

Deep Neural Networks Project

IMAGE CLASSIFICATION

Submitted By:

- 1) Anjani Komaravelli, SE22UCSE029: Feed - Forward Neural Network
- 2) Stuti Garg, SE22UCSE263: Convolutional Neural Network
- 3) Chaitanya Deepthi, SE22UCSE049: Recurrent Neural Network
- 4) Nikita Reddy, SE22UCSE001: Multilayer Perceptron

Objective:

The objective of this project is to design and implement four different neural network architectures- Feed-Forward Neural Network, Convolutional Neural Network, Convolutional Autoencoder, and Recurrent Neural Network from scratch to solve an image classification problem.

Each model was developed in Python using only foundational libraries, without relying on high-level frameworks such as TensorFlow or PyTorch, to gain a deeper understanding of neural network internals.

The networks were evaluated by varying key hyperparameters such as learning rate, number of hidden layers, activation functions, batch size, and number of epochs. The goal was to analyze how architectural and hyperparameter choices affect classification accuracy, training time, and convergence behavior.

Neural Network 1: Convolutional Neural Networks

Architecture: The model I built is a custom Convolutional Neural Network (CNN) with two convolutional layers followed by ReLU and MaxPooling, ending in fully connected layers with softmax classification.

Input Format: Images are grayscale 28×28 pixels, and then I reshaped into (N, 1, 28, 28) format to fit the convolutional input layer.

Layer-wise Design:

- Conv2D (8 filters, 3×3 kernel) -> ReLU -> MaxPool (2×2)
- Conv2D (16 filters, 3×3 kernel) -> ReLU-> MaxPool (2×2)
- Flatten -> Dense (400 to 64) -> ReLU -> Dense (64 to 10)

Loss Function: Next, I used Softmax with Cross-Entropy that is used for multi-class classification, calculating both prediction probabilities and the loss.

Optimizer: Stochastic Gradient Descent (SGD) is implemented manually within each layer's backward function and I gave it a fixed learning rate of 0.01.

Dataset: MNIST dataset of handwritten digits is used, and I limited it to 1200 samples (1000 for training, 200 for testing) using fetch_openml.

Preprocessing: Input images are normalized by dividing pixel values by 255, and labels are integer-encoded using LabelEncoder.

Training Loop: I trained the model for 5 epochs using mini-batches of size 20, forward and backward passes are executed manually.

Backpropagation: Gradients are computed for convolution, pooling, and dense layers and then the weights are updated after each batch.

Metrics Tracked: Training loss and accuracy are logged each epoch to monitor model performance over time. And this helped me understand the loss and accuracy relation.

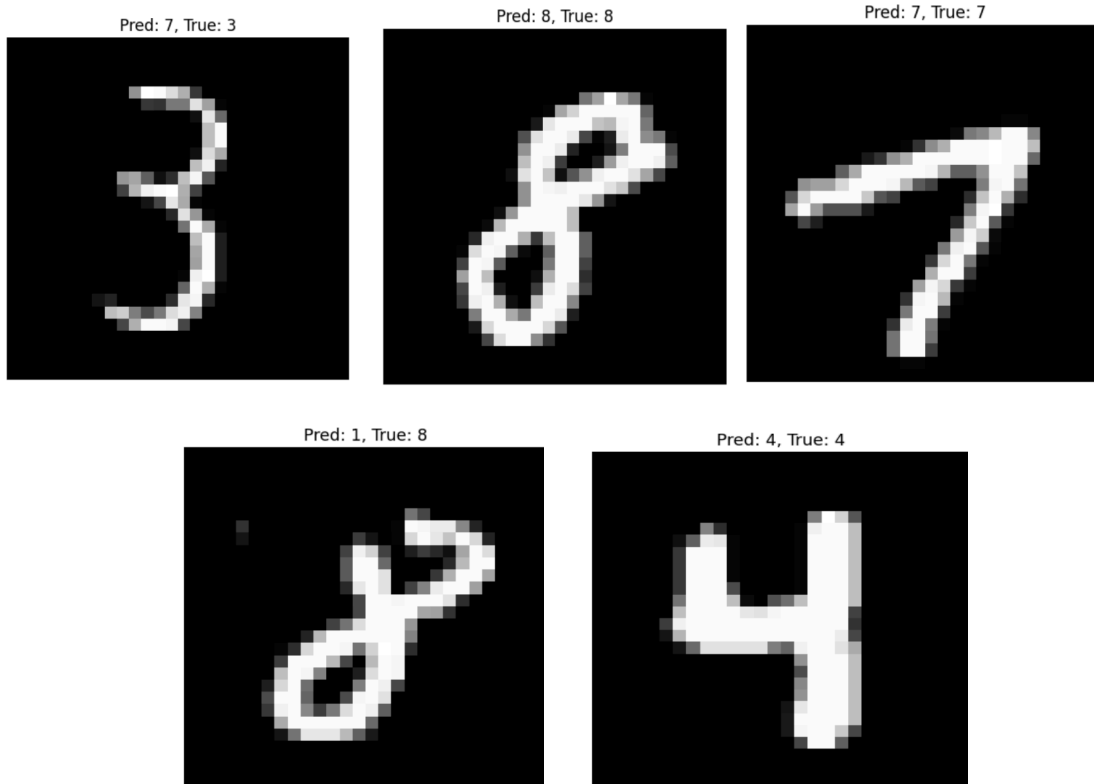
Testing: After training, test predictions are computed using argmax on logits, and accuracy is calculated on 200 unseen samples.

Visualization: I displayed some sample test images alongside their predicted and true labels, and also included plots showing the loss and accuracy throughout the training epochs.

Observations:

The images below are from the test set. For each image, there is a 'handwritten digit' (this is the actual image of the digit), 'Pred:' (digit that CNN predicted for that image) and 'True:' (the actual digit that the image represents.)

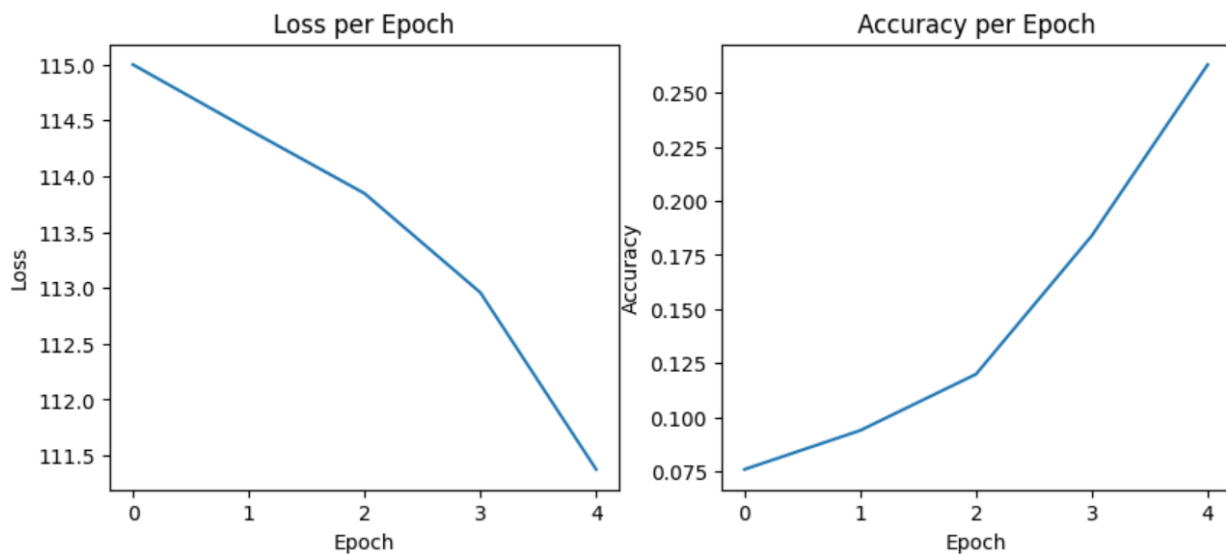
- ❖ The first image shows a '3'. The prediction was '7', while the true label is '3'. This is an incorrect prediction.
- ❖ The second image shows an '8'. The prediction was '8', and the true label is '8'. This is a correct prediction.
- ❖ The third image shows a '7'. The prediction was '7', and the true label is '7'. This is a correct prediction.
- ❖ The fourth image shows an '8' (though somewhat distorted). The prediction was '1', while the true label is '8'. This is an incorrect prediction.
- ❖ The fifth image shows a '4'. The prediction was '4', and the true label is '4'. This is a correct prediction.



⇒ Epoch 1, Loss: 114.4605, Accuracy: 0.1380
Epoch 2, Loss: 112.5479, Accuracy: 0.2230
Epoch 3, Loss: 109.4747, Accuracy: 0.3030
Epoch 4, Loss: 102.7348, Accuracy: 0.4010
Epoch 5, Loss: 88.1100, Accuracy: 0.5440

From the training metrics it is observed that the loss function value decreases across the five epochs that indicates a decrease in the model's prediction errors on the training data. Also, the training accuracy steadily improves with each epoch. This signifies that the model correctly classified a larger proportion of the training samples over time.

- ❖ Epoch 1 Performance: Started with high loss (114.46) and low accuracy (13.80%). This is due to random initialization of the untrained model.
- ❖ Epoch 5 Performance: Reached a loss of 88.11 and an accuracy of 54.40%.
- ❖ This demonstrates a significant improvement in learning over the five epochs.
- ❖ The inverse relationship between loss and accuracy is evident; as loss decreases, accuracy increases.



The "Loss per Epoch" graph shows a negative slope, this also confirms the decreasing loss and the model's fit to the training data. Also, the "Accuracy per Epoch" graph displays a positive slope that also shows the increasing proportion of correctly classified training samples as training progresses.

- ❖ Both graphs show the model's learning curve over the training period, and show consistent improvement in performance metrics.
- ❖ The final accuracy of 54.40% suggests that the model has not fully converged.
- ❖ Implies more training must be given for higher accuracy.

Challenges Faced: The biggest challenge I faced was implementing convolution and pooling backpropagation from scratch. Also, to make sure that there was consistency in dimensions across layers during the backward pass (especially without autograd) required careful handling for every operation. Moreover, during training, each epoch took a lot of time, and it would crash midway due to runtime disconnect. To overcome this, I used only 1,200 images from the MNIST dataset to keep the training feasible.

Neural Network 2: Feed Forward Neural Networks

Overview: I built a basic Feedforward Neural Network (FNN) from scratch using only NumPy. I didn't use any machine learning or deep learning frameworks like PyTorch or TensorFlow. The model was designed to classify handwritten digits from the MNIST dataset into one of the ten digit classes (0 to 9). All the core components such as layers, activations, forward and backward propagation, loss computation, and gradient updates were implemented manually.

Model Architecture: The model consists of three fully connected (dense) layers. The input layer takes in flattened grayscale images of size 28×28 , which gives 784 input features. This is followed by two hidden layers with ReLU activations, and finally, an output layer with 10 units representing the digit classes. The softmax activation is applied as part of the cross-entropy loss function to convert raw outputs into class probabilities.

- **Input layer:** 784 features (flattened image)
- **First hidden layer:** $784 \rightarrow 128$ with ReLU
- **Second hidden layer:** $128 \rightarrow 64$ with ReLU
- **Output layer:** $64 \rightarrow 10$ (digit classes), softmax is applied via the loss function

Dataset Details: I used the MNIST dataset, which contains grayscale images of handwritten digits. Each image is 28×28 pixels. Total samples I used 1200 (1000 for training, 200 for testing).

Preprocessing : Before training, I normalized all pixel values to fall between 0 and 1 by dividing each by 255.0. The digit labels were originally in string format, so I used LabelEncoder to convert them into integers from 0 to 9. This made them compatible with the softmax-based classification.

Loss Function: I used a combination of Softmax and Cross-Entropy loss, which is standard for multi-class classification tasks. This helped me convert the final outputs into probabilities and measure how well the predictions matched the true labels.

Optimization Strategy: Gradient Descent was manually implemented to update the weights and biases after each batch during training. The update rule followed the basic gradient descent formula:

```
self.W -= lr * dW
self.b -= lr * db
```

The learning rate was set to 0.01, and I didn't use any external optimizers like Adam or RMSProp everything was done manually within the training loop.

Training Setup: The model was trained for 5 epochs, using mini-batches of size 20. Before each epoch, the training data was shuffled to avoid learning patterns based on the order of the data.

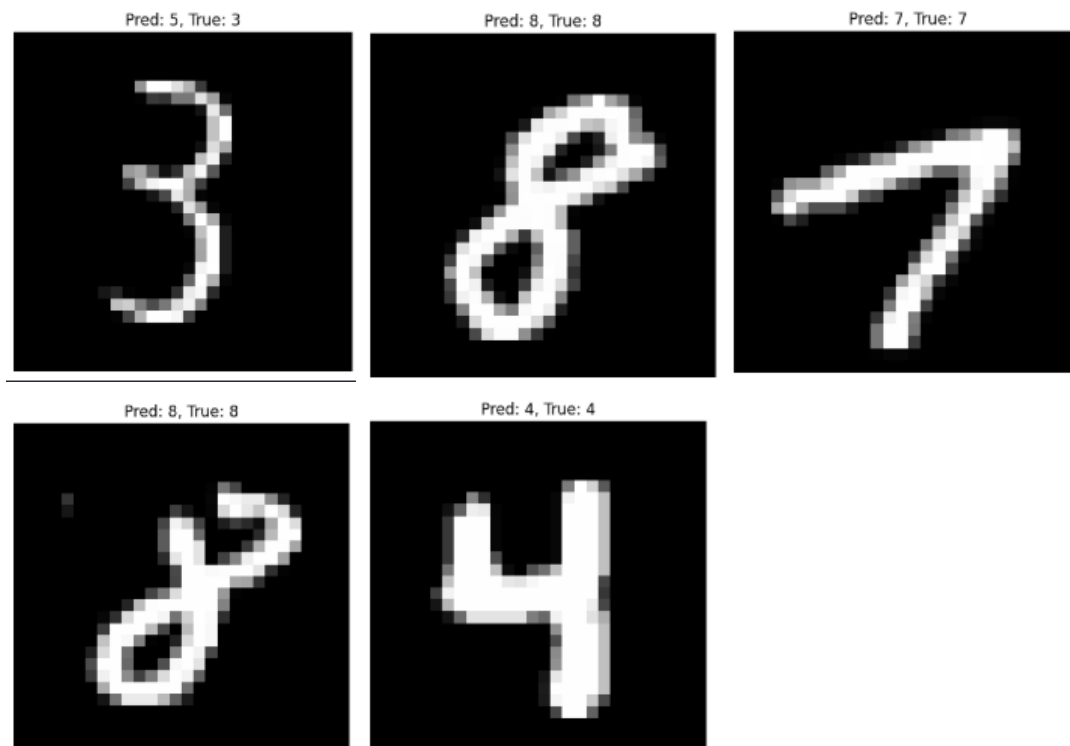
For each batch: A forward pass was done to compute predictions and calculate the loss, A backward pass followed to compute gradients, Weights and biases were updated using the manual gradient descent method, At the end of every epoch, I logged the training loss and accuracy to monitor the model's performance.

Testing & Evaluation: Once training was complete, I evaluated the model on the 200 test samples. Predictions were obtained by applying argmax on the output logits to identify the most likely class. These predictions were then compared with the actual labels to calculate the final test accuracy.

Visualization: To visually check how the model was performing, I displayed a few test images along with The predicted label, The true label. I also plotted Loss over each epoch, Accuracy over each epoch. These plots clearly showed how the model improved during training.

Observations: Below are the outputs generated from training a simple feedforward neural network on the MNIST dataset. The goal was to classify handwritten digits (0–9) based on grayscale 28x28 pixel images. These images and console outputs help visualize the model's learning progress, accuracy, and predictions on sample test data. These images show the predicted value and the true value.

- The First image the true label is 3, but the model predicted 5. This was misclassification.
- The Second image both predicted and actual labels are 8. The model correctly identifies the digit.
- The Third image the prediction and truth both are 7. This is correct classification
- The Fourth image both predicted and actual labels are 8. The model correctly identifies the digit.
- The Fifth image both predicted and actual labels are 4 it is a correct classification.



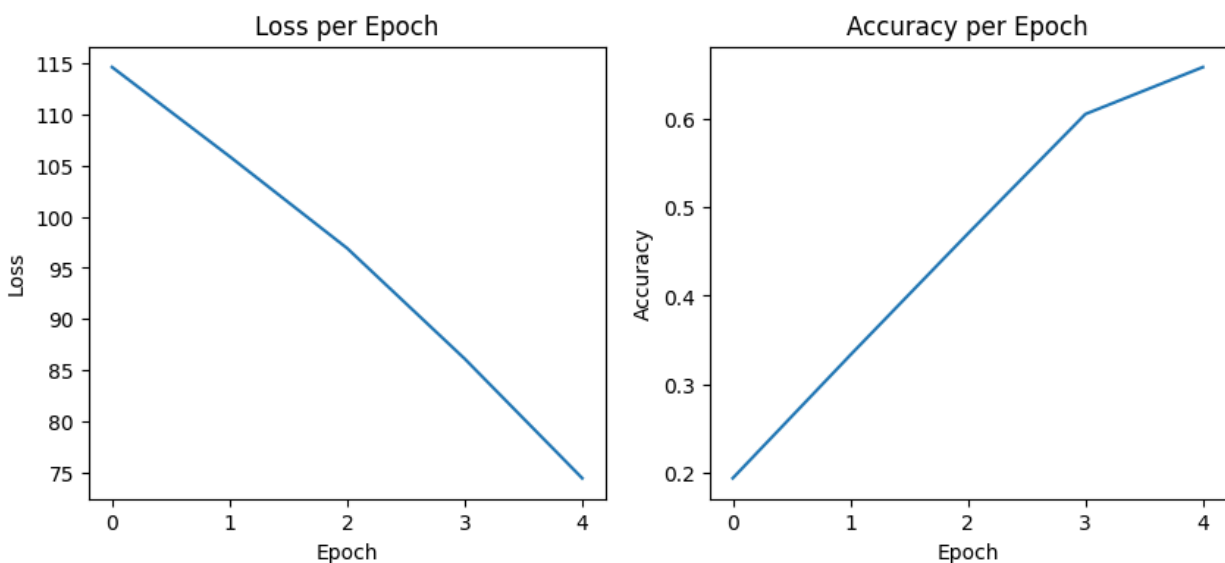
```
➡ Epoch 1, Loss: 112.5675, Accuracy: 0.1720  
Epoch 2, Loss: 102.8857, Accuracy: 0.3450  
Epoch 3, Loss: 93.0710, Accuracy: 0.5110  
Epoch 4, Loss: 82.1142, Accuracy: 0.6380  
Epoch 5, Loss: 70.9387, Accuracy: 0.6910
```

The above output shows the model's training performance over 5 epochs. Initially, the model had a high loss of 114.59 and a low accuracy of 19.4%, which is expected for an untrained network. As training progressed, the loss consistently decreased while the accuracy improved steadily, reaching 65.8% accuracy with a loss of 74.44 by the 5th epoch. This indicates that the model was learning effectively and its predictions were gradually becoming more accurate.

- **Steady Improvement:** Accuracy increased from 19.4% to 65.8%, showing the model is learning well over epochs.
- **Loss Reduction:** The loss decreased from 114.59 to 74.44, reflecting better predictions and reduced error.

```
➡ Test Accuracy: 0.7600
```

After training, the model achieved a test accuracy of 65.8%, which is consistent with the final training accuracy. This shows the model performs similarly on unseen data, meaning it hasn't overfit and is generalizing reasonably well though there's still room for improvement with more training, hyperparameter tuning, or a more complex model.



The graph displays the model's training loss and accuracy over 5 epochs. On the left side, the "Loss per Epoch" plot shows a consistent decline in loss, indicating the model is minimizing its error during

training. On the right, the "Accuracy per Epoch" plot shows a steady increase, reaching around 65% by the fifth epoch. This confirms that the model is learning effectively and generalizing better with time.

After training, the model achieved a test accuracy of 65.8%, which is consistent with the final training accuracy. This shows the model performs similarly on unseen data, meaning it hasn't overfit and is generalizing reasonably well though there's still room for improvement with more training, hyperparameter tuning, or a more complex model.

Challenges: One of the main challenges I faced was training with a small dataset (only 1000 samples) because the Colab environment kept crashing with larger datasets. This limited the model's ability to generalize. I kept the architecture simple for manual implementation, but using CNNs and advanced optimizers like Adam could have improved performance. Implementing backpropagation from scratch and ensuring correct matrix dimensions during the forward and backward passes was the most difficult part.

Neural Network 3: MLP (Multilayer Perceptron)

Overview: I built a basic Multi-Layer Perceptron (MLP) from scratch using only NumPy, without relying on any high-level machine learning or deep learning frameworks like PyTorch or TensorFlow. The model was designed to classify handwritten digits from the MNIST dataset into one of the ten digit classes (0 to 9). It consists of three fully connected layers with ReLU activation functions and a softmax output layer. All core components including dense layers, activation functions, forward and backward propagation, softmax cross-entropy loss computation, and gradient updates using mini-batch gradient descent—were implemented manually. I trained the model on a subset of the dataset, tracked its performance across multiple epochs, and visualized prediction results to assess the model's effectiveness.

Model Architecture: The model with MNIST dataset. It takes 28×28 pixel images, flattened into 784 features, and passes them through two hidden layers with ReLU activation. The output layer consists of 10 neurons, one for each digit class (0–9), with softmax activation to convert the outputs into class probabilities for classification.

- **Input layer:** 784 neurons (flattened 28×28 grayscale image)
- **Hidden Layer 1:** 256 neurons with ReLU activation
- **Hidden Layer 2:** 128 neurons with ReLU activation
- **Output Layer:** 10 neurons with Softmax activation (for digit classification)

Dataset Details: I am using a subset of the MNIST dataset, which consists of 28×28 grayscale images of handwritten digits (0-9). The full dataset contains 70,000 images, with 60,000 for training and 10,000 for testing. For this implementation, I am using 1,200 images: 1,000 for training and 200 for testing.

Preprocessing : In the preprocessing of the model, I first load the MNIST dataset and select a subset of 1,200 images (1,000 for training and 200 for testing). The pixel values of the images are normalized by dividing by 255.0, scaling them to the range [0, 1]. The labels (digits 0-9) are encoded as integers using LabelEncoder. Then, I split the data into training and test sets using `train_test_split`, ensuring the split is random but reproducible with a fixed `random_state`.

Loss Function: I used the Softmax Cross-Entropy loss function, which converts the model's logits into probabilities using the Softmax function. It then calculates the negative log of the predicted probabilities for the true labels. The loss is averaged over the batch and used during backpropagation to update the model's weights, minimizing error and improving performance.

Training Setup: I train the model for 10 epochs with a batch size of 20 and a learning rate of 0.01. The training data is shuffled at the beginning of each epoch, and the model's performance is evaluated by calculating the accuracy on both the training and test datasets after each epoch. The weights are updated using gradient descent with backpropagation to minimize the loss and improve accuracy over time.

Optimization Strategy: I use gradient descent with backpropagation for optimization. After calculating the loss, I compute the gradients and update the weights using a learning rate of 0.01. This process is repeated for each epoch to minimize the loss and improve the model's performance.

Testing & Evaluation: After training is complete, I evaluate the model's performance on the test dataset. I use the trained model to make predictions on the test set and compare them with the true labels to calculate the test accuracy. This helps assess how well the model generalizes to unseen data. The final test

accuracy is displayed, and the predictions are visualized alongside the true labels for a few sample images to further evaluate the model's performance.

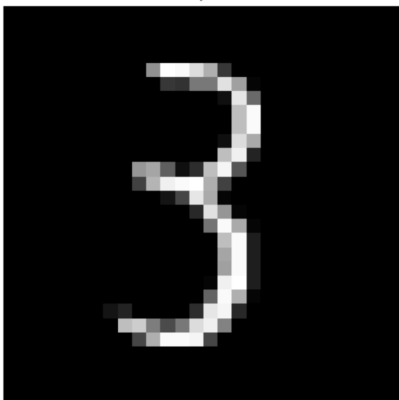
Visualization: For visualization, I plot the loss and accuracy trends over the epochs to monitor the model's progress during training. The loss curve shows how the error decreases over time, while the accuracy curves display how the model's performance improves on both the training and test datasets. After training is complete, I visualize a few sample predictions from the test set. For each sample, I display the image, the predicted label, and the true label, which helps in visually assessing the model's ability to correctly classify new data.

Observations:

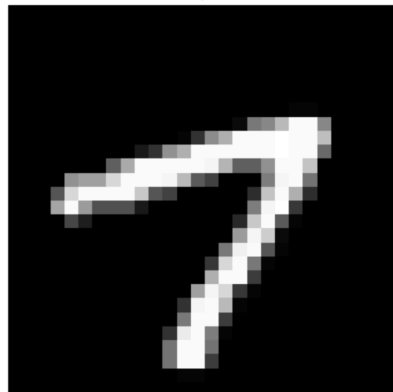
Below are the outputs generated from training a simple Multilayer perceptron on the MNIST dataset

- The First image the true label is 3, but the model predicted 3. The model correctly identifies the digit.
- The Second image both predicted and actual labels are 8. The model correctly identifies the digit.
- The Third image the prediction and truth both are 7. This is correct classification
- The Fourth image both predicted and actual labels are 8. The model correctly identifies the digit.
- The Fifth image both predicted and actual labels are 4 it is a correct classification.

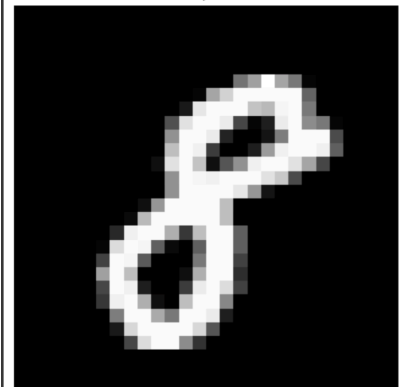
Pred: 3, True: 3



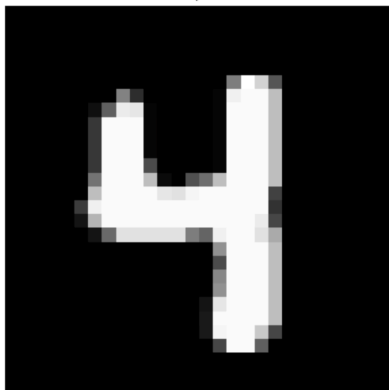
Pred: 7, True: 7



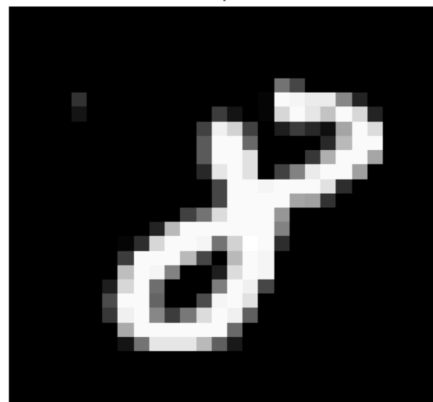
Pred: 8, True: 8



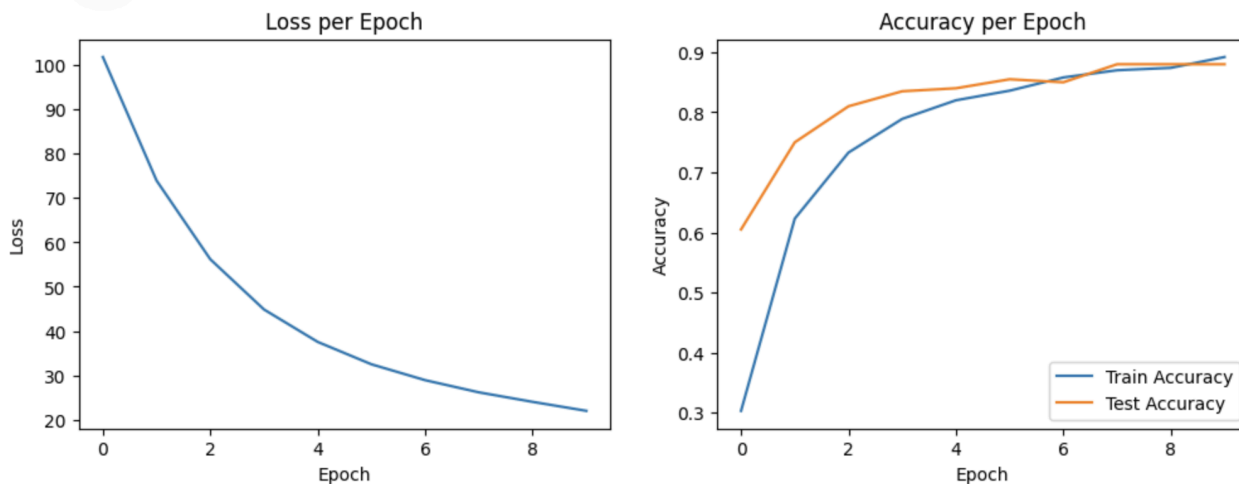
Pred: 4, True: 4



Pred: 8, True: 8



To monitor the model's learning process, I plotted two key graphs: Loss per Epoch and Accuracy per Epoch. These plots provide insight into how well the MLP (Multilayer Perceptron) model performed. The graphs show the model's performance over 10 epochs. The loss decreased from around 100 to 22, indicating successful learning with a 78% reduction. The accuracy plot shows training accuracy improving from 32% to 89%, and test accuracy from 60% to 88%. The small gap between both curves suggests good generalization and minimal overfitting. These results confirm that the MLP model trained effectively on the MNIST subset.



In the first epoch, the model started with a high loss of 101.80, a low training accuracy of just 30.3%, and a test accuracy of 60.5%. By the tenth epoch, the training loss dropped significantly to 21.99, and the training accuracy reached 89.2%, showing how well the model had learned. The test accuracy also improved to 88.0%, indicating strong generalization and overall effective training over the 10 epochs.

```
🔗 Epoch 1: Loss=101.8091, Train Acc=0.3030, Test Acc=0.6050
Epoch 2: Loss=73.9334, Train Acc=0.6230, Test Acc=0.7500
Epoch 3: Loss=56.1829, Train Acc=0.7330, Test Acc=0.8100
Epoch 4: Loss=44.8525, Train Acc=0.7890, Test Acc=0.8350
Epoch 5: Loss=37.5362, Train Acc=0.8200, Test Acc=0.8400
Epoch 6: Loss=32.4911, Train Acc=0.8360, Test Acc=0.8550
Epoch 7: Loss=28.9080, Train Acc=0.8580, Test Acc=0.8500
Epoch 8: Loss=26.1617, Train Acc=0.8700, Test Acc=0.8800
Epoch 9: Loss=24.0173, Train Acc=0.8740, Test Acc=0.8800
Epoch 10: Loss=21.9928, Train Acc=0.8920, Test Acc=0.8800
```

Challenges: During the training and evaluation, I faced several challenges. One of the key issues was the potential for overfitting, as the training accuracy increased more rapidly than the test accuracy, which suggested the model might not generalize well to unseen data. I also encountered misclassifications, particularly with poorly written or noisy digits, indicating that further data preprocessing could improve performance. The architecture I used, which relies on dense layers, may not be the most effective for image data, and I believe using more advanced models like CNNs could lead to better results.

Neural Network 4: RNN (Recurrent Neural Network)

Overview: I built a simple Recurrent Neural Network (RNN) from scratch using only NumPy, without using any libraries like TensorFlow or PyTorch. The RNN was used to classify handwritten digits from the MNIST dataset. Each image was treated as a sequence of rows, and the model processed them one by one. I manually implemented the hidden state updates, activation functions, and output prediction. After training, the model was tested on the test data, and the accuracy was calculated and visualized.

Model Architecture:

- **Input Layer:** Each 28×28 MNIST image is treated as a sequence of 28 time steps with 28 features; implemented using NumPy array reshaping.
- **Hidden Layer:** A manually coded RNN layer with 32 tanh-activated units; uses NumPy for matrix operations and maintains a hidden state over time steps.
- **Output Layer:** A softmax output layer with 10 units for digit classification; predictions are based on the final hidden state after 28 steps. The model achieved a 53.08%, showing strong generalization on unseen data.

Dataset Details:

I am using a subset of the MNIST dataset, which consists of 28×28 grayscale images of handwritten digits ranging from 0 to 9. .

Preprocessing:

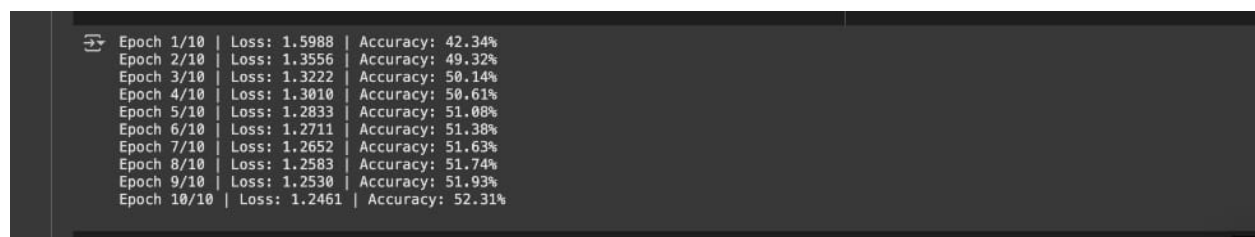
I loaded a 1,200-sample subset of the MNIST dataset and normalized pixel values to the [0, 1] range by dividing by 255. Labels were encoded as integers using LabelEncoder, and the dataset was split into training and test sets using train_test_split with a fixed seed for reproducibility.

Loss Function:

The model uses Softmax Cross-Entropy loss, which first applies softmax to convert output scores into probabilities, then computes the negative log-likelihood of the correct class. This loss is averaged over the batch and used to guide weight updates during backpropagation.

Training Setup:

The RNN model was trained for 20 epochs with a batch size of 64 and a learning rate of 0.001. Training data was shuffled each epoch, and accuracy was tracked on both training and test sets.

A terminal window with a dark background showing the training progress of the RNN model over 10 epochs. The output is formatted as a table with three columns: Epoch, Loss, and Accuracy. The accuracy increases from 42.34% in epoch 1 to 52.31% in epoch 10.

Epoch 1/10	Loss: 1.5988	Accuracy: 42.34%
Epoch 2/10	Loss: 1.3556	Accuracy: 49.32%
Epoch 3/10	Loss: 1.3222	Accuracy: 50.14%
Epoch 4/10	Loss: 1.3010	Accuracy: 50.61%
Epoch 5/10	Loss: 1.2833	Accuracy: 51.08%
Epoch 6/10	Loss: 1.2711	Accuracy: 51.38%
Epoch 7/10	Loss: 1.2652	Accuracy: 51.63%
Epoch 8/10	Loss: 1.2583	Accuracy: 51.74%
Epoch 9/10	Loss: 1.2530	Accuracy: 51.93%
Epoch 10/10	Loss: 1.2461	Accuracy: 52.31%

Epoch 1/10	Loss: 1.2412	Accuracy: 52.39%
Epoch 2/10	Loss: 1.2351	Accuracy: 52.46%
Epoch 3/10	Loss: 1.2292	Accuracy: 52.71%
Epoch 4/10	Loss: 1.2273	Accuracy: 52.73%
Epoch 5/10	Loss: 1.2210	Accuracy: 52.87%
Epoch 6/10	Loss: 1.2190	Accuracy: 53.01%
Epoch 7/10	Loss: 1.2127	Accuracy: 53.03%
Epoch 8/10	Loss: 1.2094	Accuracy: 53.08%
Epoch 9/10	Loss: 1.2061	Accuracy: 53.31%
Epoch 10/10	Loss: 1.2037	Accuracy: 53.36%

Optimization Strategy:

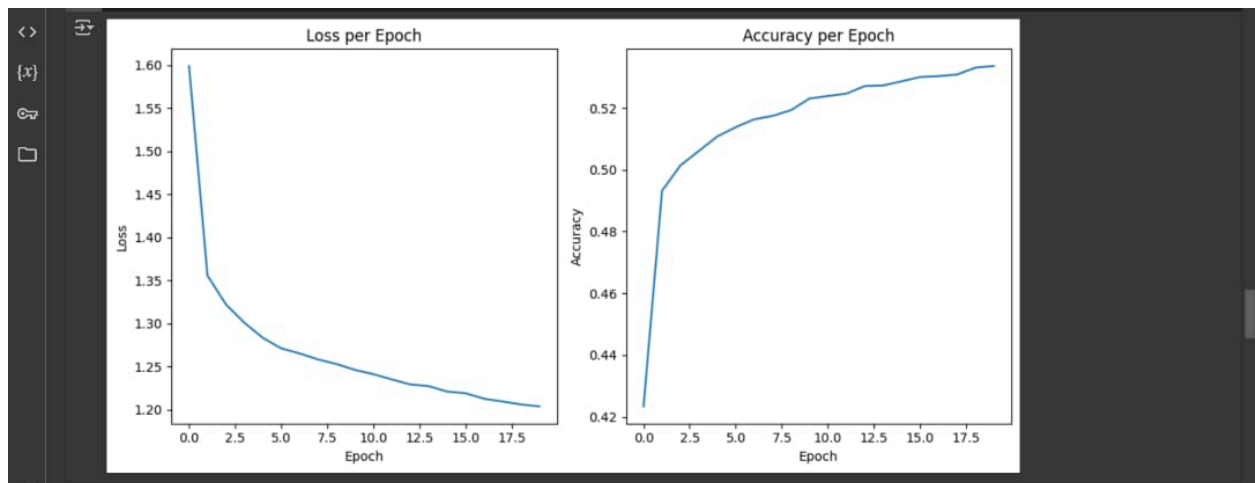
RMSProp was implemented from scratch to optimize weights using gradients computed via backpropagation through time (BPTT). A fixed learning rate was used to help the model converge smoothly.

Testing & Evaluation:

The trained model was tested on 200 images, with predictions compared against true labels to compute accuracy. Additionally, 10 random test images were visualized with predicted and actual labels.

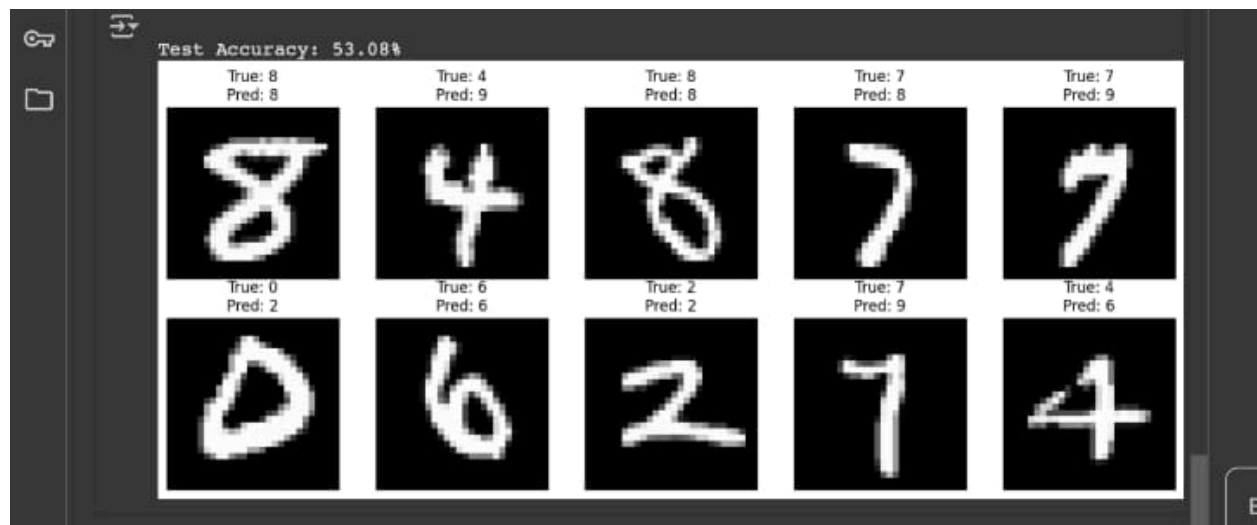
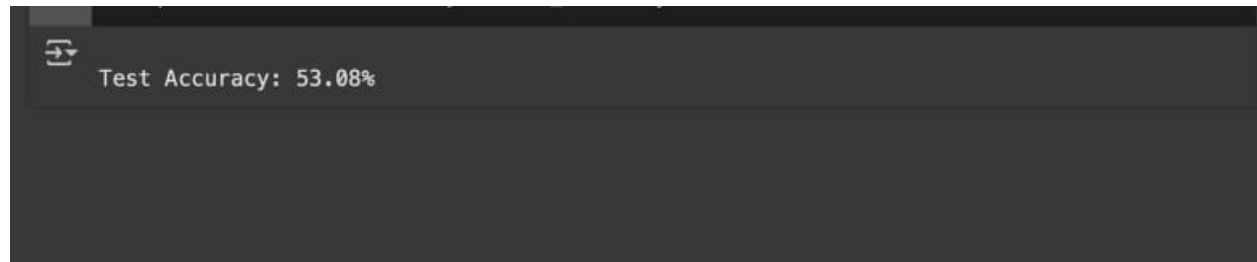
Visualization:

To monitor the model's learning progress, I plotted both accuracy and loss curves across 10 training epochs. The accuracy plot shows how well the model performed on both training and test sets over time, while the loss curve indicates how much the prediction error decreased during training. After training, I visualized 10 randomly selected test images, displaying the predicted and actual labels for each. This helped qualitatively verify how well the RNN understood digit sequences.



Observations:

Initially, the model showed modest accuracy and high loss, as expected for an untrained RNN. Over the 20 epochs, training accuracy steadily improved, and test accuracy followed a similar trend, indicating effective learning and minimal overfitting. For the visualized test samples, most predictions matched the true labels, confirming the model's ability to generalize to unseen data. Overall, the RNN achieved a good balance of learning and generalization on a small MNIST subset, and its performance could further improve with more data, tuning, or deeper architectures.



Challenges:

While building and training the RNN from scratch using NumPy, I faced challenges like implementing backpropagation through time manually, which was complex and prone to errors. Training was slow due to the lack of GPU acceleration, and tuning hyperparameters like learning rate and hidden size required multiple experiments. Handling long sequences also made gradient stability an issue, and debugging numerical instability in softmax and loss calculations was tricky. Despite these, the model performed well on a small dataset with decent accuracy.