Computer Science NEA Report

An investigation into how Artificial Neural Networks work, the effects of their hyper-parameters and their applications in Image Recognition.

Max Cotton

Contents

1 Analysis **2**
- 1.1 About . . . 2
- 1.2 Interview . . . 2
- 1.3 Project Objectives . . . 4
- 1.4 Requirements . . . 4
- 1.5 Theory behind Artificial Neural Networks . . . 4
  - 1.5.1 Structure . . . 4
  - 1.5.2 How Artificial Neural Networks learn . . . 6
- 1.6 Theory Behind Deep Artificial Neural Networks . . . 7
  - 1.6.1 Setup . . . 7
  - 1.6.2 Forward Propagation: . . . 8
  - 1.6.3 Back Propagation: . . . 8
- 1.7 Theory behind training the Artificial Neural Networks . . . 9
  - 1.7.1 Datasets . . . 10
  - 1.7.2 Theory behind using Graphics Cards to train Artificial Neural Networks . . . 11

2 Design **12**
- 2.1 Introduction . . . 12
- 2.2 System Architecture . . . 12
- 2.3 Class Diagrams . . . 13
  - 2.3.1 UI Class Diagram . . . 13
  - 2.3.2 Model Class Diagram . . . 13
- 2.4 System Flow chart . . . 14
- 2.5 Algorithms . . . 14
- 2.6 Data Structures . . . 15
- 2.7 File Structure . . . 15
- 2.8 Database Design . . . 16
- 2.9 Queries . . . 16
- 2.10 Human-Computer Interaction . . . 17
- 2.11 Hardware Design . . . 22
- 2.12 Workflow and source control . . . 22

3 Technical Solution TODO **23**
3.1 Setup . . . 23
3.1.1 File Structure . . . 23
3.1.2 Dependencies . . . 26
3.1.3 Git and Github files . . . 26
3.1.4 Organisation . . . 31
3.2 models package . . . 31
3.2.1 utils subpackage . . . 32
3.2.2 Artificial Neural Network implementations . . . 43
3.3 frames package . . . 47
3.4 __main__.py module . . . 58

4 Testing TODO **67**
4.1 Investigation . . . 67
4.1.1 test_model module . . . 67
4.1.2 Effects of Hyper-Parameters . . . 76
4.2 Manual Testing . . . 95
4.2.1 Input Validation Testing TODO . . . 95
4.3 Automated Testing . . . 95
4.3.1 Unit Tests . . . 95
4.3.2 GitHub Automated Testing . . . 99

1 Analysis

1.1 About

Artificial Intelligence mimics human cognition in order to perform tasks and learn from them, Machine Learning is a subfield of Artificial Intelligence that uses algorithms trained on data to produce models (trained programs) and Deep Learning is a subfield of Machine Learning that uses Artificial Neural Networks, a process of learning from data inspired by the human brain. Artificial Neural Networks can be trained to learn a vast number of problems, such as Image Recognition, and have uses across multiple fields, such as medical imaging in hospitals. This project is an investigation into how Artificial Neural Networks work, the effects of changing their hyper-parameters and their applications in Image Recognition. To achieve this, I will derive and research all theory behind the project, using sources such as IBM's online research, and develop Neural Networks from first principles without the use of any third-party Machine Learning libraries. I then will implement the Artificial Neural Networks in Image Recognition, by creating trained models and will allow for experimentation of the hyper-parameters of each model to allow for comparisons between each model's performances, via a Graphical User Interface.

1.2 Interview

In order to gain a better foundation for my investigation, I presented my prototype code and interviewed the head of Artificial Intelligence at Cambridge Consultants for input on what they would like to see in my project, these were their responses:

- Q:"Are there any good resources you would recommend for learning the theory behind how Artificial Neural Networks work?"

  A:"There are lots of usefull free resources on the internet to use. I particullarly like the platform 'Medium' which offers many scientific articles as well as more obvious resources such as IBMs'."

- Q:"What do you think would be a good goal for my project?"

  A:"I think it would be great to aim for applying the Neural Networks on Image Recognition for some famous datasets. For you, I would recommend the MNIST dataset as a goal."

- Q:"What features of the Artificial Neural Networks would you like to be able to experiment with?"

  A:"I'd like to be able to experiment with the number of layers and the number of neurons in each layer, and then be able to see how these changes effect the performance of the model. I can see that you've utilised the Sigmoid transfer function and I would recommend having the option to test alternatives such as the ReLu transfer function, which will help stop issues such as a vanishing gradient."

- Q:"What are some practical constraints of AI?"

  A:"Training AI models can require a large amount of computing power, also large datasets are needed for training models to a high accuracy which can be hard to obtain."

- Q:"What would you say increases the computing power required the most?"

  A:"The number of layers and neurons in each layer will have the greatest effect on the computing power required. This is another reason why I recommend adding the ReLu transfer function as it updates the values of the weights and biases faster than the Sigmoid transfer function."

- Q:"Do you think I should explore other computer architectures for training the models?"

  A:"Yes, it would be great to add support for using graphics cards for training models, as this would be a vast improvement in training time compared to using just CPU power."

- Q:"I am also creating a user interface for the program, what hyper-parameters would you like to be able to control through this?"

  A:"It would be nice to control the transfer functions used, as well as the general hyper-parameters of the model. I also think you could add a progress tracker to be displayed during training for the user."

- Q:"How do you think I should measure the performance of models?"

  A:"You should show the accuracy of the model's predictions, as well as example incorrect and correct prediction results for the trained model. Additionally, you could compare how the size of the training dataset effects the performance of the model after training, to see if a larger dataset would seem beneficial."

- Q:"Are there any other features you would like add?"

  A:"Yes, it would be nice to be able to save a model after training and have the option to load in a trained model for testing."

1.3 Project Objectives

- Learn how Artificial Neural Networks work and develop them from first principles
- Implement the Artificial Neural Networks by creating trained models on image datasets
  - Allow use of Graphics Cards for faster training
  - Allow for the saving of trained models
- Develop a Graphical User Interface
  - Provide controls for hyper-parameters of models
  - Display and compare the results each model's predictions

1.4 Requirements

ID	Description	Satisfied by	Tested by
1	test description	test location	Go to page 44

1.5 Theory behind Artificial Neural Networks

From an abstract perspective, Artificial Neural Networks are inspired by how the human mind works, by consisting of layers of 'neurons' all interconnected via different links, each with their own strength. By adjusting these links, Artificial Neural Networks can be trained to take in an input and give its best prediction as an output.

1.5.1 Structure

I have focused on Feed-Forward Artificial Neural Networks, where values are entered to the input layer and passed forwards repetitively to the next layer until reaching the output layer. Within this, I have learnt two types of Feed-Forward Artificial Neural Networks: Perceptron Artificial Neural Networks, that contain no hidden layers and are best at learning more linear patterns and Multi-Layer Perceptron Artificial Neural Networks, that contain at least one hidden layer, as a result increasing the non-linearity in the Artificial Neural Network and allowing it to learn more complex / non-linear problems.

Multi-Layer Perceptron Artificial Neural Networks consist of:

- An input layer of input neurons, where the input values are entered.
- Hidden layers of hidden neurons.
- An output layer of output neurons, which outputs the final prediction.

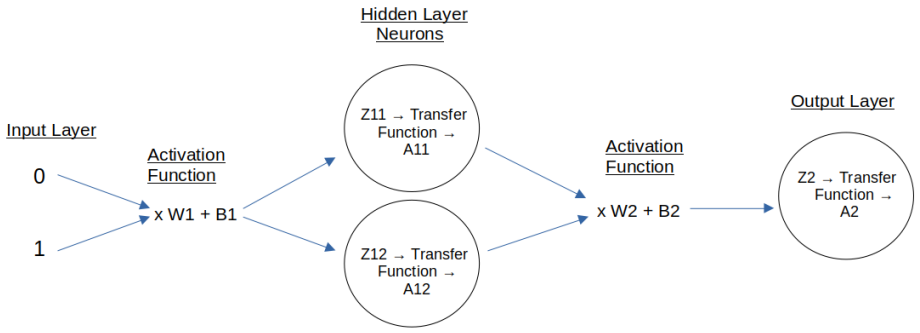


Figure 1: This shows an Artificial Neural Network with one single hidden layer and is known as a Shallow Neural Netwok.

To implement an Artificial Neural Network, matrices are used to represent the layers, where each layer is a matrice of the layer's neuron's values. In order to use matrices for this, the following basic theory must be known about them:

- When Adding two matrices, both matrices must have the same number of rows and columns. Or one of the matrices can have the same number of rows but only one column, then be added by element-wise addition where each element is added to all of the elements of the other matrix in the same row.
- In order to multiply matrices, I take the 'dot product' of the matrices, which multiplies the row of one matrice with the column of the other, by multiplying matching members and then summing up.
- When taking the dot product of two matrices, the number of columns of the 1st matrix must equal the number of rows of the 2nd matrix. And the result will have the same number of rows as the 1st matrix, and the same number of columns as the 2nd matrix. This is important, as the output of one layer must be formatted correctly to be used with the next layer.
- Alternatively, at times I take the Hadamard product of two matrices which performs element-wise multiplication of the matrices. For this, both matrices must have the same number of rows and columns.
- Transposing a matrix will turn all rows of the matrix into columns and all columns into rows.
- A matrix of values can be classified as a rank of Tensors, depending on the number of dimensions of the matrix. (Eg: A 2-dimensional matrix is a Tensor of rank 2)

I have focused on just using Fully-Connected layers, that will take in input values and apply the following calculations to produce an output of the layer:

- An Activation function

  - This calculates the dot product of the input matrix with a weight matrix, then sums the result with a bias matrix

- A Transfer function
  - This takes the result of the Activation function and transfers it to a suitable output value as well as adding more non-linearity to the Neural Network.
  - For example, the Sigmoid Transfer function converts the input to a number between zero and one, making it usefull for logistic regression where the output value can be considered as closer to zero or one allowing for a binary classification of predicting zero or one.

1.5.2 How Artificial Neural Networks learn

To train an Artificial Neural Network, the following processes will be carried out for each of a number of training epochs:

- Forward Propagation:
  - The process of feeding inputs in and getting a prediction (moving forward through the network)

- Back Propagation:
  - The process of calculating the Loss in the prediction and then adjusting the weights and biases accordingly
  - I have used Supervised Learning to train the Artificial Neural Networks, where the output prediction of the Artificial Neural Network is compared to the values it should have predicted. With this, I can calculate the Loss value of the prediction (how wrong the prediction is from the actual value).
  - I then move back through the network and update the weights and biases via Gradient Descent:
    * Gradient Descent aims to reduce the Loss value of the prediction to a minimum, by subtracting the rate of change of Loss with respect to the weights/ biases, multiplied with a learning rate, from the weights/biases.
    * To calculate the rate of change of Loss with respect to the weights/biases, you must use the following calculus methods:
      · Partial Differentiation, in order to differentiate the multivariable functions, by taking respect to one variable and treating the rest as constants.
      · The Chain Rule, where for $y = f(u)$ and $u = g(x)$, $\frac{\partial y}{\partial x} = \frac{\partial y}{\partial u} * \frac{\partial u}{\partial x}$
      · For a matrice of $f(x)$ values, the matrice of $\frac{\partial f(x)}{\partial x}$ values is known as the Jacobian matrix

* This repetitive process will continue to reduce the Loss to a minimum, if the learning rate is set to an appropriate value

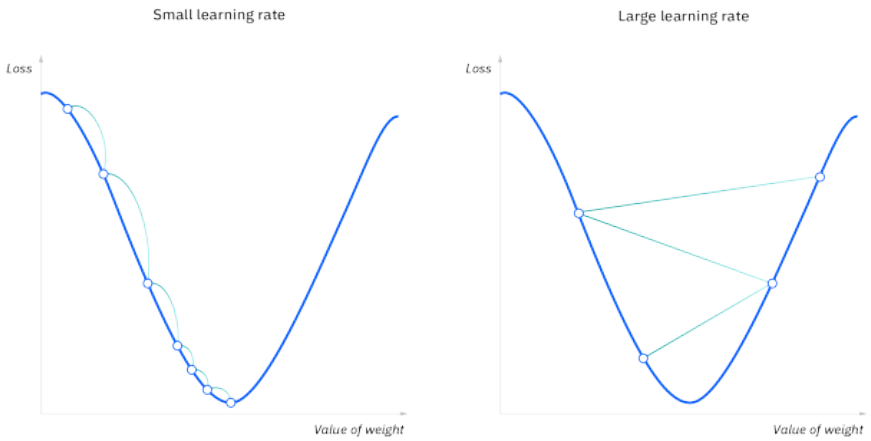


Figure 2: Gradient Descent
sourced from https://www.ibm.com/topics/gradient-descent

* However, during backpropagation some issues can occur, such as the following:
  - Finding a false local minimum rather than the global minimum of the function
  - Having an 'Exploding Gradient', where the gradient value grows exponentially to the point of overflow errors
  - Having a 'Vanishing Gradient', where the gradient value decreases to a very small value or zero, resulting in a lack of updating values during training.

1.6 Theory Behind Deep Artificial Neural Networks

1.6.1 Setup

- Where a layer takes the previous layer's output as its input X
- Then it applies an Activation function to X to obtain Z, by taking the dot product of X with a weight matrix W, then sums the result with a bias matrix B. At first the weights are intialised to random values and the biases are set to zeros.
  - $Z = W * X + B$
- Then it applies a Transfer function to Z to obtain the layer's output

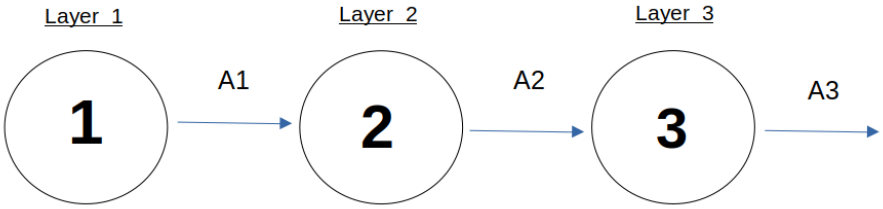


Figure 3: This shows an abstracted view of an Artificial Neural Network with multiple hidden layers and is known as a Deep Neural Netwok.

- For the output layer, the sigmoid function (explained previously) must be used for either for binary classification via logistic regression, or for multi- class classification where it predicts the output neuron, and the associated class, that has the highest value between zero and one.
  - Where $sigmoid(Z) = \frac{1}{1+e^{-Z}}$
- However, for the input layer and the hidden layers, another transfer function known as ReLu (Rectified Linear Unit) can be better suited as it produces largers values of $\frac{\partial L}{\partial W}$ and $\frac{\partial L}{\partial B}$ for Gradient Descent than Sigmoid, so updates at a quicker rate.
  - Where $relu(Z) = max(0, Z)$

1.6.2 Forward Propagation:

- For each epoch the input layer is given a matrix of input values, which are fed through the network to obtain a final prediction A from the output layer.

1.6.3 Back Propagation:

- First the Loss value L is calculated using the following Log-Loss function, which calculates the average difference between A and the value it should have predicted Y. Then the average is found by summing the result of the Loss function for each value in the matrix A, then dividing by the number of predictions m, resulting in a Loss value to show how well the network is performing.
  - Where $L = -(\frac{1}{m}) * \sum(Y * log(A) + (1 - Y) * log(1 - A))$ and "log()" is the natural logarithm
- I then move back through the network, adjusting the weights and biases via Gradient Descent. For each layer, the weights and biases are updated with the following formulae:
  - $W = W - learningRate * \frac{\partial L}{\partial W}$
  - $B = B - learningRate * \frac{\partial L}{\partial B}$

- The derivation for Layer 2's $\frac{\partial L}{\partial W}$ and $\frac{\partial L}{\partial B}$ can be seen below:
  - Functions used so far:
    1. $Z = W * X + B$
    2. $A_{relu} = max(0, Z)$
    3. $A_{sigmoid} = \frac{1}{1+e^{-Z}}$
    4. $L = -(\frac{1}{m}) * \sum(Y * log(A) + (1 - Y) * log(1 - A))$
  - $\frac{\partial L}{\partial A2} = \frac{\partial L}{\partial A3} * \frac{\partial A3}{\partial Z3} * \frac{\partial Z3}{\partial A2}$
    By using function 1, where A2 is X for the 3rd layer, $\frac{\partial Z3}{\partial A2} = W3$
    $=> \frac{\partial L}{\partial A2} = \frac{\partial L}{\partial A3} * \frac{\partial A3}{\partial Z3} * W3$
  - $\frac{\partial L}{\partial W2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * \frac{\partial Z2}{\partial W2}$
    By using function 1, where A1 is X for the 2nd layer, $\frac{\partial Z2}{\partial W2} = A1$
    $=> \frac{\partial L}{\partial W2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * A1$
  - $\frac{\partial L}{\partial B2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * \frac{\partial Z2}{\partial B2}$
    By using function 1, $\frac{\partial Z2}{\partial B2} = 1$
    $=> \frac{\partial L}{\partial W2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * 1$
- As you can see, when moving back through the network, the $\frac{\partial L}{\partial W}$ and $\frac{\partial L}{\partial B}$ of the layer can be calculated with the rate of change of loss with respect to its output, which is calculated by the previous layer using the above formula; the derviative of the layer's transfer function, and the layers input (which in this case is A1)
  - Where by using function 2, $\frac{\partial A_{relu}}{\partial Z} = 1$ when $Z >= 0$ otherwise $\frac{\partial A_{relu}}{\partial Z} = 0$
  - Where by using function 3, $\frac{\partial A_{sigmoid}}{\partial Z} = A * (1 - A)$
- At the start of backpropagation, the rate of change of loss with respect to the output layer's output has no previous layer's caluculations, so instead it can be found with the derivative of the Log-Loss function, as shown in the following:
  - Using function 4, $\frac{\partial L}{\partial A} = (-\frac{1}{m})(\frac{Y-A}{A*(1-A)})$

1.7 Theory behind training the Artificial Neural Networks

Training an Artificial Neural Network's weights and biases to predict on a dataset, will create a trained model for that dataset, so that it can predict on future images inputted. However, training Artificial Neural Networks can involve some problems such as Overfitting, where the trained model learns the patterns of the training dataset too well, causing worse prediction on a different test dataset. This can occur when the training dataset does not cover enough situations of inputs and the desired outputs (by being too small for example), if the model is trained for too many epochs on the poor dataset and having too many layers in the Neural Network. Another problem is Underfitting, where the model has not learnt the patterns of the training dataset well enough, often when it has been trained for too few epochs, or when the Neural Network is too simple (too linear).

1.7.1 Datasets

- MNIST dataset
  - The MNIST dataset is a famouse dataset of images of handwritten digits from zero to ten and is commonly used to test the performance of an Artificial Neural Network.
  - The dataset consists of 60,000 input images, made up from 28x28 pixels and each pixel has an RGB value from 0 to 255
  - To format the images into a suitable format to be inputted into the Artificial Neural Networks, each image's matrice of RGB values are 'flattened' into a 1 dimensional matrix of values, where each element is also divided by 255 (the max RGB value) to a number between 0 and 1, to standardize the dataset.
  - The output dataset is also loaded, where each output for each image is an array, where the index represents the number of the image, by having a 1 in the index that matches the number represented and zeros for all other indexes.
  - To create a trained Artificial Neural Network model on this dataset, the model will require 10 output neurons (one for each digit), then by using the Sigmoid Transfer function to output a number between one and zero to each neuron, whichever neuron has the highest value is predicted. This is multi-class classification, where the model must predict one of 10 classes (in this case, each class is one of the digits from zero to ten).
- Cat dataset
  - I will also use a dataset of images sourced from https://github.com/marcopeix, where each image is either a cat or not a cat.
  - The dataset consists of 209 input images, made up from 64x64 pixels and each pixel has an RGB value from 0 to 255
  - To format the images into a suitable format to be inputted into the Artificial Neural Networks, each image's matrice of RGB values are 'flattened' into a 1 dimensional array of values, where each element is also divided by 255 (the max RGB value) to a number between 0 and 1, to standardize the dataset.
  - The output dataset is also loaded, and is reshaped into a 1 dimensional array of 1s and 0s, to store the output of each image (1 for cat, 0 for non cat)
  - To create a trained Artificial Neural Network model on this dataset, the model will require only 1 output neuron, then by using the Sigmoid Transfer function to output a number between one and zero for the neuron, if the neuron's value is closer to 1 it predicts cat, otherwise it predicts not a cat. This is binary classification, where the model must use logistic regression to predict whether it is a cat or not a cat.

- XOR dataset
  - For experimenting with Artificial Neural Networks, I solve the XOR gate problem, where the Neural Network is fed input pairs of zeros and ones and learns to predict the output of a XOR gate used in circuits.
  - This takes much less computation time than image datasets, so is usefull for quickly comparing different hyper-parameters of a Network, whilst still not being linearly seperable.

1.7.2 Theory behind using Graphics Cards to train Artificial Neural Networks

Graphics Cards consist of many Tensor cores which are processing units specialiased for matrix operations for calculating the co-ordinates of 3D graphics, however they can be used here for operating on the matrices in the network at a much faster speed compared to CPUs. GPUs also include CUDA cores which act as an API to the GPU's computing to be used for any operations (in this case training the Artificial Neural Networks).

2 Design

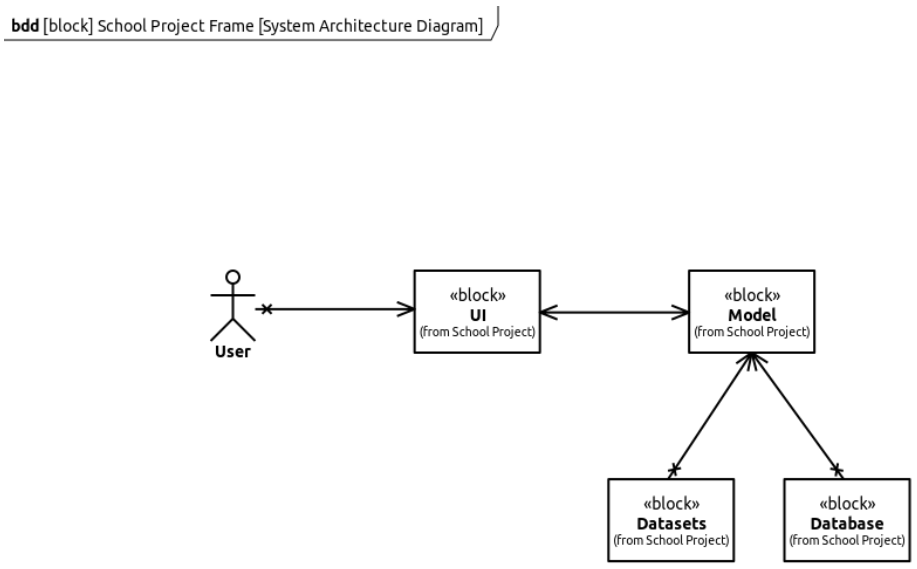
2.1 Introduction

The following design focuses have been made for the project:

- The program will support multiple platforms to run on, including Windows and Linux.
- The program will use python3 as its main programming language.
- I will take an object-orientated approach to the project.
- I will give an option to use either a Graphics Card or a CPU to train and test the Artificial Neural Networks.

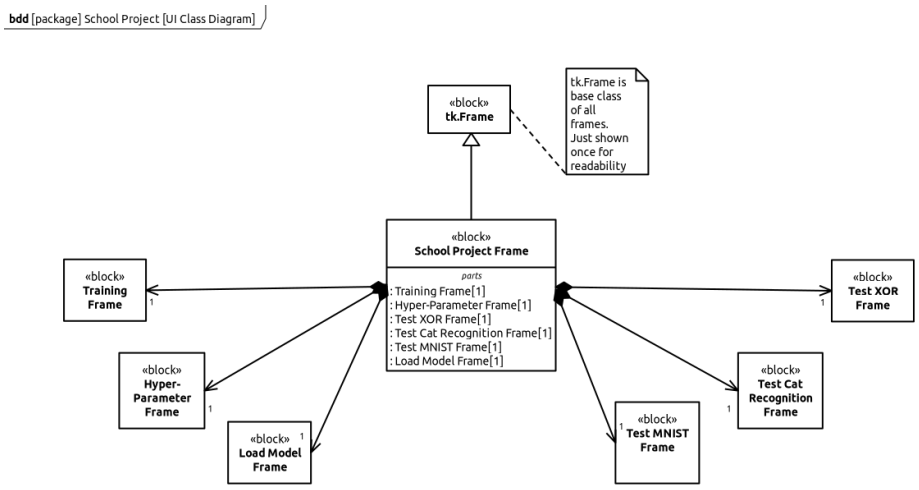
I will also be using SysML for designing the following diagrams.

2.2 System Architecture

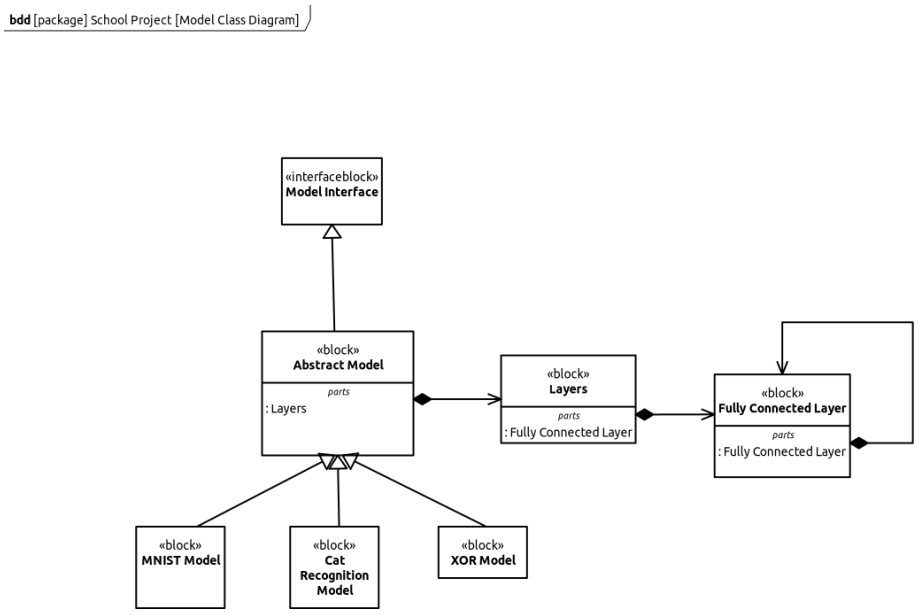


2.3 Class Diagrams

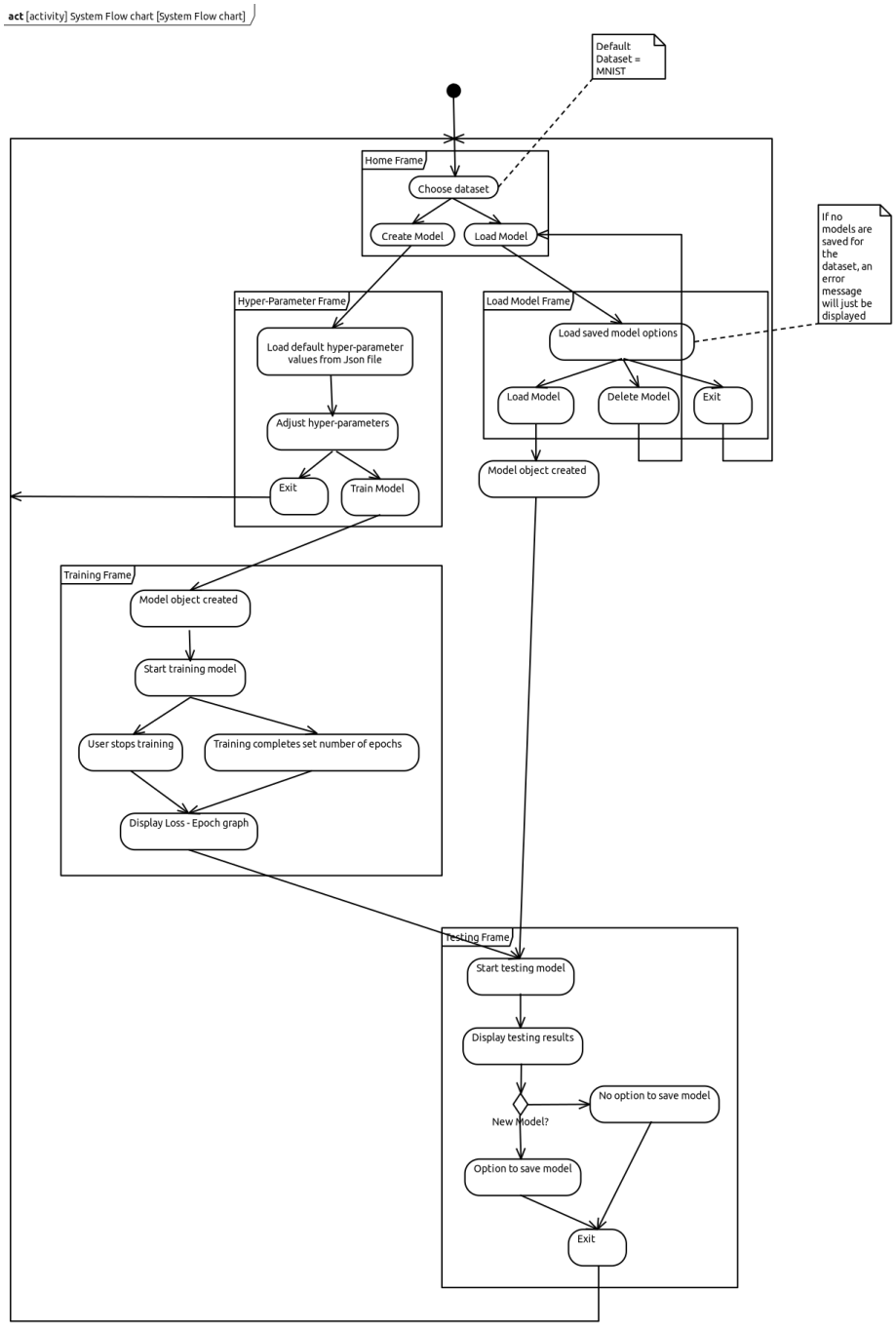
2.3.1 UI Class Diagram



2.3.2 Model Class Diagram



2.4 System Flow chart



2.5 Algorithms

Refer to Analysis for the algorithms behind the Artificial Neural Networks.

2.6 Data Structures

I will use the following data structures in the program:

- Standard lists for storing data, for example storing the shape of the Artificial Neural Network's layers.
- Tuples where tuple unpacking is usefull, such as returning multiple values from methods.
- Dictionaries for loading the default hyper-parameter values from a JSON file.
- Matrices to represent the layers and allow for a varied number of neurons in each layer. To represent the Matrices I will use both numpy arrays and cupy arrays.
- A Doubly linked list to represent the Artificial Neural Network, where each node is a layer of the network. This will allow me to traverse both forwards and backwards through the network, as well as storing the first and last layer to start forward and backward propagation respectively.

2.7 File Structure

I will use the following file structures to store necessary data for the program:

- A JSON file for storing the default hyper-parameters for creating a new model for each dataset.
- I will store the image dataset files in a 'datasets' directory. The dataset files will either be a compressed archive file (such as .pkl.gz files) or of the Hierarchical Data Format (such as .h5) for storing large datasets with fast retrieval.
- I will save the weights and biases of saved models as numpy arrays in .npz files (a zipped archive file format) in a 'saved-models' directory, due to their compatibility with the numpy library.

2.8 Database Design

I will use the following Relational database design for saving models, where the dataset, name and features of the saved model (including the location of the saved models' weights and biases and the saved models' hyper-parameters) are saved:

Models	
Model_ID	**Integer**
Dataset	text
File_Location	text
Hidden_Layers_Shape	text
Learning_Rate	float
Name	text
Train_Dataset_Size	integer
Use_ReLu	bool

- I will also use the following unique constraint, so that each dataset can not have more than one model with the same name:

```
UNIQUE (Dataset, Name)
```

2.9 Queries

Here are some example queries for interacting with the database:

- I can query the names of all saved models for a dataset with:

```
SELECT Name FROM Models WHERE Dataset=?;
```

- I can query the file location of a saved model with:

```
SELECT File_Location FROM Models WHERE Dataset=? AND Name=?;
```

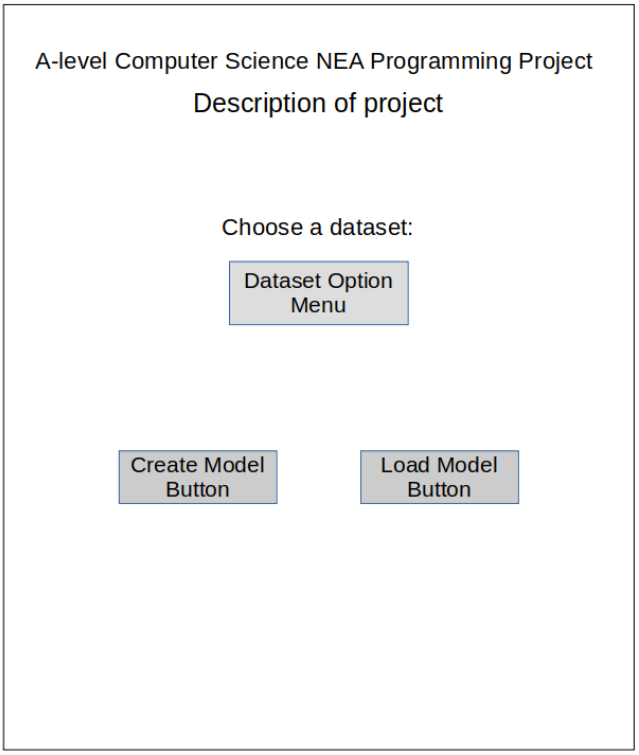
- I can query the features of a saved model with:

```
SELECT * FROM Models WHERE Dataset=? AND Name=?;
```

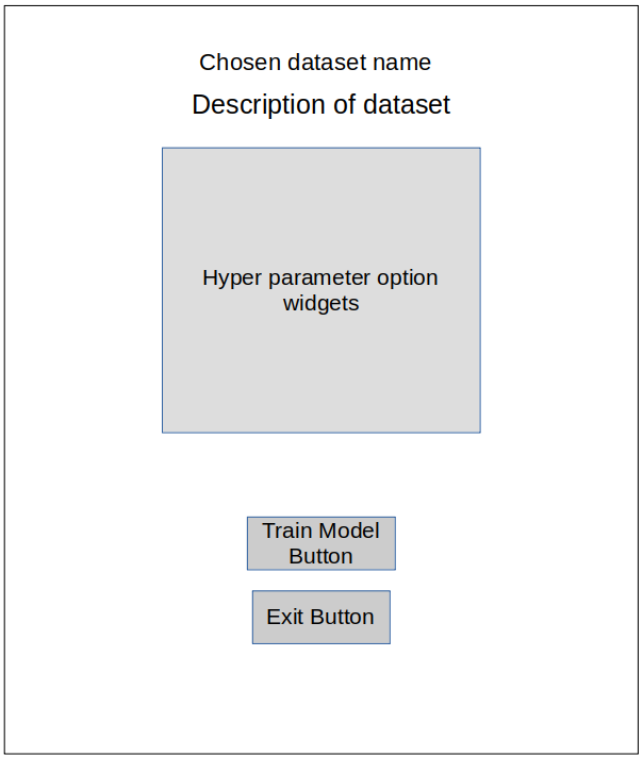
2.10 Human-Computer Interaction

Here are the designs of each tkinter frame in the User Interface:

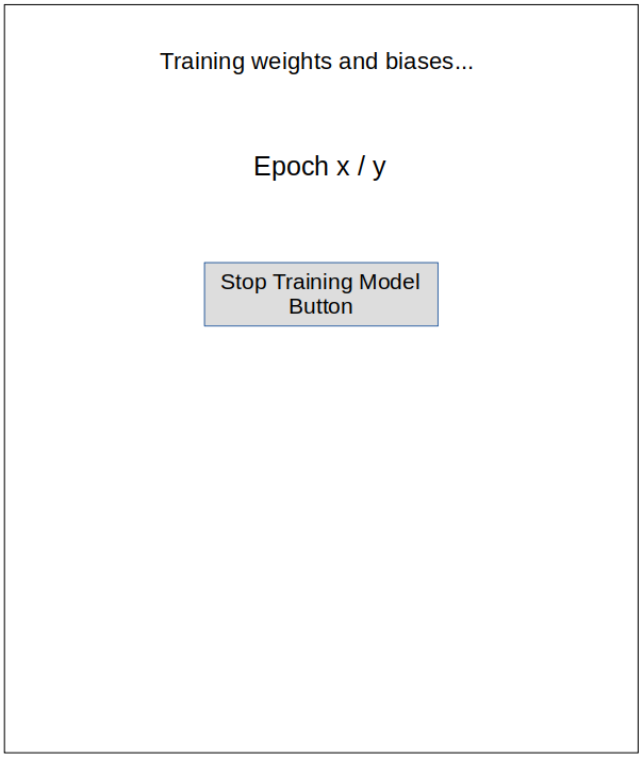
- Home Frame design:



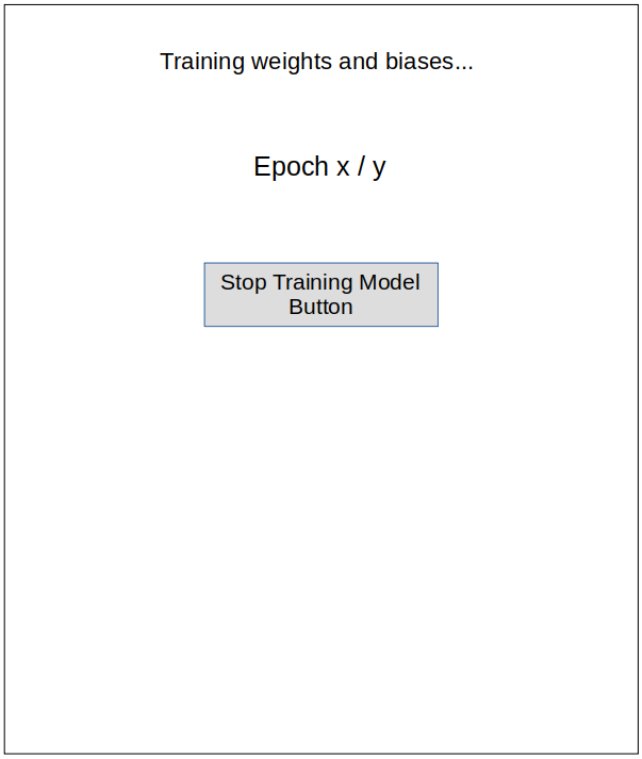
- Hyper-Parameter Frame design:



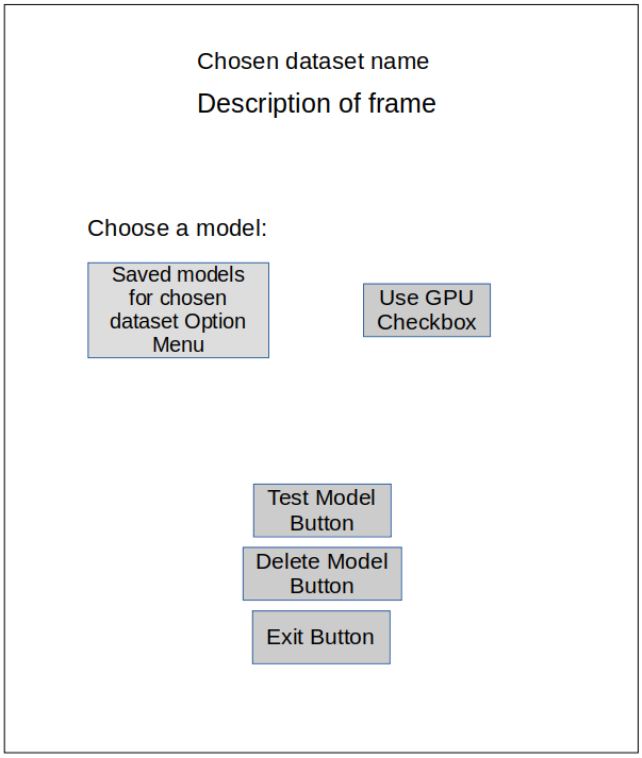
- Training Frame design:
  - During training, the following is displayed on the Training Frame:



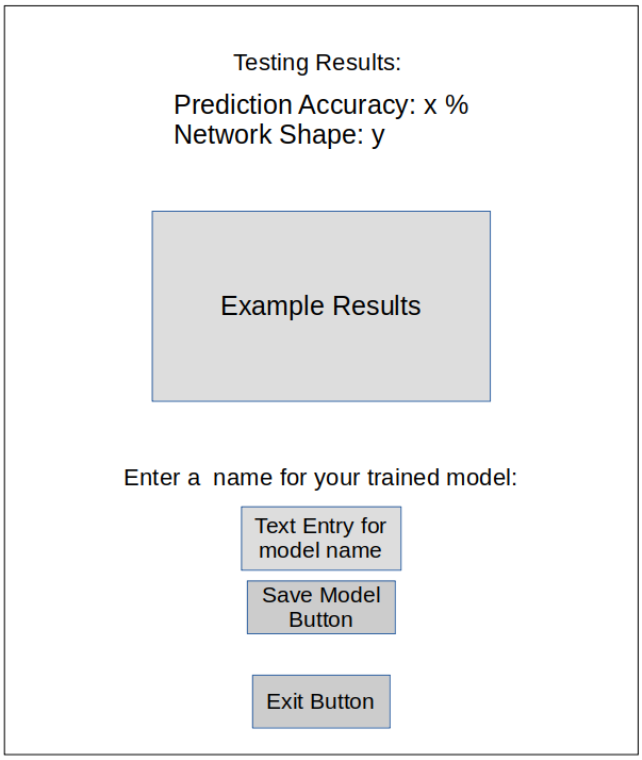
– Once training has finished, the following is displayed on the Training Frame:



- Load Model Frame design:



- Test Frame design:



2.11 Hardware Design

To allow for faster training of an Artificial Neural Network, I will give the option to use a Graphics Card to train the Artificial Neural Network if available. I will also give the option to load pretrained weights to run on less computationaly powerfull hardware using just the CPU as standard.

2.12 Workflow and source control

I will use Git along with GitHub to manage my workflow and source control as I develop the project, by utilising the following features:

- Commits and branches for adding features and fixing bugs seperately.
- Using GitHub to back up the project as a repository.
- I will setup automated testing on GitHub after each pushed commit.
- I will also provide the necessary instructions and information for the installation and usage of this project, aswell as creating releases of the project with new patches.

3 Technical Solution TODO

3.1 Setup

3.1.1 File Structure

I used the following file structure to organise the code for the project, where school_project is the main package and is constructed of two main subpackages:

- The models package, which is a self-contained package for creating trained Artificial Neural Network models.
- The frames package, which consists of tkinter frames for the User Interface.

```
.
|-- .github
|   `-- workflows
|       `-- tests.yml
|-- .gitignore
|-- LICENSE
|-- notebooks
|   |-- cpu-vs-gpu-analysis.ipynb
|   |-- epoch-count-analysis.ipynb
|   |-- layer-count-analysis.ipynb
|   |-- learning-rate-analysis.ipynb
|   |-- neuron-count-analysis.ipynb
|   |-- relu-analysis.ipynb
|   `-- train-dataset-size-analysis.ipynb
|-- README.md
|-- school_project
|   |-- frames
|   |   |-- create_model.py
|   |   |-- hyper-parameter-defaults.json
|   |   |-- __init__.py
|   |   |-- load_model.py
|   |   `-- test_model.py
|   |-- __init__.py
|   |-- __main__.py
|   |-- models
|   |   |-- cpu
|   |   |   |-- cat_recognition.py
|   |   |   |-- __init__.py
|   |   |   |-- mnist.py
|   |   |   |-- utils
|   |   |   |   |-- __init__.py
|   |   |   |   |-- model.py
|   |   |   |   `-- tools.py
|   |   |   `-- xor.py
|   |   |-- datasets
|   |   |   |-- mnist.pkl.gz
|   |   |   |-- test-cat.h5
|   |   |   `-- train-cat.h5
|   |   |-- gpu
|   |   |   |-- cat_recognition.py
|   |   |   |-- __init__.py
|   |   |   |-- mnist.py
|   |   |   |-- utils
|   |   |   |   |-- __init__.py
|   |   |   |   |-- model.py
|   |   |   |   `-- tools.py
|   |   |   `-- xor.py
|   |   `-- __init__.py
|   |-- saved-models
|   `-- test
|       |-- __init__.py
|       `-- models
|           |-- cpu
|           |   |-- __init__.py
|           |   `-- utils
|           |       |-- __init__.py
|           |       |-- test_model.py
|           |       `-- test_tools.py
|           |-- gpu
|           |   |-- __init__.py
|           |   `-- utils
|           |       |-- __init__.py
```

```
|           |       |-- test_model.py
|           |       `-- test_tools.py
|           `-- __init__.py
|-- setup.py
`-- TODO.md

18 directories, 48 files
```

Each package within the school_project package contains a __init__.py file, which allows the school_project package to be installed to a virtual environment so that the modules of the package can be imported from the installed package.

- Here is the contents of the frames package's __init__.py for example, which allows the classes of all modules in the package to be imported at once:

```
"""Package of tkinter frames for the main window."""

from .create_model import HyperParameterFrame, TrainingFrame
from .load_model import LoadModelFrame
from .test_model import TestMNISTFrame, TestCatRecognitionFrame,
↪  TestXORFrame

__all__ = ['create_model', 'load_model', 'test_model']
```

I have omitted the source code for this report, which included a Makefile for its compilation.

3.1.2 Dependencies

The python dependencies for the project can be installed simply by running the following setup.py file (as described in the README.md in the next section). Instructions on installing external dependencies, such as the CUDA Toolkit for using a GPU, are explained in the README.md in the next section also.

- setup.py code:

```
from setuptools import setup, find_packages

setup(
    name='school-project',
    version='1.0.0',
    packages=find_packages(),
    url='https://github.com/mcttn22/school-project.git',
    author='Max Cotton',
    author_email='maxcotton22@gmail.com',
    description='Year 13 Computer Science Programming Project',
    install_requires=[
                      'cupy-cuda12x',
                      'h5py',
                      'matplotlib',
                      'numpy',
                      'pympler'
    ],
)
```

3.1.3 Git and Github files

To optimise the use of Git and GitHub, I have used the following files:

- A .gitignore file for specifying which files and directories should be ignored by Git:

```
# Byte compiled files
__pycache__/

# Packaging
*.egg-info

# Database file
school_project/saved_models.db
```

- A README.md markdown file to give installation and usage instructions for the repository on GitHub:
  - Markdown code:

```
<!-- The following lines generate badges showing the current status of the automated testing (Passing or Failing) and a Python3 badge correspondingly.) -->
[![tests](https://github.com/mcttn22/school-project/actions/workflows/tests.yml/badge.svg)](https://
[![python](https://img.shields.io/badge/Python-3-3776AB.svg?style=flat&logo=python&logoColor=white)]

# A-level Computer Science NEA Programming Project

This project is an investigation into how Artificial Neural Networks (ANNs) work and their applications in Image Recognition, by documenting all theory behind the project and developing applications of the theory, that allow for experimentation via a GUI. The ANNs are created without the use of any 3rd party Machine Learning Libraries and I currently have been able to achieve a prediction accuracy of 99.6% on the MNIST dataset. The report for this project is also included in this repository.

## Installation

1. Download the Repository with:

   - ```
     git clone https://github.com/mcttn22/school-project.git
     ```
   - Or by downloading as a ZIP file

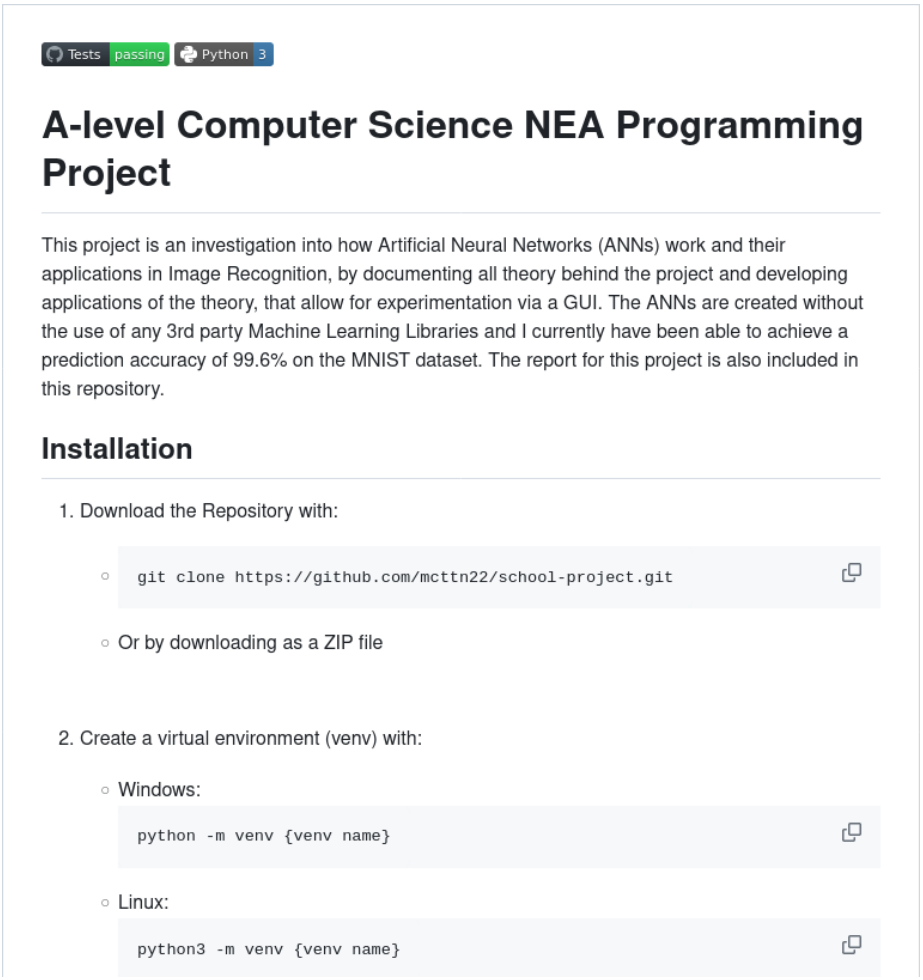
</br>

2. Create a virtual environment (venv) with:
   - Windows:
     ```
     python -m venv {venv name}
     ```
   - Linux:
     ```
     python3 -m venv {venv name}
     ```

3. Enter the venv with:
   - Windows:
     ```
     .\{venv name}\Scripts\activate
     ```
   - Linux:
     ```
     source ./{venv name}/bin/activate
     ```
```
```

````
39
40  4. Enter the project directory with:
41     ```
42     cd school-project/
43     ```
44
45  5. For normal use, install the dependencies and the project to the
    ↪  venv with:
46     - Windows:
47       ```
48       python setup.py install
49       ```
50     - Linux:
51       ```
52       python3 setup.py install
53       ```
54
55  *Note: In order to use an Nvidia GPU for training the networks, the
    ↪  latest Nvdia drivers must be installed and the CUDA Toolkit must
    ↪  be installed from
56  <a href="https://developer.nvidia.com/cuda-downloads">here</a>.*
57
58  ## Usage
59
60  Run with:
61  - Windows:
62    ```
63    python school_project
64    ```
65  - Linux:
66    ```
67    python3 school_project
68    ```
69
70  ## Development
71
72  Install the dependencies and the project to the venv in developing
    ↪  mode with:
73  - Windows:
74    ```
75    python setup.py develop
76    ```
77  - Linux:
78    ```
79    python3 setup.py develop
80    ```
81
82  Run Tests with:
83  - Windows:
84    ```
85    python -m unittest discover .\school_project\test\
86    ```
87  - Linux:
88    ```
89    python3 -m unittest discover ./school_project/test/
90    ```
91
92  Compile Project Report PDF with:
93  ```
94  make all
95  ```
96  *Note: This requires the Latexmk library*
````

– Which will generate the following:



Tests passing Python 3

A-level Computer Science NEA Programming Project

This project is an investigation into how Artificial Neural Networks (ANNs) work and their applications in Image Recognition, by documenting all theory behind the project and developing applications of the theory, that allow for experimentation via a GUI. The ANNs are created without the use of any 3rd party Machine Learning Libraries and I currently have been able to achieve a prediction accuracy of 99.6% on the MNIST dataset. The report for this project is also included in this repository.

Installation

1. Download the Repository with:
   - `git clone https://github.com/mcttn22/school-project.git`
   - Or by downloading as a ZIP file
2. Create a virtual environment (venv) with:
   - Windows:
     `python -m venv {venv name}`
   - Linux:
     `python3 -m venv {venv name}`

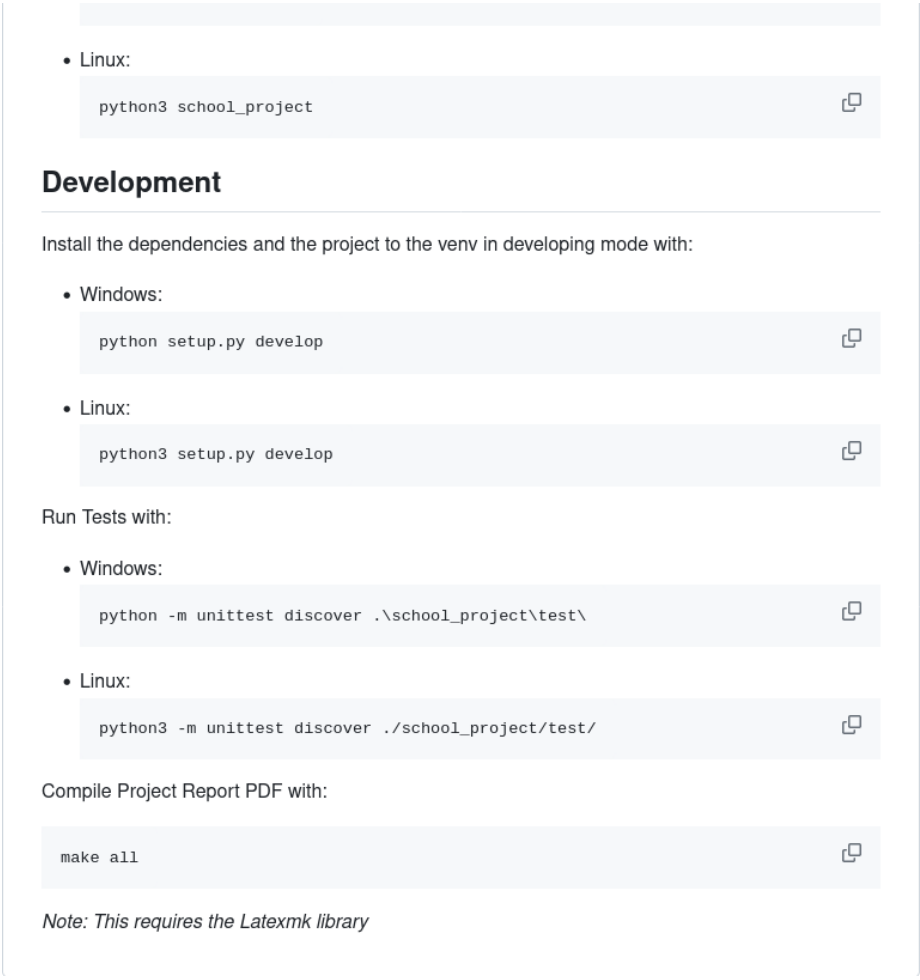
3. Enter the venv with:
    - Windows:
      ```
      .\{venv name}\Scripts\activate
      ```
    - Linux:
      ```
      source ./{venv name}/bin/activate
      ```
4. Enter the project directory with:
   ```
   cd school-project/
   ```
5. For normal use, install the dependencies and the project to the venv with:
    - Windows:
      ```
      python setup.py install
      ```
    - Linux:
      ```
      python3 setup.py install
      ```

Note: In order to use an Nvidia GPU for training the networks, the latest Nvdia drivers must be installed and the CUDA Toolkit must be installed from here.

Usage

Run with:

- Windows:
  ```
  python school_project
  ```



- Linux:

```
python3 school_project
```

Development

Install the dependencies and the project to the venv in developing mode with:

- Windows:

```
python setup.py develop
```

- Linux:

```
python3 setup.py develop
```

Run Tests with:

- Windows:

```
python -m unittest discover .\school_project\test\
```

- Linux:

```
python3 -m unittest discover ./school_project/test/
```

Compile Project Report PDF with:

```
make all
```

Note: This requires the Latexmk library

- A LICENSE file that describes how others can use my code.

3.1.4 Organisation

I also utilise a TODO.md file for keeping track of what features and/or bugs need to be worked on.

3.2 models package

This package is a self-contained package for creating trained Artificial Neural Networks and can either be used for a CPU or a GPU, as well as containing the test and training data for all three datasets in a datasets directory. Whilst both the cpu and gpu subpackage are similar in functionality, the cpu subpackage uses NumPy for matrices whereas the gpu subpackage utilise NumPy and another library CuPy which requires a GPU to be utilised for operations with the matrices. For that reason it is only worth showing the code for the cpu subpackage.

Both the cpu and gpu subpackage contain a utils subpackage that provides the tools for creating Artificial Neural Networks, and three modules that are the implementation of Artificial Neural Networks for each dataset.

3.2.1 utils subpackage

The utils subpackage consists of a tools.py module that provides a ModelInterface class and helper functions for the model.py module, that contains an AbstractModel class that implements every method from the ModelInterface except for the load_dataset method.

- tools.py module:

```
"""Helper functions and ModelInterface class for model module."""

from abc import ABC, abstractmethod

import numpy as np

class ModelInterface(ABC):
    """Interface for ANN models."""
    @abstractmethod
    def _setup_layers(setup_values: callable) -> None:
        """Decorator that sets up model layers and sets up values of each
↪   layer
           with the method given.

        Args:
            setup_values (callable): the method that sets up the values of
↪   each
             layer.
        Raises:
            NotImplementedError: if this method is not implemented.

        """
        raise NotImplementedError

    @abstractmethod
    def create_model_values(self) -> None:
        """Create weights and bias/biases

        Raises:
            NotImplementedError: if this method is not implemented.

        """
        raise NotImplementedError

    @abstractmethod
    def load_model_values(self, file_location: str) -> None:
        """Load weights and bias/biases from .npz file.

        Args:
            file_location (str): the location of the file to load from.
        Raises:
            NotImplementedError: if this method is not implemented.

        """
        raise NotImplementedError

    @abstractmethod
```

```
46      def load_datasets(self, train_dataset_size: int) -> tuple[np.ndarray,
        ↪  np.ndarray,
47                                                               np.ndarray,
                                                                 ↪  np.ndarray]:
48          """Load input and output datasets. For the input dataset, each
    ↪  column
49             should represent a piece of data and each row should store the
    ↪  values
50             of the piece of data.
51
52          Args:
53              train_dataset_size (int): the number of train dataset inputs to
    ↪  use.
54          Returns:
55              tuple of train_inputs, train_outputs,
56              test_inputs and test_outputs.
57          Raises:
58              NotImplementedError: if this method is not implemented.
59
60          """
61          raise NotImplementedError
62
63      @abstractmethod
64      def back_propagation(self, prediction: np.ndarray) -> None:
65          """Adjust the weights and bias/biases via gradient descent.
66
67          Args:
68              prediction (numpy.ndarray): the matrice of prediction values
69          Raises:
70              NotImplementedError: if this method is not implemented.
71
72          """
73          raise NotImplementedError
74
75      @abstractmethod
76      def forward_propagation(self) -> np.ndarray:
77          """Generate a prediction with the weights and bias/biases.
78
79          Returns:
80              numpy.ndarray of prediction values.
81          Raises:
82              NotImplementedError: if this method is not implemented.
83
84          """
85          raise NotImplementedError
86
87      @abstractmethod
88      def test(self) -> None:
89          """Test trained weights and bias/biases.
90
91          Raises:
92              NotImplementedError: if this method is not implemented.
93
94          """
95          raise NotImplementedError
96
97      @abstractmethod
98      def train(self, epochs: int) -> None:
99          """Train weights and bias/biases.
100
101         Args:
102             epochs (int): the number of forward and back propagations to
    ↪  do.
```

```
103             Raises:
104                 NotImplementedError: if this method is not implemented.
105 
106             """
107             raise NotImplementedError
108 
109         @abstractmethod
110         def save_model_values(self, file_location: str) -> None:
111             """Save the model by saving the weights then biases of each layer
    ↪  to
112                 a .npz file with a given file location.
113 
114                 Args:
115                     file_location (str): the file location to save the model to.
116 
117             """
118             raise NotImplementedError
119 
120     def relu(z: np.ndarray | int | float) -> np.ndarray | float:
121         """Transfer function, transform input to max number between 0 and z.
122 
123         Args:
124             z (numpy.ndarray | int | float):
125             the numpy.ndarray | int | float to be transferred.
126         Returns:
127             numpy.ndarray | float,
128             with all values | the value transferred to max number between 0-z.
129         Raises:
130             TypeError: if z is not of type numpy.ndarray | int | float.
131 
132         """
133         return np.maximum(0.1*z, 0)  # Divide by 10 to stop overflow errors
134 
135     def relu_derivative(output: np.ndarray) -> np.ndarray:
136         """Calculate derivative of ReLu Transfer function with respect to z.
137 
138         Args:
139             output (numpy.ndarray):
140             the numpy.ndarray output of the ReLu transfer function.
141         Returns:
142             numpy.ndarray,
143             derivative of the ReLu transfer function with respect to z.
144         Raises:
145             TypeError: if output is not of type numpy.ndarray.
146 
147         """
148         output[output <= 0] = 0
149         output[output > 0] = 1
150 
151         return output
152 
153     def sigmoid(z: np.ndarray | int | float) -> np.ndarray | float:
154         """Transfer function, transform input to number between 0 and 1.
155 
156         Args:
157             z (numpy.ndarray | int | float):
158             the numpy.ndarray | int | float to be transferred.
159         Returns:
160             numpy.ndarray | float,
161             with all values | the value transferred to a number between 0-1.
162         Raises:
163             TypeError: if z is not of type numpy.ndarray | int | float.
```

```
164
165         """
166         return 1 / (1 + np.exp(-z))
167
168     def sigmoid_derivative(output: np.ndarray | int | float) -> np.ndarray |
    ↪  float:
169         """Calculate derivative of sigmoid Transfer function with respect to z.
170
171         Args:
172             output (numpy.ndarray | int | float):
173             the numpy.ndarray | int | float output of the sigmoid transfer
    ↪  function.
174         Returns:
175             numpy.ndarray | float,
176             derivative of the sigmoid transfer function with respect to z.
177         Raises:
178             TypeError: if output is not of type numpy.ndarray | int | float.
179
180         """
181         return output * (1 - output)
182
183     def calculate_loss(input_count: int,
184                        outputs: np.ndarray,
185                        prediction: np.ndarray) -> float:
186         """Calculate average loss/error of the prediction to the outputs.
187
188         Args:
189             input_count (int): the number of inputs.
190             outputs (np.ndarray):
191             the train/test outputs array to compare with the prediction.
192             prediction (np.ndarray): the array of prediction values.
193         Returns:
194             float loss.
195         Raises:
196             ValueError:
197             if outputs is not a suitable multiplier with the prediction
198             (incorrect shapes)
199
200         """
201         return np.squeeze(- (1/input_count) * np.sum(outputs *
    ↪  np.log(prediction) + (1 - outputs) * np.log(1 - prediction)))
202
203     def calculate_prediction_accuracy(prediction: np.ndarray,
204                                       outputs: np.ndarray) -> float:
205         """Calculate the percentage accuracy of the predictions.
206
207         Args:
208             prediction (np.ndarray): the array of prediction values.
209             outputs (np.ndarray):
210             the train/test outputs array to compare with the prediction.
211         Returns:
212             float prediction accuracy
213
214         """
215         return 100 - np.mean(np.abs(prediction - outputs)) * 100
```

- model.py module:

```
1   """Provides an abstract class for Artificial Neural Network models."""
2
3   import time
```

```
4
5   import numpy as np
6
7   from .tools import (
8                       ModelInterface,
9                       relu,
10                      relu_derivative,
11                      sigmoid,
12                      sigmoid_derivative,
13                      calculate_loss,
14                      calculate_prediction_accuracy
15                      )
16
17  class _Layers():
18      """Manages linked list of layers."""
19      def __init__(self) -> None:
20          """Initialise linked list."""
21          self.head = None
22          self.tail = None
23
24      def __iter__(self) -> None:
25          """Iterate forward through the network."""
26          current_layer = self.head
27          while True:
28              yield current_layer
29              if current_layer.next_layer is not None:
30                  current_layer = current_layer.next_layer
31              else:
32                  break
33
34      def __reversed__(self) -> None:
35          """Iterate back through the network."""
36          current_layer = self.tail
37          while True:
38              yield current_layer
39              if current_layer.previous_layer is not None:
40                  current_layer = current_layer.previous_layer
41              else:
42                  break
43
44  class _FullyConnectedLayer():
45      """Fully connected layer for Deep ANNs,
46         represented as a node of a Doubly linked list."""
47      def __init__(self, learning_rate: float, input_neuron_count: int,
48                   output_neuron_count: int, transfer_type: str) -> None:
49          """Initialise layer values.
50
51          Args:
52              learning_rate (float): the learning rate of the model.
53              input_neuron_count (int):
54              the number of input neurons into the layer.
55              output_neuron_count (int):
56              the number of output neurons into the layer.
57              transfer_type (str): the transfer function type
58              ('sigmoid' or 'relu')
59
60          """
61          # Setup layer attributes
62          self.previous_layer = None
63          self.next_layer = None
64          self.input_neuron_count = input_neuron_count
65          self.output_neuron_count = output_neuron_count
```

```
66          self.transfer_type = transfer_type
67          self.input: np.ndarray
68          self.output: np.ndarray
69
70          # Setup weights and biases
71          self.weights: np.ndarray
72          self.biases: np.ndarray
73          self.learning_rate = learning_rate
74
75      def __repr__(self) -> str:
76          """Read values of the layer.
77
78          Returns:
79              a string description of the layers's
80              weights, bias and learning rate values.
81
82          """
83          return (f"Weights: {self.weights.tolist()}\n" +
84                  f"Biases: {self.biases.tolist()}\n")
85
86      def init_layer_values_random(self) -> None:
87          """Initialise weights to random values and biases to 0s"""
88          np.random.seed(1)  # Sets up pseudo random values for layer weight
            ↪  arrays
89          self.weights = np.random.rand(self.output_neuron_count,
            ↪  self.input_neuron_count) - 0.5
90          self.biases = np.zeros(shape=(self.output_neuron_count, 1))
91
92      def init_layer_values_zeros(self) -> None:
93          """Initialise weights to 0s and biases to 0s"""
94          self.weights = np.zeros(shape=(self.output_neuron_count,
            ↪  self.input_neuron_count))
95          self.biases = np.zeros(shape=(self.output_neuron_count, 1))
96
97      def back_propagation(self, dloss_doutput) -> np.ndarray:
98          """Adjust the weights and biases via gradient descent.
99
100         Args:
101             dloss_doutput (numpy.ndarray): the derivative of the loss of
    ↪  the
102             layer's output, with respect to the layer's output.
103         Returns:
104             a numpy.ndarray derivative of the loss of the layer's input,
105             with respect to the layer's input.
106         Raises:
107             ValueError:
108             if dloss_doutput
109             is not a suitable multiplier with the weights
110             (incorrect shape)
111
112         """
113         match self.transfer_type:
114             case 'sigmoid':
115                 dloss_dz = dloss_doutput *
                    ↪  sigmoid_derivative(output=self.output)
116             case 'relu':
117                 dloss_dz = dloss_doutput *
                    ↪  relu_derivative(output=self.output)
118
119         dloss_dweights = np.dot(dloss_dz, self.input.T)
120         dloss_dbiases = np.sum(dloss_dz)
121
```

```
122             assert dloss_dweights.shape == self.weights.shape
123
124             dloss_dinput = np.dot(self.weights.T, dloss_dz)
125
126             # Update weights and biases
127             self.weights -= self.learning_rate * dloss_dweights
128             self.biases -= self.learning_rate * dloss_dbiases
129
130             return dloss_dinput
131
132         def forward_propagation(self, inputs) -> np.ndarray:
133             """Generate a layer output with the weights and biases.
134
135             Args:
136                 inputs (np.ndarray): the input values to the layer.
137             Returns:
138                 a numpy.ndarray of the output values.
139
140             """
141             self.input = inputs
142             z = np.dot(self.weights, self.input) + self.biases
143             if self.transfer_type == 'sigmoid':
144                 self.output = sigmoid(z)
145             elif self.transfer_type == 'relu':
146                 self.output = relu(z)
147             return self.output
148
149     class AbstractModel(ModelInterface):
150         """ANN model with variable number of hidden layers"""
151         def __init__(self,
152                      hidden_layers_shape: list[int],
153                      train_dataset_size: int,
154                      learning_rate: float,
155                      use_relu: bool) -> None:
156             """Initialise model values.
157
158             Args:
159                 hidden_layers_shape (list[int]):
160                 list of the number of neurons in each hidden layer.
161                 train_dataset_size (int): the number of train dataset inputs to
    ↪  use.
162                 learning_rate (float): the learning rate of the model.
163                 use_relu (bool): True or False whether the ReLu Transfer
    ↪  function
164                 should be used.
165
166             """
167             # Setup model data
168             self.train_inputs, self.train_outputs,\
169             self.test_inputs, self.test_outputs = self.load_datasets(
170
                                                 ↪  train_dataset_size=train_dataset_size
171                                                 )
172             self.train_losses: list[float]
173             self.test_prediction: np.ndarray
174             self.test_prediction_accuracy: float
175             self.training_progress = ""
176             self.training_time: float
177
178             # Setup model attributes
179             self.__running = True
180             self.input_neuron_count: int = self.train_inputs.shape[0]
```

```
181             self.input_count = self.train_inputs.shape[1]
182             self.hidden_layers_shape = hidden_layers_shape
183             self.output_neuron_count = self.train_outputs.shape[0]
184             self.layers_shape = [f'{layer}' for layer in (
185                                  [self.input_neuron_count] +
186                                  self.hidden_layers_shape +
187                                  [self.output_neuron_count]
188                                  )]
189             self.use_relu = use_relu
190 
191             # Setup model values
192             self.layers = _Layers()
193             self.learning_rate = learning_rate
194 
195         def __repr__(self) -> str:
196             """Read current state of model.
197 
198             Returns:
199                 a string description of the model's shape,
200                 weights, bias and learning rate values.
201 
202             """
203             return (f"Layers Shape: {','.join(self.layers_shape)}\n" +
204                     f"Learning Rate: {self.learning_rate}")
205 
206         def set_running(self, value: bool) -> None:
207             """Set the running attribute to the given value.
208 
209             Args:
210                 value (bool): the value to set the running attribute to.
211 
212             """
213             self.__running = value
214 
215         def _setup_layers(setup_values: callable) -> None:
216             """Decorator that sets up model layers and sets up values of each
    ↪ layer
217                    with the method given.
218 
219             Args:
220                 setup_values (callable): the method that sets up the values of
    ↪ each
221                  layer.
222 
223             """
224             def decorator(self, *args, **kwargs) -> None:
225                 # Check if setting up Deep Network
226                 if len(self.hidden_layers_shape) > 0:
227                     if self.use_relu:
228 
229                         # Add input layer
230                         self.layers.head = _FullyConnectedLayer(
231 
                                                    ↪ learning_rate=self.learning_rate,
232 
                                                    ↪ input_neuron_count=self.input_neuron_count,
233 
                                                    ↪ output_neuron_count=self.hidden_layers_shape[0],
234                                                    transfer_type='relu'
235                                                    )
236                         current_layer = self.layers.head
237 
```

```
238                     # Add hidden layers
239                     for layer in range(len(self.hidden_layers_shape) - 1):
240                         current_layer.next_layer = _FullyConnectedLayer(
241                                     learning_rate=self.learning_rate,
242                                     ↪  input_neuron_count=self.hidden_layers_shape[layer],
243                                     ↪  output_neuron_count=self.hidden_layers_shape[layer
                                    ↪  + 1],
244                                     transfer_type='relu'
245                                     )
246                         current_layer.next_layer.previous_layer =
                        ↪  current_layer
247                         current_layer = current_layer.next_layer
248                 else:
249
250                     # Add input layer
251                     self.layers.head = _FullyConnectedLayer(
252                                         ↪  learning_rate=self.learning_rate,
253                                         ↪  input_neuron_count=self.input_neuron_count,
254                                         ↪  output_neuron_count=self.hidden_layers_shape[0],
255                                         transfer_type='sigmoid'
256                                         )
257                     current_layer = self.layers.head
258
259                     # Add hidden layers
260                     for layer in range(len(self.hidden_layers_shape) - 1):
261                         current_layer.next_layer = _FullyConnectedLayer(
262                                     learning_rate=self.learning_rate,
263                                     ↪  input_neuron_count=self.hidden_layers_shape[layer],
264                                     ↪  output_neuron_count=self.hidden_layers_shape[layer
                                    ↪  + 1],
265                                     transfer_type='sigmoid'
266                                     )
267                         current_layer.next_layer.previous_layer =
                        ↪  current_layer
268                         current_layer = current_layer.next_layer
269
270                 # Add output layer
271                 current_layer.next_layer = _FullyConnectedLayer(
272                                         learning_rate=self.learning_rate,
273                                         ↪  input_neuron_count=self.hidden_layers_shape[-1],
274                                         ↪  output_neuron_count=self.output_neuron_count,
275                                         transfer_type='sigmoid'
276                                         )
277                 current_layer.next_layer.previous_layer = current_layer
278                 self.layers.tail = current_layer.next_layer
279
280             # Setup Perceptron Network
281             else:
282                 self.layers.head = _FullyConnectedLayer(
283                                         learning_rate=self.learning_rate,
284                                         ↪  input_neuron_count=self.input_neuron_count,
285                                         ↪  output_neuron_count=self.output_neuron_count,
```

```
                                        transfer_type='sigmoid'
                                        )
                self.layers.tail = self.layers.head

            setup_values(self, *args, **kwargs)

        return decorator

    @_setup_layers
    def create_model_values(self) -> None:
        """Create weights and bias/biases"""
        # Check if setting up Deep Network
        if len(self.hidden_layers_shape) > 0:

            # Initialise Layer values to random values
            for layer in self.layers:
                layer.init_layer_values_random()

        # Setup Perceptron Network
        else:

            # Initialise Layer values to zeros
            for layer in self.layers:
                layer.init_layer_values_zeros()

    @_setup_layers
    def load_model_values(self, file_location: str) -> None:
        """Load weights and bias/biases from .npz file.

        Args:
            file_location (str): the location of the file to load from.

        """
        data: dict[str, np.ndarray] = np.load(file=file_location)

        # Initialise Layer values
        i = 0
        keys = list(data.keys())
        for layer in self.layers:
            layer.weights = data[keys[i]]
            layer.biases = data[keys[i + 1]]
            i += 2

    def back_propagation(self, dloss_doutput) -> None:
        """Train each layer's weights and biases.

        Args:
            dloss_doutput (np.ndarray): the derivative of the loss of the
            output layer's output, with respect to the output layer's
    ↪   output.

        """
        for layer in reversed(self.layers):
            dloss_doutput =
            ↪   layer.back_propagation(dloss_doutput=dloss_doutput)

    def forward_propagation(self) -> np.ndarray:
        """Generate a prediction with the layers.

        Returns:
            a numpy.ndarray of the prediction values.

```

```
346             """
347             output = self.train_inputs
348             for layer in self.layers:
349                 output = layer.forward_propagation(inputs=output)
350             return output
351 
352         def test(self) -> None:
353             """Test the layers' trained weights and biases."""
354             output = self.test_inputs
355             for layer in self.layers:
356                 output = layer.forward_propagation(inputs=output)
357             self.test_prediction = output
358 
359             # Calculate performance of model
360             self.test_prediction_accuracy = calculate_prediction_accuracy(
361 
                                                ↪  prediction=self.test_prediction,
362                                                outputs=self.test_outputs
363                                                )
364 
365         def train(self, epoch_count: int) -> None:
366             """Train layers' weights and biases.
367 
368                Args:
369                    epoch_count (int): the number of training epochs.
370 
371             """
372             self.layers_shape = [f'{layer}' for layer in (
373                                  [self.input_neuron_count] +
374                                  self.hidden_layers_shape +
375                                  [self.output_neuron_count]
376                                  )]
377             self.train_losses = []
378             training_start_time = time.time()
379             for epoch in range(epoch_count):
380                 if not self.__running:
381                     break
382                 self.training_progress = f"Epoch {epoch} / {epoch_count}"
383                 prediction = self.forward_propagation()
384                 loss = calculate_loss(input_count=self.input_count,
385                                       outputs=self.train_outputs,
386                                       prediction=prediction)
387                 self.train_losses.append(loss)
388                 if not self.__running:
389                     break
390                 dloss_doutput = -(1/self.input_count) * ((self.train_outputs -
                    ↪  prediction)/(prediction * (1 - prediction)))
391                 self.back_propagation(dloss_doutput=dloss_doutput)
392             self.training_time = round(number=time.time() -
                ↪  training_start_time,
393                                        ndigits=2)
394 
395         def save_model_values(self, file_location: str) -> None:
396             """Save the model by saving the weights then biases of each layer
    ↪  to
397                a .npz file with a given file location.
398 
399                Args:
400                    file_location (str): the file location to save the model to.
401 
402             """
403             saved_model: list[np.ndarray] = []
```

```
404             for layer in self.layers:
405                 saved_model.append(layer.weights)
406                 saved_model.append(layer.biases)
407             np.savez(file_location, *saved_model)
```

3.2.2 Artificial Neural Network implementations

The following three modules implement the AbstractModel class from the above model.py module from the utils subpackage, on the three datasets.

- cat_recognition.py module:

```
1   """Implementation of Artificial Neural Network model on Cat Recognition
    ↪ dataset."""
2
3   import h5py
4   import numpy as np
5
6   from .utils.model import AbstractModel
7
8   class CatRecognitionModel(AbstractModel):
9       """ANN model that trains to predict if an image is a cat or not a
    ↪ cat."""
10      def __init__(self,
11                   hidden_layers_shape: list[int],
12                   train_dataset_size: int,
13                   learning_rate: float,
14                   use_relu: bool) -> None:
15          """Initialise Model's Base class.
16
17          Args:
18              hidden_layers_shape (list[int]):
19              list of the number of neurons in each hidden layer.
20              train_dataset_size (int): the number of train dataset inputs to
    ↪ use.
21              learning_rate (float): the learning rate of the model.
22              use_relu (bool): True or False whether the ReLu Transfer
    ↪ function
23              should be used.
24
25          """
26          super().__init__(hidden_layers_shape=hidden_layers_shape,
27                           train_dataset_size=train_dataset_size,
28                           learning_rate=learning_rate,
29                           use_relu=use_relu)
30
31      def load_datasets(self, train_dataset_size: int) -> tuple[np.ndarray,
        ↪ np.ndarray,
32                                                                np.ndarray,
                                                                  ↪ np.ndarray]:
33          """Load image input and output datasets.
34
35          Args:
36              train_dataset_size (int): the number of train dataset inputs to
    ↪ use.
37          Returns:
38              tuple of image train_inputs, train_outputs,
39              test_inputs and test_outputs numpy.ndarrys.
40
41          Raises:
```

```
            FileNotFoundError: if file does not exist.

        """
        # Load datasets from h5 files
        # (h5 files stores large amount of data with quick access)
        train_dataset: h5py.File = h5py.File(
             r'school_project/models/datasets/train-cat.h5',
             'r'
             )
        test_dataset: h5py.File = h5py.File(
              r'school_project/models/datasets/test-cat.h5',
              'r'
              )

        # Load input arrays,
        # containing the RGB values for each pixel in each 64x64 pixel
        ↪  image,
        # for 209 images
        train_inputs: np.ndarray =
        ↪  np.array(train_dataset['train_set_x'][:])
        test_inputs: np.ndarray = np.array(test_dataset['test_set_x'][:])

        # Load output arrays of 1s for cat and 0s for not cat
        train_outputs: np.ndarray =
        ↪  np.array(train_dataset['train_set_y'][:])
        test_outputs: np.ndarray = np.array(test_dataset['test_set_y'][:])

        # Reshape input arrays into 1 dimension (flatten),
        # then divide by 255 (RGB)
        # to standardize them to a number between 0 and 1
        train_inputs = train_inputs.reshape((train_inputs.shape[0],
                                             -1)).T / 255
        test_inputs = test_inputs.reshape((test_inputs.shape[0], -1)).T /
        ↪  255

        # Reshape output arrays into a 1 dimensional list of outputs
        train_outputs = train_outputs.reshape((1, train_outputs.shape[0]))
        test_outputs = test_outputs.reshape((1, test_outputs.shape[0]))

        # Reduce train datasets' sizes to train_dataset_size
        train_inputs = (train_inputs.T[:train_dataset_size]).T
        train_outputs = (train_outputs.T[:train_dataset_size]).T

        return train_inputs, train_outputs, test_inputs, test_outputs
```

- mnist.py module:

```
"""Implementation of Artificial Neural Network model on MNIST dataset."""

import pickle
import gzip

import numpy as np

from .utils.model import AbstractModel

class MNISTModel(AbstractModel):
    """ANN model that trains to predict Numbers from images."""
    def __init__(self, hidden_layers_shape: list[int],
                 train_dataset_size: int,
                 learning_rate: float,
```

```
15                  use_relu: bool) -> None:
16          """Initialise Model's Base class.
17
18          Args:
19              hidden_layers_shape (list[int]):
20              list of the number of neurons in each hidden layer.
21              train_dataset_size (int): the number of train dataset inputs to
    ↪  use.
22              learning_rate (float): the learning rate of the model.
23              use_relu (bool): True or False whether the ReLu Transfer
    ↪  function
24              should be used.
25
26          """
27          super().__init__(hidden_layers_shape=hidden_layers_shape,
28                           train_dataset_size=train_dataset_size,
29                           learning_rate=learning_rate,
30                           use_relu=use_relu)
31
32      def load_datasets(self, train_dataset_size: int) -> tuple[np.ndarray,
    ↪  np.ndarray,
33                                                                np.ndarray,
                                                                  ↪  np.ndarray]:
34          """Load image input and output datasets.
35          Args:
36              train_dataset_size (int): the number of dataset inputs to use.
37          Returns:
38              tuple of image train_inputs, train_outputs,
39              test_inputs and test_outputs numpy.ndarrys.
40
41          Raises:
42              FileNotFoundError: if file does not exist.
43
44          """
45          # Load datasets from pkl.gz file
46          with gzip.open(
47                'school_project/models/datasets/mnist.pkl.gz',
48                'rb'
49                ) as mnist:
50              (train_inputs, train_outputs),\
51              (test_inputs, test_outputs) = pickle.load(mnist,
                ↪  encoding='bytes')
52
53          # Reshape input arrays into 1 dimension (flatten),
54          # then divide by 255 (RGB)
55          # to standardize them to a number between 0 and 1
56          train_inputs =
            ↪  np.array(train_inputs.reshape((train_inputs.shape[0],
57                                                    -1)).T / 255)
58          test_inputs = np.array(test_inputs.reshape(test_inputs.shape[0],
            ↪  -1).T / 255)
59
60          # Represent number values
61          # with a one at the matching index of an array of zeros
62          train_outputs = np.eye(np.max(train_outputs) + 1)[train_outputs].T
63          test_outputs = np.eye(np.max(test_outputs) + 1)[test_outputs].T
64
65          # Reduce train datasets' sizes to train_dataset_size
66          train_inputs = (train_inputs.T[:train_dataset_size]).T
67          train_outputs = (train_outputs.T[:train_dataset_size]).T
68
69          return train_inputs, train_outputs, test_inputs, test_outputs
```

- xor.py module

```python
"""Implementation of Artificial Neural Network model on XOR dataset."""

import numpy as np

from .utils.model import AbstractModel

class XORModel(AbstractModel):
    """ANN model that trains to predict the output of a XOR gate with two
       inputs."""
    def __init__(self,
                 hidden_layers_shape: list[int],
                 train_dataset_size: int,
                 learning_rate: float,
                 use_relu: bool) -> None:
        """Initialise Model's Base class.

        Args:
            hidden_layers_shape (list[int]):
            list of the number of neurons in each hidden layer.
            train_dataset_size (int): the number of train dataset inputs to
↪   use.
            learning_rate (float): the learning rate of the model.
            use_relu (bool): True or False whether the ReLu Transfer
↪   function
            should be used.

        """
        super().__init__(hidden_layers_shape=hidden_layers_shape,
                         train_dataset_size=train_dataset_size,
                         learning_rate=learning_rate,
                         use_relu=use_relu)

    def load_datasets(self, train_dataset_size: int) -> tuple[np.ndarray,
    ↪  np.ndarray,
                                                              np.ndarray,
                                                              ↪  np.ndarray]:
        """Load XOR input and output datasets.

        Args:
            train_dataset_size (int): the number of dataset inputs to use.
        Returns:
            tuple of XOR train_inputs, train_outputs,
            test_inputs and test_outputs numpy.ndarrys.

        """
        inputs: np.ndarray = np.array([[0, 0, 1, 1],
                                       [0, 1, 0, 1]])
        outputs: np.ndarray = np.array([[0, 1, 1, 0]])

        # Reduce train datasets' sizes to train_dataset_size
        inputs = (inputs.T[:train_dataset_size]).T
        outputs = (outputs.T[:train_dataset_size]).T

        return inputs, outputs, inputs, outputs
```

3.3 frames package

I decided to use tkinter for the User Interface and the frames package consists of tkinter frames to be loaded onto the main window when needed. The package also includes a hyper-parameter-defaults.json file, which stores optimum default values for the hyper-parameters to be set to.

- hyper-parameter-defaults.json file contents:

```
{
    "MNIST": {
        "description": "An Image model trained on recognising numbers from
↪   images.",
        "epochCount": 150,
        "hiddenLayersShape": [1000, 1000],
        "minTrainDatasetSize": 1,
        "maxTrainDatasetSize": 60000,
        "maxLearningRate": 1
    },
    "Cat Recognition": {
        "description": "An Image model trained on recognising if an image
↪   is a cat or not.",
        "epochCount": 3500,
        "hiddenLayersShape": [100, 100],
        "minTrainDatasetSize": 1,
        "maxTrainDatasetSize": 209,
        "maxLearningRate": 0.3
    },
    "XOR": {
        "description": "For experimenting with Artificial Neural Networks,
↪   a XOR gate model has been used for its lesser computation time.",
        "epochCount": 4700,
        "hiddenLayersShape": [100, 100],
        "minTrainDatasetSize":  2,
        "maxTrainDatasetSize": 4,
        "maxLearningRate": 1
    }
}
```

- create_model.py module:

```
"""Tkinter frames for creating an Artificial Neural Network model."""

import json
import threading
import tkinter as tk
import tkinter.font as tkf

from matplotlib.figure import Figure
from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg
import numpy as np

class HyperParameterFrame(tk.Frame):
    """Frame for hyper-parameter page."""
    def __init__(self, root: tk.Tk, width: int,
                 height: int, bg: str, dataset: str) -> None:
        """Initialise hyper-parameter frame widgets.

        Args:
            root (tk.Tk): the widget object that contains this widget.
```

```
            width (int): the pixel width of the frame.
            height (int): the pixel height of the frame.
            bg (str): the hex value or name of the frame's background colour.
            dataset (str): the name of the dataset to use
            ('MNIST', 'Cat Recognition' or 'XOR')
        Raises:
            TypeError: if root, width or height are not of the correct type.

        """
        super().__init__(master=root, width=width, height=height, bg=bg)
        self.root = root
        self.WIDTH = width
        self.HEIGHT = height
        self.BG = bg

        # Setup hyper-parameter frame variables
        self.dataset = dataset
        self.use_gpu: bool
        self.default_hyper_parameters = self.load_default_hyper_parameters(dataset=dataset)

        # Setup widgets
        self.title_label = tk.Label(master=self,
                                    bg=self.BG,
                                    font=('Arial', 20),
                                    text=dataset)
        self.about_label = tk.Label(
                               master=self,
                               bg=self.BG,
                               font=('Arial', 14),
                               text=self.default_hyper_parameters['description']
                               )
        self.learning_rate_scale = tk.Scale(
                           master=self,
                           bg=self.BG,
                           orient='horizontal',
                           label="Learning Rate",
                           length=185,
                           from_=0,
                           to=self.default_hyper_parameters['maxLearningRate'],
                           resolution=0.01
                           )
        self.learning_rate_scale.set(value=0.1)
        self.epoch_count_scale = tk.Scale(master=self,
                                          bg=self.BG,
                                          orient='horizontal',
                                          label="Epoch Count",
                                          length=185,
                                          from_=0,
                                          to=10_000,
                                          resolution=100)
        self.epoch_count_scale.set(
                               value=self.default_hyper_parameters['epochCount']
                               )
        self.train_dataset_size_scale = tk.Scale(
```

```
76                  master=self,
77                  bg=self.BG,
78                  orient='horizontal',
79                  label="Train Dataset Size",
80                  length=185,
81
                    ↪  from_=self.default_hyper_parameters['minTrainDatasetSize'],
82                  to=self.default_hyper_parameters['maxTrainDatasetSize'],
83                  resolution=1
84                  )
85          self.train_dataset_size_scale.set(
86
                     ↪  value=self.default_hyper_parameters['maxTrainDatasetSize']
87                   )
88          self.hidden_layers_shape_label = tk.Label(
89                                  master=self,
90                                  bg=self.BG,
91                                  font=('Arial', 12),
92                                  text="Enter the number of neurons in
                                    ↪  each\n" +
93                                          "hidden layer, separated by
                                            ↪  commas:"
94                                  )
95          self.hidden_layers_shape_entry = tk.Entry(master=self)
96          self.hidden_layers_shape_entry.insert(0, ",".join(
97              f"{neuron_count}" for neuron_count in
                ↪  self.default_hyper_parameters['hiddenLayersShape']
98              ))
99          self.use_relu_check_button_var = tk.BooleanVar(value=True)
100         self.use_relu_check_button = tk.Checkbutton(
101                                         master=self,
102                                         width=13, height=1,
103                                         font=tkf.Font(size=12),
104                                         text="Use ReLu",
105
                                            ↪  variable=self.use_relu_check_button_var
106                                                        )
107         self.use_gpu_check_button_var = tk.BooleanVar()
108         self.use_gpu_check_button = tk.Checkbutton(
109                                         master=self,
110                                         width=13, height=1,
111                                         font=tkf.Font(size=12),
112                                         text="Use GPU",
113
                                            ↪  variable=self.use_gpu_check_button_var
114                                                        )
115         self.model_status_label = tk.Label(master=self,
116                                            bg=self.BG,
117                                            font=('Arial', 15))
118
119         # Pack widgets
120         self.title_label.grid(row=0, column=0, columnspan=3)
121         self.about_label.grid(row=1, column=0, columnspan=3)
122         self.learning_rate_scale.grid(row=2, column=0, pady=(50,0))
123         self.epoch_count_scale.grid(row=3, column=0, pady=(30,0))
124         self.train_dataset_size_scale.grid(row=4, column=0, pady=(30,0))
125         self.hidden_layers_shape_label.grid(row=2, column=1,
126                                             padx=30, pady=(50,0))
127         self.hidden_layers_shape_entry.grid(row=3, column=1, padx=30)
128         self.use_relu_check_button.grid(row=2, column=2, pady=(30, 0))
129         self.use_gpu_check_button.grid(row=3, column=2, pady=(30, 0))
130         self.model_status_label.grid(row=5, column=0,
```

```
131                                         columnspan=3, pady=50)
132
133     def load_default_hyper_parameters(self, dataset: str) -> dict[
134                                                     str,
135                                                     str | int | list[int] |
                                                        ↪  float
136                                                     ]:
137         """Load the dataset's default hyper-parameters from the json file.
138
139            Args:
140                dataset (str): the name of the dataset to load
    ↪  hyper-parameters
141                for. ('MNIST', 'Cat Recognition' or 'XOR')
142             Returns:
143                 a dictionary of default hyper-parameter values.
144         """
145         with open('school_project/frames/hyper-parameter-defaults.json') as
            ↪  f:
146             return json.load(f)[dataset]
147
148     def create_model(self) -> object:
149         """Create and return a Model using the hyper-parameters set.
150
151            Returns:
152                a Model object.
153         """
154         self.use_gpu = self.use_gpu_check_button_var.get()
155
156         # Validate hidden layers shape input
157         hidden_layers_shape_input = [layer for layer in
            ↪  self.hidden_layers_shape_entry.get().replace(' ',
            ↪  '').split(',') if layer != '']
158         for layer in hidden_layers_shape_input:
159             if not layer.isdigit():
160                 self.model_status_label.configure(
161                                             text="Invalid hidden layers shape",
162                                             fg='red'
163                                             )
164                 raise ValueError
165
166         # Create Model
167         if not self.use_gpu:
168             if self.dataset == "MNIST":
169                 from school_project.models.cpu.mnist import MNISTModel as
                    ↪  Model
170             elif self.dataset == "Cat Recognition":
171                 from school_project.models.cpu.cat_recognition import
                    ↪  CatRecognitionModel as Model
172             elif self.dataset == "XOR":
173                 from school_project.models.cpu.xor import XORModel as Model
174             model = Model(
175                 hidden_layers_shape = [int(neuron_count) for neuron_count
                    ↪  in hidden_layers_shape_input],
176                 train_dataset_size = self.train_dataset_size_scale.get(),
177                 learning_rate = self.learning_rate_scale.get(),
178                 use_relu = self.use_relu_check_button_var.get()
179                 )
180             model.create_model_values()
181
182         else:
183             try:
184                 if self.dataset == "MNIST":
```

```
185                     from school_project.models.gpu.mnist import MNISTModel
                        ↪  as Model
186                 elif self.dataset == "Cat Recognition":
187                     from school_project.models.gpu.cat_recognition import
                        ↪  CatRecognitionModel as Model
188                 elif self.dataset == "XOR":
189                     from school_project.models.gpu.xor import XORModel as
                        ↪  Model
190                 model = Model(hidden_layers_shape = [int(neuron_count) for
                    ↪  neuron_count in hidden_layers_shape_input],
191                               train_dataset_size =
                                  ↪  self.train_dataset_size_scale.get(),
192                               learning_rate =
                                  ↪  self.learning_rate_scale.get(),
193                               use_relu =
                                  ↪  self.use_relu_check_button_var.get())
194                 model.create_model_values()
195             except ImportError as ie:
196                 self.model_status_label.configure(
197                                           text="Failed to initialise GPU",
198                                           fg='red'
199                                           )
200                 raise ImportError
201         return model
202
203 class TrainingFrame(tk.Frame):
204     """Frame for training page."""
205     def __init__(self, root: tk.Tk, width: int,
206                  height: int, bg: str,
207                  model: object, epoch_count: int) -> None:
208         """Initialise training frame widgets.
209
210         Args:
211             root (tk.Tk): the widget object that contains this widget.
212             width (int): the pixel width of the frame.
213             height (int): the pixel height of the frame.
214             bg (str): the hex value or name of the frame's background
    ↪  colour.
215             model (object): the Model object to be trained.
216             epoch_count (int): the number of training epochs.
217         Raises:
218             TypeError: if root, width or height are not of the correct
    ↪  type.
219
220         """
221         super().__init__(master=root, width=width, height=height, bg=bg)
222         self.root = root
223         self.WIDTH = width
224         self.HEIGHT = height
225         self.BG = bg
226
227         # Setup widgets
228         self.model_status_label = tk.Label(master=self,
229                                            bg=self.BG,
230                                            font=('Arial', 15))
231         self.training_progress_label = tk.Label(master=self,
232                                                 bg=self.BG,
233                                                 font=('Arial', 15))
234         self.loss_figure: Figure = Figure()
235         self.loss_canvas: FigureCanvasTkAgg = FigureCanvasTkAgg(
236
                                                    ↪  figure=self.loss_figure,
```

```
                                                    master=self
                                                    )

        # Pack widgets
        self.model_status_label.pack(pady=(30,0))
        self.training_progress_label.pack(pady=30)

        # Start training thread
        self.model_status_label.configure(
                                        text="Training weights and
                                        ↪  biases...",
                                        fg='red'
                                        )
        self.train_thread: threading.Thread = threading.Thread(

                                                        ↪  target=model.train,

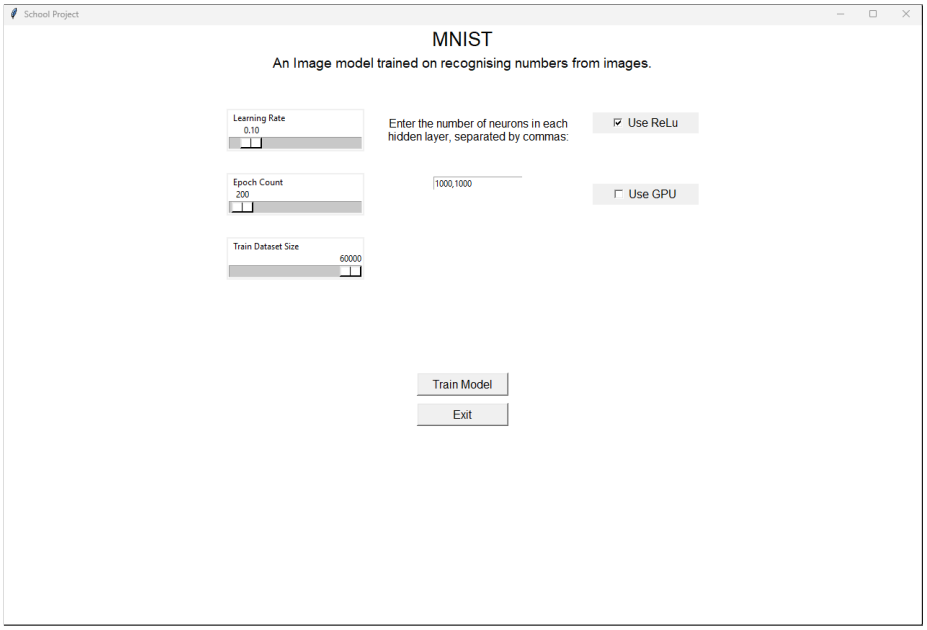
                                                        ↪  args=(epoch_count,)
                                                        )
        self.train_thread.start()

    def plot_losses(self, model: object) -> None:
        """Plot losses of Model training.

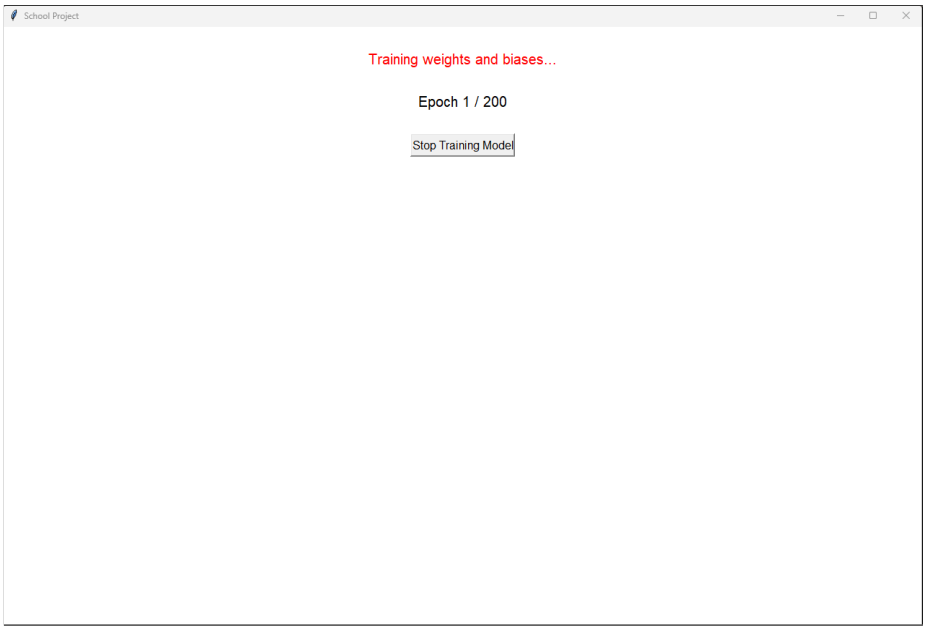
           Args:
               model (object): the Model object thats been trained.

        """
        self.model_status_label.configure(
                 text=f"Weights and biases trained in
                 ↪  {model.training_time}s",
                 fg='green'
                 )
        graph: Figure.axes = self.loss_figure.add_subplot(111)
        graph.set_title("Learning rate: " +
                        f"{model.learning_rate}")
        graph.set_xlabel("Epochs")
        graph.set_ylabel("Loss Value")
        graph.plot(np.squeeze(model.train_losses))
        self.loss_canvas.get_tk_widget().pack()
```

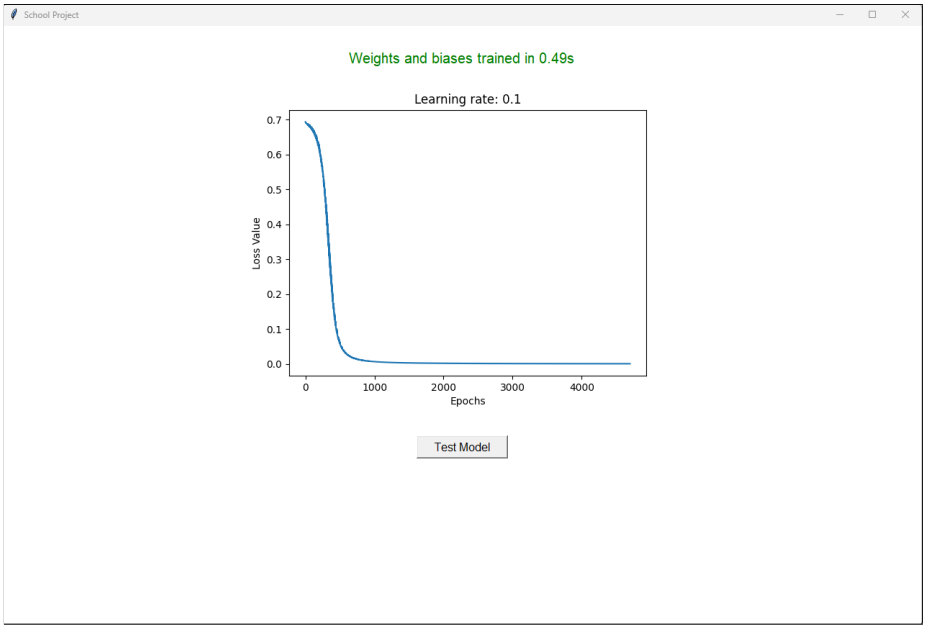
Which outputs the following for the hyper-parameter frame:



And outputs the following for the training frame during training:



And outputs the following for the training frame once training has completed:



- load_model.py module:

```
"""Tkinter frames for loading a saved Artificial Neural Network Model."""

import sqlite3
import tkinter as tk
import tkinter.font as tkf

class LoadModelFrame(tk.Frame):
    """Frame for load model page."""
    def __init__(self, root: tk.Tk,
                 width: int, height: int,
                 bg: str, connection: sqlite3.Connection,
                 cursor: sqlite3.Cursor, dataset: str) -> None:
        """Initialise load model frame widgets.

        Args:
            root (tk.Tk): the widget object that contains this widget.
            width (int): the pixel width of the frame.
            height (int): the pixel height of the frame.
            bg (str): the hex value or name of the frame's background colour.
            connection (sqlite3.Connection): the database connection object.
            cursor (sqlite3.Cursor): the database cursor object.
            dataset (str): the name of the dataset to use
            ('MNIST', 'Cat Recognition' or 'XOR')
        Raises:
            TypeError: if root, width or height are not of the correct type.

        """
```

```
28          super().__init__(master=root, width=width, height=height, bg=bg)
29          self.root = root
30          self.WIDTH = width
31          self.HEIGHT = height
32          self.BG = bg
33
34          # Setup load model frame variables
35          self.connection = connection
36          self.cursor = cursor
37          self.dataset = dataset
38          self.use_gpu: bool
39          self.model_options = self.load_model_options()
40
41          # Setup widgets
42          self.title_label = tk.Label(master=self,
43                                      bg=self.BG,
44                                      font=('Arial', 20),
45                                      text=dataset)
46          self.about_label = tk.Label(
47                      master=self,
48                      bg=self.BG,
49                      font=('Arial', 14),
50                      text=f"Load a pretrained model for the {dataset}
                        ↪  dataset."
51                      )
52          self.model_status_label = tk.Label(master=self,
53                                             bg=self.BG,
54                                             font=('Arial', 15))
55
56          # Don't give loaded model options if no models have been saved for
            ↪  the
57          # dataset.
58          if len(self.model_options) > 0:
59              self.model_option_menu_label = tk.Label(
60                                                  master=self,
61                                                  bg=self.BG,
62                                                  font=('Arial', 14),
63                                                  text="Select a model to
                                                    ↪  load or delete:"
64                                                  )
65              self.model_option_menu_var = tk.StringVar(
66                                                     master=self,
67
                                                       ↪  value=self.model_options[0]
68                                                     )
69              self.model_option_menu = tk.OptionMenu(
70                                                      self,
71
                                                       ↪  self.model_option_menu_var,
72                                                      *self.model_options
73                                                      )
74              self.use_gpu_check_button_var = tk.BooleanVar()
75              self.use_gpu_check_button = tk.Checkbutton(
76                                          master=self,
77                                          width=7, height=1,
78                                          font=tkf.Font(size=12),
79                                          text="Use GPU",
80
                                            ↪  variable=self.use_gpu_check_button_var
81                                          )
82          else:
83              self.model_status_label.configure(
```

```
                                    text='No saved models for this dataset.',
                                    fg='red'
                                    )

        # Pack widgets
        self.title_label.grid(row=0, column=0, columnspan=3)
        self.about_label.grid(row=1, column=0, columnspan=3)
        if len(self.model_options) > 0:  # Check if options should be given
            self.model_option_menu_label.grid(row=2, column=0, padx=(0,30), pady=(30,0))
            self.use_gpu_check_button.grid(row=2, column=2, rowspan=2, pady=(30,0))
            self.model_option_menu.grid(row=3, column=0, padx=(0,30), pady=(10,0))
        self.model_status_label.grid(row=4, column=0,
                                    columnspan=3, pady=50)

    def load_model_options(self) -> list[str]:
        """Load the model options from the database.

           Returns:
                a list of the model options.
        """
        sql = f"""
        SELECT Name FROM Models WHERE Dataset=?
        """
        parameters = (self.dataset.replace(" ", "_"),)
        self.cursor.execute(sql, parameters)

        # Save the string value contained within the tuple of each row
        model_options = []
        for model_option in self.cursor.fetchall():
            model_options.append(model_option[0])

        return model_options

    def load_model(self) -> object:
        """Create model using saved weights and biases.

           Returns:
               a Model object.

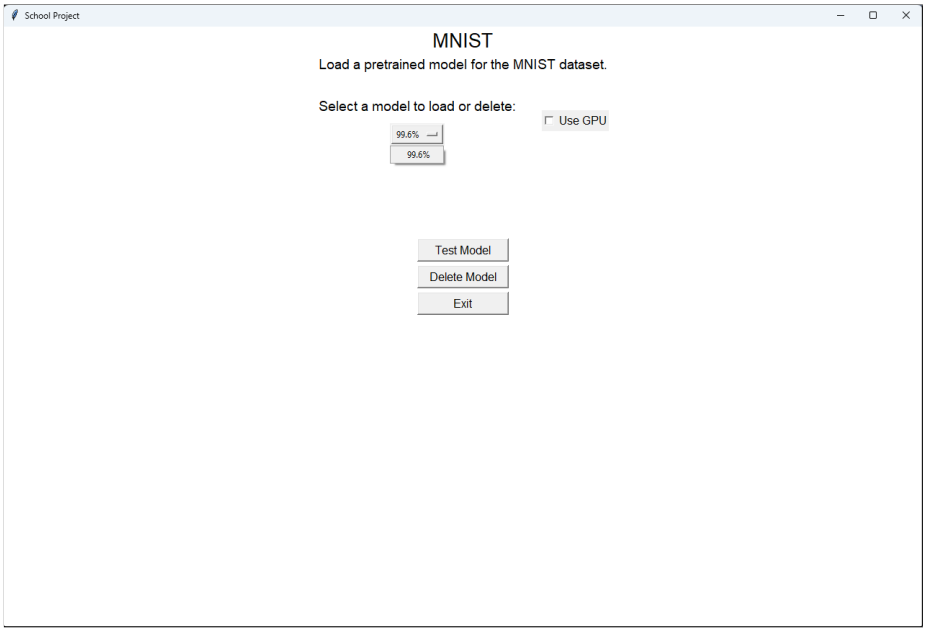
        """
        self.use_gpu = self.use_gpu_check_button_var.get()

        # Query data of selected saved model from database
        sql = """
        SELECT * FROM Models WHERE Dataset=? AND Name=?
        """
        parameters = (self.dataset.replace(" ", "_"), self.model_option_menu_var.get())
        self.cursor.execute(sql, parameters)
        data = self.cursor.fetchone()
        hidden_layers_shape_input = [layer for layer in data[3].replace(' ', '').split(',') if layer != '']

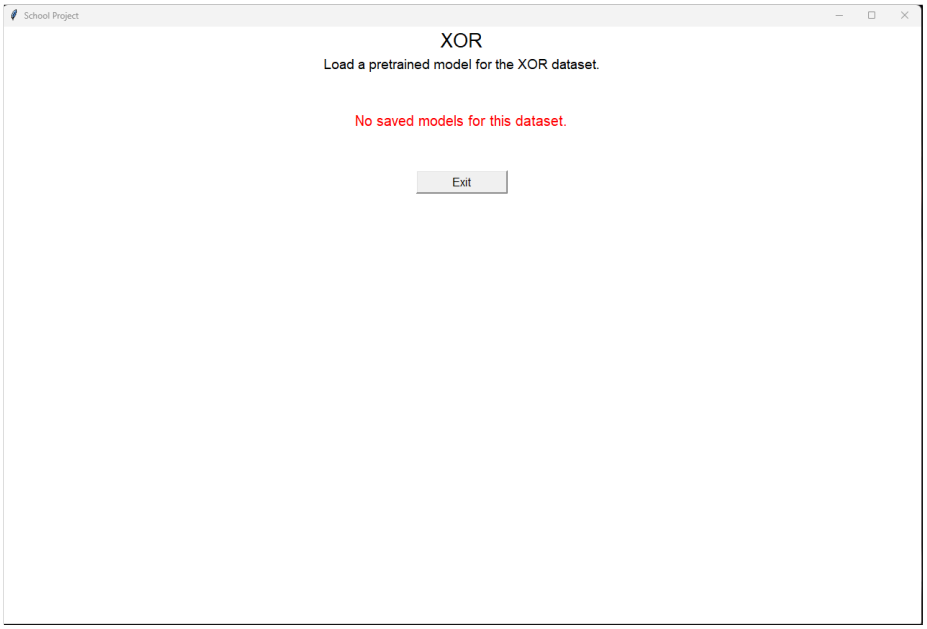
        # Create Model
        if not self.use_gpu:
            if self.dataset == "MNIST":
                from school_project.models.cpu.mnist import MNISTModel as Model
```

```
139                 elif self.dataset == "Cat Recognition":
140                     from school_project.models.cpu.cat_recognition import
                        ↪  CatRecognitionModel as Model
141                 elif self.dataset == "XOR":
142                     from school_project.models.cpu.xor import XORModel as Model
143                 model = Model(
144                     hidden_layers_shape=[int(neuron_count) for neuron_count in
                        ↪  hidden_layers_shape_input],
145                     train_dataset_size=data[6],
146                     learning_rate=data[4],
147                     use_relu=data[7]
148                     )
149                 model.load_model_values(file_location=data[2])
150 
151             else:
152                 try:
153                     if self.dataset == "MNIST":
154                         from school_project.models.gpu.mnist import MNISTModel
                            ↪  as Model
155                     elif self.dataset == "Cat Recognition":
156                         from school_project.models.gpu.cat_recognition import
                            ↪  CatRecognitionModel as Model
157                     elif self.dataset == "XOR":
158                         from school_project.models.gpu.xor import XORModel as
                            ↪  Model
159                     model = Model(
160                         hidden_layers_shape=[int(neuron_count) for neuron_count
                            ↪  in hidden_layers_shape_input],
161                         train_dataset_size=data[6],
162                         learning_rate=data[4],
163                         use_relu=data[7]
164                         )
165                     model.load_model_values(file_location=data[2])
166                 except ImportError as ie:
167                     self.model_status_label.configure(
168                                                 text="Failed to initialise
                                                    ↪  GPU",
169                                                 fg='red'
170                                                 )
171                     raise ImportError
172             return model
```

Which outputs the following for the load model frame when models have been saved for the dataset:



And outputs the following for the load model frame when no models have been saved for the dataset:



3.4 __main__.py module

This module is the entrypoint to the project and loads the main window of the User Interface:

```python
"""The entrypoint of A-level Computer Science NEA Programming Project."""

import os
import sqlite3
import threading
import tkinter as tk
import tkinter.font as tkf
import uuid

import pympler.tracker as tracker

from school_project.frames import (HyperParameterFrame, TrainingFrame,
                                   LoadModelFrame, TestMNISTFrame,
                                   TestCatRecognitionFrame, TestXORFrame)

class SchoolProjectFrame(tk.Frame):
    """Main frame of school project."""
    def __init__(self, root: tk.Tk, width: int, height: int, bg: str) -> None:
        """Initialise school project pages.

        Args:
            root (tk.Tk): the widget object that contains this widget.
            width (int): the pixel width of the frame.
            height (int): the pixel height of the frame.
            bg (str): the hex value or name of the frame's background colour.
        Raises:
            TypeError: if root, width or height are not of the correct type.

        """
        super().__init__(master=root, width=width, height=height, bg=bg)
        self.root = root.title("School Project")
        self.WIDTH = width
        self.HEIGHT = height
        self.BG = bg

        # Setup school project frame variables
        self.hyper_parameter_frame: HyperParameterFrame
        self.training_frame: TrainingFrame
        self.load_model_frame: LoadModelFrame
        self.test_frame: TestMNISTFrame | TestCatRecognitionFrame | TestXORFrame
        self.connection, self.cursor = self.setup_database()
        self.model = None

        # Record if the model should be saved after testing,
        # as only newly created models should be given the option to be saved.
        self.saving_model: bool

        # Setup school project frame widgets
        self.exit_hyper_parameter_frame_button = tk.Button(
                                    master=self,
                                    width=13,
                                    height=1,
                                    font=tkf.Font(size=12),
                                    text="Exit",
                                    command=self.exit_hyper_parameter_frame
                                    )
        self.exit_load_model_frame_button = tk.Button(
                                         master=self,
                                         width=13,
                                         height=1,
                                         font=tkf.Font(size=12),
                                         text="Exit",
```

```
63                                          command=self.exit_load_model_frame
64                                          )
65          self.train_button = tk.Button(master=self,
66                                        width=13,
67                                        height=1,
68                                        font=tkf.Font(size=12),
69                                        text="Train Model",
70                                        command=self.enter_training_frame)
71          self.stop_training_button = tk.Button(
72                                          master=self,
73                                          width=15, height=1,
74                                          font=tkf.Font(size=12),
75                                          text="Stop Training Model",
76                                          command=lambda: self.model.set_running(
77                                                                          value=False
78                                                                          )
79                                          )
80          self.test_created_model_button = tk.Button(
81                                               master=self,
82                                               width=13, height=1,
83                                               font=tkf.Font(size=12),
84                                               text="Test Model",
85                                               command=self.test_created_model
86                                               )
87          self.test_loaded_model_button = tk.Button(
88                                               master=self,
89                                               width=13, height=1,
90                                               font=tkf.Font(size=12),
91                                               text="Test Model",
92                                               command=self.test_loaded_model
93                                               )
94          self.delete_loaded_model_button = tk.Button(
95                                               master=self,
96                                               width=13, height=1,
97                                               font=tkf.Font(size=12),
98                                               text="Delete Model",
99                                               command=self.delete_loaded_model
100                                              )
101         self.save_model_label = tk.Label(
102                                    master=self,
103                                    text="Enter a name for your trained model:",
104                                    bg=self.BG,
105                                    font=('Arial', 15)
106                                    )
107         self.save_model_name_entry = tk.Entry(master=self, width=13)
108         self.save_model_button = tk.Button(master=self,
109                                            width=13,
110                                            height=1,
111                                            font=tkf.Font(size=12),
112                                            text="Save Model",
113                                            command=self.save_model)
114         self.exit_button = tk.Button(master=self,
115                                      width=13, height=1,
116                                      font=tkf.Font(size=12),
117                                      text="Exit",
118                                      command=self.enter_home_frame)
119
120         # Setup home frame
121         self.home_frame = tk.Frame(master=self,
122                                    width=self.WIDTH,
123                                    height=self.HEIGHT,
124                                    bg=self.BG)
```

```
125             self.title_label = tk.Label(
126                             master=self.home_frame,
127                             bg=self.BG,
128                             font=('Arial', 20),
129                             text="A-level Computer Science NEA Programming Project"
130                             )
131             self.about_label = tk.Label(
132                master=self.home_frame,
133                bg=self.BG,
134                font=('Arial', 14),
135                text="An investigation into how Artificial Neural Networks work, " +
136                "the effects of their hyper-parameters and their applications " +
137                "in Image Recognition.\n\n" +
138                " - Max Cotton"
139                )
140             self.model_menu_label = tk.Label(master=self.home_frame,
141                                              bg=self.BG,
142                                              font=('Arial', 14),
143                                              text="Create a new model " +
144                                              "or load a pre-trained model "
145                                              "for one of the following datasets:")
146             self.dataset_option_menu_var = tk.StringVar(master=self.home_frame,
147                                                         value="MNIST")
148             self.dataset_option_menu = tk.OptionMenu(self.home_frame,
149                                                      self.dataset_option_menu_var,
150                                                      "MNIST",
151                                                      "Cat Recognition",
152                                                      "XOR")
153             self.create_model_button = tk.Button(
154                                           master=self.home_frame,
155                                           width=13, height=1,
156                                           font=tkf.Font(size=12),
157                                           text="Create Model",
158                                           command=self.enter_hyper_parameter_frame
159                                           )
160             self.load_model_button = tk.Button(master=self.home_frame,
161                                                width=13, height=1,
162                                                font=tkf.Font(size=12),
163                                                text="Load Model",
164                                                command=self.enter_load_model_frame)
165
166             # Grid home frame widgets
167             self.title_label.grid(row=0, column=0, columnspan=4, pady=(10,0))
168             self.about_label.grid(row=1, column=0, columnspan=4, pady=(10,50))
169             self.model_menu_label.grid(row=2, column=0, columnspan=4)
170             self.dataset_option_menu.grid(row=3, column=0, columnspan=4, pady=30)
171             self.create_model_button.grid(row=4, column=1)
172             self.load_model_button.grid(row=4, column=2)
173
174             self.home_frame.pack()
175
176             # Setup frame attributes
177             self.grid_propagate(flag=False)
178             self.pack_propagate(flag=False)
179
180         @staticmethod
181         def setup_database() -> tuple[sqlite3.Connection, sqlite3.Cursor]:
182             """Create a connection to the pretrained_models database file and
183                setup base table if needed.
184
185                Returns:
186                    a tuple of the database connection and the cursor for it.
```

```
187
188         """
189         connection = sqlite3.connect(
190                                 database='school_project/saved_models.db'
191                                 )
192         cursor = connection.cursor()
193         cursor.execute("""
194         CREATE TABLE IF NOT EXISTS Models
195         (Model_ID INTEGER PRIMARY KEY,
196         Dataset TEXT,
197         File_Location TEXT,
198         Hidden_Layers_Shape TEXT,
199         Learning_Rate FLOAT,
200         Name TEXT,
201         Train_Dataset_Size INTEGER,
202         Use_ReLu INTEGER,
203         UNIQUE (Dataset, Name))
204         """)
205         return (connection, cursor)
206
207     def enter_hyper_parameter_frame(self) -> None:
208         """Unpack home frame and pack hyper-parameter frame."""
209         self.home_frame.pack_forget()
210         self.hyper_parameter_frame = HyperParameterFrame(
211                                     root=self,
212                                     width=self.WIDTH,
213                                     height=self.HEIGHT,
214                                     bg=self.BG,
215                                     dataset=self.dataset_option_menu_var.get()
216                                     )
217         self.hyper_parameter_frame.pack()
218         self.train_button.pack()
219         self.exit_hyper_parameter_frame_button.pack(pady=(10,0))
220
221     def enter_load_model_frame(self) -> None:
222         """Unpack home frame and pack load model frame."""
223         self.home_frame.pack_forget()
224         self.load_model_frame = LoadModelFrame(
225                                     root=self,
226                                     width=self.WIDTH,
227                                     height=self.HEIGHT,
228                                     bg=self.BG,
229                                     connection=self.connection,
230                                     cursor=self.cursor,
231                                     dataset=self.dataset_option_menu_var.get()
232                                     )
233         self.load_model_frame.pack()
234
235         # Don't give option to test loaded model if no models have been saved
236         # for the dataset.
237         if len(self.load_model_frame.model_options) > 0:
238             self.test_loaded_model_button.pack()
239             self.delete_loaded_model_button.pack(pady=(5,0))
240
241         self.exit_load_model_frame_button.pack(pady=(5,0))
242
243     def exit_hyper_parameter_frame(self) -> None:
244         """Unpack hyper-parameter frame and pack home frame."""
245         self.hyper_parameter_frame.pack_forget()
246         self.train_button.pack_forget()
247         self.exit_hyper_parameter_frame_button.pack_forget()
248         self.home_frame.pack()
```

```
249
250         def exit_load_model_frame(self) -> None:
251             """Unpack load model frame and pack home frame."""
252             self.load_model_frame.pack_forget()
253             self.test_loaded_model_button.pack_forget()
254             self.delete_loaded_model_button.pack_forget()
255             self.exit_load_model_frame_button.pack_forget()
256             self.home_frame.pack()
257
258         def enter_training_frame(self) -> None:
259             """Load untrained model from hyper parameter frame,
260                unpack hyper-parameter frame, pack training frame
261                and begin managing the training thread.
262             """
263             try:
264                 self.model = self.hyper_parameter_frame.create_model()
265             except (ValueError, ImportError) as e:
266                 return
267             self.hyper_parameter_frame.pack_forget()
268             self.train_button.pack_forget()
269             self.exit_hyper_parameter_frame_button.pack_forget()
270             self.training_frame = TrainingFrame(
271                     root=self,
272                     width=self.WIDTH,
273                     height=self.HEIGHT,
274                     bg=self.BG,
275                     model=self.model,
276                     epoch_count=self.hyper_parameter_frame.epoch_count_scale.get()
277                     )
278             self.training_frame.pack()
279             self.stop_training_button.pack()
280             self.manage_training(train_thread=self.training_frame.train_thread)
281
282         def manage_training(self, train_thread: threading.Thread) -> None:
283             """Wait for model training thread to finish,
284                then plot training losses on training frame.
285
286             Args:
287                 train_thread (threading.Thread):
288                 the thread running the model's train() method.
289             Raises:
290                 TypeError: if train_thread is not of type threading.Thread.
291
292             """
293             if not train_thread.is_alive():
294                 self.training_frame.training_progress_label.pack_forget()
295                 self.training_frame.plot_losses(model=self.model)
296                 self.stop_training_button.pack_forget()
297                 self.test_created_model_button.pack(pady=(30,0))
298             else:
299                 self.training_frame.training_progress_label.configure(
300                                                     text=self.model.training_progress
301                                                     )
302                 self.after(100, self.manage_training, train_thread)
303
304         def test_created_model(self) -> None:
305             """Unpack training frame, pack test frame for the dataset
306                and begin managing the test thread."""
307             self.saving_model = True
308             self.training_frame.pack_forget()
309             self.test_created_model_button.pack_forget()
310             if self.hyper_parameter_frame.dataset == "MNIST":
```

```
            self.test_frame = TestMNISTFrame(
                                    root=self,
                                    width=self.WIDTH,
                                    height=self.HEIGHT,
                                    bg=self.BG,
                                    use_gpu=self.hyper_parameter_frame.use_gpu,
                                    model=self.model
                                    )
        elif self.hyper_parameter_frame.dataset == "Cat Recognition":
            self.test_frame = TestCatRecognitionFrame(
                                    root=self,
                                    width=self.WIDTH,
                                    height=self.HEIGHT,
                                    bg=self.BG,
                                    use_gpu=self.hyper_parameter_frame.use_gpu,
                                    model=self.model
                                    )
        elif self.hyper_parameter_frame.dataset == "XOR":
            self.test_frame = TestXORFrame(root=self,
                                           width=self.WIDTH,
                                           height=self.HEIGHT,
                                           bg=self.BG,
                                           model=self.model)
        self.test_frame.pack()
        self.manage_testing(test_thread=self.test_frame.test_thread)

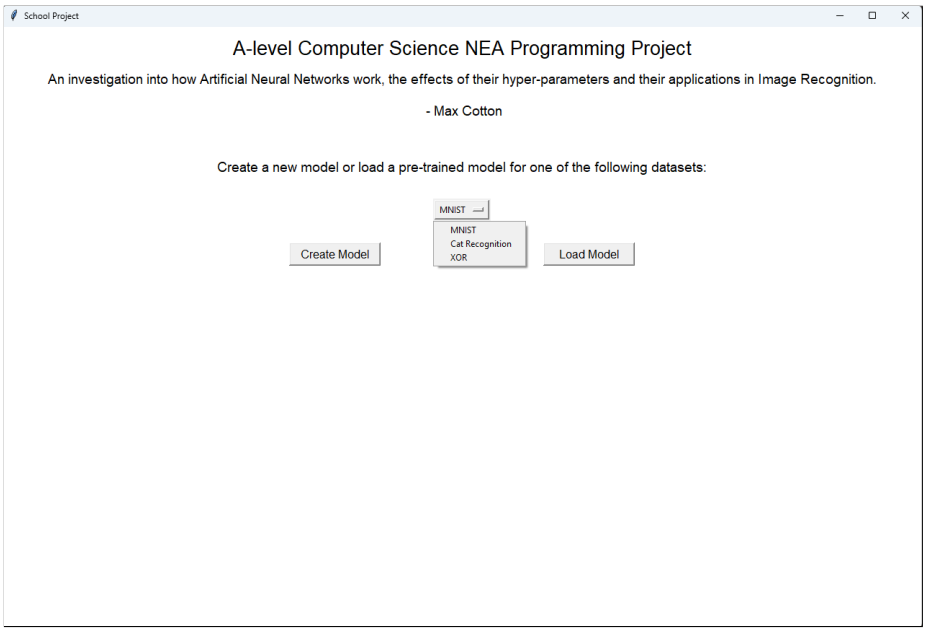
    def test_loaded_model(self) -> None:
        """Load saved model from load model frame, unpack load model frame,
           pack test frame for the dataset and begin managing the test thread."""
        self.saving_model = False
        try:
            self.model = self.load_model_frame.load_model()
        except (ValueError, ImportError) as e:
            return
        self.load_model_frame.pack_forget()
        self.test_loaded_model_button.pack_forget()
        self.delete_loaded_model_button.pack_forget()
        self.exit_load_model_frame_button.pack_forget()
        if self.load_model_frame.dataset == "MNIST":
            self.test_frame = TestMNISTFrame(
                                       root=self,
                                       width=self.WIDTH,
                                       height=self.HEIGHT,
                                       bg=self.BG,
                                       use_gpu=self.load_model_frame.use_gpu,
                                       model=self.model
                                       )
        elif self.load_model_frame.dataset == "Cat Recognition":
            self.test_frame = TestCatRecognitionFrame(
                                       root=self,
                                       width=self.WIDTH,
                                       height=self.HEIGHT,
                                       bg=self.BG,
                                       use_gpu=self.load_model_frame.use_gpu,
                                       model=self.model
                                       )
        elif self.load_model_frame.dataset == "XOR":
            self.test_frame = TestXORFrame(root=self,
                                           width=self.WIDTH,
                                           height=self.HEIGHT,
                                           bg=self.BG,
                                           model=self.model)
```

```
373             self.test_frame.pack()
374             self.manage_testing(test_thread=self.test_frame.test_thread)
375 
376         def manage_testing(self, test_thread: threading.Thread) -> None:
377             """Wait for model test thread to finish,
378                then plot results on test frame.
379 
380             Args:
381                 test_thread (threading.Thread):
382                 the thread running the model's predict() method.
383             Raises:
384                 TypeError: if test_thread is not of type threading.Thread.
385 
386             """
387             if not test_thread.is_alive():
388                 self.test_frame.plot_results(model=self.model)
389                 if self.saving_model:
390                     self.save_model_label.pack(pady=(30,0))
391                     self.save_model_name_entry.pack(pady=10)
392                     self.save_model_button.pack()
393                 self.exit_button.pack(pady=(20,0))
394             else:
395                 self.after(1_000, self.manage_testing, test_thread)
396 
397         def save_model(self) -> None:
398             """Save the model, save the model information to the database, then
399                enter the home frame."""
400             model_name = self.save_model_name_entry.get()
401 
402             # Check if model name is empty
403             if model_name == '':
404                 self.test_frame.model_status_label.configure(
405                                                 text="Model name can not be blank",
406                                                 fg='red'
407                                                 )
408                 return
409 
410             # Check if model name has already been taken
411             dataset = self.dataset_option_menu_var.get().replace(" ", "_")
412             sql = """
413             SELECT Name FROM Models WHERE Dataset=?
414             """
415             parameters = (dataset,)
416             self.cursor.execute(sql, parameters)
417             for saved_model_name in self.cursor.fetchall():
418                 if saved_model_name[0] == model_name:
419                     self.test_frame.model_status_label.configure(
420                                                         text="Model name taken",
421                                                         fg='red'
422                                                         )
423                     return
424 
425             # Save model to random hex file name
426             file_location = f"school_project/saved-models/{uuid.uuid4().hex}.npz"
427             self.model.save_model_values(file_location=file_location)
428 
429             # Save the model information to the database
430             sql = """
431             INSERT INTO Models
432             (Dataset, File_Location, Hidden_Layers_Shape, Learning_Rate, Name,
    ↪  Train_Dataset_Size, Use_ReLu)
433             VALUES (?, ?, ?, ?, ?, ?, ?)
```

```
434             """
435             parameters = (
436                         dataset,
437                         file_location,
438                         self.hyper_parameter_frame.hidden_layers_shape_entry.get(),
439                         self.hyper_parameter_frame.learning_rate_scale.get(),
440                         model_name,
441                         self.hyper_parameter_frame.train_dataset_size_scale.get(),
442                         self.hyper_parameter_frame.use_relu_check_button_var.get()
443                         )
444             self.cursor.execute(sql, parameters)
445             self.connection.commit()
446 
447             self.enter_home_frame()
448 
449         def delete_loaded_model(self) -> None:
450             """Delete saved model file and model data from the database."""
451             dataset = self.dataset_option_menu_var.get().replace(" ", "_")
452             model_name = self.load_model_frame.model_option_menu_var.get()
453 
454             # Delete saved model
455             sql = f"""SELECT File_Location FROM Models WHERE Dataset=? AND Name=?"""
456             parameters = (dataset, model_name)
457             self.cursor.execute(sql, parameters)
458             os.remove(self.cursor.fetchone()[0])
459 
460             # Remove model data from database
461             sql = """DELETE FROM Models WHERE Dataset=? AND Name=?"""
462             parameters = (dataset, model_name)
463             self.cursor.execute(sql, parameters)
464             self.connection.commit()
465 
466             # Reload load model frame with new options
467             self.exit_load_model_frame()
468             self.enter_load_model_frame()
469 
470         def enter_home_frame(self) -> None:
471             """Unpack test frame and pack home frame."""
472             self.model = None  # Free up trained Model from memory
473             self.test_frame.pack_forget()
474             if self.saving_model:
475                 self.save_model_label.pack_forget()
476                 self.save_model_name_entry.delete(0, tk.END)  # Clear entry's text
477                 self.save_model_name_entry.pack_forget()
478                 self.save_model_button.pack_forget()
479             self.exit_button.pack_forget()
480             self.home_frame.pack()
481             summary_tracker.create_summary()  # BUG: Object summary seems to reduce
482                                               # memory leak greatly
483 
484     def main() -> None:
485         """Entrypoint of project."""
486         root = tk.Tk()
487         school_project_frame = SchoolProjectFrame(root=root, width=1280,
488                                                   height=835, bg='white')
489         school_project_frame.pack(side='top', fill='both', expand=True)
490         root.mainloop()
491 
492         # Stop model training when GUI closes
493         if school_project_frame.model is not None:
494             school_project_frame.model.set_running(value=False)
495 
```

```
496 if __name__ == "__main__":
497     summary_tracker = tracker.SummaryTracker()  # Setup object tracker
498     main()
```

Which outputs the following for the home frame:



4 Testing TODO

4.1 Investigation

4.1.1 test_model module

The test_model module is contained within the frames package, and contains tkinter frames for testing the trained Artificial Neural Network models for each dataset. Each frame displays the results of the testing along with a random selection of incorrect and correct predictions.

```
1  """Tkinter frames for testing a saved Artificial Neural Network model."""
2
3  import random
4  import threading
5  import tkinter as tk
6
7  from matplotlib.figure import Figure
8  from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg
9  import numpy as np
10
11 class TestMNISTFrame(tk.Frame):
12     """Frame for Testing MNIST page."""
13     def __init__(self, root: tk.Tk, width: int,
14                  height: int, bg: str,
```

```
                use_gpu: bool, model: object) -> None:
        """Initialise test MNIST frame widgets.

        Args:
            root (tk.Tk): the widget object that contains this widget.
            width (int): the pixel width of the frame.
            height (int): the pixel height of the frame.
            bg (str): the hex value or name of the frame's background colour.
            use_gpu (bool): True or False whether the GPU should be used.
            model (object): The Model object to be tested.
        Raises:
            TypeError: if root, width or height are not of the correct type.

        """
        super().__init__(master=root, width=width, height=height, bg=bg)
        self.root = root
        self.WIDTH = width
        self.HEIGHT = height
        self.BG = bg

        # Setup test MNIST frame variables
        self.use_gpu = use_gpu

         # Setup widgets
        self.model_status_label = tk.Label(master=self,
                                           bg=self.BG,
                                           font=('Arial', 15))
        self.results_label = tk.Label(master=self,
                                      bg=self.BG,
                                      font=('Arial', 15))
        self.correct_prediction_figure = Figure()
        self.correct_prediction_canvas = FigureCanvasTkAgg(
                                         figure=self.correct_prediction_figure,
                                         master=self
                                         )
        self.incorrect_prediction_figure = Figure()
        self.incorrect_prediction_canvas = FigureCanvasTkAgg(
                                      figure=self.incorrect_prediction_figure,
                                      master=self
                                      )

        # Grid widgets
        self.model_status_label.grid(row=0, columnspan=3, pady=(30,0))
        self.results_label.grid(row=1, columnspan=3)
        self.incorrect_prediction_canvas.get_tk_widget().grid(row=2, column=0)
        self.correct_prediction_canvas.get_tk_widget().grid(row=2, column=2)

        # Start test thread
        self.model_status_label.configure(text="Testing trained model",
                                          fg='red')
        self.test_thread = threading.Thread(target=model.test)
        self.test_thread.start()

    def plot_results(self, model: object) -> None:
        """Plot results of Model test.

           Args:
               model (object): the Model object thats been tested.

        """
        self.model_status_label.configure(text="Testing Results:", fg='green')
        if not self.use_gpu:
```

```
77              self.results_label.configure(
78               text="Prediction Correctness: " +
79               f"{round(number=100 - np.mean(np.abs(model.test_prediction.round() -
                 ↪  model.test_outputs)) * 100, ndigits=1)}%\n" +
80               f"Network Shape: " +
81               f"{','.join(model.layers_shape)}\n"
82               )
83
84              test_inputs = np.squeeze(model.test_inputs).T
85              test_outputs = np.squeeze(model.test_outputs).T.tolist()
86              test_prediction = np.squeeze(model.test_prediction).T.tolist()
87
88              # Randomly shuffle order of test_inputs, test_outputs and
                ↪  test_prediciton
89              # whilst maintaining order between them
90              test_data = list(zip(test_inputs,
91                                   test_outputs,
92                                   test_prediction))
93              random.shuffle(test_data)
94              test_inputs, test_outputs, test_prediction = zip(*test_data)
95
96          elif self.use_gpu:
97
98              import cupy as cp
99
100             self.results_label.configure(
101              text="Prediction Correctness: " +
102              f"{round(number=100 -
                 ↪  np.mean(np.abs(cp.asnumpy(model.test_prediction).round() -
                 ↪  cp.asnumpy(model.test_outputs))) * 100, ndigits=1)}%\n" +
103              f"Network Shape: " +
104              f"{','.join(model.layers_shape)}\n"
105              )
106
107             test_inputs = cp.asnumpy(cp.squeeze(model.test_inputs)).T
108             test_outputs = cp.asnumpy(cp.squeeze(model.test_outputs)).T.tolist()
109             test_prediction = cp.squeeze(model.test_prediction).T.tolist()
110
111             # Randomly shuffle order of test_inputs, test_outputs and
                ↪  test_prediciton
112             # whilst maintaining order between them
113             test_data = list(zip(test_inputs,
114                                  test_outputs,
115                                  test_prediction))
116             random.shuffle(test_data)
117             test_inputs, test_outputs, test_prediction = zip(*test_data)
118
119         # Setup incorrect prediction figure
120         self.incorrect_prediction_figure.suptitle("Incorrect predictions:")
121         image_count = 0
122         for i in range(len(test_prediction)):
123             if test_prediction[i].index(max(test_prediction[i])) !=
                ↪  test_outputs[i].index(max(test_outputs[i])):
124                 if image_count == 2:
125                     break
126                 elif image_count == 0:
127                     image = self.incorrect_prediction_figure.add_subplot(121)
128                 elif image_count == 1:
129                     image = self.incorrect_prediction_figure.add_subplot(122)
130                 image.set_title(f"Predicted:
                    ↪  {test_prediction[i].index(max(test_prediction[i]))}\n" +
131                                 f"Should have predicted:
                                    ↪  {test_outputs[i].index(max(test_outputs[i]))}")
```

```
                image.imshow(test_inputs[i].reshape((28,28)))
                image_count += 1

        # Setup correct prediction figure
        self.correct_prediction_figure.suptitle("Correct predictions:")
        image_count = 0
        for i in range(len(test_prediction)):
            if test_prediction[i].index(max(test_prediction[i])) ==
            ↪  test_outputs[i].index(max(test_outputs[i])):
                if image_count == 2:
                    break
                elif image_count == 0:
                    image = self.correct_prediction_figure.add_subplot(121)
                elif image_count == 1:
                    image = self.correct_prediction_figure.add_subplot(122)
                image.set_title(f"Predicted:
                ↪  {test_prediction[i].index(max(test_prediction[i]))}")
                image.imshow(test_inputs[i].reshape((28,28)))
                image_count += 1

class TestCatRecognitionFrame(tk.Frame):
    """Frame for Testing Cat Recognition page."""
    def __init__(self, root: tk.Tk, width: int,
                 height: int, bg: str,
                 use_gpu: bool, model: object) -> None:
        """Initialise test cat recognition frame widgets.

        Args:
            root (tk.Tk): the widget object that contains this widget.
            width (int): the pixel width of the frame.
            height (int): the pixel height of the frame.
            bg (str): the hex value or name of the frame's background colour.
            use_gpu (bool): True or False whether the GPU should be used.
            model (object): the Model object to be tested.
        Raises:
            TypeError: if root, width or height are not of the correct type.

        """
        super().__init__(master=root, width=width, height=height, bg=bg)
        self.root = root
        self.WIDTH = width
        self.HEIGHT = height
        self.BG = bg

        # Setup image recognition frame variables
        self.use_gpu = use_gpu

        # Setup widgets
        self.model_status_label = tk.Label(master=self,
                                           bg=self.BG,
                                           font=('Arial', 15))
        self.results_label = tk.Label(master=self,
                                      bg=self.BG,
                                      font=('Arial', 15))
        self.correct_prediction_figure = Figure()
        self.correct_prediction_canvas = FigureCanvasTkAgg(
                                        figure=self.correct_prediction_figure,
                                        master=self
                                        )
        self.incorrect_prediction_figure = Figure()
        self.incorrect_prediction_canvas = FigureCanvasTkAgg(
                                      figure=self.incorrect_prediction_figure,
```

```
                                        master=self
                                        )

        # Grid widgets
        self.model_status_label.grid(row=0, columnspan=3, pady=(30,0))
        self.results_label.grid(row=1, columnspan=3)
        self.incorrect_prediction_canvas.get_tk_widget().grid(row=2, column=0)
        self.correct_prediction_canvas.get_tk_widget().grid(row=2, column=2)

        # Start test thread
        self.model_status_label.configure(text="Testing trained model...",
                                          fg='red')
        self.test_thread = threading.Thread(target=model.test)
        self.test_thread.start()

    def plot_results(self, model: object) -> None:
        """Plot results of Model test

           Args:
               model (object): the Model object thats been tested.

        """
        self.model_status_label.configure(text="Testing Results:", fg='green')
        if not self.use_gpu:
            self.results_label.configure(
             text="Prediction Correctness: " +
             f"{round(number=100 - np.mean(np.abs(model.test_prediction.round() -
             ↪  model.test_outputs)) * 100, ndigits=1)}%\n" +
             f"Network Shape: " +
             f"{','.join(model.layers_shape)}\n"
             )

            # Randomly shuffle order of test_inputs, test_outputs and
            ↪  test_prediciton
            # whilst maintaining order between them
            test_data = list(zip(model.test_inputs.T,
                                 np.squeeze(model.test_outputs).T.tolist(),

                                 ↪  np.squeeze(model.test_prediction.round()).T.tolist()))
            random.shuffle(test_data)
            (test_inputs,
             test_outputs,
             test_prediction) = map(lambda arr: np.array(arr).T,
                                    zip(*test_data))

        elif self.use_gpu:

            import cupy as cp

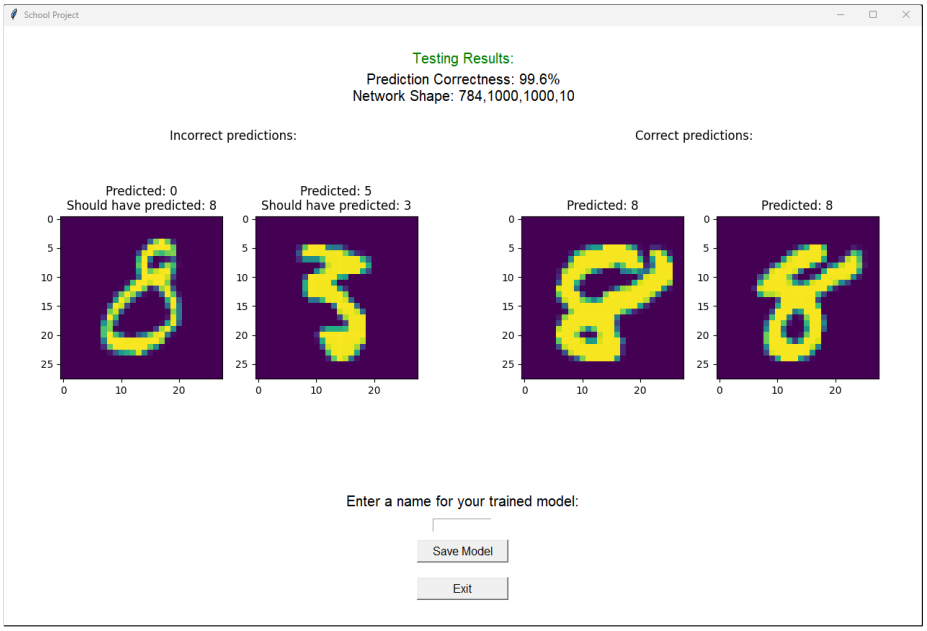
            self.results_label.configure(
             text="Prediction Correctness: " +
             f"{round(number=100 -
             ↪  np.mean(np.abs(cp.asnumpy(model.test_prediction).round() -
             ↪  cp.asnumpy(model.test_outputs))) * 100, ndigits=1)}%\n" +
             f"Network Shape: " +
             f"{','.join(model.layers_shape)}\n"
             )

            # Randomly shuffle order of test_inputs, test_outputs and
            ↪  test_prediciton
            # whilst maintaining order between them
            test_data = list(zip(cp.asnumpy(model.test_inputs).T,
```

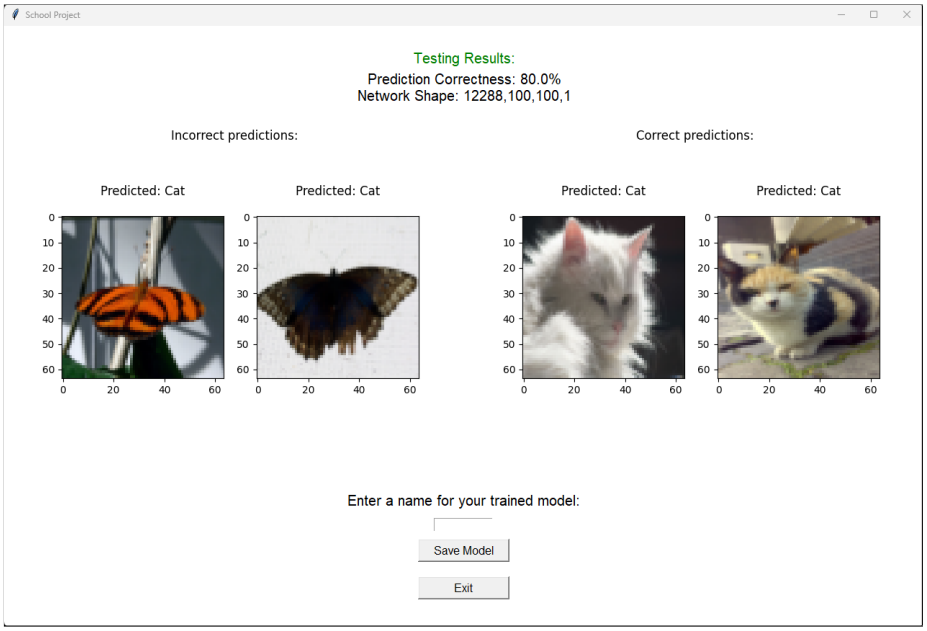
```
248
                                    ↪  cp.asnumpy(cp.squeeze(model.test_outputs)).T.tolist(),
249
                                    ↪  cp.asnumpy(cp.squeeze(model.test_prediction)).round().T.tolist()))
250             random.shuffle(test_data)
251             (test_inputs,
252              test_outputs,
253              test_prediction) = map(lambda arr: np.array(arr).T,
254                                     zip(*test_data))
255
256         # Setup incorrect prediction figure
257         self.incorrect_prediction_figure.suptitle("Incorrect predictions:")
258         image_count = 0
259         for i in range(len(test_prediction)):
260             if test_prediction[i] != test_outputs[i]:
261                 if image_count == 2:
262                     break
263                 elif image_count == 0:
264                     image = self.incorrect_prediction_figure.add_subplot(121)
265                 elif image_count == 1:
266                     image = self.incorrect_prediction_figure.add_subplot(122)
267                 image.set_title(f"Predicted: {'Cat' if test_prediction[i] == 1
                    ↪  else 'Not a cat'}\n")
268                 image.imshow(test_inputs[:,i].reshape((64,64,3)))
269                 image_count += 1
270
271         # Setup correct prediction figure
272         self.correct_prediction_figure.suptitle("Correct predictions:")
273         image_count = 0
274         for i in range(len(test_prediction)):
275             if test_prediction[i] == test_outputs[i]:
276                 if image_count == 2:
277                     break
278                 elif image_count == 0:
279                     image = self.correct_prediction_figure.add_subplot(121)
280                 elif image_count == 1:
281                     image = self.correct_prediction_figure.add_subplot(122)
282                 image.set_title(f"Predicted: {'Cat' if test_prediction[i] == 1
                    ↪  else 'Not a cat'}\n")
283                 image.imshow(test_inputs[:,i].reshape((64,64,3)))
284                 image_count += 1
285
286 class TestXORFrame(tk.Frame):
287     """Frame for Testing XOR page."""
288     def __init__(self, root: tk.Tk, width: int,
289                  height: int, bg: str, model: object) -> None:
290         """Initialise test XOR frame widgets.
291
292         Args:
293             root (tk.Tk): the widget object that contains this widget.
294             width (int): the pixel width of the frame.
295             height (int): the pixel height of the frame.
296             bg (str): the hex value or name of the frame's background colour.
297             model (object): the Model object to be tested.
298         Raises:
299             TypeError: if root, width or height are not of the correct type.
300
301         """
302         super().__init__(master=root, width=width, height=height, bg=bg)
303         self.root = root
304         self.WIDTH = width
305         self.HEIGHT = height
```

```
306         self.BG = bg
307 
308         # Setup widgets
309         self.model_status_label = tk.Label(master=self,
310                                            bg=self.BG,
311                                            font=('Arial', 15))
312         self.results_label = tk.Label(master=self,
313                                       bg=self.BG,
314                                       font=('Arial', 20))
315 
316         # Pack widgets
317         self.model_status_label.pack(pady=(30,0))
318 
319         # Start test thread
320         self.model_status_label.configure(text="Testing trained model...",
321                                           fg='red')
322         self.test_thread = threading.Thread(target=model.test)
323         self.test_thread.start()
324 
325     def plot_results(self, model: object):
326         """Plot results of Model test.
327 
328            Args:
329                model (object): the Model object thats been tested.
330 
331         """
332         self.model_status_label.configure(text="Testing Results:", fg='green')
333         results = (
334              f"Prediction Accuracy: " +
335              f"{round(number=model.test_prediction_accuracy, ndigits=1)}%\n" +
336              f"Network Shape: " +
337              f"{','.join(model.layers_shape)}\n"
338              )
339         for i in range(model.test_inputs.shape[1]):
340             results += f"{model.test_inputs[0][i]},"
341             results += f"{model.test_inputs[1][i]} = "
342             if np.squeeze(model.test_prediction)[i] >= 0.5:
343                 results += "1\n"
344             else:
345                 results += "0\n"
346         self.results_label.configure(text=results)
347         self.results_label.pack()
```

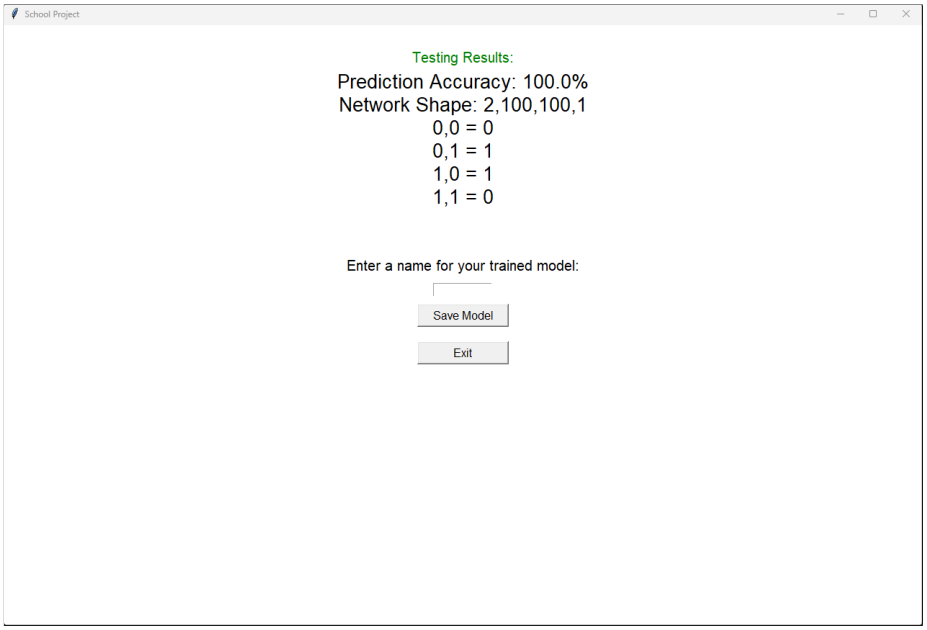
Which outputs the following for the MNIST dataset:



And outputs the following for the Cat Recognition dataset:



And outputs the following for the XOR dataset:



4.1.2 Effects of Hyper-Parameters

Learning Rate Analysis

The following code trains and tests models on the XOR dataset with varying learning rates, and then plots graphs of Loss Value against Epoch Count.

[17]:
```
import os

import matplotlib.pyplot as plt
import numpy as np

from school_project.models.cpu.xor import XORModel as Model

# Change to root directory of project
os.chdir(os.getcwd())

# Set width and height of figure
plt.rcParams["figure.figsize"] = [5, 10]

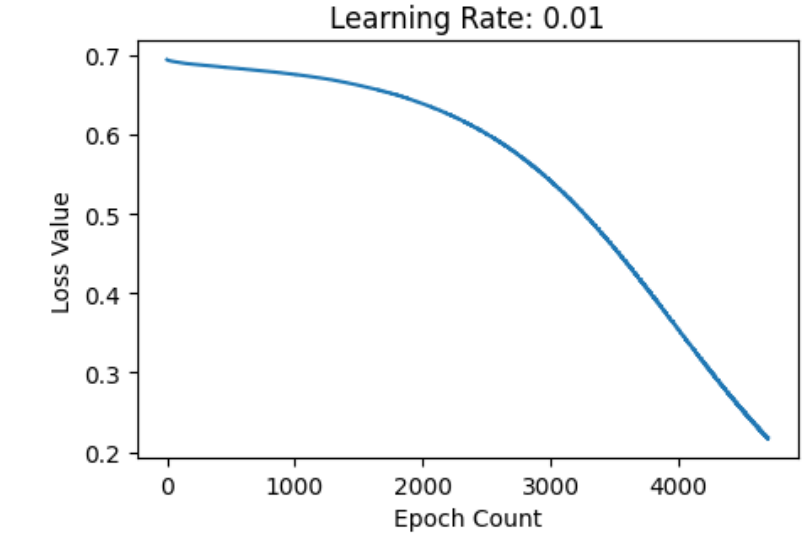
learning_rates = [0.01, 0.1, 1.0]

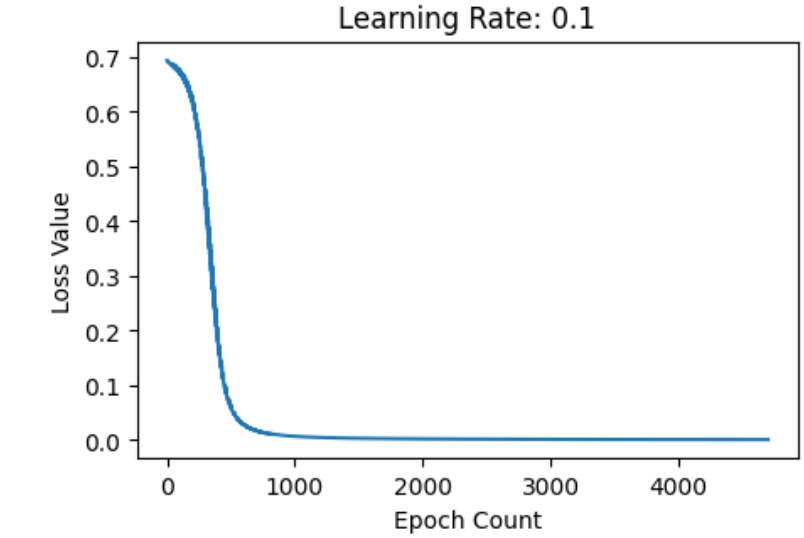
figure, axis = plt.subplots(nrows=len(learning_rates), ncols=1)

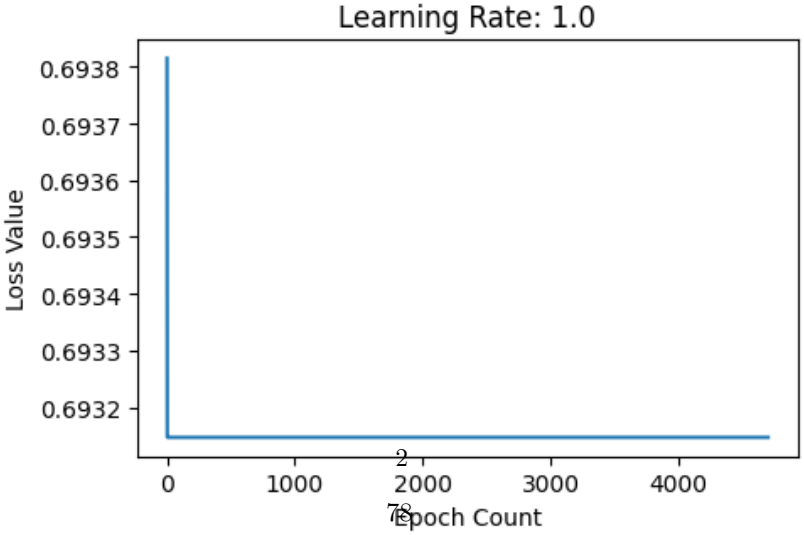
for count, learning_rate in enumerate(learning_rates):
    model = Model(hidden_layers_shape=[100, 100],
                  train_dataset_size=4,
                  learning_rate=learning_rate,
                  use_relu=True)
    model.create_model_values()
    model.train(epoch_count=4_700)
    model.test()

    axis[count].set_title(f"Learning Rate: {model.learning_rate}")
    axis[count].set_xlabel("Epoch Count")
    axis[count].set_ylabel("Loss Value")
    axis[count].plot(np.squeeze(model.train_losses))

plt.tight_layout()
plt.show()
```


Learning Rate: 0.01
Loss Value
0.7
0.6
0.5
0.4
0.3
0.2
0
1000
2000
3000
4000
Epoch Count


Learning Rate: 0.1
Loss Value
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1000
2000
3000
4000
Epoch Count


Learning Rate: 1.0
Loss Value
0.6938
0.6937
0.6936
0.6935
0.6934
0.6933
0.6932
0
1000
2000
3000
4000
Epoch Count

As shown above, if the learning rate is set to too low of a value (0.01 in this case) the model will take more epochs to reduce the loss value, and may even get stuck in unwanted local minimums. If the learning rate is set to an optimal value (0.1 in this case) the model reduces the loss value efficiently and to a small enough value for predictions. On the other hand, if the learning rate is set to too high of a value (1.0 in this case) the model may learn too quickly and even 'jump over' minima, causing the loss value to stop reducing.

Epoch Count Analysis

The following code trains models on the Cat Recognition dataset and tests the model at regular Epoch Count intervals, and then plots graphs of Test Prediction Accuracy against Epoch Count and Training Time against Epoch Count.

[6]:
```
from IPython.display import clear_output, display
import os

import matplotlib.pyplot as plt
import numpy as np

from school_project.models.gpu.cat_recognition import CatRecognitionModel as␣
 ↪Model

# Change to root directory of project
os.chdir(os.getcwd())

# Set width and height of figure
plt.rcParams["figure.figsize"] = [10, 5]

# Generate list of Epoch Counts from 1 to 5000, incremented by 500
epoch_count_interval = 500
epoch_counts = np.array(list(range(0, 5_000, epoch_count_interval)))

test_prediction_accuracies = np.array([])
training_times = np.array([])

# Create model object
model = Model(hidden_layers_shape=[100, 100],
              train_dataset_size=209,
              learning_rate=0.1,
              use_relu=True)
model.create_model_values()

for index, epoch_count in enumerate(epoch_counts):
    clear_output(wait=True)
    display(f"Progress: {round(number=index/len(epoch_counts) * 100,␣
 ↪ndigits=2)}%")
```

```
    model.train(epoch_count=epoch_count_interval)
    model.test()

    test_prediction_accuracies = np.append(test_prediction_accuracies,
                                           model.test_prediction_accuracy)

    # Add training times cumulatively
    if len(training_times) != 0:
        training_times = np.append(training_times,
                                   training_times[-1] + model.training_time)
    else:
        training_times = np.append(training_times,
                                   model.training_time)

clear_output(wait=True)
display("Progress: Complete")

figure, axis = plt.subplots(nrows=1, ncols=2)

axis[0].set_xlabel("Epoch Count")
axis[0].set_ylabel("Test Prediction Accuracy (%)")

# Plot regression line
axis[0].plot(epoch_counts, test_prediction_accuracies, marker='x')

# Determine gradient and y-intercept of training times regression line
m, c = np.polyfit(epoch_counts, training_times, deg=1)
print(f"Training Times Regression Line Gradient: {round(number=m, ndigits=2)}")

axis[1].set_xlabel("Epoch Count")
axis[1].set_ylabel("Training Time (s)")

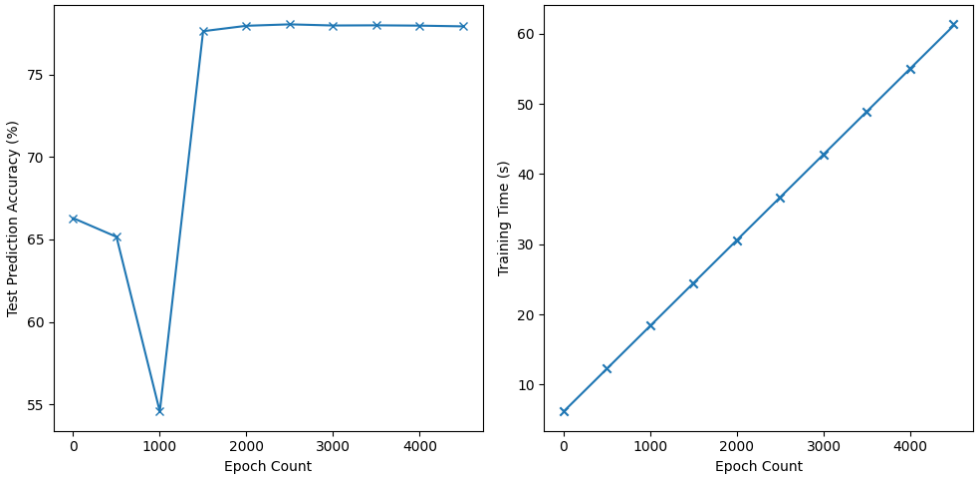
# Plot scatter graph of epoch counts and training times
axis[1].scatter(epoch_counts, training_times, marker='x')

# Plot regression line
axis[1].plot(epoch_counts, m * epoch_counts + c)

plt.tight_layout()
plt.show()
```

```
'Progress: Complete'
```

```
Training Times Regression Line Gradient: 0.01
```



As shown above, as the epoch count increases so does both the test prediction accuracy and the training time taken.

Train Dataset Size Analysis

The following code trains and tests models on the Cat Recognition dataset with varying Train Dataset Sizes, and then plots graphs of Test Prediction Accuracy against Train Dataset Size and Training Time against Train Dataset Size.

[1]:
```
from IPython.display import clear_output, display
import os

import matplotlib.pyplot as plt
import numpy as np

from school_project.models.gpu.cat_recognition import CatRecognitionModel as␣
↪Model

# Change to root directory of project
os.chdir(os.getcwd())

# Set width and height of figure
plt.rcParams["figure.figsize"] = [10, 5]

# Generate list of train dataset sizes from 1 to 210, incremented by 13
train_dataset_sizes = np.array(list(range(1, 210, 13)))

test_prediction_accuracies = np.array([])
training_times = np.array([])

for index, train_dataset_size in enumerate(train_dataset_sizes):
    clear_output(wait=True)
    display(f"Progress: {round(number=index/len(train_dataset_sizes) * 100,␣
↪ndigits=2)}%")

    model = Model(hidden_layers_shape=[100, 100],
                  train_dataset_size=train_dataset_size,
                  learning_rate=0.1,
                  use_relu=True)
    model.create_model_values()
    model.train(epoch_count=2_000)
    model.test()
```

```
    test_prediction_accuracies = np.append(test_prediction_accuracies,
                                           model.test_prediction_accuracy)
    training_times = np.append(training_times,
                               model.training_time)

clear_output(wait=True)
display("Progress: Complete")

figure, axis = plt.subplots(nrows=1, ncols=2)

# Determine gradient and y-intercept of prediction accuracies regression line
m, c = np.polyfit(train_dataset_sizes, test_prediction_accuracies, deg=1)
print(f"Test Prediction Accuracies Regression Line Gradient: {round(number=m,␣
 ↪ndigits=2)}")

axis[0].set_xlabel("Train Dataset Size")
axis[0].set_ylabel("Test Prediction Accuracy (%)")

# Plot scatter graph of train dataset sizes and prediction accuracies
axis[0].scatter(train_dataset_sizes, test_prediction_accuracies, marker='x')

axis[0].plot(train_dataset_sizes, m * train_dataset_sizes + c)

# Determine gradient and y-intercept of training times regression line
m, c = np.polyfit(train_dataset_sizes, training_times, deg=1)
print(f"Training Times Regression Line Gradient: {round(number=m, ndigits=2)}")

axis[1].set_xlabel("Train Dataset Size")
axis[1].set_ylabel("Training Time (s)")

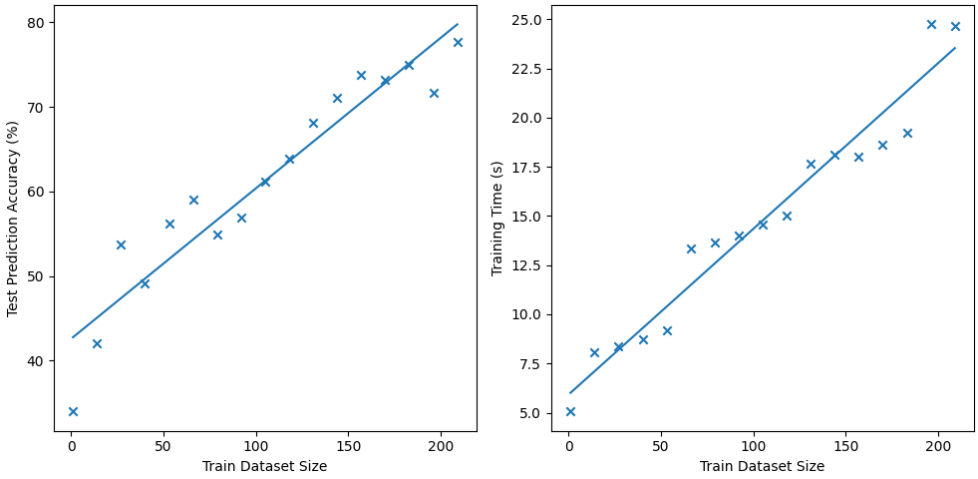
# Plot scatter graph of train dataset sizes and training times
axis[1].scatter(train_dataset_sizes, training_times, marker='x')

# Plot regression line
axis[1].plot(train_dataset_sizes, m * train_dataset_sizes + c)

plt.tight_layout()
plt.show()
```

```
'Progress: Complete'
```

```
Test Prediction Accuracies Regression Line Gradient: 0.18
Training Times Regression Line Gradient: 0.08
```



As shown above, as the train dataset size increases do does both the prediction accuracy and the training time taken. Therefore, I can predict that if I increase the size of the Cat Recognition dataset, I could improve the accuracy of the model trained on the dataset.

Layer Count Analysis

The following code trains and tests models on the Cat Recognition dataset with a varying number of layers, and then plots graphs of Test Prediction Accuracy against Layer Count and Training Time against Layer Count.

[1]:
```
from IPython.display import clear_output, display
import os

import matplotlib.pyplot as plt
import numpy as np

from school_project.models.gpu.cat_recognition import CatRecognitionModel as␣
 ↪Model

# Change to root directory of project
os.chdir(os.getcwd())

# Set width and height of figure
plt.rcParams["figure.figsize"] = [10, 5]

layer_counts = np.array(list(range(1, 5)))
neuron_count = 100
test_prediction_accuracies = np.array([])
training_times = np.array([])

for index, layer_count in enumerate(layer_counts):
    clear_output(wait=True)
    display(f"Progress: {round(number=index/len(layer_counts) * 100,␣
 ↪ndigits=2)}%")

    model = Model(
           hidden_layers_shape=[neuron_count for layer in range(layer_count)],
           train_dataset_size=209,
           learning_rate=0.1,
           use_relu=True
           )
    model.create_model_values()
    model.train(epoch_count=3_500)
    model.test()
```

```
    test_prediction_accuracies = np.append(test_prediction_accuracies,
                                           model.test_prediction_accuracy)
    training_times = np.append(training_times,
                               model.training_time)

clear_output(wait=True)
display("Progress: Complete")

figure, axis = plt.subplots(nrows=1, ncols=2)

axis[0].set_xlabel("Layer Count")
axis[0].set_ylabel("Test Prediction Accuracy (%)")

axis[0].plot(layer_counts, test_prediction_accuracies, marker='x')

# Determine gradient and y-intercept of training times regression line
m, c = np.polyfit(layer_counts, training_times, deg=1)
print(f"Training Times Regression Line Gradient: {round(number=m, ndigits=2)}")

axis[1].set_xlabel("Layer Count")
axis[1].set_ylabel("Training Time (s)")

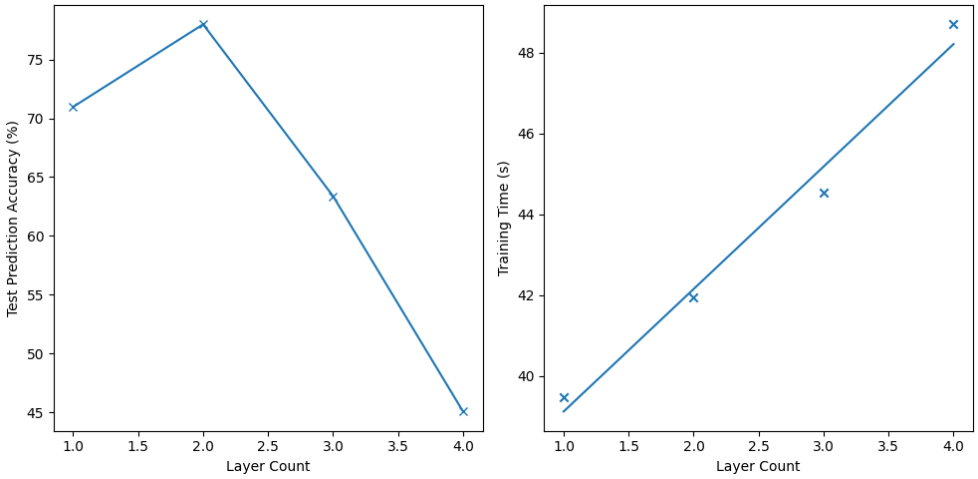
# Plot scatter graph of layer Counts and training times
axis[1].scatter(layer_counts, training_times, marker='x')

# Plot regression line
axis[1].plot(layer_counts, m * layer_counts + c)

plt.tight_layout()
plt.show()
```

```
'Progress: Complete'
```

```
Training Times Regression Line Gradient: 3.03
```



As shown above, as the layer count increases so does the training time taken and the test prediction accuracy at first. However, as the layer count continued to increase the prediction accuracy began to drop greatly (after 2 layers in this case). This is most likely due to the model overfitting and learning the training dataset too closely, causing it to fail on the new inputs of the test dataset.

Neuron Count Analysis

The following code trains and tests models on the Cat Recognition dataset with a varying number of neurons in each layer, and then plots graphs of Test Prediction Accuracy against Neuron Count and Training Time against Neuron Count.

[1]:
```
from IPython.display import clear_output, display
import os

import matplotlib.pyplot as plt
import numpy as np

from school_project.models.gpu.cat_recognition import CatRecognitionModel as␣
 ↪Model

# Change to root directory of project
os.chdir(os.getcwd())

# Set width and height of figure
plt.rcParams["figure.figsize"] = [10, 5]

# Generate list of neuron counts from 1 to 501, incremented by 100
neuron_counts = np.array(list(range(1, 501, 100)))

layer_count = 2
test_prediction_accuracies = np.array([])
training_times = np.array([])

for index, neuron_count in enumerate(neuron_counts):
    clear_output(wait=True)
    display(f"Progress: {round(number=index/len(neuron_counts) * 100,␣
 ↪ndigits=2)}%")

    model = Model(
           hidden_layers_shape=[neuron_count for layer in range(layer_count)],
           train_dataset_size=209,
           learning_rate=0.1,
           use_relu=True
           )
    model.create_model_values()
```

```
    model.train(epoch_count=3_500)
    model.test()

    test_prediction_accuracies = np.append(test_prediction_accuracies,
                                           model.test_prediction_accuracy)
    training_times = np.append(training_times,
                               model.training_time)

clear_output(wait=True)
display("Progress: Complete")

figure, axis = plt.subplots(nrows=1, ncols=2)

axis[0].set_xlabel("Neuron Count")
axis[0].set_ylabel("Test Prediction Accuracy (%)")

axis[0].plot(neuron_counts, test_prediction_accuracies, marker='x')

# Determine gradient and y-intercept of training times regression line
m, c = np.polyfit(neuron_counts, training_times, deg=1)
print(f"Training Times Regression Line Gradient: {round(number=m, ndigits=2)}")

axis[1].set_xlabel("Neuron Count")
axis[1].set_ylabel("Training Time (s)")

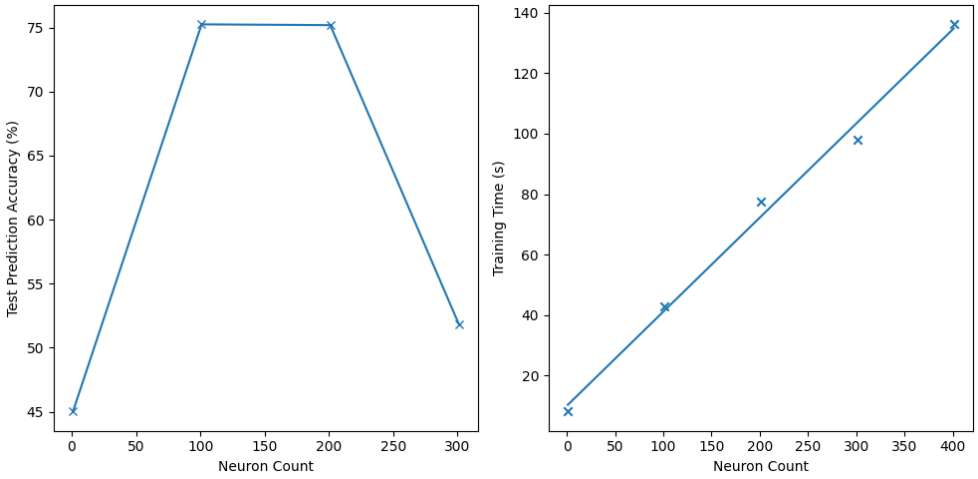
# Plot scatter graph of neuron counts and training times
axis[1].scatter(neuron_counts, training_times, marker='x')

# Plot regression line
axis[1].plot(neuron_counts, m * neuron_counts + c)

plt.tight_layout()
plt.show()
```

```
'Progress: Complete'
```

```
Training Times Regression Line Gradient: 0.31
```



As shown above, as the neuron count of each layer increases so does the training time taken and the test prediction accuracy at first. However, as the neuron count continued to increase the prediction accuracy began to drop greatly (after 200 neurons in this case). This is most likely due to the model overfitting and learning the training dataset too closely, causing it to fail on the new inputs of the test dataset.

ReLu Analysis

The following code trains and tests models on the XOR dataset using ReLu and then not using ReLu, and then plots graphs of Loss Value against Epoch Count.

[1]:
```
import os

import matplotlib.pyplot as plt
import numpy as np

from school_project.models.cpu.xor import XORModel as Model

# Change to root directory of project
os.chdir(os.getcwd())

# Set width and height of figure
plt.rcParams["figure.figsize"] = [10, 5]

figure, axis = plt.subplots(nrows=1, ncols=2)

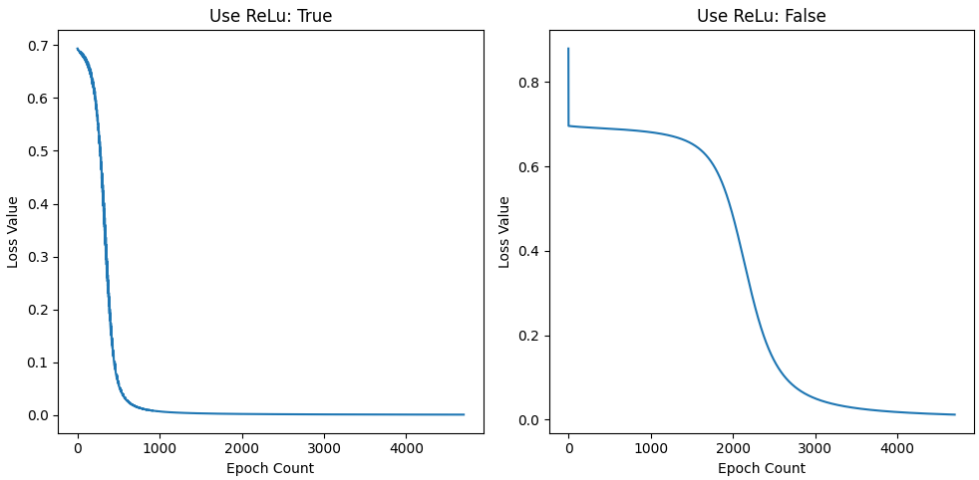
model = Model(hidden_layers_shape=[100, 100],
                train_dataset_size=4,
                learning_rate=0.1,
                use_relu=True)
model.create_model_values()
model.train(epoch_count=4_700)
model.test()

axis[0].set_title("Use ReLu: True")
axis[0].set_xlabel("Epoch Count")
axis[0].set_ylabel("Loss Value")
axis[0].plot(np.squeeze(model.train_losses))

model = Model(hidden_layers_shape=[100, 100],
                train_dataset_size=4,
                learning_rate=0.1,
                use_relu=False)
model.create_model_values()
model.train(epoch_count=4_700)
model.test()
```

```
axis[1].set_title("Use ReLu: False")
axis[1].set_xlabel("Epoch Count")
axis[1].set_ylabel("Loss Value")
axis[1].plot(np.squeeze(model.train_losses))

plt.tight_layout()
plt.show()
```



As shown above, when using the ReLu transfer function along with the Sigmoid transfer function, the loss value decreases at a much faster rate than without. The model without the ReLu transfer function does reach the same accuracy but takes far more training epochs to do so.

CPU vs GPU Analysis

The following code trains a model on the XOR dataset using the CPU and then using the GPU to train, and then outputs the training time taken.

[2]:
```
import os

from school_project.models.cpu.cat_recognition import CatRecognitionModel as␣
 ↪CPUModel
from school_project.models.gpu.cat_recognition import CatRecognitionModel as␣
 ↪GPUModel

# Change to root directory of project
os.chdir(os.getcwd())

model = CPUModel(hidden_layers_shape=[100, 100],
                 train_dataset_size=209,
                 learning_rate=0.1,
                 use_relu=True)
model.create_model_values()
model.train(epoch_count=3_500)

print(f"CPU Training Time: {model.training_time}")

model = GPUModel(hidden_layers_shape=[100, 100],
                 train_dataset_size=209,
                 learning_rate=0.1,
                 use_relu=True)
model.create_model_values()
model.train(epoch_count=3_500)

print(f"GPU Training Time: {model.training_time}")
```

```
CPU Training Time: 160.45
GPU Training Time: 42.58
```

As shown above, the GPU is approximately three times faster at training the model than the CPU, showing how beneficial it is to utilise the parallel computations of the GPU

4.2 Manual Testing

4.2.1 Input Validation Testing TODO

4.3 Automated Testing

4.3.1 Unit Tests

Within the test package, I have written the following unit tests for the utils subpackage of both the cpu and gpu subpackage of the models package. Similarly to the code for the cpu and gpu subpackage, it is only worth showing the code for the cpu version as both are very similar in functionality.

- test_model.py module:

```
"""Unit tests for model module."""

import unittest

# Test XOR implementation of Model for its lesser computation time
from school_project.models.cpu.xor import XORModel

class TestModel(unittest.TestCase):
    """Unit tests for model module."""
    def __init__(self, *args, **kwargs) -> None:
        """Initialise unit tests and inputs."""
        super(TestModel, self).__init__(*args, **kwargs)

    def test_train_dataset_size(self) -> None:
        """Test the size of training dataset to be value chosen."""
        train_dataset_size = 4
        model = XORModel(hidden_layers_shape = [100, 100],
                         train_dataset_size = train_dataset_size,
                         learning_rate = 0.1,
                         use_relu = True)
        model.create_model_values()
        model.train(epoch_count=1)
        self.assertEqual(first=model.layers.head.input.shape[1],
                         second=train_dataset_size)

    def test_network_shape(self) -> None:
        """Test the neuron count of each layer to match the set shape of
↪   the
           network."""
        layers_shape = [2, 100, 100, 1]
        model = XORModel(hidden_layers_shape = [100, 100],
                         train_dataset_size = 4,
                         learning_rate = 0.1,
                         use_relu = True)
        model.create_model_values()
        model.train(epoch_count=1)
        for count, layer in enumerate(model.layers):
            self.assertEqual(first=layer.input_neuron_count,
                             second=layers_shape[count])

    def test_learning_rates(self) -> None:
        """Test learning rate of each layer to be the same."""
        learning_rate = 0.1
        model = XORModel(hidden_layers_shape = [100, 100],
                         train_dataset_size = 4,
                         learning_rate = learning_rate,
```

```
                        use_relu = True)
        model.create_model_values()
        model.train(epoch_count=1)
        for layer in model.layers:
            self.assertEqual(first=layer.learning_rate,
            ↪  second=learning_rate)

    def test_relu_model_transfer_types(self) -> None:
        """Test transfer type of each layer to match whats set."""
        transfer_types = ['relu', 'relu', 'sigmoid']
        model = XORModel(hidden_layers_shape = [100, 100],
                         train_dataset_size = 4,
                         learning_rate = 0.1,
                         use_relu = True)
        model.create_model_values()
        model.train(epoch_count=1)
        for count, layer in enumerate(model.layers):
            self.assertEqual(first=layer.transfer_type,
                             second=transfer_types[count])

    def test_sigmoid_model_transfer_types(self) -> None:
        """Test transfer type of each layer to match whats set."""
        transfer_types = ['sigmoid', 'sigmoid', 'sigmoid']
        model = XORModel(hidden_layers_shape = [100, 100],
                             train_dataset_size = 4,
                             learning_rate = 0.1,
                             use_relu = False)
        model.create_model_values()
        model.train(epoch_count=1)
        for count, layer in enumerate(model.layers):
            self.assertEqual(first=layer.transfer_type,
                             second=transfer_types[count])

    def test_weight_matrice_shapes(self) -> None:
        """Test that each layer's weight matrix has the same number of
    ↪  columns
        as the layer's input matrix's number of rows, for the matrice
        multiplication."""
        model = XORModel(hidden_layers_shape = [100, 100],
                         train_dataset_size = 4,
                         learning_rate = 0.1,
                         use_relu = True)
        model.create_model_values()
        model.train(epoch_count=1)
        for layer in model.layers:
            self.assertEqual(first=layer.weights.shape[1],
                             second=layer.input.shape[0])

    def test_bias_matrice_shapes(self) -> None:
        """Test that each layer's bias matrix has the same number of rows
        as the result of the layer's weights and input multiplication, for
        element-wise addition of the biases."""
        model = XORModel(hidden_layers_shape = [100, 100],
                         train_dataset_size = 4,
                         learning_rate = 0.1,
                         use_relu = True)
        model.create_model_values()
        model.train(epoch_count=1)
        for layer in model.layers:
            self.assertEqual(first=layer.biases.shape[0],
                             second=layer.weights.shape[0])

```

```
    def test_layer_output_shapes(self) -> None:
        """Test the shape of each layer's activation function's output."""
        model = XORModel(hidden_layers_shape = [100, 100],
                         train_dataset_size = 4,
                         learning_rate = 0.1,
                         use_relu = True)
        model.create_model_values()
        model.train(epoch_count=1)
        for layer in model.layers:
            self.assertEqual(
                         first=(layer.weights.shape[0],
                         ↪  layer.input.shape[1]),
                         second=layer.output.shape
                         )

if __name__ == '__main__':
    unittest.main()
```

- test_tools.py module:

```
"""Unit tests for tools module."""

import unittest

from school_project.models.cpu.utils import tools

class TestTools(unittest.TestCase):
    """Unit tests for the tools module."""
    def __init__(self, *args, **kwargs) -> None:
        """Initialise unit tests."""
        super(TestTools, self).__init__(*args, **kwargs)

    def test_relu(self) -> None:
        """Test ReLu output range to be >=0."""
        test_inputs = [-100, 0, 100]
        for test_input in test_inputs:
            output = tools.relu(z=test_input)
            self.assertGreaterEqual(a=output, b=0)

    def test_sigmoid(self) -> None:
        """Test sigmoid output range to be within 0-1."""
        test_inputs = [-100, 0, 100]
        for test_input in test_inputs:
            output = tools.sigmoid(z=test_input)
            self.assertTrue(expr=output >= 0 and output <= 1)

if __name__ == '__main__':
    unittest.main()
```

```
"""Unit tests for tools module."""

import unittest

from school_project.models.cpu.utils import tools

class TestTools(unittest.TestCase):
    """Unit tests for the tools module."""
    def __init__(self, *args, **kwargs) -> None:
        """Initialise unit tests."""
        super(TestTools, self).__init__(*args, **kwargs)

    def test_relu(self) -> None:
        """Test ReLu output range to be >=0."""
        test_inputs = [-100, 0, 100]
        for test_input in test_inputs:
            output = tools.relu(z=test_input)
            self.assertGreaterEqual(a=output, b=0)

    def test_sigmoid(self) -> None:
        """Test sigmoid output range to be within 0-1."""
        test_inputs = [-100, 0, 100]
        for test_input in test_inputs:
            output = tools.sigmoid(z=test_input)
            self.assertTrue(expr=output >= 0 and output <= 1)

if __name__ == '__main__':
    unittest.main()
```

4.3.2 GitHub Automated Testing

With the following configuration programmed in the .github/workflows/tests.yml file, the unit tests are run automatically on GitHub servers after each commit that is pushed to GitHub, and the status of the tests (either passing or failing) can be viewed on the repository's page. This automatic testing allows for a faster workflow and allows me to identify which changes (commits) cause issues within the code, allowing for easier maintenance of the project.

```yaml
name: Tests

on:
  push:
    branches: [ "main" ]
  pull_request:
    branches: [ "main" ]

permissions:
  contents: read

jobs:
  build:

    runs-on: ubuntu-latest

    steps:
    - uses: actions/checkout@v3
    - name: Set up Python 3.10
      uses: actions/setup-python@v3
      with:
        python-version: "3.10"
    - name: Install dependencies
      run: |
        python -m pip install --upgrade pip
        pip install numpy
    - name: Test
      run: |
        python -m unittest discover ./school_project/test/models/cpu
```