Multi-Class Classification in Deep Learning Techniques Report

1. Introduction

This report presents the implementation and results of a multi-class image classification task using various neural network architectures in PyTorch, applied to the STL-10 dataset. STL-10 is a widely used benchmark dataset for image recognition, consisting of color images from 10 semantic classes such as airplane, bird, car, and truck. To reduce computational complexity, the images were resized to 64×64 pixels. Only the labeled training and test sets were used in this project.

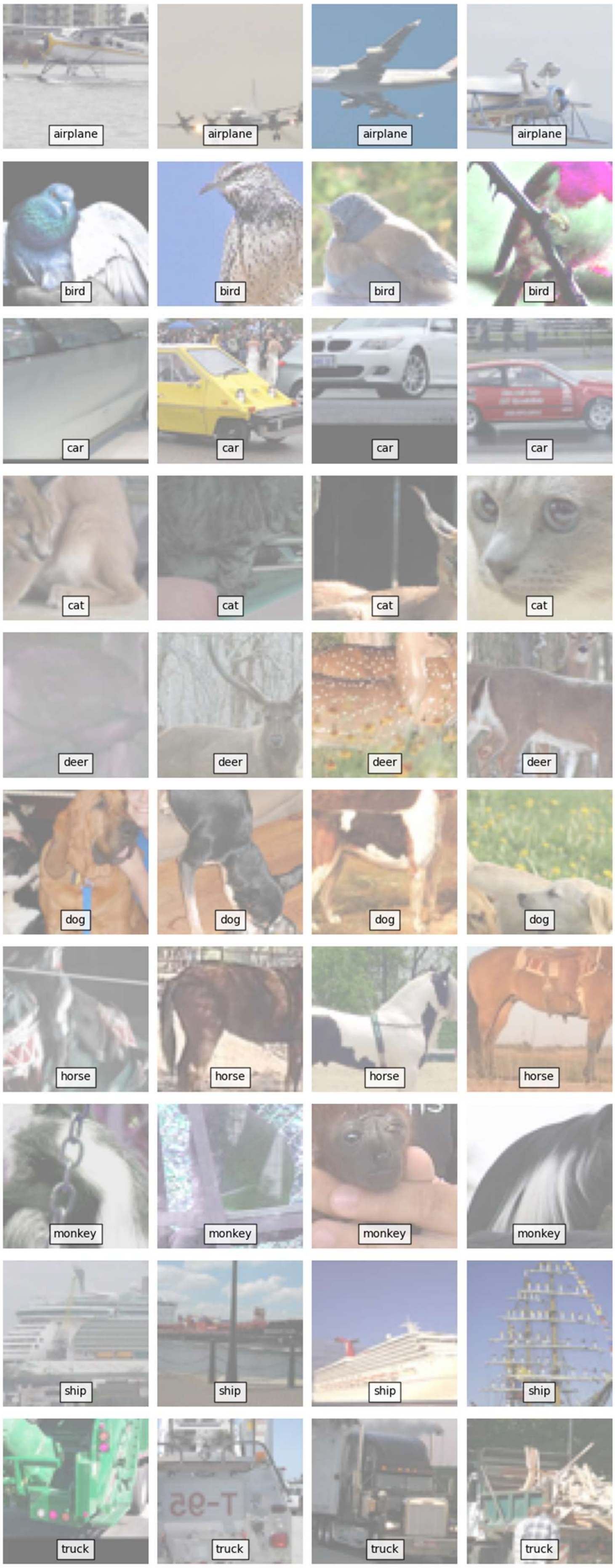
The main objective of the project was to investigate how different deep learning models and hyperparameter configurations influence classification performance. Several approaches were explored, ranging from a simple logistic regression model to deeper fully connected networks and convolutional neural networks. In addition, pre-trained MobileNetV2 models were used, both as fixed feature extractors and in a fine-tuned configuration, leveraging transfer learning to enhance performance.

By comparing these methods, the project aimed to better understand the relationship between model architecture and accuracy, as well as the trade-offs between simplicity, expressiveness, and training efficiency.

The STL-10 dataset is available in the following location: STL-10 dataset

2. Data Visualization

A 10 × 4 grid was created to visualize the dataset, where each row corresponds to a specific class, and each row contains four different images from that class. The images were labeled accordingly.

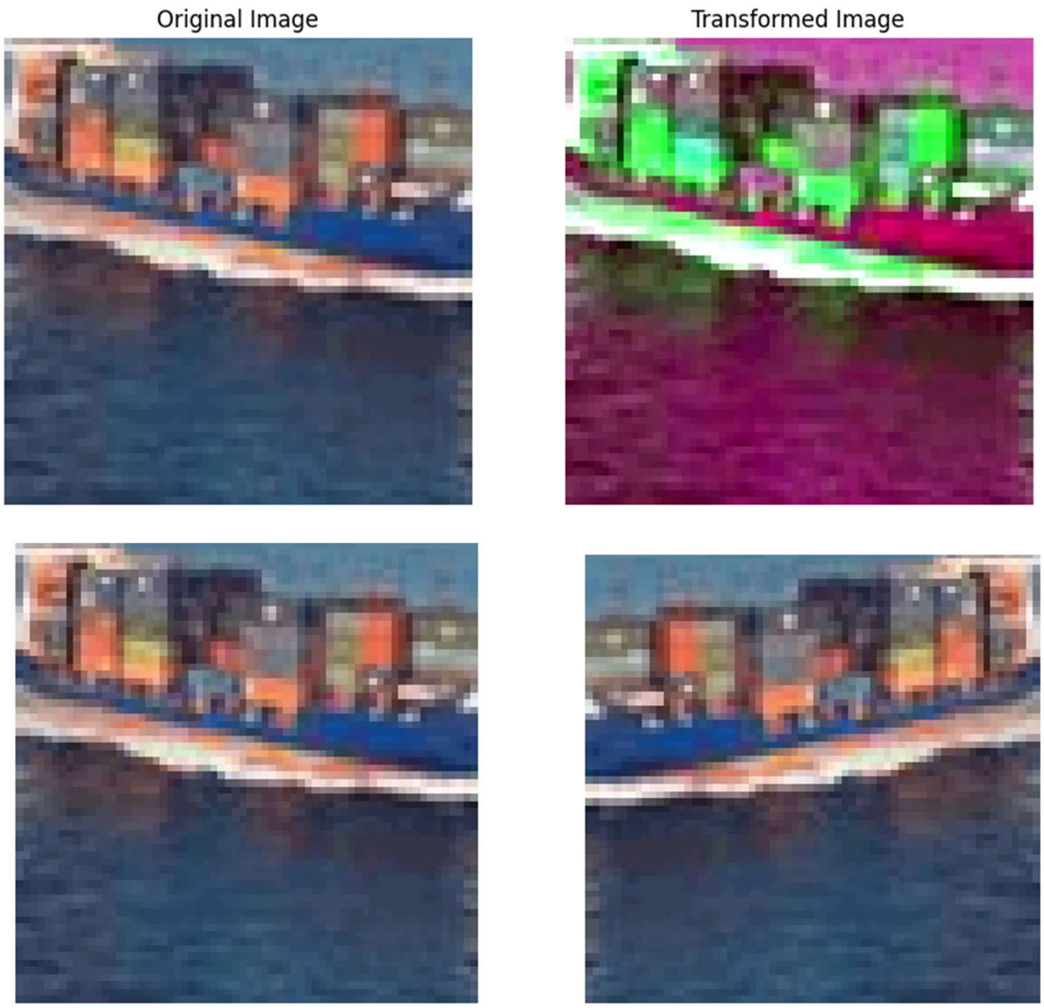


3. Data Preprocessing & Augmentation

The dataset was preprocessed using PyTorch's torchvision.transforms module. The following augmentations were applied to improve model generalization and robustness:

- **Random Horizontal Flip**: Flips images horizontally with a probability of 50% to introduce variability in orientation.
- **Random Crop**: Crops images randomly to 64x64 while retaining essential features.
- **Apply Color Jitter**: Apply Color Jitter with 30% probability.

Example of transformed images before and after:



4. Model Implementations

The following five models were implemented and tested:

4.1 Logistic Regression

- The images were flattened into a one-dimensional vector and fed into a simple linear classifier.
- The softmax activation function was used to predict class probabilities.
- This serves as a baseline model for comparison.

4.2 Fully-Connected Neural Network

- A multi-layer (MLP) with three hidden layers was implemented.
- Each hidden layer was followed by batch normalization and dropout to reduce overfitting.
- ReLU activation was applied to introduce non-linearity.

4.3 Convolutional Neural Network (CNN)

- Two convolutional layers were used, each followed by batch normalization to stabilize learning.
- Max-pooling layers reduced spatial dimensions and retained important features.
- Two fully connected layers processed the extracted features before classification.
- Dropout was applied to the fully connected layers for regularization.

4.4 Fixed Pre-trained MobileNetV2

- Two additional fully connected layers processed the extracted features.
- The classification layer produced final predictions.

4.5 Fine-tuned Pre-trained MobileNetV2

- The entire MobileNetV2 model was trained, including its convolutional layers.
- Fine-tuning allowed the model to learn task-specific features more effectively.
- The classification head consisted of two fully connected layers.

5. Hyperparameter Tuning

To optimize model performance, various hyperparameters were tested:

- **Learning Rates:** 0.01, 0. 001
- **Optimizers:** SGD , Adam
- **Batch Sizes:** 32, 64.
- **Number of Epochs:** 5, 10, 15, 20

6. Performance Analysis

For each model, training and validation loss and accuracy curves were plotted. Below are the test accuracy:

Model	Best Test Accuracy
Logistic Regression	17.04%
Fully - Connected NN	34.54%
CNN	41.76%
Fixed MobileNetV2	73.2%
Fine-tuned MobileNetV2	73.56%

6.1 Number of Learnable Parameters

The number of learnable parameters was calculated as follows:

Fully-Connected Neural Network (FCNN) (2)

- Input Layer → Hidden Layer 1: (12,288 + 1) × 512 = 6,297,088
- Hidden Layer 1 → Hidden Layer 2: (512 + 1) × 256 = 131,328
- Hidden Layer 2 → Hidden Layer 3: (256 + 1) × 128 = 32,896
- Hidden Layer 3 → Output Layer: (128 + 1) × 10 = 1,290
- Total Learnable Parameters: 6,462,602

Convolutional Neural Network (CNN) (3)

- Conv Layer 1: (3 × 3 × 3 × 32) + 32 = 896
- Conv Layer 2: (3 × 3 × 32 × 64) + 64 = 18,496
- Fully Connected Layer 1: (4096 × 256) + 256 = 1,048,832
- Fully Connected Layer 2: (256 × 128) + 128 = 32,896
- Output Layer: (128 × 10) + 10 = 1,290
- Total Learnable Parameters: 1,102,410

7. Conclusion

This report demonstrates how different architectures influence classification performance on the STL-10 dataset. The best-performing models were CNN and fine-tuned MobileNetV2, highlighting the effectiveness of convolutional feature extraction and transfer learning.

8. Attachments

Training and validation loss/accuracy curves for all models.

1. Logistic Regression:

```
Starting training model: LogisticRegression with Adam and CrossEntropyLoss, 10 epochs
Epoch [1/10], Train Loss: 3.0490, Train Accuracy: 14.64%, Validation Loss: 2.8889, Validation Accuracy: 16.93%
Epoch [2/10], Train Loss: 2.4624, Train Accuracy: 15.91%, Validation Loss: 2.4961, Validation Accuracy: 16.00%
Epoch [3/10], Train Loss: 2.4045, Train Accuracy: 17.41%, Validation Loss: 2.3813, Validation Accuracy: 20.13%
Epoch [4/10], Train Loss: 2.4717, Train Accuracy: 17.72%, Validation Loss: 2.5437, Validation Accuracy: 19.33%
Epoch [5/10], Train Loss: 2.4420, Train Accuracy: 18.78%, Validation Loss: 2.6742, Validation Accuracy: 15.73%
Epoch [6/10], Train Loss: 2.5062, Train Accuracy: 16.94%, Validation Loss: 2.3098, Validation Accuracy: 18.00%
Epoch [7/10], Train Loss: 2.4743, Train Accuracy: 17.60%, Validation Loss: 2.5363, Validation Accuracy: 18.13%
Epoch [8/10], Train Loss: 2.4631, Train Accuracy: 18.38%, Validation Loss: 2.3508, Validation Accuracy: 16.93%
Epoch [9/10], Train Loss: 2.4550, Train Accuracy: 17.58%, Validation Loss: 2.3296, Validation Accuracy: 21.07%
Epoch [10/10], Train Loss: 2.4803, Train Accuracy: 18.14%, Validation Loss: 2.7577, Validation Accuracy: 16.13%
Accuracy of the model on the test images: 17.88%
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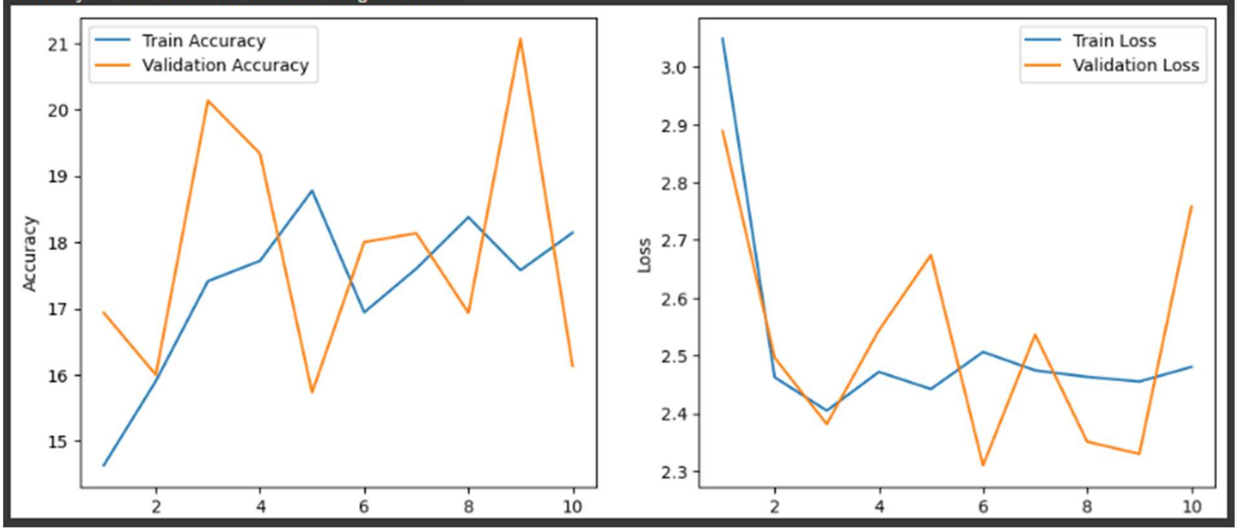
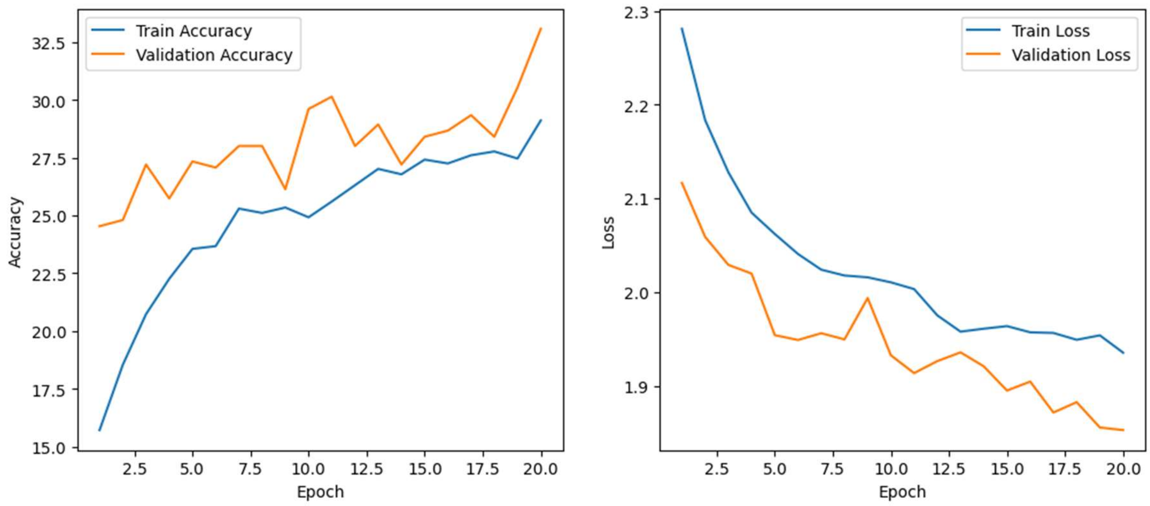


2. Fully Connected NN:




```
Starting training model: FullyConnectedNN with Adam and CrossEntropyLoss, 20 epochs
Epoch [1/20], Train Loss: 2.2809, Train Accuracy: 15.72%, Validation Loss: 2.1164, Validation Accuracy: 24.53%
Epoch [2/20], Train Loss: 2.1834, Train Accuracy: 18.54%, Validation Loss: 2.0588, Validation Accuracy: 24.80%
Epoch [3/20], Train Loss: 2.1278, Train Accuracy: 20.73%, Validation Loss: 2.0290, Validation Accuracy: 27.20%
Epoch [4/20], Train Loss: 2.0847, Train Accuracy: 22.26%, Validation Loss: 2.0197, Validation Accuracy: 25.73%
Epoch [5/20], Train Loss: 2.0619, Train Accuracy: 23.55%, Validation Loss: 1.9540, Validation Accuracy: 27.33%
Epoch [6/20], Train Loss: 2.0406, Train Accuracy: 23.67%, Validation Loss: 1.9488, Validation Accuracy: 27.07%
Epoch [7/20], Train Loss: 2.0239, Train Accuracy: 25.29%, Validation Loss: 1.9560, Validation Accuracy: 28.00%
Epoch [8/20], Train Loss: 2.0176, Train Accuracy: 25.11%, Validation Loss: 1.9494, Validation Accuracy: 28.00%
Epoch [9/20], Train Loss: 2.0157, Train Accuracy: 25.34%, Validation Loss: 1.9935, Validation Accuracy: 26.13%
Epoch [10/20], Train Loss: 2.0103, Train Accuracy: 24.92%, Validation Loss: 1.9324, Validation Accuracy: 29.60%
Epoch [11/20], Train Loss: 2.0031, Train Accuracy: 25.60%, Validation Loss: 1.9135, Validation Accuracy: 30.13%
Epoch [12/20], Train Loss: 1.9751, Train Accuracy: 26.31%, Validation Loss: 1.9263, Validation Accuracy: 28.00%
Epoch [13/20], Train Loss: 1.9577, Train Accuracy: 27.01%, Validation Loss: 1.9356, Validation Accuracy: 28.93%
Epoch [14/20], Train Loss: 1.9609, Train Accuracy: 26.78%, Validation Loss: 1.9207, Validation Accuracy: 27.20%
Epoch [15/20], Train Loss: 1.9636, Train Accuracy: 27.41%, Validation Loss: 1.8948, Validation Accuracy: 28.40%
Epoch [16/20], Train Loss: 1.9570, Train Accuracy: 27.25%, Validation Loss: 1.9044, Validation Accuracy: 28.67%
Epoch [17/20], Train Loss: 1.9563, Train Accuracy: 27.60%, Validation Loss: 1.8714, Validation Accuracy: 29.33%
Epoch [18/20], Train Loss: 1.9490, Train Accuracy: 27.76%, Validation Loss: 1.8824, Validation Accuracy: 28.40%
Epoch [19/20], Train Loss: 1.9538, Train Accuracy: 27.46%, Validation Loss: 1.8554, Validation Accuracy: 30.53%
Epoch [20/20], Train Loss: 1.9353, Train Accuracy: 29.11%, Validation Loss: 1.8527, Validation Accuracy: 33.07%
Accuracy of the model on the test images: 35.50%
```

3. CNN:

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Epoch [1/20], Train Loss: 2.5495, Train Accuracy: 13.34%, Validation Loss: 2.2322, Validation Accuracy: 14.53%
Epoch [2/20], Train Loss: 2.2318, Train Accuracy: 15.91%, Validation Loss: 2.1485, Validation Accuracy: 22.13%
Epoch [3/20], Train Loss: 2.1173, Train Accuracy: 20.19%, Validation Loss: 1.9637, Validation Accuracy: 25.33%
Epoch [4/20], Train Loss: 2.0168, Train Accuracy: 22.19%, Validation Loss: 1.9017, Validation Accuracy: 27.47%
Epoch [5/20], Train Loss: 1.9414, Train Accuracy: 23.51%, Validation Loss: 2.4579, Validation Accuracy: 14.93%
Epoch [6/20], Train Loss: 1.9151, Train Accuracy: 23.53%, Validation Loss: 1.8973, Validation Accuracy: 27.60%
Epoch [7/20], Train Loss: 1.8647, Train Accuracy: 25.20%, Validation Loss: 1.8278, Validation Accuracy: 27.73%
Epoch [8/20], Train Loss: 1.8406, Train Accuracy: 26.12%, Validation Loss: 1.8435, Validation Accuracy: 30.67%
Epoch [9/20], Train Loss: 1.8383, Train Accuracy: 27.72%, Validation Loss: 1.8971, Validation Accuracy: 28.80%
Epoch [10/20], Train Loss: 1.8015, Train Accuracy: 27.20%, Validation Loss: 1.9086, Validation Accuracy: 27.07%
Epoch [11/20], Train Loss: 1.8026, Train Accuracy: 28.21%, Validation Loss: 1.7247, Validation Accuracy: 31.87%
Epoch [12/20], Train Loss: 1.7949, Train Accuracy: 28.47%, Validation Loss: 2.0130, Validation Accuracy: 25.33%
Epoch [13/20], Train Loss: 1.7888, Train Accuracy: 28.45%, Validation Loss: 1.7072, Validation Accuracy: 33.33%
Epoch [14/20], Train Loss: 1.7790, Train Accuracy: 29.84%, Validation Loss: 1.7452, Validation Accuracy: 32.80%
Epoch [15/20], Train Loss: 1.7822, Train Accuracy: 30.09%, Validation Loss: 1.6888, Validation Accuracy: 37.87%
Epoch [16/20], Train Loss: 1.7325, Train Accuracy: 30.99%, Validation Loss: 1.6614, Validation Accuracy: 34.93%
Epoch [17/20], Train Loss: 1.7296, Train Accuracy: 33.22%, Validation Loss: 2.1372, Validation Accuracy: 26.00%
Epoch [18/20], Train Loss: 1.7384, Train Accuracy: 31.98%, Validation Loss: 1.6922, Validation Accuracy: 36.00%
Epoch [19/20], Train Loss: 1.7351, Train Accuracy: 32.96%, Validation Loss: 1.7003, Validation Accuracy: 36.67%
Epoch [20/20], Train Loss: 1.7183, Train Accuracy: 32.61%, Validation Loss: 2.0228, Validation Accuracy: 28.80%
Accuracy of the model on the test images: 33.34%
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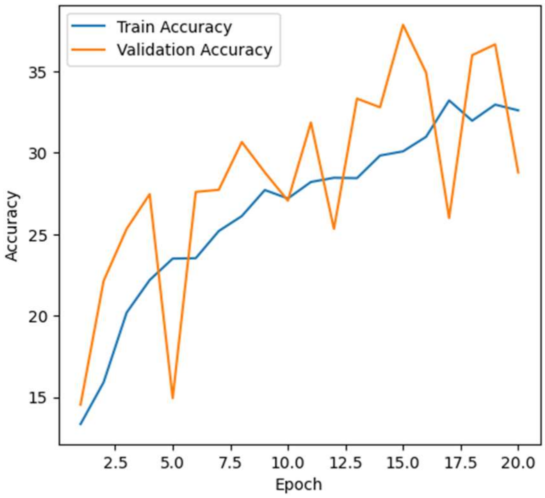

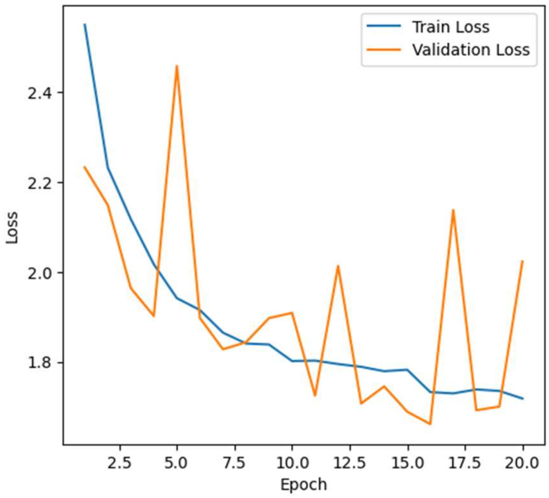

4. Pre-trained MobileNetV2

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Epoch [1/20], Train Loss: 0.8245, Train Accuracy: 70.66%, Validation Loss: 0.9285, Validation Accuracy: 67.07%
Epoch [2/20], Train Loss: 0.8238, Train Accuracy: 70.92%, Validation Loss: 0.9194, Validation Accuracy: 67.47%
Epoch [3/20], Train Loss: 0.8318, Train Accuracy: 69.93%, Validation Loss: 0.9509, Validation Accuracy: 67.47%
Epoch [4/20], Train Loss: 0.8284, Train Accuracy: 70.42%, Validation Loss: 0.9145, Validation Accuracy: 66.67%
Epoch [5/20], Train Loss: 0.8216, Train Accuracy: 70.26%, Validation Loss: 0.9084, Validation Accuracy: 67.47%
Epoch [6/20], Train Loss: 0.8216, Train Accuracy: 70.42%, Validation Loss: 0.9532, Validation Accuracy: 67.73%
Epoch [7/20], Train Loss: 0.8118, Train Accuracy: 70.87%, Validation Loss: 0.8925, Validation Accuracy: 69.33%
Epoch [8/20], Train Loss: 0.7982, Train Accuracy: 72.19%, Validation Loss: 0.9540, Validation Accuracy: 67.47%
Epoch [9/20], Train Loss: 0.8278, Train Accuracy: 70.47%, Validation Loss: 0.9243, Validation Accuracy: 66.40%
Epoch [10/20], Train Loss: 0.7999, Train Accuracy: 71.01%, Validation Loss: 0.9339, Validation Accuracy: 67.73%
Epoch [11/20], Train Loss: 0.7949, Train Accuracy: 71.48%, Validation Loss: 0.9300, Validation Accuracy: 68.40%
Epoch [12/20], Train Loss: 0.7822, Train Accuracy: 72.12%, Validation Loss: 0.9625, Validation Accuracy: 66.27%
Epoch [13/20], Train Loss: 0.7787, Train Accuracy: 73.39%, Validation Loss: 0.8786, Validation Accuracy: 68.80%
Epoch [14/20], Train Loss: 0.7688, Train Accuracy: 71.95%, Validation Loss: 0.9227, Validation Accuracy: 69.47%
Epoch [15/20], Train Loss: 0.7652, Train Accuracy: 72.73%, Validation Loss: 0.9356, Validation Accuracy: 67.47%
Epoch [16/20], Train Loss: 0.7798, Train Accuracy: 72.59%, Validation Loss: 0.8455, Validation Accuracy: 70.67%
Epoch [17/20], Train Loss: 0.7688, Train Accuracy: 72.78%, Validation Loss: 0.8854, Validation Accuracy: 67.73%
Epoch [18/20], Train Loss: 0.7507, Train Accuracy: 73.39%, Validation Loss: 0.9187, Validation Accuracy: 69.47%
Epoch [19/20], Train Loss: 0.7856, Train Accuracy: 71.67%, Validation Loss: 0.9763, Validation Accuracy: 66.53%
Epoch [20/20], Train Loss: 0.7738, Train Accuracy: 71.76%, Validation Loss: 0.9203, Validation Accuracy: 68.27%
Accuracy of the model on test images: 72.44%
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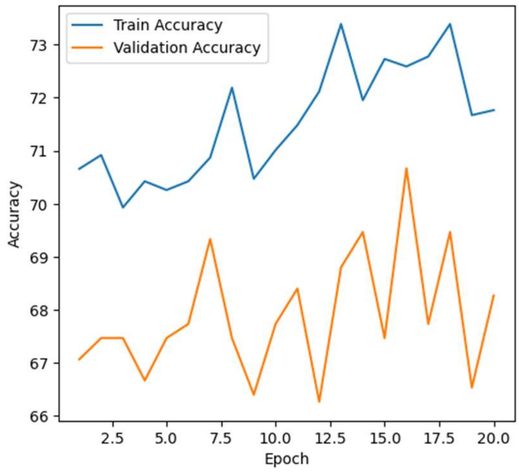

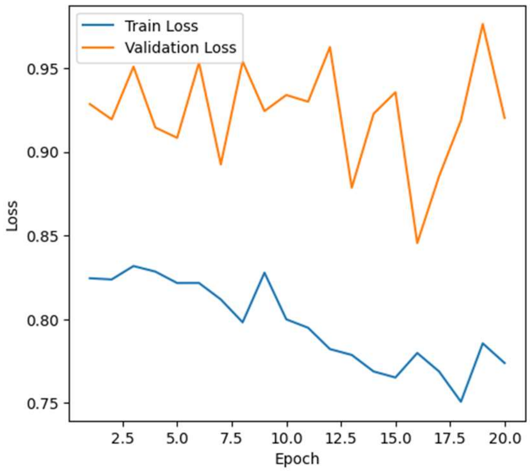

5. Fine-tuned Pre-trained MobileNetV2

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Epoch [1/20], Train Loss: 0.8494, Train Accuracy: 69.76%, Validation Loss: 0.9291, Validation Accuracy: 67.73%
Epoch [2/20], Train Loss: 0.8375, Train Accuracy: 69.53%, Validation Loss: 0.9377, Validation Accuracy: 66.67%
Epoch [3/20], Train Loss: 0.8119, Train Accuracy: 71.44%, Validation Loss: 0.9298, Validation Accuracy: 66.80%
Epoch [4/20], Train Loss: 0.8417, Train Accuracy: 69.60%, Validation Loss: 0.9768, Validation Accuracy: 65.47%
Epoch [5/20], Train Loss: 0.8243, Train Accuracy: 70.31%, Validation Loss: 0.9741, Validation Accuracy: 66.53%
Epoch [6/20], Train Loss: 0.7945, Train Accuracy: 71.53%, Validation Loss: 0.9048, Validation Accuracy: 66.53%
Epoch [7/20], Train Loss: 0.7853, Train Accuracy: 70.96%, Validation Loss: 0.9668, Validation Accuracy: 64.53%
Epoch [8/20], Train Loss: 0.8063, Train Accuracy: 71.06%, Validation Loss: 0.9263, Validation Accuracy: 70.53%
Epoch [9/20], Train Loss: 0.7917, Train Accuracy: 71.84%, Validation Loss: 0.9747, Validation Accuracy: 65.20%
Epoch [10/20], Train Loss: 0.7913, Train Accuracy: 71.88%, Validation Loss: 0.9211, Validation Accuracy: 66.00%
Epoch [11/20], Train Loss: 0.8260, Train Accuracy: 70.85%, Validation Loss: 0.9374, Validation Accuracy: 68.27%
Epoch [12/20], Train Loss: 0.7728, Train Accuracy: 71.76%, Validation Loss: 0.9185, Validation Accuracy: 67.87%
Epoch [13/20], Train Loss: 0.7868, Train Accuracy: 72.05%, Validation Loss: 0.9091, Validation Accuracy: 67.87%
Epoch [14/20], Train Loss: 0.7864, Train Accuracy: 72.26%, Validation Loss: 0.9978, Validation Accuracy: 65.60%
Epoch [15/20], Train Loss: 0.7477, Train Accuracy: 74.07%, Validation Loss: 0.9535, Validation Accuracy: 66.93%
Epoch [16/20], Train Loss: 0.7877, Train Accuracy: 71.53%, Validation Loss: 0.9532, Validation Accuracy: 67.33%
Epoch [17/20], Train Loss: 0.7634, Train Accuracy: 73.39%, Validation Loss: 0.9001, Validation Accuracy: 69.20%
Epoch [18/20], Train Loss: 0.7561, Train Accuracy: 73.08%, Validation Loss: 0.8905, Validation Accuracy: 68.40%
Epoch [19/20], Train Loss: 0.7481, Train Accuracy: 73.69%, Validation Loss: 0.9211, Validation Accuracy: 67.87%
Epoch [20/20], Train Loss: 0.7560, Train Accuracy: 72.68%, Validation Loss: 0.9200, Validation Accuracy: 68.40%
Accuracy of the model on test images: 73.25%
```