Computer Science NEA Report

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

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Contents

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

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

1.4 Requirements

The following sets out the steps that must be taken to accomplish the above objectives:

ID	Description	Satisfied by	Tested by
1	Learn how Artificial Neural Networks work	Page 5	N/A
2	Develop Artficial Neural Networks from first principles		
2.1	Provide utilities for creating Artificial Neural Networks	Page 32	Page 100
2.2	Allow for the saving and loading of trained models' weights and biases	Page 36	Page 100
2.3	Allow use of Graphics Cards for faster training	Code not included in report	Page 95
3	Implement the Artificial Neural Networks on image datasets		
3.1	Allow input of unique hyper-parameters	Page 43	Page 77
3.2	Allow unique datasets and train dataset size to be loaded	Page 43	Page 84
4	Use a database to store a model's features and the location of its weights and biases	Page 59	TODO Unit Test
5	Develop a Graphical User Interface		
5.1	Provide controls for hyper-parameters of models	Page 48	Page 96
5.2	Display details of models' training	Page 48	N/A
5.3	Display the results of each model's predictions	Page 68	User Tested
5.4	Allow for the saving of trained models	Page 68	Page 99
5.5	Allow for the loading of saved trained models	Page 55	Page 98

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.

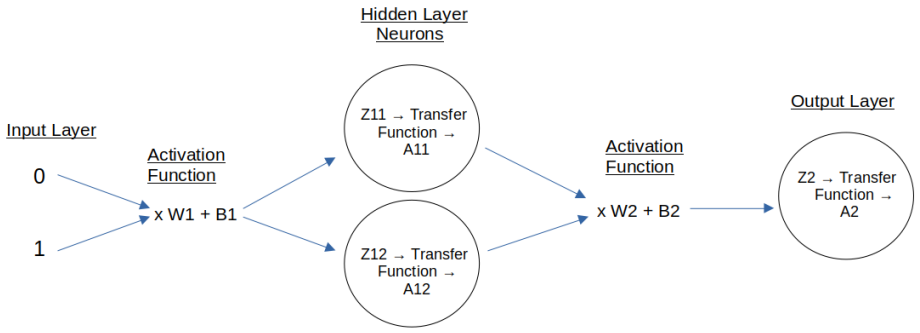


Figure 1: This shows an Artificial Neural Network with one single hidden layer and is known as a Shallow Neural Netwok.

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

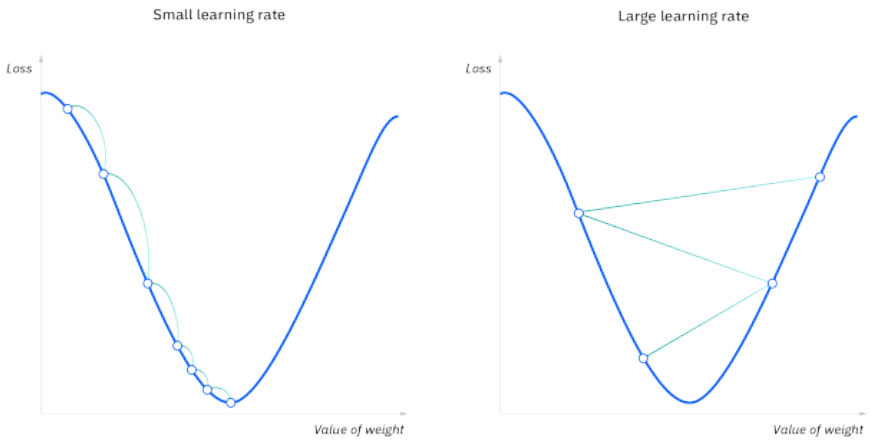


Figure 2: Gradient Descent
sourced from https://www.ibm.com/topics/gradient-descent

* 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

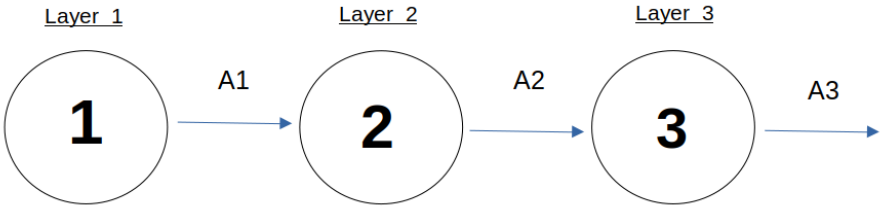


Figure 3: This shows an abstracted view of an Artificial Neural Network with multiple hidden layers and is known as a Deep Neural Netwok.

- 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

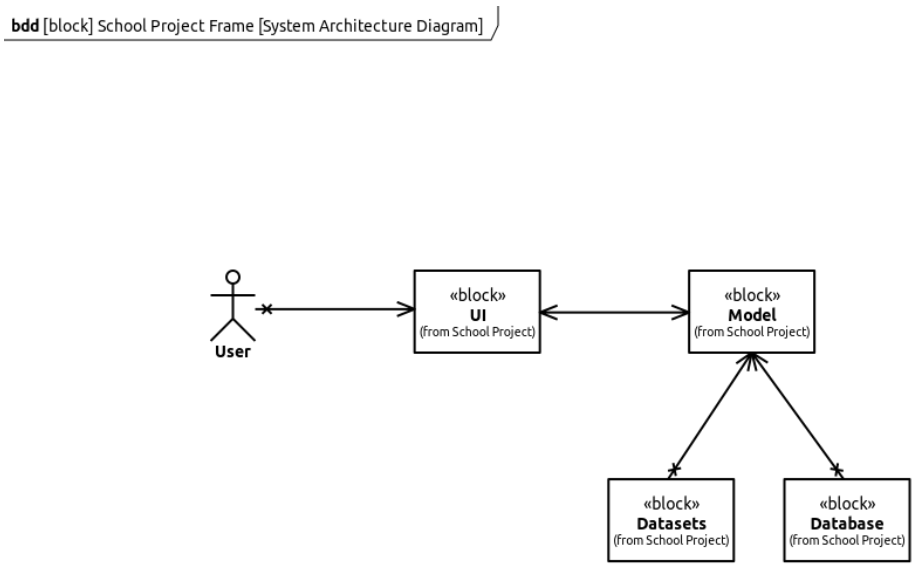
2.1 Introduction

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.

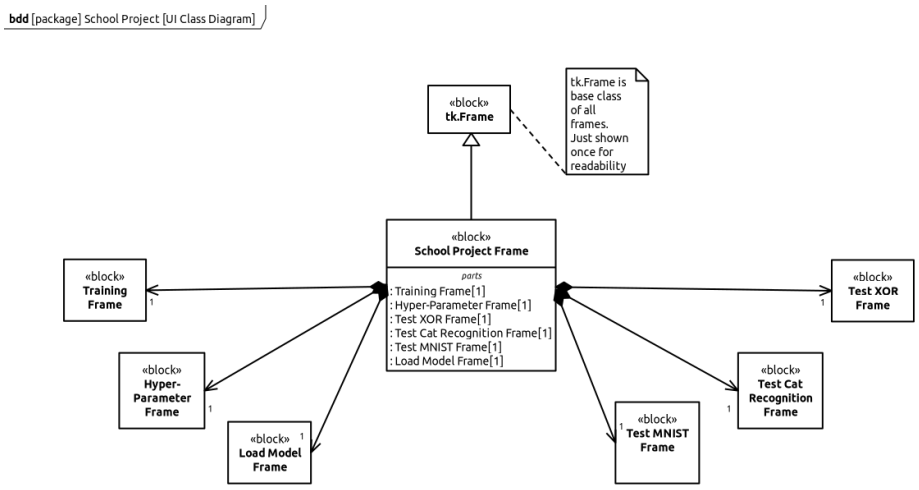
I will also be using SysML for designing the following diagrams.

2.2 System Architecture

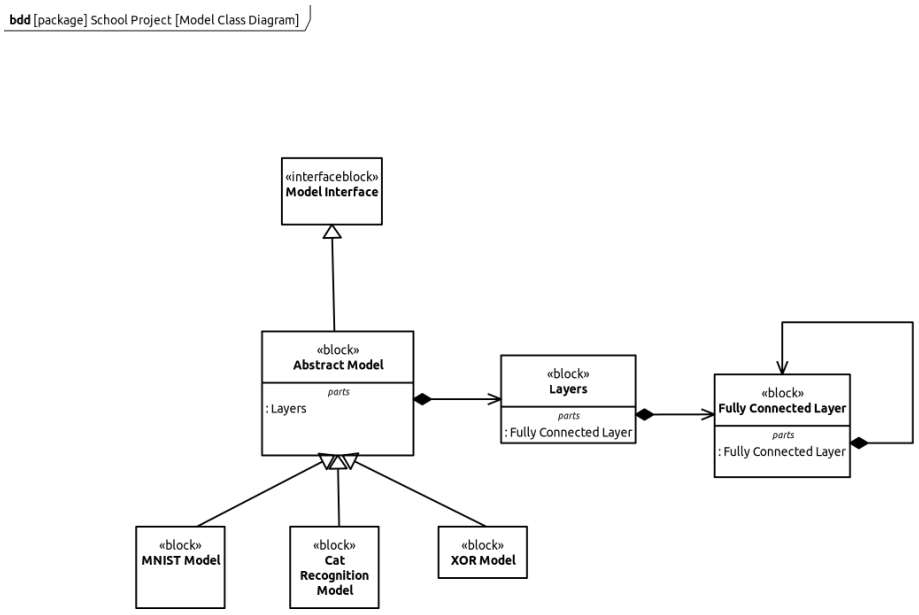


2.3 Class Diagrams

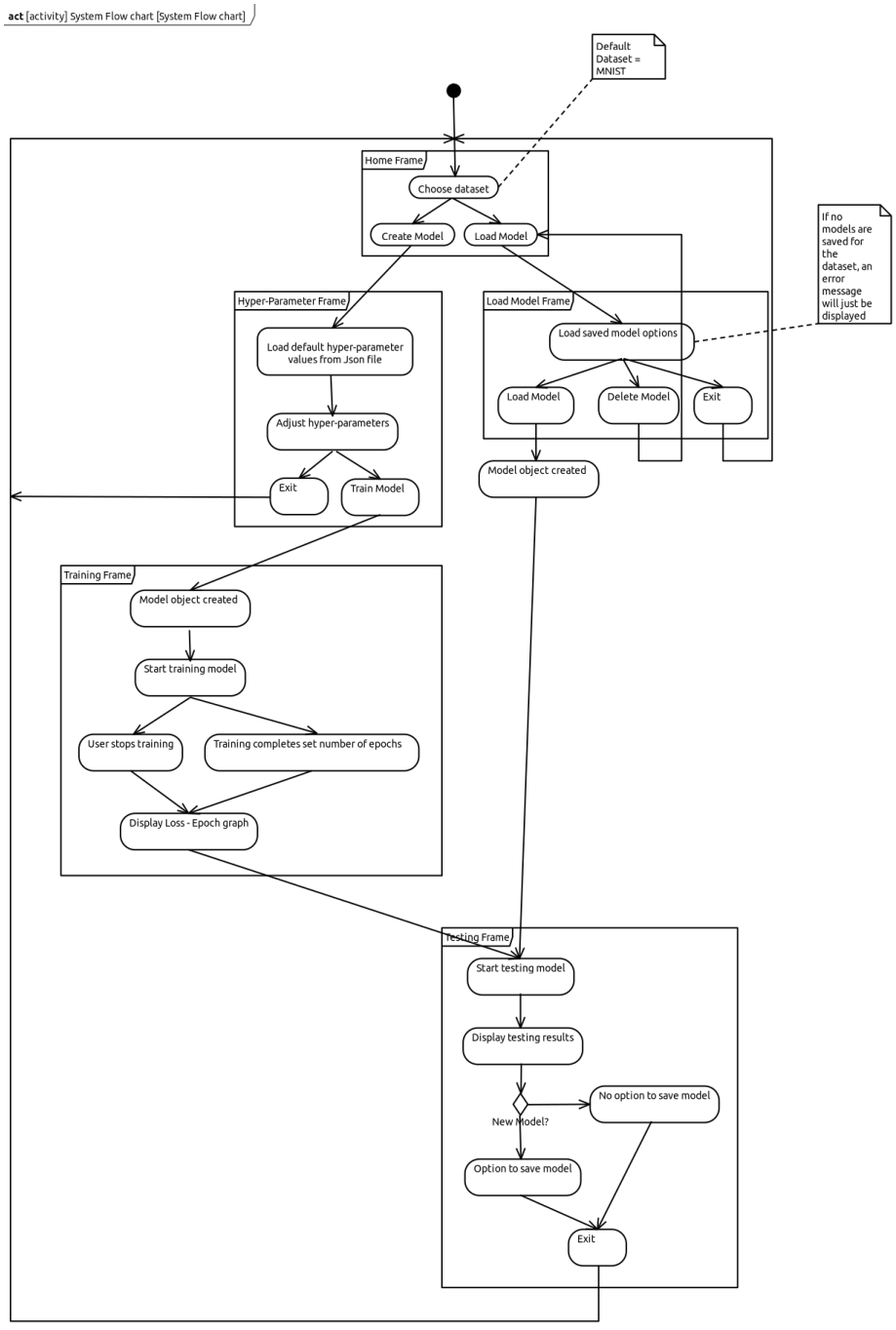
2.3.1 UI Class Diagram



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:

- 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=?;
```

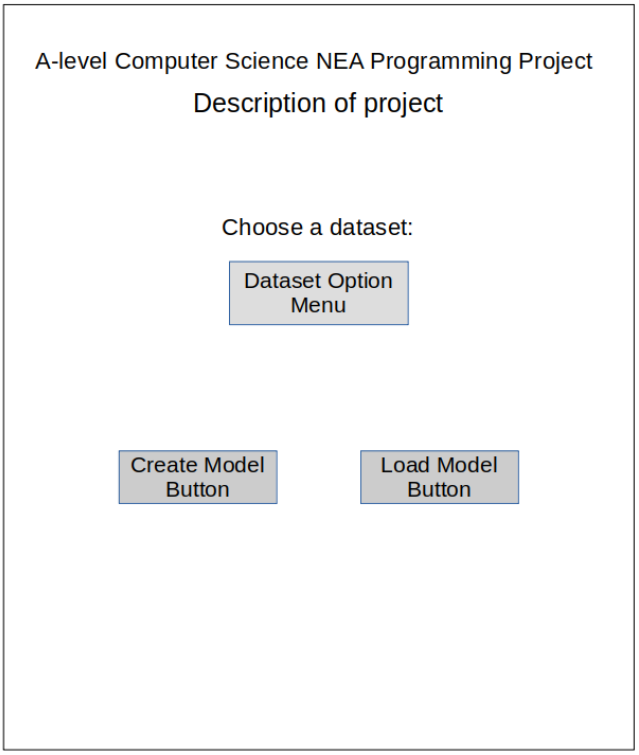
- I can query the features of a saved model with:

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

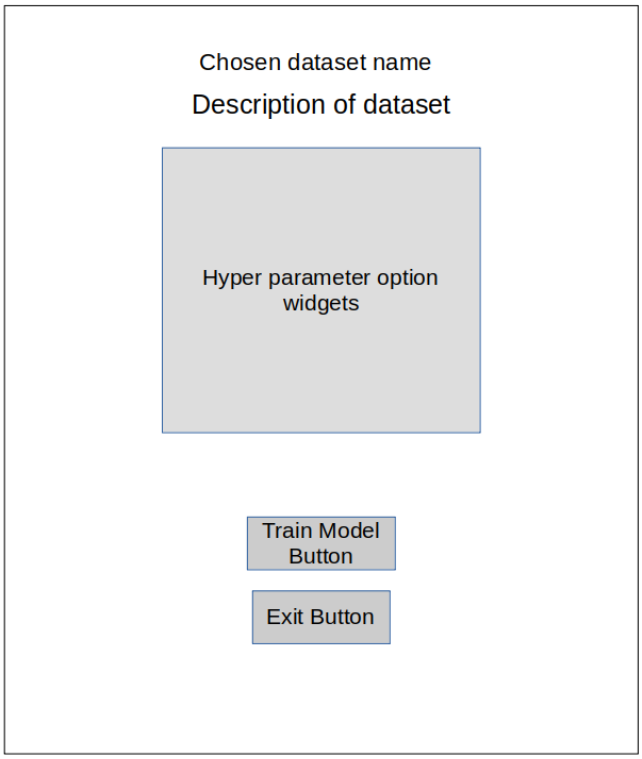
2.10 Human-Computer Interaction

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

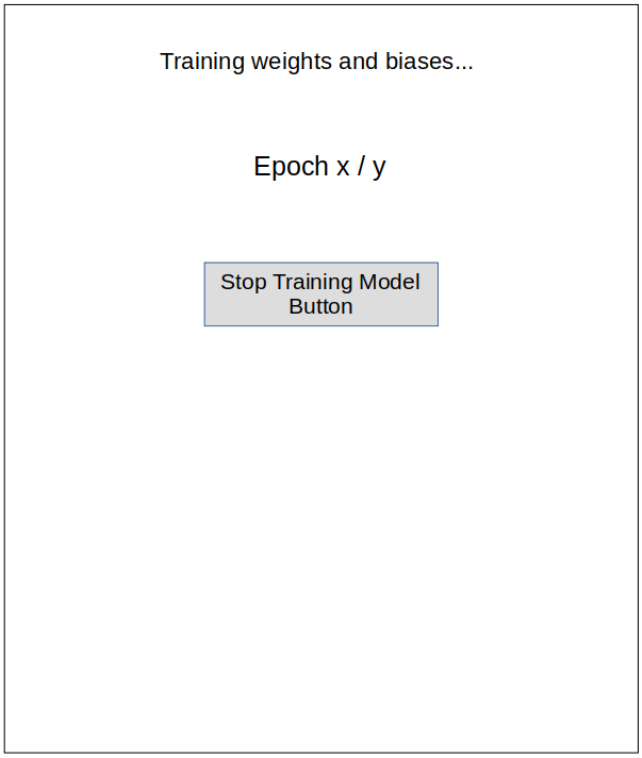
- Home Frame design:



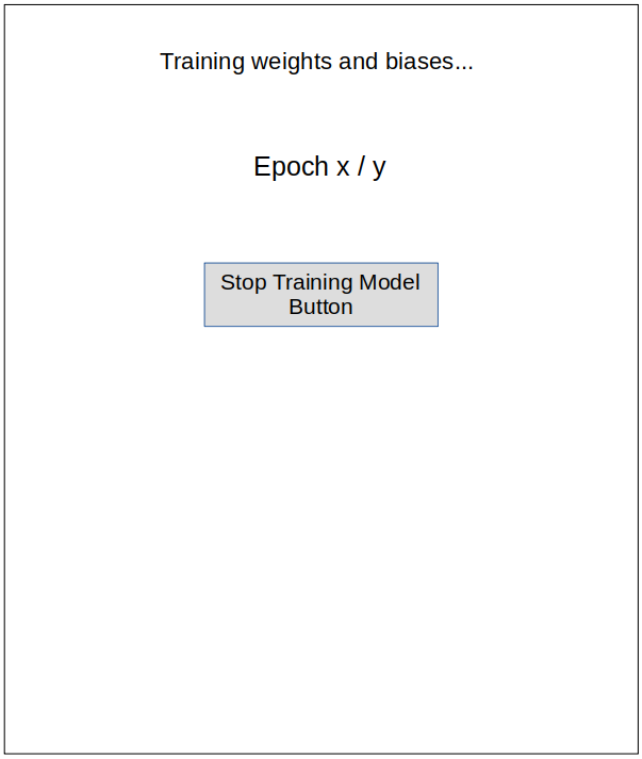
- Hyper-Parameter Frame design:



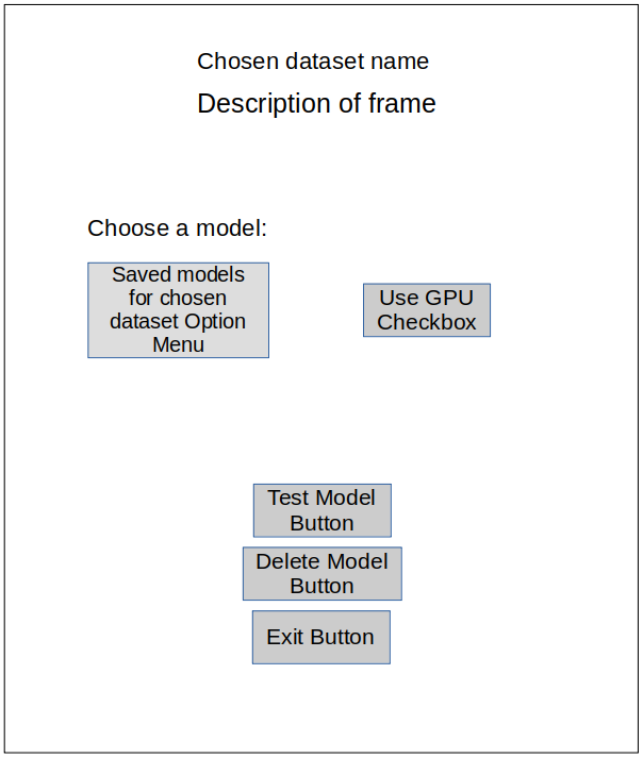
- Training Frame design:
  - During training, the following is displayed on the Training Frame:



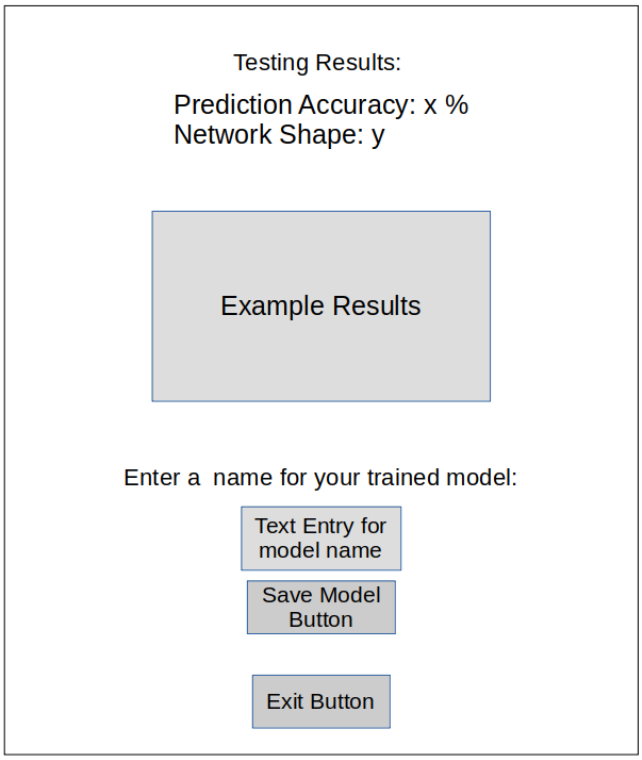
– Once training has finished, the following is displayed on the Training Frame:



- 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.

```
.
|-- Dockerfile
|-- .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, 49 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
     ```
````
````

````
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
<a href="https://developer.nvidia.com/cuda-downloads">here</a>.*

## 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/
  ```

Use Docker with:
- Build the Docker Image with:
  ```
  sudo docker build -t mcttn22/school-project ./
  ```
````

```
- Run the Docker Image with:
  ```
  sudo apt-get install x11-xserver-utils
  xhost +
  sudo docker run -v /tmp/.X11-unix:/tmp/.X11-unix -e
  ↪ DISPLAY=unix$DISPLAY mcttn22/school-project
  ```

Compile Project Report PDF with:
```
make all
```
*Note: This requires the Latexmk, pdflatek and Pygments libraries*
```

– Which will generate the following:

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/
```

Use Docker with:

- Build the Docker Image with:

```
sudo docker build -t mcttn22/school-project ./
```

- Run the Docker Image with:

```
sudo apt-get install x11-xserver-utils
xhost +
sudo docker run -v /tmp/.X11-unix:/tmp/.X11-unix -e DISPLAY=unix$DISPLAY mcttn22/school-prc
```

Compile Project Report PDF with:

```
make all
```

Note: This requires the Latexmk, pdflatek and Pygments libraries

- 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
    def load_datasets(self, train_dataset_size: int) -> tuple[np.ndarray,
    ↪   np.ndarray,
                                                              np.ndarray,
                                                              ↪   np.ndarray]:
        """Load input and output datasets. For the input dataset, each
↪   column
           should represent a piece of data and each row should store the
↪   values
           of the piece of data.

        Args:
            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
```

```
            Args:
                file_location (str): the file location to save the model to.

        """
        raise NotImplementedError

def relu(z: np.ndarray | int | float) -> np.ndarray | float:
    """Transfer function, transform input to max number between 0 and z.

    Args:
        z (numpy.ndarray | int | float):
        the numpy.ndarray | int | float to be transferred.
    Returns:
        numpy.ndarray | float,
        with all values | the value transferred to max number between 0-z.
    Raises:
        TypeError: if z is not of type numpy.ndarray | int | float.

    """
    return np.maximum(0.1*z, 0)  # Divide by 10 to stop overflow errors

def relu_derivative(output: np.ndarray) -> np.ndarray:
    """Calculate derivative of ReLu Transfer function with respect to z.

    Args:
        output (numpy.ndarray):
        the numpy.ndarray output of the ReLu transfer function.
    Returns:
        numpy.ndarray,
        derivative of the ReLu transfer function with respect to z.
    Raises:
        TypeError: if output is not of type numpy.ndarray.

    """
    output[output <= 0] = 0
    output[output > 0] = 1

    return output

def sigmoid(z: np.ndarray | int | float) -> np.ndarray | float:
    """Transfer function, transform input to number between 0 and 1.

    Args:
        z (numpy.ndarray | int | float):
        the numpy.ndarray | int | float to be transferred.
    Returns:
        numpy.ndarray | float,
        with all values | the value transferred to a number between 0-1.
    Raises:
        TypeError: if z is not of type numpy.ndarray | int | float.

    """
    return 1 / (1 + np.exp(-z))

def sigmoid_derivative(output: np.ndarray | int | float) -> np.ndarray |
↪   float:
    """Calculate derivative of sigmoid Transfer function with respect to z.

    Args:
        output (numpy.ndarray | int | float):
        the numpy.ndarray | int | float output of the sigmoid transfer
↪   function.
```

```
    Returns:
        numpy.ndarray | float,
        derivative of the sigmoid transfer function with respect to z.
    Raises:
        TypeError: if output is not of type numpy.ndarray | int | float.

    """
    return output * (1 - output)

def calculate_loss(input_count: int,
                   outputs: np.ndarray,
                   prediction: np.ndarray) -> float:
    """Calculate average loss/error of the prediction to the outputs.

    Args:
        input_count (int): the number of inputs.
        outputs (np.ndarray):
        the train/test outputs array to compare with the prediction.
        prediction (np.ndarray): the array of prediction values.
    Returns:
        float loss.
    Raises:
        ValueError:
        if outputs is not a suitable multiplier with the prediction
        (incorrect shapes)

    """
    return np.squeeze(- (1/input_count) * np.sum(outputs *
    ↪  np.log(prediction) + (1 - outputs) * np.log(1 - prediction)))

def calculate_prediction_accuracy(prediction: np.ndarray,
                                  outputs: np.ndarray) -> float:
    """Calculate the percentage accuracy of the predictions.

    Args:
        prediction (np.ndarray): the array of prediction values.
        outputs (np.ndarray):
        the train/test outputs array to compare with the prediction.
    Returns:
        float prediction accuracy

    """
    return 100 - np.mean(np.abs(prediction - outputs)) * 100
```

- model.py module:

```
"""Provides an abstract class for Artificial Neural Network models."""

from collections.abc import Generator
import time

import numpy as np

from .tools import (
                    ModelInterface,
                    relu,
                    relu_derivative,
                    sigmoid,
                    sigmoid_derivative,
                    calculate_loss,
                    calculate_prediction_accuracy
```

```
                    )

class _FullyConnectedLayer():
    """Fully connected layer for Deep ANNs,
       represented as a node of a Doubly linked list."""
    def __init__(self, learning_rate: float, input_neuron_count: int,
                 output_neuron_count: int, transfer_type: str) -> None:
        """Initialise layer values.

        Args:
            learning_rate (float): the learning rate of the model.
            input_neuron_count (int):
            the number of input neurons into the layer.
            output_neuron_count (int):
            the number of output neurons into the layer.
            transfer_type (str): the transfer function type
            ('sigmoid' or 'relu')

        """
        # Setup layer attributes
        self.previous_layer = None
        self.next_layer = None
        self.input_neuron_count = input_neuron_count
        self.output_neuron_count = output_neuron_count
        self.transfer_type = transfer_type
        self.input: np.ndarray
        self.output: np.ndarray

        # Setup weights and biases
        self.weights: np.ndarray
        self.biases: np.ndarray
        self.learning_rate = learning_rate

    def __repr__(self) -> str:
        """Read values of the layer.

        Returns:
            a string description of the layers's
            weights, bias and learning rate values.

        """
        return (f"Weights: {self.weights.tolist()}\n" +
                f"Biases: {self.biases.tolist()}\n")

    def init_layer_values_random(self) -> None:
        """Initialise weights to random values and biases to 0s"""
        np.random.seed(1)  # Sets up pseudo random values for layer weight
        ↪  arrays
        self.weights = np.random.rand(self.output_neuron_count,
        ↪  self.input_neuron_count) - 0.5
        self.biases = np.zeros(shape=(self.output_neuron_count, 1))

    def init_layer_values_zeros(self) -> None:
        """Initialise weights to 0s and biases to 0s"""
        self.weights = np.zeros(shape=(self.output_neuron_count,
        ↪  self.input_neuron_count))
        self.biases = np.zeros(shape=(self.output_neuron_count, 1))

    def back_propagation(self, dloss_doutput) -> np.ndarray:
        """Adjust the weights and biases via gradient descent.

        Args:
```

```
75              dloss_doutput (numpy.ndarray): the derivative of the loss of
    ↪  the
76              layer's output, with respect to the layer's output.
77          Returns:
78              a numpy.ndarray derivative of the loss of the layer's input,
79              with respect to the layer's input.
80          Raises:
81              ValueError:
82              if dloss_doutput
83              is not a suitable multiplier with the weights
84              (incorrect shape)
85
86          """
87          match self.transfer_type:
88              case 'sigmoid':
89                  dloss_dz = dloss_doutput *
                    ↪  sigmoid_derivative(output=self.output)
90              case 'relu':
91                  dloss_dz = dloss_doutput *
                    ↪  relu_derivative(output=self.output)
92
93          dloss_dweights = np.dot(dloss_dz, self.input.T)
94          dloss_dbiases = np.sum(dloss_dz)
95
96          assert dloss_dweights.shape == self.weights.shape
97
98          dloss_dinput = np.dot(self.weights.T, dloss_dz)
99
100         # Update weights and biases
101         self.weights -= self.learning_rate * dloss_dweights
102         self.biases -= self.learning_rate * dloss_dbiases
103
104         return dloss_dinput
105
106     def forward_propagation(self, inputs) -> np.ndarray:
107         """Generate a layer output with the weights and biases.
108
109         Args:
110             inputs (np.ndarray): the input values to the layer.
111         Returns:
112             a numpy.ndarray of the output values.
113
114         """
115         self.input = inputs
116         z = np.dot(self.weights, self.input) + self.biases
117         if self.transfer_type == 'sigmoid':
118             self.output = sigmoid(z)
119         elif self.transfer_type == 'relu':
120             self.output = relu(z)
121         return self.output
122
123 class _Layers():
124     """Manages linked list of layers."""
125     def __init__(self) -> None:
126         """Initialise linked list."""
127         self.head = None
128         self.tail = None
129
130     def __iter__(self) -> Generator[_FullyConnectedLayer, None, None]:
131         """Iterate forward through the network."""
132         current_layer = self.head
133         while True:
```

```
134             yield current_layer
135             if current_layer.next_layer is not None:
136                 current_layer = current_layer.next_layer
137             else:
138                 break
139 
140     def __reversed__(self) -> Generator[_FullyConnectedLayer, None, None]:
141         """Iterate back through the network."""
142         current_layer = self.tail
143         while True:
144             yield current_layer
145             if current_layer.previous_layer is not None:
146                 current_layer = current_layer.previous_layer
147             else:
148                 break
149 
150 class AbstractModel(ModelInterface):
151     """ANN model with variable number of hidden layers"""
152     def __init__(self,
153                  hidden_layers_shape: list[int],
154                  train_dataset_size: int,
155                  learning_rate: float,
156                  use_relu: bool) -> None:
157         """Initialise model values.
158 
159         Args:
160             hidden_layers_shape (list[int]):
161             list of the number of neurons in each hidden layer.
162             train_dataset_size (int): the number of train dataset inputs to
    ↪  use.
163             learning_rate (float): the learning rate of the model.
164             use_relu (bool): True or False whether the ReLu Transfer
    ↪  function
165             should be used.
166 
167         """
168         # Setup model data
169         self.train_inputs, self.train_outputs,\
170         self.test_inputs, self.test_outputs = self.load_datasets(
171 
                                            ↪  train_dataset_size=train_dataset_size
172                                             )
173         self.train_losses: list[float]
174         self.test_prediction: np.ndarray
175         self.test_prediction_accuracy: float
176         self.training_progress = ""
177         self.training_time: float
178 
179         # Setup model attributes
180         self.__running = True
181         self.input_neuron_count: int = self.train_inputs.shape[0]
182         self.input_count = self.train_inputs.shape[1]
183         self.hidden_layers_shape = hidden_layers_shape
184         self.output_neuron_count = self.train_outputs.shape[0]
185         self.layers_shape = [f'{layer}' for layer in (
186                              [self.input_neuron_count] +
187                              self.hidden_layers_shape +
188                              [self.output_neuron_count]
189                              )]
190         self.use_relu = use_relu
191 
192         # Setup model values
```

```
193         self.layers = _Layers()
194         self.learning_rate = learning_rate
195 
196     def __repr__(self) -> str:
197         """Read current state of model.
198 
199         Returns:
200             a string description of the model's shape,
201             weights, bias and learning rate values.
202 
203         """
204         return (f"Layers Shape: {','.join(self.layers_shape)}\n" +
205                 f"Learning Rate: {self.learning_rate}")
206 
207     def set_running(self, value: bool) -> None:
208         """Set the running attribute to the given value.
209 
210         Args:
211             value (bool): the value to set the running attribute to.
212 
213         """
214         self.__running = value
215 
216     def _setup_layers(setup_values: callable) -> None:
217         """Decorator that sets up model layers and sets up values of each
    ↪  layer
218            with the method given.
219 
220         Args:
221             setup_values (callable): the method that sets up the values of
    ↪  each
222             layer.
223 
224         """
225         def decorator(self, *args, **kwargs) -> None:
226             # Check if setting up Deep Network
227             if len(self.hidden_layers_shape) > 0:
228                 if self.use_relu:
229 
230                     # Add input layer
231                     self.layers.head = _FullyConnectedLayer(
232 
                                            ↪  learning_rate=self.learning_rate,
233 
                                            ↪  input_neuron_count=self.input_neuron_count,
234 
                                            ↪  output_neuron_count=self.hidden_layers_shape[0],
235                                            transfer_type='relu'
236                                            )
237                     current_layer = self.layers.head
238 
239                     # Add hidden layers
240                     for layer in range(len(self.hidden_layers_shape) - 1):
241                         current_layer.next_layer = _FullyConnectedLayer(
242                                     learning_rate=self.learning_rate,
243 
                                     ↪  input_neuron_count=self.hidden_layers_shape[layer],
244 
                                     ↪  output_neuron_count=self.hidden_layers_shape[layer
                                     ↪  + 1],
245                                     transfer_type='relu'
246                                     )
```

```
247                         current_layer.next_layer.previous_layer =
                            ↪  current_layer
248                         current_layer = current_layer.next_layer
249                 else:
250
251                     # Add input layer
252                     self.layers.head = _FullyConnectedLayer(
253
                                            ↪  learning_rate=self.learning_rate,
254
                                            ↪  input_neuron_count=self.input_neuron_count,
255
                                            ↪  output_neuron_count=self.hidden_layers_shape[0],
256                                         transfer_type='sigmoid'
257                                         )
258                     current_layer = self.layers.head
259
260                     # Add hidden layers
261                     for layer in range(len(self.hidden_layers_shape) - 1):
262                         current_layer.next_layer = _FullyConnectedLayer(
263                                     learning_rate=self.learning_rate,
264
                                            ↪  input_neuron_count=self.hidden_layers_shape[layer],
265
                                            ↪  output_neuron_count=self.hidden_layers_shape[layer
                                            ↪  + 1],
266                                         transfer_type='sigmoid'
267                                         )
268                         current_layer.next_layer.previous_layer =
                            ↪  current_layer
269                         current_layer = current_layer.next_layer
270
271                 # Add output layer
272                 current_layer.next_layer = _FullyConnectedLayer(
273                                         learning_rate=self.learning_rate,
274
                                            ↪  input_neuron_count=self.hidden_layers_shape[-1],
275
                                            ↪  output_neuron_count=self.output_neuron_count,
276                                         transfer_type='sigmoid'
277                                         )
278                 current_layer.next_layer.previous_layer = current_layer
279                 self.layers.tail = current_layer.next_layer
280
281             # Setup Perceptron Network
282             else:
283                 self.layers.head = _FullyConnectedLayer(
284                                         learning_rate=self.learning_rate,
285
                                            ↪  input_neuron_count=self.input_neuron_count,
286
                                            ↪  output_neuron_count=self.output_neuron_count,
287                                         transfer_type='sigmoid'
288                                         )
289                 self.layers.tail = self.layers.head
290
291             setup_values(self, *args, **kwargs)
292
293         return decorator
294
295     @_setup_layers
296     def create_model_values(self) -> None:
```

```
297             """Create weights and bias/biases"""
298             # Check if setting up Deep Network
299             if len(self.hidden_layers_shape) > 0:
300 
301                 # Initialise Layer values to random values
302                 for layer in self.layers:
303                     layer.init_layer_values_random()
304 
305             # Setup Perceptron Network
306             else:
307 
308                 # Initialise Layer values to zeros
309                 for layer in self.layers:
310                     layer.init_layer_values_zeros()
311 
312         @_setup_layers
313         def load_model_values(self, file_location: str) -> None:
314             """Load weights and bias/biases from .npz file.
315 
316             Args:
317                 file_location (str): the location of the file to load from.
318 
319             """
320             data: dict[str, np.ndarray] = np.load(file=file_location)
321 
322             # Initialise Layer values
323             i = 0
324             keys = list(data.keys())
325             for layer in self.layers:
326                 layer.weights = data[keys[i]]
327                 layer.biases = data[keys[i + 1]]
328                 i += 2
329 
330         def back_propagation(self, dloss_doutput) -> None:
331             """Train each layer's weights and biases.
332 
333             Args:
334                 dloss_doutput (np.ndarray): the derivative of the loss of the
335                 output layer's output, with respect to the output layer's
    ↪  output.
336 
337             """
338             for layer in reversed(self.layers):
339                 dloss_doutput =
                    ↪  layer.back_propagation(dloss_doutput=dloss_doutput)
340 
341         def forward_propagation(self) -> np.ndarray:
342             """Generate a prediction with the layers.
343 
344             Returns:
345                 a numpy.ndarray of the prediction values.
346 
347             """
348             output = self.train_inputs
349             for layer in self.layers:
350                 output = layer.forward_propagation(inputs=output)
351             return output
352 
353         def test(self) -> None:
354             """Test the layers' trained weights and biases."""
355             output = self.test_inputs
356             for layer in self.layers:
```

```
357             output = layer.forward_propagation(inputs=output)
358         self.test_prediction = output
359 
360         # Calculate performance of model
361         self.test_prediction_accuracy = calculate_prediction_accuracy(
362                                                 ↪  prediction=self.test_prediction,
363                                                 outputs=self.test_outputs
364                                                 )
365 
366     def train(self, epoch_count: int) -> None:
367         """Train layers' weights and biases.
368 
369            Args:
370                epoch_count (int): the number of training epochs.
371 
372         """
373         self.layers_shape = [f'{layer}' for layer in (
374                              [self.input_neuron_count] +
375                              self.hidden_layers_shape +
376                              [self.output_neuron_count]
377                              )]
378         self.train_losses = []
379         training_start_time = time.time()
380         for epoch in range(epoch_count):
381             if not self.__running:
382                 break
383             self.training_progress = f"Epoch {epoch} / {epoch_count}"
384             prediction = self.forward_propagation()
385             loss = calculate_loss(input_count=self.input_count,
386                                   outputs=self.train_outputs,
387                                   prediction=prediction)
388             self.train_losses.append(loss)
389             if not self.__running:
390                 break
391             dloss_doutput = -(1/self.input_count) * ((self.train_outputs -
                ↪  prediction)/(prediction * (1 - prediction)))
392             self.back_propagation(dloss_doutput=dloss_doutput)
393         self.training_time = round(number=time.time() -
            ↪  training_start_time,
394                                    ndigits=2)
395 
396     def save_model_values(self, file_location: str) -> None:
397         """Save the model by saving the weights then biases of each layer
    ↪  to
398            a .npz file with a given file location.
399 
400            Args:
401                file_location (str): the file location to save the model to.
402 
403         """
404         saved_model: list[np.ndarray] = []
405         for layer in self.layers:
406             saved_model.append(layer.weights)
407             saved_model.append(layer.biases)
408         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:

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

import h5py
import numpy as np

from .utils.model import AbstractModel

class CatRecognitionModel(AbstractModel):
    """ANN model that trains to predict if an image is a cat or not a cat."""
    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 image input and output datasets.

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

        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,
                 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.
```

```
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

```
1   """Implementation of Artificial Neural Network model on XOR dataset."""
2
3   import numpy as np
4
5   from .utils.model import AbstractModel
6
7   class XORModel(AbstractModel):
8       """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(
                    master=self,
                    bg=self.BG,
                    orient='horizontal',
                    label="Train Dataset Size",
                    length=185,
                    from_=self.default_hyper_parameters['minTrainDatasetSize'],
                    to=self.default_hyper_parameters['maxTrainDatasetSize'],
                    resolution=1
                    )
        self.train_dataset_size_scale.set(
                     value=self.default_hyper_parameters['maxTrainDatasetSize'])
```

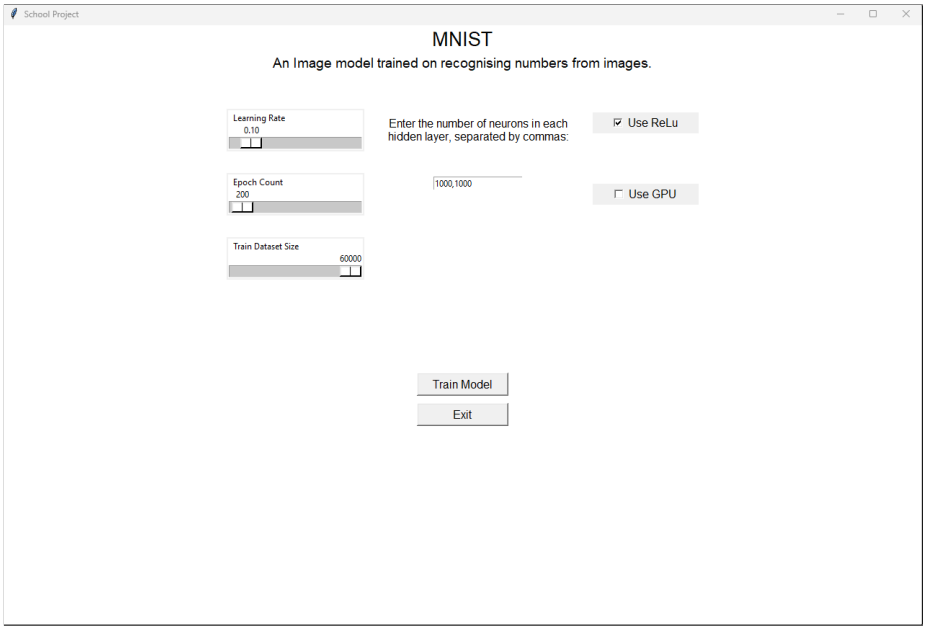
```
88          self.hidden_layers_shape_label = tk.Label(
89                                      master=self,
90                                      bg=self.BG,
91                                      font=('Arial', 12),
92                                      text="Enter the number of neurons in
                                        ↪  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(),
```

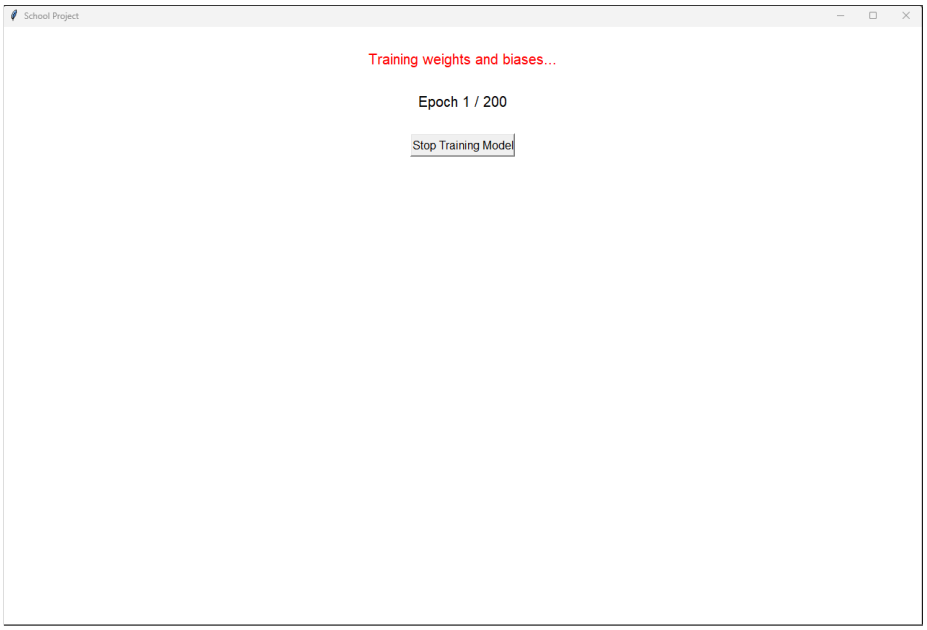
```
193                                 use_relu =
                                    ↪  self.use_relu_check_button_var.get())
194                 model.create_model_values()
195             except ImportError as ie:
196                 self.model_status_label.configure(
197                                         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,
237                                                        master=self
238                                                        )
239 
240         # Pack widgets
241         self.model_status_label.pack(pady=(30,0))
242         self.training_progress_label.pack(pady=30)
243 
244         # Start training thread
245         self.model_status_label.configure(
246                                         text="Training weights and
                                            ↪  biases...",
247                                         fg='red'
248                                         )
249         self.train_thread: threading.Thread = threading.Thread(
```

```
250
                                                        ↪  target=model.train,
251
                                                        ↪  args=(epoch_count,)
252                                                     )
253         self.train_thread.start()
254
255     def plot_losses(self, model: object) -> None:
256         """Plot losses of Model training.
257
258            Args:
259                model (object): the Model object thats been trained.
260
261         """
262         self.model_status_label.configure(
263                  text=f"Weights and biases trained in
                         ↪  {model.training_time}s",
264                  fg='green'
265                  )
266         graph: Figure.axes = self.loss_figure.add_subplot(111)
267         graph.set_title("Learning rate: " +
268                         f"{model.learning_rate}")
269         graph.set_xlabel("Epochs")
270         graph.set_ylabel("Loss Value")
271         graph.plot(np.squeeze(model.train_losses))
272         self.loss_canvas.get_tk_widget().pack()
```

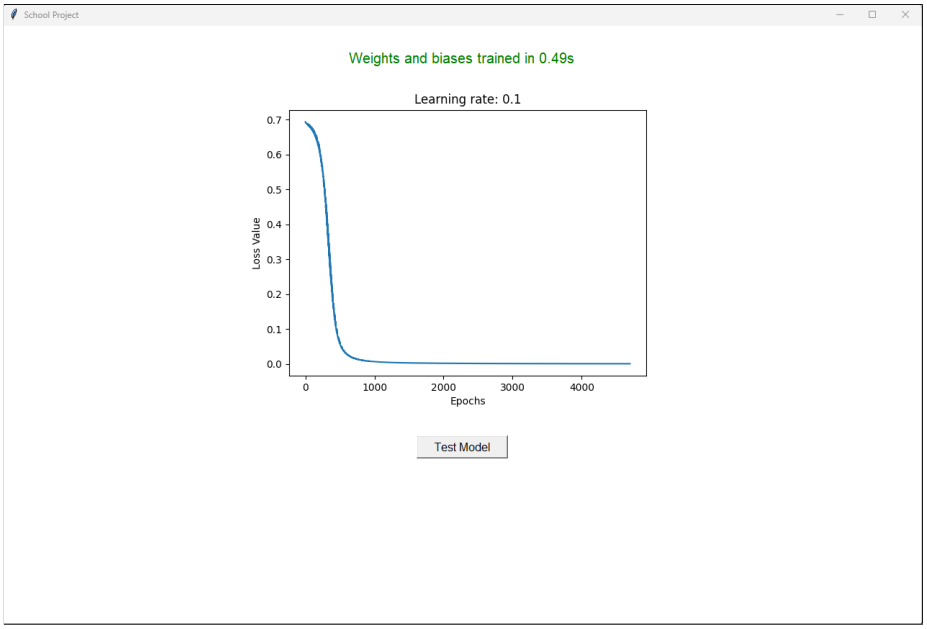
Which outputs the following for the hyper-parameter frame:



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.

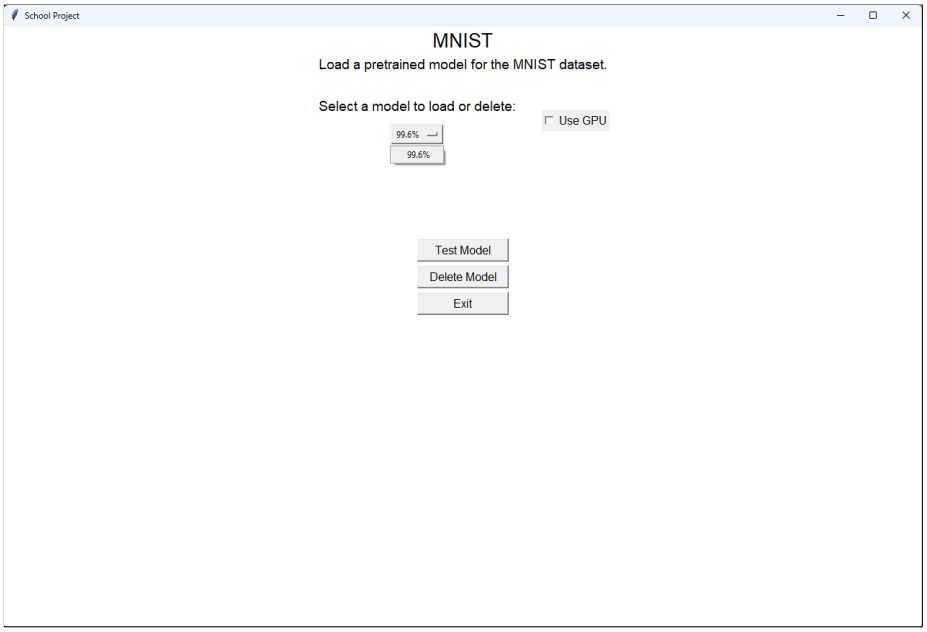
        """
```

```
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(
```

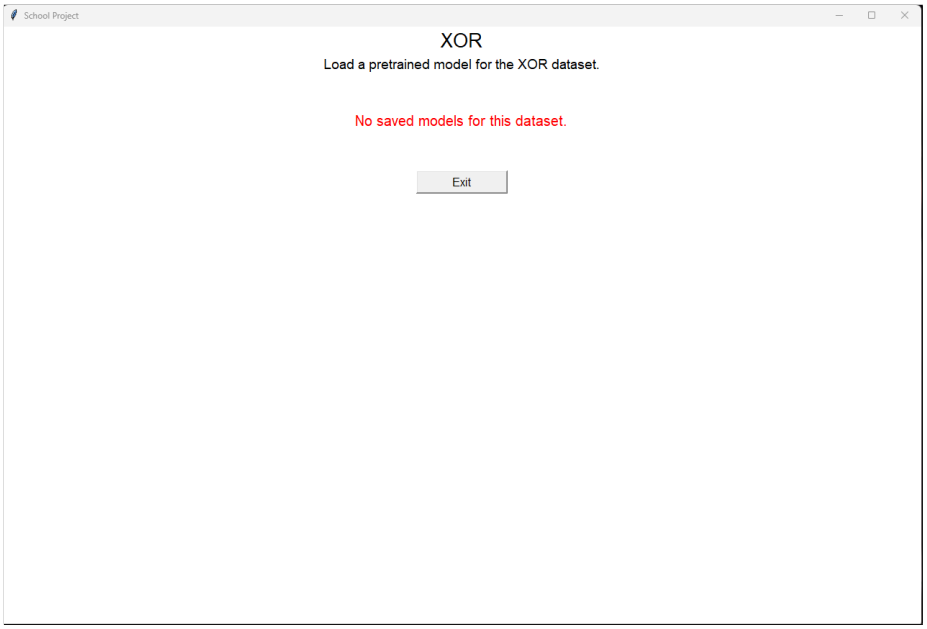
```
84                                      text='No saved models for this
                                        ↪  dataset.',
85                                      fg='red'
86                                      )
87
88          # Pack widgets
89          self.title_label.grid(row=0, column=0, columnspan=3)
90          self.about_label.grid(row=1, column=0, columnspan=3)
91          if len(self.model_options) > 0:  # Check if options should be given
92              self.model_option_menu_label.grid(row=2, column=0, padx=(0,30),
                ↪  pady=(30,0))
93              self.use_gpu_check_button.grid(row=2, column=2, rowspan=2,
                ↪  pady=(30,0))
94              self.model_option_menu.grid(row=3, column=0, padx=(0,30),
                ↪  pady=(10,0))
95          self.model_status_label.grid(row=4, column=0,
96                                       columnspan=3, pady=50)
97
98      def load_model_options(self) -> list[str]:
99          """Load the model options from the database.
100
101             Returns:
102                 a list of the model options.
103         """
104         sql = f"""
105         SELECT Name FROM Models WHERE Dataset=?
106         """
107         parameters = (self.dataset.replace(" ", "_"),)
108         self.cursor.execute(sql, parameters)
109
110         # Save the string value contained within the tuple of each row
111         model_options = []
112         for model_option in self.cursor.fetchall():
113             model_options.append(model_option[0])
114
115         return model_options
116
117     def load_model(self) -> object:
118         """Create model using saved weights and biases.
119
120            Returns:
121                a Model object.
122
123         """
124         self.use_gpu = self.use_gpu_check_button_var.get()
125
126         # Query data of selected saved model from database
127         sql = """
128         SELECT * FROM Models WHERE Dataset=? AND Name=?
129         """
130         parameters = (self.dataset.replace(" ", "_"),
        ↪  self.model_option_menu_var.get())
131         self.cursor.execute(sql, parameters)
132         data = self.cursor.fetchone()
133         hidden_layers_shape_input = [layer for layer in data[3].replace('
        ↪  ', '').split(',') if layer != '']
134
135         # Create Model
136         if not self.use_gpu:
137             if self.dataset == "MNIST":
138                 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",
```

```
                                        command=self.exit_load_model_frame
                                        )
        self.train_button = tk.Button(master=self,
                                      width=13,
                                      height=1,
                                      font=tkf.Font(size=12),
                                      text="Train Model",
                                      command=self.enter_training_frame)
        self.stop_training_button = tk.Button(
                                        master=self,
                                        width=15, height=1,
                                        font=tkf.Font(size=12),
                                        text="Stop Training Model",
                                        command=lambda: self.model.set_running(
                                                                    value=False
                                                                    )
                                        )
        self.test_created_model_button = tk.Button(
                                             master=self,
                                             width=13, height=1,
                                             font=tkf.Font(size=12),
                                             text="Test Model",
                                             command=self.test_created_model
                                             )
        self.test_loaded_model_button = tk.Button(
                                              master=self,
                                              width=13, height=1,
                                              font=tkf.Font(size=12),
                                              text="Test Model",
                                              command=self.test_loaded_model
                                              )
        self.delete_loaded_model_button = tk.Button(
                                              master=self,
                                              width=13, height=1,
                                              font=tkf.Font(size=12),
                                              text="Delete Model",
                                              command=self.delete_loaded_model
                                              )
        self.save_model_label = tk.Label(
                                    master=self,
                                    text="Enter a name for your trained model:",
                                    bg=self.BG,
                                    font=('Arial', 15)
                                    )
        self.save_model_name_entry = tk.Entry(master=self, width=13)
        self.save_model_button = tk.Button(master=self,
                                           width=13,
                                           height=1,
                                           font=tkf.Font(size=12),
                                           text="Save Model",
                                           command=self.save_model)
        self.exit_button = tk.Button(master=self,
                                     width=13, height=1,
                                     font=tkf.Font(size=12),
                                     text="Exit",
                                     command=self.enter_home_frame)

        # Setup home frame
        self.home_frame = tk.Frame(master=self,
                                   width=self.WIDTH,
                                   height=self.HEIGHT,
                                   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)

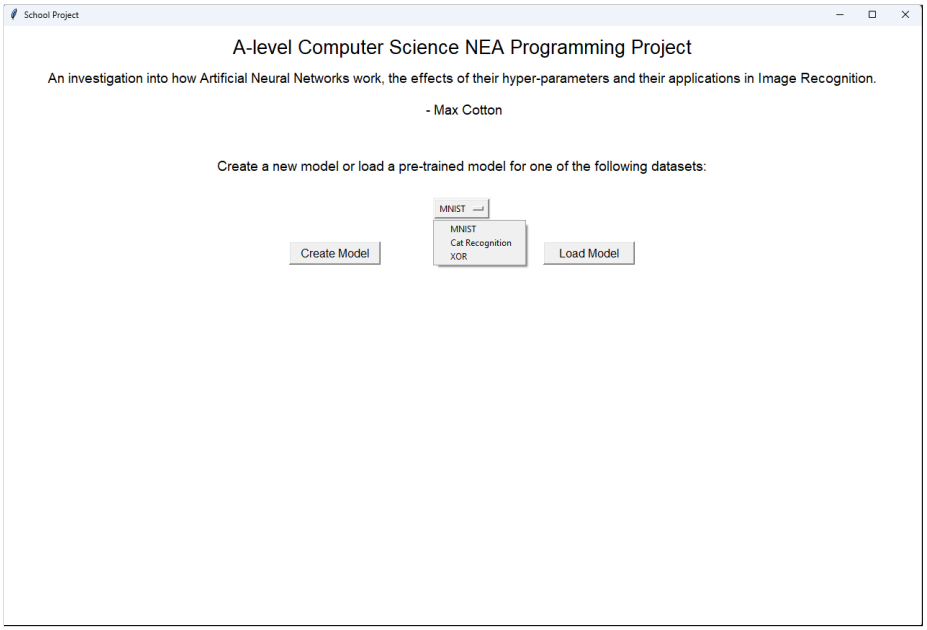
    def test_loaded_model(self) -> None:
        """Load saved model from load model frame, unpack load model frame,
           pack test frame for the dataset and begin managing the test thread."""
        self.saving_model = False
        try:
            self.model = self.load_model_frame.load_model()
        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. For each training dataset that an Artificial Neural Network is trained on, there is a corresponding test dataset with completely new images to be tested on to judge the performance of the trained model. As fewer images are needed for testing than for training, the Cat dataset only has 50 test images (compared to the 209 images for training) and the MNIST dataset only has 10,000 test images (compared to the 60,000 images for training). 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,
15                  use_gpu: bool, model: object) -> None:
16         """Initialise test MNIST frame widgets.
17
18         Args:
19             root (tk.Tk): the widget object that contains this widget.
20             width (int): the pixel width of the frame.
21             height (int): the pixel height of the frame.
22             bg (str): the hex value or name of the frame's background colour.
23             use_gpu (bool): True or False whether the GPU should be used.
24             model (object): The Model object to be tested.
25         Raises:
26             TypeError: if root, width or height are not of the correct type.
27
28         """
29         super().__init__(master=root, width=width, height=height, bg=bg)
30         self.root = root
31         self.WIDTH = width
32         self.HEIGHT = height
33         self.BG = bg
34
35         # Setup test MNIST frame variables
36         self.use_gpu = use_gpu
37
38          # Setup widgets
39         self.model_status_label = tk.Label(master=self,
40                                            bg=self.BG,
41                                            font=('Arial', 15))
42         self.results_label = tk.Label(master=self,
43                                       bg=self.BG,
44                                       font=('Arial', 15))
45         self.correct_prediction_figure = Figure()
46         self.correct_prediction_canvas = FigureCanvasTkAgg(
47                                          figure=self.correct_prediction_figure,
48                                          master=self
49                                          )
50         self.incorrect_prediction_figure = Figure()
51         self.incorrect_prediction_canvas = FigureCanvasTkAgg(
52                                       figure=self.incorrect_prediction_figure,
53                                       master=self
54                                       )
55
56         # Grid widgets
57         self.model_status_label.grid(row=0, columnspan=3, pady=(30,0))
58         self.results_label.grid(row=1, columnspan=3)
59         self.incorrect_prediction_canvas.get_tk_widget().grid(row=2, column=0)
60         self.correct_prediction_canvas.get_tk_widget().grid(row=2, column=2)
61
62         # Start test thread
63         self.model_status_label.configure(text="Testing trained model",
64                                           fg='red')
65         self.test_thread = threading.Thread(target=model.test)
66         self.test_thread.start()
67
68     def plot_results(self, model: object) -> None:
69         """Plot results of Model test.
```

```
70
71              Args:
72                  model (object): the Model object thats been tested.
73
74          """
75          self.model_status_label.configure(text="Testing Results:", fg='green')
76          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
```

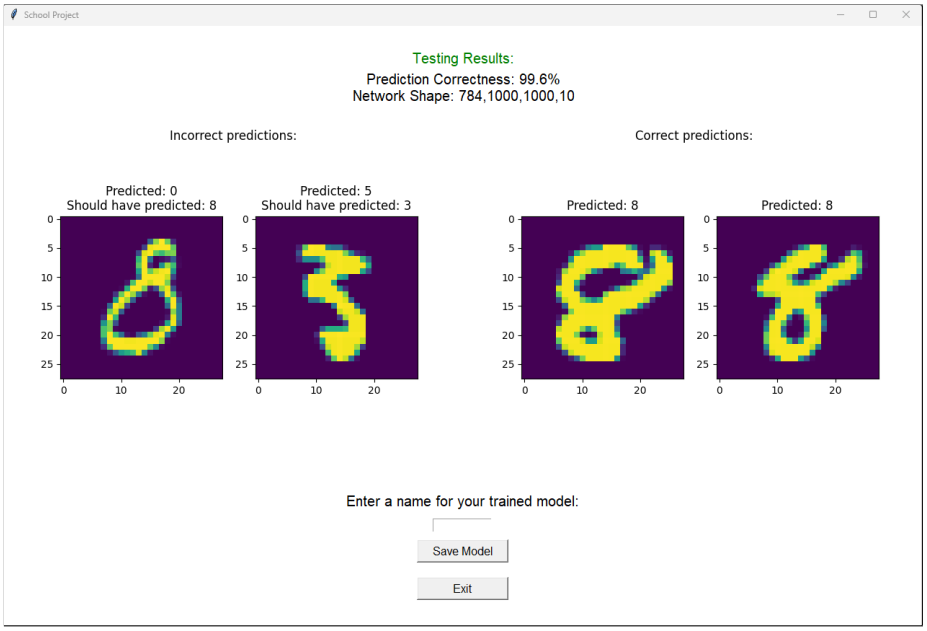
```
126                 elif image_count == 0:
127                     image = self.incorrect_prediction_figure.add_subplot(121)
128                 elif image_count == 1:
129                     image = self.incorrect_prediction_figure.add_subplot(122)
130                 image.set_title(f"Predicted:
                    ↪  {test_prediction[i].index(max(test_prediction[i]))}\n" +
131                                 f"Should have predicted:
                                    ↪  {test_outputs[i].index(max(test_outputs[i]))}")
132                 image.imshow(test_inputs[i].reshape((28,28)))
133                 image_count += 1
134 
135         # Setup correct prediction figure
136         self.correct_prediction_figure.suptitle("Correct predictions:")
137         image_count = 0
138         for i in range(len(test_prediction)):
139             if test_prediction[i].index(max(test_prediction[i])) ==
                ↪  test_outputs[i].index(max(test_outputs[i])):
140                 if image_count == 2:
141                     break
142                 elif image_count == 0:
143                     image = self.correct_prediction_figure.add_subplot(121)
144                 elif image_count == 1:
145                     image = self.correct_prediction_figure.add_subplot(122)
146                 image.set_title(f"Predicted:
                    ↪  {test_prediction[i].index(max(test_prediction[i]))}")
147                 image.imshow(test_inputs[i].reshape((28,28)))
148                 image_count += 1
149 
150 class TestCatRecognitionFrame(tk.Frame):
151     """Frame for Testing Cat Recognition page."""
152     def __init__(self, root: tk.Tk, width: int,
153                  height: int, bg: str,
154                  use_gpu: bool, model: object) -> None:
155         """Initialise test cat recognition frame widgets.
156 
157         Args:
158             root (tk.Tk): the widget object that contains this widget.
159             width (int): the pixel width of the frame.
160             height (int): the pixel height of the frame.
161             bg (str): the hex value or name of the frame's background colour.
162             use_gpu (bool): True or False whether the GPU should be used.
163             model (object): the Model object to be tested.
164         Raises:
165             TypeError: if root, width or height are not of the correct type.
166 
167         """
168         super().__init__(master=root, width=width, height=height, bg=bg)
169         self.root = root
170         self.WIDTH = width
171         self.HEIGHT = height
172         self.BG = bg
173 
174         # Setup image recognition frame variables
175         self.use_gpu = use_gpu
176 
177         # Setup widgets
178         self.model_status_label = tk.Label(master=self,
179                                            bg=self.BG,
180                                            font=('Arial', 15))
181         self.results_label = tk.Label(master=self,
182                                       bg=self.BG,
183                                       font=('Arial', 15))
```

```
184         self.correct_prediction_figure = Figure()
185         self.correct_prediction_canvas = FigureCanvasTkAgg(
186                                          figure=self.correct_prediction_figure,
187                                          master=self
188                                          )
189         self.incorrect_prediction_figure = Figure()
190         self.incorrect_prediction_canvas = FigureCanvasTkAgg(
191                                        figure=self.incorrect_prediction_figure,
192                                        master=self
193                                        )
194 
195         # Grid widgets
196         self.model_status_label.grid(row=0, columnspan=3, pady=(30,0))
197         self.results_label.grid(row=1, columnspan=3)
198         self.incorrect_prediction_canvas.get_tk_widget().grid(row=2, column=0)
199         self.correct_prediction_canvas.get_tk_widget().grid(row=2, column=2)
200 
201         # Start test thread
202         self.model_status_label.configure(text="Testing trained model...",
203                                           fg='red')
204         self.test_thread = threading.Thread(target=model.test)
205         self.test_thread.start()
206 
207     def plot_results(self, model: object) -> None:
208         """Plot results of Model test
209 
210            Args:
211                model (object): the Model object thats been tested.
212 
213         """
214         self.model_status_label.configure(text="Testing Results:", fg='green')
215         if not self.use_gpu:
216             self.results_label.configure(
217              text="Prediction Correctness: " +
218              f"{round(number=100 - np.mean(np.abs(model.test_prediction.round() -
                 ↪  model.test_outputs)) * 100, ndigits=1)}%\n" +
219              f"Network Shape: " +
220              f"{','.join(model.layers_shape)}\n"
221              )
222 
223             # Randomly shuffle order of test_inputs, test_outputs and
                 ↪  test_prediciton
224             # whilst maintaining order between them
225             test_data = list(zip(model.test_inputs.T,
226                                  np.squeeze(model.test_outputs).T.tolist(),
227 
                                     ↪  np.squeeze(model.test_prediction.round()).T.tolist()))
228             random.shuffle(test_data)
229             (test_inputs,
230              test_outputs,
231              test_prediction) = map(lambda arr: np.array(arr).T,
232                                     zip(*test_data))
233 
234         elif self.use_gpu:
235 
236             import cupy as cp
237 
238             self.results_label.configure(
239              text="Prediction Correctness: " +
240              f"{round(number=100 -
                 ↪  np.mean(np.abs(cp.asnumpy(model.test_prediction).round() -
                 ↪  cp.asnumpy(model.test_outputs))) * 100, ndigits=1)}%\n" +
```

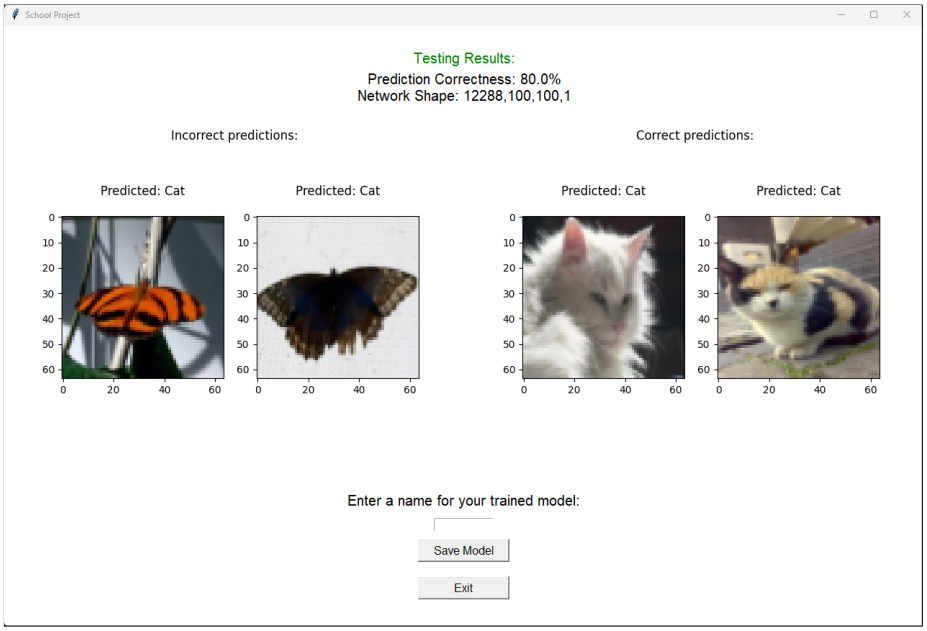
```
241                 f"Network Shape: " +
242                 f"{','.join(model.layers_shape)}\n"
243                 )
244
245             # Randomly shuffle order of test_inputs, test_outputs and
                ↪  test_prediciton
246             # whilst maintaining order between them
247             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()
```

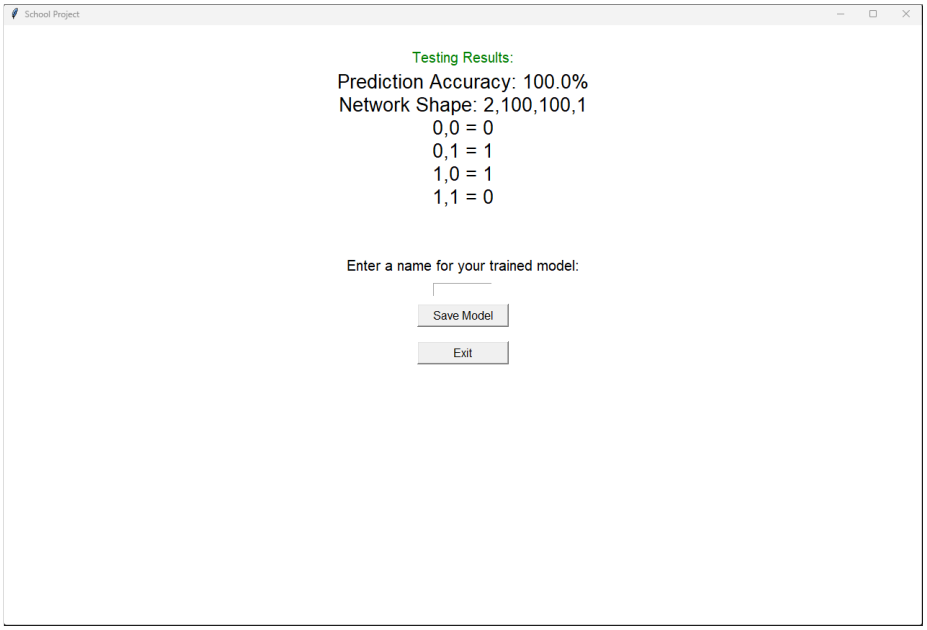
Which outputs the following for the MNIST dataset:



And outputs the following for the Cat Recognition dataset:



And outputs the following for the XOR dataset:



4.1.2 Effects of Hyper-Parameters

For the following investigations, I utilised Jupyter Notebook and have displayed the results below:

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]

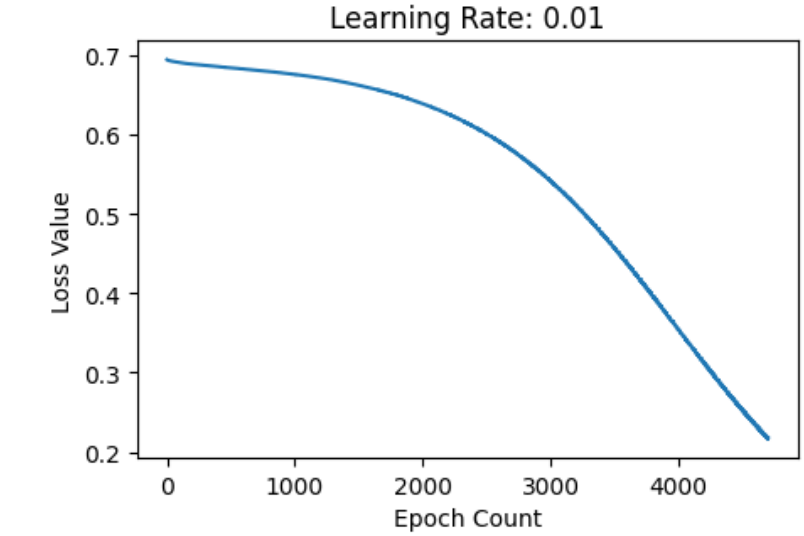
learning_rates = [0.01, 0.1, 1.0]

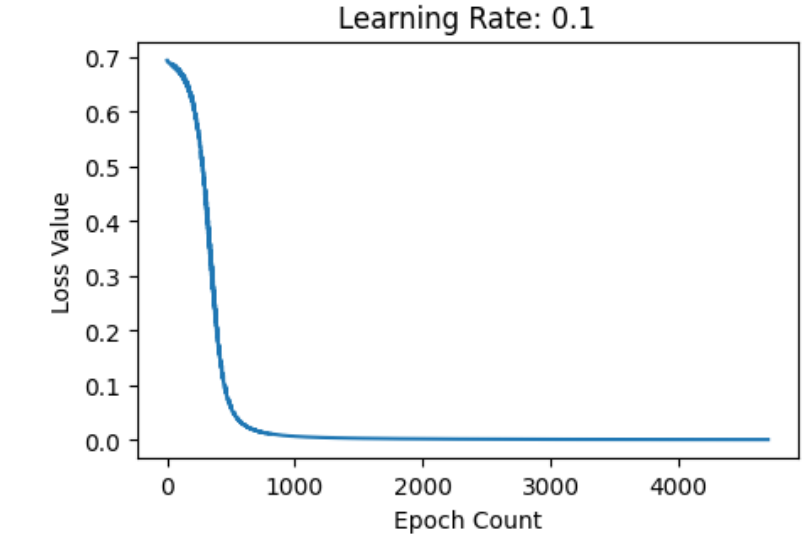
figure, axis = plt.subplots(nrows=len(learning_rates), ncols=1)

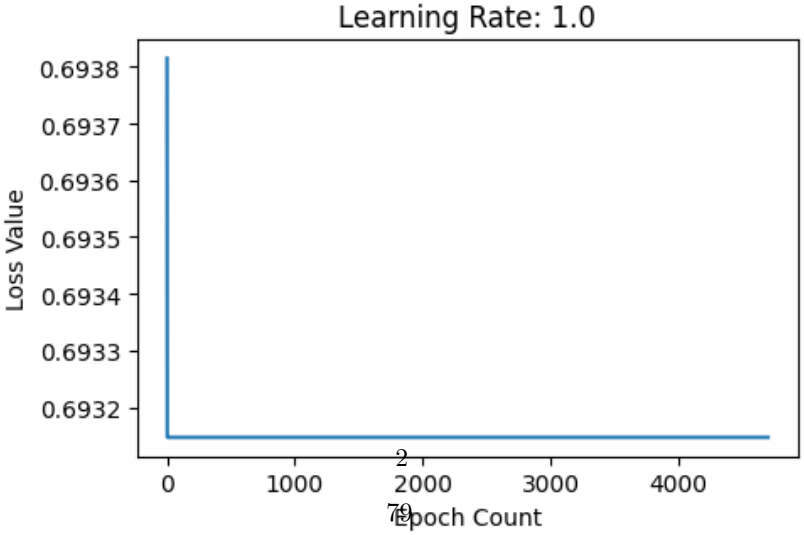
for count, learning_rate in enumerate(learning_rates):
    model = Model(hidden_layers_shape=[100, 100],
                  train_dataset_size=4,
                  learning_rate=learning_rate,
                  use_relu=True)
    model.create_model_values()
    model.train(epoch_count=4_700)
    model.test()

    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)")

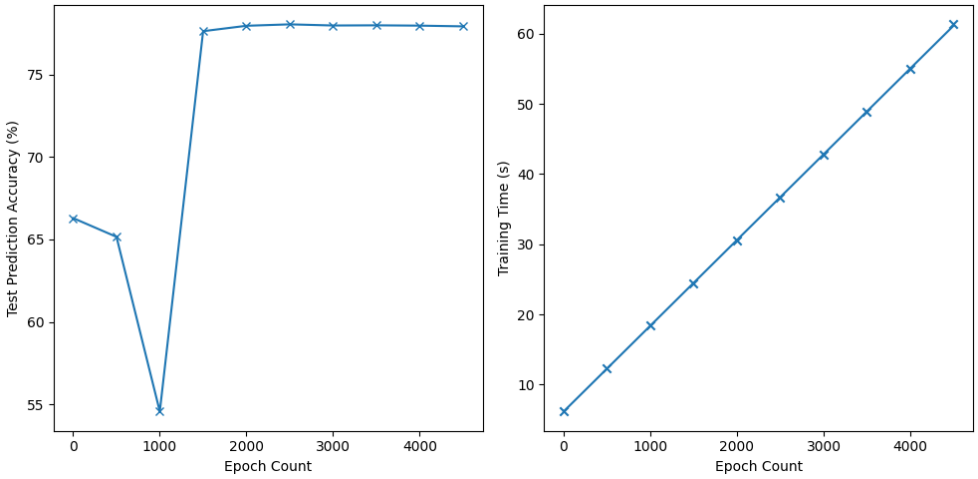
# Plot scatter graph of epoch counts and training times
axis[1].scatter(epoch_counts, training_times, marker='x')

# 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)")

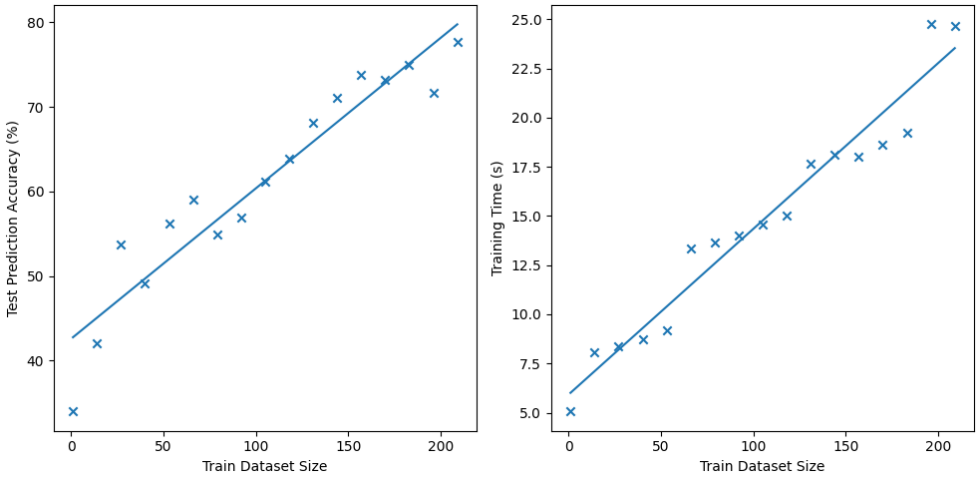
# Plot scatter graph of train dataset sizes and training times
axis[1].scatter(train_dataset_sizes, training_times, marker='x')

# 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)")

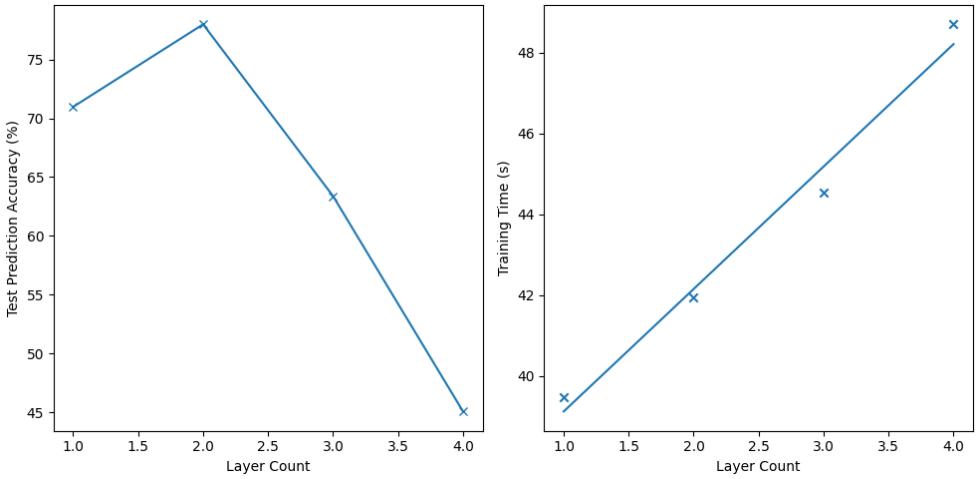
# Plot scatter graph of layer Counts and training times
axis[1].scatter(layer_counts, training_times, marker='x')

# 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)")

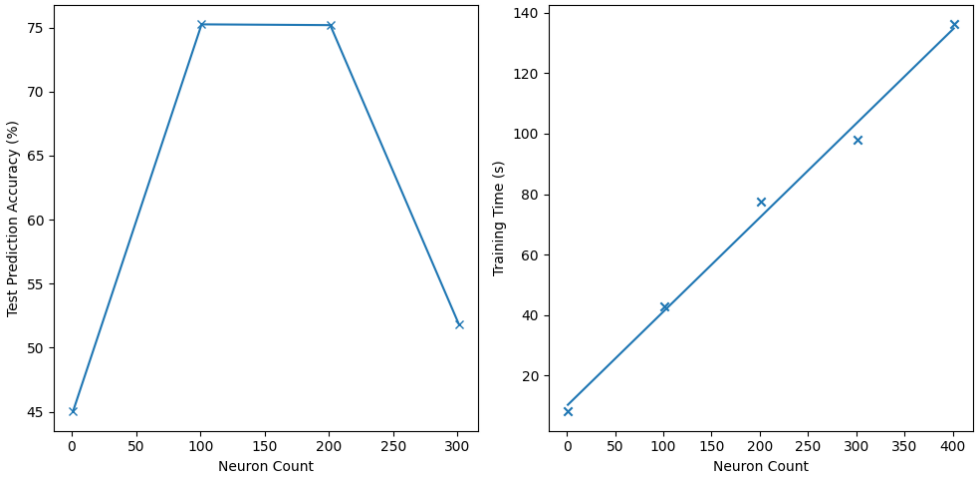
# Plot scatter graph of neuron counts and training times
axis[1].scatter(neuron_counts, training_times, marker='x')

# 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)

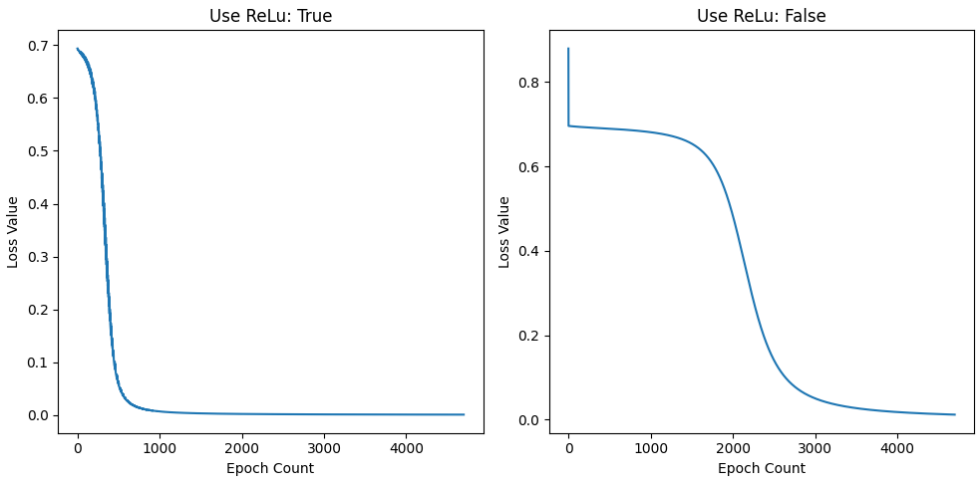
model = Model(hidden_layers_shape=[100, 100],
                train_dataset_size=4,
                learning_rate=0.1,
                use_relu=True)
model.create_model_values()
model.train(epoch_count=4_700)
model.test()

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
```

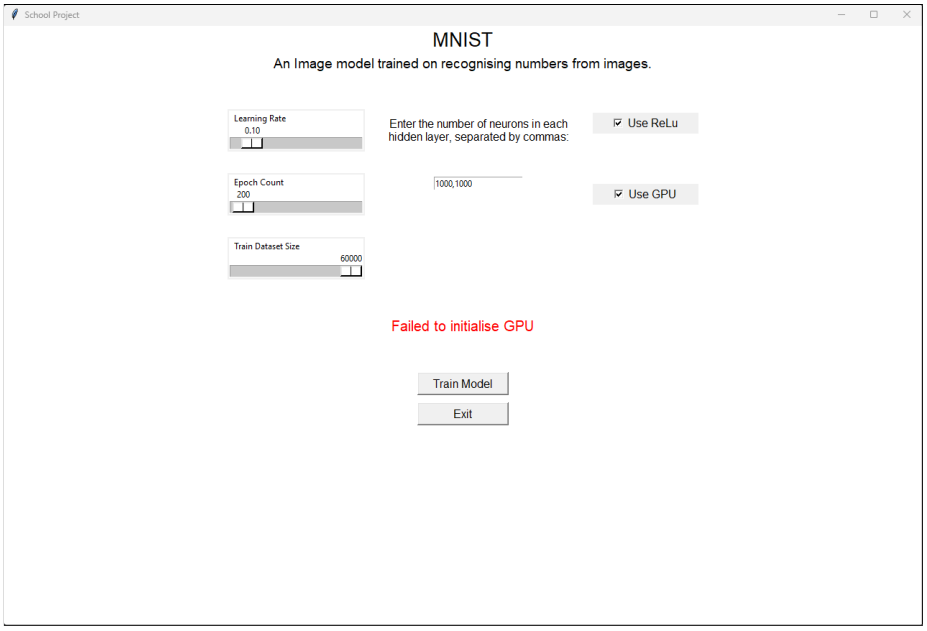
As shown above, the GPU is almost four times faster at training the model than the CPU, showing how beneficial it is to utilise the parallel computations of the GPU

4.2 Manual Testing

4.2.1 Input Validation Testing TODO

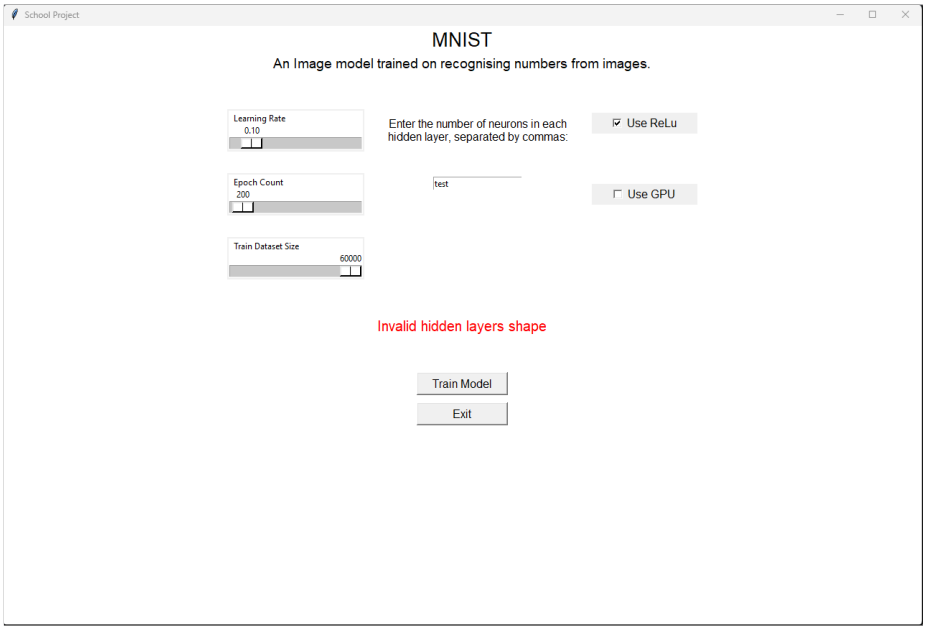
The following tests check the input validation of each frames' inputs.

- Hyper Parameter Frame:
  - Use GPU Validation:
    - Description: Select Use GPU checkbox without a GPU present.
    - Expected Result: The exception should be handled and a usefull error message should be dipslayed.
    - Actual Result: Expected Result
    - Test Status: Pass
    - Evidence:



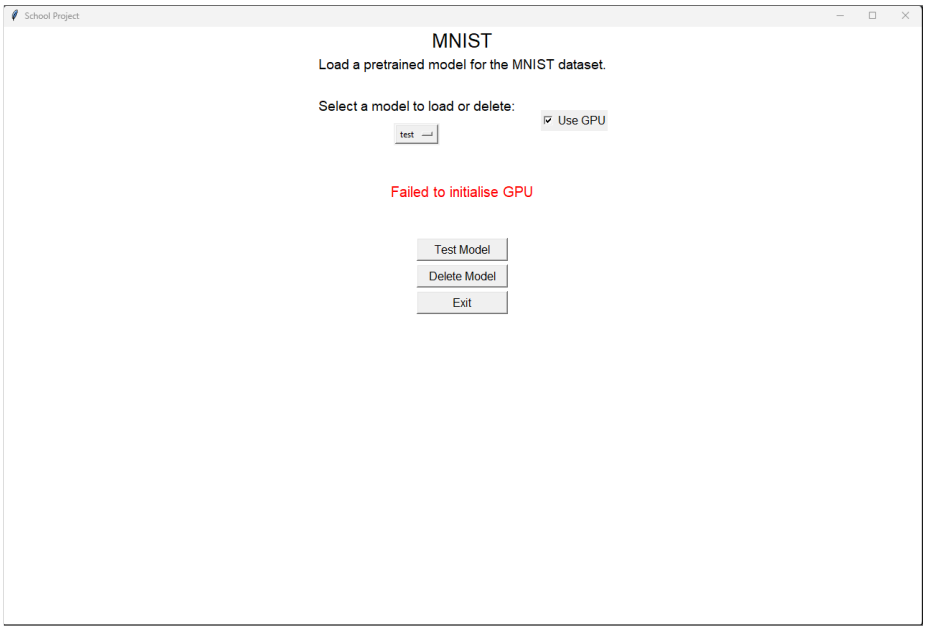
Link to video evidence: `https://github.com/mcttn22/school-project/blob/main/project-report/input-validation-testing-videos.md/#use-gpu-validation`

- Hidden Layers Shape Validation:
  - Description: Enter an invalid hidden layers shape.
  - Data Value: "test"
  - Data Type: Erroneous
  - Expected Result: The exception should be handled and a usefull error message should be dipslayed.
  - Actual Result: Expected Result
  - Test Status: Pass
  - Evidence:



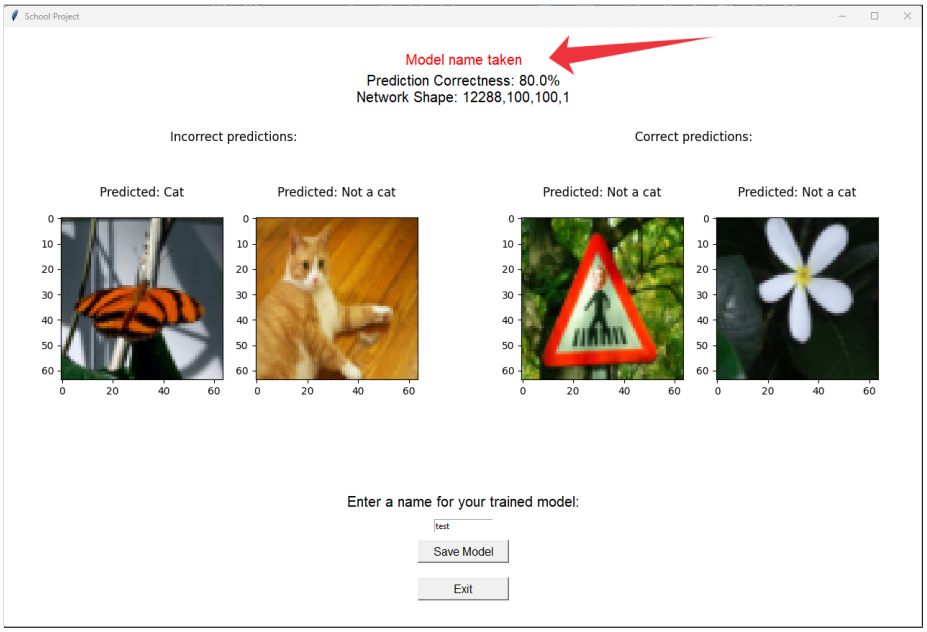
Link to video evidence: `https://github.com/mcttn22/school-project/blob/main/project-report/input-validation-testing-videos.md/#hidden-layers-shape-validation`

- Load Model Frame:
  - Use GPU Validation:
    * Description: Select Use GPU checkbox without a GPU present.
    * Expected Result: The exception should be handled and a usefull error message should be dipslayed.
    * Actual Result: Expected Result
    * Test Status: Pass
    * Evidence:



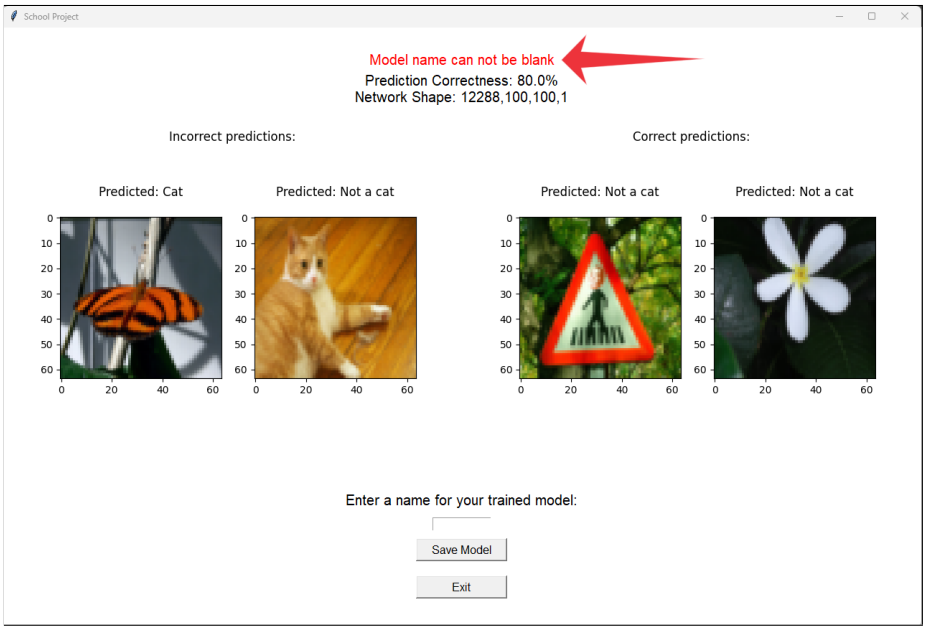
Link to video evidence: `https://github.com/mcttn22/school-project/blob/main/project-report/input-validation-testing-videos.md/#hidden-layers-shape-validation`

- Test Frames:
  - Taken Trained Model Name Validation:
    * Description: Try to save a trained model with an already taken name.
    * Data Value: "test"
    * Data Type: Erroneous
    * Expected Result: The exception should be handled and a usefull error message should be dipslayed.
    * Actual Result: Expected Result
    * Test Status: Pass
    * Evidence:



Link to video evidence: `https://github.com/mcttn22/school-project/blob/main/project-report/input-validation-testing-videos.md/#hidden-layers-shape-validation`

- Empty Trained Model Name Validation:
  - Description: Try to save a trained model with blank name.
  - Data Value: ""
  - Data Type: Erroneous
  - Expected Result: The exception should be handled and a usefull error message should be dipslayed.
  - Actual Result: Expected Result
  - Test Status: Pass
  - Evidence:



Link to video evidence: `https://github.com/mcttn22/school-project/blob/main/project-report/input-validation-testing-videos.md/#hidden-layers-shape-validation`

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:

```
1  """Unit tests for model module."""
2
3  import os
4  import unittest
5  import uuid
```

```
6
7   import numpy as np
8
9   # Test XOR implementation of Model for its lesser computation time
10  from school_project.models.cpu.xor import XORModel
11
12  class TestModel(unittest.TestCase):
13      """Unit tests for model module."""
14      def __init__(self, *args, **kwargs) -> None:
15          """Initialise unit tests and inputs."""
16          super(TestModel, self).__init__(*args, **kwargs)
17
18      def test_train_dataset_size(self) -> None:
19          """Test the size of training dataset to be value chosen."""
20          train_dataset_size = 4
21          model = XORModel(hidden_layers_shape = [100, 100],
22                           train_dataset_size = train_dataset_size,
23                           learning_rate = 0.1,
24                           use_relu = True)
25          model.create_model_values()
26          model.train(epoch_count=1)
27          self.assertEqual(first=model.layers.head.input.shape[1],
28                           second=train_dataset_size)
29
30      def test_network_shape(self) -> None:
31          """Test the neuron count of each layer to match the set shape of
    ↪  the
32             network."""
33          layers_shape = [2, 100, 100, 1]
34          model = XORModel(hidden_layers_shape = [100, 100],
35                           train_dataset_size = 4,
36                           learning_rate = 0.1,
37                           use_relu = True)
38          model.create_model_values()
39          model.train(epoch_count=1)
40          for count, layer in enumerate(model.layers):
41              self.assertEqual(first=layer.input_neuron_count,
42                               second=layers_shape[count])
43
44      def test_learning_rates(self) -> None:
45          """Test learning rate of each layer to be the same."""
46          learning_rate = 0.1
47          model = XORModel(hidden_layers_shape = [100, 100],
48                           train_dataset_size = 4,
49                           learning_rate = learning_rate,
50                           use_relu = True)
51          model.create_model_values()
52          model.train(epoch_count=1)
53          for layer in model.layers:
54              self.assertEqual(first=layer.learning_rate,
                ↪  second=learning_rate)
55
56      def test_relu_model_transfer_types(self) -> None:
57          """Test transfer type of each layer to match whats set."""
58          transfer_types = ['relu', 'relu', 'sigmoid']
59          model = XORModel(hidden_layers_shape = [100, 100],
60                           train_dataset_size = 4,
61                           learning_rate = 0.1,
62                           use_relu = True)
63          model.create_model_values()
64          model.train(epoch_count=1)
65          for count, layer in enumerate(model.layers):
```

```
66              self.assertEqual(first=layer.transfer_type,
67                               second=transfer_types[count])
68
69      def test_sigmoid_model_transfer_types(self) -> None:
70          """Test transfer type of each layer to match whats set."""
71          transfer_types = ['sigmoid', 'sigmoid', 'sigmoid']
72          model = XORModel(hidden_layers_shape = [100, 100],
73                                   train_dataset_size = 4,
74                                   learning_rate = 0.1,
75                                   use_relu = False)
76          model.create_model_values()
77          model.train(epoch_count=1)
78          for count, layer in enumerate(model.layers):
79              self.assertEqual(first=layer.transfer_type,
80                               second=transfer_types[count])
81
82      def test_weight_matrice_shapes(self) -> None:
83          """Test that each layer's weight matrix has the same number of
    ↪  columns
84          as the layer's input matrix's number of rows, for the matrice
85          multiplication."""
86          model = XORModel(hidden_layers_shape = [100, 100],
87                           train_dataset_size = 4,
88                           learning_rate = 0.1,
89                           use_relu = True)
90          model.create_model_values()
91          model.train(epoch_count=1)
92          for layer in model.layers:
93              self.assertEqual(first=layer.weights.shape[1],
94                               second=layer.input.shape[0])
95
96      def test_bias_matrice_shapes(self) -> None:
97          """Test that each layer's bias matrix has the same number of rows
98          as the result of the layer's weights and input multiplication, for
99          element-wise addition of the biases."""
100         model = XORModel(hidden_layers_shape = [100, 100],
101                          train_dataset_size = 4,
102                          learning_rate = 0.1,
103                          use_relu = True)
104         model.create_model_values()
105         model.train(epoch_count=1)
106         for layer in model.layers:
107             self.assertEqual(first=layer.biases.shape[0],
108                              second=layer.weights.shape[0])
109
110     def test_layer_output_shapes(self) -> None:
111         """Test the shape of each layer's activation function's output."""
112         model = XORModel(hidden_layers_shape = [100, 100],
113                          train_dataset_size = 4,
114                          learning_rate = 0.1,
115                          use_relu = True)
116         model.create_model_values()
117         model.train(epoch_count=1)
118         for layer in model.layers:
119             self.assertEqual(
120                          first=(layer.weights.shape[0],
                             ↪  layer.input.shape[1]),
121                          second=layer.output.shape
122                          )
123
124     def test_save_model(self) -> None:
125         """Test that the weights and biases are saved correctly."""
```

```
126         initial_model = XORModel(hidden_layers_shape = [100, 100],
127                                  train_dataset_size = 4,
128                                  learning_rate = 0.1,
129                                  use_relu = True)
130         initial_model.create_model_values()
131         initial_model.train(epoch_count=1)
132 
133         # Save model values
134         file_location =
            ↪  f"school_project/saved-models/{uuid.uuid4().hex}.npz"
135         initial_model.save_model_values(file_location=file_location)
136 
137         # Create model from the saved values
138         loaded_model = XORModel(hidden_layers_shape = [100, 100],
139                                 train_dataset_size = 4,
140                                 learning_rate = 0.1,
141                                 use_relu = True)
142         loaded_model.load_model_values(file_location=file_location)
143 
144         # Remove the saved model values
145         os.remove(path=file_location)
146 
147         # Compare initial and loaded model values
148         for layer1, layer2 in zip(initial_model.layers,
            ↪  loaded_model.layers):
149             self.assertTrue(np.array_equal(a1=layer1.weights,
150                                            a2=layer2.weights))
151             self.assertTrue(np.array_equal(a1=layer1.biases,
152                                            a2=layer2.biases))
153 
154 if __name__ == '__main__':
155     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()
```

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.

```
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
```

4.3.3 Docker

I also provide a basic Dockerfile and instructions for its use in the README.md file, so that the project can be quickly run and tested in Docker containers. Below shows the contents of the basic Dockerfile:

```
FROM python:3.11

# Set a directory for the app
WORKDIR /usr/src/app

# Copy all the files to the container
COPY . .

# Install dependencies
RUN python setup.py install

# Run the project
CMD ["python", "./school_project"]
```

5 Evaluation TODO

5.1 Project Objectives Evaluation

5.1.1 Project Objectives

For the reader's convenience, I have restated the project objectives below:

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

5.1.2 Project Objective Evaluations

Objective ID	Evaluation
1	x
2	x
2.1	x
2.2	x
3	x
3.1	x
3.2	x

5.2 Third Party Feedback

5.3 Future Improvements