

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

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

1.4 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.

1.4.1 Structure

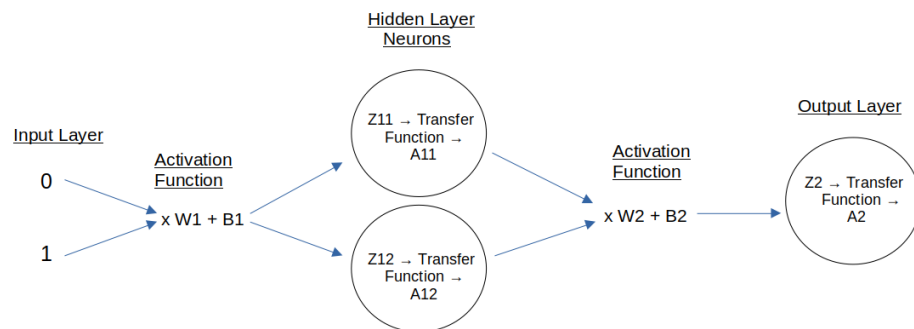


Figure 1: This shows an Artificial Neural Network with one single hidden layer and is known as a Shallow Neural Network.

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.

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.

1.4.2 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 $u = g(x)$, $\frac{\partial y}{\partial x} = \frac{\partial y}{\partial u} * \frac{\partial u}{\partial x}$
 - 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
 - * However, during backpropagation some issues can occur, such as the following:



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

- 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.

1.5 Theory Behind Deep Artificial Neural Networks

1.5.1 Setup

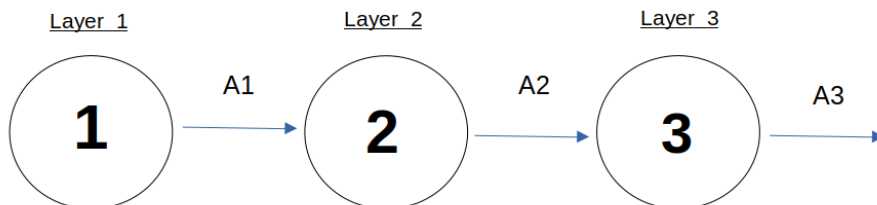


Figure 3: This shows an abstracted view of an Artificial Neural Network with multiple hidden layers and is known as a Deep Neural Network.

- 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.
 - * 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 largers values of $\frac{\partial L}{\partial W}$ and $\frac{\partial L}{\partial B}$ for Gradient Descent than Sigmoid, so updates at a quicker rate.
 - * Where $\text{relu}(Z) = \max(0, Z)$

1.5.2 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.

1.5.3 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:
 - $W = W - \text{learningRate} * \frac{\partial L}{\partial W}$
 - $B = B - \text{learningRate} * \frac{\partial L}{\partial B}$
- 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. $Z = W * X + B$

$$\begin{aligned}
& 2. A_{relu} = \max(0, Z) \\
& 3. A_{sigmoid} = \frac{1}{1+e^{-Z}} \\
& 4. L = -\left(\frac{1}{m}\right) * \sum(Y * \log(A) + (1 - Y) * \log(1 - A)) \\
- & \frac{\partial L}{\partial A2} = \frac{\partial L}{\partial A3} * \frac{\partial A3}{\partial Z3} * \frac{\partial Z3}{\partial A2} \\
& \text{By using function 1, where A2 is X for the 3rd layer, } \frac{\partial Z3}{\partial A2} = W3 \\
& \Rightarrow \frac{\partial L}{\partial A2} = \frac{\partial L}{\partial A3} * \frac{\partial A3}{\partial Z3} * W3 \\
- & \frac{\partial L}{\partial W2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * \frac{\partial Z2}{\partial W2} \\
& \text{By using function 1, where A1 is X for the 2nd layer, } \frac{\partial Z2}{\partial W2} = A1 \\
& \Rightarrow \frac{\partial L}{\partial W2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * A1 \\
- & \frac{\partial L}{\partial B2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * \frac{\partial Z2}{\partial B2} \\
& \text{By using function 1, } \frac{\partial Z2}{\partial B2} = 1 \\
& \Rightarrow \frac{\partial L}{\partial W2} = \frac{\partial L}{\partial A2} * \frac{\partial A2}{\partial Z2} * 1
\end{aligned}$$

- 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, $\frac{\partial L}{\partial A} = \left(-\frac{1}{m}\right) \left(\frac{Y-A}{A*(1-A)}\right)$

1.6 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).

1.6.1 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.

1.6.2 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

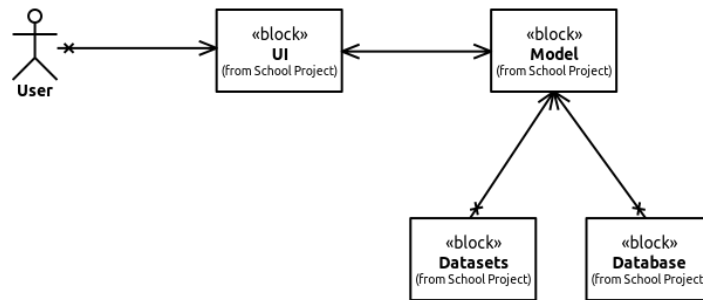
The following design focuses have been made for the project:

- 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

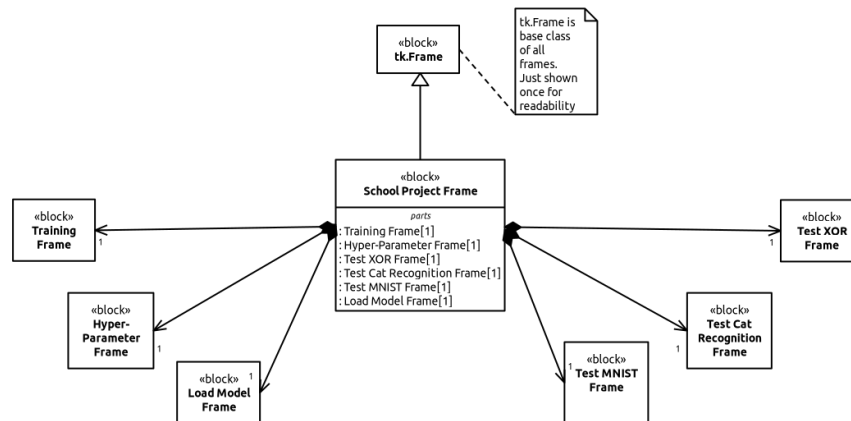
bdd [block] School Project Frame [System Architecture Diagram]



2.3 Class Diagrams

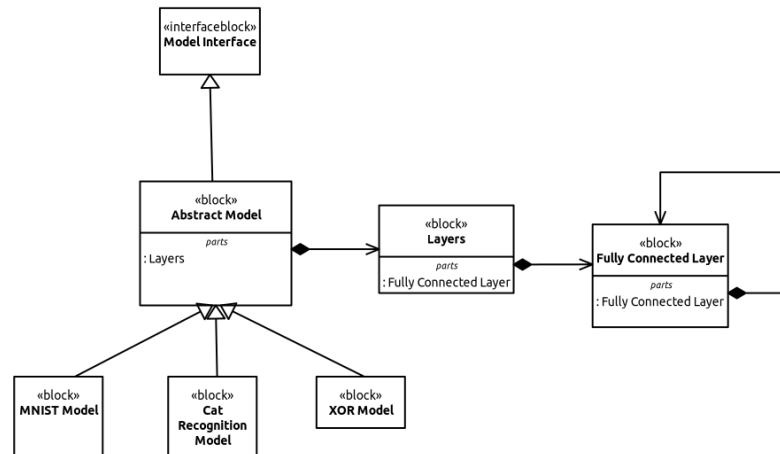
2.3.1 UI Class Diagram

bdd [package] School Project [UI Class Diagram]



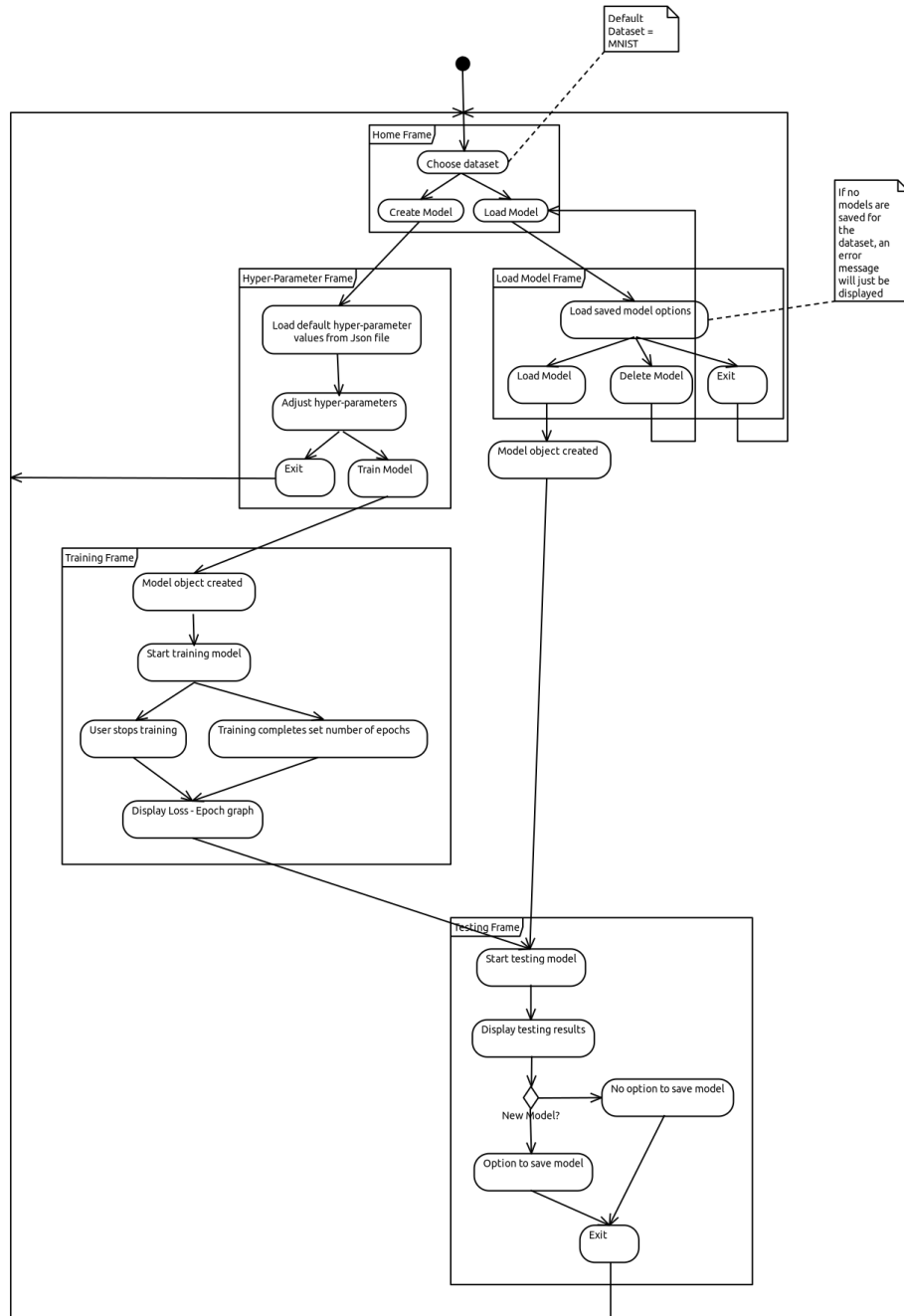
2.3.2 Model Class Diagram

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=?;
```

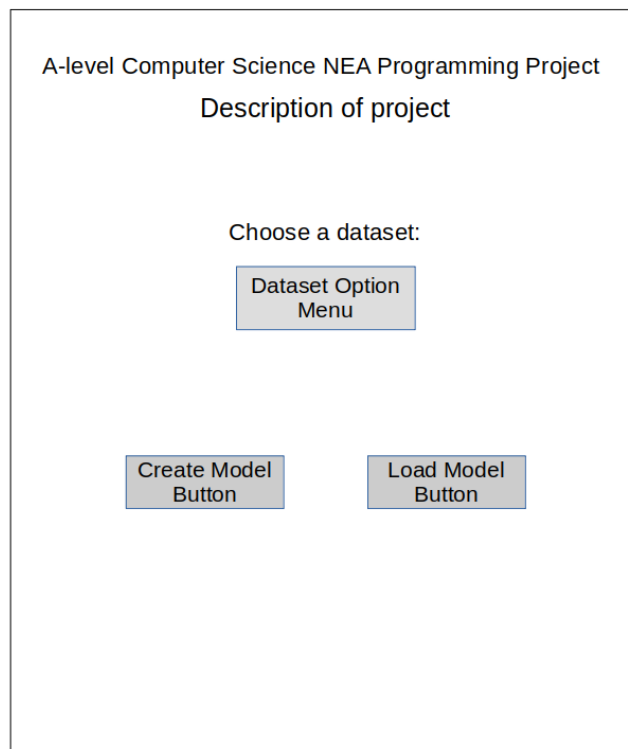

- I can query the features of a saved model with:

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

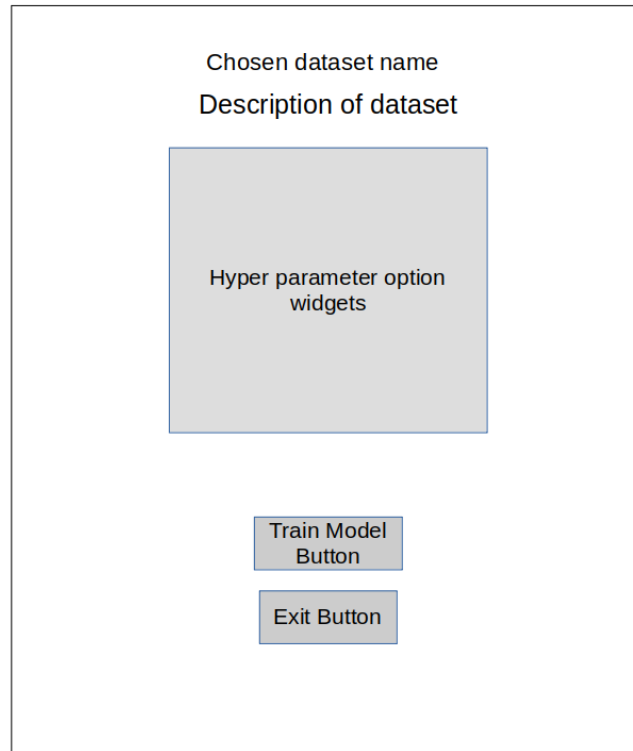
2.10 Human-Computer Interaction

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

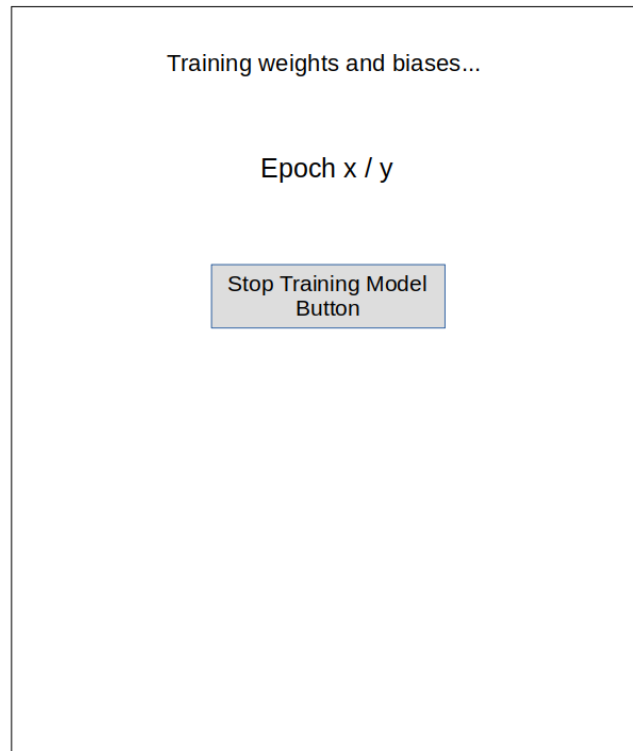
- Home Frame design:



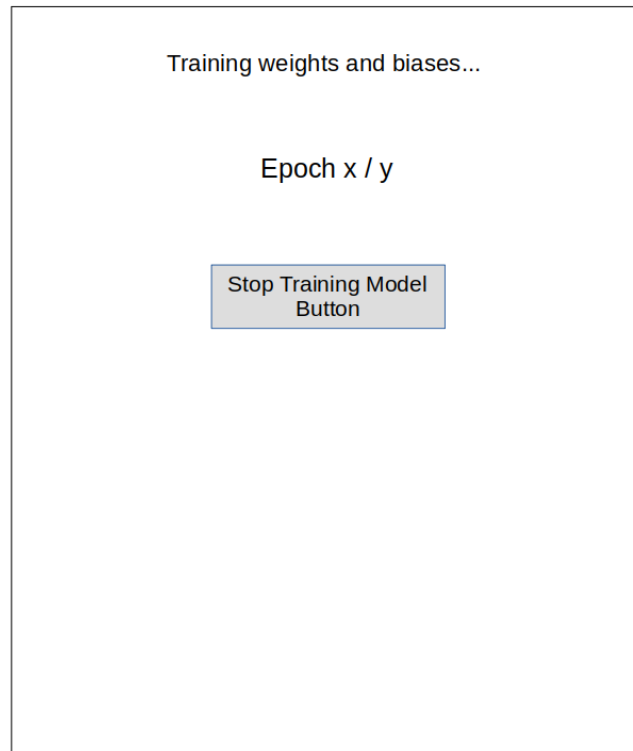
- Hyper-Parameter Frame design:



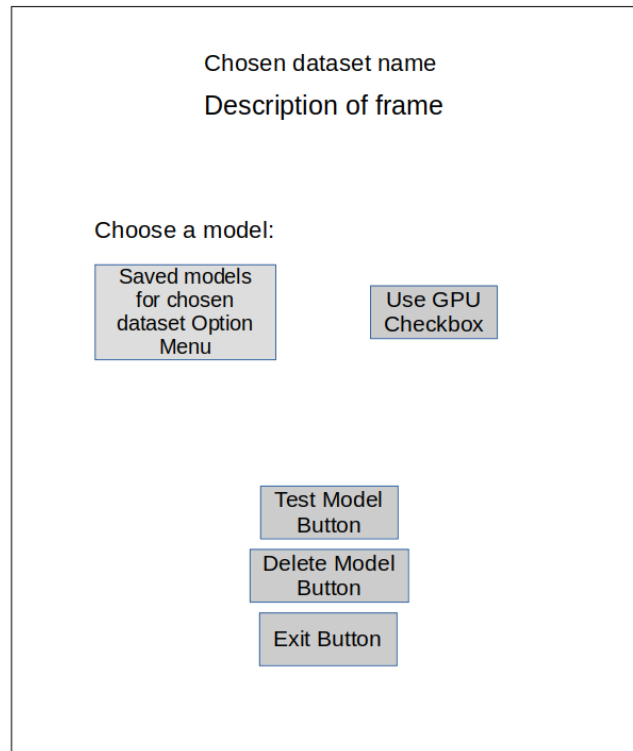
- Training Frame design:
 - During training, the following is displayed on the Training Frame:



- 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 powerfull hardware using just the CPU as standard.

2.12 Workflow and source control

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

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

3 Technical Solution TODO

3.1 Setup

3.1.1 File Structure

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

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

```

.
|-- .github
|   |-- workflows
|   |-- tests.yml
|-- .gitignore
|-- LICENSE
|-- 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

```

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

```


– Which will generate the following:

 Tests passing  Python 3


A-level Computer Science NEA Programming Project

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


Installation

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

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


 - Linux:

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



3. Enter the venv with:

◦ Windows:

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



◦ Linux:

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



4. Enter the project directory with:

```
cd school-project/
```



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

◦ Windows:

```
python setup.py install
```



◦ Linux:

```
python3 setup.py install
```



Note: In order to use an Nvidia GPU for training the networks, the latest 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/
```



Compile Project Report PDF with:

```
make all
```



Note: This requires the Latexmk library

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

3.1.4 Organisation

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

3.2 models package

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

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

3.2.1 utils subpackage

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

- tools.py module:

```

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

```

- model.py module:

```

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

```

```

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

```

```

66     self.transfer_type = transfer_type
67     self.input: np.ndarray
68     self.output: np.ndarray
69
70     # Setup weights and biases
71     self.weights: np.ndarray
72     self.biases: np.ndarray
73     self.learning_rate = learning_rate
74
75     def __repr__(self) -> str:
76         """Read values of the layer.
77
78         Returns:
79             a string description of the layers's
80             weights, bias and learning rate values.
81
82         """
83         return (f"Weights: {self.weights.tolist()}\n" +
84                 f"Biases: {self.biases.tolist()}\n")
85
86     def init_layer_values_random(self) -> None:
87         """Initialise weights to random values and biases to 0s"""
88         np.random.seed(1) # Sets up pseudo random values for layer weight
89         ↪ arrays
90         self.weights = np.random.rand(self.output_neuron_count,
91         ↪ self.input_neuron_count) - 0.5
92         self.biases = np.zeros(shape=(self.output_neuron_count, 1))
93
94     def init_layer_values_zeros(self) -> None:
95         """Initialise weights to 0s and biases to 0s"""
96         self.weights = np.zeros(shape=(self.output_neuron_count,
97         ↪ self.input_neuron_count))
98         self.biases = np.zeros(shape=(self.output_neuron_count, 1))
99
100     def back_propagation(self, dloss_doutput) -> np.ndarray:
101         """Adjust the weights and biases via gradient descent.
102
103         Args:
104             dloss_doutput (numpy.ndarray): the derivative of the loss of
105             ↪ the
106             layer's output, with respect to the layer's output.
107         Returns:
108             a numpy.ndarray derivative of the loss of the layer's input,
109             with respect to the layer's input.
110         Raises:
111             ValueError:
112             if dloss_doutput
113             is not a suitable multiplier with the weights
114             (incorrect shape)
115
116         """
117         match self.transfer_type:
118             case 'sigmoid':
119                 dloss_dz = dloss_doutput *
120                 ↪ sigmoid_derivative(output=self.output)
121             case 'relu':
122                 dloss_dz = dloss_doutput *
123                 ↪ relu_derivative(output=self.output)
124
125         dloss_dweights = np.dot(dloss_dz, self.input.T)
126         dloss_dbias = np.sum(dloss_dz)
127

```

```

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

```

```

181         self.input_count = self.train_inputs.shape[1]
182         self.hidden_layers_shape = hidden_layers_shape
183         self.output_neuron_count = self.train_outputs.shape[0]
184         self.layers_shape = [f'{layer}' for layer in (
185             [self.input_neuron_count] +
186             self.hidden_layers_shape +
187             [self.output_neuron_count]
188         )]
189         self.use_relu = use_relu
190
191         # Setup model values
192         self.layers = _Layers()
193         self.learning_rate = learning_rate
194
195     def __repr__(self) -> str:
196         """Read current state of model.
197
198         Returns:
199             a string description of the model's shape,
200             weights, bias and learning rate values.
201
202         """
203         return (f"Layers Shape: {' '.join(self.layers_shape)}\n" +
204             f"Learning Rate: {self.learning_rate}")
205
206     def set_running(self, value: bool) -> None:
207         """Set the running attribute to the given value.
208
209         Args:
210             value (bool): the value to set the running attribute to.
211
212         """
213         self.__running = value
214
215     def _setup_layers(setup_values: callable) -> None:
216         """Decorator that sets up model layers and sets up values of each
217         ↪ layer
218             with the method given.
219
220         Args:
221             ↪ each setup_values (callable): the method that sets up the values of
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                     # Add input layer
230                     self.layers.head = _FullyConnectedLayer(
231
232                         ↪ learning_rate=self.learning_rate,
233
234                         ↪ input_neuron_count=self.input_neuron_count,
235
236                         ↪ output_neuron_count=self.hidden_layers_shape[0],
237                         transfer_type='relu'
238                     )
239                     current_layer = self.layers.head

```

```

238         # Add hidden layers
239         for layer in range(len(self.hidden_layers_shape) - 1):
240             current_layer.next_layer = _FullyConnectedLayer(
241                 learning_rate=self.learning_rate,
242
243                 ↪ input_neuron_count=self.hidden_layers_shape[layer],
244
245                 ↪ output_neuron_count=self.hidden_layers_shape[layer
246                 ↪ + 1],
247                 transfer_type='relu'
248             )
249             current_layer.next_layer.previous_layer =
250             ↪ current_layer
251             current_layer = current_layer.next_layer
252         else:
253
254             # Add input layer
255             self.layers.head = _FullyConnectedLayer(
256
257                 ↪ learning_rate=self.learning_rate,
258
259                 ↪ input_neuron_count=self.input_neuron_count,
260
261                 ↪ output_neuron_count=self.hidden_layers_shape[0],
262                 transfer_type='sigmoid'
263             )
264             current_layer = self.layers.head
265
266             # Add hidden layers
267             for layer in range(len(self.hidden_layers_shape) - 1):
268                 current_layer.next_layer = _FullyConnectedLayer(
269                     learning_rate=self.learning_rate,
270
271                     ↪ input_neuron_count=self.hidden_layers_shape[layer],
272
273                     ↪ output_neuron_count=self.hidden_layers_shape[layer
274                     ↪ + 1],
275                     transfer_type='sigmoid'
276                 )
277                 current_layer.next_layer.previous_layer =
278                 ↪ current_layer
279                 current_layer = current_layer.next_layer
280
281             # Add output layer
282             current_layer.next_layer = _FullyConnectedLayer(
283                 learning_rate=self.learning_rate,
284
285                 ↪ input_neuron_count=self.hidden_layers_shape[-1],
286
287                 ↪ output_neuron_count=self.output_neuron_count,
288                 transfer_type='sigmoid'
289             )
290             current_layer.next_layer.previous_layer = current_layer
291             self.layers.tail = current_layer.next_layer
292
293     # Setup Perceptron Network
294     else:
295         self.layers.head = _FullyConnectedLayer(
296             learning_rate=self.learning_rate,
297
298             ↪ input_neuron_count=self.input_neuron_count,
299
300             ↪ output_neuron_count=self.output_neuron_count,

```

```

286                                     transfer_type='sigmoid'
287                                     )
288         self.layers.tail = self.layers.head
289
290         setup_values(self, *args, **kwargs)
291
292     return decorator
293
294 @_setup_layers
295 def create_model_values(self) -> None:
296     """Create weights and bias/biases"""
297     # Check if setting up Deep Network
298     if len(self.hidden_layers_shape) > 0:
299
300         # Initialise Layer values to random values
301         for layer in self.layers:
302             layer.init_layer_values_random()
303
304     # Setup Perceptron Network
305     else:
306
307         # Initialise Layer values to zeros
308         for layer in self.layers:
309             layer.init_layer_values_zeros()
310
311 @_setup_layers
312 def load_model_values(self, file_location: str) -> None:
313     """Load weights and bias/biases from .npz file.
314
315     Args:
316         file_location (str): the location of the file to load from.
317
318     """
319     data: dict[str, np.ndarray] = np.load(file=file_location)
320
321     # Initialise Layer values
322     i = 0
323     keys = list(data.keys())
324     for layer in self.layers:
325         layer.weights = data[keys[i]]
326         layer.biases = data[keys[i + 1]]
327         i += 2
328
329 def back_propagation(self, dloss_doutput) -> None:
330     """Train each layer's weights and biases.
331
332     Args:
333         dloss_doutput (np.ndarray): the derivative of the loss of the
334         output layer's output, with respect to the output layer's
↪ output.
335
336     """
337     for layer in reversed(self.layers):
338         dloss_doutput =
↪ layer.back_propagation(dloss_doutput=dloss_doutput)
339
340 def forward_propagation(self) -> np.ndarray:
341     """Generate a prediction with the layers.
342
343     Returns:
344         a numpy.ndarray of the prediction values.
345

```



```

346         """
347         output = self.train_inputs
348         for layer in self.layers:
349             output = layer.forward_propagation(inputs=output)
350         return output
351
352     def test(self) -> None:
353         """Test the layers' trained weights and biases."""
354         output = self.test_inputs
355         for layer in self.layers:
356             output = layer.forward_propagation(inputs=output)
357         self.test_prediction = output
358
359         # Calculate performance of model
360         self.test_prediction_accuracy = calculate_prediction_accuracy(
361             ↪ prediction=self.test_prediction,
362             ↪ outputs=self.test_outputs
363         )
364
365     def train(self, epoch_count: int) -> None:
366         """Train layers' weights and biases.
367
368         Args:
369             epoch_count (int): the number of training epochs.
370
371         """
372         self.layers_shape = [f'{layer}' for layer in (
373             [self.input_neuron_count] +
374             self.hidden_layers_shape +
375             [self.output_neuron_count]
376         )]
377         self.train_losses = []
378         training_start_time = time.time()
379         for epoch in range(epoch_count):
380             if not self.__running:
381                 break
382             self.training_progress = f"Epoch {epoch} / {epoch_count}"
383             prediction = self.forward_propagation()
384             loss = calculate_loss(input_count=self.input_count,
385                                 ↪ outputs=self.train_outputs,
386                                 ↪ prediction=prediction)
387             self.train_losses.append(loss)
388             if not self.__running:
389                 break
390             dloss_doutput = -(1/self.input_count) * ((self.train_outputs -
391             ↪ prediction)/(prediction * (1 - prediction)))
392             self.back_propagation(dloss_doutput=dloss_doutput)
393             self.training_time = round(number=time.time() -
394             ↪ training_start_time,
395                                     ndigits=2)
396
397     def save_model_values(self, file_location: str) -> None:
398         """Save the model by saving the weights then biases of each layer
399         ↪ to
400             a .npz file with a given file location.
401
402         Args:
403             file_location (str): the file location to save the model to.
404
405         """
406         saved_model: list[np.ndarray] = []

```

```

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

```

3.2.2 Artificial Neural Network implementations

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

- cat_recognition.py module:

```

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

```

```

42         FileNotFoundError: if file does not exist.
43
44     """
45     # Load datasets from h5 files
46     # (h5 files stores large amount of data with quick access)
47     train_dataset: h5py.File = h5py.File(
48         r'school_project/models/datasets/train-cat.h5',
49         'r'
50     )
51     test_dataset: h5py.File = h5py.File(
52         r'school_project/models/datasets/test-cat.h5',
53         '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
↪ use.
22         learning_rate (float): the learning rate of the model.
23         use_relu (bool): True or False whether the ReLu Transfer
↪ function
24             should be used.
25
26     """
27     super().__init__(hidden_layers_shape=hidden_layers_shape,
28                     train_dataset_size=train_dataset_size,
29                     learning_rate=learning_rate,
30                     use_relu=use_relu)
31
32     def load_datasets(self, train_dataset_size: int) -> tuple[np.ndarray,
↪ np.ndarray,
33                                                             np.ndarray,
34                                                             ↪ np.ndarray]:
35
36         """Load image input and output datasets.
37         Args:
38             train_dataset_size (int): the number of dataset inputs to use.
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 pkl.gz file
48     with gzip.open(
49         'school_project/models/datasets/mnist.pkl.gz',
50         'rb'
51     ) as mnist:
52         (train_inputs, train_outputs),\
53         (test_inputs, test_outputs) = pickle.load(mnist,
54         ↪ encoding='bytes')
55
56     # Reshape input arrays into 1 dimension (flatten),
57     # then divide by 255 (RGB)
58     # to standardize them to a number between 0 and 1
59     train_inputs =
60     ↪ np.array(train_inputs.reshape((train_inputs.shape[0],
61                                     -1)).T / 255)
62     test_inputs = np.array(test_inputs.reshape(test_inputs.shape[0],
63     ↪ -1)).T / 255)
64
65     # Represent number values
66     # with a one at the matching index of an array of zeros
67     train_outputs = np.eye(np.max(train_outputs) + 1)[train_outputs].T
68     test_outputs = np.eye(np.max(test_outputs) + 1)[test_outputs].T
69
70     # Reduce train datasets' sizes to train_dataset_size
71     train_inputs = (train_inputs.T[:train_dataset_size]).T
72     train_outputs = (train_outputs.T[:train_dataset_size]).T
73
74     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
23     ↪ colour.
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
30     """
31     super().__init__(master=root, width=width, height=height, bg=bg)
32     self.root = root
33     self.WIDTH = width
34     self.HEIGHT = height
35     self.BG = bg
36
37     # Setup hyper-parameter frame variables
38     self.dataset = dataset
39     self.use_gpu: bool
40     self.default_hyper_parameters = self.load_default_hyper_parameters(
41         ↪ dataset=dataset
42     )
43
44     # Setup widgets
45     self.title_label = tk.Label(master=self,
46                                bg=self.BG,
47                                font=('Arial', 20),
48                                text=dataset)
49
50     self.about_label = tk.Label(
51         master=self,
52         bg=self.BG,
53         font=('Arial', 14),
54         ↪ text=self.default_hyper_parameters['description']
55     )
56
57     self.learning_rate_scale = tk.Scale(
58         master=self,
59         bg=self.BG,
60         orient='horizontal',
61         label="Learning Rate",
62         length=185,
63         from_=0,
64         ↪ to=self.default_hyper_parameters['maxLearningRate'],
65         resolution=0.01
66     )
67
68     self.learning_rate_scale.set(value=0.1)
69     self.epoch_count_scale = tk.Scale(master=self,
70                                      bg=self.BG,
71                                      orient='horizontal',
72                                      label="Epoch Count",
73                                      length=185,
74                                      from_=0,
75                                      to=10_000,
76                                      resolution=100)
77
78     self.epoch_count_scale.set(
79         ↪ value=self.default_hyper_parameters['epochCount']
80     )
81
82     self.train_dataset_size_scale = tk.Scale(

```

```

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

```



```

131         colspan=3, pady=50)
132
133     def load_default_hyper_parameters(self, dataset: str) -> dict[
134         str,
135         str | int | list[int] |
136         ↪ float
137         ]:
138         """Load the dataset's default hyper-parameters from the json file.
139
140         Args:
141             dataset (str): the name of the dataset to load
142             ↪ hyper-parameters
143             for. ('MNIST', 'Cat Recognition' or 'XOR')
144         Returns:
145             a dictionary of default hyper-parameter values.
146         """
147         with open('school_project/frames/hyper-parameter-defaults.json') as
148             ↪ f:
149             return json.load(f)[dataset]
150
151     def create_model(self) -> object:
152         """Create and return a Model using the hyper-parameters set.
153
154         Returns:
155             a Model object.
156         """
157         self.use_gpu = self.use_gpu_check_button_var.get()
158
159         # Validate hidden layers shape input
160         hidden_layers_shape_input = [layer for layer in
161             ↪ self.hidden_layers_shape_entry.get().replace(' ',
162             ↪ '').split(',') if layer != '']
163         for layer in hidden_layers_shape_input:
164             if not layer.isdigit():
165                 self.model_status_label.configure(
166                     text="Invalid hidden layers shape",
167                     fg='red'
168                 )
169                 raise ValueError
170
171         # Create Model
172         if not self.use_gpu:
173             if self.dataset == "MNIST":
174                 from school_project.models.cpu.mnist import MNISTModel as
175                 ↪ Model
176             elif self.dataset == "Cat Recognition":
177                 from school_project.models.cpu.cat_recognition import
178                 ↪ CatRecognitionModel as Model
179             elif self.dataset == "XOR":
180                 from school_project.models.cpu.xor import XORModel as Model
181             model = Model(
182                 hidden_layers_shape = [int(neuron_count) for neuron_count
183                     ↪ in hidden_layers_shape_input],
184                 train_dataset_size = self.train_dataset_size_scale.get(),
185                 learning_rate = self.learning_rate_scale.get(),
186                 use_relu = self.use_relu_check_button_var.get()
187             )
188             model.create_model_values()
189
190         else:
191             try:
192                 if self.dataset == "MNIST":

```

```

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

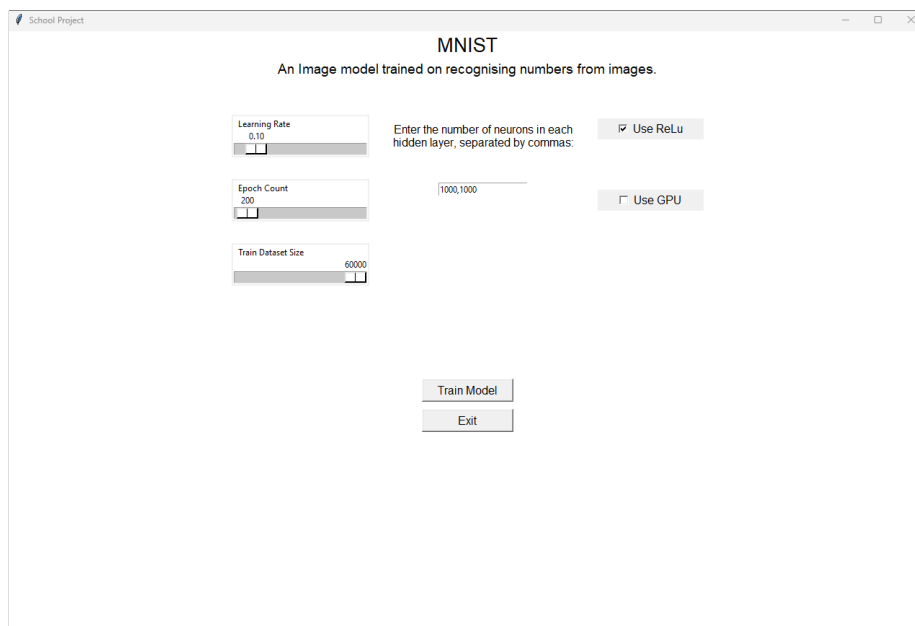
```

```

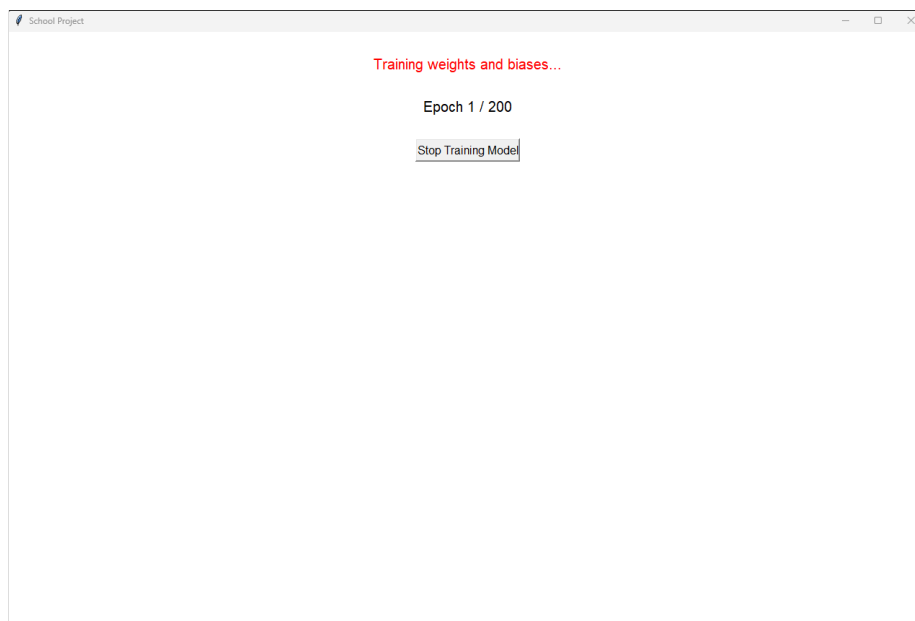
237                                     master=self
238                                     )
239
240     # Pack widgets
241     self.model_status_label.pack(pady=(30,0))
242     self.training_progress_label.pack(pady=30)
243
244     # Start training thread
245     self.model_status_label.configure(
246         text="Training weights and
247             ↳ biases...",
248             fg='red'
249         )
250     self.train_thread: threading.Thread = threading.Thread(
251
252             ↳ target=model.train,
253             ↳ args=(epoch_count,)
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     self.model_status_label.configure(
264         text=f"Weights and biases trained in
265             ↳ {model.training_time}s",
266         fg='green'
267     )
268     graph: Figure.axes = self.loss_figure.add_subplot(111)
269     graph.set_title("Learning rate: " +
270                     f"{model.learning_rate}")
271     graph.set_xlabel("Epochs")
272     graph.set_ylabel("Loss Value")
273     graph.plot(np.squeeze(model.train_losses))
274     self.loss_canvas.get_tk_widget().pack()

```

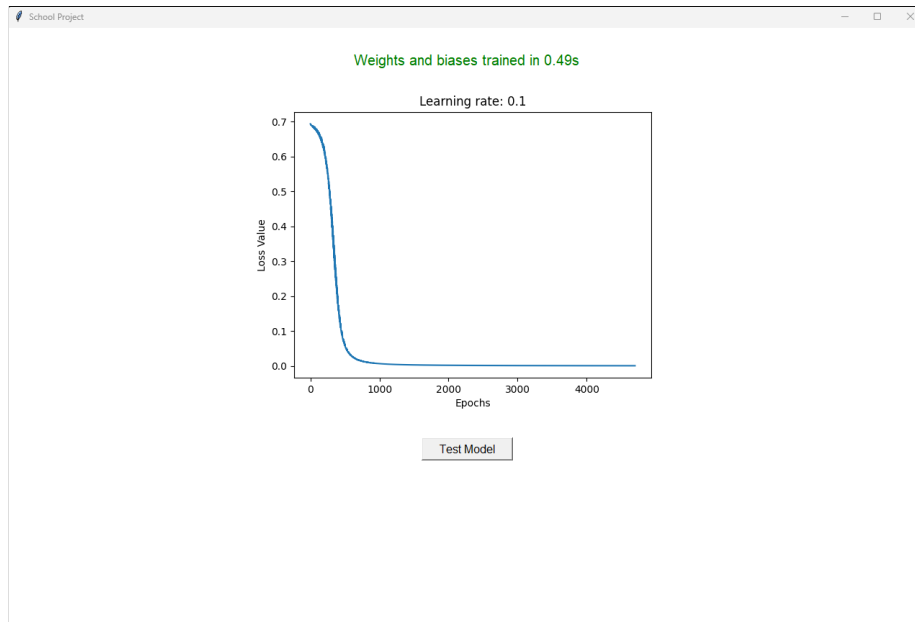
Which outputs the following for the hyper-parameter frame:



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
27          Raises:
28              TypeError: if root, width or height are not of the correct
29      ↪ type.
30
31          """

```

```

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

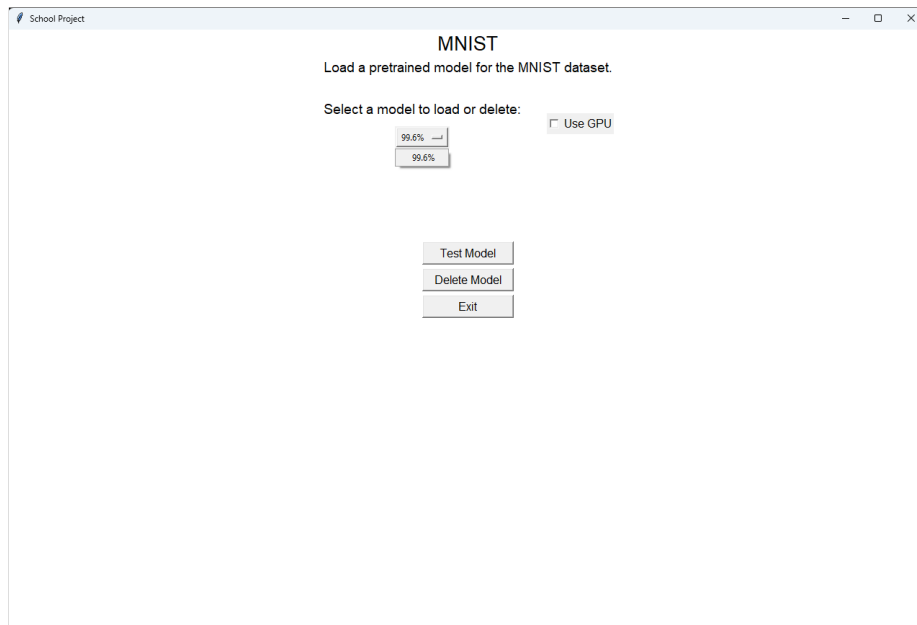
```

```

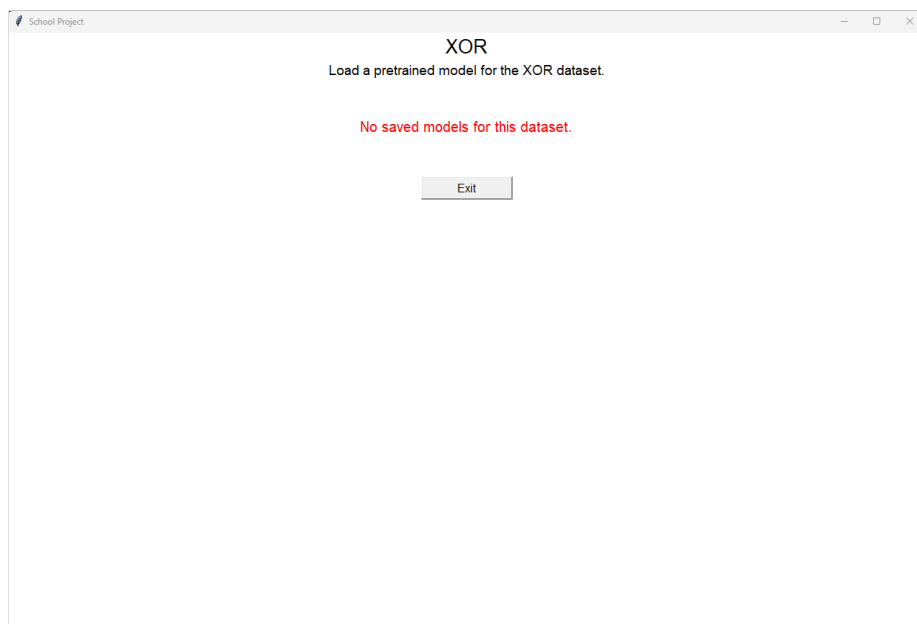
139         elif self.dataset == "Cat Recognition":
140             from school_project.models.cpu.cat_recognition import
141                 ↪ CatRecognitionModel as Model
142         elif self.dataset == "XOR":
143             from school_project.models.cpu.xor import XORModel as Model
144         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         Raises:
27             TypeError: if root, width or height are not of the correct type.
28
29         """
30         super().__init__(master=root, width=width, height=height, bg=bg)
31         self.root = root.title("School Project")
32         self.WIDTH = width
33         self.HEIGHT = height
34         self.BG = bg
35
36         # Setup school project frame variables
37         self.hyper_parameter_frame: HyperParameterFrame
38         self.training_frame: TrainingFrame
39         self.load_model_frame: LoadModelFrame
40         self.test_frame: TestMNISTFrame | TestCatRecognitionFrame | TestXORFrame
41         self.connection, self.cursor = self.setup_database()
42         self.model = None
43
44         # Record if the model should be saved after testing,
45         # as only newly created models should be given the option to be saved.
46         self.saving_model: bool
47
48         # Setup school project frame widgets
49         self.exit_hyper_parameter_frame_button = tk.Button(
50             master=self,
51             width=13,
52             height=1,
53             font=tkf.Font(size=12),
54             text="Exit",
55             command=self.exit_hyper_parameter_frame
56         )
57         self.exit_load_model_frame_button = tk.Button(
58             master=self,
59             width=13,
60             height=1,
61             font=tkf.Font(size=12),
62             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 (?, ?, ?, ?, ?, ?, ?)

```



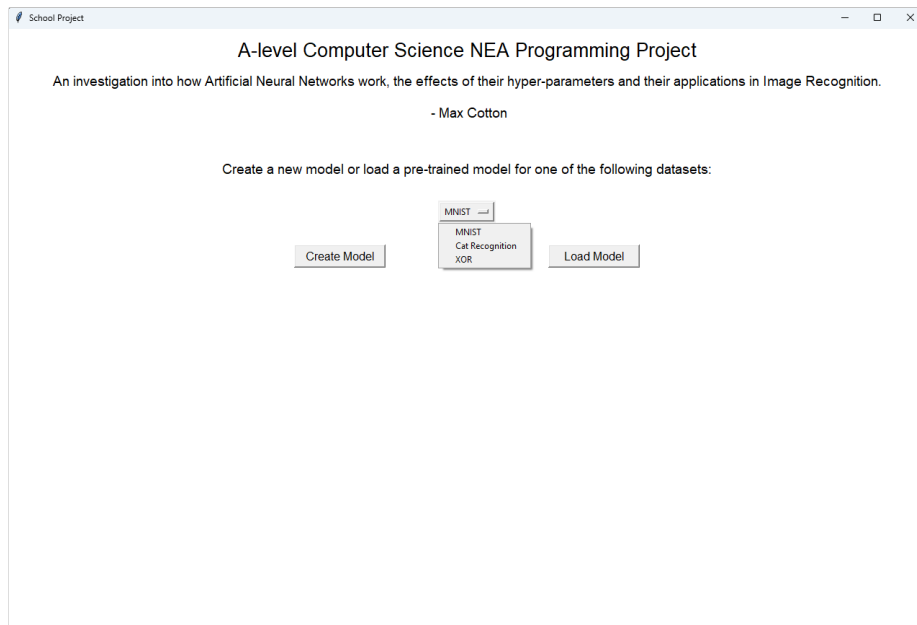
```

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 TODO

4.1 Investigation

4.1.1 test_model module

4.1.2 Effects of Hyper-Parameters

4.2 Manual Testing

4.2.1 Input Validation Testing

4.3 Automated Testing

4.3.1 Unit Tests

4.3.2 GitHub Automated Testing