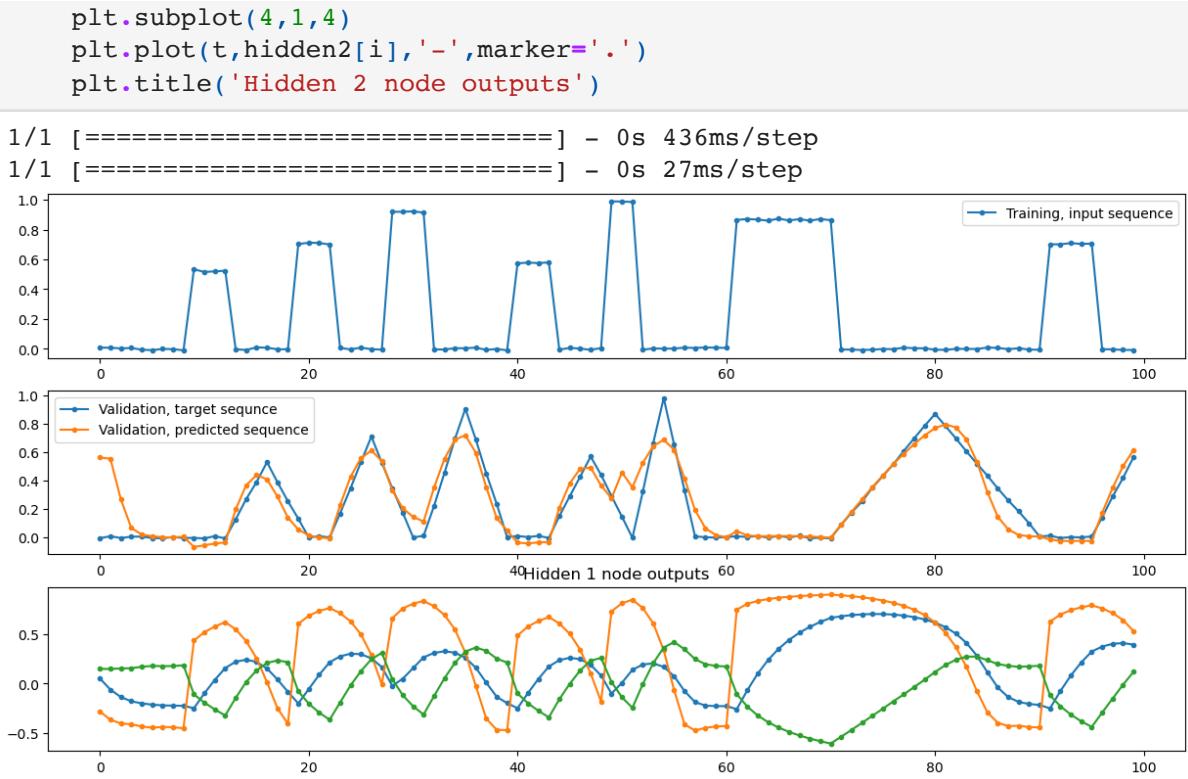
plt.figure(figsize=(15,10))

plt.subplot(4,1,1)
plt.plot(t,xshow[i],'-',marker='.')
plt.legend(['Training, input sequence'], loc=0)

plt.subplot(4,1,2)
plt.plot(t,dshow[i],'-',marker='.')
plt.plot(t,dout[i],'-',marker='.')
plt.legend(['Validation, target sequnce', 'Validation, predicted sequence'], loc=0)

plt.subplot(4,1,3)
plt.plot(t,hidden1[i],'-',marker='.')
plt.title('Hidden 1 node outputs')

if len(model.layers) > 2 :
```



The report!

We have added instructions inside this report template. As you write your report, remove the instructions.

Name

Introduction

This exercise aims to generate deeper insight about more exotic network architectures than the standard MLPs used in previous computer exercises. This is done through exploring how convolutional networks are effective in image classification tasks, both in terms of performance and computational efficiency. Secondly recurrent architectures are experiment with in order to show how these can handle sequential tasks.

Answers to questions

Provide enough information to clarify the meaning of your answers, so that they can be understood by someone who does not scroll up and read the entire instruction.

The questions are repeated here, for clarity of what is demanded. If it does not fit your style to quote them verbatim, change the format.

Question 1

What is your validation set performance in terms of the accuracy?

Answer: The validation performance of the initial CNN is displayed in the table below.

Metric	Value
Accuracy	0.9946
Sensitivity	0.9906
Specificity	0.9989

Question 2

How many parameters do you have in your trimmed model? What is your architecture?

Answer: By reducing the amount of fully connected(FC) nodes in the network one can decrease the network size from 1,209 parameters down to 109 while maintaining an accuracy of approximately 99 %. One of the FC layers is unnecessary for the simple task of classifying fives and sixes. To further reduce the network size one may decrease the kernel sizes of the convolutional layers from 4 to 2. The final architecture is displayed below.

Layer (type)	Output Shape	Param #
<hr/>		
conv2d_15 (Conv2D)	(None, 26, 26, 2)	20
max_pooling2d_15 (MaxPooling2D)	(None, 13, 13, 2)	0
conv2d_16 (Conv2D)	(None, 11, 11, 2)	38
max_pooling2d_16 (MaxPooling2D)	(None, 5, 5, 2)	0
flatten_8 (Flatten)	(None, 50)	0
dense_13 (Dense)	(None, 1)	51
<hr/>		
Total params: 109		
Trainable params: 109		
Non-trainable params: 0		

Question 3

Can you find and describe some property in the filters that makes sense when it comes to separating "5" from "6"?

Answer: By using the suggested network and inspecting the provided visualization one gets an idea of how the network discriminates between fives and sixes. The first filter appears to be trained to detect the edges of the digits, i.e the main feature of the image such as a six having a full loop and a five having a straight line. The second visualization, using post-pooling, shows how another feature becomes the average pixel value in each quadrant of the image. This visualization suggests that it is more common for a six to have darker lower quadrants and a five to have brighter ones. A convolutional neural net

is somewhat of a black box however by inspecting the filters one can get an intuition for what features the network learns to classify from.

Question 4

Provide the details of your CNN model for the CRT problem and present the validation result.

Answer: By modifying the network used in the previous questions one may use it for classification on the CRT data set. This is done by using the softmax output activation function in order to handle the multi-class problem, and adding some more nodes to increase the performance. Using the CNN architecture displayed below one may reach a validation accuracy of approximately 98 %. The network needs to be larger than the one used for the subset of MNIST to reach the same performance which is expected since it is used to solve a more complex problem.

Layer (type) #	Output Shape	Param
conv2d_31 (Conv2D)	(None, 62, 62, 4)	40
max_pooling2d_29 (MaxPooling2D)	(None, 20, 20, 4)	0
conv2d_32 (Conv2D)	(None, 18, 18, 4)	148
max_pooling2d_30 (MaxPooling2D)	(None, 6, 6, 4)	0
flatten_16 (Flatten)	(None, 144)	0
dense_28 (Dense)	(None, 10)	1450
dense_29 (Dense)	(None, 3)	33
<hr/>		
Total params: 1,671		
Trainable params: 1,671		
Non-trainable params: 0		

Question 5

Provide the details of your CNN model for the R3 problem and present the validation result.

Why is this a more difficult problem than Question 4?

Answer: Using a copy of the CRT network architecture on the R3 data set yields a worse performance of approximately 78 %. This problem is more difficult as none of the tried architectures yields a performance above 78 % accuracy that was achieved using the architecture below. This might stem from there being a greater class-inbalance in the R3

data set. Another reason might be that the images from objects in different classes are more similar.

Layer (type) #	Output Shape	Param
conv2d_66 (Conv2D)	(None, 62, 62, 3)	30
max_pooling2d_63 (MaxPooling2D)	(None, 20, 20, 3)	0
conv2d_67 (Conv2D)	(None, 18, 18, 3)	84
max_pooling2d_64 (MaxPooling2D)	(None, 6, 6, 3)	0
flatten_29 (Flatten)	(None, 108)	0
dense_56 (Dense)	(None, 10)	1090
dense_57 (Dense)	(None, 3)	33

Total params: 1,237
Trainable params: 1,237
Non-trainable params: 0

Question 6

What validation error do you obtain?

Answer: The Simple RNN yields a validation error of 0.26866.

Question 7

Present three different models, *simpleRNN*, *GRU* and *LSTM*, using roughly the same number weights.

Which one worked best?

Answer: The results for the three different model types are displayed in the table below. The GRU appears to be the best model type for this task.

Model	Final Validation Error
Simple RNN	0.26866
GRU	0.03874
LSTM	0.08070

Question 8

Try to explain what the different hidden nodes are detecting. *Comment: This is of course a question with no definite true answer. We just want you to interpret what the different*

nodes are doing.

Answer:

One of the nodes, visualized in orange, appears to be detecting the rough parts of the signal corresponding to a binary signal being turned off or on. Another, visualized in blue, appears to be detecting if the signal is changing, i.e if the signal is increasing or decreasing. The third node, visualized in green, appears to be detecting the slope of the signal, i.e how much the signal is decreasing or increasing.

Question 9

Why is the reverse of the pulse problem (input signal and target signal change roles, time is reversed) more difficult?

Present a RNN model that can "solve" this reverse problem (i.e. below 0.1 in test error).

Answer: The more challenging reversed problem can be solved by increasing the number of nodes and training the network longer. Using the architecture below yields a final validation error of 0.09330.

Layer (type) #	Output Shape	Param
gru_15 (GRU)	(20, 50, 25)	2100
time_distributed_21 (TimeDistributed)	(20, 50, 1)	26
time_distributed_22 (TimeDistributed)	(20, 50, 1)	2
<hr/>		
Total params: 2,128		
Trainable params: 2,128		
Non-trainable params: 0		

Summary

All exercises show how different neural network architectures are suitable for different tasks. In the exercises handling the vision modality one experiences how the addition of convolutional layers vastly decreases the amount of trainable parameters in the network, whilst still maintaining a high performance. Secondly, it also gives intuition in regards to how the network actually learns. A visualisation of the network filters shows the concept of a neural network learning the features in the hidden layers, as opposed to these being explicitly defined as in standard supervised learning. The filter visualisations for example shows how edges, or dark spots become features that the network uses to classify digits or symbols. The tasks handling the recurrent architectures show how different type of recurrent structures are suitable for different problems. The final problem provides a fun challenge where one learns to experiment with different

configurations. An example would be how the amount of hidden states impacts the networks ability to solve the signal processing exercise.

In []: