In [1]:

```
import torch
from torch import nn
import torch.optim as optim
from torch.utils.data import Dataset, DataLoader
from torchvision import datasets
from torchvision.transforms import ToTensor
import time
from sklearn.model_selection import KFold
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd
import torch.nn.functional as F
import gc
from ptflops import get_model_complexity_info
```

Problem 1

In [2]:

```
train_path = r"C:\Users\ccm51\OneDrive\Desktop\ECGR 4106\fashion-mnist_trai
test_path = r"C:\Users\ccm51\OneDrive\Desktop\ECGR 4106\fashion-mnist_test.
train_numpy = np.loadtxt(train_path, dtype = np.float32, delimiter = ",", s
test_numpy = np.loadtxt(test_path, dtype = np.float32, delimiter = ",", ski
print(train_numpy.shape)
```

```
(60000, 785)
```

In [3]:

```
data_path = '../data-unversioned/ecgr4106/'
fashion_MNIST = datasets.FashionMNIST(data_path, train=True, download=True,
fashion_MNIST_val = datasets.FashionMNIST(data_path, train=False, download=
```

In [123]:

```
len(fashion_MNIST_val)
```

Out[123]:

```
10000
```

In [4]:

```
def try_gpu(i=0):
    if torch.cuda.device_count() >= i+1:
        return torch.device(f'cuda:{i}')
    return torch.device('cpu')
```

In [5]:

```
def training_loop(n_epochs, optimizer, model, loss_fn, train_loader, val_lo
    train_loss_hist = []
    train_acc_hist = []
    val_acc_hist = []
    main_tic = time.perf_counter()

    for epoch in range(1, n_epochs + 1):
        tic = time.perf_counter()
        loss_train = 0.0
        correct_train = 0
        correct_val = 0

        for imgs, labels in train_loader:
            # if torch.cuda.is_available():
            imgs = imgs.to(device=try_gpu())
            labels = labels.to(device=try_gpu())
            outputs = model(imgs)
            loss = loss_fn(outputs, labels)
            optimizer.zero_grad()
            loss.backward()
            optimizer.step()
            loss_train += loss.item()

        toc = time.perf_counter()

        with torch.no_grad():
            total = 0
            for imgs, labels in train_loader:
                outputs = model(imgs.to(device=try_gpu()))
                _, predicted = torch.max(outputs, dim=1)
                total += labels.shape[0]
                correct_train += int((predicted == labels.to(device=try_gpu
            train_acc = round(correct_train/total, 3)
            total = 0
            for imgs, labels in val_loader:
                outputs = model(imgs.to(device=try_gpu()))
                _, predicted = torch.max(outputs, dim=1)
                total += labels.shape[0]
                correct_val += int((predicted == labels.to(device=try_gpu()
            val_acc = round(correct_val/total, 3)

        train_loss_hist.append(round(loss_train / len(train_loader), 5))
        train_acc_hist.append(train_acc)
        val_acc_hist.append(val_acc)

        if epoch == 1 or epoch == n_epochs or epoch % update_freq == 0:
            print(f"Epoch {epoch}:\n\tDuration = {round(toc - tic, 3)} seco

    main_toc = time.perf_counter()
    print(f"\nTotal Training Time = {round(main_toc - main_tic, 3)} seconds
    return train_loss_hist, train_acc_hist, val_acc_hist
```

In [6]:

```
def plot_model(title, fig_num, loss_hist, train_hist, test_hist, leg_loc):
    plot = plt.figure(fig_num)
    x = range(1, len(loss_hist)+1)
    plt.plot(x, loss_hist)
    plt.plot(x, train_hist)
    plt.plot(x, test_hist)
    plt.legend(["Training Loss", "Training Accuracy", "Testing Accuracy"],
    plt.xlabel('Epoch')
    plt.ylabel('Error/Accuracy')
    plt.title(title)
```

In [14]:

```
class alt1_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(6, kernel_size=5, padding=2)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv2 = nn.LazyConv2d(16, kernel_size=5)
        self.maxp2 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.fc1 = nn.LazyLinear(120)
        self.fc2 = nn.LazyLinear(84)
        self.fc3 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.maxp2(self.relu(self.conv2(out)))
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.relu(self.fc2(out))
        out = self.fc3(out)
        return out

model_1 = alt1_LeNet().to(device=try_gpu())
optimizer_1 = optim.SGD(model_1.parameters(), lr=1e-1)
model_1.eval()
```

Out[14]:

```
alt1_LeNet(
  (conv1): LazyConv2d(0, 6, kernel_size=(5, 5), stride=(1, 1), padding=
(2, 2))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv2): LazyConv2d(0, 16, kernel_size=(5, 5), stride=(1, 1))
  (maxp2): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (fc1): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc3): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

In [15]:

```
train_loader_1 = DataLoader(fashion_MNIST, batch_size=128, shuffle=True)
val_loader_1 = DataLoader(fashion_MNIST_val, batch_size=len(fashion_MNIST_v
```

In [16]:

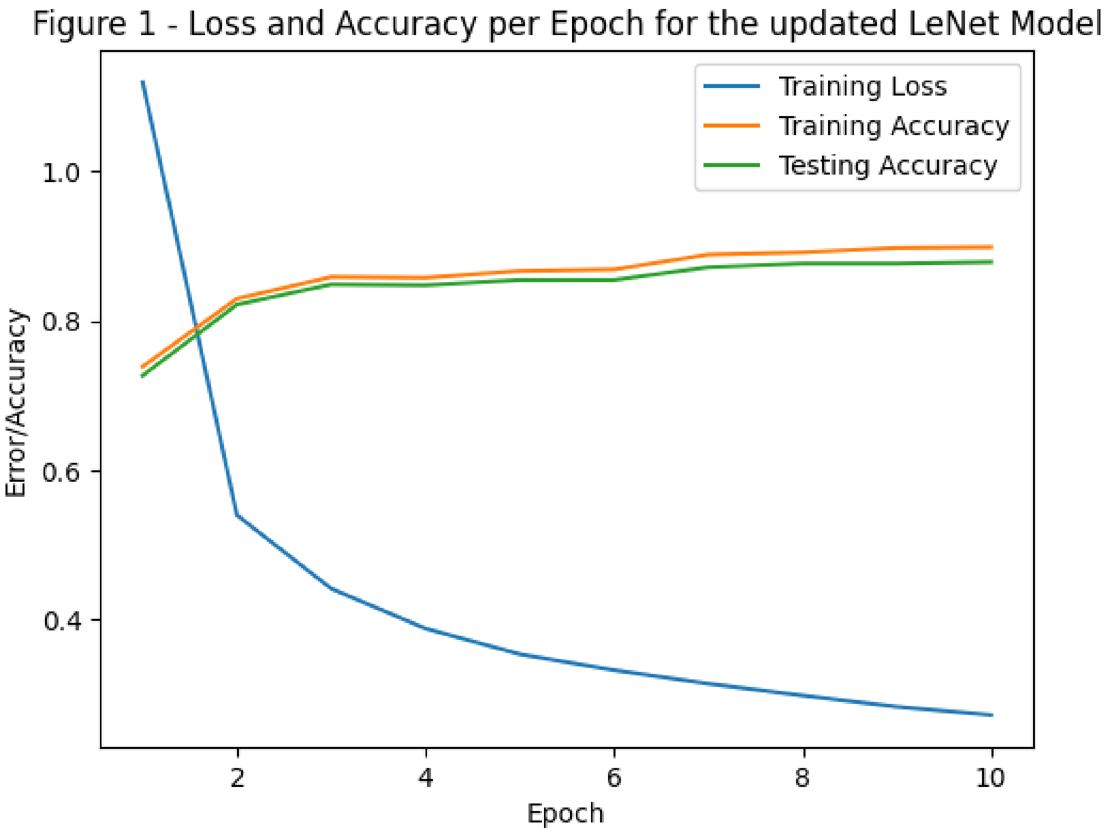
```
t_loss_hist_1, t_acc_hist_1, v_acc_hist_1 = training_loop(10,
                                                        optimizer_1,
                                                        model_1,
                                                        nn.CrossEntropyLoss
                                                        train_loader_1,
                                                        val_loader_1,
                                                        1)
```

```
Epoch 1:
        Duration = 19.818 seconds
        Training Loss: 1.16621
        Training Accuracy: 0.754
        Validation Accuracy: 0.746
Epoch 2:
        Duration = 20.963 seconds
        Training Loss: 0.52571
        Training Accuracy: 0.819
        Validation Accuracy: 0.809
Epoch 3:
        Duration = 19.146 seconds
        Training Loss: 0.42693
        Training Accuracy: 0.86
        Validation Accuracy: 0.851
Epoch 4:
        Duration = 18.765 seconds
        Training Loss: 0.38071
        Training Accuracy: 0.873
        Validation Accuracy: 0.859
Epoch 5:
        Duration = 18.794 seconds
        Training Loss: 0.35066
        Training Accuracy: 0.858
        Validation Accuracy: 0.845
Epoch 6:
        Duration = 18.724 seconds
        Training Loss: 0.32908
        Training Accuracy: 0.89
        Validation Accuracy: 0.875
Epoch 7:
        Duration = 18.646 seconds
        Training Loss: 0.31203
        Training Accuracy: 0.887
        Validation Accuracy: 0.87
Epoch 8:
        Duration = 18.85 seconds
        Training Loss: 0.29782
        Training Accuracy: 0.888
        Validation Accuracy: 0.875
Epoch 9:
        Duration = 18.87 seconds
        Training Loss: 0.28718
        Training Accuracy: 0.9
        Validation Accuracy: 0.884
Epoch 10:
        Duration = 18.473 seconds
        Training Loss: 0.27909
        Training Accuracy: 0.874
        Validation Accuracy: 0.858

Total Training Time = 381.495 seconds
Average Training Time per Epoch = 38.149 seconds
```

In [162]:

```
title_1 = "Figure 1 - Loss and Accuracy per Epoch for the updated LeNet Moc
plot_model(title_1, 1, t_loss_hist_1, t_acc_hist_1, v_acc_hist_1, 'upper ri
```



Problem 2

In [164]:

```
class alt2a_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(6, kernel_size=3, padding=1)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv2 = nn.LazyConv2d(16, kernel_size=3)
        self.maxp2 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.fc1 = nn.LazyLinear(120)
        self.fc2 = nn.LazyLinear(84)
        self.fc3 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.maxp2(self.relu(self.conv2(out)))
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.relu(self.fc2(out))
        out = self.fc3(out)
        return out

model_2a = alt2a_LeNet().to(device=try_gpu())
optimizer_2a = optim.SGD(model_2a.parameters(), lr=1e-1)
model_2a.eval()
```

Out[164]:

```
alt2a_LeNet(
  (conv1): LazyConv2d(0, 6, kernel_size=(3, 3), stride=(1, 1), padding=
(1, 1))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv2): LazyConv2d(0, 16, kernel_size=(3, 3), stride=(1, 1))
  (maxp2): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (fc1): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc3): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

In [166]:

```
t_loss_hist_2a, t_acc_hist_2a, v_acc_hist_2a = training_loop(10,
                                                              optimizer_2a,
                                                              model_2a,
                                                              nn.CrossEntropyLoss
                                                              train_loader_1,
                                                              val_loader_1,
                                                              5)
```

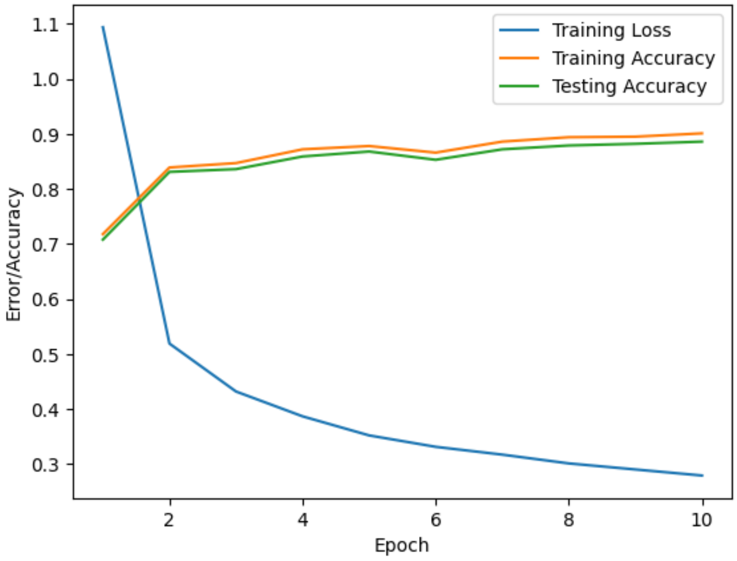
```
Epoch 1:
        Duration = 8.57 seconds
        Training Loss: 1.0938
        Training Accuracy: 0.718
        Validation Accuracy: 0.708
Epoch 5:
        Duration = 9.154 seconds
        Training Loss: 0.35228
        Training Accuracy: 0.878
        Validation Accuracy: 0.868
Epoch 10:
        Duration = 8.199 seconds
        Training Loss: 0.27944
        Training Accuracy: 0.901
        Validation Accuracy: 0.886

Total Training Time = 157.307 seconds
Average Training Time per Epoch = 15.731 seconds
```

In [167]:

```
title_2a = "Figure 2a - Loss and Accuracy per Epoch for the altered LeNet M
plot_model(title_2a, 2, t_loss_hist_2a, t_acc_hist_2a, v_acc_hist_2a, 'uppe
```

Figure 2a - Loss and Accuracy per Epoch for the altered LeNet Model (shrinking convolution window)



In [168]:

```
class alt2b_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(6, kernel_size=7, padding=3)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv2 = nn.LazyConv2d(16, kernel_size=7)
        self.maxp2 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.fc1 = nn.LazyLinear(120)
        self.fc2 = nn.LazyLinear(84)
        self.fc3 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.maxp2(self.relu(self.conv2(out)))
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.relu(self.fc2(out))
        out = self.fc3(out)
        return out

model_2b = alt2b_LeNet().to(device=try_gpu())
optimizer_2b = optim.SGD(model_2b.parameters(), lr=1e-1)
model_2b.eval()
```

Out[168]:

```
alt2b_LeNet(
  (conv1): LazyConv2d(0, 6, kernel_size=(7, 7), stride=(1, 1), padding=
(3, 3))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv2): LazyConv2d(0, 16, kernel_size=(7, 7), stride=(1, 1))
  (maxp2): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (fc1): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc3): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

In [169]:

```
t_loss_hist_2b, t_acc_hist_2b, v_acc_hist_2b = training_loop(10,
                                                        optimizer_2b,
                                                        model_2b,
                                                        nn.CrossEntropyLoss
                                                        train_loader_1,
                                                        val_loader_1,
                                                        5)
```

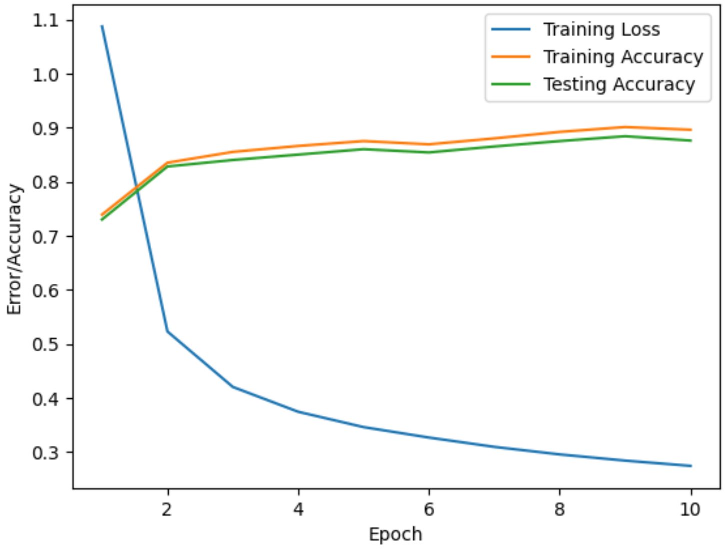
```
Epoch 1:
        Duration = 9.395 seconds
        Training Loss: 1.08711
        Training Accuracy: 0.739
        Validation Accuracy: 0.73
Epoch 5:
        Duration = 9.349 seconds
        Training Loss: 0.34582
        Training Accuracy: 0.875
        Validation Accuracy: 0.86
Epoch 10:
        Duration = 10.162 seconds
        Training Loss: 0.27412
        Training Accuracy: 0.896
        Validation Accuracy: 0.876

Total Training Time = 186.064 seconds
Average Training Time per Epoch = 18.606 seconds
```

In [170]:

```
title_2b = "Figure 2b - Loss and Accuracy per Epoch for the altered LeNet M
plot_model(title_2b, 3, t_loss_hist_2b, t_acc_hist_2b, v_acc_hist_2b, 'uppe
```

Figure 2b - Loss and Accuracy per Epoch for the altered LeNet Model (Expanding Convolution Window)



In [181]:

```
class alt3_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(12, kernel_size=5, padding=2)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv2 = nn.LazyConv2d(32, kernel_size=5)
        self.maxp2 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.fc1 = nn.LazyLinear(120)
        self.fc2 = nn.LazyLinear(84)
        self.fc3 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.maxp2(self.relu(self.conv2(out)))
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.relu(self.fc2(out))
        out = self.fc3(out)
        return out

model_3 = alt3_LeNet().to(device=try_gpu())
optimizer_3 = optim.SGD(model_3.parameters(), lr=1e-1)
model_3.eval()
```

Out[181]:

```
alt3_LeNet(
  (conv1): LazyConv2d(0, 12, kernel_size=(5, 5), stride=(1, 1), padding=
(2, 2))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv2): LazyConv2d(0, 32, kernel_size=(5, 5), stride=(1, 1))
  (maxp2): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (fc1): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc3): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

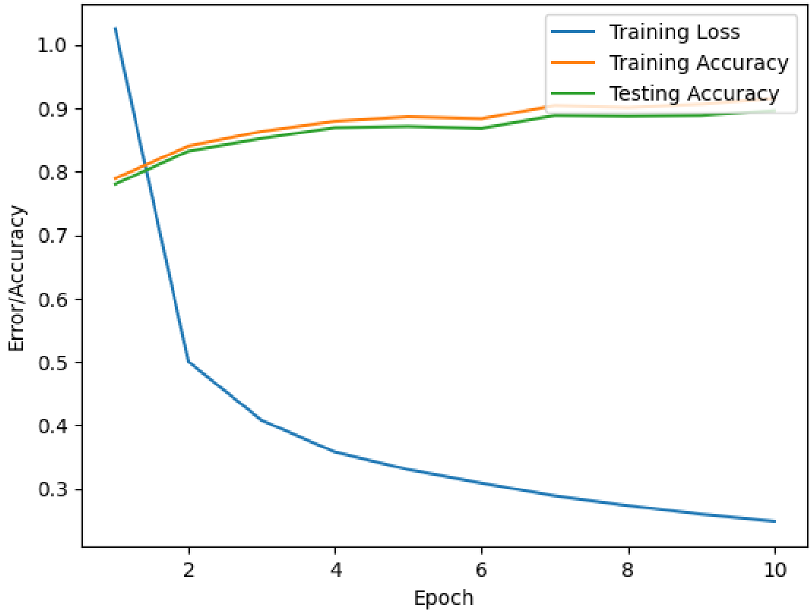
In [182]:
```
t_loss_hist_3, t_acc_hist_3, v_acc_hist_3 = training_loop(10,
                                                           optimizer_3,
                                                           model_3,
                                                           nn.CrossEntropyLoss
                                                           train_loader_1,
                                                           val_loader_1,
                                                           5)
```

```
Epoch 1:
        Duration = 11.009 seconds
        Training Loss: 1.02504
        Training Accuracy: 0.789
        Validation Accuracy: 0.78
Epoch 5:
        Duration = 10.568 seconds
        Training Loss: 0.32999
        Training Accuracy: 0.886
        Validation Accuracy: 0.871
Epoch 10:
        Duration = 11.317 seconds
        Training Loss: 0.24853
        Training Accuracy: 0.915
        Validation Accuracy: 0.896

Total Training Time = 190.937 seconds
Average Training Time per Epoch = 19.094 seconds
```

In [183]:
```
title_3 = "Figure 3 - Loss and Accuracy per Epoch for the altered LeNet Mo
plot_model(title_3, 4, t_loss_hist_3, t_acc_hist_3, v_acc_hist_3, 'upper ri
```

Figure 3 - Loss and Accuracy per Epoch for the altered LeNet Model (Doubling Layer Width)



In [196]:

```
class alt4_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(6, kernel_size=5, padding=2)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv2 = nn.LazyConv2d(16, kernel_size=5)
        self.maxp2 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv3 = nn.LazyConv2d(8, kernel_size=5, padding=2)
        self.maxp3 = nn.MaxPool2d(kernel_size=2, stride=1)
        self.fc1 = nn.LazyLinear(120)
        self.fc2 = nn.LazyLinear(84)
        self.fc3 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.maxp2(self.relu(self.conv2(out)))
        out = self.maxp3(self.relu(self.conv3(out)))
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.relu(self.fc2(out))
        out = self.fc3(out)
        return out

model_4 = alt4_LeNet().to(device=try_gpu())
optimizer_4 = optim.SGD(model_4.parameters(), lr=1e-1)
model_4.eval()
```

Out[196]:

```
alt4_LeNet(
  (conv1): LazyConv2d(0, 6, kernel_size=(5, 5), stride=(1, 1), padding=
(2, 2))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv2): LazyConv2d(0, 16, kernel_size=(5, 5), stride=(1, 1))
  (maxp2): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv3): LazyConv2d(0, 8, kernel_size=(5, 5), stride=(1, 1), padding=
(2, 2))
  (maxp3): MaxPool2d(kernel_size=2, stride=1, padding=0, dilation=1, ceil
_mode=False)
  (fc1): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc3): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

In [197]:

```
t_loss_hist_4, t_acc_hist_4, v_acc_hist_4 = training_loop(10,
                                                         optimizer_4,
                                                         model_4,
                                                         nn.CrossEntropyLoss
                                                         train_loader_1,
                                                         val_loader_1,
                                                         5)
```

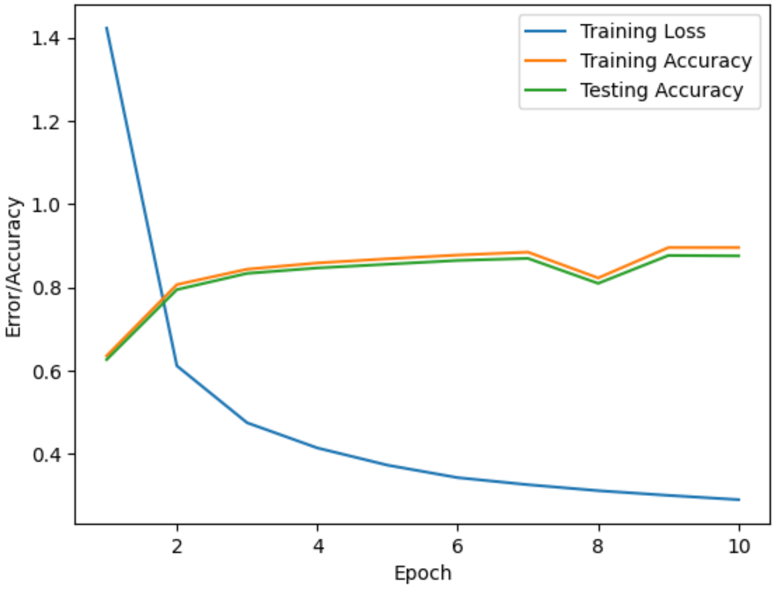
```
Epoch 1:
        Duration = 9.411 seconds
        Training Loss: 1.42292
        Training Accuracy: 0.636
        Validation Accuracy: 0.627
Epoch 5:
        Duration = 9.522 seconds
        Training Loss: 0.37345
        Training Accuracy: 0.869
        Validation Accuracy: 0.856
Epoch 10:
        Duration = 9.648 seconds
        Training Loss: 0.29061
        Training Accuracy: 0.896
        Validation Accuracy: 0.876

Total Training Time = 172.741 seconds
Average Training Time per Epoch = 17.274 seconds
```

In [198]:

```
title_4 = "Figure 4 - Loss and Accuracy per Epoch for the altered LeNet Mod
plot_model(title_4, 5, t_loss_hist_4, t_acc_hist_4, v_acc_hist_4, 'upper ri
```

Figure 4 - Loss and Accuracy per Epoch for the altered LeNet Model (Adding Convolution Layer)



In [199]:

```
class alt5_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(6, kernel_size=5, padding=2)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv2 = nn.LazyConv2d(16, kernel_size=5)
        self.maxp2 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.fc1 = nn.LazyLinear(256)
        self.fc2 = nn.LazyLinear(120)
        self.fc3 = nn.LazyLinear(84)
        self.fc4 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.maxp2(self.relu(self.conv2(out)))
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.relu(self.fc2(out))
        out = self.relu(self.fc3(out))
        out = self.fc4(out)
        return out

model_5 = alt5_LeNet().to(device=try_gpu())
optimizer_5 = optim.SGD(model_5.parameters(), lr=1e-1)
model_5.eval()
```

Out[199]:

```
alt5_LeNet(
  (conv1): LazyConv2d(0, 6, kernel_size=(5, 5), stride=(1, 1), padding=
(2, 2))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv2): LazyConv2d(0, 16, kernel_size=(5, 5), stride=(1, 1))
  (maxp2): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (fc1): LazyLinear(in_features=0, out_features=256, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc3): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc4): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

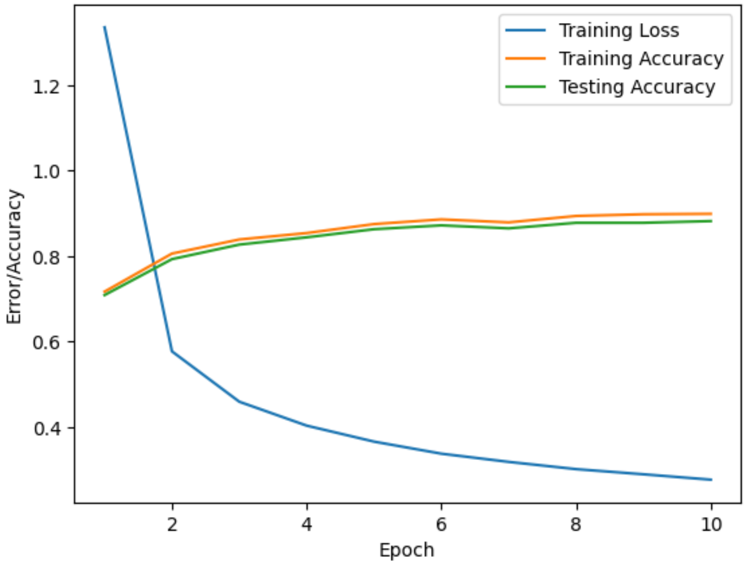
In [200]:
```
t_loss_hist_5, t_acc_hist_5, v_acc_hist_5 = training_loop(10,
                                                        optimizer_5,
                                                        model_5,
                                                        nn.CrossEntropyLoss
                                                        train_loader_1,
                                                        val_loader_1,
                                                        5)
```

```
Epoch 1:
        Duration = 9.023 seconds
        Training Loss: 1.3352
        Training Accuracy: 0.717
        Validation Accuracy: 0.709
Epoch 5:
        Duration = 9.593 seconds
        Training Loss: 0.36617
        Training Accuracy: 0.875
        Validation Accuracy: 0.863
Epoch 10:
        Duration = 11.919 seconds
        Training Loss: 0.27715
        Training Accuracy: 0.899
        Validation Accuracy: 0.882

Total Training Time = 195.642 seconds
Average Training Time per Epoch = 19.564 seconds
```

In [201]:
```
title_5 = "Figure 5 - Loss and Accuracy per Epoch for the altered LeNet Mod
plot_model(title_5, 6, t_loss_hist_5, t_acc_hist_5, v_acc_hist_5, 'upper ri
```

Figure 5 - Loss and Accuracy per Epoch for the altered LeNet Model (Adding Fully Connected Layer)



In [204]:

```
class alt6a_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(6, kernel_size=5, padding=2)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv2 = nn.LazyConv2d(16, kernel_size=5)
        self.maxp2 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.fc1 = nn.LazyLinear(120)
        self.fc2 = nn.LazyLinear(84)
        self.fc3 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.maxp2(self.relu(self.conv2(out)))
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.relu(self.fc2(out))
        out = self.fc3(out)
        return out

model_6a = alt6a_LeNet().to(device=try_gpu())
optimizer_6a = optim.SGD(model_6a.parameters(), lr=2e-1)
model_6a.eval()
```

Out[204]:

```
alt6a_LeNet(
  (conv1): LazyConv2d(0, 6, kernel_size=(5, 5), stride=(1, 1), padding=
(2, 2))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv2): LazyConv2d(0, 16, kernel_size=(5, 5), stride=(1, 1))
  (maxp2): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (fc1): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc3): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

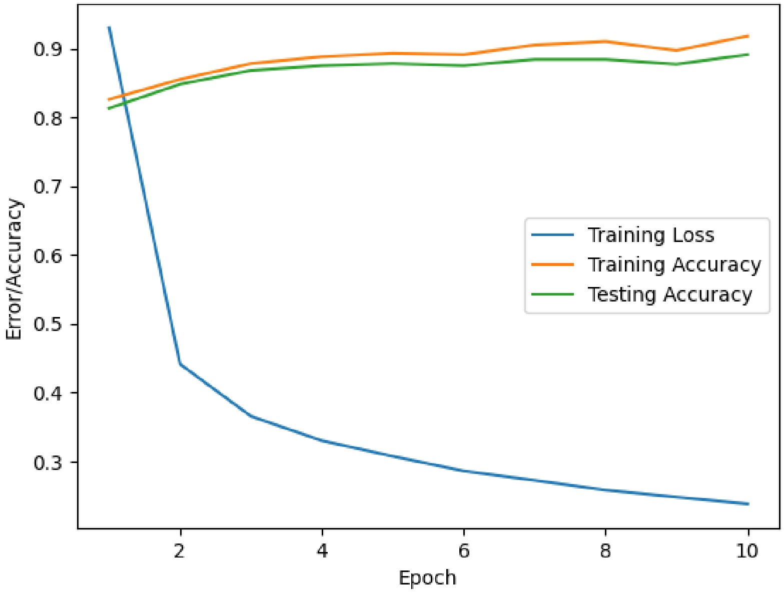
```
In [205]:  t_loss_hist_6a, t_acc_hist_6a, v_acc_hist_6a = training_loop(10,
                                                                  optimizer_6a,
                                                                  model_6a,
                                                                  nn.CrossEntropyLoss
                                                                  train_loader_1,
                                                                  val_loader_1,
                                                                  5)
```

```
Epoch 1:
        Duration = 8.659 seconds
        Training Loss: 0.93004
        Training Accuracy: 0.826
        Validation Accuracy: 0.813
Epoch 5:
        Duration = 11.621 seconds
        Training Loss: 0.30714
        Training Accuracy: 0.893
        Validation Accuracy: 0.878
Epoch 10:
        Duration = 10.245 seconds
        Training Loss: 0.23812
        Training Accuracy: 0.918
        Validation Accuracy: 0.891

Total Training Time = 190.071 seconds
Average Training Time per Epoch = 19.007 seconds
```

```
In [289]:  title_6a = "Figure 6a - Loss and Accuracy per Epoch for the altered LeNet M
           plot_model(title_6a, 7, t_loss_hist_6a, t_acc_hist_6a, v_acc_hist_6a, 'righ
```

Figure 6a - Loss and Accuracy per Epoch for the altered LeNet Model (Doubling Learning Rate)



In [207]:

```
class alt6b_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(6, kernel_size=5, padding=2)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv2 = nn.LazyConv2d(16, kernel_size=5)
        self.maxp2 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.fc1 = nn.LazyLinear(120)
        self.fc2 = nn.LazyLinear(84)
        self.fc3 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.maxp2(self.relu(self.conv2(out)))
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.relu(self.fc2(out))
        out = self.fc3(out)
        return out

model_6b = alt6b_LeNet().to(device=try_gpu())
optimizer_6b = optim.SGD(model_6b.parameters(), lr=5e-2)
model_6b.eval()
```

Out[207]:

```
alt6b_LeNet(
  (conv1): LazyConv2d(0, 6, kernel_size=(5, 5), stride=(1, 1), padding=
(2, 2))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv2): LazyConv2d(0, 16, kernel_size=(5, 5), stride=(1, 1))
  (maxp2): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (fc1): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc3): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

In [208]:

```
t_loss_hist_6b, t_acc_hist_6b, v_acc_hist_6b = training_loop(10,
                                                        optimizer_6b,
                                                        model_6b,
                                                        nn.CrossEntropyLoss
                                                        train_loader_1,
                                                        val_loader_1,
                                                        5)
```

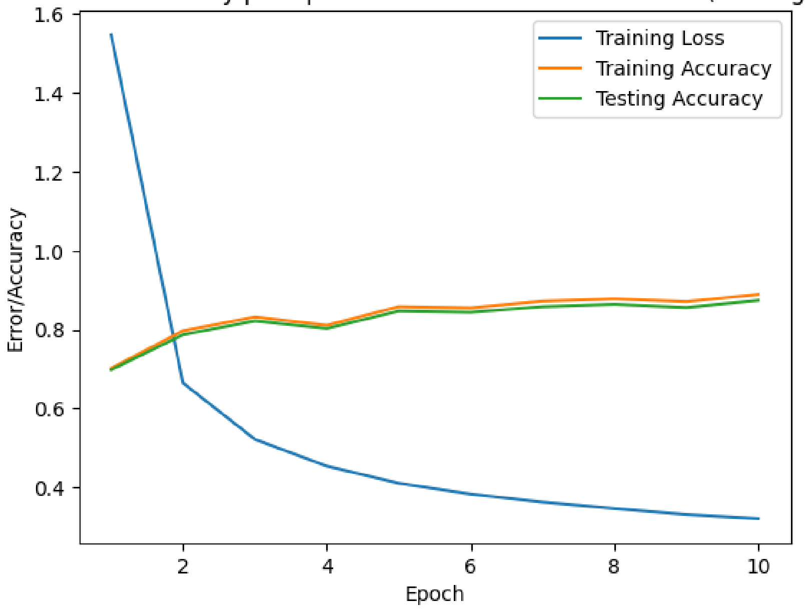
```
Epoch 1:
        Duration = 10.28 seconds
        Training Loss: 1.54733
        Training Accuracy: 0.702
        Validation Accuracy: 0.698
Epoch 5:
        Duration = 8.634 seconds
        Training Loss: 0.41036
        Training Accuracy: 0.858
        Validation Accuracy: 0.847
Epoch 10:
        Duration = 11.12 seconds
        Training Loss: 0.32063
        Training Accuracy: 0.889
        Validation Accuracy: 0.874

Total Training Time = 193.704 seconds
Average Training Time per Epoch = 19.37 seconds
```

In [209]:

```
title_6b = "Figure 6b - Loss and Accuracy per Epoch for the altered LeNet M
plot_model(title_6b, 8, t_loss_hist_6b, t_acc_hist_6b, v_acc_hist_6b, 'uppe
```

Figure 6b - Loss and Accuracy per Epoch for the altered LeNet Model (Halving Learning Rate)



In [236]:

```
class alt7_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(10, kernel_size=3, padding=1)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv2 = nn.LazyConv2d(25, kernel_size=3)
        self.maxp2 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.fc1 = nn.LazyLinear(200)
        self.fc2 = nn.LazyLinear(120)
        self.fc3 = nn.LazyLinear(84)
        self.fc4 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.maxp2(self.relu(self.conv2(out)))
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.relu(self.fc2(out))
        out = self.relu(self.fc3(out))
        out = self.fc4(out)
        return out

model_7 = alt7_LeNet().to(device=try_gpu())
optimizer_7 = optim.SGD(model_7.parameters(), lr=2e-1, weight_decay=1e-4)
model_7.eval()
```

Out[236]:

```
alt7_LeNet(
  (conv1): LazyConv2d(0, 10, kernel_size=(3, 3), stride=(1, 1), padding=
(1, 1))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv2): LazyConv2d(0, 25, kernel_size=(3, 3), stride=(1, 1))
  (maxp2): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (fc1): LazyLinear(in_features=0, out_features=200, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc3): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc4): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

In [237]:

```
train_loader_2 = DataLoader(fashion_MNIST, batch_size=32, shuffle=True)
val_loader_2 = DataLoader(fashion_MNIST_val, batch_size=int(len(fashion_MNI
# Had to reload the loaders with smaller batch sizes because of running Low
```

In [239]:

```
t_loss_hist_7, t_acc_hist_7, v_acc_hist_7 = training_loop(10,
                                                        optimizer_7,
                                                        model_7,
                                                        nn.CrossEntropyLoss
                                                        train_loader_2,
                                                        val_loader_2,
                                                        5)
```

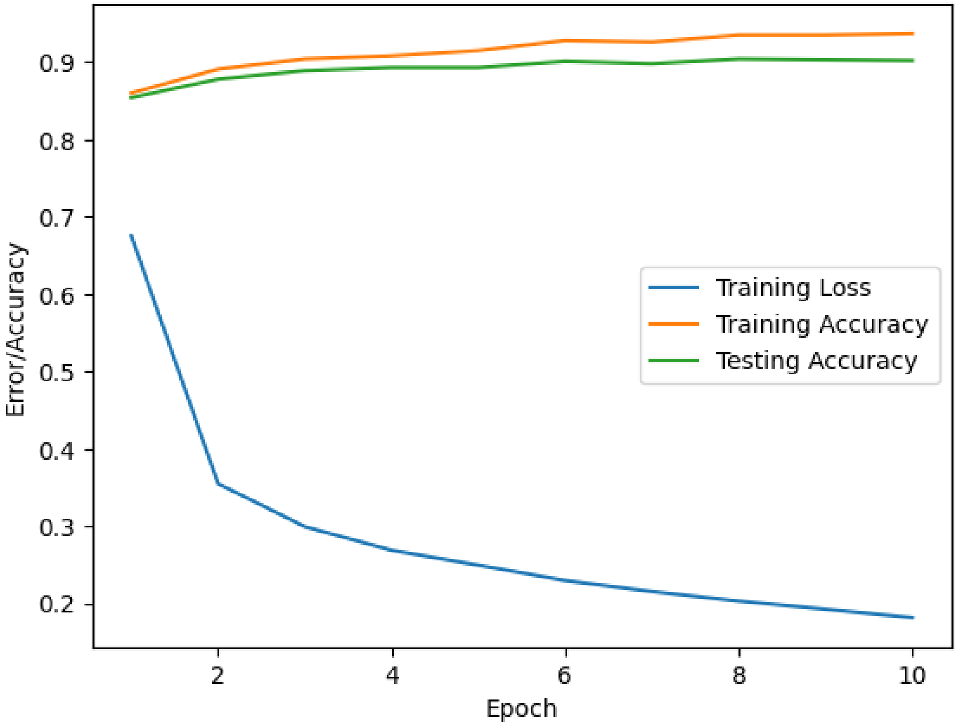
```
Epoch 1:
        Duration = 13.155 seconds
        Training Loss: 0.67564
        Training Accuracy: 0.86
        Validation Accuracy: 0.854
Epoch 5:
        Duration = 13.621 seconds
        Training Loss: 0.24963
        Training Accuracy: 0.915
        Validation Accuracy: 0.893
Epoch 10:
        Duration = 13.613 seconds
        Training Loss: 0.18169
        Training Accuracy: 0.937
        Validation Accuracy: 0.902

Total Training Time = 224.505 seconds
Average Training Time per Epoch = 22.45 seconds
```

In [240]:

```
title_7 = "Figure 7 - Loss and Accuracy per Epoch for the altered LeNet Moc
plot_model(title_7, 9, t_loss_hist_7, t_acc_hist_7, v_acc_hist_7, 'right')
```

Figure 7 - Loss and Accuracy per Epoch for the altered LeNet Model (Variety)



Problem 3

In [243]:

```
class drop_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(10, kernel_size=3, padding=1)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv1_drop = nn.Dropout2d(p=0.4)
        self.conv2 = nn.LazyConv2d(25, kernel_size=3)
        self.maxp2 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv2_drop = nn.Dropout2d(p=0.4)
        self.fc1 = nn.LazyLinear(200)
        self.fc1_drop = nn.Dropout(p=0.3)
        self.fc2 = nn.LazyLinear(120)
        self.fc2_drop = nn.Dropout(p=0.2)
        self.fc3 = nn.LazyLinear(84)
        self.fc4 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.conv1_drop(out)
        out = self.maxp2(self.relu(self.conv2(out)))
        out = self.conv2_drop(out)
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.fc1_drop(out)
        out = self.relu(self.fc2(out))
        out = self.fc2_drop(out)
        out = self.relu(self.fc3(out))
        out = self.fc4(out)
        return out

model_8 = drop_LeNet().to(device=try_gpu())
optimizer_8 = optim.SGD(model_8.parameters(), lr=2e-1, weight_decay=1e-4)
model_8.eval()
```

Out[243]:

```
drop_LeNet(
  (conv1): LazyConv2d(0, 10, kernel_size=(3, 3), stride=(1, 1), padding=
(1, 1))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv1_drop): Dropout2d(p=0.4, inplace=False)
  (conv2): LazyConv2d(0, 25, kernel_size=(3, 3), stride=(1, 1))
  (maxp2): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv2_drop): Dropout2d(p=0.4, inplace=False)
  (fc1): LazyLinear(in_features=0, out_features=200, bias=True)
  (fc1_drop): Dropout(p=0.3, inplace=False)
  (fc2): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc2_drop): Dropout(p=0.2, inplace=False)
  (fc3): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc4): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

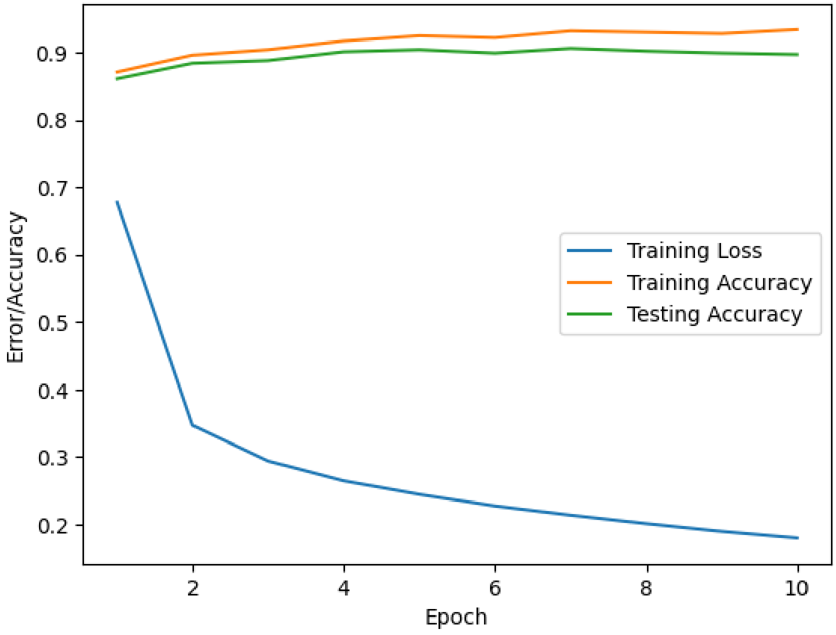
```
In [244]: t_loss_hist_8, t_acc_hist_8, v_acc_hist_8 = training_loop(10,
                                                             optimizer_8,
                                                             model_8,
                                                             nn.CrossEntropyLoss
                                                             train_loader_2,
                                                             val_loader_2,
                                                             5)
```

```
Epoch 1:
        Duration = 13.207 seconds
        Training Loss: 0.67757
        Training Accuracy: 0.871
        Validation Accuracy: 0.861
Epoch 5:
        Duration = 13.294 seconds
        Training Loss: 0.2448
        Training Accuracy: 0.925
        Validation Accuracy: 0.904
Epoch 10:
        Duration = 14.133 seconds
        Training Loss: 0.18009
        Training Accuracy: 0.934
        Validation Accuracy: 0.897

Total Training Time = 228.715 seconds
Average Training Time per Epoch = 22.871 seconds
```

```
In [246]: title_8 = "Figure 8 - Loss and Accuracy per Epoch for the altered LeNet Mod
          plot_model(title_8, 10, t_loss_hist_8, t_acc_hist_8, v_acc_hist_8, 'right')
```

Figure 8 - Loss and Accuracy per Epoch for the altered LeNet Model (Variety w/ Dropout)



Problem 4

In [279]:

```
class drop_LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(8, kernel_size=3, stride=2)
        self.maxp1 = nn.MaxPool2d(kernel_size=2, stride=2)
        self.conv1_drop = nn.Dropout2d(p=0.3)
        self.fc1 = nn.LazyLinear(40)
        self.fc2 = nn.LazyLinear(10)
        self.relu = nn.ReLU()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.maxp1(self.relu(self.conv1(x)))
        out = self.conv1_drop(out)
        out = self.flat(out)
        out = self.relu(self.fc1(out))
        out = self.fc2(out)
        return out

model_9 = drop_LeNet().to(device=try_gpu())
optimizer_9 = optim.SGD(model_9.parameters(), lr=2e-1)
model_9.eval()
```

Out[279]:

```
drop_LeNet(
  (conv1): LazyConv2d(0, 8, kernel_size=(3, 3), stride=(2, 2))
  (maxp1): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil
_mode=False)
  (conv1_drop): Dropout2d(p=0.3, inplace=False)
  (fc1): LazyLinear(in_features=0, out_features=40, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=10, bias=True)
  (relu): ReLU()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

In [280]:

```
t_loss_hist_9, t_acc_hist_9, v_acc_hist_9 = training_loop(10,
                                                           optimizer_9,
                                                           model_9,
                                                           nn.CrossEntropyLos
                                                           train_loader_1,
                                                           val_loader_1,
                                                           5)
```

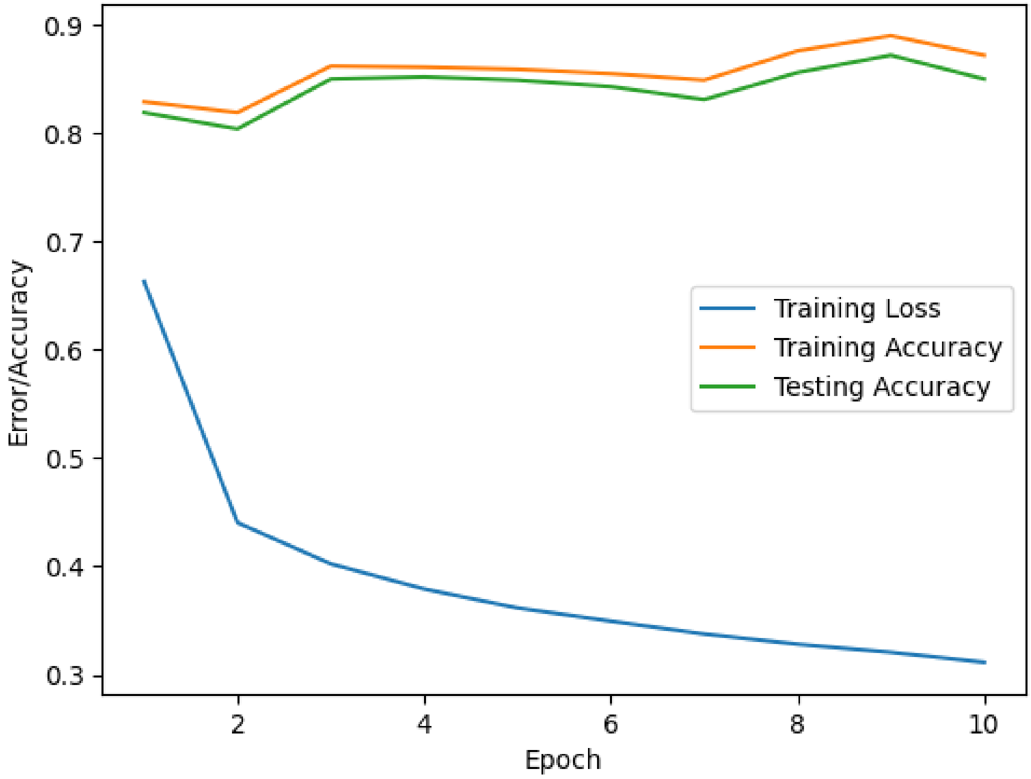
```
Epoch 1:
        Duration = 7.261 seconds
        Training Loss: 0.66293
        Training Accuracy: 0.829
        Validation Accuracy: 0.819
Epoch 5:
        Duration = 7.352 seconds
        Training Loss: 0.36155
        Training Accuracy: 0.859
        Validation Accuracy: 0.849
Epoch 10:
        Duration = 7.29 seconds
        Training Loss: 0.31137
        Training Accuracy: 0.872
        Validation Accuracy: 0.85

Total Training Time = 143.395 seconds
Average Training Time per Epoch = 14.34 seconds
```

In [281]:

```
title_9 = "Figure 9 - Loss and Accuracy per Epoch for the simplified LeNet
plot_model(title_9, 11, t_loss_hist_9, t_acc_hist_9, v_acc_hist_9, 'right'
```

Figure 9 - Loss and Accuracy per Epoch for the simplified LeNet Model



In [288]:

```
with torch.cuda.device(0):
    macs_LN, params_LN = get_model_complexity_info(model_1, (1, 28, 28), as
                                                   print_per_layer_stat=False, \
    macs_alt, params_alt = get_model_complexity_info(model_7, (1, 28, 28),
                                                      print_per_layer_stat=Fals
    macs_simp, params_simp = get_model_complexity_info(model_9, (1, 28, 28)
                                                        print_per_layer_stat=Fals
    print('{:<30}  {:<8}'.format('Computational complexity for LeNet: ', ma
    print('{:<30}  {:<8}'.format('Number of parameters for LeNet: ', params
    print('\n{:<30}  {:<8}'.format('Computational complexity for Altered Le
    print('{:<30}  {:<8}'.format('Number of parameters for Altered LeNet Mo
    print('\n{:<30}  {:<8}'.format('Computational complexity for Simple Mod
    print('{:<30}  {:<8}'.format('Number of parameters for Simple Model: ',
```

```
Computational complexity for LeNet:   435.85 KMac
Number of parameters for LeNet:   61.71 k

Computational complexity for Altered LeNet Model:   644.62 KMac
Number of parameters for Altered LeNet Model:   217.71 k

Computational complexity for Simple Model:   28.23 KMac
Number of parameters for Simple Model:   12.05 k
```

In [20]:

```
class LeNet(nn.Module):
    def __init__(self):
        super().__init__()
        self.conv1 = nn.LazyConv2d(6, kernel_size=5, padding=2)
        self.avgp1 = nn.AvgPool2d(kernel_size=2, stride=2)
        self.conv2 = nn.LazyConv2d(16, kernel_size=5)
        self.avgp2 = nn.AvgPool2d(kernel_size=2, stride=2)
        self.fc1 = nn.LazyLinear(120)
        self.fc2 = nn.LazyLinear(84)
        self.fc3 = nn.LazyLinear(10)
        self.sgmd = nn.Sigmoid()
        self.flat = nn.Flatten()

    def forward(self, x):
        out = self.avgp1(self.sgmd(self.conv1(x)))
        out = self.avgp2(self.sgmd(self.conv2(out)))
        out = self.flat(out)
        out = self.sgmd(self.fc1(out))
        out = self.sgmd(self.fc2(out))
        out = self.fc3(out)
        return out

model_lenet = LeNet().to(device=try_gpu())
optimizer_lenet = optim.SGD(model_lenet.parameters(), lr=1e-1)
model_lenet.eval()
```

Out[20]:

```
LeNet(
  (conv1): LazyConv2d(0, 6, kernel_size=(5, 5), stride=(1, 1), padding=
(2, 2))
  (avgp1): AvgPool2d(kernel_size=2, stride=2, padding=0)
  (conv2): LazyConv2d(0, 16, kernel_size=(5, 5), stride=(1, 1))
  (avgp2): AvgPool2d(kernel_size=2, stride=2, padding=0)
  (fc1): LazyLinear(in_features=0, out_features=120, bias=True)
  (fc2): LazyLinear(in_features=0, out_features=84, bias=True)
  (fc3): LazyLinear(in_features=0, out_features=10, bias=True)
  (sgmd): Sigmoid()
  (flat): Flatten(start_dim=1, end_dim=-1)
)
```

In [21]:

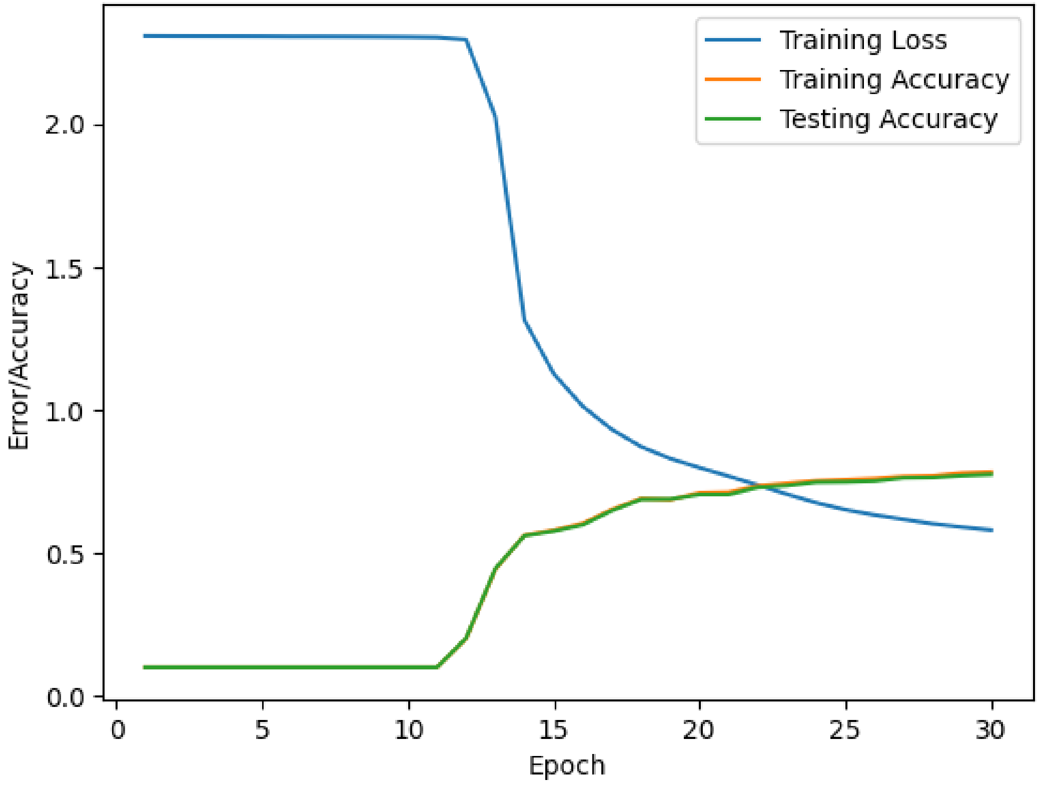
```
t_loss_hist_lenet, t_acc_hist_lenet, v_acc_hist_lenet = training_loop(30,
                                                        optimizer_lenet,
                                                        model_lenet,
                                                        nn.CrossEntropyLoss
                                                        train_loader_1,
                                                        val_loader_1,
                                                        5)
```

```
Epoch 1:
        Duration = 19.269 seconds
        Training Loss: 2.30714
        Training Accuracy: 0.1
        Validation Accuracy: 0.1
Epoch 5:
        Duration = 18.21 seconds
        Training Loss: 2.3059
        Training Accuracy: 0.1
        Validation Accuracy: 0.1
Epoch 10:
        Duration = 18.659 seconds
        Training Loss: 2.30354
        Training Accuracy: 0.1
        Validation Accuracy: 0.1
Epoch 15:
        Duration = 19.801 seconds
        Training Loss: 1.1266
        Training Accuracy: 0.579
        Validation Accuracy: 0.576
Epoch 20:
        Duration = 17.896 seconds
        Training Loss: 0.79771
        Training Accuracy: 0.71
        Validation Accuracy: 0.704
Epoch 25:
        Duration = 19.274 seconds
        Training Loss: 0.65109
        Training Accuracy: 0.756
        Validation Accuracy: 0.748
Epoch 30:
        Duration = 18.923 seconds
        Training Loss: 0.57976
        Training Accuracy: 0.783
        Validation Accuracy: 0.774

Total Training Time = 1143.003 seconds
Average Training Time per Epoch = 38.1 seconds
```

```
In [23]:  title_10 = "Figure 10 - Loss and Accuracy per Epoch for the original LeNet
          plot_model(title_10, 12, t_loss_hist_lenet, t_acc_hist_lenet, v_acc_hist_le
```

Figure 10 - Loss and Accuracy per Epoch for the original LeNet Model


Training Loss
Training Accuracy
Testing Accuracy
Error/Accuracy
Epoch