Project 5: Recognition using Deep Networks

Due Apr 8 by 8:59pm **Points** 30

Overview

This project is about learning how to build, train, analyze, and modify a deep network for a recognition task. We will be using the MNIST digit recognition data set, primarily because it is simple enough to build and train a network without a GPU, but also because it is challenging enough to provide a good example of what deep networks can do.

As this is the last defined project. The last task of this project is to propose and design your final project.

Tasks

1. **Build and train a network to recognize digits**

   The first task is to build and train a network to do digit recognition using the MNIST data base, then save the network to a file so it can be re-used for the later tasks. My strong recommendation is to use the python package pyTorch (torch) and the associated torchvision package. You can install both torch and torchvision using pip.

   PyTorch Home Page (https://northeastern.instructure.com/courses/103147/assignments/pytorch.org)

   There are a number of different tutorials on building and training a convolutional network to solve the MNIST digit recognition task. You can follow the **pyTorch Tutorial (https://pytorch.org/tutorials/beginner/basics/intro.html)** for the Fashion MNIST data set, but use the MNIST digit data set instead. A different tutorial that uses the MNIST digits is **here (https://nextjournal.com/gkoehler/pytorch-mnist)**

   As you write your python code, write well-structured python code. **All** of your code should be in functions except for the top level function call which should be conditioned on whether the file is being executed or imported. Please use the following overall structure. This will be part of the grading.

```
# Your name here and a short header

# import statements
import sys

# class definitions
class MyNetwork(nn.Module):
    def __init__(self):
        pass
    # computes a forward pass for the network
    # methods need a summary comment
    def forward(self, x):
        return x

# useful functions with a comment for each function
def train_network( arguments ):
    return

# main function (yes, it needs a comment too)
def main(argv):
    # handle any command line arguments in argv

    # main function code
    return

if __name__ == "__main__":
    main(sys.argv)
```

A. **Get the MNIST digit data set**

The MNIST digit data consists of a training set of 60k 28x28 labeled digits and a test set of 10k 28x28 labeled digits. The data set can be imported directly from the torchvision package as torchvision.datasets.MNIST. Use the matplotlib pyplot package or OpenCV to look at the first six example digits. Look up examples that make use of the pyplot subplot method to create a grid of plots.

Include a plot of the first six example digits in your report.

B. **Make your network code repeatable**

In order to make your code repeatable, set the random seed for the torch package, `torch.manual_seed(42)`, at the start of your main function. Remove this line if you want to create different networks. You can use any number you like, it doesn't have to be 42. To make your processing truly repeatable, you will also need to turn off CUDA using `torch.backends.cudnn.enabled = False`

C. **Build a network model**

Similar to the example in the tutorial, create a network with the following layers.

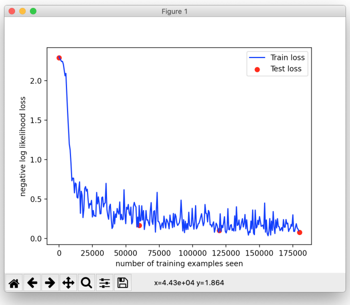
- A convolution layer with 10 5x5 filters
- A max pooling layer with a 2x2 window and a ReLU function applied.
- A convolution layer with 20 5x5 filters
- A dropout layer with a 0.5 dropout rate (50%)
- A max pooling layer with a 2x2 window and a ReLU function applied
- A flattening operation followed by a fully connected Linear layer with 50 nodes and a ReLU function on the output
- A final fully connected Linear layer with 10 nodes and the log_softmax function applied to the output.

The design of your network class will be in the constructor and forward method of your Network class, derived from the torch nn.Module class.

Put a diagram of your network in your report.

D. **Train the model**

Train the model for five epochs, one epoch at a time, evaluating the model on both the training and test sets after each epoch. An epoch is one complete pass through the training data. Pick a batch size of your choice. Make a plot, such as the one below, of the training and testing error.



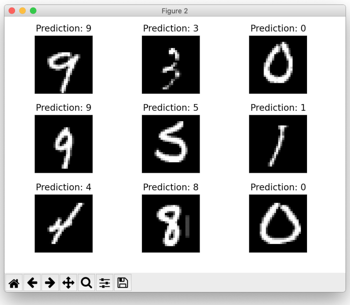
Collect the accuracy scores and plot the training and testing accuracy in a graph. Include this plot in your report.

E. **Save the network to a file**

When the network is trained, save it to a file.

F. **Read the network and run it on the test set**

In a separate python file, read the network and run the model on the first 10 examples in the test set. Before you run the samples through the network, make sure you set the it to evaluation mode rather than training mode (`network.eval()`). In training mode the dropout layer randomly sets node values to zero. In evaluation mode, it multiplies each value by 1-dropout rate so the same pattern will generate the same output each time. For each example, have your program print out the 10 output values (use only 2 decimal places), the index of the max output value, and the correct label of the digit. The network should correctly classify all 10 of the examples. Have your program also plot the first 9 digits as a 3x3 grid with the prediction for each example below it, as below.



Include a table (or screen shot) of your printed values and the plot of the first 9 digits in your report.

G. **Test the network on new inputs**

Write out the ten digits [0-9] in your own handwriting on a piece of white paper (not too close together). You will want to use thick (really thick) lines when writing the digits. I suggest using a marker or sharpie. Writing them on a white board may also work. Take a picture of the digits, crop each digit to its own square image. You may want to scale them to 28x28 and look at them to make sure the digits are visible. If you don't already have it installed, the ImageMagick package can be very useful for cropping and resizing images using the command line.

In a separate file, or as the last step in your code from the prior task, read the images, convert them to greyscale, resize them to 28x28 (if necessary) and run them through the network. During the resize process, double-check that the digits are still clearly visible. Make sure to match the intensities of the new images to the intensities of the test data. Are the MNIST data set digits white on black or are the digits black on white? You may need to invert the intensities for them to match.

Display how well the network performed on this new input in your report

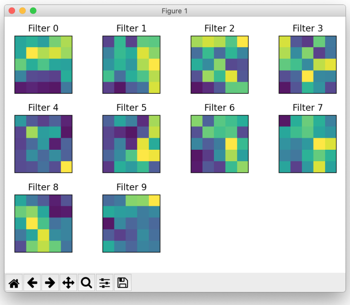
2. **Examine your network**

The second task is to examine your network and analyze how it processes the data. Make this a separate code file from task one. Read in the trained network as the first step and print the model. This should show you the structure of the network and the name of each layer.

A. **Analyze the first layer**

Get the weights of the first layer. When accessing a network, use the name of the layer as specified in the model printout. In this case, the name should be conv1. You access the weights using model.conv1.weight. The result is a tensor that should have the shape [10, 1, 5, 5]. That means there are ten filters, each 5x5 in size. To access the ith 5x5 filter, use weights[i, 0]. Print the filter weights and their shape.

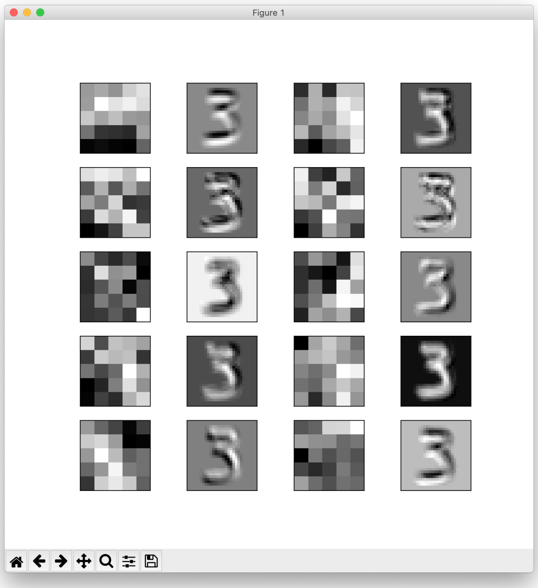
Visualize the ten filters using pyplot. You can use the pyplot functions figure, subplot, and imshow to make a 3x4 grid of figures such as the image below. If you set xticks and yticks to the empty list [], it will give you a cleaner plot.



B. **Show the effect of the filters**

Use OpenCV's filter2D function to apply the 10 filters to the first training example image. Generate a plot of the 10 filtered images such as the one below. When working with the weights, you will need to tell pyTorch it does not need to calculate gradients. You can do this using the following structure.

```
with torch.no_grad():
    # put your code here
```



In your report, include the plot and note whether the results make sense given the filters.

C. **Build a truncated model**

Build a new model using only the first two convolutional layers. A simple way to do this is to create a subclass of the Net class you created where the forward function is only the first two steps.

```
class Submodel(mnist.Net):

    def __init__(self, *args, **kwargs):
        super().__init__(*args, **kwargs)

    # override the forward method
    def forward( self, x ):
        x = F.relu( F.max_pool2d( self.conv1(x), 2 ) ) # relu on max pooled results of conv1
        x = F.relu( F.max_pool2d( self.conv2_drop( self.conv2(x)), 2 ) ) # relu on max pooled
results of dropout of conv2
        return x
```

Create a Submodel object and then load the state dictionary you read from the file. Don't forget to set the mode of the submodel to eval. The weights of the model are still the same, but only the first two layers will be used if you apply the model to some data. Apply the truncated model to the first example image. The output should have 20 channels that are 4x4 in size. Display a few of these channels. They may not make any sense. Try modifying the forward function so it returns after only the first layer. Double-check that these look like filtered versions of the input image.

Include in your report a plot of the second layer output and discuss whether your results look reasonable.

3. **Create a digit embedding space**

The third task is to use the trained network as an embedding space for images of written symbols. In this case, you'll use it to differentiate images of the greek letters alpha, beta, and gamma. Make new code files from the prior tasks. Read in your trained network as the first step and make a submodel that includes everything but the output layer..

A. **Create a greek symbol data set**

Download this collection of 27 280x280 images of **greek symbols (https://northeastern.instructure.com/courses/103147/files/14542998?wrap=1)** **(https://northeastern.instructure.com/courses/103147/files/14542998/download?download_frd=1)** . There are nine images each of alpha, beta, and gamma. Write a program to read in the images, scale them down to 28x28, convert them to greyscale, invert the intensities, and write out the data set as two CSV files: one file should contain a header row and 27 data rows with 784 intensity values in each row, one file should contain a header row and 27 data rows with just the category (alpha = 0, beta = 1, gamma = 2). If you're smart about your design, this program should be able to take in any number of input images with any number of different categories identified by the filename, just in case you want to try adding more greek symbols.

B. **Create a truncated model**

Read in the trained model and build a new model from the old network that terminates at the Dense layer with 50 outputs. Show that if you apply the network to the first training input image that it gives 50 numbers as its output.

C. **Project the greek symbols into the embedding space**

Apply the truncated network to the greek symbols (read from the CSV file) to get a set of 27 50 element vectors.

D. **Compute distances in the embedding space**

Select one example from each set of nine (i.e. one alpha, one beta, and one gamma). Compute the sum-squared distance in the 50 dimensional embedding space between each example and all 27 examples. Note that the SSD with itself should be 0. For each example show all 27 SSD values. What pattern do you find? How well would a nearest neighbor or K-NN classifier in the embedding space do for this task?

E. **Create your own greek symbol data**

Take a picture of a couple of examples of your own alpha, beta, and gamma symbols. Crop and rescale them as appropriate and see if they match their corresponding symbol examples in the embedding space.

4. **Design your own experiment**

The final task is to undertake some experimentation with the deep network for the MNIST task. Your goal is to evaluate the effect of changing different aspects of the network. Pick at least three dimensions along which you can change the network architecture and see if you can optimize the network performance and/or training time along those three dimensions. Do your best to automate the process.

If you want to try using the MNIST Fashion data set instead for this step, please do so. That data set is a little more challenging, but similar in size.

Potential dimensions to evaluate include:

- The number of convolution layers
- The size of the convolution filters
- The number of convolution filters in a layer
- The number of hidden nodes in the Dense layer
- The dropout rates of the Dropout layer
- Whether to add another dropout layer after the fully connected layer
- The size of the pooling layer filters
- The number or location of pooling layers
- The activation function for each layer
- The number of epochs of training
- The batch size while training

A. **Develop a plan**

Come up with a plan for what you want to explore and the metrics you will use. Determine the range of options in each dimension to explore (e.g. L options in dimension 1, M options in dimension 2, and N options in dimension 3). You don't have to evaluate all L * M * N options unless you want to. Instead, think about using a linear search strategy where you hold two parameters constant and optimize the third, then switch things up, optimizing one parameter at a time in a round-robin or randomized fashion. Overall, plan to evaluate 50-100 network variations (again, automate this process).

B. **Predict the results**

Before starting your evaluation, come up with a hypothesis for how you expect the network to behave along each dimension. Include these hypotheses in your report and then discuss whether the evaluation supported the hypothesis.

C. **Execute your plan**

Run the evaluation and report on the results.

Final Project Design

Think about what you are going to do for a final project. Form your groups, if you wish, up to four people per group. The project should be a little larger than one of the defined projects, scaled up a little if you have more than two people. Possible projects include:

- A significant continuation of one of the defined projects.
- Machine learning applied to a new data set.
- An application of your choice (e.g. tracking billiard balls and showing the path of each ball)
- Look at some of the computer vision competitions (e.g. Kaggle) and see what you can do.

Submit a one-page final project proposal as a pdf along with your code on GradeScope. Include the names of everyone in your group.

Extensions

- Evaluate more dimensions on task 3.
- Try more greek letters and build an actual KNN classifier that can take in any square image and classify it.
- Explore a different computer vision task with available data.
- There are many pre-trained networks available in the PyTorch package. Try loading one and evaluate its first couple of convolutional layers as in task 2.
- Replace the first layer of the MNIST network with a filter bank of your choosing (e.g. Gabor filters) and retrain the rest of the network, holding the first layer constant. How does it do?
- Build a live video digit recognition application using the trained network.

Report

When you are done with your project, write a short report on the **Khoury wiki** **(https://wiki.khoury.northeastern.edu/)** that demonstrates the functionality of each task. You will need to adjust the permissions of your home space and your report wiki pages so that other people can see it (by default, no one but you can view them). Your report should have the following structure. Please **do not** include code in your report.

1. A short description of the overall project in your own words. (200 words or less)
2. Any required images along with a short description of the meaning of the image.
3. A description and example images of any extensions.
4. A short reflection of what you learned.
5. Acknowledgement of any materials or people you consulted for the assignment.

Submission

We will be using **Gradescope** **(https://www.gradescope.com/)** for project code submission. You should receive an invitation to enroll in Gradescope using your Northeastern email address. You will be submitting your code and readme file to Gradescope and writing your report using the wiki.

When you are ready to submit, upload your code and a readme.txt (or readme.md) text file. The readme file should contain the following information.

- Your name and the name of any partners.
- Links/URLs to any videos you created and want to submit as part of your report.
- The URL for your wiki report for this project.
- What operating system and IDE you used to run and compile your code.
- Instructions for running your executables.
- Instructions for testing any extensions you completed.
- Whether received an accommodation for the project or you are using one or more time travel days.

For project 5, submit your Python files and readme.txt (readme.md). Note, if you find any errors or need to update your code, you can resubmit as many times as you wish up until the deadline.

As noted in the syllabus, projects submitted by the deadline can receive full credit for the base project and extensions. (max 30/30). Projects submitted up to a week after the deadline can receive full credit for the base project, but not extensions (max 26/30). You also have eight time travel days you can use during the semester to adjust any deadline, using up to three days on any one assignment (no fractional days). If you want to use your time travel days, email the instructor prior to the deadline for which you plan to use them. If you need to make use of the "stuff happens" clause of the syllabus, contact the instructor as soon as possible to make alternative arrangements.

Receiving grades and feedback

After your project has been graded, you can find your grade and feedback on Gradescope. Pay attention to the feedback, because it will probably help you do better on your next assignment.