

# 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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# 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 useful free resources on the internet to use. I particularly 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 Artificial 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.

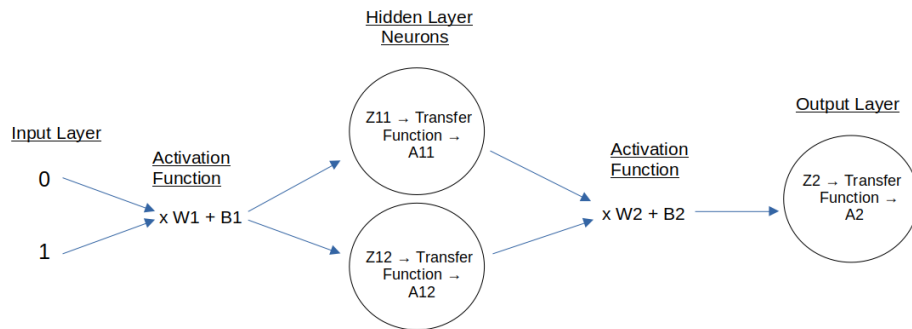


Figure 1: This shows an Artificial Neural Network with one single hidden layer and is known as a Shallow Neural Network.

To implement an Artificial Neural Network, matrices are used to represent the layers, where each layer is a matrix 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 matrix 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 useful 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 multi-variable functions, by taking respect to one variable and treating the rest as constants.
      - The Chain Rule, where for  $y = f(u)$  and  $u = g(x)$ ,  $\frac{\partial y}{\partial u} = \frac{\partial y}{\partial u} * \frac{\partial u}{\partial x}$
      - For a matrix of  $f(x)$  values, the matrix 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

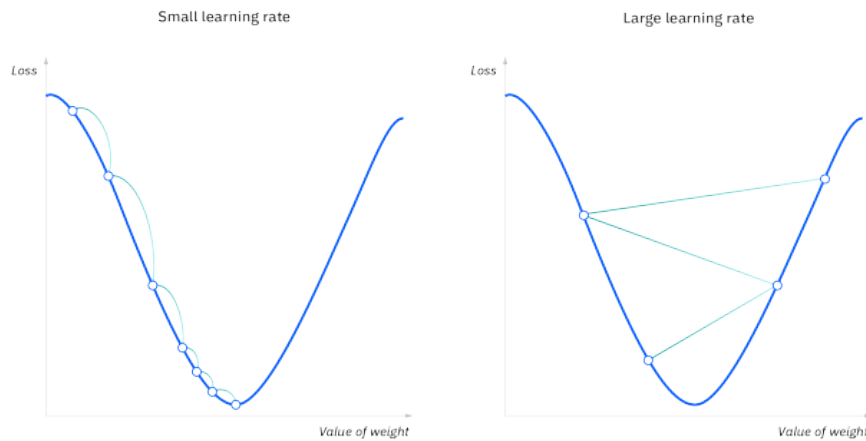


Figure 2: Gradient Descent  
sourced from <https://www.ibm.com/topics/gradient-descent>

- \* 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





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

- 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 initialised 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
  - 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.

$$* \text{ Where } \text{sigmoid}(Z) = \frac{1}{1+e^{-Z}}$$

- 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 larger values of  $\frac{\partial L}{\partial W}$  and  $\frac{\partial L}{\partial B}$  for Gradient Descent than Sigmoid, so updates at a quicker rate.

$$* \text{ Where } \text{relu}(Z) = \max(0, Z)$$

### 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,  $\frac{\partial Z3}{\partial A2} = W3$   
 $\Rightarrow \frac{\partial L}{\partial A2} = \frac{\partial L}{\partial A3} * \frac{\partial A3}{\partial Z3} * W3$
  - $\frac{\partial L}{\partial W2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * \frac{\partial Z2}{\partial W2}$   
 By using function 1, where A1 is X for the 2nd layer,  $\frac{\partial Z2}{\partial W2} = A1$   
 $\Rightarrow \frac{\partial L}{\partial W2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * A1$
  - $\frac{\partial L}{\partial B2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * \frac{\partial Z2}{\partial B2}$   
 By using function 1,  $\frac{\partial Z2}{\partial B2} = 1$   
 $\Rightarrow \frac{\partial L}{\partial W2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * 1$
- 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 derivative 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  $Z \geq 0$  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 calculations, 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 famous 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 matrix 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 matrix 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 useful for quickly comparing different hyper-parameters of a Network, whilst still not being linearly separable.

### 1.7.2 Theory behind using Graphics Cards to train Artificial Neural Networks

Graphics Cards consist of many Tensor cores which are processing units specialised 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

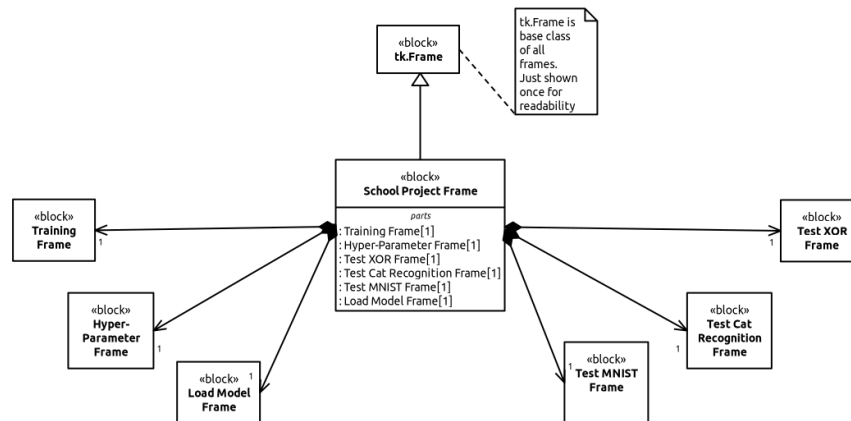
bdd [block] School Project Frame [System Architecture Diagram]



## 2.3 Class Diagrams

### 2.3.1 UI Class Diagram

bdd [package] School Project [UI Class Diagram]



### 2.3.2 Model Class Diagram

bdd [package] School Project [Model Class Diagram]



## 2.4 System Flow chart

act [activity] System Flow chart [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 useful, such as returning multiple values from methods.
- Dictionaries for loading the default hyper-parameter values from a JSON file.
- Matrices to represent the layers and allow for a varied number of neurons in each layer. To represent the Matrices I will use both numpy arrays and cupy arrays.
- A Doubly linked list to represent the Artificial Neural Network, where each node is a layer of the network. This will allow me to traverse both forwards and backwards through the network, as well as storing the first and last layer to start forward and backward propagation respectively.

## 2.7 File Structure

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

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



## 2.8 Database Design

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

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

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

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

## 2.9 Queries

Here are some example queries for interacting with the database:

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

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

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

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

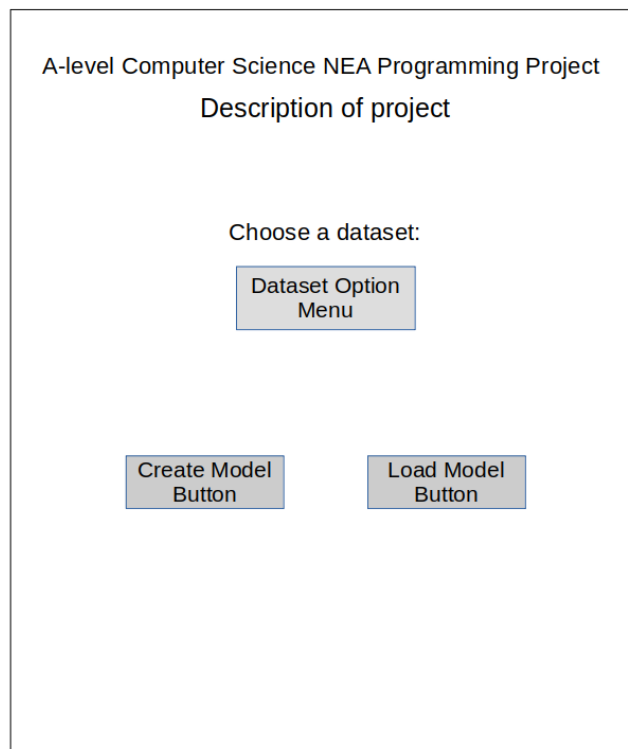
- I can query the features of a saved model with:

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

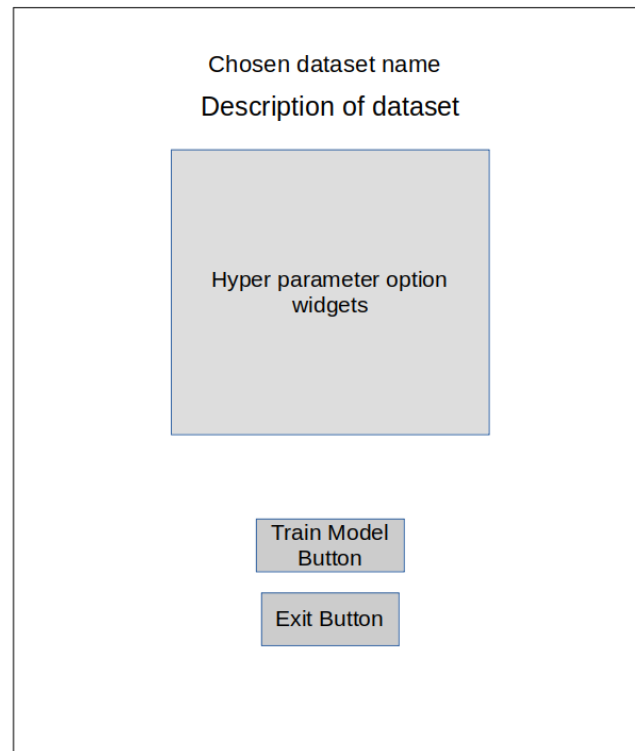
## 2.10 Human-Computer Interaction

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

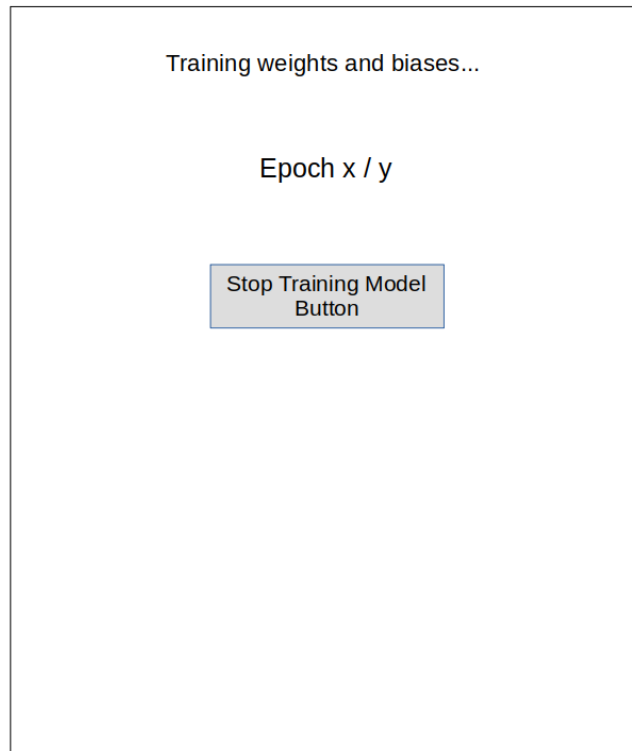
- Home Frame design:



- Hyper-Parameter Frame design:



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



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



- Load Model Frame design:



- Test Frame design:

Testing Results:  
Prediction Accuracy: x %  
Network Shape: y

Example Results

Enter a name for your trained model:

Text Entry for  
model name

Save Model  
Button

Exit Button

## 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 computationally powerful 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 separately.
- 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**

### **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:

---

```
1  """Package of tkinter frames for the main window."""
2
3  from .create_model import HyperParameterFrame, TrainingFrame
4  from .load_model import LoadModelFrame
5  from .test_model import TestMNISTFrame, TestCatRecognitionFrame,
6  ↪ TestXORFrame
7  __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:

---

```
1  from setuptools import setup, find_packages
2
3  setup(
4      name='school-project',
5      version='1.0.0',
6      packages=find_packages(),
7      url='https://github.com/mcttn22/school-project.git',
8      author='Max Cotton',
9      author_email='maxcotton22@gmail.com',
10     description='Year 13 Computer Science Programming Project',
11     install_requires=[
12         'cupy-cuda12x',
13         'h5py',
14         'matplotlib',
15         'numpy',
16         'pympler'
17     ],
18 )
```

---

### 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:

---

```

1 # Byte compiled files
2 __pycache__/_
3
4 # Packaging
5 *.egg-info
6
7 # Database file
8 school_project/saved_models.db

```

---

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

– Markdown code:

---

```

1 <!-- The following lines generate badges showing the current status of
   ↳ the automated testing (Passing or Failing) and a Python3 badge
   ↳ correspondingly.) -->
2 [![tests](https://github.com/mcttn22/school-project/actions/workflows/tests.yml/badge.svg)](https://
3 [!python](https://img.shields.io/badge/Python-3-3776AB.svg?style=flat&logo=python&logoColor=white)]
4
5 # A-level Computer Science NEA Programming Project
6
7 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.
8
9 ## Installation
10
11 1. Download the Repository with:
12
13 - ```
14   git clone https://github.com/mcttn22/school-project.git
15   ```
16 - Or by downloading as a ZIP file
17
18 </br>
19
20 2. Create a virtual environment (venv) with:
21 - Windows:
22   ```
23   python -m venv {venv name}
24   ```
25 - Linux:
26   ```
27   python3 -m venv {venv name}
28   ```
29
30 3. Enter the venv with:
31 - Windows:
32   ```
33   .\{venv name}\Scripts\activate
34   ```
35 - Linux:
36   ```
37   source ./{venv name}/bin/activate
38   ```

```

```

39
40 4. Enter the project directory with:
41     ````
42     cd school-project/
43     ````
44
45 5. For normal use, install the dependencies and the project to the
   ↳ venv with:
46     - Windows:
47         ````
48         python setup.py install
49         ````
50     - Linux:
51         ````
52         python3 setup.py install
53         ````
54
55 *Note: In order to use an Nvidia GPU for training the networks, the
   ↳ latest Nvidia drivers must be installed and the CUDA Toolkit must
   ↳ be installed from
56 <a href="https://developer.nvidia.com/cuda-downloads">here</a>.*
57
58 ## Usage
59
60 Run with:
61 - Windows:
62     ````
63     python school_project
64     ````
65 - Linux:
66     ````
67     python3 school_project
68     ````
69
70 ## Development
71
72 Install the dependencies and the project to the venv in developing
   ↳ mode with:
73 - Windows:
74     ````
75     python setup.py develop
76     ````
77 - Linux:
78     ````
79     python3 setup.py develop
80     ````
81
82 Run Tests with:
83 - Windows:
84     ````
85     python -m unittest discover .\school_project\test\
86     ````
87 - Linux:
88     ````
89     python3 -m unittest discover ./school_project/test/
90     ````
91
92 Use Docker with:
93 - Build the Docker Image with:
94     ````
95     sudo docker build -t mcttn22/school-project ./
96     ````

```

```

97 - Run the Docker Image with:
98   ```
99   sudo apt-get install x11-xserver-utils
100  xhost +
101  sudo docker run -v /tmp/.X11-unix:/tmp/.X11-unix -e
102  ↵ DISPLAY=unix$DISPLAY mcttn22/school-project
103  ```
104  Compile Project Report PDF with:
105  ```
106  make all
107  ```
108  *Note: This requires the Late $\mathit{x}$ mk, pdflat $\mathit{e}$ ck and Pygments libraries*

```

---

- Which will generate the following:

 Tests passing
 Python 3

## A-level Computer Science NEA Programming Project

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

### Installation

1. Download the Repository with:

- `git clone https://github.com/mcttn22/school-project.git` 

- Or by downloading as a ZIP file

2. Create a virtual environment (venv) with:

- Windows:

```
python -m venv {venv name}
```



- Linux:

```
python3 -m venv {venv name}
```



3. Enter the venv with:

- Windows:

```
.\{venv name}\Scripts\activate
```



- Linux:

```
source ./{venv name}/bin/activate
```



4. Enter the project directory with:

```
cd school-project/
```



5. For normal use, install the dependencies and the project to the venv with:

- Windows:

```
python setup.py install
```



- Linux:

```
python3 setup.py install
```



*Note: In order to use an Nvidia GPU for training the networks, the latest Nvidia 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, pdflatex 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:

---

```

1  """Helper functions and ModelInterface class for model module."""
2
3  from abc import ABC, abstractmethod
4
5  import numpy as np
6
7  class ModelInterface(ABC):
8      """Interface for ANN models."""
9      @abstractmethod
10     def _setup_layers(setup_values: callable) -> None:
11         """Decorator that sets up model layers and sets up values of each
↪ layer
12         with the method given.
13
14         Args:
15             setup_values (callable): the method that sets up the values of
↪ each
16             layer.
17         Raises:
18             NotImplementedError: if this method is not implemented.
19
20         """
21         raise NotImplementedError
22
23     @abstractmethod
24     def create_model_values(self) -> None:
25         """Create weights and bias/biases
26
27         Raises:
28             NotImplementedError: if this method is not implemented.
29
30         """
31         raise NotImplementedError
32
33     @abstractmethod
34     def load_model_values(self, file_location: str) -> None:
35         """Load weights and bias/biases from .npz file.
36
37         Args:
38             file_location (str): the location of the file to load from.
39         Raises:
40             NotImplementedError: if this method is not implemented.
41
42         """
43         raise NotImplementedError
44
45     @abstractmethod
46     def load_datasets(self, train_dataset_size: int) -> tuple[np.ndarray,
↪ np.ndarray,
47                                                                np.ndarray,
↪ np.ndarray]:
48         """Load input and output datasets. For the input dataset, each
↪ column
49         should represent a piece of data and each row should store the
↪ values
50         of the piece of data.
51
52         Args:
53             train_dataset_size (int): the number of train dataset inputs to
↪ use.

```

```

54         Returns:
55             tuple of train_inputs, train_outputs,
56             test_inputs and test_outputs.
57         Raises:
58             NotImplementedError: if this method is not implemented.
59
60         """
61         raise NotImplementedError
62
63     @abstractmethod
64     def back_propagation(self, prediction: np.ndarray) -> None:
65         """Adjust the weights and bias/biases via gradient descent.
66
67         Args:
68             prediction (numpy.ndarray): the matrice of prediction values
69         Raises:
70             NotImplementedError: if this method is not implemented.
71
72         """
73         raise NotImplementedError
74
75     @abstractmethod
76     def forward_propagation(self) -> np.ndarray:
77         """Generate a prediction with the weights and bias/biases.
78
79         Returns:
80             numpy.ndarray of prediction values.
81         Raises:
82             NotImplementedError: if this method is not implemented.
83
84         """
85         raise NotImplementedError
86
87     @abstractmethod
88     def test(self) -> None:
89         """Test trained weights and bias/biases.
90
91         Raises:
92             NotImplementedError: if this method is not implemented.
93
94         """
95         raise NotImplementedError
96
97     @abstractmethod
98     def train(self, epochs: int) -> None:
99         """Train weights and bias/biases.
100
101         Args:
102             epochs (int): the number of forward and back propagations to
↪ do.
103         Raises:
104             NotImplementedError: if this method is not implemented.
105
106         """
107         raise NotImplementedError
108
109     @abstractmethod
110     def save_model_values(self, file_location: str) -> None:
111         """Save the model by saving the weights then biases of each layer
↪ to
112             a .npz file with a given file location.
113

```

```

114         Args:
115             file_location (str): the file location to save the model to.
116
117         """
118         raise NotImplementedError
119
120 def relu(z: np.ndarray | int | float) -> np.ndarray | float:
121     """Transfer function, transform input to max number between 0 and z.
122
123     Args:
124         z (numpy.ndarray | int | float):
125             the numpy.ndarray | int | float to be transferred.
126     Returns:
127         numpy.ndarray | float,
128         with all values / the value transferred to max number between 0-z.
129     Raises:
130         TypeError: if z is not of type numpy.ndarray | int | float.
131
132     """
133     return np.maximum(0.1*z, 0) # Divide by 10 to stop overflow errors
134
135 def relu_derivative(output: np.ndarray) -> np.ndarray:
136     """Calculate derivative of ReLu Transfer function with respect to z.
137
138     Args:
139         output (numpy.ndarray):
140             the numpy.ndarray output of the ReLu transfer function.
141     Returns:
142         numpy.ndarray,
143         derivative of the ReLu transfer function with respect to z.
144     Raises:
145         TypeError: if output is not of type numpy.ndarray.
146
147     """
148     output[output <= 0] = 0
149     output[output > 0] = 1
150
151     return output
152
153 def sigmoid(z: np.ndarray | int | float) -> np.ndarray | float:
154     """Transfer function, transform input to number between 0 and 1.
155
156     Args:
157         z (numpy.ndarray | int | float):
158             the numpy.ndarray | int | float to be transferred.
159     Returns:
160         numpy.ndarray | float,
161         with all values / the value transferred to a number between 0-1.
162     Raises:
163         TypeError: if z is not of type numpy.ndarray | int | float.
164
165     """
166     return 1 / (1 + np.exp(-z))
167
168 def sigmoid_derivative(output: np.ndarray | int | float) -> np.ndarray |
169     ↪ float:
170     """Calculate derivative of sigmoid Transfer function with respect to z.
171
172     Args:
173         output (numpy.ndarray | int | float):
174             the numpy.ndarray | int | float output of the sigmoid transfer
175     ↪ function.

```

```

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

```

---

- model.py module:

```

1     """Provides an abstract class for Artificial Neural Network models."""
2
3     from collections.abc import Generator
4     import time
5
6     import numpy as np
7
8     from .tools import (
9         ModelInterface,
10        relu,
11        relu_derivative,
12        sigmoid,
13        sigmoid_derivative,
14        calculate_loss,
15        calculate_prediction_accuracy

```

```

16         )
17
18     class _FullyConnectedLayer():
19         """Fully connected layer for Deep ANNs,
20         represented as a node of a Doubly linked list."""
21         def __init__(self, learning_rate: float, input_neuron_count: int,
22                     output_neuron_count: int, transfer_type: str) -> None:
23             """Initialise layer values.
24
25             Args:
26                 learning_rate (float): the learning rate of the model.
27                 input_neuron_count (int):
28                 the number of input neurons into the layer.
29                 output_neuron_count (int):
30                 the number of output neurons into the layer.
31                 transfer_type (str): the transfer function type
32                 ('sigmoid' or 'relu')
33
34             """
35             # Setup layer attributes
36             self.previous_layer = None
37             self.next_layer = None
38             self.input_neuron_count = input_neuron_count
39             self.output_neuron_count = output_neuron_count
40             self.transfer_type = transfer_type
41             self.input: np.ndarray
42             self.output: np.ndarray
43
44             # Setup weights and biases
45             self.weights: np.ndarray
46             self.biases: np.ndarray
47             self.learning_rate = learning_rate
48
49         def __repr__(self) -> str:
50             """Read values of the layer.
51
52             Returns:
53                 a string description of the layers's
54                 weights, bias and learning rate values.
55
56             """
57             return (f"Weights: {self.weights.tolist()}\n" +
58                     f"Biases: {self.biases.tolist()}\n")
59
60         def init_layer_values_random(self) -> None:
61             """Initialise weights to random values and biases to 0s"""
62             np.random.seed(1) # Sets up pseudo random values for layer weight
63                               ↪ arrays
64             self.weights = np.random.rand(self.output_neuron_count,
65                               ↪ self.input_neuron_count) - 0.5
66             self.biases = np.zeros(shape=(self.output_neuron_count, 1))
67
68         def init_layer_values_zeros(self) -> None:
69             """Initialise weights to 0s and biases to 0s"""
70             self.weights = np.zeros(shape=(self.output_neuron_count,
71                               ↪ self.input_neuron_count))
72             self.biases = np.zeros(shape=(self.output_neuron_count, 1))
73
74         def back_propagation(self, dloss_doutput) -> np.ndarray:
75             """Adjust the weights and biases via gradient descent.
76
77             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_dbases = 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_dbases
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
163             ↪ use.
164             learning_rate (float): the learning rate of the model.
165             use_relu (bool): True or False whether the ReLu Transfer
166             ↪ function
167             should be used.
168
169         """
170         # Setup model data
171         self.train_inputs, self.train_outputs, \
172         self.test_inputs, self.test_outputs = self.load_datasets(
173
174             ↪ train_dataset_size=train_dataset_size
175             )
176
177         self.train_losses: list[float]
178         self.test_prediction: np.ndarray
179         self.test_prediction_accuracy: float
180         self.training_progress = ""
181         self.training_time: float
182
183         # Setup model attributes
184         self._running = True
185         self.input_neuron_count: int = self.train_inputs.shape[0]
186         self.input_count = self.train_inputs.shape[1]
187         self.hidden_layers_shape = hidden_layers_shape
188         self.output_neuron_count = self.train_outputs.shape[0]
189         self.layers_shape = [f'{layer}' for layer in (
190             [self.input_neuron_count] +
191             self.hidden_layers_shape +
192             [self.output_neuron_count]
193         )]
194         self.use_relu = use_relu
195
196         # 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
233                     ↪ learning_rate=self.learning_rate,
234
235                     ↪ input_neuron_count=self.input_neuron_count,
236
237                     ↪ output_neuron_count=self.hidden_layers_shape[0],
238                     transfer_type='relu'
239                 )
240                 current_layer = self.layers.head
241
242                 # Add hidden layers
243                 for layer in range(len(self.hidden_layers_shape) - 1):
244                     current_layer.next_layer = _FullyConnectedLayer(
245                         learning_rate=self.learning_rate,
246
247                         ↪ input_neuron_count=self.hidden_layers_shape[layer],
248
249                         ↪ output_neuron_count=self.hidden_layers_shape[layer
250                         ↪ + 1],
251                         transfer_type='relu'
252                     )

```



```

247         current_layer.next_layer.previous_layer =
248             ↪ current_layer
249         current_layer = current_layer.next_layer
250     else:
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         # Add hidden layers
260         for layer in range(len(self.hidden_layers_shape) - 1):
261             current_layer.next_layer = _FullyConnectedLayer(
262                 learning_rate=self.learning_rate,
263                 ↪ input_neuron_count=self.hidden_layers_shape[layer],
264                 ↪ output_neuron_count=self.hidden_layers_shape[layer
265                     ↪ + 1],
266                 transfer_type='sigmoid'
267             )
268             current_layer.next_layer.previous_layer =
269                 ↪ current_layer
270             current_layer = current_layer.next_layer
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     # Setup Perceptron Network
281     else:
282         self.layers.head = _FullyConnectedLayer(
283             learning_rate=self.learning_rate,
284             ↪ input_neuron_count=self.input_neuron_count,
285             ↪ output_neuron_count=self.output_neuron_count,
286             transfer_type='sigmoid'
287         )
288         self.layers.tail = self.layers.head
289     setup_values(self, *args, **kwargs)
290
291     return decorator
292
293 @setup_layers
294 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
336         ↪ output.
337
338         """
339         for layer in reversed(self.layers):
340             dloss_doutput =
341             ↪ layer.back_propagation(dloss_doutput=dloss_doutput)
342
343     def forward_propagation(self) -> np.ndarray:
344         """Generate a prediction with the layers.
345
346         Returns:
347         a numpy.ndarray of the prediction values.
348
349         """
350         output = self.train_inputs
351         for layer in self.layers:
352             output = layer.forward_propagation(inputs=output)
353         return output
354
355     def test(self) -> None:
356         """Test the layers' trained weights and biases."""
357         output = self.test_inputs
358         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
363                                     ↪ prediction=self.test_prediction,
364                                     ↪ outputs=self.test_outputs
365                                     )
366
367     def train(self, epoch_count: int) -> None:
368         """Train layers' weights and biases.
369
370         Args:
371             epoch_count (int): the number of training epochs.
372
373         """
374         self.layers_shape = [f'{layer}' for layer in (
375             [self.input_neuron_count] +
376             self.hidden_layers_shape +
377             [self.output_neuron_count]
378         )]
379         self.train_losses = []
380         training_start_time = time.time()
381         for epoch in range(epoch_count):
382             if not self.__running:
383                 break
384             self.training_progress = f"Epoch {epoch} / {epoch_count}"
385             prediction = self.forward_propagation()
386             loss = calculate_loss(input_count=self.input_count,
387                                 ↪ outputs=self.train_outputs,
388                                 ↪ prediction=prediction)
389             self.train_losses.append(loss)
390             if not self.__running:
391                 break
392             dloss_doutput = -(1/self.input_count) * ((self.train_outputs -
393                 ↪ prediction)/(prediction * (1 - prediction)))
394             self.back_propagation(dloss_doutput=dloss_doutput)
395             self.training_time = round(number=time.time() -
396                 ↪ training_start_time,
397                                     ↪ ndigits=2)
398
399     def save_model_values(self, file_location: str) -> None:
400         """Save the model by saving the weights then biases of each layer
401         ↪ to
402         a .npz file with a given file location.
403
404         Args:
405             file_location (str): the file location to save the model to.
406
407         """
408         saved_model: list[np.ndarray] = []
409         for layer in self.layers:
410             saved_model.append(layer.weights)
411             saved_model.append(layer.biases)
412         np.savez(file_location, *saved_model)

```

---

### 3.2.2 Artificial Neural Network implementations

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

- cat\_recognition.py module:

---

```

1  """Implementation of Artificial Neural Network model on Cat Recognition
    ↪ dataset."""
2
3  import h5py
4  import numpy as np
5
6  from .utils.model import AbstractModel
7
8  class CatRecognitionModel(AbstractModel):
9      """ANN model that trains to predict if an image is a cat or not a
    ↪ cat."""
10     def __init__(self,
11                  hidden_layers_shape: list[int],
12                  train_dataset_size: int,
13                  learning_rate: float,
14                  use_relu: bool) -> None:
15         """Initialise Model's Base class.
16
17         Args:
18             hidden_layers_shape (list[int]):
19                 list of the number of neurons in each hidden layer.
20             train_dataset_size (int): the number of train dataset inputs to
    ↪ use.
21             learning_rate (float): the learning rate of the model.
22             use_relu (bool): True or False whether the ReLu Transfer
    ↪ function
23                 should be used.
24
25         """
26         super().__init__(hidden_layers_shape=hidden_layers_shape,
27                          train_dataset_size=train_dataset_size,
28                          learning_rate=learning_rate,
29                          use_relu=use_relu)
30
31     def load_datasets(self, train_dataset_size: int) -> tuple[np.ndarray,
    ↪ np.ndarray,
32                                                                np.ndarray,
    ↪ np.ndarray]:
33
34         """Load image input and output datasets.
35
36         Args:
37             train_dataset_size (int): the number of train dataset inputs to
    ↪ use.
38
39         Returns:
40             tuple of image train_inputs, train_outputs,
41             test_inputs and test_outputs numpy.ndarrays.
42
43         Raises:
44             FileNotFoundError: if file does not exist.
45
46         """
47         # Load datasets from h5 files
48         # (h5 files stores large amount of data with quick access)
49         train_dataset: h5py.File = h5py.File(
50             r'school_project/models/datasets/train-cat.h5',
51             'r'
52         )
53         test_dataset: h5py.File = h5py.File(
54             r'school_project/models/datasets/test-cat.h5',
55             'r'

```

```

54         )
55
56     # Load input arrays,
57     # containing the RGB values for each pixel in each 64x64 pixel
58     ↪ image,
59     # for 209 images
60     train_inputs: np.ndarray =
61     ↪ np.array(train_dataset['train_set_x'][:])
62     test_inputs: np.ndarray = np.array(test_dataset['test_set_x'][:])
63
64     # Load output arrays of 1s for cat and 0s for not cat
65     train_outputs: np.ndarray =
66     ↪ np.array(train_dataset['train_set_y'][:])
67     test_outputs: np.ndarray = np.array(test_dataset['test_set_y'][:])
68
69     # Reshape input arrays into 1 dimension (flatten),
70     # then divide by 255 (RGB)
71     # to standardize them to a number between 0 and 1
72     train_inputs = train_inputs.reshape((train_inputs.shape[0],
73     -1)).T / 255
74     test_inputs = test_inputs.reshape((test_inputs.shape[0], -1)).T /
75     ↪ 255
76
77     # Reshape output arrays into a 1 dimensional list of outputs
78     train_outputs = train_outputs.reshape((1, train_outputs.shape[0]))
79     test_outputs = test_outputs.reshape((1, test_outputs.shape[0]))
80
81     # Reduce train datasets' sizes to train_dataset_size
82     train_inputs = (train_inputs.T[:train_dataset_size]).T
83     train_outputs = (train_outputs.T[:train_dataset_size]).T
84
85     return train_inputs, train_outputs, test_inputs, test_outputs

```

---

- mnist.py module:

```

1  """Implementation of Artificial Neural Network model on MNIST dataset."""
2
3  import pickle
4  import gzip
5
6  import numpy as np
7
8  from .utils.model import AbstractModel
9
10 class MNISTModel(AbstractModel):
11     """ANN model that trains to predict Numbers from images."""
12     def __init__(self, hidden_layers_shape: list[int],
13                 train_dataset_size: int,
14                 learning_rate: float,
15                 use_relu: bool) -> None:
16         """Initialise Model's Base class.
17
18         Args:
19             hidden_layers_shape (list[int]):
20                 list of the number of neurons in each hidden layer.
21             train_dataset_size (int): the number of train dataset inputs to
22     ↪ use.
23             learning_rate (float): the learning rate of the model.
24             use_relu (bool): True or False whether the ReLu Transfer
25     ↪ function
26             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,
33     ↪ np.ndarray,
34                                                           np.ndarray,
35                                                           ↪ np.ndarray]:
36
37         """Load image input and output datasets.
38         Args:
39             train_dataset_size (int): the number of dataset inputs to use.
40         Returns:
41             tuple of image train_inputs, train_outputs,
42             test_inputs and test_outputs numpy.ndarrays.
43
44         Raises:
45             FileNotFoundError: if file does not exist.
46
47         """
48         # Load datasets from.pkl.gz file
49         with gzip.open(
50             'school_project/models/datasets/mnist.pkl.gz',
51             'rb'
52         ) as mnist:
53             (train_inputs, train_outputs), \
54             (test_inputs, test_outputs) = pickle.load(mnist,
55             ↪ encoding='bytes')
56
57         # Reshape input arrays into 1 dimension (flatten),
58         # then divide by 255 (RGB)
59         # to standardize them to a number between 0 and 1
60         train_inputs =
61         ↪ np.array(train_inputs.reshape((train_inputs.shape[0],
62                                         -1)).T / 255)
63
64         test_inputs = np.array(test_inputs.reshape(test_inputs.shape[0],
65         ↪ -1).T / 255)
66
67         # Represent number values
68         # with a one at the matching index of an array of zeros
69         train_outputs = np.eye(np.max(train_outputs) + 1)[train_outputs].T
70         test_outputs = np.eye(np.max(test_outputs) + 1)[test_outputs].T
71
72         # Reduce train datasets' sizes to train_dataset_size
73         train_inputs = (train_inputs.T[:train_dataset_size]).T
74         train_outputs = (train_outputs.T[:train_dataset_size]).T
75
76         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

```

```

9         inputs."""
10     def __init__(self,
11                 hidden_layers_shape: list[int],
12                 train_dataset_size: int,
13                 learning_rate: float,
14                 use_relu: bool) -> None:
15         """Initialise Model's Base class.
16
17         Args:
18             hidden_layers_shape (list[int]):
19                 list of the number of neurons in each hidden layer.
20             train_dataset_size (int): the number of train dataset inputs to
21 ↪ use.
22             learning_rate (float): the learning rate of the model.
23             use_relu (bool): True or False whether the ReLu Transfer
24 ↪ function
25                 should be used.
26
27         """
28         super().__init__(hidden_layers_shape=hidden_layers_shape,
29                         train_dataset_size=train_dataset_size,
30                         learning_rate=learning_rate,
31                         use_relu=use_relu)
32
33     def load_datasets(self, train_dataset_size: int) -> tuple[np.ndarray,
34 ↪ np.ndarray,
35                                     np.ndarray,
36 ↪ np.ndarray]:
37
38         """Load XOR input and output datasets.
39
40         Args:
41             train_dataset_size (int): the number of dataset inputs to use.
42         Returns:
43             tuple of XOR train_inputs, train_outputs,
44             test_inputs and test_outputs numpy.ndarrays.
45
46         """
47         inputs: np.ndarray = np.array([[0, 0, 1, 1],
48                                       [0, 1, 0, 1]])
49         outputs: np.ndarray = np.array([[0, 1, 1, 0]])
50
51         # Reduce train datasets' sizes to train_dataset_size
52         inputs = (inputs.T[:train_dataset_size]).T
53         outputs = (outputs.T[:train_dataset_size]).T
54
55         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:

```

1 {
2     "MNIST": {
3         "description": "An Image model trained on recognising numbers from
↪ images.",

```

```

4         "epochCount": 150,
5         "hiddenLayersShape": [1000, 1000],
6         "minTrainDatasetSize": 1,
7         "maxTrainDatasetSize": 60000,
8         "maxLearningRate": 1
9     },
10    "Cat Recognition": {
11        "description": "An Image model trained on recognising if an image
↪ is a cat or not.",
12        "epochCount": 3500,
13        "hiddenLayersShape": [100, 100],
14        "minTrainDatasetSize": 1,
15        "maxTrainDatasetSize": 209,
16        "maxLearningRate": 0.3
17    },
18    "XOR": {
19        "description": "For experimenting with Artificial Neural Networks,
↪ a XOR gate model has been used for its lesser computation time.",
20        "epochCount": 4700,
21        "hiddenLayersShape": [100, 100],
22        "minTrainDatasetSize": 2,
23        "maxTrainDatasetSize": 4,
24        "maxLearningRate": 1
25    }
26 }

```

---

- create\_model.py module:

```

1  """Tkinter frames for creating an Artificial Neural Network model."""
2
3  import json
4  import threading
5  import tkinter as tk
6  import tkinter.font as tkf
7
8  from matplotlib.figure import Figure
9  from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg
10 import numpy as np
11
12 class HyperParameterFrame(tk.Frame):
13     """Frame for hyper-parameter page."""
14     def __init__(self, root: tk.Tk, width: int,
15                 height: int, bg: str, dataset: str) -> None:
16         """Initialise hyper-parameter 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             dataset (str): the name of the dataset to use
24             ('MNIST', 'Cat Recognition' or 'XOR')
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 hyper-parameter frame variables
36     self.dataset = dataset
37     self.use_gpu: bool
38     self.default_hyper_parameters = self.load_default_hyper_parameters(
39
40                                     ↪ dataset=dataset
41                                     )
42
43     # Setup widgets
44     self.title_label = tk.Label(master=self,
45                                bg=self.BG,
46                                font=('Arial', 20),
47                                text=dataset)
48     self.about_label = tk.Label(
49         master=self,
50         bg=self.BG,
51         font=('Arial', 14),
52
53         ↪ text=self.default_hyper_parameters['description']
54         )
55     self.learning_rate_scale = tk.Scale(
56         master=self,
57         bg=self.BG,
58         orient='horizontal',
59         label="Learning Rate",
60         length=185,
61         from_=0,
62
63         ↪ to=self.default_hyper_parameters['maxLearningRate'],
64         resolution=0.01
65         )
66     self.learning_rate_scale.set(value=0.1)
67     self.epoch_count_scale = tk.Scale(master=self,
68                                       bg=self.BG,
69                                       orient='horizontal',
70                                       label="Epoch Count",
71                                       length=185,
72                                       from_=0,
73                                       to=10_000,
74                                       resolution=100)
75     self.epoch_count_scale.set(
76
77         ↪ value=self.default_hyper_parameters['epochCount']
78         )
79     self.train_dataset_size_scale = tk.Scale(
80         master=self,
81         bg=self.BG,
82         orient='horizontal',
83         label="Train Dataset Size",
84         length=185,
85
86         ↪ from_=self.default_hyper_parameters['minTrainDatasetSize'],
87         to=self.default_hyper_parameters['maxTrainDatasetSize'],
88         resolution=1
89         )
90     self.train_dataset_size_scale.set(
91
92         ↪ value=self.default_hyper_parameters['maxTrainDatasetSize']
93         )

```

```

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" +
           "hidden layer, separated by
           ↳ commas:"
93     )
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
141            ↳ hyper-parameters
142                for. ('MNIST', 'Cat Recognition' or 'XOR')
143        Returns:

```

```

143         a dictionary of default hyper-parameter values.
144         """
145         with open('school_project/frames/hyper-parameter-defaults.json') as
146             ↪ f:
147             return json.load(f)[dataset]
148
149 def create_model(self) -> object:
150     """Create and return a Model using the hyper-parameters set.
151
152     Returns:
153     a Model object.
154     """
155     self.use_gpu = self.use_gpu_check_button_var.get()
156
157     # Validate hidden layers shape input
158     hidden_layers_shape_input = [layer for layer in
159     ↪ self.hidden_layers_shape_entry.get().replace(' ',
160     ↪ '').split(',') if layer != '']
161     for layer in hidden_layers_shape_input:
162         if not layer.isdigit():
163             self.model_status_label.configure(
164                 text="Invalid hidden layers shape",
165                 fg='red'
166             )
167             raise ValueError
168
169     # Create Model
170     if not self.use_gpu:
171         if self.dataset == "MNIST":
172             from school_project.models.cpu.mnist import MNISTModel as
173             ↪ Model
174         elif self.dataset == "Cat Recognition":
175             from school_project.models.cpu.cat_recognition import
176             ↪ CatRecognitionModel as Model
177         elif self.dataset == "XOR":
178             from school_project.models.cpu.xor import XORModel as Model
179         model = Model(
180             hidden_layers_shape = [int(neuron_count) for neuron_count
181             ↪ in hidden_layers_shape_input],
182             train_dataset_size = self.train_dataset_size_scale.get(),
183             learning_rate = self.learning_rate_scale.get(),
184             use_relu = self.use_relu_check_button_var.get()
185         )
186         model.create_model_values()
187
188     else:
189         try:
190             if self.dataset == "MNIST":
191                 from school_project.models.gpu.mnist import MNISTModel
192                 ↪ as Model
193             elif self.dataset == "Cat Recognition":
194                 from school_project.models.gpu.cat_recognition import
195                 ↪ CatRecognitionModel as Model
196             elif self.dataset == "XOR":
197                 from school_project.models.gpu.xor import XORModel as
198                 ↪ Model
199             model = Model(hidden_layers_shape = [int(neuron_count) for
200             ↪ neuron_count in hidden_layers_shape_input],
201                 train_dataset_size =
202                 ↪ self.train_dataset_size_scale.get(),
203                 learning_rate =
204                 ↪ self.learning_rate_scale.get(),

```

```

193         use_relu =
194             ↪ self.use_relu_check_button_var.get()
195         model.create_model_values()
196     except ImportError as ie:
197         self.model_status_label.configure(
198             text="Failed to initialise GPU",
199             fg='red'
200         )
201         raise ImportError
202     return model
203
204 class TrainingFrame(tk.Frame):
205     """Frame for training page."""
206     def __init__(self, root: tk.Tk, width: int,
207                 height: int, bg: str,
208                 model: object, epoch_count: int) -> None:
209         """Initialise training frame widgets.
210
211         Args:
212             root (tk.Tk): the widget object that contains this widget.
213             width (int): the pixel width of the frame.
214             height (int): the pixel height of the frame.
215             bg (str): the hex value or name of the frame's background
216             ↪ colour.
217             model (object): the Model object to be trained.
218             epoch_count (int): the number of training epochs.
219
220         Raises:
221             TypeError: if root, width or height are not of the correct
222             ↪ type.
223
224         """
225         super().__init__(master=root, width=width, height=height, bg=bg)
226         self.root = root
227         self.WIDTH = width
228         self.HEIGHT = height
229         self.BG = bg
230
231         # Setup widgets
232         self.model_status_label = tk.Label(master=self,
233             bg=self.BG,
234             font=('Arial', 15))
235         self.training_progress_label = tk.Label(master=self,
236             bg=self.BG,
237             font=('Arial', 15))
238         self.loss_figure: Figure = Figure()
239         self.loss_canvas: FigureCanvasTkAgg = FigureCanvasTkAgg(
240             ↪ figure=self.loss_figure,
241             master=self
242         )
243
244         # Pack widgets
245         self.model_status_label.pack(pady=(30,0))
246         self.training_progress_label.pack(pady=30)
247
248         # Start training thread
249         self.model_status_label.configure(
250             text="Training weights and
251             ↪ biases...",
252             fg='red'
253         )
254         self.train_thread: threading.Thread = threading.Thread(

```

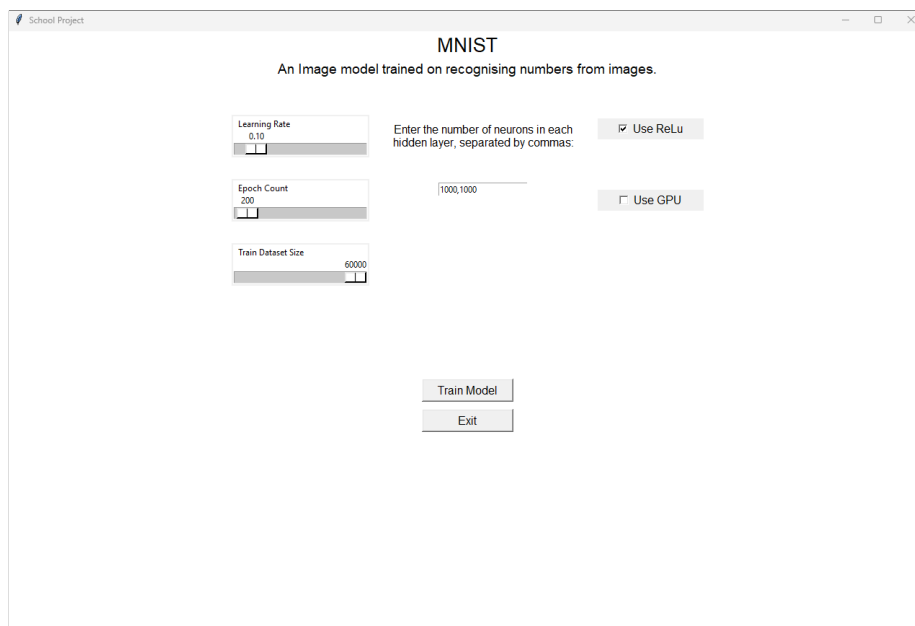
```

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

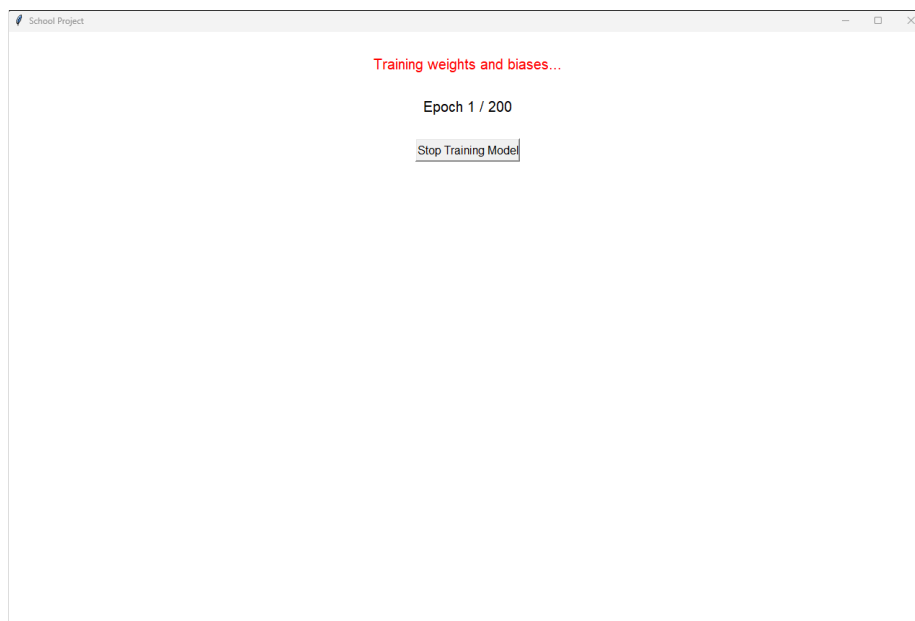
```

---

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:

```

1  """Tkinter frames for loading a saved Artificial Neural Network Model."""
2
3  import sqlite3
4  import tkinter as tk
5  import tkinter.font as tkf
6
7  class LoadModelFrame(tk.Frame):
8      """Frame for load model page."""
9      def __init__(self, root: tk.Tk,
10                  width: int, height: int,
11                  bg: str, connection: sqlite3.Connection,
12                  cursor: sqlite3.Cursor, dataset: str) -> None:
13          """Initialise load model frame widgets.
14
15          Args:
16              root (tk.Tk): the widget object that contains this widget.
17              width (int): the pixel width of the frame.
18              height (int): the pixel height of the frame.
19              bg (str): the hex value or name of the frame's background
20  ↪ colour.
21              connection (sqlite3.Connection): the database connection
22  ↪ object.
23              cursor (sqlite3.Cursor): the database cursor object.
24              dataset (str): the name of the dataset to use
25                  ('MNIST', 'Cat Recognition' or 'XOR')
26          Raises:
27              TypeError: if root, width or height are not of the correct
28  ↪ type.
29          """

```

```

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}"
51         ↪ dataset."
52     )
53     self.model_status_label = tk.Label(master=self,
54                                        bg=self.BG,
55                                        font=('Arial', 15))
56
57     # Don't give loaded model options if no models have been saved for
58     ↪ the
59     # dataset.
60     if len(self.model_options) > 0:
61         self.model_option_menu_label = tk.Label(
62             master=self,
63             bg=self.BG,
64             font=('Arial', 14),
65             text="Select a model to"
66             ↪ load or delete:"
67         )
68         self.model_option_menu_var = tk.StringVar(
69             master=self,
70             ↪ value=self.model_options[0]
71         )
72         self.model_option_menu = tk.OptionMenu(
73             self,
74             ↪ self.model_option_menu_var,
75             *self.model_options
76         )
77         self.use_gpu_check_button_var = tk.BooleanVar()
78         self.use_gpu_check_button = tk.Checkbutton(
79             master=self,
80             width=7, height=1,
81             font=tkf.Font(size=12),
82             text="Use GPU",
83             ↪ variable=self.use_gpu_check_button_var
84         )
85     else:
86         self.model_status_label.configure(

```



```

84                                     text='No saved models for this
85                                     ↪ dataset.',
86                                     fg='red'
87                                     )
88
89     # Pack widgets
90     self.title_label.grid(row=0, column=0, columnspan=3)
91     self.about_label.grid(row=1, column=0, columnspan=3)
92     if len(self.model_options) > 0: # Check if options should be given
93         self.model_option_menu_label.grid(row=2, column=0, padx=(0,30),
94         ↪ pady=(30,0))
95         self.use_gpu_check_button.grid(row=2, column=2, rowspan=2,
96         ↪ pady=(30,0))
97         self.model_option_menu.grid(row=3, column=0, padx=(0,30),
98         ↪ pady=(10,0))
99     self.model_status_label.grid(row=4, column=0,
100                                columnspan=3, pady=50)
101
102 def load_model_options(self) -> list[str]:
103     """Load the model options from the database.
104
105     Returns:
106         a list of the model options.
107     """
108     sql = f"""
109     SELECT Name FROM Models WHERE Dataset=?
110     """
111     parameters = (self.dataset.replace(" ", "_"),)
112     self.cursor.execute(sql, parameters)
113
114     # Save the string value contained within the tuple of each row
115     model_options = []
116     for model_option in self.cursor.fetchall():
117         model_options.append(model_option[0])
118
119     return model_options
120
121 def load_model(self) -> object:
122     """Create model using saved weights and biases.
123
124     Returns:
125         a Model object.
126     """
127     self.use_gpu = self.use_gpu_check_button_var.get()
128
129     # Query data of selected saved model from database
130     sql = """
131     SELECT * FROM Models WHERE Dataset=? AND Name=?
132     """
133     parameters = (self.dataset.replace(" ", "_"),
134     ↪ self.model_option_menu_var.get())
135     self.cursor.execute(sql, parameters)
136     data = self.cursor.fetchone()
137     hidden_layers_shape_input = [layer for layer in data[3].replace('
138     ↪ ', '').split(',') if layer != '']
139
140     # Create Model
141     if not self.use_gpu:
142         if self.dataset == "MNIST":
143             from school_project.models.cpu.mnist import MNISTModel as
144             ↪ Model

```

```

139         elif self.dataset == "Cat Recognition":
140             from school_project.models.cpu.cat_recognition import
141                 ↪ CatRecognitionModel as Model
142         elif self.dataset == "XOR":
143             from school_project.models.cpu.xor import XORModel as Model
144         model = Model(
145             hidden_layers_shape=[int(neuron_count) for neuron_count in
146                 ↪ hidden_layers_shape_input],
147             train_dataset_size=data[6],
148             learning_rate=data[4],
149             use_relu=data[7]
150         )
151         model.load_model_values(file_location=data[2])
152     else:
153         try:
154             if self.dataset == "MNIST":
155                 from school_project.models.gpu.mnist import MNISTModel
156                 ↪ as Model
157             elif self.dataset == "Cat Recognition":
158                 from school_project.models.gpu.cat_recognition import
159                 ↪ CatRecognitionModel as Model
160             elif self.dataset == "XOR":
161                 from school_project.models.gpu.xor import XORModel as
162                 ↪ Model
163             model = Model(
164                 hidden_layers_shape=[int(neuron_count) for neuron_count
165                 ↪ in hidden_layers_shape_input],
166                 train_dataset_size=data[6],
167                 learning_rate=data[4],
168                 use_relu=data[7]
169             )
170             model.load_model_values(file_location=data[2])
171         except ImportError as ie:
172             self.model_status_label.configure(
173                 text="Failed to initialise
174                 ↪ GPU",
175                 fg='red'
176             )
177             raise ImportError
178     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:

---

```

1  """The entrypoint of A-level Computer Science NEA Programming Project."""
2
3  import os
4  import sqlite3
5  import threading
6  import tkinter as tk
7  import tkinter.font as tkf
8  import uuid
9
10 import pympler.tracker as tracker
11
12 from school_project.frames import (HyperParameterFrame, TrainingFrame,
13                                   LoadModelFrame, TestMNISTFrame,
14                                   TestCatRecognitionFrame, TestXORFrame)
15
16 class SchoolProjectFrame(tk.Frame):
17     """Main frame of school project."""
18     def __init__(self, root: tk.Tk, width: int, height: int, bg: str) -> None:
19         """Initialise school project pages.
20
21         Args:
22             root (tk.Tk): the widget object that contains this widget.
23             width (int): the pixel width of the frame.
24             height (int): the pixel height of the frame.
25             bg (str): the hex value or name of the frame's background colour.
26
27         Raises:
28             TypeError: if root, width or height are not of the correct type.
29
30         """
31         super().__init__(master=root, width=width, height=height, bg=bg)
32         self.root = root.title("School Project")
33         self.WIDTH = width
34         self.HEIGHT = height
35         self.BG = bg
36
37         # Setup school project frame variables
38         self.hyper_parameter_frame: HyperParameterFrame
39         self.training_frame: TrainingFrame
40         self.load_model_frame: LoadModelFrame
41         self.test_frame: TestMNISTFrame | TestCatRecognitionFrame | TestXORFrame
42         self.connection, self.cursor = self.setup_database()
43         self.model = None
44
45         # Record if the model should be saved after testing,
46         # as only newly created models should be given the option to be saved.
47         self.saving_model: bool
48
49         # Setup school project frame widgets
50         self.exit_hyper_parameter_frame_button = tk.Button(
51             master=self,
52             width=13,
53             height=1,
54             font=tkf.Font(size=12),
55             text="Exit",
56             command=self.exit_hyper_parameter_frame
57         )
58         self.exit_load_model_frame_button = tk.Button(
59             master=self,
60             width=13,
61             height=1,
62             font=tkf.Font(size=12),
63             text="Exit",

```

```

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

```

```

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

```

```

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

```

```

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

```



```

311         self.test_frame = TestMNISTFrame(
312             root=self,
313             width=self.WIDTH,
314             height=self.HEIGHT,
315             bg=self.BG,
316             use_gpu=self.hyper_parameter_frame.use_gpu,
317             model=self.model
318         )
319     elif self.hyper_parameter_frame.dataset == "Cat Recognition":
320         self.test_frame = TestCatRecognitionFrame(
321             root=self,
322             width=self.WIDTH,
323             height=self.HEIGHT,
324             bg=self.BG,
325             use_gpu=self.hyper_parameter_frame.use_gpu,
326             model=self.model
327         )
328     elif self.hyper_parameter_frame.dataset == "XOR":
329         self.test_frame = TestXORFrame(root=self,
330                                         width=self.WIDTH,
331                                         height=self.HEIGHT,
332                                         bg=self.BG,
333                                         model=self.model)
334     self.test_frame.pack()
335     self.manage_testing(test_thread=self.test_frame.test_thread)
336
337 def test_loaded_model(self) -> None:
338     """Load saved model from load model frame, unpack load model frame,
339     pack test frame for the dataset and begin managing the test thread."""
340     self.saving_model = False
341     try:
342         self.model = self.load_model_frame.load_model()
343     except (ValueError, ImportError) as e:
344         return
345     self.load_model_frame.pack_forget()
346     self.test_loaded_model_button.pack_forget()
347     self.delete_loaded_model_button.pack_forget()
348     self.exit_load_model_frame_button.pack_forget()
349     if self.load_model_frame.dataset == "MNIST":
350         self.test_frame = TestMNISTFrame(
351             root=self,
352             width=self.WIDTH,
353             height=self.HEIGHT,
354             bg=self.BG,
355             use_gpu=self.load_model_frame.use_gpu,
356             model=self.model
357         )
358     elif self.load_model_frame.dataset == "Cat Recognition":
359         self.test_frame = TestCatRecognitionFrame(
360             root=self,
361             width=self.WIDTH,
362             height=self.HEIGHT,
363             bg=self.BG,
364             use_gpu=self.load_model_frame.use_gpu,
365             model=self.model
366         )
367     elif self.load_model_frame.dataset == "XOR":
368         self.test_frame = TestXORFrame(root=self,
369                                         width=self.WIDTH,
370                                         height=self.HEIGHT,
371                                         bg=self.BG,
372                                         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,
433         ↩ Train_Dataset_Size, Use_ReLu)
434         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

```

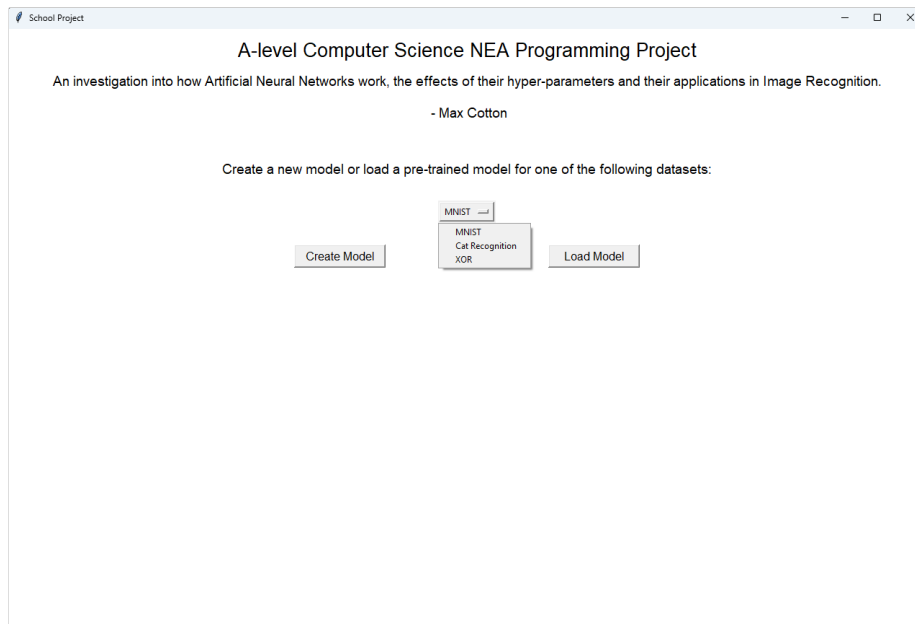
```

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

```

---

Which outputs the following for the home frame:



## 4 Testing

### 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() -
80             ↪ model.test_outputs)) * 100, ndigits=1)}%\n" +
81             f"Network Shape: " +
82             f"{', '.join(model.layers_shape)}\n"
83         )
84
85         test_inputs = np.squeeze(model.test_inputs).T
86         test_outputs = np.squeeze(model.test_outputs).T.tolist()
87         test_prediction = np.squeeze(model.test_prediction).T.tolist()
88
89         # Randomly shuffle order of test_inputs, test_outputs and
90         ↪ test_prediction
91         # whilst maintaining order between them
92         test_data = list(zip(test_inputs,
93                             test_outputs,
94                             test_prediction))
95         random.shuffle(test_data)
96         test_inputs, test_outputs, test_prediction = zip(*test_data)
97
98     elif self.use_gpu:
99
100         import cupy as cp
101
102         self.results_label.configure(
103             text="Prediction Correctness: " +
104             f"{round(number=100 -
105             ↪ np.mean(np.abs(cp.asnumpy(model.test_prediction).round() -
106             ↪ cp.asnumpy(model.test_outputs))) * 100, ndigits=1)}%\n" +
107             f"Network Shape: " +
108             f"{', '.join(model.layers_shape)}\n"
109         )
110
111         test_inputs = cp.asnumpy(cp.squeeze(model.test_inputs)).T
112         test_outputs = cp.asnumpy(cp.squeeze(model.test_outputs)).T.tolist()
113         test_prediction = cp.squeeze(model.test_prediction).T.tolist()
114
115         # Randomly shuffle order of test_inputs, test_outputs and
116         ↪ test_prediction
117         # whilst maintaining order between them
118         test_data = list(zip(test_inputs,
119                             test_outputs,
120                             test_prediction))
121         random.shuffle(test_data)
122         test_inputs, test_outputs, test_prediction = zip(*test_data)
123
124         # Setup incorrect prediction figure
125         self.incorrect_prediction_figure.suptitle("Incorrect predictions:")
126         image_count = 0
127         for i in range(len(test_prediction)):
128             if test_prediction[i].index(max(test_prediction[i])) !=
129             ↪ test_outputs[i].index(max(test_outputs[i])):
130                 if image_count == 2:
131                     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:
131         ↳ {test_prediction[i].index(max(test_prediction[i]))}\n" +
132             f"Should have predicted:
133             ↳ {test_outputs[i].index(max(test_outputs[i]))}")
134         image.imshow(test_inputs[i].reshape((28,28)))
135         image_count += 1
136
137     # Setup correct prediction figure
138     self.correct_prediction_figure.suptitle("Correct predictions:")
139     image_count = 0
140     for i in range(len(test_prediction)):
141         if test_prediction[i].index(max(test_prediction[i])) ==
142             ↳ test_outputs[i].index(max(test_outputs[i])):
143             if image_count == 2:
144                 break
145             elif image_count == 0:
146                 image = self.correct_prediction_figure.add_subplot(121)
147             elif image_count == 1:
148                 image = self.correct_prediction_figure.add_subplot(122)
149             image.set_title(f"Predicted:
150             ↳ {test_prediction[i].index(max(test_prediction[i]))}")
151             image.imshow(test_inputs[i].reshape((28,28)))
152             image_count += 1
153
154 class TestCatRecognitionFrame(tk.Frame):
155     """Frame for Testing Cat Recognition page."""
156     def __init__(self, root: tk.Tk, width: int,
157                 height: int, bg: str,
158                 use_gpu: bool, model: object) -> None:
159         """Initialise test cat recognition frame widgets.
160
161         Args:
162             root (tk.Tk): the widget object that contains this widget.
163             width (int): the pixel width of the frame.
164             height (int): the pixel height of the frame.
165             bg (str): the hex value or name of the frame's background colour.
166             use_gpu (bool): True or False whether the GPU should be used.
167             model (object): the Model object to be tested.
168
169         Raises:
170             TypeError: if root, width or height are not of the correct type.
171
172         """
173         super().__init__(master=root, width=width, height=height, bg=bg)
174         self.root = root
175         self.WIDTH = width
176         self.HEIGHT = height
177         self.BG = bg
178
179         # Setup image recognition frame variables
180         self.use_gpu = use_gpu
181
182         # Setup widgets
183         self.model_status_label = tk.Label(master=self,
184                                           bg=self.BG,
185                                           font=('Arial', 15))
186         self.results_label = tk.Label(master=self,
187                                      bg=self.BG,
188                                      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() -
219             ↪ 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
224         ↪ test_prediction
225         # whilst maintaining order between them
226         test_data = list(zip(model.test_inputs.T,
227                             np.squeeze(model.test_outputs).T.tolist(),
228                             ↪ np.squeeze(model.test_prediction.round()).T.tolist()))
229         random.shuffle(test_data)
230         (test_inputs,
231          test_outputs,
232          test_prediction) = map(lambda arr: np.array(arr).T,
233                               zip(*test_data))
234
235     elif self.use_gpu:
236         import cupy as cp
237
238         self.results_label.configure(
239             text="Prediction Correctness: " +
240             f"{round(number=100 -
241             ↪ np.mean(np.abs(cp.asnumpy(model.test_prediction).round() -
242             ↪ 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
246     ↪ test_prediction
247     # whilst maintaining order between them
248     test_data = list(zip(cp.asnumpy(model.test_inputs).T,
249
250                         ↪ cp.asnumpy(cp.squeeze(model.test_outputs)).T.tolist(),
251
252                         ↪ cp.asnumpy(cp.squeeze(model.test_prediction)).round().T.tolist()))
253     random.shuffle(test_data)
254     (test_inputs,
255     test_outputs,
256     test_prediction) = map(lambda arr: np.array(arr).T,
257                           zip(*test_data))
258
259     # Setup incorrect prediction figure
260     self.incorrect_prediction_figure.suptitle("Incorrect predictions:")
261     image_count = 0
262     for i in range(len(test_prediction)):
263         if test_prediction[i] != test_outputs[i]:
264             if image_count == 2:
265                 break
266             elif image_count == 0:
267                 image = self.incorrect_prediction_figure.add_subplot(121)
268             elif image_count == 1:
269                 image = self.incorrect_prediction_figure.add_subplot(122)
270             image.set_title(f"Predicted: {'Cat' if test_prediction[i] == 1
271                               ↪ else 'Not a cat'}\n")
272             image.imshow(test_inputs[:,i].reshape((64,64,3)))
273             image_count += 1
274
275     # Setup correct prediction figure
276     self.correct_prediction_figure.suptitle("Correct predictions:")
277     image_count = 0
278     for i in range(len(test_prediction)):
279         if test_prediction[i] == test_outputs[i]:
280             if image_count == 2:
281                 break
282             elif image_count == 0:
283                 image = self.correct_prediction_figure.add_subplot(121)
284             elif image_count == 1:
285                 image = self.correct_prediction_figure.add_subplot(122)
286             image.set_title(f"Predicted: {'Cat' if test_prediction[i] == 1
287                               ↪ else 'Not a cat'}\n")
288             image.imshow(test_inputs[:,i].reshape((64,64,3)))
289             image_count += 1
290
291     class TestXORFrame(tk.Frame):
292         """Frame for Testing XOR page."""
293         def __init__(self, root: tk.Tk, width: int,
294                     height: int, bg: str, model: object) -> None:
295             """Initialise test XOR frame widgets.
296
297             Args:
298             root (tk.Tk): the widget object that contains this widget.
299             width (int): the pixel width of the frame.
300             height (int): the pixel height of the frame.
301             bg (str): the hex value or name of the frame's background colour.
302             model (object): the Model object to be tested.

```

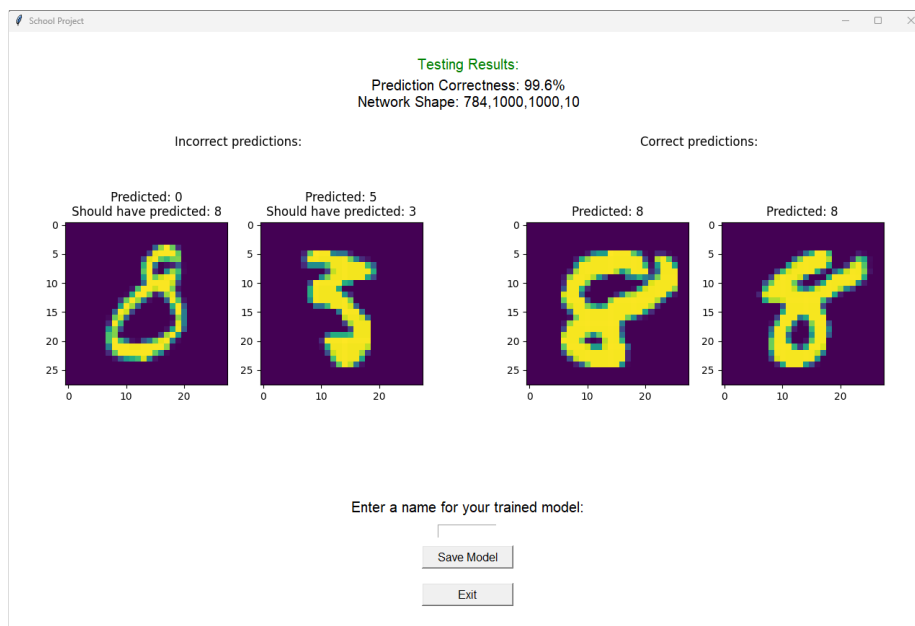
```

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()

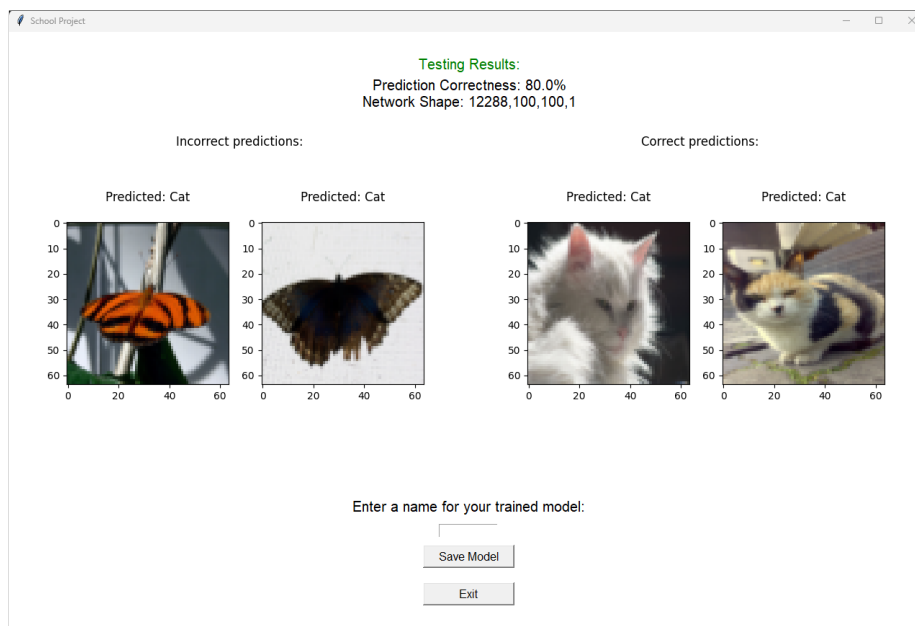
```

---

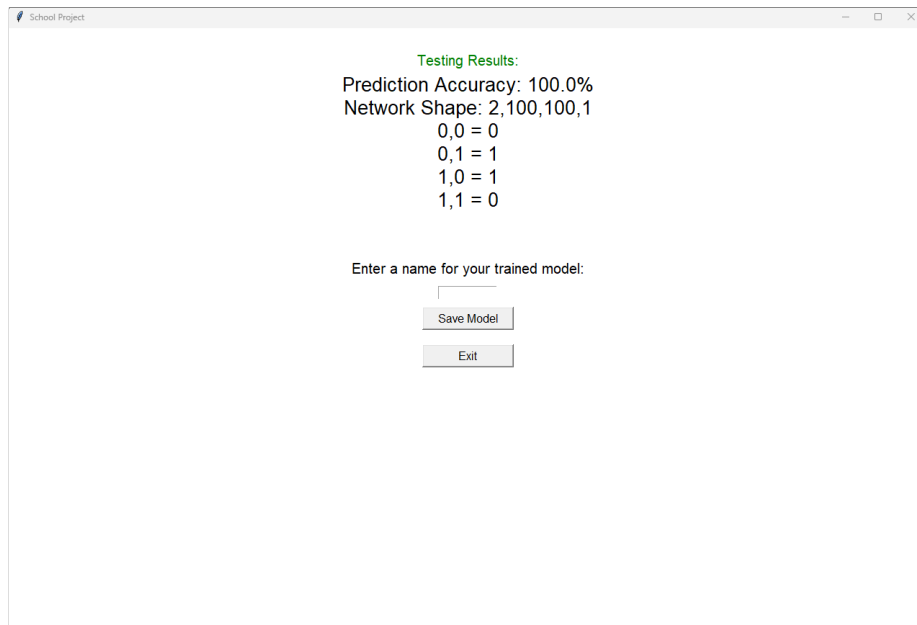
Which outputs the following for the MNIST dataset:



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]

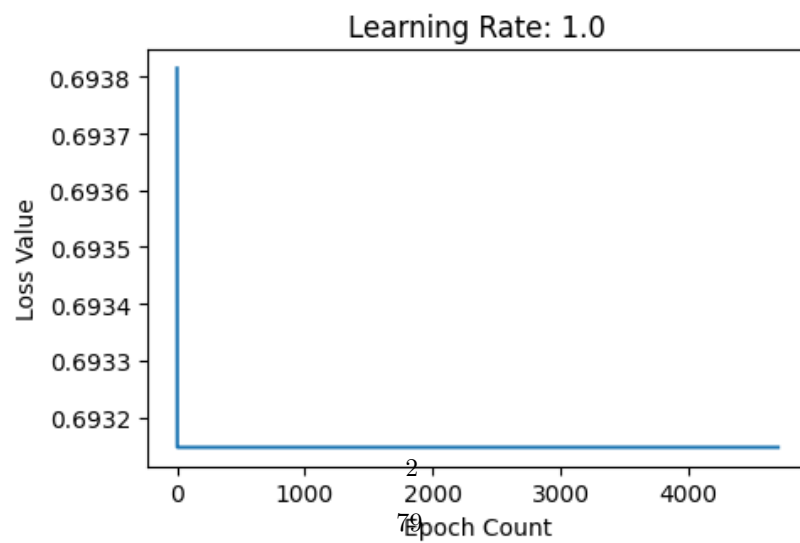
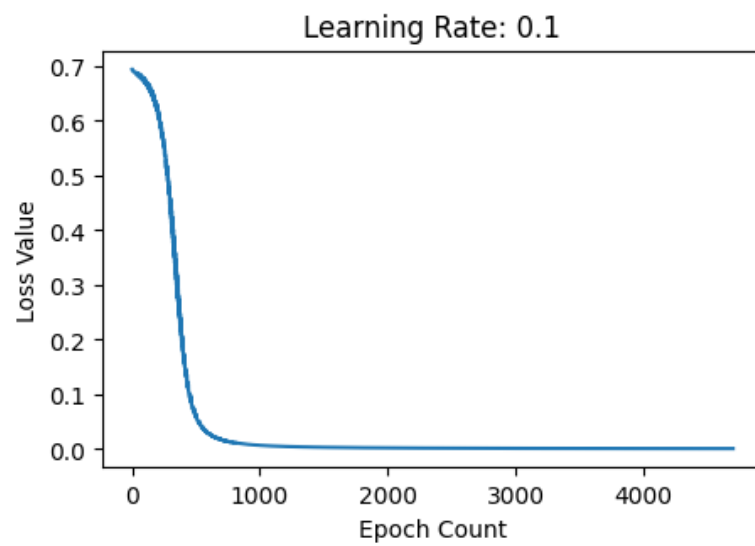
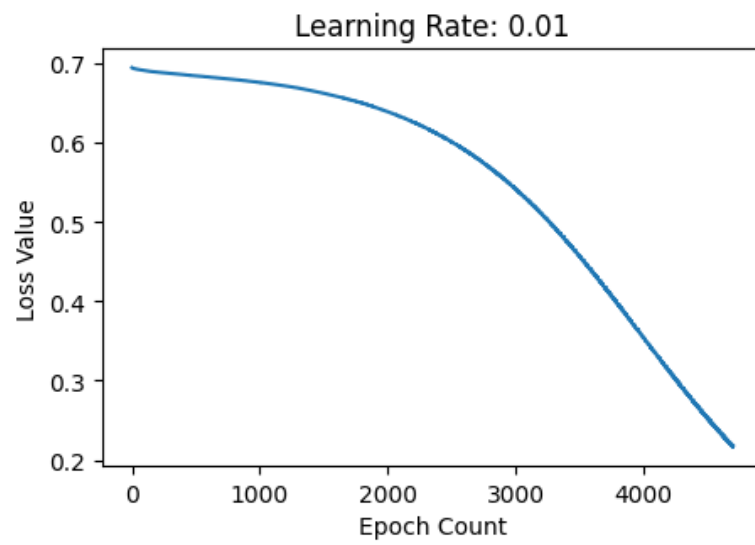
learning_rates = [0.01, 0.1, 1.0]

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()
```



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')

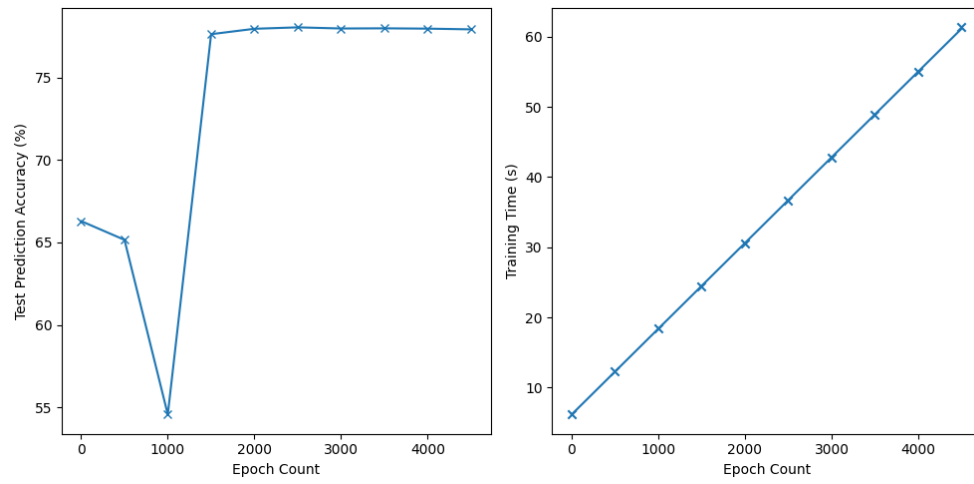
# Plot regression line
axis[1].plot(epoch_counts, m * epoch_counts + c)

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)

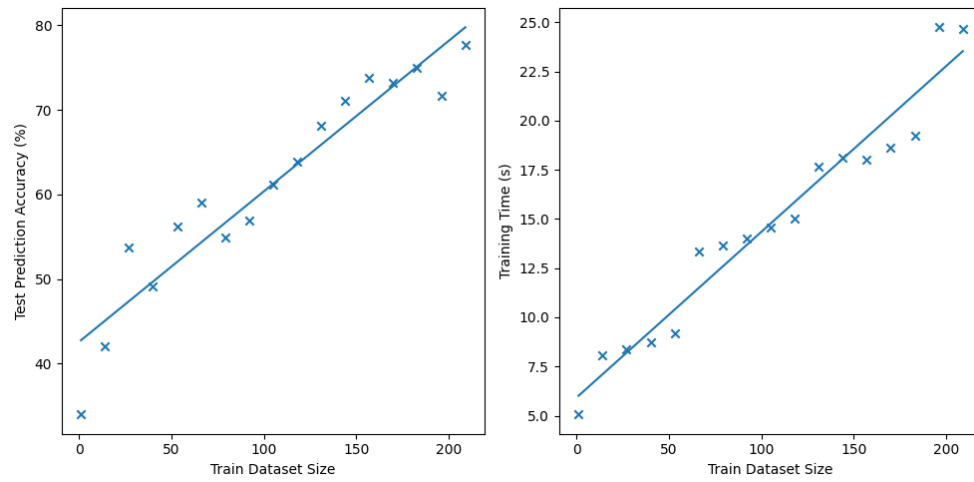
plt.tight_layout()
plt.show()

```

'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 so 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)

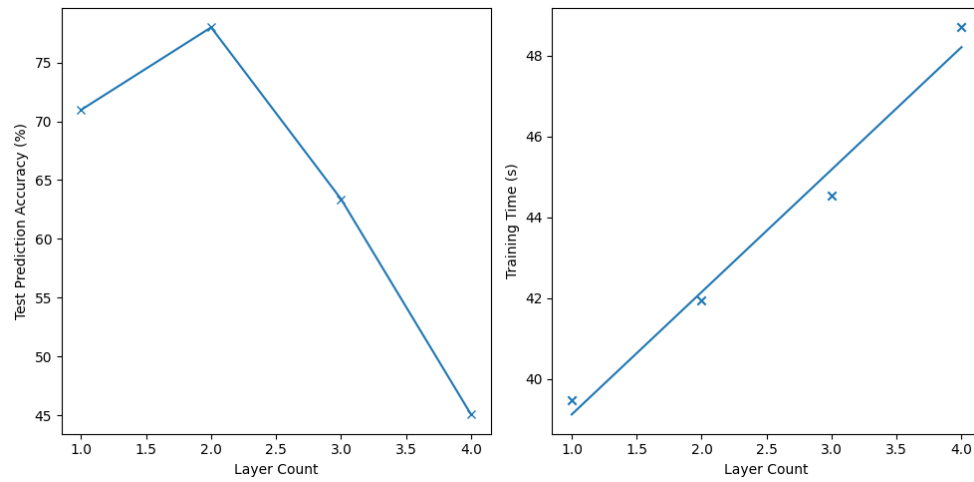
plt.tight_layout()
plt.show()

```

'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')

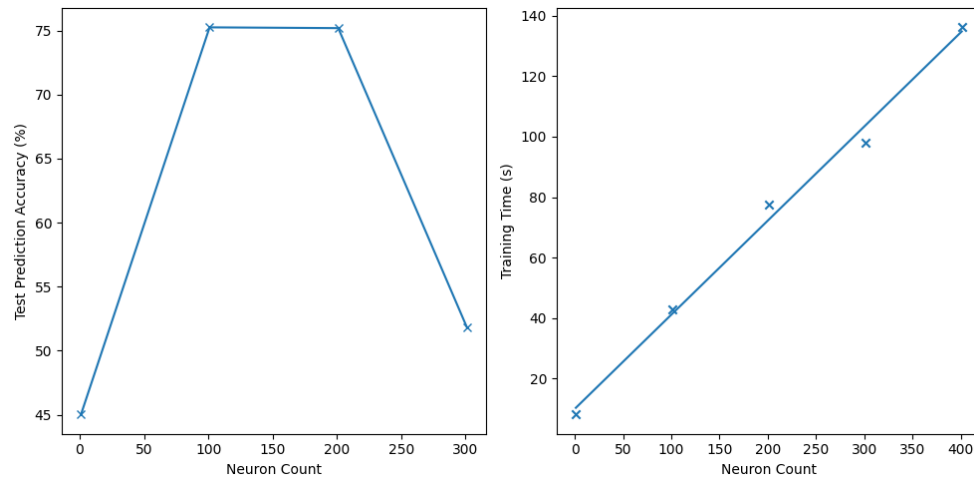
# Plot regression line
axis[1].plot(neuron_counts, m * neuron_counts + c)

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))

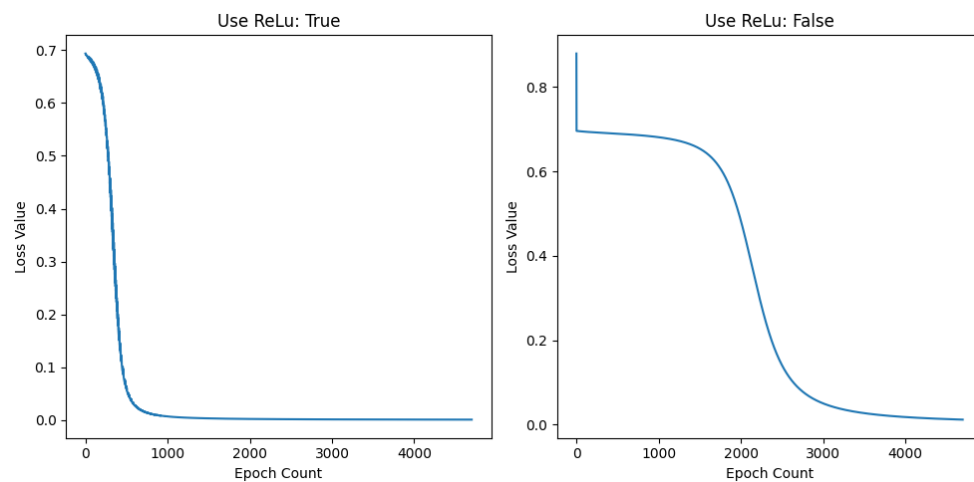
model = Model(hidden_layers_shape=[100, 100],
               train_dataset_size=4,
               learning_rate=0.1,
               use_relu=False)
model.create_model_values()
model.train(epoch_count=4_700)
model.test()
```

```

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.

```
[5]: 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}s")

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}s")
```

CPU Training Time: 160.33s

GPU Training Time: 43.24s

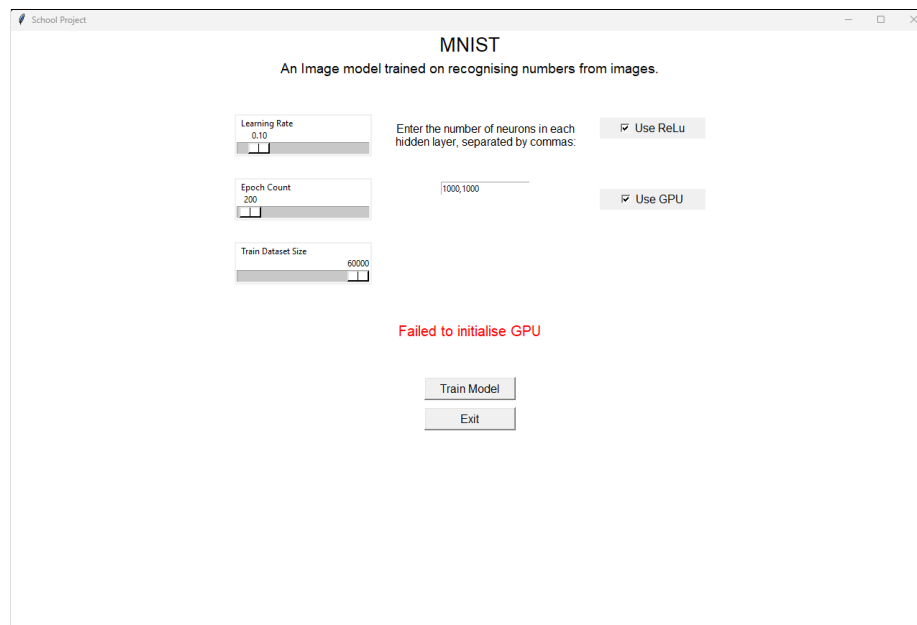
As shown above, the GPU is almost four times faster at training the model than the CPU, showing how beneficial it is to utilise the parallel computations of the GPU

## 4.2 Manual Testing

### 4.2.1 Input Validation Testing

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 useful error message should be displayed.
    - \* Actual Result: Expected Result
    - \* Test Status: Pass
    - \* Evidence:

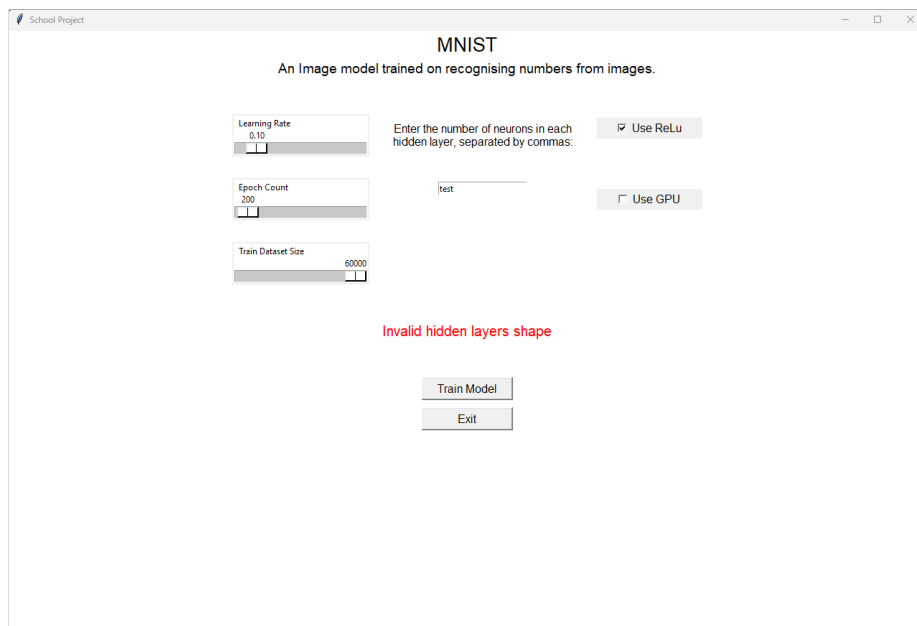


Link to video evidence: <https://github.com/mcttn22/school-project/blob/main/project-report/input-validation-testing-videos.md/#use-gpu-validation>



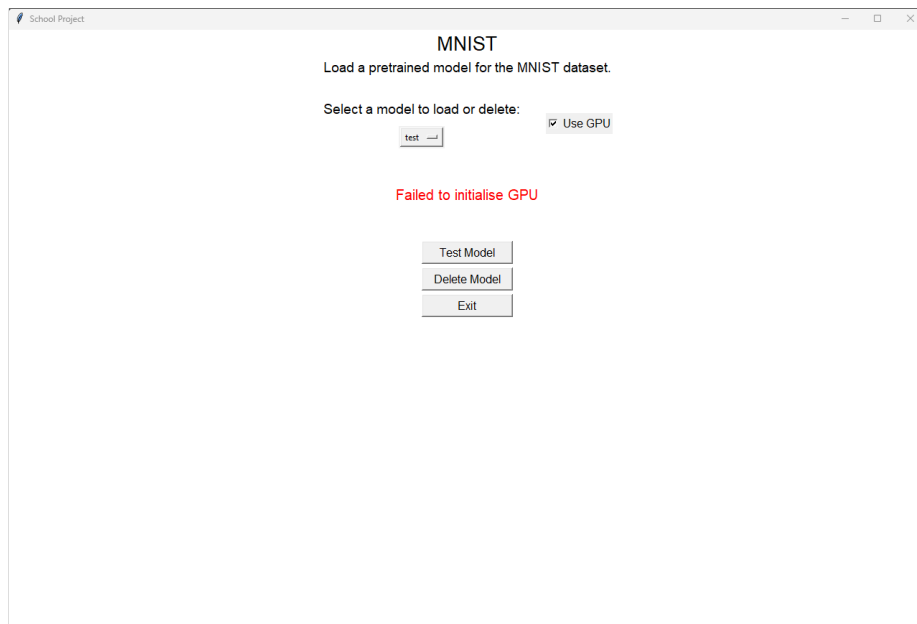
– Hidden Layers Shape Validation:

- \* Description: Enter an invalid hidden layers shape.
- \* Data Value: "test"
- \* Data Type: Erroneous
- \* Expected Result: The exception should be handled and a useful error message should be displayed.
- \* 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 useful error message should be displayed.
    - \* Actual Result: Expected Result
    - \* Test Status: Pass
    - \* Evidence:

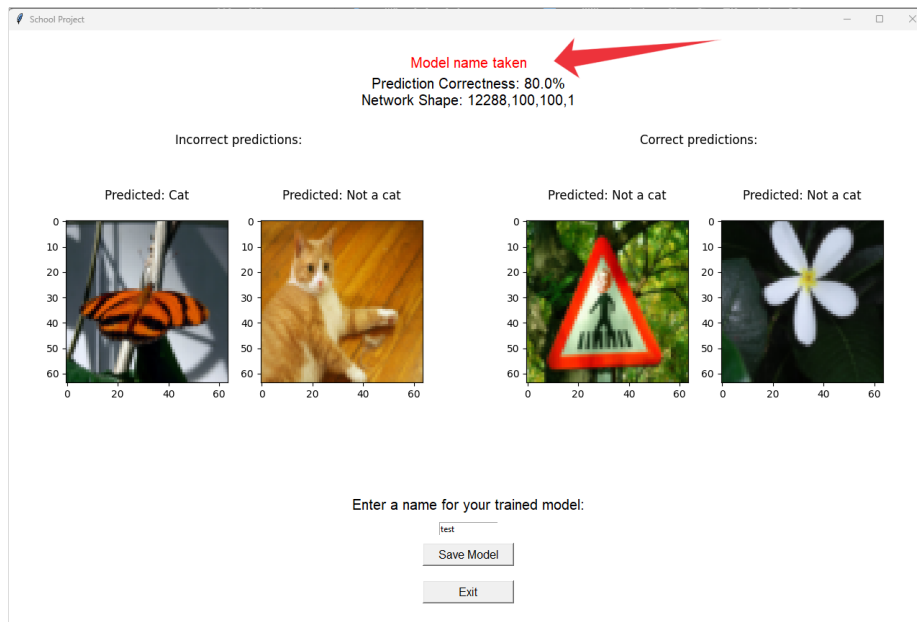


Link to video evidence: <https://github.com/mcttn22/school-project/blob/main/project-report/input-validation-testing-videos.md/#hidden-layers-shape-validation>

- Test Frames:

- Taken Trained Model Name Validation:

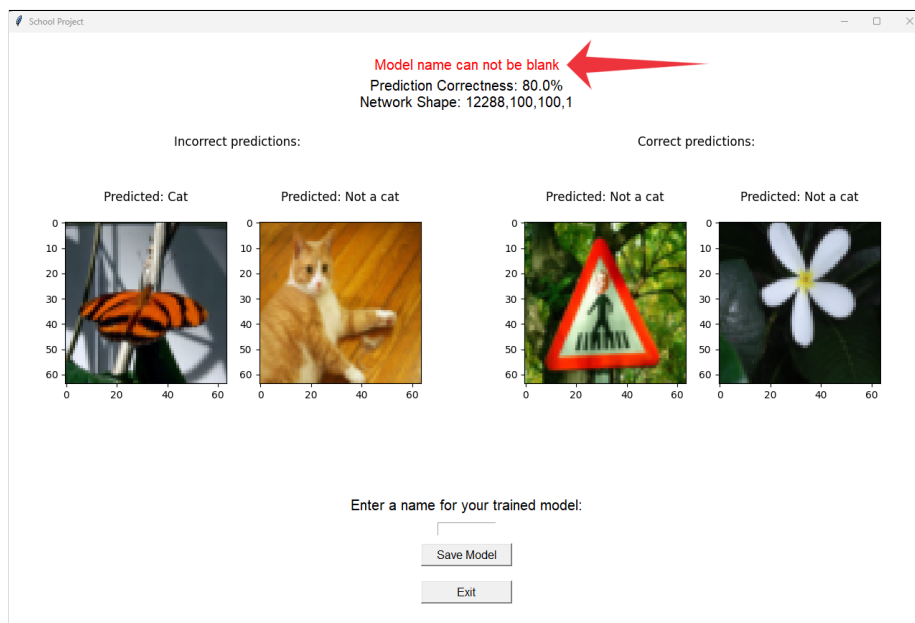
- \* Description: Try to save a trained model with an already taken name.
    - \* Data Value: "test"
    - \* Data Type: Erroneous
    - \* Expected Result: The exception should be handled and a useful error message should be displayed.
    - \* Actual Result: Expected Result
    - \* Test Status: Pass
    - \* 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 useful error message should be displayed.
- \* 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 matrixe
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],
121                       ↪ layer.input.shape[1]),
122                second=layer.output.shape
123                )
124
125    def test_save_model(self) -> None:
126        """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 =
135     ↪ f"school_project/saved-models/{uuid.uuid4().hex}.npz"
136     initial_model.save_model_values(file_location=file_location)
137
138     # Create model from the saved values
139     loaded_model = XORModel(hidden_layers_shape = [100, 100],
140                              train_dataset_size = 4,
141                              learning_rate = 0.1,
142                              use_relu = True)
143     loaded_model.load_model_values(file_location=file_location)
144
145     # Remove the saved model values
146     os.remove(path=file_location)
147
148     # Compare initial and loaded model values
149     for layer1, layer2 in zip(initial_model.layers,
150                               ↪ loaded_model.layers):
151         self.assertTrue(np.array_equal(a1=layer1.weights,
152                                         a2=layer2.weights))
153         self.assertTrue(np.array_equal(a1=layer1.biases,
154                                         a2=layer2.biases))
155
156 if __name__ == '__main__':
157     unittest.main()

```

---

- test\_tools.py module:

---

```

1  """Unit tests for tools module."""
2
3  import unittest
4
5  from school_project.models.cpu.utils import tools
6
7  class TestTools(unittest.TestCase):
8      """Unit tests for the tools module."""
9      def __init__(self, *args, **kwargs) -> None:
10         """Initialise unit tests."""
11         super(TestTools, self).__init__(*args, **kwargs)
12
13     def test_relu(self) -> None:
14         """Test ReLu output range to be >=0."""
15         test_inputs = [-100, 0, 100]
16         for test_input in test_inputs:
17             output = tools.relu(z=test_input)
18             self.assertGreaterEqual(a=output, b=0)
19
20     def test_sigmoid(self) -> None:
21         """Test sigmoid output range to be within 0-1."""
22         test_inputs = [-100, 0, 100]
23         for test_input in test_inputs:
24             output = tools.sigmoid(z=test_input)
25             self.assertTrue(expr=output >= 0 and output <= 1)
26
27 if __name__ == '__main__':
28     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.

---

```

1  name: Tests
2
3  on:
4      push:
5          branches: [ "main" ]
6      pull_request:
7          branches: [ "main" ]
8
9  permissions:
10     contents: read
11
12  jobs:
13      build:
14
15          runs-on: ubuntu-latest
16
17          steps:
18              - uses: actions/checkout@v3
19              - name: Set up Python 3.10

```



```

20     uses: actions/setup-python@v3
21     with:
22       python-version: "3.10"
23   - name: Install dependencies
24     run: |
25       python -m pip install --upgrade pip
26       pip install numpy
27   - name: Test
28     run: |
29       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:

```

1 FROM python:3.11
2
3 # Set a directory for the app
4 WORKDIR /usr/src/app
5
6 # Copy all the files to the container
7 COPY . .
8
9 # Install dependencies
10 RUN python setup.py install
11
12 # Run the project
13 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	Status
1	I have learnt how Artificial Neural Networks work from online resources, reports and interviewing a subject matter expert. I have proven the key mathematical principles from first principles and implemented these structures within Python code.	Fully met
2	I have implemented trainable Artificial Neural Networks with configurable numbers of layers, number of neurons in each layer and the nature of the Transfer Functions. The Artificial Neural Networks have been trained and tested on a variety of datasets and operates at an accuracy level comparable with the resources learnt from.	Fully met
2.1	The Artificial Neural Networks allow the use of a graphics card where applicable.	Fully met
2.2	The trained Artificial Neural Networks' weights and biases can be saved to a data file and the features of the corresponding Artificial Neural Networks are saved to a database. These saved Artificial Neural Networks can be loaded independently.	Fully met
3	A Graphical User Interface allowing configuration of all hyper-parameters, loading and saving of trained models and testing has been developed.	Fully met
3.1	The Graphical User Interface allows user configuration of all utilised model hyper-parameters.	Fully met
3.2	The model predictions can be compared in terms of both learning rate and overall accuracy.	Fully met

### 5.2 Third Party Feedback TODO

### 5.3 Future Improvements TODO